CERN–2015–002
CERN–ATS–2015–002
22 May 2015

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Chamonix 2014 Workshop on LHC Performance

Chamonix, France, 22–25 September 2014

Proceedings

Editor: M. Draper

GENEVA
2015

ISBN 978–92–9083–413–7
ISSN 0007–8328
DOI http://dx.doi.org/10.5170/CERN–2015–002
Available online at https://cds.cern.ch/

This report is indexed in: CERN Document Server (CDS), INSPIRE.

This report should be cited as:

Proceedings of Chamonix 2014 Workshop on LHC Performance, Chamonix, France, 22–25 September 2014, edited by M. Draper, CERN–2015–002 (CERN, Geneva, 2015), http://dx.doi.org/10.5170/CERN–2015–002

A contribution in this report should be cited as:

[Author name(s)], in Proceedings of Chamonix 2014 Workshop on LHC Performance, Chamonix, France, 22–25 September 2014, edited by M. Draper, CERN–2015–002 (CERN, Geneva, 2015), pp. [first page] – [lastpage], http://dx.doi.org/10.5170/CERN–2015–002.[first page]

During the Chamonix 2014 workshop on LHC performance, operation of the machine in 2012, activities during the first long shutdown LS1 aiming at peparing for operation at 7 TeV per beam and substantial long term upgrades of both the injector chain and the LHC have been discussed. After a session dedicated to observations and lessons from the run 2011, strategies for the run 2012 have been discussed in order to optimize the machine performance and, in particular, the maximum and integrated luminosity provided to the main experiments. Two session were dedicated to the preparation of the first long shutdown LS1 followed by a session aiming at optimizing the perfromance to be expected after this first shutdown. The last two session of the workshop were dedicated to substantial upgrades of the injector complex and the LHC aiming at increasing the integrated luminosity to 250 inverse femtobarn per year after implementation in a second long shutdown. Improvements of the injector complex comprise increased injection energies in the PS Booster and the PS, an upgrade of the SPS vacuum chamber to alleviate limitations due to electron cloud build up and many more upgrades required for the generation of beams with higher brightness and smaller meittances than possible with the present machines. Plans for the LHC comprise an upgrade of the interaction regions to allow for a smaller beta*, crab cavities for luminosity levelling and, upgrades of the collimation and other systems.

Table of Contents:

Sessions Summaries

Session 1: LS1, HW Commissioning, Powering Tests - Coming out of LS1

Session 2: Injector Status and Beams for LHC, Dry Runs, Sector Tests with Beam

Session 3: 2015 Commissioning with Beam

Session 4: LHC - Challenges and Strategy for Run 2

Session 5: LIU

Session 6: HL-LHC

Session 7: Accelerators and non-LHC Experiment Areas Consolidation up to LS3

Session 8: Long Shutdown 2 Strategy and Preparation

Author Index

CHAMONIX 2014 CONCLUSIONS: MAIN POINTS AND ACTIONS

F. Bordry (Chair), F. Zimmermann (Scientific secretary)
CERN, Geneva, Switzerland

Abstract

The summary session of the LHC Performance Workshop in Chamonix, 22-25 September 2014 [1], held at CERN on 8 October 2014 [2] synthesized one week of presentations and intense discussions on the near-, medium- and long-term strategy for the LHC, including the upgrades of the LHC and its injectors.

In particular, Chamonix 2014 discussed the lessons from, and the end of the Long Shutdown 1 (LS1) up to powering tests and cold checkout, the injector status, the beam commissioning in 2015, the challenges and strategy for LHC Run 2, the LHC Injector Upgrade (LIU), the High-Luminosity LHC (HL-LHC), the consolidation of accelerator and non-LHC experiment areas through Long Shutdown 3 (LS3), as well as the strategy and preparation for the Long Shutdown 2 (LS2).

We report the main points and actions which have emerged at the Chamonix 2014 workshop.

PREPARATION PROCESS

The 1st preparation meeting for Chamonix 2014 was held on 21 March 2014. This meeting identified the key topics to be addressed:

- How to restart the machine?
- Strategy for first year and for all of Run 2
- Consolidation strategy
- LS2 preparation
- HL-LHC & LIU

In total 6 general preparation meetings had been organized between March 2014 and the end of the summer.

It had been decided that the spirit of the workshop would be not to encourage status reports, but rather to address open questions and options.

The selection of the participants through the Department Heads and Session Chairs proved difficult. Finally, there were about 130-140 attendees per session.

WORKSHOP STRUCTURE

The following session structure had been worked out during the preparation phase:

Session 1: "LS1, HW Commissioning, Powering Tests and Cold Check-out - Coming out of LS1." Chair: Mirko Pojer, Scientific secretary: Laurette Ponce

Session 2: "Injector Status and Beams for LHC, Dry Runs, Sector Tests with Beam."
Chair: Rende Steerenberg; Scientific Secretary: Reyes Alemany

Session 3: "2015 Commissioning with Beam."
Chair: Mike Lamont, Scientific secretary: Giulia Papotti

Session 4: "LHC: Challenges and Strategy for Run2." Chair: Markus Zerlauth, Scientific secretary: Belen Maria Salvachua Ferrando

Session 5: "LIU (LHC Injector Upgrade)."
Chair: Malika Meddahi, Giovanni Rumolo

Session 6: "HL-LHC (High-Luminosity LHC)."
Chair: Oliver Brüning; Scientific secretary: Paolo Ferracin

Session 7: "Accelerators and non LHC Experiment Areas Consolidation up to LS3."
Chairs: Michael Benedikt, Florian Sonnemann

Session 8: "Long Shutdown 2 Strategy and Preparation."
Chair: José Miguel Jiménez; Scientific secretary: Jean-Philippe Tock

The session organization and specific topics addressed at Chamonix 2014 reflect the timing of this workshop with respect to the short-term schedule of the LHC and its injector complex, which is illustrated in Fig. 1. Chamonix 2014 took place 3 months before the end of the Long Shutdown 1, which had extended from 16 February 2013 to December 2014. The PS and PS Booster were already operating for physics, and beam commissioning had just started in the SPS.

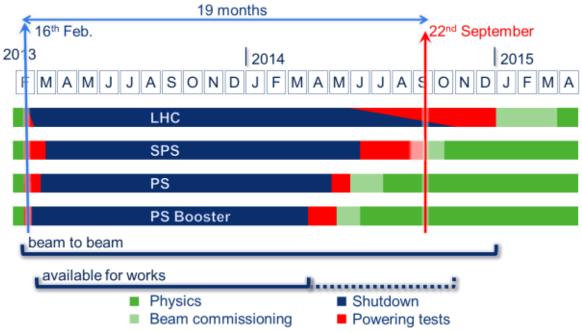


Figure 1: Timing of Chamonix 2014 with respect to the LHC Long Shutdown 1 and the schedule of the LHC injectors [3].

PS PHYSICS

The PS physics programme was already ongoing.

A run of nTOF originally planned for 15 July 2014 had been slightly delayed due to EAR2 installation work. The first beam had been on target by 25 July 2014. Since then, physics had been scheduled during night and weekends while installation continued during day time.

The East Area operation had also been planned to begin on 15 July. Here, indeed the first beam had been available as scheduled, and physics had started on the following day (16 July).

Concerning the AD beam, in March 2014, the beam on target had been delayed by 3 weeks due to a horn strip line problem, which had resulted in 1 August 2014 as the revised new optimistic date for beam on target. In the end, the first AD beam had been delivered on 5 August and the AD physics had begun on 16 September.

The starting date of ion beam preparation for the 2015 run had been 25 August 2014. Argon ions had been successfully injected, accelerated and extracted from PS the following day.

As one **important conclusion**, for the PS a **better definition is needed for the different periods allocated to shutdown, hardware commissioning, cold checkout, and beam commissioning., respectively, together with a clear definition of roles and responsibilities** for each period and for the interfaces. The IEFC will follow up this issue.

SPS STARTUP

The SPS start-up with beam had been more or less on schedule. The beam had been foreseen for Monday 8 September. Despite longer than expected conditioning of injection and dump kickers after LS1, hardware testing of main circuits and debugging of converter software issues after updates during LS1, and a water leak on water cooled main bus bar in SPS point 3 (detected on 8 September), the first beam had been injected into the SPS on Saturday 13 September. The North Area was going to start physics on 6 October, and HiRadMat would commence its first run on 13 October. Beam would be sent to the LHC only in 2015.

LHC STATUS

Figure 2 illustrates that all LHC sectors were being cooled down. The LHC schedule version 4.1 is shown in Figure 3. This schedule was developed respecting the rule “safety first, quality second, schedule third”. The first beam in the LHC was expected for week 11 (starting 9 March 2015).

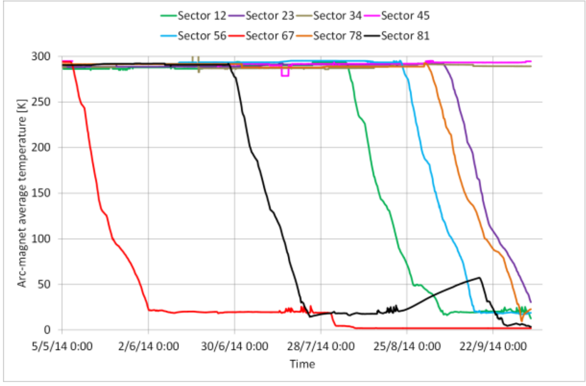


Figure 2: Temperature in LHC sectors from May to September 2014 [Courtesy L. Tavian].

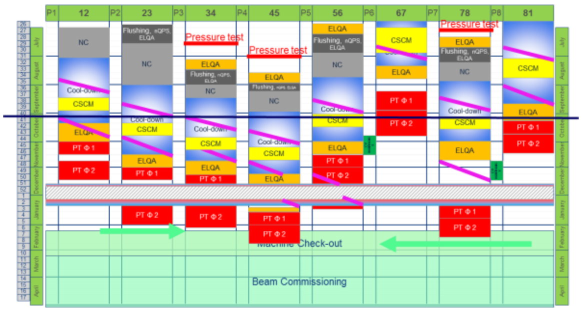


Figure 3: LHC schedule version 4.1 (Courtesy K. Foraz) [4].

MAXIMUM BEAM ENERGY IN 2015

The centre-of-mass energy for 2015 has been fixed at 6.5 TeV. Namely the decision had been taken to run at a maximum energy of 6.5 TeV per beam during the powering tests and during 2015. A total of 10 to 15 training quenches per sector were expected to be needed to reach this energy.

There had also existed a risk that results from late quench tests could force running at lower energy. This risk had been accepted by the experiments [5].

In summary, there will be NO change of the target beam energy for 2015. A decision regarding the possibility of increasing the energy will be taken later in 2015, based on the experience gained in all eight sectors at 6.5 TeV per beam during the powering tests and in operation with beams.

LHC STRATEGY FOR 2015

The strategy for 2015 pursues the following objectives:

1. Restart with beam parameters similar to those in 2012 and a relaxed β* (80 cm) (ALICE 10 m, LHCb 3 m), and establish as soon as possible collisions at 13 TeV with 50 ns bunch spacing, without a combined collide & squeeze, without a combined ramp & squeeze, etc.
2. Fulfil the LHCf request and perform VdM scans with the same optics.
3. Perform a first scrubbing run (50 ns + 25 ns; 7-9 days) and to accumulate up to 1 fb^{-1} with 50 ns bunch spacing (taking around 20 days).
4. Establish the running with 25 ns, and allocate sufficient time for the scrubbing (10-15 days and without any pressure for physics production).
5. Run at 25 ns bunch spacing at a β* of 80 cm during 2 months (45 days), and then decrease the β* to 60 cm or 40 cm, so as to have around 45 days of operation in the latter conditions in preparation for 2016 and 2017.
6. Allocate one month for heavy-ion collisions.

The schedule of Fig. 4 meets all these objectives.

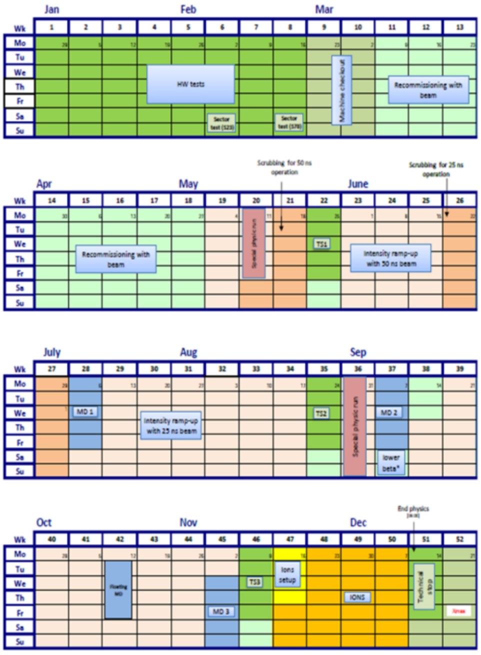


Figure 4: LHC schedule for 2015 [6].

RADIATION TO ELECTRONICS

The radiation-to-electronics (R2E) project was, and is, a major effort. From 2008 to 2011 it analysed and mitigated all safety relevant cases and limited the global impact. In 2011-2012, the emphasis was on avoiding long downtimes and on adding shielding. The LS1 period (2013/2014) was used for final relocation and more shielding. During LHC Run 2 through LS2 (2015-2018) the R2E effort will focus on tunnel equipment and power converters. Figure 5 illustrates the large past and future improvement resulting from this effort.

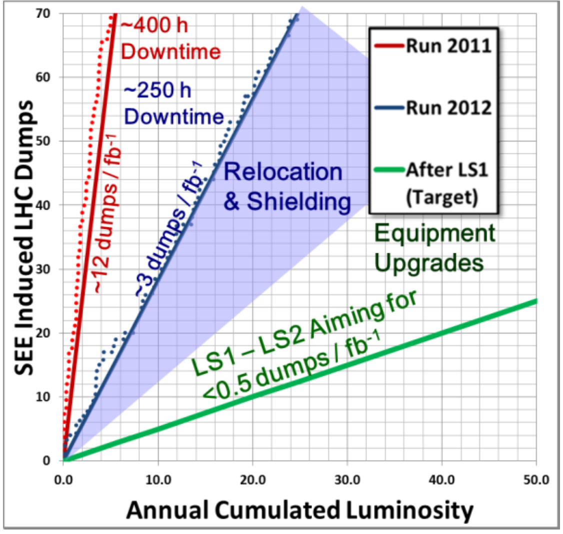


Figure 5: LHC beam dumps due to single-event upsets as a function of integrated annual luminosity for 2011 and 2012, together with a forecast for the post-LS1 period [7].

UFOS

The UFO situation may get worse at higher beam energy, where the UFO rate is expected to increase. The UFO rate is further known to be higher with 25 ns spacing than for 50 ns. In addition the energy loss per UFO increases at 6.5 TeV, while the quench margin is reduced. As a further complication, for higher beam energies the duration of the UFOs decreases and the rise time becomes faster; see Fig.6.

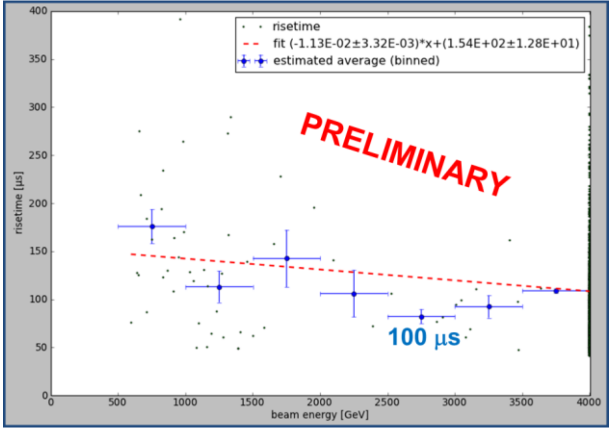


Figure 6: UFO rise time versus beam energy extracted from 683 UFO events observed in the arc (≥ cell 12) during operation with 1374 or 1380 bunches until 20.08.2012, considering signals with BLM running sum 4 above $2\cdot10^{-4}$ Gy/s. Only datasets with $R^2 \geq 0.95$ are included [8].

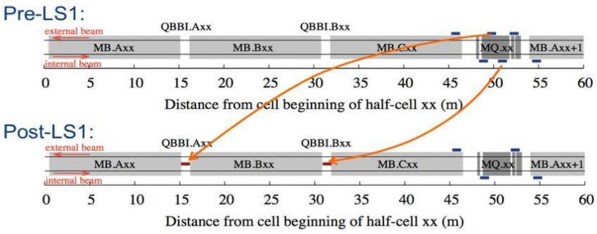


Figure 7: Relocation of BLMs during LS1 [9].

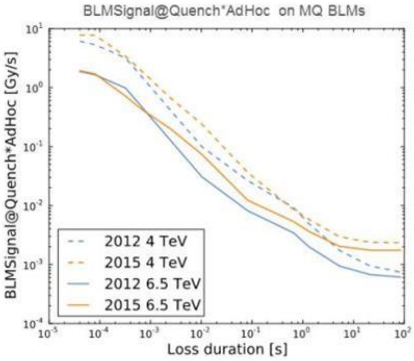


Figure 8: BLM thresholds vs. loss duration in 2012 and 2015 at beam energies of 4 and 6.5 TeV [9].

During LS1 there had been no mitigation measures to reduce UFO activity. However, two other measures were adopted:

(1) BLMs had been relocated for 100% coverage of SC magnets to allow localizing and quantifying UFOs. Specifically, BLMs were moved from the centre of MQ to a position above MB-MB interconnects (Fig. 7). The initial numbers of UFO events will be larger than in 2012, but conditioning should help.

(2) BLM thresholds had been refined, based on quench tests, to avoid unnecessary triggers and quenches; this is illustrated in Fig. 8.

LHC GOALS FOR 2015, RUN 2 AND RUN 3

The priorities for the 2015 run are to establish proton-proton collision at 13 TeV with 25 ns and low β^*, to prepare a production run in 2016, and to optimize the physics-to-physics duration (i.e. to minimize the "turn-around" time). One of the present limitations of the turnaround time is illustrated in Fig. 9. Later in 2015 there would be a decision on timing and duration on the special runs, e.g. 90 m optics. These would not be scheduled in the first part of the year. An LHCC recommendation was awaited. The 2015 run will also include a *Pb-Pb* run of one month.

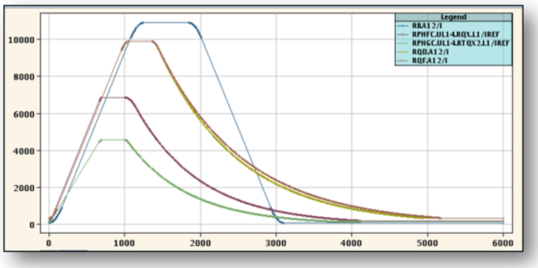


Figure 9: Ramp up and down cycles of the main LHC magnet circuits, indicating a possible improvement for the ramp down, and a shortening of the overall turnaround time, through the use of 4-quadrant power converters [10].

The goal for Run 2 is to reach a luminosity of 1.3× 10^{34} $cm^{-2}s^{-1}$ in operation with 25 ns bunch spacing (2800 bunches), corresponding to a pile-up of ~40 events per bunch crossing. A maximum pileup of ~50 is considered to be acceptable for ATLAS and CMS. **The integrated luminosity goal for 2015 is 10 fb^{-1}, until the end of Run 2 ~100-120 fb^{-1}** (a better estimate will be available by the end of 2015), **and 300 fb^{-1} by LS3** (Fig. 10).

Figure 10: LHC run schedule with luminosity goals through 2025 [11].

THE LIU & HL-LHC PROJECTS COST AND SCHEDULE REVIEW

A cost & schedule review will be organized from 9 to 11 March 2015, in the frame of CERN-MAC meeting no. 10 (CMAC10). The review will be chaired by Norbert Holtkamp of SLAC. The goal of this cost and schedule review is to assess the status and risks of both projects.

Presently four major activities are ongoing in parallel at CERN: the operation of the accelerator complex, the Accelerator Consolidation Program, the LHC Injector Upgrades (LIU), and the High Luminosity LHC upgrade. The Cost & Schedule Review will cover the LIU and HL-LHC projects, taking into consideration their working hypotheses linked to the Consolidation project and to the operation of the CERN accelerator complex. However this review will not assess the cost and schedule of the Consolidation project nor the operation of the accelerator complex.

The following specific questions will be addressed:

- Is the estimated budget of the two projects adequate (for the baseline scenarios)?
- Are there any options to reduce the budget and does the review team see opportunities for savings? What is the possible scope contingency?
- What are the areas of high risk for scope, schedule or cost overrun? What would be the adequate related contingency, testing, mitigation measures…?
- Is the schedule well developed, credible and synchronized between the ongoing activities (operation, consolidation, diversity program, as well as the LHC experiments)?
- Are the foreseen resources correctly evaluated?
- Will the expertise (managerial and technical) be available when needed?

LS2 STRATEGY AND PREPARATION

The goal for Run 2 was to reach a luminosity of 1.3× 10^{34} $cm^{-2}s^{-1}$ in operation with 25 ns bunch spacing (2800 bunches), corresponding to an estimated pile-up of 40 events per bunch crossing. A maximum pileup of ~50 is considered to be acceptable for ATLAS and CMS. Figure 11 shows the injector schedule through the end of LS2. Figure 12 presents preliminary estimates of injector downtimes required during LS2.

Figure 11: Injector schedule through the end of LS2 [12].

LIU MASTER SCHEDULE

A preliminary plan and time requirements for the LIU project during LS2 is presented in Fig. 13. This is still to be detailed by machine and coordinated across projects (for resource levelling).

A few first remarks can, however, already be made:

- The **PSB upgrade represents the critical path of the LIU project** in terms of workload on site.
- The **connection of the Linac4 has to be scheduled at the most appropriate time** according to the manpower needs.
- **Radioprotection conditions** to work in the various machine areas according to beam operation and other constraints will have to be identified (Linac3, dismantling of Linac2?)

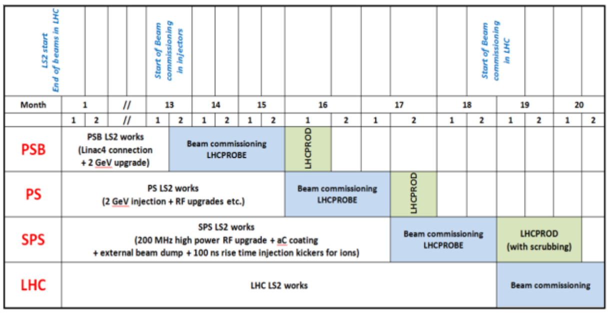


Figure 12: Preliminary estimates of shutdown time required for the LHC injectors during LS2.

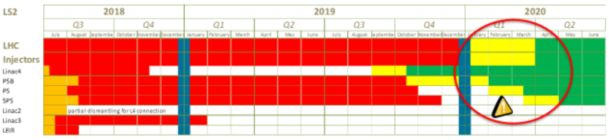


Figure 13: Preliminary LIU master plan [13].

LHC ACTIVITIES IN LS2

A proposal for a first **draft skeleton of LHC activities during LS2** is shown in Fig. 14. Details will depend on the cool down and warm up sequence. The time windows available for the activities vary between 9 and 13 months.

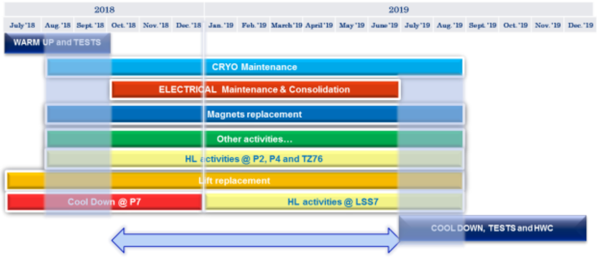


Figure 14: Skeleton of LHC Master Schedule for LS2 (indicative) [14].

CMAC9 RECOMMENDATIONS

CMAC9 issued the following 10 recommendations:

- R1: **The re-commissioning time for Heavy Ions** should be clarified with well-defined milestones.
- R2: Develop **integrated luminosity evolution plan for 2015 and Run 2** as a whole.
- R3: Schedule sufficient **study time** to resolve the luminosity limitation due **to instabilities during LHC commissioning** in 2015.
- R4: Develop a robust system to identify and prevent the unnecessary beam aborts due to UFOs.
- R5: Prepare a **minimum SPS upgrade plan** that satisfies the beam performance requirements of the HL-LHC project as soon as possible.
- R6: Investigate the **loss mechanism during the first hour of LHC stores** and develop mitigating efforts for the HL-LHC project.
- R7: Document the **scope, schedule and cost estimates for the HL-LHC in time for the cost & schedule review planned in March 2015** and pick one scenario for the purpose of costing and scheduling. Clearly distinguish the options from the baseline and define the advantages/ risks/ cost/ timelines
- R8: Perform a **sensitivity study from beginning to end (LINAC → HL-LHC) that demonstrates the margins/losses/beam requirements system by system** (accelerator by accelerator) in synchronization with LIU planning.
- R9: Perform **"the return on investment" analysis for the proposed consolidation activities** and take that into account when deciding what to fund when.
- R10: Determine the **effects of recent and expected changes in radiation regulations on the material handling in LS2**. Extend the estimation of radiation safety beyond LS2 through the entire HL-LHC to evaluate the impact on the project and the inevitable cost.

OUTLOOK

After huge work during LS1, the hardware & beam commissioning and the operation of the LHC machine at higher energy will be an absorbing and captivating period.

Beams are back in the injectors and are knocking at the door of the LHC.

ACKNOWLEDGEMENTS

Chamonix 2014 was a very fruitful workshop with very good proposals, overviews and strategies, with valuable information and discussions, and with an active participation of the LHC experiments.

We thank all the session chairs and scientific secretaries for a high-quality programme, the speakers together with all the persons involved in the preparation for their excellent presentations, as well as all participants for the open and lively discussions. We warmly thank Evelyne Delucinge for the practical organization of the Chamonix 2014 workshop.

REFERENCES

[1] LHC Performance Workshop (Chamonix 2014) https://indico.cern.ch/event/315665/

[2] Summary of the LHC Performance Workshop - Chamonix 2014, CERN, 8 October 2014 http://indico.cern.ch/event/341704/

[3] F. Bordry, Introduction, Chamonix 2014.

[4] M. Albert, D. Jacquet et al., “Dry Runs and Cold Checkout,” Chamonix 2014, these proceedings

[5] E. Meschi, official statement, 2014

[6] J. Wenninger, “Strategy for Run 2,” Chamonix 2014, these proceedings.

[7] M. Brugger, “R2E and Availability,: Proc. Chamonix 2014.

[8] T. Baer, “UFO Study Working Group,” 4 Sept. 2012

[9] B. Auchmann et al., “BLM Threshold Strategy (vis-a-vis UFOs and Quenches),” Proc. Chamonix 2014, these proceedings.

[10] M. Solfaroli Camillocci, M. Lamont, J. Wenninger, “Nominal Cycle and Options,” Proc. Chamonix 2014, these proceedings.

[11] M. Meddahi and G. Rumolo, “Session 5 – LIU – Summary,” Chamonix 2014, these proceedings.

[12] J.M. Jimenez and J.-Ph. Tock, “Summary of Session 8: Long Shutdown 2 Strategy and Preparation,” Chamonix 2014, these proceedings.

[13] J. Coupard et al., “LIU Planned Activities,” Chamonix 2014, these proceedings.

[14] M. Bernardini, K. Foraz, “Long Shutdown 2 at LHC,” Chamonix 2014, these proceedings.

SUMMARY OF SESSION 1: LS1, HW COMMISSIONING, POWERING TESTS - COMING OUT OF LS1

M. Pojer and L. Ponce, CERN, Geneva, Switzerland

INTRODUCTION

The main objective of the first session (as it was oriented) was not to list what has been done in LS1, but to clarify what is left to do in the LHC before beam, in two senses: what is left to do for the completion of LS1 and the preparation of the machine for beam, and what will not be completed during LS1. In particular, the speakers where asked to focus on items which could have an impact on the first run at 13 TeV and the main questions they were asked to answer are:

- From the issues before LS1, what was addressed and what could not be modified?
- What is the predicted impact of hardware changes?
- Can we expect surprises after LS1?
- What can be done to mitigate issues in case they come up?

The first part of the session focused on the powering tests, with two presentation on the status of the superconducting circuits:

- Non-conformities (solved and pending) on the Superconducting Circuits, A. Verweij
- Re-commissioning of the Superconducting Circuits, M. Solfaroli

In the second part, the attention was moved to the “rest” of the machine, with two talks on the remaining NCs all around the ring and the expected performance in terms of impedance and RF heating:

- Other Non-solved NC's across the LHC Ring and Potential Impact on Performance, V. Baglin
- Expected impact of hardware changes on impedance and beam induced heating during run 2, B. Salvant

Finally, the status was presented of the most critical systems in the machine, RF/ADT and injection/extraction elements:

- ADT and RF after LS1, A. Butterworth
- LBDS and Kickers after LS1, W. Bartman

As an additional element, CMAC noticed that “there appear to be two main categories of NCs; those that are critical to performance of the machine and those that are not. It would be helpful to clearly identify these two categories of Non-Conformities”.

Some elements in this direction are already highlighted in this summary.

NON-CONFORMITIES (SOLVED AND PENDING) ON THE SUPERCONDUCTING CIRCUITS

Arjan gave an update on the status of readiness of all superconducting circuits for Run II. In fact, during LS1, all non-conformities that were limiting the performance of the machine were addressed and all those preventing to operate at high energy were fixed. Nevertheless, some non-critical non-conformities are still present.

Concerning the main circuits, 15 main dipoles and 2 main quadrupoles were replaced within the SMACC (Superconducting Magnets And Circuits Consolidation) project, due to electrical and magnetic NCs. The quality of the splices after SMACC is extremely good and they are all below the 5 μΩ excess resistance.

No issue is finally expected from the main circuits for operation at high energy, even if a number of quenches is expected during the commissioning campaign, which is estimated between 90 and 130 for the main dipoles.

Concerning the other circuits, some non-conformities or local limitations apply:

- For RD3.L4, the max current was reduced from 5850 to 5600 A, sufficient for 6.74 TeV;
- Four 120 A circuits in the inner triplets in L1 and L2 were not repaired during LS1 and are then still condemned;
- Some magnets on the 600 A circuits have been bypassed due to electrical problems, but in agreement with ABP colleagues and with an estimate negligible impact on the performance.

Finally, no limitation from the superconducting circuits is expected for the operation at high energy.

Q&A

Q. King asked why current is reduced in some low current circuits. A. Verweij answered that these circuits present probably an internal short that cannot be fixed during LS1.

P. Collier asked if the limits on the inner triplet correctors could be a potential limit for performance (β^*reach). M. Giovanozzi answered that these correctors are not needed till 60 cm β^* as observed during the machine developments in Run 1. For lower β^*, MD time is required to explore the impact on performance.

M. Pojer asked if it is planned to change the detection threshold for the undulator which was a weak point in Run 1. A. Verweij answered that tests are on-going in SM18 to see if we could increase the ramp rate. This will be presented at the next LMC.

RE-COMMISSIONING OF THE SUPERCONDUCTING CIRCUITS

The re-commissioning of the superconducting circuits after LS1 requires the execution of more than 10000 powering tests on the almost 1600 circuits. And this will have to be done in about 5 months: this constitutes a challenge similar to the one of 2009. The main differences with respect to that period is that not all the circuits were heavily modified as done during LS1 and (more important) the energy was at that time limited to 3.5 TeV. Now the objective is to run at 6.5 TeV, with an expectation, as said, of more than 100 quenches for the main dipoles only.

Matteo illustrated all efforts that were put in place to have good hardware and software for this campaign, with a special attention to the automation of test.

Prior to the powering tests, the short-circuit tests and the CSCM were performed. The first ones revealed some non-conformities that could have been critical for the machine and would have slowed down the powering tests. The Copper Stabilizer Continuity Measurements are done to validate the full busbars-splices-diodes path, and the results so far obtained show the good quality of the consolidation job done during LS1.

Q&A

N. Holtkamp asked for precision about the so-called “new” QPS board. M. Solfaroli precised that the New QPS is indeed the one already installed before LS1 and used during RUN 1. What is presented in the talk is a new detection system for the CSCM test.

The time to recover from a quench was questioned, to evaluate how long will be the training campaign. The estimation with 2 quenches per sector per day is about 1 week of training to reach 6.5 TeV.

OTHER NON-SOLVED NC'S ACROSS THE LHC RING AND POTENTIAL IMPACT ON PERFORMANCE

Vincent gave an overview of other non-conformities (mainly related to vacuum) that have not been fixed in LS1 and tried to draw for them the possible impact on operation or on the activity during the coming technical stops.

Among the non-conformities that could have an impact on operation, the most important are those related to the collimator 5th axis for the TCTPs in IP1 and IP5 (which implies that we cannot afford the risk of damaging them and will require an intervention during 2015 YETS to fix them) and the presence of ferrite in several components, that, if heated, could outgas and produce a pressure rise. Concerning the TDI, it has been sectorised during LS1, to allow exchange or reconditioning if needed, and the pumping systems has been upgraded with NEG cartridge; nevertheless, it will still suffer from resistive wall effects and beam induced heating and outgassing.

The impact on the technical stops will mainly come from the discovery, during LS1, of the multiply bellows leaks: to avoid producing new ones, thermal transients should be limited as much as possible. In addition, some leaks were not fixed in LS1 and will be fixed in LS2.

Also the bake-ability of some components will be an issue for future interventions, and this will have the consequence of a reduction of the NEG coating life time and the lengthening of the intervention time.

Q&A

M. Pojer wanted to know where vacuum activities stand in the general planning. V. Baglin answered that all sectors are closed, LHCb is under closure and within one month all LSS should also be closed, which corresponds to the planning.

P. Collier asked if the solenoids around MKI will be put back in place for RUN 2. V. Baglin specified that upstream of vacuum valves, in warm regions, the solenoid have been replaced by NEG system. The solenoids will be put back only in the warm-cold transition region around IPs. A second question concerned the dilution kicker (MKB) status. V. Baglin answered that the system is now completed, the new module has been installed and with the same pumping speed as before LS1, so with the same possible limitation on vacuum performance.

S. Redaelli mentioned that the ferrite in the collimator is by design and cannot be called a non-conformity. M. Jimenez specified that in the functional specification of the LHC it was explicitly mentioned that no equipment should go above 120 degree when installed so that all equipment containing ferrite should be thermalized before installation.

EXPECTED IMPACT OF HARDWARE CHANGES ON IMPEDANCE AND BEAM INDUCED HEATING DURING RUN 2

An impressive effort has been done during LS1 by all equipment groups to assess and reduce the impedance of their devices. Benoit listed many of the interventions done and stressed on the fact that new equipment should by default remain in the shadow of the current LHC impedance.

Concerning the beam induced heating issue, Benoit listed the predicted impact of consolidations on the RF heating and the result of the simulations with changing bunch length: an increase of the bunch length from 1 to 1.25 ns, would drive a reduction of the heating from 30 to 95%, depending on the systems.

Concerning the most critical systems in terms of beam induced heating during Run I, Benoit showed the modifications done on the TDI, the BSRT and the MKIs. For the TDI, a stiffening of the beam screen was applied, together with the refurbishment of jaw mechanics; the copper coating was removed from the beam screen and temperature probes were added on the lower jaw. In the BSRT, the mirror and mirror holder geometry were modified to attenuate the RF mode; no ferrite was installed and RF studies were done, to validate the design. Lastly, in the MKIs 24 screen conductors are installed and systematic measurements are done before installation.

Q&A

P. Collier asked if we may expect problems at the recombination chamber with the increased bunch intensity. B. Salvant answered that the estimation with HL-LHC numbers are OK.

Following a question on the source of the heating, B. Salvant answered that with the intensity and bunch length expected for RUN 2, the heating is mainly due to single bunch effect.

ADT AND RF AFTER LS1

The main change during LS1 on the RF side was the replacement of a faulty cavity module (limited to 1.2 MV). Andy showed also all upgrades done to improve the reliability of the system, and he talked about the new diagnostic installed for the bunch-by-bunch phase measurement. Concerning the controls, CPUs were replaced and moved to linux, but the upgrade to FESA3 will be done only during Run II. For the operation in RunII, the capture will be done with 6 MV, as in Run I. A long and detailed planning of re-commissioning is already underway, but the real commissioning will only start after cool-down.

A lot of hardware and software modifications were done on the ADT too. New important feature are four pick-ups per beam/plane, an improved S/N ratio and other implementations. In particular, an “observation box” is being developed, which make ADT and RF bunch-by-bunch data available to external applications and which should be connected to the LHC instability trigger network.

A possible issue to be checked for the ADT is its compatibility with the new UPS: the ADT base-band signals (3 kHz-20 MHz) are transmitted over coaxial lines from SR4 and they were perturbed by ground currents from old UPS, with switching frequency 5-8-16kHz. The newly installed UPS's produce very different noise spectra and their compatibility with the ADT system will have to be studied in detail.

Q&A

W. Hofle questioned about the commitment of the RF group to provide the cavity phase noise measurement tool. A. Butterworth answered that it is planned for mid-2015.

O. Bruning asked if the issue with the “America” cavity has been investigated. E. Jensen answered that there was a request from LMC to not start dismantling “America” for investigation till the commissioning of “Europa” is completed to keep it as spare in case of need.

M. Pojer asked when the tests with the new UPS system are planned. A. Butterworth answered that they are now planned for end of October 2014.

LBDS AND KICKERS AFTER LS1

Wolfgang started showing the new 24 screen-conductor design for all MKIs: with respect to the old 15 conductor design, this will bring a net reduction of the deposited power, which will go down to 50 W/m. In addition, the improved cleaning procedure of the ceramic tube will reduce the UFOs. For what concerns the hardware modifications on the extraction system, the main ones are the new TSDS powering scheme and the new TCDQ. The new scheme is meant to cope with missing dump request in case of powering issues: 3 independent VME crates (1 crate for each TSU) are separately powered; in case of internal failure, a synchronous dump is issued from the redundant crate. This means an improved safety, but a higher complexity in the system and, of course, a reduced availability.

For the new TCDQ, the graphite absorbers have been replaced by a sandwich of graphite and Carbon fibre reinforced Carbon (CFC).

Important software modification are also foreseen for the injection and extraction systems. Mentioning two, the TDI gap interlock, with redundant interferometric measurement, and the interlock for the MSI current, which will be ramped down, while beam energy ramps up.

Q&A

R. Jacobson asked what are the expected losses at injection for the 25 ns bunch spacing beam and with the BCMS type beam for LHCb. W. Bartman answered that the 25 ns beam should be cleaner from injection losses point of view than the 50 ns beam.

SUMMARY OF SESSION 2: INJECTOR STATUS AND BEAMS FOR LHC, DRY RUNS, SECTOR TESTS WITH BEAM

R. Steerenberg (Chair) and R. Alemany (Scientific Secretary), CERN, Geneva, Switzerland

Abstract

This paper summarises the presentations and the subsequent discussions during the second session of the LHC Performance Workshop in Chamonix 2014.

LIST OF PRESENTATIONS

The following five presentations were included in the second session:

- "LHC Injectors Complex Status", K. Hanke;
- "SPS Scrubbing 2014", H. Bartosik;
- "Operational beams for the LHC", Y. Papaphilippou;
- "LHC Dry Runs and Cold Checkout", D. Jacquet;
- "LHC Transfer Line and Sector Test", R. Alemany.

A brief summary of the presentations and the subsequent discussions are given in the following.

LHC INJECTORS COMPLEX STATUS

Summary

K. Hanke gave an overview of the work done in the LHC injector chain during LS1, the re-commissioning after LS1 and the present status, for both ions and protons. He highlighted the most important issues encountered and lessons learnt. The presentation represents a preliminary post-mortem of the injectors start up after a long shutdown during which substantial modifications were made to the installed hardware and software. Despite the good preparations and the dry runs it was not trivial to make all systems operational again in the time allocated and an intensive period of debugging was required. One of the major concerns has been the availability of equipment experts in the CCC to support the operation teams in order to bring the different systems into operation again, which was principally due to the high workload. Actually the items that caused most worries worked quite well whereas the more standard items were not or could not be given sufficient attention. Another point that was emphasised is that deadlines for the different re-commissioning phases could not or were not always respected, compromising, on several occasions, the schedule for machine checkout.

K. Hanke ended his presentation with a brief outlook on the 2015 YETS and the restart afterwards. He commented that only the absolutely necessary interventions will be allowed in view of a 'hot' restart of the injector complex for an early begin of the 2015 Argon ion physics run and to be ready in time for the LHC commissioning with beam, starting with a sector test on February 7th.

Discussion

F. Bordry commented that we should acknowledge all the equipment experts that made a huge effort to perform an enormous amount of work of the highest quality during LS1 and that now, during the start up of the machines, they are still required to perform at the same level, which in some cases is not possible. He would rather prefer to convey the message that now we should profit from the lessons learned and pick up those points where improvement is required. Those should then be worked out in view of future Long Shutdowns. R. Losito commented that from his point of view a more systematic approach to the commissioning phase is needed in the injectors, as it is done in LHC. This would help the equipment experts to prepare and schedule their work. M. Lamont remarked that from his perspective, the missing cable issues and similar problems mentioned during the talk could have been avoided if the operations team would have checked them before beam commissioning, as it is done in the SPS, for example. K. Hanke answered that it is the responsibility of the equipment groups to check and ensure that the equipment is ready for use from the CCC and that the missing cable actually happened in the SPS.

N. Holtcamp asked if the transverse emittance has been measured in the injectors and if it is comparable w.r.t. run 1. K. Hanke answered that it has been measured only in the booster and that it is slightly larger than in run 1. The transverse beam emittance in the SPS could not yet be measured because the wire scanners broke at the beginning of the beam commissioning.

O. Brunning asked about more details concerning the PS alignment mentioned in the talk. R. Steerenberg explained that in the PS orbit measurements were done with beam, calculations of the corrections were performed and that the proposed magnet displacements were applied. Following this beam-based realignment the orbit was measured again and was found to be different with respect to the calculated correction. The issue was traced back to a shift in the numbering of the BPMs following the insertion of three new BPMs, but not due to any magnet alignment problem. A second iteration with the correct BPM sequence provided a good orbit.

K. Hanke also mentioned that the PS Finemet cavity was found to be ringing at 40 MHz and that as a result some gaps were short-circuited to avoid potential impact on the beam performance, although presently no performance limitation have been observed. S. Gilardoni stressed that the problem is not affecting the beam production performance.

SPS SCRUBBING 2014

Summary

H. Bartosik gave a detailed presentation about the strategy for the scrubbing run in 2014, a description of the doublet scrubbing beam, together with details on the preparation of the scrubbing in 2015, including the required measurements and instrumentation readiness.

H. Bartosik started with recalling that the SPS suffered in the past from a strong limitation due to e-cloud. This situation did improve gradually thanks to scrubbing, which was done systematically every year since 2002, apart from the years 2010 and 2011

The goal of the 2014 scrubbing run is to qualify the loss of conditioning due to the LS1 activities, to recover the 2012 performance, to quantify the amount of beam and time required and finally to test the doublet beam scheme, which is foreseen to be used in the LHC in 2015.

He then detailed the schedule and the choices made with respect to dividing the scrubbing run in shorter blocks. For each of the scrubbing blocks clear strategies and goals have been defined.

H. Bartosik explained in detail the production of the doublet beam, its structure in the SPS together with the advantages of using this beam rather than the standard 25 ns beam, which is the increased e-cloud production, hence enhanced scrubbing. Simulation results show that the scrubbing profile depends on the beam intensity and is very different w.r.t. the standard 25 ns beam. In fact the scrubbing takes place around the centre of the MBB dipole, in contrast with the standard beam that is more efficient at the extremities of the dipole section. This will require the modulation of the beam orbit in order to cover a sufficiently large area of the vacuum chamber. First tests with beam in 2012 showed a nice agreement between simulations and measurements and confirmed a substantial increase of the dynamic pressure for the doublet beam in the SPS arcs.

Regarding the preparations H. Bartosik gave an overview of the beam characteristics requirements out of the PS together with the setting up of the cycle in the SPS. He also listed the measurements that are required and requested the devices to be operationally available.

Discussion

P. Collier asked that given the doublets scrub different surfaces of the magnets, what is it planned to steer the beam around in order to cover the whole surface? H. Bartosik answered that the cleanest way is using the orbit correctors.

M. Lamont asked what the capture efficiency is for a beam intensity of 1.7 10^{11} p+ during the non-adiabatic splitting in the SPS? H. Bartosik replied that they have measured efficiencies in the order of 90% at injection, but remarked that this beam has not yet been accelerated.

R. Steerenberg noted that as soon as beam is put in the SPS machine, the machine is being scrubbed; therefore this should be quantified and taken into account for the scrubbing results.

OPERATIONAL BEAMS FOR THE LHC

Summary

Y. Papaphilippou gave a clear review of the performance expectations for all the LHC beams, protons and ions, which have to be set-up for LHC operation. He started with an overview of the LHC restart schedule as it was discussed in the LMC of September 9th. From that schedule he then deduced which beams will have to be prepared and in what order. The first requirement is the single bunch beams: LHCPROBE (also called LHCPILOT), with intensities $\leq 10^{10}$ p/b and the LHCINDIV beam with up to 4×10^{11} p/b. The production scheme of these beams was consolidated in 2012, allowing the preservation of the 6D phase space volume for different intensity values and an excellent shot-to-shot reproducibility together with good control of the intensity and the longitudinal emittance.

Y. Papaphilippou then presented the different production schemes for the multi-bunch LHC beams, together with their pre-LS1 status. These schemes can be divided in the standard scheme, as it was used operationally in 2012 for the 50 ns beam, and the BCMS (Bunch Compression, Merging and Splitting) scheme, which resulted in smaller transverse emittances for similar bunch intensities. Both production schemes are very close to the performance limit of the present injectors.

Post-LS1 the aim is first to recover the performance that was obtained in 2012 followed by potential performance improvements that are within reach ensuing some hardware modifications made during LS1 and possible improvement on the production scheme, as proposed and discussed during the RLIUP workshop.

Y. Papaphilippou then compared the performance of the standard production scheme and the BCMS scheme with some potential improvements from optimised PSB-PS transfer and an intensity increase in the SPS, reminding the audience that these performances will depend highly on the success of the SPS scrubbing.

He also briefly addressed the less standard beams such as the doublet scrubbing beam and the 8b+4e beam. The successful Pb-Pb ion beam performance in 2011 and the P-Pb run in 2013 were briefly reviewed. From this the 2015 Pb ion performance was projected, addressing the changes to the production scheme. For the injectors the main change will take place in the PS where the bunch spacing will be reduced from 200 ns to 100 ns, which together with a reduction of the β^* in the LHC should result in an increase of the luminosity by a factor ~ 10.

Y. Papaphilippou concluded his presentation with the revised 2014 injector schedule to which he added the setting up sequence of the different LHC beams.

Discussion

T. Roser asked what are the disadvantages of BCMS beams? V. Kain answered that from a machine protection point of view, the current LHC – Transfer Lines protection devices cannot cope with such dense beams and added that she will address this during her talk in session 5. E. Metral recalled that the small beam sizes the BCMS provides might trigger more beam instabilities. Y. Papaphilippou completed the answer by reminding that the 25 ns BCMS beams, with the complete number of bunches injected and ramped in LHC, have not been proven yet, so there are still many unknowns and one first needs to learn how to operate those beams. The eventual increase of pile-up in the experiment is not an argument, as was reminded by CMS, since the experiments are prepared to take 1.5 10^{34} $cm^{-2}s^{-1}$ after LS1, but not during the firsts weeks though.

S. Gilardoni gave, in contrast, some arguments in favour of BCMS beams: they provide more aperture margin due to the smaller emittance, and if instabilities are an issue, the beams can be blown up with a relative small loss in luminosity since they imply less number of bunches as compared to standard 25 ns. On the other hand, if e-cloud is still an issue, the smaller emittance leave margin in case of e-cloud induced blow up.

P. Collier asked how much time is needed to recover a good vacuum for ion operation in SPS and if sublimation pumps are active? P. Chigiatto answered that the amount of time depends on the length of the vacuum sector, but gave ~ 2 weeks as a typical duration. He added that sublimation pumps are not active, however, they could be activated if needed, but with a significant cost in time. M. Jimenez commented that there are no pressure problems in SPS with the fully stripped ions and that sublimation pumps are useless in the SPS. B. Goddard added that discussions are on going to reduce the length of the vacuum sectors in order to reduce the time needed for conditioning.

John Jowett corrected the number concerning the integrated luminosity for the Pb-Pb run in 2011, which was 150 μb^{-1} instead of 100 μb^{-1}.

LHC DRY RUNS AND COLD CHECKOUT

Summary

D. Jacquet presented the systematic approach that LHC operation has adopted since 2008 to tackle the complexity of LHC in view of the preparation for beam commissioning, dry runs of equipment and software, coordinated with the equipment experts and performed from the CCC at an early stage, followed by a thorough cold machine checkout when the whole machine is practically handed over to operations.

She started by stating that during LS1 besides consolidation, many modifications were made to the LHC and added that there were also non-negligible changes to the team operating the LHC. This has lead to a similar level of preparation for beam commissioning as was applied during the 2008/2009 start up.

One of the main messages was that the testing from the control room should start early (i.e. May 2014), even though not all systems are fully deployed or stable. The reason for this is the early detection of issues and it allows allocating sufficient time for corrective actions. She mentioned that the restart of the LHC injectors made that experts were not always available to help and solve arising issues immediately. A prerequisite for successful testing is that the basic controls environment has to be in place in the CCC.

D. Jacquet then provided examples of tests made so far and results obtained. Although a new timing system will be deployed in October many tests related to the telegram, timing tables, etc. were performed. Similar approaches were used for other systems such as RF synchronisation and frequency map, handshakes and beam modes, post-mortem events, etc. The available time was also used to perform reliability runs on the beam dump systems, using the BETS simulator for the energy ramp.

She then presented a list of tests that have to take place until the beam commissioning. The pre-conditions for the final machine check were clearly listed together with the organisation of the check out period.

Discussion

R. Steerenberg acknowledges that the strategy of early start of dry runs is very beneficial and that the injectors could potentially benefit from a similar approach.

LHC TRANSFER LINES & SECTOR TEST

Summary

R. Alemany presented the motivation and goals to perform a transfer line test and sector tests in LHC. She showed the proposed schedule, which are an update of the previous ones following a major LHC schedule revision.

She started by explaining that the transfer line and sector test will allow testing a substantial number of systems across its different layers. These tests are then representative for the same systems in the ring, such as BLM, BTV, BPM, etc. It will also allow testing and confirming the optics models and will allow probing the aperture available. The sector tests are now foreseen for 7 and 8 February for sector 2-3 and 21-22 February for sectors 6-7, 7-8 and the beam dump. These tests need to be carefully planned, as partial closure of the LHC and the ALICE and LHCb experiments are required. For these tests the LHCPROBE (also called LHCPILOT) beam is required with an intensity of 2–5 × 10^9 p/b.

R. Alemany then concluded by presenting the stepwise strategy for the sector test together with the list of systems to test together with a preliminary, but detailed, schedule for beam in both directions.

Discussion

M. Lamont asked if it makes sense to do a sector test just before the machine checkout starts. R. Alemany answered that experience has shown that even if the sector test was performed the day before beam commissioning, as it was done for the sector tests in 2008, it brought very positive results. M. Lamont emphasised that he fully agrees with this approach.

SUMMARY OF SESSION 3: 2015 COMMISSIONING WITH BEAM

M. Lamont (Chairperson) and G. Papotti (Scientific Secretary), CERN, Geneva, Switzerland

Abstract

This paper summarizes the discussion that took place during the third session of the LHC Performance Workshop, Chamonix 2014.

INTRODUCTION

The third session of LHC Beam Commissioning Workshop was dedicated to the 2015 commissioning with beam. It included the following presentations:

- "Introduction", by M. Lamont;
- "Experiments' Expectations for 2015", by E. Meschi;
- "Baseline Machine Parameters and Configuration for 2015", by R. Bruce;
- "Optics options for the 2015 LHC run", by M. Giovannozzi;
- "Nominal Cycle and Options", by M. Solfaroli Camillocci;
- "Scrubbing: Expectations and Strategy, Long Range Perspective", by G. Iadarola.

For each presentation of the session, summaries of the discussion that followed the presentations are given.

INTRODUCTION (M. LAMONT)

L. Rossi asked whether synchrotron radiation could be useful for damping at the higher energy. *O. Bruening* recalled that the damping times are about 25 hours in the horizontal plane and 12.5 hours in the longitudinal plane, so slightly too long. *G. Arduini* added that it will be positive for longitudinal emittance, but long fills are needed to profit from it. *J. Jowett* recalled that for ions the phenomena is twice as fast, so rather significant.

EXPERIMENTS' EXPECTATIONS FOR 2015 (E. MESCHI)

R. Alemany commented that concerning the first VdM scan, a crossing angle is applied only in IP1, not in the other IPs. *R. Jacobsson* underlined that it is important to avoid satellites collisions.

A member of the CMAC asked what the expected integrated luminosity is for 2015. *M. Lamont* replied that 10–20 fb^{-1} is the working assumption.

S. Redaelli asked whether the experiments are willing to consider levelling by separation also in IP1/5, as technically it would be easier than β^* levelling. *E. Meschi* explained that with the natural luminosity decay, a short time at high pileup is tolerable. With levelling, on the other hand, the pileup is kept constant during the fill. So, in case of levelling, it is desirable to keep the pileup at an optimized level (lower than maximum acceptable). *S. Fartoukh* added that it is in theory feasible also to level at a non-constant pileup. *L. Rossi* clarified that what is called the peak pileup is in fact the average at the beginning of the fill. He also pointed out that a pileup of 50, with 25 ns beams, gives a luminosity of around $2 \times 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$.

J. Jowett clarified that, concerning the heavy ion run, the only figure for integrated luminosity in 2015 was 0.8 nb^{-1}, quoted at the RLIUP workshop by himself (even though this number is not particularly optimistic).

BASELINE MACHINE PARAMETERS AND CONFIGURATION FOR 2015 (R.BRUCE)

R. Schmidt commented on where to use the additional margins for Machine Protection. He pointed out that the choice might depend on the targeted failure cases: if protection is targeted towards an asynchronous beam dump for example, or to protect the aperture. *R. Bruce* agreed that a detailed discussion could follow concerning where to use the margins.

P. Collier stressed that the available 2 sigma margin is based on various assumptions, which are still to be verified, e.g. the aperture. *R. Bruce* agreed, adding that during commissioning we will see where the margins are needed.

W. Hofle asked why the Design Report 55 cm β^* is not considered. *R. Bruce* replied that the Design Report settings on collimators cannot be used due to the need for increased margins, so in order to consider 55 cm some margins have to be gained elsewhere (e.g. during Run 1 the aperture allowed extra margins). *S. Redaelli* added that it is a complicated parameter space: during Run 1 the aperture was indeed better than expected, the TCT-triplet margin from orbit stability might have been an artefact from instrumentation, the hierarchy in IR7 is driven by impedance needs.

R. Tomas asked why the Design Report bunch length of 1 ns is not considered. *E. Shaposhnikova* recalled B. Salvants presentation and the fact that the limitations concerning heat load are now resolved. *R. Jacobsson* added that from the experiments point of view, a few clear options are needed so that they can be studied. The impact for LHCb is non-negligible and a longer luminous region is generally preferred. *E. Shaposhnikova* added that changes during the fill will be small, at the 10% level, and that synchrotron radiation will shrink the longitudinal emittance, so bunches may become too short.

G. Arduini stressed that the choice of the initial parameters has a strong impact on the later evolution. E.g. the choice of collimator settings will have implications on the next step: tighter settings would allow smaller β^*, and more relaxed settings might ease initial operation but will later require more time to the push performance. *S. Redaelli* agreed. He also added that he prefers not to change the settings of the primary collimators (settings in mm equivalent to TeV). In 2012 they had given origin to loss spikes, and it would be useful to learn about that early on. Anyway, if the TCPs are to stay at nominal settings, others collimators could be opened slightly to relax the operation from the point of view of impedance.

P. Collier highlighted that if Collide&Squeeze or β^* levelling are to be used operationally, a robust orbit feedback is needed in operation first so that the beams can be kept reliably in collisions with negligible separation. *J. Wenninger* suggested to test C&S and R&S during commissioning, and postpone the decision of whether to use them operationally to later. Indeed though, the first ramps should be simple, then e.g. R&S could be prepared in parallel.

G. Arduini added it is very difficult to qualify the feasibility of the C&S in MD, as the reproducibility on longer time scales is needed. *P. Collier* replied that he would not rely on reproducibility only, but on a robust feedback, which he considers a prerequisite for operation. A 1-sigma separation between the colliding beams can easily give stability issues. *J. Wenninger* recalled that once the LHC is in high intensity operation, changes are slow. Some experience should be gained with few bunches during commissioning, or parasitically with LHCb. *S. Redaelli* added that C&S is not exactly operationally the same as β^* levelling: C&S profits from additional flexibility and shorter validation period.

OPTICS OPTIONS FOR THE 2015 LHC RUN (M. GIOVANNOZZI)

R. Bruce commented on the comparison of the β^* reach for the nominal and ATS optics: the two optics are not fully equivalent. He recalled that for ATS an extra margin of 1 sigma is needed between the TCDQ and the TCTs. This effectively reduces the β^* reach (which can possibly be recovered with oval beams). *M. Giovannozzi* agreed that the ATS optics needs to be studied further, both in simulation and with beam studies.

M. Lamont asked when the validation for option-med will be presented at the LMC (including the change of tune). *M. Giovannozzi* replied in a month or two, and added that also the aperture with collision tunes needs to be proven to be as good as with injection tunes.

M. Deile stressed that injection at higher β should be pursued, as it could be useful not only in 2015, but also in the later runs (until LS3 there will be requests for high β runs). *M. Giovannozzi* recalled that injection at 30 m is probably already at the limit. *J. Wenninger* added that with an injection β of 30 m, the gain would be around 15 minutes per cycle. But the investment in commissioning the different injection optics would be gained back only with 2–3 weeks of running, so it might not pay off overall. Also, every year revalidation would be required. *H. Burkhardt* added that on the plus side it would simplify the high β runs, e.g. concerning the tune change (which would be smaller).

NOMINAL CYCLE AND OPTIONS (M. SOLFAROLI CAMILLOCCI)

P. Collier asked whether any improvement is possible on the main quadrupole precycle which at present are the limiting factor in length. *L. Bottura* said that the task will be taken up by the FiDeL team. *E. Todesco* replied that a precycle to lower current would change the tune decay. This might be ok if the tune feedback system can take care of that. *M. Lamont* pointed out that from the hardware commissioning one cold gain better estimates for the decay constants (the ones used at present are very conservative). *M. Solfaroli* added that in the longer term new power converters might be useful. *R. Tomas* also recalled the option to precycle the MQXs to lower current (with implicaations on β beating).

SCRUBBING: EXPECTATIONS AND STRATEGY, LONG RANGE PERSPECTIVE (G. IADAROLA)

P. Collier asked about the effectiveness of the doublet scrubbing in the quadrupoles. *G. Iadarola* replied that it is similar to the nominal beam, and that the enhancement is mostly in the dipoles.

W. Zeuner asked why a second scrubbing exercise is not an option. *G. Iadarola* replied that if improvements are seen while scrubbing, it will be carried on. Later improvements in scrubbing will happen while producing luminosity, with physics fills. The change to the other schemes (8b4e or 50 ns) will be done only if they would give much better performance.

L. Tavian worried that operation with doublet beams might saturate the cryogenic cooling capacity: 250 W/half cell is close to the local limit due to the size of the valve, but might not be fully available if operating with two beams (then we might be limited globally from the cryogenic plant itself, at 200 W/half cell. *G. Iadarola* recalled that the strategy was to check online with the cryogenics operator and inject only enough to get to the bottleneck, and when the new beam could be coped with.

G. Arduini stressed the importance of the online diagnostics tools to optimize the scrubbing strategy. While little improvement was seen on the quadrupoles, the transition between the different phases is given by the dipole improvements. Doublet beams are more efficient, so they should be used as soon as possible. *G. Iadarola* added that in 2012, had the doublet beam been available, it would have been used on the last day of scrubbing.

P. Baudrenghien pointed out that the bunches at injection are short due to the mismatched capture, chosen to reduce capture losses, but this could be changed. *E. Shaposhnkova* added that at injection the maximum voltage available should be used, as the momentum spread should be high. *G. Iadarola* mentioned that the batch-by-batch blow up to increase the bunch length could be used.

R. Schimdt wondered whether a higher density of beam loss monitor could be useful at some particular location in the machine. The discussion will be followed up offline.

S. Fartoukh asked whether simulations off-axis were performed in the quadrupoles. *G. Iadarola* replied negatively. He recalled that for the triplet, electrons are guided from the field lines. In quadrupoles, similarly, there is a trapping mechanism.

SUMMARY OF SESSION 4: LHC - CHALLENGES AND STRATEGY FOR RUN 2

B. Salvachua and M. Zerlauth, CERN, Geneva, Switzerland

Abstract

The session aimed at addressing the challenges and overall strategy for the second operational period of CERNs Large Hadron Collider, expected to restart beam operation in early 2015. While the main focus was the identification of a strategy for the commissioning year 2015 (concentrating on 6.5 TeV, 25 ns/2800b per beam), the presentations provided as well an outlook for plans to reach the nominal machine performance by further decreasing β* and by maximizing the luminosity output of the machine as of 2016, while maintaining the pile-up at the level currently acceptable for the LHC experiments.

STRATEGY FOR THE FIRST TWO MONTHS OF THE 2015 BEAM COMMISSIONING

The main target of the first two months of the 2015 beam commissioning is to establish collisions in all 4 experiments of the LHC with 2-3 nominal bunches. Around two months are foreseen for this period, providing the basis for the following intensity ramp up with 50 ns, respectively 25 ns. The following main commissioning steps have to be completed during this period:

- Establish the key beam commissioning steps like first threading, beam capture, orbit and optics corrections, IR bumps, aperture (β*), polarities, energy ramp (combined ramp & squeeze) and collisions.
- Commission with beam the key accelerator systems like feedback systems (FB), transverse damper (ADT), collimation (+ embedded beam position monitors, BPMs), radio frequency (RF), injection, dump and diagnostics taking into account the many system changes during LS1, hence expected to be very different to the very fast 2012 re-commissioning.
- Execute all relevant machine protection (MP) commissioning, as all MP-related systems must operate in their final configurations by the first Stable Beams. It should be noted that changes during the run might become very time consuming, hence special runs should be scheduled early on.
- Validate the machine configuration with the relevant optics measurements, as the challenges of Run 2 require new measurements compared to the standard commissioning of previous years.
- Start preparation of the scheduled β* change planned for mid-end 2015 to speed up the later optics re-commissioning.

In addition to this standard commission, measurements for the insertion region (IR) should be performed such as aperture at injection and top energy, if possible, (providing already a first estimation of the β* reach), local orbit and optics corrections in the IRs to conclude on the feasibility of levelling scenarios and the orbit stability/BPM signals as the basis for a good reproducibility and stability of the machine.

In view of the additional overhead to repeat a complete validation at a later stage, the initial optics measurements and corrections as well as the aperture verification with squeezed beams are ideally already performed and verified down to the final target value of β*=40 cm in order to validate the feasibility and understand the margins of this configuration early on in the commissioning program.

OVERALL STRATEGY FOR RUN 2

The start-up configuration of the LHC for 2015 has been discussed at a recent LMC meeting, confirming to concentrate on operation at 6.5 TeV, 25 ns/2800b per beam and opting for reduced complexity by adopting a relaxed β*=80 cm. A similar strategy has already been applied during Run 1, during which β* could be reduced twice due to the excellent stability and increased understanding of the machine, first in 2011 from 1.5 m to 1 m and a second time in early 2012 from 1 m to 0.6 m as shown in Figure 1.

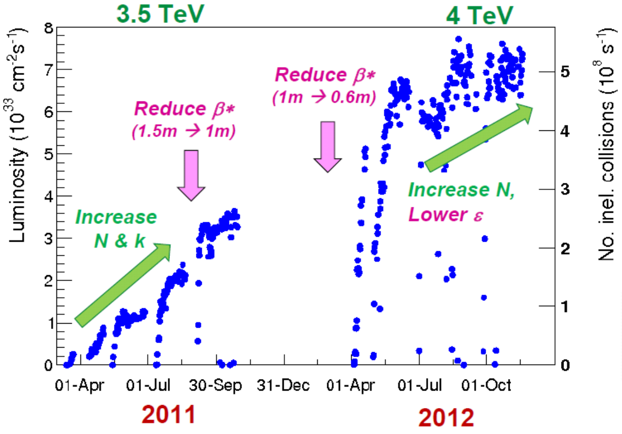


Figure 1: Evolution of machine performance during Run1.

Different to previous (re-)commission periods the 2015 commissioning will include two intensity ramp-ups, first with 50 ns beams (following an initial scrubbing run with 50 ns and 25 ns beams) to re-establish stable machine operation after the two yearlong shutdown. This phase will be limited to ~3 weeks and will mainly serve as a debugging phase for operations, since various equipment systems will be exposed for the first time again to higher beam intensities and bunch trains. In the following, a second scrubbing run (using 25 ns beam and eventually doublet beams) will be used to prepare the machine for the following 25 ns operation, which will be taking place in two periods around the 2nd technical stop of ~45days each. If the previous measurements and experience allow for it, the 2nd 25 ns block could eventually take already place at a slightly reduced β* value.

The year will be concluded by the traditional ion run, for which a slightly lower energy of 6.37 TeV is preferred by the experiments. Due to the limited time available for an already very dense program, the overhead of other special runs like LHCf, high β* and VdM scans has to be carefully weighed against the priority of establishing stable 25 ns operation and to prepare an organized path to lower β*, which will entail mastering considerable new challenges like electron clouds, instabilities and reduced quench margins in presence of the expected increase of UFO rates.

MPS STRAGEY FOR COMMISSIONING AND OPERATION

Machine operation at 6.5 TeV and 25 ns bunch spacing will increase the energy stored in the LHC magnet system and beams well beyond the levels mastered during the first operational run. The main challenges for machine protection will be to achieve reliable operation of the magnet system at higher energies (and hence much reduced quench margins) in presence of higher beam intensities and the expected beam instabilities and increased UFO rates.

In addition, the levels of the so-called ‘Setup beam flag’ (representing the beam intensity as a function of energy at which no damage should be possible to any accelerator equipment in case of full beam impact) will be as low as 1.1×10^{10}p (~intensity of a probe bunch) at 6.5 TeV as shown in Figure 2.

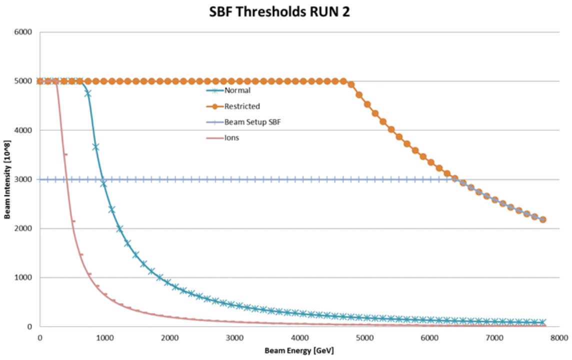


Figure 2: Setup Beam Flag values for Run 2.

For the initial beam setup (including loss maps, finding collisions…) a special equation will be available in the Safe Machine Parameter (SMP) system, allowing under certain conditions and for limited periods of time the use of up to 3 nominal bunches in order to allow for an efficient machine setup.

After a first full commissioning of the machine protection systems for the adopted start-up configuration, any changes in the machine configuration will require the requalification of the relevant machine protection elements (collimator settings, asynchronous beam dump, loss-maps…). The restricted Machine Protection Panel (rMPP) will closely follow and validate the intensity ramp-up periods and stable beam periods through dedicated check-lists for the main equipment and protection systems.

MACHINE DEVELOPMENT PRIORITIES

The machine development (MD) priorities for Run 2 will be largely determined by the overall strategy and commissioning plan for the machine in 2015. The assessment of many of the known and expected new operational challenges such as single and multi-bunch instabilities, optics, β* and aperture… will require considerable time early on in the commission program to confirm the adopted roadmap. It has been decided that any measurement which is vital for machine operation will hence be part of the Run 2 commissioning and not of the limited MD blocks. MD time will be allocated instead for (long-term) performance improvements of the machine. High priority MDs will include studies related to the change of intensity limits, the modified impedance and beam stabilities, long-range beam-beam effects with 25 ns bunch spacing, collimation hierarchy and impedance, β* levelling and collide & squeeze tests.

Following the experience during Run 1, strict procedures and formal written requests will be required for each MD as this has shown to increase the efficiency and success of the allocated testing time.

BLM THRESHOLD STRATEGY (VS UFOS AND QUENCHES)

One of the major challenges for Run 2 is to define BLM thresholds for operation of the cold and warm elements of the LHC machine at 6.5 TeV, which will protect critical machine elements from any damage while optimizing the availability of the magnet powering system by avoiding unnecessary quenches after e.g. UFO events.

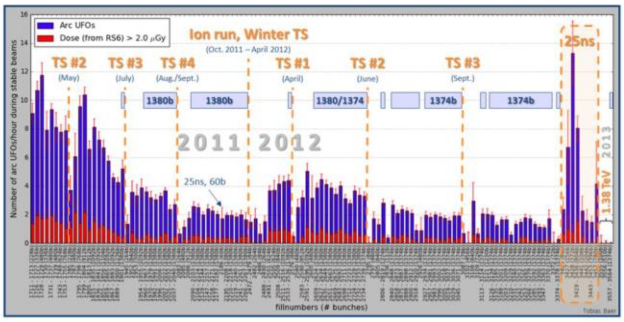


Figure 3: UFO rates during 2011 and 2012.

While in known sensitive locations, like the MKIs, mitigation measures have been adopted to decrease the UFO rate during Run 2, the UFO rates in the arc are expected to increase again after the long shutdown and due to the 25 ns operation (as already observed during Run 1 – illustrated in Figure 3). As counter-measure, 2 out of the 6 BLM monitors on the arc quadrupoles have been relocated into the interconnections between two arc dipole magnets, which will allow for efficient protection against such UFO loss scenarios without unnecessarily decreasing the BLM thresholds on the arc quadrupoles.

Considerable efforts are currently going into the analysis of the recent quench tests and the benchmarking of simulation codes with these results in order to establish new reference values for the quench levels of the LHC magnets in the relevant running sums of the beam loss monitoring system. First results are encouraging as they suggest that the true quench levels are a factor of 5-10 higher than previously predicted in Note 44. These new findings will be the basis for an efficient tuning of the BLM thresholds in preparation and during Run 2. As a consequence of this optimisation, a number of UFO/beam-induced quenches are however to be expected during the second operational period of the LHC.

R2E AND AVAILABILITY

Besides the beam parameters chosen for the Run 2, the availability of the machine to allow for luminosity production will be another decisive ingredient to reach the ambitious goals of Run 2 as shown in Figure 4. Machine availability during Run 1 has been dominated by equipment failures (accounting in average for more than 2 out of 3 beam dumps).

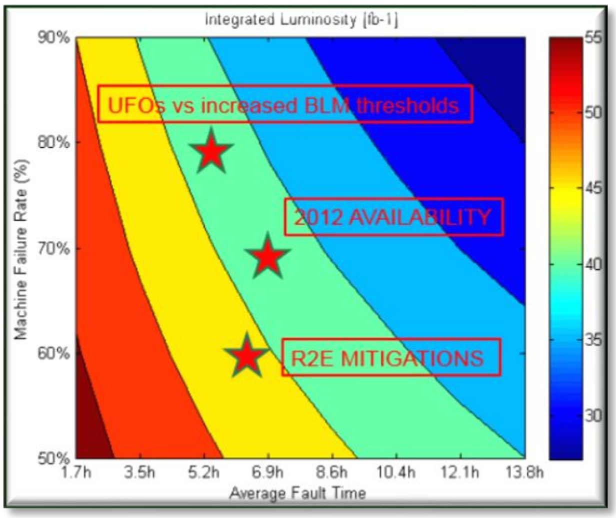


Figure 4: Simulated integrated luminosity/LHC operational year as a function of machine failure rate and fault time based on 2012 availability and variations due to R2E mitigations and increased UFO rates/new BLM thresholds.

A considerable fraction of these failures could be traced back to radiation induced effects, hence considerable efforts have been undertaken during LS1 to install additional shielding wherever possible and to relocate further sensitive equipment from exposed areas (UJ14/16, UJ56).

The R2E team is also assisting equipment groups in the re-design of electronic components installed in radiation areas, by using error correction algorithms or radiation tolerant components in the designs. Thanks to these ongoing efforts, the number of radiation induced beam dumps is expected to decrease from an initial value of ~12 dumps/fb^{-1} to less than 0.1 dumps/fb^{-1} for the HL-LHC period.

In parallel, efforts to better quantify, track and improve the availability of the various equipment systems are vital to agree on future priorities of consolidation activities. These efforts are coordinated by the Availability Working Group, and will be supported by new tools to quantitatively measure the availability of the individual LHC systems by tracking in detail the caused down times of the machine. While initially focusing on the LHC machine, this Accelerator Fault Tracking Project (AFT) is expected to be used as well in the injector complex in the future.

SUMMARY

The 2015 run presents us with a fantastic mix of challenges. In parallel to learning how to operate at 6.5 TeV and with 25 ns beams we will have to prepare the future of LHC operation. During the initial commissioning year it will be important to remain focused on the challenges of 25 ns operation and to define an organized path to lower β* rather than searching for immediate performance gains. MD periods are likely to be too short (and very late) for a full program, hence many MD like items will have to be performed during periods of 'operational development'.

Assuming that things move on reasonably, a reduction of β* should be foreseen in the second 25 ns period based on the available information. The traditional ion run at the end of the year and other special runs should be carefully slotted in at an acceptable overhead.

ACKNOWLEDGMENTS

The session conveners would like to express their gratitude for the assistance and numerous discussions with the various members of the Machine Protection Panel, the Availability Working Group, the various equipment groups and the colleagues from BE-OP. In particular, we wish to thank the speakers, S. Redaelli, J.Wenninger, B. Salvachua, J. Uythoven, B. Auchmann and M. Brugger for their excellent presentations, which were well timed and focused on the relevant items that were asked to be addressed.

DISCUSSION

Stefano Redaelli

Strategy for the first two months of the 2015 beam commissioning

M. Lamont asked if the alignment and operation of the Roman Pots would be included in the initial beam setup. M. Deile comments that Roman Pots stations will be used during low beta runs and during high beta runs. For the low beta runs only some 14 individual pots have to be aligned, while for high beta runs the full set of pots will have to be aligned. He points out that the alignment and validation of the pots should be included during commissioning as it will be more time consuming if done later on due to the required additional loss maps. S.Redaelli replies that the operation of the Roman Pots is challenging, as they should be inserted very close to the beam. He reminds that in 2012 the alignment and operation with pots was done only after acquiring a good knowledge of the machine. For the 2015 run period, he thinks that it might be too challenging to operate them as close to the beam right after the first collimator alignment and without the knowledge of machine stability. P.Collier comments that it should be considered the possibility to operate with the pots only after week 23 (after the first technical stop) when the machine will probably need to be re-qualified.

M. Zerlauth comments that one of the limitations during machine validation with beams was the number of fills needed to validate the off-momentum cleaning. He asks if there is something that can be tried during initial commissioning with beam to improve the situation in the future. S. Redaelli replies that in the Machine Protection Workshop in March 2013 (Annecy), a possibility to change the particle momentum in a more controlled way was presented. However, this method stills needs to be verified in conjunction with the RF team but he agrees that it is certainly something that should be planned during commissioning.

Jorg Wenninger

Overall Strategy for Run 2

S. Redaelli enquires about the expected problems during special runs with many bunches. J. Wenninger comments that we will need to wait for the first experiences with the beam in order to evaluate this.

M. Meddahi asks, since the priority for operation during Run 2 is the 25 ns option, about the possibility to shorten the 50 ns period or even skip it completely and give e.g. higher priority and time to the scrubbing. J. Wenninger replies that a shorter running at 50 ns can be considered, but currently this serves as a contingency in case of problems. M. Zerlauth adds that the idea for this run is also to accumulate enough machine time during a more controlled period to fully validate the machine protection system.

Belen Salvachua

MPS Strategy for Commissioning and Operation

No questions or comments.

Jan Uythoven

Machine Development Priorities

M. Zerlauth comments that it will be challenging to make sure that all the items quoted in the current talk as commissioning measurements can be accommodated during the initial beam-commissioning phase.

L. Rossi points out that the use of ATS optics should be anticipated in the LHC as soon as possible. He comments that the decision not to use it right after LS1 is understood and that he is in agreement with it, but the possibility to use this optics version in the close future has to be strongly considered as it is the HL-LHC baseline and any problem should be addressed as soon as possible.

R. Schmidt enquires about the plan to use the new instrumentation to measure and interlock for the fast changes of beam current (dI/dt aka BCCM). T. Lefevre comments that the strategy is to test as much as possible already during commissioning and if there is some time left continue during Machine Development periods. M.Zerlauth adds that new hardware has been already produced, so the first tests should certainly be able to start during early beam commissioning in 2015.

J. Uythoven comments that the overall strategy is to complete during commissioning everything that is absolutely essential for physics operation in 2015 and leave for the Machine Developments the studies needed to further improve the performance of the run, like e.g. a step down in beta-star.

V. Kain comments that the assignment of MD time seems quite advanced and asks if there is a deadline for sending MD requests, as she thinks that it will be better to have some experience with the beam before proposing MDs. J.Uythoven replies that written requests are welcome at any time now, however the final decision will be done shortly before the MD period depending of the current needs and operational experiences.

J. Jowett reminds that in 2013 no quench test was performed for ions and asks about the possibility to include this in the agenda for the next quench test period.

R. Jacobsson mentions that for the organization/allocation of commissioning time BE-OP should take into account that systematic commissioning during normal working hours and stable beams during the night is not ideal for the experiments as they also have to complete developments and upgrades during that period.

Bernhard Auchmann

BLM Thresholds Strategy (vs UFO and quenches)

S. Redaelli comments that we should be ready to prepare some BLM factors that we still consider safe for the losses in the Dispersion Suppressor regions (DS and he points out that if UFO losses are under control the DS will very likely be the limiting location.

S. Redaelli asks whether the change of the BLM locations in the arc region is mainly motivated to better observe UFO's that were not seen before. B. Auchmann indicates that this is indeed the case (in addition to better protection possibilities), as there were potentially UFO's that occurred in the arc and were not measurable in Run 1.

J. Ph. Tock points out that there are some magnets more difficult to replace than others and asks if this can be taken into account when preparing the BLM thresholds to protect them. B. Auchmann replies that his current talk covers, for the time being, only main dipoles and quadrupoles; for other locations we can consider to add a safety factor. J. Ph. Tock replies that indeed he is more worried about other magnets than the main dipoles and quadruples.

E. Todesco comments on arc thresholds as a function of loss duration (slide 14). He points out that the behavior seems linear in the log scale and asks if this is understood. B. Auchmann replies that it is complicated to have an argument to explain the behavior of the thresholds over the full range.

Markus Brugger

R2E and availability

M. Lamont asks if the 0.5 failures per fb^{-1} can be further reduced. M. Brugger replies that these failures due to radiation will disappear but we will observe other types of failures (which are however predictable and understood). M. Zerlauth comments that it is important to start the redesigned of the systems taking into account radiation issues.

Q. King asks about the preferable approach for the power converters. M. Brugger replies that in the next R2E workshop, to be held in October 2014 at CERN, this will be discussed.

P. Baudrenghien comments that most of the effort seems to be on re-location and asks if there is also some effort put on the design of radiation resistant components. M.Brugger replies that there is also a strong effort on redesigning electronics and points out that the QPS group had to design and produce many (types of) cards in a few years.

CHAMONIX WORKSHOP, SESSION 5 – LIU – SUMMARY

M. Meddahi and G. Rumolo

GOALS AND MEANS OF THE LIU PROJECT

The goal of the LHC Injectors Upgrade project (thereafter 'LIU') is to increase the intensity/brightness in the injectors in order to match the High Luminosity LHC (thereafter 'HL-LHC') requirements. It means for the proton accelerator complex to enable Linac4/PSB/PS/SPS to produce, accelerate and manipulate higher intensity beams (based on efficient production schemes, space charge and electron cloud mitigation measures, impedance reduction, feedback systems, hardware upgrade and improvement). For the heavy ion complex, an important upgrade of the injector chain (Linac3, LEIR, PS, SPS) is planned to produce the required beam parameters at the LHC injection that can meet the luminosity goal.

In addition, the LIU project should ensure the increased injectors' reliability and lifetime to cover the HL-LHC era (until ~2035). This part is closely related to the CONSolidation, project, and concerns the upgrade/replacement of ageing equipment (power supplies, magnets, RF…) and the improvement of radioprotection measures (shielding, ventilation…).

The timeline of the LIU project is sketched in Fig.1.

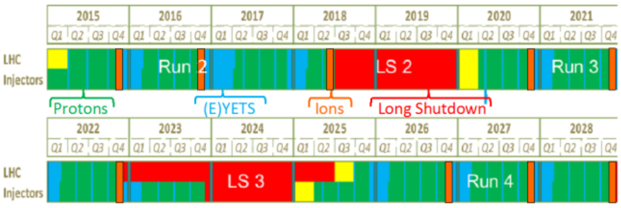


Figure 1: LHC (upper row) and Injectors (lower row) operation schedule (green: proton operation, blue: technical stops, orange: ion operation, red: long shutdown -LS)

The simulation studies, beam measurements and equipment procurement will take place during Run 2 until the start of LS2. During this time, key dates for pending decisions have been set in order to define the baseline program of all the interventions by end of 2016. All LIU installations and hardware works will then take place during Long Shutdown 2 (LS2). For some of these installation activities, it is checked if they could be anticipated to Year-End-Technical-Stop (YETS) or Extended-Year-End-Technical-Stop (EYETS).

Commissioning of LIU beams will take place in 2020 for the Pb ion beams, as the full beam performances are already needed for the 2020 ion run. The proton beam commissioning up to the LIU beam parameters will gradually be performed during Run 3 to be ready after LS3. This strategy would as well allow performing any further hardware corrective actions during the Run 3 technical stops or LS3, if needed.

LIU-IONS

The main target of the LIU-IONS can be described in a simplified form as reaching 7 times the nominal peak luminosity. This also translates into multiplying by a factor 14 the peak luminosity achieved during the 2011 Pb-Pb run. Table 1 summarises the desired versus achieved ion performance.

	L_{peak}	**Beam energy**
Achieved in 2011	**5×10^{26} Hz/cm^2**	**3.5 Z TeV**
LIU-IONS	**7×10^{27} Hz/cm^2**	**7 Z TeV**

Table 1: LIU-IONS beam parameters, compared to the 2011 achievements

The bunch intensity was already at the limit on the SPS flat bottom during the 2013 p-Pb run in terms of acceptable intra beam scattering and space-charge effects. It is therefore needed to accumulate a larger number of possibly slightly less intense (as compared to 2013) bunches in LHC. The targets for the p beams needed during the p-Pb runs are being defined.

The means to achieve the LIU-IONS target luminosity are the following:

- Increase the beam current from **Source & Linac3** by improving the Low Energy Beam Transport (LEBT). This requires identifying and removing bottlenecks by performing beam dynamics simulations, beam measurements, and installing new diagnostics when needed. The increase of the injection rate from 5 Hz to 10 Hz will also allow injecting more intensity into LEIR;
- Increase the beam current out of **LEIR** by both increasing the amount of injected beam (compatibly with the electron cooling capabilities) and mitigating the large beam losses at RF capture. For that, more advanced machine modelling and Machine Developments are needed;
- Use bunch splitting in the **PS** to produce 4 bunches with 100 ns bunch spacing;
- Increase the number of bunches in the **SPS**, thanks to an upgraded injection system with a 100 ns rise time, and longitudinal slip-stacking allowing the production of trains with 50 ns bunch spacing. Furthermore, mitigation of the beam degradation at flat bottom will rely on the reduction of the RF noise. The use of Q20 optics will be kept as it proved efficient during the 2013 p-Pb run.

In summary, a list of actions has been defined to achieve the target ion beam parameters at LHC injection to fulfil the luminosity goals. However, big challenges are ahead to increase the beam current into and out of LEIR (see Fig. 2), as well as to reduce the beam degradation along the chain, As the LIU-IONS beam is the first in line to be required for physics production after LS2, much effort is presently being put to solve all the related issues.

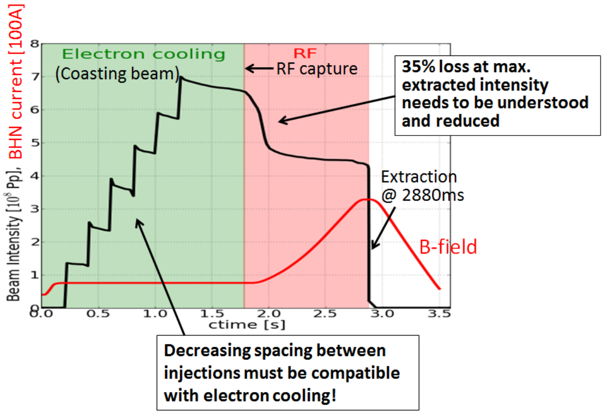


Figure 2: Open questions to improve LEIR performance to reach the LIU-IONS goals.

LIU PROTON INJECTORS

The LIU proton target is to reach the very demanding beam parameters needed by the HL-LHC project. This target is summarized in Table 2. The injectors must produce 25 ns proton beams with about double intensity and higher brightness than nowadays.

25 ns	**N (x 10^{11} p/b)**	**ε (μm)**	**B_l (ns)**
Achieved in 2012	1.2	2.6 (std) 1.4 (BCMS)	1.5
HL-LHC	**2.3**	**2.1**	**1.7**

Table 2: HL-LHC beam parameters, compared to the 2013 beam parameters

- To reach this goal, a cascade of improvements is needed across the whole injectors chain. The main items are listed below:
- Replace Linac2 with Linac4. This will allow injecting H$^-$ into the PSB at 160 MeV and producing higher brightness beams. It implies re-designing the injection into the PSB.
- Raise the injection energy in the PS to 2 GeV to allow for higher beam brightness at the same space charge tune spread. This requires increasing the PSB magnet field, replacing its main power supply, upgrading the main PSB-RF system (C02+C04), changing the PSB-PS transfer equipment and re-designing the PS injection. The intensity out of the PS can also be increased thanks to the newly installed longitudinal feedback against the longitudinal coupled bunch instabilities and possibly the transverse feedback against the electron cloud instabilities.
- Increase the beam intensity accelerated in the SPS. This relies mainly on two actions. The first one is the RF power upgrade by adding a new 200 MHz power plant, rearranging the 200 MHz cavities, increasing the power and installing a new low-level RF for the higher harmonic 800 MHz cavity. The second one is to actively suppress electron cloud by coating with a-C the vacuum chambers in the SPS main magnets. The final decision between a-C coating versus beam induced scrubbing will be taken in mid-2015, after all the data about the SPS performance recovery after LS1 will be available and analysed.

LINAC4 STATUS

Linac4 (an approved CERN project) will be replacing Linac2, providing H$^-$ injection into the PSB at 160 MeV, and leading to an expected double brightness for the LHC beam type out of the PSB.

The Linac4 is currently being commissioned stage by stage with a temporary source. Acceleration to 12 MeV has been successfully validated. The RFQ and chopper behave as expected and the DTL tank1 can accelerate the beam without losses. Emittance measurements agree very well with code predictions (PARMTEQ, PATH, TRACEWIN) and the phase space reconstruction methods for transverse and longitudinal emittances are also validated.

The new caesiated source (which is the baseline source) is ready for use and is projected to provide 40 mA within 0.35 μm (acceptance of the RFQ). This indicates that about 20 turns injection will be needed for the future LHC beams and simulations are ongoing to establish the future emittance vs. intensity curve. About 100 turns injection are estimated to be required for the future ISOLDE beams, having an intensity higher than present ISOLDE beams, however the attainable maximum injected intensity needs to be assessed via simulations. The source will then need to be upgraded to a magnetron, with the relative R&D program, if there is an interest to achieve the originally specified 80 mA. However, increasing the beam current will also have consequences on the attainable transverse emittance (due to the strongly space charge dominated beam transport) and will come at a significantly high cost.

A half-sector beam test is planned for June 2016 to “simulate” injection from Linac4 into PSB with the real equipment.

LIU TARGET PARAMETERS

After connecting the PSB to Linac4 and implementing all the improvements for the LIU programme, as outlined in the previous section, the beam performance reach at the extraction of the SPS at 450 GeV can be estimated as 2.0x10^{11}p/b in 1.9μm. The main limitations to these values are longitudinal instabilities/beam loading in the SPS and the PSB brightness, as illustrated in Fig.3.

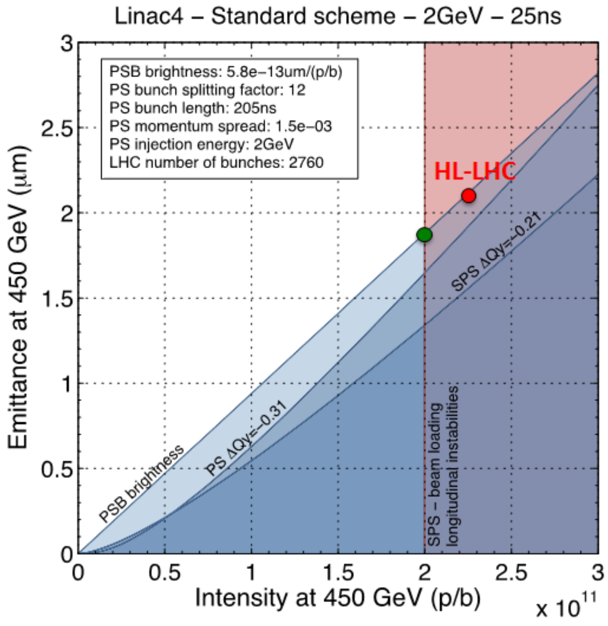


Figure 3: Proton performance reach after implementation of all the Injectors upgrades

CAN WE DO BETTER FOR HL-LHC?

The following options were discussed in the course on the LIU session:

a- Provide higher bunch current out of the SPS (larger longitudinal emittance at flat top) through the following means: using the SPS an intermediate optics (Q22), which would provide a trade-off between margin in Transverse Mode Coupling Instability threshold and constraint on RF power; reducing the ramp rate and performing bunch rotation at 450 GeV to help the CBI limitation on the ramp and the constraint on the bunch length at the SPS extraction, respectively; clearly identifying the impedance source responsible for the longitudinal limitations and suggesting techniques to reduce it. It is worth noting that the LHC could also ease this optimisation process if it becomes able to receive longer bunches from the SPS with a 200 MHz RF system. This is as well being investigated within the HL-LHC project.

b- Provide a higher number of bunches to the LHC, by injecting trains of 80 bunches into the SPS, instead of the nominal 72 bunches. The scheme is based on injecting 4+3 bunches from the PSB into the PS, with one out of 21 bunches kicked out with the transverse damper after the triple splitting at 2.5 GeV. The use of the transverse feedback to kick out a single bunch from the PS has been already validated in Machine Development.

c- Provide higher brightness beams from the injectors, i.e. using the BCMS production scheme. This results however in injecting trains of 48 bunches from the PS into SPS and requires a careful study of the potential high damage for beam intercepting devices in the SPS, transfer lines and LHC.

Concerning the SPS impedance identification and reduction, particle tracking simulations have shown that the intensity threshold for longitudinal instabilities is indeed reduced by a factor of 2 because of the impedance of the ≈550 vacuum flanges. Preliminary suggestions to reduce the impedance of the SPS vacuum flanges (requiring 15 – 30 weeks of work) are i- partial shielding and damping (a R/Q reduction factor 8 could be achieved and only half of the flanges could be modified) or ii- complete flange redesign (providing a minimum impedance, a R/Q reduction by a factor 20, all flanges could be changed, at a higher cost). This would be a major extra activity to be possibly added to the baseline project. A final decision needs no later than 2015 is needed in order to be able to prepare for LS2 installation.

Concerning BCMS beams, the performance reach is of high interest (2.0x10^{11}p/b in 1.4μm at 450GeV), see Fig. 4.

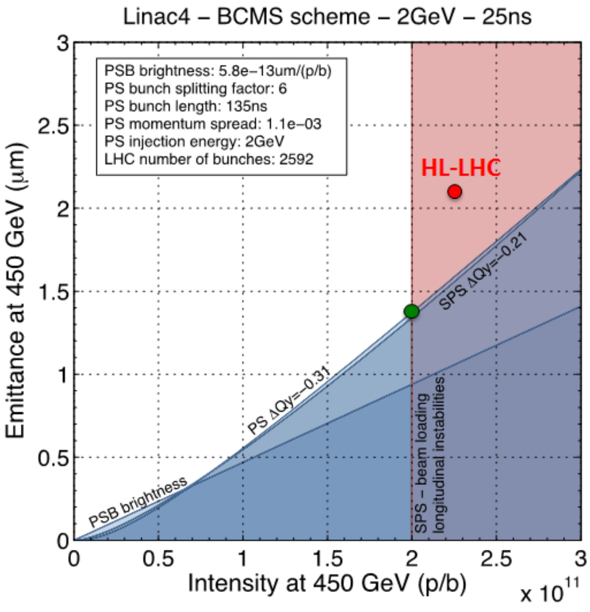


Figure 4: Proton performance reach with BCMS beams

However, high brightness beams come with larger Intra Beam Scattering rates in LHC, challenges for emittance measurement devices, fewer bunches in LHC (~5%), and less effective LHC octupoles to stabilize the beam. The added high damage risk of the protection devices in the SPS, the SPS-to-LHC transfer lines and the LHC was also stressed and the dangers further discussed. The energy deposition depends on the total intensity as well as on the spot size. It was demonstrated that the protection devices for Run2 BCMS beams and LIU beams, might need to attenuate 100-200% more than present design. The choice of material is challenging and many activities are on-going to find an appropriate material. The stresses in case of impact of high brightness beams are estimated to be beyond the strength of materials presently used in passive protection absorbers (even standard HL-LHC can pose problems). R&D is needed to possibly find suitable materials for new absorbers in post LS2 run. Beam tests in the HiRadMat facility with 440 GeV SPS beam are essential to check the material properties used as input for simulations, the robustness against 'simulated' future beams and all new promising materials -e.g. 3D Carbon-Carbon.

In conclusion, concerning the proton injectors chain, the LIU baseline program is established to ensure production of LHC proton beams with parameters close to HL-LHC request (right brightness, and for the moment ~15% lower intensity per bunch than requested). A very dense machine and simulation study program is being carried out until 2016 to further improve our parameter estimates and take decisions at the latest during 2015 for few remaining pending items. In parallel, hardware specification, design and procurement activities are being conducted and should be completed to meet the LS2 installation target. Promising options have been also identified and are under study to increase the intensity and/or brightness of the LIU beams delivered to LHC. Additional studies are planned to validate these options, after which action planning and cost estimates will have to be defined. The use of high brightness has been shown to have some disadvantages and may clash with safety of the machine protection devices. Extensive studies are being performed on this subject to ensure safe operation of the machines.

DISCUSSION

Alessandra Lombardi

LINAC 4: Progress on Hardware and Beam Commissioning

N. Holtkamp asked about the nominal value of the current at the end of the Linac4. A. Lombardi replied that, as explained in her slides, this was 80 mA and overspecified for LHC beams, since they can also be efficiently produced with lower current from Linac4. M. Vretenar said that the specification of 80 mA came specifically from the target of doubling the intensity of the high intensity ISOLDE beam. This high value of current is only necessary if the PSB needs to deliver twice the present intensity to ISOLDE. Simulations of injection of LHC beams into the PSB are presently ongoing and the target is to establish the new emittance vs. intensity curve. N. Holtkamp asked how much budget is available to improve the source. Since the future source will use the power supply and extraction system already in place from baseline, this would be in the order of 1 MCHF.

B. Mikulec remarked that the PSB will be able to accelerate 2e13p only with full Finemet upgrade, otherwise the maximum current will be limited to 1.4e13p.

F. Bordry asked how much time would be needed to set up an emergency connection to Linac4 with protons in 2015, in case of Linac2 failure. A. Lombardi replied that this will strongly depend when the request comes, i.e. what is installed at that moment, but it can be estimated to be in the order of two months. R. Scrivens added that it would be desirable to have some test run with protons in order to be ready in case of emergency connection.

E. Benedetto pointed out that the number of turns needed to inject the future LHC beams is important to determine the final beam brightness, because the degradation through the foil has an impact on the final emittance.

Giovanni Rumolo

Protons: Baseline and Alternatives, Studies Plan

N. Holtkamp asked where the assumption of twice brighter beam from the PSB after connection to Linac4 come from. G. Rumolo replied that, in absence of detailed simulations of the future injection process, the assumption is just an extrapolation from the original idea of being able to produce with Linac4 LHC beams twice as intense as nowadays but within the same transverse emittance. Therefore, double brightness becomes our working assumption to calculate the future beam parameters. Detailed simulations of the H- injection process are being carried out and the simulated intensity vs. emittance curve (similar to the one presently measured that represents the PSB performance for LHC beams) will be in the future used for improving the parameter tables.

O. Bruning asked whether a bunch intensity of 1.7e11 ppb was already achieved in the SPS with 25ns. G. Rumolo replied that presently 1.3e11 ppb is considered the maximum bunch intensity achieved in MDs at the SPS flat top with four batches, because then signs of electron cloud and longitudinal instability appeared for slightly higher intensity, which led to no increase of the extracted intensity per bunch even while increasing the injected intensity. TMCI at 26 GeV is not a limitation and is not expected to be a limitation not even for the ultimate LIU bunch intensities, because the Q20 optics has extended the acceptable bunch intensity for stability from 1.7e11 ppb to about 4e11 ppb, leaving enough margin (as is discussed in detail in H. Bartosik's talk)

F. Bordry asked whether a decision on the coating of vacuum chamber needs to be taken by mid 2015 and why coating needs to be done in LS2 and could not be postponed to LS3. G. Rumolo replied that the idea of taking the decision in mid 2015 is motivated by the fact that by that point all the information from the SPS scrubbing runs will have been collected and will be available, thus we can draw a clear picture whether scrubbing is possible and efficient also up to high intensities or a-C coating is needed. B. Goddard added that, if a-C coating turns out to be necessary, we need to be ready after LS2, so that during Run 3 we can first recover the performance and then ramp up the performance of the injectors up to the LIU targets. Commissioning of the required high intensities for the HL-LHC run cannot be done quickly after the post-LS3 restart.

L. Rossi remarked that the gain from the longitudinal feedback in the PS is clear because it allows increasing the estimated maximum bunch current from 2e13 to 3e13 ppb at the PS extraction. He asked what the gain given by the increase of the injection energy to 2 GeV. G. Rumolo showed the performance diagram that shows the gain coming from the upgrade to 2 GeV alone. It is clear that in absence of this upgrade, we would not be able to produce the necessary brightness to meet the HL-LHC request because of a strong bottleneck of space charge at the PS injection.

N. Holtkamp_asked about the logics about coating and high bandwidth feedback in the SPS. If the new feedback system is meant to damp electron cloud instabilities, it would become useless if a positive decision on coating is taken. G. Rumolo answered that, if we look at the functionality of the feedback as a damper for electron cloud instabilities, this is strictly true. However, one should not neglect that the high bandwidth feedback system could be useful also against TMCI (and allow moving to different optics with weaker constraints on the required voltage, see talks of H. Bartosik and T. Argyropoulos) and that this system has a potential interest for other machines, like LHC.

N. Holtkamp asked whether it is possible to profit from the LIU upgrades as they are implemented, possibly also already before LS2. G. Rumolo replied that this is already the case. S. Gilardoni added that also during Run 2 all upgrades that are ready are already being used on operational beams, delivering an improvement on beam quality more than on the achievable beam intensity.

Verena Kain

Concerns with Low Emittance Beams Operation

N. Holtkamp asked when and where the HiRadMat tests can be done. V. Kain replied that the experimental area uses the beam coming from SPS and the line has a tunable optics to simulate the size of the future beams.

S. Redaelli asked how many spares are available for the TCDI. V. Kain replied that there are two horizontal ones and one vertical one. He also asked about the model for properties used in dynamic simulations, i.e. whether possible variations vs. temperature and stresses are taken into account. V. Kain said that, when available, dynamic models are taken into account, but often they are not available in great detail.

R. Losito asked which are the expectations from experiments, i.e. whether they will really need in the future extra-bright BCMS beams. Lucio Rossi replied that the emphasis is anyway on producing higher intensity rather than lower emittances.

R. Alemany asked whether 1) it is possible to change the optics in the transfer line to alleviate the limitation of the TCDI with the small emittance of the BCMS beam, and 2) what happens if the TDI breaks. V. Kain replied that detailed studies have not been done for post-LS1, however the margin to increase the beta function at the TCDI is very limited. Concerning the TDI, V. Kain explained that even if it cracked, it would still attenuate the beam as it is supposed to.

M. Lamont asked whether it is possible to better tailor the BCMS emittances to remain within the specs for the protection devices (specifically the TDI). V. Kain said that probably this is possible, but then we would need a reliable transverse beam quality monitoring (BQM) system to be sure that devices are protected against accidentally low emittances.

R. Schmidt and G. Arduini inquired about the uncertainties on the material properties in these estimations. A. Lechner said that for instance Boron Nitride (BN) is supposed to become very weak at high temperature, although there are doubts on the characterization.

O. Bruning asked whether collimators with rotatable jaws from SLAC could be an option. V. Kain replied that this is being considered. Tests are foreseen in HiRadMat first, and then in the SPS.

Hannes Bartosik

Other Means to increase the SPS 25 ns Performance - Transverse Plane

M. Meddahi remarked that MDs in the SPS to test and qualify the new Q22 optics will be done during Run 2.

N. Holtkamp asked whether the new transverse feedback system could help. H. Bartosik said it should help against TMCI. G. Arduini remarked that the 80-bunch option seems very promising and he asked whether it is possible to measure the bunch by bunch emittance for beam qualification, in particular to check if the transverse damper of the PS also affects the neighbouring bunches. H. Bartosik replied that this can be done at the SPS flat bottom, as was already done also in 2012. S. Gilardoni added that in principle the bunch-by-bunch measurement of the transverse emittance is also available at the PS extraction, as the necessary hardware has been installed.

Theodoros Argyropoulos

Other Means to Increase the SPS 25 ns Performance - Longitudinal Plane

G. Rumolo asked whether the 800 MHz system could, be used for the bunch rotation at flat top. E. Shaposhnikova replied that it is already used for bunch shortening, but beyond that the available voltage will not be enough for a real bunch rotation at flat top even after the ongoing renovation.

R. Alemany asked why there are visible differences between measurements and simulations of the bunch lengthening due to microwave instability at flat top:. T. Argyropulos replied that there could be different reasons to account for this difference, for example the impedance model is not complete, or there are also errors in the bunch length measurements.

N. Holtkamp asked what is presently within the LIU baseline in terms of improvement against the longitudinal instabilities. T. Argyropoulos replied that the power upgrade of the 200 MHz system is in the baseline, while there are not yet any concrete proposals in terms of reduction of the impedance of the vacuum flanges. N. Holtkamp asked then whether the option of having longer magnetic cycles can have an impact on the power supplies. E. Shaposhnikova replied that in principle this is not the case, but this will be anyway tested experimentally soon with the doublet production.

Michael Bodendorfer

Ions: Baseline, Studies Plan and Strategy for Pending Options

M. Meddahi remarked that the LHC will be ready for the upgraded ion beam soon after LS2, therefore it is crucial that we are sure we can deliver it already before going into LS2.

J. Jowett said that we should remember that proton beams are also important for the p-Pb part of the programme. In particular, special proton beams of moderate bunch intensity should be prepared with filling schemes designed to match those of the Pb beams. This was not trivial for the 2013 p-Pb run. A scheme still has to be worked out to match the alternating 100/225 ns Pb beam in Run 2, although it might be easier for the more regular 50 ns spacing that we now expect after LS2. Moreover, it is not so easy to gain factors in integrated luminosity beyond what was achieved for p-Pb in 2013, especially if the LHC will run at the same energy, as may be requested. Therefore, it is probable that, unlike in the present schedule, to achieve the requested p-Pb luminosity goals, it will be needed to have more than 3 p-Pb runs and fewer than 8 Pb-Pb runs during the HL-LHC period. This will of course make it harder to reach the long-term integrated luminosity goal for Pb-Pb. Another way in which a substantial gain in performance could be made is to mitigate the degradation along the trains in the SPS (due to IBS, space charge and RF noise). D. Manglunki observed that some measures will be already taken in Run 2 to make progress on this front, i.e. RF noise reduction through the fixed harmonic at flat bottom and the use of the Q20 optics, which has also already helped a lot for the SPS performance. The improvement of the SPS performance will keep receiving the necessary attention.

W. Höfle asked what is needed to achieve an increased Linac3 repetition rate. R. Scrivens replied that it requires an upgrade of the RF system and some power converters. He also clarified that inside the baseline for LIU-IONS for Linac3, is an increase of the injection rate to 100ms, and a study to investigate production of higher intensity improving the low energy transport. The higher intensity is speculative and therefore not itself part of the baseline.

R. Alemany asked how long the injection time into LHC will be. A longer injection time could spoil the potential of luminosity increase with the new ion beam parameters at LHC injection due to IBS at 450 GeV. D. Manglunki replied that the LHC filling time will be between 45’ and 1 hour.

S. Redaelli asked why the target peak luminosity is 7e27 Hz/cm^2. J. Jowett replied that Michael’s focus on the peak luminosity formula was only for simplicity of presentation. In reality, it is integrated luminosity that counts and this value would probably not be reached with the beam parameters described. However, we should keep looking for ways to increase it. In any case, there is a detailed model of luminosity that takes into account the variations along the trains, injection times, luminosity evolution during a fill, etc. and this will be used to optimise the SPS train length. This will result in somewhat shorter bunch trains in the SPS and somewhat fewer bunches in the LHC (see talk at RLIUP last year).

ACKNOWLEDGMENTS

The session conveners are particularly grateful for the assistance given by the members of the LIU Project Team, J. Coupard, H. Damerau, A. Funken, S. Gilardoni, B. Goddard, K. Hanke, B. Holzer, A. Lombardi, D. Manglunki, B. Mikulec, E. Shaposhnikova, M. Vretenar. Furthermore, we wish to thank the speakers, T. Argyropoulos, H. Bartosik, M. Bodendorfer, V. Kain, A. Lombardi, for their excellent presentations, which were well timed and focused on the relevant items. Last but not least, we would like to express our great appreciation to the former LIU project leader, R. Garoby, for all the work done on the project up to the very moment of his departure and the full support offered to the new management.

SUMMARY OF SESSION 6: HL-LHC

O.S. Brüning and P. Ferracin, CERN, Geneva, Switzerland

Abstract

This paper summarizes the HL-LHC session of the 2014 Chamonix performance workshop that took place from 22^{nd} until 25^{th} September 2014 in Hotel Les Aiglons in Chamonix.

HL-LHC SESSION LAYOUT

The HL-LHC session featured 6 dedicated individual presentations:

- A summary of the HL-LHC parameter and layout baseline by Paolo Fessia;
- A presentation of the HL-LHC Roadmap for magnet development by Ezio Todesco;
- A presentation of the HL-LHC Roadmap for SC RF development by Rama Calaga;
- A discussion of alternative scenarios for the HL-LHC parameters and layout by Rogelio Tomas;
- An outline of the Roadmap for the HL-LHC Collimations and Machine Protection (MP) by Stefano Redaelli;
- A summary of Down-Selection criteria and requirements for Machine Development studies in the SPS and LHC prior to LS3 by Gianluigi Arduini.

HL-LHC PARAMETER AND LAYOUT BASLINE

Paolo Fessia started the presentation with a summary of the HL-LHC baseline parameters for operation with 25ns bunch spacing and compared the parameters to the nominal LHC, the BCMS parameters for operation with 25ns bunch spacing and a 50ns backup option for the HL-LHC and highlighted that all HL-LHC equipment should not only be designed for the nominal HL-LHC parameters, but rather for the most demanding parameters that arise from the various options that are currently studied in addition to the HL-LHC baseline (e.g. higher than nominal beam brightness due to bunch schemes with lower emittances). This part of the presentation triggered the need for a clear identification of what maximum beam brightness the HL-LHC equipment should be designed for. The discussions concluded that a first iteration should identify the maximum acceptable parameters for the current equipment designs. These discussions should be carried out in collaboration with the LIU team.

Concerning the HL-LHC harder modifications, Paolo divided the activities and required changes for the HL-LHC upgrade into three separate categories: changes for equipment that will act on the beams, other equipment in the LHC tunnel and equipment changes on the surface. He presented the main required modifications for the HL-LHC baseline and for some of the potential variations. The layout discussions for the HL-LHC have mainly been focused on the IR1 and IR5 insertions and Paolo presented detailed studies for both of these insertions including discussions on the options for underground and on-surface installations of the power generators for the new Crab Cavities and variations coming from flat beam versus round beam operation (e.g. implications on the TAXN design).

The presentation triggered the following main questions and comments:

- Questions about the baseline scenario and budget lead to the following statements
  - The crab cavities are in the baseline, including the engineering work. The crab kissing is not in the baseline.
  - Everything of the baseline is included in the budget, except for the civil engineering work in the underground areas.
- Considering the issue of the event pile-up limitations in the detectors and the resulting limitation on the peak luminosity, it is important to quantify the required availability for all systems to reach the HL-LHC performance goals.
- Concerning the question of stochastic cooling it was stated that this is not part of the HL-LHC baseline.
- Concerning the request for new, large aperture Q5 magnets in the experimental insertions, it was observed that this configuration is not compatible with large β^* configurations ($\beta^* > 40m - 50m$).
- In light of the current number of quenches expected in the machine, is it realistic to plan for an operation at 'ultimate' performance for the HL-LHC machine? Yes, this is important for the system design point of view and should be considered like an operational margin for the HL-LHC equipment.

HL-LHC MAGNET ROADMAP

Ezio Todesco summarized the magnet design evolution for the HL-LHC triplet magnets within the USLARP program and presented the new triplet layout with the 150mm coil diameter Nb_3Sn magnets. The layout features two magnet lengths: 6.8m and 8.0m. The magnets will operate at a gradient of 140 T/m. The 150mm diameter magnets use an Al shell with bladders and keys and two strands (PIT and RRP) with identical specifications. The new triplet requires the production of 16 magnets plus 4 spares. Half of the units will be produced as an external contribution from the US and the other half by CERN. The production planning foresees prototype production from 2016 to 2018 and series production from 2018 to 2021. Ezio also presented the status and plans for the triplet corrector magnets (orbit corrector and nonlinear field corrector magnets), for the new, superconducting D1 and D2 separation and recombination dipole magnets, for the new large aperture standalone quadruple magnets and for the 11T dipole magnets for the dispersion suppressor collimator installation.

The presentation triggered the following main questions and comments:

- Concerning the risk assessment and mitigation it was commented that one big risk is that the 'series production' comprises only small numbers of magnets which might make it difficult to find companies that are willing to produce them.
- Concerning the absence of quench heaters in some of the new insertion magnets it was commented that this implies an energy extraction system which may be more expensive. It was asked if this is really the best solutions? Ezio replied that different protection options are still being considered and investigated. This is still work in progress.

HL-LHC RF ROADMAP

Rama Calaga gave an overview of the past experience with superconducting (SC) RF development at CERN and presented the HL-LHC RF baseline, featuring 32 new superconducting Crab Cavities (SC CC), making this new system the largest RF installation of the HL-LHC. The SC CC development featured the development of three different conceptual designs that have been developed to prototype construction. Following the successful tests of all prototypes the options have been down selected to only two options in order to assure an in time production of fully cryostated prototypes for installation in the SPS during the technical stop 2016/2017. The operation in the SPS with beam is a vital validation procedure that needs to be completed before one can launch the series production of the SC CC for the HL-LHC upgrade. Rama presented the new cryostat design for the SC CC and presented the experimental setup in the SPS machine. The rather large infrastructure requirements in the LHC tunnel impose rather challenging civil engineering problems that are still being evaluated.

Additional options for the HL-LHC upgrade include either a second higher (e.g. 800MHz) or lower-harmonic (e.g. 200MHz) RF system.

The presentation triggered the following main questions and comments:

- The question about spare cavity modules was raised. Rama replied there is currently no valid spare cavity module for the nominal 400MHz system. However, the removed faulty 400MHz module could be refurbished and prepared as a new spare once the commissioning of the newly installed 400MHz module has been successfully finished.
- Erk Jensen comments that the SC RF development and R&D efforts are not only beneficial for the HL-LHC but serve several potential future developments. Only the SC CC development if entirely funded within the HL-LHC project.

ALTERNATIVE SCENARIOS FOR THE HL-LHC

Rogelio Tomas presented several areas and scenarios where alternative configurations could offer additional performance reach or mitigation of performance limitations:

- Longitudinal coupled bunch instabilities could be mitigated by a second higher or lower RF system.
- Limitations due to the electron cloud effect could be mitigated by special filling schemes (e.g. 8 bunches followed by 4 empty bunches, the 8b+4e filling scheme).
- In case crab cavities are not operational, the performance could be boosted by the operation with flat beams at the Interaction Point (IP), the use of Beam-Beam Long Range Compensators (BBLRC), and a lower-harmonic 200MHz RF system.
- β^* levelling for peak pileup, Crab kissing and flat longitudinal beam profiles via 200MHz, 800MHz or RF phase modulation could improve the HL-LHC performance in case the peak longitudinal event pileup density in the detectors limits the leveled luminosity.

All the above HL-LHC options could, off curse, also be used for boosting the HL-LHC beyond the nominal performance target of $250fb^{-1}$ per year with an event pileup density limit of 1.2 events per mm per bunch crossing.

The presentation triggered the following main questions and comments:

- The presentation seems to imply that the HL-LHC can accept much longer bunches as compared to the LHC baseline. It was asked what changed with respect to the LHC baseline? Rogelio replied that:
  - The experiments are willing to take longer bunches, but this could create problems. Work is in progress. Nevertheless, longer bunches will not increase the luminous region assuming to be limited by the crab cavity RF curvature.

- In the LHC design phase, 200 MHz superconducting cavities were not an option.

- Concerning the operation with Crab Cavities it was asked if we are sure that a 200 MHz RF system does not increase the non-linearities of the crab-cavities and does not degrade the machine performance? Rogelio replied that current and previous studies do not show any problems due to the Crab Cavity operation with longer bunches.
- It was observed that the performance indications rely on rather complex computations and it was asked how confident we are about the projections? Rogelio replied that the main uncertainty is related to the wire compensation of the long range beam-beam effects. For the wire compensation there will be a task focusing on simulations and experiments. Furthermore, the HL-LHC project plans for an experimental validation of this option in the LHC before LS3 using new prototype wire compensators for MD studies. For the performance projections due to the use of new cavities and magnets, we are rather confident.
- Are there any issue of beam instability related to the 200 MHz RF scenario? Rogelio replies this is difficult to predict right now as the LHC RunI operation was already affected by beam instabilities. Answering this requires more machine studies in the LHC.

HL-LHC COLLIMATION AND MACHINE PROTECTION ROADMAP

Stefano Redaelli showed a summary of the collimation performance during LHC RunII and summarized the planed collimation modifications for the LHC consolidation and the HL-LHC upgrade. The modifications address five main areas:

- Impedance issues and collimator robustness.
- Cleaning efficiency and setup time.
- Loss spikes and drops in the beam lifetime and beam halo control.
- Collimation next to the experiments.

Studies options include new collimator materials and coatings, rotatable collimators, the integration of Beam Position Monitors (BPMs) in the collimator jaws, installation of collimators inside the cold regions of the dispersion suppressors, hollow electron lenses for beam halo control, crystal collimators and dedicated collimators (e.g. next to the TAXN) next to the experiments.

Stefano Redaelli also reported on the upgrade plans for WP8 (machine detector interface) and WP14 (injection and dump protection), recalling that, as part of HL, it is planned to change the injection protection devices in IR2/8 (mainly, the TDI's that will be replaced in LS2) and the present TAN that will be replaced by a TAXN at the same functional position.

There was no time for questions after the presentation.

DOWN SELECTION CRITERIA AND REQUIRED MD STUDIES PRIOR TO LS3

Gianluigi Arduini summarized the main points that still require a validation via Machine Development (MD) studies. The main studies are related to:

- Chromatic properties of an optics with very low β^* and identification of the maximum acceptable chromatic aberrations during operation.
- Efficiency of the electron cloud mitigation via beam scrubbing (this will be addressed during the startup of the LHC RunII in 2015).
- Operation with β^* levelling.
- Operation with large beam-beam tune spread (what is the beam-beam limit in the LHC with long-range beam-beam encounters?).
- Possibility of operating the LHC with a combined collide and squeeze process.
- Determination of the dynamic aperture in the machine with flat beam configuration.
- Measurement and experimental demonstration of an active manipulation (depletion) of the beam halo population.
- Detailed impedance measurement at 6.5TeV and estimation of the maximum acce[table beam intensities.
- Experimental demonstration of long-range beam-beam compensation using a wire.
- Operation with flat longitudinal beam profiles (e.g. generated via RF phase modulation).
- Efficiency of Crystal collimators during LHC operation.

Gianluigi Arduini underlined that most of the above studies could already be relevant for the LHC RunII and RunIII. There is therefore a strong case to aim for a validation of most of the above points already during the LHC RunII period.

The presentation triggered the following main questions and comments:

- It was asked if there are any plans to test the Crab Cavities the LHC following the tests in the SPS? Gianluigi Arduini replied that there are at the moment no tests foreseen in the LHC.

- What is the possibility of levelling the luminosity with Crab Cavities? Gianluigi Arduini replies that this method increases the longitudinal pile-up density and is therefore not the preferred solution for luminosity levelling.

MAIN POINTS FROM THE GENERAL QUESTIONS AND ANSWER SESSIONS

The general Q&A period at the end of session raised the following main points:

- It is important to quantify the required availability and efficiency for each component and the HL-LHC machine as a whole for reaching the HL-LHC performance goals (the HL-LHC must be a high reliability machine!).
- Stochastic Cooling (for Ion operation) is not in the HL-LHC Baseline.
- Issue of small series production and risk mitigation (multiple producers).
- Need for clarification of spare RF components for new HL-LHC equipment.
- Interplay of 200MHz LH RF system and 400MHz Crab-Cavities (non-linearity).
- Are there plans for testing Crab Cavities in the LHC after the SPS tests and before HL-LHC? This has been looked at at in IP4 but the implementation would have an impact on LHC schedule!
- Dynamic β^* levelling and NOT Crab cavities adjustment is the preferred luminosity levelling method (pending MD validation).

SUMMARY OF SESSION 7: ACCELERATORS AND NON-LHC EXPERIMENT AREAS CONSOLIDATION UP TO LS3

M. Benedikt, F. Sonnemann, CERN, Geneva, Switzerland

Abstract

The session on non-LHC consolidation aimed at establishing a coherent view of the main consolidation activities planned until end of LS2 (2019), with an outlook on major activities until 2023, grouped by machine(s) or experimental area(s), across all the technical groups and covering all accelerators and experimental areas, except the LHC. The session did not include items covered by the LIU or other construction projects. A focus was put on the analysis of consolidation requests per machine/facility, as seen from operations. Therefore the analysis was limited to technical systems and system groups closely linked to machine operation.

This paper summarises Session 7 on the non-LHC accelerators and experimental areas consolidation up to LS3. The main topics covered during the presentations are briefly recalled.

SESSION PROGRAM

The program of the session included 6 talks addressing ongoing, planned and longer-term consolidation activities for the non LHC accelerators and experimental areas:

- “Linacs” by Richard Scrivens (BE).
- “PSB and PS consolidation for LS2 and beyond” by Simone Gilardoni (BE).
- “SPS consolidation for LS2 and beyond” by James Ridewood (BE).
- “AD and LEIR” by Tommy Eriksson (BE).
- “North Area and East Area” by Adrian Fabich (BE).
- “ISOLDE and n_TOF consolidation” by Richard Catherall (EN).

To enable the fact-finding in the preparation phase, the different technical groups concerned with consolidation activities have been asked to present their planning in IEFC meetings, with the request to address in particular the following aspects:

- A complete overview of already planned consolidation work units together with those considered necessary, but that are not yet planned.
- A tentative and realistic planning for all consolidation work units.
- Identification of the amount of manpower required as a function of the planning.
- Estimation of the financial resources required for the planned or proposed spending profile.
- Identification of “consolidation” requests that might interfere with or fall under a construction project to enable discussion and clarification.

TALKS SUMMARY

Linacs

The consolidation requests for Linacs 2 and 3 were summarised and prioritised, as well as the requests for the transfer line between Linac2 and the PSB which will be reused for Linac4 beams in the future.

PSB and PS Consolidation for LS2 and Beyond

The consolidation activities proposed for the PSB and PS until the end of LS2 were revised. Particular attention was given to the activities with direct impact on machine operation and machine performances. An analysis on the interventions and priorities proposed was done on a system basis (e.g. injection, extraction, RF, beam instrumentation, etc...), with the goal of verifying that the consolidation activities of a specific item or system are consistently taken into account by the different technical groups.

SPS Consolidation for LS2 and Beyond

This presentation gave an overview of the consolidation plans concerning the SPS and its transfer lines as provided by each of the equipment groups to the IEFC committee. The overview was presented from a perspective of machine operation. These proposed consolidation activities were reviewed, focusing principally on the impact on operation with beam, with the aim to highlight any of the works which are of particular interest or represent a particular concern for SPS machine operations.

AD and LEIR

As the AD programme now faces a renewed lease of life following the start of construction of the ELENA project, it is essential to ensure best possible reliability and performance for the next 20 years or so. The AD machine, which was started in 1999, is based on the Antiproton Collector (AC) ring of the Antiproton Accumulator Complex (AAC) which in turn was constructed in the mid-80ies meaning that there is a significant amount of 30-year old technical equipment to deal with.

The situation is similar for LEIR, having started life in the 80-ies, supplying antiproton beams at various energies for the PS physics programme. After having been transformed into a heavy ion accumulator in 2004 and subsequently used in operation, some consolidation needs became apparent. LEIR is expected to keep delivering heavy ions to the North Area and to the LHC until 2035.

The consolidation programme for both machines was discussed, focusing on the main items of ongoing and planned activities from an operational point of view.

North Area and East Area Consolidation

The PS East Area (EA) and the SPS North Area (NA) are world-wide unique facilities of CERN that provide secondary beams to numerous different experiments every year. They represent a core activity of the laboratory and are beside LHC, the main reason for continuous operation of the injector complex to high energies.

The amount of technical installations related to the experimental areas is large, in terms of km of tunnels, installed equipment, infrastructure needs, etc., comparable to that of SPS machine. The relevant consolidation items identified by the technical groups as presented in the IEFC sessions were summarized in the presentation.

ISOLDE and n_TOF Consolidation

While progress continues on the upgrade of the REX-ISOLDE post-accelerator within the HIE-ISOLDE project, assuring the production of RIB for an approved and demanding physics program will require extensive maintenance of the existing facility. The main consolidation requests driven by operation include: replacement of the ISOLDE target stations, more commonly known as Frontends, renovation of the Resonant Laser Ionization (RILIS) equipment and operation of the REXEBIS and REXTRAP - the low energy systems of the REX-ISOLDE post-accelerator.

However, the radiation protection issues associated with the present performance of ISOLDE and the potential consequences associated with a possible increase in p-beam power should be considered. Consequently, consolidation of the overall shielding of the ISOLDE target area was presented along with the need to replace the ISOLDE beam dumps, both crucial to the exploitation of ISOLDE after the commissioning of Linac 4.

The n_TOF Facility also successfully started its physics program in July 2014 making more efficient use of the neutron flux following the commissioning of EAR2, the second experimental area above the n_TOF target. However, installed in 2008 and with a projected lifetime of approximately 10 years, the present n_TOF neutron spallation target is already showing initial signs of surface corrosion. The monolithic Pb block along with its cooling system cannot be repaired due to both its design and expected dose rate after removal and will therefore have to be replaced during the LS2 period to ensure reliable physics after LS2. Further major consolidation requirements include the dismantling of the first n_TOF target cooling station and the replacement of the power converter and controls of the sweeping magnet in EAR1.

Finally, common to both facilities is the radioactive environment of each target area and the need to intervene within a given time window to benefit from a maximum of radioactive cooling. This implies that all preparation and construction of replacement equipment be ideally completed before the start of the LS2 period.

CLOSING REMARKS

The session dedicated to non-LHC consolidation turned out very beneficial to discuss and understand priorities for consolidation requests from machine operation point of view. It completed input for decisions on consolidation budget allocations in autumn 2014.

Amongst the issues that came up in discussions were e.g. the responsibility for DC cables that was assigned to EN-EL group. Other important technical aspects were the cable cleaning campaigns for PS and SPS complex that disserve major attention because of the large impact on many systems to be installed during LS2. Another major point that needs to be addressed is the apparent incompatibility of North Area consolidation with LS2 planning in terms of personnel availability for the LHC injector consolidation and LIU project. In a more general context it was noted that there is a divergence between the identified areas requiring consolidation and the available (personnel) resources to execute the work packages, leading systematically to too high requests on material budget for consolidation and constant carry-forward.

To enable adequate planning and coordination, a centralized documentation of all consolidation requests is being created using APT, CERN’s standard management tools for resources allocation. This will be complemented by standardized documentation for all consolidation requests in EDMS, containing a brief technical description of the system concerned, a risk analysis, estimates of budget and personnel resources as well as considerations on impact on operation and maintenance and other relevant information.

This approach is also expected to provide a clearer picture of the support required from other groups, which should ease the prioritization and planning process as well as the execution of the work in line with the approved resources allocations. However, consolidations activities need also to be reviewed in co-ordination with the progress of the HL-LHC, LIU and other construction projects, in particular in view of the very limited available personnel resources until and during the LS2 period.

ACKNOWLEDGMENTS

Many thanks to all speakers and to the contributors to the presentations.

Particular thanks to Roberto Saban and Rende Steerenberg for their help in the preparation of this session and for organising a series of preparatory meetings with all technical groups concerned in the IEFC.

SUMMARY OF SESSION 8: LONG SHUTDOWN 2 STRATEGY AND PREPARATION

J.M. Jimenez, J-Ph. Tock, CERN, Geneva, Switzerland

Abstract

This paper summarises Session 8 on the Long Shutdown 2 (LS2) Strategy and Preparation. The main messages addressed during the presentations are reviewed and the key elements discussed are detailed.

SESSION PROGRAM

The program of the session included 7 talks addressing general aspects (Organisation & Safety), LHC Experimental areas and the two main projects on Injectors and LHC:

- Scope of LS2 (making best use of the period 2015-2018) by José Miguel Jiménez (TE).
- What has been learnt from LS1 by Katy Foraz (EN-MEF).
- Safety & Radiation Aspects by Doris Forkel-Wirth (HSE-RP).
- LIU Planned Activities by Julie Coupard (EN-MEF).
- HL-LHC Planned Activities – Accelerator by Isabel Bejar Alonso (HL-LHC Project Office).
- LHC Experiments Upgrade and Maintenance by Werner Riegler (on behalf of LHC Experiments).
- LS2 @ LHC by Marzia Bernardini (EN-MEF).

TALKS SUMMARY

Scope of LS2

The project scope covers all activities carried out and resources needed in the context of Long Shutdown 2 over the whole CERN accelerator facilities. It includes the preparation, coordination and follow-up till completion of all LS2 activities done in the frame of the LIU, HL-LHC Projects and other CERN approved projects (Fig.1).

The flexibility to use the end-of-year technical stops before and after the LS2 to decrease the workload during the LS2 is left at the discretion of the LS2 Coordinator and is also part of the scope of the project.

What has been learnt from LS1

The importance of implementing a tool (PLAN.CERN.CH) to collect and prioritize the activities using a unique repository has been underlined. This repository will ease the information exchange between groups since, they will have a clearer picture of the support to be given to other groups. This attenuates bad surprises and eases the prioritization process for the LS2 Coordination Team, allowing focusing only on discordance points. The feedback from LS1 showed that:

- the tool should have come earlier,
- not all activities were announced,
- duplication of resources between APT and PLAN.

To improve the situation in the future, LS2 will use an upgraded version of the PLAN tool to collect future activities. Groups will be given enough time to upload their requests and provide feedback on the requested support. The tool will get improved to better fit with Users and Coordination needs, homogenising the granularity between items and avoiding redundancy with other tools.

The central role of the coordination has been recalled, focusing on the added value to help keeping a very good follow-up on fields, to enhance team spirit & eases information flow and, last but not least, improve safety by reducing as much as possible co-activity

In terms of schedule management, it is proposed to keep a member of coordination team (scheduler) within projects; this would allow a decrease in the impact of delays in component availability or acceptance tests by globally optimising the schedule. Actions need to be taken to optimize the start of an activity w.r.t. radiation cooling period, to avoid shortening too much the available working period.

The documentation will remain a priority, ensuring that the Engineering Change Requests (ECR) get presented on a regular basis in the LS2 Committee (LSC) and then in the LMC or IEFC for LHC and Injectors respectively. This implies proactive actions to have the ECRs edited in due time.

The daily management will be maintained since helping to keep working with the same references. The information exchange will get reinforced to ensure that information flows down to the worksites. One pending difficulty is to rationalise the information provided by Projects since an excess of details, important for the Project follow-up, can create confusion when delivered at a coordination level. This will be compensated by maintaining a web page indicating hyperlinks to the Projects.

In terms of logistics, temporary storage, buffer zones and “bases de chantier” have to be sized and planned sufficiently in advance. Finally, the need to implement and maintain a repository of service unavailability is positively considered.

Safety & Radiation Aspects

The Regulatory Landscape is introducing new constraints which need to be seriously considered during the LS2 preparation. Indeed, it will impact work frames, co-activities, logistics and overall safety. The impact will be evaluated in the coming months and scenarios will be prepared and discussed with concerned Groups.

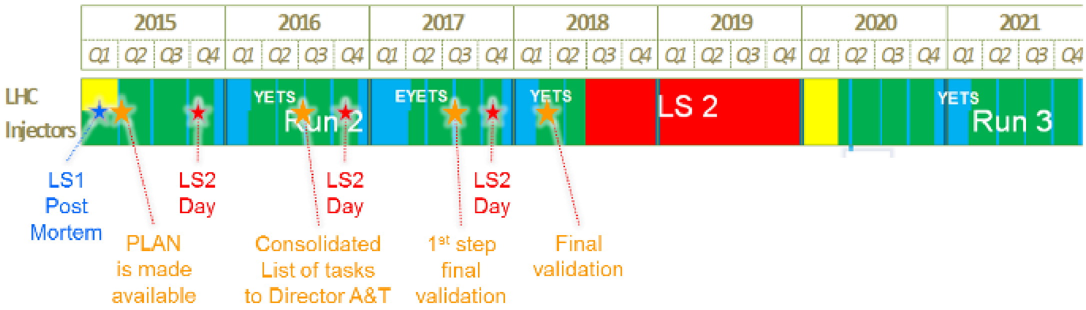
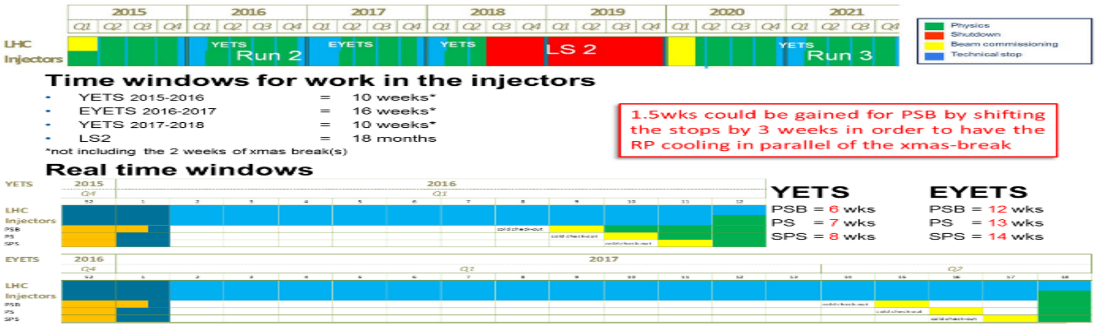


Figure 1: LS2 Period with main milestones.



Time windows for work in the injectors

- YETS 2015-2016 = 10 weeks*
- EYETS 2016-2017 = 16 weeks*
- YETS 2017-2018 = 10 weeks*
- LS2 = 18 months

*not including the 2 weeks of xmas break(s)

1.5wks could be gained for PSB by shifting the stops by 3 weeks in order to have the RP cooling in parallel of the xmas-break

Real time windows

YETS
PSB = 6 wks
PS = 7 wks
SPS = 8 wks

EYETS
PSB = 12 wks
PS = 13 wks
SPS = 14 wks

Figure 2: Schedule of LIU.

The training preparation and communication will get high priority. Actions will be taken to have all information and training sessions prepared in due time.

The needs for radioactive storage in surface building and the required handling means will need to be actively evaluated to be better prepared. The case of radioactive waste management (volume & weight) is a major issue. Indeed, all components coming out from the tunnel need to be considered as potential radioactive wastes and follow a severe checking path, requesting lot of resources. In view of LS2, the Group’s projections will need to be more accurate.

Some impact must be expected following the decisions to delay the construction of the Bld181 radioactive magnets facility. Thus, the need to share other infrastructures by radioactive and non-radioactive components is a reality and needs to be discussed.

Looking at the dose rates to personnel, the Injectors will dominate the personnel dose rates even though situation in LHC will not improve. CERN individual dose objective of 3 mSv over 12 consecutive months will be more challenging. Some Groups already concerned by this limit during LS1 shall study the situation and give feedback on the opportunity to keep this threshold value. It is important to highlight that during LS1, ALARA procedure has become an essential and natural part of CERN culture. This will help to set the roadmap towards LS2, thanks to the lessons learnt from LS1.

LIU Planned Activities

The LIU activities fit in the LS2 time window defined for the injectors but the schedules are very tight with not much margin and already assuming shift work. This implies that the consolidation prioritization needs to be coherent with LIU activities.

However, at this stage, still additional studies are required:

- Evaluation of the cabling work load as early as possible in order to estimate the EN/EL workload and integration.
- Levelling of the resources of the support/client groups, for example: EN/MME, EN/HE, EN/CV, EN/EL, EN/MEF-SU, GS/CE, TE/VSC. A typical case is the EN-EL cabling for LIU-PSB is already planned in 3 shifts per day.
- Integration studies which need to be completed: 3D models of infrastructures and general services.
- Finalization of the needs for design and production of manufacturing drawings.
- Definition of the works that can be anticipated in YETS and EYETS.

An optimisation of the planning is still possible, as an example, shifting the stop of PSB by 3 weeks could result in a net gain of 1.5 weeks since the radiation cooling time will get in parallel with the Christmas Break (Fig.2). This potential optimisations will be followed in the future in collaboration with the Operation Group.

HL-LHC Planned Activities - Accelerator

Despite the fact that the main interventions in the CERN accelerator complex for HL-LHC will take place during LS3, a substantial amount of work will occur /many work packages have foreseen activities during LS2.The HL-LHC is less advanced in term of shutdown preparation, many activities are getting defined. However, at this stage, it is important to outline that Groups must identify and prepare the work which can be done in LS2 on the time frame allocated and provided that the technology/solution is mature and cannot bring any risk to the Run 3 start date and machine availability.

The driving concern is obviously the integration of components as early as possible in the 3D integration drawings and in the HL-LHC work planning of LS2 (Fig.3 and 4).

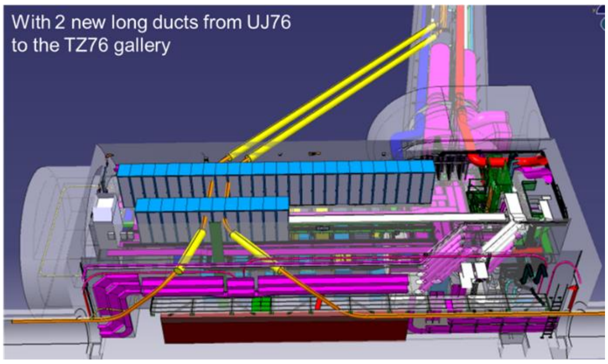


Figure 3: Example of integration of the superconducting links in UJ76.

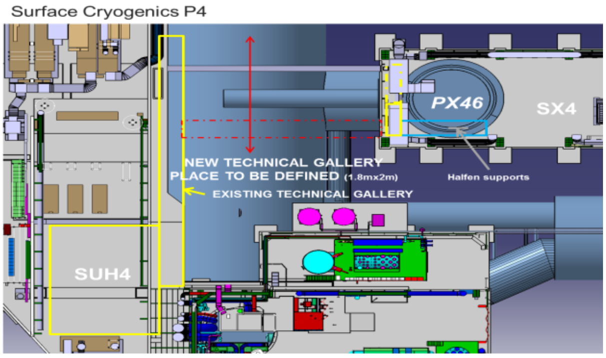


Figure 4: Example of integration of cryogenic components in surface buildings.

Experiments Upgrade and Maintenance

The four LHC Experiments have foreseen major overall during the LS2 period (Fig.5) and already announced that they will need more support from infrastructure Groups of the Accelerators and Technology Sector during that period but also for the preparation **before** LS2. ALICE and LHCb will implement major upgrades with important changes to the entire apparatus, while ATLAS and CMS will perform their major detector upgrades only during LS3. However, the overall scale of the LS2 operations is quite similar for all experiments and especially, the LS2 plans for the IP1 and 5 forward regions (Totem, Alfa, roman pots, movable beam pipes) are being developed.

ATLAS (Fig.6) has implemented many upgrades and medium term consolidation items for Run 2 and Run 3 already during LS1. A new central beam pipe and an additional layer of Pixel detectors, the insertable B-Layer (IBL), were installed during LS1. The experimental beam pipes made from stainless steel were changed to Beryllium and Aluminium for reasons of background and activation. The planned PHASE1 upgrade for ATLAS is detailed in four technical design reports. Beyond the standard maintenance there are at this moment no major foreseen implications on the technical department.

The CMS Phase 1 upgrade was started in LS1 but will continue till LS2, using all opportunities during Run 2 [TS, YETS and EYETS] between 2015 and LS2 (Fig.7) as described in three technical design reports.

The central beam pipe was changed in LS1, the forward experimental beam pipes will be changed to Aluminium in LS2. The UPS system will be upgraded and the electrical infrastructure has to be upgraded as well. An increase of chilled water production and a dry gas system upgrade for Phase2 detectors will also be implemented.

The installation of a second UXC crane with suspended cage for personnel access and replacement of the elevator will also be done during LS2.

Since the detector will be completely opened, the upgrades and detector maintenance efforts are on the same scale as LS1, so transport, rigging, survey & FSU support on the same scale as during LS1 are needed.

The Phase1 upgrade of ALICE (Fig.8) will see major changes to the entire apparatus. This upgrade is detailed in 5 technical design reports referring to the Inner Tracking System (ITS), the readout and trigger system, the Time Projection Chamber (TPC), the Muon Forward Tracker (MFT) and the Online-Offline System. The space and electrical power availability for the computing farm needs to be checked to act consequently.

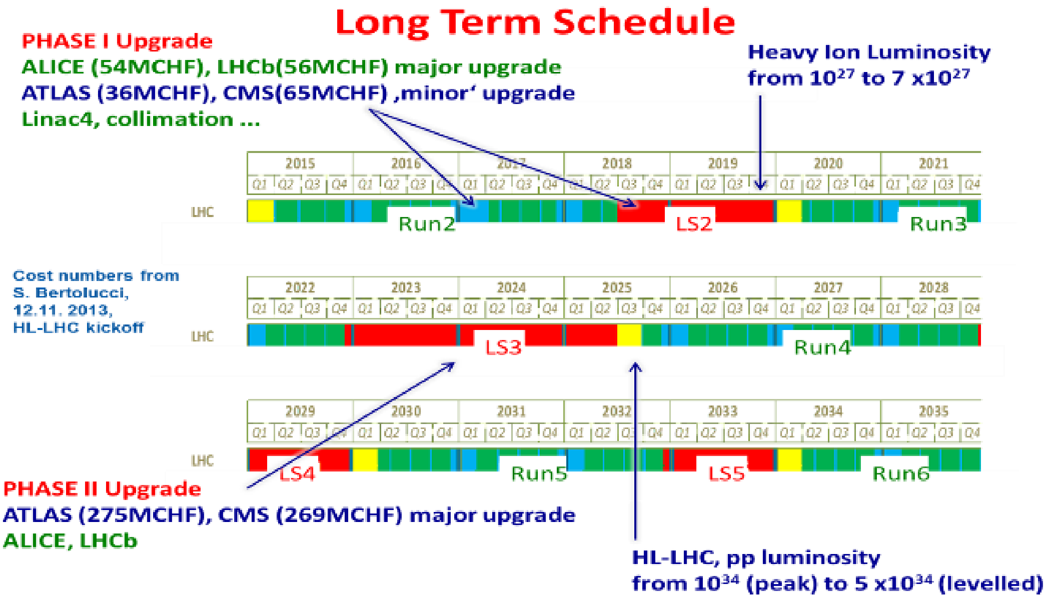
A new central beam pipe and its mobile bake-out equipment have to be developed. A modification of Miniframe beam pipe, the displacement of the central gauge as well as the implementation of an ion pump made using an Aluminium body are foreseen. Optic fibres have to be installed, the option to use the EYETS 2016/2017 is studied. A new cooling plant is needed for the new ITS detector, and a possible new dry air ventilation system is studied. The change of the elevator to the UX cavern is essential at the earliest possible time.

Vacuum consolidation to achieve the lowest possible level of beam-gas background is essential. To allow maximum Pb-Pb luminosity, collimators in dispersion suppressor region need to be implemented.

The Phase1 (Fig.9) upgrade of LHCb foresees major changes to the detector. All frontends are upgraded to read events at the full 40MHz collision rate into the online farm and several detector systems are exchanged in order to cope with much higher readout frequency. The upgrade is detailed in four technical design reports referring to the Vertex Locator (Velo), the Tracker, the Particle Identification (PID) and the Trigger and Online system.

A large new computing farm will need a surface building or a dedicated container. All beam pipes in the cavern must be removed and then reinstalled during LS2 without changes. Probably a TAN will have to be installed around LHCb. Optical fibres will get pulled from the experimental hall up to the surface. The EYETS 2016/2017 is an option. The planned changes of elevator and crane have to be properly scheduled to minimise impact.

For integration of cables, cable trays, cooling lines, access platforms as well as supervision of the service installation activities, LHCb relies on the EN-MEF Group.


Long Term Schedule

PHASE I Upgrade
ALICE (54MCHF), LHCb(56MCHF) major upgrade
ATLAS (36MCHF), CMS(65MCHF) ,minor' upgrade
Linac4, collimation ...

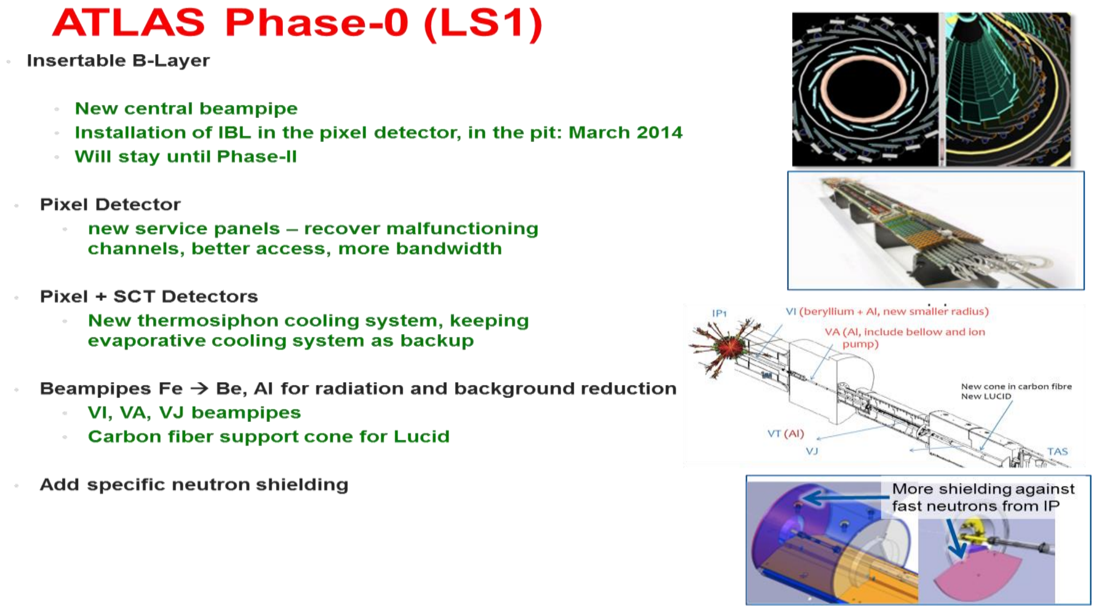
Heavy Ion Luminosity
from 10^{27} to 7 x10^{27}

Cost numbers from
S. Bertolucci,
12.11. 2013,
HL-LHC kickoff

PHASE II Upgrade
ATLAS (275MCHF), CMS (269MCHF) major upgrade
ALICE, LHCb

HL-LHC, pp luminosity
from 10^{34} (peak) to 5 x10^{34} (levelled)

Figure 5: Long Term schedule of the LHC Experiments.


ATLAS Phase-0 (LS1)

- Insertable B-Layer
  - New central beampipe
  - Installation of IBL in the pixel detector, in the pit: March 2014
  - Will stay until Phase-II
- Pixel Detector
  - new service panels – recover malfunctioning channels, better access, more bandwidth
- Pixel + SCT Detectors
  - New thermosiphon cooling system, keeping evaporative cooling system as backup
- Beampipes Fe → Be, Al for radiation and background reduction
  - VI, VA, VJ beampipes
  - Carbon fiber support cone for Lucid
- Add specific neutron shielding

Figure 6: ATLAS upgrades done during LS1.

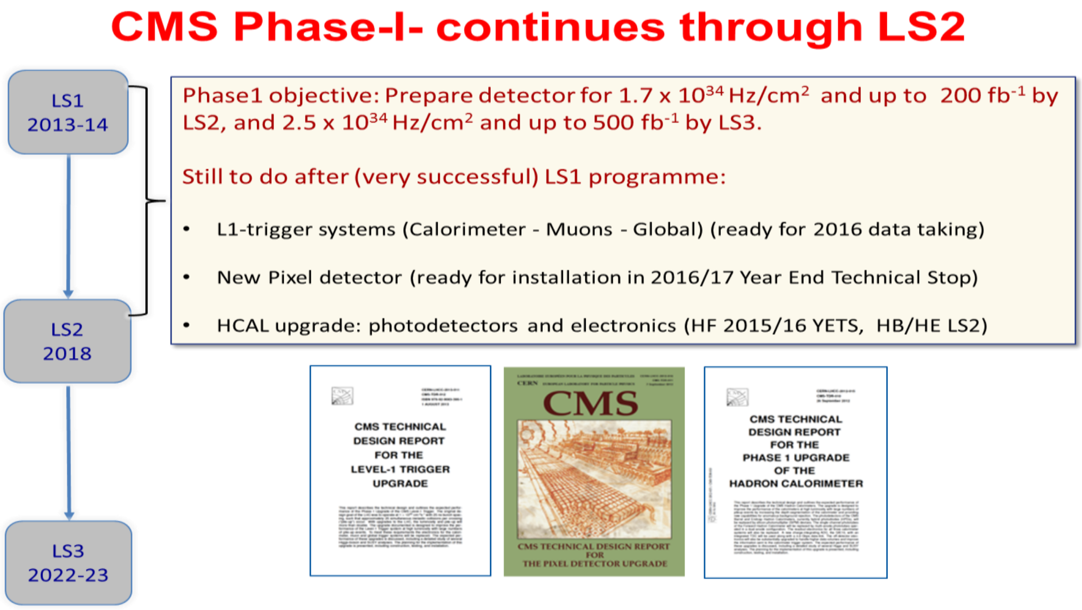
LHC @ LS2

The LS1 Schedule Coordinator insisted on several key messages: LS2 needs to be prepared NOW! LS2 is mainly dedicated to Injectors and to LHC Detectors. However, it is important not to minimise the maintenance and consolidations in the LHC, which will be of primary importance to preserve the high reliability.

During the preparatory discussions, it became clear that in view of the huge work to be carried on during LS3 and to prevent coactivity incompatibility problems (Fig.10), LS2 has also to be seen as an opportunity to prepare LS3 in the LHC. Whenever possible, one should anticipate as much as possible HL-LHC activities from LS3.

As done for LS1, focusing on Radio Protection issues and ALARA procedures stays a priority and this workload shall be anticipated. Anticipating and/or preparing LS3 activities to LS2 would also be beneficial in terms of radioprotection.

The support activities will be on the critical path and coordination will be challenged, even more than during the LS1 which was following the main streamline of the SMACC (Superconducting Magnets And Circuits Consolidation) project. The LS2 activities should not compromise the LS3 preparation; this shall be constantly discussed with HL-LHC Coordination. The optimisation of resources across the Accelerators and Experiments will be THE key point of the LS2!



CMS Phase-I- continues through LS2

LS1
2013-14

LS2
2018

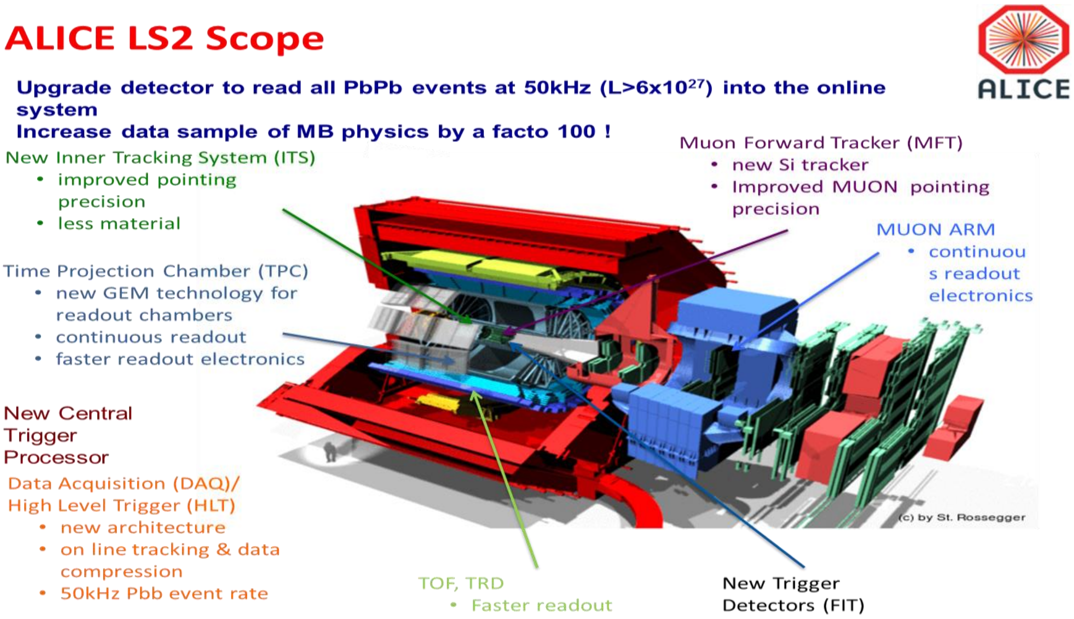
LS3
2022-23

Phase1 objective: Prepare detector for 1.7 x 10^{34} Hz/cm^2 and up to 200 fb^{-1} by LS2, and 2.5 x 10^{34} Hz/cm^2 and up to 500 fb^{-1} by LS3.

Still to do after (very successful) LS1 programme:

- L1-trigger systems (Calorimeter - Muons - Global) (ready for 2016 data taking)
- New Pixel detector (ready for installation in 2016/17 Year End Technical Stop)
- HCAL upgrade: photodetectors and electronics (HF 2015/16 YETS, HB/HE LS2)

Figure 7: CMS upgrades Phase-I schedule.



ALICE LS2 Scope

ALICE

Upgrade detector to read all PbPb events at 50kHz (L>6x10^{27}) into the online system
Increase data sample of MB physics by a facto 100 !

New Inner Tracking System (ITS)
- improved pointing precision
- less material

Time Projection Chamber (TPC)
- new GEM technology for readout chambers
- continuous readout
- faster readout electronics

New Central Trigger Processor

Data Acquisition (DAQ)/ High Level Trigger (HLT)
- new architecture
- on line tracking & data compression
- 50kHz Pbb event rate

Muon Forward Tracker (MFT)
- new Si tracker
- Improved MUON pointing precision

MUON ARM
- continuou s readout electronics

TOF, TRD
- Faster readout

New Trigger Detectors (FIT)

Figure 8: ALICE upgrades planed during LS2.

CLOSING REMARKS

The priorities of the LS2 Coordination will remain first towards Safety & Radiation readiness, with a careful evaluation of applicable rules, training, communication, temporary storages and waste management. The classification levels and dose rates will be of primary criticality as well as the advanced and proper estimation of temporary storages and waste's volume and weight. Draft information should get available by 2016.

The support to the Injectors (LIU) and to the LHC Experiments in order to allow them matching the "compressed" schedule will get followed-up with the corresponding Technical Coordinators.

The skeleton of the LS2 Master Schedule is already available since LIU and maintenances are well defined, using LS1 feedback (Fig.10). However, HL-LHC activities and Consolidations need to be reviewed and tuned. In particular, the prioritisation of Consolidations will need to be assessed in the frame of the available resources during the LS2 period, their impacts on other groups and coherence with LIU project. Even if the LS2 duration is estimated to 18 months, removing the warm-up, cool-down and tests phases, only between 9 and 13 months remain for activities on cryo-elements. (Fig. 10)

As done for the preparation of LS1, the collection and prioritization of activities will rely on an advanced version of "PLAN" tool which will represent the unique repository, useful source of information to exchange between groups. As happened for LS1, it will provide Groups with a clearer picture of the support to be given to other groups, helping to mitigate bad surprises. This will ease the prioritization process and will allow focusing only on discordances.

ACKNOWLEDGMENT

Many thanks to all speakers and to the contributors from all CERN Groups and also to the LHC Experiment Technical Coordinators for their helpful feedback.

LHCb LS2 Scope

- ✓ upgrade ALL sub-systems to 40 MHz Front-End (FE) electronics
- ✓ replace complete sub-systems with embedded FE electronics
- ✓ adapt sub-systems to increased occupancies due to higher luminosity
- ➢ keep excellent performance of sub-systems with 5 times higher luminosity and 40 MHz R/O

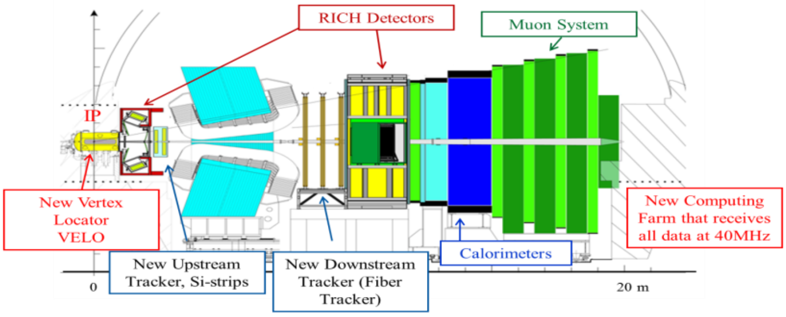


Figure 9: LHCb upgrades planed during LS2.

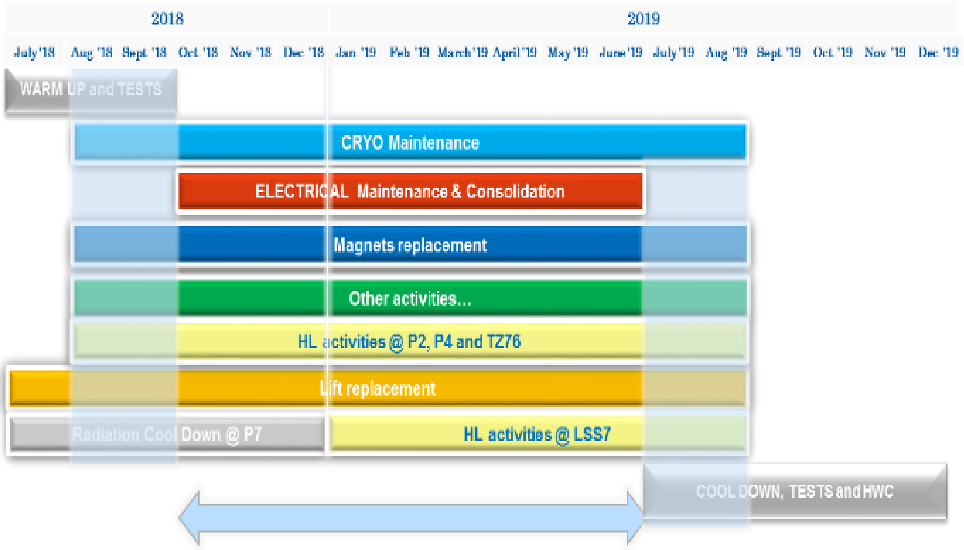


Figure 10: Skeleton of LS2 Master Schedule (indicative)

SOLVED AND REMAINING NON-CONFORMITIES IN THE SUPERCONDUCTING CIRCUITS

A. Verweij, CERN, Geneva, Switzerland

Abstract

Before and during Run 1 several non-conformities (NC's) in the superconducting circuits of the LHC were identified. During the long shutdown 1 (LS1) the NC's that could give a strong impact on the machine performance have been solved whereas other, less critical, NC's still remain. In this paper and overview is presented of the status of the NC's on the superconducting circuits as of mid Sept 2014.

INTRODUCTION

This paper gives the status of the NC's of mid Sept 2014. At this moment 8 sectors have passed the Electrical Quality Assurance (ELQA) tests at warm (300 K), one sector has passed the ELQA tests at cold (1.9 K), whereas the powering tests have yet been performed. It is therefore possible that during the remaining ELQA tests and especially during the powering tests (foreseen for end 2014 and beginning of 2015), new NC's will come up. Therefore, please refer to the MP3 web site https://twiki.cern.ch/twiki/bin/view/MP3/SummaryIssues for an up-to-date overview of all issues in the circuits.

In previous HWC campaigns we had frequently quenches at flat-top, especially in the 600 A circuits. For the 2014/15 campaign all circuits will be commissioned to a slightly larger current than required for operation at 6.5 TeV beam energy, in order to guarantee as much as possible 'quench-free' operation. The additional current margin IDELTA varies per type of circuit, as shown in Table 1.

Table 1. Overview of I_{DELTA} values for the various circuits.

Circuit	**Description**	**I_{DELTA} [A]**
RB	Main dipole	100
RQD/F	Main (de)focussing quadrupoles	100
IT	Inner triplet	100
IPQ	Individually powered quadrupoles	50
IPD	Individually powered dipoles	50
600 A	600 A corrector circuits (including RCO)	10
80-120 A	80-120 A corrector circuits	5
60 A	60 A corrector circuits	5

In the next section the results of the consolidation campaign of the 13 kA joints will be presented. In the following sections the main issues and NC's will be presented per circuit type.

CONSOLIDATION OF THE 13 kA JOINTS

Insufficient contact between the superconducting cable and the stabiliser coinciding with a lack of longitudinal continuity of the stabiliser caused the incident in the main dipole circuit sector 34 in Sept. 2008 [1], and was later on shown to be also present in many other 13 kA busbar joints of all main dipole and quadrupole circuits of the machine. All these joints were therefore consolidated during LS1, adding as well additional copper shunts. The resistance R8 measured between the bus stabiliser and the splice stabiliser over a length of 8 cm turned out to be a good measurable to quantify the continuity of the bus. A perfectly soldered joint has a R8 value of about 5.6 μΩ for RB joints and 9.3 μΩ for RQ joints. The excess resistance is therefore defined as $R8_{excess}$=R8-5.6 μΩ for RB joints and $R8_{excess}$=R8-9.3 μΩ for RQ joints. Figure 1 shows the excess resistance on each side of the joints [2].

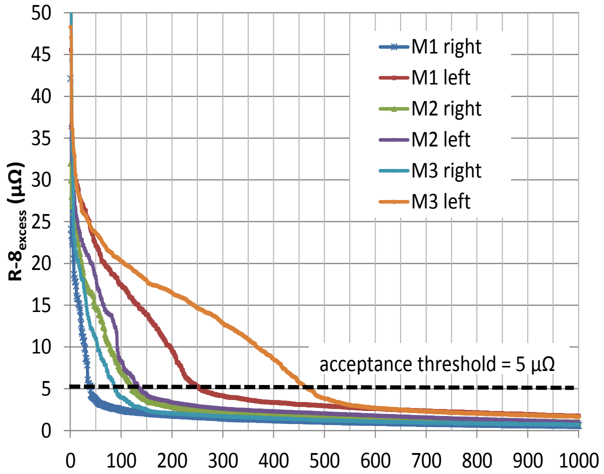


Figure 1. Excess joint resistance $R8_{excess}$ for the dipole (line M3) and quadrupole (line M1 and M2) busbars. Note that the two largest values (72 and 107 μΩ) are not shown [2].

Table 2 shows as well the maximum measured $R8_{excess}$ in each sector, and Table 3 shows the percentage of joints for which $R8_{excess}$ is larger than the acceptance criteria of 5 μΩ. These results led to the conclusion that the tooling on the M2 joints, which are better accessible from the tunnel side, was better centred.

Table 2. Overview of the maximum R8$_{excess}$ per sector [2].

Sector	RB max R8$_{excess}$ (μΩ)	RQ max R8$_{excess}$ (μΩ)
56	28.6	21.1
67	35.0	32.4
78	71.9	107
81	41.8	34.4
12	29.6	45.5
23	27.8	43.2
34	33.6	36.3
45	48.3	34.9

Table 3. Overview of the percentage of R8$_{excess}$ values exceeding the acceptance criteria [2].

Joint	R8$_{excess}$ > 5 μΩ (%)
M1-Left	8.2
M1-Right	1.3
M2-Left	4.4
M2-Right	3.8
M3-Left	15
M3-Right	2.7

About 30% of the splices needed to be machined before shunting due to high R8 value or due to geometrical imperfections. Shunts were then soldered on all splices. Figures 2 and 3 present the R8 values after machining and after shunting, showing a maximum excess resistance of only about 1 μΩ.

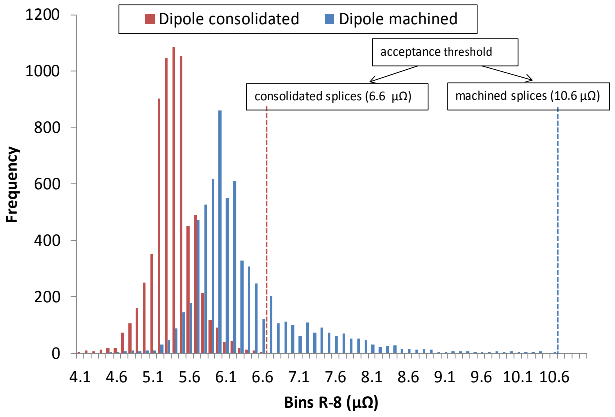


Figure 2. R8 distribution of all dipole busbar splices after machining and after shunting [2].

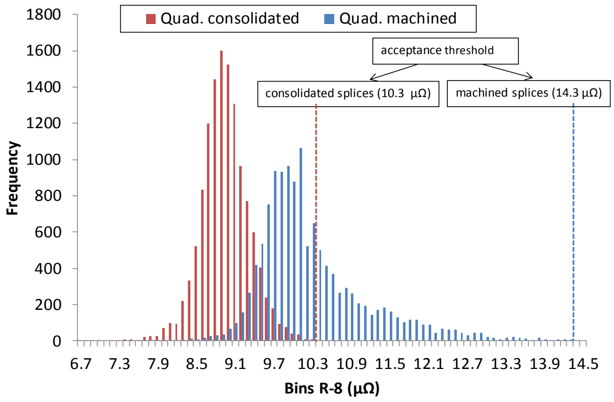


Figure 3. R8 distribution of all quadrupole busbar splices after machining and after shunting [2].

NC'S IN THE RB CIRCUITS

Besides the consolidation of the busbar joints, as described before, the main remarks to be made on the RB circuits are the following:

- 15 main dipole magnets (MB's) have been exchanged during LS1:
  - 1 magnet with high internal splice resistance (18 nΩ) and a quench heater issue.
  - 7 magnets with high internal splice resistances (>16 nΩ).
  - 4 magnets with quench heater issues.
  - 2 magnets with the wrong beam screen.
  - 1 magnet with limited High-Voltage Qualification during ELQA.
- Two shorts to ground in RB.A12 (discovered after warm-up before LS1) have been repaired. One on a diode and one at a lyra-MCS contact.
- The decay time constant is back to the design value of 104 s (30 s during Run 1).
- The diode leads have been measured at warm, and a 200 μΩ contact in a "half moon" has been repaired.

All MB's now have a full set of high-field and low-field quench heaters, and internal splices smaller than 16 nΩ. All RB circuits should be able to reach 6.5 TeV with probably considerable training. About 90-130 training quenches are expected, assuming that all sectors train in a similar way as the training of sector 56 in 2008 [3], [4].

There are no remaining issues limiting the operation.

NC'S IN THE RQ CIRCUITS

Besides the consolidation of the busbar joints, as described before, the main remarks to be made on the RQ circuits are the following:

- Two main quadrupole magnets (MQ's) have been exchanged during LS1 (Q23.R3 and Q27.R3), recovering the default configuration for the RQS circuits.
- The connections to the diodes are consolidated.
- The decay time constant is back to the design value of 30 s (9.2 s during Run 1).
- Some minor issues with open/loose voltage taps remain, but this has no effect on the quench detection and protection.

All MQ's have a full set of high-field and low-field quench heaters, and internal splices smallet than 27 nΩ. All RQ circuits should be able to reach 6.5 TeV with possibly some training quenches (much less than the MB's).

There are no remaining issues limiting the operation.

NC'S IN THE INNER TRIPLETS

Main Quadrupoles:

All main quads of the IT's have a full set of 4 quench heater strips, wired into two independent redundant circuits. RQX.R1 has one circuit with reduced heater voltage and increased heater discharge capacitance, without impact on protection and operation.

All IT circuits should be able to reach 6.5 TeV equivalent with possibly a few training quenches.

There are no remaining issues limiting the operation.

MCBX circuits:

All 24 RCBXH/V pairs were limited to 350 A during Run 1, see the red square in Fig 4. After LS1 they will be commissioned individually to IPNO=540 A, except RCBXH1.L5 (490 A).

During simultaneous powering they will be limited to $(I_V^2+I_H^2)<I_M^2$, with I_V the current in the MCBXV, I_H the current in the MCBXH, and I_M=540 A for 14 out of 24 circuits (see the green curve in Fig. 4). For ten RCBXH/V pairs I_M has a reduced value, between 400 A and 508 A (see the green surface).

For optics requirements, one could also foresee to operate these ten pairs on an ellipse with 540 A in either horizontal or vertical direction (see the blue curves)

Six RCBXH/V pairs also have combined MCSX-MCTX magnets, which unfortunately affect the quench behaviour of the MCBXH/V. The RCSX3 and RCTX3 circuits will be commissioned ***individually*** to 100 resp. 80 A, and then limited to 10 A for operation.

If needed for operation or for special MD's, the operational range will be optimized on an individual base.

Other triplet correctors:

The following four circuits are condemned:

- RCOSX3.L1
- RCOSX3.L2
- RCOX3.L2
- RCSSX3.L2

Circuit RCSSX3.L1 has a reduced nominal current (60 A instead of 100 A).

NC'S IN THE IPD CIRCUITS

The main remarks to be made on the IPD circuits are the following:

- The RD1.R8 circuit operates with one out of two quench heaters. This has no impact on the operating current.
- The RD3.L4 circuit show slow training behaviour. The nominal current is reduced from 5850 A to 5600 A, which is sufficient for operation up to 6.74 TeV.

There are no remaining issues limiting the operation.

NC'S IN THE IPQ CIRCUITS

The main remarks to be made on the IPQ circuits are the following:

- In position RQ5.L8 the magnet SSS606 has been replaced by magnet SSS696 during LS1 in order to resolve a NC with the corrector RCBCHS5.L8B1.
- Circuit RQ4.L8 operates with 7 out of 8 quench heaters. This has no impact for operation and protection.
- Circuit RQ5.R2 shows a slow training behaviour. This has no impact for 6.5 TeV operation.
- The MQY magnets in positions RQ4.L5 and RQ4.R5 will be operated during Run 2 with a so called "4-lead" instead of "3-lead" configuration. From a converter point of view they can now be used with arbitrary ratio I_{B1}/I_{B2}. However, the two apertures have a very strong magnetic cross-talk.

There are no remaining issues limiting operation.

NC's IN THE 600 A CIRCUITS

The main remarks to be made on the 600 A circuits are the following:

- The acceleration in all RSD/F circuits is reduced from 0.25 to 0.15 A/s^2.
- The ramp rate in RU.R8 is reduced to 0.1 A/s.
- In circuit RQTF.A81B1 four out of eight magnets are bypassed.
- Circuit RCO.A12B2 will be operational after LS1; it was condemned during Run 1.
- In circuit RCO.A78B2 two out of 77 magnets are bypassed (in positions B20L8 and C19L8).
- In circuit RCO.A81B2 two out of 77 magnets are bypassed (in positions B11L1 and B12L1).
- Circuits ROD.A34B1 and ROF.A34B2 both contain only 11 MO magnets instead of 13. Exchange of the SSS's in Q28 and Q32 is required to solve this NC.
- Circuit RSS.A34B1 is condemned
- Circuit RSS.A81B1 will be operational after LS1; it was not operated during Run 1 for unknown reason.
- Circuit RQS.A34B2 will operate after LS1 with the design configuration of four MQS magnets in series; during Run 1 two magnets (out of four) were missing.
- Circuit RQS.R3B1 will operate after LS1 with the design configuration of two MQS magnets in series; during Run 1 this circuit contained no magnets.
- In circuit RCS.A34B2 four out of 154 magnets will be bypassed.

All 600 A circuits have a nominal current of 550 A, except:

- all ROD/F circuits for which the nominal current is 590 A, with I_{DELTA}=0 A.
- the RSD circuits in S12, S45, S56, S81 for which the nominal current is 590 A, with I_{DELTA}=0 A.
- the RQ6 circuits in points 3 and 7 which operate at 4.5 K with a nominal current of 400 A.
- 28 600 A circuits that have a nominal current between 300 and 500 A, see Table 4.

Table 4. Overview of 28 circuits with nominal current smaller than the default value of 550 A.

Circuit	I_{PNO}
RQTL8.L3B1	450 A
RQTL8.L3B2	450 A
RQTL8.L7B1	300 A
RQTL8.L7B2	300 A
RQTL9.L7B1	400 A
RQTL9.L7B2	400 A
RQTL9.R3B1	450 A
RQTL9.R3B2	425 A
RQTL9.R7B1	500 A
RQTL9.R7B2	500 A
RQTL10.L7B1	500 A
RQTL10.L7B2	500 A
RQTL10.R3B1	450 A
RQTL10.R3B2	450 A
RQTL11.L3B1	400 A
RQTL11.L3B2	400 A
RQTL11.L6B1	350 A
RQTL11.L6B2	400 A
RQTL11.L7B1	300 A
RQTL11.L7B2	300 A
RQTL11.R3B1	500 A
RQTL11.R3B2	500 A
RQTL11.R5B1	500 A
RQTL11.R5B2	500 A
RQTL11.R6B1	300 A
RQTL11.R6B2	300 A
RU.L4	400 A
RU.R4	400 A

NC's IN THE 80-120 A CIRCUITS

The main remarks to be made on the 80-120 A circuits are the following:

- Circuit RCBCH6.L2B2 will be operational after LS1; the circuit was condemned during Run 1.
- A small reduction of the nominal current in circuit RCBCH7.R3B1 from 100 to 80-90 A might be needed.
- A reduction of the nominal current in circuit RCBCH10.R3B2 from 100 to 60 A might be needed.
- The magnet in circuit RCBCHS5.L8B1 was replaced during LS1 (as part of Q5.L8) and the circuit will be operational after LS1; the circuit was condemned during Run 1 since there was a high magnet resistance of 20 mΩ.
- The nominal current in circuit RCBYH4.R8B1 is limited to 50 A.
- The nominal current in circuit RCBYHS4.L5B1 is limited to 50 A.
- The nominal current in circuit RCBYHS5.R8B1 is limited to 40 A, with dI/dt reduced to 0.3 A/s.
- The nominal current in circuit RCBYV5.L4B2 is limited to 50 A.

NC'S IN THE 60 A CIRCUITS

All 60 A corrector circuits can be run up to nominal current after LS1 except for the circuits RCBH31.R7B1 and RCBV26.R5B1 which are condemned due to too high resistance.

CONCLUSIONS

During LS1 the most important limiting factor for operation at 6.5 TeV beam energy has been solved by consolidation of the 13 kA busbar joints. In the same period a certain number of NC's have been resolved through exchange of magnets, or bypasses of parts of circuits. A number of NC's still remain in the superconducting circuits after LS1. However, none of these NC's limits the operation for 6.5 TeV beam energy. It is of course possible that during the 2014/15 HWC campaign new NC's will come up. An up to date overview of all NC's and issues can be found on: https://twiki.cern.ch/twiki/bin/view/MP3/SummaryIssues.

ACKNOWLEDGEMENTS

The author would like to thank all members from the MP3 (www.cern.ch/MP3), M. Pojer and M. Solfaroli Camillocci for their help in preparing and checking the data presented in the slides and the paper.

REFERENCES

[1] A. Verweij, "Busbar and Joints Stability and Protection", https://espace.cern.ch/acc-tec-sector/Chamonix/Chamx2009/papers/AV_4_03.pdf .
[2] S. Heck, et al., "Non-destructive testing and quality control of the LHC main interconnection splices", IEEE Trans. Appl. Supercond., Vol. 25(2), 2015.
[3] A. Verweij, "Training the dipoles", https://espace.cern.ch/acc-tec-sector/Chamonix/Chamx2009/papers/AV_1_01.pdf .
[4] B. Bellesia, N. Catalan Lasheras, E. Todesco, "Magnet (re)training", https://espace.cern.ch/acc-tec-sector/Chamonix/Chamx2009/papers/ET_8_06.pdf .

RE-COMMISSIONING OF THE SUPERCONDUCTING CIRCUITS

M. Solfaroli Camillocci, M. Pojer, CERN, Geneva, Switzerland

Abstract

During LS1, the first planned LHC long shutdown, several modifications have been carried out on the technical systems, besides the superconducting circuits consolidation, with the goal of increasing the system performance and availability, while raising the energy to its design value. The plan and present status of the superconducting circuits re-commissioning is presented.

THE LS1 MODIFICATIONS

Besides the Superconducting Magnet And Circuit Consolidation (SMACC) project, many other interventions have been carried out during the LS1. A big maintenance campaign was performed with the scope of increasing the availability of the machine and various special modifications have been carried out to increase the performance and modify the functionality of different systems; all these changes might impact the machine efficiency. As a consequence, they have to be carefully tested, to ensure a safe re-start of the accelerator [1].

THE SHORT CIRCUIT TESTS

During LS1, a campaign of short circuit tests has been performed in the LHC, in order to validate the warm part of the superconducting circuits and spot potential problems early enough to implement necessary corrections. For these tests, a short circuit block is installed at the end of the water-cooled cables, at the level of the Distribution Feed-Box (DFB). The current then flows from the power converter through the cables and (if present) into the Energy Extraction (EE) system. These tests allow verifying the cooling system for the different circuits, the current sharing into the EE, the quality of the conical connections and the global ventilation in the area where the power converters are located.

After a long preparation phase that started in October 2012, these tests were done in different configurations in all points of the machine. Some problems (i.e. few wrong interlock cabling, several lose conical connections and few cable damages) have been spotted and the necessary corrective actions taken.

One of the water-cooled cables of the RQX.L5 that have been exchanged during LS1 was found defective, several weeks after the completion of the short circuit campaign. The cable was then removed, repaired and re-installed. A new heat run of this circuit will be done, once the intervention is completed.

The Copper Stabilizer Continuity Measurement

The Copper Stabilizer Continuity Measurement (CSCM) is a series of tests meant to validate all interconnect splices, all bypass diode paths and all current lead to busbar connections on the DFBAs. The test reproduces similar conditions to those during a quench, but with no energy stored in the magnets, so that an interlock process can safely stop the thermal runaway. This is achieved by doing the test at a temperature of about 20 K; in this condition the magnets are no longer superconducting then the current passes through the bypass diode, connected to each magnet. In case of a thermal runaway, a special configuration of the Quench Protection System (QPS) boards issue an interlock and stop the current that quickly reaches 0 A, as there is very little energy stored in the circuit. An analysis and a resistance measurement cycle are needed between all steps in order to verify the integrity of the circuit and calculate the QPS compensation parameters for the following test.

This measurement will be performed on all main dipole circuits of the LHC to assess the quality of the system before commissioning and operation at 6.5 TeV equivalent current. The test has been fully automated to reduce the risks due to manual operation. The principle of the test is that the absence of thermal runaway proves the integrity of the circuit.

The CSCM consists of seven test steps at increasing current level to gradually reach 11.1 kA. Due to the very low inductance of the circuit, the current rises quickly to reach the maximum level and after a 2 s plateau decreases exponentially. At the moment of the writing two out of eight main dipole circuits have been already fully validated.

POWERING TESTS

A large campaign of powering tests has also to be carried out on all superconducting circuits to ensure their correct performance and functionality and, above all, to push the main circuits close to the design energy.

Strategy and Changes

A total of more than 10.000 powering steps have to be performed and analyzed in less than four months. In 2009 the LHC was commissioned with a completely new QPS system in a similar amount of time. Nevertheless, the other systems had not undertaken massive changes (3 sectors were not even warmed up) and the main circuits were only commissioned for energy of 3.5 TeV. To cope with this challenge the powering tests campaign has to be carefully planned and the tools optimized.

A team in charge of the “organization and coordination” will coordinate the powering tests campaign, while the “automation” team is in charge of ensuring the correct functionality of the software infrastructure; finally a renewed MP3 (Magnet circuits, Protection and Performance Panel) is entitle to assess the magnet and circuit protection and performance.

In order to reach the goal energy of 6.5 TeV, a training campaign has to be performed on the main dipole circuits; a strategy with a maximum acceptable number of training quenches per sector (after which the situation will have to be assessed) has been defined; in total, on all eight main dipole circuits, about 100 quenches are expected to be needed in order to reach the current of 10980 A (6.5 TeV equivalent).

The MP3 team in collaboration with the system responsible has updated all powering procedures in order to cope with the new functionality and interlock. A detailed mapping of which tests have to be executed to ensure correct re-commissioning has been done.

The separation of powering phases [2] in Phase 1 and Phase 2 implying different access restrictions has been also updated:

- Phase I: all circuits are limited to the current value corresponding to 100 kJ stored in the magnets. None is allowed into the tunnel where powering tests are ongoing. No restriction for the service areas. A special procedure has been defined to allow special tests that need the presence of experts in he tunnel. In this case, only one circuit can be powered, to the current corresponding to a maximum of 30 kJ of energy stored in the circuit.
- Phase II: none is allowed in the sector (both tunnel and service areas) where powering tests are carried out. In addition, restrictions to the adjacent sectors are also applied [3].

All tools for the automated execution and analysis of the powering tests have been updated with enhanced functionality. The procedures to power the different circuits and the related software sequences have also been updated.

The Present Status

In this paragraph the status of the LHC powering tests at the moment of writing is described.

Only one (sector 67) of the eight LHC sectors is at nominal cryogenic conditions. In two sectors the final non-conformities found during the SMACC are being repaired. The remaining five sectors are presently being cooled-down.

Prior to the powering tests, a campaign of electrical tests (ElQA) has been performed on all circuits of sector 67 to assess their electrical insulation and proprieties. During the validation of one of the lines of the main dipole circuit, a breakdown appeared.

Due to an error in the documentation layouts, the installed QPS cards (called mDQQBS v.2) cannot withstand 2.1 kV to ground, provoking a breakdown which leads to the HV part be directly connected to a supply voltage (this problem does not appear on the v.3 of the cards). A campaign was then performed to check the diodes status, as the high voltage transients during the breakdown could have generated degradations; no problem was found. It was then decided to change the ElQA procedure:

- Hi-pot at 2.1 kV the cold masses with only the so-called old QPS (oQPS) connected (the old QPS is the original system that contains the magnet quench protection, the current leads protection and the global quench detection);
- Hi-pot at 1.5 kV the full system once the so-called new QPS (nQPS) is connected. This decision was taken, as the nQPS instrumentation does not “see” the voltages developed internally in the magnet coils during a quench (the new QPS is the second layer of the system, added in 2009 to provide the symmetric quench and the busbar splices detector).

After solving minor problems, the full system was validated.

Present powering status:

- 60 A circuits: all circuits have been powered, their commissioning is presently completed at 97%;
- 80-120 A: commissioning status 72%;
- 600 A: the commissioning of the 47 systems is ongoing, presently at 36%;
- IPQs – IPDs: QPS preparation still needs to be completed (radiation-hard board under preparation);
- 13 kA: QPS preparation is ongoing; the triggering cables check is completed and the quench heater power supplies are undertaking the individual tests, including current discharge. The QPS validation will last one more week.

Due to the large amount of software changes implemented during LS1 and despite of the dry-runs performed before the powering tests campaign, minor problems and bugs were expected to appear in the software system. Several minor malfunctions were indeed found and corrected during the first weeks of powering tests:

CONCLUSIONS

The LHC superconducting circuit re-qualification has been carefully studied and its planning started already in October 2012.

Besides the general maintenance, many changes have been applied with the goal of increasing availability, reliability and performance of the different systems. These modifications will have an impact on the time needed to re-start the LHC and on the machine efficiency. To limit this effect and to ensure a safe re-start, various test campaigns are planned.

During the short circuit tests campaign several NCs were highlighted then fixed and all polarities verified.

The ongoing powering tests and CSCM campaign are crucial for a quick and safe re-start of beam operation; the team is ready to take the challenge ahead.

ACKNOWLEDGMENT

The authors wish to express their sincerest thanks for the useful discussion, corrections and suggestions to all the teams involved in the LHC superconducting circuit tests.

REFERENCES

[1] "Powering tests – Machine status coming out of LS1" Proceedings of the 5th Evian workshop pp. 191-193

[2] "Access and powering conditions for the superconducting circuits in LHC" EDMS Doc. LHC-MPP-ES-0002 n. 100198

[3] "Access restrictions in LHC and SPS during LHC powering Phase II" EDMS Doc LHC-OP-OSP-0016 num. 1010617

OTHER NON-SOLVED NC ACROSS THE LHC RING AND POTENTIAL IMPACT ON PERFORMANCES

V. Baglin, CERN, Geneva, Switzerland

Abstract

During Run 1, several non-conformities across the ring with impact on machine performances were identified and planned to be solved during the long shutdown 1 (LS1). During this long shutdown, new non conformities were also produced and / or identified. In this talk, some of these non-conformities are presented and discussed together with their impact on machine operation, technical stops and LS2.

INTRODUCTION

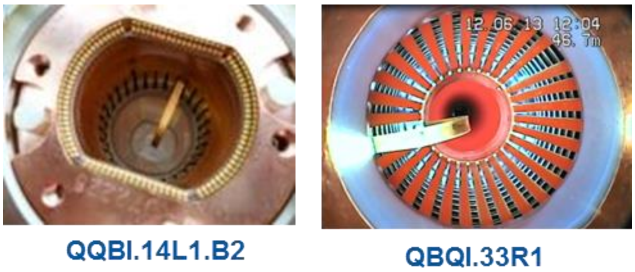
Following Run 1, several consolidations and upgrades have been identified across the LHC ring. The activity which took place during almost 2 years represents a challenge not only in terms of volume but also in terms of quality.

Thanks to the training of non-expert personnel, application of procedures, systematic vacuum validation checks, write up of activity reports and quality control checks, the amount of remaining non comformity (NC) in the ring has been minimised. This paper presents an overview of these NC together with their impact on machine operation, technical stops and LS2.

SYSTEMS AT CRYOGENIC TEMPERATURE

Beam Vacuum System

One of the most critical equipment of the cryogenic vacuum system is the plug-in-module, PIM. These components are non-conform since the installation of the LHC. The first non-conform PIM was found by chance at QQBI.26.R7 in August 2007 after the warm up of sector 78. The origin of this NC has been traced back to a NC during manufacturing which was not properly documented and followed-up. Two bending angles of the RF fingers of the PIMs are out of tolerances which, as a consequence, might lead to buckling during warm up. In particular, the QQBI type PIM (interconnect quadrupole-dipole) are the most critical. A systematic check is therefore mandatory once the PIM temperature is higher than 120-130 K. Possible means of checks are RF ball test, tomography, x-ray and endoscopy. Moreover, a systematic repair of the PIM is done when magnets are consolidated [1]. For LS1, in parallel to the arc repair, the PIMs located at the arc extremity: QQBI.7R and QBQI.8L were consolidated. Today, after LS1, 13 % of the PIMs are consolidated *i.e.* 456 out of 3443. All RF-ball tests were ok before cool down. As shown in Figure 1, after the arc warm up, 2 PIMs were found buckled: in the arc 81 and the arc 12. It must be noted that the arc 12 was already warmed up in 2009. Therefore, systematic check of the PIM is needed even if an arc was already warmed up.



QQBI.14L1.B2 QBQI.33R1

Figure 1: The tow PIMs which were founded buckled following the LHC arcs warm up after Run 1.

The PIMs located in semi-stand-alone-Magnet (SAM) were all checked ok by tomography except D3-LU (QBUI.5L4) in LSS4L and D2-Q4 (QBQM.4R2) in LSS2R. These last two PIMs were repaired.

All the PIMS located in the inner triplets (IT) were checked ok by endoscopy. In the meantime, the aperture check confirmed the presence of a protrusion of small contact strip in Q1/Q2 of IT5R (at QQQI.2R5). This NC already observed in 2009 did not evolve since. Therefore, it was decided to classify this NC “use as is” during an ad-hoc meeting [2].

For LS2, if the consolidation strategy remains unchanged; no significant impact of this NC is expected. However, it must be remembered that, any warm up above 120-130 K during technical stop, (E)YETS or long shutdown will requires inspection to ensure proper operation of the LHC.

During Run 1, several UFO storms were observed in some specific area of the LHC, in particular s34 [3]. The beam line was inspected and cleaned again during LS1. A few small pieces of MLI/fibres were removed from s34: 99 for about 6 km of beam screen. However, there was no systematic presence of debris where high UFO rates are observed indicating that there is no clear correlation between the presence of debris and UFO storms.

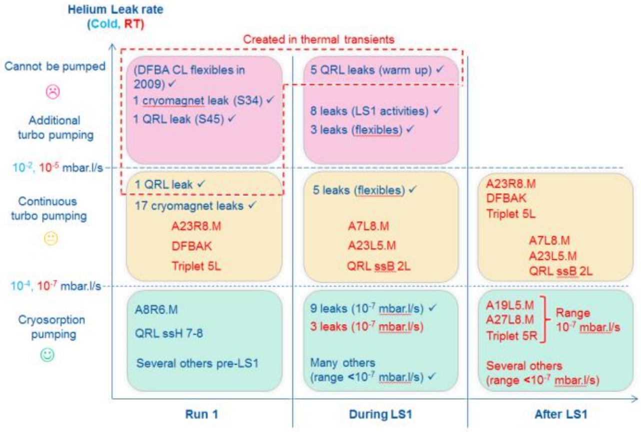
Finally, as already announced by the TE-CRG team [4], all the beam screen heaters have been consolidated to allow heating to 200W (only Q20L2 is not operating). The upgrade of the beam screen valves in s34 with some SAM and semi-SAM was also done. The cryogenic system can therefore reach the same level of cooling capacity all across the ring. The local cooling capacity is homogenised and upgraded to ~ 2 W/m for the scrubbing. This will allow a full usage of the cryoplants available capacity (estimated at ~ 1.6 W/m per aperture).

Insulation Vacuum System

The 7 major leaks, which were created during thermal transient, were repaired during LS1. In s34, the repair of line M in the cold mass circuit of A27L4.M was done. In s45, the repair of the QRL line C of subsector B was achieved with the support of TE-CRG. The leaks in the QRL due to multiply bellows failure were repaired and managed with the support of TE-CRG.

As shown in Figure 2, the machine operated during Run 1 with several leaks above 10^{-5} mbar.l/s. Such large leak level required the use of additional turbo pumping. After LS1, most of the leaks are in the range 10^{-8} - 10^{-7} mbar.l/s which can be managed by simple cryosorption pumping. Only 6 leaks are in the range 10^{-7} - 10^{-5} mbar.l/s but can still be managed by the fixed turbomolecular pumping system. It is worth underlying that several leaks ($>10^{-7}$ mbar.l/s) were created during LS1 due to collateral damage. Fortunately, these leaks could have been repaired. To this date, the vacuum insulation system behaves as expected.

During technical stops or long shutdown, any thermal transient occurring during quench of warm up will increase the risk of major leak. For LS2, several leaks will need to be repaired (IT5L, DFBAK, A23R8.M …).



	Run 1	During LS1	After LS1
Cannot be pumped ☹ Additional turbo pumping	(DFBA CL flexibles in 2009) ✓ 1 cryomagnet leak (S34) ✓ 1 QRL leak (S45) ✓	5 QRL leaks (warm up) ✓ 8 leaks (LS1 activities) ✓ 3 leaks (flexibles) ✓	
Continuous turbo pumping 😐	1 QRL leak ✓ 17 cryomagnet leaks ✓ A23R8.M DFBAK Triplet 5L	5 leaks (flexibles) ✓ A7L8.M A23L5.M QRL ssB 2L	A23R8.M DFBAK Triplet 5L A7L8.M A23L5.M QRL ssB 2L
Cryosorption pumping ☺	A8R6.M QRL ssH 7-8 Several others pre-LS1	9 leaks (10^{-7} mbar.l/s) ✓ 3 leaks (10^{-7} mbar.l/s) Many others (range $<10^{-7}$ mbar.l/s) ✓	A19L5.M A27L8.M Triplet 5R Range 10^{-7} mbar.l/s Several others (range $<10^{-7}$ mbar.l/s)

Figure 2: Time classification of leaks observed in the vacuum insulation system

SYSTEMS AT ROOM TEMPERATURE

5th Axis for Collimator

The 5th axis is defined as the possibility to move the collimator's vacuum vessel by +/- 10 mm. This functionality allows restoring the collimator performance in the case the jaws are locally damaged by a 7 TeV beam of less than 10^{11} protons for a tungsten TCTP. The onset of damaged is 5 10^{9} protons at 7 TeV [5].

In the current layout, the TCTs are installed between TAN and D2. In these recombination areas, the systems are very tight and the integration is very difficult. This is the case in particular in LSS 1 and 5 where the 5th axis is condemned. As shown in Figure 3, the vacuum system needs to accommodate the presence of sector valves, collimators, mask and BPMs. This can only be done by using connecting module not compatible with the 5th axis movement of the TCTPH and TCTPV.

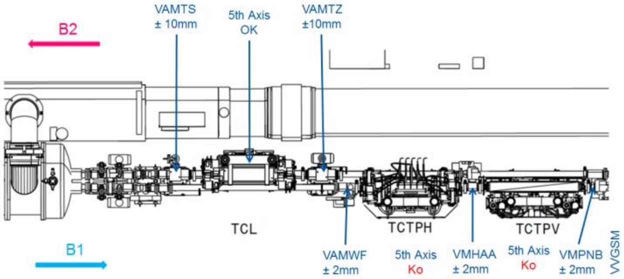


Figure 3: Schematic layout of the TAN-D2 area in C4L5 (courtesy Y. Muttoni EN/MEF).

In order to restore the 5th axis functionality, a new layout including new position of TCTs and new interconnecting modules (to be designed and procured) has to be validated.

The implementation of this new layout must take placed by YETS 2015, consequently, interventions in vacuum sectors A4L1, A4R1, B4L5, B4R5 must be planned. In the meantime, the collimator system cannot afford the risk to damage the TCTs limiting accordingly the machine operation.

RF Bridges Consolidation

The RF bridge is a fragile element of the room temperature (RT) vacuum system. This component ensures the electrical continuity and minimise the impedance at the connecting bellow between vacuum chambers. Its design, based on the LEP expertise and develop all around the world, is reliable within the working tolerance. In LHC, beside the large amount of such equipments, 1781, there is also a large amount of variants. Indeed, more than 40 different type of transition (circular, elliptical, race track, 52 mm to 212.7 mm etc.) are existing.

During Run 1, all these equipments were strongly solicited by the intense bunch current. In particular, some equipment, such as VMTSA (VAMTF), were identified as very sensitive to misalignment and all replaced by other equipment during YETS 2011 and LS1 [6,7]. Thus, the remaining RF bridges were systematically X-ray during Run 1 for inspection. A total of 96 NC were classified priority 1, P1. These NC were spread over 52 RT vacuum sectors (the LHC has a total of 185 RT vacuum sectors). In order to fix all these NCs during LS1, 29 RT vacuum sectors were specifically opened for this purpose.

To comply with the Quality Assurance Plan, a systematic visual inspection of all the vacuum modules was performed and 809 RF bridges were X-ray check at the end of LS1.

Following this campaign, 17 NC issued were classified P1, out of which 6 were repaired. So, 11 P1 NC issues need to be followed-up during Run2. These P1 NC are located in ten different vacuum sectors: B1R1.X, A4R1.X, C4L2.C, B4L2.C, A4R2.C, B4L5.B, A4L6.B, A4L6.R, A4R6.R and B5R7.B. These P1 NC will be repaired if opening of the vacuum sector is needed for performance reasons.

Despite the apparent large amount of remaining P1 NC, a large progress has been made in the work quality since the percentage of P1 NC is decreased from 6 % after LHC installation to 1 % after LS1. This good achievement must be placed in perspective to the large amount of RT vacuum sectors which were opened during LS1 (146 vacuum sectors) and in perspective to the more stringent tolerance as compared to the LHC installation (5 mm length tolerance for the bellow as opposed to 10 mm during installation).

It is worth mentioning also that new concepts of RF bridge are presently under development and ready to be vacuum and impedance qualified. As shown in Figure 4, this type of RF bridge do not have any sliding contact in such a way the electrical continuity is always guaranteed at a price of a relaxation in impedance tolerance. This RF bridge could be used in the future in high radiation areas of the LHC. However, it must be stressed that one limitation of such a system is the demanding alignment accuracy which is not always compatible with the field limitations. More dedicated studies are needed to validate this proposal.

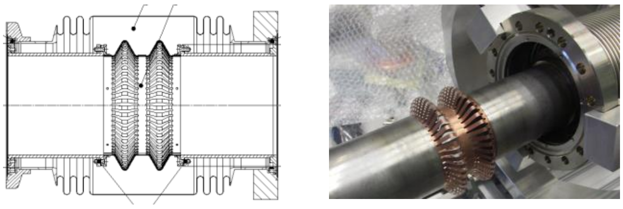


Figure 4: A possible new type of RF bridge for high radiation areas (courtesy J. Perez Espino TE/VSC).

MKBs Outgassing Rate

The LHC diluter magnets, MKB, suffer from a vacuum NC known since the LHC installation. The large outgassing rate of the kilos of epoxy material which is installed inside the unbaked vacuum is not compatible with the actual vacuum performance of the dump line. As a consequence, the vacuum system was partially upgraded during LHC installation by adding fixed turbomolecular pumps to faster the pump down. However, the large gas load and possibly the outgassed species, degraded up to the destruction several 400 l/s ion pumps during Run 1. For this reason, all the 400 l/s ion pumps were replaced during LS1.

However, further potential ion pump trips and destruction cannot be excluded during Run 2. As a consequence, replacement of ion pumps might be needed during technical stops or (E)YETS. Moreover, a development study of a new pumping scheme should be launched during Run 2 to allow implementation during LS2.

Bake-ability of Components

The LHC RT vacuum system is a bake able system by design. However, some components cannot be baked to nominal value with nominal heating rate and adequate bakeout system. The origin of such NC is usually mechanical and sometime electrical.

The consequence of such weakness can be harmful for the LHC Run 2. Larger gas load can be observed, longer bake out time might be needed (with increasing the risk of damage and increasing the exposure of personnel to radiation) and increase of the risk of leak are possible.

Impacts on operation are: increase of background to the experiment, increase of radiation to electronic and reduction of NEG coating life time. Impact on technical stops, (E)YETS are: longer intervention time, increase of the risk of leak during bake out, increase of radiation to the personnel. Impact on LS2 is possible upgrade of specific equipment or rejection of the equipment for installation in the ring.

The TCDQ installed in 115 m long vacuum sectors (A4L6.R and A4R6.B) were upgraded during LS1. These components were validated at the surface in an oven (*i.e.* not in the tunnel configuration) with a specific bakeout procedure having stops at 80 and 120 °C during temperature ramp up and ramp down. As a consequence of this temperature stop and the limiting heating rate to 13 °C/h, the bakeout duration of such a vacuum sector last 2 weeks. Despite the same procedure (with stops at 80 and 120 °C) was applied in the tunnel, a systematic leak appeared at the flange extremity of the 6 TCDQs. Several trials were needed to commission the vacuum sector within the leak tightness specification while degrading the heating temperature of the vessel.

Specific studies must be conducted during Run 2 to understand and eliminate the origin of the leak.

During Run 2, no impact is expected except a reduction of the NEG pumping speed / life time in the vicinity of the TCDQs. However, if for some reason the concerned vacuum sectors are requested to be opened during a (E)YETS, very long intervention time with large risk of leak opening during bakeout must be expected.

Modification and / or sectorisation of the TCDQ must be envisaged for LS2.

The BGI installed in 22 m long vacuum sectors (D5L4.B, D5R4.R) were upgrade during LS1. During the validation phase at surface, several leaks opened systematically on the same feed trough. Given the approaching closing date of the LSS4 with respect to the arcs cool down, in agreement with BE-BI, it was decided to reduce the bakeout temperature to 140 °C at 10 °C/h. This decision allowed to tested the BGI at surface and installed it, in due time, in the tunnel with the potential impact of performances as described earlier

During Run 2, developments should be conducted to reach LHC nominal bakeout performances (250 °C with 50 °C/h heating rate) to guarantee proper operation with LHC beams. A possible upgrade of this equipment during LS2 might therefore be expected.

The BWS installed in 35 m long vacuum sectors (E5L4.R, E5R4.B) were upgrade during LS1. Again, during the construction phase, this equipment could not be delivered on time with the required robustness at the bellow’s weld. In agreement with BE-BI, it was therefore decided to reduce the bakeout temperature to 120 °C with 25 °C/h heating rate which allowed the validation at surface and tunnel installation accepting the impact of the system on the machine performances. Indeed, despite its expected relative cleanliness with respect to more complex equipment, the outgassing rate of the BWS in the present condition is as large as the outgassing rate specification of a LHC collimator (10^{-7} mbar.l/s) !

Similarly to the BGI case, developments should be conducted during Run 2 to restore the vacuum performances. Thus, a possible upgrade of this equipment during LS2 might be expected.

The crystal collimation system is an experiment to increase the efficiency of the LHC collimation (LUA9 experiment). Two goniometers were installed in B5L7.B and A4L7.B vacuum sectors of 37 and 45 m long respectively. After LS1, these equipments will be completed by 2 Cerenkov detectors located in vacuum sectors A5L7.B and IP7.B (30 and 83 m long respectively) [8]. Due to the presence of a piezzo electric material, the bakeout temperature of the goniometer is limited to 100 °C and 10 °C/h. Since it is planned to operate with low beam intensity and since the measuring system will be in parking position, screened by a standard circular Cu tube, when operating with nominal LHC beams, the hardware was installed in the LHC tunnel [9].

The system being installed and operated in a high radiation environment, developments are mandatory to restore the nominal bakeout performance (250 °C, 50 °C/h heating rate) of present and future devices in order to respect the ALARA principle.

Internal (Virtual) Leaks

All the equipments installed on the beam vacuum system during LS1 were qualified at surface before tunnel installation. A total of ~ 1200 components were tested [10]. During these tests, outgassing rate was measured, cleanliness was quantified and leak detection performed.

During the last process, external (from atmosphere) but also internal leaks were quantified. Internal leak, often called “virtual leaks”, originates from diffused/trapped molecules in porous material or welds and closed volumes. Typical closed volumes are threaded holes for screws which have not been ventilated properly.

Figure 5 show a typical signature of internal leak. Once external leak have been eliminated, the complementary pumping system is switched off (in this case an ion pump). NEG is then the only remaining pumping system which does not pump noble gas and hydrocarbons. With time accumulation, if an internal leak (composed by air molecules) is present, Ar increase with time. The level of the internal leak can also be estimated from this measurement.

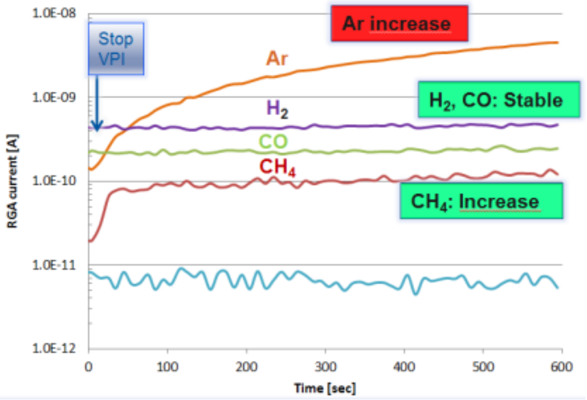


Figure 5: Typical signature of an internal leak (courtesy G. Cattenoz TE/VSC).

Two equipments, installed in the LHC ring during LS1 exhibit large internal leaks level: BQSV.5R4.B1 and TCSP.4L6.B2 with 5 10^{-7} and 6 10^{-7} mbar.l/s leak rate respectively. If needed, these equipments might be upgraded during LS2.

As a result of the internal leak, the leak detection sensitivity limit in the concerned vacuum sector is altered. If not spotted during the surface test, the field operator will spend (and lose) significant amount of time (~ day) to identify an external leak which is not existing! Moreover, this internal leak will progressively saturate the NEG coating in its vicinity and affect the conditioning level in the nearby stand alone magnets.

In the LHC, any leak rate of a vacuum sector must be $< 10^{-9}$ mbar.l/s, a level which saturates about a meter of NEG coating per year. Therefore, the leak rate per components must be $< 10^{-10}$ mbar.l/s.

Beam Induced Heating

Beam induced heating can be significant for some LHC equipments [11,12]. In order to optimise the impedance of the system, ferrites are inserted to damp the high order modes at specific location in some equipment. This is the case for MKI, Totem and Alfa roman pots and TCTP equipments. During operation, despite the ferrite will reduce the power loss (by lowering the quality factor Q of the resonance), the temperature of the ferrites increase due to the remaining power loss [13,14].

Figure 6 shows the specific outgassing rate of standard ferrites used at CERN and compared to baked stainless steel and vacuum fired stainless steel. These data were obtained followed a degassing treatment of the ferrite at 400 or 1000 °C. The specific outgassing rate is inversely exponentially dependent with the inverse of the temperature.

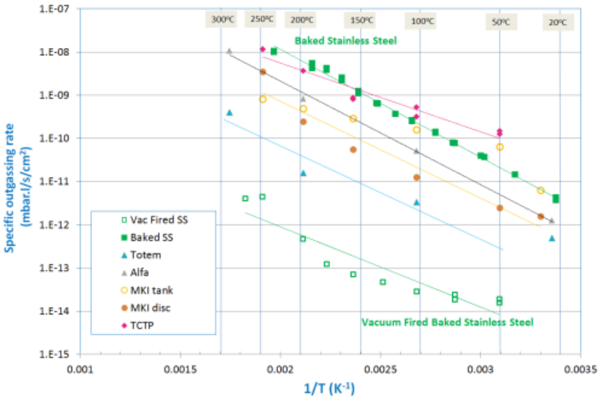


Figure 6: Specific outgassing rate of ferrites compared to baked stainless steel and vacuum fired stainless steel (courtesy G. Cattenoz TE/VSC).

Therefore, as shown in Table 1, increasing the ferrite temperature from RT to 50 °C will multiply its outgassing rate by 5. Increasing further the temperature, the ferrite outgassing rate can be multiplied by several orders of magnitude increasing significantly locally the vacuum pressure. Long term operation will then saturates the NEG coating and induce radiation to the electronic. Finally, the equipment will need to be repaired during LS2.

Table 1: Outgassing rate increase as a function of ferrite temperature

°C	50	100	150	200
q/q_{RT}	5	40	150	600

TDI

During Run 1, TDI was the source of background to the ALICE experiment while operating with proton beam. A possible origin of the beam induced pressure rise (in the 10^{-8} mbar range) is beam induced heating.

To allow exchange and/or reconditioning both LHC TDI were sectorised during LS1. The pumping speed was also upgraded by adding 2000 l/s NEG cartridges.

However, the TDI will still suffer from resistive wall (~ 400 W on jaws at injection and 60 W at flat top when jaws are in parking position) and trapped modes during Run 2. Therefore, despite that the TDI base pressure are back to nominal values (~ 10^{-10} mbar), beam induced heating could still stimulated thermal outgassing [12].

Thanks to the sectorisation, the TDI could be exchanged during technical stops or (E)YETs if needed. A new TDI system is presently under design for a possible implementation during LS2.

Damage and Potential NCs

During LS1, the vacuum system suffered from several collateral damages. As an example, bellows, beam pipe, valves were damaged or operated outside their working range. The conformity of these equipments was systematically checked and a repair was performed when needed. Two accidental venting of room temperature vacuum sector happened also. Those took place in June 2014 in vacuum sector A7L8.R (3/6) when a tractor snatched the pumping group just before s78 cool down and in vacuum sector A4L5.C (20/6) for unknown reason (local inspection revealed that the leak was placed at a loosely bolted flange). Finally, an uncontrolled pump down of the MKB's vacuum sector (BTD68.DB) was done the 18/6/2013. A port was sealed with Al foil which explodes during pump down. As a result, 1.5 month of *in-situ* cleaning was needed to restore the MKB's performance. The origin was traced back to a lack of documentation (the blank flange was removed from the port and replaced by an Al foil the Friday afternoon and documented by a phone call) and a lack of systematic inspection before pump down.

Obviously, the time needed to manage these collateral damages extended the requested time by the planning team to conclude the beam vacuum activity on the field.

For LS2, it is planned to continue to upgrade the quality level and reinforce the quality control teams. Progress must continue to provide systematic and well defined procedures, activity reports and quality control. In particular, a few teams, independent from the field team, are needed to perform these controls.

CONCLUSIONS

Many activities have been performed during LS1 with great success. However, despite all the precaution taken and the efforts made during the design, test, installation and commissioning phase, several NC could not be avoided and corrected in due time before tunnel closure.

In particular, the 5th axis for collimator is condemned for the TCTP located in the recombination area of LSS1 and 5. A few RF bridge (1% of the total) have been identified as critical. The MKBs large outgassing rate can provoke pressure spikes triggering beam dumps. Several installed equipments (TCDQ, BGI, BWS, LUA9) are not compatible with bake out specification or exhibit internal leaks (BQSV, TCSP). A few equipments containing ferrites are sensitive to beam induce heating *e.g.* TDI. If needed, any of these NC might be corrected either during technical stops, (E)YETS or LS2.

Quality has been an important aspect of the LS1: from design to commissioning. After a state of the art design and fabrication phase, vacuum tested performed at the surface have eliminated potential issues before installation into the ring. Quality control checks, performed in the tunnel, have allowed identifying potential issues while correcting them when possible. For LS2, the use of dedicated and independent quality control teams is mandatory to increase the machine efficiency as requested for HL-LHC operation. Such teams are needed to control and document the work made all across the ring. An immediate consequence of such an approach is that the commissioning time of a "standard" room temperature vacuum sector will be increased from 3.5 weeks to about 4 weeks.

ACKNOWLEDGEMENTS

The author would like to thank G. Bregliozzi, K. Brodzinsky, G. Cattenoz, P. Cruikshank, C. Garion, G. Ferlin, J. Perez Espino and L. Tavian for their precious contribution to this presentation.

The author would like also to warmly acknowledge the members of the LBV section for their strong commitment during LS1 and in particular for their investment to the quest of “zero default”.

REFERENCES

[1] What was wrong with the plug-In-Modules (PIMs) in the cold part of the LHC? P. Strubin, LHC RF Fingers Task Force, 17th April 2012, CERN, Geneva.

[2] LHC Beam Operation Committee, 17th September 2013.

[3] UFOs will they take over? T. Baer, LHC Beam Performance Workshop, Chamonix 2012, February 2012.

[4] Going towards LHC Run 2 Cryogenics. K. Brodzinski, LHC Beam Operation Workshop, Evian 2014, June 2014.

[5] Updated Robustness Limits for Collimator Materials. A. Bertarelli *et al.*, LHC Beam Machine Protection Workshop, Annecy, March 2013.

[6] Vacuum Performances and Lessons for 2012. V. Baglin, LHC Beam Performance Workshop, Chamonix 2012, February 2012.

[7] CERN Vacuum System Activites during the Long Shutdown 1; the LHC Beam Vacuum. V. Baglin *et al.*, Proceedings of IPAC 2014, Dresden, June 2014, Germany.

[8] Installation of the LUA9 equipment in IR7 of the LHC. S. Montesano *et al.*, ECR 1329235, February 2014.

[9] Summary of the 173rd LMC meeting held on 5th February 2014.

[10] Vacuum acceptance tests for the UHV room temperature vacuum system of the LHC during LS1. G. Cattenoz *et al.*, Proceedings of IPAC 2014, Dresden, June 2014, Germany.

[11] Beam-induced heating / bunch length / RF and lessons for 2012. E. Metral, LHC Beam Performance Workshop, Chamonix 2012, February 2012.

[12] Heat load and impedance. B. Salvant, LHC Beam Performance Workshop, Chamonix 2014, September 2014.

[13] Lessons learnt and mitigation measures for the CERN LHC equipment with RF fingers. E. Metral *et al.*, Proceedings of IPAC 2013, Shangai, June 2013, China.

[14] Design guidelines for ferrite absorbers submitted to RF-induced heating. A. Bertarelli *et al.*, Proceedings of IPAC 2013, Shangai, June 2013, China.

EXPECTED IMPACT OF HARDWARE CHANGES ON IMPEDANCE AND BEAM INDUCED HEATING DURING RUN 2

B. Salvant, G. Arduini, M. J. Barnes, O. Berrig, N. Biancacci, F. Caspers, H. Day, J. Esteban Mueller, A. Grudiev, J. Kuczerowski, E. Métral, N. Minafra, N. Mounet, A. Nosych, A. Passarelli, S. Redaelli, G. Rumolo, E. Shaposhnikova, J. Varela, C. Vollinger, M. Wendt, C. Zannini, CERN, Geneva, Switzerland, O. Frasciello and M. Zobov, INFN-LNF Frascati, Italy

Abstract

Following the significant impedance related issues that occurred during the LHC Run 1, all involved equipment groups made an impressive effort to assess and reduce the impedance of their near-beam components.

Concerning beam induced RF heating, many problems in Run 1 were linked to unexpected non-conformities. Mitigations were put in place but new non-conformities are likely to appear in Run 2, and this is why efficient monitoring and alarms are currently put in place. Besides, known limitations that led to increase the bunch length from 1 ns to 1.25 ns were removed, which would open the possibility to try and reduce the target bunch length at top energy. Regardless of the target bunch length, many components will need careful follow up in 2015 (e.g. TDI, BSRT, Roman pots, MKI, BGV).

Concerning the LHC impedance, announced hardware changes are expected to be transparent, but the new TCTP and TCSP collimators with BPMs and ferrites should be monitored closely, as well as the modified Roman pots, new TCL4 and especially new TCL6 collimators if they approach the beam with very low gaps at high beam intensity.

INTRODUCTION

During LS1, many hardware changes affected the CERN Large Hadron Collider (LHC) beam surroundings: consolidations, upgrades and new equipment. The expected consequences of these changes on the LHC beam coupling impedance will be reviewed in this contribution, as well as their consequences on the related intensity limitations: beam instabilities and beam induced RF heating. These collective effects have indeed affected the performance of the LHC before the Long Shutdown 1 (LS1), and this contribution will provide a status of the expected issues that may come up, as well as suggest mitigation strategies in case of problems.

CONTEXT

When an ultrarelativistic beam of particles traverses a device, which is not smooth (resp. is not a perfect conductor), it generates geometric (resp. resistive) wakefields that perturb the following particles. These electromagnetic perturbations are usually decomposed into longitudinal and transverse wakefields (or beam coupling impedance in frequency domain).

The longitudinal impedance leads to energy lost from the particle, dissipated at the surface or in the bulk of the neighbouring devices, which results in heating of the beam surroundings, temperature interlocks and/or degradation of machine devices. In fact, during Run 1, the LHC bunch length needed to be increased from 1 ns to 1.25 ns (4 sigma) to mitigate beam induced heating issues on several LHC components [1].

The longitudinal (resp. transverse) impedance also leads to perturbation of the synchrotron (resp. betatron) oscillations, which can excite longitudinal (resp. transverse) instabilities as well as degrade the beam quality (e.g. beam losses, emittance growth and dumps). Longitudinal instabilities could be generated during Run 1, but have never been a limitation, while many transverse instabilities occurred in LHC during Run 1, limiting the LHC performance in particular in the Summer of 2012 [2].

In case of a request for a modification, upgrade or installation of new components the current policy enforced by the impedance team is:

- The new/modified component should by default remain in the shadow of the current LHC impedance model in the relevant frequency range (8 kHz to about 2.5 GHz).
- New longitudinal resonant modes should present a shunt impedance below 200 kΩ (in circuit convention).
- The impact of new transverse resonant modes should be checked with beam dynamics computations or simulations.
- Expected heat loads are communicated to the equipment owner so that he can take appropriate action (e.g. cooling, improve thermal conduction and/or radiation to evacuate the heat load).

In case the beam induced RF heating is predicted to be too large, then there are several potential solutions:

- Reduce the longitudinal impedance at the LHC beam spectrum harmonics.
- Extract the heat and/or improve the resistance to heat of the critical parts of the device.
- Reduce the intensity per bunch, which is equally efficient with broadband and narrow band impedances.
- Reduce the number of bunches, which is less efficient with broadband impedances than with narrow band impedances.
- Optimize the beam power spectrum by changing bunch length but also bunch shape, e.g. with flat bunches [3].

It is clear that the equipment owner can only optimize the first two of these potential solutions. It is important to note that it is risky to design devices so that sharp high Q resonant modes are placed in between beam harmonic lines since both RF simulations and manufacturing/handling can lead to large uncertainties in the determination of the frequencies of these modes.

In case of unexpected issue, the beam parameters can be optimized, at the possible cost of adding new constraints to the operational parameter space if the solution has to be implemented on a permanent basis (as for the bunch length increase at flat top since mid-2011). For instance, in case a temporary heating problem is observed on a component during a fill, the bunch length and/or bunch shape could be optimized, instead of abruptly dumping the beam.

HARDWARE CHANGES DURING LS1

The changes before LS1 with potential impact on impedance were categorized into:

Consolidation changes that followed an issue observed before LS1:

The consolidation of damaged injection protection collimators TDIs (reinforced beam screen, refurbished motor control and jaw holder) [4]; the replacement of the skew primary collimator TCP.B6L7.B1 with a spare due to temperature increase of the order of 50 degrees, which is larger by 1 to 2 orders of magnitude compared to all other LHC TCP collimators [5]; the replacement of the damaged mirror systems of the two synchrotron light monitors (BSRT) by new designs that are expected to generate less beam induced heating [6]; the replacement of non-conforming RF fingers [7]; the addition of shielding to the ATLAS-ALFA Roman pot in order to reduce beam induced heating [8].

Upgrade of existing components:

The replacement of all tertiary collimators (TCTs) and the secondary collimator in IR6 (TCS) with the designs with embedded BPMs (TCTPs and TCSP) [9]: in particular, the two remaining two-beam vertical tertiary collimators (TCTVBs), for which the temperature was observed to increase significantly before LS1, were relocated outside the combined regions and replaced by these new TCT designs; the “TOTEM consolidation” of existing Roman pots by addition of new shielding [8]; the upgrade of the MKI beam screen design to include all 24 screen conductors instead of 15 or 19 before LS1 [10]; the new experimental beam pipe with smaller aperture in the central region of the ATLAS and CMS experiments [11]; the upgrade of the Schottky monitors [6]; the insertion of a NEG coated insert in the large diameter vacuum chambers [12].

Installation of new equipment:

The collimators to protect from physics debris (TCL4 and TCL6 in IR1 and IR5) [9]; the installation of a third TCDQ module [10]; the installation of a new beam size monitor BGV on beam 2 [6]; the new “TOTEM upgrade” cylindrical Roman pots [8]; two goniometers for crystal collimation tests in IR7 [13].

Besides, some non-conformities were detected but it was decided to leave them in place: small RF contacts sticking inside the beam screens at three locations, including one triplet [7].

IMPACT OF HARDWARE CHANGES ON BEAM INDUCED RF HEATING

This section covers the changes that are expected to have the largest impact on beam induced RF heating after LS1: TDIs, BSRTs, Roman pots and MKIs (acknowledging the removal of the TCTVBs).

Injection Protection Collimators TDIs

The TDI suffered from various problems before LS1: large outgassing with beam - which was a significant cause of background for the neighbouring experiments -, as well as several mechanical issues (deformation of the copper beam screen and beam induced deformation of the jaw), which have been a worry for the integrity of the device and machine protection. All these problems are believed to be linked to the large longitudinal impedance of the device and to the related beam induced heating that could not be mitigated by the water cooling that turned out to be inefficient [4]. Since there was no temperature monitoring installed before LS1, it has been difficult to understand what was going on only from vacuum pressure measurements. It has to be noted that the specification of the TDI as an internal dump, which requires very long jaws, large unshielded volumes, abrupt steps, and a dielectric material as absorber, did not make it easy to reduce the impedance at the design stage and still represent an issue for the new TDIs that are being designed for installation during LS2.

Significant effort was invested in modifications and studies during LS1 to improve the situation [4]: more pumping power was installed [7], the beam screen was stiffened (stainless steel instead of copper with the addition of more supports), the jaw mechanism was refurbished, the copper coating was removed from the beam screen (which reduces the shunt impedance from the resonant modes). In addition, temperature probes could finally be added on the lower jaw (4) on the support (2), and on the beam screen (2), but despite a lot of effort by EN-STI and TE-VSC, the copper coating on the jaw could not be implemented due to an unforeseen issue with the integrity of the sandwich of coating layers [4]. As a consequence, the heat load to the TDI jaw is expected to be unchanged for Run 2 and it cannot be excluded that heating issues come back after LS1. However, the refurbished TDIs should cope better with this heat load and they should be monitored closely after LS1. It is in particular recommended that the time spent with the TDI jaw gap closed when high intensity beams circulate in the machine should be minimized: ideally the TDI should be opened after each injection when the circulating beam intensity becomes significant and a trade-off should be found with the mechanical reliability and the machine availability.

If heating problems come back, the additional diagnostics and the TDI8 impedance measurements before installation should indicate the best mitigation mechanism (bunch length increase or bunch shape change, bunch intensity decrease or total intensity decrease). Besides, new spares with copper coating - among other improvements - are planned to be installed during the Christmas stop 2015/2016.

Synchrotron Light Monitor BSRT

In 2012, the BSRT mirror system was damaged by proton beam induced RF heating. Significant increase of temperature was observed, as well as deformation of the mirror - that affected the transverse emittance measurement - and damage on the mirror holder and ferrite, which were worrying for machine protection.

These problems were linked to the difficulty of evacuating the heat from the ferrite that was placed to damp a large RF mode generated by the mirror and mirror holder. During LS1, the mirror and mirror holder geometries were modified to attenuate the RF mode (see Fig. 1). The metallic holder that was acting as an antenna was removed and the first RF mode is now expected to be small enough so that no ferrite needs to be installed. RF measurements and simulations were performed to validate the design, and simulations currently predict 50 to 200 W on the whole device in case the mode is excited by the 40 MHz beam frequencies (only 1 to 8 W would heat the mirror in that case, since the rest would heat the copper coated surroundings), while before LS1 almost all of the 30 W were continuously heating the ferrite ring. It is crucial to note that the removal of the ferrite turned the mode from broadband to narrow band, and changed the probability to hit a beam spectrum line from 100% before LS1 to an order of 0.1% (considering that the first RF mode would have a width of 40 kHz in a comb of sharp 40-MHz-spaced exciting beam frequencies).

In case these heating problems come back after LS1, the beam intensities and bunch lengths can be optimized. The vacuum chamber could also be cooled from the outside since a large proportion of the heat should be dissipated in the copper coated vacuum pipe. Slightly moving the mirror holder to try and avoid overlapping of the sharp RF mode with the sharp beam frequencies could also be tried (if mechanically possible after installation).

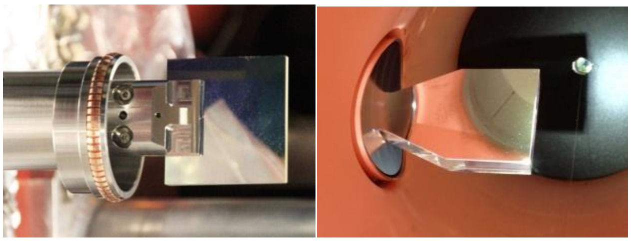


Figure 1: BSRT design installed before LS1 (left) and after LS1 (right) (courtesy BE-BI).

Roman Pots

The temperature of the ATLAS-ALFA detectors inside the Roman pots got very close to the damage limit in September-October 2012 [14], while Cryo regulation issues on neighbouring Q6R5 could have been caused by heating/outgassing on one of the neighbouring TOTEM Roman pots XRPH.A6R5.B1. In fact, evidence of overheating of the ferrites was found during LS1 and they turned out to be damaged [15]. Since it was efficiently cooled, the TOTEM detector was not threatened to be damaged.

Also in this case, significant redesign of the Roman pots was launched before LS1 to reduce beam induced heating and the ferrites were relocated where they can be cooled more easily (see Fig. 2). For ATLAS-ALFA, heat extraction and cooling capacity was also improved [16].

If heating problems come back, the cooling capacity from the outside can be increased (e.g. fans or water cooling), and the Roman pots should be kept far from the high intensity beams.

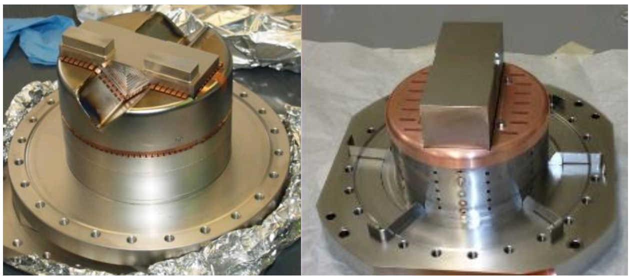


Figure 2: Shielding of ATLAS-ALFA (left) and consolidated TOTEM (right) roman pots installed during LS1 to improve the impedance (courtesy ATLAS-ALFA and TOTEM).

Injection Kickers MKI

The screen conductors allow the shielding of the ferrite from the beam and thereby reduce the longitudinal impedance and the related heating. For all the MKIs installed pre-LS1, 9 screen conductors (out of 24) were not installed to avoid electrical breakdowns. Before LS1, the temperature of all injection kickers was increasing with beam in the LHC. However, prior to Technical Stop 3 (TS3) in 2012 the temperature of one injection kicker in particular (MKI8D) approached the Curie temperature of the ferrite, which was measured to start to affect the kicker performance [10]. Therefore, on several occasions prior to TS3, one had to wait after a fill that the temperature of this MKI8D decreased below the SIS threshold before taking new injections from the SPS. This MKI8D was exchanged during TS3 2012. Finally, when the MKI8D was inspected the 15 screen conductors were found to be twisted by 90 degrees, from one end to the other, and hence were not screening the ferrite efficiently.

Results of pre-LS1 studies to redesign the screen conductors (now staggered and without metallization around the ceramic at the end), were implemented during LS1 on all injection kickers so that all 24 screen conductors could be installed. The situation with respect to heating is therefore expected to be much more favourable than before LS1 and heating is not expected to be a problem during run 2. Besides, the impedance of all MKIs was systematically measured before reinstallation for Run 2 and no non-conformities were detected. In addition to upgrading the beam screen, treatment of the inside of the MKI tanks, to improve radiative cooling of the ferrite, was tested but was not successful: other studies to improve future cooling are ongoing.

Although heating of the MKIs is not expected to be a problem, during run 2, SoftStarts will continue to be carried out, following a physics run, to refine and validate the SIS temperature interlocks after LS1. Before LS1 (with 50 ns beam), the decrease of the intensity per bunch and the increase of bunch length were efficient knobs to mitigate beam induced heating.

It can finally be noted that the three systems, for which the temperature increase led to increase the bunch length from 1ns to 1.25 ns in 2011, were better controlled (Cryo) upgraded (MKIs) or removed (TCTVBs). There is therefore in principle no known showstopper to reduce the bunch length closer to nominal bunch length after LS1, as a dedicated operational test at injection with 50 ns beam indicated in 2012 [3]. However, it cannot be guaranteed that all systems - by design or following non-conformities - will not limit the bunch length reduction for a given beam intensity.

IMPACT OF HARDWARE CHANGES ON BEAM STABILITY

This chapter covers the changes that are expected to have the largest impact on beam stability after LS1: new collimators with BPMs and ferrites, and Roman Pots/TCL6 insertions during high luminosity fills.

New Collimators with BPMs and Ferrites

A new proposal of tertiary collimators with embedded BPMs made the design of the lateral RF contacts difficult. At the request of the collimation project team and following the issues with RF contacts that occurred in 2011, the impedance team recommended in 2011 to leave the gap open and install ferrites (only for the 8 TCTPs and 1 TCSG in 6 per beam, provided the gap is not too small).

Following new benchmarks with simulation tools that became available in the meantime, it was realized that a transverse RF mode at around 100 MHz enhanced by the large beta function at these tertiary collimators was not damped enough by the ferrite (contrary to the other modes at higher frequencies) and was emerging out of the current LHC impedance model (see Fig. 3) [17, 18]. These impedance simulations were later confirmed by impedance measurements [19]. The codes DELPHI and HEADTAIL [20], as well as NHTVS [22] expected a small impact on beam stability of this additional "TCTP mode" (see for instance DELPHI results in Fig. 4).

Besides, following the issues with ferrites heating on other LHC equipment, it was checked that most of the beam induced heat load occur on the jaw and not on the ferrites (~1 W expected on the ferrites after LS1).

In case problems occur, it is again crucial to check if it is linked to a non-conformity or to a design problem to decide if useful to exchange with spare(s). For stability, the jaw gap could be increased, or at constant gap the beta function at the TCTs could be decreased (if possible and desirable since this would require increasing β*). For heating, increasing bunch length and decreasing jaw gap should help. For both collective effects, decreasing bunch intensity would help.

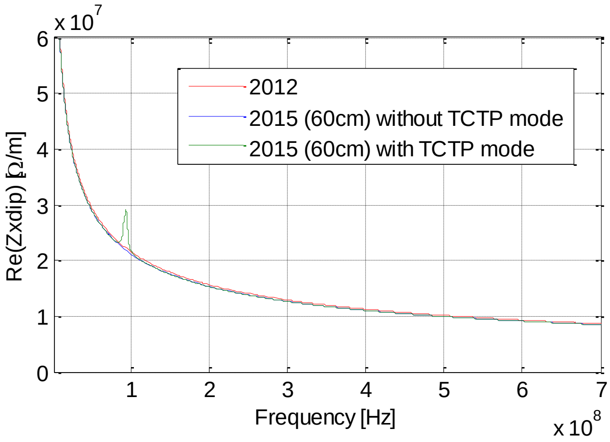


Figure 3: Impact of the 100 MHz mode of the 8 TCTP and 1 TCSG per beam on the real part of the horizontal impedance of the current LHC model for β*=60 cm (in green), compared to the case without this "TCTP mode" (in blue) and to the 2012 impedance model (in red).

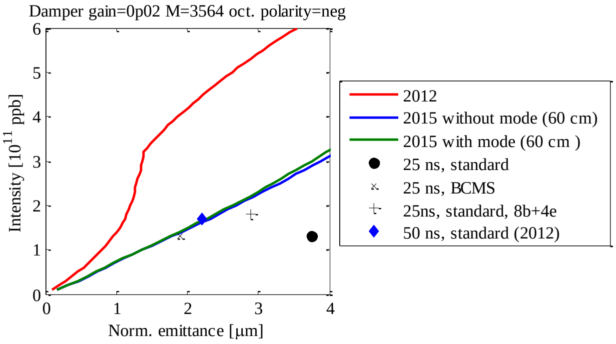


Figure 4: Impact of the 100 MHz mode of the 8 TCTP and 1 TCSG per beam on the stability limit as computed by the DELPHI code for a filled LHC with 25 ns bunch spacing, negative octupole polarity and β*=60 cm (in green), compared to the case without this "TCTP mode" (in blue) and to the 2012 case (in red). The beam is stable below the lines, unstable above the lines. The large difference between 2012 and 2015 is the result of the change of beam energy.

Finally, following these studies, the recommendation from impedance point of view for future designs of collimators with embedded BPMs would now be to use lateral RF contacts instead of/in addition to the ferrites to completely avoid these potential issues. However the operational experience with these new TCTPs after LS1 will allow assessing whether the predictions that these issues have a small impact on heating and stability are confirmed.

New TCL4, TCL6 Collimators and Roman Pots Operation during High Luminosity Physics Fills

Proposals for operational scenarios for Run 2 foresee very small gaps for Roman pots and TCL6 in IP5 due to the very low horizontal beta function at this location, which would lead to significant impedance [22]. TCL6 settings should therefore be optimized taking impedance into account. On the other hand, the newly installed TCL4 is predicted to have a smaller impact (metallic collimator at standard gaps).

The operational scenarios for these collimators and Roman pots are planned to be discussed at the collimation working group, LHCC and LMC, and a tradeoff should eventually be found between (1) TOTEM protection and performance and (2) the requirements by the impedance, energy deposition, collimation and machine protection teams.

It is important to note that these components should only move in with colliding beams, which means that stability issues are expected to be less critical thanks to the large landau damping provided by the head-on beam-beam effect. However heating issues would not be reduced unless these insertions are performed later in the fill when the intensity per bunch decreases and the stabilization of the bunch shape can significantly reduce the heating.

In case there are problems after LS1 when inserting the Roman pots and or TCL6, the solution will be straightforward: keep the Roman pots and associated TCL6 retracted until the collective effects have reduced enough during the fill.

OTHER RELEVANT CHANGES

Additional modifications are worth mentioning:

- A third TCDQ module was added but the simulated impact on impedance is expected to be small [23].
- No impact is expected from the additional passive absorbers in IR3 [24].
- The installation of the new BGV was carefully followed up by the impedance team and potential heating by RF mode at high frequency should be monitored. Cooling has been foreseen by the BE-BI team [25].
- A goniometer for UA9 was installed to be used during MDs but no impact is expected since it was designed to be efficiently screened from the beam during regular operation. Impedance measurements confirmed the efficiency of this screening [26].
- No issue is expected from the new beam pipe with lower aperture installed in CMS and ATLAS [27].

Besides, it can be noted that the 8b+4e beam, which could replace the 25 ns beam in case electron cloud is an issue, may lead to more heating for some equipment than the standard 25 or 50 ns beam due to the additional beam spectral lines that are not present with either regular 50 ns or 25 ns beams.

Finally, new studies account for the impact of 2 counter-rotating beams on beam induced heating in the beam screen (with weld). The coupling of the two beams seems small so far from power loss point of view: 2 beams in the same aperture are not too different from 2 beams in distinct apertures [28].

STATUS OF BEAM INDUCED RF HEATING ISSUES

The following tables summarize the status of the beam induced heating issues before and after LS1.

Table 1: List of devices affected by beam induced heating before LS1 and expectations for 2015 (black means that equipment was damaged, red means that operation was limited due to equipment at some point, yellow means that operation required close follow up, green means that the problem was thought to be solved).

Element	**Problem**	**2011**	**2012**	**2015 (expected)**
VMTSA	Damage	⬛	🟩	🟩 All removed
TDI	Damage	⬛	⬛	🟨 Refurbished
MKI	Delay (cooldown)	🟥	🟥	🟩 Upgraded
TCP B6L7 On beam 1	Few dumps	🟥	🟥	🟩 Exchanged
TCTVB	Few dumps	🟨	🟨	🟩 Removed
Q6R5	Regulation at the limit	🟨	🟩	🟩 Valves upgraded Neighboring TOTEM pot upgraded
ATLAS-ALFA	Damage risk	🟨	🟥	🟨 New design installed
BSRT	Damaged	🟨	⬛	🟨 New design installed

Table 2: Summary of expected heat load from interaction of the impedance before LS1 (1374 bunches with 1.7 10^{11} p/b, with 4 sigma bunch length of 1.25 ns), after LS1 (2748 bunches with 1.2 10^{11} p/b, with 4 sigma bunch length of 1.25 ns) and after LS1 in case the bunch length is reduced to 1 ns. It can be concluded that significant improvements are expected after LS1 with the consolidation of many devices. These improvements are planned to be carefully monitored during Run 2 thanks to the many temperature probes that were added during LS1.

Element	**Before LS1**	**After LS1 (1.25 ns)**	**After LS1 (1 ns)**
TDI[*]	36 W	36 W (~)	48 W (+33%)
Arc beam screens	186 mW/m	215 mW/m (+15%)	300 mW/m (+60%)
Triplet beam screens (Q1/Q2-Q3)	286/360 mW/m	331/419 mW/m (+15%)	460/590 mW/m (+60%)
MKI	70 W/m[†] 160 W/m[‡]	20-40 W/m	36-55 W/m
MKD	22 W	22 W (~)	30 W (+35%)
TCP collimator	62 W	60 W (~)	92 W (+48%)
TCTP (at +/- 5 mm)	-	3 W	5 W
TOTEM** at 40 mm at 2 mm	 10 W 57 W	 5 W (-50%) 10W(-80%)	 13 W (+30%) 27 W (-32%)
ATLAS-ALFA at 40 mm	37 W	7 W (-80%)	20 W (-45%)
BSRT mirror broadband narrowband	 30 W 0 W	 1 W 1 to 4 W[§]	 4 W 2 to 8 W[§]
BGV[**]	-	50 W[§]	1 kW[§]
ALICE cone[**] CMS cone[**] LHCb cone[**]	200 W[§] 55 W[§] 50 W[§]	400 W[§] 110 W[§] 100 W[§]	640 W[§] 300 W[§] 190 W[§]

STATUS OF SINGLE BEAM STABILITY

Margin was expected and measured in the longitudinal plane and lower longitudinal emittances/bunch length after LS1 could be feasible, if interesting for the experiments [3].

Concerning transverse impedance related single beam stability, the current impedance model expects that the nominal 25 ns beam (2808 bunches with 1.15 10^{11} p/b within 3.75 mm.mrad norm. transverse emittance) would be stable at 6.5 TeV and $\beta^*=65$ cm with octupole polarities powered to their maximum positive or negative current, high chromaticity and maximum ADT gain [29]. In the frame of these assumptions, the stability limit for this beam would be expected at ~1.3 10^{11} p/b within ~2.8 mm.mrad norm. transverse emittance.

CONCLUSIONS

Following the significant impedance related issues during Run 1, the effort by all involved equipment groups to assess and reduce impedance is expected to pay off, so that most beam induced RF heating issues should be solved. Concerning the global LHC impedance, the hardware changes are expected to be transparent. However, heating and stability diagnostics and their continuous monitoring will be crucial after LS1 to diagnose and mitigate potential unexpected issues.

ACKNOWLEDGMENTS

The impedance team would like to thank the equipment groups, the experiments, as well as collimation, machine protection, operation teams and HL-LHC WP2.4 collaborators for their invaluable help.

REFERENCES

[1] J. Uythoven et al, Beam induced heating and bunch length dependence, “Mini-Chamonix” workshop, July 15th 2011.

[2] Contributions of E. Métral et al, T. Pieloni et al and N. Mounet et al, Evian workshop December 19th 2012.

[3] J.E. Mueller et al, Longitudinal parameters and beam induced heating, Evian workshop, June 2nd 2014.

[4] R. Losito, TDI update, LHC Machine Committee 182, June 11th 2014.

[5] Contributions of B. Salvant et al and M. Garlasche et al, Collimation working group 148, September 12th 2012.

[6] F. Roncarolo, LHC Machine Committee 179, April 14th 2014.

[7] V. Baglin, Other Non-solved NC's across the LHC Ring and Potential Impact on Performance, these proceedings.

[8] Contributions of S. Jakobsen, N. Minafra and B. Salvant, 20th LTEX meeting, July 11th 2013.

[9] S. Redaelli, LHC Machine Committee 174, February 19th 2014.

[10] W. Bartmann, LBDS and Kickers after LS1, these proceedings.

[11] M. Gallilee and R. Veness for the LEB working group, LHC Machine Committees 87 on April 2011 (ATLAS) and 104 on August 24th (CMS).

[12] V. Baglin, LHC Machine Committee 180, May 14th 2014.

---

[*] Resistive wall of the TDI jaws retracted to 55 mm

[†] For conform MKIs with 15 screen conductors

[‡] For non-conforming MKI8D pre TS3 2012

[§] Potential heat load (if interacts with beam spectral line)

[**] Main mode

[13] S. Montesano, LHC Machine Committee 173, February 5th 2014.
[14] B. Salvant et al, Update on BSRT and ALFA heating, LHC Machine Committee 155, October 31st 2012.
[15] J. Baechler, TOTEM – CMS upgrade of Roman Pot system, LMC 176, 19.03.2014.
[16] S. Jakobsen, Commissioning of the Absolute Luminosity For ATLAS detector at the LHC, PhD thesis, University of Copenhagen, January 2014.
[17] B. Salvant, Collimation working group 159, April 24th 2014.
[18] O. Frasciello, M. Zobov et al, Geometrical beam coupling impedance of LHC collimators, Impedance Workshop, ICFA mini-Workshop on "Electromagnetic wake fields and impedances in particle accelerators", Erice, Sicily, April 28th 2014.
[19] N. Biancacci et al, TCTP impedance measurements, Impedance Working Group meeting, August 8th 2014.
[20] N. Mounet, BE-ABP/HSC section meeting and 24th TCTP Prototyping & Manufacturing Meeting 25/04/2013.
[21] A. Burov, 24th TCTP Prototyping & Manufacturing Meeting 25/04/2013.
[22] N. Mounet, TCL6 impedance consideration, Collimation Working Group 174, April 7th 2014.
[23] B. Goddard, W. Wetterings, Upgrade of TCDQ Collimator, EDMS document 1167537, April 24th 2014.
[24] S. Redaelli, A. Rossi, Installation of Additional Passive Absorbers in IR3 to Protect the Warm Q5, EDMS document 1273450, September 12th 2013.
[25] BGV meetings, https://indico.cern.ch/event/347682/
[26] A. Danisi et al, outcome of the UA9 impedance bench measurements, impedance meeting, March 3rd 2014.
[27] N. Mounet and B. Salvant, LEB meetings 9 and 10, January and February 2011.
[28] C. Zannini, G. Iadarola, G. Rumolo, Power Loss Calculation in Separated and Common Beam Chambers of the LHC, proceedings of IPAC 2014, Dresden, Germany, June 2014.
[29] E. Métral et al, Additional margins that could be gained by relaxing beta*: Collective effects, LHC Machine Committee 188, September 3rd 2014.

RF AND ADT AFTER LS1

A. Butterworth, P. Baudrenghien, D. Valuch, CERN, Geneva, Switzerland

Abstract

During LS1 a number of consolidations and upgrades have been undertaken in the LHC RF, including replacement of a cryomodule (four cavities, beam 2), upgrade of klystron collectors and new solid state crowbar systems. The RF parameters will be outlined in view of the consequences of the increased beam current and energy, and the exotic bunch spacing for the scrubbing beams.

The LHC Transverse feedback system (ADT) is also undergoing a major upgrade during LS1, with double the total number of pickups to reduce the noise floor of the system, new beam position electronics and an upgraded digital signal processing system to accommodate all of the extra functionality that had been introduced during LHC Run I, and more sophisticated signal processing algorithms to be deployed for Run II. An external "observation box" to record transverse and longitudinal data from the RF and ADT systems is being implemented.

RF UPGRADES DURING LS1

Replacement of Faulty Cavity Module

During Run I, cavity 3 of beam 2 could not be operated reliably above a voltage of 1.2 MV, compared with the nominal value of 2 MV, and it was decided to replace the cavity cryomodule M1B2 ("America") with the spare ("Europa"). This was done at the start of 2014, and the new module will be commissioned along with the remaining three. No special issues with this module are anticipated.

Upgrades for Improved Reliability

A number of upgrades to the RF systems have been performed with the aim of improving reliability:

Crowbar systems: The old thyratron based crowbars [1] have been replaced by a new solid state thyristor stack design, which is less prone to misfiring.

Klystron HV cables: Faulty spring contacts and poor welding in the HV connectors frequently led to spurious drops in the klystron filament current. The connectors have all been replaced using an improved induction welding technique which avoids damaging the cable insulation.

Waveguide arc detectors: These are based on photodiode sensors which detect the light emitted by an arc in the waveguide [2]. The radiation sensitivity of the diodes led to frequent spurious trips. A mitigation was put in place during Run I using an AND logic between the detectors to eliminate the spurious trips. A new design with a more sophisticated voting logic between multiple detectors has been developed, is used in Linac4, and is the object of a knowledge transfer to industry. The new system will be installed on the new cavity module; however, there are no plans to install it systematically in all LHC cavities before LS2.

Klystron collectors: During Run I, the DC power handling of the klystrons was limited to 400 kW by a design fault in the collector water cooling assembly. All klystrons have now been upgraded by Thales to handle the design DC power of 500 kW. In addition, eight of the sixteen klystrons have been swapped with spares for purposes of wear levelling.

Renovation of RF zone in SR4: During Run I the RF racks in SR4 were open to the hall, making them subject to phase and frequency drifts due to temperature and humidity variations. A roof has now been installed on the RF zone and a new air conditioning system installed to maintain constant conditions.

Remaining Items for Run II Startup

RF noise monitoring: On a few occasions, malfunctioning LLRF has resulted in severe RF noise, debunching and population of the abort gap. A Phase Noise Power Spectral Density (PSD) display was made available in CCC, which compares the vector sum of the 8 cavities for each beam against a reference spectrum and generates audible warnings in the case of excessive noise. After LS1 (mid 2015) we aim to have a measurement of the amplitude and phase noise PSD for each individual cavity implemented in custom-design VME module, to allow immediate identification of the problem cavity.

Studies on shaping of the longitudinal distribution with RF phase noise: Controlled injection of RF phase noise is used to increase longitudinal stability via emittance blow-up [3]. This technique can also be used to shape the bunch according to the noise spectrum chosen. Controlled blowup may be needed to compensate the synchrotron radiation damping at 6.5 TeV. Many data are available from Run I, but several observations are not understood. The first goal of the study is to reproduce the Run I blow-up measurements with the simulations. Studies are ongoing to find an optimum noise spectrum for a targeted bunch profile. A simulation code, BLonD (Beam Longitudinal Dynamics) [4], is being implemented into PyHEADTAIL [5].

Bunch-by-bunch phase measurement: The LLRF measures the phase of each bunch individually, then averages over the beam to correct the phase of the RF drive. Bunch-by-bunch phase measurements have been used in electron cloud studies to give information on the energy loss for each bunch [6]. Individual bunch phase observations has also been used to estimate longitudinal coupled-bunch instability growth rate [7] and will become extremely important if we suffer from longitudinal instabilities with high intensity 25 ns operation. It is measured in the custom-designed LLRF VME module but it was not practically feasible to extract the data in real time, nor to store it for analysis. These issues are being addressed via the "observation box" development described later in this paper.

Outstanding RF Controls Items

Replacement of CPUs and move to Linux: All RIO3 VME crate CPUs running LynxOS are being replaced by the new MEN A20 boards running Linux. Around 95% of the FESA classes have already been migrated, but a large campaign of installation and test is still required.

FESA3 upgrade: At LHC startup, only the new signal processing hardware of the Transverse Damper system will have front-end software under FESA3 [8]. Other LHC systems will remain on FESA 2.10 but will be migrated to FESA3 during 2015 technical stops and the winter shutdown.

Expert RF application software: The LabVIEW panels used by RF experts to configure the hardware, as well as the MATLAB scripts used for setting-up the LLRF, are using version 2 of Remote Device Access (RDA2). In order to follow the programmed FESA evolution to FESA3 version 2, these applications must be upgraded to use RDA3 [9] or JAPC (Java API for parameter control) [10]. However, as a medium-term solution, the BE-CO middleware team offers a proxy service to enable RDA2 clients to access RDA3 servers, and we will use this facility in 2015. In addition, it is desirable to use the LSA settings management rather than directly accessing the FESA devices.

It has not yet been decided whether to progressively migrate the LabVIEW applications to RDA3 and LSA, or to re-implement them using another tool such as Inspector [11].

RF RE-COMMISSIONING

The re-commissioning of the RF system will be performed in four distinct steps:

1. *Re-commissioning of the High-Voltage:* The HV (50-60 kV) supply for the klystrons will be commissioned, including tests of the HV interlocks and commissioning of the new crowbars.
2. *Re-commissioning of the High-Power RF:* The klystrons will be re-commissioned with the waveguide short-circuits in place, including the 8 new klystrons installed during LS1. Tests of the klystron interlocks and power calibrations will be performed.
3. *Re-commissioning of the cavities:* The cavities will be re-commissioned, including the new module (4 cavities) installed during LS1. The cavity interlocks will be tested, the cavities conditioned, and voltage calibrations performed.
4. *Re-commissioning of the Low-Level RF:* The tuning and feedback loops will be commissioned, with calibration of the cavity loaded Q vs. power coupler position, and optimization of the LLRF parameters.

In order for commissioning to start, a certain number of pre-conditions are necessary: general services (240/400 V) should be available, as well as demineralized water. Access to UX45 will be required, which is incompatible with magnet powering. The 18 kV cells must be powered, and the HV power converters operational, including power converter controls. The front-end crates and controls software must be operational for the RF equipment, with the expert application software available. Cavity commissioning requires in addition the cavities to be cold and filled with liquid He under stable cryogenic conditions.

RF PARAMETERS FOR 2015

Capture Voltage

Extensive measurements of SPS longitudinal emittance and bunch length exist from the 2012 proton run with 50 ns bunch spacing (Table 1). At SPS extraction with the Q20 optics, the $\Delta p/p$ is about 15% less than with the classic Q26, but the bunch length is slightly longer. The beam was captured with an RF voltage of 6 MV in LHC, giving a bucket area of 1.24 eVs.

SPS optics	Longitudinal emittance (mean)	4 sigma bunch length (mean)
Q26	0.5 eVs	1.45 ns
Q20	0.45 eVs	1.6 ns

Table 1: SPS longitudinal emittance and bunch length from 2012 run (50 ns):

Under these conditions, the measured capture losses were consistently below 0.5 % [12].

In 2015, with 25 ns spacing, the bunch intensity will be lower (1.1 10^{11} compared with 1.4-1.65 10^{11}) but the total current will be higher (0.55A DC compared with 0.35 A DC). We do not expect lower longitudinal emittance and bunch length from the SPS than in 2012, and it is therefore proposed to start with a capture voltage of 6 MV.

Flat-top Voltage and Power

The cavity loaded Q can be optimized giving the minimal required power

$$P = \frac{V\, I_{rf,pk}}{8}$$

where V is the total RF voltage and $I_{rf,pk}$ is the 400 MHz RF component of the beam current during the beam segment.

Each LHC klystron can provide 300 kW RF with the nominal DC settings of 8.8A and 58 kV. Keeping 20%

margin for RF voltage regulation limits the theoretical power to 250 kW, which determines the maximum voltage per cavity (Table 2).

With 8 cavities, taking a cosine^2 bunch profile with a nominal 1.25 ns bunch length [13], the maximum achievable total voltage is 13.4 MV with 0.55 A DC beam current, and 14.9 MV with 0.5 A DC beam current.

I_{DC}/A	4 sigma bunch length/ns	$I_{rf,pk}$/A (cosine^2 profile)	V @ 250 kW (MV)
0.55	1.0	1.269	**1.58**
	1.25	1.196	**1.67**
0.50	1.0	1.142	**1.75**
	1.25	1.076	**1.86**

Table 2: Maximum achievable voltage per cavity for different DC beam currents and bunch lengths

Bunch Spacing: 25ns and 5+20ns

The RF beam control was designed for the nominal LHC beam, and thus should function without problem with 25 ns bunch spacing [14]. With the 5+20 ns spacing of the doublet scrubbing beams, the wavelets produced by the two bunches passing in the same 25ns sampling window superpose to produce a valid sum signal, providing the signal is sampled at the correct instant (Fig. 1). Therefore with careful adjustment the beam control can be made to function correctly with the doublet scrubbing beams.

The same considerations apply to the beam position measurements of the Transverse Damper.

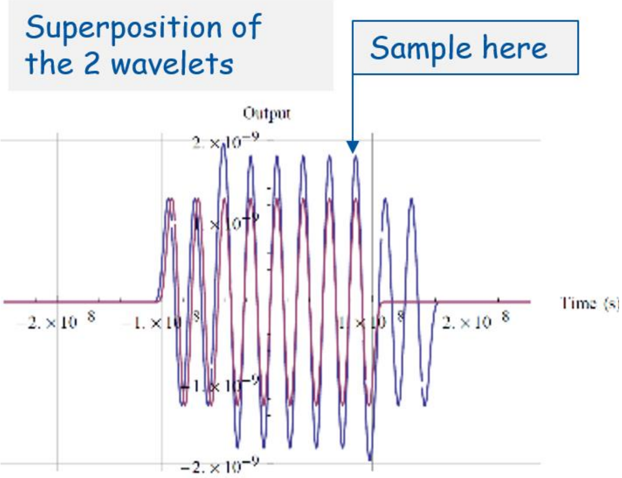


Figure 1: Adjustment of sampling in beam phase measurement for 5+20ns bunch spacing

ADT NEW FEATURES FOR RUN II

The LHC Transverse Damper (ADT) was primarily designed for damping of injection oscillations and of oscillations driven by coupled bunch instability. It plays an important role in the preservation of the transverse beam emittance.

Digital Processing Hardware

Since the LHC start in 2008 the feature set has grown to include injection and abort gap cleaning, transverse blowup used for loss map measurements, detection of instabilities using the damper pickups, and extraction of tune signals with the aim of eventually alleviating some of the co-existence problems between the damper and the BBQ [15].

The ADT upgrade foreseen for Run II provides more powerful digital signal processing hardware in a larger FPGA in order to accommodate all of the features added during Run I and some new additional functionality (Fig. 2). Three independent output DACs allow combination of the main damper loop signal with those for excitation and abort gap cleaning, each with independent gain control [16].

The new ADT Low level RF hardware is being developed in synergy with the SPS transverse damper upgrade, which is now installed and operational in SPS.

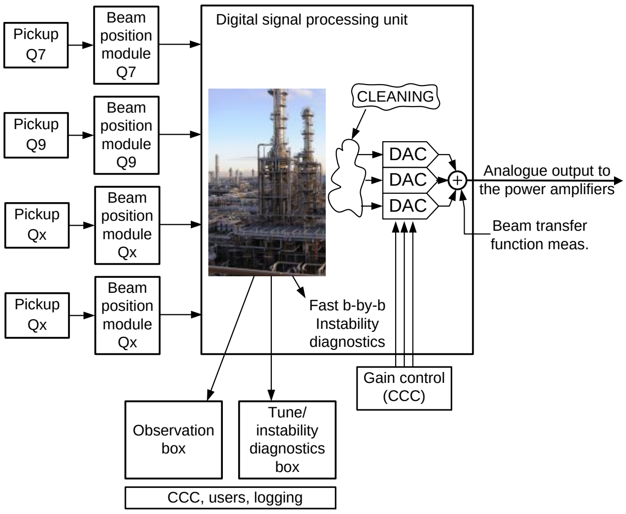


Figure 2: Signal processing in new ADT hardware

Signal to Noise Ratio and Pickup Layout

The number of pickups used by ADT has been doubled to four pick-ups per beam per plane. The signal to noise ratio for N pickups with respect to a single pickup at β=100m can be expressed by

$$\left(\frac{S}{N}\right)_{improvement} = 20\mathrm{dB}\times\log_{10}\frac{\sum_{n=1}^{N}\sqrt{\beta_n/100\mathrm{m}}}{\sqrt{N}}$$

In agreement with the BI group, the BPMC coupler-type pickups at Q7 and Q8 either side of Point 4 have been swapped with those of the Beam Presence Flag system in order to benefit from the higher beta values at these pickups. Table 3 shows the estimated improvement signal-to-noise with respect to the Run I situation.

New Data Processing Algorithm Features

The current normalization scheme sees only even-symmetric oscillation patterns which are needed for the closed loop feedback. If the longitudinal bunch profile is symmetric, the odd-symmetric transverse oscillation modes are not visible to the damper, since they do not produce a movement of the bunch centroid [17]. The new data processing implementation has an additional algorithm which can detect odd-mode head-tail & higher order oscillations. It cannot resolve the original oscillation nor the absolute oscillation amplitude accurately, but it can detect oscillation activity and distinguish between the symmetric and asymmetric modes of every bunch. This information can be used in real time to generate a measurement trigger.

	Run I (2 PU) Q7,Q9	**Run II (4 PU) Q7,Q9,Q10**	**After BI swap Q7,Q8, Q9,Q10**	**Run I → II dB (relative)**
H.B1	3.8 dB	5.6 dB	7.0 dB	**3.2**
V.B1	4.2 dB	7.4 dB	8.0 dB	**3.8**
H.B2	4.4 dB	5.9 dB	8.0 dB	**3.6**
V.B2	4.9 dB	6.6 dB	8.2 dB	**3.3**

Table 3. Estimated improvement in S/N wrt a single pick-up at beta =100 m

Compatibility with New UPS

The ADT base-band signals, from 3 kHz to 20 MHz, are transmitted over coaxial lines from SR4 to the driver amplifiers in UX45. These signals were perturbed by ground currents from the uninterruptible power supplies (UPS) which had a switching frequency of 5, 8 or 16 kHz. A measurement campaign in 2010 followed by the installation of noise suppression chokes allowed the problem to be mitigated [18]. However, the newly installed UPSs produce very different noise spectra, with some frequencies less prominent, but some components up to 40 times stronger.

The ADT team is in contact with the EN/EL group, and a measurement campaign will be carried out in order to identify and quantify a possible perturbation of the ADT by the new UPS.

RF OBSERVATION BOX

New Facilities for Signal Observation

The ADT and RF VME hardware incorporates memory buffers for the acquisition of bunch-by-bunch diagnostic data. However, these buffers are limited in size, and the demand for bunch-by-bunch data for use in beam studies has overtaken the technical possibilities. This has motivated the launch of an “Observation Box” development which aims to make available the bunch-by-bunch data to external applications. The sample data from the ADT and RF VME boards is streamed over optical fibre links to an external PC with large memory & processing capabilities, allowing data to be made available for a quasi-unlimited number of turns. On-the-fly data analysis opens the possibility of tune measurements and instability detection, which can in turn be connected to the LHC instability trigger network [19].

The data transmission and reception firmware has been developed, and the front-end software implementation is well advanced. Discussions are underway with OP for the development of an application for bunch-by-bunch beam phase measurements.

CONCLUSIONS

Large-scale modifications to the high-power RF are being implemented: a new cryomodule has been installed to replace one with a defective cavity, new solid-state crowbars aim to reduce spurious trips, and all klystrons have now been upgraded for full DC power handling.

It is envisaged to capture with 6 MV at injection as in 2011-2012, and the maximum available RF voltage at flat-top will be 13.4 MV with the nominal DC beam current of 0.55 A DC, or 14.9 MV with 0.5 A DC, assuming a cosine^2 profile and the baseline value for the 4 sigma bunch length of 1.25 ns. Operation with 250 kW of effective RF power requires the maximum 8.8A/58 kV klystron DC settings.

With a minor adjustment the RF will cope with the 5-20 ns bunch spacing of the doublet scrubbing beams.

Controlled injection of RF phase noise is being implemented in the PyHEADTAIL simulation code. The goal is to fully understand and improve the longitudinal blow-up and to precisely control the bunch profile in physics.

The ADT system is undergoing a major upgrade during LS1 to further improve flexibility and performance. An increased number of pickups and optimisation of the pickup locations result in an improved signal to noise ratio. More powerful signal processing permits the implementation of additional algorithms for fast bunch-by-bunch symmetric and anti-symmetric intra bunch instability detection. Dedicated signal paths are provided for witness bunches or cleaning.

The new hardware is developed in synergy with the new SPS damper which is currently being commissioned in the SPS machine.

New diagnostics are in preparation for measurements in the transverse and longitudinal planes which will make large-volume bunch-by-bunch data available to external software applications. New facilities are also being developed for monitoring of the RF noise.

ACKNOWLEDGMENTS

The material in this Chamonix presentation was drawn largely from the talks at Evian 2014 of P. Baudrenghien

[20] and D. Valuch [16]. The work presented is that of the LHC RF and Transverse Damper teams including L. Arnaudon, T. Bohl, O. Brunner, W. Höfle, M. Jaussi, G. Kotzian, T. Levens, P. Maesen, J.E. Muller, G. Ravida, E. Shaposhnikova and H. Timko.

REFERENCES

[1] G. Ravidà, O. Brunner, D. Valuch, *Performance of the crowbar of the LHC high power RF system*, IPAC 2012, New Orleans, USA, 2012

[2] D. Valuch, N. Schwerg, O. Brunner, *Performance of the arc detectors of LHC high power RF system*, IPAC 2011, San Sebastian, Spain, 2011

[3] P. Baudrenghien et al., *Longitudinal emittance blow-up in the LHC*, IPAC 2011, San Sebastian, Spain, 2011

[4] http://blond.web.cern.ch/

[5] http://like2000.github.io/PyHEADTAIL/

[6] J. Esteban Muller et al., *High-accuracy diagnostic tool for electron cloud observation in the LHC based on synchronous phase measurements*, IPAC 2014, Dresden, Germany, 2014

[7] T. Mastoridis, P. Baudrenghien, *Fundamental Cavity Impedance and Coupled-Bunch Instabilities at the High Luminosity Large Hadron Collider*, to be published

[8] A. Schwinn et al, FESA3, *The New Front-end Software Framework at CERN and the FAIR Facility*, PCaPAC 2010, Saskatoon, 2010

[9] V. Rapp and W. Sliwinski, *ControlsMiddleware for FAIR*, PCaPAC 2014, Karlsruhe, Germany, 2014

[10] V. Baggiolini et al, *JAPC - the Java API for Parameter Control*, ICALEPCS 2005, Geneva, October 2005.

[11] B. Lefort and M. Ferrari, *Inspector User Manual*, CERN, 2013

[12] P. Baudrenghien, T. Mastoridis, *The LHC RF: 2011 and beyond*, LHC Beam Operation Workshop, Evian 2011

[13] B. Gorini and E. Meschi, *Experiments' expectations*, LHC Beam Operation Workshop, Evian, 2014

[14] *LHC Design Report*, CERN-2004-003

[15] W. Hofle, *LHC Transverse Damper*, LHC Performance Workshop (Chamonix 2012), February 2012, CERN-2012-006, CERN-ATS-2012-069, 157-162.

[16] W. Hofle et al, *LHC Transverse Feedback*, LHC Beam Operation Workshop, Evian 2014

[17] G. Kotzian, W. Hofle, D. Valuch, *Sensitivity of LHC ADT to intra-bunch motion*, CERN EDMS 1404633

[18] A. Butterworth, *RF Performance & Operational Issues*, LHC Beam Commissioning Workshop, Evian, 2010

[19] T. Wlostowski, *LHC Instability Trigger Distribution project (LIST), Functional Specification*, CERN, June 2014, EDMS 1377705

[20] P. Baudrenghien et al, *Status and commissioning plans for LHC Run2: the RF system*, LHC Beam Operation Workshop, Evian 2014

LBDS AND KICKERS AFTER LS1

W. Bartmann, M.J. Barnes, J. Borburgh, C. Bracco, E. Carlier, B. Dehning, L. Ducimetiere, M. Fraser,
B. Goddard, S. Grishin, E.B. Holzer, V. Kain, N. Magnin, A. Masi, M. Meddahi, V. Mertens,
A. Patsouli, V. Senaj, H. Thiesen, J. Uythoven, N. Voumard, J. Wenninger,
C. Zamantzas, M. Zerlauth, CERN, Geneva, Switzerland

Abstract

Modifications of the injection kickers(MKI) during LS1 will be reviewed together with the expected performance for the coming run with respect to heating and UFOs.

The beam dump system has undergone several foreseen upgrades like a new link between the trigger synchronisation unit (TSU) to the beam interlock system, an additional retriggering line in case of TSU failure, a new dump protection absorber (TCDQ) and the installation of an additional vertical dilution kicker (MKBV) tank. Difficulties in holding off the voltage in the beam dump kickers (MKD) generators lead to an improved design of insulators and spacers. Results from the first week of reliability runs at 7 TeV will be shown.

A set of new interlocks for the injection and dump systems has been introduced during LS1 and will be reviewed: transfer line collimators (TCDI) gap control via virtual beta* and injection dump (TDI) gap control, injection septum (MSI) current and TCDQ position linked to the beam energy tracking system (BETS). The strategy for deploying blindable beam loss monitors at injection will be presented.

INJECTION KICKERS AFTER LS1

MKI Heating

Prior to LS1 only 15 out of 24 screen conductors were installed, in the LHC injection kicker magnets (MKIs), to avoid flashovers. The 15 conductors were arranged such that the ferrite is screened and - in order to reduce the flashover probability - the lower part of the chamber close to the high voltage bus bar was left without screen conductors. In this configuration most of the MKI magnets had a power deposition of 70 W/m; a value which - known from operation in 2012 - does not limit injection. However, the MKI8D magnet had a power deposition of 160 W/m which limited injection between high-luminosity fills due to extended waiting times to let the ferrite yoke cool down. The increased heating in the MKI8D originated from twisted conductors. The beam screens of all 8 MKIs have been upgraded during LS1. The outside metallization has been removed from the ceramic tube starting about 20 mm before the open-circuit end of the screen conductors. A conducting metal cylinder with a vacuum gap of 1 – 3 mm to the ceramic tube has been added. These modifications allow all 24 screen conductors to be installed: in addition the predicted maximum electrical field, on the surface of the ceramic tube, with 24 screen conductors installed is 40% less than was the situation for the 15 screen conductors pre-LS1. The 90° twist of the conductor slots, in the old MKI8D, along the length of the ceramic chamber, orientated the 9 screen conductor gap, at the downstream end of the MKI8D, from the high voltage bus bar to the ferrites, and therefore caused a significant increase of heating of the magnet yoke, especially at the downstream end. The newly manufactured ceramic tubes are carefully inspected to ensure that they do not have a twist: however a twist of the conductor slots, with the now installed full complement of 24 screen conductors, would not have a significant effect upon yoke heating. The expected power deposition after LS1 is approximately 50 W/m, thus, heating of the MKI ferrite yoke is not expected to limit injection.

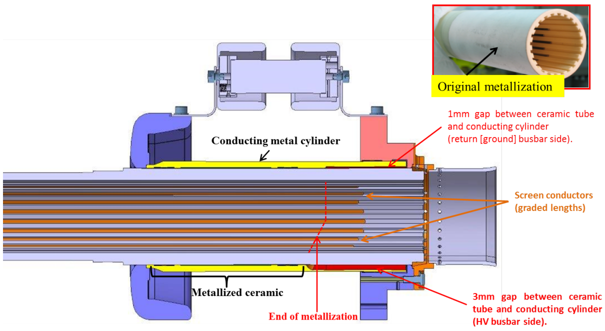


Figure 1: Improved MKI beam screen with 24 graded length conductors and a conducting metal cylinder with a vacuum gap of between 1 to 3 mm to the ceramic tube.

In order to validate the high voltage performance of the MKI magnet with the full complement of screen conductors the magnets have been tested up to 56.4 kV pulse forming network (PFN) voltage (nominal at Point 8 is 51.3 kV): as expected from predictions the flashover performance is even better than for the originally installed screen with 15 conductors. Tests of the beam screen have also been carried out outside the magnet, with background pressure of neutral hydrogen in the range of $1 \cdot 10^{-9}$ to $1 \cdot 10^{-7}$ mbar. The test setup will be modified such that the injected hydrogen gas can be ionized during the tests, to better represent the effect of the beam in the LHC.

MKI UFOs

In view of dust particles creating beam loss (UFOs), improved cleaning of the ceramic tube has given a substantial reduction of dust particles relative to the MKI8D installed during the technical stop 3 (TS), 2012, – which itself had the lowest rate of UFOs at Point 8. During the LS1 upgrades, the ceramic chambers have been flushed with high pressure dry nitrogen and the dust particles captured in a filter: subsequently the number of dust particles in the filter has been estimated by the CERN material and metrology section (EN-MME-MM). The MKI8D installed during TS3 in 2012 resulted in $390 \pm 47 \cdot 10^6$ particles after flushing and this unit showed low UFO occurrence in beam based measurements; with the new cleaning procedure the number of particles is reduced by another factor of 20 – 40, thus, the occurrence of UFOs in the MKI magnets should be significantly reduced after LS1. It is assumed that the installation of the full complement of screen conductors is beneficial also for UFOs. Figure 2 shows the induced voltage on the screen conductors: this occurs during the rise and fall of an MKI field pulse. On the flattop, pre-LS1, electric field could enter at the unscreened part of the chamber close to the high-voltage bus bar (Fig. 3), and potentially detach and accelerate charged dust particles. After LS1 the chamber will be fully screened and ressemble a Faraday cage. This should further reduce the possibility of generating UFOs in the MKIs.

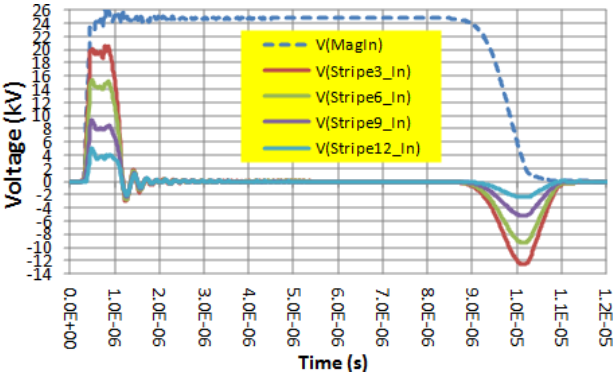


Figure 2: Induced voltage on the screen conductors during MKI pulsing.

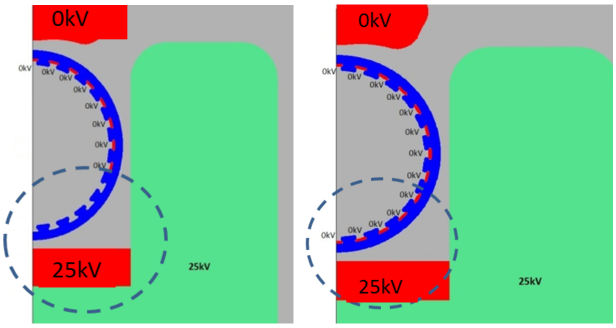


Figure 3: Area where electric field lines can penetrate into the ceramic chamber (left) and fully screened chamber after LS1 (right).

MKI Electron Cloud

The nine additional screen conductors have a high chromium content which conditions well compared to the ceramic chamber. Together with many additionally NEG-coated parts around the MKI [1] it is expected the the electron cloud level around the MKIs will be reduced. In addition, NEG cartridges have been installed on the MKI interconnects during LS1, and these are expected to limit pressure excursions due to electron cloud. In the LHC a conditioning effect of the MKI ceramic chamber is seen: after installation of the MKI8D unit during run 1, it took 250 h to recover the pre-exchange normalised vacuum pressure. Thus a certain conditioning time has to be taken into account for the machine startup.

LBDS AFTER LS1

TCDS Powering

A powering weakness of the trigger synchronisation and distribution system (TSDS) in the LHC beam dump system (LBDS) was discovered in 2012. A short circuit of the +12V TCDS crate could have prevented any trigger being propagated to the dump kickers and consequently have lead to a case where no dump is triggered although requested. As mitigation the redundant trigger synchronisation units (TSU) with separate powering which were located within a single crate were separated into two independently powered crates, Fig 4. All other systems were relocated into a third VME crate. In case of an internal failure, a synchronous dump from the redundant crate would be triggered. These modifications increase the complexity of the system which might lead to reduced availability but improved safety. There is no degraded running mode of the system foreseen. If any of the redundancy is lost, a dump will be requested and the system be repaired.

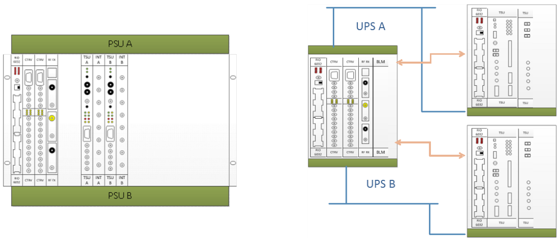


Figure 4: Changed TCDS powering after LS1. Both TSUs are located in separated VME crates with independent powering.

Retriggering Line

The Beam Interlock System (BIS) will generate retrigger pulses 250 μs after the initial dump request directly linked to the retrigger line, Fig. 5. In case the TSDS system - for a yet unidentified failure mode - does not send a synchronous trigger, an asynchronous dump will be triggered via the direct BIS link. On a longer time scale of a few 100 ms, an external surveillance was put in place to guarantee a synchronous dump in case the main and uninterruptable power supplies are lost. The functionality of the retriggering line was successfully tested with the local BIS over several weeks.

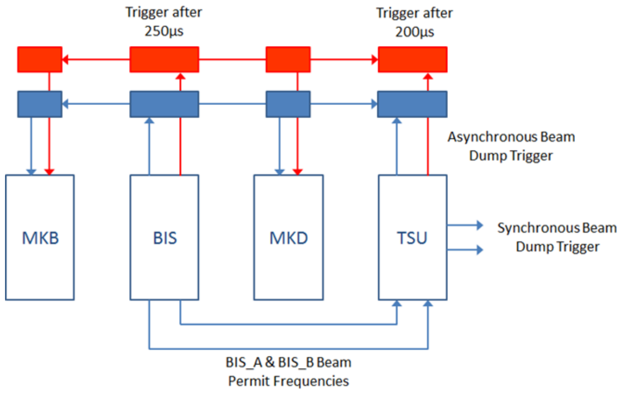


Figure 5: Direct link between BIS and retriggering line [2].

TCDQ Upgrade

In order to be compatible with HL-LHC beams at 7 TeV, the TCDQ absorber was upgraded with an additional tank increasing the jaw length from 6 to 9 m, Fig 8. The graphite absorbers with the density 1.8 g/cm^3 were replaced by a sandwich of graphite (1.83 g/cm^3) and Carbon Fiber reinforced Carbon (CFC) of 1.75 and 1.4 g/cm^3, Figures 6 and 8. Collimators of this length require an angular alignment to assure their protection functionality. During run 1 it was not possible to correctly measure the angle of the TCDQ jaw with respect to the beam since no tilt possibility was mechanically foreseen. After the upgrade in LS1 an angular movement of ± 1 mrad will be allowed.

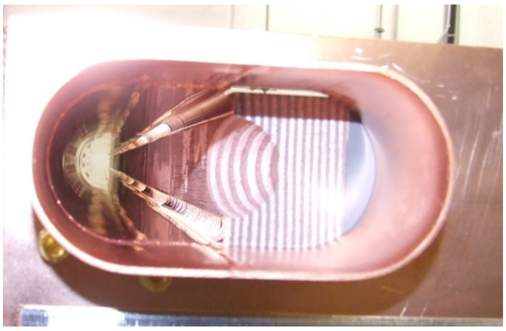


Figure 6: The sandwich structure of the TCDQ jaw and the beam screen. The left part of the jaw close to the beam is made of CFC, while further away from the beam the graphite in dark can be seen.

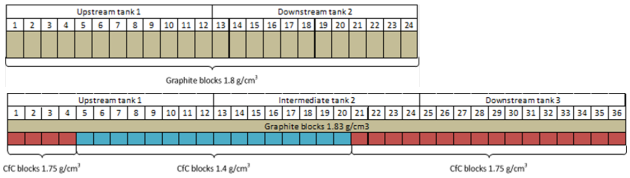


Figure 7: Before (top) and after (bottom) LS1 TCDQ with changed material composition.

The TCDQ electronics was upgraded as well to mitigate a potential common mode failure of position control and its readout which were implemented in a single PLC. This PLC was placed close to the TCDQ and thus prone to radiation issues. With the upgrade, the two functionalities were split into two separate PLCs which were placed in different locations [3]. The LVDT measurement was replaced by potentiometers and an additional interlock was added on the jaw position via the Beam Energy Tracking System (BETS) system. This interlock accepts a position tolerance of $\pm 0.35\sigma$ and is redundant with the existing collimator motor position interlock with the tolerance of $\pm 0.25\sigma$.

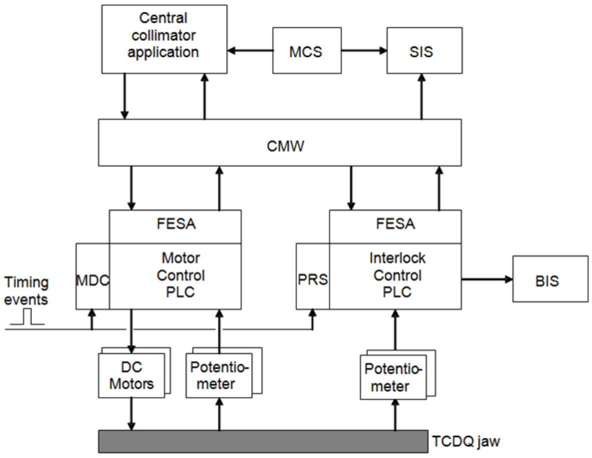


Figure 8: Upgraded TCDQ electronics with position control and readout in separate PLCs [3].

Final Dilution Kicker Installation

One tank with two magnets of the vertical dilution kickers (MKBV) was outstanding to be installed due to cost spreading. The installation has taken place during LS1. Figures 9 and 10 show the dilution shape on the dump screen BTVDD before and after LS1, respectively. The images are results of tracking studies with real machine currents in 2012 and 2014.

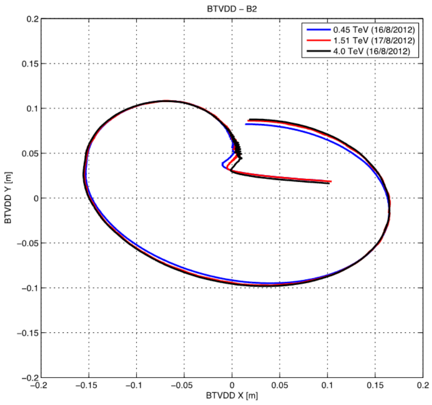


Figure 9: Beam dilution on the dump screen before LS1. Courtesy M. Fraser.

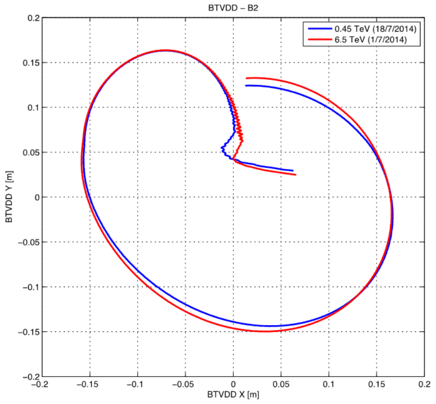


Figure 10: Beam dilution on the dump screen after LS1. Courtesy M. Fraser.

Dump kicker generators

When the dump kicker (MKD) generators were tested up to nominal energy of 7 TeV, electrostatic discharge on the semiconductor switches caused spontaneous self triggering at around 6 TeV. For run 1 the system was therefore limited to 5 TeV. During LS1 high-voltage insulators have been added between the return current Plexiglas isolated rods and the Gate-turn-off thyristor (GTO) high-voltage deflectors, Fig. 11. Up to LS1 two GTO brands were in use. Measurements of Single Event Burnout lead to the choice of using a single brand from run 2 onwards.

Figure 11: GTO stacks before LS1 (left) and after LS1 (right) with additional high-voltage insulation.

Reliability Run

The aim of the LBDS reliability run is to get statistics for the self-trigger probability of the system. A self trigger of the system would lead to a beam dump where the MKDs fire asynchronously. During this run the voltage discharge problem was detected and mitigated. Since August all measures are in place and the system was until now successfully cycled up to 7.1 TeV, Fig. 12. The reliability run shall be extended until the end of the year which means continuous running of the LBDS.

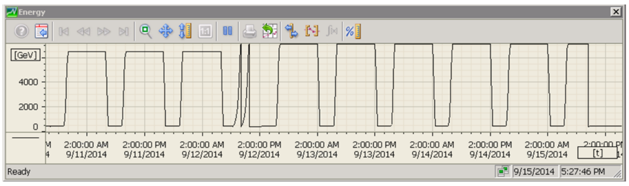


Figure 12: Cycling of the MKD generators up to 7 TeV without self triggers.

NEW INTERLOCKS

Two new interlocks for the injection septum current and the injection dump gap were put in place during LS1, an additional interlock on the gap of the transfer line collimators (TCDIs) will be put in place in the following weeks.

TDI Gap Interlock

During the LHC Run 1 the TDI jaws suffered from elastic deformations due to beam induced heating. The jaw position measurement with linear variable differential transformers (LVDT) was compromised because of the flexible junction between jaw and its mount, Fig. 13. This caused reduced machine availability due to the interlocked tight TDI jaw position tolerances. The criticality of the TDI as injection protection element gave rise to add a redundant measurement of the gap between the jaws based on interferometry, Fig. 14. The angular acceptance of the interferometric system is increased by using reflecting tubes instead of mirrors. Also the position measurement shall be kept at all times, from beam position to parking with all possible jaw angles to avoid a re-initialisation of the position. All elements have undergone radiation tests up to 10 MGy. The feedthroughs will be tested for vacuum tightness on a spare for a duration of 6 months. The spare TDI should be ready for installation in the end of year stop 2015/2016. As a difference compared to Run 1, this gap measurement will be connected to the Beam Energy Tracking System (BETS). The BETS will allow for 3 positions:

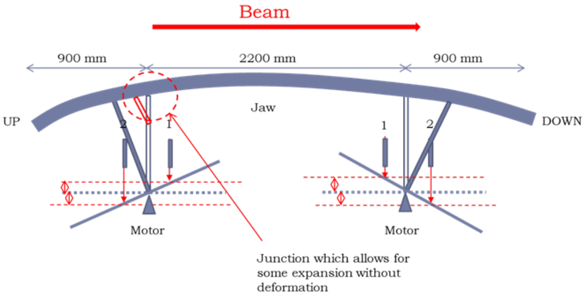


Figure 13: Deformation of the TDI jaw due to beam induced heating. Courtesy C. Bracco.

- *Injection:* 10 mm gap for normal injection operation; the interlock is triggered only if the gap is outside the tolerance or an BETS internal failure occurs.

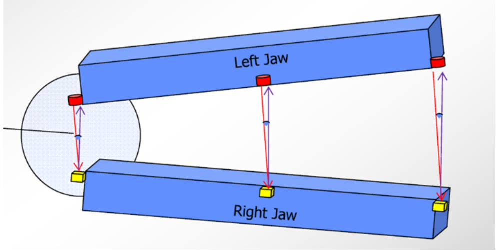


Figure 14: Position of interferometric sensors on the TDI jaw. Courtesy A. Masi.

- *Dump:* In case the TDI is positioned such that the injected beam is stopped, the BETS will be put on a maskable input to allow for the setup of injection system and the TDI itself.
- *Parking:* After injection the TDI is retracted to its parking position of ±50 mm to reduce the impedance, beam induced heating and the background for the experiments. In this case the BETS interlocks the SPS extraction.

Until the interferometric measurement is ready, the value for the gap calculated from the LVDTs will be used as BETS input. The change from the LVDT gap calculation to the interferometric gap measurement as input is transparent for the BETS.

MSI Current Interlock

The current in the injection septa (MSI) are presently protected against fast changes by the Fast Magnet Current Change Monitors (FMCM) interlock. The current value itself is protected by the SPS power converter hardware interlock (FEI) which is based on the measured current and calibration tables. Due to the lack of passive protection elements downstream the MSI it was deemed important to monitor and interlock the MSI current by the BETS. To keep modifications on the BETS side to a minimum, the present MSI power converter electronics will be replaced by an FGC LHC power converter electronics. This also allows to easily synchronise foreseen de-gaussing cycles of the MSI with the LHC ramp. The MSI power converter will be linked via fiber optics to the BETS. The BETS transfer function translates the current into an energy value; on the BETS side it is checked if the current stays within its limits corresponding to a 1-σ trajectory oscillation and the energy within 450±1 GeV.

The same argument of missing horizontal passive protection elements holds for the strong bending magnets at the end of the transfer lines downstream of the TCDI collimators. Extending the BETS interlock on these magnets shall be envisaged.

TCDI Gap Interlock

After changing to the Q20 optics in the SPS and deploying a new optics also for the transfer lines TI 2 and TI 8 in September 2012 the gaps of the injection protection collimators (TCDI) were not adapted. To avoid such a failure in the future a concept similar to the SIS β^* check as for the LHC ring is suggested. A TCDI gap control parameter (TGCP) needs to be defined for the transfer line optics, just as β^* is defined for the squeeze functions. This will be used by the SIS-SMP-MTG chain to check the gaps in the TCDI, just as β^* is used for the gap control of the tertiary collimators (TCTs). For each transfer line optics the quadrupole currents have to be stored and associated with a unique virtual β^*. The SIS reads reference settings, compares to published extraction currents for every cycle and in case the settings are within tolerance the value is published, otherwise zero is published.

On the TCDI side the TGCP value is read and checked if within limits.

The TCDI settings, TGCP values and optics are stored in a single beam process; if the beam process is wrong, the SIS check will fail.

Certain features need to be added to the existing infrastructure, like reference settings for the transfer line quadrupoles and TGCP values, TGCP limits for the TCDIs and additional SIS code. These implementations will be done until the end of the year, the interlock functionality can be tested without beam during machine checkout.

Injection Beam Loss Monitors

The motivation to modify the beam loss monitoring (BLM) system in the injection region originates from avoidable beam dumps at injection. Loss showers from the transfer line collimators (TCDI) hit from the outside of the cryostat the sensitive LHC loss monitors where the tunnels of the transfer lines TI 2 and TI 8 merge with the ring tunnel. Even if higher dump thresholds were acceptable in this region at injection energy, the saturation level of the ionization chambers presents a limit. To overcome this dynamic range limitation, little ionization chambers (LIC) were tested and after validation installed. They allow to move the upper dynamic range limit by a factor 10 compared to the standard ionization chambers (IC). For the new monitors the threshold limit can be overcome if the higher thresholds are accepted during the time the machine is at 450 GeV injection energy. The new monitors are installed such that redundancy between the well tested ICs and the new LICs is kept. The ICs where higher thresholds would be required to keep machine availability at injection, are connected to blindable crates. These crates will have the possibility to receive a timing signal and accordingly blind out the interlock input at the moment of injection. The criterion to select monitors which shall have the blind out possibility is a factor 5 margin between the operational loss level and the dump thresholds. Also, the expected loss levels should be within a reasonable signal to noise ratio. The loss levels which entered the analysis considered operation with TCDI half gap openings of 4.5 σ. Since the measured LHC aperture was larger than expected, the TCDIs were opened by 0.5 σ to reduce the number of unnecessary dumps at injection. The future TCDI opening depends on the available aperture after LS1. During LS1 two new processing crates were installed, one per injection point, and the cabling was modified to route all blindable monitors to those crates. The deployment strategy of this blindable system includes as first step for the BLM team to finish off all LS1 upgrades of the BLM core system. Then a 'firmware light' will be prepared to be ready for deployment in technical stop 1 (May-2015). This firmware will be used in the blindable crates only and not affect the standard BLM firmware. From TS1 onwards the blinding functionality will be commissioned, deployed and monitored. The commissioning experience with beam will allow to decide on the eventual need of the blinding option.

CONCLUSIONS

The injection kickers have been improved in terms of heating, UFOs and electron cloud and re-installed in the tunnel. Presently the high-voltage conditioning and vacuum tests are ongoing. Both systems should be ready for the transfer line tests at the end of November.

The beam dump system modifications included upgrades of the TSDS powering and retriggering line with the consequence of potentially reduced availability but improved safety. The remaining vertical dilution kicker tank was installed. The dump absorber TCDQ was replaced by a 50% longer jaw of different material and improved electronics. Unforeseen sparking in the dump kicker generator switches was solved; the system should be ready for 7 TeV operation. Margins in the planning allow to recuperate the delay of the reliability run by the end of the year.

New interlocks are foreseen or have already been installed. A redundant position interlock of the TCDQ jaw on a new BETS is ready. The gap control of the transfer line collimators will be implemented during the coming weeks and can be tested without beam in the machine checkout. An interlock on the injection septum current will be connected as soon as the FGC power converter has been installed. The interlock on the direct TDI gap measurement is installed and being tested on a spare; its installation is foreseen for the winter stop 2015/16.

For the blindable beam loss monitors it is planned to have a hardware solution ready for the first technical stop; from then on the system shall be commissioned, deployed and monitored. The experience with beam will allow to decide on the eventual need of the blinding option.

REFERENCES

[1] W. Bartmann et al., "LHC Transfer Lines and Injection Systems", 5th Evian Workshop, Evian, France, June 2014, `http://indico.cern.ch/event/310353/session/4/contribution/16/material/paper/0.pdf`

[2] N. Magnin et al., "LBDS Kickers Operational Experience During LHC Run 1 and Planned Changes During LHC Long Shutdown 1", MPP Workshop, Annecy, France, March 2013, `https://indico.cern.ch/event/227895/session/4/contribution/19/material/paper/0.pdf`

[3] N. Magnin et al., "LHC Beam Dumping System Status and Readiness for LHC Run II", 5th Evian Workshop, Evian, France, June 2014, `http://indico.cern.ch/event/310353/session/4/contribution/17/material/paper/1.pdf`

LHC INJECTOR COMPLEX STATUS

K. Hanke, K. Cornelis, S. S. Gilardoni, B. Goddard, V. Kain, D. Küchler, M. Lamont, D. Manglunki, G. Metral, B. Mikulec, R. Scrivens, R. Steerenberg, CERN, Geneva, Switzerland

Abstract

We will present the status of the LHC proton and ion injector chain as of September 2014. We will briefly recap the main modifications done during LS1, in particular those which influence the LHC beam quality. Then we will review the first months of beam operation of the PS complex machines and the status and plans for commissioning of the SPS. We will in particular focus on the re-start of the injectors after LS1, and highlight the lessons learned and possible improvements for the re-start after LS2. Finally we will have a first look at the first months of the 2015 injector schedule.

INTRODUCTION

The re-start of the LHC proton and ion injectors was the first start-up after a long LHC shutdown (except for the long stop in 2005, when only Linac2, PSB and ISOLDE continued operation). The large amount of software and hardware interventions during LS1 required an extended check-out period and made the actual start-up phase an unprecedented challenge for the operations teams and equipment experts. We try a first analysis of the start-up and first months of operation, and attempt to derive the lessons learned in view of the re-commissioning of the complex after LS2. Figure 1 shows quarters 2 and 3 of the 2014 injector schedule (v 1.7) with the main time lines.

LINAC2

LS1 Work

No interventions were done during LS1 which would influence the Linac2 beam parameters. The work done during LS1 was standard maintenance work, aiming at ensuring reliable operation until the replacement of Linac2 by Linac4 during LS2.

Start-up and First Months of Operation

As the first machine of the injector chain to start up, Linac2 had to face a number of issues and teething problems with the general services (e.g. access system). On the machine side itself, the late delivery of some FESA classes caused delays. Once this was solved, the actual start-up went rapidly and without particular issues. Linac2 delivered beam to the PS Booster on 2nd June 2014. During the first months of running, operation has been stable and with nominal beam parameters.

PS BOOSTER

LS1 Work

Extensive maintenance work was done on the PS Booster, shared between maintenance and work related to the LIU upgrade. Much of the work has no direct influence on the beam quality. Apart from the standard maintenance work, a number of LIU upgrades were completed. The major intervention of which was the exchange of the beam dump. A newly designed beam dump was installed, appropriate for intensities expected with Linac4 and 2 GeV beam energy. The intervention involved dismantling and re-installation of parts of the measurement line. The intervention went according to plan, but the air cooling system and related interlock had some delays. Five additional Finemet cavity cells were installed in ring 4 (in addition to the already installed five cells), in order to continue testing the new technology. Some limited cabling work (and identification of obsolete cables) was done, as well as some related civil engineering work (new trenches). A new BIC (beam interlock controller) was installed for the extraction, and the handling equipment was consolidated in order for it to be fully operational during the coming shutdowns.

Among the numerous shutdown works the following will have (even if not immediately) impact on the beam performance: the implementation of the new digital low-level RF control, the upgrade of beam instrumentation (BLMs, orbit, BPMs and BCTs in the transfer lines), the renovation of the multipole power supplies and the alignment of the machine.

Start-up and First Months of Operation

First beam was injected into the PSB on 2 June 2014 and made a few turns in the machine immediately. Within one day low intensity was injected and accelerated in all rings. During the first weeks of operation, the machine was progressively debugged, a time consuming and tedious process. The heavily modified control system was behaving reasonably well, and remaining issues were attacked as they arose. The main issues that were encountered were related to hardware that had not sufficiently been commissioned, cabling errors, erratic alignment and late deployment of FESA classes that had to be changed due to the controls modifications. Good progress was made on the new digital LL-RF control, which was successfully commissioned during the first weeks. At the time of the workshop the PSB had set up the non-LHC physics beams for EAST Area, TOF, AD, ISOLDE and SFTPRO. The beam for multi-turn extraction in the PS had also been prepared in the PSB.

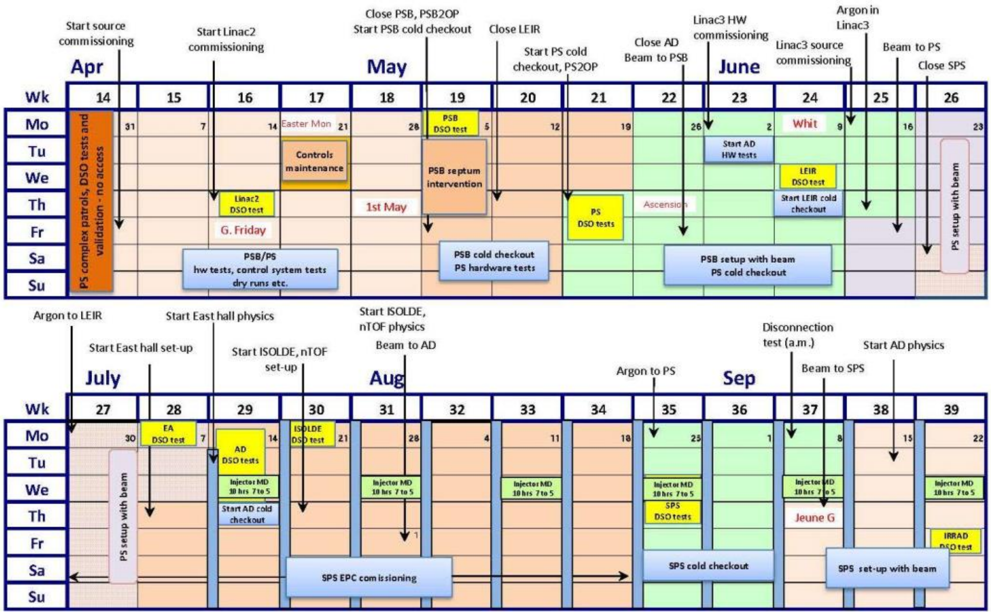


Figure 1: Quarters 2 and 3 of the 2014 injector schedule (v 1.7), indicating the key dates of the start-up.

On the LHC side, the single bunch LHCINDIV and LHCPROBE beams as well as the 25ns and 50ns physics beams had been set up. At this point, the PSB seemed to enter into a more stable phase, although even at present the full beam specifications from before LS1 had not been recovered.

PS

LS1 Work

A number of maintenance and upgrade items were included during LS1. Main items that will eventually impact on the beam performance were the alignment of the main magnets, upgrade of the diagnostics (new BCTs, new DAQ for the BCTs, calibration of the wire scanners, and new pick-up for ion tune measurement), recabling of the 10 MHz RF system, installation of a new, digital 1-turn delay feedback and the installation of a Finemet cavity as longitudinal damper. Furthermore seven magnets were refurbished (PFWs renovated). The ventilation system of the PS ring was renovated in order to minimise temperature fluctuations and to be conform to the legislation, the septa were changed with spares (preventive maintenance), the kicker controls for the CT extraction was renovated and the power supplies for the auxiliary magnets were renewed. On the side of the main power supply (POPS), some improvements to the capacitor banks and the control system have been implemented, which facilitates operation of the degraded modes. The interlock for the high-harmonics RF systems was improved and a dummy septum for the MTE extraction was installed (transparent for LHC beams).

Start-up and First Months of Operation

As in the PSB, beam was injected according to schedule and very rapidly. Rather quickly a 26 GeV beam for orbit measurements was available. On the instrumentation side, the basic tools were available, but there were some subtle issues to be identified.

During the first phase of beam operation a number of issues needed to be followed up by the operations and equipment teams. The beam-based alignment needed to be repeated twice, due to an error in the FESA class which sends orbit data to YASP. A voltage probe of the newly installed Finemet cavity was detecting a signal at 40 MHz; some of the RF gaps were temporarily short-circuited to avoid possible damage to the RF components while investigating the source of the signal. The beam was never affected by the observed phenomena. This issue is presently under investigation. Also a magnetic field non-reproducibility at injection is being investigated. During the start-up phase a vacuum intervention on kicker 79 needed to be done, and the PFNs of the kickers for the MTE needed repair (still ongoing). Two wire scanners broke after a short while, and after having been replaced one of them broke again. This issue is presently under investigation. Apart from that some teething issues with the control system and some minor hardware issues were tackled as they arose.

At the time of the workshop the PS was delivering the following LHC-type beams: LHCINDIV, 25ns and 50ns physics beams (the RF gymnastics have been established and setting up of the double-batch injection had started). On the non-LHC physics side the following beams had been set up: EAST Area, AD, TOF, and SFTPRO. Setting up of the MTE beam had started, but was put on hold due to the kicker and wire scanner problems. Although all user beams were set up and delivered according to specifications and schedule, the PS was at this time still not back to the stable and efficient operation as before LS1.

SPS

LS1 Work

A number of maintenance and upgrade items were implemented during LS1. The alignment of the TT10 following the tunnel maintenance was beneficial and beam went through the transfer line at the first shot. Apart from that a major alignment campaign was done everywhere, especially in LSS1, 5 and 6. Some earth loops in the machine were removed, and graphite (aC) coated magnets installed in four complete half cells. A serigraphed kicker has been installed to reduce the heating with 25ns operation. On the RF side, a new power system for the second 800 MHz cavity, new cavity probes and a new low-level RF system (commissioning foreseen for 2015) have been put in place. The SPS damper has undergone a complete re-design of the electronics system and controls, new pick-ups have been installed and the power system has been consolidated. Presently it is being commissioned and progress is very promising. A vacuum tank for the new type of wire scanners has been installed in the machine, but for the moment the scanner is not yet installed. A synchrotron light monitor has been installed and other instrumentation items have been repaired. A complete survey of the ring for impedance sources has been performed. As part of the LIU upgrades, construction of the new building for the 200 MHz upgrade has started.

Start-up and Commissioning Status

First beam was injected into the SPS on 13 September. Beam was rapidly accelerated on a fixed-target cycle. Besides that 12 bunches of 25 ns LHC beam were accelerated. The issues encountered during the start-up were mainly standard issues. The machine seemed to be rather misaligned, with an RMS orbit of about 10 mm (normally around 2 mm). A beam based alignment performed for Q20 and Q26 optics yielded good results. At the time of the workshop, the commissioning was going reasonably smoothly.

LINAC3

LS1 Work

No shutdown work was done in Linac3 during LS1 which would influence the beam parameters.

Start-up and Commissioning Status

Linac3 started up with Ar for the fixed-target program. Pb ions for the LHC have not yet been produced to date. The start-up was hampered by some delayed hardware, but the linac is by now running up to specifications. In order to change to Pb ions, the source needs to be dismantled and parts be exchanged. This is not expected to be a major issue, as the general start-up issues have by now been solved.

LEIR

LS1 Work

No shutdown work was done in LEIR during LS1 which would influence the beam parameters.

Start-up and Commissioning Status

Due to an overrun of the hardware test period, the check-out of LEIR without beam could not be done and all the debugging took place during the setting up with beam. The unavoidable controls issues could rapidly been solved thanks to good support. Also other normal start-up issues could be tackled as they arose. Presently LEIR is running with Ar ions for the fixed target program. As for Linac3, it is expected that the change-over to Pb ions will be smooth since the general issues will have been solved by then. As a general comment, dedicated manpower is an issue (mainly part-time contributors).

CONTROLS

Dry Runs

A large number of controls upgrades and changes have been implemented during LS1, representing a concern for a smooth and rapid start-up. Figure 2 shows the percentage of front-end computers changed per machine.

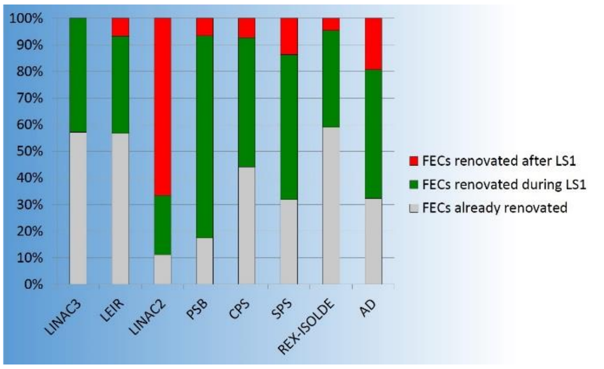


Figure 2: Percentage of FECs changed in the different machines during LS1.

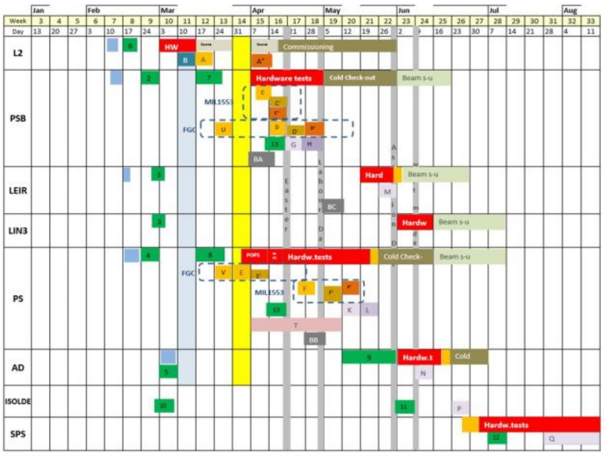


Figure 3: Planning of controls dry runs per machine.

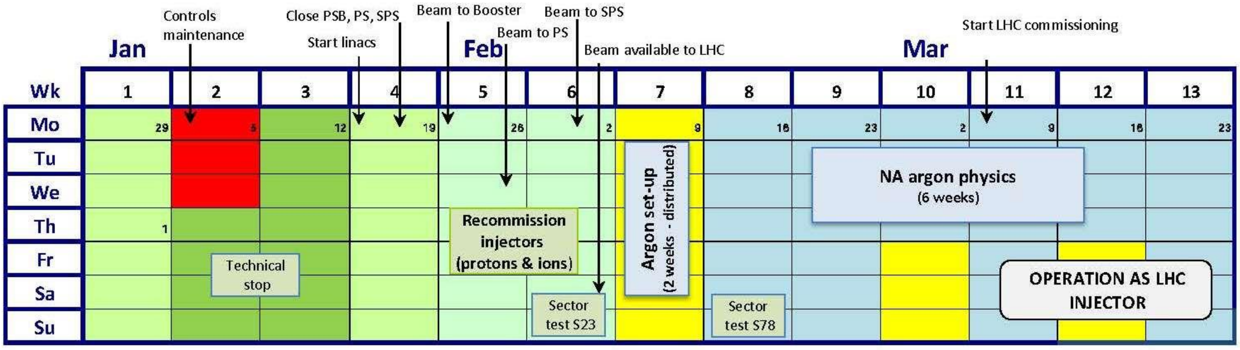


Figure 4: Quarter 1 of the draft 2015 injector schedule, indicating the main time lines.

In order to mitigate this risk, the CO group have organised dry runs in all machines. There were debriefing meetings, where the issues identified were followed up, and renewed tests were scheduled where necessary. The complete process was documented in EDMS. This procedure has proven to be very efficient to capture and fix issues before the actual start-up of the machines. The unavoidable remaining items where then tackled by the specialists, who were present in the control room during the first period to work with the OP teams. Figure 3 shows the planning of the dry runs per machine [1].

LESSONS LEARNED FROM THE START-UP AFTER LS1

Schedule

In order for the check-out and start-up to proceed smoothly, it is important to allocate sufficient time for hardware test and check-out, but also that the different parties respect the time lines. Any overrun of shutdown work or hardware test will propagate down to the next phase, and eventually into the beam setting up. It is also worth noticing that non-respect of the time lines can lead to safety issues, for example the need to give access to machines which are already powered. Good coordination is the key to success. A coherent follow-up of the whole process (shutdown – hardware test – cold check-out – beam setting up) is essential.

Quality of the Hardware Tests

Some issues encountered during the start-up of the different machines suggest a more rigorous hardware test. While certain issues become only apparent when injecting beam, one would hope to capture other issues like missing or inverted cabling already before. Check-lists would be helpful. Certain safety relevant equipment may need to be signed off after having been tested.

Delayed Delivery

Delayed delivery of FESA classes was reported throughout the accelerator complex. This is obviously a consequence of work overload in the equipment groups and of the restructuring of the controls organisation. While there is no obvious solution to this underlying reason, it is recommended to make the timely delivery of FESA classes part of the check-lists.

Issues with Equipment

Certain problems may only become apparent when beam is injected into the machines. In order to tackle these in the most efficient and timely manner, the presence and proactive approach of equipment experts in the control room is the key to success.

Pre-shutdown Reference

Equipment that is modified or replaced should be documented before the intervention, in order to ensure correct re-installation.

Lessons for the Start-up after LS2

LS1 was very much dedicated to LHC work, and despite the impressive list of work done in the injectors this represents only a small fraction of upgrades planned in the frame of the LIU project. The focus of LS2 will be the upgrade of the LHC injectors, and we will face quantitatively more and qualitatively new problems. An example is the connection of Linac4 to the PSB which comes along with a completely new injection scheme. This means that the standard maintenance has to be perfectly transparent, such that the OP and equipment teams can be fully dedicated to the new equipment and no time is lost to do avoidable debugging. Scheduling-wise sufficient time must be allocated for check-out and commissioning. A thorough planning has been presented at the RLIUP workshop [2]. As mentioned above, hardware tests must be rigorous and comprehensive, and dry runs per equipment group shall be organised.

2015 START-UP

A draft schedule for the re-start of the LHC injectors in 2015 is available (Fig. 4).

The actual end-year stop will comprise weeks 51 and 52 of 2014, and weeks 1-3 in 2015. Afterwards the machines have to start up rapidly with both protons and ions. As can be seen from the schedule, the key dates are to start the linacs in week 4, send beam to the PSB and PS in week 5, and to inject into the SPS in week 6. Therefore any interventions during the 2014/15 technical stop need to be compatible with a rapid start-up (e.g. no venting of sensitive equipment). The requests will be collected and approved beforehand.

The fixed-target ion run is scheduled for weeks 8-14. It is worth noticing that the requirements for the vacuum are particularly demanding for ion operation.

Re-start of the LHC is presently foreseen as from week 11. By then all LHC-type beams must be available in the injector chain in a stable and reliable way and within specifications.

SUMMARY

The start-up of the LHC injectors in 2014 was the first start-up after a long shutdown, except for 2005 when the PSB and ISOLDE continued operation. In summary the injectors were able to deliver the beams on request and within specifications. Points of improvement have been identified and listed in the preceding sections. From this experience lessons can be drawn for the re-start after coming long stops, and improved procedures be put in place.

ACKNOWLEDGMENTS

We would like to thank the operations and machine supervisor teams as well as the equipment and support groups who have in a common effort contributed to the successful re-start of the injector complex after LS1. We wish also to thank the teams responsible for the shutdown work for their collaboration in ensuring the transition from the shutdown into the check-out and start-up phase.

REFERENCES

[1] https://edms.cern.ch/document/1340573/1

[2] Review of LHC and Injector Upgrade Plans Workshop (RLIUP), Archamps, France, 2013, CERN–2014–006

Proceedings of Chamonix 2014 Workshop on LHC Performance

SPS SCRUBBING RUN IN 2014

H. Bartosik, G. Iadarola, G. Rumolo, CERN, Geneva, Switzerland

Abstract

Yearly machine scrubbing has been applied in the SPS since 2002 in order to reduce the amount of electron cloud in the machine and permit smooth operation with 25 ns beams. While a quick scrubbing is usually necessary to recover performance after any extended technical stop due to in vacuum deconditioning, a longer period needs to be envisaged when the machine stop is long and a large fraction of the machine is exposed to air. Therefore, the restart of the SPS after LS1 will offer a unique opportunity to qualify the machine degradation due to a long stop as well as quantify length and efficiency of a scrubbing run to recover the previous performance and possibly extend it to higher intensity beams. This information will be the key input to decide on the upgrade strategy for the SPS, as it will show whether the SPS can be operated with scrubbing also for future intensities or electron cloud needs to be actively suppressed through a-C coating. Goals, requirements (in terms of beam and instrumentation) and a possible planning of the SPS scrubbing run in 2014 will be covered by this presentation. In this context, we will also describe the doublet beam, which can be potentially used for enhancing the scrubbing efficiency.

INTRODUCTION

The electron cloud effect has been identified as a possible performance limitation for the SPS since LHC type beams with 25 ns spacing were injected into the machine for the first time in the early years of 2000. At that time a severe pressure rise was observed all around the machine together with transverse beam instabilities, important losses and emittance blow-up on the trailing bunches of the train [1]. Since 2002, Scrubbing Runs with a duration of one or two weeks were carried out almost every year of operation in order to condition the inner surfaces of the vacuum chambers and therefore mitigate the electron cloud. These Scrubbing Runs were usually performed at 26 GeV in cycling mode (with a cycle length of about 40 s) and are typically limited by heating and/or outgassing of critical machine elements (e.g. kickers, extraction septum, beam dump, . . .). The electron dose accumulated on the vacuum chambers throughout the years allowed achieving a very good conditioning state of the SPS in 2012, both in terms of dynamic pressure rise and beam quality. During the Scrubbing Run of the LHC at the end of 2012, the 25 ns beam was regularly extracted from the SPS Q20 optics with four batches of 72 bunches with $N \approx 1.2{\times}10^{11}$ p/b and normalized transverse emittances of about 2.6 μm [2]. Extensive machine studies showed that for this beam intensity the 2012 conditioning state of the SPS is sufficient for suppressing any possible beam degradation due to electron cloud on the cycle timescale [3].

THE 2014 SPS SCRUBBING RUN

While a quick scrubbing is usually necessary to recover performance after any extended technical stop due to in vacuum deconditioning, a longer period needs to be envisaged when the machine stop is long and a large fraction of the machine is exposed to air. The goals for the 2014 Scrubbing Run are therefore to qualify the loss of conditioning due to Long Shutdown 1 (LS1), to recover the 2012 performance with 25 ns beams and to quantify amount of beam/time needed for this recovery. The qualification criteria will be based on beam measurements. Ideally, 4 batches of the 25 ns beam with an intensity of up to $1.3{\times}10^{11}$ p/b and emittances below nominal with no blow-up along the train should be achieved by the end of the allocated scrubbing time, which corresponds to the beam parameters achieved during machine development studies in 2012. Furthermore, it is planned to test the scrubbing efficiency of the doublet beam, which will be discussed in more detail below. The results of this Scrubbing Run will be the basis for setting the LIU strategy on electron cloud mitigation, i.e. the decision coating vs. scrubbing.

In the original planning of the 2014 Injector Schedule the Scrubbing Run was planned for two consecutive weeks (Weeks 39-40) before the start-up of the NA physics. In the end, the Scrubbing Run was split into a 7 day block in Week 45 plus an additional two-day mini-block in Week 50. Splitting the scrubbing run into two blocks was requested by the LIU-SPS due to several reasons:

- It gives time to analyze the first block?s results and adapt the strategy for the second block accordingly.
- It allows to Untangle the scrubbing from the machine commissioning, NA setup and vacuum conditioning of all the newly-installed or vented equipment.
- It allows for the setting up of the doublet scrubbing beam before the second scrubbing block and so its potential to scrub the SPS can be explored already in 2014. The experience gained will be also useful for the preparation of the LHC scrubbing in 2015.

In the first scrubbing block the intensity with 25 ns beams will be ramped up during the first three days (ideally up to 5 injections – trying to push bunch intensity up to 1.5×10^{11} p/b) on a long 26 GeV cycle. The aim is to accumulate as much electron dose as possible and to monitor the evolution of beam parameters for both coherent and incoherent effects. During the remaining days, studies of residual electron cloud effects on beam lifetime and quality could be performed for the nominal beam (e.g. emittance growth, bunch shortening over long flat bottom) while keeping the vertical chromaticity at the minimum value that is required for beam stability. This scrubbing qualification includes beam quality measurements on both the long 26 GeV cycle and at the LHC filling cycle with acceleration to 450 GeV.

By the time of the second scrubbing block in Week 50 the doublet beam could be ready to be used for scrubbing in the SPS. The results of the tests with the doublet beam, such as the scrubbing efficiency and first experience with acceleration to 450 GeV will be important for the LHC scrubbing in 2015 [4].

THE DOUBLET SCRUBBING BEAM

Several studies have been devoted in 2012 to the optimization of the scrubbing process and in particular to the definition and test of a possible "scrubbing beam", i.e. a beam produced specifically for scrubbing purposes, providing a higher scrubbing efficiency compared to the standard LHC type 25 ns beam. A 25 ns spaced train of "doublets", each of these consisting of two 5 ns spaced bunches, has been proposed [5]. As shown in Fig. 1, PyECLOUD simulations predict that this beam has indeed a significantly lower multipacting threshold for large enough intensities compared to the standard 25 ns beam due to the shorter empty gap between subsequent doublets, which enhances the accumulation of electrons in the vacuum chambers of the SPS MBA and MBB type dipoles. For producing this beam with the existing RF systems of the injectors, long bunches from the PS ($\tau \approx 10$ ns full length) have to be injected into the SPS on the unstable phase of the 200 MHz RF system and captured in two neighboring buckets by raising the voltage within the first few milliseconds. Very good capture efficiency (above 90%) could be achieved for intensities up to 1.7×10^{11} p/doublet.

Figure 2 (top) shows the evolution of the longitudinal profile of the beam during the "splitting" right after the injection in the SPS. Figure 2 (bottom) shows the "final" beam profile, measured one second after injection. It was also verified that it is possible to rapidly lower the RF voltage and inject a second train from the PS without any important degradation of the circulating beam. Observations on the dynamic pressure rise in the SPS arcs confirmed the enhancement of the electron cloud activity as expected from PyECLOUD simulations. The enhancement was also observed with the dedicated SPS strip detectors as shown in Fig. 3 for the two SPS vacuum chamber types, MBA and MBB, where the electron cloud profiles measured with the standard 25 ns beam and with the doublet beam are compared for the same total intensity. In this experiment with a single batch from the PS, electron cloud formation in the MBA is only observed with the doublet beam due

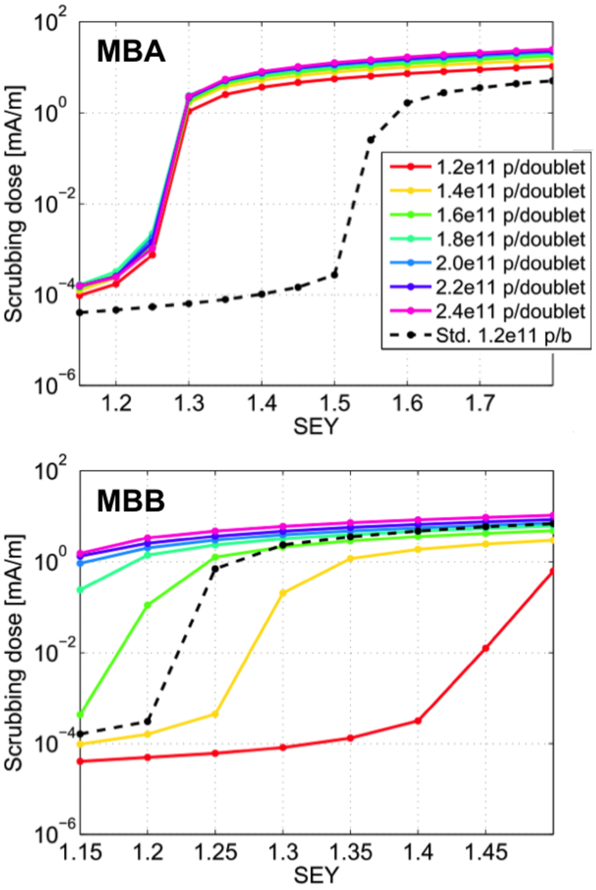


Figure 1: Scrubbing dose as a function of the SEY for different beam intensities of the doublet beam (coloured lines) in comparison to the nominal LHC beam (dashed lines) in the MBA and the MBB type dipole chambers of the SPS at injection energy.

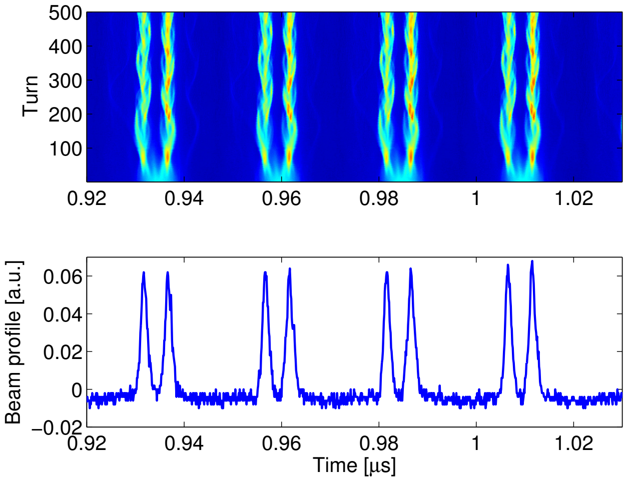


Figure 2: Evolution of the longitudinal beam profile in the SPS during the splitting at injection for the production of the doublet beam (top) and longitudinal bunch profiles of the doublet beam measured 1 s after injection (bottom).

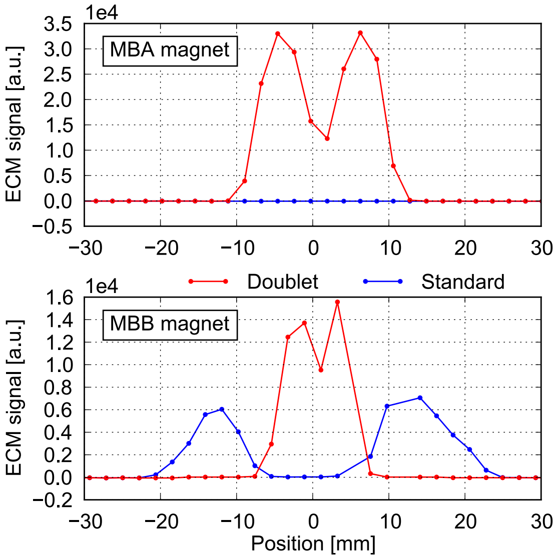


Figure 3: Electron cloud profiles measured in the strip detectors with MBA (top) and MBB (bottom) chambers with the standard 25 ns beam and with the doublet beam (same total intensity, 72 bunches from the PS with $N \approx 1.65 \times 10^{11}$ p/b).

to its lower multipacting threshold compared to the standard beam. In the MBB, where the nominal beam was still able to produce electron cloud, a clear enhancement of the peak electron density can be observed. It is important to note that the electron cloud produced by the doublets does not cover the full region to be conditioned for the standard beam. Therefore it is necessary to periodically displace the beam (using radial steering and orbit correction dipoles) during the scrubbing in order to achieve a satisfactory conditioning across the chamber surface.

The SPS transverse feedback system has been upgraded during LS1 and has now a special mode for the doublet beam, in particular for coping with the transients during the bunch splitting at injection. The new system needs to be commissioned for all beam types and tested for the first time for the doublet beams. Furthermore, the SPS beam quality monitor (BQM) software has been also prepared to work for the doublet beam. This will be important in particular for the LHC, which might have to rely on the doublet beam for scrubbing in 2015, provided that 1) the required intensity for LHC scrubbing can be stably and successfully accelerated in the SPS, possibly on a cycle with slow acceleration, and transferred to the LHC, and 2) the interlock threshold on the BPMs in IR6 can be reduced according to the results on error studies for unbalanced doublets foreseen at the SPS in 2014 and at the LHC with single doublets in 2015 [4].

If we can produce and preserve a good quality (two batches, large bunch intensity), this beam will be already used during the two-day mini-scrubbing run at the end of the 2014 run. The acquired experience will be very important for the definition of the LIU-SPS strategy with respect to e-cloud and scrubbing as well as for the success of the LHC scrubbing in 2015.

SCRUBBING REQUIREMENTS

The main goal of the 2014 scrubbing run is to maximise the scrubbing efficiency. For this purpose, the following beam will be needed from the pre-injectors:

- 25 ns beam (standard production scheme and BCMS) with intensity up to 1.5×10^{11} p/b;
- 25 ns beam (standard production scheme and BCMS) with intensity up to 1.7×10^{11} p/b (as back up);
- 25 ns beam for doublet production with intensity up to 1.5×10^{11} p/b, long bunches at the PS extraction.

At same time, in order to collect new information about electron cloud effects and scrubbing in the SPS, it will be necessary to record data from the following instruments:

- Beam Current Transformers (BCT, FBCT);
- Beam Quality Monitor (BQM), mountain range (MR), Faraday cage scope;
- BBQ tune-meter, LHC type Beam Position Monitors (BPMs), Headtail monitor, fast pickup from High Bandwidth Transverse Feedback setup, new digitizers on BPW exponential pickups;
- Beam Gas Ionization (BGI) Monitor, Beam Synchrotron Radiation Telescope (BSRT), Beam Wire Scanners (BWS) in bunch by bunch mode;
- Pressure gauges along the ring (1 Hz sampling rate, with special attention to the a-C coated cells);
- Dedicated e-cloud equipment, i.e. electron cloud monitors (with lMBA StSt, MBB StSt, MBB a-C, MBB copper liners), shielded pickup, in situ SEY measurement (if available), removable StSt sample (for lab SEY measurement), COLDEX.

SUMMARY AND CONCLUSIONS

In the past, the SPS was strongly limited by electron cloud and it is likely to suffer again from electron cloud in the range of intensities required by LIU. After several dedicated SPS scrubbing runs between 2002 and 2012, beam induced conditioning proved to be an effective mitigation for electron cloud effects for 25 ns beams up to nominal intensity, so that 25 ns beams could be delivered to LHC in 2012 well within design report specifications.

A scrubbing run is foreseen in 2014 to recondition the SPS after LS1, since large parts of the machine were exposed to air. In the first block (7 days in Week 45), the main goals are to: 1) qualify the loss of conditioning due to LS1, and 2) recover the 2012 performance with 25 ns beams. The second block will only last 2.5 days (week 50) and will aim to test scrubbing with doublet beams (also in view of LHC in 2015 and for the future challenging LIU beam intensities). The experience gained will be invaluable to take the final LIU decision about the coating of SPS magnet chambers. The success of the 2014 scrubbing run will strongly rely on an adequate beam preparation from the pre-injectors and the correct functioning of all key beam diagnostics instruments in the SPS.

ACKNOWLEDGEMENTS

The authors would like to thank G. Arduini, T. Argyropoulos, T. Bohl, K. Cornelis, H. Damerau, J. Esteban Müller, B. Goddard, S. Hancock, W. Höfle, L. Kopylov, H. Neupert, Y. Papaphilippou, G. Papotti, E. Shaposhnikova, M. Taborelli and the SPS operator crew for support and helpful discussion.

REFERENCES

[1] G. Arduini *et al.*, “Beam observations with electron cloud in the CERN PS and SPS complex”, Proceedings of the ECLOUD04 workshop, Napa, CA, USA (2005).

[2] Y. Papaphilippou *et al.*, “Operational performance of the LHC proton beams with the SPS low transition optics”, CERN-ACC-2013-0124.

[3] H. Bartosik *et al.*, “Electron Cloud and Scrubbing Studies for the SPS in 2012”, CERN-ATS-Note-2013-019 MD.

[4] G. Iadarola *et al.*, “Scrubbing: Expectations and Strategy, Long Range Perspective”, these proceedings.

[5] G. Iadarola *et al.*, “Recent electron cloud studies in the SPS”, CERN-ACC-2013-0115.

OPERATIONAL BEAMS FOR THE LHC

Y. Papaphilippou, H. Bartosik, G. Rumolo, D. Manglunki, CERN, Geneva, Switzerland

Abstract

The variety of beams, needed to set-up in the injectors as requested in the LHC, are reviewed, in terms of priority but also performance expectations and reach during 2015. This includes the single bunch beams for machine commissioning and measurements (probe, Indiv) but also the standard physics beams with 50 ns and 25 ns bunch spacing and their high brightness variants using the Bunch Compression Merging and Splitting (BCMS) scheme. The required parameters and target performance of special beams like the doublet for electron cloud enhancement and the more exotic 8b+4e beam, compatible with some post-scrubbing scenarios are also described. The progress and plans for the LHC ion production beams during 2014-2015 are detailed. Highlights on the current progress of the setting up of the various beams are finally presented with special emphasis on potential performance issues across the proton and ion injector chain.

INTRODUCTION

During the LHC Run 1, the LHC physics production was based on beams with 50 ns bunch spacing. Beams with 25 ns bunch spacing were injected into LHC on few occasions for injection tests, Machine Developments (MDs), the scrubbing run followed by a pilot physics run [1]. After the startup in 2015, apart from the LHC collision energy which will be raised to 6.5 TeV per beam, it will be crucial to establish physics operation with the nominal 25 ns bunch spacing in order to maximise the integrated luminosity in Run 2 for the limited event pile-up acceptable by the LHC experiments [2]. The LHC will thus request a large variety of beams, including single bunches for machine commissioning and measurements but also the standard physics beams with 50 ns and 25 ns bunch spacing and their high brightness variants using the Bunch Compression Merging and Splitting (BCMS) scheme [4, 5]. In addition, special beams like the doublet for electron cloud enhancement [1] and the more exotic 8b+4e beam [7], compatible with some post-scrubbing scenarios should be also prepared and made available from the injectors.

This paper reviews the parameters of the LHC physics beams achieved in the injectors until 2012 and the expectations for their performance in the following run (for a detailed analysis see [3]). The progress and plans for the LHC ion production beams during 2014-2015 are also finally presented.

SINGLE BUNCH BEAMS

During the preparation of the LHC p-Pb run in 2013, a new improved production scheme has been developed [8], with which single bunch LHC beams can be generated in the PSB. The main ingredient was the revision of the controlled longitudinal blow up during first part of PSB cycle, through optimisation of C16 and C02 parameters. Thereby, the C16 voltage can be used for intensity control. This assures the preservation of the 6D phase space volume for different intensities with excellent shot-to-shot reproducibility and control of both intensity and longitudinal emittance. It is therefore expected that after Long Shutdown 1 (LS1) the injectors will be able to deliver LHCPROBE bunches ($5\times10^9 - 2\times10^{10}$ p/b) and LHCINDIV bunches ($2\times10^{10} - 3\times10^{11}$ p/b) to the LHC with smaller intensity fluctuations compared to the operation during Run 1. The LHCINDIV parameter range was also extended in MDs to produce single bunches with up to 4×10^{11} p/b and/or with lower longitudinal emittances (down to 0.15 eVs), at SPS injection. These high intensity variants can be used for impedance or beam-beam studies. Finally, a procedure for producing Gaussian bunches for Van der Meer scans was established in 2012. It is based on longitudinal and transverse shaving in the PSB to obtain large emittance (more than 2.5 μm) single bunches with under-populated tails. Because of diffusion processes in the PS and SPS, these bunches evolve into almost perfect Gaussian shapes at the exit of the SPS and at collision in the LHC as confirmed by the experiments. This beam will need to be ready for the van der Meer scans at the beginning of the 2015 run and can profit from the newly established single bunch production scheme in the PSB.

LHC PHYSICS BEAMS

LHC operation during Run 1 used mainly 50 ns beams produced with the standard scheme of bunch splittings in the PS. Beams with the nominal 25 ns bunch spacing have been used in the LHC for the scrubbing run and machine development studies. With the successful implementation of the BCMS scheme [4, 5] in the PS in 2012, the injectors were also able to provide LHC beams with almost twice the brightness compared to the standard production schemes. While the 50 ns BCMS beam was injected into the LHC only an emittance preservation study of a high brightness beam along the LHC ramp, the 25 ns BCMS beam was used for the 25 ns pilot physics run at the end of 2012. It should be emphasised that all these LHC beams were produced close to the performance limits of the injector chain: For the 50 ns beam the intensity per bunch is close to the limit of longitudinal instability in the PS, whereas the brightness of the BCMS beam is at the present space charge limit in the SPS. For the 25 ns beam, the intensity per bunch is close to the limit of RF power and longitudinal instability in the SPS while the brightness is at the present space charge limit in the PS. Figure 1 shows the beam parameters for the two types of beams as achieved in 2012 after the operational deployment of the Q20 low gamma transition optics in the SPS [10, 11]. The transverse emittances shown in these plots are deduced from combined wire-scans at the end of the SPS flat bottom and the values were cross-checked with measurements in the LHC. The error bars include the spread over several measurements as well as a systematic uncertainty of 10%. The bunch intensity is measured at the SPS flat top after the scraping of the beam tails, as required prior to extraction into LHC. The solid lines correspond to the PSB brightness curve (i.e. the emittance as a function of intensity measured at PSB extraction) translated into protons per SPS bunch for each beam type assuming intensity loss and emittance growth budgets of 5 % in the PS and 10 % in the SPS, respectively. All beams were produced within the allocated budgets for beam degradation along the injector chain apart from the standard 25 ns beam, which suffers from slow losses at the SPS flat bottom and maybe also from space charge effects at the PS injection. Nevertheless, the nominal 25 ns beam is well within the original specifications (i.e. 1.15×10^{11} p/b and 3.5 μm transverse emittance [12]). The beam parameters achieved operationally in 2012 are summarized in Table 1.

Table 1: Operational beam parameters in 2012.

Beam type	**Intensity**	**Emittance**
Standard (25 ns)	1.20×10^{11} p/b	2.6 μm
BCMS (25 ns)	1.15×10^{11} p/b	1.4 μm
Standard (50 ns)	1.70×10^{11} p/b	1.7 μm
BCMS (50 ns)	1.70×10^{11} p/b	1.1 μm

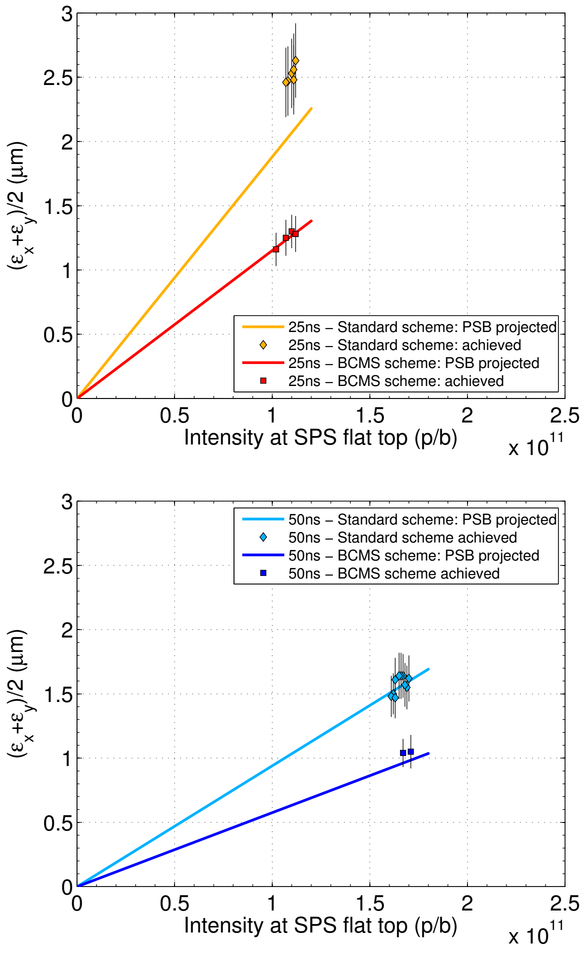


Figure 1: Beam parameters achieved operationally in the SPS in 2012 with the Q20 optics for 50 ns beams (bottom) and 25 ns beams (top) extracted to the LHC.

The first part of the re-commissioning of the LHC beams in the injector chain in 2014 is focused on re-establishing the beam parameters achieved before LS1. This will rely to a large extent on the successful scrubbing of the SPS in order to suppress the electron cloud effect, which is expected to be a performance limitation during the first weeks after the start-up since large parts of the vacuum chambers have been exposed to air [13].

Once the 2012 beam parameters are reproduced, it should be possible to reach slightly higher beam intensity and potentially also higher beam brightness. Already during MDs at the end of 2012 a standard 25 ns beam was accelerated to flat top with an intensity of about 1.3×10^{11} p/b and longitudinal beam parameters compatible with injection into LHC. In addition, high intensity LHC beams will benefit from the upgraded 1-turn delay feedback for the 10 MHz cavities and the upgraded longitudinal coupled-bunch feedback in the PS, which was commissioned in 2014. It should also be possible to enhance the beam brightness by optimising the beam production schemes as discussed at the RLIUP workshop [6]: the space charge tune spread in the PS can be reduced by injecting bunches with larger longitudinal emittance, i.e. increasing the bunch length and the momentum spread at PSB extraction. The maximum bunch length at the PSB-to-PS transfer is determined by the recombination kicker rise time. The maximum longitudinal emittance is determined by the RF manipulations and by the momentum acceptance at transition crossing in the PS cycle, but also by the constraint that the final bunches should not exceed 0.35 eVs for injection into the SPS. Optimising the longitudinal beam parameters at PS injection requires therefore controlled longitudinal blow-up during the PSB cycle with the C16 cavity and the use of the h=1 and h=2 PSB RF harmonics in phase at extraction to keep the larger longitudinal emittance bunches within the recombination kicker gap. Furthermore, the triple splitting in the PS was recently commissioned at an intermediate plateau of 2.5 GeV instead of

Table 2: Expected performance limits after LS1.

Beam type	Intensity	Emittance
Standard (25 ns)	1.30×10^{11} p/b	2.4 μm
BCMS (25 ns)	1.30×10^{11} p/b	1.3 μm
Standard (50 ns)	1.70×10^{11} p/b	1.6 μm
BCMS (50 ns)	1.70×10^{11} p/b	1.1 μm

the flat bottom for providing sufficient bucket area. Further details are given in Ref. [6]. A summary of the expected performance limits of LHC physics beams for the run in 2015 is given in Table 2.

SPECIAL BEAMS: DOUBLET AND 8b+4e

The doublet beam was originally proposed for enhancing the scrubbing efficiency in the SPS at low energy [14]. This beam is produced by injecting a 25 ns beam with enlarged bunch length ($\tau \approx 10$ ns full length) from the PS onto the unstable phase of the 200 MHz RF system in the SPS. By raising the SPS RF voltage within the first few milliseconds after injection, each bunch is captured in two neighbouring RF buckets resulting in a train of 25 ns spaced doublets, i.e. pairs of bunches spaced by 5 ns. Very good capture efficiency (above 90%) for intensities up to 1.7×10^{11} p/doublet could be achieved in first experimental tests in 2012. Observations on the dynamic pressure rise in the SPS arcs confirmed the enhancement of the elec-tron cloud activity as expected from the lower multipacting threshold compared to the standard 25 ns beams predicted by numerical simulations [14]. The experimental studies performed up to now concentrated on SPS injection energy and thus the acceleration of the doublet beam will be an important milestone during the 2014 MDs (for more details see [13]).

Thanks to its micro-batch train structure, the 8b+4e beam was considered as an alternative to the standard 25 ns beam in case the electron cloud remains a limitation for the operation of the LHC during the HL-LHC era [7]. Start-ing from 7 bunches from the PSB, the triple splitting in the PS is replaced by a direct h = 7→21 bunch pair split-ting, which results in pairs of bunches separated by empty buckets. Each bunch is split in four at PS flat top such that the bunch pattern 6×(8b+4e)+8b is obtained. In this case the bunch train out of the PS is longer than the 72 bunches of the standard scheme, but the remaining gap of 4 empty buckets (about 100 ns) is expected to be sufficiently long for the PS ejection kicker. Without optimization of the LHC filling pattern, the total number of bunches per LHC beam is estimated as 1840. More details about the performance of this beam can be found in [15].

The estimated beam parameters are summarized in Table 3. Finally it should be emphasized that this beam has not been produced in the injectors so far since it was developed during LS1. First tests of this new beam production scheme will be subject of MD studies in 2014 or at latest in the beginning of 2015, depending on the availability of MD time in the injectors.

Table 3: Expected parameters of the 8b+4e beam.

Beam type	Intensity	Emittance
Standard (8b+4e)	1.80×10^{11} p/b	2.3 μm
BCMS (8b+4e)	1.80×10^{11} p/b	1.4 μm

PROGRESS IN 2014

The first part of the PSB and the PS startup in 2014 were devoted to the setup of the beams needed for physics. During the time of the Chamonix workshop 2014, the single bunch beam were in good shape in PSB and PS, and short trains of 12 to 24 bunches were taken in SPS for the realignment campaign and RF setting-up (energy matching). The setup of the LHC beams in the PS complex was done in parallel to physics operation and starting from re-establishing the beam conditions from 2012 (but already with the triple splitting in the PS at 2.5 GeV instead of the flat bottom).

The PS complex is ready to deliver the LHC beams at the startup of the SPS in September. As large parts of the SPS have been vented and exposed to air in the course of the works performed during LS1, it is expected that the good conditioning state of the SPS will be degraded. Therefore, two weeks of SPS scrubbing are planned for 2014 with the goal of reconditioning the SPS to the state of before LS1. The success of this scrubbing run is the critical milestone for the preparation of the 25 ns LHC beams for physics in 2015.

The setup of the doublet scrubbing beam for the use in the LHC will be the subject of extensive MD studies in the SPS in 2014 in several dedicated MD blocks, for establishing accelerations and pushing the intensity to the requested 1.6×10^{11} p/doublet. During these MDs, also the behaviour of the LHC BPMs in the SPS with the doublet beam need to be tested in preparation of the LHC scrubbing, [17].

At the same time, there are many requests for dedicated MD time in the SPS for 2014 [18]. Careful planning and prioritization of studies will be crucial, as the total amount of requested dedicated MD time exceeds the MD slots available. For example, although there are first successful recent studies in the PSB and the PS, the full qualification of 8b+4e beam production scheme will be done in 2015. In general, it should be stressed that 2014 will be a very busy period for the injectors: Besides the physics operation after the beam commissioning with partially new or upgraded hardware, the setup and commissioning of the different LHC beams including the doublet scrubbing beam, the various dedicated and parallel MD studies, substantial amount of beam time will be needed in the PS and SPS for the first-time setup of the Ar-ion beams in preparation for the physics run beginning of 2015.

Finally, it is worth mentioning that there will be another period of dedicated scrubbing of the SPS in 2015. While

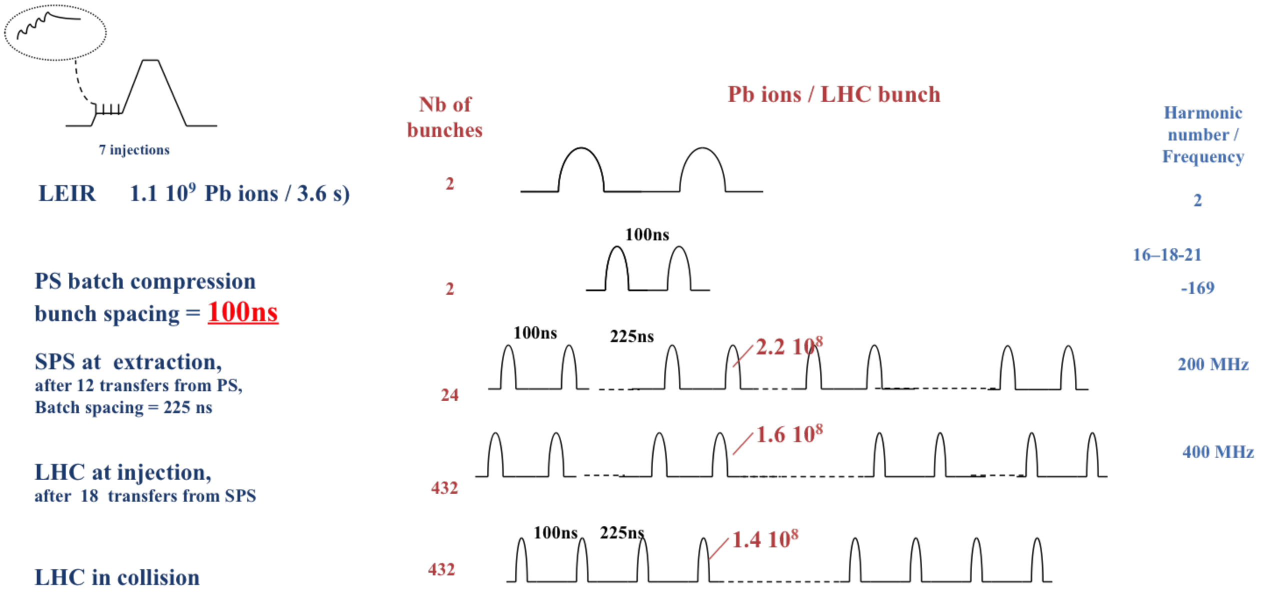


Figure 2: Ions production scheme for 2015 [21].

with the scrubbing run in 2014 the scrubbing efficiency and the time required for achieving acceptable conditioning after a long shutdown will be qualified, the aim of the scrubbing run in 2015 will be to condition the SPS for high intensity 25 ns beams. The outcome of these scrubbing runs will determine if the SPS vacuum chamber really need to be coated with amorphous Carbon [19] as presently part of the baseline of the LIU project for suppressing the electron cloud for the future high intensity LHC beams [20].

ION BEAMS

The Pb-Pb run in 2011 initially projected an integrated luminosity of around 30-50 μb-1 in 4 weeks, with peak luminosity Lpeak $= 1.4 \times 10^{26}$ Hz/cm^2. In fact, the peak luminosity was increased to around half of the nominal (5×10^{26} Hz/cm^2) exceeding by far the expectations to almost 150 μb-1 integrated luminosity at 3.5 ZTeV. This was due to the increased LEIR brightness with nominal bunch population of 4.5×10^8 Pb^{54+} ions per bunch but smaller emittances. Additional ingredients of this success were the preservation of the brightness at low energy in PS due to excellent vacuum conditions, the modified production scheme (no splitting in PS allowing half as many bunches with twice the intensity/bunch) and the good behaviour of bunches on SPS flat bottom (improved low level RF to reduce noise, IBS and space charge less critical than expected and delivered with Q20 optics after 2013). For the p-Pb run in 2013, the LEIR bunch intensity was further increased to5.5×10^8 Pb^{54+} ions per bunch, exceeding the nominal value by a factor of 1.2. Assuming the same scheme as in 2011 and the performance of 2013, a Pb-Pb peak luminosity of Lpeak $= 2.3 \times 10^{27}$ Hz/cm^2 at 6.5 ZTeV can be expected. A further 20% increase in peak luminosity can be gained by squeezing 20% more bunches in LHC. The ion generation scheme is presented in Figure 2 (for more details see [21]). A batch compression already tested in the PS in 2012 can allow a bunch spacing of 100 ns between two ion bunches. Twelve of these two-bunch batches can be accumulated for every cycle of the SPS, with a batch spacing of 225 ns. After 36 injections from the SPS, assuming once again the same brightness as in February 2013, this scheme can deliver up to 432 bunches of 1.6×10^8 Pb^{82+} ions per LHC ring, corresponding to a peak luminosity at 6.5 ZTeV of peak $= 2.8 \times 10^{27}$ Hz/cm^2.

SUMMARY AND CONCLUSIONS

Several optimizations of the beam production schemes will be implemented for the LHC Run after LS1. Single bunch beams already benefit from a better control and better reproducibility of intensity and longitudinal emittance. The longitudinal parameters at PSB-to-PS transfer of the 25 ns and 50 ns physics beams are optimized for allowing even higher beam brightness and, if requested by the LHC, the intensity of the 25 ns beams can also be slightly pushed compared to the 2012 beam parameters. The first step in the beam commissioning of these LHC beams in 2014 will be however to recover their 2012 performance. In this respect, the critical milestone will be the success of the SPS Scrubbing Run, as it is expected that the good conditioning state of the SPS will be degraded due to the long period without beam operation and the venting of machine sectors related to the interventions during LS1.

The setup of the doublet scrubbing beam with acceleration in the SPS in preparation for the LHC scrubbing in 2015 will be one of the main topics of MDs in 2014. Careful planning and prioritisation of the dedicated MDs in the

SPS will be crucial due to the limited MD time available. First tests of the 8b+4e beam already demonstrated the feasibility of the scheme and need to be tested further in 2015, in the SPS.

Besides the various physics users, the commissioning of the LHC beams and the MDs related to the new beams requested by the LHC, lots of beam time will be needed in 2014 for the first-time setup of Ar-ion beams. Regarding the ion performance, a batch compression scheme in the PS can increase the projected 2013 performance by around 20% in peak luminosity.

ACKNOWLEDGEMENTS

The authors would like to thank G. Arduini, T. Argyropoulos, M. Bodendorfer, T. Bohl, R. Bruce, C. Cornelis, H. Damerau, J. Esteban-Mller, A. Findlay, R. Garoby, S. Gilardoni, B. Goddard, S. Hancock, K. Hanke, G. Iadarola, B. Mikulec, E. Shaposhnikova, R. Steerenberg and the PSB & PS & SPS Operation crews for support and helpful discussion.

REFERENCES

[1] G. Iadarola and G. Rumolo, “Electron cloud/scrubbing”, Proceedings of the 2014 Evian Workshop on LHC Beam Operation, CERN-ACC-2014-0319 (2014).

[2] B. Gorini, “Experiments’ expectations”, , Proceedings of the 2014 Evian Workshop on LHC Beam Operation, CERN-ACC-2014-0319 (2014).

[3] H. Bartosik and G. Rumolo, “Beams in the injectors”, Proceedings of the 2014 Evian Workshop on LHC Beam Oper-ation, CERN-ACC-2014-0319 (2014).

[4] R. Garoby, “New RF Exercises Envisaged in the CERN-PS for the Antiprotons Production Beam of the ACOL Machine”, IEEE Transactions on Nuclear Science, Vol. NS-32., No. 5 (1985).

[5] H. Damerau *et al.*, “RF manipulations for higher beam brightness LHC-type beams”, CERN-ACC-2013-0210.

[6] G. Rumolo *et al.*, “Expected performance in the injectors at 25 ns without and with LINAC4”, proceedings of the Review of LHC and Injector Upgrade Plans Workshop (2013).

[7] H. Damerau *et al.*, “LIU: Exploring alternative ideas”, proceedings of the Review of LHC and Injector Upgrade Plans Workshop (2013).

[8] S. Hancock, CERN-ATS-Note-2013-040 MD (2013).

[9] H. Bartosik and G. Rumolo, CERN-ACC-NOTE-2013-0008 (2013).

[10] H. Bartosik *et al.*, “Increasing instability thresholds in the SPS by lowering transition energy”, CERN-ATS-2012-177, IPAC2011.

[11] Y. Papaphilippou *et al.*, “Operational performance of the LHC proton beams with the SPS low transition energy op-tics”, CERN-ACC-2013-0124, IPAC2013.

[12] LHC Design Report, edited by O. Br¨uning, P. Collier, P. Lebrun, S. Myers, R. Ostojic, J. Poole, P. Proudlock, CERN-2004-003-V-1

[13] H. Bartosik *et al.*, “SPS scrubbing 2014”, these proceedings.

[14] G. Iadarola *et al.*, “Recent electron cloud studies in the SPS”, CERN-ACC-2013-0115.

[15] H. Rumolo *et al.*, “Protons: Baseline and Alternatives, Studies Plan”, these proceedings.

[16] H.Bartosik *et al.*, “Special e-cloud bunch spacing: injectors”, LBOC meeting of November 5th (2013).

[17] T. Lefevre et al., “Special e-cloud bunch spacing: BI compatibility”, LBOC meeting of November 5th (2013).

[18] G. Rumolo and H. Bartosik, “Injector MD planning and requests for 2014”, MSWG meeting of May 30th (2014).

[19] C. Vallgren *et al.*, “Amorphous carbon coatings for the mitigation of electron cloud in the CERN Super Proton Synchrotron”, Phys. Rev. ST Accel. Beams, 14, 071001 (2011).

[20] H. Bartosik *et al.*, “Can we ever reach the HL-LHC requirements with the injectors?”, proceedings of the Review of LHC and Injector Upgrade Plans Workshop (2013).

[21] D.Manglunki, “Performance of the LHC ion injectors after LS1”, proceedings of the Review of LHC and Injector Up-grade Plans Workshop (2013).

LHC DRY-RUNS AND MACHINE CHECK-OUT

D. Jacquet, M. Albert, R. Fernandez, R. Giachino, M. Solfaroli Camillocci,

CERN, Geneva, Switzerland

Abstract

During LS1 most of the equipment groups took the opportunity to upgrade, improve and refactor their hardware and software. A particular care is necessary for the operation team during the testing phase before beam commissioning. Some equipment and software tests from the control room have already started early in the year, including the communication with the experiments, RF frequency ramp, LBDS arming sequence etc… The results will be presented. In parallel, regular meetings between OP and the equipment's group have started for the establishment of a working plan for the final machine check-out. The strategy for the machine preparation from now to the beam commissioning will explained.

INTRODUCTION

Since March 2013 the LHC is in shutdown mode and most of its systems are undergoing major upgrades. This will improve their reliability, availability and performance for run II, which is scheduled to start with the beam commissioning phase in February 2015.

Because of the huge number of modifications which have been applied to the various LHC systems during the course of LS1, the 2015 start-up will be similar to the initial LHC start-up in September 2008 and its restart in November 2009. Therefore the same strategy, that had proved its efficiency then, will be adopted. Beside the essential individual system tests by the experts, early tests campaign of operational use-cases is performed by the operation team from the control room. Then a dedicated machine checkout period with full integration tests is planned after the end of LS1. This should ensure a smooth transition from LS1 to beam commissioning.

STRATEGY UNTIL BEAM COMMISSIONING

The operation team has started to organise systems tests from the control room already in May 2014. The aim of starting such a long time before beam is to detect the issues as soon as possible. Then equipment and software team have time for the corrective actions, even for a complete review of the system if need. In addition some equipment like collimators, beam dump and timing systems are running reliability run or stress tests from the control room for several weeks.

Nevertheless, starting systems tests very early also have drawbacks. Lots of the systems are not stable yet and most of the time only partial tests are possible. They will often have to be repeated once the situation is steadier. Finally with the priority given to the restart of the injectors, experts are not always available to help with the tests and solve the issues immediately.

A basic control environment needed to be available and operational already in May 2014 before the dry run. The LSA core applications and services where operational, used to check, trim and drive machine parameters. The LHC sequencer was made operational, and tests sequences could be created and run. The logging service was available so that the logged data for each system could be checked. Page one and DIP gateway were mandatory for communication with the experiments.

The timing system was up and running since the beginning of tests, events could be sent and timing tables triggered.

The period from now to beam commissioning will continue to be dedicated to system tests from the control room. More and more systems will be available and the control room tests more and more complete. The collaboration with the expert will then be essential. This will lead to the transfer line test that will take place at the end of week 6 and at the end of week 8.

SYSTEMS TO TEST

Continuous Interlock Systems Tests

The interlocks systems will need to be tested carefully and as soon as possible. All Beam Interlock System input will have to be tested one by one. There are almost 200 entries, for PIC, FMCM, vacuum, collimators, and experimental magnets, beam position monitors etc…

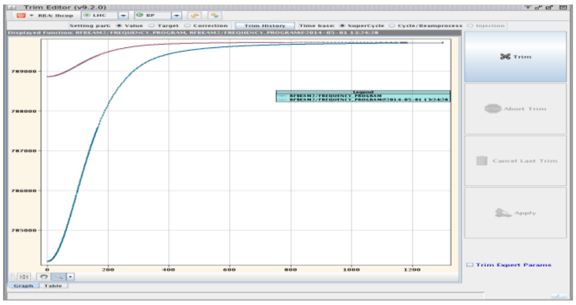
The tests will be organised following the readiness of the systems. For example, the vacuum interlock test is already planned at the end of September.

This is a huge systematic work that is essential to ensure the machine protection before any beam injection can be allowed.

The Software Interlock System (SIS), even if a bit less critical for safety, also needs intensive testing. The system is quite complex, with a lot of entries with each a proper logic.

RF systems

The RF resynchronisation sequence and RF frequency ramp have already been tested. More ramps are needed for the experiments to test their instrumentation and synchronisation systems, both for ions and protons.

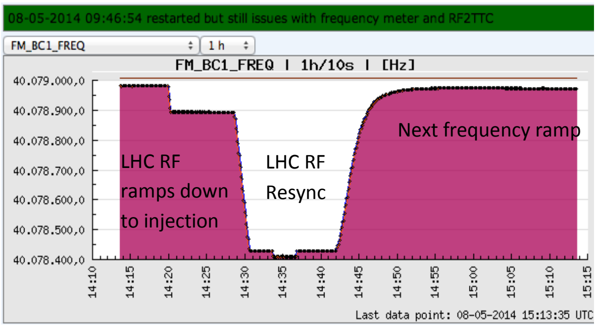


Setting part: ● Value ○ Target ○ Correction

Time base: ● SuperCycle ○ Cycle/Beamprocess ○ Injection

Displayed Function: RFBEAM2/FREQUENCY_PROGRAM, RFBEAM2/FREQUENCY_PROGRAM@2014-05-01 13:24:28

Figure 1: Proton and Ions frequency ramp to 6.5TeV


08-05-2014 09:46:54 restarted but still issues with frequency meter and RF2TTC

Last data point: 08-05-2014 15:13:35 UTC

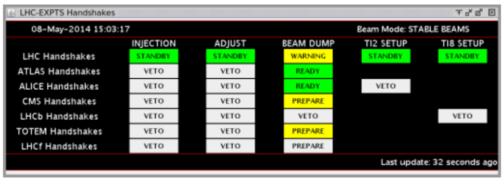
Figure 2: Signal from Alice Frequency meter

Tests of the SPS frequency rephasing with the LHC RF frequency will be organised. All the RF sequences to load and run the operational settings will be tested.

The ADT systems knows a major upgrade during LS1, dry runs will be organised to test the sequences and the control room applications.

Communication with the Experiments

A sequence has been prepared to mimic the consecutive handshakes and beam mode changes of the nominal sequence.


LHC-EXPTS Handshakes

08-May-2014 15:03:17

Beam Mode: STABLE BEAMS

	INJECTION	ADJUST	BEAM DUMP	TI2 SETUP	TI8 SETUP
LHC Handshakes	STANDBY	STANDBY	WARNING	STANDBY	STANDBY
ATLAS Handshakes	VETO	VETO	READY		
ALICE Handshakes	VETO	VETO	READY	VETO	
CMS Handshakes	VETO	VETO	PREPARE		
LHCb Handshakes	VETO	VETO	VETO		VETO
TOTEM Handshakes	VETO	VETO	PREPARE		
LHCf Handshakes	VETO	VETO	PREPARE		

Last update: 32 seconds ago

Figure 3: Beam dump handshake with experiments

The reception of the post mortem event by the experiment have been tested. The Safe Machine Parameter distribution to the experiments will need to be checked as well.

Collimators

The collimator tests from the control room have already started. Settings have been generated for the 6.5 TeV cycle, but the handling of critical settings still need to be sorted out. A sequence has been created to drive collimators to parking, injection and ramp position. This sequence is run continuously for several hours; collimators are added to the test pool as soon as available.

New collimators with embedded beam position monitor have been installed and will need to be tested.

The injection protection and transfer line collimator will be tested during the transfer line tests.

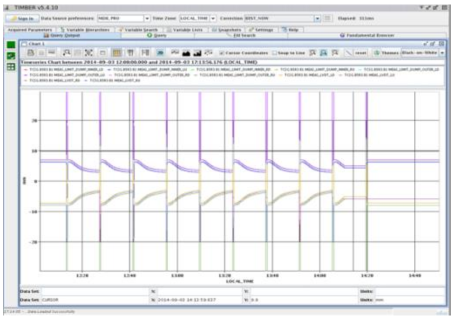


Figure 4: TCSG.B5R3.B1 jaw positions and threshold as logged in timber during reliability test.

Instrumentation

The instrumentation tests have started partially, mainly the BPM concentrators and the acquisition’s trigger and synchronisation. Instruments are gradually coming together and the necessary tools will be ready for the transfer line tests. All systems should be ready for control room tests at the beginning of 2015.

Orbit and tune feedback will have a new implementation and intensive tests of the system will be needed.

Kickers

The arming sequence for the beam dump has been modified to adapt to the new interface between the beam dump and the BIS (Beam Interlock System) for the retriggering. A sequence for reliability run has been established, it arms the beam dump, simulate a ramp thanks to the BETS simulator and triggers a beam dump. This sequence is played continuously during several weeks. This first dry run campaign was done with a local BIS loop, it will have to be repeated with the global BIS (with all inputs bridged), and a new version of the TSU.

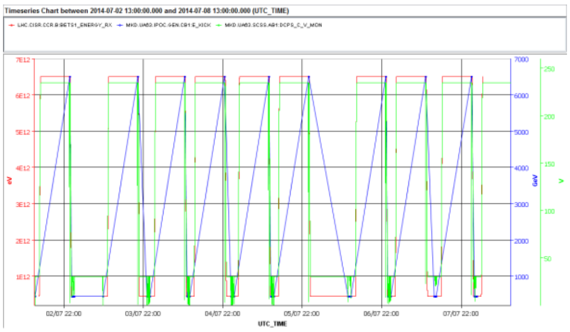


Figure 5: LBDS reliability run

The inject and dump sequence will have to be re-commissioned and the mechanism tested. It will be used during the transfer line tests.

For the MKI (injection kicker), test the pre-pulse from RF, the behaviour with the dynamic destination, the system interlocks (i.e. the abort gap keeper) and the BIS interlocks.

The AC dipoles and MKQ have stated to be tested but still need some work before being fully operational.

Timing

The timing system has already been tested as needed since the first dry runs: send events, run tables, take mastership over SPS beam and request injection. These tests will need to be repeated after the major timing system upgrade foreseen at the end of October. A new protocol for injection requests will be deployed. A dedicated dry-run will be organised before the transfer line tests. It is expected to perform the beam request from the LHC injection sequencer or the LHC inject and dump sequence during the transfer lines test.

Access System Tests

The LHC access system needs to be tested and validated before any beam can be extracted down to TI2 and TI8.

The access tests are difficult to organise because the system has to be available all the time. Therefore, in June and July five dedicated Fridays have been planned. The aim of this first tests campaign was to check all the input/output signals, and test the new access powering interlock (software interlock that prevent the powering of magnets above a current limit when access conditions are unsafe). Once this validation made, the access system was secured for powering phase II.

To secure the access system for beam, two other tests are still needed. They will by organised during two dedicated week-ends.

During the first one, the system’s experts will test the beam mode: ensures that the beam imminent warning sirens are working properly and test the redundant cable loop. The new maintenance doors that allow an access to the access devices while in beam mode will also be validated.

The second week-end, tests by the DSO (Department Safety Officer) will be organised. This is an independent verification of the access system validating that the access system ensures the protection and safety of the staff. This test is mandatory to allow beam in the LHC. If successful, the access system is ready for beam.

FINAL MACHINE CHECKOUT

End of LS1

LS1 stops at the end of week 6, before the dedicated machine checkout planned weeks 7 and 8. By this time, all equipment and systems need to be ready for beam and released to operations. The first week of machine check out will be in parallel with the last tests of circuit commissioning in sectors 45 and 78, this will request careful organisation of the different tests to progress on both activity in parallel.

Objective and Machine Conditions

The aim of this final machine checkout is to run full integration tests: the entire LHC systems will be tested together for the first time. It requires the LHC to be closed and the access system ready for beam. All systems have to be operational, i.e. the magnet circuits qualified individually, PIC (Power converter interlock controller) and QPS (Quench Protection System), beam vacuum system and BIS (Beam Interlock Controller).

Tests

- Final validation of the Beam Interlock System (BIS) verifying all hardware interlocks without beam.
- Final validation of the Software Interlock System (SIS) checking the logic of all software interlocks without beam.
- The beam dump energy tracking system (BETS) under real conditions using the four energy defining sectors and the additional magnets (extraction septa & Q4 quadrupoles).
- Final validation of the LHC beam dump system (LBDS). The test consists in arming and firing the LBDS, once the following conditions have been fulfilled:
    - LHC machine closed, access key in position “beam mode”.
    - BIS loop closed.
    - BETS operational.
    - Injection BIS enabled.
- The beam vacuum valves and their interlock logic.
- Final tests of the injection, tune and aperture kickers and the AC dipole.
- Heat runs of all warm magnets.
- Testing the full operational LHC cycle (injection, ramp-up, squeeze, collision, ramp down and pre-cycle) driving all equipment.
- Final tests of all beam instrumentation and their associated applications.

Organisation

The machine checkout is coordinated by Rossano Giachino and Markus Albert of the operations team. There will be an EIC and an operator on shift 24/24 to perform the tests.

A daily 8:30 meeting in the CCC will be organised to:

- review the test results of the previous day
- define the test plan of the day
- negotiate access requests

CONCLUSION

Aside from individual system tests, the operations team has already organised various tests from the CCC with the equipment expert and experiments. It is aimed to start testing systems as early as possible from the CCC to anticipate on software bugs or hardware issues and get some time for fixes. A tight collaboration between OP and the equipment specialists is mandatory for the tests organisation and follow-up. This will become even more important toward the beam commissioning as more and more systems will be tested together.

The readiness deadline for all equipment and controls is the start of the machine checkout period beginning in week 7.

During the final checkout period, full operational condition and machine closed are needed. The final tests without beam will hopefully lead smoothly to the beam commissioning.

LHC TRANSFER LINES AND SECTOR TESTS IN LHC

V. Kain, R. Alemany, CERN, Geneva, Switzerland

Abstract

Transfer Line and Sector tests were conducted in the past and proved to be invaluable, fully meting their goals. They resolved a long list of problems, debugged and tested the control system, the beam instrumentation, timing and synchronization, software, etc. Measurements with beam allowed detailed optics and apertures checks to be performed, discovering aperture bottlenecks and polarity issues that could be solved before beam commissioning.

Being those tests an essential precursor and a high profile milestone in preparation for full beam commissioning, transfer line and sector tests are again proposed before beam commissioning starts in 2015. This paper summarizes the proposed dates, the pre-requisites, how to stop the beam with collimators and the goals in what accelerator equipment commissioning and beam measurements are concerned.

MOTIVATION

During LS1 most of the accelerator subsystems and the control system underwent important changes in view of improving availability and reliability. Most of the magnet interconnections have been opened and the machine has been exposed to air. Fifteen main dipole magnets and other equipment have even been changed. The accelerator control system was upgraded with effects on most of the accelerator equipment. A complete summary of all the interventions made in all the accelerator subsystems can be found in these proceedings.

The proposed transfer line and sector tests will provide the unique opportunity to debug and test the accelerator subsystems involved, resolve possible problems at an early phase, carry out the first commissioning of the most critical systems, injection and dump, and perform the first measurements with beam, assessing the performance of the beam instrumentation and, in general, of the accelerator subsystems after the Long Shutdown One (LS1).

Several sector tests have been performed in the past in preparation for final beam commissioning. The TI8 transfer line was commissioned for the first time with beam in 2004 [1, 2]. In 2005 the TI8 test was repeated with high intensity beams. TI2 saw beam for the first time in 2007 [3]. In preparation for first circulating beam in 2008, five sector tests were performed [4]. Finally, after the 2009 shutdown, following the sector 34 incident, two injection tests were accomplished, together with the first ion injection in the LHC. On all occasions the tests were undoubtedly an essential precursor to the successful start of LHC Beam Commissioning.

STRATEGY

Three weekends are proposed to carry out the transfer line and sector tests in LHC. The dates are different from the ones presented in [5] since the overall LHC schedule has changed and new dates had to be found to make those tests compatible with the new plan:

- Transfer Line TI2 and TI8: 22-23 Nov 2014 - beams dumped in the movable beam dump block (TED) down stream the lines.
- Sector Test 1: 7-8 Feb 2015 - beam 1 through sector 23 and dumped in the IR3 collimators.
- Sector Test 2: 21-22 Feb 2015 - beam 2 through sectors 78 and 67 up to the beam 2 dump block in point 6.

The tests are scheduled weekends to minimize the impact on the experiments and hardware commissioning.

Single pilot bunches of 2-5×10^9 protons will be used for the test in order to reduce the ambient radiation and therefore have less or no impact on post-test tunnel activities.

The setting up of SPS TT60/TT40 extraction region will be done before the transfer lines and sector tests.

Goals of the Transfer Lines Test

During the transfer lines test the beams will be sent to the down stream TED. The goals of these tests are listed below:

1. With SPS as mastership of the injection request:
    a. threading and steering of the lines;
    b. commissioning with beam of the beam instrumentation: Beam Position Monitors (BPM), Beam Loss Monitors (BLM), beam screens (BTV), Beam Current Transformer (BCT), etc;
    c. commissioning of the beam interlock system of the SPS extraction and LHC injection;
    d. SPS-Transfer Line energy matching and energy acceptance.
2. Commissioning of the LHC mastership injection request.
3. LHC injection septa (MSI) and injection kickers (MKI) synchronization.
4. Beam measurements:
    a. BPM and orbit corrector polarity and gain checks.
    b. Rough linear optics and dispersion checks.
    c. Trajectory stability
5. SPS Extraction Kicker (MKE) waveform scans (LSS4/LSS6).
6. Extraction region aperture scans.

7. Initial commissioning of transfer line collimators (TCDI) and set up with automatic application.
8. LHC Beam Dump System-MKI synchronization (without beam).
9. Inject and dump commissioning (without beam).

The transfer line tests require closing the following areas:

- Transfer Line TI2: TI2, PM25, PM32, UJ23, UJ27, UP2 and PX24 (ALICE).
- Transfer Line TI8: TI8, PM85, UJ83, UJ87 and UX85 (LHCb).

CMS and ATLAS are not concerned, however, the other sectors might be closed because of powering test activities that can be performed in parallel to the transfer line tests.

A preliminary plan for the different commissioning steps to be performed during the transfer line tests is under preparation and it will be circulated soon for comments in order to elaborate the final version by middle of October 2014.

Goals of the Sector Tests

During the first sector test, beam will be sent to the TED down stream TI2 and some time will be dedicated to re-setup the line, assuming the full commissioning was performed during the transfer line test in November 2014. Then the beam will be sent to the LHC injection beam stopper (TDI) with the injection kickers of beam 1 off. After the required setup time in this configuration, the same exercise will be done with the injection kickers on. Once the injection region is properly set up, the TDI will be retracted and the beam will be sent to the insertion region 3 where the momentum collimators are located. From then onwards, a series of measurements will be performed as detailed in the BEAM MEASUREMENTS section.

The same steps will be carried out during the second sector test, except that the TI8 transfer line will have been commissioned before. In addition, beam 2 dump line and the associated systems will be commissioned this time.

PREREQUISITIES

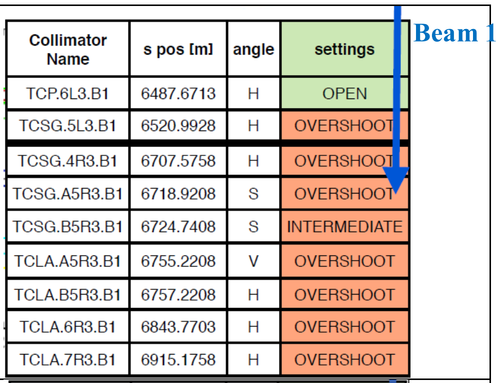
The success of the transfer lines and sector tests relies heavily on the success of the preparation activities carried out during the year like: hardware commissioning, individual system tests, powering tests, dry runs, access system commissioning, Departmental Safety Officer (DSO) acceptance test and machine checkout. A detail review of those activities can be found in these proceedings.

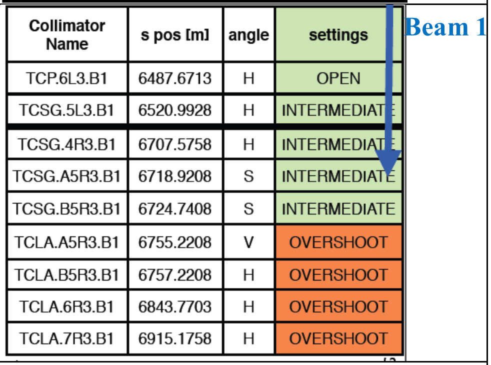
Those activities will exercise all the required systems and debug their integration, which is crucial to narrow down the problems or solve them before the beam comes.

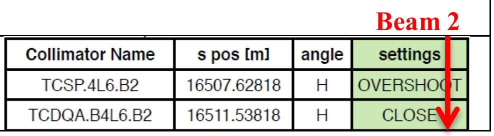
The LHC access system commissioning with beam conditions i.e. machine closed and patrolled including the experiments, is scheduled November 8 and 9 2014. The DSO test will take place at the following weekend, November 15 and 16 2014, and again the LHC will be closed and patrol including the experiments.

During the sector tests the experiments involved in the tests, i.e. ALICE and LHCb must have their full shielding in place.

Table 1: Summary of collimators used for the different injection tests in 2008 with the corresponding type of settings. The arrows indicate the direction of the beam.

<table>
<tr><td>Beam 1 stopped at LEFT of IR3</td><td>


<table>
<tr><th>Collimator Name</th><th>s pos [m]</th><th>angle</th><th>settings</th></tr>
<tr><td>TCP.6L3.B1</td><td>6487.6713</td><td>H</td><td>OPEN</td></tr>
<tr><td>TCSG.5L3.B1</td><td>6520.9928</td><td>H</td><td>OVERSHOOT</td></tr>
<tr><td>TCSG.4R3.B1</td><td>6707.5758</td><td>H</td><td>OVERSHOOT</td></tr>
<tr><td>TCSG.A5R3.B1</td><td>6718.9208</td><td>S</td><td>OVERSHOOT</td></tr>
<tr><td>TCSG.B5R3.B1</td><td>6724.7408</td><td>S</td><td>INTERMEDIATE</td></tr>
<tr><td>TCLA.A5R3.B1</td><td>6755.2208</td><td>V</td><td>OVERSHOOT</td></tr>
<tr><td>TCLA.B5R3.B1</td><td>6757.2208</td><td>H</td><td>OVERSHOOT</td></tr>
<tr><td>TCLA.6R3.B1</td><td>6843.7703</td><td>H</td><td>OVERSHOOT</td></tr>
<tr><td>TCLA.7R3.B1</td><td>6915.1758</td><td>H</td><td>OVERSHOOT</td></tr>
</table>
</td></tr>
<tr><td>Beam 1 stopped at RIGHT of IR3</td><td>


<table>
<tr><th>Collimator Name</th><th>s pos [m]</th><th>angle</th><th>settings</th></tr>
<tr><td>TCP.6L3.B1</td><td>6487.6713</td><td>H</td><td>OPEN</td></tr>
<tr><td>TCSG.5L3.B1</td><td>6520.9928</td><td>H</td><td>INTERMEDIATE</td></tr>
<tr><td>TCSG.4R3.B1</td><td>6707.5758</td><td>H</td><td>INTERMEDIATE</td></tr>
<tr><td>TCSG.A5R3.B1</td><td>6718.9208</td><td>S</td><td>INTERMEDIATE</td></tr>
<tr><td>TCSG.B5R3.B1</td><td>6724.7408</td><td>S</td><td>INTERMEDIATE</td></tr>
<tr><td>TCLA.A5R3.B1</td><td>6755.2208</td><td>V</td><td>OVERSHOOT</td></tr>
<tr><td>TCLA.B5R3.B1</td><td>6757.2208</td><td>H</td><td>OVERSHOOT</td></tr>
<tr><td>TCLA.6R3.B1</td><td>6843.7703</td><td>H</td><td>OVERSHOOT</td></tr>
<tr><td>TCLA.7R3.B1</td><td>6915.1758</td><td>H</td><td>OVERSHOOT</td></tr>
</table>
</td></tr>
<tr><td>Beam 2 stopped at RIGHT of IR7</td><td>All IR7 collimators closed with overshoot technique</td></tr>
<tr><td>Beam 2 stopped at LEFT of IR7</td><td>TCLA.A6L7 (W collimator) overshoot</td></tr>
<tr><td>Beam 2 dumped in IR6</td><td>


<table>
<tr><th>Collimator Name</th><th>s pos [m]</th><th>angle</th><th>settings</th></tr>
<tr><td>TCSP.4L6.B2</td><td>16507.62818</td><td>H</td><td>OVERSHOOT</td></tr>
<tr><td>TCDQA.B4L6.B2</td><td>16511.53818</td><td>H</td><td>CLOSE</td></tr>
</table>
</td></tr>
</table>

HOW TO STOP THE BEAM

The same strategy as used in 2008 and 2009 for stopping the beams safely and reliably with collimators will be used. The technique is called overshoot and it is described in the following. The collimators will be set up with the minimum possible gap between jaws on anti-collision switches; which corresponds to 0.5 mm gap. Then the collimator gap will be moved 5 mm aside from the reference orbit to assure the beam impacts on the jaw. If required, the collimator can in addition be tilted.

Table 1 lists the collimators used during the injection tests in 2008. Open settings means the collimator is fully retracted to let the beam go through. Intermediate settings correspond to gaps of the order of +/-10 mm and +/-12 mm depending on the collimator.

BEAM INTERLOCK CONFIGURATION

Two configurations have been prepared, one for the beam 1 sector test and the other for the beam 2 sector test. The configurations are summarized in Table 2 and 3.Only the inputs relevant for the sector tests will be enabled. To avoid modifying the hard-wired Power Interlock Controller (PIC) arrangement, the interlocking of the magnet circuits will be done with the Software Interlock System (SIS). The PIC input to the Beam Interlock System (BIS) will be disabled.

Table 2: User permits needed for the first sector test.

INJ1	CIB.SR2.INJ1.1	CIB.SR2.INJ1.2
	LHC Beam 1 Permit	Nothing needed
	Operator switch	
	MKI2 status	
	Vacuum	
	MKI2 erratic	
IR2 (B1)	CIB.UA27.R2.B1	L2.B1
	MKI	BLM
	Vacuum	Vacuum
	ALICE detector	
IR3 (B1)	CIB.UJ33.U3.B1	CIB.SR3.S3.B1
	ACCESS_SB	BLM
	WIC	

Table 3: User permits needed for the second sector test.

INJ2	CIB.SR8.INJ2.1	CIB.SR8.INJ2.2
	LHC Beam 2 Permit	LBDS.B2
	Operator switch	
	MKI8 status	
	Vacuum	
	MKI8 erratic	
IR6 (B2)	CIB.UA67.R6.B2	CIB.UA63.L6.B2
	Vacuum	Vacuum
	LBDS (TSU)	WIC (septa)
	LBDS (PLC)	BLM
	CIBDS B2	
IR7 (B2)	CIB.SR7.S7.B2	CIB.TZ76.U7.B2
	BLM	Vacuum
		WIC
IR8 (B2)	CIB.UA87.R8.B2	L8.B2
	Vacuum	Vacuum
	MKI	BLM
	LHCb detector	
	LHCb movable	

ENERGY INFORMATION

The Beam Energy Tracking System (BETS) of the Beam Dump System will get the energy from the BETS simulator. The main dipoles of the four sectors that provide the energy measurement under normal circumstances might not be available at that time. Those sectors are 45, 56, 67 and 78.

BEAM MEASUREMENTS

The beam measurements to be done during the sector tests are the following:

- Transfer line optics and aperture checks (if not done during the transfer line test) and matching between the transfer lines and LHC injection region.
- Establish injection:
    - kicker synchronization
    - kicker wave form study
    - kicker control
    - SPS-LHC RF synchronization
    - pre-pulse transmission
    - timing system functionality
    - injection sequencer commissioning
    - aperture checks
- Beam Position Monitor system commissioning:
    - response
    - acquisition
    - concentrator
- Threading:
    - establish first trajectory and first orbit correction
    - application software commissioning
- Kick response:
    - check BPM and orbit corrector polarities
    - linear optics checks
    - other circuits polarity checks
- Aperture measurement
- Beam Loss Monitors commissioning
- Collimators:
    - BLM response
    - Control system commissioning
    - BPM collimators first commissioning

Reference [4] compiles all the details of the tests performed in 2008 together with the beam measurements.

The preliminary measurement plans for the two sector tests have been presented in [5]. Those plans will have to be updated according to the results of the transfer line test in November 2014, and in particular the final plan for the second sector test will depend on the outcome of the first one.

CONCLUSIONS

Transfer lines and sector tests are essential precursor and a high profile milestone in preparation for full beam commissioning.

The TI2 and TI8 transfer line tests are scheduled in November 2014 and two sector tests are proposed for 2015:

- Transfer Line TI2 and TI8: 22-23 Nov 2014 - beams dumped in the TED down stream the lines.

- Sector Test 1: 7-8 Feb 2015 - beam 1 through sector 23 and dumped in the IR3 collimators.
- Sector Test 2: 21-22 Feb 2015 - beam 2 through sectors 78 and 67 up to the beam 2 dump block in point 6.

A draft measurement plan for the transfer line tests is under preparation and it will be circulated for comments and optimization. The plan for the sector tests have been already presented in [5] but an update will be needed that takes into account the results of the transfer line test.

REFERENCES

[1] B. Goddard, V. Mertens, T. Risselada, "Status and Plans for the SPS to LHC Beam Transfer Lines TI2 and TI8", LHC Project Report 751, EPAC 2004 Conference Proceedings.

[2] J. Uythoven et *al.*, "Commissioning of the LHC Beam Transfer Line TI8", PAC 2005 Conference Proceedings.

[3] J. Uythoven et *al.*, "Beam Commissioning of the SPS-TO-LHC Transfer Line TI2", EPAC 2008 Conference Proceedings.

[4] M. Lamont et *al.*, "The LHC Injection Tests", LHC Performance Note 2008-10-21, PAC 2009 Conference Proceedings.

[5] V. Kain, R. Alemany, "LHC Transfer Lines and Sector Tests in 2014", EVIAN 2014 Workshop Proceedings

Proceedings of Chamonix 2014 Workshop on LHC Performance

2015 COMMISSIONING WITH BEAM - INTRODUCTION

M. Lamont, CERN, Geneva, Switzerland

Abstract

In motivating the session, the challenges of re-commissioning the LHC in 2015 are introduced.

INTRODUCTION

The LHC has been pulled apart and put back together again. There have been major system consolidation and upgrades including significant control system upgrades at all levels. Besides this a number of innovative suggestions have be proposed to improve operational performance; these will have to be introduced judiciously to avoid compromising initial commissioning.

The good performance of Run 1 performance was based on a number of factors, all of which have to be re-established for Run 2. These factors are listed below.

- Beam from the injectors featuring high intensity with impressively low emittance.
- Beam in the LHC enjoyed, in general, good lifetimes and good transmission through the cycle – despite high bunch population.
- Exploitation – there was efficient passage through all phases of the LHC cycle on a regular, operational basis.
- Understanding - great strides were made in establishing optics, aperture, a robust and accurate magnetic model. Collective effects received a lot of attention and significant progress was made in understanding the interplay of beam-beam, impedance and instability.
- Machine protection unpinned operation with unprecedented beam and magnetic energy.
- System performance was, in general, excellent. Systems included: RF, power converters, collimators, beam dumps, injection, magnets, vacuum, transverse feedback, machine protection, magnets, magnet protection, beam instrumentation, beam based feedbacks, controls, databases, high level software, cryogenics, survey, technical infrastructure, access, radiation protection.
- System availability was also acceptable thanks to a concerted effort by the system teams and a focussed global effort by the R2E project team.
- Problem solving was also necessary. Looking forward to Run 2, known unknowns include: UFOs, electron cloud and beam stability.

The main re-commissioning objectives are:

- Measure and re-establish appropriate beam behaviour in terms of lifetime, beam loss, and stability.
- Measure and establish the key operational limits: aperture; minimum β^*
- Set-up optics, injection, beam dumps, collimation and validate the set-up through all phases of the operational cycle. It is note that the final optics choice still to be made.
- Given the above, establish the nominal cycle with a robust set of operating parameters.
- Commission beam based systems: transverse feedback, RF, injection, beam dump system, beam instrumentation, power converters, orbit and tune feedbacks.
- Commission and test machine protection and re-establish the required, high level of protection.
- Along the way check the understanding of: magnet model; optics; quench levels; UFO rates; stability limits.

CHALLENGES

Operationally the LHC is not a new machine. The teams involved carry forward considerable experience. However they will face familiar and new challenges. Principal among these challenges are the higher operational energy and the move to 25 ns bunch spacing. The latter brings with it significantly worse electron cloud, implying that scrubbing will be one of the main drivers of commissioning in 2015. 2015 challenges are summarized in the tables 1, 2, and 3.

System Modifications

It is also important to note that an impressive range of system modifications across the board have taken place during LS1. These have addressed:

- reliability, availability, performance, functionality, and system protection;
- improvements which realize creative thinking based on experience at all levels (hardware, software, controls);
- hardware grades giving increase processing speed and data transfer rates;
- improved analysis tools and diagnostics;
- noise reduction, better stability, and resolution;
- better fault tracking.

These modifications are going to take some shaking out both without and with beam.

Table 1: Challenges of High Energy

Issue	Consequences
Higher stored beam energy	Potential for serious damage
Lower tolerance to beam loss, lower quench margins	Premature beam dumps Tighter parameter control
More energy dumped in triplets and collimator regions	Beam loss, heat load
Lower intensity set-up beams	Commissioning efficiency
Systems closer to maximum (RF, converters, beam dump)	Premature dumps, asynchronous dumps

Table 2: Challenges of 25 ns Operation

Issue	Consequences
Injection of 25 ns beams	Bigger beam size, higher intensity per injection
Electron cloud	Instabilities, emittance growth, desorption, heat-load
UFOs	Premature dumps
Long range beam-beam	Poor lifetime, larger crossing angle

Table 3: Other Challenges

Issue	Consequences
Radiation to electronics	Premature dumps
Emittance blow-up (non e-cloud)	Performance
Reset of vacuum system and vacuum non-conformities	All conditioning lost: MKI, TCQQ, TDI local heating - out-gassing
Impedance	Beam stability
Reduction in beam size - natural	Beam stability
Reduction in beam size - BCMS	Beam stability, brightness - limitations of protection devices
Loss of expertise	Commissioning efficiency

Beam Stability

One interesting issue referenced in table 3 is that of beam stability. In 2012 with high bunch population single beam head-tail instabilities were observed at various phases of the operational cycle. There were also signs of an interplay between the two beams at the end of the squeeze and while going into collisions. The standard cure is Laudau octupoles. These provide a amplitude dependent tune shift and thus a betatron frequency spread in the bunch which provides Landau damping. The octupoles have been essential to LHC thus far. As regards Laudau damping the negative de-tuning given by the negative polarity setting is more effective than positive de-tuning. However, in the squeeze at lower β^* there is apparently interference between the tune spread from the octupoles with that from long-range beam-beam and in this case positive detuning is preferred.

Looking forward to 6.5 TeV, betatron amplitudes naturally go down with energy, and there is the possibility of using lower emittances. Both these reduce the effectiveness of the octupoles, suggesting the use of negative polarity. However, the issue in the squeeze might still have to be faced. There are some uncertainties and we will need to establish the limits with beam during commissioning and ramp-up and then make the choice.

CONCLUSIONS

There is a lot to sort out (safely). It is important to reduce the dimension of problem space during initial commissioning wherever possible.

EXPERIMENTS EXPECTATIONS

B. Gorini, E. Meschi, CERN, Geneva, Switzerland

Abstract

In this paper the experiment expectations for the 2015 data taking period, including the period of commissioning with beam and the initial phase of collisions with 50ns bunch spacing are discussed. Experiments views concerning various beam parameters for the p-p period, beam energy, maximum pileup, bunch spacing and luminosity limitation in IP2 and IP8, are presented, as well as the physics goals and the constraints of the 2015 program, including the heavy ions period as well as special running conditions.

STANDARD p-p RUNNING CONDITIONS

The principle guideline for the discussion on beam conditions from the physics standpoint is the maximization of the *total integrated* luminosity *usable for physics.* On the one hand, conditions for the 2015 data-taking period should be analyzed in view of the integrated luminosity reach of the whole Run 2; on the other hand, considering machine performance, reaching ultimate peak luminosity may not be the optimal choice in terms of commissioning time and machine availability, as well as e.g. pileup. It is important to note that especially an excess of the latter could dramatically degrade the data taking and analysis efficiency of the experiments.

Energy and Bunch Separation

Any increase in beam energy will significantly improve the potential for discovery of new physics even with moderate luminosity (figure 1). This augmented reach must however be weighted against the need of fixing the energy early enough to allow MC production. The experiments assume hereafter that 6.5 TeV will be defined as the initial energy (after the Chamonix final decision) and NOT changed in 2015. Results from late quench tests could force to run at lower energy and that is considered an unavoidable risk. In the course of Run 2, in general, small step increases towards ultimate energy during the year should be avoided wherever possible in favor of a single change applied during the end-of-the-year technical stop.

As always stated the most critical parameter for the high luminosity experiments is the number of interactions per crossing. A higher level of pileup has negative implications on several aspects of the experiments, and ultimately affects the experimental accuracy of the results. These include the readout capability, because of increased occupancy, the trigger efficiency, the reconstruction and analysis efficiencies, as well as the systematic uncertainties. Higher pileup also demands larger online and offline computing resources.

ATLAS and CMS have studied carefully several effects and agree that a maximum level of pileup of about 50 would be manageable in Run 2, and would not require the introduction of any mechanism for luminosity leveling.

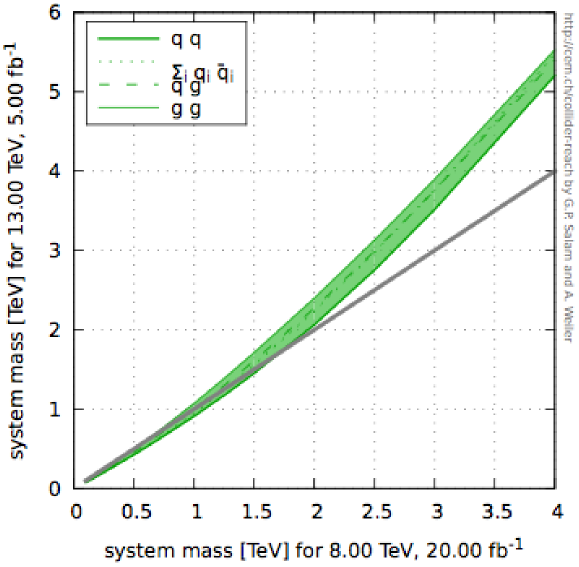


Figure 1: Discovery potential comparison: profiles of equal statistics as a function of the parton-parton system mass for 5 fb^{-1} delivered at a center of mass energy of 13 TeV with respect to 20 fb^{-1} at 8 TeV [1].

It must be made clear though that handling such a level of pileup is challenging and it is hence only considered acceptable as an initial fill value, assuming the natural luminosity decay. Values of acceptable constant pileup in the case of luminosity leveling range between 30 and 40.

Effects of pileup are not linear, and depend of the specific physics channel considered; there is therefore no sharp threshold below which pileup has no effect and above which the experiments would stop working. Rather, pileup should be considered as the key parameter to optimize the physics yield of LHC in conjunction with all other relevant machine parameters.

Running the LHC with a bunch spacing of 25 ns is considered of maximum importance to maximize the ultimate physics reach of the machine. It is accepted by all experiments that 25 ns bunch spacing will require a longer commissioning period and could result in lower integrated luminosity delivered in 2015 with respect to 50 ns, but it is still considered as the supported scenario in view of the longer term scientific goals. It is also understood that a phase of machine re-commissioning with 50 ns spacing will be needed, but it is expected to be limited to what is required for establishing the machine conditions.

Luminous Region and Optics

At constant total pileup, the density of collisions in the luminous region is of particular relevance for the efficiency of the reconstruction of the primary vertex in the tracking detectors. Considering that the luminous region in Run 2 will be smaller due to larger crossing angles, the experiments would prefer to have bunch lengths at the beginning of the fill yielding a luminous region not significantly shorter than those of Run 1. Decreases and increases of the order of about 10% would be acceptable, while larger changes will require further study.

There is no major concern with adjusting the bunch length or the crossing angle as a proposed mechanism to reduce the luminous region during the fill, in view of moderating the luminosity decay.

It is to be noted that lengthening the luminous region may also reduce track reconstruction efficiency in ATLAS and CMS, as well as the LHCb VELO acceptance for long-lived B mesons. As a general remark, it would be important for the experiments to know the expected beam parameters as early as possible for MC production.

ATLAS and CMS express no specific concern with respect to the choices of optics at the IP. Injecting at lower β* would not be a problem as the Van der Meer scan campaign will anyway require ad-hoc optics. Even the possible adoption of flat optics is not seen as a problem, at least up to a β_x/β_y ratio of 2-3.

Filling Schemes

The only constraint with respect to filling schemes for physics data taking is that they should include few bunches not colliding in IP 1 and IP5, for both beam 1 and beam 2. These bunches have proven to be essential to background studies, as otherwise the experiments would have no direct way to evaluate the level of beam-gas interactions (figure 2).

It is proposed to shift, for one of the two beams only, the initial injection of 12 bunches, required for machine protection checks. Despite the fact that the non-colliding bunches should be as similar as possible to the colliding ones, it would be acceptable to inject lower charge to mitigate potential instabilities due to lack of Landau damping.

Leveling and Crossing in LHCb

Analysis of the LHCb's Run 1 data did not show a significant improvement of systematic uncertainties from the tilted crossing angle scheme. This requirement is thus relaxed for Run 2. Differences between the crossing angles for the two experiment's magnet polarities should anyway be minimised. Regular polarity swaps will still be necessary about every 100 pb^{-1} delivered to LHCb.

In 2015 LHCb will need luminosity leveling at 4-6 10^{32} $cm^{-2}s^{-1}$in IP8. Leveling by separation is assumed as the default. All experiments agree that commissioning the leveling based on modulation of β* in IP 8 could prove useful in case such a mechanism should need to be deployed at a later stage in IP1 and IP5. Hence it is supported, if seen as beneficial, only if not significantly affecting physics time.

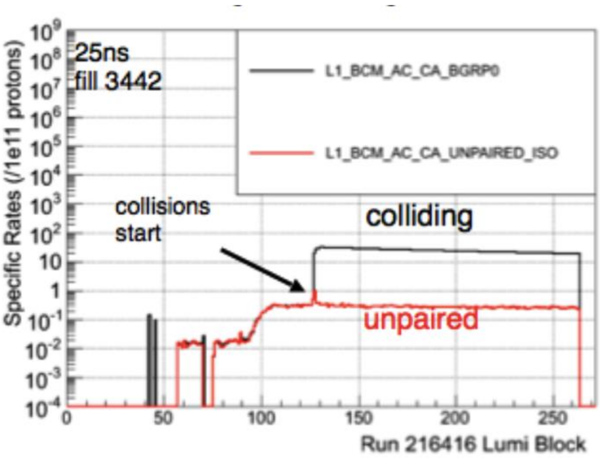


Figure 2: Rates from beam monitors for paired and unpaired bunches. The rate from unpaired bunches is and indispensable tool to evaluate the beam-gas background

ALICE Conditions during the p-p Period

The ALICE experiment needs to collect data in minimum-bias conditions during the whole p-p data taking period. This means that the luminosity in IP 2 should be leveled in a range between 5 10^{29} $cm^{-2}s^{-1}$ and 2 10^{30} $cm^{-2}s^{-1}$. With 25 ns bunch spacing most bunches collide head-on in IP 2 and the required reduction of luminosity must be achieved mostly by beam separation. Looking at beam profiles measured in Run 1 during Van der Meer scan campaigns (figure 3) one concludes that a separations of 5-6 σ will be needed.

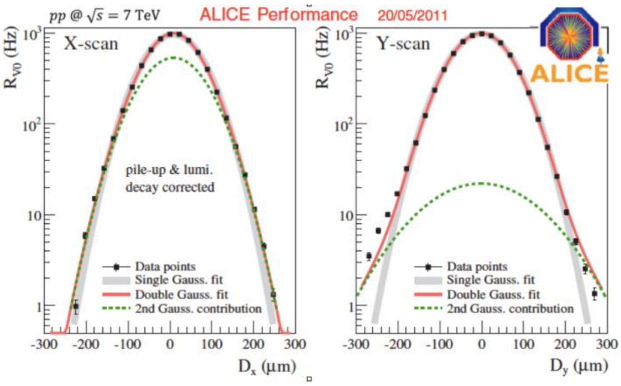


Figure 3: Beam Profiles at IP2 in a 2011 Van der Meer scan. Rate drops at the limit of the scan range are only 300 (Y), and 1000 (X), respectively

Dedicated studies must be carried on early on to assess the feasibility and the stability of such conditions. In particular the stability of luminosity conditions at such extreme separations should be addressed, as well as the operational procedure to bring ALICE into collisions with a large enough separation, to avoid the risk of a beam dump when removing the separation bump, as ALICE BCMs are currently set at a dump threshold estimated to correspond to about 6 10^{31} cm^{-2} s^{-1} [2].

ALICE requires to have few bunches colliding in IP 2 during the 50 ns period. An ad-hoc filling scheme with few head-on collisions would be preferable given the relative instability of conditions achieved with the main-satellite collisions approach followed in Run 1.

HEAVY IONS CONDITIONS

Four weeks of Heavy Ion collider operation are assumed in 2015. It has been decided to run with Pb-Pb collisions. The equivalent nucleon energy should be 5.1 TeV. A value of 5.02 TeV would be considered preferable but only if the additional cost in commissioning is negligible.

Since luminosity is expected to exceed the maximum value acceptable by ALICE of 3-4 10^{27} cm^{-2} s^{-1} [3], a leveling mechanism will have to be set up at least in IP 2. Due to the importance of burn-off in heavy ion collisions, alternative leveling scenarios including the 3 experiments are under evaluation, based on the machine potential for peak luminosity and turnaround times. Despite being not directly needed by ATLAS and CMS, these are meant to limit the performance penalty in ALICE.

ATLAS and CMS require a reference sample of p-p collisions at the equivalent proton energy with an integrated luminosity given by

$$\int Ldt\ (pp) = 3\text{-}4\ 10^4 \times \int Ldt\ (PbPb)$$

The actual extent of this data taking period, as well as its detailed schedule are still being discussed in the LPC meetings, but it is required that the necessary commissioning is carried out before the start of the Heavy Ions period.

EARLY COMMISSIONING PERIOD

At this moment the only specific request from the experiments for the initial machine commissioning period is to deliver about 20 beam splashes per beam in both IP1 and IP 5 as well as few TED shots, during the sector tests of sector 78, for LHCb alignment studies. It is also expected that stable beams conditions will be established as soon as possible to allow detectors and triggers commissioning. Some data taking in stable beams conditions will be regularly requested during the phases of intensity ramp up.

Unsqueeze for VdM scans and the LHCf special run are expected to be part of the initial commissioning as needed (see below). Performing ALFA and TOTEM alignment and loss maps for Roman Pots as part of the initial commissioning should also be considered.

Dedicated runs with low or very low pileup are not requested at the moment as these are expected to be collected parasitically during the special run for LHCf.

SPECIAL RUNS

Given the shortness of the 2015 data taking period and the extent of the commissioning campaign, it has been decided to limit the program of special runs to a minimum. The only exceptions foreseen at this moment are special runs for LHCf and an high β* period for diffractive physics in ALFA and TOTEM, as well as two Van der Meer scan campaigns.

LHCf Run and VdM Scans

The LHCf run with special optics for low luminosity and pileup ($\mu<0.01$) is expected to be scheduled in the very first days of the 2015 physics production (within about a week of data taking). LHCf also requires large bunch separation (>2μs) and a half crossing angle of 145 μrad. The goal for the LHCf run is to collect approximately 10 nb^{-1} of integrated luminosity.

An early VdM scan is necessary to provide initial calibration of the luminometers at the new beam energy. Due to the increased beam energy and the subsequent natural reduction of the beam size, it is established that the VdM scan will need to be performed with un-squeezed optics in order to keep the luminous width significantly larger than the vertex resolution, to study the non-linear x-y beam correlations that are a dominant source of uncertainty for the luminosity calibration (figure 4).

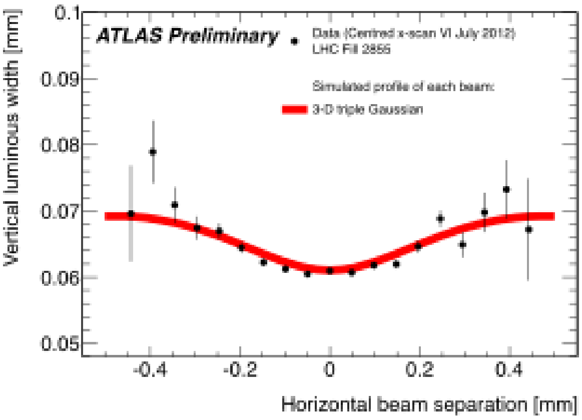


Figure 4: Nonlinear x-y correlations can be studied quantitatively by fitting the evolution of the beamspot position and luminous width during scans. This is only possible if the vertex resolution does not dominate the luminous width.

The LHCf run must be scheduled before about 500 pb^{-1} of luminosity are delivered to IP 1, to prevent significant degradation of the LHCf detector due to radiation damage. For the VdM scan ATLAS requires a minimum of 5 pb^{-1} delivered in order to condition their luminometer. Thus, it is proposed to combine the two special runs using ad-hoc optics to accommodate both programs. The requested values of β* are 19 m for IP 1 and IP 5, while LHCb would benefit from a larger value, between 30 and 40 m.

The luminosity per bunch requirements are significantly different for the two programs, hence it is considered acceptable, if it can save setup time, to use similar bunch intensities for the two programs, of order 7 10^{10} protons, ideal for the VdM scans, and reduce the pileup in IP 1 by separation when providing data to LHCf.

It is foreseen to start this special run campaign with the VdM scans in the four interaction points and then proceed with the LHCf data taking. LHCf will ideally start collecting data during the scan in IP 5. It is still unclear if a filling scheme can be established to allow LHCf to also take data parasitically during the scans in IP 2 and IP 8 and yet have a total current compatible with operating the DCCT detectors in their preferred range.

High Beta Runs

Both ALFA and TOTEM have requested data taking with β^* of 90 m for diffractive physics studies. TOTEM in particular has requested a joint data-taking period with CMS with the target of collecting about 10 pb^{-1} of central diffractive event data. Given the need for low pileup conditions, it is foreseen to inject bunches with a charge of about $7\ 10^{10}$ protons. To maximize total luminosity and yet respect the minimal bunch separation requirements of TOTEM, an ideal setup would require a filling scheme with about 1000 bunches and 75 ns of bunch spacing. This requires the development of a machine setup with a crossing angle.

It is important to state that even in those ideal conditions one would only reach a luminosity of about 10^{31} $cm^{-2}s^{-1}$, making the TOTEM statistics goal quite difficult to reach in an already tight schedule. In addition, ALFA, even with an upgraded trigger, can only take data with up to 700 bunches.

Insertion of the Roman Pots with standard optics is envisaged for TOTEM in the context of the CMS/PPS program. It is suggested that end of fill studies be scheduled to test the mechanism during the machine commissioning and intensity ramp-up.

ACKNOWLEDGMENTS

We wish to thank, in particular, the Run Coordinators of ALICE, ATLAS, CMS, LHCb, LHCf and TOTEM for their essential input as well as our colleagues working on the LHC and injectors operations for countless explanations and discussions about machine parameters and constraints.

REFERENCES

[1] G. Salam, A. Weiler, Collider Reach webpage; http://collider-reach.web.cern.ch/collider-reach/

[2] A. Di Mauro, presentation to the 91st LHC Machine Protection Panel Meeting; https://indico.cern.ch/event/318640/contribution/0/material/slides/1.pdf

[3] J. Jowett, M. Schaumann, LBOC Meeting No 17; https://indico.cern.ch/event/311453/contribution/2/material/slides/1.pdf

BASELINE LHC MACHINE PARAMETERS AND CONFIGURATION FOR THE 2015 PROTON RUN

R. Bruce[*], G. Arduini, S. Fartoukh, M. Giovannozzi,
M. Lamont, E. Metral, T. Pieloni, S. Redaelli, J. Wenninger
CERN, Geneva, Switzerland

Abstract

This paper shows the baseline LHC machine parameters for the 2015 start-up. Many systems have been upgraded during LS1 and in 2015 the LHC will operate at a higher energy than before and with a tighter filling scheme. Therefore, the 2015 commissioning phase risks to be less smooth than in 2012. The proposed starting configuration puts the focus on feasibility rather than peak performance and includes margins for operational uncertainties. Instead, once beam experience and a better machine knowledge has been obtained, a push in β^* and performance can be envisaged. In this paper, the focus is on collimation settings and reach in β^*—other parameters are covered in greater depth by other papers in these proceedings.

INTRODUCTION

The first running period of the LHC, Run I [1], was very successful and resulted in important discoveries in physics. In spring 2013, the LHC was shut down for about 2 years, in order to allow consolidation of the superconducting splices in the magnet interconnects, following the incident of 2008. In parallel, numerous other machine systems have been consolidated or upgraded. A common goal of the upgrades is to improve the machine so that it can safely operate closer to its design energy and thus extend the physics discovery potential. For the restart of the LHC in 2015, several challenges can be anticipated, and it is important to carefully define its operational parameters at the start-up in order to maximize the chances of a smooth and successful second running period.

In this paper, we discuss first the general strategy for 2015, which leads up to a proposed choice of starting configuration. Our focus is on collimator settings and reach in β^*, since most other parameters are covered by other papers in these proceedings [2, 3, 4, 5, 6, 7, 8, 9]. We discuss also how the performance can be increased later in the run, when the operational behavior of the machine is better known.

STRATEGY FOR 2015

When the LHC restarts in 2015, it will operate at a higher energy and shorter bunch spacing than in 2012 (6.5 TeV and 25 ns compared to 4 TeV and 50 ns) [2, 3]. These changes imply new major operational and beam physics challenges. Furthermore, the higher beam energy and potentially larger total beam intensities make the LHC beams more dangerous. Fewer protons are needed to cause quenches or damage of sensitive machine components. At the same time, the risk of a known serious failure mode, the asynchronous beam dump, increases at higher energy [10], and a higher rate of UFOs is expected [11]. It is also uncertain how the operational issues encountered in 2012, such as instabilities and beam lifetime drops, will be manifested at 6.5 TeV.

Because of the many uncertainties, the operational behavior of the machine in 2015 is not as well known as in the end of Run I, which means that the beam commissioning risks to be less smooth as in 2012. Therefore, we envisage in the operational strategy for 2015 a careful start of the LHC in a relaxed configuration, which allows larger operational margins. The focus is put on feasibility, stability, and ease of commissioning, and the main priority is not peak performance but rather to establish a running machine at 6.5 TeV and 25 ns. Where possible, it should be avoided to introduce too many new features at once. On the other hand, the starting parameters should also not be overly pessimistic. Therefore, the operational achievements in Run I are used, where possible, to deduce what is likely to work.

The main focus in this paper is to define the machine parameters for the start-up, but we discuss also, at the end of the paper, what changes can be made later in the year. Once sufficient beam experience is gathered through machine development sessions [12] or routine operation, the luminosity performance could be pushed. The ultimate reach in luminosity is hard to predict but we give an overview of the different parameters that can be adjusted.

Even though the final goal is to operate at 25 ns, a short initial run will take place at 50 ns. In order to save commissioning time, this run will use the same machine configuration as the 25 ns run. Therefore, we do not discuss in further detail the 50 ns run.

These different stages of the 2015 proton physics period are schematically summarized in Fig. **??**. Each physics run has to be preceded by a scrubbing period to mitigate the effects of electron cloud [5] and possibly by additional commissioning.

Further details of the 2015 run can be found in Ref. [4].

BEAM CHARACTERISTICS

Although the design proton beam energy of the LHC is 7 TeV, the baseline energy for 2015 is 6.5 TeV. The reason is that, in order to reach 7 TeV, it is estimated that an unfeasibly large number of training quenches is needed [13],

---

[*] roderik.bruce@cern.ch

although this estimate might be adjusted in the future, when more results of powering tests become available [2].

There has been a strong request from the experiments to operate with the design bunch spacing of 25 ns, since it provides potentially higher luminosity and lower pileup [3]. The 25 ns scheme is, however, coupled to several potential complications, for example stronger electron cloud [5] and the need of a larger crossing angle to compensate for the stronger long-range beam-beam effect [14].

The characteristics of the LHC bunches in physics operation are strongly dependent on the beam provided by the injectors. Presently, the injectors can provide two different types of beams: BCMS (batch compression and merging and splittings) and nominal [6]. In both schemes, the achievable bunch intensity is, under optimistic assumptions, up to about 1.3×10^{11}, which is slightly higher than the nominal 1.15×10^{11}. The BCMS beams have significantly smaller emittances (at LHC injection down to 1.3 μm normalized emittance compared to 2.4 μm for nominal) but fewer bunches (2544 or 2592 colliding in IR1 and IR5, depending on the number of trains, compared to 2736 for nominal).

Once injected in the LHC, intensity loss and emittance growth are very likely to occur. Using typical numbers from Run I, an intensity loss of about 5% could be expected, which leaves a bunch intensity up to about 1.2×10^{11} in collision. The emittance is affected by several physical processes. If only the unavoidable effect from intra-beam scattering (IBS) is accounted for, growths of 20% or 5% have been calculated [15] for BMCS and nominal respectively. However, if the scrubbing runs are not fully successful in mitigating the electron clouds, a much larger emittance growth is likely to occur [5].

Although with a potentially much higher peak luminosity, it is not obvious that BCMS is the better choice, since the very small emittance could have a detrimental effect on the single-beam stability [16]. In addition, the small emittances are more challenging for machine protection [7]. Therefore, the choice between the two beams is still at the time of writing (September 2014) an open question.

In the longitudinal plane, a bunch length of 1.25 ns can be expected at injection and 1.2 ns in collision, for the RF voltages of 6 MV (injection) and 12 MV (collision) [17, 8]. Shorter bunches of nominal length (about 1 ns) could be within reach from the machine side and could be put into operation. Possibly, the increased pileup density can be handled by the experimental detectors [3]. A shorter bunch length would be beneficial for the luminosity since the geometric reduction factor is increased.

LHC CYCLE AND OPTICS

Several significant changes to the LHC operational cycle are under study. Examples of such changes are luminosity leveling by dynamically changing β^* during stable beams (in order to reduce the pileup), putting the beams into collision already before the squeeze starts (in order to stabilize the beams in the squeeze using the tune spread introduced by the collisions) [18] or combining the ramp and the squeeze (to make the cycle shorter) [19]. With the philosophy that it should be avoided, where possible, to introduce untested features at the 2015 start-up, these operational improvements are a priori not a part of the start-up baseline, but could instead be introduced at a later stage in the run when more experience has been gained. A detailed account of the nominal cycle is given in Ref. [20].

Two different optics schemes have been under consideration: the nominal optics [21], used in Run I, and the achromatic telescopic squeeze (ATS) [22]. ATS is a promising option that could provide several advantages, but it has also some outstanding points that need further study [23]. Therefore, it has been decided to start with nominal optics, while keeping the possibility to switch to ATS at a later point. Further details are given in Ref. [9].

The injection optics for 2015 will thus stay the same as in 2012. At top energy, a new final point of the β^* squeeze has to be decided upon, together with a new crossing angle. This is discussed in detail in the following sections for IR1 and IR5, where β^* is limited by the available aperture. In IR2 and IR8, β^* is instead adjusted to the luminosity that the detectors can handle, and the aperture is less critical. IR2 will therefore stay at the injection value of β^* =10 m with an external half crossing angle of 120 μrad, while IR8 will use the same configuration of β^* =3 m as in 2012 and an external half crossing angle of -250 μrad. It should be noted though that the crossing angles in IR2 and IR8 are under review by the ABP/HSC section to ensure that beam-beam effects are in the shadow of IR1 and IR5. In all IRs except IR8, a parallel separation of 2 mm will be used at injection, as in 2012. In IR8, the parallel separation has to be increased to 3.5 mm with the addition of a parallel angle of 40 μrad [24]. In collision, the 2012 value of the parallel separation is rescaled by the energy and rounded to obtain 0.55 mm at all IRs.

COLLIMATOR SETTINGS

The LHC collimation system [21, 25, 26, 27] influences directly the peak luminosity performance in several ways. Firstly, the cleaning inefficiency (the local losses in a cold element normalized by the total losses on collimators), together with the beam lifetime and the quench limit, define the maximum acceptable intensity. Secondly, when pushing the β^* to smaller values, the β-function in the inner triplets increases, meaning that the normalized aperture margin between the central orbit and the mechanical aperture decreases. If this margin becomes too small, the aperture can no longer be fully protected by the collimation system. At what aperture this occurs depends on the collimator settings. The loss in aperture is further enhanced by the fact that a larger crossing angle is needed at smaller β^* in order to keep the same normalized beam-beam separation. The collimators are also the main contribution to the LHC impedance, which is crucial for beam stability.

Table 1: Settings of different collimator families for different scenarios for 6.5 TeV operation after LS1, where either the 2012 settings are kept in mm, in σ or more open (relaxed). All settings are given in units of the local transverse beam size σ, which is calculated using the β-function at each collimator and the nominal emittance of 3.5 μm.

Collimators	Relaxed settings (σ)	mm settings kept (σ)	σ settings kept (σ)
TCP7	6.7	5.5	5.5
TCS7	9.9	8.0	7.5
TCLA7	12.5	10.6	9.5
TCS6	10.7	9.1	8.3
TCDQ6	11.2	9.6	8.8
TCT	13.2	11.5	10.7
protected aperture (σ)	14.8	13.4	12.3

Different collimator settings have been under consideration for the 2015 start-up and the three main scenarios are shown in Table 1. In terms of cleaning, the relaxed settings are close to the limit of preventing a beam dump at a beam lifetime of 12 minutes and full nominal intensity, even though significant uncertainties exist [28]. Although a detailed verification with final optics is pending at the time of writing, it is expected that the other two types of settings have better cleaning efficiency that should suffice, unless the beam lifetime drops significantly below the 12 minutes specification, or the quench limit would be much worse than expected. Therefore, we do not expect the cleaning inefficiency to be a limiting factor for the total beam intensity.

In order to be on the safe side for the cleaning, but without going to the tighter gaps with the 2 σ retraction that are more challenging in terms of impedance, Run II will start with the 2012 settings kept in mm (middle column in Table 1). They also have a well-proven long-term stability in terms of preserving the hierarchy under unavoidable drifts of optics and orbit.

The impedance and single-beam stability for the different collimator settings are discussed in Ref. [16]. It is shown that for the nominal, large-emittance beam, all proposed collimator settings should provide sufficient stability with both octupole polarities, while stability could be an issue with the BCMS beams. The two-beam effects and octupole polarities are discussed in detail in Ref. [14].

For machine protection, the settings in Table 1 fulfill the same demands as used during Run I [29, 30] in terms of the IR6 dump protection shadowing the tertiary collimators (TCTs) and the TCTs shadowing the triplets. The margins between different collimator families are calculated based on what was achieved in Run I. If the stability of the optics or orbit correction for post-LS1 would be worse, larger margins are needed. Furthermore, the TCT damage limit in number of protons is lower and the baseline 25 ns filling scheme means that there is a risk to have double the number of bunches within the critical time window during asynchronous dumps when bunches pass the dump kickers and receive intermediate kicks. Therefore, it could be wise to introduce more margins at the start-up, before the machine stability is well known, in order to be sure that the TCTs and aperture are protected. This is especially true at more relaxed values of β^*, where the orbit in mm scales to a larger variation in units of σ so that larger margins in σ are needed.

For the calculation of β^* we first investigate the limiting configuration with a protected aperture of 13.4 σ from Table 1 and then evaluate more relaxed scenarios.

APERTURE AND CROSSING ANGLE

Given the aperture that is protected by the collimation system, the achievable β^* can be calculated, if also the required aperture as a function of β^* is known. This function depends both on which tolerances are included in the aperture calculation and on the required crossing angle.

The aperture was measured during Run I on several occasions [31, 32, 33, 34, 35, 36, 37], using the circulating beam, and it was found that the results were compatible with a very well aligned machine with very small errors [38]. During the shutdown, all magnets have been realigned, so the alignment should a priori not be worse than at the start of Run I.

For the aperture calculation, we therefore assume that the aperture has not become worse during LS1 and, at this stage, we do not include additional safety margins on orbit or optics. However, we base our calculations on the most pessimistic measurement from 2012. We scale this measured value by β^* and add the change in orbit due to a different crossing angle, in order to estimate the crossing plane aperture at any other configuration. This straightforward, analytic method has proven to give results very close to the MAD-X aperture model [39].

To verify the calculations, it is very important that the aperture is measured with beam very early on during the commissioning, after the reference orbit has been established and the optics corrected. If it turns out that the assumptions were too optimistic, the time loss when stepping back to a larger β^*, if needed, should be very small.

The criteria for choosing an appropriate crossing angle for 2015 are discussed in Ref. [14]. It needs to be sufficiently large to minimize the detrimental effects of the long-range beam-beam interactions, but when the angle is increased, the available aperture margin goes down. In order to calculate the needed crossing angle as a function of β^*, Ref. [14] suggests to use a normalized beam-beam separation of 11 σ for the start-up, based on simulations of dynamic aperture and operational experience from Run I. The larger-than-nominal separation is motivated by the possibility to have also larger intensities, e.g. 1.3×10^{11} protons per bunch.

In the calculation, a normalized emittance of 3.75 μm is used. If the real beam would have a smaller emittance, the calculated crossing angles in μrad still provide sufficient beam-beam separation.

β^* AT START-UP

The required aperture as a function of β^* is shown in Fig. **??**, assuming a constant beam-beam separation of 11 σ (blue line). Under the assumption that the protected aperture is 13.4 σ, and that we operate at points rounded to a 5 cm spacing, the limiting β^* that could be achieved is 65 cm (illustrated by the red dot in Fig. **??**). This configuration, corresponding to a 160 μrad half crossing angle, has been discussed in detail in Ref. [39]. It should be noted that the rounding up to 65 cm introduces a small aperture margin—the aperture prediction has anyway an error margin not smaller than the measurement precision of 0.5 σ.

It should be noted that several of the underlying assumptions on protection and stability contain uncertainties. For example, it cannot be guaranteed a priori that the orbit stability and optics correction will be as good as in 2012. Furthermore, the scaling to higher energy of instabilities and lifetime drops, presumably connected to the collimator impedance, is not known with a high accuracy. Therefore, in view of the approach of a relaxed start-up, it is wise not to start at the limiting configuration, but instead allow some additional margins.

Based on these considerations, it has been decided to start the 2015 LHC run at β^* =80 cm [23]. If the beam-beam separation is kept constant at 11 σ, the baseline operating configuration is therefore the blue dot in Fig. **??**, where a half crossing angle of 145μrad is found. It can be seen in the figure that the step to β^* =80 cm frees about 2 σ of aperture margin, which could be used in different ways depending on where it turns out to be needed.

If no collimators are moved, the additional margin just increases the aperture budget and makes it more certain that the real measured aperture will be compatible with the protected one. This is illustrated schematically in steps (1) and (2) in Fig. **??**.

In order to compensate for the uncertainty in orbit stability and optics correction, as well as the higher risk of asynchronous dumps at 6.5 TeV, the margin can be used to move out the TCTs so that they are better protected, as shown in step (3).

Step (4) in Fig. **??** illustrates yet another possibility, where all collimators are moved out in order to reduce the total machine impedance. This option could be envisaged if the beam stability turns out to be limited by impedance effects. A similar option, where all collimators but the primary (TCP) are moved out, could also be envisaged. This option would allow a learning curve for loss spikes with small TCP gaps.

In case the long-range beam-beam tune shift would turn out to be limiting, the additional aperture margin could also be used to increase crossing angle. This is illustrated by the green dot in Fig. **??**. As can be seen, if all additional margin would be dedicated to the beam-beam separation, it could be increased to about 15 σ at β^* =80 cm. This configuration corresponds to a half crossing angle of 195 μrad.

It is not yet decided which of the different options for using the additional margin that will be used. One could also use a split between several of them. The partition of the margins could even be changed during the 2015 commissioning, when it is clearer where it is mostly needed, although some changes would require additional commissioning time. We list here some examples of realistic suggestions for the start-up:

- All margin on machine protection: This option compensates for uncertainties on failure probabilities and, with the 11 σ beam-beam separation and tight collimators, it allows us to learn early on about potential limitations on beam stability.

- 1 σ on machine protection and 1 σ on beam-beam separation: This option allows a more relaxed squeeze with lower probability of instabilities, while maintaining a higher level of protection. It should be noted that 1 σ of aperture translates approximately into 2 σ of beam-beam separation, meaning a total separation of 13 σ and a half crossing angle of 170 μrad.

WAYS TO PUSH PERFORMANCE

Once the LHC has been successfully put into operation and a first period of stable beams has been established, it is reasonable to assume that the performance limitations will be better known. Then, the performance could be increased based on the operational experience and possible MDs. Several machine parameters could be changed to gain in luminosity performance:

- Bunch intensity: As the peak luminosity depends on the square of the bunch intensity, increasing it is a very efficient (and well-known) way to boost the performance. The intensity is mainly limited by the performance of the LHC injectors [6] and by the beam stability in the LHC [14, 16].

- Smaller emittance: This is also a well-known and straightforward way to increase the luminosity. It is also limited by the injectors and beam stability, but also by machine protection considerations [7]. It introduces also an additional gain by allowing a smaller crossing angle in μrad and therefore a larger aperture margin.

- Collimator settings: If the margins in the hierarchy are reduced, e.g. by establishing the 2 σ retraction settings in Table 1, a smaller aperture can be protected, and thus a smaller β^* tolerated. However, with tighter settings, the impedance increases. Whether this is tolerable has to be evaluated with beam. Based on further operational experience, the margins between the dump protection and the TCTs, as well as the margins between TCTs and triplets, might be decreased if the new integrated BPM buttons can be used to reduce orbit drifts from the center of the collimators. The less temperature-sensitive BPM electronics could also be used to determine whether some of the large orbit drifts between TCTs and triplets, observed in Run I, are real or an artifact of the measurements. In the future, we still hope to achieve nominal collimator settings in IR7 with a 1 σ retraction between the TCP and the secondary collimators (TCS). However, because of the impedance constraints, this is unlikely to be usable during Run II. Installing new TCSs made of materials with lower impedance could help. Furthermore, integrated BPMs in the TCS would help to ensure that the hierarchy is maintained in spite of the smaller margin.

- Crossing angle: reducing the crossing angle at a given β^* implies a gain in the required aperture. However, if the beam-beam separation is decreased, the long-range effect becomes more critical, in particular during the squeeze [14], which limits the smallest achievable crossing angle.

- Aperture: unless additional margins are introduced at the start-up, the gain should be rather small. The aperture in Run I was found in measurements to be very close to the ideal one, and the same assumptions are used for Run II.

- Bunch length: with a shorter bunch length, the geometric reduction factor is closer to one and the luminosity loss smaller. A shorter bunch length is likely to be within reach from the machine side [17, 8] and could possibly be put in place.

We cannot a priori determine the exact limit of actual β^*-values that could be reached later in the run, as many underlying parameters must be examined with beam. Instead, we give a few examples of possible configurations with pushed performance:

- **β^*=65 cm:** From Fig. **??** it is clear that β^* =65 cm could be within reach even with rather conservative assumptions.

- **β^*=55 cm:** If beam studies show that the impedance is acceptable for reduced collimator settings with a 2 σ retraction in IR7 (see Table 1) β^* =55 cm could be within reach if the aperture is at the limit of what can be tolerated. Alternatively, the main gain could come from the crossing angle. Keeping the mm kept settings, β^* =55 cm and a crossing angle of 130 μrad fits almost exactly within the protected aperture. This configuration corresponds to a beam-beam separation of 8.3 σ for an emittance of 3.75 μm. If the emittance can be reduced to 2.5 μm, the beam-beam separation with this crossing angle is about 10 σ. This configuration is possibly compatible with 6 σ dynamic aperture [14] but the limit would have to be deduced from beam studies.

- **β^*=40 cm:** This configuration could be within reach under optimistic assumptions [39]. For this ultimate scenario for Run II we assume the 2 σ retraction collimator settings, with the addition of using the BPM button collimators to their full potential. Furthermore, we assume a beam-beam separation of 10 σ at an emittance of 2.5 μm. These assumptions are considered challenging but possible, although it is not given that this configuration can be used. It could also require significant beam experience and additional commissioning time. Based on the possibilities of reaching β^* =40 cm, the optics will be commissioned down to this value already at the start-up, in order to have maximum flexibility. As an alternative to round optics, the configuration with β^* =40/50 cm in the two planes might be easier to reach in terms of aperture and gives comparable luminosity.

CONCLUSIONS AND OUTLOOK

The LHC will be re-started in 2015 after about two years of shutdown. Many hardware changes and upgrades have taken place and the machine will operate at a higher energy of 6.5 TeV energy and a shorter bunch spacing of 25 ns. Therefore, the machine behavior is less well known than at the end of Run I and the strategy for 2015 is to start carefully with the main aim to get the machine running safely and stably.

Based on these considerations, we have presented the LHC baseline parameters for the 2015 start-up, which we summarize for convenience in Table 2. Most notably, the LHC will start proton physics at β^* =80 cm, a 145 μrad half crossing angle, and 2012 the collimator settings kept in mm. It is at the time of writing not decided whether the nominal or BCMS beams from the injectors will be used. These parameters contain some margins which could be used for increased machine protection, or, in case of need, for a relaxed beam-beam separation or impedance.

Later in the run, a push in β^* and performance can be envisaged, when the operational limits are well established based on beam experience. This pushed β^*-value could be as low as 40 cm under optimistic assumptions.

ACKNOWLEDGMENTS

The authors would like to thank numerous colleagues for input and discussions: H. Bartosik, X. Buffat, E. Chapoc-

Table 2: Summary of the main LHC beam and machine parameters for 2015. It should be noted that the emittance values in collision are optimistic and assume emittance growth only from IBS with values from Ref. [15]. If the scrubbing is not fully successful, larger emittances should be expected. Furthermore, the intensity in collision assumes a 95% transmission of the injected intensity. It should also be noted that the 2012 mm kept collimator settings in collision might still be modified to achieve a larger margin for machine protection between the TCDQ and the TCTs.

Parameter	Unit	Value at injection	Value at collision
Beam energy	TeV	0.45	6.5
β^* at IR1/IR2/IR5/IR8	m	11 / 10 / 11 / 10	0.8 / 10 / 0.8 / 3
half crossing angle at IR1/IR2/IR5/IR8	μrad	-170 / 170 / 170 / 170	-145 / 120 / 145 / -250
Tunes (H/V)	–	64.28/59.31	64.31/59.32
Parallel separation at IR1/IR2/IR5/IR8	mm	2 / 2 / 2 / 3.5	0.55 / 0.55 / 0.55 / 0.55
Normalized emittance (BCMS/nominal)	μm	$\geq 1.3 / \geq 2.4$	$\geq 1.7 / \geq 2.7$
Total number of bunches (BCMS/Nominal)	–	$\leq 2604 / 2748$	
Number of bunches colliding at IR1/5 (BCMS/Nominal)	–	$\leq 2592 / 2736$	
Bunch intensity	p	$\leq 1.3 \times 10^{11}$	$\leq 1.2 \times 10^{11}$
Bunch length (4σ)	ns	1.0–1.2	1.0–1.25
Collimator settings	–	2012 mm kept	2012 mm kept

hnikova, P. Collier, R. de Maria, G. Iadarola, V. Kain, E. Meschi, N. Mounet, Y. Papaphilippou, G. Papotti, G. Rumolo, B. Salvachua, B. Salvant, M. Solfaroli, R. Tomas, G. Valentino, D. Valuch, and M. Zerlauth

REFERENCES

[1] S. Myers. The Large Hadron Collider 2008-2013. *Int. J. Mod. Phys. A*, 28:1330035, 2013.

[2] M. Solfaroli *et al.* Re-commissioning of the Superconducting Circuits. *Proceedings of the LHC Performance Workshop (Chamonix 2014), Chamonix, France*, 2014.

[3] E. Meschi *et al.* Experiments' Expectations for 2015. *Proceedings of the LHC Performance Workshop (Chamonix 2014), Chamonix, France*, 2014.

[4] J. Wenninger *et al.* Overall Strategy for Run 2. *Proceedings of the LHC Performance Workshop (Chamonix 2014), Chamonix, France*, 2014.

[5] G. Iadarola *et al.* Scrubbing: Expectations and Strategy, Long Range Perspective. *Proceedings of the LHC Performance Workshop (Chamonix 2014), Chamonix, France*, 2014.

[6] Y. Papaphilippou *et al.* Operational Beams for the LHC. *Proceedings of the LHC Performance Workshop (Chamonix 2014), Chamonix, France*, 2014.

[7] V. Kain *et al.* Concerns with Low Emittance Beams Operation. *Proceedings of the LHC Performance Workshop (Chamonix 2014), Chamonix, France*, 2014.

[8] A. Butterworth *et al.* ADT and RF after LS1. *Proceedings of the LHC Performance Workshop (Chamonix 2014), Chamonix, France*, 2014.

[9] M. Giovannozzi *et al.* Optics options for the 2015 LHC run. *Proceedings of the LHC Performance Workshop (Chamonix 2014), Chamonix, France*, 2014.

[10] N. Magnin *et al.* LHC beam dumping system status and readiness for LHC run II. *Proceedings of the 5th Evian Workshop, Evian, France*, 2014.

[11] B. Auchmann *et al.* BLM Threshold Strategy (vs UFOs and Quenches). *Proceedings of the LHC Performance Workshop (Chamonix 2014), Chamonix, France*, 2014.

[12] LHC Studies Working Group Day, 2014.09.02, 2014.

[13] E. Todesco *et al.* Energy of the LHC after the 2013-2014 shutdown. *Proceedings of the LHC Performance Workshop (Chamonix 2012)*, 2012.

[14] T. Pieloni *et al.* Two beam effects. *Proceedings of the 5th Evian Workshop, Evian, France*, 2014.

[15] M. Kuhn *et al.* Transverse emittance through the cycle. *Proceedings of the 5th Evian Workshop, Evian, France*, 2014.

[16] N. Mounet *et al.* Impedance and instabilities. *Proceedings of the 5th Evian Workshop, Evian, France*, 2014.

[17] J.E. Muller *et al.* Longitudinal parameters and beam induced heating. *Proceedings of the 5th Evian Workshop, Evian, France*, 2014.

[18] E. Metral. Collective effects. *presentation in the LHC Machine Committee, 2014.09.03.*, 2014.

[19] S. Redaelli *et al.* Combined Ramp and Squeeze at the Large Hadron Collider. *Proceedings of IPAC12, New Orleans, Louisiana, USA*, page 157, 2012.

[20] M. Solfaroli *et al.* Nominal Cycle and Options. *Proceedings of the LHC Performance Workshop (Chamonix 2014), Chamonix, France*, 2014.

[21] O. S. Brüning *et al.* LHC design report v.1 : The LHC main ring. *CERN-2004-003-V1*, 2004.

[22] S. Fartoukh. Achromatic telescopic squeezing scheme and application to the lhc and its luminosity upgrade. *Phys. Rev. ST Accel. Beams*, 16:111002, 2013.

[23] LHC Machine Committee, 2014.09.03, 2014.

[24] S. Fartoukh. LHCb crossing scheme for Run II and III. *presentation in the LHC Machine Committee, 2014.06.19*, 2013.

[25] R.W. Assmann. Collimators and Beam Absorbers for Cleaning and Machine Protection. *LHC Project Workshop - Chamonix XIV*, page 261, 2005.

[26] R.W. Assmann *et al.* The Final Collimation System for the LHC. *Proc. of the European Particle Accelerator Conference 2006, Edinburgh, Scotland*, page 986, 2006.

[27] R. Bruce *et al.* Simulations and measurements of beam loss patterns at the cern large hadron collider. *Phys. Rev. ST Accel. Beams*, 17:081004, Aug 2014.

[28] A. Verwei *et al.* Quench limits. *Presentation in the LHC collimation review 2013*, 2013.

[29] R. Bruce and R.W. Assmann. LHC β^*-reach in 2012. *Proceedings of the 2011 LHC beam operation workshop, Evian, France*, 2011.

[30] R. Bruce *et al.* Calculation method for safe β^* in the LHC. *Proceedings of IPAC11, San Sebastian, Spain*, page 1828, 2011.

[31] C. Alabau Pons *et al.* LHC aperture measurements. *Proceedings of IPAC10, Kyoto, Japan*, page 477, 2010.

[32] C. Alabau Pons *et al.* IR1 and IR5 aperture at 3.5 TeV. *CERN-ATS-Note-2011-110 MD*, 2011.

[33] R.W. Assmann *et al.* Aperture Determination in the LHC Based on an Emittance Blowup Technique with Collimator Position Scan. *Proceedings of IPAC11, San Sebastian, Spain*, page 1810, 2011.

[34] S. Redaelli *et al.* aperture measurements in the LHC interaction regions. *Proceedings of IPAC12, New Orleans, Louisiana, USA*, page 508, 2012.

[35] C. Alabau Pons *et al.* IR2 aperture measurements at 3.5 TeV. *CERN-ATS-Note-2012-017 MD*, 2012.

[36] R. Bruce *et al.* IR8 aperture measurements at injection energy. *CERN-ATS-Note-2013-026 MD*, 2013.

[37] R. Bruce *et al.* IR2 aperture measurements at 4.0 TeV. *CERN-ACC-NOTE-2013-0011 MD*, 2013.

[38] R. Bruce *et al.* Parameters for HL-LHC aperture calculations. *CERN Report CERN-ACC-2014-0044*, 2014.

[39] R. Bruce and S. Redaelli. Collimation and β^*-reach. *Proceedings of the 5th Evian Workshop, Evian, France*, 2014.

OPTICS OPTIONS FOR THE 2015 LHC RUN

M. Giovannozzi, CERN, Geneva, Switzerland

Abstract

A review of the possible optics configurations for the 2015 LHC run will be made. The rationale behind the various scenarios will also be presented together with the latest results of the validation studies. Special runs, such as Van der Meer and high-beta, will be discussed too. Finally, the next steps and the related milestones will be discussed with the goal of achieving a consensual decision on the optics configuration to be used for the LHC in the coming weeks.

POSSIBLE OPTICS CONFIGURATIONS

The overall beam and optical parameters proposed for the 2015 run can be found in Ref. [1], where the rationale behind these choices is discussed in detail. In this paper these values are taken as input and various optical configurations, all compatible with them, are discussed.

The potential changes to the Run I optics can be grouped into three categories depending on their goal, namely:

- Take into account the experience gained during Run I.
- Extend the performance reach of the LHC.
- Prepare for the future.

Of course, a more prudent approach can be applied, considering that the LHC ring underwent important modifications affecting the magnetic circuits. Therefore, sticking to the Run I nominal optics might be a suitable option in view of minimising the risk of additional unforeseen difficulties during the 2015 beam commissioning.

The items presented in this paper as possible optics configurations for the 2015 run have been worked out and presented in detail in Refs. [2-4]. Three options have been devised [3, 4]:

- Option-min: it is the closest configuration to the one used during Run I. Only the change of crossing angle scheme in IR8 [2] is implemented, which is mandatory for operation with 25 ns bunch spacing beams, and the use of all MCBXs for the generation of the crossing and separation schemes. It is worth mentioning that some slight changes have to be made to the squeeze sequences of IR2 [5] (ions [6]) and IR8 [7] to make them compatible with the higher energy with respect to Run I.
- Option-med: with respect to Option-min, the optics of IR4 is modified in order to increase the values of the beta functions at the location of the D3 separation dipole in view of improving the performance of the synchrotron radiation monitor (BSRT). This has also positive side effects on the beam size at several instruments for measuring beam profiles [8, 9] as well as a beneficial impact on the effective strength of the transverse damper [10, 11]. In principle, also the IR6 optics could be upgraded according to what presented in Ref. [12] and assessed in Ref. [13]. This option has been considered not to be necessary.
- Option-max: it consists of an ATS-compatible [14] optics, with a configuration of IR4 fulfilling the requirement of increased beta functions as for Option-med, even if the two solutions are not exactly the same.

It is worth noting that Option-max fulfils all three criteria listed before, as it has been basically tested with pilot beams during Run I [15-19] and it incorporates the required changes in IR4. Moreover, it increases the performance reach by opening the possibility of using flat optics, which provides an interesting boost in performance with longer than nominal bunch length, very large β^* values and clean chromatic properties of collision optics, including low spurious dispersion. Finally, it is the HL-LHC baseline optics [20-22] and its implementation in operation would allow gaining experience with such a novel optics concept and it would be therefore beneficial for the upgrade project.

SOME ADDITIONAL POINTS

There are a number of generic aspects that should be taken into consideration in view of finalising the optics configuration for the 2015 run.

Tune Control

The control of the fractional part of the tune is currently made by means of the phase advance of the local optics of IR1 and 5 [23]. At top energy, the first matched optics of the squeeze sequence performs a variation of phase advance in IR1 and 5 so to change the fractional part of the tune from the injection value of (0.28, 0.31) for the horizontal and vertical plane, respectively, to (0.31, 0.32). This change is performed at constant value of β^*. During Run I beam losses have been observed during this stage of the squeeze [24], which has been correlated with a too strong orbit change due to the feed down stemming from the quadrupoles that vary the phase advance. A natural solution would be an increase in the duration of such an optics transition. Nevertheless, this would have an adverse impact on the overall duration of the beta-squeeze process, which is certainly not going in the right direction, i.e., of optimising the cycle length for physics.

At the same time, it should not be forgotten that the fractional part of the tune can be controlled via the MQTs [25] with a minimum impact on the beta-beating. Therefore, it is proposed to use these quadrupole correctors to vary the machine tunes. In principle, the optics can be kept constant and the MQTs changed in order to achieve the target tune values for each moment during the cycle. This approach would provide a very flexible means of acting upon the tunes as the duration of the tune transition stage and its location in the LHC magnetic cycle can be changed at will, without any need for additional re-commissioning time.

The most likely choice of the optics to be used could be the one providing as natural tune values the collision ones. The performance in terms of aperture at injection should be carefully checked though [26].

Another aspect of the tune control is the choice of the value of injection tunes. In fact, the nominal working point was meant to cope with relatively large coupling at injection. The experience of Run I showed that coupling is well under control and using the collision tunes at injection does not seem to have any harmful effect as tested in MD studies [27]. Therefore, the flexibility of the proposed solution could be used to start the beam commissioning using the nominal tunes at injection and then to move to the collision tunes at top energy with a transition of the appropriate duration to ensure a gentle effect onto the orbit. Moreover, the tune transition could also overlap with part of the squeeze, but possibly avoiding to perform this gymnastics at too low β^* values.

Special Runs

The 2015 proton run features a non-negligible number of special runs requested by the Experiments. The situation in terms of optics configurations can be summarised as follows [28]:

- LHCf run: the preferred value of β^* ranges in the interval between 11 m and 20 m with a negative crossing angle.
- Van der Meer scans: the requests depend on the Experiments. ATLAS, CMS, and Alice aim at a β^* value around 20 m, while LHCb requests a β^* value in the interval between 30 m and 40 m. The crossing angle should be set to zero.
- High-beta run: the target value of β^* is 90 m.

The straightforward approach would consist in combining LHCf and Van der Meer scans in one group, leaving the high-beta run in a second group. This would mean two separate un-squeeze processes.

A first level of improvement could be having a common un-squeeze up to 20 m β^*. The high-beta un-squeeze would then branch off the common part.

A second level of improvement could be obtained by having a different injection process, in which β^* in IR1 and 5 would be around 20 m or 30 m. This would have the advantage of shortening the un-squeeze time required for the high-beta run. Of course, it should be stressed that the reduction of the un-squeeze time would call for the maximum possible value of β^* at injection, which should be compatible with aperture constraints. Such constraints, however, might reduce the overall gain in terms of un-squeeze time. On the other hand, this approach would require commissioning a new injection configuration, which would be an overhead for the corresponding physics run. Basically, it has been estimated that such an approach is worth only if the high-beta run is longer than a couple of weeks [29].

To note that another possibility to improve the efficiency would be to perform a combined ramp-and-squeeze [30], but this is not part of the baseline for the beginning of the 2015 run.

Triplets in IR2 and 8

Another point to consider is the management of the strength of the triplets in IR2 and 8. It is well known that the constraints from injection and its protection devices impose to run the triplet at higher-than-nominal gradients, i.e., at value of the order of 220 T/m [25] at 7 TeV if the optics is not changed during the ramp. The corresponding circuit rating imposes that the injection optics cannot be kept constant above energies of 6.78 TeV. Hence, beyond this threshold, ramp-and-squeeze gymnastics should be envisaged.

Another constraint is that the triplets' gradient has to be at its nominal value, i.e., 205 T/m, when the beams are put in collision. The reason behind this request is to avoid excessive heat load on the triplets due to the collision debris. This implies that the matching between the injection and the collision strength can be performed either as a separate process from the squeeze proper, the so-called pre-squeeze where the triplets' strength is reduced at constant β^* value, or simultaneously with the squeeze process.

The request of operating in collisions with the triplets at their nominal gradient is certainly well justified for the high-luminosity insertions IR1 and 5, but the luminosity for Alice and LHCb is much lower, at the level of 1-10×10^{29} $\mathrm{cm^{-2}s^{-1}}$ and 4-6×10^{32} $\mathrm{cm^{-2}s^{-1}}$, respectively, during Run II. Therefore, this point has been raised and a formal statement is expected from the MP3 [31]. A confirmation that a reduction of the triplets' strength is indeed possible would highly simplify the optics changes at least below 6.78 TeV.

STATUS OF VALIDATION STUDIES

As a follow up of the proposal presented in Ref. [4], the validation of Option-max has been launched, based on the comparison with Option-min of: dynamic aperture (DA) [32], cleaning efficiency, and machine protection [33]. At the same time, the proposed crossing scheme in IR8 has been evaluated in terms of aperture for injection failure scenarios [34].

The detailed numerical simulations of DA including several configurations, i.e., with or without beam-beam effects, with or without Landau octupoles, did not show any relevant difference between Option-min and Option-max. Also, the situation of beam aperture at injection for the new crossing scheme is compatible with the requirements.

On the other hand, the simulations of the cleaning efficiency did reveal differences between the two optics configurations. Moreover, the situation in terms of machine protection is made worse for Option-max by the imposed phase advance between the dump kicker and the TCT for Beam 2. To mitigate this, a certain reduction in β* reach should be accepted. All in all, the LMC decided that further clarification of the actual cleaning performance of Option-max should be carried out with dedicated measurements in 2015 and that this option would not have been the one for the initial beam commissioning. Given the relative comparison, the validation process essentially gave the green light to Option-min as suitable optics configuration for 2015, with the need of some further verifications for the case with β* =80 cm. Nonetheless, the LMC asked to proceed with the validation of Option-med in view of the benefits for instrumentation and transverse damper.

NEXT STEPS

The forthcoming weeks, four to eight, will see the optics activities focusing on two main fronts.

Validation of Optics-med

The validation task will be performed by assessing the performance in terms of DA, cleaning efficiency, and machine protection. For Beam 1, only the IR4 optics has changed and at constant IR phase advance. On the other hand, for Beam 2 the change of IR4 optics is also accompanied by a change of IR phase advance, which has been compensated in IR8 [35]. While the overall machine phase advance is kept constant, the phase relation between locations far away in the ring is changed with respect to Option-min. In particular, between IP1 and 5 the phase advance is different with respect to the nominal optics, thus requiring a careful check in particular in terms of beam-beam effects.

Preparation of Optics Database

The validation activities require preparation of the LHC optics database, which is also needed for the generation of the settings required for LHC operation in 2015.

The repository is maintained under afs, and a number of changes are in any case needed, such as the preparation of a new sequence extracted from the layout database, which is compatible with the actual configuration of the LHC ring after LS1, in particular including the non-conformities found [36]. Moreover, the overall structure of the directories will be reviewed taking into account the experience gained during Run I, in particular the need to simply the structure of the various directories and the naming convention used for the strength files, in view of making easier assembling the machine configuration when starting from the configuration of the individual insertions.

In addition, one should not forget that Option-med is built upon Option-min configuration, by adding the specific configuration for IR4 and IR8 (for Beam 2). Therefore, the configuration files for Option-min have to be generated, starting from the clean-up of the nominal optics files.

In particular, the squeeze of IR1, 2, and 5 has to be adapted to avoid that some trim quadrupoles running out of strength. The crossing schemes have to be reviewed by spreading the strength on the three MCBXs. The new crossing scheme in IR8 has to be implemented.

CONCLUSIONS

After the astonishing performance of the LHC during Run I, the machine underwent an important consolidation during LS1. Several optics options are at hand for Run II and in this paper the three main configurations for 2015 have been presented and discussed in detail.

These configurations differ for the amount of changes with respect to the nominal LHC optics as described in the LHC design report.

A number of more general aspects has been discussed, whose implementation does not depend on the final choice of the optics.

Validations studies are in progress to assess the suitability of each of the available configurations. The first step has been a direct comparison of Option-min and Option-max, which resulted in the decision of not starting the beam commissioning in 2015 with Option-max and to perform additional checks with beam during dedicated beam study periods. It is clear that in the meantime additional efforts will be devoted to the further analysis and understanding of the behaviour of option-max.

The next step will consist of assessing the performance of Option-med, which will then be presented at the LMC for approval as optics configuration for the 2015 run. In case of doubts Option-min will remain as fall back solution for the beginning of Run II.

ACKNOWLEDGEMENTS

Several discussions and invaluable input from G. Arduini, R. Bruce, H. Burkhardt, B. Dehning, B. Gorini, W. Höfle, J. Jowett, M. Lamont, R. de Maria, E. Meschi, D. Mirarchi, S. Redaelli, T. Risselada, R. Tomas, and J. Wenninger are warmly and gratefully acknowledged. S. Fartoukh deserves a special thank as he has been the driving force of most of the activities covered in this paper.

REFERENCES

[1] R. Bruce, G. Arduini, S. Fartoukh, M. Giovannozzi, M. Lamont, E. Métral, T. Pieloni, S. Redaelli, J. Wenninger, “Baseline Machine Parameters and Configuration for 2015”, these Proceedings.

[2] S. Fartoukh, “LHCb crossing scheme for Run II and Run III”, presentation given at the 167th LMC meeting, 19 June 2013.

[3] S. Fartoukh,. “Optics change requests for Run II and possible options for 2015”, presentation given at the 18th LS1 LBOC meeting, 29 April 2014.

[4] S. Fartoukh, “Optics for 2015”, presentation given at the 179th meeting of the LMC, 30 April 2014.

[5] T. Risselada, private communication, 2014.

[6] J. Jowett, M. Schaumann, “Optics for the 2015 Pb-Pb run”, presentation given at the 17th LS1 LBOC meeting, 15 April 2014.

[7] R. de Maria, private communication, 2014.

[8] G. Trad, "IR 4 Change of Optics: Implications on beam size measurements", presentation given at the 17th LS1 LBOC meeting, 15 April 2014.

[9] F. Roncarolo, "LHC Beam Instrumentation Status Changes and Plans for 2014", talk given at the 179th meeting of the LMC, 30 April 2014.

[10] W. Höfle, "Transverse Feedback changes Status and Plans for 2014", presentation given at the 173rd LMC meeting, 5 February 2014.

[11] W. Höfle, G. Kotzian, D. Valuch, "PU Choices for ADT Plans for Run 2", presentation given at the 17th LS1 LBOC meeting, 15 April 2014.

[12] S. Fartoukh, "New IR6 Optics with Optimized Phase Between MKD and TCSG", presentation given at the LBOC meeting, 31 January 2012.

[13] B. Goddard, "Check of LBDS for New IR6 Optics", presentation given at the LBOC meeting, 31 January 2012.

[14] S. Fartoukh, "Achromatic telescopic squeezing scheme and application to the LHC and its luminosity upgrade", Phys. Rev. Spec. Top. Accel. Beams 16 (2013) 111002.

[15] S. Fartoukh, G. Vanbavinckhove, M. C. Alabau Pons, R. Alemany Fernandez, R. Assmann, A. Butterworth, M. Giovannozzi, B. Goddard, P. Hagen, W. Höfle, D. Jacquet, R. de Maria, R. Miyamoto, G. Müller, S. Redaelli, R. Steinhagen, M. Strzelczyk, R. Suykerbuyk, E. Todesco, R. Tomás, W. Venturini, J. Wenninger, F. Zimmermann, "The Achromatic Telescopic Squeezing (ATS) MD part I", CERN-ATS-Note-2011-033 MD, 2011.

[16] S. Fartoukh, M. Lamont, R. De Maria, R. Miyamoto, G. Müller, L. Ponce, S. Redaelli, M. Strzelczyk, R. Tomás, G. Vanbavinckhove, J. Wenninger, M. Albert, R. Giachino, M. Giovannozzi, B. Goddard, P. Hagen, W. Höfle, V. Kain, A. Macpherson, L. Normann, G. Papotti, R. Steinhagen, D. Valuch, D. Wollman, "The Achromatic Telescopic Squeezing (ATS) MD part II", CERN-ATS-Note-2011-060 MD, 2011.

[17] S. Fartoukh, R. Tomás, B. Goddard, W. Höfle, D. Jacquet, G. Kruk, M. Lamont, R. de Maria, R. Miyamoto, G. Müller, M. Pojer, L. Ponce, S. Redaelli, N. Ryckx, R. Steinhagen, M. Strzelczyk, G. Vanbavinckhove, J. Wenninger, "The Achromatic Telescopic Squeezing (ATS) MD part III", CERN-ATS-Note-2011-132 MD, 2011.

[18] S. Fartoukh, V. Kain, Y. Levinsen, E. Maclean, R. de Maria, T. Persson, M. Pojer, L. Ponce, P. Skowronski, M. Solfaroli, R. Tomás, J. Wenninger, "The 10 cm beta* ATS MD", CERN-ATS-Note-2013-004 MD, 2013.

[19] S. Fartoukh, "First demonstration with beam of the Achromatic Telescopic Squeezing (ATS) scheme", in Chamonix 2012 Workshop on LHC Performance, Chamonix, France, 6 - 10 Feb 2012, pp.128-134.

[20] S. Fartoukh, "Towards the LHC Upgrade using the LHC well-characterized technology", CERN-sLHC-Project-Report-0049, 2010.

[21] S. Fartoukh, "Breaching the Phase I Optics Limitations for the HL-LHC", CERN-sLHC-PROJECT-Report-0053, 2011.

[22] S. Fartoukh, "An Achromatic Telescopic Squeezing (ATS) Scheme For The LHC Upgrade", IPAC11 Proceedings.

[23] S. Fartoukh, private communication, September 2014.

[24] J. Wenninger, private communication, September 2014.

[25] O. Brüning, P. Collier, P. Lebrun, S. Myers, R. Ostojic, J. Poole, P. Proudlock, (eds.), "LHC Design Report , v.1: the LHC Main Ring", CERN-2004-003-V-1. 2004.

[26] S. Fartoukh, private communication, September 2014.

[27] R. Calaga, D. Jacquet, E. Métral, R. Miyamoto, N. Mounet, L. Ponce, S. Redaelli, B. Salvant, F. Schmidt, R. Steinhagen, R. Tomas, G. Vanbavinckhove, F. Zimmermann, "Collision tunes at injection and ramp", ATS-MD-Note- 2011-034.

[28] B. Gorini and E. Meschi, private communication, September 2014.

[29] J. Wenninger, private communication, September 2014.

[30] H. Burkhardt and J. Wenninger, private communication, September 2014.

[31] A. Siemko and A. Verweij, private communication, September 2014.

[32] S. Fartoukh, "Post-LS1 optics development and Tracking results", presentation given at the 188th LMC meeting, 3 September 2014.

[33] R. Bruce, S. Fartoukh, D. Mirarchi, S. Redaelli, "Status of validation of 2015 ATS optics for collimation", presentation given at the 188th LMC meeting, 3 September 2014.

[34] J. Uythoven, "Apertures in the case of injection failures including the new IR8 crossing scheme", presentation given at the 188th LMC meeting, 3 September 2014.

[35] S. Fartoukh, private communication, September 2014.

[36] A. Verweij, "Solved and remaining NC's in the SC circuits", these proceedings.

NOMINAL CYCLE AND OPTIONS

M. Solfaroli Camillocci, M. Lamont, J. Wenninger, CERN, Geneva, Switzerland

Abstract

During Run 2 the LHC operation will be based on the experience gained in Run 1. However the LHC will be operated near to its design energy. Many operational configurations can be considered to improve efficiency and reduce the impact of the longer time required by each operational phase. The expected changes in the magnetic model and the impact of the data updates with the corrections calculated during LS1 are presented together with a general overview of the operational cycle, including time, challenges and possible improvements of each phase.

THE MAGNETIC MODEL CHANGES

LHC operation requires the calculation of the required currents of the magnet circuits for all phases of the cycle. These settings are based on a parametric model whose coefficients are calculated from magnetic field measurements. The core of the so-called FIDEL model is already present in LSA and has been used extensively during Run 1. Due to improvements of the model, incongruences discovered, and changes implemented during LS1, some modifications to the parametric model need to be implemented for Run 2. These changes should improve the machine quality. The recalculation of the MQY and MQM warm to cold data correlation will impact the field quality for some magnets, resulting in lower local magnetic errors. The impact of this change has been already evaluated with a machine study during Run 1. The new data also contains the hysteresis implementation for MSF/MSD magnets, which could potentially solve some differences noticed during Run 1 between the measured and calculated chromaticity. The geometrical contribution to the field quality of the exchanged dipole magnets has been also re-calculated; the effect of this change should nevertheless be transparent for machine operation.

Some changes in behavior are also expected because of the energy increase:

- The tune decay amplitude at injection will increase and the snapback amplitude will increase accordingly (to be carefully measured and corrected) [1][2][3];
- The decay amplitude at flat-top will likely become negligible (to be measured);
- The calibration curves for the different classes of magnet have to be reviewed;
- Some magnets (MB, MQD/F and MQX) will enter the saturation regime. Nevertheless, no surprises are expected, as saturation is implemented in FIDEL.

Maximum energy	4 TeV	6.5 TeV
Tune	-0.022	-0.035
b3	0.4	0.5 – 0.6

Table 1: Expected tune and b3 decay amplitude at 450 GeV

THE NOMINAL CYCLE

Precycle

All LHC magnets (both superconducting and resistive) need a pre-cycle to ensure reproducibility of the magnetic field. This means powering the magnets up to the nominal operational current, down to below injection current, and then to injection current before injecting the beam. The level of current and duration of the flat-top needed vary considerably from one type of magnet to another. The strategy for precycle that was established for the first LHC run [4] will be used also for the second one:

- MB: Ramp to nominal current, 600 s plateau, ramp-down
- MQMs: Ramp to maximum operational current, 1000 s plateau, ramp down
- MQYs: Ramp to maximum operational current, 300 s plateau, ramp down
- Magnets with negligible decay (MBRs, MQD/F, MQX,…): Ramp to maximum operational current, 300 s plateau, ramp down
- Magnets with no decay: Differences according to uni/bi-polar PC, and optical functions
- Warm magnets: Differences according to uni/bi-polar PC, several cycles

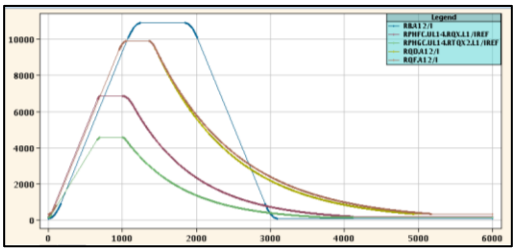


Figure 1: Precycle at 6.5 TeV

Due to the much higher energy at which the main circuits will be operated during Run 2 the precycle for the main quadrupoles is potentially the longest. This is due to the fact that these circuits have a 1-quadrant power converter - the current cannot be driven down – and has to decay via the L/R time constant of the circuit. The length of a precycle for the quadrupole circuit will be around 5200 sec. In order to increase machine efficiency, some improvements are foreseen; however the main quadrupoles and potentially the inner triplets will define the length of the precycle.

Injection

The injection process is less affected by the energy change. Many parameters and processes that proved to be efficient can be used in the same way. The BBQ gating and ADT un-gating on the first 12 bunches, for example, proved to be a good solution to ensure good signal-to-noise for tune measurements. Setting the tune work-point at .28/.31 also allows reasonable measurement and control.

Nevertheless, some changes are expected due change in energy and beam intensity. The highest energy plateau will require careful measurements and parameterization of b2 and b3 to ensure good response of the magnetic model and reproducibility. The use of 25 ns beams will result in higher beam intensity, larger emittance and higher intensity per injection.

Besides all this, the recently discovered weakness of the SPS high energy dump will required careful SPS setup that might have a potential impact on LHC operation. The vacuum situation around ALICE after the LS! interventions and the TDI consolidation will have to be checked to assess whether the de-coupled injection of B1 and B2 (as done during Run 1 to reduce the background) is still required.

Ramp

The ramp process has been well optimized during Run 1, passing from an initial length of 1400 sec (to 3.5 TeV) to 770 sec (to 4 TeV). The ramp to 6.5 TeV will take 1200 sec. The large gain has been obtained thanks to two main changes: a faster start and the separation of the settings of all system synchronized with energy from the spool pieces. The former was possible as the effects of the snapback were mitigated by a very careful measurement and efficient parameterization of the magnetic model. The latter because the spool pieces correctors have settings longer than the other energy synchronized systems to compensate the flat-top decay.

Finally the highest energy foreseen for Run 2 requires ramping the octupole correctors to their maximum strength.

Flat-top

During Run 1 the instability of the tune feedback during the ramp due to a complex tune spectrum forced the re-adjustment of the tune, once the ramp was completed. This was done by adjusting the current of the tune correction circuits with respect to a reference. This manipulation proved to be effective. During Run 2, if still needed, it will be automated.

Squeeze

Several changes are foreseen. The LHC will be initially commissioned to 80 cm beta* in IP1/IP5, 10 m in IP2 and 10 to 3 m in IP8. Nevertheless during the commissioning phase test will be performed to prepare the operation up to 40 cm.

Some of the intermediate optics that were removed to reduce the overall length will be reinserted to optimize beam parameter behavior.

As discussed in [5] the tune change during the squeeze can be performed using the quadrupole trim correctors rather than the matching quadrupoles. De-coupling the two operations provides flexibility - the tune change could also be done after the squeeze, improving the resolution of the tune signal in the process.

At 6.5 TeV there is still no need for initial pre-squeeze of IP2 and IP8 as the triplet gradient limit is only reached at 6.78 TeV.

Collisions

Three main beta* collision configurations are considered for Run 2 :

- Low: between 40 and 80 cm
- Medium: 20 m (30-40 m for LHCb) for LHCf runs and vdM scans
- High: 90 m

The collision process has been optimized during Run 1 and is not expected to change (little gain might come from the performance increase of the RCBX correctors)

The separation between collisions in IP1/IP5 and IP2/IP8 proved to reduce beam-beam effects, thus increasing the beam stability. For this reason the strategy will be maintained.

COMBINED RAMP AND SQUEEZE

Operation at 6.5 TeV requires a 1200 sec long ramp. It might be possible to perform some optics changes in the ramp to reduce the time needed for the squeeze (Combined Ramp and Squeeze). These changes should be performed during the linear part of the ramp. Assuming an optics change to 3 m beta* (Run 1 measurements show that large beta beating arises below this value) would result in overall gain of 430 sec per LHC fill.

Despite the problem discussed in [6], settings for CRS have been generated and prove the feasibility of the process. Machine development studies performed in 2012 demonstrated that both optics measurements and loss maps can be also performed during the ramp. The new tertiary collimators equipped with BPMs could also ease the problem of closed orbit variations from simultaneous crossing angle reduction and bump shape change.

CONCLUSIONS

Run 2 start-up machine configuration will be similar to the one used during Run 1, with an identical operational cycle (but to 6.5 TeV). Some minor changes have to be implemented to the magnetic model. These should have a small but positive impact on the beam quality.

Many changes are possible in the near future including: smaller beta* and CRS. The latter seems to be possible and has the potential to increase the LHC efficiency.

Some additional studies will be done during machine development periods, to finally assess its feasibility and integrate it in the LHC operation at a later stage.

ACKNOWLEDGMENT

The authors wish to express their sincerest gratitude for the useful discussions to all people involved in LHC operation and FIDEL team.

REFERENCES

[1] Aquilina. N. et al.”The FiDeL model at 7 TeV” CERN-ACC-2014-0092

[2] Aquilina N. “Expected and measured behaviour of the tune in the LHC operation at 3.5 TeV” CERN-ATS-2012-196

[3] Aquilina N. et al “The Magnetic Field Model of the Large Hadron Collider: Overview of Operation at 3.5 and 4 TeV” CERN-ATS-2012-195

[4] L. Bottura et al. “Pre-cycles of the LHC magnets during operation” CERN-ATS 2010-174

[5] M. Giovannozzi “Optics options for the 2015 LHC run”, these proceedings.

[6] J. Wenninger et al. “The LHC nominal cycle, precycle and variations in 2015”, Proceedings of the 5th Evian workshop pp. 43-48

SCRUBBING: EXPECTATIONS AND STRATEGY, LONG RANGE PERSPECTIVE

G. Iadarola* and G. Rumolo (CERN, Geneva)

Abstract

Electron cloud buildup simulations and machine experience during Run 1 showed that electron cloud effects could significantly limit the performance of the LHC when operating with 25 ns bunch spacing. Beam induced scrubbing will have to be used to lower the Secondary Electron Yield (SEY) of the beam chambers and therefore reduce electron cloud induced pressure rises, heat load and beam degradation. This contribution reviews the experience accumulated on electron cloud effects during Run 1 and define a possible scrubbing strategy to allow operation with 25 ns beams in 2015. Several measures taken during LS1 should allow for an improved scrubbing efficiency compared with Run 1. Moreover, the potential of using a dedicated scrubbing scheme based on the doublet beam, following the promising SPS tests in 2012, is described and analyzed. To conclude, possible alternatives of operation scenarios are defined, which will depend on the degree of success of the scrubbing runs.

INTRODUCTION

During Run 1, electron cloud effects proved to have an important impact on the performance of the LHC, especially when operating the machine with beams with 25 ns bunch spacing.

Before 2011, while the LHC was producing physics with 150 ns spaced beams, electron cloud effects could be mainly seen in the interaction regions when both beams were circulating in the machine. Only when 50 and 75 ns spaced beams were first injected into the LHC, electron cloud effects became visible with single beam. In 2011, the LHC evidently suffered from electron cloud both at the beginning of the 50 ns run and then later, during all the machine study sessions with 25 ns beams. An initial scrubbing run with 50 ns beams, which took place at the beginning of April 2011 [1], could scrub the beam chambers just enough as to allow the LHC to move into physics with 50 ns beam and guarantee safe operation at both 450 GeV and 3.5 TeV. Further scrubbing was later achieved by using trains of 25 ns beams. The first injection attempts of this type of beams were hindered by severe electron cloud effects in terms of heat load in the arc screen, emittance growth of the bunches located at the tails of 24-bunch trains [2] and coherent instabilities at the tails of 48-bunch trains leading to dumps due to fast beam losses or large orbit excursions [3]. As LHC got gradually further scrubbed, 72-bunch trains of 25 ns beams could be injected with high chromaticity settings, reaching 2100 bunches for Beam 1 and 1020 for Beam 2. Though initially these beams suffered heavy degradation from electron cloud, a considerable amount of additional scrubbing could be achieved. The maximum Secondary Electron Yield (SEY or $\delta_{\max}$), on the screen of the arc dipoles, as estimated from PyECLOUD simulations, decreased from a value of about 2.1 at the end of the 50 ns scrubbing run to 1.5. By the end of 2011, trains of 72 bunches with 25 ns spacing exhibited much reduced degradation with respect to the first injections, although both their lifetime and emittance evolution still indicated the presence of a significant amount of electron cloud in the LHC [4]. The top plot of Fig. 1 shows the calculated electron cloud induced heat load in the arc dipole screen as a function of $\delta_{\max}$ for both 25 and 50 ns beams. From the two curves it is clear that, while a $\delta_{\max}$ value of 2.1 can be sufficient to ensure low electron cloud operation with 50 ns beams, the achieved value of 1.5 is still not enough as to completely suppress the electron cloud in the arc dipoles with 25 ns beams.

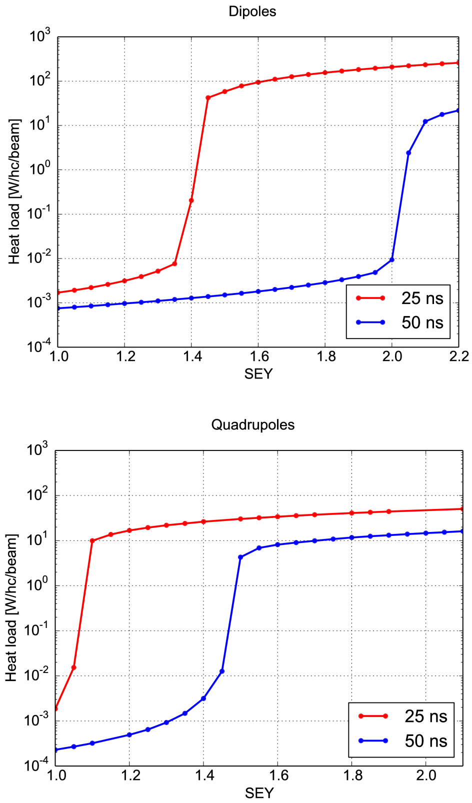


Figure 1: Calculated electron cloud induced heat load on the arc screen (top: dipole, bottom: quadrupole) as a function of $\delta_{\max}$ for both 25 (red)and 50 ns (blue) beams.

---

* Giovanni.Iadarola@cern.ch

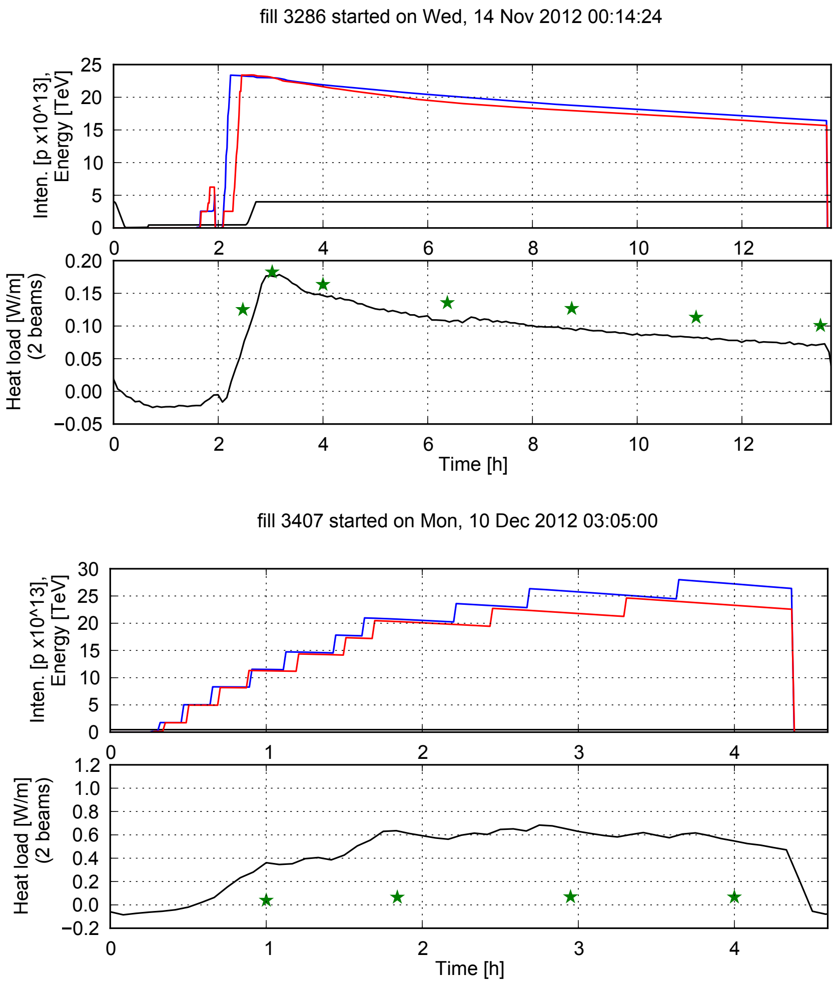


Figure 2: Top plot: Typical 50 ns fill with measured heat load in the arc beam screen and calculated values from the beam screen impedance model (green stars). Bottom plot: Scrubbing fill with 25 ns beam with measured heat load in the arc beam screen and calculated values from the beam screen impedance model (green stars).

The bottom plot of Fig. 1 depicts the calculated electron cloud induced heat load on the arc quadrupole screen as a function of $\delta_{\max}$ for both 25 and 50 ns beams. Due to the length ratio between arc dipoles and quadrupoles ($\approx$15), as long as the electron cloud in the dipoles is strong enough, the dominant contribution seen in the measured heat load comes from the dipoles and no conclusion can be made on the $\delta_{\max}$ of the quad screens. The quadrupole heat load becomes significant in the balance only when the $\delta_{\max}$ of the dipole screen has reached down the knee of the heat load curve (i.e. for values below 1.5 with 25 ns beams).

Thanks to the margin gained with the 25 ns beams in 2011, operation with 50 ns in 2012 was smooth and electron cloud free. It was only during the scrubbing run in December 2012, when the LHC was filled with 25 ns beams (up to 2748 bunches per beam) and reached the record intensity of 2.7×10^{14} p stored per beam, that heat load, emittance growth at the tails of the trains and poor beam lifetime indicated again the presence of a strong electron cloud with this mode of operation. However, a clear improvement in the electron cloud indicators over the first 70 hours was observed, followed by a sharp slow-down of the scrubbing process. The emittances of the bunches at the tails of the trains were blown up during the injection process, especially for sufficiently long bunch trains. The electron cloud continued to be present also during a few test ramps to 4 TeV and the two days of pilot 25 ns physics run and exhibited an important dependence on energy. A detailed summary of the observations and our present degree of understanding is presented in [5] summarized the next sections.

LESSONS LEARNT IN RUN 1

Both the MDs with 25 ns beams in 2011 and a relatively little deconditioning over the 2011-2012 end-of-year technical stop (EYTS) were the basic reasons why the LHC could be operated with 50 ns beams throughout the 2012 proton-proton run without electron cloud in the arcs [6]. This can be concluded from Fig. 2, top plot, which displays the evolution of the heat load in the arc screen measured during a typical 50 ns physics fill (solid black line) together with the calculated values of power loss obtained summing the contribution from impedance and that from synchrotron radiation (green stars). The agreement within less than 10% between calculated and estimated values shows that in this case no additional contribution to the heat load of the arc beam screen is expected from electron cloud. However, when the 25 ns beam was injected into the LHC in 2012 (notably during the scrubbing run, 6 – 8 December, 2012), the electron cloud returned, which manifested in a heat load in the arcs becoming one order of magnitude larger than the values expected from the theoretical calculation based on impedance and synchrotron radiation. This is depicted in the bottom plot of Fig. 2, in which both the measured and calculated heat loads are plotted for a typical 25 ns scrubbing fill.

Distribution of electron cloud in the LHC arcs

As was mentioned in the introduction, a decreasing trend in the measured heat load as well as an improvement of the beam quality and lifetime were observed in the first part of the 2012 scrubbing run, while any improvement tended to become marginal in the later scrubbing phases [6]. This observation suggested that the process of beam scrubbing was saturating in the arcs, in the sense that any further little improvement would require increasingly longer running times with 25 ns beams.

Based on the simulated heat load curves in dipoles and quadrupoles shown in Fig. 1, an attempt was made to interpret the observed saturation of the scrubbing process and thus envisage possible solutions for Run 2. In particular, assuming the different SEY thresholds in dipoles and quadrupoles discussed above, the behaviour of the electron cloud evolution during the scrubbing run could be compatible with the following scenario:

1. The SEY in the dipole beam screen might be coming asymptotically closer to the threshold value for electron cloud build up leading to indeed much lower electron cloud in the dipole chambers, but not yet full suppression;
2. The SEY in the quadrupole beam screen, though probably scrubbed to a similarly low value as the dipole one, is still high enough to cause strong electron cloud in the quadrupole chambers.

Since in the arc cells it is not possible to disentangle the contribution to the heat load given by the dipole chamber (total length 14.2 m×3 per half cell) from that given by the quadrupole chamber (total length 3 m per half cell), the only way to have an indication on the plausibility of the above scenario is to look into the heat load in the so-called Stand Alone Modules (SAM). These include several matching quadrupoles and separation dipoles situated the Insertion Regions (IRs). Several matching quadrupoles have their own cooling circuits and their heat loads can be independently evaluated. The separation dipoles D3 at left and right of point 4 (D3L4 and D3R4) are the only dipoles to be equipped with independent cooling circuits. Other matching quadrupoles are paired with the close-by separation dipoles in one single cooling circuit. These are called semi-SAMs and their heat load would still come from the combination of a dipole and a quadrupole (though with different length ratio than in the arcs). A full inventory of SAMs and semi-SAMs in the LHC can be found in [7].

Figure 3 shows the evolution of the heat load per unit length at the beam screen of the matching quads Q5's (taking the average of the values measured in Q5 left and right of points 1 and 5) and that at the beam screen of the separation dipoles D3's (taking the average of the values measured in D3 left and right of point 4) over a 25 ns fill towards the end of the scrubbing run.

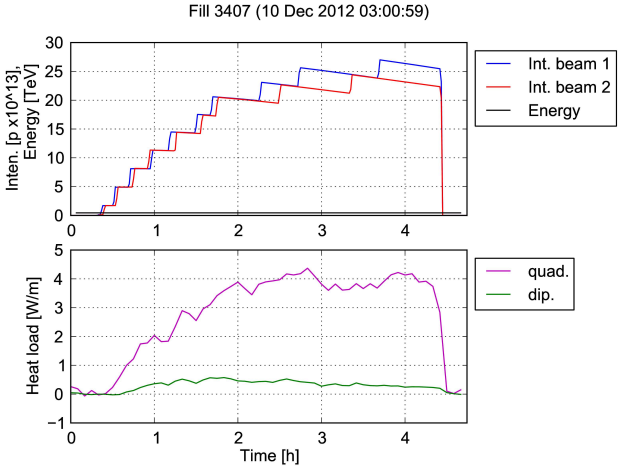


Figure 3: Heat load per unit length (W/m) measured in the matching quadrupoles Q5 on both sides of the IRs 1 and 5 (purple, average among the four magnets) and in the separation dipoles D3 of the IR 4 (green, average between the two magnets) over one of the last fills of the 2012 scrubbing run. Beam currents for both beams are shown in the upper plot.

This plot strongly supports the scenario presented above. First of all, the specific heat load in the quadrupole beam screen exceeds by over one order of magnitude that in the dipole beam screen. Considering the factor about 15 difference in length, this would translate in basically equivalent contributions to the heat load from the dipoles and the quadrupole in an arc half cell. Secondly, the heat load in the dipoles exhibits a decay with the beam degradation even despite new injections, while that in the quadrupoles hardly decreases with deteriorating beam conditions. This suggests that, while the SEY of the dipole beam screens could be close to the electron cloud build up threshold value, that of the quadrupole beam screens is still far from it. The scenario of an electron cloud close to suppression in the dipoles at 450 GeV means that an electron cloud enhancing technique could be applied to achieve full scrubbing in the dipoles (see following section on the doublet beam), although a significant amount of electron cloud could still survive in the quadrupoles.

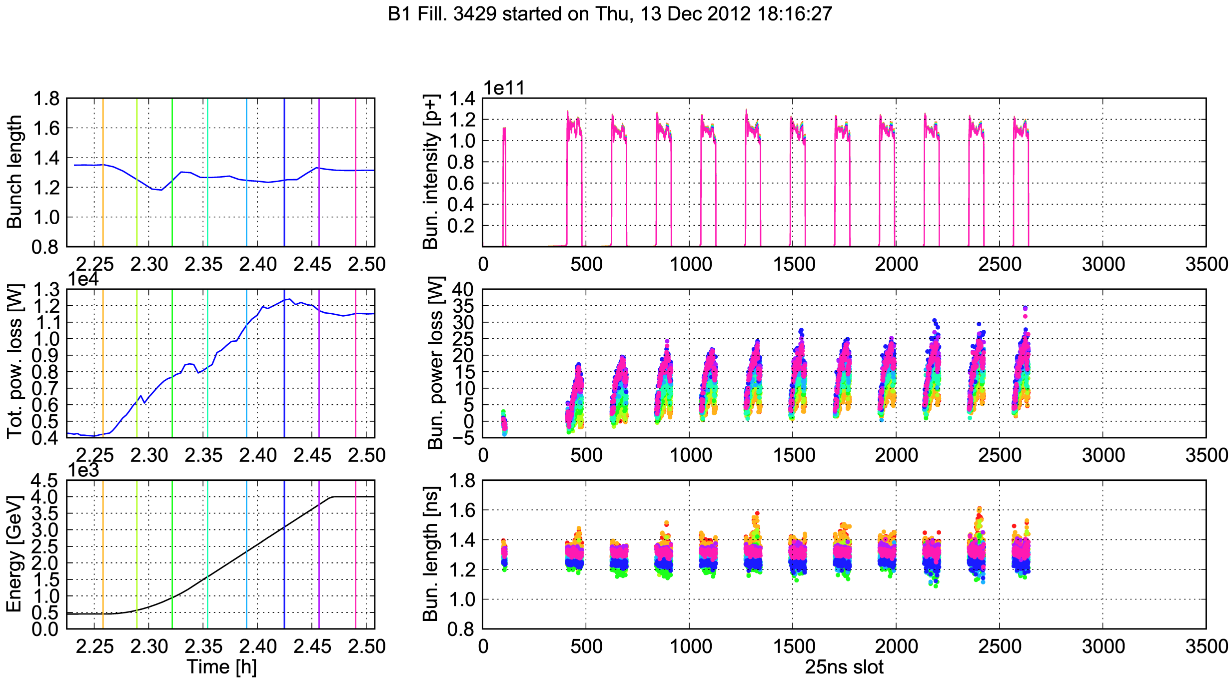


Figure 4: Beam energy and bunch-by-bunch energy loss measurements for beam 1 during the energy ramp of a fill with about 800 bunches with 25 ns spacing. The different traces in the right plot correspond to different times indicated by vertical bars in the left plot.

Energy dependence of the electron cloud in the arcs and effect on the beam

After the 2012 scrubbing run, increasing numbers of bunches of 25 ns beam were ramped to 4 TeV over several subsequent fills. Both heat load in the arcs and beam energy loss measurements from the bunch-by-bunch synchronous phase shift [8] showed a sharp increase over the ramp, which would be consistent with a growing electron cloud with the beam energy. An example of beam energy loss behaviour for an energy ramp with 800 bunches distributed in equally spaced trains of 72 bunches is fully displayed in Fig. 4. The plots on the left side share the same time axis and represent, from bottom to top, the energy ramp, the sum of the bunch-by-bunch energy loss as estimated from the synchronous phase shift and the average bunch length. At the eight time cuts highlighted with coloured vertical bars, on the right hand side the snapshots of the bunch-by-bunch intensity, energy loss and bunch length are depicted from top to bottom using the same colour convention. A steady increase of beam energy loss, which reveals an increasing electron cloud activity, is clearly visible along the energy ramp. One possible explanation of this behaviour is that the electron cloud enhancement is first triggered by the bunch shortening occurring at the beginning of the ramp and is later sustained by the photoelectrons, whose rate of production becomes significantly higher than that due to gas ionisation only at around 2 TeV. The fact that the electron cloud is most likely responsible for this increase is also confirmed by the snapshots of the bunch-by-bunch energy loss along the ramp. The bunches suffering the highest enhancement of energy loss are those located towards the end of each bunch train, while those at the beginning of the trains even at 4 TeV keep losing the same amount of energy as at 450 GeV. The pattern of the energy loss is also reminiscent of an electron cloud build up with the rise over one train to a defined saturation value and basically little memory between trains (only visible in the slower rise of the first train, probably due to the electron cleaning effect of the 12-bunch train). Hardly any sign of beam loss or anomalous lengthening or shortening for selected bunches can be spotted along the ramp, which leads to the encouraging conclusion that the enhanced electron cloud, probably thanks to the increasing beam energy, is not detrimental to the beam (although it is responsible for a fourfold increase of the heat load in the arcs).

One question concerning the electron cloud enhancement over the energy ramp is again whether it is localised in some specific elements of the LHC. In principle, a way to determine its distribution would be applying a similar approach to that shown in the previous section to disentangle the contributions to heat load from dipoles and quadrupoles in the arcs. Figure 5 shows the evolution of the heat load per unit length at the beam screen of the matching Q5's (average of the values measured left and right of points 1 and 5) and that at the beam screen of the separation dipole D3's (average of the values measured left and right of point 4) over the injection and ramp phases of the 25 ns fill already discussed for Fig. 4. It is clear that, while at 450 GeV the heat load in the quads is more than one order of magnitude larger than the one in the dipoles, the ramp causes an enhancement of the heat load only in the dipoles. This is not surprising, because the SEY in the dipoles is close to

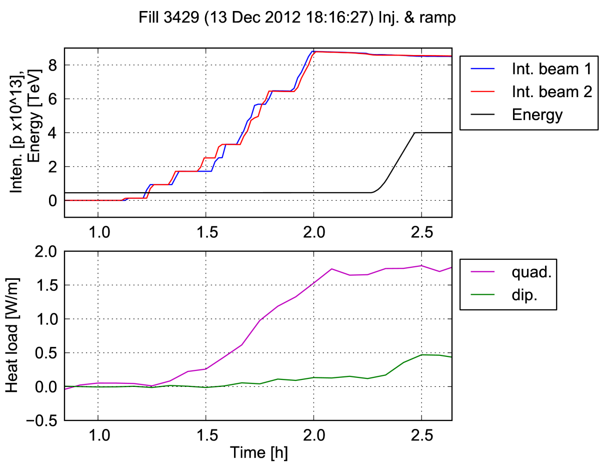


Figure 5: Heat load measured in the matching quadrupoles Q5 on both sides of the IRs 1 and 5 (purple, average among the four magnets) and in the separation dipoles D3 of the IR 4 (green, average between the two magnets).

the build up threshold and the electron cloud there is most sensitive to the bunch shortening and/or enriched seeding from photoelectrons, while these effects would play only a marginal role if the SEY had been far above this threshold (e.g. in the quadrupoles). At 4 TeV, the specific heat load measured in D3 becomes only about one third of that measured in the quadrupoles. By merely applying these values to the arc dipoles and quadruples, and scaling by their lengths, one finds that, while at 450 GeV arc dipoles and quadrupoles would contribute about equally to the measured heat load, at 4 TeV the integrated contribution of the dipoles becomes again dominant and at least fivefold that of the quadrupoles. The fact however that this heat load remains then nearly constant over the whole fill duration (8 hours of 4 TeV store) [5, 6] also indicates that the SEY of the dipole screen has entered a region in which the increase of scrubbing flux associated to the electron cloud enhancement is not sufficient to impart a significant acceleration to the scrubbing process.

The beam behaviour at 4 TeV has been analysed through the evolution of the bunch-by-bunch transverse emittance over the stores of 25 ns beams. The store discussed above in this subsection was not a physics fill and the beams were not squeezed nor brought into collision. Therefore, the only emittance measurements available at 4 TeV for this store were those from the Beam Synchrotron Radiation Telescope (BSRT), which unfortunately worked only for Beam 1 at the time of the 2012 scrubbing run. A look at the snapshots taken over the eight hours during which the beam was stored in the LHC reveals that only a small emittance growth can be measured, affecting uniformly all bunches of the train and therefore not ascribable to electron cloud effects [6]. Later on in the 2012 run, three physics fills with 25 ns beams took place. For these fills, the bunch-by-bunch emittance evolution could be reconstructed from the luminosity in ATLAS and CMS, providing a very reliable measurement all over the whole length of the physics store. A very interesting case was the last physics fill of the 25 ns pilot physics run, with 396 bunches per beam distributed in trains of 2 × 48 bunches collided for over six hours. Figure 6 shows seven snapshots of the bunch-by-bunch emittances from the moment of declaration of stable beams (time 0h) to six hours later (6h). The emittance pattern over the trains clearly exhibits the imprint of the electron cloud, with typically growing emittances towards the tails of the trains. The zoom on the second train displayed in the picture, however, allows us to spot even more interesting features of the emittance distribution and its evolution. Firstly, the electron cloud patten is present already from the first snapshot (i.e. at time 0h), meaning that the shape was created at injection energy (this could be also confirmed by means of BSRT measurements on Beam 1). Secondly, the emittance growth over the fill duration is such that the electron cloud pattern tends to even out, which suggests a blow up rate that is larger for the first bunches of the trains (with lower initial emittances) and lower for those at the tails (with higher initial emittances). This observation is consistent with an emittance growth mechanism at 4 TeV certainly different from electron cloud and emittance dependent. To summarise, the available 2012 beam observations seem to point to the electron cloud as a fast degrading effect for the beam at 450 GeV but not the main determinant of the beam quality at 4 TeV.

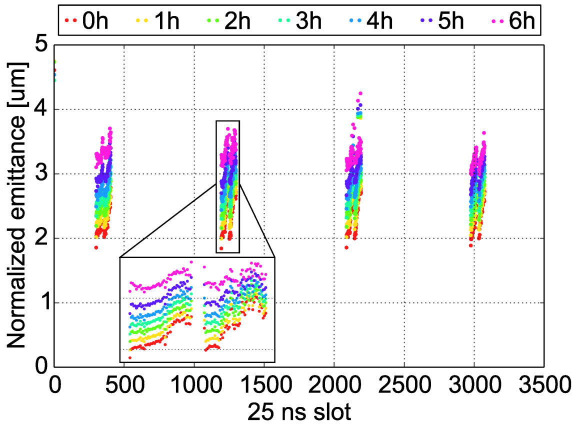


Figure 6: Bunch-by-bunch transverse emittances estimated from luminosity at the ATLAS experiment during a fill with 396 bunches with 25 ns spacing. Different traces correspond to different moments during the store.

Extrapolation to 2015 beam parameters

Before describing the roadmap of the 2015 scrubbing run, which should enable operation of LHC at 6.5 TeV with 25 ns beams, it could be useful to extrapolate the expected heat load in the arcs in 2015 if we run in the same conditions as we had after the 25 ns scrubbing run of December 2012. This exercise is fully summarised in Table 1.

The reference fill for this extrapolation is the one of eight hours with 800 bunches in trains of 72, which was dis-

	Measured in 2012 with 800 b. at 4 TeV	Rescaled to 2800 b.	Effect of tighter filling scheme	Effect of higher energy (6.5 TeV)
Dipoles	40 W/hcell	(×3.4) 136 W/hcell	(×2) 272 W/hcell	(×1.6) 435 W/hcell
Quadrupoles	5 W/hcell	(×3.4) 17 W/hcell	(×1) 17 W/hcell	(×1) 17 W/hcell
Total	45 W/hcell	153 W/hcell	289 W/hcell	450 W/hcell

Table 1: Expected distribution of the heat load in the arc dipoles and quadrupoles for the 25 ns 8 hours store with 800 bunches (reconstructed from 2012 measurements in the first column, rescaled to full machine in the second column, rescaled for the packed filling scheme in the third column and rescaled to 6.5 TeV in the fourth column)

cussed in the previous subsection. Assuming that the measured heat load in the arcs of 10 W/(half cell) after the end of the injection of both Beam 1 and Beam 2 is attributable in equal parts to dipoles and quadrupoles and that the increase to 45 W/(half call) with the ramp only comes from the dipoles, one can conclude that, after the scrubbing of December 2012, the heat load of 800 bunches at 4 TeV would be distributed 11% on the quadrupole beam screen (5 W/(half cell)) and the remaining 89% on the dipole beam screen (40 W/(half cell)). To extrapolate to 2015, we need to first rescale both these numbers by 2800/800 to account for the increased number of bunches (full machine). Then, we can further apply a factor 2 to the value in the dipoles as an effect of the more packed filling pattern and a factor 1.6 as an effect of ramping to 6.5 TeV instead of 4. For the quadrupoles, given the experience of 2012, we would expect neither the filling scheme nor the beam energy to significantly affect the electron cloud build up (heat load scaling factor 1). Table 1 shows that, after applying these scalings and regrouping together the heat load from dipoles and quadrupoles with full machine at 6.5 TeV, we find a value of 450 W/(half cell), which exceeds by almost a factor three the available cooling power of 160 W/(half cell) available in the LHC at 6.5 TeV.

In conclusion, even assuming that we can live with the beam degradation induced by electron cloud at injection, it would be impossible to fill LHC with a standard 25 ns beam, because the cryogenic system would not have enough power to cope with the induced heat load in the arcs. A strategy to achieve more scrubbing of the dipole beam screens (ideally, full suppression of the electron cloud in the dipoles) is therefore necessary to guarantee 25 ns operation for the LHC during Run 2.

SCRUBBING IN 2015

The experience of LHC Run 1 has shown that the electron cloud can potentially limit the achievable performance with 25 ns beams mainly through both beam quality degradation (transverse emittance blow-up, poor lifetime) at low energy and intolerable heat load on the arc beam screens at high energy. To avoid this scenario, a scrubbing program aiming at a significant mitigation (ideally, suppression) of the electron cloud in the dipole beam screens must be envisaged. This would benefit both the heat load at top energy, which would be brought back within the limits of the cooling capacity, and the preservation of the beam quality throughout the 450 GeV injection plateau.

Several improvements implemented during LS1 are expected to have a beneficial impact on our knowledge on the electron cloud in LHC and/or the efficiency of the scrubbing run:

- *Cryogenics* [9]. The cooling capacity of the SAMs, which limited the speed of the injection process in 2012 by delaying the time between successive injections, and leading thereby to beam deterioration, has been increased by about a factor 2. The cooling capacity for Sector 34, which was half in 2012, has been restored to nominal. In terms of diagnostics, three half cells in Sector 45 have been equipped with extra thermometers. This will allow for magnet-by-magnet heat load measurements and disentangling the heat load in the arc dipoles from that in the quadrupole.

- *Vacuum* [10]. In general, pressure rises did not limit the efficiency of the 2012 scrubbing run, but it was not possible to monitor the pressure in the arcs due to the sensitivity of the vacuum gauges. High sensitivity vacuum gauges have been installed in the same Sector 45 half cells equipped with thermometers. Vacuum Pilot Sectors (Q5L8-Q4L8) are being equipped with gauges and e-cloud detectors to study behaviour of NEG coated vs. unbaked Cu beam pipe.

- *Injection kickers* [11]. At the very first stages of the scrubbing run, another limitation for the speed of the injection process was also the outgassing at the injection kickers (MKI). A new design of the beam screen with capacitively coupled ends allows for 24 screen conductors and, consequently, reduced beam induced heating. The by-pass tubes have been NEG coated and a NEG cartridge has been also added at the interconnects, which should result in a much improved vacuum.

- *TDIs* [12]. During the 2012 scrubbing run, heating and outgassing of these injection protection devices could be kept under control by retracting them between subsequent injections. Besides, a few problems with detected misalignment or stuck jaws were

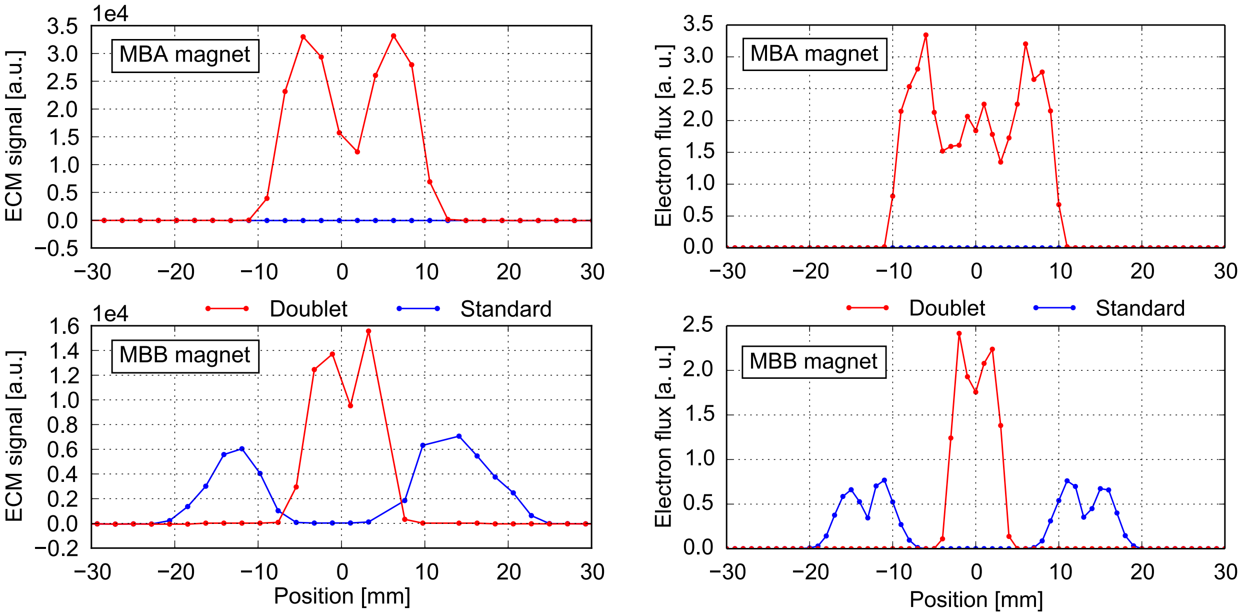


Figure 7: Electron flux to the wall of an MBA-type chamber with SEY=1.5 (top) and an MBB-type chamber with SEY=1.3 (bottom) as a function of the horizontal position for the standard 25 ns beam (1.7×10^{11} p/b, blue trace) and a doublet beam (1.7×10^{11} p/doublet, red trace). In the left column are the measured signals while in the right column are the simulated distributions.

encountered especially toward the end of the scrubbing run. The improvements introduced during LS1 include a reinforced beam screen made of Stainless Steel, a Ti flash to reduce SEY on the Al blocks, the installation of temperature probes that will allow monitoring heating, mechanics disassembled and serviced, which should minimise the risk of alignment problems.

- *On-line electron cloud monitoring*. New software tools for on-line monitoring of the scrubbing process and its steering are being prepared. Virtual variables for the heat load in the beam screen of the arc half cells for all sectors as well as SAMs and triplets have been implemented in the LHC logging database [13]. Furthermore, a specific application for the on line reconstruction of the bunch-by-bunch energy loss data from the RF stable phase is also under development.

Beside the above list, during Run 1 a special beam to enhance electron cloud production with respect to a standard 25 ns beam was developed and successfully produced at the SPS at 26 GeV. If accelerated to 450 GeV and then extracted to the LHC, this beam, called the doublet beam and described in detail in the next subsection, will be shown to have the potential to perform the further scrubbing step needed to run the LHC with 25 ns beams.

The "doublet" scrubbing beam

The idea of facilitating the scrubbing process by enhancing the EC while keeping the beam stable with high chromaticity was already proposed in order to speed up the scrubbing process in the SPS [14]. Exploratory studies in 2011 indicated that a promising technique for EC enhancement consists of creating beams with the hybrid bunch spacings compatible with the 200 MHz main SPS RF system and tighter than the nominal 25 ns. The schemes initially envisioned to produce these beams, i.e. slip stacking in the SPS or RF manipulations in the PS, turned out to be inapplicable due to technical limitations of the RF systems in the two accelerators. However, a novel production scheme was proposed to create a beam with (20+5) ns spacing. The scheme is based on the injection of long bunches in 25 ns spaced trains from the PS on the unstable phase of the 200 MHz SPS RF system, resulting in the capture in two neighbouring buckets and the generation of 5 ns spaced "doublets" out of each incoming PS bunch. Successful tests were conducted in the SPS and further details can be found in [15]. As a highlight, we display in Fig. 7, right column, the signals from the electron cloud detectors (in both the SPS dipole chamber types, i.e. MBA and MBB) during a machine development session with a standard 25 ns beam with 1.7×10^{11} p/b and a doublet beam with the same intensity per doublet. This measurement provided a direct evidence of the stronger electron cloud production and showed that the signals measured in the machine matched the distributions anticipated in simulations to a high degree of ac-

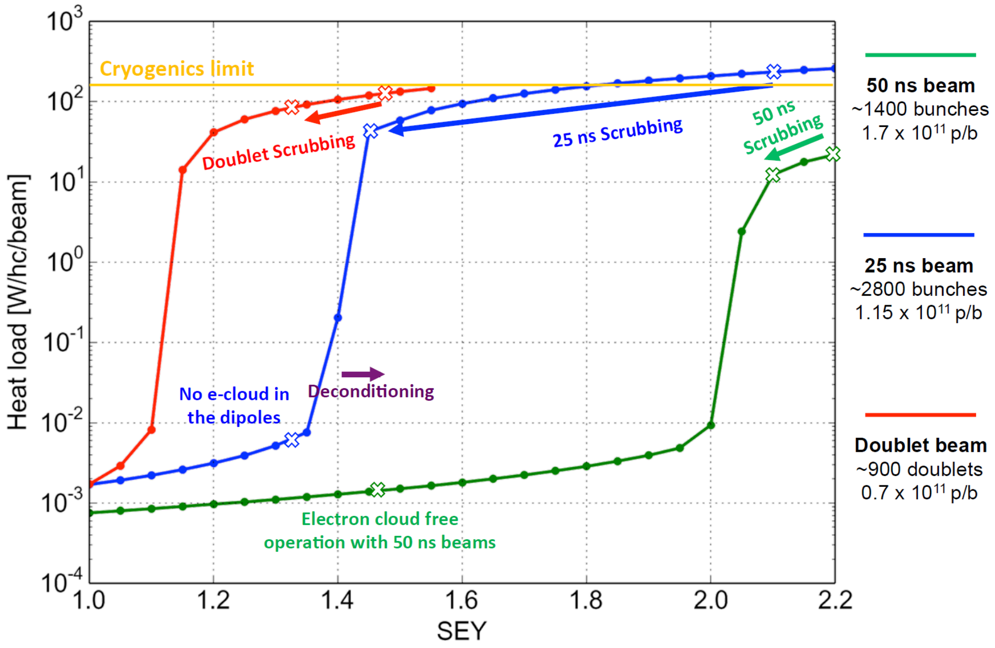


Figure 8: Heat load in the LHC dipole beam screen as a function of the SEY for 50 ns (1400 bunches, green line)), 25 ns (2800 bunches, blue line) and doublet beams (900 doublets, red line).

curacy (Fig. 7, left column). So far the doublet beam has been only produced in the SPS and stored at 26 GeV for few seconds. To be used in the LHC, it will be necessary to accelerate it with the desired intensity and preserving the beam quality before extraction to LHC.

The proof-of-principle of the production and efficiency of the doublet beam in the SPS, as well as the validation of our simulation tools for predictions, was an essential milestone to consider this beam as a future option for scrubbing the SPS after LS1. The capability of the doublet beam of further scrubbing the LHC dipole beam screens in order to lower the electron cloud level with 25 ns beams can be fully explained looking at Fig. 8. Here the simulated heat load is plotted as a function of the SEY for the 50 ns beam (1400 bunches), the 25 ns beam (2800 bunches) and the doublet beam (900 doublets in trains of 144 doublets per injection from the SPS, limited by the cryogenic capacity). Simulations were done for an LHC arc dipole at injection energy. As a reference, the line of the cryogenic limit, given by the cooling capacity, is also drawn as a yellow line. Scrubbing first with 50 and 25 ns beam can lead in a reasonable amount of time (4–5 days from previous experience) to the blue point close to the knee of the 25 ns blue curve. At this point, we can inject the doublet beam (red curve) and rely on high chromaticity settings to enhance the electron cloud without triggering instabilities, thus increasing the scrubbing flux on the dipole beam screens up to the available cooling capacity. One of the main challenges for this phase will be to keep an acceptable quality of the doublet beam while scrubbing at 450 GeV. If we succeed in maintaining a large scrubbing flux with the doublet beam (we can also top up with more injections if needed), further scrubbing down the red curve can be accumulated, leading eventually to an SEY point, for which the electron cloud in the dipoles has been completely suppressed with standard 25 ns beams.

Table 2, upper line, shows the values of expected heat load in the arcs for a full machine with 25 ns beam (2800 bunches) and the relative distribution of specific heat loads in dipoles and quadrupoles at the end of the 25 ns scrubbing (blue point at the knee of the heat load curve in Fig. 8). At this stage, the arc heat load with this type of beam is about evenly distributed in the dipoles and quadrupole. Furthermore, as an example, also the power loss in a sensitive element like the TDI is displayed. The lower line of the table shows the same quantities calculated for the fill with 900 doublets, which has been envisaged as the natural step following the saturation of the scrubbing process with 25 ns beams (higher red point in Fig. 8). The total heat load in the arcs increases to the value of the cooling capacity and becomes mainly located in the dipoles. The heating of the TDI is four times less severe than with the full 25 ns beam.

Figure 9 shows the horizontal distribution of the simulated electron current hitting the chamber's wall of the LHC main dipoles. As for the case of the SPS (see Fig. 7), for relatively low "bunchlet" intensities the scrubbing flux does not cover the entire region occupied by electron cloud with the standard 25 ns beam. Therefore, if it turns out not to be possible to operate the LHC with sufficiently high doublet intensity, the beam would have to be horizontally displaced by a few millimeters in order to condition the whole required area.

A general review on the use of doublet beams in LHC

	N_{bunches}	Bunch intensity	Total intensity	Heat load	P_{dip}	P_{quad}	P_{TDI}
Std. 25 ns beam	~2800 bunches	1.15×10^{11} p/bunch	3.2×10^{14} p/beam	71 W/hcell/beam	1 W/m	9.2 W/m	415 W
Doublet beam	~900 doublets	1.4×10^{11} p/doublet	1.2×10^{14} p/beam	125 W/hcell/beam	2.6 W/m	3.2 W/m	107 W

Table 2: LHC beam parameters and heat loads (arc dipoles, arc quadrupoles and TDI) for full machine with a standard 25 ns beam (upper line) and for a fill with 900 doublets (lower line)

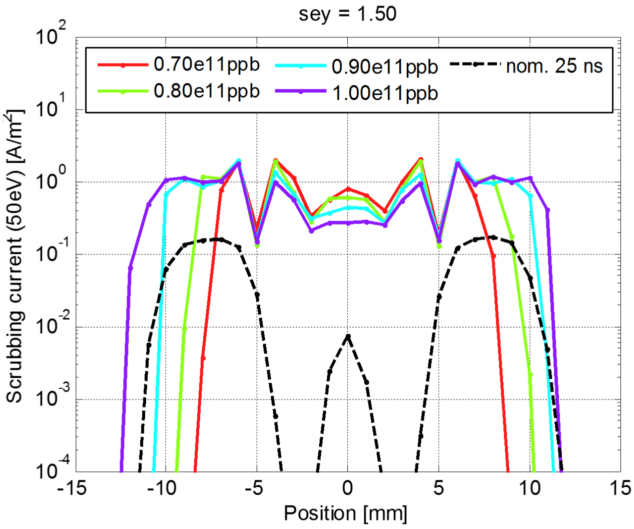


Figure 9: Horizontal distribution of the simulated electron current hitting the chamber's wall of the LHC main dipoles for doublet beams with different bunch intensity.

[16] has assessed the following points:

- *Production*. Splitting at SPS injection is the most favourable scheme (compared to splitting at high energy in SPS, or at LHC injection) both for beam quality and electron cloud enhancement

- *RF*. No major issue has been found. The phase measurement will average over each doublet, for which the Low Pass Filter bandwidth needs to be optimised. If the bunch length from SPS stays below 1.8 ns, the capture losses will be comparable to those for standard 25 ns beam

- *Transverse Damper*. The common mode oscillations of the doublets are damped correctly, but the system will not react to pi-mode oscillations, i.e. when the two bunchlets oscillate in counter phase. This kind of instabilities (if observed) will have to be controlled with chromaticity and/or octupoles

- *Beam Instrumentation*. No problem is anticipated for Beam Loss Monitors (BLMs), DC Current Transformers (DCCTs), Abort Gap Monitors, Longitudinal Density Monitors (LDMs), DOROS and collimator Beam Position Monitors (BPMs). BBQ (gated tune), Fast Beam Current Transformers (FBCTs), Wire Scanners, Beam Synchrotron Radiation Telescopes (BSRTs) will integrate over the two bunchlets. The Beam Quality Monitor (BQM) or LDM will be adapted to monitor the relative bunch intensity information. The BPMs might suffer errors up to 2-4 mm, especially for unbalanced doublets in intensity or position. Orbit measurements could still rely on the synchronous mode and gating on a standard bunch. However, the interlocked BPMs in IR6 will suffer the same issues as the other BPMs, but need to be fully operational on all bunches to protect the aperture of the dump channel. A possible strategy to circumvent this issue could be a reduction of the interlock setting (presently 3.5 mm) according to the results on error studies conducted in the SPS first (2014) and then in LHC with single doublet.

Scrubbing stages and operational scenarios

The different phases of the LHC start up, including all the stages relevant for scrubbing and 25 ns operation with mitigated electron cloud, are detailed in Fig. 10.

After LS1, the situation of the beam screen in the arcs will be likely reset. Upon resuming of the LHC operation in 2015, since most of the machine parts will be either new or exposed to air, it is reasonable to assume that the SEY in the arcs will have returned to values above 2.3, as was before the 2011-2012 machine scrubbing. For this reason, it will be necessary to envisage and schedule a period devoted to machine conditioning in order to get into physics production with 50 ns first, and later on with 25 ns beams. After an initial re-commissioning with low intensity, based on the experience of 2011, five to seven days with increasingly longer trains of 50 ns beams will be needed for vacuum conditioning and first scrubbing of all the machine parts exposed to air during LS1 or never exposed to beam before. This will lead to a general reduction of the desorption yield all over the machine and will also lower the SEY in the arcs to a value close to the threshold for electron cloud build up for 50 ns beams. At this point, to allow LHC to gain enough margin to ensure electron cloud free operation with 50 ns beams, this phase could be ide-

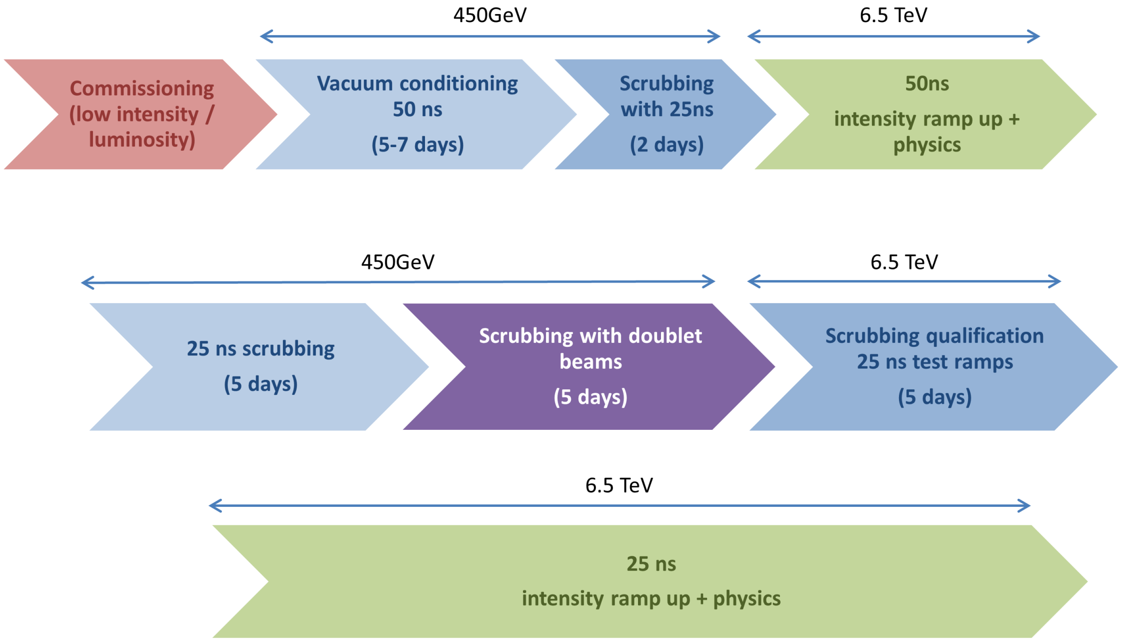


Figure 10: Timeline of the LHC scrubbing in 2015.

ally ended by one or two days with injections of trains of 25 ns beams aiming at lowering the SEY in the arcs below 2.0. After a short physics production period with 50 ns beams at 6.5 TeV, during which the 6.5 TeV operation will be established with the well mastered 50 ns beams and further surface conditioning will be achieved thanks to the enhanced synchrotron radiation, the switch to 25 ns operation will rely on performing a second scrubbing step with the 25 ns beam and doublet beams. By simply adding up the 50 hours of 25 ns MDs in 2011 and the 60 to 70 hours of efficient scrubbing in 2012, we obtain that a maximum of 5 days of run with increasingly longer trains of 25 ns beams at injection energy should be sufficient to get back to the same situation we had in December 2012 after the 25 ns scrubbing run. After that, the machine will be ready to receive doublet beams to enhance the electron cloud in the arc dipoles and continue the scrubbing down to values lower than the build up threshold in the dipoles for 25 ns beams. The next step is to ramp the 25 ns beams up to 6.5 TeV, while the number of bunches can be gradually increased.

If all the previous phases have been successful, the LHC will finally be able to move into physics production with 25 ns beams at 6.5 TeV under controlled electron cloud effects. However, it is worth noticing that during the 25 ns operation of the LHC, the electron cloud, though mitigated, will still be present in the quadrupoles (and possibly other machine regions, e.g. the higher order multipoles, the inner triplets) even after scrubbing. This entails the following effects, which shall be taken into consideration:

- The integrated effect of this residual electron cloud might result into a significant emittance blow-up at injection. To limit the luminosity loss due to this effect, the injection speed will be crucial, but also some beam parameters could be better tuned to minimise the amount of electron cloud seen by the beam at 450 GeV (e.g. bunches can be lengthened);
- If there is still a heat load limitation on the ramp or at 6.5 TeV, an optimal configuration in terms of number of bunches, bunch intensity and bunch length might have to be sought and applied;
- It was observed in 2012 that some degree of deconditioning occurs in absence of scrubbing beam for some time. If the extent of the deconditioning is such as to re-awaken the electron cloud with 25 ns beams, a few hours for scrubbing could become necessary after each longer stop (i.e. certainly after every Winter stop, but possibly also after each Technical Stop).

If the scrubbing phases detailed above will not be sufficient to eliminate the electron cloud from the machine dipoles and 25 ns operation will still be hampered by heat load on the ramp and beam quality degradation, the main fallback option foresees the use of the 8b+4b filling scheme [15]. This will allow storing up to 1900 bunches/beam in the LHC with the advantage of having both a higher multipacting threshold compared to the standard 25 ns beam (shown by PyECLOUD simulations) and the potential to accept a higher intensity per bunch (to push up luminosity within the desirable limits of the pile-up). This scheme, although already proven in simulations, still needs to be confirmed experimentally in the injector chain. The gain in terms of electron cloud build up also needs to be assessed experimentally, once this beam will be available in the SPS. A second option would be to stick to the 50 ns spacing and run the LHC again like in Run 1 (although instabilities at 6.5 TeV could be an important intensity limiting factor for this scenario). In this way we could store up to 1380 bunches in the LHC and rely on a multipacting threshold much larger than for the standard 25 ns beam or the 8b+4e.

CONCLUSIONS

To conclude, the experience from LHC Run 1 has taught that the electron cloud can seriously limit the achievable performance with 25 ns beams mainly through beam degradation (poor lifetime, emittance blow up) at low energy and high heat load at top energy. The scrubbing achieved in 2012 could strongly weaken the electron cloud in the beam screen of the dipoles, but did not fully suppress it. After LS1, to cope with the nominal number of bunches, we need to scrub LHC more efficiently than in 2012 and aim at the total suppression of the electron cloud from the dipole beam screens. To accomplish that, we will benefit from:

- Several hardware and instrumentation improvements, which will allow for better scrubbing efficiency;
- The doublet scrubbing beam based on 5 ns spaced bunchlets separated by 25 ns, which was produced and tested at the SPS, and looks very attractive for LHC scrubbing. The compatibility of this type of beam with the LHC equipment was reviewed and no major showstopper has been found. Presently, the only pending issue is the possible offset on the interlock BPMs in IR6 and this is being followed up.

A two stage scrubbing strategy is proposed for the LHC start up in 2015. This will rely on: 1) a first scubbing/conditioning run with 50 ns beams (and possibly one or two days with 25 ns beams) to allow for safe operation with 50 ns beams at 6.5 TeV; 2) A second scrubbing run with 25 ns and doublet beams to allow for operation with 25 ns beams at 6.5 TeV. If scrubbing will turn out to be still insufficient, even with the doublet beam, the 8b+4e scheme could be used for providing a significant electron cloud reduction with 50% more bunches than the 50 ns beam and similar bunch intensities.

ACKNOWLEDGEMENTS

The authors would like to thank G. Arduini, V. Baglin, D. Banfi, M. Barnes, H. Bartosik, P. Baudrenghien, E. Calvo, S. Claudet, J. Esteban-Mller, W. Hofle, L. Kopylov, G. Kotzian, T. Lefevre, E. Metral, S. Popescu, F. Roncarolo, B. Salvant, E. Shaposhnikova, J. Uythoven, M. Taborelli, G. Trad, L. Tavian, D. Valuch, J. Wenninger, C. Zannini and many colleagues from BE/ABP, BE/BI, BE/OP, BE/RF, EN/STI, TE/ABT, TE/CRG and TE/VSC for the expert support they provided throughout the presented studies.

REFERENCES

[1] G. Arduini *et al.*, “50 and 75 ns operation in the LHC: Vacuum and Cryogenics observations”, CERN-ATS-Note-2011-046 MD (2011)

[2] B. Goddard *et al.*, “Injection into LHC of bunches at 25 ns spacing”, CERN-ATS-Note-2011-050 MD (2011)

[3] H. Bartosik and W. Höfle, “Analysis of bunch by bunch oscillations with bunch trains at injection into LHC at 25 ns bunch spacing”, CERN-ATS-Note-2012-027 MD (2012)

[4] G. Rumolo *et al.*, “LHC experience with different bunch spacings in 2011 (25, 50 & 75 ns)” in Proceedings of LHC Performance Workshop Chamonix 2012 (6-10 February, 2012, Chamonix, France)

[5] G. Iadarola, “Electron Cloud studies for CERN particle accelerators and simulation code development”, CERN-THESIS-2014-047 and references therein.

[6] G. Iadarola, G. Arduini, H. Bartosik and G. Rumolo, “Electron cloud and scrubbing in 2012 in the LHC ’ in Proceedings of LHC Operation Workshop Evian 2012 (18-20 December, 2012, Evian, France)

[7] L. Tavian *et al.*, “Performance limitations: 2012 review and 2015 outlook – Cryogenics”, in Proceedings of LHC Operation Workshop Evian 2012 (18-20 December, 2012, Evian, France)

[8] J. Esteban Müller and E. Shaposhnikova, “Synchronous phase measurements in the LHC for electron cloud observations”, CERN-ACC-NOTE-2013-0007

[9] S. Claudet and L. Tavian, ”Maximum heat load acceptable by cryogenics in 2015”, presented at LBOC Meeting 08/10/2013

[10] V. Baglin, ”Electron cloud vacuum instrumentation and solenoids ”, presented at LBOC Meeting 24/03/2014

[11] M. Barnes, ”Summary of the mini-review on MKI upgrades in LS1” at LBOC Meeting 21/01/2014

[12] J. Uythoven, in Minutes from the LIBD meeting on 18 March 2014, EDMS Document 1367271

[13] S. Popescu, ”Cryogenic heat load information for operation” presented at LBOC Meeting 06/05/2014

[14] H. Bartosik *et al.*, CERN-ATS-Note-2013-019-MD

[15] H. Bartosik and G. Rumolo, elsewhere these proceedings

[16] H. Bartosik, E. Shaposhnikova, P. Baudrenghien, G. Kotzian, T. Lefevre, E. Calvo, in LBOC meetings No. 7 5/11/2013, No. 8 26/11/2013, No 9 3/12/2013

STRATEGY FOR THE FIRST TWO MONTHS OF LHC BEAM COMMISSIONING (COMMISSIONING TO FIRST STABLE BEAMS)

S. Redaelli, G. Arduini, M. Giovannozzi, M. Lamont, R. Tomás, J. Wenninger
CERN, Geneva, Switzerland

Abstract

The 2015 LHC schedule tentatively allocates two months between the start of beam commissioning and the establishment of the first stable beams with a few nominal bunches at top energy. This phase will address the commissioning with beam of all key accelerator systems, taking into account the changes occurred in Long Shutodown 1 (LS1) and new commissioning requirements for the 2015 operational goals. In presence of uncertainties on the key machine and beam parameters, a set of critical measurements to be performed early on in the commissioning are identified in order to establish a validation plan for the machine configuration for the intensity ramp up. In this paper, the strategy for the initial commissioning until the first stable beams is reviewed.

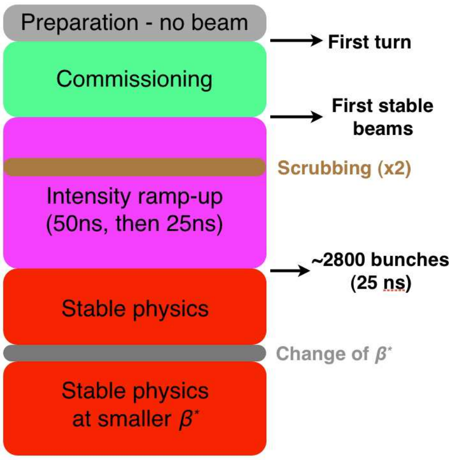


Figure 1: Schematic illustration of the main 2015 commissioning phases.

INTRODUCTION

The setup of the first collisions in the experiments at the Large Hadron Collider (LHC) represents an important commissioning milestone. During the data taking phase, usually referred to as *stable beams* (SB), all experiment components are switched on. This is also the phase when the machine sits idle for the longest period of time, being exposed to system failures. It is therefore important to ensure that all the machine protection-related accelerator systems are fully commissioned and operational when the first SB phase is declared. This is done by setting up the SB initially with a few individual nominal bunches, before then proceeding with the beam intensity ramp-up. Tentatively, two months of beam time are allocated in the 2015 LHC schedule to establish the first SB [1].

The validation of a machine configuration entails a lengthy series of beam measurements that culminate with the complete set of loss maps and asynchronous dump tests [2]. If this validation is successful, the following commissioning step consists in beam intensity ramp-up that is performed without any further change of machine configurations, only by increasing the number of bunches. It is crucial that the key parameters such as collimator settings, β^* and bump configurations in the interaction regions (IRs) are finalized before the first SB as later changes would be very costly in terms of commissioning time, mainly driven by the re-commissioning of machine protection systems.

This paper provides an update of the contribution presented at the LHC Beam Operations Workshop, Evian2014 [3], taking into account recent decisions on the choice of machine configuration for the startup in 2015, as well as the updated machine schedule. These items include the decisions (1) to start with a β^* of 80 cm in ATLAS and CMS and (2) to foresee a change of optics later in 2015 [4]. The latter was proposed in [3] as staged deployment of small β^* that leaves time to assess experimentally the LHC performance at higher energies. The commissioning at larger β^* is chosen following the definition of the main priority for the 2015 run as the establishment of a solid operation of the LHC at 25 ns. This is in preparation for the 2016 run that should be a physics production run with the best achievable performance. Detailed parameters for the startup configuration are discussed in [5]. Note that the operational cycle will be as in Run I, with squeeze at flat-top energy. Scenarios like β^* levelling, combined ramp and squeeze, and collide and squeeze will not be deployed at the beginning of the run [6] and hence are not discussed here.

After a recapitulation of the initial commissioning strategy, some relevant inputs from the LHC Run I are recalled. Some of the system changes occurred in LS1 that have impact on the commissioning plans are discussed. New beam measurements required in the initial commissioning phase to optimally prepare the 2015 run are discussed before drawing some conclusions.

OVERALL COMMISSIONING STRATEGY

An illustrative scheme with the main phases of the 2015 proton run commissioning is given in Fig. 1 (see [1] for the detailed 2015 schedule). Two months are allocated until the setup of the first SB. This initial phase is then followed by the intensity ramp-up. Two scrubbing periods are planned to prepare the machine for an initial ramp-up at 50 ns, then followed by the 25 ns operation. Once the operation at the maximum number of bunches is established, the machine will enter a period of physics runs. After adequate operational experience is accumulated, it is planned to push further the optics in a dedicated re-commissioning period before the end of 2015.

The main goals for the 2015 commissioning until first SB can be summarized as follows.

1) Establish the key operational phases with beam (threading, beam capture, orbit and optics corrections, IR bump setup, aperture measurements, energy ramp, betatron squeeze, collisions; setup of feedbacks, collimation, RF, injection, LBDS, ...) [7];
2) commission with beam the key accelerator systems;
3) carry out the machine protection commissioning [2];
4) validate by measurements the machine configuration;
5) prepare the β^* optics change planned for later in 2015.

A detailed discussion of the initial commissioning steps is outside the scope of this paper. The operational experience of Run I provides a mature baseline that makes us confident that the standard phases [7] can be addressed successfully. Adequate commissioning time will have to be allocated to cope with the system changes and upgrades that occurred in LS1 and new requirements for the commissioning at a higher beam energy, as discussed below.

RELEVANT INPUT FROM RUN I COMMISSIONING EXPERIENCE

The beam commissioning in 2012 was remarkable as it was carried out in record times [3]. The first stable beams were achieved only 22 days after the beginning of beam commissioning. The intensity ramp-up was then completed in eleven days, achieving the maximum number of bunches – 1380 at 50 ns spacing – after about 1 month from the start of beam operation. This is illustrated by the graph of peak luminosity recorded in ATLAS, see Fig. 2, which reached 80 % of the typical operational values in only about one month.

In the attempt to identify key ingredients for this outstanding operational achievement, one could point out that, amongst others:

- The commissioning effort was focused on high-intensity proton operation. Set up of special runs was left for later phases.
- A minimum number of hardware changes to the key accelerator systems had occurred compared to the 2011 run.
- Up to 3 nominal bunches at top energy were within the safe limit for machine protection. This eased and made more efficient several commissioning procedures.

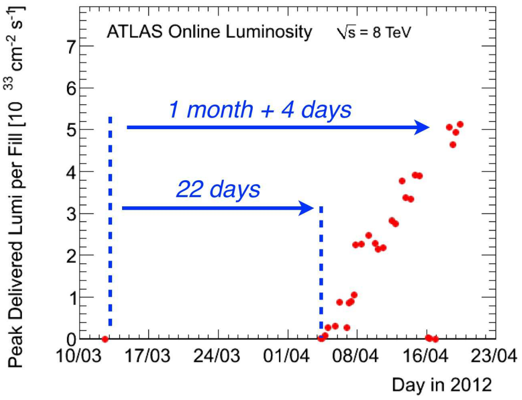


Figure 2: Luminosity versus time as recorded in ATLAS in the first weeks of the 2012 run. Courtesy of the ATLAS collaboration.

These aspects come in addition to the excellent performance of the accelerator systems, which were very efficiently commissioned thanks to the experience accumulated until 2011. The same efficiency cannot be expected in 2015 due to system changes occurred in LS1 (see below).

The careful choice of 2012 machine parameters was based on a solid knowledge of the LHC and of the accelerator systems. For example, the triplet aperture was predicted [8] within 0.5 beam sigmas and the beta-beating errors were kept below 10 % [9] based on what was achieved in 2011. For 2015, the machine has to be considered as brand new under several aspects due to the long stop of about 2 years. Other uncertainties also apply, like the reproducibility of the machine aperture after having opened the vacuum and the behaviour of magnets at 6.5 TeV and of beam losses and beam instabilities at higher energies [10].

The machine protection aspects pointed out in the list above should not be underestimated [2]. At 4 TeV, 3 nominal bunches were still below the safe limit. This allowed an efficient setup of the collisions in all interaction points and in some cases allowed speeding up the validation (transverse loss maps followed by asynchronous dump tests in the same fill). At higher energy, operational efficiency might in some cases be reduced if validations have to be split over several fills.

Is it interesting to recall, as a comparison, that in 2011 the preparation of the first stable beam took almost the same time as in 2012, i.e. 23 days from first circulating beams (February 19^{th}) until stable collisions (March) 13^{th}. Several observations made above apply also to the commissioning experience of 2011. The initial machine configuration at β^* of 1.5 m was decided as an evolution of the previous operational experience from 2010. As opposed to 2012, the intensity ramp-up in 2011 was more tedious as it was done for the first time with 50 ns bunch spacing, respecting a strict validation imposed by machine protection constraints [2].

SYSTEM CHANGES AND REQUIREMENTS

The hardware changes that have taken place during LS1 and the corresponding new system requirements were discussed in detail at the recent LHC Operations workshop in Evian [11]. It was pointed out that important system upgrades will need adequate recommissioning time. Some key points are listed.

- Injection and dump systems [12]: new hardware will be used for the TDI and TCDQ protection blocks; new interlocks on the TDI and TCDQ, based on hardware implementations into the beam energy tracking system [13], will be deployed; dedicated beam measurements are requested for the TDI heating; measurements done at the beginning of Run I, such as wave form scans and kick response, are planned to be repeated.

- Collimation [14]: 18 new devices with in-jaw BPMs have been installed and 8 new IR collimators will need to be commissioned. The new BPM functionality will need dedicated time from the collimation and BI teams.

- Beam instrumentation [15, 16]: there will be new beam size measurements, new BLM layouts, new *little ionization chambers* in the injection regions [12].

- The FiDeL model will have to be assessed for the new pre-cycle. Saturation effects in the magnet yoke will become relevant for the first time and should be take into account.

- RF: several hardware and software changes occurred for the main RF system as well as for the transverse damper, see [17, 18, 19].

This list is not exhaustive, but gives rather a selection of topics that will have an impact on the initial beam commissioning time.

The experiments presented their views and wishes for 2015 in [20]. It is requested to prepare early on various special physics runs such as the ones for Van Der Meer scans and for the LHCf data taking as well as the setup of Roman pots in IR1 and IR5. Contrary to the case of Run I, some of these activities now require different optics than the one used in the standard operational cycle for high-intensity operation. The impact of this requirement on the commissioning time should not be underestimated as it will add new constraints (additional optics measurements, new machine configuration validations, etc.) in a phase when the machine might not yet be fully under control.

2015 BEAM MEASUREMENTS AND DECISION POINTS

In addition to the new commissioning requirements, additional measurements are proposed at the 2015 startup. These are measurements that were not part of the initial beam commissioning but are now considered crucial to validate early on the choice of 2015 machine configuration. It is proposed to define several decision points along the initial commissioning when the choice of parameters is reassessed before moving to the next step.

- ◇ **IR aperture at injection**: the Run I measurements showed that IR aperture measurements at injection can already provide a solid base for extrapolations of β^* reach [21]. IR1/5 aperture at injection was only measured in the 2009 pilot run. This should be done as soon as possible in 2015 after establishing the reference orbit at 450 GeV.

- ◇ **Dedicated local orbit and optics correction in the IRs**: Dedicated time to establish local corrections of IR orbit and optics are essential to provide feedback on the feasibility of various scenarios like β^* levelling. Compared to what was done in the past, one should try to ensure that non-local transients are minimized (e.g., orbit leakage around the ring while changing IR8 β).

- ◇ **Collimator impedance with single bunch**: One important question that could not be solved during Run I is the role of collimation impedance on the instability observed in 2012 [13, 22]. Early measurements with nominal single bunches should be carried out to identify potential impedance issues with the different collimator settings [5].

- ◇ **Stability of orbit and BPM signals**: reproducibility and stability of the machine are crucial inputs for the tolerance margins used to define the achievable β^* and should thus be monitored regularly.

Additional decision points that can only be addressed during the intensity ramp-up phase are: multi-bunch impedance and beam-beam effects (for possible iteration on crossing angle values), two-beam effects and octupoles, monitoring of machine stability and UFOs. The treatment of these measurements beyond the initial commissioning is not in the scope of this paper.

New measurements requirements are:

- ▷ **Chromaticity measurements in different conditions**: Regular chromaticity measurements should be performed to assess the accuracy of the measurement and the reproducibility along the cycle.

- ▷ **Detuning versus amplitude and MCO/MCD settings**: Dedicated tests with octupole and decapole correctors are considered mandatory in order to establish clean conditions for the setup of Landau octupoles. Although in principle the set values should compensate the predicted errors in the main dipoles, the models of de-tuning with amplitude at 450 GeV were not fully understood in Run I. The deployed settings might have played against the Landau octupoles.

- ▷ **Optics measurements and corrections down to 40 cm**: the optics change in the second half of 2015, can only be deployed efficiently if optics measurements and correction of the target β^* are prepared earlier on. Measurement and corrections for the match points between β^* 80 cm and 40 cm should be part of the initial squeeze setup.
- ▷ **Aperture verification with squeezed beams** should be performed in detail at the target β^* value of 80 cm in order to validate the feasibility of this configuration and understand the margins for pushing further the performance.

CONCLUSIONS

Plans for the initial beam commissioning of the LHC Run II were presented, addressing the new requirements after the LS1. A first crucial milestone will be to establish first stable beams at 6.5 TeV after having re-commissioned the machine. Important goals of this exercise will be to validate the proposed machine configuration and ensure that the choice of beam and machine parameters is adequate for the intensity ramp-up. While several key validations will only be possible later on with 25 ns beams, we proposed a number of measurements that should be performed early on to provide important feedback already during the initial commissioning phases. Here, changes can still be made with a reasonable overhead, i.e. before the full validation of machine protection that precedes the intensity ramp-up. Other than these additional decision points, the commissioning will follow the very mature experience of Run I. Clearly, changes occurred in LS1 must be taken into proper account.

Taking all these constraints in consideration, and the additional requirements from the experiments that require early on the preparation of various special runs, we consider that achieving the first stable beams in the allocated time of two months is probably still feasible, but certainly very challenging.

ACKNOWLEDGMENTS

The authors would like to sincerely acknowledge all the colleagues from the BE-OP-LHC, BE-ABP-HSS, BE-ABP-HSC sections who provided useful inputs to the preparation of this paper.

REFERENCES

[1] J. Wenninger, “Strategy for Run II,” these proceedings.

[2] B. Salvachua, “MPS Strategy for Commissioning and Operation,” these proceedings.

[3] S. Redaelli *at al.*, “Strategy for the first two months of the LHC beam commissioning and key early measurements,” proceedings of Evian 2014.

[4] Minutes of the 188$^{\rm th}$ LHC Machine Committee held on 3$^{\rm rd}$ Sep. 2014.

[5] R. Bruce *et al.*, “Baseline machine parameters and configuration for 2015,” these proceedings.

[6] Minutes of the 194$^{\rm th}$ LHC Machine Committee held on 5$^{\rm rd}$ Nov. 2014.

[7] `http://lhccwg.web.cern.ch/lhccwg/Procedures/stageA/stageA_index.htm`

[8] R. Bruce *et al.*, “β^* reach,” in proceedings of Evian 2012.

[9] R. Tomás *et al.*, “Record low β beating in the LHC,” Phys. Rev. ST Accel. Beams **15**, 091001 (2012).

[10] E. Todesco, “Cycles and pre-cycles definitions for 2015,” presentation at the LBOC meeting of July 8, 2014. `https://indico.cern.ch/event/295975`

[11] `http://indico.cern.ch/event/310353/`

[12] W. Bartmann, “Injection: status and plans,” Evian 2014.

[13] N. Magnin, “LBDS: status and plans,” Evian 2014.

[14] G. Valentino, “Collimation: status and plans,” Evian 2014.

[15] T. Lefévre, “Status of tune and orbit measurement and correction, testing strategy,” Evian 2014.

[16] G. Trad, “Transverse beam size measurement,” Evian 2014.

[17] Ph. Baudrenghien, “RF: status and plans,” Evian 2014.

[18] D. Valuch, “ADT: status and plans,” Evian 2014.

[19] J.E. Muller, “Longitudinal parameters and beam induced heating ,” these proceedings.

[20] E. Meschi, “Experiments’ expectations in 2015,” these proceedings.

[21] C. Alabau Pons, M. Giovannozzi, G. Müller, S. Redaelli, F. Schmidt, R. Tomas, J. Wenninger, “LHC aperture measurements,” IPAC2010.

[22] T. Pieloni, “Two beam effects,” these proceedings.

OVERALL STRATEGY FOR RUN 2

J. Wenninger, CERN, Geneva, Switzerland

Abstract

This documents is focused on the strategy for the first year of Run 2. Global strategies and various scenarios for Run 2 were already discussed in details at the RLIUP workshop in October 2013. The top goal of LHC operation for 2015 is to establish reliable operation at 6.5 TeV with 25 ns bunch spacing, and with a competitive luminosity. The overall strategy for the year 2015 will be discussed; this includes scrubbing runs, intensity ramp ups, reaching out for lower β^* and higher luminosity. Besides high intensity proton operation, high β^* and ion runs will also be discussed.

RUN 2 TARGETS

The performance of future LHC runs was discussed at the RLIUP review [1] in October 2013. The performance targets have not varied over one year and they are used as reference target in this document. For Run 2 the target integrated luminosity is 100 fb^{-1}, while at the end of Run 3 (around 2022) the total collected integrated luminosity should reach 300 fb^{-1}. A summary of the assumed beam parameters in collision (with and without Linac4, including emittance blow-up) are given in Table 1. The yearly performance is evaluated for runs with 160 days of scheduled physics time in Table 2 and Figure 1 [2]. For 35% efficiency of stable beams the yearly integrated luminosity reaches up to 50-60 fb^{-1}. Some luminosity leveling is required in all scenarios except for the standard 25 ns beam. The performance loss with 50 ns beams is roughly 50% due to the pile-up limitation of the experiments. The cooling of the triplet magnets sets a limit to the maximum achievable luminosity of $1.75 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, with an uncertainty of 10 to 20% [3]. This limit will have to be explored during Run 2.

To achieve the targets set out at the RLIUP workshop, the following ingredients will be required:

- Small β^* (around 40 cm),
- Very bright and stable beams,
- Luminosity leveling.

GUIDELINES FOR RUN 2

Possible parameters for the startup configuration were discussed at the last Evian workshop on LHC operation in June 2014 [4]. Some parameters that were still open for discussion at the Evian Workshop were defined at recent LMC meetings: the main strategy is to concentrate on 6.5 TeV and 25 ns beam to reduce the complexity [5]. A relaxed β^* of 80 cm will be used for the startup. This provides for example an extra margin of 2σ at the TCT as compared to the β^* of 65 cm proposed at Evian. From the side of the experiments, there is a strong interest to use 2015 as a test year and ensure that in 2016 the LHC can be operated at its peak performance.

Possible 25 ns beams in 2015 (emittances correspond to injection):

- The BCMS beam with very low emittance (1.3×10^{11} p/b, $\varepsilon = 1.3$ μm) is limited to a maximum of

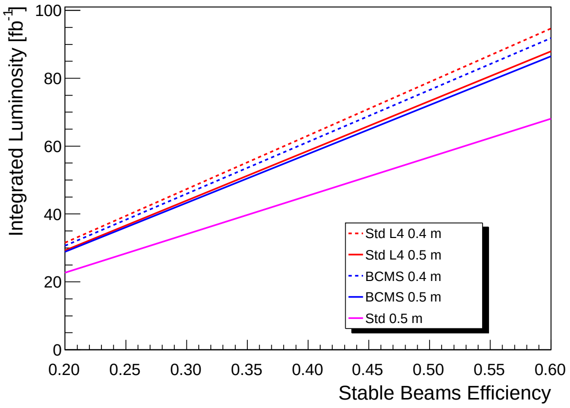


Figure 1: Integrated performance per year for the different beams as a function of the stable beams efficiency in case the luminosity is leveled according to Table 2 [2].

Table 1: Expected beam parameters of 25 ns beams at start of collisions after LS1 for the BCMS beam, the standard 25 ns beam and the standard beam with Linac4 (only for Run 3) [2]. For the BCMS beam there is no difference with or without Linac4. k is represents the number of colliding bunch pairs in ATLAS/CMS, θ is the half-crossing angle.

Beam type	N (10^{11})	ε^* (μm)	k	β^* (m)	θ (μrad)
BCMS	1.25	1.65	2590	40/50	150/140
Standard	1.25	2.9	2740	50	190
Standard+L4	1.25	2.0	2740	40/50	150/140

Table 2: Peak ($\mathcal{L}_p$) and leveled luminosity ($\mathcal{L}_l$) after LS1 for the various 25 ns beams in collision at the LHC.

Beam type	β^* (m)	$\mathcal{L}_l/10^{34}$ ($\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	$\mathcal{L}_p/10^{34}$ ($\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	Leveling time (h)
BCMS	0.4	1.54	2.2	2.5
Standard	0.5	1.65	1.2	–
Standard+L4	0.4	1.65	2.1	1.6

144 bunches per injection to ensure that in case of a failure the TCDIs are not damaged [6].

- The standard 25 ns beam (1.3×10^{11} p/b, $\varepsilon = 2.6$ μm) with up to 288 bunches per injection.

Despite stronger IBS and expected issues with beam stability, the smaller BCMS beams may provide margins for emittance blow-up that eventually yields higher performance. So far small emittance beams were used rather effectively during Run 1 despite the worries on the beam stability.

2015 Startup

The current schedule of the LHC run in 2015 is split into the following phases as shown on Fig. 2:

1. Low intensity commissioning (2 months),
2. First physics with a few isolated bunches, LHCf run,
3. First scrubbing run (50 ns),
4. 50 ns operation up to 1380 bunches/beam (3 weeks),
5. 25 ns scrubbing run,
6. 25 ns operation, special runs (90 days), potentially with two β^* values,
7. Ion run

For the performance estimates presented in this document, the values for the standard 25 ns beam are aligned to the presentation by R. Bruce [5]. For the BCMS beam an emittance in collision of 2.5 μm is assumed. This is at the limit of the beam stability and provides margin for blow-up from various sources as compared to an injected emittance of 1.3 μm. The margin gained from the relaxed β^* is assigned to MP, and the LRBB separation is maintained at 11σ.

50 ns Operation

The objective for the 50 ns operation phase is to reproduce a performance similar to 2012 at 6.5 TeV without having to worry too much about e-clouds. This phase begins with a scrubbing run - initially with 50 ns and later with 25 ns beams, see Fig. 3 - a well established scenario from Run 1 [7].

Figure 2: Schedule of the LHC for 2015. The different periods are marked with the numbers.

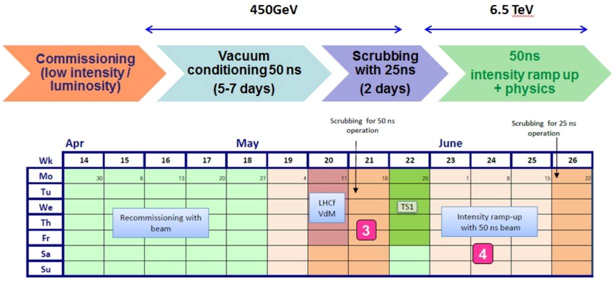


Figure 3: Scrubbing run strategy for 50 ns beams.

The scrubbing run is followed by a 21 day long intensity ramp up. The scheduled 3 weeks seem too short to reach 1380 bunches (full 50 ns beam). During Run 1 the ramp up durations were (see Fig. 4):

- The 2011 intensity ramp up took 9 effective weeks - spread over 11 intensity steps - where the progress was dictated by non-MPS issues as soon as 600 bunches were reached. Losses and BLM threshold adjustments, heating and beam stability slowed down the progress.
- With the experience gained in 2012, the intensity ramp up took only 2 weeks - spread over 7 intensity steps.

The following preliminary ramp up scenario (pending decision by rMPP) of 9 steps is envisioned for 2015: 50, 100, 250, 500, 760, 900, 1100, 1240 and finally 1380 bunches. One step in intensity will last around 3 days if there are no issues. If no show stoppers are encountered, it should be possible to reach the 1000 bunch regime which is a reasonable target for the 50 ns period. During this phase there should not be significant e-cloud problems, but the UFOs will already strike. The first heating effects may be observable. The current plan is to use similar bunch intensities than for 25 ns beams (1.2×10^{11} p/b). Pushing the bunch population toward 1.5×10^{11} may be used to probe the beam stability (also later as test during the 25 ns phase).

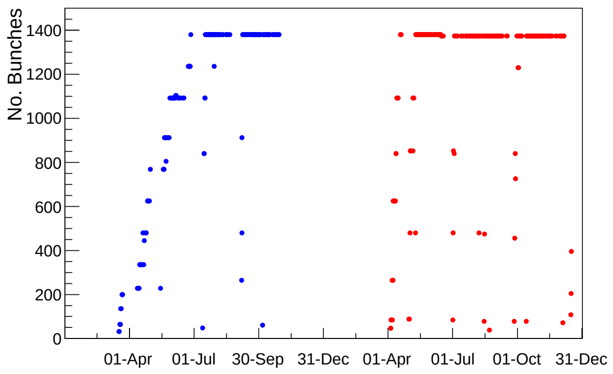


Figure 4: Evolution of the number of bunches per beam in the LHC for 2011 and 2012. The intensity ramp up periods of 2011 (blue) and 2012 (red) are clearly visible

25 ns Operation

The central issue for the 25 ns beam is evidently scrubbing and e-cloud control. The December 2012 experience indicates that we may have to change the strategy and introduce a more powerful scrubbing beam, the 5-20 ns doublets [7], as indicated in Fig. 5. Duration and outcome of the scrubbing run are not as clear as for 50 ns case.

The double beam may be absolutely essential for scrubbing, and it requires adequate time for preparation in the SPS and the LHC:

- SPS: capture, slow ramp (intensity per doublet 1.6×10^{11} p/b), extraction.
- LHC: injection, capture, instrumentation.

Most LHC instruments or systems will be able to cope with the doublets, in general by averaging the over the doublets. Critical items on the LHC side are the interlock BPMs in IR6 (protection of dump channel). The systematic orbit shifts associated to the doublet structure will require tighter interlocks, but the configuration must remain manageable in terms of tolerances. Very important tests will be performed at the SPS this year, and it is essential to test the doublet beam (typically 12 doublets) as soon as possible during the early LHC commissioning.

During Run 1 400 bunches per beam were collided with 25 ns spacing, and collisions with 800 bunches were almost achieved (beam dump unrelated to e-cloud effects): this corresponds to almost 30% of the target, but it is also the easier part of the ramp up. With the conditions (SEY) of December 2014 the machine filling will be limited to approximately 30-50% of the total intensity due to the heat load into the cryogenics system [7].

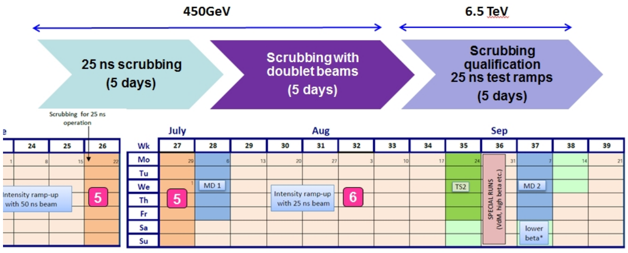


Figure 5: Scrubbing run strategy for 25 ns beams.

The intensity ramp up for 25 ns beam is tentatively split in 11 steps (to be discussed and approved by rMPP): 140, 300, 600, 900, 1200, 1500, 1750, 2000, 2300, 2600 and finally 2800 bunches. On the way UFOs will appear, stability issues are likely to be encountered (depending on the emittance of the beam), heating may be observed etc. Operation and machine coordination will have to be reactive and be ready to invest into tests and MDs. Slow scrubbing during physics operation is probably the most annoying scenario, leading to an endless intensity ramping. Special beams with low e-cloud activity are a safety net (for example 8b+4e which is a 25 ns variant with many holes [8]), but not a real solution (around 1800 bunches instead of more than 2500 bunches for a more standard 25 ns beam).

In parallel to the 50 ns and 25 ns intensity ramp up and operation periods, it will be necessary to prepare the future, i.e. to push to peak performance with ALARA-type β^* and the highest possible beam brightness and stability. The 2015 running period has only 3 MDs, and one is already before the 25 ns ramp up. It is unlikely that all tests fit into so little time, see the presentation by J. Uythoven [9]. Tests interleaved with physics operation will be required to fill the gaps. Many studies must be performed in parallel to early 25 ns operation. Since this will set limits on achievable beam parameters, one may have to use 50 ns beams and alternate standard/BCMS beams for some of the tests.

PRIORITIES AND PERFORMANCE

There is a large phase space for tuning the beams in 2015, there are many players and significant time requirements. It will be essentially to remain focused on the first priority of **operating with 2800 bunches and 25 ns spacing at 6.5 TeV**. The second priority is to prepare for operation at lower β^*. Reaching β^* below 50 cm is essential

Table 3: Expected 2015 performance at 6.5 TeV assuming 35% efficiency for stable beams. The run has been split into 3 phases, 50 ns operation, early 25 ns operation (both with β^* of 80 cm), 25 ns pushed to low β^*. μ is the peak average pile-up.

Beam	N (10^{11})	ε^* (μm)	k	β^* (m)	$\mathcal{L}_p$ (cm$^{-2}s^{-1}$)	μ	Days	$\mathcal{L}_{int}$ (pb^{-1}/day)
50 ns	1.2	2.5	1370	80	5.3×10^{33}	30	21	≈ 1
25 ns	1.2	2.5	2500	80	8.1×10^{33}	26	44	≈ 4
25 ns	1.2	2.5	2500	40	14.7×10^{33}	45	46	≈ 13

to achieve the performance goal of 100 fb^{-1} for Run 2. It will be essential to prioritize MDs and tests along a coherent line. Starting from a higher β^* (80 cm instead of the achievable 65 cm) has the drawback of a significantly longer distance to the target.

A step towards lower β^* should be made in 2015 independently of a potential gain in integrated luminosity. It is also important to foresee an operation period of 3-4 weeks after the change of β^* to have a chance of operating with high intensity (ramp up!). A step to β^* around 60 cm should be realizable from the MP and collimation perspective as soon as we confirm the aperture (early commissioning) as well as the orbit and optics reproducibility. With improved temperature stabilization of the BPM crates the reproducibility of the orbit should improve. A combined ramp and squeeze to β^* of 3 m could be injected at this stage (if not done earlier) as a step towards higher efficiency.

Performance estimates for 2015 are given in Table 3 for a stable beams efficiency of 35%. To evaluate the integrated luminosity it was assumed that the first intensity ramp up with 25 ns beam takes the entire 7 weeks of operation at β^* of 80 cm. The integrated luminosity will be around 10-15 fb^{-1}.

SPECIAL RUNS AND IONS

LHCf and VdM Scans

The LHC luminosity (cross-section) calibration is performed in special fills with van de Meer scans (VdM). For a good measurement accuracy, larger β^* (injection value for 4 TeV operation) and emittances are used to lower pile-up and increase the spot sizes for diagnostics. To maintain the same performance than at 4 TeV the scans should be performed with β^* of 20-40 m at 6.5 TeV VdM. A de-squeeze is therefore required with respect to the injection β^* of 10-11 m.

LHCf requested a special low intensity run with β^* in the range of 7-20 m during the first days of operation (radiation damage). Since both LHCf (radiation) and VdM scans (initial calibration) must be scheduled in the first week(s) of operation, it was proposed to combine the LHCf and VdM setups with the same β^*. VdM scans may be performed in all IRs except IR1 in parallel to the LHCf run which saves some operation time. This means however that two setups (low and medium β^*) must be prepared during initial commissioning.

High β^*

The high intensity 90 m run foreseen for 2015 requires a significant setup time, followed by an intensity ramp up. The beam should have up to 1000 bunches of near-nominal intensity with a spacing larger or equal to 75 ns. Assuming that standard injection and ramp are re-used, the preparation of this run requires:

- Low intensity commissioning of the de-squeeze (flat machine) including optics measurements and corrections, preferably done in advance.
- Collision setup and collimator (TCT) alignment,
- MP validation and short intensity ramp up.

The estimated total commissioning time is around 3 days, of similar scale than the VdM setup and ion runs.

Ion Run

The 2015 running period ends with the traditional ion run (Pb-Pb). The preferred energy is 6.37 Z TeV and not 6.5 Z TeV to match the centre-of-mass energy per nucleon of the 2012 p-Pb run at 4 Z TeV. No energy change with respect of the proton run is evidently always simpler, but the overhead of an energy change may be marginal. Since all MPS validations must be repeated with ions and a new combined squeeze of IR1+IR5+IR2 must be setup, changing the energy does create any overhead for the flat top, squeeze and collision. Only the ramp must be shortened a bit and re-tested (with truncated settings). The overhead of lowering the energy should not exceed around 1 shift.

Intermediate Energy Run

An intermediate energy run at 2.56 TeV per beam will be requested for comparison with the Pb-Pb data at 6.5 Z TeV. This run will be setup in a similar way than in 2013:

- The ramp is shortened,
- β^* will remain at its injection value of 10 or 11 m (no squeeze),
- Trains of 25 or 50 ns may be used.

Table 4: Expected performance at 2.56 TeV assuming 35% efficiency for stable beams, β^* of 11 m and a half crossing angle of 170 μrad.

Beam	N (10^{11})	ε^* (μm)	k	$\mathcal{L}_p$ ($\mathrm{cm}^{-2}s^{-1}$)	$\mathcal{L}_{int}$ (pb^{-1}/day)
50 ns	1.2	2.5	1370	1.7×10^{32}	≈ 4
25 ns	1.1	2.5	2500	3.1×10^{32}	≈ 7

In 2013 the setup time was approximately 2 days (1.38 TeV), it is expected to be similar for 2.56 TeV. The expected performance assuming 35% efficiency for stable beams and a half crossing angle of 170 μrad in given in Table 4. With 25 ns beams the requested 30-40 pb^{-1} can be collected in 4-6 days.

SUMMARY

The 2015 run presents the LHC operation teams with a fantastic mix of challenges. In parallel to learning how to operate at 6.5 TeV and with 25 ns beams, it will be essential to prepare the high luminosity operation in 2016 and beyond. It will be essential to remain focused on 25 ns beams. MD periods are likely to be too short for a full program, some time for tests will have to come from the physics operation time. It will be important to define an organized path to lower β^*. Assuming that things progress reasonably, a reduction of β^* should be foreseen in the second 25 ns operation period based on the available information.

REFERENCES

[1] Review of LHC Injectors Upgrade Plans, Archamps, October 2013, https://indico.cern.ch/event/260492,

[2] J. Wenninger, "Integrated Performance of the LHC at 25ns with and without LINAC4", RLIUP Workshop, Archamps, October 2013.

[3] L. Tavian, *Cryogenics*, LHC Beam Operation workshop - Evian 2012, Evian, December 2012, https://indico.cern.ch/conferenceDisplay.py?confId=211614.

[4] 5th Evian Workshop on LHC performance, Evian, 2014, https://indico.cern.ch/event/310353.

[5] R. Bruce, "Baseline Machine Parameters and Configuration for 2015", these proceedings.

[6] V. Kain, "Concerns with Low Emittance Beams Operation", these proceedings.

[7] G. Iadarola, "Scrubbing: Expectations and Strategy, Long Range Perspective", these proceedings.

[8] Y. Papaphilippou, "Operational Beams for the LHC", these proceedings.

[9] J. Uythoven, "Machine Development Priorities", these proceedings.

[10] B. Gorini, "Experiments expectations", these proceedings.

MACHINE PROTECTION STRATEGY FOR LHC COMMISSIONING AND OUTLOOK FOR FUTURE CHALLENGES

B. Salvachua*, C. Bracco, R. Bruce, V. Chetvertkova, L. Ponce,
S. Redaelli, R. Schmidt, J. Uythoven, G.Valentino,
J. Wenninger, D. Wollmann and M. Zerlauth, CERN, Geneva, Switzerland

Abstract

During Run 2, when operating at $6.5\ \mathrm{TeV}$ and $25\ \mathrm{ns}$ bunch spacing, the LHC will accelerate and store beams with an energy of up to $372\ \mathrm{MJ}$. A very tiny fraction of this beam can cause severe damage to accelerator equipment if the energy is released in an uncontrolled way. The note addresses the machine protection considerations for the initial commissioning with and without beam and discusses the required (re-)qualifications for subsequent changes of beam/optics parameters during the run. The definition of the new setup beam intensity - impacting commissioning and later operation and machine developments - is recalled. The note will conclude with an outlook on future challenges with respect to machine protection in view of the injector upgrade and HL-LHC.

INTRODUCTION

After a long shutdown of about 2 years the LHC will start in 2015 producing proton-proton collisions at the new beam energy of $6.5\ \mathrm{TeV}$. The procedures to qualify the machine protection system functionality are being reviewed. The new definition of the maximum intensity allowed in the machine for setup and loss map qualification at the new top energy is presented.

The preferred option by the experiments is the use of $25\ \mathrm{ns}$ bunch spacing filling. In 2012, $50\ \mathrm{ns}$ bunch spacing was used. This has special importance during the intensity ramp-up. Shorter space between bunches may increase electron cloud and this can generate beam emittance growth and increase of beam losses. This note describes the strategy to qualify the machine for the setup with nominal bunches and outlines the different steps during the intensity ramp-up.

On-going studies related to Machine Protection (MP) aspects at injection and an overview of future challenges for High Luminosity LHC with brighter beams will be described in the last section.

MACHINE PROTECTION PROCEDURES

Machine Protection procedures describe all the tests that need to be done by each sub-system in order to qualify its machine protection functionality. A total of 11 procedures are being reviewed before the re-start, see Table 1. In particular, the periodicity of the tests has been addressed as well as the definition of the steps with beam.

Table 1: List of current Machine Protection procedures.

EDMS Nb.	**System**
LHC-OP-MPS-002	Collimation
LHC-OP-MPS-003	Injection Protection
LHC-OP-MPS-004	Beam Interlock
LHC-OP-MPS-005	Powering Interlock
LHC-OP-MPS-006	Vacuum
LHC-OP-MPS-007	Beam Dump
LHC-OP-MPS-008	FMCM
LHC-OP-MPS-009	BLM
LHC-OP-MPS-010	Warm Magnet Interlock
LHC-OP-MPS-014	Software Interlock
In progress	FBCCM

Many systems have been intensively upgraded during the LHC long shutdown, including key elements on the MP chain, like the Quench Protection System (QPS), Beam Loss Monitor (BLM) System and the Collimation System. In several cases, relocation and recabling of several interlock units occurred. For this reason the machine needs a full revalidation during commissioning as for the initial start up.

In order to perform these tests each sub-system should be operationally available and the dependences with other systems as for example LHC Software Architecture (LSA) database, Safe Machine Parameters (SMP),etc. confirmed. The tests without beam include the verification of the input connections to the Beam Interlock System (BIS), the proper triggering of a beam dump from each possible interlock and the correct propagation of the beam interlock signal.

Validation with beam, like loss maps and asynchronous beam dumps are also part of these procedures and will be discussed later.

INITIAL SETUP STRATEGY

The initial setup strategy was outlined in [1]. The first injections at $450\ \mathrm{GeV}$ will be done with pilot bunches ($10^9\ \mathrm{p}$) but a reference machine with a well-established orbit will have to be done with nominal bunches ($\sim 10^{11}\ \mathrm{p}$). This will be followed by collimator alignments, collimator settings validation and LBDS asynchronous beam dump tests.

Definition of Setup Beam Flag

The setup beam flag (SBF) is a parameter used in operation defined to allow the mask of several interlocks. This

---

* belen.salvachua@cern.ch

flag can be used only if the intensity in the machine is smaller than a certain limit.

It is considered to be safe when the beam intensity is below the Copper damage limit. This is 1×10^{12} protons at 450 GeV. A scaling with energy shown in Eq. 1 is applied in order to get the intensity limit at top energy [2].

$$I \text{ [protons]} \leq 1 \times 10^{12} \text{ [protons]} \times \left(\frac{450 \text{ [GeV]}}{E \text{ [GeV]}}\right)^{1.7} . \tag{1}$$

Eq. 1 gives the so-called *Normal* limit, which at 4 TeV is 2.4×10^{10} p, which is smaller than one LHC nominal bunch. This formula provides a very approximate figure of the damage potential of the beam. It does not take into account time and space distribution of losses, bunch structure and material exposed to damage. It is used here as a pessimistic assumption.

This limit at top energy is below the practical to guarantee the correct orbit and collisions. The main constrains are the need of at least 2 nominal bunches for the setup of collisions in all 4 experiments, the sensitivity of the Beam Position Monitors (BPMs) and the beam scraped during the collimation setup alignment, validation through loss maps and asynchronous beam dump test. For the 4 TeV operation period, two additional levels were defined to allow the needed intensity for commissioning and measurements, the so-called *Relaxed* that was established to allow 1 nominal bunch at 4 TeV and the *Very Relaxed* that allowed 3 nominal bunches at 4 TeV. Notice that these 2 levels used during Run 1 were above the damage limit.

The requirements for setup and validation at 6.5 TeV are now reviewed. Taking into account the requirements for collision, setup, collimation alignments and validation, the proposed limits at 6.5 TeV are:

- **Normal SBF:** 5×10^{11} protons at injection and 1.2×10^{10} protons at 6.5 TeV, which is considered to be safe.
- **Restricted SBF:** 5×10^{11} protons at injection and 3×10^{11} protons at 6.5 TeV. This intensity should be distributed in up to 30 probe bunches (with intensity 1×10^{10} protons/bunch) enforced by a software interlock. This setup could be used for specific machine developments with approved MP document.
- **Setup Beam SBF:** up to 3×10^{11} protons, constant from 450 GeV up to 7 TeV, distributed in fewer bunches, 2-3 bunches. This is a more restricted flag, only used for machine setup and collimation alignment and validation. These numbers were reviewed after the workshop, the updated reference can be found in [3].

The scaling with energy is shown in Figure 1. A constant upper limit to the intensity is also enforced to 0.5×10^{12} protons to account for smaller emittances. Notice that the *Restricted* and *Setup Beam* modes have the same limit on the total intensity, but a software interlock forces the distribution of protons over more bunches.

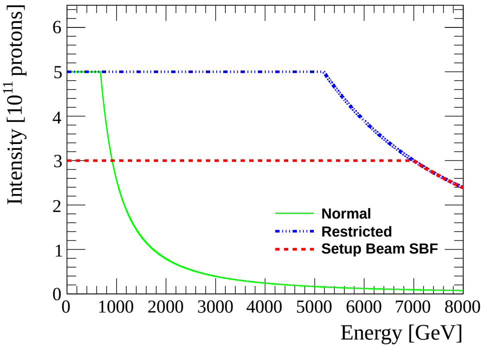


Figure 1: Maximum beam intensity allowed in the machine with the setup beam flag.

MACHINE QUALIFICATION FOR HIGH INTENSITY

The machine must always be qualified after changes in optics, energy, aperture and collimation settings. This is done by analyzing controlled beam losses on the transverse planes, off-momentum losses and asynchronous beam dumps. Table 2 shows the minimum required validation at the start-up. Loss maps and asynchronous beam dump test are required at all stable stages, i.e. injection, flat top, squeezed beam and collisions (or stable beam mode). The betatron loss maps are done exciting each beam independently in the two planes (vertical and horizontal). The off-momentum loss maps are done by changing the RF frequency up and down (both signs also) by a small amount, typically ±500 Hz. In this case the loss map is done simultaneously for Beam 1 and Beam 2. Validation during dynamic stages as energy ramp and beam squeeze is still to be decided depending on the final choice for beam operation.

Table 2: Minimum required validation after changes in the machine.

Beam Mode	**Betatron lossmaps**	**Off-mom. lossmaps**	**Asyn. dump**
Injection	X	X	X
Flat top	X	X	X
Squeezed	X	X	X
Collisions	X	X	X

Provided that the orbit is stable and that there are no changes and the machine has been qualified for the corresponding collimator settings no additional tests are required. However a minimum validation of the cleaning must be guaranteed and monitored through loss maps at regular intervals. During Run 1 this minimum periodicity was set to 3 months or a technical stop [4].

Intensity Ramp-up

The overall intensity ramp-up strategy is presented in [5] and can start after the machine is qualified at low intensity. The restricted Machine Protection Panel (rMPP) will follow the intensity ramp-up, they will analyze each intensity step and decide whether to proceed to the next step. A detailed check list for each intensity step will be filled by the rMPP [6]. The proposed baseline is to have a minimum of 3 fills with more than 20 h of stable beam running in total for each intensity step but, as it was done in the past, the panel might request to reduce or increase the number of stable beam hours depending on the operational performance.

Experience from Run 1

In 2011 the intensity ramp-up was similar to what it is proposed for Run 2. There were 2 phases, the first being the ramp-up at 75 ns which happened without major problems. In the middle there were scrubbing runs to reduce the electron cloud. The second phase corresponds to the intensity ramp-up with reduced bunch spacing (50 ns), see Figure 2. The first steps were also smooth but after some running hours we started to find technical problems such as cooling, controls, etc. We should think about this phase as the debugging and validation period of the new operational settings. It is later, when the intensity exceeded 500 bunches that were observed beam related issues, like vacuum spikes in IR2 and IR8 and the first fast losses due to macro particles falling into the beam [7]. In some cases it was difficult to continue with the ramp-up, it took 41 fills to go from 912 b to 1092 b. Overall, the ramp-up in 2011 took 9 weeks.

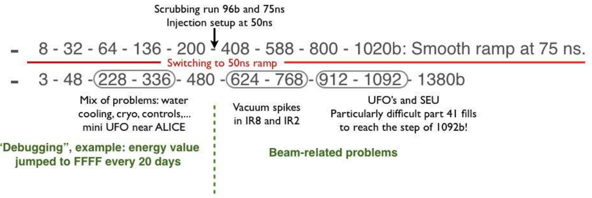


Figure 2: Intensity ramp-up in 2011.

In 2012, however, the ramp-up was very fast, only 15 days. The bunch spacing was 50 ns, identical to 2011, but the main change was the increase of beam energy from 3.5 TeV to 4 TeV. The shutdown was very short and the machine showed an excellent reproducibility. The number of intensity steps could be reduced to 6, and the number of stable beam running hours for 264 b and 624 b was also reduced to $4-6$ h.

Proposal for Run 2

For 2015 many systems have been changed, including the most relevant for Machine Protection like collimation, beam loss monitors and quench protection system. The debugging of the system will be done during machine checkout and low intensity commissioning, nevertheless an intensity ramp-up at 50 ns has been proposed to reproduce the same operational scenario as in Run 1 with higher energy (6.5 TeV). This ramp-up will be done in 9 steps from 50 bunches up to 1380 bunches and is supposed to last up to 3 weeks [5]. At this new energy beam losses are more important and the machine will operate with losses closer to the quench limit of the magnets. Unavoidable phenomena like the interaction of dust particles with the beam (UFO losses) and beam losses due to diffusion and collimation cleaning will have to be addressed and the beam loss monitor thresholds adapted accordingly to allow a safe operation of the machine [8].

After the machine has been trained at 50 ns there will be the intensity ramp-up at 25 ns. Six weeks are scheduled for this second ramp-up as it is assumed that the system will be completely debugged. For this case 11 steps are proposed from 140 bunches up to 2800 bunches [5]. However, electron-cloud might become more important at 25 ns and it could be the source of additional beam losses. Depending on the performance during the first intensity steps rMPP could decide the change the number of stable beam hours required before injecting up to 2800 bunches.

ON-GOING STUDIES

In preparation for Run 2 and Run 3 several studies are currently on-going to re-evaluate aperture limitation in the injection areas.

- **LHCb spectrometer crossing and separation bump amplitudes:** In order to solve the problem of the LHCb spectrometer polarity for the 25 ns bunch spacing the crossing and separation bump amplitudes in IR8 were modified. Table 3 shows the crossing angle and separation for Run 1 and Run 2. The n1 values were re-calculated for Run 1 and Run 2 scenarios and they were found to be very similar. The calculation includes the tilt on Q5 in both IPs (2 mm down on the septum side and 1 mm up on the other side). The critical aperture for the injected beam (kicked or not) is Q5, with $n1 = 4.4$ in IP8 and $n1 = 5.95$ in IP2 which is sufficient margin. For the stored beam (kicked) the critical aperture is D2 with $n1 = 5.5$ for both IP2 and IP8, which is also sufficient [9].
- **ALICE new chamber:** In preparation for High Luminosity LHC (HL-LHC), ALICE is preparing to install a smaller beam pipe during the next LHC Long Shutdown II. The first proposal was limiting the aperture in the experiment to $4\ \sigma$. The beam pipe designed was modified to keep the bottleneck in the arc and to guarantee a minimum aperture of $7.5\ \sigma$ [10, 11].

FUTURE CHALLENGES

LHC has highly overpopulated beam tails. This was measured in dedicated scraping beam tests in 2012 and it was found that at 450 GeV about 4 % of the beam is distributed after $4\ \sigma$ [12]. For the nominal LHC this corresponds to 14.5 MJ of stored energy in the beam tails. The

Table 3: Crossing angle and parallel beam separation in the injection regions for Run 1 and Run 2 [9].

	IP2 Run 1	**IP2 Run 2**	**IP8 Run 1**	**IP8 Run 2**
V-crossing $\mu\mathrm{rad}$	±170	±170	0	-40
H-parallel sep. mm	±2	±2	0	0
H-crossing $\mu\mathrm{rad}$	0	0	∓170	∓170
V-parallel sep. mm	0	0	∓2	∓3.5

situation does not improve with HL-LHC parameters, the stored energy will be almost doubled and thus the beam tail population will be about $30\ \mathrm{MJ}$ assuming similar overpopulated distributions. The collimation system is designed for fast accidental beam losses of up to $1\ \mathrm{MJ}$ [13]. This is of more importance during HL-LHC, with new failures scenarios on the ultra-fast loss time scale, relying on passive protection (collimation system). These are:

- very fast perturbation of beam orbit due to missing long range beam-beam deflection [7],
- ultra-fast failures of crab-cavities [7] and
- injection losses after the injectors upgrade that will reduce the beam size with BCMS scheme [14].

In order to ensure the protection of the machine in the next years there are several studies to improve the cleaning and the monitoring of fast losses. In particular the upgrade on the collimation system [15] with the study of more robust materials and better control of beam tails.

CONCLUSIONS

During LHC long shutdown 1 we took the opportunity to review and update the machine protection procedures that will be followed during the start-up. As a result, the definition of the Setup Beam Flag for the operation of $6.5\ \mathrm{TeV}$ was established, evaluating the needs of different levels of setup beam: for machine developments and measurement and for beam commissioning.

Before moving to higher intensities, the role of the restricted machine protection panel will be re-established and, as it was done in Run 1, they will analyze every step on intensity following the check list procedures. The baseline for moving a step up in intensity is requiring 3 fills with more than $20\ \mathrm{h}$ of stable beam conditions. However, rMPP will keep the flexibility to modify this baseline based on the results of the check list analysis.

Run 2 will provide additional insights on approaching future challenges in Machine Protection with operation at $25\ \mathrm{ns}$ in view of high brightness beams with HL-LHC.

ACKNOWLEDGMENTS

The authors would like to acknowledge the contribution from LHC operation, collimation and machine protection teams.

REFERENCES

[1] L. Ponce et al., “Commissioning and Operation of Machine Protection systems”, 5th Evian Workshop, 2014.

[2] V. Kain, “Machine Protection and Beam Quality during the LHC Injection Process”, CERN-THESIS-2005-047.

[3] J. Wenninger, “LBOC report including detailed commissioning plans, and tools for beta* levelling”, LHC Machine Committee, 10th September 2014.

[4] B. Salvachua et al. “LHC Collimation Cleaning and Operation Outlook”, LHC Beam Operation Workshop, Evian, 2012.

[5] J. Wenninger, “Strategy for Run 2”, these proceedings.

[6] rMPP check list: EDMS Doc. LHC-0000005946.

[7] T. Baer, “Very Fast Losses of the Circulating LHC Beam, their Mitigation and Machine Protection”, CERN-THESIS-2013-233.

[8] B. Auchmann, “BLM Threshold Strategy (vs UFOs and Quenches)’, these proceedings.

[9] J. Uythoven, “Apertures in the case of injection failures including the new IR8 crossing scheme”, LHC Machine Committee, 3rd September 2014.

[10] M. Giovannozzi, New ALICE beam pipe: aperture, 2nd TREX meeting, 31st July 2014.

[11] M. Lamont, ”ALICE beam pipe, 189th LMC meeting, 10th September 2014.

[12] F. Burkart et al. “Halo Scraping with collimators in the LHC”, IPAC2011, San Sebastian, Spain.

[13] O. Bruning et al. “LHC Design Report”, CERN, Geneva, 2004, CERN-2004-003-V-1.

[14] V. Kain et al. “Concerns with low emittance beam operation”, these proceedings.

[15] S. Redaelli et al. “Collimation and MP Roadmap”, these proceedings.

MACHINE DEVELOPMENT PRIORITIES

J. Uythoven, G. Arduini, R. Tomas, G. Papotti
CERN, Geneva, Switzerland

Abstract

The Machine Development requirements for Run 2 are largely determined by the overall commissioning plan of the LHC in 2015 and foreseen operational challenges related to optics, beta* squeeze, instabilities and equipment performance. Electron cloud scrubbing is not part of the MDs. The requests from the different groups involved, expressed during the "MD Day" on 2 September 2014, are presented and evaluated in the context of importance for the machine performance, the constraints imposed by the available beams (from the injectors and in the LHC) and the available MD time. Organisational aspects of the MDs, like procedures, contact persons and MD notes, will also be outlined.

INTRODUCTION

Machine Development (MD) aims at improving the understanding of the LHC, its equipment and beam physics in general. This should result in the improvement of machine performance (=integrated luminosity) *on the longer term*. MDs are performed in designated periods on the LHC schedule and some days of floating MD, which are indicated as such on the MD schedule.

MDs have to be compared to 'Operational Development' and 'Commissioning' defined work, which have an *immediate* impact on the machine performance and are performed during the foreseen commissioning period, intensity ramp-up period or physics time. Electron cloud scrubbing and related beam tests are not part of the MD time either.

A correct balance between measurements to be done as MD and work done during Operational Development or Commissioning time needs to be found.

As a start-up year after the Long Shutdown 1, 2015 will be a special year with a large part of the year devoted to the re-commissioning of the machine at the new top energy of 6.5 TeV and with the new nominal bunch spacing of 25 ns. No MD periods are foreseen during this re-commissioning period [1]. Many results of what would normally be qualified as MD will be required before the first MD period. On top of this, some MD like measurements can be performed very efficiently during the initial start-up because of the different energy ramps with low beam intensities foreseen. For these reasons it is very important to determine before start-up the measurements that should be part of the re-commissioning period and the measurements that have to be performed as MD.

In this paper the measurements required for 2015, either during the commissioning period or during the MD periods, will be outlined by analysing the presentations by the different interest groups during the LHC Studies Working Group Day on 2 September 2014 [2]. Longer term MD request, going up to LS3, are presented in [3]. Finally the organisational framework for the MDs in Run 2 will be outlined, taking into account organisational and machine protection aspects.

STATISTICS OF MDS DURING RUN 1

The MD time during the LHC Run 1, attributed to the main user groups, is shown in Fig. 1. The distribution is based on a total of 657 MD hours. It clearly shows that the ABP group is the main user with optics, aperture, collimation, instabilities and beam-beam related topics. Second largest user is the RF group, followed by injection studies.

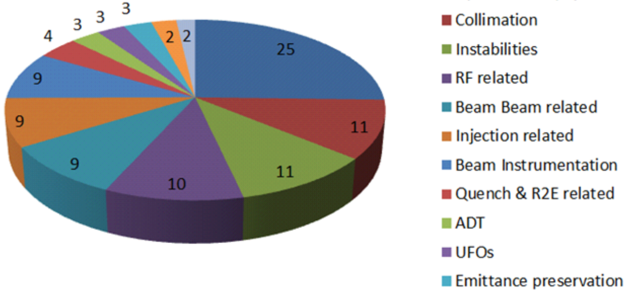


Figure 1: Main MD users in % of total MD time for the LHC run 1.

PLANNING FOR RUN 2

Presently three MD blocks of 5 days are foreseen in week 28, 37 and 45 plus an additional floating MD of 4 days, see Fig. 2. Due to the time required for re-commissioning after LS1, this is less than during a normal operational year. The first MD is foreseen late July. This means that 'urgent' MD-like measurements need to be done during the initial commissioning period. It also needs to be noted that during the first MD block no high intensity 25 ns beams will be available.

The second MD block is presently foreseen just before a change to lower beta*. Results from this MD block come too late to be included in the timely planning for the run with lower beta* and therefore the studies required to define the minimum values of the beta* in operation in the second half of the run will have to be performed well before the second MD block as part of the operational development.

As in other years it is foreseen to combine the MD blocks with dedicated runs or studies, e.g. scrubbing runs or special physics run. This will have a positive impact on the overall physics programme (fewer interruptions) but implies a heavy load on the operational teams and experts.

Figure 2: Provisional LHC schedule [1] with foreseen MD periods.

SUMMARY PER INTEREST GROUP

Below a brief summary of the LSWG meeting [2] is given per interest group. The meeting took place over ¾ of a day with 58 people present. The presenters were asked to recall the main MD results of LHC Run 1 and give a first look at requests for LHC Run 2, differentiating between measurements as part of the commissioning period and measurements as MDs.

Linear and Non-linear Optics, Measurements and Corrections (E.H. Maclean)

During Run 1 there were 10 MDs used for Optics Measurements and Corrections, 3 for linear and 3 for non-linear optics plus 4 MDs on ATS optics, all resulting in one MD note.

For Run 2 commissioning the following measurements are required: polarity checks, chromatic coupling, coupling feedback, beam based corrections of b4 and amplitude detuning throughout the cycle.

MD requests for Run 2 concerning the linear optics consist of stability of nominal optics and modular corrections for dynamic beta* changes (e.g. for beta* levelling); study of off-momentum optics corrections especially at half integer tunes. The choice of working point at injection and throughout the cycle is also of interest. Concerning the non-linear optics possible MD topics consist of the Q’ and Q’’ discrepancy, natural chromaticity measurements and Q’’ in the ramp, Q’’’ and chromatic amplitude detuning and improvement of the non-linear model of the LHC, especially at point 5.

ATS Optics (S. Fartoukh)

During Run 1 four MDs were dedicated to the ATS optics. It was demonstrated that a beta* of about 12 cm could be reached. It has been decided [4] that the ATS optics is not part of the initial commissioning in 2015 but its validation is sufficiently close and the appropriate MD time/OP time for the validation studies of ATS compatible optics should be found in the schedule to move to the ATS optics.

MDs concerning ATS optics can be dedicated to ATS flat optics, to be validated with few nominal bunches, the development and validation of special telescopic round optics for maximising the MO efficiency. Anti-ATS optics can be investigated for obtaining very large beta*.

Collimations, Crystals and Halo Control (S. Redaelli)

MDs during Run 1 were used for developing fast alignment of the collimators, quench tests, tight collimator settings and impedance measurements.

The new collimators, including those with integrated BPMs, will need to be brought into operation during commissioning. Effectiveness of the new TCLs and measurement of collimation impedance and improving the loss maps should all be part of the commissioning.

Run 2 MD request contain the following topics: collimation quench tests at 6.5 TeV; tighter collimation hierarchy, linked to impedance limits; faster collimator alignment with BLMs and integrated BPMs; passive abort gap cleaning in IR3; halo population scans at 6.5 TeV; an ambitious programme of crystal collimation experiments and finally halo control measurements.

Single and Two beam Stability (T. Pieloni)

During Run 1 MDs the growth rate of instabilities, related to octupole thresholds, chromaticity settings and damper gain were measured. Stability diagrams were obtained and coherent beam-beam and impedance measurements made (good beam 1 data are still missing).

During the commissioning period MO polarity and current, chromaticity and damper gain will need to be optimised to stabilise the beam throughout the cycle. The knowledge of machine parameters throughout the cycle remains very important and one will need to profit from set-up of pilot, single nominal bunches and trains during the commissioning period for the measurements.

For Run 2 the combination of single and two beam stability studies is possible. Topics are: remaining studies on instability growth vs. chromaticity, damper gain and octupole polarity; diffusion mechanism and impact on distribution profiles; collide and squeeze development; bunch-by-bunch and turn-by-turn measurements; beam-beam long-range studies with 25 ns, noise on colliding beams, flat beams, half-integer tune.

Impedance and Beam Induced Heating (B. Salvant)

Tune shift measurements during Run 1 gave discrepancies with the impedance model of up to a factor 2. The effect of bunch length reduction on the beam induced heating of the different devices has been measured.

During the beam commissioning in 2015 many of the beam impedance measurements can be performed parasitically. The impedance of the modified elements (TDI, TCDQ, TCTP and Roman Pots) need to be measured early in the run.

As MDs in 2015 the re-assessment of intensity limits due to impedances, compared to Run 1, is important. Other MDs consist of the localisation of impedance sources and the related heating of non-modified devices. The effect of changing bunch length and/or profile on the beam induced heating, impedance with changing gaps versus the number of bunches and the feasibility to optimise the beta function to reduce the transverse impedance are of interest.

Beta Levelling and Collide and Squeeze (A. Gorzawski)*

During Run 1 there were three MDs on beta* levelling and collide and squeeze. The feasibility has been proven, see Fig. 3, with a beta* being varied from 3 m to 0.6 m and from 9 m to 3 m. During these tests the TCTs were kept at the 0.6 m settings.

During the commissioning period of Run 2 no beta* and collide and squeeze are foreseen and it remains to be determined when these options will be put in operation. MDs can be used at the end of fills, including loss maps and asynchronous dump tests. Set-up time and validation will be required before it can be used in normal operation.

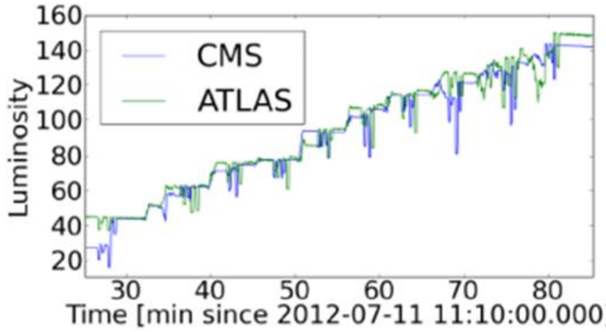


Figure 3: The measured luminosity during the variation of the beta* in collision (fill 2829).

RF studies in the LHC (E. Shaposhnikova)

Over the various RF MDs in Run 1 in total 16 MD notes have been written. During the initial commissioning in Run2 the various RF parameters will need to be optimised: main RF voltage, phase modulation, longitudinal emittance, bunch length and profile (related to beam induced heating).

Several MDs can be foreseen for Run 2: minimal RF voltage required to maintain Landau damping at 6.5 TeV; longitudinal bunch profile evolution during coast with and without collision; controlled RF phase modulation; longitudinal single and multiple bunch instabilities; emittance blow-up and shaping at 6.5 TeV in the presence of synchrotron radiation and longitudinal impedance evaluation, where there is discrepancy of a factor 2 to 3 with the model.

Transverse Damper (W. Höfle)

Run 1 has seen a combination of operational development and MDs related to the transverse damper. The transverse damper has been used in many other MDs of other groups.

During the commissioning in 2015 the new transverse damper diagnostics, including the new “Observation Box”, should be brought into operation. This diagnostic tool will be vital for the understanding of potential instabilities during operation. Improvements in abort gap cleaning, using bipolar pulses, will need be brought into operation if needed. The damping will be required during the scrubbing runs and the stabilisation of the beam during 25 ns running will need to be optimised. The active excitation of the leading bunch for tune measurements can be further developed as can the measurement of the tune with the transverse damper. Loss maps with full beam by selective excitation of some bunches at the end of the fill can also be envisaged.

As part of the MDs for Run 2 a collaboration with the collimation team is foreseen to test halo cleaning with the transverse damper. Another possible MD is the benchmarking of the equations describing the transverse emittance blow-up resulting from the noise in the transverse feedback system.

Beam Instrumentation (T. Lefevre)

In Run 1 there was one MD period used for dedicated beam instrumentation measurements with 4 – 5 different activities per MD period. The aim was to measure performance limitation of the different operational devices.

All beam instrumentation will need to be commissioned during the Run 2 setting-up period, taking into account that all instrumentation has been modified in one way or another. In MDs the measurements that are not possible parasitically during normal beam operation and are not part of initial commissioning need to be made: further work on the dI/dt interlocking, directional strip-lines and the BPMs in the LSSs; bunch intensity scraping of nominal bunches and bunch length dependency of the different measurements; instability monitoring and triggering, emittance blow-up, different cross-calibrations etc.

Injection and Dump (J. Uythoven)

Injection studies during Run 1 were used for optimising the shielding in the injection regions, TDI alignment, quench margin measurements and studying the effect of tails on injection losses. UFO studies at the MKIs and MKQs were performed. On the beam dump side the TCDQ alignment studies were performed, quench margins were determined and abort gap studies took place.

Part of the normal commissioning will be the set-up of injection of 50 ns and 25 ns beams and the beam dump system together with injection gap and abort gap cleaning. The different injection and beam dump movable absorbers will need to be set up with beam. The new BETS systems on the TDI, MSI and TCDQ will need to be commissioned. Beam induced heating of the modified TDI will need to be verified. On the beam dumping system the effective rise time of the MKD system will need be determined with beam during the set-up of the Abort Gap Keeper.

MDs during Run 2 will concern injection stability, steering and injection losses, setting-up of the blindable BLMs, matching monitors and special set-up of the TCDIs and TDIs if required. Simulation of MKI failure losses and measurements, abort gap cleaning algorithms, tests of the new BSRA hardware and software, studies of the interlocked BPMs, relative TCDQ / TCT retraction and losses and Q4 quench levels in Point 6 belong to possible topics of study.

Quench Tests (B. Auchmann)

During Run 1 eight different quench tests were performed, including end-of-run tests. Tests took place for three different loss time scales: single turn, UFO time scale and steady-state losses.

No dedicated measurements are foreseen during the Run 2 commissioning period. However, a lot of data might come for free, especially UFO related. BLM thresholds need to be set accordingly.

MDs during Run 2 will again concentrate on quench tests for the three different time scales mentioned above. Improved diagnostics with LICs will be available for the Q4s in Point 6. ADT quench tests can be repeated for UFO time scale losses and steady-state losses, with improvements concerning the experimental set-up and the underlying model.

PROCEDURES

To improve the efficiency certain MD ‘rules’ will be tightened for Run 2. A written procedure will be required for *each* MD, to be submitted at least two weeks before the start of the MD period. In the past this was only required for the approval from the restricted Machine Protection Panel (rMPP), but it was noted that good procedures significantly improved the efficiency during the MD. Approval of the MD topics is to take place prior to the MD period by the LMC (at least one week). The approval by rMPP for those MDs that are considered as potentially dangerous for the machine will remain and should also be part of the approval by the LMC

The plan is to have each MD linked to a contact person within the OP group, either EIC or operator, who should help to prepare the MD and the procedures, taking into account the available beams and set-up time required in the LHC and injectors. For practical reasons, it will be difficult to always have this same person on shift for the MD, although this is preferable.

Each MD should be written up in an MD note, to be published in the four weeks following the MD. This does not have to be a full analysis of the measurements, but should at least refer to all the measurements made. This will help in the planning of any future MDs on similar topics and will be obligatory before any future MDs on the same topic are scheduled.

CONCLUSIONS

The list of possible MD topics is at least as long as for Run 1 and the limited MD time will need to be distributed carefully. Formal, written requests will be collected in early 2015. Priorities will be decided when the requests have been received. A Web page is under preparation for an efficient MD request management.

Anything which is vital for machine operation will be part of the initial Run 2 commissioning and not the MDs. The MD programme will also be affected by issues encountered during the commissioning. High priority measurements during the commissioning period are: aperture measurements; measurement of impedance of modified elements close to the beam, especially collimators; stability of the beam with octupoles, chromaticity and transverse damper; tune measurements with the transverse damper and the initial tests with the Observation Box of the transverse damper and parasitic UFO quench tests.

High priority early MDs are: change of intensity limits compared to Run 1, related to modified impedance; more beam stability studies; long range beam-beam effects with 25 ns bunch spacing and variation of the crossing angle; collimation hierarchy and tight collimation settings related to the impedance of the collimators; additional measurements with the BPMs integrated in the collimators; beta* levelling and collide & squeeze tests. Other important MDs concern the ATS optics, including the simulation of asynchronous dump losses for this optics with the less favourable phase advances.

If it is decided to apply beta* levelling during normal operation many measurements (like orbit stability and optics) should already have been done during normal operation. Required information from MD results consists of: collimator hierarchy linked to collimator impedance, beam stability limits and instability growth rates and long range beam-beam effects. During the commissioning of the low beta* optics the collimation set-up should be performed.

Finally it is to be noted that strict procedures before, during and after the MDs will be applied to optimise the efficiency.

REFERENCES

[1] J.Wenninger, "Strategy for Run 2", these proceedings.
[2] http://indico.cern.ch/event/331020/
[3] G.Arduini, "Down selection criteria and MDs prior to LS3", these proceedings.
[4] Minutes of the 188th LMC meeting 03/09/2014, https://espace.cern.ch/lhc-machine-committee/Minutes/1/lmc_188.pdf

BLM THRESHOLD STRATEGY (UFOs AND QUENCHES)

B. Auchmann, T. Baer, R. Bruce, F. Cerutti, B. Dehning, L. Esposito, E.B. Holzer,
A. Lechner, O. Picha, S. Redaelli, M. Sapinski, N. Shetty, E. Skordis

Abstract

The interaction of the LHC's proton beam with falling macroparticles (dust) in the beam tube causes beam losses with durations ranging from tens of microseconds to several milliseconds. After the long shutdown, the beam energy will be increased from 4 towards 6.5 TeV, as a consequence of which some of these beam-particle interactions, colloquially called "UFOs", are predicted to cause quenches in superconducting magnets. In-depth experimental and numerical studies have been performed to make the most efficient use possible of the LHCs beam-loss monitoring (BLM) system to minimize the number of quenches, while keeping the number of avoidable beam dumps due to the BLM system to a minimum. The results of these studies are presented here, as well as preliminary strategies for the setting of BLM thresholds for the protection of warm magnets and collimators.

ARC UFOS PRE AND POST LS 1

Predictions for UFOs in the Arcs

As the beam energy in the LHC will be increased from 4 to 6.5 TeV, the energy-deposition in superconducting coils due to collisions of the proton-beam with falling macroparticles (UFOs) will increase by a factor 2.4 . At the same time, the minimum quench-energy in the superconducting coils will decrease by a factor 2-3, depending on the duration of the UFO losses [1]. The combination of these two effects means that some UFO losses are expected to be sufficiently important to quench superconducting magnets in the LHC; compare [2]. The most likely functional region around the LHC ring for UFO-induced quenches and/or beam dumps is expected to be the arc region[3]. This assumption is supported by the observation that the UFO hotspots in the injection-kicker regions, which exhibited a high rate of activity prior to the LHC long shutdown (LS 1), have been overhauled with measures that have proven their efficiency in selected locations already during Run 1 [5].

Another relevant observation from Run 1 is the (de)conditioning seen during 2011/12 and illustrated in Fig. 1. After every winter stop, the rate of UFOs in the arcs increased (deconditioning), slowly approaching a lower asymptotic value over the subsequent weeks (conditioning). Another marked increase in UFO rate was observed during opertion with 25-ns bunch spacing. For the early weeks of Run 2 we have to expect an increased UFO activity with a subsequent conditioning, both, during the initial 50-ns operation, and after the switch to 25-ns bunch spacing.

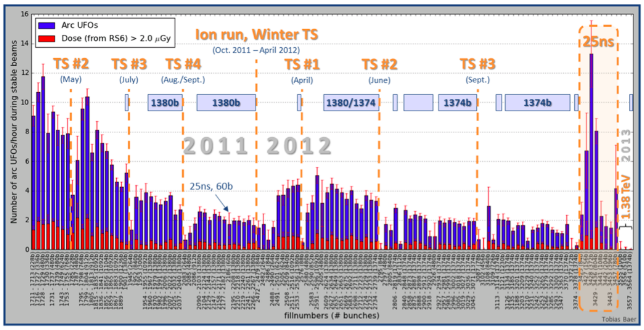


Figure 1: Number of arc UFOs per hour during stable beams in 2011 and 2012. Courtesy T. Baer, [2].

Based on the semi-analytical model of beam-macroparticle interactions of [6, 7], the loss-duration of UFO events decreases linearly with beam size. The reduced beam size at 6.5 TeV will therefore lead to ∼20% shorter losses than at 4 TeV. The significance of this lies in the comparison of the maximum design-response time of the LHC machine protection system (MPS) with the rise time of UFO-induced losses. The maximum MPS response time is 3 turns or $\sim 270\,\mu$s, with typical response times ranging between 80 and $170\,\mu$s [8]. UFO-loss rise-times in ~6000 events recorded during 2011-2012 (3.5 and 4 TeV beam energy, respectively) were found in the range between 50 and $300\,\mu$s [9]. Even though the semi-analytical model predicts that UFO events with higher losses also have longer durations, it cannot be excluded that some UFOs can cause a magnet to quench *before* the MPS can dump the beam due to a BLM trigger.

Measures Taken during LS 1

A mitigation of the origin of UFOs in the arcs, similar to the actions taken in the injection kickers, was not possible during LS 1. Certainly, the risk attached to quenches in the main circuits of the LHC are a lesser after LS 1. This is due to the refurbishment and control of all interconnections, and the qualification by CSCM tests [10] of the current bypass in the RB circuits. Nonetheless, quenches in main magnets at currents equivalent to 6.5 TeV beam energy are expected to lead to more than eight hours of down time – considerably more than a beam dump due to a BLM trigger. The avoidance of quenches, as well as the avoidance of unnecessary beam dumps, are, therefore, decisive factors for the availability of the machine at 6.5 TeV in the

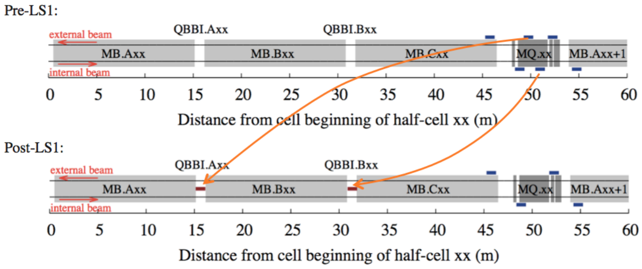


Figure 2: Relocation of BLMs in the arcs and DS from horizontal positions on MQ magnets to vertical positions above the MB-MB interconnects; courtesy A. Lechner [1].

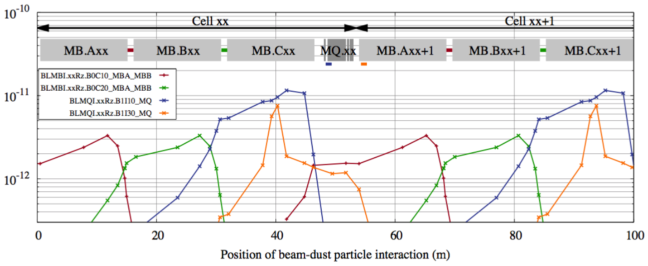


Figure 3: BLM signals in the in the new BLM locations in an arc cell. The signals are plotted as a function of UFO location. Courtesy A. Lechner [1].

presence of UFOs.

Prior to the observation of UFOs, it was assumed that beam-losses in the arcs could occur only in the MQ magnets, where the beta-function is largest. As a consequence, all MQ magnets were equipped with six BLMs each, mounted horizontally, three on either side of the cryostat. For the detection of UFOs in MB magnets, this configuration is not well suited. According to FLUKA simulations [11, 12], the ratio in BLM signal between a macroparticle-proton interaction at the beginning of a half-cell, and the signal of the same type of interaction at the MB-MQ interconnect was 70. The consequence of this bad spatial resolution was that, in order to avoid all UFO-induced quenches, UFOs at the MB-MQ interconnects would have caused dumps already at loss levels 70 times below the actual quench level – with dire consequences for LHC availability.

To mitigate this effect, the central BLMs were relocated from their horizontal MQ positions to vertical positions above the MB-MB interconnects; see Fig. 2. Figure 3 shows FLUKA simulations of BLM signals in the new locations as a function of UFO location. Each signal corresponds to a single interaction between a proton and a macro-particle (carbon). It can be seen that three BLMs (red, green, and blue) together cover the full length of a half-cell. For each detector, the ratio between minimal and maximal signal within its range is down to two or three from the factor of 70 that was mentioned above.

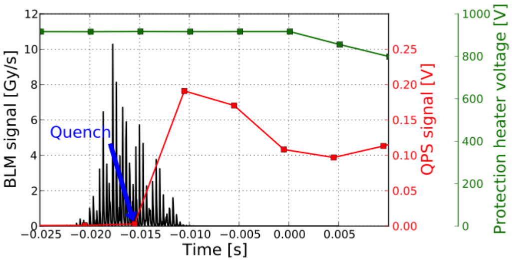


Figure 4: BLM signals and QPS signals recorded during the fast orbit-bump quench test in MQ.12L6.

Lessons Learnt from Quench Tests

After a first beam-induced quenches at injection in 2008 and 2009, dedicated quench tests were performed in 2010, 2011, and 2013. The goal of these experiments was to induce quenches in accelerator magnets by controlled beam losses, the analysis of which would permit to quantify the quench level in the affected magnets at their respective operating points. Losses were induced in the nano-second regime (single-turn losses), over several milliseconds, or over several seconds, thus testing the quench level for different relevant loss mechanisms. The test most relevant for UFOs int he arcs is the fast orbit-bump quench test of 2013 [15, 14, 13], quenching an MQ magnet after roughly ten milliseconds.

The analysis of this test revealed that the magnet quenched after a deposition of four times more energy than expected. This result gives grounds for hope as far as the electrothermal stability of arc magnets vis-a-vis UFOs is concerned. The interpretation of the result is, however, not straight forward. Figure 4 shows BLM and QPS signals recorded during the event. Not only is the precise moment of quench difficult to determine (given the five-millisecond resolution of QPS data), but the BLM signals reveal a substructure of short pulses. This substructure may well have been responsible for the elevated quench levels that were observed.

We conclude that the real quench level in case of UFO events may be up to a factor four higher than the model; an overview of quench test results and quench-level estimates is shown in Fig. 5. For this reason, we propose to implement a correction factor four in the BLM thresholds of all integration times below 80 milliseconds for arc BLMs. Experience will show whether this optimistic assumption is justified.

New BLM Thresholds for the Arcs

BLM thresholds for the protection from quenches in superconducting magnets are formulated by the three below

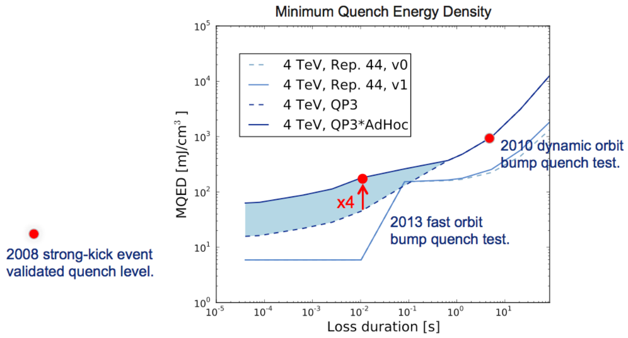


Figure 5: Electro-thermal estimate of quench levels as a function of loss duration in MB mid-plane inner-layer turn at 6.5-TeV equivalent current. The horizontal axis of the graph spans the range of BLM signals, i.e., the relevant range of integration-times for the setting of BLM thresholds.

formulas:

$$\text{BLMSignal@Quench} = \frac{\text{BLMSignal}(E) * \text{QuenchLevel}(E,t)}{\text{EnergyDeposit}(E)} \tag{1}$$

$$\text{MasterThreshold}(E,t) = N * \text{BLMSignal@Quench} * \text{AdHoc}(E,t) \tag{2}$$

$$\text{AppliedThreshold}(E,t) = \text{MonitorFactor} * \text{MasterThreshold}(E,t). \tag{3}$$

The QuenchLevel factor, given in mJ/cm^3, is the electro-thermal estimate given by the QP3 software [16]. The BLMSignal, given in Gy/proton, and the EnergyDeposit, given in mJ/(cm^3 proton), are the results of FLUKA simulations. The FLUKA simulation represents the type of loss scenario to which the BLMs are set to react. Results for the UFO scenario are shown in Figs. 3 and 6 [17]. Note that, even if the FLUKA and QP3 simulations are highly accurate w.r.t. the given beam-loss scenario, any deviation of a real event from that scenario means that thresholds will not be set in the optimum way to protect from quenches and avoid unnecessary dumps. The ratio of QuenchLevel and EnergyDeposit gives the number of protons lost to provoke a quench in the given scenario. This number is multiplied by the BLMSignal to give the BLMSignal@Quench.

AdHoc corrections are foreseen to implement operational experience, and to implement missing features in the FLUKA and QP3 models. For example, the factor four mentioned above is implemented as an AdHoc correction. The factor N, where $N > 1$ deliberately sets the master threshold higher than the presumed BLMSignal@Quench. It works in conjunction with the MonitorFactor, where $0 < \text{MonitorFactor} \leq 1$, which allows to tune thresholds efficiently during operations on a per-monitor basis. The factor N, which allows to set thresholds above quench levels, has to ensure that any beam-loss event is intercepted safely below damage levels. Note, howver, that quench levels are expressed in mJ/cm^3, whereas damage-levels are expected to be many J/cm^3, leaving some latitude for threshold tuning. In 2009, $N = 3$ and $\text{MonitorFactor} = 0.1$ was the standard setting. For after LS1, we propose for the arcs $N = 3$ and $\text{MonitorFactor} = 0.33$, i.e., to set the AppliedThreshold to the BLMSignal@Quench, adjusted by AdHoc corrections. This is done to find, in the most efficient way possible, the optimal BLM thresholds in terms of protection and availability. Figure 7 compares pre-LS1 settings (BLMSignal@Quench$*$AdHoc) with the proposal for post-LS1 settings. It can be seen that, despite a large discrepancy in the quench-level data (see Fig. 5), the thresholds are very similar. This is due to the fact that the increase in QuenchLevel is more than counterbalanced by the worse BLMSignal/EnergyDeposit ratio of the UFO scenario w.r.t. the scenario used during Run 1 (losses on the MB-MQ interconnects).

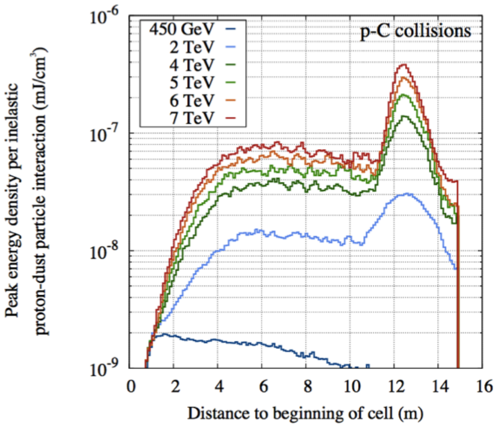


Figure 6: Peak energy deposition in MB coil per proton-dust-particle interaction for different beam energies. The dust particle is assumed to be made of carbon. The characteristic peak is due to neutral particles hitting the downstream beam pipe due to the slight curvature of the MB magnets. Courtesy A. Lechner [1].

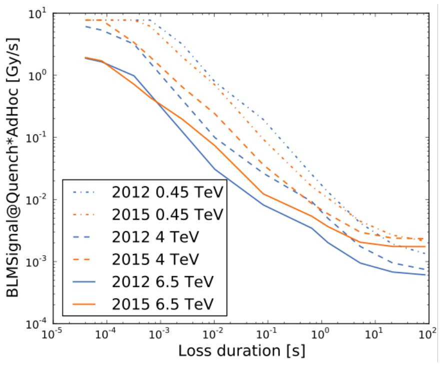


Figure 7: Comparison of BLMSignal@Quench$*$AdHoc between pre- and post-LS1 settings in a BLM mounted in position 1 of an MQ magnet in the arc for different energies and loss durations.

It is interesting to note that BLMs in the arcs are set to prevent quenches in MB magnets only. MQ magnets are then implicitly covered as well. UFO locations that produce the highest losses in the MQ magnet are found in Fig. 3 at the location of the the narrow orange peak. Quench levels in MQ magnets, however, are higher than MB inner layer quench levels, and neutral particles in quadrupoles are much smaller and, hence, the energy deposition in quadrupoles is lower than in dipoles.

Since UFO losses are relevant only in time intervals below 10 ms and for energies above 4 TeV, another beam-loss scenario should be adopted to set thresholds for losses longer than 10 ms and lower energies. The scenario of an inadvertently set orbit bump was studied, based on the analysis of several orbit-bump type quench tests. The orbit-bump scenario would lead to lower thresholds than the UFO scenario at very low energies (where the peak of neutral particles fades away; see Fig. 6), and to higher thresholds at longer time intervals and higher energies. In order to cover both scenarios, UFOs and orbit-bumps, we are currently studying whether the orbit-bump scenario could be applied for the settings of the downstream BLM at the MQ (orange in Fig. 3), and the UFO scenario for the upstream BLM at the MQ (blue in Fig. 3).

BLM THRESHOLDS IN OTHER LOCATIONS

Cold Magnets

The UFO scenario is relevant for all cold magnets around the ring. Only very specific regions need to be studied for other scenarios. Note that it is proposed to use a less aggressive setting for magnets in the matching section, separation dipoles, and inner-triplet quadrupoles. If in the arcs and dispersion suppressors we use a MonitorFactor of 0.33 to set the AppliedThreshold to the BLMSignal@Quench, in those other regions, we propose a MonitorFactor of 0.1, as in LS 1. The reason for this decision is that fewer spare magnets are available, and the likelihood for quenches due to UFOs in the affected magnets is much smaller due to geometrical considerations and larger margins.

Dispersion Suppressor Most of the dispersion-suppressor region is handled analogously to the arcs. Only few monitors in IRs 3 and 7 may see their thresholds raised in the long integration times to accommodate non-quench-provoking losses from the collimation regions, which have a very large BLMResponse/EnergyDeposit ratio. A number of dipole magnets close to the IPs and collimation regions are equipped with horizontally mounted BLMs. These have been installed for ion operation, to monitor specific loss locations due to secondary ion beams. These monitors will be set for the specific ion-loss scenario, and raised if necessary to prevent them from interfering with proton operation.

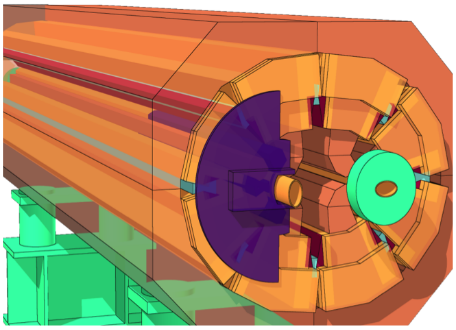


Figure 8: Detail of the FLUKA model of MQW magnets. Courtesy of E. Skordis.

Matching Section Quadrupoles The UFO scenario for BLM thresholds in the matching-section quadrupoles has been studied, based on similar FLUKA models as the ones presented above. Since the resulting thresholds would be very high (close to the electronic maximum), we are studying an orbit-bump scenario, taking into account the different cable properties of individual magnet types in the quench-level model.

Separation Dipoles Similarly, separation dipoles will be protected against quenches from UFO losses. They require a different FLUKA model from arc dipoles as they are not bent and, therefore, are not exposed to the neutral particles emanating from the proton-macro-particle collisions.

Inner Triplets Three differente loss scenarios are considered for the triplet. The UFO scenario is used in Q1 and Q3. For Q2, due to the very large beta function, an orbit-bump-like scenario is used, documented in [21]. In addition, it must be made sure that collision debris, with its much larger BLMSignal/EnergyDeposit ratio, cannot trigger beam dumps in the longer integration times at top energy [18]. This is ensured by means of AdHoc corrections.

Warm Magnets

Detailed FLUKA models of MQW magnets, including the shielding elements installed during LS 1 (see Fig. 8), are used to set thresholds in warm magnets. The protection goal here is to stay safely away from damage to the beam pipe (for short integration times) [19], and from overheating the water-cooled coils (for long integration times).

Collimators

The goals for the setting of BLM thresholds for collimators are to ensure their protection from damage, and to ensure the hierarchy of collimators. The proposed strategy is to set the thresholds as tight as possible, based on loss-maps to be carried out at the beginning of Run 2. A combination of updated damage levels in terms of the allowable number of protons lost for the respective scenario [22], and FLUKA models will provide a cross-check to ensure that the thresholds thus obtained protect the collimators from damage under all circumstances.

SUMMARY

We have presented the rationale for the setting of BLM thresholds in the LHC after LS 1. The most important topic is the determination of optimal BLM settings in the arcs vis-a-vis UFO-induced losses. A body of knowledge in terms of FLUKA models and quench-test analyses are at our disposal to make a first setting. For the arcs thresholds are chosen rather optimistically. Some UFO-induced quenches in the arcs are to be expected. This will serve to find the final and optimal settings in the most efficient way possible. With the new BLM locations we will be able to localize UFOs all around the arcs and prevent UFO-induced quenches while causing a minimal amount of unnecessary beam dumps. BLM thresholds are under preparation for all BLM families around the ring, to be ready for first beams in spring 2015.

REFERENCES

[1] A. Lechner, B. Auchmann, T. Baer, F. Cerutti, V. Chetvertkova, B. Dehning, E. B. Holzer, O. Picha, M. Sapinski, N. V. Shetty, and E. Skordis. BLM thresholds for post-LS 1 LHC operation: UFOs and orbit bumps in the arcs and straight sections. Presentation at the Workshop on Beam-Induced Quenches, September 2014.

[2] T. Baer. *Very fast losses of the circulating LHC beam, their mitigation and machine protection*. PhD thesis, Universität Hamburg, 2013.

[3] T. Baer, M. J. Barnes, E. Carlier, F. Cerutti, B. Dehning, L. Ducimetiere, A. Ferrari, N. Garrel, A. Gerardin, B. Goddard, E. B. Holzer, S. Jackson, J. M. Jimenez, V. Kain, A. Lechner, V. Mertens, M. Misiowiec, R. Ballester, E. Nebot, L. Drosdal, A. Nordt, J. Uythoven, B. Belghe, V. Vlachoudis, J. Wenninger, C. Zamantzas, F. Zimmermann, and N. Fuster. UFOs in the LHC after LS1. *Proceedings of the 2012 LHC Performance Workshop*, January 2012.

[4] T. Baer, M. J. Barnes, F. Cerutti, A. Ferrari, N. Fuster, N. Garrel, B. Goddard, E. B. Holzer, S. Jackson, A. Lechner, V. Mertens, M. Misiowiec, E. Nebot, A. Nordt, J. Uythoven, V. Vlachoudis, J. Wenninger, C. Zamantzas, and F. Zimmermann. UFOs in the LHC: Observations, studies, and extrapolations. *Proceedings of IPAC 2012, New Orleans, Louisiana, USA*, (THPPP086):3936–3938, 2012.

[5] W. Bartmann, LBDS and Kickers after LS 1, these proceedings.

[6] F. Zimmermann, M. Giovannozzi, and A. Xagkoni. Interaction of macro-particles with LHC proton beam. *Proceedings of IPAC 2010, Kyoto, Japan*, (MOPEC016):492–494, 2010.

[7] N. F. Martinez, U. Valencia, F. Zimmermann, T. Baer, M. Giovannozzi, E. B. Holzer, E. Nebot, A. Nordt, M. Sapinski, and Z. Yang. Simulation studies of macroparticles falling into the LHC proton beam. *Proceedings of IPAC 2011, San Sebastian, Spain*, (MOPS017):634–636, 2011.

[8] M. Zerlauth. private communication, 2014.

[9] T. Baer. Statistics on temporal UFO profiles based on BLM study buffer data. Presentation at the UFO Study Working Group, September 2012.

[10] S. Rowan, B. Auchmann, K. Brodzinski, Z. Charifoulline, R. Denz, H. Pfeffer, I. Romera, V. Roger, A. Siemko, R. Schmidt, J. Steckert, H. Thiesen, A. Verweij, G. Willering, D. Wollmann, and M. Zerlauth. CSCM: Experimental and simulation results. *Proceedings of IPAC 2014, Dresden Germany*, (THPRI093):3988–3990, June 2014.

[11] A. Fasso, et al., "FLUKA: a Multi-Particle Transport Code", CERN-2005-10, INFN/TC_05/11, SLAC-R-773, 2005.

[12] G. Battistoni, et al., "The FLUKA Code: Description and Benchmarking", Proceedings of the Hadronic Shower Simulation Workshop 2006 at Fermilab, Batavia, IL, USA, AIP Conference Proceeding, Vol. 896, p. 31–49, 2007.

[13] V. Chetvertkova, B. Auchmann, T. Baer, W. Hofle, A. Priebe, M. Sapinski, R. Schmidt, A. Verweij, and D. Wollmann. MADX tracking simulations to determine the beam loss distributions for the LHC quench tests with adt excitation. *Proceedings of IPAC2014, Dresden Germany*, (THPRI094):3991–3993, 2014.

[14] M. Sapinski, B. Auchmann, T. Baer, W. Bartmann, M. Bednarek, S. Bozyigit, C. Bracco, R. Bruce, F. Cerutti, V. Chetvertkova, K. Dahlerup-Petersen, B. Dehning, E. Nebot, E. Effinger, J. Emery, A. Guerrero, W. Hofle, E. B. Holzer, A. Lechner, A. Priebe, S. Redaelli, B. Salvachua, R. Schmidt, N. V. Shetty, A. Siemko, E. Skordis, M. Solfaroli, J. Steckert, J. Uythoven, D. Valuch, A. Verweij, J. Wenninger, D. Wollmann, and M. Zerlauth. Beam-induced quench tests of LHC magnets. *Proceedings of IPAC 2014, Dresden Germany*, (MOOCB01):52–54, 2014.

[15] N. V. Shetty, B. Auchmann, V. Chetvertkova, A. Lechner, A. Priebe, M. Sapinski, A. Verweij, and D. Wollmann. Energy deposition and quench level calculations in the millisecond and steady-state quench tests of lhc arc quadrupoles at 4 TeV. *Proceedings of IPAC 2014, Dresden Germany*, (MOPRO019):105–107, 2014.

[16] A. Verweij. *QP3: Users Manual.* CERN, 2008.

[17] A. Lechner. BLM thresholds for post-LS1 LHC operation: UFOs and orbit bumps in the arcs and straight sections. Presentation at the BIQ2014 Workshop on Beam-Induced Quenches, CERN, Geneva, September 2014.

[18] L. Esposito. Luminosity debris and Inner Triplet BLMs. Presentation at the BIQ2014 Workshop on Beam-Induced Quenches, CERN, Geneva, September 2014.

[19] V. Kain, J. Ramillon, R. Schmidt, K. Vorderwinkler, J. Wenninger. Material damage test with 450 GeV LHC-type beam. Proceedings of PAC05, Knoxville, USA, p. 1607–1609, May 2005.

[20] S. Redaelli. Collimator BLM threshold strategy. Presentation at the BIQ2014 Workshop on Beam-Induced Quenches, CERN, Geneva, September 2014.

[21] F. Cerutti, B. Dehning, A. Ferrari, C. Hoa, M. Mauri, A. Mereghetti, M. Sapinski, and E. Wildner. Estimation of thresholds for the signals of the BLMs around the LHC final focus triplet magnets. ATS-Note 2012-014 TECH, CERN, Geneva, Switzerland, January 2012.

[22] M. Sapinski, A. G. Alonso, and T. Böhlen. Initial settings of beam loss monitors thresholds on LHC collimators. Technical Report EDMS 995569, CERN, August 2009.

[23] E. Todesco (Editor). Proceedings of the BIQ2014 Workshop on Beam-Induced Quenches, CERN, Geneva, September 2014, to be published.

R2E AND AVAILABILITY

M. Brugger on behalf of the R2E Mitigation Project
CERN, Geneva, Switzerland.

Abstract

The Radiation to Electronics (R2E) Project is responsible for the development and the implementation of mitigation actions to minimize the radiation induced failures in the electronics and thus to optimize the availability of the Large Hadron Collider (LHC). Significant shielding and relocation mitigation actions, coupled with a large number of equipment upgrades are being implemented during the first LHC Long Shutdown of 2013/2014 (LS1) in five LHC Points (Points 1, 4, 5, 7 and 8) and for electronics deployed in the remaining critical areas such as the LHC tunnel and adjacent RRs. This report first provides a brief summary of the radiation levels, the observed failures during Run-1, the LS1 R2E activities with particular focus on the expected improvements on the overall system failures. The last part of the report focuses on the qualification strategy, including radiation hardness assurance procedures and test facilities.

INTRODUCTION

Particle debris emerging from the experiments, secondary showers from collimators or other beam intercepting devices, as well as beam–gas interactions impact equipment being present inside and areas adjacent to the LHC tunnel (UJs, RRs). Respectively installed (present or future) control systems are either fully commercial or based on so-called COTS (Commercial-Off-The-Shelf) components, both possibly affected by radiation. This includes the immediate risk of so-called Single Event Effects (SEE) and a possible direct impact on beam operation, as well as in the long-term, also cumulative dose effects (impacting the component/system lifetime) which additionally have to be considered.

For the tunnel equipment in the existing LHC, certain radiation tolerant design criteria were already taken into account prior first LHC operation. However, most of the equipment placed in adjacent and partly shielded areas was not conceived nor tested for their current radiation environment. Therefore, given the large amount of electronics being installed in these areas, during the past years a CERN wide project called R2E (Radiation To Electronics) [1] has been initiated to quantify the danger of radiation-induced failures and to mitigate the risk for nominal beams and beyond to below one failure a week. The respective mitigation process included a detailed analysis of involved radiation fields, intensities and related Monte-Carlo calculations; radiation monitoring and benchmarking; the behaviour of commercial equipment/systems and their use in the LHC radiation fields; as well as radiation tests with dedicated test areas and facilities [2, 3].

In parallel, radiation induced failures were analysed in detail in order to confirm early predictions of failure rates [4, 5], as well as to study the effectiveness of implemented mitigation measures. Figure 1 shows the actual number of SEE failures measured during 2011 and 2012 operation, the achieved improvement (please note that the failure rate measured during 2011 already included mitigation measures implemented during 2009 and 2010), as well as the goal for operation after LS1 and later during HL-LHC.

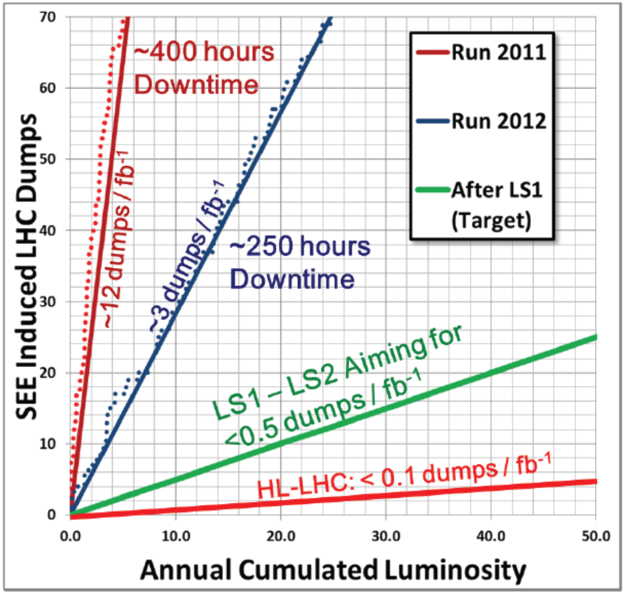


Figure 1: LHC beam dumps due to single-event effects against beam luminosity. Dots (2011 and 2012) refer to measurements, whereas lines show annual averages for both, past and future operation.

This implies that electronic control systems are either installed in fully safe areas, sufficiently protected by shielding or adequately radiation tolerant. The last implies existing equipment, but also any future equipment to be possibly installed in R2E critical areas to be conceived in a specific and qualified way – a procedure usually referred to as 'Radiation Hardness Assurance (RHA)' [6].

RADIATION ENVIRONMENT AND CRITICAL AREAS

Radiation damage to electronics is often considered with space applications. However, it is important to note that the radiation environment encountered at the LHC, the high number of electronic systems and components partly exposed to radiation, as well as the actual impact of radiation induced failures strongly differ from the context of space applications. While for the latter application design, test and monitoring standards are already well defined, additional constraints, but in some cases also simplifications have to be considered for accelerator environment. The mixed particle type and energy field encountered in the relevant LHC areas is composed of charged and neutral hadrons (protons, pions, kaons and neutrons), photons, electrons and muons ranging from thermal energies up to the GeV range [7].

Over the past years, this complex field has been extensively simulated by the FLUKA Monte Carlo code and benchmarked in detail for radiation damage issues at the LHC [8-11]. The observed radiation is due to particles generated by proton–proton (or ion–ion) collisions in the LHC experimental areas, distributed beam losses (protons, ions) around the machine, and to beam interacting with the residual gas inside the beam pipe. The proportion of the different particle species in the field depends on the distance and on the angle with respect to the original loss point, as well as on the amount (if any) of installed shielding material. In this environment, electronic components and systems exposed to a mixed radiation field will experience three different types of radiation damages: these are displacement damage, damage from the Total Ionising Dose (TID) and the SEEs [11]. The first two are of cumulative nature and are measured through TID and nonionizing energy deposition (NIEL, generally quantified through accumulated 1-MeV neutron equivalent fluence), where the steady accumulation of defects cause measurable effects which can ultimately lead to device failure. As for stochastic SEE failures, they form an entirely different group as they are due to the direct ionization by a single particle, able to deposit sufficient energy through ionization processes in order to disturb the operation of the device. They can only be characterized in terms of their probability to occur as a function of accumulated High Energy (>5–20 MeV) Hadron fluence. The probability of failure will strongly depend on the device as well as on the flux and nature of the particles. In the context of HL-LHC, several tunnel areas close to the LHC tunnel, and partly not sufficiently shielded, are equipped with commercial or not specifically designed electronics which are mostly affected by the risk of SEEs, whereas electronics installed in the LHC tunnel will also suffer from accumulated damage in the long-term.

For this purpose, during the first years of LHC operation, the radiation levels in the LHC tunnel and in the shielded areas have been measured by using the CERN RadMon system [12] dedicated to the analysis of radiation levels possibly impacting installed electronic equipment. Table 1 summarises the level of accumulated High Energy Hadron (HEH) fluence measured during 2012 for the most critical LHC areas where electronic equipment is and will be installed. The HEH fluence measurements are based on the RadMon reading of the Single Event Upsets (SEU) of SRAM memories whose sensitivity was extensively calibrated in various facilities [13-16]. The results obtained during 2012 LHC proton operation show that the measurements very well compare with previously performed FLUKA calculations and observed differences can actually be attributed to changes of operational parameters not considered in the calculations [5].

EQUIPMENT FAILURE ANALYSIS

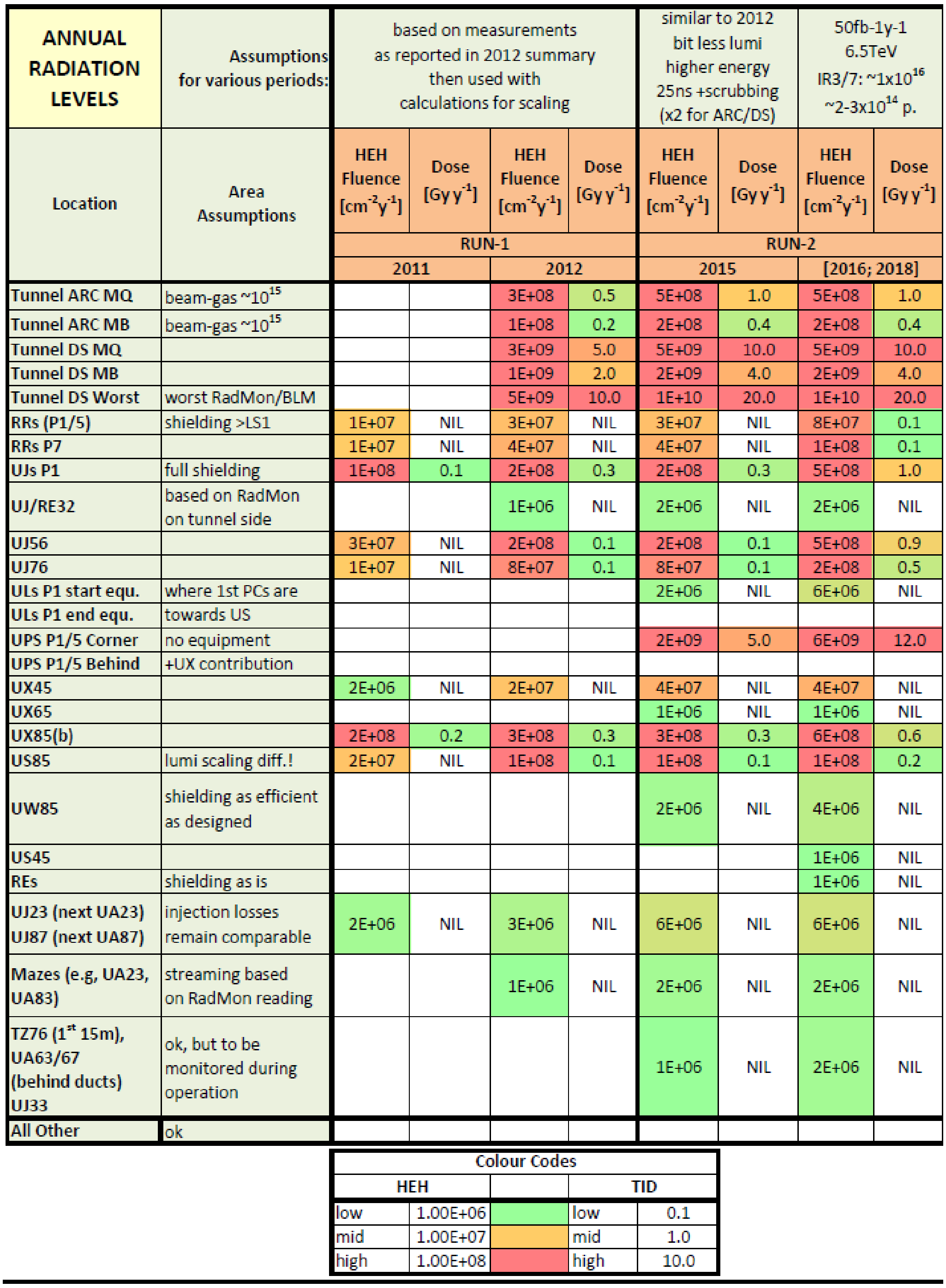
2012 LHC operation was a key period for the analysis of radiation induced failures on machine equipment. As briefly shown in the previous section, the very successful LHC operation has confirmed the estimates of the radiation levels provided in Chamonix 2012 and successfully confirmed the strategy of early mitigation measures taken in previous years. During 2012 a strong emphasis was put in the detailed analysis of equipment failures which could possibly be linked to radiation effects and to verify if all of them are addressed throughout the LS1 mitigation measures. To study the correlation with radiation in detail, a number of criteria have been set, implying one, several and, ideally, all of the following conditions to be fulfilled:

- equipment failure occurs during periods with beam-on/collisions/losses (*i.e.*, source of radiation)
- the failure(s) is/are not reproducible in the laboratory
- the failure signature was already observed during radiation tests (CNRAD, H4IRRAD and others)
- failure frequency increases with higher radiation

For rare cases this implies remaining uncertainties which can lead to failures being incorrectly attributed to radiation. However, the performed detailed studies over the 2012 operation period limited these uncertainty cases to only a few. In addition, there is the complementary limitation that the analysis is likely to miss radiation induced failures which do not lead to a beam dump. In addition more complex events where a particular unit is affected by radiation, then in turn indirectly causing a problem to another one, thus eventually leading to either longer downtimes or beam dumps.

The radiation induced failures on the LHC equipment have been analysed by organizing a weekly shift within the R2E project team. The main sources of information were the LHC e-logbook and the meeting on the LHC operation follow-up, daily held at 8h30. During the year, the collaboration of all the equipment groups was highly appreciated and permitted to improve the performed failure analysis. Once a failure is suspected to be related to radiation effects, the following information is collected and stored on the web page of the RADiation Working Group (RADWG) [6]: a) equipment, b) type of failure, c) location, d) consequence of the failure, e) number of beam fill. In some cases, it is not straight forward to understand if a failure was effectively due to radiation effects. Thus, the event is marked as *to be confirmed (TBC)* if a further analysis is required to understand what happened. In addition, the number of the beam fill was used as a direct link to insert information also in the Post Mortem (PM) database and in order to track the beam dumps that were due, or possibly due (*to be confirmed*), to radiations and require a respective detailed analysis by the operators and the equipment groups. Table 2 shows the failures due to SEEs.

Table 1. Overview of critical areas and respective radiation levels (please note that local distributions can vary according to the detailed location – values refer to worst case locations).



ANNUAL RADIATION LEVELS	Assumptions for various periods:	based on measurements as reported in 2012 summary then used with calculations for scaling				similar to 2012 bit less lumi higher energy 25ns +scrubbing (x2 for ARC/DS)		50fb-1y-1 6.5TeV IR3/7: ~1x10^{16} ~2-3x10^{14} p.	
Location	Area Assumptions	HEH Fluence [cm^{-2}y^{-1}]	Dose [Gy y^{-1}]	HEH Fluence [cm^{-2}y^{-1}]	Dose [Gy y^{-1}]	HEH Fluence [cm^{-2}y^{-1}]	Dose [Gy y^{-1}]	HEH Fluence [cm^{-2}y^{-1}]	Dose [Gy y^{-1}]
		RUN-1				RUN-2			
		2011		2012		2015		[2016; 2018]	
Tunnel ARC MQ	beam-gas ~10^{15}			3E+08	0.5	5E+08	1.0	5E+08	1.0
Tunnel ARC MB	beam-gas ~10^{15}			1E+08	0.2	2E+08	0.4	2E+08	0.4
Tunnel DS MQ				3E+09	5.0	5E+09	10.0	5E+09	10.0
Tunnel DS MB				1E+09	2.0	2E+09	4.0	2E+09	4.0
Tunnel DS Worst	worst RadMon/BLM			5E+09	10.0	1E+10	20.0	1E+10	20.0
RRs (P1/5)	shielding >LS1	1E+07	NIL	3E+07	NIL	3E+07	NIL	8E+07	0.1
RRs P7		1E+07	NIL	4E+07	NIL	4E+07	NIL	1E+08	0.1
UJs P1	full shielding	1E+08	0.1	2E+08	0.3	2E+08	0.3	5E+08	1.0
UJ/RE32	based on RadMon on tunnel side			1E+06	NIL	2E+06	NIL	2E+06	NIL
UJ56		3E+07	NIL	2E+08	0.1	2E+08	0.1	5E+08	0.9
UJ76		1E+07	NIL	8E+07	0.1	8E+07	0.1	2E+08	0.5
ULs P1 start equ.	where 1st PCs are					2E+06	NIL	6E+06	NIL
ULs P1 end equ.	towards US								
UPS P1/5 Corner	no equipment					2E+09	5.0	6E+09	12.0
UPS P1/5 Behind	+UX contribution								
UX45		2E+06	NIL	2E+07	NIL	4E+07	NIL	4E+07	NIL
UX65						1E+06	NIL	1E+06	NIL
UX85(b)		2E+08	0.2	3E+08	0.3	3E+08	0.3	6E+08	0.6
US85	lumi scaling diff.!	2E+07	NIL	1E+08	0.1	1E+08	0.1	1E+08	0.2
UW85	shielding as efficient as designed					2E+06	NIL	4E+06	NIL
US45								1E+06	NIL
REs	shielding as is							1E+06	NIL
UJ23 (next UA23) UJ87 (next UA87)	injection losses remain comparable	2E+06	NIL	3E+06	NIL	6E+06	NIL	6E+06	NIL
Mazes (e.g, UA23, UA83)	streaming based on RadMon reading			1E+06	NIL	2E+06	NIL	2E+06	NIL
TZ76 (1st 15m), UA63/67 (behind ducts) UJ33	ok, but to be monitored during operation					1E+06	NIL	2E+06	NIL
All Other	ok								

Colour Codes				
HEH			TID	
low	1.00E+06	🟩	low	0.1
mid	1.00E+07	🟧	mid	1.0
high	1.00E+08	🟥	high	10.0

Table 2: Number of failures due to radiation. A detail view of the destructive events is given below.

Dump Confirmed	**Dump TBC**	**No Dump**	**No Dump TBC**
58	10	36	7
Destructive Failures			
17	1	4	0

Four distinct failure cases are reported:

a) Events leading to beam dump (Dump confirmed).
b) Events leading to beam dump which are possibly due to radiation (Dump TBC).
c) Failures which did not lead to beam dump (No Dump).
d) Failures which do not lead to beam dump and are possibly due to radiation (No Dump TBC).

The second part of Table 2 highlights the observed destructive failures, i.e. failures which triggered an intervention in the machine to replace a component/system. They represent ~30% of the total number of events leading to a beam dump. It is important to note that the number of events to be confirmed represents only a small fraction and will thus not affect the overall conclusion. Figure 2 shows the distribution of the failures per area (a) and per equipment (b). The failures per area are almost equally distributed among the alcoves which were known to be prone to radiations.

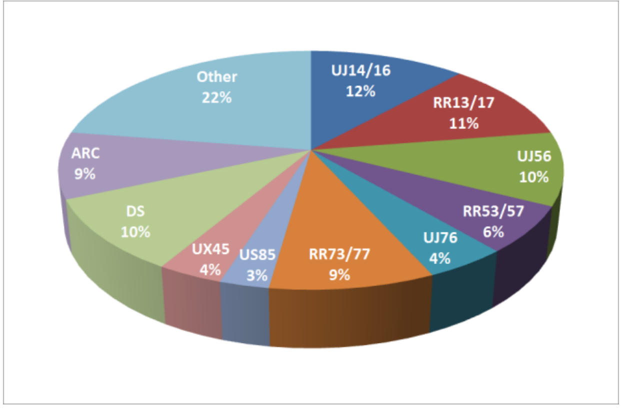


Figure 1a: Failure distribution per area

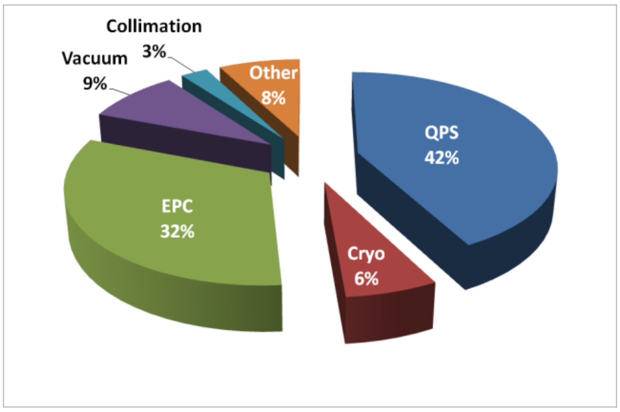


Figure 1b. Failure distribution per equipment.

As compared to 2011 operation and the respective observed SEE related failures [4], this also reflects the successful implementation of R2E countermeasures where the focus was put on the most exposed areas, thus bringing all of the critical areas more or less to the same exposure level (also visible in the reported radiation levels for 2012). I.e, the number of failures in the UJs of Point 1 is not as dominant as along 2011, showing the effectiveness of the shielding that was put in place in the 2011-12 xMasBreak [2, 3]. The majority of the failures that occurred in the tunnel was related to the Quench Protection System (QPS) electronics. The EPC equipment, installed in the RR areas, presented a recurrent failure due to a destructive event on an auxiliary power supply. In addition to the shielding at point 1, the relocation of a few sensitive equipment (Cryogenic, Beam, Power interlocks, and UPS devices), as well as the patch solutions applied on the equipment that could not be moved yet, allowed to significantly decrease the overall number of failures with respect to 2011.

LS1 RELOCATION & SHIELDING ACTIVITIES

During 2012 operation, monitored radiation levels as well as in parallel carried out Monte-Carlo simulations (FLUKA) have motivated additional actions to be performed in Point 4, in addition to those already scheduled in Points 1, 5, 7 and 8 (see Figure 3) and the respective implementation involves fifteen groups across the different CERN Departments [17-19].

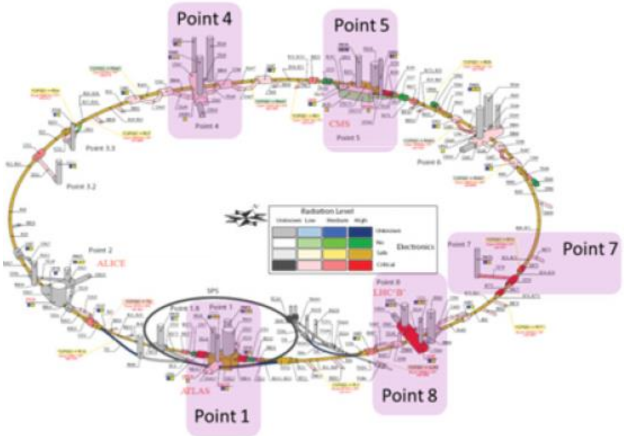


Figure 3: LHC critical areas considered for shielding and relocation activities.

The foreseen improvements to mitigate the effects of radiation to electronics were studied in detail. This will allow the beam dumps caused by SEEs to be further reduced according to the requirements for nominal LHC operation (from originally ranging in the few hundreds to only a few tens). As mentioned above, already only for the relocation activities, in total fifteen groups are involved in the relocation of a total of 90 racks, ranging from power converters, electrical equipment, to safety control units located in Points 1, 4, 5, 7 and 8. The existing concrete shielding of the RRs located in Points 1 and 5 is at the same time replaced by cast iron. Additional shielding is installed at Point 8 and major civil engineering works are carried out at Point 5 and Point 7 (ducts, removal of walls).

Point-4

During 2012 LHC operation, only very few failures (but major as impacting cryogenics control equipment) were observed on the cryogenics equipment located in

LHC Point 4. A possible future increase of the radiation levels could not be excluded during future changes in beam operation, however at first the relocation of the cryogenics equipment was put on hold, mainly due to the cable length limitation of special existing cables (15 metres) avoiding the equipment relocation outside the close surrounding area. In parallel, the cryogenics team (TE/CRG) successfully collaborated with firms to develop longer cables which resulted in the first production and test of longer cables (40 m) during the first semester of 2013. This provided us the opportunity to study together with the cryogenics team and other impacted equipment groups the relocation options for all critical equipment installed in Point 4. It turned out that several months were required for the relocation activities that could thus only be carried out during a Long Shutdown (LS). After a preliminary planning and the confirmation of the availability of required resources, by the end of May 2013 the LHC LS1 Committee gave its approval to perform these relocation activities during LS1.

The work towards implementation followed three main phases. The first phase was the identification/definition of the sensitive equipment to be relocated [20]. In addition to one Personal Access Door (PAD) and one fire detection control unit the following cryogenics equipment was identified as equipment to be relocated: the cold compressor system, the cold box 1.8 K, the cryogenics distribution box 4.5 K, the associated SIPART valves positioners and the control system of the cryogenics RF cavities. The second phase was the study of the activities to be performed with their associated technical and integration issues. The third phase was the definition of the activities sequence and then the definition of the baseline planning. The mitigation activities started in January 2014. They were scheduled over 26 weeks with only two weeks of margin with the start of the 'flushing' activity in the adjacent sectors.

Safe Rooms

The electrical services dedicated to personal safety as general emergency stop, safety lighting etc., are installed underground in dedicated 'safe - rooms' ensuring the functionality of their inner equipment during two hours in case of external fire. Part of this equipment was found to be sensitive to radiation (Single Event Effects (SEE)) and in the Points 5 and 7 the 'safe - rooms' were located in areas identified as critical in terms of radiation. It was thus decided to relocate the sensitive parts respectively, to the UL557 and in the TZ76 galleries. Due to space constraints, a classical implementation of a 'safe room' (constructed through walls, etc.) in the TZ76 gallery was not possible. The only respective way would have implied long and costly civil engineering work. The alternative solution was to relocate the equipment inside several individual and certified fire resistant enclosure with a dedicated and integrated ventilation system (see Figure 4).

In Point 5, due to safety constraints linked to the CMS experiment emergency exit path and due to integration issues, the optimal solution was to build a new 'mini safe room' in the UL557 with reduced dimensions. The associated ventilation system had to be located in the adjacent UL558 gallery. The design and implementation of this ventilation system were not trivial and required to solve several technical and safety issues (e.g., the respective ventilation control system allowing for highly reliable and fully redundant cooling during LHC operation).

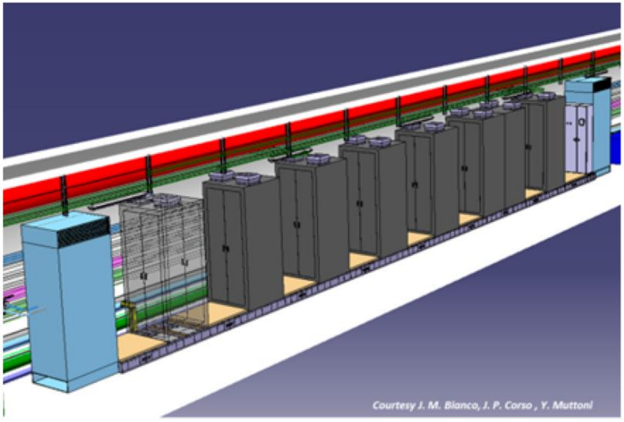


Figure 4: Relocation of Point 7 safe room equipment inside individual fire resistant enclosure.

EQUIPMENT UPGRADES & DEVELOPMENTS

To provide an example for very complex accelerator control systems and respective design/mitigation constraints to be carried out during LS1, we give a brief description of two key systems for the LHC machine: the Quench Protection System and the Power Converters, and how radiation tolerant strategies are applied taking into account the criticality of the system, the location, the impact of its failure on machine operation and the available timeline for developments and required upgrades.

For both cases, a review of the initial design with radiation tolerant constraints was required because a large number of individual units are installed in locations exposed to various radiation levels. In particular, the QPS case study provides an example of radiation tolerant development where a trade-off and simplifications had to be considered because of tight time line constraints (as upgrades were required in a very short available time-frame). The power converter case study provides an example of a radiation tolerant development over a longer time period where design and mitigation measures can be included and tested for at various levels.

QPS

The protection systems for the LHC main dipole, lattice quadruple magnets, and the corresponding bus-bars are located in racks placed underneath the main dipoles inside the accelerator tunnel (ARC) together with the data acquisition system and the associated quench heater power supplies. In case of a quench the latter energize the heater strips mounted on the magnet coils. Annual radiation levels of more than 10 Gy or $1x10^{10}cm^{-2}$ high-energy hadrons have to be considered. In addition, the electronics for protecting the dipoles and the quadrupoles of the insertion region, and the inner triplets is located in partly shielded areas where radiation levels are lower, but still a factor of 100-10000 times higher than at surface.

The QPS equipment consists of custom boards, developed at CERN by using COTS ("Components Of The Shelf) components. The equipment to be installed in the tunnel was conceived to be radiation tolerant up to a total dose of 200 Gy, which corresponds to a high-energy hadron fluence of $\sim 2x10^{11}cm^{-2}$, considered for the evaluation of the SEE cross section, however, not all components were qualified according to the system requirements as implemented in the final installation. In addition, no radiation constraints were imposed for the design of the electronics of the partly shielded areas. With those requirements, the QPS team designed the tunnel equipment with robust solutions based on classical analogue and digital circuitry, which were tested individually against radiations. Conversely, more sophisticated components such as micro-controllers and digital signal processors (DSP) were used for the shielded area boards.

A strict radiation test and qualification strategy could not be followed due to production time-line constraints. The main critical components of the tunnel boards were tested but the component lots were not individually qualified, neither a systematic tests of the entire boards in its actual functioning mode could be carried out prior installation. This was acceptable due to the expected continuous increase of LHC performance, thus a respective increase also in terms of radiation exposure, in this way allowing for corrective measures to be taken during early operation [21].

As expected, the first years of LHC operation confirmed the very good system design, nicely showing that the QPS system never compromised the safety of the machine and of the superconducting magnets. Faults which could damage the machine permanently, causing significant down-time (months of stop) never happened and were protected for at several levels. However, as anticipated, radiation-induced operational failures did happen on both the boards of the tunnel and shielded areas causing beam dumps and thus downtime to the accelerator, requiring mitigation measures to be implemented.

Concerning the tunnel equipment, most SEEs have been observed on a digital isolator linking the detection electronics to the supervising data acquisition system (DAQ). While not causing beam dumps the malfunction required initially machine access to restart the DAQ but could be eventually mitigated by a firmware upgrade. The incriminated component was tested against radiation using a setup which checked the output while the input of the isolator was fed with a square wave. However, the digital isolator is finally used in static mode in the real application and having a fixed input made it thus more vulnerable to SEEs. Radiation-induced failures also happened on the data acquisition system and were, due to a loss of communication on the field bus, provoked by a SEFI on the chip which manages the bus. The vulnerability of the device was known but accepted since this fault only provoked a loss of the monitoring data; however, it turned out to be still a limiting factor since the post-mortem data, transmitted after the activation of an interlock signal, were lost, making impossible the diagnostic of the fault which triggered the interlock.

Concerning the shielded area equipment, the radiation levels turned out to be higher than originally anticipated during the system design and especially the DSP based digital quench detection systems suffered SEEs causing spurious system triggers.

In this way, the operation of the machine put in evidence the vulnerability of the system to SEEs. At that stage, with the machine in operation (2010-2012), a new design or the replacement of the vulnerable components were not possible due to the large number of impacted electronic cards. Still, prompt mitigation actions were required in order to allow for acceptable operation conditions until 2013. According to the strategy described above, two solutions were adopted. Additional shielding was added to the galleries in order to decrease the radiation levels. In addition, firmware modifications were deployed to the system, limiting the impact of the SEEs on the optical isolator and on the microcontroller. By doing so, the failure rate was decreased to an acceptable level for the operation.

The analysis of the pitfalls, the efficiency of the mitigation actions formed then the basis to plan a suitable mid/long-term solution to be applied during the first Long Shutdown (LS1) of the machine (2013) and also afterwards. For the LS1 it was decided to

- relocate the equipment or parts of it in more protected areas wherever possible. These measures concern in particular the inner triplet protection systems formerly located in partly shielded areas.
- re-design the DSP based quench detection boards by replacing its functionality with a radiation tolerant FPGA and an ADC, properly tested. During LS1 this is applied to the protection systems for insertion region magnets and 600 A corrector magnet circuits installed in partly shielded areas.
- apply power cycle functionality to the microchip which manages the fieldbus to restore its functionality.

This is an intermediate measure, which will be superseded by a fully radiation tolerant DAQ system at a later stage.

For LHC operation after LS2 more systems upgrades will become necessary in order to comply with the increasing radiation load especially in the dispersion suppressor areas. This is subject to a dedicated design study within the LHC high luminosity project.

Power Converters

The 60 A converter had to be installed in the tunnel ARC while all the other converters types were placed in adjacent shielded areas. Table 3 lists the total number of units per converter types, specifying the number of parts which are in safe areas (radiation levels comparable to the surface) and those which are not. This poses a clear design challenge given the high number of exposed systems and respective annual cumulated radiation levels: up to some 10 Gy for TID and up to a few 10^{10} $\mathrm{cm}^{-2}\mathrm{y}^{-1}$ for high-energy hadrons (about 10^{11} cm^{-2} of 1MeV neutron equivalent fluence) for the tunnel areas and about a factor of 10 less for the worst exposed shielded areas.

At the design stage, some of these power converters, the 60 A type, were known to be operated in a radioactive environment, thus this has been taken in consideration from their initial conception phase, however also not following component or device batch-control, system tests or individual checks for the high-energy radiation environment. In addition, there is a large number of standard design Power Converters that were not foreseen for installation in irradiated areas and are still exposed to significant radiation levels. Moreover some converter types were not designed or constructed at CERN [22].

Table 3: Overview of the number of power converter units in the various radiation critical LHC locations.

Converter Type units	**Safe Area Units**	**Irrad. Area Units**	**Rad-Tol Design**	**Rad. Location**	
			Tunnel		
60A-08V (752 Units)	000	752	yes	ARC	
			Shielded areas		
120A-10V (290 Units)	183	107	no	RR1x RR5x RR7x UJ1x UJ56	(36) (36) (20) (10) (05)
600A-10V (400 Units)	272	128	no	RR1x RR5x RR7x UJ1x UJ56	(28) (28) (48) (16) (08)
600A-40V (37 Units)	025	012	no	UJ76	(12)
4..8kA-08V (189 Units)	123	066	no	RR1x RR5x UJ1x UJ56	(30) (30) (04) (02)

When it became clear that several power converters of the shielded areas will be impacted by radiation effects and that also the power converters of the tunnel, although tested under radiation, could still suffer destructive events and not be radiation tolerant to the TID level expected for the nominal LHC conditions, different mitigation proposals were evaluated in a dedicated R2E review in 2010. Additional shielding and in some cases relocation actions helped (Point-7) and will help (Point-1 and Point-5) to reduce the number and level of exposed equipment. However, a significant number of systems remain not sufficiently protected because they are not easily to be relocated. Mitigation actions applied at the system level are only possible within certain limits since the design of many converters was outsourced in the past and partial upgrade options are limited.

On this basis, it was decided to study a re-design the power converters which could not be moved respecting the radiation tolerant criterions fixed after the reviewing of the radiation levels of the areas where the converters are installed. Based on this, a long term plan was developed. The long term plan for the power-converter upgrades foresees first and most urgently the redesign of the controller part (FGClite and Rad-DIM), ready for installation right after the first long shutdown, and the power part for the 600 A, and 4-6-8 kA to install the new parts during the second long shutdown of the LHC machine.

In addition, the choice of redesigning the 600A as well as the 4-6-8kA was based on the fact that these converters were initially directly developed by and purchased from industry, thus are considered as highly critical regarding any (even not radiation related) patch or other crash solution to be put in place without having the full knowledge of the detailed design and electronic boards. Furthermore, the 600A is intended to be redesigned as a fully redundant converter which can then re-used as well for the 60A and 120A converter in the context of the LHC High Luminosity project.

The power converter group organized the project to have the maximum efficiency in dissociating the already demanding and challenging power design phase from the rad-tolerant aspects. By doing so, different teams (see Figure 5) work in parallel and limit the delay of each one on the other. It was possible to follow this approach since it was assumed that a power converter designer shall focus on the circuit topology, keeping in mind radiation tolerant requirements and suggesting the use of simple techniques and robust components of a few families and types, but not necessarily having any special constraints on the specific reference of the single components.

Figure 5: The radiation tolerant design of the power converters is based along three teams: the converter design, radiation test and management/documentation.

Thus, the converter design team focuses on the electrical design of the different converter types and associated functional controller; the radiation test team carries out the tests on the components, the management/documentation team leads the projects and assures the link between the former two teams.

The project aims at having the power converters designed at CERN based on COTS components. Provided the available timing a full radiation test strategy can be adopted by foreseeing

- the screening test for the component selection
- the purchase of the component lot and respective radiation qualification
- the test of the system (or parts) according to the qualification procedure outlined in the following section.

RADIATION TESTING & FACILITIES

The first important element required for an efficient and successful qualification procedure is the knowledge of the radiation environment. The peculiarities of the LHC radiation environment and the differences among the different areas, shielded zones and tunnel, are described in more detail in [6], where the respective critical radiation effects on electronics have been described as well. Electronic components and systems exposed to a mixed radiation field will experience three different types of radiation damages: Displacement Damage (DD), damage from the Total Ionising Dose (TID) and so-called Single Event Effects (SEEs). The first two are of cumulative nature, where the steady accumulation of defects causes measurable effects which can ultimately lead to device failure. In terms of stochastic SEE failures, they form an entirely different group as they are due to the direct ionization by a single particle, able to deposit sufficient energy through ionization processes in order to disturb the operation of the device. They can only be characterized in terms of their probability to occur as a function of accumulated High Energy (>few MeV) Hadron fluence. The failure probability will strongly depend on the device as well as on the nature of the particles and its energy [15, 16].

As shown earlier, several areas close to the accelerator tunnel and partly not sufficiently shielded, are equipped with commercial or COTS based systems which are mostly affected by the risk of SEEs, whereas electronics installed in the accelerator tunnel, based on custom design, will in the long-term also suffer from additional cumulated damage (TID and DD).

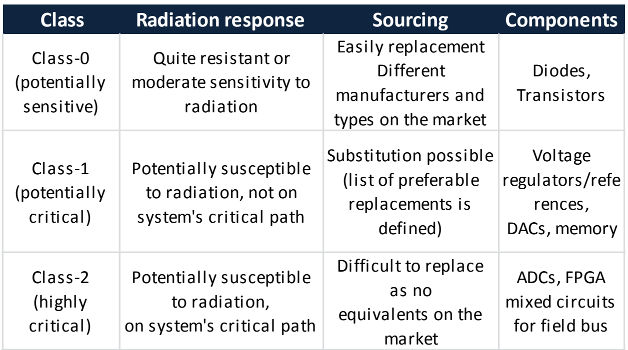
On this basis, all three types of radiation effects must be considered for testing although they will not impact in the same way the electronic systems. This implies having the appropriate facilities where two, partly parallel, strategies can be pursued:

- The first one consists in selecting and using external facilities which are recognized by the radiation community [23]: e.g., a) the Paul Scherrer Institute (PSI) providing a monochromatic proton beam, b) the Centre Energie Atomique (CEA) providing a neutron environment at ~1 MeV, c) Fraunhofer INT institute offering a ^{60}Co or neutron source, d) the European Space Agency (ESA) offering a ^{Co}60 source and several others. In addition, specific facilities, such as the PTB (Physikalisch-Technische Bundensanstalt), the Nuclear Research Institute (NRI in Rez), and the nuclear reactor in Kijeller can be exploited for calibration purposes (e.g., for the RadMon project).
- The second strategy aims at building a mixed radiation facility capable of reproducing the representative accelerator environments (e.g., of both the shielded and tunnel areas). In the past, two test areas, CNRAD and H4IRRAD, have been used for this purpose, although their operation was not fully optimized for radiation testing (limited availability, intensity, etc.). On the basis of this experience, a dedicated new radiation facility (CHARM) is being built during LS1 and will be briefly described in a later section of this paper.

As for the radiation qualification procedure, in a first stage, the design team specifies the list of components required for making a converter defining the type of the components, the main electrical performance, and possibly indicating a couple of references. The radiation test team then takes the list of components and organized the setup for the tests, trying to match as much as possible the bias conditions in which the component will be used. If this information is not available, the test setup is organized to evaluate the generic characteristics of the device under test.

Given the high number of components to be tested, they are classified into one of three different classes (C0, C1, and C2) presented in detail in Table 4. Based on this, Table 5 shows the respective radiation test methodology applied for the screening test. The classification takes into account the overall failure impact level of individual components [24].

Table 4. Component classification.



Class	Radiation response	Sourcing	Components
Class-0 (potentially sensitive)	Quite resistant or moderate sensitivity to radiation	Easily replacement Different manufacturers and types on the market	Diodes, Transistors
Class-1 (potentially critical)	Potentially susceptible to radiation, not on system's critical path	Substitution possible (list of preferable replacements is defined)	Voltage regulators/references, DACs, memory
Class-2 (highly critical)	Potentially susceptible to radiation, on system's critical path	Difficult to replace as no equivalents on the market	ADCs, FPGA mixed circuits for field bus

Class-0 (C0) components are tested with mixed-field radiation environment at CERN which is equivalent to LHC tunnel conditions, thus showing the direct functioning of the device in the final application. These tests can be done using a dedicated test setup for component tests or done on the electronic card level with components implemented and fulfilling their function in the design. The drawback of these tests is the very long irradiation time due to the relatively low fluence that can be obtained. In addition, CERN's complex is in a shutdown period during 2013 and 2014 and the mixed-field facility is not available during this time. A new test facility (CHARM) is thus under construction to be able to overcome these limitations and is presented in the last chapter of this document.

Table 5. Test methodology per class of components.

Class	Mixed-Field	Proton (PSI)	Heavy-ion
Class-0 (potentially sensitive)	**Mandatory** Component tests or tests of the complete board for SEE and TID	N/A	N/A
Class-1 (potentially critical	**Optional** Component tests or tests of the complete board for SEE and TID	**Mandatory** Component tests for SEE and TID (margin to account for >1GeV)	N/A
Class-2 (highly critical)	**Optional** Component tests or tests of the complete board for SEE and TID	**Mandatory** Component tests for SEE and TID (margin to account for >1GeV)	**Mandatory** Component tests for better SEL assessment

Class-1 (C1) components have to be irradiated with mono-energetic protons at the PSI radiation facility to measure their susceptibility to SEE and TID. Dedicated component tests are required for C1. In the LHC tunnel the particle energies range up to several tens of GeV, so the 230 MeV mono-energetic protons at PSI cannot reveal the component's response to such energies. On the other hand, for many components, the proton cross-section saturates already for energies in the range of tens of MeV. One has thus to take either a safety margin factor into account for the high energies not possible to test at PSI, or in some cases, foresee an additional test to be performed within a mixed-field radiation facility to study in detail its response to LHC radiation environment.

Class-2 (C2) components are to be tested exactly in the same way as the C1 components and additionally the heavy-ion radiation campaign has to be performed in order to better assess their Single-Event-Latch-up cross-section already during the component selection process. As all C2 components are highly critical to the project design, their destructive event cross-section is the biggest concern while the other non-destructive SEEs can be mitigated on the design level (e.g, using Error Correcting Codes (ECC), Triple Modular Redundancy (TMR) or other adapted mitigation methods). As all C2 components are highly critical to the design, their destructive event cross section is the biggest concern and needs to be verified through dedicated tests in a mixed-radiation facility.

The targets limit for the high-energy hadron fluence, 1-MeV eq. neutron fluence, and TID is fixed according to the expected radiation levels of the critical areas where the components will be installed for a minimum lifetime of 10 years.

Once the components are selected, they are bought per lot. The lot is qualified by testing 5-10 samples per lot. The lot will be tested in the same facility where the screening test was performed. If a TID test at low dose rate (100-400 rad/h) is to be performed for critical bipolar devices, a Co-60 source will be used.

Finally, at least three samples of the entire system or subsystems are tested in a CERN test area where the mixed radiation field is reproduced.

Therefore, any installation of non-tested (and not specifically designed) electronic equipment in the UJs, part of the ULs and RRs is clearly to be avoided or subject to a detailed analysis process prior an exceptional installation can be granted under the following conditions:

- the equipment is not linked to any safety system,
- the failure of the equipment will not lead to a beam dump,
- the failure of the equipment does not require quick access (thus lead to downtime),
- there is no any other operational impact (loss of important data, etc.).

In all other cases requiring installation in critical areas, a respective radiation tolerant electronics development must be considered from the very early stage onward. Related expertise exists at CERN within the equipment groups, the R2E project [1] and a dedicated working group [6]. In a first approximation and by limiting the total number of exposed systems, the above mentioned annual radiation design level of 10^7 cm^{-2}y^{-1} can also be chosen as acceptable upper limit aiming to achieve an overall performance of less than one radiation induced failure per one or two weeks of operation.

THE NEW FACILITY: CHARM

As explained in the previous sections, within the framework of the Radiation to Electronics (R2E) project, the testing of electronic equipment in a radiation field similar to the one occurring at CERN accelerators (e.g. in the Large Hadron Collider (LHC)) in order to study the respective equipment sensitivity is an important condition to assure mid/long-term operation requirements. High intensity and high-energy radiation fields are needed for realistic radiation tests. For this purpose, a new irradiation facility called CHARM (Cern High-energy AcceleRator Mixed field/facility) is currently being constructed [25, 26]. The commissioning of this unique mixed field facility will be carried out during summer of 2014 in order to be ready for standard operation after LS1.

This facility is not only useful for testing devices within accelerator representative environments, but its available radiation fields will also be characteristic for ground and atmospheric environments (neutron energy spectra) as well as the space environment (representative for the inner proton radiation belt). In addition, the size of the available test area is such that also larger objects can be irradiated and ultimately even objects requiring special services (power, cooling, etc.) to be connected for operation.

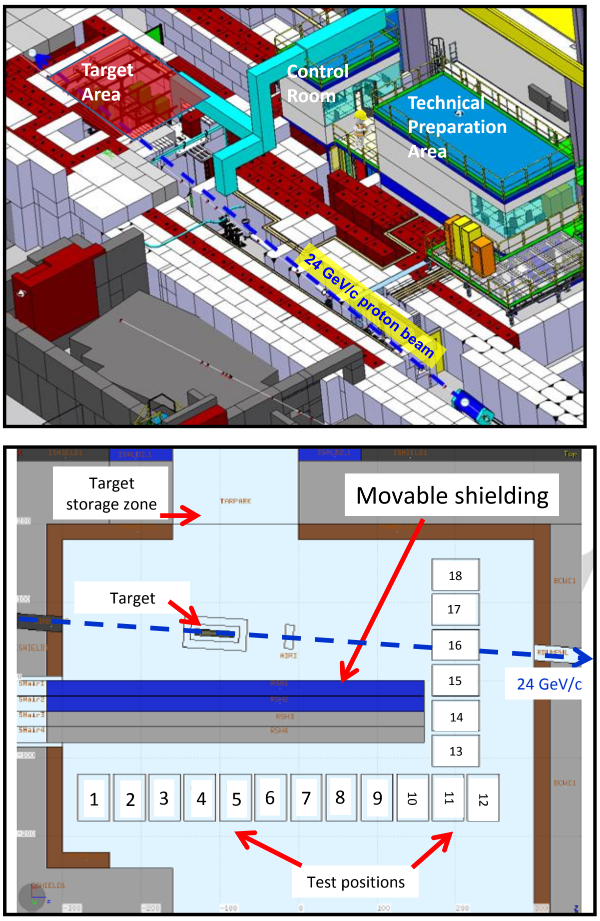


Figure 6: (top) 3D view of the facility and (bottom) FLUKA geometry for the target area. Racks 1 to 18 are the regions representing the test locations. The blue, grey and brown plates are respectively iron, concrete and marbles blocks.

The CHARM facility will be located in one of the experimental halls at CERN (East Area, T8 beam-line). Figure 6: (a) 3D view of the facility and (b) FLUKA geometry for the target area. Racks 1 to 18 are the regions representing the test locations. The blue, grey and brown plates are respectively iron, concrete and marbles blocks.

Its surrounding layout is composed of iron and concrete blocks in order to reduce at maximum the radiation outside of the shielding structure. A 3D view of the facility and a horizontal cut of the inner target chamber are shown respectively in Figure 6 (a) and (b). As it can be seen from Figure 6(a), the target chamber is large enough to host bulky and complete systems (e.g. full power converter or UPS units) since around 70 m3 of space will be available for radiation tests.

Within the facility, a 24 GeV/c proton beam extracted from the Proton Synchrotron (PS) accelerator impacts on a cylindrical copper or aluminium target (see Figure 6 (b)), and the created secondary radiation field is used to test electronic equipment installed at predefined test positions. Copper and aluminium as material's choices for the primary beam target are good compromises not only because of their mechanical and thermal properties, but together with the mobile shielding configuration they also allow the creation of a secondary particle spectrum representative for the source term of those present in the atmospheric, space and accelerators environment.

To model and choose between the various representatives spectra, different shielding configurations are available in the facility. Four movable layers of an individual thickness of 40 cm made out of concrete and iron can be placed between the target and the test locations in different combinations (see movable shielding in Figure 6 (b), thus allowing to modulate the test spectra and adopt them as closely as possible to the radiation field (energy and intensity) aimed for during the tests. The shielding plates are motorized with remote control.

The intensity of the radiation field can be further modulated by varying the primary beam intensity, the choice of target head, e.g. two massive ones (Al or Cu – the yield of the massive Al target is about 2.5 times smaller than for the massive Cu target) or one with reduced effective density (Al target with holes – it gives an additional reduction by a factor 4), allowing for an overall reduction factor of the primary radiation field of 10-100 in total.

It is important to note that even for large volumes and also when including the shielding configuration, even a full year of exposure e.g., in the LHC (a few 10^{11} HEH/cm^2) can be easily emulated within a few days of exposure in this facility (see Figure 7).

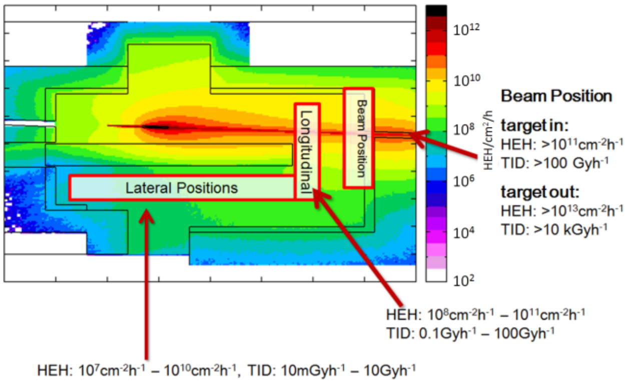


Figure 7: HEH flux (cm^{-2}/h) inside the radiation zone.

The dose rate ranges for the various test positions are shown in a qualitative way. For that hourly radiation values are provided for overall longitudinal, lateral, or direct exposure positions shown. The beam is impinging on the target from the left. "Target in" and "Target out" correspond to test at "beam position" with and without target respectively.

The installation of equipment inside the target chamber will be mostly automatized with remote controlled transporters. Two transporter systems will be used, one to carry heavy and bulky equipment (called "large transporter") and one to transport small samples to the test position in direct line of sight with the beam axis (usually referred to as "small train").

CONCLUSIONS

In this report we summarized the radiation environment and levels encountered during the first years of LHC operation high-energy accelerators and their particularities at critical LHC areas. The energy distribution, as well as the proportion of the different particle species depends on the distance and on the angle with respect to the interaction point, as well as the amount of installed shielding material. Electronic components and systems exposed to a such mixed radiation field thus experience at once all three different types of radiation damages: Single Event Effects (SEEs), damage from Total Ionizing Dose (TID) and displacement damage (DD), where in all cases, not only the particle type, but also the respective energy distribution are to be considered, especially if high-Z materials are present near the device's sensitive region, as well as that the impact of thermal neutrons can not to be neglected for several cases.

A summary of the induced failures for the LHC operation in 2012 has been given with about 60 beam dumps which were provoked by radiation effects on electronic equipment during 2012 operation and causing a downtime for the machine of about 250-300 hours. The impact of the radiation effects would have been significantly higher without the countermeasures that were already applied in the past years. Furthermore, the prompt reaction of the groups to design patch solutions for mitigating radiation effects allowed throughout the year 2012 to reduce the number of failures which could have led to a beam dump. In total, the radiation induced failures were reduced by a factor 4 with respect to the 2011 operation.

Additional mitigation actions are planned for the LS1 period to further reduce the radiation vulnerability of the equipment. Thanks to those efforts, the expected number of radiation induced dumps per fb^{-1} is expected to be <1. This objective will permit to classify the radiation induced failures as minor, and to operate the LHC smoothly without any significant number of stops related to radiation.

The monitoring of the radiation levels will be a continuous work which aims at reducing the uncertainty factors, mainly related to the beam gas effects and the losses in the collimation areas, as well as to closely monitor the long-term radiation impact on exposed electronic systems. This will allow verifying design assumptions, as well as scheduling preventive maintenance actions when required. The detailed follow-up of the system upgrades and developments remains crucial to reach the above goal.

Both the requirement as well as the challenge of using commercial components for accelerator applications have be highlighted and respective mitigation measures have been illustrated together with the requirements and solutions for radiation monitoring and radiation test facilities.

For operation critical equipment, the r2e project foresees respective radiation tolerant developments already at an early stage of the design phase, taking into account that:

- for the LHC-tunnel: in addition to SEEs also cumulative damage has to be considered for both existing and future equipment,
- for partly shielded areas (UJs, RRs, ULs): cumulative damage should be carefully analyzed but can most likely be mitigated by preventive maintenance (detailed monitoring mandatory), but radiation tolerant design is mandatory in order to limit SEE induced failures,
- the knowledge of radiation induced failures and radiation tolerant development within the equipment groups and in the overall A&T sector has to be maintained and further strengthened,
- the access and availability of radiation test facilities (CERN internal and external) has to be ensured providing efficient support to equipment groups, building on the experience obtained during the LHC R2E project and in view of the HL-LHC time-scale, it is important that the expertise of and support to radiation tolerant developments (currently available through the Radiation Working Group) is maintained and ensured from the early project stage onwards.

AKNOWLEDGMENTS

We would like to thank all the project members for their continuous support and contributions, as well as all involved equipment groups for their active collaboration.

REFERENCES

[1] R2E Mitigation Project: www.cern.ch/r2e

[2] M. Brugger et al., R2E Experience and Outlook for 2012, in Proceedings of LHC Performance Workshop, Chamonix 2012.

[3] M. Brugger, "Radiation Damage to Electronics at the LHC," in Conf. Proc., vol. 1205201, no. CERN-ATS-2012-255, 2012, p. THPPP006.

[4] G. Spiezia et al., R2E Experience and Outlook for 2012, LHC Beam Operation workshop, Evian 2011.

[5] G. Spiezia et al., R2E Experience and Outlook, LHC Beam Operation workshop, Evian 2012.

[6] Radiation Working Group, www.cern.ch/radwg

[7] K. Roed, M. Brugger, and G. Spiezia, "An overview of the radiation environment at the LHC in light of the R2E irradiation test activities," CERN ATS Note 2011-077, 2011.

[8] A. Ferrari, P. R. Sala, A. Fasso, and J. Ranft, “FLUKA, a multi-particle transport code,” CERN-2005-10-2005, INFN/TC-05/11, SLAC-R-773, 2005.[Online].Available: http://www.fluka.org/content/manuals/FM.pdf

[9] G. Battistoni et al., “The FLUKA code: description and benchmarking,” Proceedings of the Hadronic Shower Simulation Workshop 2006, Fermilab, Sept. 2006.

[10] F. Ballarini et al., “The physics of the FLUKA code: Recent developments,” Advances in Space Research, vol. 40, no. 9, pp. 1339 – 1349, 2007. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0273117707004905

[11] K. Roed et al., “FLUKA simulations for SEE studies of critical LHC underground areas,” Nuclear Science, IEEE Transactions on, vol. 58, no. 3, pp. 932 –938, June 2011.

[12] G. Spiezia et al., “The LHC radiation monitoring system-RadMon,” Proc. RD11, 2011. [Online]. Available: http://pos.sissa.it/archive/conferences/143/024/RD11_024.pdf

[13] K. Roeed et al., “Method for measuring mixed field radiation levels relevant for SEEs at the LHC,” in Radiation and Its Effects on Components and Systems, 2011. RADECS 2011, Sept. 2011, pp. H2–1 –H2–4.

[14] R. Garcia Alia et al., “SEU measurements and simulations in a mixed field environment,” Nuclear Science, IEEE Transactions on, vol. 60, no. 4, pp. 2469–2476, 2013.

[15] R. Garcia Alia et al., “SEE measurements and simulations using mono-energetic Gev-energy hadron beams,” Nuclear Science, IEEE Transactions on, vol. 60, no. 6, pp. 4142–4149, 2013.

[16] R. Garcia Alia et al., “SEL cross section energy dependence impact on the high-energy accelerator error rate,” 2014.

[17] A.L. Perrot et al, Actions to Mitigate the Radiation Damage to Electronics at the LHC, CERN-ACC-2013-0290, IPAC 2013.

[18] K. Foraz et al, LHC Long Shutdown: A Parenthesis for a Challenge, CERN-ACC-2013-0276, IPAC 2013.

[19] A.L. Perrot et al, Optimisation and Implementation of the R2E Shielding and Relocation Mitigation Measures at the LHC during LS1, CERN-ACC-2014-0224, IPAC 2014.

[20] P. Oser et al., ‘Point 4- UX45 –equipment inventory’, CERN, October 2013, edms: 1307741.

[21] R. Denz, K. Dahlerup-Petersen, A. Siemko, J. Steckert, "Upgrade of the Protection System for the Superconducting Elements of the LHC during LS1", MT23, Boston, July 2013.

[22] Y. Thurel, Q. King, M.C. Bastos, "LHC power converters, the proposed approach", LHC Workshop Chamonix 2010.

[23] http://radwg.web.cern.ch/RadWG/Pages/test_facilities.htm

[24] S. Uznanski et al., Radiation Hardness Assurance Methodology of Radiation Tolerant Power Converter Controls for the Large Hadron Collider, NSS 2013, to be published in IEEE.

[25] R. G. Alia et al., "Preliminary FLUKA spectra study for the CHARM radiation facility", http://edms.cern.ch/document/1306704/1

[26] www.cern.ch/charm

LINAC4: PROGRESS ON HARDWARE AND BEAM COMMISSIONING

A.M. Lombardi, CERN, Geneva, Switzerland

Abstract

Linac4 has been commissioned, with a temporary source, up to an energy of 12 MeV. The dynamics in the LEBT, in the RFQ and in the chopper line have been verified, as well as the acceleration to 12 MeV with the first DTL tank. Future plans foresee stages of commissioning at the energy of 50, 100 and finally 160 MeV interlaced with periods of installation and followed by a year-long reliability run. In this talk we will present the status of the Linac4 beam commissioning, the status of readiness of the remaining accelerating structures as well as the path to the final source. The possibility of delivering to the PSB a 50 MeV proton beam from Linac4 will be discussed together with its impact on the overall schedule and the achievable beam characteristics

INTRODUCTION

Linac4 will replace the present 50 MeV proton Linac2 as injector of the CERN PS Booster, as a first step of the LHC Injector Upgrade project. A sketch of Linac4 is shown in Fig. 1 and a detailed description of the layout and beam dynamics can be found in [1,2]

The pre-injector includes a source followed by a Low Energy Beam Transport at 45 keV, a Radio Frequency Quadrupole which accelerates the beam to 3MeV and a Medium Energy Beam Transport line (MEBT). The MEBT, 3.6 m in length, houses a fast chopper with the purpose of removing selected micro-bunches in the 352 MHz sequence and therefore avoid losses at capture in the CERN PSB (1MHz). Presently the preferred scheme envisages to chop out 133 bunches over 352 with a resulting average current reduced by 40%. The beam is then further accelerated to 50 MeV by a conventional Drift Tube Linac (DTL) equipped with Permanent Magnet Quadrupoles (PMQ), to 100 MeV by a Cell-Coupled Drift Tube Linac and to 160 MeV by a Pi-mode structure. The focusing after 100 MeV is provided by Electromagntic Quadrupoles (EMQ) whereas between 50 and 100 MeV by a combination of PMQs and EMQs.

Note that the chapter on measurements has been published in the proceedings of LINAC14.

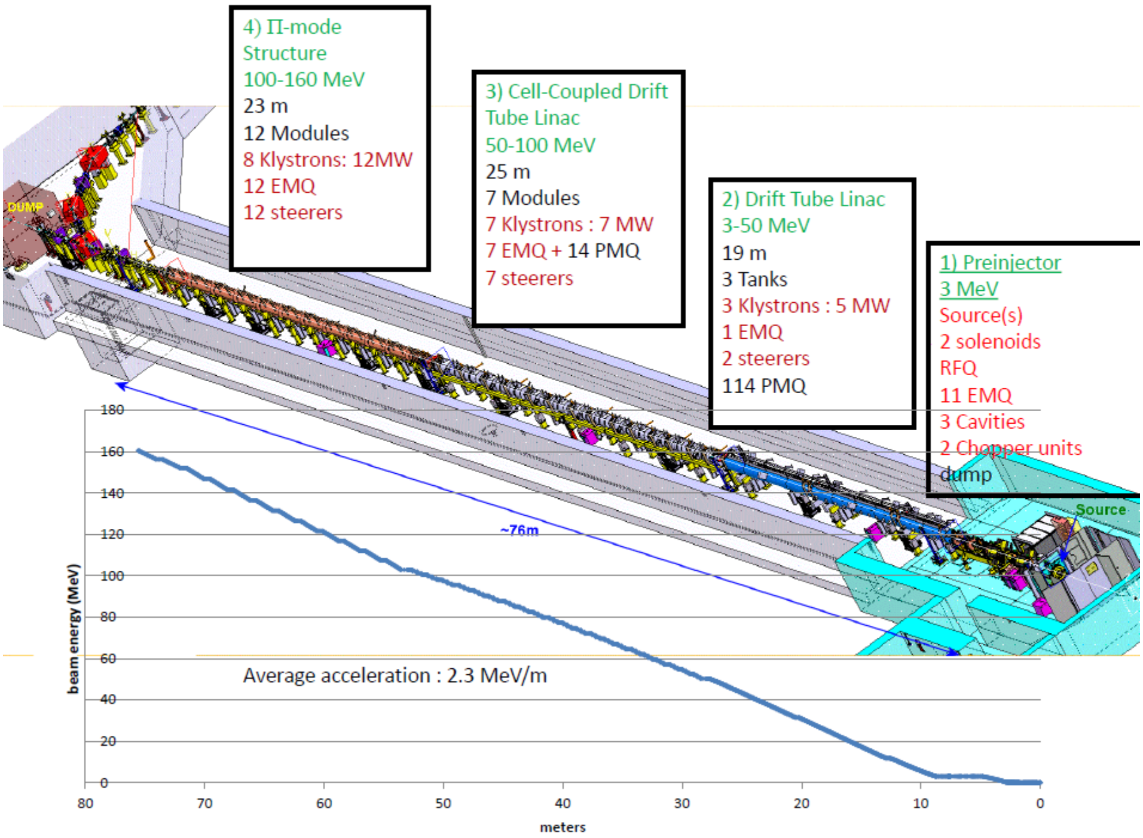


Figure 1: Sketch of Linac4.

COMMISSIONING STAGES

Linac4 is being commissioned with the aim of reaching the final energy in 2015. The commissioning is staged both for simplifying the task as well as for matching the production schedule of the different accelerating structures. The so-called pre-injector, including the source, the Low Energy Beam Transport, the Radio Frequency Quadrupole and the Medium Energy Beam Transport Line has been commissioned in a dedicated test stand before being installed in the final location with the final power supplies and control system. Since October 2013 the commissioning takes place in the final location, the underground tunnel, where periods of beam commissioning are interlaced with period of installation. Six commissioning stages are planned, at the energies of 45 keV, 3 MeV, 12 MeV, 50 MeV, 100 MeV and finally 160 MeV. After the final energy is reached, Linac4 will be run for about 12 months to assess its reliability and to improve it if necessary. At the time of writing, the 12 MeV stage has been started, although with a temporary version of the ion source. At each stage a dedicated suite of diagnostics has been temporarily installed to address the specific needs of that particular stage. At each stage the transverse emittance, the average energy and energy spread have and will be measured, with some extra specific measurements which will be detailed in the following.

MEASUREMENTS

Some of the measurements that follow have been taken at a dedicated test stand during the period January 2012-June 2013[3], others in the final location in the tunnel starting October 2013. Unless necessary, the location and time of the measurements are not indicated and the chronological order is not respected.

Measurements at 45 keV

The 45 keV stage comprises a temporary source giving about 20 mA of H^-, two solenoids for matching to the RFQ and a pre-chopper located in between the solenoids. A profile harp and a beam transformer are located between the two solenoids as well. A gas injection system, capable of injecting different gases (hydrogen and nitrogen) and controlling the pressure to 10^{-6} mbar, is used to influence beam neutralisation during transport to the RFQ with the intention of enhancing beam quality. Temporary diagnostics including a slit-and-grid emittance metre and a spectrometer have been installed at different locations along this 2 m long line. Measurements of emittance have been taken under different source regimes, different gas pressures and for different solenoid's settings. The aim of these measurements is to gain an understanding of the dynamics in the LEBT, to correlate the phase space portraits at the RFQ input plane with the solenoid settings and to reconstruct a representative beam distribution to be able to predict with sufficient accuracy the behaviour of the beam further down the accelerator.

The first measurements were done after the first solenoid with the set-up shown in Fig. 2.

Figure 2: Set-up for emittance measurements at 45 keV.

Emittance measurements were taken for different solenoid settings in both transverse planes at a fixed source configuration. A series of 5 measurements, for increasing solenoid field is shown in Fig. 3. For simulations, a beam is created from the measured transverse phase spaces, and populated with a cloud of 500k macro-particles using a dedicated module built into the PATH code [4] and interfaced with the measurement system. The two transverse planes are assumed to be uncorrelated as information on the cross-correlation cannot be gained with a slit and grid system. The cloud of particles mimicking the measured data has been back-traced to the source output. The beam distribution obtained for the five cases of Fig. 3 is shown in Fig. 4. We can notice that the phase space tracked back to the source is consistent for the five cases and most importantly is consistent with what is expected out of the source from IBSimu simulations (a strongly divergent beam with a radius of 25 mm) [5]. After this stage we have an input distribution that very well represents the distribution that comes out of the source. Matching to the next stage of acceleration has been done starting from this input distribution and using statistical computer optimisation techniques to find the solenoid settings that optimise transmission and beam quality into the RFQ acceptance. These settings were confirmed by a series of emittance measurements at the location of the RFQ input plane.

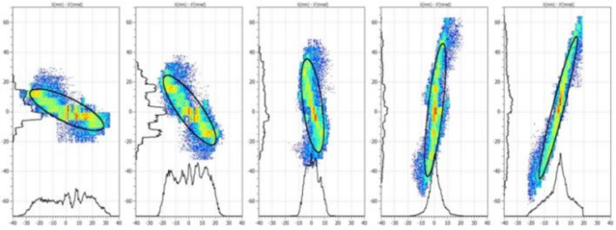


Figure 3: Transverse phase space profile for increasing solenoid field, units of mm and mrad.

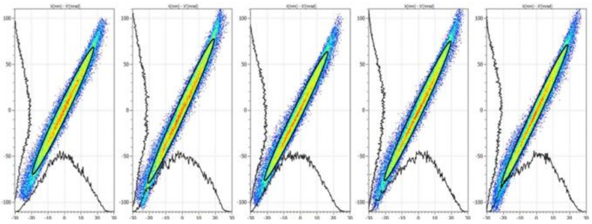


Figure 4: Transverse phase space profile of Fig.3 back-traced at the source output, units of mm and mrad.

At the end of this stage a 16 mA H^- beam was matched to the RFQ acceptance. As the source is not yet the final one, the emittance of the beam exceeds the acceptance of the RFQ and a transmission of about 75% is expected, instead of the nominal 90%.

Measurements at 3 MeV

A beam was very swiftly accelerated to 3 MeV after connecting the RFQ to the LEBT and setting the solenoids to the values predicted by PATH [4]. The maximum expected transmission of 75% was obtained within hours. The correct functioning and the calibration of the RFQ were further confirmed by measuring the transmission of accelerated particles through the RFQ when varying the RF power and comparing it to the expectations from PARMTEQ [6] and TOUTATIS [7]. The results are shown on Fig. 6. A very good agreement is obtained thus validating the RFQ mechanical and conceptual design, the RF calibration and the simulation accuracy. This measurement was repeated after the RFQ was moved into the final location in the tunnel to confirm that no damage had occurred during the transport.

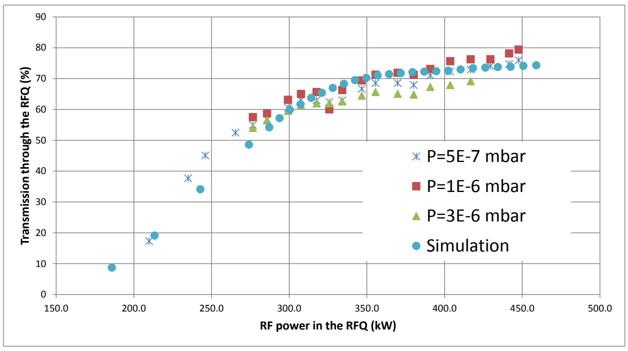


Figure 6: Transmission vs. RF power in the RFQ for different LEBT pressure. The nominal RFQ power is 400kW. Simulations in light blue dots.

After confirming the performance of the RFQ, the 3 MeV beam was passed through the MEBT line and analysed in the temporary diagnostics line. The MEBT line is composed of eleven EMQs, three buncher cavities and an electro-static chopper system integrated in the quadrupoles. Diagnostics including two wire scanners and two beam transformers are located permanently in the line whereas a diagnostics bench comprising a slit-and-grid emittance meter, a spectrometer, a laser and diamond detector, a Bunch Shape Monitor (BSM) and a halo monitor was fitted temporarily at the end of the line. There are multiple issues to address in the MEBT line: first and foremost the correct functioning of the chopping system [8]. The chopping system is composed of 4 plates with a meander line which are meant to selectively kick unwanted micro-bunches so that they are fully separated in phase space at the end of the 800 mm long plates. Subsequently the beam enters a system of three quadrupoles (and a buncher) set such that the separation in phase space is transformed into a separation in real space and the unwanted bunches can be safely disposed of on an in-line dump (a section of a cone that limits the beam aperture over 20 cm). This choice has allowed limiting the voltage needed on the chopper plates and keeping the system as compact as possible but it has the drawback that the dynamics of the through-beam is strongly coupled to the dynamics of the chopped beam, as the same three quadrupoles have to guarantee maximum transmission through the cone for the main beam and maximum extinction factor for the chopped beam. Measurements of the chopping efficiency were a high priority for Linac4. The results are reported in the following.

First the current in a beam transformer downstream the inline dump (BCT04040) has been measured as a function of the quadrupole (L4L.QFC03130) settings between the chopper and the dump. Results are shown in Fig. 7. The top curve shows the transmission of the main beam, the bottom curve the transmission of the chopped beam. It was confirmed that it is possible to maximise the transmission of the main beam and extinguish the chopped beam simultaneously.

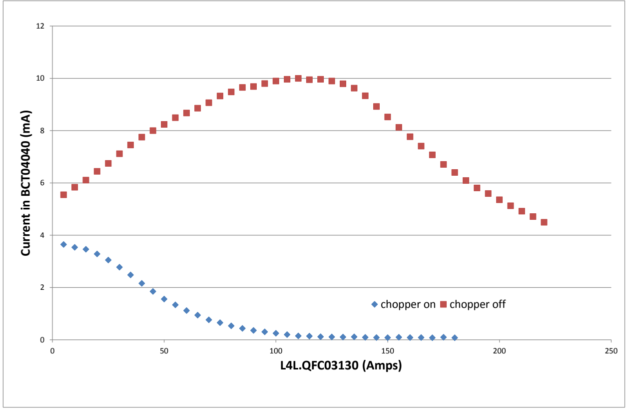
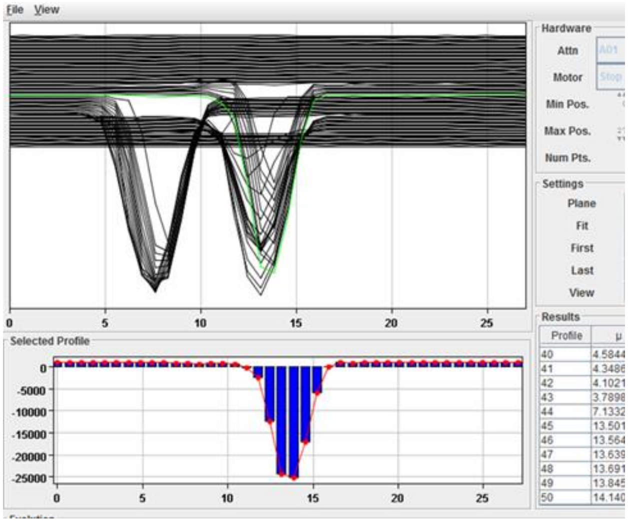


Figure 7: Measured Current in BCT04040 (mA) vs L4L.QFC03130

The two, fully separated beams are also visible at the time-resolved wire scanner located in the vicinity of the dump, see Fig. 8. It was also confirmed that emittance of the main beam didn’t change either in orientation or in size when the chopper was turned on.

The transverse emittance of the main beam was measured with three different methods: a traditional slit-and-grid emittance meter, a newly designed laser-plus-diamond detector [9] and an indirect method based on reconstructing the emittance from several profile measurements at varying quadrupole settings[10]. The main purpose of this campaign was to cross-check the indirect method against a direct one as for the higher-energy stages a direct method is not foreseen.



Results

Profile	μ
40	4.5844
41	4.3486
42	4.1021
43	3.7898
44	7.1332
45	13.501
46	13.564
47	13.639
48	13.691
49	13.845
50	14.140

Figure 8: Beam transverse profile on the wire scanner before the in-line dump. Top : A profile (solid black line) is taken every 6 µs. Bottom : Profile of a slice of the main beam . Horizontal scale in mm, vertical a.u.

The values of the emittance obtained with the 3 methods are consistent as all measurements considered are within 10% of each other (see Table 1). The alpha and beta parameters of the measurements differ because they have been taken at different locations of the line, but when tracked to the same location they are consistent as well. The most difficult part in this analysis was to choose the appropriate threshold for each case. Finally the best approach turned out to be choosing the minimum threshold on the raw data, which is not necessarily the same threshold for the three different measurement methods. More details can be found in [10].

Table 1: Transverse emittance

Method	**Ex norm rms**	**Ey norm rms**	**Threshold**
Slit-grid	0.27	0.24	1%
Laser-diamond	0.27	0.27	0.1%
From profiles	0.31	0.34	0.5%

The diagnostics bench is equipped with a Bunch Shape Monitor BSM [11], a device capable of measuring the phase extent of the micro bunch, by analysing the time of arrival of electrons emitted by a wire positioned in the beam. The BSM is located 4.9m from the RFQ and 4.4m, 2.9m and 1.6m from the three buncher cavities respectively. We have used the BSM to measure the beam phase extent for different amplitudes and phases of the second buncher. Starting from those measurements we have been able to reconstruct the **longitudinal beam emittance**, compare it with our expectation from the RFQ simulations and compare the energy spread with the direct measurements at the spectrometer [12]. The results are summarised in Table 2.

Table 2: Longitudinal emittance

Method	$\varepsilon_{\mathbf{rms}}$ deg MeV	**ΔW** MeV
simulations	0.19	0.022
From BSM phase profiles	0.16	0.021
spectrometer	-	0.019

Measurements at 12 MeV

Before moving the temporary bench, the MEBT settings for matching the beam to tank1 of the DTL were found. The transverse phase spaces are compared to the matched beam in Fig. 9. The longitudinal matching and the corresponding buncher settings have been found with the help of the BSM and the spectrometer. The expected transmission through the DTL with the measured beam is 95%.

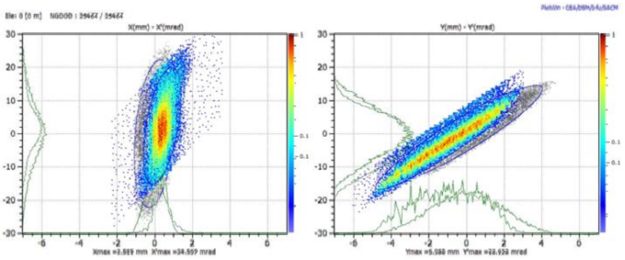


Figure 9: Measured transverse beam phase space (colour) compared to the nominal matched beam (grayscale) at the input to the DTL.

The commissioning of the first DTL tank started with the RF buncher cavities between the RFQ and DTL switched off, with the purpose of sending into the DTL a quasi-continuous beam and sampling the empirical longitudinal acceptance, which is a key to finding the correct longitudinal matching. Preliminary measurements are shown in Fig. 10.

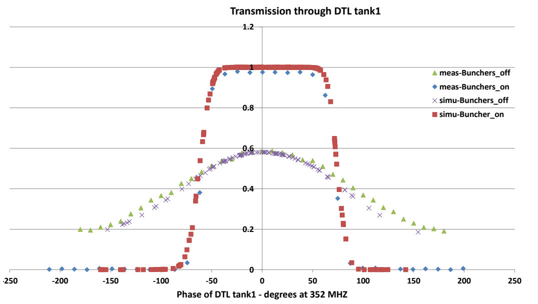


Figure 10: Transmission through the DTL tank1 vs. DTL phase for bunchers off and bunchers on.

THE SOURCE

Linac4 has been commissioned up to the energy of 12 MeV with a temporary source which gives a current of about 15 mA in an emittance that exceeds the RFQ acceptance. In this paragraph we discuss the beam quality needed from the source and the path to the final source.

The source current and emittance were (over-) specified in the Technical Design Report [13]. The requirements on the source at the time were an H- current of 80 mA in an emittance of 0.25 π µm rms norm at RFQ input; at an energy of 45keV (±2keV) and a pulse duration of 400 µsec (100 turns injection into each of the PSB rings). This specification came from the high intensity beam in the PSB, and the aim was to double the intensity for ISOLDE with a 50% extra margin.

The requirement on the source exceeds by far what is obtained in other laboratories and especially what can be safely operated in stable conditions. During the 5 years of R&D at CERN it was found that 80 mA of H- in the acceptance of the RFQ are not an easy target for a conventional non-cesiated source. A source review took place at CERN in 2011 and the reviewer recommended orienting the R&D towards a cesiated source of the type used at the SNS [14] which could reach a stable current in the 50mA range. If higher current was still needed a solution employing a magnetron type source should be explored at a second stage.

Since then the baseline source for Linac4 is a cesiated surface-production RF-source from which we expect a maximum current of up to 50 mA. With such a current there is the added advantage that the space charge is not extreme and the beam can be manipulated more easily in the accelerator and will end up with better beam quality at the PSB injection. Such current will require a minimum of 25 turns injected in the PSB to make $3*10^{12}$ protons per bunch in a 650 nsec bunch as specified in the LIU summary document [15]. With a current of 50 mA from the source an ISOLDE-type beam ($1.3*10^{13}$ ppb) can be obtained by injecting 100 turns in the PSB. Simulations of PSB injection are underway to evaluate the resulting emittance in the PSB.

PROTONS AT 50 MeV FROM LINAC4

The possibility of producing protons at 50 MeV from Linac4 has already been discussed [16]. The hardware necessary includes, besides a complete Drift Tube Linac, CCDTL module number 4. This is needed to adjust the energy spread to the PSB longitudinal. Besides all the quadrupoles of the line, together with the corresponding vacuum pipes need to be operational. It is estimated that from August 2015 all the necessary equipment for a connection will be in place. The switching magnet to be placed at the location of BHZ20 has been documented in [17].

The 50 MeV beam can be produced also after the commissioning to 160 MeV (by detuning all the structures between 50 MeV and 160 MeV), as the beam can pass through these structures without losses.

CONCLUSIONS

Linac4 has been commissioned with a temporary source up to the energy of 12 MeV. Measurements of transmission, emittance and profiles have been taken at several locations along the accelerator with the help of a movable diagnostics bench. The results of the measurements have been compared with the expectation from simulations and a sound model of the beam dynamics in the machine has been obtained.

A new source has been installed and we expect a peak current of 40 mA in the RFQ acceptance.

A 50 MeV proton beam from Linac4 could be available from August 2015.

REFERENCES

[1] F. Gerigk, M. Vretenar (eds.), Linac4 Technical Design Report, CERN-AB-2006-084.

[2] A.M. Lombardi, et al , “Beam Dynamics in Linac4 at CERN”, HB’08, Nashville, Tennessee 2008; http://www.JACoW.org

[3] G Bellodi,et al, “3 MeV Test Stand commissioning report”,CERN-ACC-2013-0259.

[4] A. Perrin, JF. Amand, Travel v4.06 user manual, CERN internal note , 2003.

[5] O. Middtun, et al Rev. Sci. Instrum. 85, 02A701 (2014).

[6] KR. Crandall, TP. Wangler, PARMTEQ-a beam-dynamics code for the RFQ linear accelerator, 8. AIP Conference Proceedings 11/1988; 177(1):22-28.

[7] R. Duperrier et al., Toutatis, the CEA Saclay RFQ code, Linac2000, Monterey, USA (2000).

[8] M. Paoluzzi et al., CERN-AB-Note-2008-040 (2008) F.Caspers et al., “The CERN-SPL Chopper Concept and Final Layout”, EPAC’04, Luzern, Switzerland (2004)

[9] S. M. Gibson, et al. “A Fibre Coupled, Low Power Laserwire Emittance Scanner at CERN Linac4”, THPME190, IPAC’14, Dresden, Germany (2014).

[10] J.B. Lallement, et al, “Linac4 Transverse and Longitudinal Emittance Reconstruction in the Presence of Space Charge”, THPP033, LINAC14, Geneva, Switzerland (2014).

[11] AV. Feshenko, Methods and instrumentation for bunch shape monitor, PAC 2001, Chicago, USA (2001).

[12] G. Bellodi, et al , “Longitudinal beam profile measurements in Linac4 commissioning”,MOPPO25, LINAC14,Geneva, Switzerland (2014).

[13] “Linac4 Technical Design Report” CARE-Note-2006-022-HIPPI

[14] source review

[15] "LIU-TDR: executive summary", by LIU Project Team, https://edms.cern.ch/document/1407085/1

[16] A. Lombardi, “LINAC4 as BKP for LINAC2”, IEFC workshop -23 march 2011

[17] https://indico.cern.ch/event/309297/material/minutes/0.pdf

PROTONS: BASELINE AND ALTERNATIVES, STUDIES PLAN

G. Rumolo, H. Bartosik, T. Bohl, H. Damerau, A. Findlay, R. Garoby, S. Gilardoni,
B. Goddard, S. Hancock, K. Hanke, G. Iadarola, M. Meddahi, B. Mikulec,
Y. Papaphilippou, E. Shaposhnikova
CERN, Geneva, Switzerland

Abstract

This paper focuses on the injector improvements and upgrades foreseen within the LHC Injectors Upgrade (LIU) project as well as the expected benefits in terms of proton beam characteristics resulting from their implementation. The roadmap of the main upgrades will be illustrated, with special emphasis on the machine studies and milestones during Run 2 that will have an impact on it. In this framework, a strategy to choose between scrubbing and a–C coating of the SPS will be also presented and discussed. Concerning the beams in Run 2, we will not review here the possible physics production beams, which are the subject of [1], but rather some special LIU beams, like: 1) beams needed for electron cloud enhancement and efficient LHC scrubbing (doublets); 2) extra–bright 25 ns beams produced with the pure batch compression scheme; 3) 8b+4e beams, which have the advantage of allowing for higher bunch current while potentially reducing the electron cloud build up. Finally, the beam performances across the full injector chain will be estimated for the operation after Long Shutdown 2 (LS2).

INTRODUCTION

The main goal of the LIU project is to boost the performance of the LHC injectors in order to match the HL-LHC requirements [2]. For this purpose, brightness and intensity of the physics production beams must be increased by:

- Replacing Linac2 with Linac4 and using H^- charge exchange injection into the PSB at 160 MeV;
- Raising the injection energy into the PS from the present 1.4 GeV to 2 GeV;
- Doubling the RF power and mitigating the electron cloud in SPS;
- Putting in place all the other necessary upgrades across PSB, PS and SPS to make them capable of accelerating and manipulating higher intensity beams (e.g., impedance reduction, feedback systems, resonance compensation, improved instrumentation);
- Upgrading the injectors of the ion chain (Linac3, LEIR, PS, SPS) to produce beam parameters at the LHC injection that can meet the post-LS2 luminosity goal [3] compatibly with the achievement of the goals for proton beams in the common injectors.

At the same time, complementary to what is being already put in place within the CONS (consolidation) project [4], LIU also needs to take actions to guarantee the injectors reliable operation and lifetime into the HL-LHC era (i.e. until 2035), such as upgrade or replace all ageing equipment (e.g. power supplies, magnets, RF) and improve radioprotection measures (e.g., shielding, ventilation).

The baseline, and optional items, of the works to be done within the LIU project has been already solidly established, with only a few remaining items for which a final decision still needs to be taken (mainly based on ongoing studies). In terms of timelines, all critical LIU related (both machine and simulation) studies need to be carried out during Run 2 and finished well before the beginning of LS2, in order to provide all the necessary information to take the final decisions and launch the necessary actions. Presently, all key dates to define the pending items have been set no later than end 2015. All LIU hardware modifications and installations will then mainly take place during LS2, although some works could be advanced to the previous Year-End Technical Stops (YETS), whenever this is possible. The final part of the LIU project will include the commissioning of the new LIU beams during Run 3. The LIU goals in terms of beam characteristics are, by definition, new territory. Reaching them will require fine optimization and extensive beam physics and machine development studies in all the accelerators. To achieve the desired performance either technical or beam physics issues might have to be sorted out after LS2 and it could be envisaged to modify the installed equipment over the following YETS periods, if necessary. However, we should also bear in mind that, while the proton beams can be carefully prepared and tuned during Run 3 in order to be ready after Long Shutdown 3 (LS3), the Pb ion beams will need to be already available for physics production by the ion run scheduled at the end of 2020,

This paper will only focus on the protons beams. Before discussing all upgrades planned within the LIU project and the performance reach of the injector complex after their implementation, it is useful to briefly review the operational beam characteristics achieved in 2012. Using the standard production scheme with 72 bunches per PS batch, the injectors delivered the 25 ns beam with $N \approx 1.2 \times 10^{11}$ p/b and transverse emittances of $\varepsilon_n \approx 2.6\,\mu$m for the LHC Scrubbing Run. The successful implementation of the Batch Compression bunch Merging and Splitting (BCMS) scheme [5, 6] in the PS allowed the number of splittings of each PSB bunch to be reduced by a factor two at the expense of reducing the number of bunches per PS batch from 72 to 48. With this scheme a high brightness 25 ns beam with similar intensity per bunch but a transverse emittance $\varepsilon_n \approx 1.4\,\mu$m at SPS extraction was provided to the LHC for the 25 ns pilot physics run. For both beam types, the achievable beam brightness is determined by the multi-turn injection in the PSB and space charge in the PS. The main intensity limitations for the 25 ns beams in the injector complex are due to electron cloud effects and longitudinal instabilities in the SPS. Stable beam conditions with four PS batches and bunch lengths at SPS extraction compatible with injection into the LHC were achieved for a maximum intensity of about $N \approx 1.3 \times 10^{11}$ p/b, while injecting higher intensity values only resulted in an increase of the losses along the cycle and a visible deterioration of the beam quality at 450 GeV.

All upgrades for the PSB, PS and SPS foreseen by the LIU project as well as the resulting parameter reach for proton beams will be described in the following sections. For the estimation of the achievable beam parameters out of the LHC injectors in the future, it is assumed that emittance growth and losses amount to 5 % in the PSB and in the PS, respectively, and to 10 % in the SPS, as summarized in Table 1. These budgets have been found to be consistent with the optimized performance of LHC beams across the injector chain in 2012 and are thus considered as LIU targets.

Table 1: Beam loss and emittance growth budgets.

Machine	$-\Delta N/N_0$	$\Delta\varepsilon/\varepsilon_0$
PSB injection to extraction	5 %	5 %
PS injection to extraction	5 %	5 %
SPS injection to extraction	10 %	10 %
End-to-end	19 %	21 %

PS COMPLEX

Brightness Limitations for 25 ns Beams

In the present configuration with Linac2, the LHC beams are produced in the PSB at a constant beam brightness [7], which is mainly determined by the efficiency of the multi-turn injection process and space charge effects in the low energy part of the cycle. Extrapolating from the original target to obtain twice the intensity within the same transverse emittance as today's LHC beams, it is assumed that the connection of Linac4 and the H^- charge exchange injection at 160 MeV will allow doubling the beam brightness out of the PSB for LHC beams [8]. This is illustrated in the limitation diagrams for the standard and the BCMS beam production schemes shown in Fig. 1, where the shaded areas correspond to beam parameters not accessible after the LIU upgrade. Note that the normalized transverse emittance is plotted as a function of the intensity per bunch at LHC injection (450 GeV) including already the budgets for emittance growth and losses through the injector chain as defined in Table 1. Recently, a working group devoted to studies of injection from Linac4 into the PSB has been set up to define via simulations: 1) the future PSB brightness curve, and 2) the intensity reach of future ISOLDE beams. Studies are based on the assumption that Linac4 will be able to provide 40 mA within 0.35 μm rms emittance [9]. Chopping to 650 ns per injected turn will then lower the average beam current injected into the PSB to 26 mA. As a consequence, injection of HL-LHC beams [2] will require about 20 turns, while injecting 100 turns could result into beam intensities of about 1.5×10^{13} p/ring with a few percent loss in the injection process.

In order to mitigate space charge effects on the PS injection plateau with the higher beam brightness available with Linac4, the PSB-PS transfer energy will be increased from the present 1.4 GeV to 2 GeV as part of the baseline LIU PSB and PS upgrades. This will require some important upgrades in the PSB (increase of the magnetic field in the magnets, new main power supply, upgrade of the existing main C02 and C04 RF systems – or their replacement by a Finemet cavity based RF system – redesign of the beam extraction and subsequent transfer) as well as a redesign of the injection into the PS. Based on measurements with single bunch beams [10] and the operational experience with the high brightness 25 ns BCMS beam at 1.4 GeV, a maximum vertical space charge tune shift of $\Delta Q_y \approx -0.31$ on the PS injection plateau can be considered acceptable with respect to blow-up and losses [8]. The corresponding transverse emittance as a function of intensity per LHC bunch for this tune shift is shown in Fig. 1 together with the beam parameters at LHC injection achieved in 2012. The highest beam brightness in the PS achievable with the 2 GeV upgrade is then estimated assuming the maximum bunch length compatible with the PSB recombination kicker rise time, i.e. $\tau = 205$ ns for the standard production scheme (6 PSB bunches injected on harmonic number $h = 7$ in the PS) and $\tau = 135$ ns for the BCMS beams (8 PSB bunches injected on $h = 9$), and the largest longitudinal emittance compatible with the RF gymnastics. Note that after the implementation of the LIU upgrades, i.e. the connection of Linac4 and the 2 GeV PSB-PS transfer, the PS complex is expected routinely to deliver 25 ns beams with twice higher brightness as compared to the present performance.

Intensity Limitations for 25 ns Beams

Considering the operational experience with other high intensity beams, no intensity limitations from coherent beam instabilities are to be expected in the PSB within the parameter range of interest for HL-LHC.

In the PS, longitudinal coupled-bunch instabilities during acceleration and at flat top presently limit the intensity of LHC beams to about $N \approx 2.0 \times 10^{11}$ p/b at extraction. Furthermore, transient beam loading induces asymmetries of the various bunch splittings and thus a bunch-to-bunch intensity variation along the bunch train. However, within

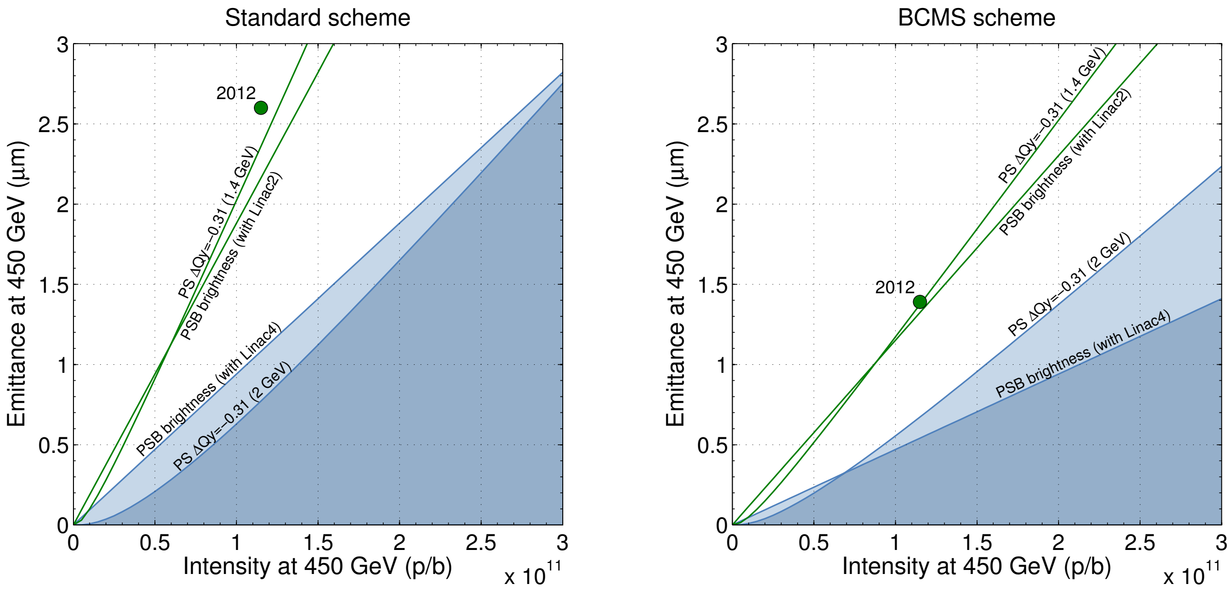


Figure 1: Beam brightness limitations in the PS complex for the standard 25 ns beam production scheme (left) and the 25 ns BCMS scheme (right) after the LIU upgrades (blue curves) and at present (green curves) together with the beam performance achieved in 2012 (green dots).

the LIU project a new coupled-bunch feedback system with a dedicated wide-band Finemet cavity as a kicker and new 1-turn delay feedback boards for beam loading compensation on the main 10 MHz RF system have been installed during LS1 and are ready for testing during Run 2. They are expected to push the intensity limit to values around $N = 3.0 \times 10^{11}$ p/b, i.e. well beyond the requirement for the 25 ns HL-LHC beam.

Various instabilities in the transverse plane can be observed with LHC beams in the PS. Horizontal head-tail instabilities are encountered at flat bottom [11], which are presently cured by introducing linear coupling between the transverse planes and operating close to the coupling resonance. It was demonstrated in Machine Development (MD) studies that these head-tail instabilities at 1.4 GeV can be suppressed also by the PS transverse feedback system commissioned in 2012 [12], which has the advantage of providing additional flexibility for optimizing the machine working point for the space charge dominated LHC beams. The power amplifiers of this feedback have been upgraded in the frame of the LIU project in preparation for the future injection at 2 GeV. Another important use of the transverse feedback that has recently emerged is its potential capability of kicking out one out of 21 bunches at low energy after triple splitting (obtained from a 4+3 bunch injection from the PSB) in order to produce trains of 80 bunches instead of the usual 72 [13].

The fast vertical instability observed in the PS during transition crossing with high intensity (TOF-like) beams is not expected to be a limitation for the HL-LHC beams [14]. However, a similar instability discovered recently with single bunch beams of small longitudinal emittance needs to be analyzed further in future MD studies, as it could not be cured with the aforementioned PS transverse feedback system due to its limited bandwidth [12].

After the final bunch splittings at the PS top energy resulting in the 25 ns bunch spacing, an electron cloud develops during the bunch shortening and bunch rotation before extraction to the SPS [15]. Nevertheless, no beam degradation has been observed so far in operational conditions as the time of interaction between the beam and the electron cloud is restricted to a few tens of milliseconds. It was observed in dedicated MD studies that the electron cloud drives a horizontal coupled bunch instability if the 25 ns beam is stored at top energy [16]. The onset time of this instability could be efficiently delayed by the PS transverse feedback system [12]. The electron cloud is therefore not likely to become a limitation for the HL-LHC beams. Nevertheless, future machine studies with HL-LHC-like bunch intensities (hopefully available thanks to the new wide-band longitudinal feedback system) will be conducted during Run 2 to measure the possible beam degradation driven by electron cloud in that parameter range.

SPS

The main challenges for future high intensity 25 ns LHC beams in the SPS are instabilities in the transverse and longitudinal planes, beam loading and RF power, electron cloud and space charge effects on the long injection plateau. Since the end of 2010, extensive machine studies have been performed with a low gamma transition optics. In comparison to the Q26 optics used in the past, which has 26 as the integer part of the betatron tunes and a gamma transition of $\gamma_t = 22.8$, the working point is lowered by 6 integer units in both planes in the Q20 optics [17] such that the transition energy is reduced to $\gamma_t = 18$. Consequently, the phase slip factor $\eta \equiv 1/\gamma_t^2 - 1/\gamma^2$ is increased throughout the acceleration cycle with the largest relative gain of a factor 3 at injection energy. As the intensity thresholds for all instabilities observed in the SPS scale with the slip factor η, a significant improvement of beam stability is achieved with the Q20 optics as discussed in more detail below. The Q20 optics is being used successfully in routine operation for LHC filling since September 2012 [18] and will be the default machine configuration for LHC beams in the SPS in the future.

Transverse Plane

The vertical single bunch Transverse Mode Coupling Instability (TMCI) at injection was identified as one of the main intensity limitations in the Q26 optics. For bunches injected with the nominal longitudinal emittance $\varepsilon_l = 0.35\,\text{eVs}$, the corresponding instability threshold is around $N_{th} \approx 1.6 \times 10^{11}$ p/b (with vertical chromaticity close to zero) [19]. The instability manifests itself through emittance blow-up and fast losses. Slightly higher intensities can be reached when increasing the chromaticity, however at the expense of enhanced incoherent emittance growth and losses on the flat bottom. Analytical models based on a broadband impedance predict that the instability threshold with zero chromaticity scales like $N_{th} \propto |\eta|\varepsilon_l/\beta_y$ [20], where β_y denotes the vertical beta function averaged over the locations of the impedance source. Thus, the instability threshold can be raised by injecting bunches with larger longitudinal emittance. However, the beam transmission between PS and SPS is degrading for larger longitudinal emittances, unless an additional 40 (or 80) MHz cavity is installed in the PS for improving the bunch shape at extraction [21] (which will be studied in MDs during Run 2). On the other hand, a significant increase of the instability threshold is expected in the Q20 optics even with the nominal longitudinal emittance, since the product of the slip factor and the vertical beta function at important impedance sources ($\eta\,\beta_y$) is about 2.5 times higher compared to the Q26 optics. An extensive measurement campaign with high intensity single bunch beams has confirmed this expectation. The instability threshold in the Q20 optics for chromaticity close to zero and nominal longitudinal emittance was found at around $N_{th} \approx 4.5 \times 10^{11}$ p/b in excellent agreement with numerical simulations using the latest SPS impedance model [22, 23]. With the Q20 optics the TMCI is not of concern for the beam parameters envisaged by the HL-LHC, even for the 50 ns "back-up" scenario [24], which requires significantly higher intensities per bunch compared to the 25 ns beams. However, the factor two margin in terms of bunch intensity with respect to the HL-LHC target value provided by the Q20 optics can be partly traded off choosing an intermediate γ_t optics (e.g. Q22), which can still provide enough stability against TMCI to fulfil the HL-LHC target, but puts less constraint on the required voltage at extraction. This will be briefly addressed in the next subsection, and is discussed in detail in [13].

To determine the brightness that can be swallowed by the SPS, a working point scan was performed with the Q20 optics using a beam with a large estimated vertical tune spread (about $\Delta Q_y = -0.20$). The goal was to check experimentally how much space in the tune diagram is needed to accommodate the incoherent space charge tune spread and thus to minimize emittance blow-up on the long injection plateau. The results of this MD are described in detail in [25]. Based on these results and considering the budgets for emittance blow-up and losses defined in Table 1, which permit slightly larger blow-up in the SPS than observed in the measurements, the presently maximum acceptable space charge tune shift in the SPS for an optimized working point is set to $\Delta Q_y = -0.21$.

Longitudinal Instabilities and RF Power

The longitudinal instabilities observed with LHC beams in the SPS are a combination of single bunch and coupled bunch effects [26]. The beam is stabilized in routine operation by increasing the synchrotron frequency spread using the 4th harmonic (800 MHz) RF system in bunch-shortening mode in combination with controlled longitudinal emittance blow-up along the ramp, which is performed with band-limited phase noise in the main 200 MHz RF system.

For a given longitudinal emittance and matched RF voltage the thresholds of the longitudinal coupled bunch instability and the single bunch instability due to loss of Landau damping scale proportional to the slip factor η [27]. Improved longitudinal beam stability was therefore observed in measurements with the Q20 optics at injection and during the ramp [28], where sufficient RF voltage is available to restore the same bucket area as with the Q26 optics. In fact, the Q20 optics provides significant margin for increasing the beam intensity at injection energy, where the attainable longitudinal emittance is limited by capture losses and the transfer efficiency between the PS and SPS. The situation is different at flat top. The maximum voltage is applied in both optics in order to shorten the bunches for the transfer into the 400 MHz buckets of the LHC. Better beam stability would still be achieved in the Q20 optics for a given longitudinal emittance, however, in this case the bunches would be longer. In order to have the same bunch length in the two optics, the longitudinal emittance has to be smaller in the Q20 optics. From the scaling of the instability threshold for loss of Landau damping (LD) [27] it follows that the same beam stability is obtained in both optics for the same bunch length at extraction.

At the end of 2012, a series of MD sessions were devoted to the study of high intensity 25 ns beams in the Q20 optics. The larger longitudinal emittance of beams with $N > 1.2 \times 10^{11}$ p/b already at injection and the controlled longitudinal emittance blow-up in the SPS required for their stabilization result in an average bunch length at extraction close to the limit $\tau \approx 1.7$ ns, acceptable for transfer into LHC. Presently, $N \approx 1.35 \times 10^{11}$ p/b is considered to be the maximum intensity reachable with the current RF system in the SPS that can be stably accelerated and extracted with bunch lengths within specification. Using the scaling law for single bunch instability due to loss of Landau damping, the RF voltage needs to be increased proportionally to the intensity to keep the bunch length constant [29].

The 200 MHz main RF system of the SPS consists of four travelling wave cavities, of which two are made of four sections and the other two are made of five sections [30]. The maximum RF power presently available in continuous mode is about 0.75 MW per cavity, which corresponds to a maximum total RF voltage of about 7.5 MV at nominal intensity of the 25 ns beam. However, less RF voltage is available for higher beam intensity due to the effect of beam loading and the limited RF power [31]. This voltage reduction is larger for longer cavities, i.e., it is increasing with the number of cavity sections. The LIU baseline upgrades for the SPS include an upgrade of the low-level RF and a major upgrade of the 200 MHz RF system [32]. Upgrading the low-level RF alone will allow pulsing the RF amplifiers with the revolution frequency (the LHC beam occupies less than a half of the SPS circumference), leading to an increase of the peak RF power up to about 1.05 MW per cavity. Furthermore, the LIU upgrade foresees the rearrangement of the four existing cavities and two spare sections into two 4-section cavities and four 3-section cavities, and the construction of two additional power plants providing 1.6 MW each. This will entail a reduction of the beam loading per cavity, an increase of the available RF voltage and a reduction of the beam coupling impedance (its peak value at the fundamental frequency).

Figure 2 shows the maximum total RF voltage of the SPS 200 MHz system as a function of the beam current with and without the RF upgrades. The RF voltage required for keeping the bunch length constant with increasing intensity taking into account the compensation of potential well distortion (PWD) and the required longitudinal emittance blow-up for stabilizing the beam against the single bunch instability (loss of Landau damping) is indicated in the same graph. The presently maximum achieved intensity of $N \approx 1.35 \times 10^{11}$ p/b (corresponding to 1.7 A beam current) together with the corresponding maximum RF voltage of 7 MV serves as reference point. It follows that a maximum beam current of 1.9 A will be in reach after the low-level upgrade (4 times 1.05 MW pulsed) and 2.7 A after the full RF upgrade (cavities rearranged into six with 4×1.05 MW and 2×1.6 MW) [29]. These values correspond to maximum intensities at extraction of about $N \approx 1.45 \times 10^{11}$ p/b and $N \approx 2.0 \times 10^{11}$ p/b, respectively, when taking into account 3% intensity reduction due to scraping before extraction for cleaning transverse beam tails. However, it should be emphasized that this estimation is based on simplified scaling laws and that slightly longer bunches, if accepted by the LHC, are significantly more stable ($\sim \tau^5$).

If the major impedance source determining the red line in the above plot is found and mitigated, the slope of the line could be reduced and, therefore, the intensity reach of the 25 ns beams at SPS extraction could be significantly extended and cover the HL-LHC range (see, for example, green line in Fig. 2). In 2013-14, two dedicated studies were conducted in parallel, aiming at identifying the cause of the longitudinal instabilities: on one hand, the longitudinal impedance model of the SPS was progressively refined adding the contributions of all vacuum flanges and other elements, while, on the other hand, the impedance measurement data from the 2012-13 machine development sessions were fitted with macroparticle simulations based on the updated impedance model. The main result of these studies seemed to point to the impedance of the vacuum flanges as responsible for halving the value of the intensity threshold for longitudinal instabilities. Reducing, or even suppressing, this source of impedance by means of shielding or redesigning of the flanges would be a possible key to accessing larger beam currents out of the SPS [33]. If the finding is confirmed and the related mitigating action is clearly identified and endorsed by LIU by end 2015 (in order to be able to prepare for LS2), this would become a major extra activity to be added to the baseline with its time requirements and additional budget implications.

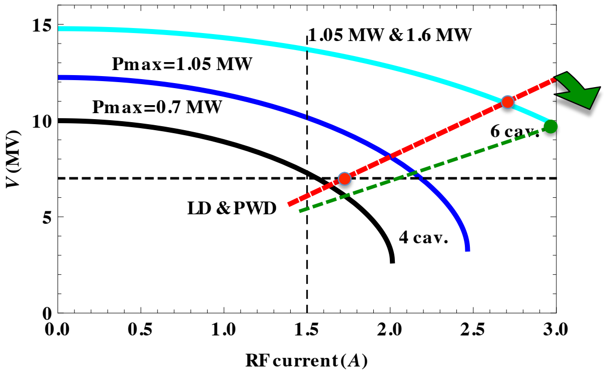


Figure 2: Maximum total RF voltage as a function of the beam current for different cases: present situation (black line), after the low-level RF upgrade to operate in pulsed mode (blue line) and after the cavity rearrangement and the construction of two additional power plants of 1.6 MW each (light blue line). The voltage required to maintain constant bunch length at extraction taking into account the single bunch longitudinal instability and the voltage reduction due to potential well distortion is also shown as a red line together with the present and future points (red dots). A possible line after impedance reduction is also shown (green) together with the achievable point (green dot).

Electron Cloud

The electron cloud effect has been identified as a possible performance limitation for the SPS since LHC type beams with 25 ns spacing were injected into the machine for the first time in the early years of 2000. At that time a severe pressure rise was observed all around the machine together with transverse beam instabilities, significant losses and emittance blow-up on the trailing bunches of the train [34]. Since 2002, Scrubbing Runs with 25 ns beams were carried out almost every year of operation in order to condition the inner surfaces of the vacuum chambers and therefore mitigate the electron cloud. This allowed achieving a good conditioning state of the SPS up to 2012, both in terms of dynamic pressure rise and beam quality. During the Scrubbing Run of the LHC at the end of 2012, the 25 ns beam was regularly extracted from the SPS Q20 optics with four batches of 72 bunches with $N \approx 1.2 \times 10^{11}$ p/b and normalized transverse emittances of about 2.6 μm [18]. Extensive machine studies showed that for this beam intensity the 2012 conditioning state of the SPS was sufficient to suppress any possible beam degradation due to electron cloud on the cycle timescale [35].

Further experiments performed with the Q20 optics showed that it was possible to inject the full train of the 25 ns beam with up to $N \approx 1.35 \times 10^{11}$ p/b without transverse emittance blow-up and preserve the beam quality up to extraction energy, as shown in Fig. 3 (top). For higher intensities ($N \approx 1.45 \times 10^{11}$ p/b injected) a transverse instability was observed after the injection of the third and the fourth batch, leading to emittance blow up as shown in Fig. 3 (bottom) and particle losses on the trailing bunches of the injected trains. The observed pattern on the bunch-by-bunch emittance is typical of electron cloud effects. Since the SPS was never scrubbed with such high beam intensities, an additional scrubbing step might be required for suppressing these effects.

Several studies have been devoted in 2012 to the optimization of the scrubbing process and in particular to the definition and test of a possible ”scrubbing beam”, i.e., a beam able to produce a higher electron cloud density in the beam chambers and, therefore, a higher scrubbing efficiency compared to the standard LHC type 25 ns beam. A 25 ns spaced train of “doublets”, each of which consisting of two 5 ns spaced bunches, has been proposed [36]. As shown in simulations, this beam has indeed a lower multipacting threshold compared to the standard 25 ns beam due to the shorter empty gap between subsequent doublets, which enhances the accumulation of electrons in the vacuum chamber. For producing this beam with the existing RF systems of the injectors, long bunches from the PS ($\tau \approx 10$ ns full length) have to be injected into the SPS on the unstable phase of the 200 MHz RF system and captured in two neighboring buckets by raising the voltage within the first few milliseconds. Very good capture efficiency (above 90%) could be achieved in machine studies for intensities up to 1.7×10^{11} p/doublet.

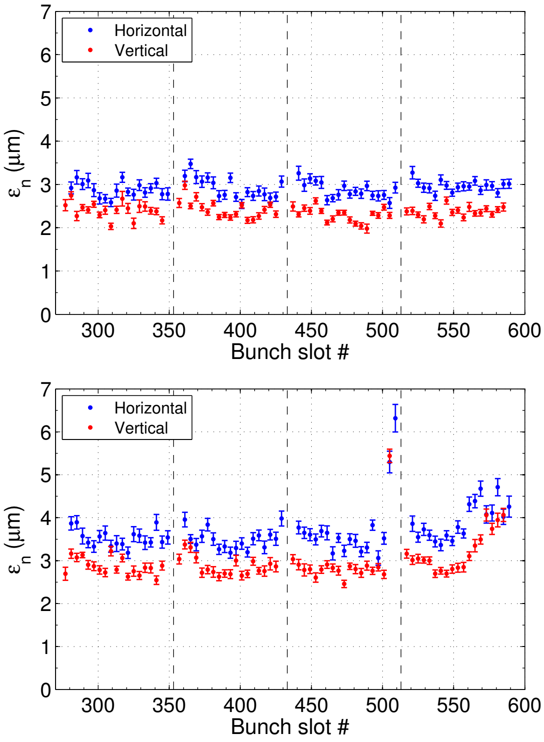


Figure 3: Bunch by bunch emittances measured at the SPS flat top for 4×72 bunches of the 25 ns LHC beam with intensities at injection of $N \approx 1.35 \times 10^{11}$ p/b (top) and $N \approx 1.45 \times 10^{11}$ p/b (bottom).

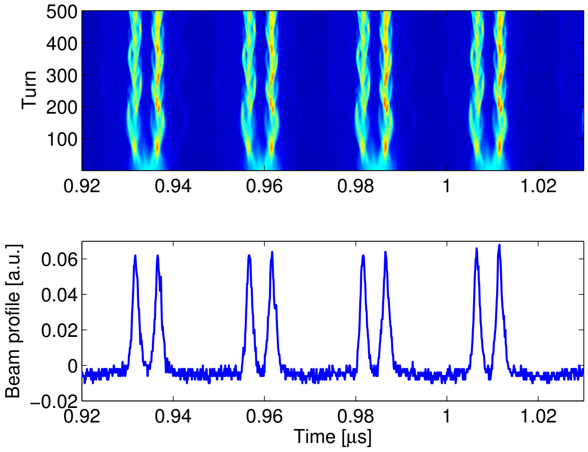


Figure 4: Evolution of the longitudinal beam profile in the SPS during the splitting at injection for the production of the doublet beam (top) and longitudinal bunch profiles of the doublet beam measured 1 s after injection (bottom).

Figure 4 (top) shows the evolution of the longitudinal profile of the beam during the “splitting” right after the injection in the SPS. Figure 4 (bottom) shows the “final” beam profile, measured one second after injection. It was also verified that it is possible to rapidly lower the RF voltage and inject a second train from the PS without any im-

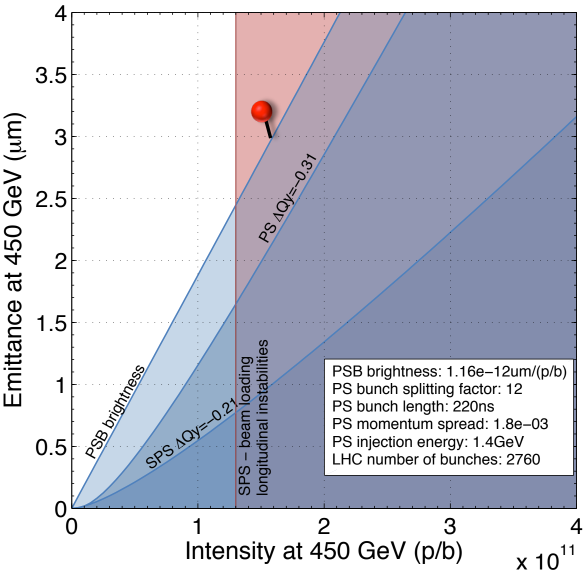


Figure 5: Limitation diagram for the doublet beam

portant degradation of the circulating beam. Observations on the dynamic pressure rise in the SPS arcs confirmed the enhancement of the electron cloud activity as expected from simulations. The enhancement was also observed with the dedicated SPS strip detectors.

Although successfully produced at 26 GeV/c in the SPS, this beam was never accelerated during the 2012-13 tests. In order to permit acceleration of intensities larger than 1.3×10^{11} p/(25 ns slot), it is planned to accelerate the doublet beam on a slower ramp (possibly up to three times slower), which will require dedicated machine time for setting up and development. The achievable quality at 450 GeV/c is widely unknown, as slow acceleration, longitudinal instability and, not least, the effects from the enhanced electron cloud could contribute to beam degradation. However, the best achievable parameters for the doublet beam at SPS top energy can be found from the post-LS1 limitation diagram for LHC beams, as discussed in [8]. Figure 5 shows the desired point for the doublet beam placed in the plane intensity – emittance, in which the areas corresponding to regions in the parameter space not accessible in standard operational conditions, due to brightness or intensity limitations in the different accelerators, have been shaded. The point lies in the "forbidden" zone due to its high intensity (however considered achievable thanks to the slow ramp, as discussed above) and is expected to be produced with transverse emittances of at best 3 μm, but very likely above this value due to reasons already mentioned.

A high bandwidth (intra-bunch) transverse feedback system is being developed for the SPS as part of the LIU project in collaboration with the LHC Accelerator Research Program (LARP), with the goal of fighting electron cloud instabilities and improving the beam quality during the scrubbing for making it more efficient. In 2013, experimental studies with prototype hardware already demonstrated the successful suppression of slow headtail instabilities of mode 0 (dipole mode) with single bunches. Further studies with improved hardware will follow in 2014 and 2015.

In case scrubbing is not sufficient for suppressing the electron cloud effect with the high beam intensity and small transverse emittance required for HL-LHC, or in case the reconditioning process is very slow after large parts of the machine are vented (like during a long shutdown), the inner surface of the SPS vacuum chambers has to be coated with a low Secondary Electron Yield (SEY) material. The solution developed at CERN is to produce a thin film of amorphous Carbon (a-C) using DC Hollow Cathode sputtering directly inside the vacuum chamber [37]. The suppression of electron cloud in coated prototype vacuum chambers has been fully validated with beam in the SPS [35]. An additional four SPS half cells (including quadrupoles) have been coated with a-C during LS1 for further testing in Run 2.

The coating of the entire machine circumference of the SPS with a-C is a major task, which requires careful preparation and planning of resources (as all magnets need to be transported to a workshop). The decision whether the SPS needs to be coated or scrubbing alone can guarantee enough electron cloud mitigation has therefore to be taken not later than mid-2015. After the long shutdown, a Scrubbing Run of one week plus three days will take place by the end of 2014 with the goal of recovering the operational performance, as it is expected that the good conditioning state of the SPS will be degraded due to the long period without beam operation and the related interventions on the machine. Another Scrubbing Run, split into two weeks, will be performed in the first half of 2015 in order to scrub the machine for high intensity 25 ns beams. After collecting all the additional experience from post-LS1 operation and the important information from the extensive experimental scrubbing and high intensity studies with 25 ns beams (and doublets), the final choice between coating and scrubbing will be made in mid-2015.

SPECIAL BEAMS

Both to increase the accessible area in the beam parameter space and to create beams that could be useful for future MD studies and/or physics operation, new beams with alternative filling patterns are planned to be produced in MDs during Run 2. Two examples, for which we will briefly review here the parameter reach, are the Pure Batch Compression (PBC) scheme and the 8b+4e scheme.

The PBC scheme is based on the direct compression in the PS of an eight bunch train – injected in two consecutive batches from the PSB – from $h = 9$ into $h = 21$ at 2.5 GeV, and eventually the application of two subsequent double splittings at 26 GeV/c. The result of this gymnastics is a train of 32 bunches for the SPS (instead of the nominal 72, which translates into a decrease by 11% of the number

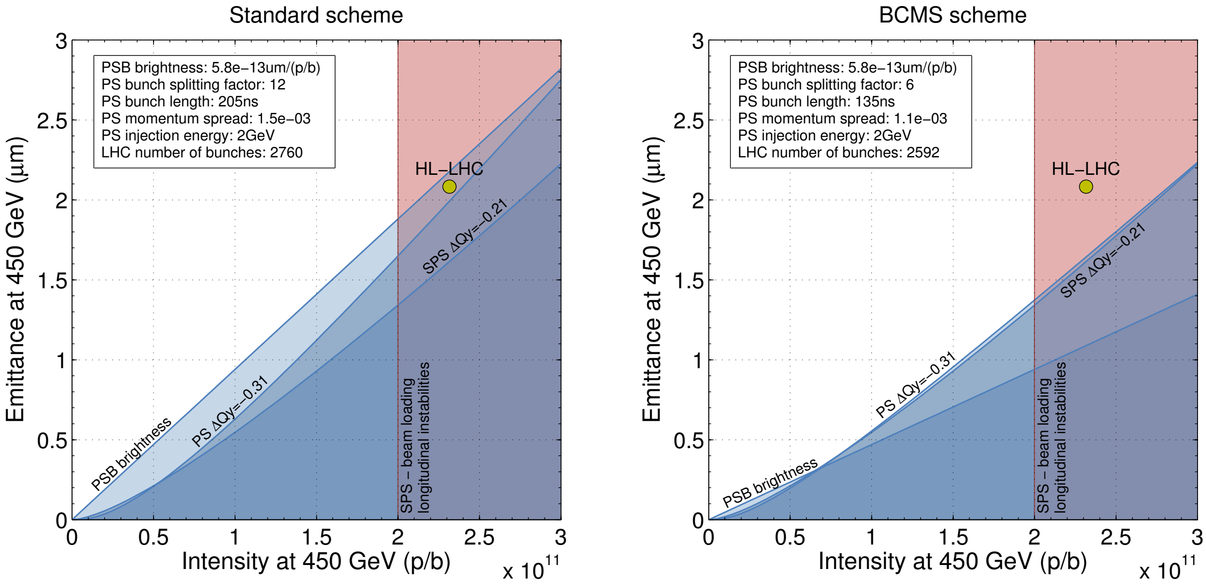


Figure 6: Limitation diagrams for 25 ns beams produced with the standard scheme (left) and the BCMS scheme (right) after implementation of the LIU upgrades.

of bunches in LHC). These bunches can be, however, very bright, as they could potentially pack $N = 1.3 \times 10^{11}$ p/b within $\varepsilon_n \approx 0.9\,\mu$m at the SPS extraction. These beams could be interesting to study transport of sub-μm emittance beams through the LHC injector chain (still widely unexplored) as well as to conduct advanced space charge studies in the SPS (especially in their 50 ns variant, which is based on only one double splitting at the flat top in the PS and can result in even brighter bunches).

The 8b+4e scheme is basically the same as the standard production scheme, but uses 7 bunches (instead of 6) from the PSB injected into $h = 7$ and then converts the first triple splitting from $h = 7$ to $h = 21$ into a double splitting with an empty bucket. By doing that, the train obtained at 26 GeV/c after the two double splittings will be made of 7 sequences of 8 bunches and 4 empty gaps (hence the name 8b+4e). Since both beam loading and longitudinal instabilities in the SPS could be somewhat relaxed by the batch structure with micro-trains shorter than the RF cavity filling time, the intensity reach of this beam should be almost 50% larger than the standard 25 ns beam. This means that $N = 1.8 \times 10^{11}$ p/b can be obtained within a transverse emittance slightly lower than the standard 25 ns beam, $\varepsilon_n \approx 2.3\,\mu$m. The interest in this beam lies in that it could be envisaged as a future candidate for luminosity production in LHC, as it might relax electron cloud formation in the arc dipoles (having a significantly higher multipacting threshold) and can pack higher bunch current. Because of the filling pattern however, it will result in a lower number of bunches in LHC (about 1900). It is worth mentioning, finally, that the 8b+4e beam can also be produced in its BCMS variant. In this case, it is necessary to suppress bunch merging and subsequent triple splitting and end up with pairs of bunches separated by an empty bucket at 2.5 GeV. In this case, only 4 sequences of 8 bunches and 4 empty gaps can be sent to the SPS, but the transverse emittance achievable for $N = 1.8 \times 10^{11}$ p/b would be as low as $\varepsilon_n \approx 1.4\,\mu$m.

INJECTORS PERFORMANCE REACH

The expected performance reach of the entire LHC injector chain after implementation of the LIU upgrades is shown in Fig. 6 for the standard and the BCMS scheme. The beam parameters are given at LHC injection taking into account the emittance growth and loss budgets from Table 1. The best beam parameters correspond to an intensity of $N = 2.0 \times 10^{11}$ p/b (limited by longitudinal instabilities and RF power in the SPS) within transverse emittances of $\varepsilon_n = 1.9\,\mu$m for the standard scheme (limited by the PSB brightness). Although the bunch intensity is about 15% lower than the value requested by HL-LHC, the target brightness is found to be achievable. If methods to extend the intensity reach of the SPS are successfully implemented (e.g. impedance reduction, slow ramp and bunch rotation or intermediate optics, [33]), the HL-LHC parameter values can be achieved. Alternatively, the missing intensity could be compensated by a larger brightness. The BCMS beam, with $N = 2.0 \times 10^{11}$ p/b within $\varepsilon_n = 1.4\,\mu$m (limited by space charge in the PS and SPS) as displayed in Fig. 6, right plot, has this potential. However, high brightness beams also come with larger IntraBeam Scattering (IBS) rates and fewer bunches (5%) in the LHC, are less effectively stabilized by the octupoles, if necessary, and can be a challenge for the emittance measurement devices. Besides, they hold a high damage risk for protection devices in SPS, transfer lines and LHC [38]. A complete overview on the beam

Table 2: Achievable beam parameters after implementation of LIU upgrades in comparison with HL-LHC request.

		PSB						
		N (10^{11} p)	$\epsilon_{x,y}$ (μm)	E (GeV)	ϵ_z (eVs)	B_l (ns)	$\delta p/p_0$	$\Delta Q_{x,y}$
LIU	Standard	29.55	1.55	0.16	1.4	650	$1.8 \cdot 10^{-3}$	(0.55, 0.66)
	BCMS	14.77	1.13	0.16	1.4	650	$1.8 \cdot 10^{-3}$	(0.35, 0.44)
HL-LHC		34.21	1.72	0.16	1.4	650	$1.8 \cdot 10^{-3}$	(0.58, 0.69)

		PS (double injection)						
		N (10^{11} p/b)	$\epsilon_{x,y}$ (μm)	E (GeV)	ϵ_z (eVs/b)	B_l (ns)	$\delta p/p_0$	$\Delta Q_{x,y}$
LIU	Standard	28.07	1.63	2.0	3.00	205	$1.5 \cdot 10^{-3}$	(0.16, 0.28)
	BCMS	14.04	1.19	2.0	1.48	135	$1.1 \cdot 10^{-3}$	(0.19, 0.31)
HL-LHC		32.50	1.80	2.0	3.00	205	$1.5 \cdot 10^{-3}$	(0.18, 0.30)

		SPS (several injections)						
		N (10^{11} p/b)	$\epsilon_{x,y}$ (μm)	p (GeV/c)	ϵ_z (eVs/b)	B_l (ns)	$\delta p/p_0$	$\Delta Q_{x,y}$
LIU	Standard	2.22	1.71	26	0.37	3.0	$1.5 \cdot 10^{-3}$	(0.09, 0.16)
	BCMS	2.22	1.25	26	0.37	3.0	$1.5 \cdot 10^{-3}$	(0.12, 0.21)
HL-LHC		2.57	1.89	26	0.37	3.0	$1.5 \cdot 10^{-3}$	(0.10, 0.17)

		LHC					
		N (10^{11} p/b)	$\epsilon_{x,y}$ (μm)	p (GeV/c)	ϵ_z (eVs/b)	B_l (ns)	bunches/train
LIU	Standard	2.00	1.88	450	0.60	1.65	72
	BCMS	2.00	1.37	450	0.60	1.65	48
HL-LHC		2.32	2.08	450	0.65	1.65	72

parameters throughout the LHC injector chain is given in Table 2.

SUMMARY AND CONCLUSIONS

The connection of Linac4 is anticipated to double the beam brightness out of the PSB compared to the present operation, thanks to the H$^-$ charge exchange injection and the higher injection energy of 160 MeV. Raising the PS injection energy to 2 GeV will mitigate space charge effects on the injection plateau and match the performance of the PS to the higher brightness available with Linac4. The upgrades of the transverse and longitudinal feedbacks in the PS together with the RF upgrades will push present intensity limits beyond the requirements for HL-HLC. With the SPS Q20 optics the TMCI at injection is not an issue. The major SPS RF upgrade with two new power plants and rearranged RF cavities will push the achievable intensity from the present $N = 1.3 \times 10^{11}$ p/b to $N = 2.0 \times 10^{11}$ p/b. The possibility to extend this intensity limit depends on the success in reducing the main sources of longitudinal impedance, presently identified in the vacuum flanges. Alternatively, the use of of a slower acceleration rate combined with bunch rotation before extraction (or intermediate gamma transition optics or a 200 MHz RF system installed in LHC for capture) might also serve the purpose. Additional studies and a definition of the action planning and cost estimates are needed to decide whether an impedance reduction strategy should eventually be pursued. The other point on which the future SPS performance critically depends is electron cloud mitigation. The decision if the SPS vacuum chambers all around the machine will be coated with a-C in order to completely suppress the electron cloud will be taken in mid 2015 based on the experience and experimental studies from two Scrubbing Runs to be performed in 2014 and 2015. The main questions to be addressed are whether 1) scrubbing (for example with the doublet scrubbing beam), instead of coating, can be proved to be a viable path for recovering the operational performance after a long shutdown, and 2) scrubbing can suppress the electron cloud also for the future high intensity beams.

The overall performance of the LHC injectors after the implementation of all baseline LIU upgrades, i.e. an intensity of $N = 2.0 \times 10^{11}$ p/b and a transverse emittance of $\varepsilon_n = 1.9\,\mu$m for the 25 ns beam with 72 bunches per PS batch (standard scheme), nearly matches the parameters needed by HL-LHC with the presently assumed pile-up limit and machine physics efficiency. The possible use of BCMS beams in the future, which, in spite of the lower number of bunches, could compensate with a larger brightness the 15% lower intensity given by the SPS, may be hindered by its high damage potential for protection devices. For achieving the anticipated performance, all upgrades must be effective, including those not explicitly mentioned in this paper but important for overcoming operational limitations or assuring reliability of the complex. Finally, a very dense program of machine and simulation studies has been established until end of 2015 in order to further improve our parameter estimates and steer decisions on the few remaining pending items.

REFERENCES

[1] Y. Papaphilippou, *et al.*, "Operational Beams for the LHC", elsewhere in these proceedings.

[2] R. de Maria *et al.*, "How to maximize the HL-LHC performance?", in Proceedings of RLIUP Workshop, 29-31 Octo-ber 2013, Centre de Convention, Archamps, France.

[3] J. Jowett *et al.*, "Future heavy-ion performance of the LHC", in Proceedings of RLIUP Workshop, 29-31 October 2013, Centre de Convention, Archamps, France.

[4] M. Benedikt *et al.* "Summary of Session 7: Accelerators and non LHC Experiment Areas Consolidation up to LS3", elsewhere in these proceedings.

[5] R. Garoby, "New RF Exercises Envisaged in the CERN-PS for the Antiprotons Production Beam of the ACOL Machine", IEEE Transactions on Nuclear Science, Vol. NS-32., No. 5 (1985).

[6] H. Damerau *et al.*, "RF manipulations for higher beam brightness LHC-type beams", CERN-ACC-2013-0210.

[7] B. Mikulec *et al.*, "Performance reach of LHC beams", in LIU Beam Studies Review, 28 August 2013, CERN (2012).

[8] G. Rumolo *et al.*, "Expected performance in the injectors at 25 ns without and with LINAC4", in in Proceedings of RLIUP Workshop, 29-31 October 2013, Centre de Convention, Archamps, France.

[9] A. Lombardi *et al.*, "LINAC 4: Progress on Hardware and Beam Commissioning", elsewhere in these proceedings.

[10] R. Wasef *et al.*, "Space Charge Effects and Limitations in the CERN Proton Synchrotron", CERN-ACC-2013-0176.

[11] R. Cappi, "Observation of high-order head-tail instabilities at the CERN-PS", CERN-PS-95-02-PA.

[12] G. Sterbini *et al.*, "Beam Tests and Plans for the Cern PS Transverse Damper System", CERN-ACC-2013-0215.

[13] H. Bartosik *et al.*, "Other Means to increase the SPS 25 ns Performance – Transverse Plane", elsewhere in these pro-ceedings.

[14] S. Aumon, "High Intensity Beam Issues in the CERN Proton Synchrotron", CERN-THESIS-2012-261, PhD. thesis (2012).

[15] G. Iadarola *et al.*, "Electron Cloud Studies for the Upgrade of the CERN PS", CERN-ACC-2013-0095.

[16] R. Cappi *et al.*, "Electron cloud buildup and related instability in the CERN Proton Synchrotron", PRST-AB 5, 094401 (2002).

[17] H. Bartosik *et al.*, "Optics considerations for lowering transition energy in the SPS", CERN-ATS-2011-088.

[18] Y. Papaphilippou *et al.*, "Operational performance of the LHC proton beams with the SPS low transition optics", CERN-ACC-2013-0124.

[19] B. Salvant *et al.*, "Probing intensity limits of LHC-Type bunches in CERN SPS with nominal optics", CERN-ATS-2011-176.

[20] E. Metral, "Overview of Single-Beam Coherent Instabilities in Circular Accelerators", in Proceedings of the 1st CARE-HHH-APD Workshop on Beam Dynamics in Future Hadron Colliders and Rapidly Cycling High-Intensity Synchrotrons, Geneva, Switzerland (2004).

[21] H. Timko *et al.*, "Experimental and simulation studies of the PS-to-SPS beam transfer efficiency", CERN-ATS-Note-2012-059 PERF.

[22] H. Bartosik, "Beam dynamics and optics studies for the LHC injectors upgrade", CERN-THESIS-2013-257, PhD. thesis (2013).

[23] C. Zannini, "SPS: instabilities and impedance model in the transverse plane", in LIU Day 2014, 11 April 2014, CERN (2014).

[24] V. Kain *et al.*, "50 ns back-up scenario", in Proceedings of RLIUP Workshop, 29-31 October 2013, Centre de Conven-tion, Archamps, France.

[25] H. Bartosik *et al.*, "Experimental Studies for Future LHC Beams in the SPS", CERN-ACC-2013-0151.

[26] E. Shaposhnikova *et al.*, "Longitudinal Instabilities in the SPS and Beam Dynamics Issues with High Harmonic RF Systems", Proceedings of HB2012, Beijing, China (2012).

[27] E. Shaposhnikova, "Longitudinal stability of the LHC beam in the SPS", SL-Note-2001-031-HRF.

[28] H. Bartosik *et al.*, "Experimental studies with low transition energy optics in the SPS", CERN-ATS-2011-086.

[29] E. Shaposhnikova, "SPS intensity limitation with and without 200 MHz RF upgrade", in the LIU SPS-Beam Dynamics Working Group meeting, CERN (2013).

[30] G. Dome, "The SPS acceleration system travelling wave drift-tube structure for the CERN SPS", CERN-SPS-ARF-77-11.

[31] T. Bohl, "The 200 MHz Travelling Wave Cavities in the SPS", Proceedings of the 10th Chamonix SPS and LEP Per-formance workshop, Chamonix, France (2000).

[32] E. Shaposhnikova *et al.*, "Upgrade of the 200 MHZ RF System in the CERN SPS", CERN-ATS-2011-042.

[33] T. Argyropoulos *et al.*, "Other Means to Increase the SPS 25 ns Performance – Longitudinal Plane", elsewhere in these proceedings.

[34] G. Arduini *et al.*, "Beam observations with electron cloud in the CERN PS and SPS complex", Proceedings of the ECLOUD04 workshop, Napa, CA, USA (2005).

[35] H. Bartosik *et al.*, "Electron Cloud and Scrubbing Studies for the SPS in 2012", CERN-ATS-Note-2013-019 MD.

[36] G. Iadarola *et al.*, "Recent electron cloud studies in the SPS", CERN-ACC-2013-0115.

[37] C. Vallgren *et al.*, "Amorphous carbon coatings for the mitigation of electron cloud in the CERN Super Proton Synchrotron", Phys. Rev. ST Accel. Beams, 14, 071001 (2011).

[38] V. Kain *et al.*, "Concerns with Low Emittance Beams Operation", elsewhere in these proceedings.

CONCERNS WITH LOW EMITTANCE BEAM OPERATION

V. Kain, C. Bracco, M. Fraser, Y. Kadi, A. Lechner, F. Maciariello, M. Meddahi, A. Mereghetti,
G. Steele, F. Velotti, J. Uythoven, CERN, Geneva, Switzerland

Abstract

New techniques for the production of 25 ns bunch trains in the LHC injector chain have been successfully tested in the last year of the LHC run 1. These new techniques can produce bunches with unprecedented brightness for bunch intensities similar to the nominal scheme, but with significantly reduced emittances. The material damage potential depends however roughly on the ratio of intensity to emittance. The effect of the new beams in case of impact on protection devices and their attenuation therefore has to be carefully evaluated. This talk will summarize the result of material survival simulations for various possible beams after LS1 and LS2 for protection devices and dumps. Possible implications on operation with these beams and limitations of emittance measurement devices will be discussed as well. The talk will also highlight the necessity of beam based material tests in HiRadMat to fully understand material properties under the severe conditions of shock impact from high intensity beams.

INTRODUCTION

The LHC injectors will have to provide beams with unprecedented brightness to meet the performance goals of the High-Luminosity LHC (HL LHC) [1]. New techniques for the production of the 25 ns trains in the injectors have been developed in the recent years involving significantly reducing the transverse emittance. An example is the BCMS beam from the CERN PS [1]. The HL beam parameters from the injectors for the standard production scheme and the BCMS parameters after the LHC Injector Upgrade (LIU) are summarized in Table 1.

Table 1: Number of protons per bunch, normalized transverse emittance and number of bunches per SPS batch for the HL LHC 25 ns standard beam and the low emittance BCMS LIU beam.

	$p^+/bunch$	ε	$N_{bunches}$
HL 25 ns standard	2.3×10^{11}	$2.1\mu m$	288
BCMS LIU	2×10^{11}	$1.3\ \mu m$	288

Low emittance beams like BCMS have many advantages. The LHC peak luminosity is higher for BCMS than for the standard scheme for the same β^* and intensity. At the same time lower β^* is possible due to more available aperture in sigma and the requirement of smaller crossing angles. Other advantages include reduced injection losses on the transfer line collimators for the same collimator settings in mm and more margin for emittance growth through the LHC cycle.

On the other hand very low emittance beams also bring a number of disadvantages. The Intra-beam Scattering growth rate will be larger and hence the luminosity life time worse. Preliminary estimates for the growth rates during the LHC injection flat bottom for LHC run 2 indicate 50 % more growth than for the 25 ns standard scheme [2]. Emittance measurements with the LHC profile monitors will be close to the limit at 7 TeV and even more so with the significantly smaller beam sizes with BCMS emittances [2]. Due to the production technique of the BCMS beams in the injectors more holes will be in the filling scheme resulting in 5 % fewer bunches (if 288 bunches can be extracted from the SPS). The stabilizing effect of the Landau octupoles with the smaller beams might also be reduced. The main topic of this paper is however the increased energy density from high brightness, small emittance beams in case of beam impact and the arising attenuation and robustness issues for passive protection devices.

Attenuation Requirements for Protection Devices

The peak energy deposition in material and hence the damage potential of a beam does not only depend on the intensity but also on the spot size of the beam $\sigma_x \times \sigma_y$ at the impact location. The peak energy deposition ΔE is proportional to

$$\Delta E \propto \frac{I_{beam}}{\sigma_x \cdot \sigma_y} \tag{1}$$

where I_{beam} is the beam intensity. If the effect of different beams is compared at locations with the same optics, then the energy deposition scales with the brightness of the beam:

$$\Delta E \propto \frac{I_{beam}}{\varepsilon} \tag{2}$$

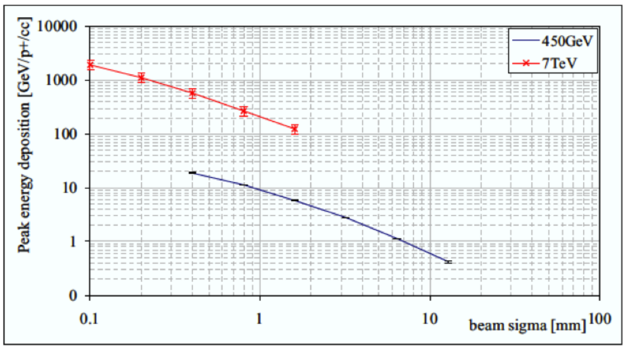


Figure 1: Peak energy deposition in Cu for 450 GeV and 7 TeV as a function of the spot size. Round beams were assumed in the FLUKA simulations.

Passive protection devices are designed to attenuate the beam energy density to a safe level for downstream equipment. Protection devices have to attenuate by a factor A:

$$\frac{I_{after}}{\varepsilon_{after}} = \frac{1}{A} \cdot \frac{I_{beam}}{\varepsilon_{beam}} \tag{3}$$

The acceptable energy density $I_{after}/\varepsilon_{after}$ for equipment comes from either experiment or simulation. In the case of the passive absorbers for the LHC injection protection system the damage limit was obtained from the TT40 material damage test [3]. Most of the LHC passive protection devices have been designed for ultimate LHC intensity (1.7×10^{11} protons per bunch in $3.5\mu m$ normalized emittance) with material and length of absorber to match the required attenuation from the TT40 experiment. Table 2 compares the brightness of the different types of LHC beams with the brightness of the ultimate beam $N_b/\varepsilon : N_u/\varepsilon_u$ and hence the attenuation requirement.

Table 2: The brightness of the different LHC beams compared to the ultimate brightness. The maximum number of injected bunches for all schemes is 288 bunches with 25 ns bunch spacing.

	$p^+/bunch$ $[10^{11}]$	ε $[\mu m]$	$\frac{N_b/\varepsilon}{N_u/\varepsilon_u}$
nominal	1.15	3.5	0.68
ultimate	1.7	3.5	1
standard run 2	1.2	2.6	0.95
BCMS run 2	1.3	1.3	2.1
HL standard	2.3	2.1	2.3
BCMS LIU	2	1.3	3.1

As can be seen from Table 2 the protection devices for LIU beams (beams for run 3) and BCMS after LS1 will have to attenuate a factor 2 to 3 more than currently required. For example for BCMS after LS1 the protection devices will have to attenuate 100 % more than the current design. If the design does not provide sufficient margin - as is the case for the transfer line collimation system - the protection devices will have to become either longer or their jaws have to be made of higher Z materials to deal with the future beams.

Attenuation is only one of the issues for protection devices for very bright beams. The other problem is insufficient robustness in case of beam impact. This topic will be discussed in detail in the following section with the example of the LHC transfer line collimation system for LIU.

LIU TRANSFER LINE COLLIMATORS

To cope with LIU BCMS beams, the transfer line graphite collimators will have to become significantly longer. For graphite this attenuation requirement at 450 GeV implies a collimator length of ~ 1.9 m instead of 1.2 m.

Thermo-mechanical simulations including shock waves revealed another problem with the increased brightness of the LIU beams. Beam impact close to the surface of the graphite collimator, e.g. 1 σ impact parameter, causes stresses above the material strength. The generated stresses depend strongly on the beam size of the impacting beam. It was hence decided to not only look for locations with sufficient space to install 1.9 m long jaws, but also to modify the optics of the lines such that the beta functions at the entrance of the collimators fulfill the criterion $\beta_x \times \beta_y > 3500\, m^2$. A full redesign of the LHC transfer line collimation system was inevitable to deal with LIU beams. Optics changes in the lines in this range were still deemed feasible.

With the spot size criterion the maximum temperature reached with BCMS stays below 1500° C. As is however discussed in [4], the beam size increase is still not sufficient to safely conclude that the transfer line collimators would survive beam impact under all conditions. Different materials were studied. Graphite R4550 - as is currently used for the transfer line collimators - is still the best compromise compared to other materials such as hBN5000 or 2D - CfC.

The most severe conditions are reached with LIU BCMS beams, nevertheless also for impact with the HL 25 ns standard beam the material strength limit is reached, see Table 3.

Table 3: Comparison of the maximum stresses in graphite R4550 for BCMS LIU and HL 25 ns standard for 1 sigma impact. The Mohr-Coulomb Safety (M.-C. S.F.) factor indicates the ratio of maximum stress versus strength of the material and has to be > 1 for the material to survive [5]. Column three shows the tensile strength versus the maximum tensile stress and column four the compressive strength versus the maximum compressive stress.

	M.-C. S.F.	$\frac{\sigma_{1limit}}{\sigma_1}$	$\frac{\sigma_{3limit}}{\sigma_3}$
BCMS LIU	0.8	30/37	118/87
HL standard	0.98	30/29	118/69

OTHER SPS AND LHC PROTECTION DEVICES

Robustness limitations with BCMS beams have not yet been evaluated for all passive protection devices. The extraction septum protection in the SPS - the TPSG, the LHC collimators and the LHC moveable dump protection absorber TCDQ have not been studied in detail concerning this aspect. Many studies have however been carried out for the high energy beam dump in the SPS, the TIDVG. Due to the sweep, emittance is of less importance in this case and the HL 25 ns standard beam with the higher total intensity causes more severe conditions. The TIDVG will have to be upgraded for LIU beams.

The other passive protection device that was studied in great detail, is the TDI LHC injection stopper - the protection against injection kicker errors. At the TDI, the beam size with BCMS LIU will be similar to the smallest spot sizes at the transfer line collimators with the LIU optics change. The first part of the jaws is made of hBN5000 and will not be robust enough for small impact parameters with LIU beams. There is however enough margin in terms of attenuation.

BCMS BEAMS AFTER LS1

Energy deposition and thermo-structural simulations were carried out for the transfer line collimators and the TDI injection stopper with the 25 ns beam parameters after LS1. Different number of bunches were simulated to be able to compare. The results are summarized in Table 4. In case of BCMS beams after LS1, the TDI injection stopper will be robust enough only for 192 bunches maximum per batch from the SPS. In terms of robustness the TCDI transfer line collimators could take up to 240 BCMS bunches at 450 GeV, but they only provide sufficient attenuation for maximum 144 BCMS bunches. For the 25 ns standard scheme no limitations have been found for run 2. The possible 80 bunch schemes from the PS have not been studied.

MATERIAL TESTS

The error on the so far obtained results for robustness is not known. This is due to the fact that material properties for the highly dynamic regime with shock waves and high temperatures are rarely available. Room temperature properties are therefore very often used. To gain more confidence on the results and understand the properties of typical collimator materials better, two tests are proposed for the HiRadMat test facility [6].

One test will address probing the material properties with high intensity LHC beam. The test setup will be similar to the HiRadMat experiment HRMT14-LCMAT. The different material samples will have simple geometries - discs and half-moon discs - to easily measure and cross-check different properties, see Fig. 2. The material samples will be heavily instrumented to obtain as much information as possible.

The other proposed test will address the robustness of a TCDI transfer line collimator assembly under the impact with LIU energy density. As the LIU intensities are not available yet in the SPS, an optics will be used that results in a smaller beam size at the test location than what is proposed for the collimators in the LIU transfer lines. The beam size was matched to provide the same energy density and stress during beam impact as for the LIU case. The current TCDI design will be used with some modifications for additional instrumentation. The two TCDI jaws will allow for precise alignment and hence for small impact parameters to create the maximum stress in the jaw material.

PRELIMINARY LATEST NEWS

The baseline material choice for the new transfer line collimators and new TDI injection stopper for LHC run 3 is Graphite R4550 despite of its insufficient robustness for 1 σ impact parameters and LIU beams. It was still the best out of all studied materials and the HiRadMat tests will show whether the so far applied criteria for robustness were too conservative. However, the recently investigated 3D Carbon-Carbon by SAFRAN-Herakles would withstand the stress from LIU BCMS beam impact in all directions according to FLUKA and ANSYS simulations. This material will also be possibly tested in HiRadMat if samples can be purchased in time.

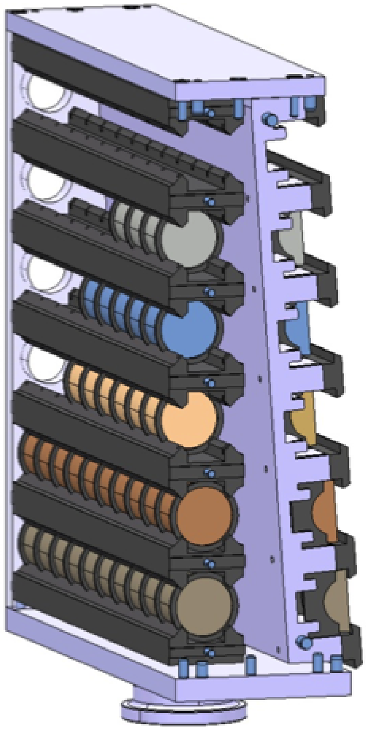


Figure 2: Material HiRadMat test sample holder for test HRMT14-LCMAT. Courtesy A. Bertarelli

SUMMARY & CONCLUSION

High brightness beams with very small transverse emittances like the proposed BCMS beam have many operational advantages. Considerable disadvantages are however the increased energy density and the resulting stresses in case of beam impact on protection devices. The stresses are beyond material strength. Also the High Luminosity 25 ns standard beam parameters are challenging in this respect.

Research is still ongoing to find new absorber materials. HiRadMat tests have been proposed to test new materials or confirm the design material choice.

For LHC run 2 the passive protection devices will still have the current limitations and operation with BCMS beam will be significantly limited. For more than 144 BCMS bunches the TCDI transfer line collimators cannot guarantee sufficient protection and an impact of more than 192 BCMS bunches could damage the TDI.

REFERENCES

[1] G. Rumolo et al., ”Protons: Baseline and Alternatives, Studies Plan", these proceedings.

[2] M. Kuhn et al., "Transverse Emittance through the LHC Cycle - an Update", LHC Evian Workshop 2014 proceedings.

[3] V. Kain et al., Conf.Proc. C0505161 (2005) 1607.

[4] A. Mereghetti et al.,"Design studies of the upgraded collimation system in the SPS-to-LHC transfer lines", IPAC'14, Dresden, Germany.

[5] J. Uythoven et al.,"Upgrade to the LHC Injection and Beam Dumping Systems for the HL-LHC Project", IPAC'14, Dresden, Germany.

[6] I. Efthymiopoulus et al., Conf.Proc. C110904 (2011) 1665-1667.

Table 4: Comparison of the maximum stresses in the absorbers TDI and TCDIs for run 2 BCMS and 25 ns standard beam for 1 sigma impact. The Mohr-Coulomb Safety (M.-C. S.F.) factor indicates the ratio of maximum stress versus strength of the material and has to be > 1 for the material to survive. Tensile strength versus the maximum tensile stress and compressive strength versus the maximum compressive stress are shown for different numbers of bunches. The status column indicates whether the absorber material is robust enough for impact under these conditions.

Absorber	beam	ε	p^+/bunch	# bunches	$\frac{\sigma_{1_{limit}}}{\sigma_1}$	$\frac{\sigma_{3_{limit}}}{\sigma_3}$	M.-C. S.F.	Status
TDI (h-BN5000)	BCMS run 2	1.39	1.3	288	7/12	59/37	0.53	NOT OK
				240	22/13	59/32	1.1	(OK)
				192	27/12	59/26	1.28	OK
	standard run 2	2.6	1.2	288	39/12	74/25	1.88	OK
TCDI (graphite)	BCMS run 2	1.39	1.3	288	30/32	118/81	0.9	NOT OK
				240	30/24	118/75	1.44	OK
				192	30/18	118/58	1.75	OK
	standard run 2	2.6	1.2	288	30/15	118/42.5	2	OK

OTHER MEANS TO INCREASE THE SPS 25 ns PERFORMANCE – TRANSVERSE PLANE

H. Bartosik, G. Arduini, A. Blas, C. Bracco, T. Bohl, K. Cornelis, H. Damerau, S. Gilardoni,
S. Hancock, B. Goddard, W. Höfle, G. Iadarola, M. Meddahi, E. Métral, G. Papotti,
Y. Papaphilippou, G. Rumolo, E. Shaposhnikova, B. Salvant, G. Sterbini, F. M. Velotti,
C. Zannini, CERN, Geneva, Switzerland

Abstract

The LHC Injectors Upgrade (LIU) project aims at extending the brightness and intensity reach of the injector complex. After the implementation of all LIU upgrades, beam loading and longitudinal instabilities in the SPS will likely remain the main limitations for the achievable intensity of the 25 ns beam. The goal of this paper is to present options to circumvent this limitation and increase the intensity of the 25 ns beams out of the SPS. In particular, two aspects will be addressed: 1) Alternative SPS optics configurations with intermediate transition energy between Q20 and Q26. Although the presently operational Q20 optics pushed the TMCI threshold from 1.6×10^{11} p/b to 4×10^{11} p/b, it might not be the optimal choice for maximizing the intensity of the 25 ns beam due to the RF power limitations. Possible optics configurations with intermediate transition energy are investigated, aiming at a better balance between TMCI threshold and RF power requirements. 2) Increase of the number of colliding bunches in the LHC by transferring a larger number of bunches between the PS and the SPS. In this context, schemes for transferring 80 or more bunches per PS batch and their operational implications are discussed, together with possible advantages for mitigating other limits in the SPS and LHC. Finally, machine development studies during Run 2 for evaluating the feasibility and potential of these schemes are addressed.

INTRODUCTION

The LHC Injectors Upgrade (LIU) project aims at extending the brightness and intensity reach of the injector complex in view of the beam parameters requested by the High Luminosity LHC (HL-LHC) project [1]. After the implementation of all LIU upgrades the performance of the injectors will match the HL-LHC requirements in terms of beam brightness. However, despite the significant increase of the achievable beam intensity expected from the LIU upgrades of the SPS RF system [2], reaching the HL-LHC target beam intensity of 2.3×10^{11} p/b with 25 ns beams will still remain challenging due to beam loading and longitudinal instabilities in the SPS at high energy [3].

In what follows, two possible options for circumventing this limitation will be presented. The focus here is put on the transverse plane. Possible options for the longitudinal plane are discussed in Ref. [4].

SPS OPTICS WITH INTERMEDIATE TRANSITION ENERGY

The first option for mitigating intensity limitations along the SPS ramp consists of an SPS optics with a gamma at transition γ_t in between the Q26 optics used in the past and the Q20 low γ_t optics [5], which is operational for LHC beams since October 2012. The main motivation for implementing the Q20 optics came from the Transverse Mode Coupling Instability (TMCI) at injection: In Q26, the measured TMCI threshold for bunches injected with the nominal longitudinal emittance $\varepsilon_l = 0.35$ eVs is at around $N_{th} \approx 1.6\times10^{11}$ p/b for vertical chromaticity close to zero. As expected from analytical scaling laws, the threshold is raised to more than $N_{th} \approx 4.0\times10^{11}$ p/b in the Q20 optics due to the lower transition energy, i.e. $\gamma_t = 18$ instead of $\gamma_t = 22.8$, and the resulting increase of the phase slip factor $\eta \equiv 1/\gamma_t^2 - 1/\gamma^2$ (LHC beams are injected above transition) [6]. Furthermore, for a given longitudinal emittance, the Q20 optics provides also better beam stability in the longitudinal plane compared to the Q26 optics. However, in order to achieve the same bucket area, higher RF voltage and consequently more RF power are needed in the Q20 optics, especially during the first part of the ramp. A new SPS optics with intermediate transition energy in between the Q20 and the Q26 optics could therefore help to reduce the required RF power during acceleration. With the Q20 optics the achievable intensity may remain limited, even after the foreseen LIU upgrade of the SPS RF power [2] and after reducing the acceleration rate. Furthermore, additional flexibility in the choice of transition energy could be useful for optimizing the machine performance in case the longitudinal instability scaling is less favourable for the Q20 optics than assumed so far [4]. On the other hand, such a new optics must provide enough margin with respect to the TMCI threshold in order to allow for stable beam operation with 25 ns beams of about $N \approx 2.6\times10^{11}$ p/b at injection, as required for achieving the HL-LHC target intensity at SPS flat top.

The transition energy in the SPS is determined by the choice of the horizontal betatron tune as shown in Fig. 1. For Q_x close to multiples of the machine super period of 6, resonant dispersion waves with large amplitude are excited around the ring resulting in the asymptotic behaviour of γ_t [7]. These working points are not suited for regular machine operation. On the other hand, an interesting option

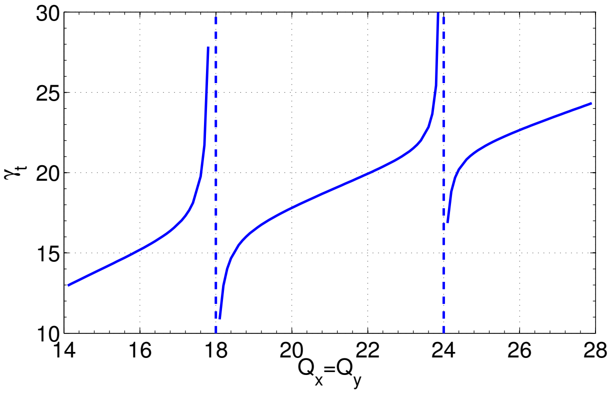


Figure 1: Gamma at transition as a function of the betatron tunes in the SPS.

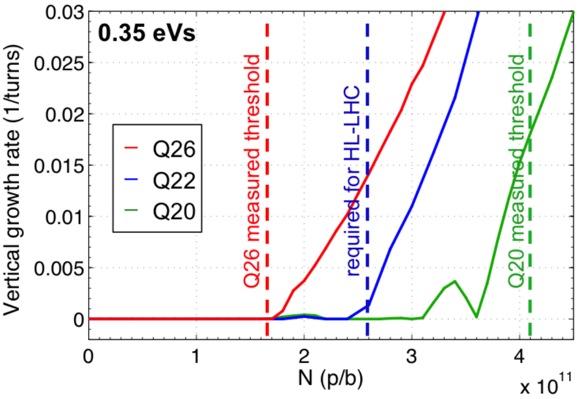


Figure 2: Simulated vertical growth rates as function of intensity for different SPS optics.

for an intermediate transition energy is achieved for working points around $Q_x \approx 22$, for which $\gamma_t \approx 20$: Assuming the well established fractional tunes for LHC beams, the "Q22" optics with $(Q_x, Q_y) = (22.13, 22.18)$ [8] has a similar structure of low-order resonances around the working point as the Q20 and Q26 optics. Furthermore, the Q22 optics provides sufficient aperture for LHC beams and the rematching of the TT10 injection transfer line optics is feasible. The rematching of the extraction transfer lines TI2 and TI8 towards the LHC has not been looked into yet, but is expected to be also feasible. It should be pointed out that the Q22 optics has about twice higher dispersion at the location of the RF cavities compared to Q26 and Q20. Although not expected, this could potentially cause problems because of synchro-betatron resonances.

The TMCI intensity threshold to be expected in the Q22 optics was studied in macroparticle simulations using the HEADTAIL code. The simulations are based on the SPS transverse impedance model [9], which is obtained by summing the contributions of the different devices along the machine weighted by the β-functions at their respective locations. The model includes the SPS kickers, the resistive wall impedance, the BPMs, the RF cavities and the flanges and the transition pieces between the different vacuum chamber types. It has been benchmarked with measurements and reproduces more than 90% of the vertical coherent tune shift and of the headtail growth rate of mode 0 for negative chromaticity, as well as the TMCI thresholds in the Q20 and Q26 optics for different longitudinal emittances [10, 6]. In addition to the operational setting of $Q'_y = 1$ for the linear chromaticity, the non-linear chromaticity up to third order as obtained from machine experiments was used in the simulations for the Q20 and Q26 optics [11]. Only linear chromaticity with a setting of $Q'_y = 2$ was used for the Q22 optics, since there are no reliable estimations of the non-linear chromaticity available. The solid lines in Fig. 2 show the simulation results for the TMCI growth rate as a function of intensity in the different SPS optics configurations for the case of the nominal longitudinal emittance at injection $\varepsilon_l = 0.35$ eVs and scaled RF voltages for maintaining the same bucket area for the different transition energies. The vertical dashed lines show the experimentally observed instability threshold for the Q26 and the Q20 optics as well as the required intensity for reaching the HL-LHC target. Excellent agreement with the simulation model is observed for the Q26 optics. For the Q20 optics the onset of the instability predicted by the model is slightly below the measured threshold, i.e. the prediction is conservative. As expected, the simulations for the Q22 optics predict an intermediate instability threshold, which is very close to the intensity required for reaching the HL-LHC target.

The following key studies for demonstrating the Q22 optics as viable alternative to the baseline Q20 optics have been identified:

- Measurement of the TMCI threshold in the Q22 optics and verification of sufficient intensity margin for reliable production of the HL-LHC target beam parameters. Possible gain from a reduction of the vertical beam coupling impedance, e.g. by removing the MKE extraction kickers in LSS4 only needed for CNGS-like extraction.
- Experimental verification that indeed higher intensities with sufficient longitudinal stability at flat top can be reached with the Q22 optics in case the RF voltage and RF power required in the Q20 optics remain an intensity limitation after the 200 MHz RF upgrade.
- Resonance behaviour for high brightness LHC beams in comparison to Q20 and Q26. Possible impact from synchro-betatron resonances due to the larger dispersion in the locations of the RF cavities in Q22.
- Rematching of the TI2/TI8 transfer lines to the LHC including the SPS extraction bumps for the Q22 optics.
- Effect of injection dogleg on closed orbit and dumped beam trajectory in the Q22 optics.

80 BUNCH SCHEME

The yearly integrated luminosity in the LHC will be limited by the pileup in experiments, the LHC availability and the number of colliding bunches. The nominal LHC 25 ns filling scheme is based on the injection of trains of 4 (or 2)×72 bunches from the SPS [12], where the gap length between the individual batches of 72 bunches is determined by the rise time of the SPS injection kickers (225 ns) and the flat top length of the SPS extraction kickers and LHC injection kicker limits the total length of the injected bunch train. The gap between these trains in the LHC is determined by the LHC injection kicker rise time (900 ns). The LHC dump kicker rise time (3000 ns) defines the length of the abort gap. As such the standard filling scheme for 25 ns beams allows for 2736 colliding bunches in the main LHC experiments at IP1 and IP5 plus 12 non-colliding bunches per beam as requested by the experiments for background calibration.

A possible way of improving the performance of the 25 ns beam is to increase the number of colliding bunches in the LHC, which can be achieved by increasing the number of bunches transferred from the PS to the SPS. In fact, in an early version of the LHC 25 ns filling scheme it was foreseen to generate 84 bunches at PS flat top by adiabatic debunching of 16 bunches followed by recapture on harmonic $h = 84$ and extract only 81 of them while deliberately losing 3 bunches due to the PS extraction kicker rise time [13]. First experiments with this beam were performed in 2000, where even 82 bunches were injected into the SPS [14]. Due to problems with longitudinal beam stability at PS flat top [15], this scheme was replaced by the nominal production scheme [12], nowadays also referred to as “standard scheme”, in which a train of 72 bunches is produced in the PS by injecting 4+2 PSB bunches into harmonic $h = 7$, followed by a triple splitting at low energy and two double splittings at flat top before extraction at $h = 84$. Besides the improved beam stability at PS flat top, this scheme provides a gap in the bunch train to allow for a clean beam transfer to the SPS. However, the PS extraction kicker has a rise time (1-99%) of only 89 ns, which would allow for a clean extraction of up to 81 bunches. Recently, a scheme for producing trains of 80 bunches in the PS has been proposed [16]. Figure 3 shows a sketch of the required beam manipulations during the PS cycle. All RF gymnastics are identical to the standard production scheme (thus the same brightness as for the standard scheme [1] can be expected). However, the starting point is that 4+3 instead of 4+2 bunches are injected into the PS at harmonic $h = 7$, i.e. the machine needs to be completely filled. After acceleration to an intermediate plateau of 2.5 GeV for the triple splitting, one out of the resulting 21 bunches is eliminated from the train by gated excitation with the transverse damper. The remaining 20 bunches are accelerated to flat top and twice double split into 80 bunches. In principle, the bunch removal could be done also at higher energy and after the final bunch splittings, which would provide additional flexibility to produce bunch trains of 80, 81 or even 82 bunches. However the low energy option is preferred due to the following advantages:

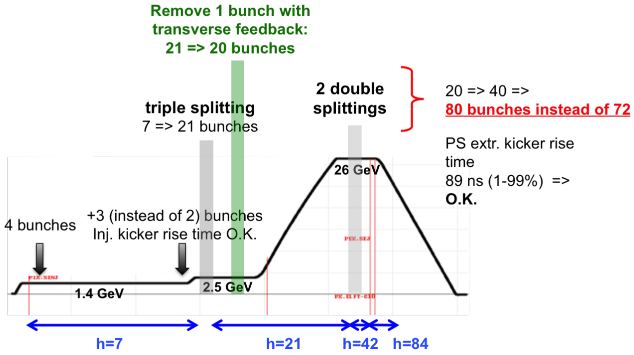


Figure 3: Sketch of the proposed scheme for the production of 80 bunches in the PS.

- The transverse damper power amplifiers presently installed in the PS provide sufficient power (0.8 kW in CW) to induce large transverse oscillations at 2.5 GeV and sufficient band-width (23 MHz at -3 dB) at harmonic $h = 21$ in order to excite a single bunch without affecting neighbouring bunches.
- It is better to lose particles at low energy in order to minimise the activation of the machine. Furthermore, the PS low energy correctors can be used to create an orbit bump and thus an artificial aperture restriction in order to localize the beam losses at one position in the machine, e.g. the new dummy septum which was installed in Straight Section 15 in order to protect the extraction septum SMH16 during the Multi-Turn Extraction (MTE) of SPS fixed target beams [17].
- The largest number of colliding bunches in the LHC is achieved with 80 rather than with 81 or 82 bunches per PS extraction.

Possible LHC filling schemes based on the transfer of 80 bunches from the PS to the SPS have been studied. With 4×80 bunches per LHC injection plus a single injection of 12 bunches per ring it should be possible to achieve a maximum of 2892 colliding bunches in IP1/IP5. If the LHC experiments prefer to have a few non-colliding bunches, the maximum number of bunches colliding in IP1/IP5 would be 2880, which is still 5% more compared to the present 25 ns filling scheme and directly translates into an increase of the integrated luminosity. It is presently under investigation if the flat-top lengths of the SPS extraction kickers (MKEs) and the LHC injection kickers (MKIs) are sufficient for the transfer of 4×80 bunches, or if modifications of the pulse forming networks (PFNs) would be required. Furthermore, it should be emphasized that the transfer of 320 instead of 288 bunches and the corresponding increase of the total beam intensity has strong implications for the

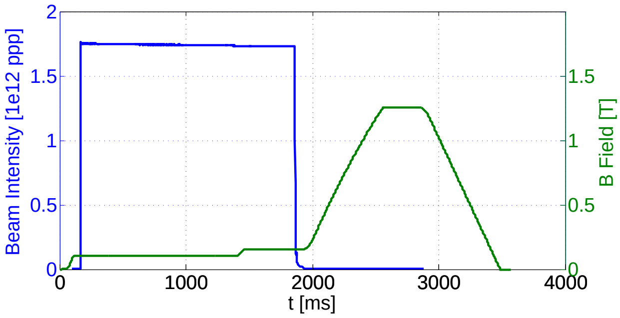


Figure 4: Elimination of a triple split PSB bunch by excitation with the PS transverse feedback at 2.5 GeV.

specification of the SPS beam dump and the protection devices in the transfer lines (TCDIs) and the LHC injection regions (TDIs). It is therefore interesting to note that with 3×80 bunches per LHC injection, up to 2732 colliding bunches in IP1/IP5 (or 2720 with few non-colliding bunches) can be achieved, which is almost the same number as in the present filling scheme. This option could thus also be considered as a back-up in case of limitations of total intensity per SPS-to-LHC transfer (e.g. LHC protection devices, SPS beam dump, SPS RF power, . . .).

First machine development studies in view of the 80 bunch scheme have been performed with single bunch beams. Figure 4 shows the promising result: It was demonstrated that a triple split PSB bunch can be almost completely eliminated by a sinusoidal excitation with the PS transverse feedback system in open loop on the 2.5 GeV plateau of a 3 basic period cycle when reducing the horizontal chromaticity from $\xi_h = -0.8$ to -0.1. Unfortunately it is not yet possible to excite only a selected bunch within a bunch train. This requires a new firmware for the digital card controlling the feedback. Furthermore, a bunch synchronous trigger is needed in order to gate the damper gain.

Once the required firmware and hardware modifications are implemented, the following machine development studies will be performed in order to fully demonstrate the feasibility of the 80 bunch scheme and to address possible issues:

- Elimination of a single bunch with the feedback system in closed loop but with inverted gain.
- Elimination of a selected bunch out of a bunch train. Verification that neighbouring bunches are not affected by measurements of the bunch-by-bunch emittance in the SPS.
- Localization of losses on the dummy septum in SS15 with the help of a closed orbit bump.
- Beam transfer of 80 bunches to the SPS and check of the level of “ghost” bunches potentially created in case of insufficient bunch elimination in the PS. Check the possibility to eliminate bunch residuals with rising edge of PS extraction kicker pulse.
- Study of the impact on longitudinal stability in the PS and SPS.
- Determine the maximum acceptable flat top lengths of the SPS MKEs and the LHC MKIs with low intensity beams (within the safe beam limit).
- Study of potentially enhanced electron cloud effects in the LHC, the SPS and also at PS flat top.

SUMMARY AND CONCLUSIONS

The SPS Q22 optics with intermediate transition energy could help to reduce the required RF power during acceleration. However, it needs to be verified that it allows to reach higher intensities compared to the Q20 optics with sufficient longitudinal stability at flat top and that it provides sufficient intensity margin with respect to the TMCI threshold in order to guarantee reliable production of the HL-LHC target beam parameters.

The 80 bunch scheme seems very promising, as it allows to increase the integrated luminosity by more than 5% for the same pile-up limit through a larger number of colliding bunches compared to the present LHC filling scheme, or alternatively to reach the same number of colliding bunches in the LHC with a maximum of only 240 bunches per transfer from the SPS. This could be already interesting for boosting the performance or to mitigate existing limitations during the LHC Run 2. The validation of the 80 bunch production scheme in the PS will be performed in machine development studies as soon as the necessary firmware and hardware modifications are implemented.

REFERENCES

[1] G. Rumolo *et al.*, “Protons: Baseline and Alternatives, Studies Plan”, these proceedings.

[2] E. Shaposhnikova *et al.*, “Upgrade of the 200 MHZ RF System in the CERN SPS”, CERN-ATS-2011-042.

[3] H. Bartosik *et al.*, “Can we ever reach the HL-LHC requirements with the Injectors?”, proceedings of the Review of LHC and Injector Upgrade Plans Workshop.

[4] T. Argyropoulos *et al.*, “Other means to increase the SPS 25 ns performance – Longitudinal plane”, these proceedings.

[5] H. Bartosik *et al.*, “Optics considerations for lowering transition energy in the SPS”, CERN-ATS-2011-088.

[6] H. Bartosik *et al.*, “TMCI thresholds for LHC single bunches in the CERN SPS and comparison with simulations”, CERN-ACC-2014-0119.

[7] G. Arduini *et al.*, “Test of a low gamma transition optics”, SL-Note-98-001-MD.

[8] Y. Papaphilippou *et al.*, “Low transition energy optics (limitations, possible alternatives?)”, Joint HL-LHC and LIU Brainstorming Session.

[9] C. Zannini, PhD thesis, CERN-THESIS-2013-076.

[10] C. Zannini, “SPS: instabilities and impedance model in the transverse plane”, in LIU Day 2014.

[11] H. Bartosik, PhD thesis, CERN-THESIS-2013-257.

[12] “Beam Requirements & Fundamental Choices”, LHC Design Report Volume III, Ch. 2, CERN-2004-003-V-1.

[13] M. Benedikt *et al.*, “PS Complex as LHC Injector”, Design and Implementation Report.

[14] T. Bohl, “LHC Type Beams in the SPS Bunch Length and Longitudinal Emittance”, 11th Chamonix - LHC Workshop.

[15] R. Cappi, Garoby R. and E. Metral, “Collective Effects in the CERN-PS beam for LHC”, CERN-PS-99-049-CA.

[16] H. Damerau, S. Gilardoni, B. Goddard, private communication (2013).

[17] H. Bartosik *et al.*, “Proposal of a Dummy Septum to Mitigate ring irradiation for the CERN PS Multi-Turn Extrac-tion”, CERN-ATS-2012-165.

OTHER MEANS TO INCREASE THE SPS 25 ns PERFORMANCE - LONGITUDINAL PLANE

T. Argyropoulos, E. Shaposhnikova, J. E. Varela, CERN, Geneva, Switzerland

Abstract

At the end of the LHC run 2 in 2012 the 25 ns beam with an intensity of 1.3×10^{11} p/b was successfully accelerated in the SPS. Further significant increase of bunch intensity in the SPS requires that all LIU baseline upgrades are in place (for 200 MHz and 800 MHz RF systems and e-cloud mitigation), but even then the bunch intensity could be limited below the HL-LHC value of 2.5×10^{11} by beam-loading and longitudinal beam instabilities. In this paper other means to increase the 25 ns beam performance are considered. In particular, we study the potential gain in stability for bunches with larger longitudinal emittance at the SPS extraction, possible in the scenario with a 200 MHz RF system in the LHC. The expected longitudinal limitations (coupled-bunch instability, loss of Landau damping, microwave instability and RF power during the ramp) are analyzed for a single and double RF operation and different optics (Q20, Q26 and intermediate one). Bunch rotation before extraction to the LHC is also addressed as a potential technique to decrease capture losses of long bunches in the LHC.

STATUS BEFORE LS1

The nominal LHC beam with 25 ns spacing was used in the LHC for scrubbing against the e-cloud. Measurements with high intensity 25 ns LHC beam were performed in the SPS during a few machine development (MD) sessions at the end of 2012 (before the long shutdown 1, LS1). As a result 4 batches with an intensity of 1.35×10^{11} p/b and an average bunch length $\tau_{4\sigma} \approx 1.7$ ns were successfully accelerated to the SPS flat top [1]. However, during these MDs high beam losses ($>$10%) were observed for injected intensities more than 1.4×10^{11} p/b, as shown in Fig. 1. Note that to reduce losses it was necessary to program the 200 MHz RF voltage amplitude to the maximum available value of 7 MV, defined by the beam-loading effect. In addition, for these intensities longitudinal beam instabilities were also observed during the ramp or at the flat top.

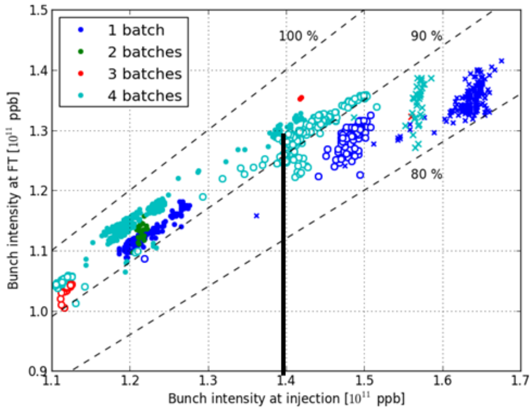


Figure 1: Bunch intensity at the SPS flat top versus the intensity at injection. The black vertical line indicates the point above which the intensity on the flat top doesn't increase anymore and the losses become larger than 10%.

PERFORMANCE LIMITATIONS FOR THE HL-LHC PARAMETERS

According to the HL-LHC project [2], beams with an intensity up to 2.4×10^{11} p/b will be requested from the SPS. This means that one needs to almost double the bunch intensity N_b in the SPS while maintaining the same bunch length at extraction ($\tau_{4\sigma} \leq 1.7$ ns), restricted by the LHC 400 MHz RF system. At the moment $\tau = 1.9$ ns is the maximum bunch length (even for a single bunch) allowed by the Beam Quality Monitor (BQM) [3] for injection into the LHC. However, for higher intensities, larger longitudinal emittance ε_l is needed for longitudinal beam stability in the SPS. To avoid loss of Landau damping during acceleration (single bunch effect) the emittance should be increased according to the scaling $\varepsilon_l \propto N_b^{1/2}$ and that will require a higher RF voltage than used now. However, due to the effects of beam-loading and potential-well distortion a limitation to the available RF voltage exists now and is still expected in future, after the RF upgrade (but at the different level).

RF Voltage Limitation

The calculated available RF voltage at the SPS flat top is shown in Fig. 2 for the present situation (2 cavities of 2 sections and 2 cavities of 5 sections, black curve) and after the upgrade of the 200 MHz RF system [4] (cyan curve), when more 200 MHz RF cavities will be installed with two additional RF power plants (2 cavities of 4 sections with 1.6 MW maximum power at cavity input and 4 cavities of 3 sections with 1.05 MW). The upgrade of the low level RF (LLRF) will allow operation in the pulsing mode at revolution frequency, using the fact that the LHC beam occupies less than half of the SPS ring.

Starting from the reference point, defined by the latest experimental achievement (point in Fig. 2 at ~1.7 A with N_b $\sim 1.35\times10^{11}$ p/b and $\tau_{4\sigma} = 1.7$ ns) and assuming constant bunch length at the SPS extraction, the minimum emittance (and therefore voltage) needed for beam stability (avoiding possible loss of Landau damping) can be calculated. Moreover, for this calculation the RF voltage reduc-

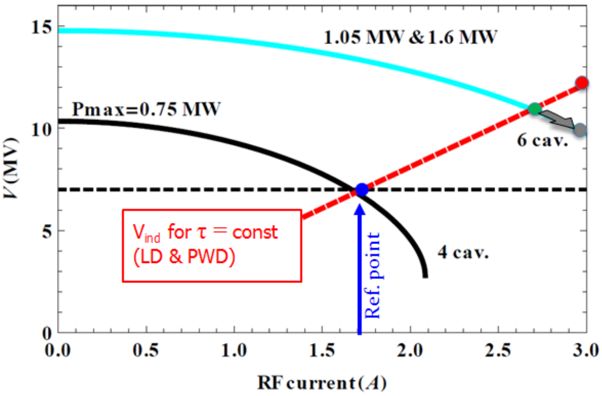


Figure 2: Voltage in the 200 MHz RF system available at the SPS flat top as a function of the RF current. The RF current of 1.47 A corresponds to the 25 ns beam with nominal bunch intensity. The black curve corresponds to the present situation and the cyan curve to the situation after the upgrade of the 200 MHz RF system (in 2020) [4].

tion due to voltage induced in the reactive part of the SPS impedance, $\mathrm{ImZ/n} = 3.5\ \Omega$, (effect called potential-well distortion) was also taken into account. From the intersection of the two curves for the needed and the available voltage after the 200 MHz RF system upgrade, an intensity of around 2.7 A (2.1×10^{11} p/b) can be reached without performance degradation. For higher bunch intensity (3 A or 2.3×10^{11} p/b) only 10 MV will be provided, while 12.5 MV are required for beam stability. Therefore, some additional measures should be taken in order to satisfy the HL-LHC needs. This can be achieved either by reducing the uncontrolled emittance blow-up observed in the SPS or by increasing the limit for the longitudinal emittance acceptable on the SPS flat top. These options are analyzed below in more detail.

Uncontrolled Emittance Blow-up

Longitudinal emittance blow-up is observed in the SPS for both single and multi-bunch beams pointing out that some high frequency resonant impedance could be responsible for this effect. To identify the guilty impedance, measurements with very long bunches ($\tau \approx 25$ ns) and RF off were performed at the SPS flat bottom and a strong peak at frequency around 1.4 GHz was observed [5]. An example of these measurements is presented in Fig. 3.

As has been found later this resonant peak originates from the impedance of certain SPS vacuum flanges [6]. Several types of these flanges are used for the connection of various machine elements and their total number in the ring is around 500.

Macro particle simulations based on the SPS impedance model which includes RF cavities, resistive wall, injection and extraction kickers [7], as well as the impedance of the vacuum flanges were performed in order to compare their results with different measurements, both for single- and multi-bunch beams. An example for single high intensity bunches with the Q20 optics and a double RF system (bunch shortening mode) is shown in Fig. 4, where bunch lengths found from simulations and measurements at the SPS flat top are plotted together.

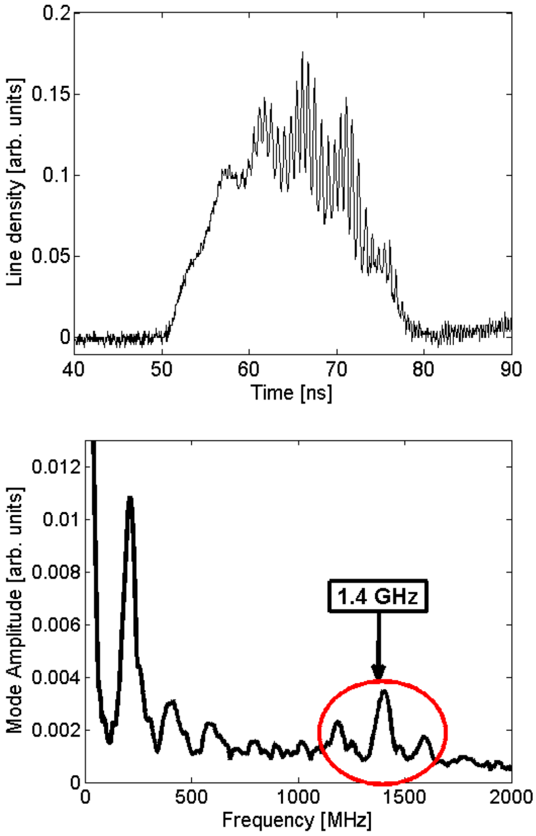


Figure 3: Example of measurements performed on the SPS flat bottom with long bunches ($\tau \approx 25$ ns) and RF off [5]. Top: bunch profile modulated at 200 MHz and a higher frequency (~ 1.4 GHz). Bottom: projection of the Fourier spectra of all the bunch profiles acquired during ~ 100 ms. Measurements in the Q26 optics with bunch intensity $\sim 1\times10^{11}$.

The results are in good agreement since both in measurements and simulations a strong increase of the bunch length with intensity is observed. This increase can not be attributed to the potential well distortion. Therefore, a blow-up of the bunch must have occurred during the cycle, pointing to a microwave type of instability due to a high frequency resonant impedance. In simulations there is a clear instability threshold at $N_{\rm th} = 2\times10^{11}$ p, not visible from these measurements. Note that in these measurements the 200 MHz voltage was very low (2 MV), which is good for Landau damping but unfavorable for microwave instability. The main contribution to this uncontrolled blow-up is coming from the resonant impedance of the vacuum flanges. Indeed, simulations show that without the vacuum flanges the instability threshold is twice higher ($N_{\rm th} \sim 4\times10^{11}$ p).

Simulations were also carried out with a multi-bunch beam at the SPS flat top. At the moment only six bunches

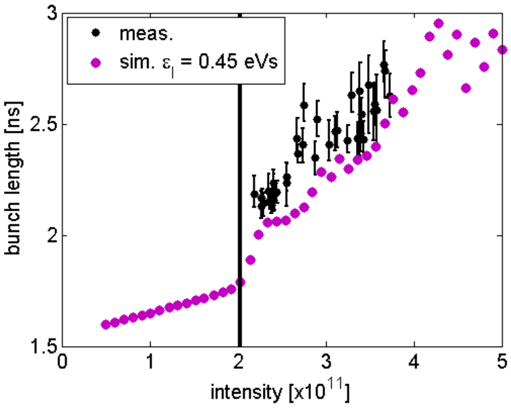


Figure 4: Measured and simulated bunch length as a function of intensity for a single bunch at the SPS flat top in the Q20 optics and a double RF system (bunch shortening mode). The voltage at 200 MHz was $V_{200} = 2$ MV and at 800 MHz $V_{800} = 200$ kV.

(spaced by 25 ns) could be simulated and thus only qualitative conclusions can be drawn. For the same longitudinal emittance the instability threshold for 6 bunches has been found to be almost twice lower than that for a single bunch. This result, presented in Fig. 5, is in agreement with measurements in a double RF system (200 MHz and 800 MHz), where the single bunch instability threshold is approximately twice higher than the multi-bunch one.

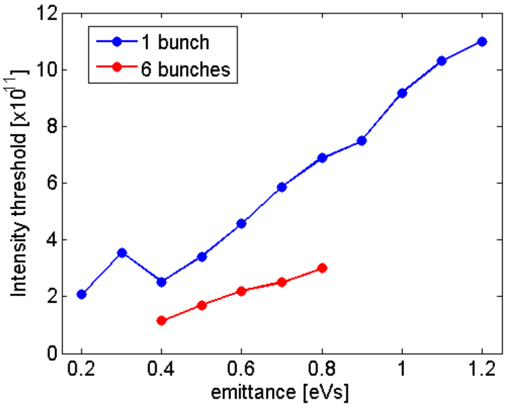


Figure 5: Instability threshold found in simulations for a single- and a 6-bunch beam at the SPS flat top in the Q20 optics and a double RF system (bunch shortening mode). The voltage at 200 MHz was $V_{200} = 7$ MV and at 800 MHz $V_{800} = 640$ kV.

In addition, in simulations only a coupling between a few bunches (3 or 4) was observed and no coupled-bunch mode could be identified, similar to all beam observations. Indeed, in measurements bunches spaced by 25 ns or 50 ns are coupled, but the distance of 225 ns between the PS batches is enough to practically fully decouple them (instability thresholds in the SPS with 1 or 4 batches are very similar). Finally, as expected and shown in Fig. 5, stability is higher for larger emittances, both for single and multi-bunch beams.

POSSIBLE MEANS TO INCREASE INTENSITY AT SPS EXTRACTION

For high bunch intensities required by the HL-LHC project, large longitudinal emittance ($\varepsilon_l > 0.6$ eVs) will be unavoidable at the SPS flat top either from controlled or uncontrolled emittance blow-up (due to beam instability). However, according to the present situation, this will lead to significant particle losses at beam transfer to the LHC. To overcome this limitation three solutions are considered below.

Bunch Rotation on the SPS Flat Top

Bunch length can be reduced by bunch rotation in the longitudinal phase space during a quarter of the synchrotron period. This rotation can be done after step-wise voltage increase and was already successfully tested on the SPS flat top during an MD in 2012 (for the AWAKE experiment) [8] with single, high intensity ($\sim 2.5 - 3 \times 10^{11}$ p) bunches. An example is presented in Fig. 6, where starting from $\tau_{4\sigma} \sim 2.2$ ns a bunch length of $\tau \sim 1.2$ ns was obtained.

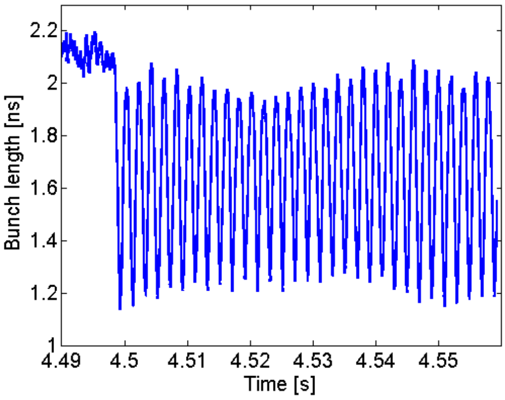


Figure 6: Example of measured synchrotron oscillations of a single bunch with intensity of 2.8×10^{11} on the SPS flat top after the 200 MHz RF voltage was increased from 2 MV to 7.5 MV [8].

However, during these measurements bunches with small emittances of ($\varepsilon_l \sim 0.3$ eVs) were used, while for the future LHC beam much larger values of the longitudinal emittance are needed (at least double). This means that much larger bunch tails can be expected, so that particle losses in the LHC may still remain an issue. In order to study this RF manipulation, particle simulations were performed for a full batch (72 bunches) both on the SPS flat top and the LHC flat bottom, using the SPS and LHC impedance models respectively. In particular, for the SPS case, a simplified model of the feed-back and feed-forward loops that are installed around the 200 MHz RF cavities, was also introduced. The results for a bunch by bunch position variation along the bunch, similar to the one found from measurements are shown in Fig. 7.

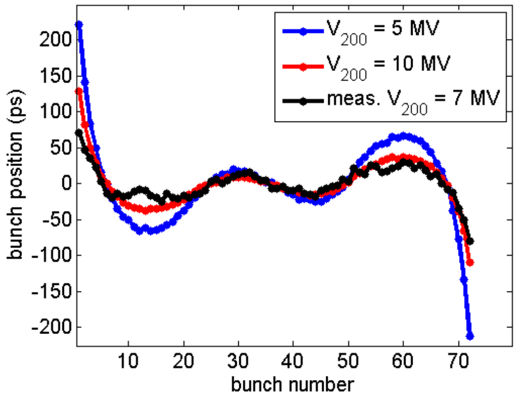


Figure 7: Measured (black curve) and simulated bunch by bunch position variation along the batch. In simulations the 200 MHz RF voltage was increased from 5 MV to 10 MV, intensity 2.4×10^{11} p/b. In measurements $V_{200} = 7$ MV and intensity 1.3×10^{11} p/b.

In the simulations the SPS voltage at 200 MHz was increased from 5 MV to 10 MV (will be available at flat top after the RF upgrade for intensities $\sim 2.3 \times 10^{11}$ p/b, see Fig. 2). Furthermore, a longitudinal emittance of $\varepsilon_l = 0.7$ eVs (required for single bunch stability from scaling discussed above) was used. The results are presented in Fig. 8, where starting from an average bunch length $\tau_{\text{mean}} = 2.2$ ns the beam ended with $\tau_{\text{mean}} = 1.56$ ns, acceptable for extraction to the LHC.

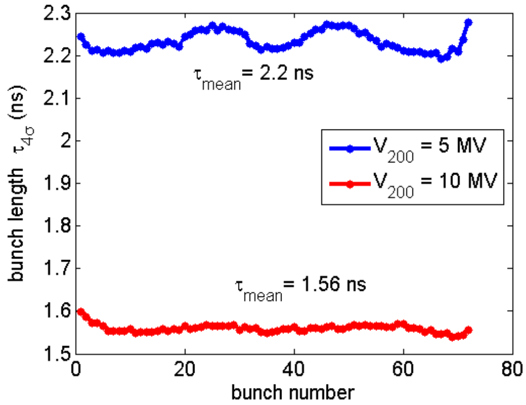


Figure 8: Bunch length along the batch before (blue) and after (red) rotation, obtained from particle simulations.

As a second step, in order to quantify the effect of bunch distribution and of the bunch position variation along the batch on the particle losses, these bunches were “injected” in simulations into the LHC and captured with an RF voltage of 8 MV at 400 MHz. Figure 9 presents examples of the LHC longitudinal phase space for bunches at the beginning, the middle and the end of the batch. It is clear from the figure that due to beam loading in the SPS, the bunches at the batch edges are shifted with respect to the bucket centers.

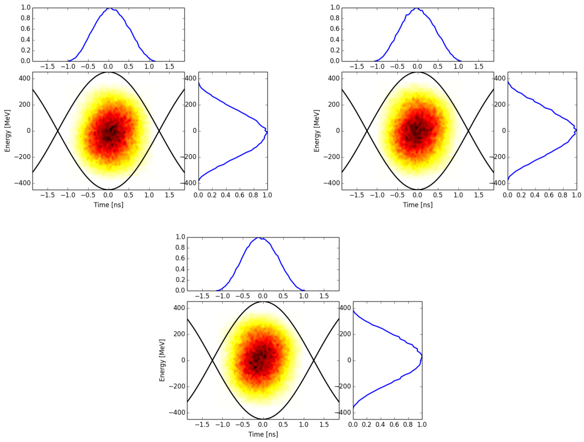


Figure 9: Bunches at different positions in the batch inside the LHC buckets (8 MV) after rotation on the SPS flat top: bunch 1 (top left), 36 (top right) and 72 (bottom). Bunches 1 and 72 are shifted with respect to the bucket center. Courtesy J. E. Müller.

The beam loss pattern along the batch obtained from tracking this beam in the LHC is shown in Fig. 10. As expected, for the bunches at the edges more losses are observed but they are less than 0.6%.

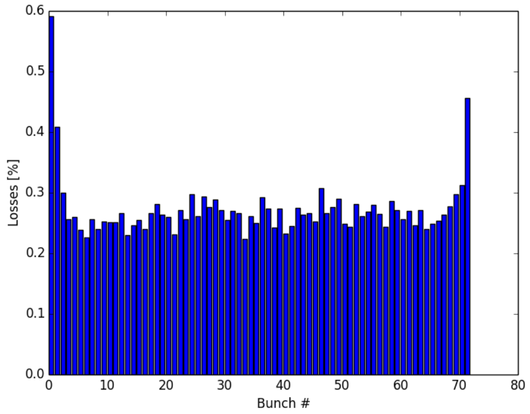


Figure 10: Beam loss pattern of the rotated batch (72 bunches) in the SPS after capture in the LHC. Courtesy J. E. Müller.

200 MHz RF System in the LHC

An alternative solution for increasing the acceptable longitudinal emittance at extraction from the SPS is an installation of the 200 MHz RF system in the LHC. The capture system based on the warm cavities was foreseen already in the LHC DR [9]. Recently a new super-conducting 200 MHz RF system was proposed [10]. This system of course will eliminate capture losses even for much longer SPS bunches. Furthermore, it will allow the operation in a double RF system with all the benefits that this entails (better longitudinal stability, e-cloud effects, flat bunches, etc.), but at the same time with all the complications that this can imply (phase control, maintenance, reliability issue, etc.). In addition, installing a new RF system in the LHC will lead to an increase of the beam impedance (for more information see [10, 11]).

Impedance Reduction in the SPS

Another solution is to decrease the emittance blow-up by reducing the longitudinal impedance of the SPS and thus increasing the longitudinal instability threshold. Great effort was made during the last 2 years to identify the responsible impedance sources by beam measurements and simulations [5, 12] as well as by electromagnetic simulations and measurements in the lab of the impedance of different devices in the SPS ring.

As aforementioned, the impedance spectrum of the SPS was measured with beam and a strong resonance at 1.4 GHz was found. A thorough, element-by-element, impedance assessment was then started to find the source of the 1.4 GHz resonance.

A subset of $\sim$ 120 vacuum flanges, all similar to the one shown in Fig. 11(a), has been found to resonate at 1.4 GHz. Electromagnetic simulations and RF measurements [13] were carried out to determine the impedance of these elements. For the whole subset, the R/Q contribution is $\sim$ 9 kΩ. In addition, the impedance of the other types of vacuum flanges has been also calculated. Significant resonances were found around 1.2, 1.8 and 2.5 GHz.

Overall, there are around 500 high-impedance vacuum flanges in the SPS ring. These vacuum flanges can be classified in the two main groups, with elliptical and circular beam pipes attached, hereafter groups I and II respectively. Group I is responsible for the 1.2 and 1.4 GHz resonances and group II for the higher frequency resonances (1.8 and 2.5 GHz).

Recently, several possibilities for impedance reduction of the vacuum flanges were studied. The different alternatives were narrowed down to the two most promising ones, namely, partial shielding and redesign of the flanges [14].

The impedance of the vacuum flanges from group I could be significantly reduced by partial shielding of the empty volume produced by the bellows, as shown in Fig. 11(b). This partial shielding can reduce the R/Q of the 1.4 GHz resonance by a factor from 8 to 12, depending on the implementation. On the one hand, this is a relatively cheap and easy to implement solution. On the other hand, only flanges from group I (roughly half of the total number of high-impedance flanges) could be acted upon.

The second possible alternative is to redesign the flanges and bellows to minimize their impedance. This solution implies manufacturing elliptical bellows and redesigning current circular ones. Initial studies show a factor 20 reduction for the R/Q of the 1.4 GHz resonance. In addition, the impedance of the flanges from group II could also be minimized. However, this is a more expensive solution, not only due to the cost of producing elliptical bellows but also because their installation involves cutting and welding.

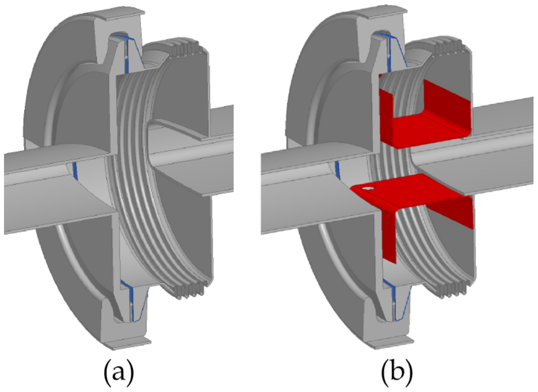

(a) (b)

Figure 11: Model of a QF-MBA enamelled SPS vacuum flange, the source of a strong 1.4 GHz resonance (longitudinal cut). (a) Empty flange. (b) Possible implementation of the partial shielding (highlighted in red).

LIMITATIONS DURING THE ACCELERATION RAMP

Assuming that the restrictions for having large longitudinal emittance at the SPS flat top have been removed, the acceleration of these bunches should be also analyzed with respect to the limited RF power available in future.

Below, the necessary RF voltage during the cycle is calculated for a varying longitudinal emittance ε_l and a constant filing factor in momentum q_p. On flat bottom, ε_l is taken from measurements (0.4 eVs for the Q20 optics), while on flat top a larger value is required for beam stability, defined by the bunch intensity N_b. A controlled emittance blow-up should be applied from certain energy, which depends on the final emittance (N_b). For $N_b = 2.4 \times 10^{11}$ p/b the latter should be 0.7 eVs in the Q20 optics (scaled for single bunch stability). Concerning the filling factor, the value of $q_p = 0.75$ was assumed to provide some margin for beam losses. Note that for a similar filing factor in MDs of 2012, losses of more than 10% were observed (Fig. 1). In addition, the effect of the potential well distortion should be also taken into account. In particular, during cycle the induced voltage for a given bunch length and for $\mathrm{Im}Z/n = 3.5\ \Omega$ was calculated and added to the RF voltage.

For this total voltage, the required RF power can then be calculated for each type of RF cavity, assuming power partition proportional to the maximum available power. The RF power during the cycle is plotted in Fig. 12 for the present (2014) duration of the acceleration ramp (8.5 s) and intensity of 2.5×10^{11} p/b (assumed to take into account the $\sim$4% losses due to the beam scraping that is applied at the end of the ramp). As shown in the Fig. 12, even after the 200 MHz upgrade, the required RF power is well above the power limits both for 3- and 4-section cavities (horizontal dotted lines), making impossible the acceleration of this high intensity beam with the same ramp length.

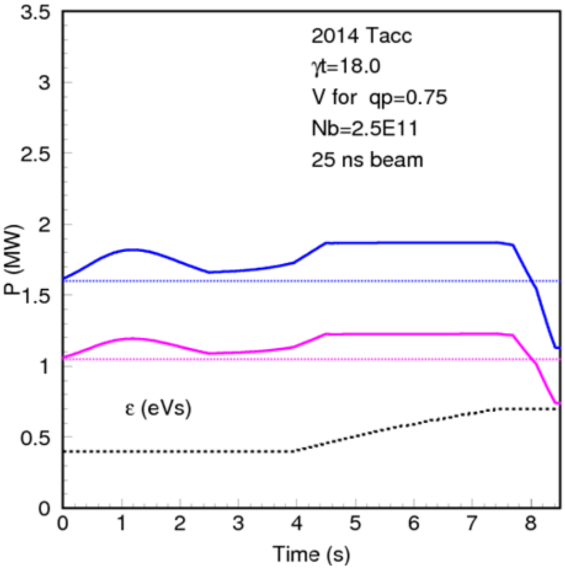


Figure 12: RF power in the Q20 optics required by 3- (magenta) and 4- (blue) section cavities, through the present (2014) acceleration cycle for intensity of 2.5×10^{11} p/b together with the corresponding power limits. A controlled emittance blow-up applied from $\varepsilon_l = 0.4$ eVs to 0.7 eVs (dotted black line). Voltage program calculated for $q_p = 0.75$.

A possible solution is to increase the duration of the SPS acceleration cycle and as shown in Fig.13, twice longer time compared to the 2012 SPS cycle is almost sufficient for acceleration of intensities required by the HL-LHC. The initial part, where higher power is needed can be possibly improved by redesigning the magnetic cycle.

Nevertheless, increasing the length of the SPS acceleration cycle will result in longer filling time of the LHC (30% more than in 2012 for dedicated filling) and will increase the average power consumption in the SPS. Furthermore, the bunches will stay longer in the SPS and this may give more time for instabilities to develop. First conclusions about the consequences of a longer SPS cycle can be deduced already this year, since a longer cycle is also necessary for acceleration of the doublets required for scrubbing of the LHC in 2015 [15].

NEW OPTICS

In case the RF power during the ramp is still an issue with the Q20 optics ($\gamma_t = 18$) one can consider increasing the transition energy (decreasing the slippage factor η). However, going back to the Q26 optics ($\gamma_t = 22.8$) is not an option due to beam stability issues at injection energy. Therefore, a compromise between the two options is an intermediate γ_t. In particular, as shown in [16] a possible solution is $\gamma_t = 20$ (Q22 optics).

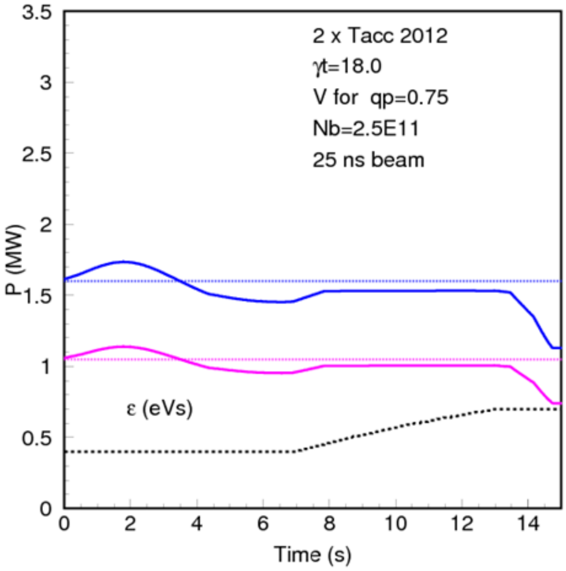


Figure 13: RF power required by 3- (magenta) and 4- (blue) section cavities, through a twice longer than the 2012 acceleration cycle. Similar conditions as in Fig. 12.

Initially, in order to study the beam stability with the Q22 optics, particle simulations with the SPS impedance model were performed for a single bunch at the flat top and for comparison the results are presented in Fig. 14 together with those for Q20 and Q26. As expected, from stability point of view the Q22 optics is practically between Q20 and Q26.

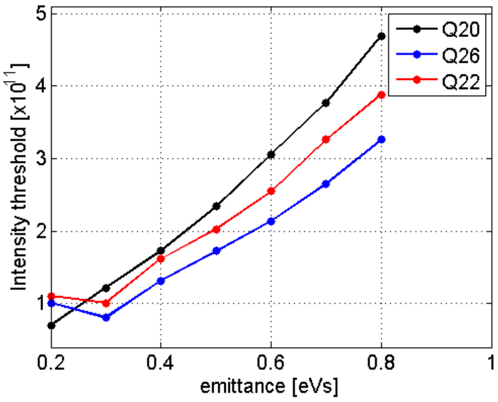


Figure 14: Instability threshold found in simulations for different SPS optics, for a single bunch at the SPS flat top in a double RF system (bunch shortening mode). The voltage at 200 MHz $V_{200} = 2$ MV and at 800 MHz $V_{800} = 200$ kV.

The power requirements during the acceleration cycle in the Q22 optics calculated for the intensity of 2.5×10^{11} p/b and a twice longer ramp (as in Fig. 13) are presented in Fig. 15. Note that even with these optics a longer cycle is still needed due to a strong beam loading, since a larger controlled emittance blow-up is necessary to be applied during the ramp to ensure beam stability. However, comparing with the Q20 optics (Fig. 13) one can see that the Q22 optics provides more margin in the RF power.

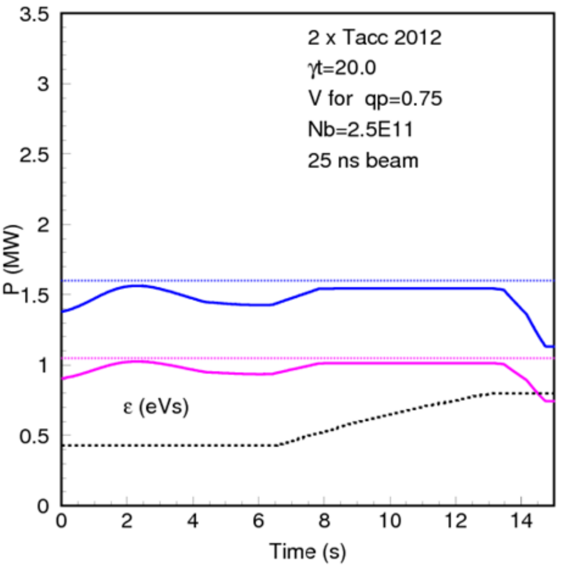


Figure 15: RF power in the Q22 optics required by 3- (magenta) and 4- (blue) section cavities through a twice longer than the acceleration cycle used in 2012. Controlled emittance blow-up applied from $\varepsilon_l = 0.425$ eVs to 0.8 eVs (dotted black line). Similar conditions as in Fig. 12.

CONCLUSIONS

The SPS intensity is limited by the available RF voltage (due to beam loading) and by the longitudinal emittance blow-up (due to instabilities). These limitations are coming from both the acceleration ramp (losses in the SPS) and the SPS-LHC transfer (LHC capture losses). For the 25 ns beam, the intensity limitation is now around 1.3×10^{11} p/b and is expected to become $\sim 2.0 \times 10^{11}$ p/b after the upgrade of the 200 MHz RF system. Possible measures to reach the intensities required by the HL-LHC (2.4×10^{11} p/b) were discussed. In particular, doubling the duration of the acceleration ramp will allow the acceleration of the large emittances, needed for beam stability. Later in the cycle, at top energy, it would be possible to transfer these long bunches into the LHC either by performing a bunch rotation in the SPS or by installing a new SC 200 MHz RF system in the LHC. On the other hand, the uncontrolled emittance blow-up can be avoided by reducing the responsible impedance sources. This, most robust solution, will improve the situation both during the SPS ramp and on the flat top, but first these impedance sources should be definitely identified. Finally, it was shown that the Q22 optics will provide additional flexibility between the Q20 and Q26 optics, but the Q20 is still considered as the main option for Run 2.

ACKNOWLEDGMENTS

The authors would like to thank H. Bartosik, T. Bohl, F. Caspers, H. Damerau, B. Goddard, A. Lasheen, E. Montesinos, J. E. Müller, D. Quartullo, G. Rumolo, B. Salvant, J. F. Somoza, H. Timkó, C. Zannini for their contributions to the work summarized here.

REFERENCES

[1] T. Argyropoulos et al., talks at LIU-SPS Beam Dynamics Working Group, Oct., Nov., Dec. 2012 http://paf-spsu.web.cern.ch/paf-spsu/meetings/2008.htm

[2] L. Rossi, “LHC Upgrade Plans: Options and Strategy,” IPAC’11, San Sebastian, Spain, Sep. 2011.

[3] G. Papotti, “The SPS Beam Quality Monitor, from Design to Operation,” IPAC’11, San Sebastian, Spain, Sep. 2011.

[4] E. Shaposhnikova, E. Ciapala, E. Montesinos, “Upgrade of the 200 MHZ RF System in the CERN SPS,” IPAC’11, San Sebastian, Spain, Sep. 2011.

[5] T. Argyropoulos et al., “Identification of the SPS Impedance at 1.4 GHz,” IPAC’13, Shanghai, China, May 2013.

[6] E. Shaposhnikova et al., “ Identification of High-frequency Resonant Impedance in the CERN SPS,” IPAC’14, Dresden, Germany, June 2014.

[7] C. Zannini et al., talk at LIU-SPS Beam Dynamics Working Group, March 2013 http://paf-spsu.web.cern.ch/paf-spsu/meetings/2008.htm

[8] H. Timkó et al., “Short High-Intensity Bunches for Plasma Wakefield Experiment AWAKE in the CERN SPS,” IPAC’13, Shanghai, China, May 2013.

[9] O. Brüning, P. Collier, P. Lebrun, S. Myers, R. Ostojic, J. Poole, P. Proudlock, “LHC Design Report Vol. I: The LHC Main Ring,” CERN-2004-003-V-1, CERN, Geneva, 2004.

[10] R. Calaga, “HL-LHC RF Roadmap,” these proceedings.

[11] R. Tomas, et al., “HL-LHC alternative scenarios, parameters and lay-out,” these proceedings.

[12] T. Argyropoulos et al., talk at LIU-SPS Beam Dynamics Working Group, Feb. 2013 http://paf-spsu.web.cern.ch/paf-spsu/meetings/2008.htm

[13] J. E. Varela et al., talks at LIU-SPS Beam Dynamics Working Group, May, July, Aug., Sep., Oct. 2013 http://paf-spsu.web.cern.ch/paf-spsu/meetings/2008.htm

[14] J. E. Varela et al., talk at LIU-SPS Beam Dynamics Working Group, Oct. 2014 http://paf-spsu.web.cern.ch/paf-spsu/meetings/2008.htm

[15] G. Iadarola et al. “Scrubbing: Expectations and Strategy, Long Range Perspective,” these proceedings.

[16] H. Bartosik et al., “Other Means to increase the SPS 25 ns Performance - Transverse Plane,” these proceedings.

IONS: BASELINE, STUDIES PLAN AND STRATEGY FOR PENDING OPTIONS

M. Bodendorfer, S. Gilardoni, D. Manglunki, G. Rumolo, R. Scrivens for the LIU-Ions team.
CERN, Geneva, Switzerland

Abstract

We will review the performance of the ion injector chain of the LHC during LR1, and the baseline of the upgrades, which are planned in order to reach the performance required after LS2. After overviewing the open issues and a tentative list of planned machine developments, we present the beam characteristics expected during LR2 and beyond.

MOTIVATION

In the light of the first two successful Pb-Pb runs in the LHC [1], the ALICE experiment will be implementing a detector upgrade for the exploitation period following LS2 [2]. As can be seen in Fig. 1, there will only be about 8 Pb-Pb runs between LS2 and 2035 [3], so a peak luminosity exceeding 7x10^{27} Hz/cm^2 is expected in order to fulfil the goal of 10 nb^{-1} [4].

Figure 1: LHC schedule beyond LS1, approved in December 2013. Pb-Pb and p-Pb runs have been added in orange.

We propose a realistic baseline strategy for the injectors to achieve this ambitious goal. The feasibility of this baseline strategy is being studied on paper and will be demonstrated experimentally. A series of measures will have to be taken in the whole ion injector chain: Linac3, LEIR, the PS and the SPS.

This work is a part of the LHC Injector Upgrade (LIU) project [5].

BASELINE SCHEME

As the bunch population is already at the limit for the collective effects (space charge and IBS) on the long flat-bottom of the SPS, the scheme is based on an increase by a factor ~3.5 of the number of bunches in the LHC, compared to the latest Pb-Pb, performed in 2011. It is summarized in Fig. 2 below. Just like today, Linac3 will deliver Pb^{29+} ion pulses for the duration of 200 µs at 4.2 MeV/nucleon, stripped to Pb^{54+}. In order to provide the required beam quality, the Linac3 beam intensity should be increased towards the performance described in the design report [6]. The LEIR machine will inject up to 13 Linac3 pulses every 200ms on a long flat bottom. After cooling, the LEIR beam will be bunched on harmonic $h = 2$ and accelerated to 72 MeV/nucleon, before extraction to the PS. In the PS the two bunches will be accelerated to 5.9 GeV/nucleon. On an intermediate flat-top, the batch will be expanded and the bunches split, with a harmonic sequence $h = 16, 14, 12, 24, 21$, as was originally intended and described in the LHC design report [7], the difference being a bunch population twice larger. At high energy, the bunches will be rebucketed to $h = 169$ by one of the three 80 MHz cavities before extraction towards the SPS. As is already the case, the ions will be fully stripped to Pb^{82+} on a 1mm thick aluminium plate located inside a low-beta insertion to minimize the transverse emittance blow-up.

In the SPS, the beam will be injected and captured on a fixed harmonic RF system in order to minimize the RF noise, using the Q20-optics to mitigate the effects of space charge and IBS [8]. Twelve four-bunch batches will be injected with 100 ns batch spacing, apart from a 1 µs gap between the 6th and the 7th batches. In the SPS, after acceleration on fixed frequency to 177 GeV/c/nucleon, momentum slip-stacking will reduce the bunch spacing to 50 ns. The trains supplied to the LHC by the injector chain will then eventually consist of 48 bunches, with a constant bunch spacing of 50 ns. Twenty-six transfers from the SPS will be necessary to fill each LHC ring with up to 1248 bunches. The expected beam parameters can be found in Table 1 below and in [9].

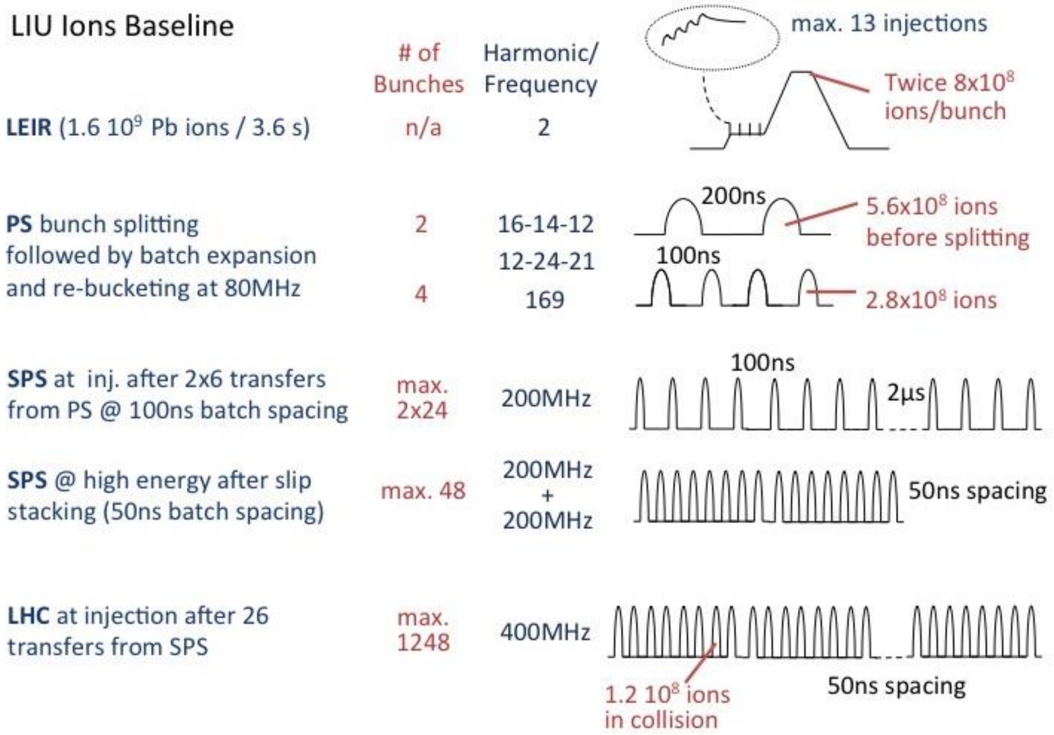


Figure 2: LIU-ION baseline scheme.

Table 1: LHC design parameters, achieved value in 2013 and LIU Ions base line beam parameters by machine in a simplified list. For the full LIU Ions beam parameter table with references, please see [9].

	LEIR before RF-capture (coasting beam)			After RF-capture and per bunch					
Variable, convention & units	Beam int.	$\beta\gamma\varepsilon_{H,V}$	Kin. E.	ε_z ($4\pi\sigma_E\sigma_T$)	Bunch len.	Δp/p	no. of B.	max. $\Delta Qsc_{H,V}$	
	[ions]	RMS [μm]	[GeV/n]	[eVs/n]	4 RMS [ns]	RMS[-]	[-]	[-]	[-]
LHC design rep.	1.0E+09	0.67	0.0042	0.040	800	2.0E-03	2	-0.11	-0.11
Achieved 2013	**1.7E+09**	**0.73, 0.33**	**0.0042**	**0.035**	**860**	**1.3E-03**	**2**	**-0.10**	**-0.16**
LIU Ions	2.0E+09	0.67	0.0042	0.035	860	1.3E-03	2	-0.12	-0.19

	PS @ injection (one injection from LEIR)								
Variable, convention & units	Beam int.	$\beta\gamma\varepsilon_{H,V}$	Kin. E.	ε_z ($4\pi\sigma_E\sigma_T$)	Bunch len.	Δp/p	no. of B.	max. $\Delta Qsc_{H,V}$	
	[ions/B]	RMS [μm]	[GeV/n]	[eVs/n]	4 RMS [ns]	RMS [-]	[-]	[-]	[-]
LHC design rep.	4.50E+08	0.7	0.0722	0.050	200	6.0E-04	2 -> 4	-0.11	-0.11
Achieved 2013	**5.5E+08**	**0.73, 0.33**	**0.0722**	**0.039**	**177**	**4.4E-04**	**2**	**-0.18**	**-0.27**
LIU Ions	8.0E+08	0.73, 0.47	0.0722	0.039	177	4.4E-04	2 -> 4	-0.24	-0.30

	SPS @ injection (12 injections from PS)								
Variable, convention & units	Beam int.	$\beta\gamma\varepsilon_{H,V}$	Kin. E.	ε_z ($4\pi\sigma_E\sigma_T$)	Bunch len.	Δp/p	no. of B.	max. $\Delta Qsc_{H,V}$	
	[ions/B]	RMS [μm]	[GeV/n]	[eVs/n]	4 RMS [ns]	RMS [-]	[-]	[-]	[-]
LHC design rep.	1.2E+08	1	5.9	0.050	3.9	3.3E-04	12x4	-0.03	-0.04
Achieved 2013	**3.8E+08**	**0.5**	**5.9**	**0.042**	**3.9**	**5.4E-04**	**12x2**	**-0.16**	**-0.20**
LIU Ions	2.8E+08	**0.5**	5.9	0.042	3.9	5.4E-04	12x4	-0.12	-0.15

	LHC @ injection								
Variable, convention & units	Beam int.	$\beta\gamma\varepsilon_{H,V}$	Kin. E.	ε_z ($4\pi\sigma_E\sigma_T$)	Bunch len.	Δp/p	no. of B.	max. $\Delta Qsc_{H,V}$	
	[ions/B]	RMS [μm]	[GeV/n]	[eVs/n]	4 RMS [ns]	RMS [-]	[-]	[-]	[-]
LHC design rep.	7.0E+07	1.4	176.4	0.280	1.8	3.2E-04	592	-1.5E-04	-1.0E-04
Achieved 2013	**1.6E+08**	**1.3**	**176.4**	**0.2…0.52**	**0.9…1.4**	**1.1…1.6E-4**	**358**	**-8.9E-04**	**-9.4E-04**
LIU Ions	1.2E+08	**1.3**	176.4	0.351	1.8	3.5E-04	1248	-2.7E-04	-3.3E-04

SUMMARY OF UPGRADES

In order to deliver the beam quality described above, the ion injector chain will need to undergo the following series of upgrades:

Linac3

Linac3 will deliver ion beam pulses of 20µA for the duration of 200µs at 4.2MeV/n. These pulses will be spaced by 100ms for the post LS2 injector scheme, versus 200 ms in 2013.

The LEIR machine will accept a maximum of 13 injections from Linac3 during a 3.6 second cycle time. Averaged over a 3.6 second cycle, this results in 3.61 Hz. Linac3 is currently capable of producing continuously pulses at 5 Hz. The air-cooling and ventilation system is running at the limit for operation at 5 Hz, and its renovation to restore the required cooling power is requested to the consolidation project, and should be done in LS2.

The GTS ion source of Linac3 is currently operating at 10 Hz continuous repetition rate. See Fig. 3.

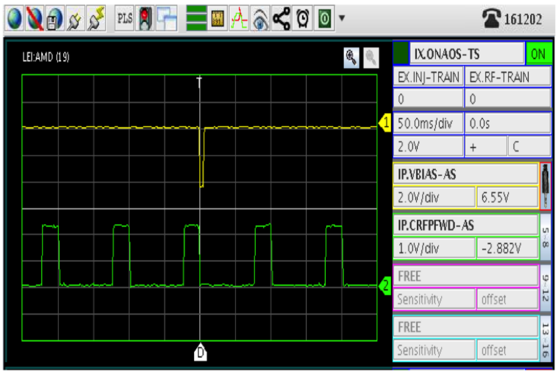


Figure 3: Analog signal of the GTS ion source of Linac3, showing the ion source pulsing with a bunch spacing of 100ms and a bunch duration of 200µs.

The low-energy-beam-transport (LEBT) of Linac3 is under investigation in order to further increase the ion beam intensity delivered to LEIR after LS2 and to get closer to the LHC design report value of the Linac3 current of 50 µA. Numerical simulations suggest that approximately half [10] the ions could be lost from the source extraction system to the RFQ of Linac3 (see Fig. 4). The goal is to reduce the ion beam loss in the LEBT and to increase the overall transmission of Linac3.

Before LS2, a series of machine development sessions are planned to crosscheck measurement and simulation. Before 2015, Linac3 will receive a pepper pot at a location after the LEBT spectrometer bending magnets and before the RFQ. With this it is possible to measure the beam profile and its emittance in the horizontal and the vertical plane. These measurements will serve as input for the numerical simulation of the LEBT and Linac3. It will allow gaining insight into why and where a large fraction of the GTS extracted ion beam is lost.

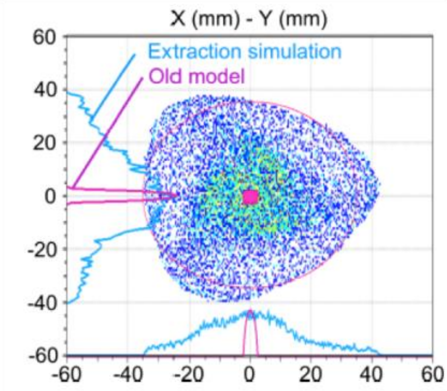


Figure 4: The initial particle distribution as input for the simulation of the LEBT in Linac3. A comparison is shown between the old (blue) input distribution and the new (in red) input distribution leading to a significantly lower beam transmission.

LEIR

To reach the LIU Ions luminosity goal in LHC following the proposed post-LS2 injection scheme, LEIR will need to deliver $8x10^8$ ions per bunch in two bunches to the PS. This ion beam intensity represents an increase of 45% with respect to the ion beam intensity achieved during the 2013 proton-lead run [11].

As explained above, the Linac3 repetition rate will be increased to 10 Hz. This will allow filling LEIR with up to 13 multi-turn injections. Each multi-turn injection will fill LEIR for 72 turns, see Fig. 5.

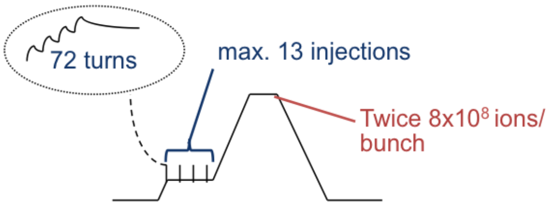


Figure 5: A maximum of 13 multi-turn injections will be accommodated on the low energy plateau in the LEIR machine. Two bunches of $8x10^8$ ions per bunch will be extracted from the LEIR machine and sent to the PS.

LEIR operations in 2013 revealed that effective electron cooling has required the full time span of 200 ms between the individual multi-turn injections. Decreasing the injection spacing to 100 ms will reduce the time available between injections to cool and to shrink the ion beam. Hence, improving the electron-cooling rate is imperative. Extensive machine developments will be conducted before LS2 to investigate quicker electron cooling rates by increasing the electron beam current and by optimizing the LEIR machine optics.

With an injection spacing of 100 ms and the improved electron-cooling rate, LEIR is planned to accumulate up to $2x10^9$ ions on the low energy plateau. From this accumulated beam intensity, LEIR will need to extract two bunches of $8x10^8$ ions each to the. This increase of extracted intensity will require a significant mitigation of the low energy ion beam loss after RF capture in LEIR (see Fig. 6).

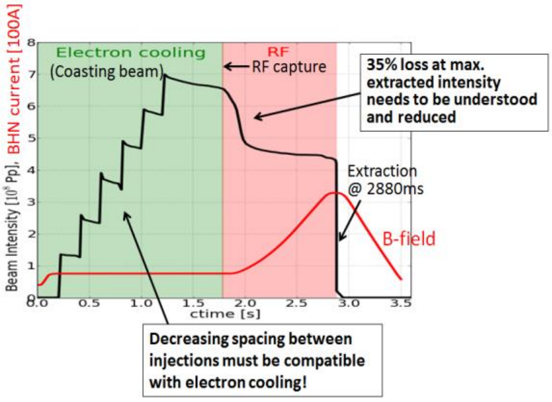


Figure 6: A typical NOMINAL cycle in LEIR with ion beam intensity (black) and main magnet current (red) vs. cycle time. The ion beam loss after RF-capture is currently the performance limiting ion beam loss in LEIR.

We plan to approach this loss mitigation by the following measures:

- More robust and operable beam diagnostics, in particular a fully operational:
    - transverse and longitudinal emittance measurement from Schottky signals.
    - gas ionization profile monitor measurement system.
- Extensive list of machine developments:
    - Re-establish the 2013 beam intensity and low energy loss phenomenon. Check its behaviour to be consistent with the observations from 2013.
    - Compare Ar findings from 2014 and 2015 with re-established Pb beam.
    - Run LEIR with negative chromaticity [12] and design tune with findings from Ar run.
    - Test LEIR Pb-beam with newly found tune from Ar run.
    - Test machine behaviour with higher intensity electron beam of the electron cooler and shortened cooling times.
- In machine modelling and beam dynamics theory, test and refute working hypothesis of:
    - Space charge
    - Faulty transverse damper
    - Impedance
    - Other types of instabilities, not yet considered so far.

PS

In the PS machine, the RF gymnastics originally intended in the design report for the nominal LHC beam will have to be recreated:

- Batch expansion (h = 16 – 14 – 12)
- Bunch splitting (h = 12 – 24)
- Batch expansion (h = 24 – 21)
- Rebucketing at h = 169 (80 MHz)

These gymnastics have been demonstrated during the previous runs, and the needed hardware is currently the same as the one, which has been used until now for the ions, but its maintenance should be included in the consolidation programme.

SPS

The SPS is the machine which will be modified the most for the LIU-ION project, as it will need to implement a new ion injection and the momentum slip-stacking.

Thanks to an improved 100 ns rise time, the new ion injection system will allow stacking the four-bunch batches from the PS with a bunch spacing of 100 ns in the SPS [13]. It will consist in:

- new pulsers for the fast kicker magnets, allowing a rise time of 100 ns. These fast pulsers had already been foreseen at the time of design [14],
- a new injection septum, which will be recuperated from the PS Booster extraction line, after its upgrade to 2 GeV,
- an improved injection damper to mitigate the large oscillations of the bunches situated at the limit of the kick.

The momentum slip-stacking gymnastics [15][16] need two independent RF-cavity controls, which rely on the upgrade of the low level RF. New hardware is needed for this upgrade. The two trains of 24 bunches will be captured independently, and detuned in momentum in opposite directions. The resulting frequency difference will make the two trains slip towards each other. Once the bunches are completely interleaved, they will be recaptured by a common RF, tuned to the average frequency. One issue is the larger resulting longitudinal emittance, but early simulations indicate the bunch length would still be within the accepted limits of the LHC RF at injection [17]. A continuation of this simulation study is required to detail and to understand the performance behaviour of the planned SPS momentum slip-stacking for LIU Ions.

Improvements on RF noise (fixed harmonic system on flat bottom) will be achieved by switching to fixed frequency for acceleration of 48 bunches on the low energy plateau. This will improve the emittance growth rate and the consequential energy beam loss.

ADDITIONAL MEASURES

In addition to the above upgrades, the following measures will be implemented to facilitate the required machine studies in order to achieve the LIU Ion goals for intensity in the injector chain and for the peak luminosity in the LHC.

LBS

[18] The LBS line measures the energy and energy spread of the beam from CERN proton Linac2 as well as the ions from Linac3. For Linac3 it is essential to have an energy measurement after the debuncher cavity. The LBS

line essentially consists of a spectrometer magnet, slits and a SEMGrid. The Linac4 project would have renovated this LBS line for 160MeV H- ions, but recently has chosen an alternative energy measurement system, and hence the LBS line will be renovated within LIU-Ions. For this renovation the spectrometer magnet will be replaced with almost identical ones recovered from Linac2, the power convertor will be exchanged for a new one recovered from the Linac4 project, and the controls of the transfer line between Linac3 and the LBS line that is in common with Linac4 will be migrated to FGC3s, and configured in a way to allow simpler sharing of the line between the 160 MeV H- and the 4.2 MeV/nucleon Pb^{54+} ions.

Spare source [option]

As an option, building a second, identical ion source, would allow training new supervisors and machine specialists on real conditions, as well as perform machine experiments on Pb or new species, without jeopardizing the current operations. It could also be used as a hot spare in case of a serious damage of the operation source.

LEIR Dump

At the moment each beam, which is accelerated in LEIR but not requested by the LHC, is either lost on the PS injection septum, or worse, inside the LEIR machine itself. This situation is deemed intolerable for the higher intensity of the LIU Ions beam, which should be disposed of cleanly and safely. A new dump is being designed to this effect between LEIR and the PS. It will be installed at the exit of the switching magnet ETL.BHN10, at the junction between the LEIR transfer line ETL and the PS injection line ETP.

PERFORMANCE BEFORE LS2

[19][20] For the first Pb-Pb run, currently planned for November 2015, batch compression RF gymnastics, already tried and tested in 2012, will be implemented in the PS, bringing the spacing between the two bunches down to 100 ns. Up to twelve such two-bunch batches will be accumulated for every cycle of the SPS, with a batch spacing of 225 ns. After 36 injections from the SPS, assuming once again the same performance (intensity per bunch and transverse emittances) as in February 2013, this scheme can deliver up to 432 bunches of 1.6×10^{8} Pb^{82+} ions per LHC ring [21], corresponding to a peak luminosity of $\mathcal{L}_{peak} = 2.8\times10^{27}$ cm^{-2} s^{-1} at 6.5 ZTeV.

CONCLUSIONS

- A baseline scheme is presented, which ensures bringing the peak Pb-Pb luminosity at 7 ZTeV to $\mathcal{L}_{peak} = 7.0\times10^{27}$ cm^{-2} s^{-1} .
- It consists of the following upgrades in the whole ion injection chain:
  - New LEBT optics, possibly an Einzel-lens.
  - Doubling the Linac3 repetition rate.
  - Increasing the electron-cooling rate for the new 100ms injection spacing.
  - Mitigating or solving the LEIR intensity limitation.
  - Re-establishing the bunch splitting in the PS, as originally planned at the design stage.
  - A new ion injection system in the SPS, allowing a 100 ns batch spacing.
  - Profiting from the upgrade of the Low-Level RF in the SPS, implement a momentum slip-stacking scheme.
- In addition, the following measures are considered:
  - Renewed spectrometer line to replace the old LBS line (Linac Booster Spectrometer), made obsolete by the connection of Linac4.
  - New dump in the LEIR transfer line, to cleanly dispose of the ion beam when not desired by the PS or the LHC.
  - Optionally, building a spare source for training the specialists and as a spare.
- Until the SPS injection is upgraded, new RF gymnastics in the PS (demonstrated in 2012) already bring a 22% increase to $\mathcal{L}_{peak} = 2.8\times10^{27}$ cm^{-2} s^{-1} at 6.5 ZTeV for the first LHC run after LS1.

ACKNOWLEDGMENTS

We deeply appreciate the solid and substantial support, the constructive conversations and the great many contributions from our working colleagues to this very document: M.E. Angoletta, F. Antoniou, G. Arduini, T. Argyropoulos, J. Axensalva, G. Bellodi, T. Bohl, C. Carli, K. Cornelis, H. Damerau, A. Findlay, A. Frassier, R. Garoby, B. Goddard, S. Hancock, S. Jensen, J.M. Jowett, D. Küchler, M. Meddahi, E. Métral, Y. Papaphilippou, S. Pasinelli, M. Schaumann, E. Shaposhnikova, and V. Toivanen.

REFERENCES

[1] D. Manglunki et al, “Performance of the CERN Heavy Ion production complex”, 3rd International Particle Accelerator Conference, IPAC12, New Orleans, USA, May 20-25, 2012.

[2] The ALICE Collaboration, “Upgrade of the Inner Tracking System Conceptual Design Report”, CERN-LHCC-2012-013 (LHCC-P-005), September 2012

[3] F. Bordry, “LHC Schedule beyond LS1”, http://lhc-commissioning.web.cern.ch/lhc-commissioning/schedule/LHC%20schedule%202015-2034%20FkBordry%202-december-2013.pdf

[4] E. Meschi, B. Gorini, “Heavy ion plans: experiments perspective”, Review of LHC and Injectors Upgrade Plans Workshop (RLIUPW), October 2013, Archamps, France.

[5] K. Hanke et al., ”Status of the LIU project at CERN”, THPME070, 5th International Particle Accelerator Conference (IPAC'14), Dresden, Germany, 15 - 20 June 2014.

[6] LHC design report, Vol. III, Part 4, Chap. 34, “source and Linac3”.

[7] LHC design report, Vol. III, Part 4, Chap. 37, “The LHC Ion Injector Chain: PS and transfer line to SPS”.

[8] F. Antoniou et al, “Performance of SPS Low Transition Energy Optics for LHC Ion Beams”, TUPME046, 4th International Particle Accelerator Conference, IPAC13, Shanghai, China, May 12-17, 2013.

[9] M. Bodendorfer, “LIU ION beam parameters”, https://edms.cern.ch/file/1420286/1/LIU_Ions_beam_parameters_EDMS.pdf, EDMS 1420286, October 2014.

[10] V. Toivanen, G. Bellodi, D. Küchler, A. Lombardi, R. Scrivens, J. Stafford-Haworth, “Simulation of the CERN GTS-LHC ECR Ion Source Extraction System with Lead and Argon Ion Beams”, Presented at ECRIS2014 Workshop, Nizhny Novgorad, Russia, August 2014.

[11] D. Manglunki et al., “The first LHC p-Pb run: performance of the heavy ion production complex”, WEPEA061, IPAC’13, Shanghai, China.

[12] M. Bodendorfer, “Chromaticity in LEIR performance”, CERN-ACC-NOTE-2013-0032.

[13] M. Benedikt et al., “LIU-SPS 50ns Injection review”, EDMS 1331860, https://edms.cern.ch/file/1331860/1.0/LIU-SPS_50ns_Injection_review_ExecutiveSummary_22Nov2013.pdf, November 2013,

[14] LHC design report, Vol. III, Part 4, Chap. 38, “The LHC Ion Injector Chain: SPS”.

[15] R. Garoby, “RF Gymnastics in a synchrotron”, in Handbook of accelerator physics and engineering, World Scientific ed., 1999, pp 286-287.

[16] D. Boussard and Y. Mizumachi, “Production of Beams with High Line-Density by Azimuthal Combination of Bunches in a Synchrotron”, CERN-SPS/ARF/79-11.

[17] T. Argyropoulos, Th.Bohl, E. Shaposhnikova, private communication, 2014.

[18] R. Scrivens, LIU Ions technical design report.

[19] D. Manglunki, “Performance of the LHC ion injectors after LS1”, Review of LHC and Injectors Upgrade Plans Workshop (RLIUPW, Archamps, France, October 2013.

[20] Y. Papaphilippou, ”Operational Beams for the LHC”, these proceedings.

[21] J. M. Jowett et al, “Future heavy-ion performance of the LHC”, Review of LHC and Injectors Upgrade Plans Workshop (RLIUPW), Archamps, France, October 2013.

HL-LHC PARAMETER AND LAY-OUT BASELINE

P. Fessia, M. Zerlauth, HL-PLC members, CERN, Geneva, Switzerland

Abstract

In this contribution the authors will present the baseline parameters of the HL-LHC project. The lay-out necessary to reach the project objectives will be described. The document will list other modifications that shall be carried out on the present LHC machine in order to reach the ambitious goal of 300 fb^{-1} delivered luminosity to the ATLAS and CMS experiments per year up to 2035. The main focus will be the foreseen modifications to be carried out during LS3, while more details concerning the relevant changes planned during LS2 are dealt with in the session "Long Shutdown 2 Strategy and Preparation" publication at this workshop.

HL-LHC BASELINE PARAMETERS

The performance of the HL-LHC machine is boxed in between the request for high integrated luminosity (ca. 3000fb^{-1} by the end of the HL-LHC exploitation over ca. 10 years of operation and translating to an annual integrated luminosity of ca. 250fb^{-1} assuming scheduled 160 days for proton physics production per year and that the HL-LHC exploitation starts with an integrated luminosity of ca. 300fb^{-1} at the end of the LHC Run III in 2022) and a maximum number of 140 events per bunch crossing. While the request for maximum integrated luminosity asks for the largest possible peak luminosity, the request for limited number of events per bunch crossing limits the peak luminosity to a maximum value of ca. $5 \cdot 10^{34}$ cm^{-2} s^{-1}. Operating the HL-LHC with the maximum number of bunches and utilizing luminosity levelling provides the best compromise for satisfying both requests. Table 1 shows the resulting baseline parameters approved by the HL-LHC Parameter and Layout Committee [1] for the standard 25ns bunch spacing configuration together with the parameters for the nominal LHC configuration and two alternative scenarios. These alternative scenarios are interesting in case LHC operation during Run II reveals problems either related to the emittance preservation along the LHC cycle for high intensity operation (the so called BCMS filling scheme allows the preparation of small emittance beams at the price of a reduced number of bunches) or enhanced electron-cloud effects at 25ns operation. The fall back solution for the latter scenario is a 50 ns bunch separation scheme at which electron cloud effects are expected to be less of an issue, but where the peak luminosity needs to be levelled at a lower value in order to keep the number of events per bunch crossing below 140. The luminosity levelling time is of the order of 8 hours and an efficient operation of the HL-LHC machine hence requires an average physics fill length that is larger than the levelling time (e.g. ca. 10 hours). The required HL-LHC average fill length is approximately 30% larger than the average fill length of the LHC achieved during Run I (ca. 6 hours).

The baseline parameters are based on a β^* value of 15cm at the IP and the operation with Crab Cavities for compensating the geometric luminosity loss factor that becomes significant when operating with such small β^* values and a large crossing angle. These parameters coupled together imply larger aperture insertion magnets (triplet magnets, D1 and D2 and Q4 magnets) and the exploitation of a novel optics matching scheme ATS [2] that utilizes the neighbouring arcs for matching the insertion optics to the rest of the machine. The larger aperture triplet magnets of the HL-LHC insertion increases the peak fields at the coils for constant magnet gradients and implies for the HL-LHC the use of novel Nb_3Sn magnet technology and a reduction of the triplet magnet gradients with respect to the nominal LHC configuration. The use of lower quadrupole gradients implies in turn longer triplet magnets (the functional quantity is given by the integrated magnet gradients) and an increase in length of the common beam pipe region next to the IP. The use of superconducting recombination dipole magnets in IR1 and IR5 allows to a large extend a compensation of the length increase of the common vacuum beam pipe region and it limits the increase in unwanted parasitic collision points of the two beams to an acceptable level. The schematic machine lay-out from the TAXS till the start of the continuous cryostat is published and kept up to date in the drawing LHCLSXH_0010 [3]

HL-LHC: THE UPGRADE INTERVENTIONS FROM A GEOGRAPHICAL DISTRIBUTION POINT OF VIEW

HL-LHC will require modifying the machine and infrastructure installations of the LHC in several points along the ring. In particular:

- Point 4
- Point 7
- Point 2
- Point 6
- Point 1
- Point 5

The locations are listed according to the chronological order presently foreseen for the installation of the HL-LHC systems.

Point 4

Point 4 will be equipped with a new cryogenic plant dedicated to the RF systems (and other cryogenic equipment that might be installed in IR4). The installation will require a warm compressor system on surface and a

Table 1: High Luminosity LHC parameters (LHC nominal ones for comparison)

Parameter	**Nominal LHC (design report)**	**HL-LHC 25ns (standard)**	**HL-LHC 25ns (BCMS)**	**HL-LHC 50ns**
Beam energy in collision [TeV]	7	7	7	7
N_b	1.15E+11	2.2E+11	2.2E+11	3.5E+11
n_b	2808	2748	2604	1404
Number of collisions in IP1 and IP5	2808	2736 [1]	2592	1404
N_{tot}	3.2E+14	6.0E+14	5.7E+14	4.9E+14
beam current [A]	0.58	1.09	1.03	0.89
x-ing angle [μrad]	285	590	590	590
beam separation [σ]	9.4	12.5	12.5	11.4
β^* [m]	0.55	0.15	0.15	0.15
ε_n [μm]	3.75	2.50	2.50	3
ε_L [eVs]	2.50	2.50	2.50	2.50
r.m.s. energy spread	1.13E-04	1.13E-04	1.13E-04	1.13E-04
r.m.s. bunch length [m]	7.55E-02	7.55E-02	7.55E-02	7.55E-02
IBS horizontal [h]	80 -> 106	18.5	18.5	17.2
IBS longitudinal [h]	61 -> 60	20.4	20.4	16.1
Piwinski parameter	0.65	3.14	3.14	2.87
Geometric loss factor R0 without crab-cavity	0.836	0.305	0.305	0.331
Geometric loss factor R1 with crab-cavity	(0.981)	0.829	0.829	0.838
beam-beam / IP without Crab Cavity	3.1E-03	3.3E-03	3.3E-03	4.7E-03
beam-beam / IP with Crab cavity	3.8E-03	1.1E-02	1.1E-02	1.4E-02
Peak Luminosity without crab-cavity [cm^{-2} s^{-1}]	1.00E+34	7.18E+34	6.80E+34	8.44E+34
Virtual Luminosity with crab-cavity: Lpeak*R1/R0 [cm^{-2} s^{-1}]	(1.18E+34)	19.54E+34	18.52E+34	21.38E+34
Events / crossing without levelling and without crab-cavity	27	198	198	454
Levelled Luminosity [cm^{-2} s^{-1}]	-	5.00E+34 [5]	5.00E+34	2.50E+34
Events / crossing (with leveling and crab-cavities for HL-LHC)	27	138	146	135
Peak line density of pile up event [event/mm] (max over stable beams)	0.21	1.25	1.31	1.20
Leveling time [h] (assuming no emittance growth)	-	8.3	7.6	18.0
Number of collisions in IP2/IP8	2808	2452/2524 [7]	2288/2396	0[4]/1404
N_b at SPS extraction [2]	1.20E+11	2.30E+11	2.30E+11	3.68E+11
n_b / injection	288	288	288	144
N_{tot} / injection	3.46E+13	6.62E+13	6.62E+13	5.30E+13
ε_n at SPS extraction [μm] [3]	3.40	2.00	< 2.00 [6]	2.30

---

[1] Assuming one less batch from the PS for machine protection (pilot injection, TL steering with 12 nominal bunches) and non-colliding bunches for experiments (background studies…). Note that due to RF beam loading the abort gap length must not exceed the 3μs design value.

[2] An intensity loss of 5% distributed along the cycle is assumed from SPS extraction to collisions in the LHC.

[3] A transverse emittance blow-up of 10 to 15% on the average H/V emittance in addition to the 15% to 20% expected from intra-beam scattering (IBS) is assumed (to reach the 2.5 μm/3.0 μm of emittance in collision for 25ns/50ns operation)

[4] As of 2012 ALICE collided main bunches against low intensity. satellite bunches (few per-mill of main bunch) produced during the generation of the 50ns beam in the injectors rather than two main bunches, hence the number of collisions is given as zero.

[5] For the design of the HL-LHC systems (collimators, triplet magnets,..), a design margin of 50% on the stated peak luminosity was agreed upon.

[6] For the BCMS scheme emittances well below 2.0 μm have already been achieved at LHC injection.

[7] The lower number of collisions in IR2/8 wrt to the general purpose detectors is a result of the agreed filling scheme, aiming as much as possible at a democratic sharing of collisions between the experiments.

junction from the surface to the underground installation where a new cold box will be placed. The cold box will then feed a dedicated RF cryogenic distribution line.

Point 7

The Horizontal Superconducting Links

In Point 7 two horizontal SC links will be installed in order to electrically feed the 600 A circuits connected to the 2 DFBAs (DFBAM and DFBAN).

The related power converters will be installed in the TZ76 and will be connected to the superconducting links via short warm cables. The two superconducting links will then run for about 220 meters in the TZ76 and then enter into the LHC machine tunnel via the UJ76. They will then be routed for about 250 m in the LHC tunnel in order to be connected to the DFBAM and DFBAN.

New collimators in the Dispersion Suppressor

In order to protect the superconducting magnets (excess heat deposition) from off-momentum proton leakage from the main collimator system itself, some special collimators must be installed in the Dispersion Suppression region, i.e. in the continuous cryostat. The evaluation of the real need of this modification will be completed on the base of the first results of the LHC Run II.

In order to cope with the proton losses in the Dispersion Suppressor area it has been decided to install two collimators on each side of the IP in the slots presently occupied by the Main Bending Magnets MB.B8L7 plus the MB.B10L7 and the symmetric MB.B8R7 plus the MB.B10R7. Each removed dipole will be replaced by a unit composed of two 11 T dipoles separated by a cryogenic by-pass. The collimator will be positioned in the beam lines on the top of the cryogenic by pass.

Point 2

In order to limit the heat deposition from collision debris in the superconducting magnets during the ion run, collimators in the dispersion suppressor will also be installed in Point 2. In this case the installation will take place only in one slot on each side of the IP replacing the MB.A10L2 and MB.A10R2 main bends.

Point 6

In Point 6 the two quadrupole magnets Q5 will be modified in order to fulfil the needs of the new HL-LHC ATS optics. The two options presently under evaluation lead either to the exchange of the present Q5 with a new and higher gradient Q5, but featuring a type of magnet already built and in use for the present LHC, or to the design and construction of a new quadrupole with larger aperture.

Point 1 and Point 5

The largest part of the new equipment, required by the HL-LHC performance objectives, will be installed in Point 1 and Point 5. The items to be installed and actions to be carried out are listed below and are applicable to both points if not otherwise specified. The list is organized by geographical areas.

LHC machine tunnel

- De-installation: all the machine equipment from the interface with the experimental cavern, starting with the TAS, up to the DFBA (included) need to be removed. The present QRL will be also removed in the same tunnel section and a new return module will be installed to allow separating the flows of the coolant coming from the LHC QRL and the one from the new HL-LHC QRL.
- Installation of the new equipment will most likely take place in the following sequence:
    - TAXS
    - Services
    - QRL with related valve and service modules
    - Horizontal superconducting links from the DFM to the magnets
    - Magnets and crab cavity support system
    - Magnets and crab cavity
    - Distribution feed boxes for the Q1 to D1 magnet system (DFX) and for the D2 to Q6 magnet system (DFM)

The sequence of installation of the vertical superconducting links to be connected to the DFX and DFM still needs to be assessed according to the options retained for its routing.

Existing LHC tunnel service areas

The RRs on both sides of Point 1 and Point 5 will need to be re-organized and in particular it will be necessary to: de-install the power converters and other related systems linked to the powering of the removed LHC matching section and then to re-organize the remaining equipment in order to increase, if necessary, the radiation shielding.

New HL-LHC tunnel service areas

The installation of the new cryogenic plant in Point 1 and Point 5 will have two main objectives:

- Provide independent and redundant cooling capacity to feed the final focusing and matching sections left and right of each of the two High Luminosity insertions of the LHC.
- Provide redundancy to the cryogenic plant installed to cool the experimental systems.

The cold box shall be installed in underground areas (Figure 5). Presently the required volume does not exist. Therefore conceptual studies have started in order to identify the best options for building new underground caverns to install this equipment and the related service and control system. Two possible approaches are under more detailed study: the baseline corresponds to solutions with magnet power converters on the surface, and a second one with power converters in the underground areas.

New connection from the LHC tunnel and HL-LHC service areas to the surface

The following connections between the surface and the underground installation shall be made available:

- LHC tunnel, crab cavity area, to the surface. The crab cavities need to be connected to the dedicated RF power system and their control system. The present baseline is to install these services in dedicated surface buildings.
- New HL-LHC service area to the surface. These connections are necessary to link the surface part of the cryogenic plant with the cold box installed in the new underground HL-LHC service areas.
- Vertical routing of the superconducting links. In each point at least four superconducting links (2xDFBX, 2xDFBL) will need to be routed from the surface to the underground areas.

New surface installation

The following installations shall find space on surface in Point 1 and Point 5 and in their proximities:

- Crab cavity RF power and services hosted in two ad hoc surface buildings. They shall be positioned on the surface, vertically directly above the tunnel position where the crab cavities will be installed. There will be two surface buildings for each point, one on the left part of the machine and one on the right part. The surface extremities of the ducts/shaft for the crab cavity coax or shaft shall be housed inside this building.
- Cryogenic installation. On surface the warm compressors and the other part of the cryogenic plant shall be installed.
- Power converters, upper extremities of the superconducting links, protection systems and energy extraction system related to the circuits fed via the superconducting link. This area shall be possibly located near the surface part of the cryogenic plant and in any case on the top of the surface extremity of the routing of the vertical superconducting link.

CONCLUSIONS

The HL-LHC project has produced a reference table for the baseline parameters and a sound lay-out baseline that will allow meeting the set targets. In this contribution both the parameter table and general lay-out modifications including main machine infrastructure have been discussed. It is worth recalling that, in addition to the baseline here described, the project has also developed a list of technical options with the objective to provide a robust risk mitigation plan and keep the path open towards further performance improvements.

ACKNOWLEDGEMENTS

In addition to the HL-LHC WP leaders and members, the authors would like to thank for the their contributions G. Arduini, I. Bejar Alonso, V. Baglin, O. Bruning, F. Cerutti, S. Chemli, S. Claudet, R. Calaga, R. De Maria, D. Duarte Ramos, I. Efthymiopoulos, L. Esposito, S. Fartoukh, C. Garion, M. Giovannozzi, M. Manfredi, Y. Muttoni, J. Osborne, H. Prin, L. Rossi, F. Sanchez Galan, E. Todesco.

REFERENCES

[1] HL-LHC Layout and Parameter Committee, https://espace.cern.ch/HiLumi/PLC/default.aspx

[2] S. Fartouk, “Achromatic telescopic squeezing scheme and application to the LHC and its luminosity upgrade”, CERN-ACC-2013-0289, 2013 Published in: Phys. Rev. Spec. Top. Accel. Beams 16 (2013) 111002APS.

[3] CERN CDD Drawing number LHCLSXH_0010.

HL-LHC MAGNETS ROADMAP

E. Todesco on behalf of WP3, and F. Savary on behalf of WP11
CERN, Geneva, Switzerland

Abstract

We will first give an overview of the 11 T project, giving a summary of the main technical choices made at CERN and in FNAL, test results and future milestones. We then focus on the IR magnets in the HL-LHC. After a short description of the layout, and a catalogue of the numerous magnet types, we will give for each magnet family a summary of the main technical choices. We will then discuss how the magnets have been shared between collaborations, what are the main achievements until now, and the future milestones. The critical points of the project will be reviewed, with a tentative schedule of the prototyping, production and installation phase.

11 T PROGRAM

The 11 T program aims at creating space in the LHC lattice for additional collimators by replacing the 15-m-long Nb-Ti 8.3-T-magnet with a stronger magnet in Nb_3Sn, providing the same integrated strength on a shorter length (see Fig. 1). After the initial study [1], the baseline that has been adopted is to have an 11 T magnet split in two 5.5 m long units [2], with a room temperature collimator in between (see Fig. 2). The magnet is in series with the other LHC dipoles, and therefore has to provide the same field for the same current.

Design Choices

The required design features proved to be feasible with two layers of a 15-mm-width cable, based on a 0.7-mm-diameter strand [1-4]. With this strong constraint on the electromagnetic design, which practically forces the coil to be very similar to the coil of the LHC main dipole, but with a thinner cable to match the current, the whole field increase from 8.3 to 11 T is given by a higher current density. The only main difference is that the LHC dipole has grading (~30% larger current density in the outer layer, obtained through two different cables), whereas in the 11 T there was a general consensus on not using graded coils to avoid complexity in a novel technology. With these choices, the magnet works at about 80% of the loadline, i.e. with a 20% margin – this is a challenging value but still more conservative than the 14% margin adopted for the LHC dipoles.

Two teams started working on this magnet, the first one at CERN [4-6] and the second one at FNAL [7-11], adopting the same choices of electromagnetic design. For the mechanical structure, which is considered to be a critical issue due to the large stresses, both teams selected the design based on collars, but adopted two different variants: FNAL opted for the technology already used in LHC accelerator research program, with a pole integrated in the coil (see Fig. 3). CERN team chose the technology of removable pole (see Fig. 4), used in MSUT dipole [12]. This design keeps the possibility of shimming not only in the midplane but also on the pole, to minimize the adverse effects of bending. In both structures, the iron yoke gives a non-negligible contribution to the mechanical structure since with this level of field and current density the collars alone cannot withstand the electromagnetic forces. Both teams opted for a structure based on separate collars.

For the cable insulation, CERN team selected the insulation scheme based on Mica plus braided fiberglass as done in MSUT dipole [12], and FNAL used the braided S2 glass sleeve as developed in the US-LARP and core programs.

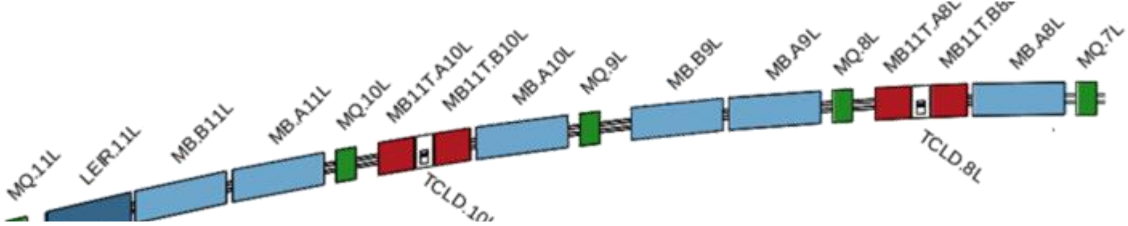


Figure 1: Replacement of an 8.3 T LHC dipole with 11 T dipole plus collimator

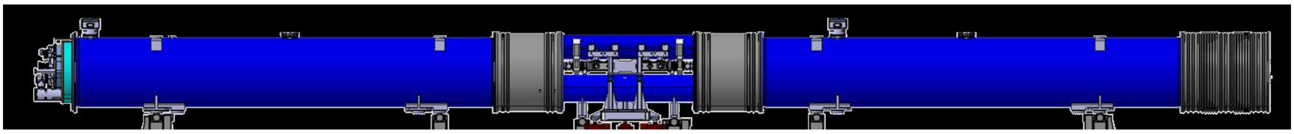


Figure 2: The 11 T unit, composed of two 5.5-m-long magnets with a room temperature collimator

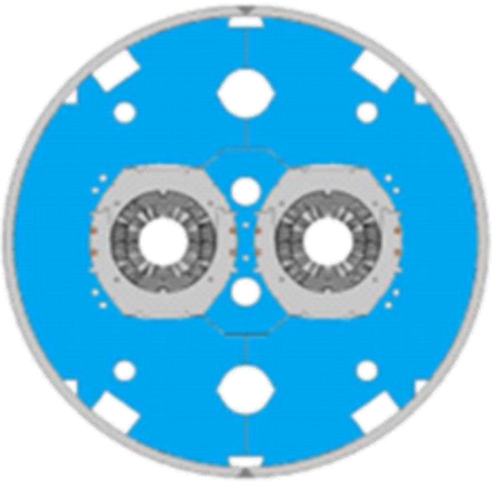


Figure 3: FNAL Cross-section of the 11 T dipole.

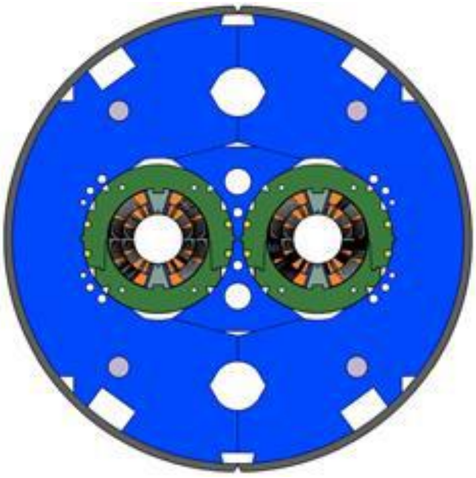


Figure 4: CERN Cross-section of the 11 T dipole.

Required Units

One 11 T unit is made of two 5.5-m-long dipoles with a room temperature collimator (see Fig. 3). In the second long shutdown [2], foreseen for 2018, two 11 T units are needed around the interaction point 2 (Alice) for ion collimation. In the third long shutdown [2], four units are needed around point 7, in the section used for cleaning. As an option [2], eight additional units could be installed around ATLAS and CMS (four units for each interaction point). Since one unit is made by two 5.5-m-long magnets, each one with 4 coils (double aperture dipole), this implies the construction of 16 coils for LS2 and 32 coils for LS3, with an option of 64 more coils, plus spares.

Present Status

During the past years, FNAL built an initial single aperture 2-m-long model [3], and two more 1-m-long models [9-11], that have been recently assembled in the first two-in-one Nb_3Sn magnet ever made. Performances were showing encouraging results of the mirror, with nominal reached with ~10 quenches, and ~90% of short sample reached after training. This proves that manufactured strand, cable and coil can reach the required performance with adequate margin. On the other hand, longer training was observed in the full model, with a nominal current reached with several tens of quenches, and limited margin (see for instance Fig. 5 where the mirror and the full model built at FNAL are compared – nominal current is 11.8 kA); moreover, in some cases the magnet quenches after reaching at nominal current (so called "holding quenches"); in other cases, a significant detraining has been observed. These points need to be addressed to have magnets that can be installed in the LHC.

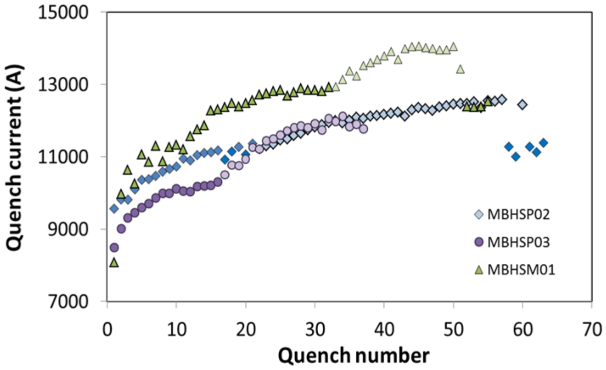


Figure 5: Training of the FNAL mirror, and of the first and second 1-m-long apertures. Nominal current is 11.8 kA

Production Plans

The FNAL contribution to the project is expected to end with the construction and test of a short two-in-one model. CERN continues the short model program, consisting of four single apertures and two double apertures, and is planning to build a long prototype in 2016. For the production of the series, no external collaboration is foreseen at the moment; due to the large quantity of coils and the temporal overlap with the Nb_3Sn inner triplet (see next section), it is probable that the production of the coil has to be done in the industry [13]. At the same time, the solutions needed for the cryostat bypass to house the room temperature collimator are being engineered and will be tested in the first magnet for IP2.

MAGNETS FOR THE IR UPGRADE

The new layout of the insertion regions aims at doubling the aperture of the present triplet to allow reducing the beam size by a factor two in the interaction point [14]. This gives a potential increase in peak luminosity of a factor four. Nb_3Sn is the enabling technology since, thanks to the 50% higher gradient reachable in the same aperture, it allows to increase the aperture, still keeping the triplet compact, i.e. less than 10 m longer than in the LHC layout (see Fig. 6). The other magnets between the triplet and the matching section quadrupole have to be replaced, to match the aperture increase. They are all in Nb-Ti technology since their length is not critical for performance.

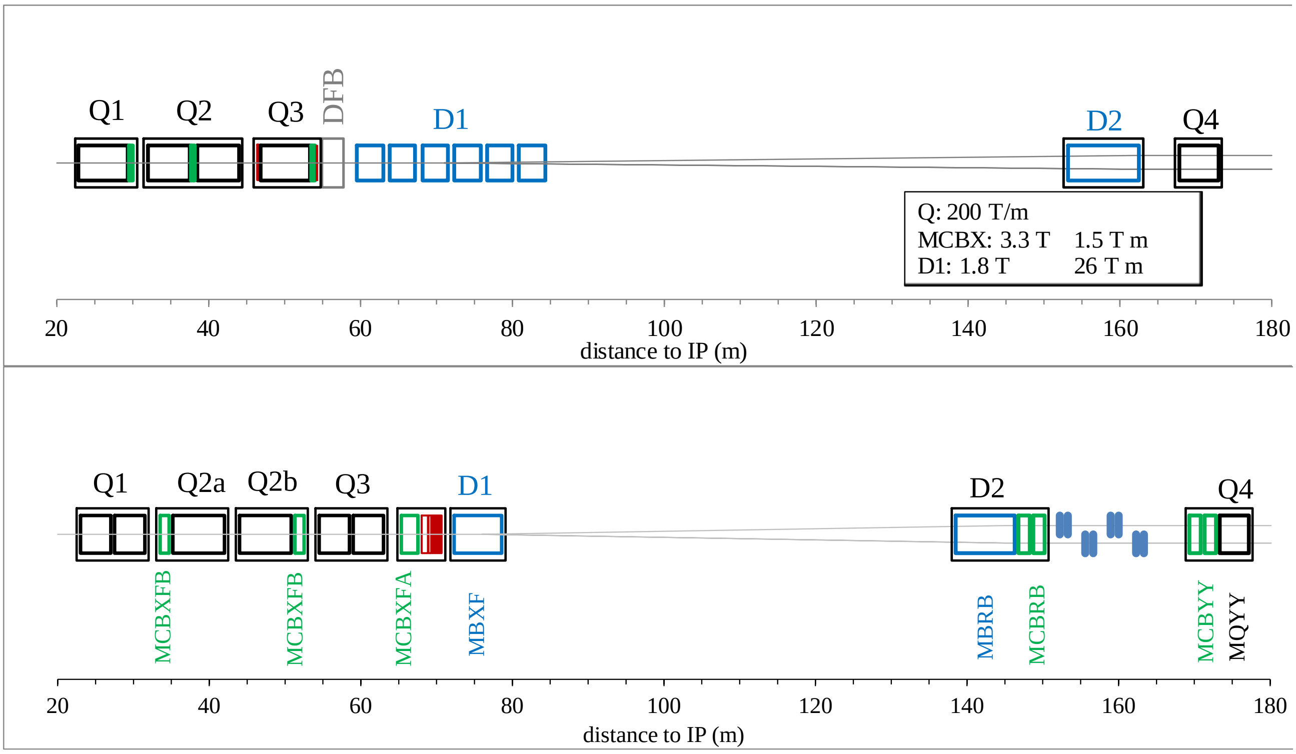


Figure 6: Layout of the interaction region around ATLAS and CMS foreseen for 2024 (after long shutdown 3), compared to present layout

Main Design Choices

The main guidelines of the design were (i) to have the maximum performance, i.e. aiming at the largest possible aperture in the triplet using Nb_3Sn [15], pushed at the maximum performance with a peak field in the coil of ~12 T; (ii) have the other main magnets in Nb-Ti technology [16-18] with peak fields of the order of 6 T; (iii) to have the full set of correctors required by beam dynamics, given the large values of beta function in the triplet region, which make the beam sensitive to any small imperfection in that region [19-20]. The complete list of parameters can be found in the preliminary design report and in the WP3 web site [14]. Here we briefly outline the main design choices.

The triplet is made of four 150 mm aperture Nb_3Sn quadrupoles, with nominal gradient of 140 T/m at 80% of the loadline [15]. The four magnets (Q2 is split in two, as in the LHC, see Fig. 6) have lengths of 7 to 8 m. Recently, it has been decided to increase these lengths by ~35-40 cm, thus allowing to reduce the operational gradient to 132.6 T/m, increasing the margin on the loadline from 20 to 25 %. The magnet deign (see Fig. 7) is a scale-up of the 120 mm aperture quadrupole HQ successfully developed by LARP [21]: (i) double layer coil, with four blocks, (ii) bladders and key structure allowing a very precise control of mechanical loading at room temperature, and (iii) an aluminium shell to support the electromagnetic forces.

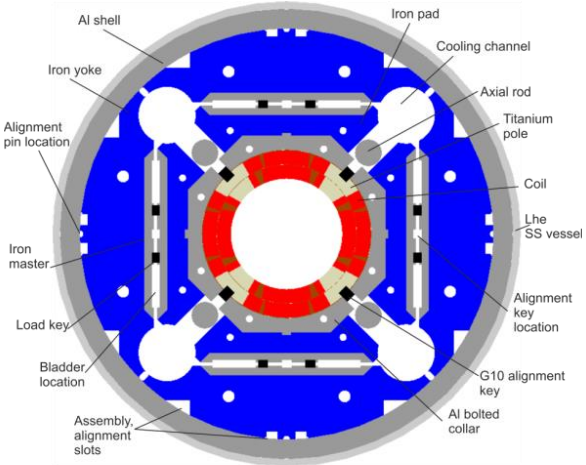


Figure 7: CERN Cross-section of the triplet QXF.

The separation dipole is a 150-mm-aperture Nb-Ti dipole, with an operational field of 5.6 T at 75% of the loadline, and 6 m length. It is a single layer coil with thin collars (see Fig. 8) to maximize the quantity of iron, thus reducing saturation effect below the targets [16]. The mechanical structure relies on the iron to keep the electromagnetic forces (collars are too thin to have a self-standing collar structure as in the LHC dipole).

The recombination dipole is a Nb-Ti two-in-one 105-mm-aperture magnet with 4.5 T operational field, working at 65% of the loadline. Here the limitation is the electromagnetic cross-talk between the apertures, imposing (i) a rectangular frame to reduce the saturation on b_3 and (ii) no iron between the apertures, and left right asymmetric coils, as proposed in [22], to reduce the saturation effect on b_2. A sketch of the design is given in Fig. 9. Note the elliptic iron yoke to reduce the fringe field and the saturation effects.

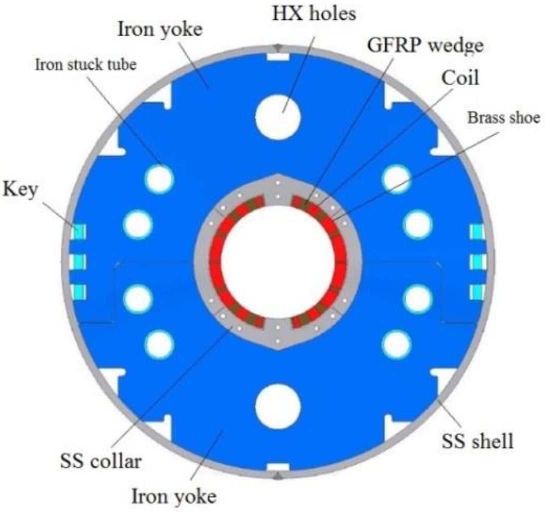


Figure 8: Cross-section of the separation dipole D1.

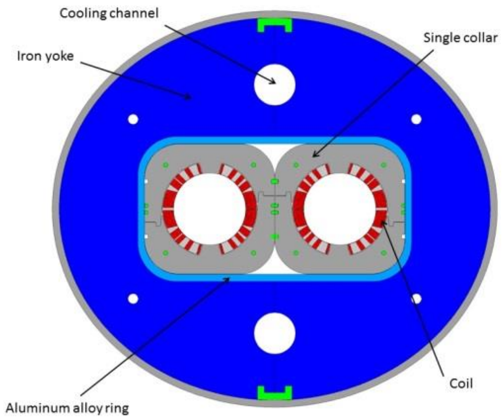


Figure 9: Cross-section of the recombination dipole D2.

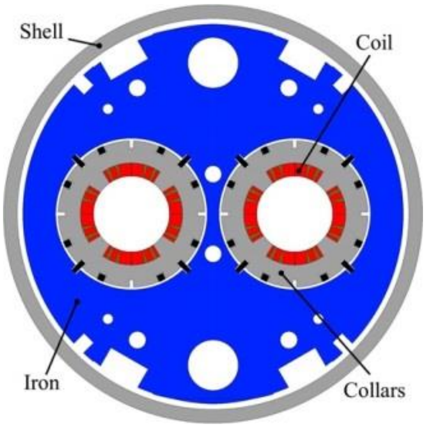


Figure 10: Cross-section of the quadrupole Q4.

The two-in-one quadruple Q4 [18] is a Nb-Ti 90-mm-aperture magnet with 115 T/m operational gradient, working at 80% of the loadline (see Fig. 10).

The single aperture corrector magnets provide a considerable integrated field (2.5 and 4.5 T m). They are based on nested coils [19], giving 2.1 T maximum fields in horizontal and vertical plane (see Fig. 11). A two-layer coil in each plane, using a 4.5-mm-width Rutherford cable, provides the required field with a comfortable margin (~60% on the loadline). The mechanical structure relies on self-standing collars, with the external coil being collared on the internal one. An inner tube is needed to keep the electromagnetic forces from bending the coil towards the beam tube, when both coils are powered.

The high order correctors are superferric magnets [20] with peak field of the order of 1.5 T, and length of ~10 cm, with the exception of the skew quadrupole (~85 cm) and the normal dodecapole (~45 cm). The coil is made with Nb-Ti wire, giving operational currents of the order of 100 A, and the iron is at 1.9 K (see Fig. 12 for the skew quadrupole).

The two-in-one orbit correctors close to D2 and Q4 provide 4.5 T m, with a nominal field of 2.8 T. As in D2, the main issue in the design of this magnet is the magnetic cross-talk between the apertures, given the large aperture (105 mm) and the fixed LHC interbeam distance of 192 mm (see Fig. 13).

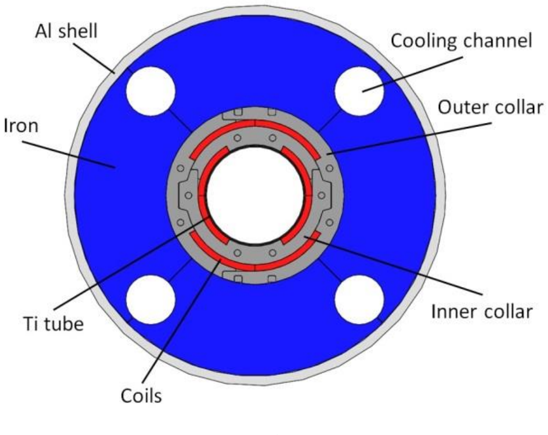


Figure 11: Cross-section of the nested orbit corrector.

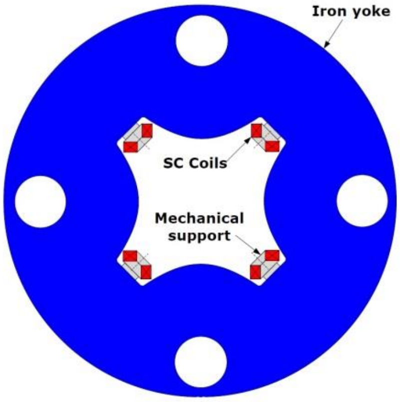


Figure 12: Cross-section of the skew quadrupole.

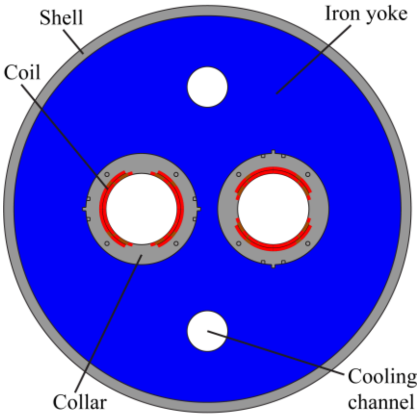


Figure 13: Cross-section of the two-in-one orbit corrector.

Status and Production Plan: Triplet

The inner triplet will be shared between CERN and US-HiLumi, with the Europeans building the Q2 (eight units plus two spares), and the Americans the Q1 and the Q3 (eight units plus two spares). The collaboration has chosen the same design to maximize the synergies. The added value is particularly evident in the short model program, where coils built at CERN and in the US can be exchanged and assembled in the same magnet.

The first short model will be assembled and tested in 2015, and four more models are foreseen. At the prototype stage, the two collaborations will have magnets with different lengths. The US collaboration also decided to have a split magnet, with a minimal loss of performance. Two prototypes are foreseen at CERN, and one and a half (three 4-m-long magnets) in the US, to be tested in 2016-2018. Production is foreseen for the period 2019-2023. Schedule is tight, allowing a very limited possibility of feedback.

Status and Production Plan: Main Magnets

The main magnets are characterized by similar features: (i) a very small series (4 units plus two spares), (ii) same Nb-Ti technology (iii) lengths in the 4 to 8 m range.

The separation dipole activity is steered by KEK, where the conceptual design started already in 2013 [16]. The test of the first short model is foreseen for 2015, and a second one to be manufactured in 2016. The series could be a in-kind contribution of Japan, and could be realized in the Japanese industry in the period 2019-2021.

The recombination dipole design study started in early 2014 in INFN Genova [17]. The team rapidly converged on a conceptual design during 2014, and now the engineering of a short model is in progress. The plan is to have a short model manufactured by industry in 2016, with a test at the end of 2016 or beginning of 2017. The series should also be built in the industry, in the period 2019-2021.

The activities related to the matching section quadrupole Q4 started in CEA-Saclay in 2012 [18]. Conceptual design has been completed in 2013, and engineering started in 2014. First winding test have been carried out in early 2015 in CEA. The plan is to have a short model manufactured during 2016, and a test in single and double aperture configuration in 2017. Also in this case production should be carried out in the industry in the period 2019-2021.

Status and Production Plan: Correctors

The orbit corrector magnets are designed by CIEMAT; conceptual design of the magnet was completed in 2015 [19], with sill some decisions to be taken on the cable insulations scheme and on the option of impregnating the coil. First winding tests will be carried out in 2015, and a short model will be built in collaboration between CIEMAT (winding) and CERN (collaring), and tested in 2016. The series is foreseen to be built in the industry during the years 2018-2020.

The nonlinear corrector prototypes are a contribution of INFN-LASA [20]. The Italian laboratory carried out the conceptual design and has made the first winding tests in early 2015. Prototypes of each of the five different types of magnets (from skew quadrupole to dodecapole) are planned to be built and tested in LASA in the period 2015-2017. Production could start right after in 2018-2019 in the industry.

The double aperture orbit corrector will be developed at CERN in 2017. Due to the larger number of coils (64 plus spares), also this production goes beyond a laboratory optimal charge, and it is planned for the industry. A summary of the first tentative sharing between CERN, collaborations and industry of the different phases of the model, prototyping and production is given in Fig 14.

		Q1/Q3	Q2	orbit	orbit	HO correctors	D1	D2	Q4	D2 Q4 correctors
		MQXFA	MQXFB	MCBXFB	MCBXFA		MBXF	MBRB	MQYY	MCBRB/YY
Model	Coil	US-HILUMI	CERN MDT				KEK	Industry-4	CEA	
	Assembly	US-HILUMI	CERN MDT				KEK	Industry-4	CERN MDT	
	Cold mass						KEK			
	V test	US-HILUMI	CERN TF				KEK	INFN LASA	CEA	
Prototype	Coil	US-HILUMI	CERN LMF	CIEMAT	Industry-1	INFN LASA	Industry-3	Industry-4	Industry-5	CERN MDT
	Assembly	US-HILUMI	CERN LMF	CIEMAT	Industry-1	INFN LASA	Industry-3	Industry-4	Industry-5	CERN MDT
	Cold mass	US-HILUMI	CERN LMF			CERN LMF	Industry-3	CERN LMF	CERN LMF	
	V test	US-HILUMI		CERN TF	CERN TF	INFN LASA	KEK		CEA	CERN TF
	Cryostat	CERN CMI	CERN CMI			CERN CMI	KEK	CERN CMI	CERN CMI	
	H test	US-HILUMI	CERN TF			CERN TF	CERN TF	CERN TF	CERN TF	
Series	Coil	US-HILUMI	CERN LMF	Industry-1	Industry-1	Industry-2	Industry-3	Industry-4	Industry-5	Industry-6
	Assembly	US-HILUMI	CERN LMF	Industry-1	Industry-1	Industry-2	Industry-3	Industry-4	Industry-5	Industry-6
	V test	US-HILUMI		CERN TF	CERN TF	INFN LASA	KEK		CEA	CERN TF
	Cold mass	US-HILUMI	CERN LMF			CERN LMF	Industry-3	CERN LMF	CEA	
	Cryostat	CERN CMI	CERN CMI			CERN CMI	KEK	CERN CMI	CERN CMI	
	H test	CERN TF	CERN TF			CERN TF	CERN TF	CERN TF	CERN TF	

Figure 14: First plan for the sharing of the IR magnets for HL-LHC.

CONCLUSIONS

We presented here the roadmap for the new magnets of the HL-LHC project. For the 11 T results of few short models built at FNAL and at CERN are already available. The construction of a first 5.5-m-long magnet will be an important milestone for the project. The plan foresees the installation of 2 units within the tight deadline of 2018, and four units in 2023.

For the IR magnets, to be installed in 2023, nearly 100 units have to be built. The layout and the conceptual design of all magnets have been completed. Fine tuning of the layout is in progress, taking into account of minor changes of margins and lengths, and a better definition of the interfaces between magnets. The sharing of the magnets design and/or construction between five international collaborations (US HiLumi, CIEMAT, CEA, INFN, KEK) is taking shape and a first baseline is available, summarized in Fig. 14. The test of the first three magnets of HL LHC IR regions (triplet, separation dipole and sextupole corrector) is foreseen for 2015.

REFERENCES

[1] G. De Rijk, A. Milanese, E. Todesco, "11 Tesla Nb3Sn dipoles for phase II collimation in the Large Hadron Collider", CERN SLHC Project Note **19** (2010).

[2] M. Karppinen, D. Ramos, F. Savary, S. Zlobin, "11 T dipole for the dispersion suppressor collimators, in "Preliminary design report of HL LHC", CERN-ACC-2014-103 (2014) 227-233.

[3] A. Zlobin, et al., "Design and fabrication of a single-aperture 11 T Nb3Sn dipole model for LHC upgrades", IEEE Trans. Appl. Supercond. 22 (2012) 4001705.

[4] M. Karppinen, et al., "Design of 11 T twin-aperture Nb3Sn dipole demonstrator magnet for LHC upgrades", IEEE Trans. Appl. Supercond. 22 (2012) 4901504.

[5] F. Savary, et al., "Status of the 11 T Nb3Sn dipole project for the LHC", IEEE Trans. Appl. Supercond. 25 (2015) 4003205.

[6] F. Savary, et al., "Design, assembly and test of the CERN 2-m-long 11 T dipole in single coil configuration", IEEE Trans. Appl. Supercond. 25 (2015) 4004105.

[7] A. Zlobin, et al., "Development and test of a single-aperture 11 T Nb3Sn demonstrator dipole for LHC upgrades", IEEE Trans. Appl. Supercond. 23 (2013) 4000904.

[8] N. Andreev, et al., "Field quality measurements in a single aperture 11 T Nb3Sn demonstrator dipole for LHC upgrades", IEEE Trans. Appl. Supercond. 23 (2013) 4001804.

[9] A. Zlobin, et al., "Quench performance of a 1-m-long single-aperture 11 T Nb3Sn dipole model for LHC upgrades", IEEE Trans. Appl. Supercond. 24 (2014) 4000305.

[10] G. Chlachidze, et al., "Field quality study of a 1-m-long single-aperture 11-T Nb3Sn dipole model for LHC upgrades", IEEE Trans. Appl. Supercond. 24 (2014).

[11] A. Zlobin, et al., "11 T twin-aperture Nb3Sn dipole development for LHC upgrades", IEEE Trans. Appl. Supercond. 25 (2015) 4002209.

[12] H. ten Kate, et al., "An experimental 11.5 T Nb3Sn LC type of dipole magnet, IEEE Trans. Magn. 30 (1994) 2320-2323.

[13] L. Bottura, talk at the cost and schedule review, March 2015.

[14] E. Todesco, et al., "Insertion Magnets", in "Preliminary design report of HL LHC", CERN-ACC-2014-103 (2014) 87-106 and updated parameters on www.cern.ch/hilumi/wp3

[15] P. Ferracin, et al., “Magnet design of the 150 mm aperture low-beta quadrupole for the high luminosity LHC”, IEEE Trans. Appl. Supercond. 24 (2014) 4002306.

[16] T. Nakamoto, et al., “Model magnet development of D1 beam separation dipole for the HL-LHC upgrade”, IEEE Trans. Appl. Supercond. 25 (2015) 4000505.

[17] P. Fabbricatore, et al., “The design of superconducting separation dipoles D2 for the high luminosity upgrade of LHC”, IEEE Trans. Appl. Supercond. 26 (2016) to be published.

[18] J. M. Rifflet, et al., “A Nb-Ti 90 mm double aperture quadrupole for the high luminosity LHC upgrade”, IEEE Trans. Appl. Supercond. 25 (2015) 4001905.

[19] F. Toral, et al., “Magnetic and mechanical design of the nested orbit correctors for HL-LHC”, IEEE Trans. Appl. Supercond. 26 (2016) to be published.

[20] G. Volpini, et al., “Nb-Ti superferric corrector magnets for the LHC luminosity upgrade”, IEEE Trans. Appl. Supercond. 25 (2015) 4002605.

[21] H. Felice, et al., “Design of HQ, a high field large bore Nb3Sn quadrupole magnet for LARP”, IEEE Trans. Appl. Supercond. 19 (2009) 1235-39.

[22] V. Kashikin, et al., “Design study of 2-in-1 large aperture IR dipole (D2) for the LHC luminosity upgrade”, Particle Accelerator Conference. (2007) 464-6.

HL-LHC RF Roadmap

R. Calaga, CERN, Geneva, Switzerland

Abstract

In view of the HL-LHC parameters, the present and the future RF systems for the LHC are reviewed with a focus on technological aspects. This paper will describe the preparation and the test program of the SPS beam tests with crab cavities. Some aspects related to the integration of the crab cavity RF system in the LHC and the potential impact of the crab kissing scheme are addressed. The mode of operation for the 400 MHz accelerating RF system with HL-LHC beam currents and the associated issues are briefly outlined with possible improvements to the ACS system. Finally, the use of a harmonic system both at 200 MHz and 800 MHz for bunch profile manipulation and the associated technological challenges are described.

INTRODUCTION

The HL-LHC upgrade to enhance the integrated luminosity by a factor 10 will require that the present and the foreseen RF systems to be compatible with beam currents exceeding 1.1 A. This paper will cover the following RF systems:

- Crab cavity R&D upgrade status for SPS tests
- Compatibility of the existing RF system for HL-LHC
- Harmonic RF system for bunch manipulation and increased stability

Some relevant beam and machine parameters used to design the RF systems. are listed in Table 1. A more detailed parameter list is found in Ref. [1].

Table 1: Some relevant parameters for the LHC nominal and upgrade lattices.

	Unit	Nominal	Upgrade
Energy	[TeV]	3.5-7	7
p/bunch	[10^{11}]	1.15	2.2
Bunch Spacing	[ns]	50-25	25
Bunch Length (4σ)	[ns]	1.0	1.0
ϵ_n (x,y)	[μm]	2.5	2.5
IP$_{1,5}$ β^*	[cm]	55	15
Betatron Tunes	-	$\{62.31, 60.32\}$	
X-Angle: $2\phi_c$	[μrad]	285	590
Piwinski Angle	$\frac{\sigma_z}{\sigma^*}\phi_c$	0.65	3.14
Main/Crab RF	[MHz]	400.79	
Peak lumi ($\times 10^{34}$)	[$1/cm^2 s^1$]	1.18	19.54

All RF systems being considered for the HL-LHC rely on the RF superconductivity (SRF) as the driving technology. The benefits from the high stored energy and low surface losses therefore allowing for large aperture and lower impedance is vital. The SRF history at CERN dates back to the 70's with the RF separator in the SPS in collaboration with Karlsrushe [2]. Over four decades, significant developments in the SRF took place in the context of LEP, LHC, HIE-ISOLDE, crab cavities, SPL and other R&D projects.

For crab cavities, the demand of 3.4-5.0 MV kick voltage corresponds to surface fields in excess of 40 MV/m and 100 mT. Therefore, the challenge remains to robustly produce the kick voltage with adequate margin. For longitudinal RF systems, the main challenge is to cope with the strong transient beam loading and reliably provide the required RF power.

STATUS OF SPS CRAB CAVITIES

A test of crab cavities in a hadron machine (for example the SPS) prior to a final installation in the LHC was deemed as a pre-requisite [3]. The test will first address important aspects such as cavity performance and reliability, RF controls, machine protection and other operational aspects. These tests are regarded as a vital step to identify the possible differences between electrons and protons and to quantify the associated emittance growth and other crab cavity induced beam perturbations. A dedicated working group (CCTC) was put in place to address various aspects including integration, cryogenics, infrastructure of a two-cavity prototype [4].

Cavity Performance Tests

As a result of R&D in collaboration with USLARP and UK, three very compact superconducting cavity designs were conceived and prototyped in bulk Niobium. All three cavities reached design kick voltage of 3.4 MV or higher (in some cases factor 2) within a surface resistance higher than the specified 10 nΩ. Fig. 1 shows the three compact prototype cavities, the double quarter wave (DQW), the RF dipole (RFD) and the 4-Rod designs fabricated for field performance tests.

A technical review in May 2014 provided a recommendation to proceed with only two cavity types (DQW and RFD) based on several technical aspects and schedule constraints [6].

Figure 1: Prototype Niobium cavities of the DQW, RFD and the 4-Rod respectively [5].

Cryomodule Development

A detailed conceptual design of a cryomodule for the three cavities was performed prior to the technical review decision. However, following the review recommendation, only the DQW and the RFD designs were followed up towards an engineering design for fabrication. Fig. 2 shows a sequential development of the cavity, interfaces, service and the cryomodule concept with all the ancillary equipment. The Helium vessel was chosen to be made of Titanium to minimize the differential contraction between the Niobium cavity and the cold mass due to the numerous asymmetric interfaces [8]. A double insulation for magnetic shielding, one inside the He-vessel and one outside, is used to bring the stray magnetic fields to below the required 1μT level. A novel tuning concept using concentric cylinders to differentially apply a push-pull force on the cavity body is also employed [9]. Using a special frame a symmetric force on opposite sides of the cavity for a symmetric deformation. A warm actuation system is used to ease the maintenance. A rectangular vacuum vessel with side loading concept is adopted to provide adequate access for all major components during assembly and testing at this R&D stage [10].

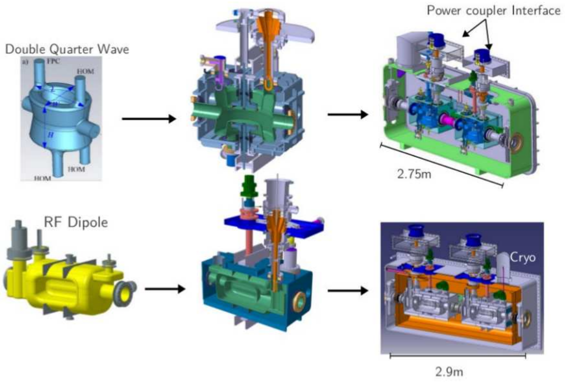


Figure 2: Schematics of the cavity interfaces, Helium vessel and the two cavity cryomodule with all the ancillary equipment (courtesy EN-MME).

It is presently planned that USLARP along with DOE-SBIR program will fabricate four cold masses (commonly referred to a the dressed cavity) including the Titanium Helium vessels and HOM couplers towards the SPS tests [7]. The dressed cavities are tested and qualified to the nominal kick voltage prior to their assembly in the cryostat. The RF power coupler and the cryomodule assembly will be carried out in collaboration between CERN and the UK collaboration. The assembled cryostat is expected to be completed by mid-2016 and then put through a comprehensive horizontal test in the SM18 prior to an installation into the SPS.

Integration

A special region in the BA4 section of the SPS hosting the present COLDEX experiment was identified as the best location for a test of the crab crab cavity This region consists of a movable horizontal bypass and essential cryogenic infrastructure for future crab cavity tests. The bypass allows for an easy displacement of the cavities during regular SPS operation (see Fig. 3). The complete infrastructure requirements including cryomodule integration, vacuum, cryogenics, RF power and all other services is being carried out under the CCTC working group [4]. Recent considerations to equip the SPS with a second bypass in LSS5 is under investigation as an alternative to LSS4 to allow for COLDEX to continue for a longer period [11].

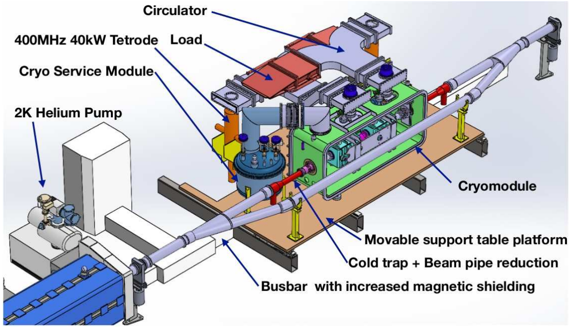


Figure 3: Schematic of the two-cavity installation in the SPS-BA4 region [4].

Test Objectives & Challenges

The SPS beam tests are foreseen to take place during the run period of 2017 until the start of Long Shutdown 2 (LS2).

The primary test objective in the SPS is the demonstration of cavity deflecting field with proton beam and active control of cavity field (amplitude and phase) along with Multi-Cavity Feedback (MFB). Following the verification of operational frequency, tuning sensitivity, input coupling, power overhead and HOM signals, the comprehensive operational cycle as foreseen in the LHC will then be established. The possibility to operate w/o crab cavity action (make them invisible) by both counter-phasing the two cavities or by appropriate detuning (to parking position) at energies ranging from 26-450 GeV will be performed. Beam measurements for orbit centering, crab dispersive orbit and bunch rotation with available instrumentation such as BPMs and head-tail monitors will also be carried out.

Other aspects such as the demonstration of non-correlated operation of two cavities in a common CM (triggering a quench in one cavity without inducing quench in the other), implementation of interlock hierarchy and verification of machine protection aspects and functioning of slow and fast interlocks will also be studied. It will be important to test HOM coupler operation with high beam currents, different filling schemes and associated power levels. Measurements of impedance and instability thresholds for the main deflecting mode and HOMs are vital. Finally, the emittance growth measurements induced by the crab cavities and general long term behavior with proton beams is also necessary objective.

The beam tests (or MDs) in the SPS can be generally classified into three main categories:

- RF commissioning with low intensity beam, single to few bunches. Establish the proper RF parameters, including cavity tune, phase and operating kick amplitude. Verify both, crab cavity action and invisibility.

- High intensity single bunches to trains of bunches to investigate the effect of cavity performance, impedance, machine protection and characterize the transient behavior of the crab cavity system as a function of beam current. Verify cavity stability over several hours (as relevant for LHC physics fill).

- Long term behavior of coasting beams in the SPS with relatively low intensity to study the effects of emittance growth and possibly non-linear effects such as RF multipoles.

Despite the extended winter shutdown in 2016-17, a complete installation during this shutdown appears challenging. The continued running of COLDEX precludes any pre-installation. A careful coordination is required between the different equipment groups to perform the installation. In the LHC, several challenges exist including machine protection, impedance, RF noise, installation and maintenance of a large RF system in a highly radioactive environment.

Impact of CK Scheme

The crab kissing (CK) scheme is proposed as one of the schemes to reduce the pile-up density, a key feature desired by the experiments [12]. The baseline scheme requires 4 cavities per IP side and per beam with a nominal cavity voltage of 3.4 MV or less. In the CK scheme, two of the four cavities are needed in the crossing plane while the other two are oriented in the opposite (parallel) plane. The present optics requires that the cavities operate between 5-6 MV which lead to cavity surface fields close to the typical quench fields.

The change in orientation of two cavities implies that the CK scheme is not backward compatible to the original crab crossing scheme. Due to the 50-70% higher voltage requirements, degradation in cavity performance or a failure will have a significant impact on the performance and possibly on machine protection. If the newer optics allows for reduction in the required voltage, the baseline scheme can also be implemented with fewer cavities in the ring in view of impedance reduction. Hence, a phased installation approach where only half the system followed with beam experience can be envisioned to leave open the choice of installation plane at a later stage.

MAIN RF, ACS-400 MHZ

The accelerating RF system in the LHC (ACS) comprises of 8-cavities per beam operating at 400 MHz to provide a nominal voltage of up to 2 MV/cavity. The system is described in detail in Ref. [13]. The primary functions of the ACS cavities include the injection and energy ramping of 2808 bunches of up to 1eV-s and more importantly store the high intensity beams at 7 TeV. The longitudinal emittance is increased by controlled blow up to 2.5 eVs to keep the bunch length approximately constant (see Table 1). Fig. 4 shows the approximate bunch length as a function of emittance for LHC injection and for 4.0 TeV run in 2013 and 6.5 TeV run in 2015. A 6 MV capture voltage and 12 MV at flattop was used in 2013. A similar voltage program is likely to be used in the 2015 run [14].

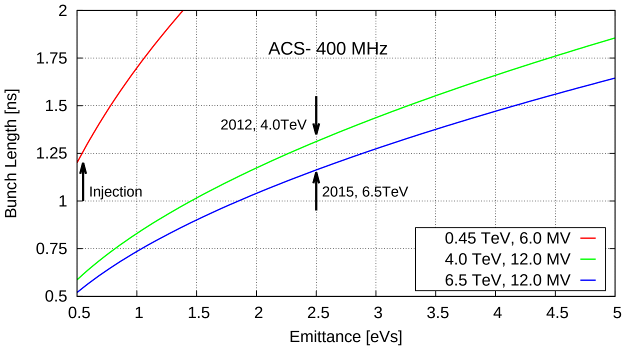


Figure 4: Bunch length vs emittance for injection and flattop voltages in the ACS-400 MHz system.

The primary limitation in the operation of the ACS-400 MHz system comes from the installed and available RF power. Due to the uneven filling scheme, the voltage vector is strongly modulated. The present scheme employs a $\frac{1}{2}$-detuning scheme [15]. In this scheme, the cavity detuning is set to value where the RF power required is equal in the segments with and without beam and only the sign of the klystron phase is flipped. Therefore, the required peak power and bucket spacing is kept constant. The present RF power chain (Klystrons, circulators, loads and RF power coupler) are all limited to approximately 300 kW-CW. To provide a 20% margin for operations, the klystron power is further limited to 250 kW. Fig. 5 shows the power requirements as a function of Q$_L$ for nominal and HL-LHC beam parameters assuming the present $\frac{1}{2}$-detuning scheme.

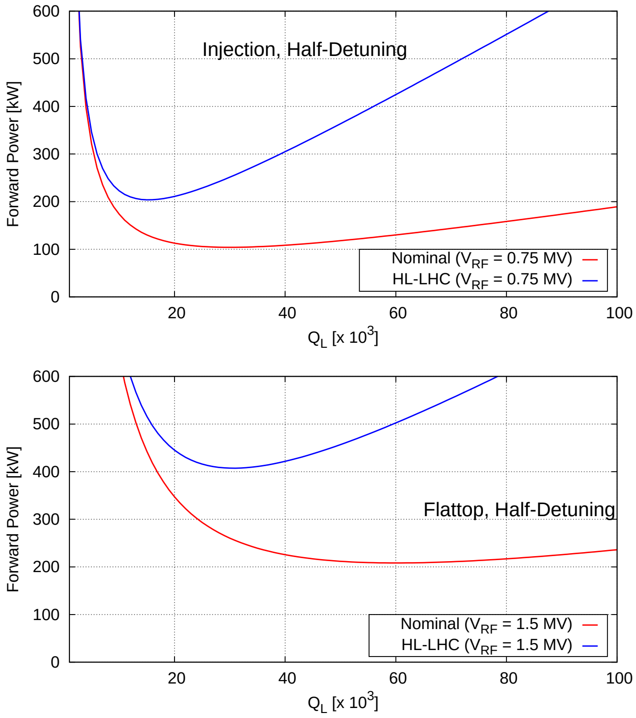


Figure 5: Forward power at injection (top) and flattop (bottom) required in the ACS-400 MHz system operated in the $\frac{1}{2}$-detuning scheme for HL-LHC beam parameters and cavity voltage of 1.5 MV. The nominal LHC is plotted as comparison.

At injection with a total voltage of 6-8 MV, the HL-LHC beams are still compatible with the 300 kW limit. It is important to use the $\frac{1}{2}$-detuning scheme during beam injection to preserve the regular bucket spacing and minimize transfer losses between SPS and LHC. However, at flattop, the power is exceeded significantly even at a total voltage of 12 MV and much more for the nominal 16 MV.

The baseline solution to overcome the power limitation is to use the optimal detuning (AKA Full Detuning) as discussed in Ref. [16]. The consequence of the optimal cavity detuning (Δf=10 kHz for HL-LHC parameters) during the beam presence is the strong modulation of the RF phase by gaps in the beam. If one allows the inter-bunch distance to slide w.r.t each other, the forward power is minimized and becomes independent of the beam current. Fig. 6 shows the RF phase modulation over one full turn for a standard 25ns LHC filling scheme.

The required voltage for an optimal Q$_L$ $= 3.5 \times 10^4$ is 180 kW for a I$_B$ $= 1.1$A and a voltage V=12MV which is within the power capability of the present RF power chain. The power simply scales inversely with the Q$_L$ and can be further reduced if needed. In this scenario, the inter-bunch distance as seen in Fig. 6 changes by about 85 ps (or 25mm). However, due to the symmetric filling schemes in both rings, the luminosity is not effected. Only the collision time is modulated by 85 ps over the full turn which is quite small compared to nominal bunch spacing of 25ns.

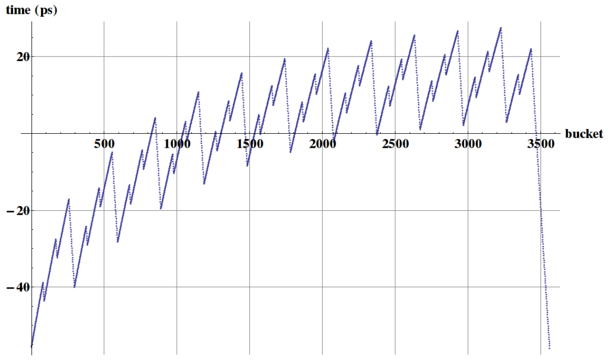


Figure 6: Phase modulation over one full turn with an optimal detuning and HL-LHC beam parameters (Courtesy P. Baudrenghien).

Potential Issues for HL-LHC

Operation of HL-LHC will begin approximately 15 yrs or more from the first start of the LHC nominal. This implies certain aging effects of the RF power systems and the cryomodule components. In particular, the power coupler operating at high power is susceptible to failures. Some statistics from past coupler experiences from LEP, SPS and other machines indicate first development of failures in the time span of 15yrs [17]. A replacement of a power coupler will imply a replacement of the module and lead to significant down time. The re-qualification of the complete module removed from the LHC and the preparation of a second spare is underway [18].

Possible New Strategy

The preparation of a second identical spare module will require a non-negligible time to recuperate or build four cavities, cold masses and cryomodule with all the required components including the power couplers [18]. It should be noted that 8-spare couplers are presently available [17].

It is however prudent, in the view of the future operation of HL-LHC, to embark on an upgrade of the ACS module (ACS-Gen II). The aim of the Gen II module would be to generate higher RF performance from a compact 2-cavity module (4 MV and 500 kW per cavity) as compared to the present system. A possible 2-cell extension with dual power couplers could also be considered in view of projects beyond HL-LHC. The two main advantages are:

- A more compact module with upgraded hardware with similar voltage reach, thereby giving higher modularity and improve spare policy.
- Significant reduction in static heat load (Table 4).

The Gen II module can become the second spare or possibly replace the existing modules with higher reliability in the future. As an alternative option, the Gen II module can be added to existing machine to recover the 1/2-detuning scheme if necessary by operating the present modules at reduced voltages. The Gen II module would mainly require a cryostat update for minimizing the static heat load and an update of the power coupler design to reach the 500 kW level. The klystrons, circulators and loads would also need to be updated to the 500 kW level. The cavity design could be identical to that of the present module with improved performance on Nb-coating.

HARMONIC RF SYSTEMS FOR HL-LHC

Two categories of harmonic RF systems are considered for HL-LHC but not presently in the baseline:

- A higher harmonic (800 MHz) for changing the bunch profile in bunch lengthening (BL) mode or change the synchrotron frequency distribution to improve the beam stability in BL or bunch shortening (BS) mode. Depending on the mode of operation, the RF system can be used to reduce the beam induced heating, effect of intra-beam scattering, improve longitudinal beam stability and in some scenarios help level the luminosity. The detailed overview and past studies can be found in Ref. [19].
- 2. A sub-harmonic (200 MHz) system can either completely replace the existing main RF system or work with the 400 MHz RF system. The main aim of a lower harmonic RF system is to improve the capture efficiency for longer and very high intensity bunches. The benefits of operating in conjunction with the exiting 400 MHz system are similar to that of the second harmonic system.

ACS-400 + 800 MHz

For the higher harmonic system, the maximum required voltage is 8 MV to maintain the ratio between the 400 MHz and the 800 MHz to 1/2. The key challenge in the operation of the harmonic system is to maintain the fixed phase w.r.t to the main RF system. The phase modulation of the main RF system over one full turn is 85 ps which implies a 25° modulation at 800 MHz. In the BL-mode the phase difference between the main RF system and the 2^{nd} harmonic has to be controlled to within 1-5° to ensure stability. In the BS-mode, the phase difference between the main RF and the 2^{nd} harmonic system is less critical [19].

A detailed cavity and HOM coupler design from the scaled 400 MHz ACS cavity was carried out [20]. A 300 kW maximum RF input power is assumed with fixed coupling. A possible 4-cavity configuration similar to the ACS module is shown in Fig. 7. The flange-to-flange longitudinal distance would be approximately 3.5m. A 2-cavity configuration would approximately be 15% longer, but will provide additional modularity, ease of maintenance and reduction in the number of spares.

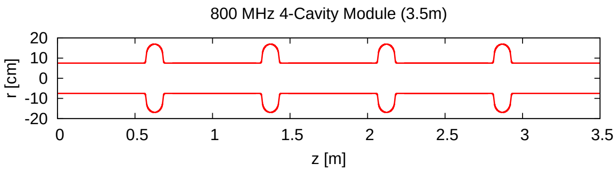


Figure 7: Four cavity configuration for 2^{nd} harmonic RF system in the LHC at 800 MHz.

During beam injection and energy ramp, the 2^{nd} harmonic system in the LHC, will present a large impedance. Parking the cavities in a detuned stage and passively damping them is not ideal. It is possible to use them with a reduced voltage in conjunction with the ACS-400 or possibly counter-phasing them. During injection, the ACS-400 MHz will be operated in the 1/2-detuning scheme for efficient transfer between the SPS and LHC.

The main RF will be moved to an optimal detuning with large phase swing before the energy ramp. The 800 MHz system has to strictly follow the phase swing in the 800 MHz cavities and this phase difference is much more constrained in the BL-mode [19]. The power requirements for the two modes of operation are calculated in detail in Ref. [21] and are summarized in Table 2.

Table 2: Power requirements in the 800 MHz with phase modulation.

Mode	V [MV]	Q_L	RF Power [kW]
BS-mode	1.6	10^5	80
BL-mode	1.0	10^4	260

In the BS-mode, the power required is significantly reduced by choosing an optimum ratio of the detuning between ACS-400 and the 800 MHz systems. Approximately 2-4 cavities are sufficient to provide the maximum 8 MV with ample margin in power capability. Note that in the BS-mode, the 1/2-detuning scheme could also be recovered using four 800 MHz cavities and operating the ACS-400 at a reduced voltage of 8 MV at flattop.

However, the power requirement in the BL-mode is significant and the voltage per cavity is reduced to 1 MV to stay within the 300 kW. Therefore, at least 8-10 cavities are required in the BL-mode to provide the 8 MV total voltage and therefore at least doubling the RF system. A more detailed analysis is required to quantify the exact number of cavities including realistic phase differences between the RF systems during the entire operational cycle of the LHC.

The benefit of generating flat longitudinal profile using the BL-mode can possibly be realized phase modulation close to f_s as shown in machine developments in LHC-RUN I [26]. Further machine development is required to robustly establish the procedure in operations over long fill time.

ACS-400 + 200 MHz

A normal conducting 200 MHz system was already planned as a capture system if the extracted emittance from the SPS becomes large [13]. The bunches are then transferred adiabatically to the ACS-400 prior to energy ramp. An superconducting system at 200 MHz with conventional elliptical cavities was discarded due to the physical size.

However, a new concept using $\lambda/4$ resonators at frequencies of 200 MHz or below become very attractive. A similar system was conceived at 56 MHz for the RHIC accelerator and presently under commissioning [23]. Fig. 8 shows a preliminary design of a such a 200 MHz $\lambda/4$ resonator compared to the e existing ACS-400 system.

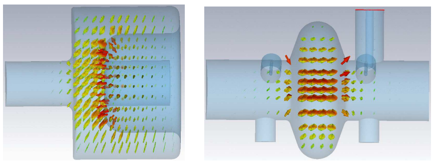


Figure 8: Preliminary design of a 200 MHz $\lambda/4$ resonator (left) for the LHC compared to the existing ACS-400 MHz system (right).

Table 3 shows some relevant RF parameters of the 200 MHz system compared to the existing ACS-400 system in the LHC. It is important to note that the $\lambda/4$-resonator is 20% smaller in transverse size as compared to the existing ACS-400 MHz system.

Table 3: Relevant cavity parameters for the 200 MHz compared to ACS-400.

Voltage	[MV]	2.0	2.0
Cavity Type		Co-axial	Ellipitcal
Frequency	[MHz]	200.3	400.7
Gap Length	[mm]	133.5	377.3
R/Q (circuit)	[Ω]	51	45
Aperture	[mm]	168	300
E_{pk}, B_{pk}	[MV/m, mT]	29, 68	12.5, 30
Cavity Envelope	[mm]	284	344

R&D to develop the 200 MHz $\lambda/4$ resonator is mandatory. However, advances on the HIE-ISOLDE Nb-Cu program have shown promising results to reach beyond the surface fields shown in Table 3 at Q_0 values exceeding 5×10^8 which is at least a factor 2 better than the ACS-400 cavity performance. Another significant advantage of $\lambda/4$ resonator is the large spacing between the accelerating mode and the higher order modes which makes the damping scheme simpler.

A detailed study both from electromagnetic simulations and beam stability is required to establish the path of using a 200 MHz system as a main RF system for which several advantages can be foreseen. The primary advantage is the ability to capture more intense (up to 2.5×1011) and longer bunches offering an alternative scenario for luminosity optimization and possible mitigation of the electron cloud effect [24]. With the SPS RF power upgrade and manipulations, it is shown in simulations to extract up to 2.4×10^{11} p/bunch [25]. Although, only a minimum of 3 MV is required to inject, ramp and store the LHC beams [19], 6 MV is assumed as a baseline. Fig. 9 shows the bunch length as a function of the longitudinal emittance injection and flattop in a single 200 MHz RF system.

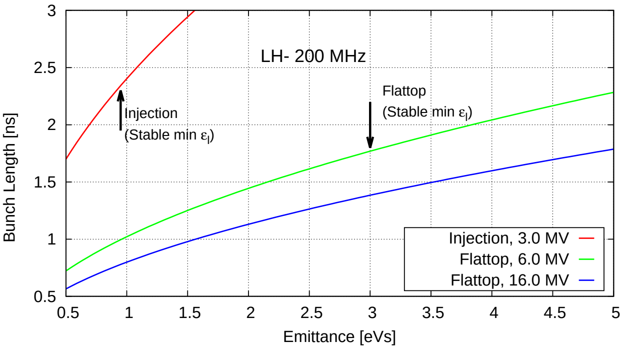


Figure 9: Bunch length vs emittance for injection and flattop voltages in the 200 MHz system.

A minimum stable injection emittance in the 200 MHz is estimated to be 1 eVs while at flattop is 3 eVs in the 200 MHz system alone [26]. It would be a natural choice to use the existing ACS-400 to achieve smaller bunch lengths ($\leq$ 1.5ns) and with a modest voltage requirement in both systems as opposed to using only 200 MHz RF system. In addition, the ACS-400 MHz system as a second harmonic could help provide stability with smaller emittances.

Fig.11 shows that with an optimized Q_L of approximately 2×10^4, the forward power in the 200 MHz system with 1/2-detuning scheme is 420 kW. Existing expertise from SPS and LHC can be used to develop a power coupler and the RF chain capable of handling power levels of 500 kW [17]. The Q_L is also compatible at injection energy and sufficiently low enough to act against injection transients. This allows for fixed coupling, thus greatly easing the design of the high power coupler. Commercial power sources at this frequency and power levels already exist in the form of diacrodes.

If the maximum voltage is limited to 6 MV in the 200 MHz system, four cavities will be sufficient. It is also possible to envision dual couplers per cavity to reduce longitudinal footprint if necessary. However, a proposed four cavity module is quite compact with a length of 3.5 m as shown in Fig. 11 and approximately 15% longer with x2 two cavity modules.

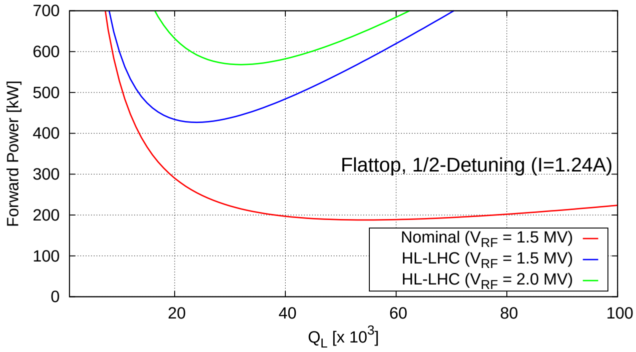


Figure 10: Forward RF power as a function of Q_L at flattop assuming I_b = 1.24 A for a 200 MHz RF system.

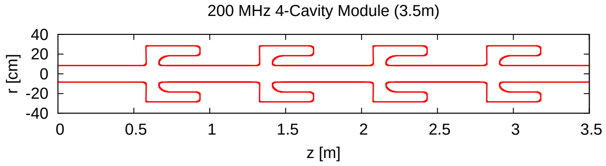


Figure 11: Four cavity configuration for the 200 MHz $\lambda/4$ resonator as the fundamental RF system for the LHC.

With this configuration, a maximum of only 3 MV in the 400 MHz is sufficient to provide the RF voltage at the 2^{nd} harmonic. This can be easily provided by a single existing 4-cavity module or possibly even with only two cavities. With the addition of the 2^{nd} harmonic, the bunch lengths can be brought down to approximately 1.35 ns in the BS-mode and well beyond 1.8 ns in the BL-mode depending on the maximum acceptable bunch length (luminous region) by the experiments.

HEAT LOADS

The heat loads for the existing ACS-400 MHz and the future RF systems in the LHC are estimated in Table 4. For the crab cavities, the heat load constraint is primarily in the SPS. The existing TCF20 plant has a maximum liquefaction capacity of 1.5 g/s with a LN_2 boost [27]. However, the total estimated heat load at 2K is 1.6 g/s ($\sim$ 30 W) and therefore not operationally practical. A new cryogenic plant was identified to increase the capacity to 2.1 g/s and is the installation is under study [27]. This new plant along with a buffer tank of 150 L gives sufficient capacity to handle higher heat loads and continued operation over 10h. For the LHC, assuming similar heat load at 2K, each IP with 8 modules (16 cavities) would account of 0.48 kW.

For the longitudinal RF systems, the static heat load of the existing ACS-system exceeds 60 W at 4.5 K per cavity. A new Gen II module will aim to reduce this heat load by at least a factor 2-3 with improved cryostat design. For the 800 MHz harmonic system, the dynamic heat load at 4.5 K is quite low due to the low voltage (1 MV) per cavity. At 2 MV, the heat load can reach 60 W mainly due to the BCS resistance. Therefore, it might be beneficial to operate at 2 K. The exact heat loads for the higher and lower harmonic systems will have to be determined after a detailed cryomodule design is prepared.

CONCLUSIONS

A brief outline of the RF systems in the HL-LHC era and their performance limitations were presented. For the crab cavities, the hardware and infrastructure preparation towards the SPS tests are in an advanced state. The main challenge comes from the simultaneous installation activities all concentrated during the long shutdown prior to the 2017 run.

The longitudinal RF system choices for HL-LHC can be summarized as follows:

- Option I, ACS-400 MHz: A full detuning scheme as outlined by Ref. [16] will be sufficient to ramp and store the HL-LHC beams and overcome the present RF power bottleneck. However, the consequence of phase modulation of up to 85 ps over a full LHC turn is inevitable. A new proposal to develop a Gen II module will provide added flexibility and lifetime in a more compact footprint than the present ACS module. It could in addition recuperate the 1/2-detuning scheme acting along with the present system.
- Option II, ACS-400 + 2^{nd} harmonic 800 MHz: The higher harmonic in the BS-mode appears feasible with 4-cavities operating at 1 MV each with fixed coupling. They could both provide stability margin and possibly restore 1/2-detuning. In the BL-mode the system is at least twice as large with tight constraints on phase errors and potentially needing a variable coupler operating at 300 kW.
- Option III, 200 MHz + 2^{nd} harmonic with ACS-400: This option can be realized with compact $\lambda/4$ resonators which will require some R&D to establish the technology. However, the benefits by pursuing the path of longer bunches (1.3-2 ns) both for luminosity and e-cloud mitigation is promising [24]. The technology could potentially be used to alleviate bottlenecks in the SPS.

ACKNOWLEDGMENTS

The author would like to thank all the members of LHC-CC collaboration for valuable contributions and discussions. The author would also like to extend a special thanks to T. Argyropoulos, P. Baudrenghien, O. Brunner, O. Capatina, E. Jensen, A. Machpherson, P. Maesen, E. Montesinos, J.E. Mueller, K. Schrimm, E. Shaposhnikova and EN-MME for valuable discussions and suggestions.

Table 4: Estimated static and dynamic heat loads for the different RF systems foreseen in the LHC.

	Crab Cavities	ACS- 400 MHz	HH- 800 MHz	LH- 200 MHz
Temperature	2K	4.5 K		
Voltage [MV]	3.4	2.0	1.0	1.5
Static Load [W]	8	$\approx$50	10	10
Dynamic Cavity [W]	3	25	15	5
Dynamic Other [W]	4	$\approx$10		
Total/4-cavities [W]	60	340	140	100

REFERENCES

[1] Parameter Layout Committee, 2014.

[2] A. Citron et al., The Karlsruhe-CERN superconducting RF separator, NIM v.164 (1), 1979.

[3] G. Arduini et al., Summary of the LHC-CC11 workshop, CERN-ATS-2012-055, 2013.

[4] Crab cavity technical coordination.

[5] S. De Silva et al., in the proceedings of IPAC13, Shanghai, 2013; B. Hall et al., in the proceedings of IPAC12, New Orleans, 2012; G. Burt et al., in the proceedings of IPAC13, Shanghai, 2013; R. Calaga et al., in the proceedings of IPAC13, Shanghai, 2013; Q. Wu et al., in the proceedings of IPAC13, Shanghai, 2013.

[6] A. Yamamoto et al.,Report of the HiLumi-LHC/LARP C rab Cavity System External Review Committee, CERN-ACC-2014-0093, 2014.

[7] G. Apollinari, A. Ratti, *Private communication*.

[8] G. Burt et al., Preliminary Design Report - WP4, ... 2014.

[9] K. Artoos et al., Crab cavity tuning system,

[10] S. Pattalwar et al., Key Design features of the Crab-Cavity cryomodule for HI-LUMI LHC, in the proceedings of IPAC14, Dresden, 2014.

[11] L. Rossi, presented at the IEFC meeting 121, 2014.

[12] S. Fartoukh, “Pile up management at the High Luminosity LHC and introduction to the crab-kissing concept”, CERN-ACC-2014-0076 (2014).

[13] D. Bousard, T. Linnecar, LHC-Project Report 316, 1999.

[14] P. Baudrenghien, proceedings of the Evian Workshop, 2014.

[15] D. Boussard, CERN SL/91-16 (RFS), 1991.

[16] P. Baudrenghien et al., Proposal for an RF Roadmap Towards Ultimate Intensity in the LHC, IPAC12, New Orleans, 2012.

[17] E. Montesinos, *Private communication*.

[18] K. .M. Schrimm, *Private communication*.

[19] E. Shaposhnikova, E. Mueller, presented at the 4^{th} HiLumi collaboration meeting, KEK, 2014.

[20] L. Ficcadenti et al., 2^{nd} HILUMI workshop, Frascati, 2012; T. Roggen *Private communication*.

[21] P. Baudrenghien, 2^{nd} WP4 higher harmonic meeting, CERN, 2013.

[22] J. Mueller et al., CERN-ACC-NOTE-2014-0011.

[23] I. Ben-Zvi et al., QWR for $\beta \sim 1$ Accelerators, SRF2011, Chicago, 2011.

[24] R. Tomas, Alternative scenarios, proceedings of the Chamonix 2014.

[25] T. Argyropoulos et al., proceedings of the Chamonix 2014.

[26] J. E. Mueller, *Private communication*; To be presented at the 4^{th} Joint HiLumi LARP meeting, KEK, 2014.

[27] K. Brodzinski, presented at the LHC-CC13 workshop, CERN, 2013.

Proceedings of Chamonix 2014 Workshop on LHC Performance

HL-LHC ALTERNATIVES SCENARIOS

R. Tomás, G. Arduini, D. Banfi, J. Barranco, H. Bartosik, O. Brüning, R. Calaga, O. Dominguez,
H. Damerau, S. Fartoukh, S. Hancock, G. Iadarola, R. de Maria, E. Métral, T. Pieloni, G. Rumolo,
B. Salvant, E. Shaposhnikova and S. White, CERN, Geneva, Switzerland

Abstract

The HL-LHC parameters assume unexplored regimes for hadron colliders in various aspects of accelerator beam dynamics and technology. This paper reviews the possible alternatives that could potentially improve the HL-LHC baseline performance or lower the risks assumed by the project. The alternatives under consideration range between using flat beams at the IP, compensate the long-range beam-beam encounters with wires and adding new RF cavities with larger or lower frequencies with respect to the existing RF system.

ALTERNATIVES TO BASELINE

The HL-LHC project aims at achieving unprecedented peak luminosity and event pile-up per crossing by reducing the IP beta functions, increasing the bunch population and providing crab collisions with crab cavities. In the following three failure scenarios that could limit the HL-LHC performance are listed together with possible alternatives to the baseline HL-LHC configuration in order to still reach a reasonable performance.

Longitudinal Multi-Bunch Instabilities Appearing

These might be mitigated in a double RF operation either with 800 MHz RF system as a higher harmonic or for longer bunches with 200 MHz RF system as a main system [1] (the LHC 400 MHz system remains taking the function of a higher harmonic RF). In both cases the RF systems should be operated in bunch shortening mode as this has been experimentally demonstrated to be the robust approach in the SPS. This is in conflict with using the 800 MHz system for bunch flattening for peak pile-up density mitigation.

Electron Cloud Producing too Large Heat-load

This might be mitigated by using the 8b+4e filling scheme [2] or longer bunches with an 200 MHz main RF system. The 8b+4e scheme provides larger bunch charge with about 30% fewer bunches. The 200 MHz system might allow to provide bunches as long as 20 cm. Both options show a suppression of electron-cloud in the dipoles in simulations throughout the LHC cycle.

Crab Cavities Demonstrating not Operational for Hadrons

SPS tests, machine protection issues, crab cavity impedance, or emittance growth due to RF phase noise might eventually suggest that crab cavities cannot be operated in the HL-LHC. In this scenario it is mandatory to resort to flat optics at the IP. Magnetic or electromagnetic wires [3] might be placed near the separation dipoles in order to compensate for the long-range interactions allowing for a reduction of the crossing angle and therefore increasing the luminous region. A 200 MHz RF system might also help if it allows to increase the bunch intensity. This is expected for single bunch limitations, however multi-bunch instabilities might dominate the intensity reach. The latter limit is unknown and hence bunch intensity is assumed to be the same as for the baseline in the 200 MHz scenario.

ALTERNATIVES FOR PERFORMANCE

Another set of alternatives to the HL-LHC baseline configuration offer a better luminosity quality by reducing the pile-up density. It has been proposed that lowering the pile-up density might allow for a larger total pile-up and therefore larger luminosity. Three alternatives in this direction follow:

Peak Pile-up Density Leveling with β^*

This alternative does not require any extra hardware and only slows down the baseline β^* leveling to ensure a peak pile-up density below certain value. Since in the baseline the largest peak pile-up is reached for a short time at the end of the β^* leveling process it is possible to reduce this largest peak pile-up with little or negligible impact in the integrated luminosity [4].

Longitudinal Bunch Profile Flattening

A higher harmonic RF system might be used to lengthen and flatten the longitudinal bunch profile, however it has been remarked that this operational mode is not robust and demonstrated impractical in the SPS. Instead, RF phase modulation has already demonstrated to slightly flatten the longitudinal bunch profile [5] in the LHC. Further studies of this promising technique are required to assess its potential for the HL-LHC. Combining this last option with peak pile-up leveling with β^* offers the lowest possible peak pile-up without significant impact on performance and without any hardware modification to the current baseline.

Crab Kissing

Crab kissing [6, 7, 8] can be realized in various ways. The initial proposal uses flat bunches, a magnetic or electromagnetic wire to reduce the crossing angle (to lower the crab cavity voltage) and crab cavities in the separation plane to maximize the luminous region. The compensating wire might not be needed if each crab cavity achieves 5 MV. The possibility of doing crab kissing in the crossing plane has also been explored.

MERITS AND PERFORMANCE

In the following sections the various alternatives are compared in terms of their merits, integrated luminosity, length of the optimum physics fill, peak pile-up density (μ_{peak}) and beam-beam tuneshift ($\xi_{x,y}$). These are calculated via simulations of the physics fill evolution. The estimate of the integrated luminosity requires determining the luminosity evolution during a fill. The beam intensity evolution has been evaluated taking into account the burn-off due to luminosity considering a total cross-section of 100 mb. The emittance evolution has been determined including Intra-Beam Scattering (IBS) with a coupling of 10% and Synchrotron Radiation (SR) damping. The bunch charge and emittances are updated every 10 minutes according to the current luminosity burn-off, IBS growth rates and SR damping. The bunch length is either kept constant assuming the use of longitudinal emittance blow-up techniques or purposely reduced by increasing RF voltage and/or letting SR damp the longitudinal emittance.

The overlap luminosity integral including the crab cavity RF curvature is derived from [9] by adding the hour-glass effect. The peak pile-up density is evaluated as the density of physics events exactly at the IP (s=0).

The effect of the RF curvature on the beam-beam tuneshift is only considered for the 200 MHz cases, where bunch length is assumed to be about 15 cm.

The yearly integrated performance is computed assuming 160 days dedicated to proton physics (including the turn-around time of 3 hours) with a 50% efficiency at and energy of 6.5 TeV. Efficiency is defined as:

$$N_{fills}\frac{T_{physics}+T_{turn-around}}{T_{run}}$$

where N_{fills} is the number of fills leading to physics, $T_{physics}+T_{turn-around}$ is the sum of the time in physics and the time needed to come back to physics and T_{run} is 160 days. All the fills are assumed to have the same length. This could correspond to the optimum fill length or to 6 hours. Both cases are presented in the following to assess the sensitivity to the fill length. Further details on beam parameters can be found at [10].

8b+4e Filling Scheme

The 8b+4e filling scheme has shown to strongly suppress electron cloud in the LHC dipoles for having fewer bunches but with larger bunch charge [4]. A brief description of the generation of this filling scheme in the injectors follows. Up to seven bunches are injected with two transfers from the PSB into h=7-buckets in the PS and accelerated to an intermediate flat-top at a kinetic energy of 2.5 GeV. Instead of the usual triple splitting RF manipulation involving RF systems at harmonics h=7, 14 and 21, a direct splitting from h=7 to h=21 in counter-phase results in pairs of bunches at h=21 with empty buckets in between. These bunch pairs are then accelerated in the PS to the flat-top energy on h=21 where each bunch is subsequently split in four as with the nominal production scheme for 25 ns bunch spacing. The PS circumference is thus filled with up to 7 batches of eight bunches spaced 25 ns with gaps of 120 ns between them. These gaps are short enough for the PS ejection kicker to trigger, so that in total 56 bunches with a pattern of 6×(8b+4e)+8b are transferred to the the SPS. It is worth noting that replacing the triple splitting by the direct double splitting in the PS should result in up to 50% higher intensity per bunch at first sight. However, due to longitudinal stability and beam loading considerations in the SPS, the intensity per bunch deliverable to the LHC injection is expected to be about 2.3×10^{11} ppb.

First experimental demonstrations of the 8b+4e filling scheme have already been conducted in the PS, see Fig. 1.

The 8b+4e filling scheme performance is compared to the HL-LHC baseline in Fig. 2. The lower number of bunches of the 8b+4e scheme implies a lower peak luminosity at the same number of pile-up events per crossing (μ). Thanks to the larger bunch population and lower emittances the yearly integrated luminosity is only reduced by about 24%.

200 MHz as Main RF

Electron cloud is most critical at injection for emittance dilution (due to the lower beam rigidity) and during the ramp for the total heat deposition in the beam screens (due to the extra sources of heat load). The 200 MHz system offers the possibility of using extremely long bunches (up to 20 cm) at injection and during the ramp. Once at flattop the bunch length could be explored to find a balance between electron cloud effects and luminosity production.

Figures 3 and 4 show the heat load at injection in the dipoles and in the quadrupoles versus Secondary Emission Yield (SEY) and for different bunch lengths. From the 2012 experience it is expected that a SEY between 1.4 and 1.5 or even lower is at reach already in 2015. In this SEY window a 19 cm bunch length would almost totally suppress electron cloud effects in the dipoles. In the quadrupoles the heat load for the baseline parameters is considerably smaller and the dependence with bunch length is very weak. An interesting observation is that heat load increases for long bunches at very low values of SEY between 1.2 and 1.3.

Figures 5 and 6 show the heat load at 7 TeV in the dipoles and in the quadrupoles versus SEY and for different bunch

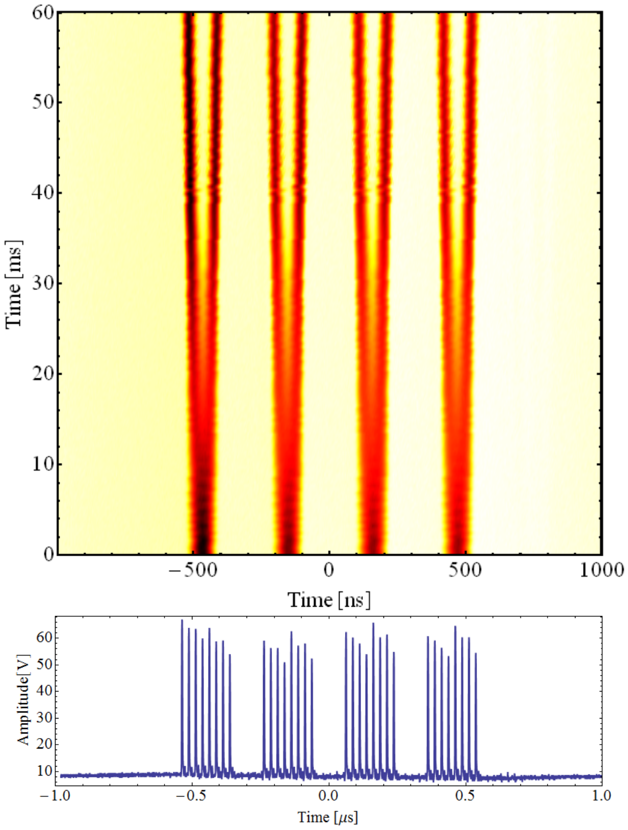


Figure 1: Proof-of-principle for the 8b+4e production scheme in the PS. Direct splitting of four bunches from h=7 to h=21 at E_{kin} = 2.5 GeV (upper plot), leaving an empty bucket between each pair of bunches. The subsequent splittings on the flat-top yield batches of 8 bunches spaced by 4 empty buckets at PS extraction (lower plot).

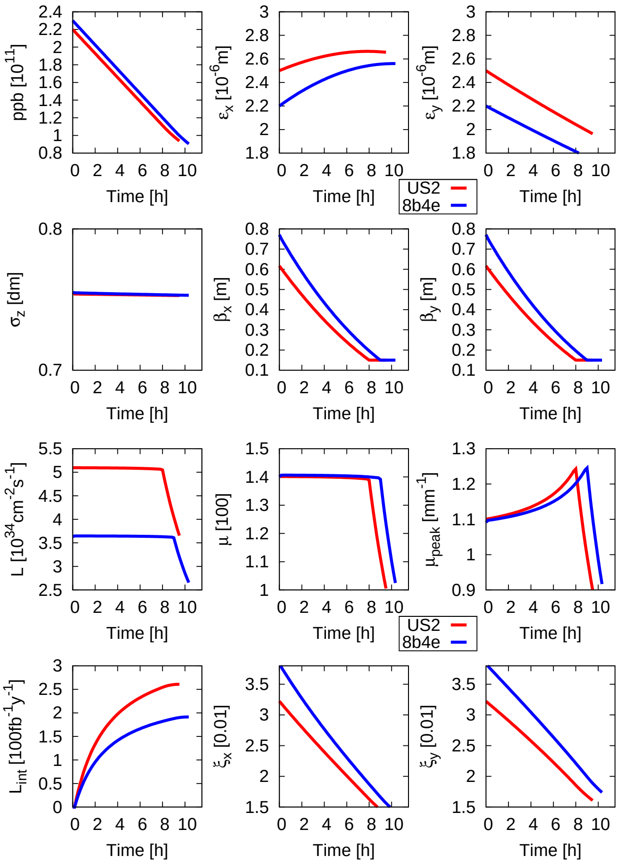


Figure 2: Performance comparison of the HL-LHC baseline (red) to the alternative 8b+4e filling scheme (blue). A reduction on the integrated luminosity of about 24% is observed in the 8b+4e scenario.

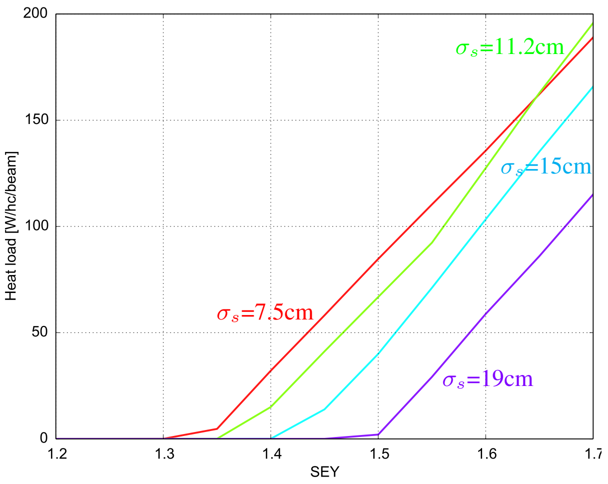


Figure 3: Heat load per half cell and per aperture at injection induced by electron cloud in dipoles versus SEY for 4 different bunch lengths.

lengths. The electron cloud heat load at 7 TeV is almost identical to injection. The only significant difference is that at a SEY of 1.4 short bunches are more favorable in the quadrupoles. This might suggest that at top energy there might be an optimal bunch length below 20 cm that minimizes total electron cloud heat load.

The following operational scenario is therefore conceivable. Electron cloud effects render impractical the injection of the full beam with baseline parameters, while 19 cm long bunches generated with a 200 MHz main RF system strongly mitigate heat load and allow injection and ramp. At top energy an optimal bunch length is established considering luminosity performance and heat load. For practical reasons and to be conservative with performance, a bunch length of 15 cm at top energy is assumed in the simulations. Figure 7 compares the HL-LHC baseline fill evolution to the 200 MHz alternative.

The main limitation arising from the lower RF frequency is a reduction of the TMCI threshold. The LHC impedance is dominated by collimators and one can assume the TMCI threshold to be driven by the tune shift of the mode 0. In this case it is possible to analytically estimate the maximum

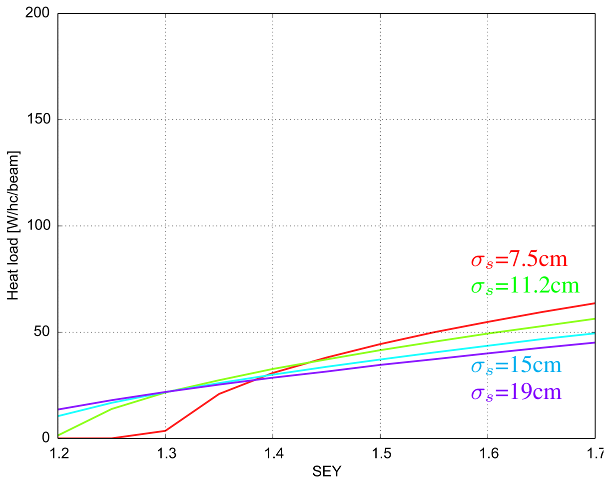


Figure 4: Heat load per half cell and per aperture at injection induced by electron cloud in quadrupoles versus SEY for 4 different bunch lengths.

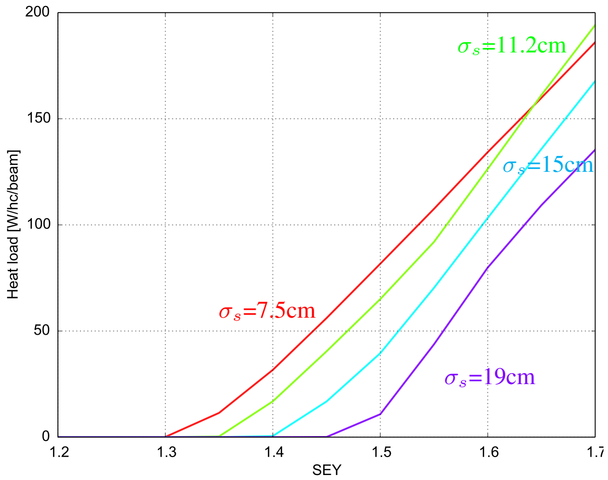


Figure 5: Heat load per half cell and per aperture at top energy induced by electron cloud in dipoles versus SEY for 4 different bunch lengths.

effective impedance by [11]

$$\Im {Z_y^{eff}}_{max} = \frac{4\pi(E_t/e)\tau_b Q_s}{N_b e \beta_y^{av}} \qquad (1)$$

where E_t is the beam energy, τ_b is the bunch length in seconds, Q_s is the synchrotron tune, N_b is the bunch population and β_y^{av} is the average β-function. The TMCI threshold is therefore proportional to the bunch length and the synchrotron tune. Using a bunch length of 12.6 cm and $Q_s = 9 \times 10^{-4}$ for the 200 MHz scenario the relative reduction of the TMCI threshold is 1.36.

Figure 8 shows a simulation of the TMCI threshold at zero chromaticity for 200 MHz and 400 MHz main RF systems. The HL-LHC impedance model as presented in [12] is used in the eigenvalue solver code presented in [13] assuming Gaussian bunch densities. The degradation by

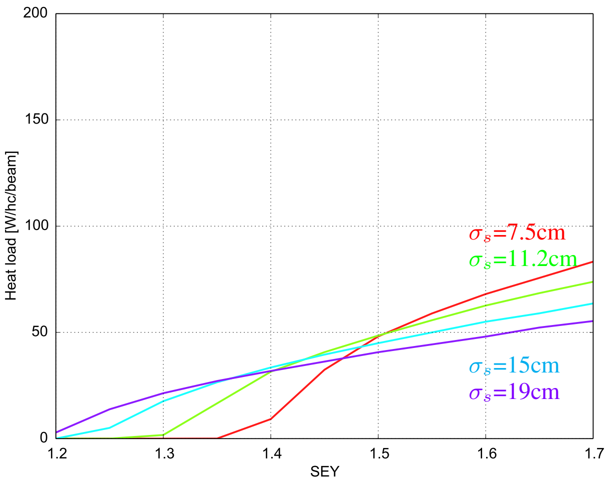


Figure 6: Heat load per half cell and per aperture at top energy induced by electron cloud in quadrupoles versus SEY for 4 different bunch lengths.

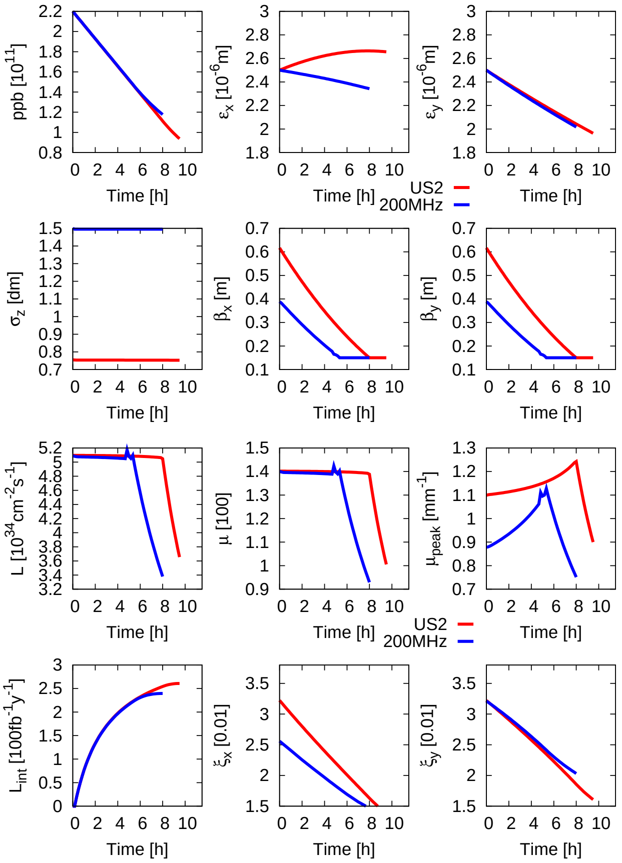


Figure 7: Performance comparison of the HL-LHC baseline (red) to the alternative of 200 MHz (blue) in order to suppress the electrons cloud effects. A bunch length of 15 cm is assumed during collision while at injection it could be as long as 20 cm. Performance is reduced only by about 7%.

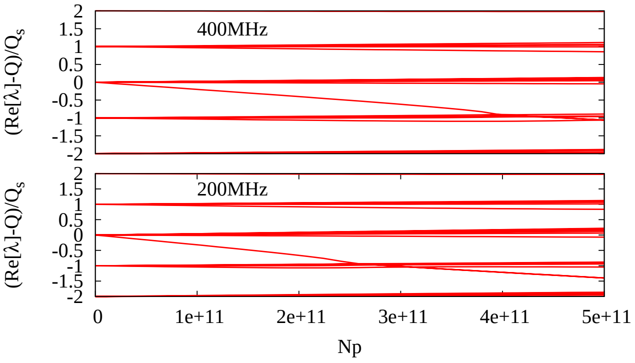


Figure 8: Comparison of the TMCI threshold at zero chromaticity between the design RF system (top) and the alternative at 200 MHz.

about a factor 1.5 is confirmed and the threshold is decreased to 2.6 × 10^{11} ppb which is above the foreseen operational bunch charge. It is possible that multi-bunch effects slightly decrease this threshold bringing the operational bunch charge below the target. This could be of some concern for beam stability but it has been shown that the use of transverse damper and chromaticity can increase intensity thresholds in various machines [14, 15, 16]. Note that for the LEP case, the same approach revealed almost no beneficial effect but it is thought to be caused by the large synchrotron tune [17].

Alternative materials for the HL-LHC collimators are also under consideration which could significantly reduce their contribution to the global impedance of the machine and hence increase the TMCI threshold.

Another concern of the 200 MHz system is its compatibility with 400 MHz crab cavities. An illustration of the beams encounter at the IP is depicted in Fig. 9 for the baseline and the 200 MHz alternative. The core of the beam (1 σ corresponding to the red area) is basically unaffected by the crab cavity RF curvature. A similar situation was studied when 800 MHz elliptical crab cavities and β^*= 25 cm were considered for the luminosity upgrade without finding any problem in Dynamic Aperture (DA) [9] or strong-strong [18] simulations.

Weak strong DA simulations have been performed for the new configuration of 200 MHz main RF and a crab cavity of 400 MHz. The strong bunch features a bunch length of σ_s=13 cm and is modeled with 19 slices transversely displaced according to Fig. 9. The particles in the weak bunch are tracked with 6 MV of 200 MHz and the local IR crab cavities. Again no degradation of DA is observed due to the RF curvature of the crab cavity, see Fig. 10. For reference, complete baseline DA studies can be found at [19].

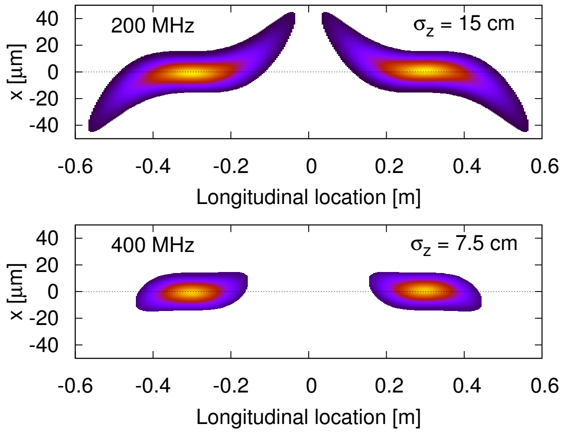


Figure 9: Illustration of the crab cavity RF curvature effect on the collision process for the nominal RF system (400 MHz) and the alternative of 200 MHz. The beams contours correspond to 2 σ envelope for a β^*= 15 cm.

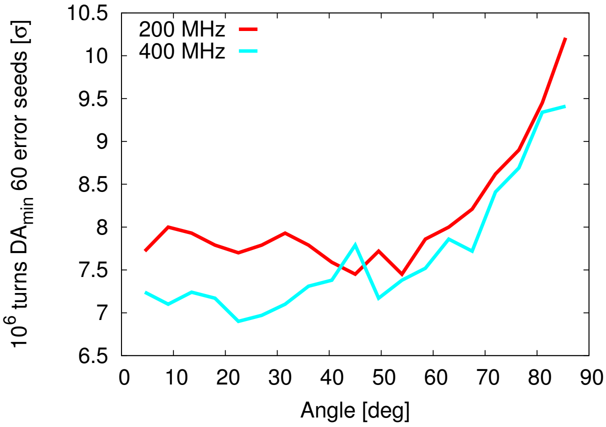


Figure 10: Dynamic aperture versus angle in the transverse plane including beam-beam interaction with the effect of the crab cavity RF curvature for the baseline HL-LHC scenario (cyan) and for the 200 MHz alternative (red). The initial momentum deviation follows the usual criteria of being at 2/3 of the RF bucket. The bunch charge is 1.1×10^{11} protons and β^* =15 cm corresponding to the last step of the β^* leveling.

Flat IP Optics and Beam-Beam Long-range Compensation

In the scenario that crab cavities turn out to be not operational in the HL-LHC it is mandatory to use flat IP optics to reduce the crossing angle and minimize the peak pile-up density. In [20] it is proposed to use $\beta^*_{x,sep}$=30,7.5 cm and a crossing angle of θ=320 μrad thanks to beam-beam long-range compensator devices. Figure 11, taken from [20], shows the feasibility of this proposal with dynamic aperture calculations. The usual criteria is that a dynamic aperture of at least 6σ is required for operation. In the case that beam-beam long-range compensators were not available the same study [20] suggests an operational configuration with the same IP beta functions and a slightly larger crossing angle θ=390 μrad, see Fig. 11. The feasibility of this crossing angle is also confirmed with more realistic

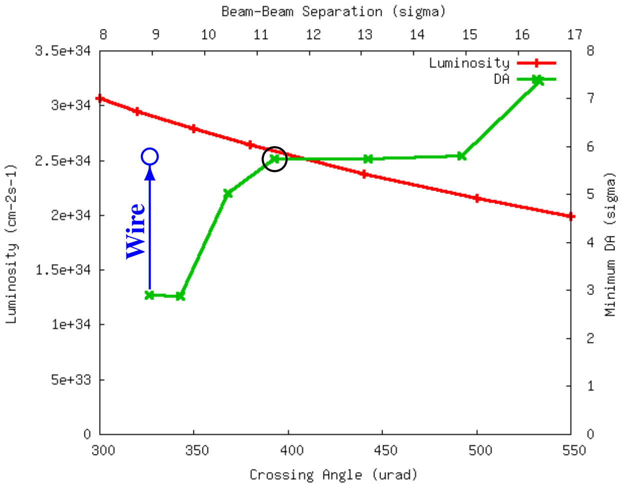


Figure 11: Dynamic aperture versus crossing angle for $\beta^*_{x,sep}$=30,7.5 cm, σ_z=10 cm, N=1.1×10^{11} ppb and including beam-beam interaction taken from [20]. Two operational conditions are highlighted with circles: using long-range compensator (blue) at θ =320 μrad and without long-range compensator (black) at θ =390 μrad.

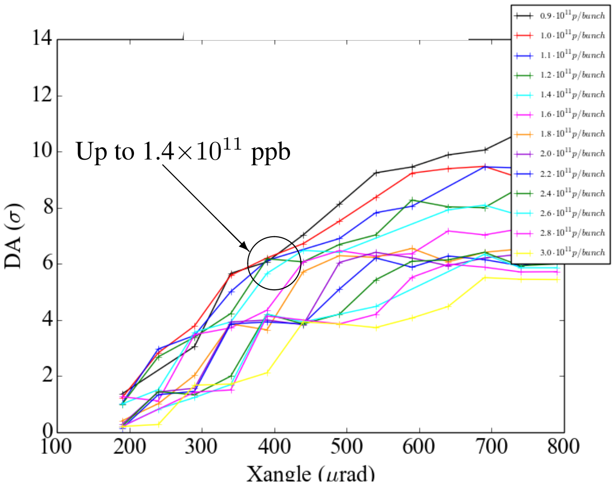


Figure 12: Dynamic aperture without long-range compensator versus crossing angle for $\beta^*_{x,sep}$=30,7.5 cm, σ_z=7.5 cm for various bunch intensities ranging between 0.9×10^{11} and 3×10^{11} ppb. The operational scenario highlighted with a circle at θ =390 μrad allows up to 1.4×10^{11} ppb.

simulations including the lattice errors [21, 22], see Fig. 12. Up to 1.4×10^{11} ppb are allowed with a crossing angle of θ =390 μrad for flat optics without long-range compensator. Intermediate optics and intensities during the β^* leveling process have also been verified to have a DA larger than or equal to 6σ.

Figure 13 compares the performance of the two scenarios considered above using flat optics, without crab cavities, with and without long-range compensator. The absence of crab cavities reduces the baseline performance by about 7% with a considerably larger peak pile-up density of 1.9 mm^{-1}. A wire can be used to reduce the crossing angle partially mitigating the large peak pile-up to 1.6 mm^{-1} but with similar performance.

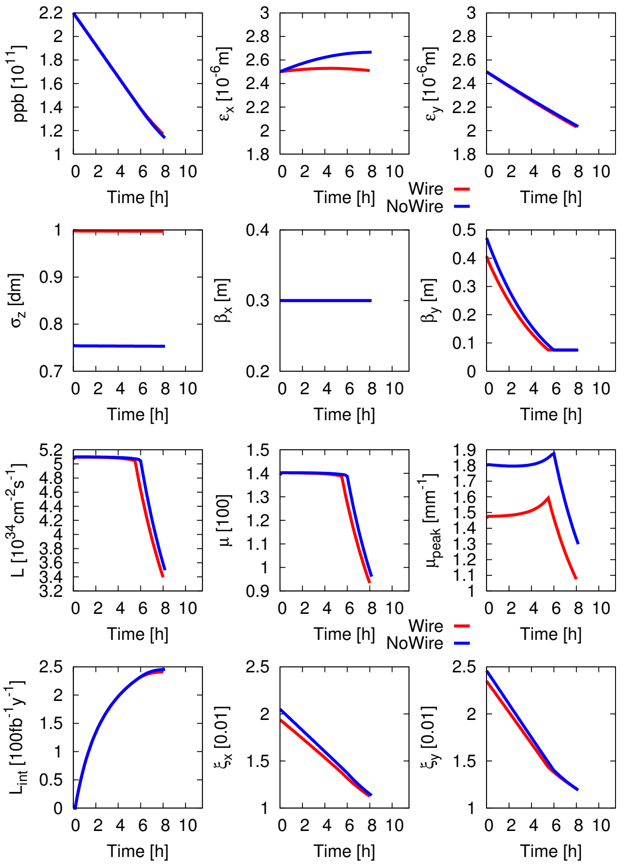


Figure 13: Performance for the scenarios without crab cavities as presented in Fig. 11 and 12 with and without beam-beam long-range compensator. Note that bunch lengths are different. Integrated luminosity is very similar while peak pile-up density is about 0.3 mm^{-1} larger in the absence of a long range compensator.

Larger Peak Luminosity

In [8, 23] the option of allowing for larger pile-up but with lower peak pile-up density thanks to crab kissing is proposed. The main goal is to reach at least 3000 fb^{-1} in ten years. For this a lower β^* of 0.1 m was also assumed.

This scenario of allowing for larger pile-up can also be considered in the framework of the HL-LHC baseline leveling luminosity at 7.5×10^{34}cm^{-2}s^{-1} and keeping the minimum β^*=0.15 m. As shown in Fig. 14 the integrated luminosity per year reaches 310 fb^{-1} with a peak pile-up density of 1.7 mm^{-1}. This large peak pile-up density can be mitigated without assuming any extra hardware, just slowing the reduction of β^*. Figure 14 shows that a peak pile-up density of 1.4 mm^{-1} can be achieved with this technique keeping the 300 fb^{-1} per year. It is estimated that crab kissing with flat longitudinal distributions and β^*=0.15 m

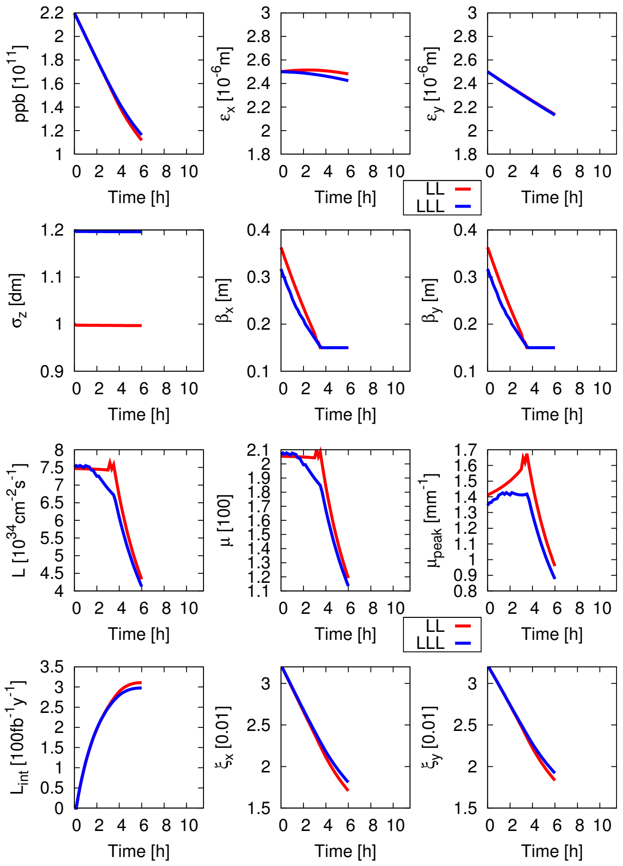


Figure 14: Performance for the baseline scenario with larger peak luminosity (LL) and another scenario where peak pile-up density is leveled with β^* (LLL).

	L_{int} [fb^{-1}]	Peak pile-up [mm^{-1}]
Larger Lumi.	310	1.7
Larger Lumi. leveled	300	1.4
Crab Kissing	300	1

Table 1: Scenarios with larger peak luminosity. Peak pile-up density is mitigated either with β^* leveling or with crab kissing.

should achieve similar performance with a significantly lower peak pile-up density of 1 mm^{-1}. Table 1 summarizes these 3 scenarios with larger peak luminosity.

SUMMARY AND OUTLOOK

We have shown that alternatives to the HL-LHC baseline exist to make the luminosity upgrade robust against foreseeable problems as e-cloud, non-operational crab cavities or too large peak pile-up density. Figure 15 summarizes the performance of all scenarios discussed in this work.

New promising alternatives have been proposed during this workshop, as the 80 bunch scheme [24]. New alternative scenarios are being discussed considering these new options and further optimized configurations [25].

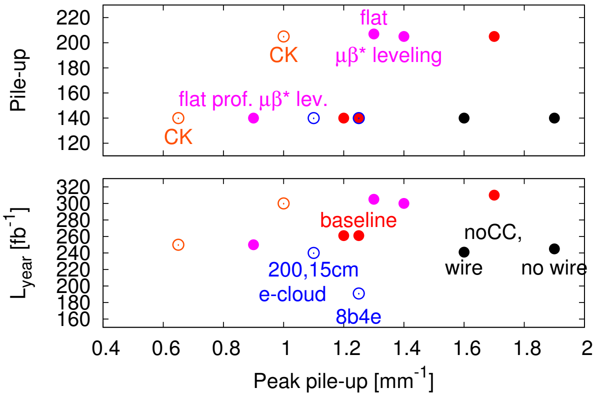


Figure 15: Summary chart showing pile-up (top) and integrated luminosity per year (bottom) versus peak pile-up density for the various scenarios considered in this work.

REFERENCES

[1] R. Calaga, "HL-LHC roadmap", LHC performance workshop, Chamonix 2014.

[2] H. Damerau, "LIU: Exploring alternative ideas", RLIUP, Archamps 2013.

[3] A. Valishev and G. Stancari, arXiv:1312.1660

[4] R. Tomas et al, "HL-LHC exploring alternative ideas", RLIUP, Archamps 2013.

[5] E. Shaposhnikova et al, "Flat bunches in the LHC", IPAC 2014.

[6] S. Fartoukh, "Pile up management at the high-luminosity LHC and introduction to the crab-kissing concept" Phys. Rev. ST Accel. Beams **17**, 111001.

[7] S. Fartoukh, "Pile-Up density management at HL-LHC and the crab-kissing scheme", HL-LHC brainstorming coordination meeting, July 2013.
http://indico.cern.ch/conferenceDisplay.py?confId=263083

[8] S. Fartoukh, "Pile up density at HL-LHC with new shaping and leveling techniques", ECFA High Luminosity LHC Experiment Workshop, 1-3 October 2013, Aix-Les-Bains, France (2103):
http://indico.cern.ch/conferenceDisplay.py?confId=252045

[9] Y. Sun, R. Assmann, J. Barranco, R. Tomas, T. Weiler, F. Zimmermann, R. Calaga and A. Morita, "Beam dynamics aspects of crab cavities in the CERN Large Hadron Collider" Phys. Rev. ST Accel. Beams **12**, 101002, 2009.

[10] G. Arduini et al, Beam Parameters at LHC injection, CERN-ACC-2014-0006.

[11] E. Métral F. Caspers, T. Kroyer, N. Mounet, F. Roncarolo, B. Salvant and B. Zotter, "Collimation-driven impedance", Collimation working group meeting,102nd meeting, 2009:
lhc-impedance.../LHCcollimation-driven-impedance.pdf

[12] N. Mounet, "Transverse impedance in the HL-LHC era", 3rd joint HiLumi LHC-LARP annual meeting, 2013:
https://espace.cern.ch/HiLumi/2013/SitePages/Home.aspx

[13] S. White, “Beam-beam and impedance”, ICFA Mini-Workshop on Beam-Beam Effects in Hadron Colliders (BB2013):
http://indico.cern.ch/conferenceDisplay.py?confId=189544

[14] M. Karliner, K. Popov, “Theory of a feedback to cure transverse mode coupling instability”, NIM-A, Volume **537**, Issue 3, 2005, Pages 481500.

[15] A. Burov, “Nested Head Tail Vlasov Solver”, AP Forum, December 2012.

[16] R. Nagaoka, “Transverse Feedback Systems at SOLEIL”, Low Emittance Rings 2010:
http://ler2010.web.cern.ch/ler2010/

[17] N. Mounet and E. Métral, “TLEP: effect of cavity impedance for operation at high current and low energy”, 4^{th} TLEP workshop, April 2013:
http://indico.cern.ch/event/240814/

[18] K. Ohmi, “Beambeam effect for collision with Large Piwinski angle scheme and high frequency crab cavity in LHC”, CAREHHH, LHC beambeam and beambeam compensation workshop, 2008:
http://indico.cern.ch/conferenceDisplay.py?confId=38353

[19] T. Pieloni, D. Banfi, J. Barranco, “Criteria for dynamic aperture limits and impact of the multipolar errors: summary of the simulations with beam-beam for levelling scenarios at 5 and 7.5×10^{34}”, 20th HiLumi WP2 Task Leader Meeting, October 2013:
https://indico.cern.ch/event/326148/session/21/contribution/40

[20] A. Valishev, S. Fartoukh and D. Shatilov, “BBLR compensation for HL-LHC” 3^{rd} Joint HiLumi LHC-22^{nd} LARP Collaboration Meeting, May 8, 2014.

[21] D. Banfi, J. Barranco, T. Pieloni, A. Valishev, “ Task 2.5: Beam-beam studies”, 20th HiLumi WP2 Task Leader Meeting, October 2013:
https://indico.cern.ch/event/278765/

[22] D. Banfi, J. Barranco, T. Pieloni, A. Valishev, “Beam-beam effects for round and flat optics: DA simulations”, Joint HiLumi LHC-LARP Annual Meeting 2014::
https://indico.cern.ch/event/326148/session/12/contribution/26

[23] L. Rossi, “How to implement all the HL-LHC upgrades (HL-LHC)”, RLIUP:
indico.cern.ch/event/260492/session/4/contribution/19

[24] H. Bartosik, “Other Means to increase the SPS 25 ns Performance - Transverse Plane” these proceedings:
https://indico.cern.ch/event/315665/session/5/contribution/23

[25] R. Tomás et al, “Alternative scenarions”, Joint HiLumi LHC-LARP Annual Meeting 2014:
https://indico.cern.ch/event/326148/session/9/contribution/20

COLLIMATION UPGRADES FOR HL-LHC

S. Redaelli, A. Bertarelli, R. Bruce, I. Efthymiopoulos, A. Lechner, J. Uythoven
CERN, Geneva, Switzerland

Abstract

The upgrade of the LHC collimation system is essential to handle the challenging parameters foreseen for the HL-LHC that aims at colliding beams of up to 700 MJ. Depending of the performance limitations of the LHC Run II at higher energy, we are preparing for a possible staged implementation of collimation upgrades starting already in the LHC long shutdown 2. In this paper, the main collimation upgrade studies are presented, recalling motivations and improved performance goals. The time line for collimation upgrades, synchronized with the LHC long shutdown planning, is discussed. Relevant machine protection aspects, including injection protection device upgrades in the LHC ring, are also discussed.

INTRODUCTION

The challenges of the High-Luminosity (HL) upgrade of the Large Hadron Collider (LHC) require improving various accelerator systems in order to handle higher stored energies up to about 700 MJ, smaller beam emittances down to 2.5 μm in collision and larger peak luminosities of $5{\times}10^{34}$cm^{-2}s^{-1} [1]. These challenging beam parameters, necessary to achieve the integrated luminosity goal of 3000 fb^{-1}, poses concerns for the beam collimation. The present system [2] was designed for 360 MJ stored beam energies and for beams with reduced damage potential. It is therefore important to plan adequate upgrades of the collimation system to ensure the success of HL-LHC.

Larger stored energies require better beam cleaning as well as an improvement of the collimator design, addressing aspects related to machine protection (MP). The single-bunch intensity is almost doubled compared to the design value of 1.15e11 protons and this poses concerns about beam stability from collimation impedance, as the collimator contribution dominates the LHC impedance budget at top energy. Last but not least, the update of the interaction region (IR) layout imposes a re-design of the collimation layouts, both in terms of cleaning and protection from incoming beams and collimation of physics debris.

The present upgrade baseline for collimation includes dispersion suppressor collimation in different insertions, achieved thanks to the new high-field 11 T dipoles, upgrade of the secondary collimators in the cleaning insertions for an improved robustness and a reduced impedance, better shielding of the magnets around the experiments and more efficient physics debris cleaning. New IR requirements impose also a re-design of the IR collimation and of the neutral particle absorber (TAN, whose upgraded version is referred to as TAXN), under the responsibility of HL-WP8, and of the injection protection systems in IR2 and IR8 that are studied by WP14. Other collimation upgrades not yet in the baseline include hollow electron lenses to improve beam collimation by providing an active control of beam halos. Other advanced techniques being studied include crystal collimation and new designs such as the jaws with embedded wires and the rotatable jaw concept.

In this paper the various collimator upgrade solutions that are presently being studied for the LHC upgrade are presented. The present upgrade strategy relies on detailed analysis of the Run I operational experience. After a review of upgrades that already took place in LS1, the planned upgrade works are described. The time line for collimation upgrades is also presented, including necessary steps for the required prototyping and beam validation phases. already in the second LHC long shutodown (LS2).

COLLIMATION ACTIVITIES IN LS1

Important upgrades of the collimation system have taken place already in the LHC long shutdown 1 (LS1). The main collimation activities are listed below (see [3] and references therein).

- The tertiary collimators in all experimental regions (16 devices) and the secondary collimators (2 devices) in the dump region have been replaced with new collimators with integrated beam position monitors (BPM).
- The layout of physics debris collimation has been upgraded around the high-luminosity experiments: 2 TCL collimators per beam have been added in cells 4 and 6 of IR1 and IR5 (8 new collimators).
- One passive absorber per beam in IR3 have been added to reduce doses on the warm quadrupoles in cell 5.
- An improved collimation vacuum layout has been deployed in IR8, where the 2-in-1 vertical collimators (TCTVB) have been replaced with single-beam collimators.

Consolidation activities of the system, such as the replacement of a primary collimator (TCP) in IR7 that showed over-heating during Run I [4] and the improvements of the control systems [5], also took place. The detailed analysis of performance improvements from the dif-

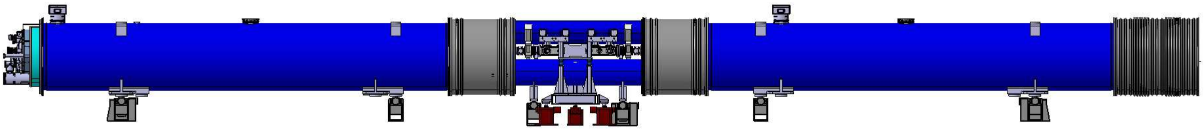


Figure 1: Layout of the unit based on new TCLD collimator and 11 T dipole that replaces a standard LHC dipole to provide local dispersion suppressor cleaning. *Courtesy of D. Duarte Ramos.*

ferent upgrades are reported in various collimation working group meetings [6] and are not reviewed in detail here.

It is noted that the new collimator design with integrated BPM for orbit measurements and faster beam-based alignment is considered as baseline for all future collimators to be produced.

COLLIMATION UPGRADE SOLUTIONS

Dispersion Suppressor Collimation

The present collimation system is not optimized to catch efficiently dispersive losses occurring in the dispersion suppressors (DSs) around collimation and experimental insertions. Particles experiencing diffractive interactions with collimator materials or with the opposing beam are lost in the cold DS magnets at the first high dispersion locations. The proposed solution to cure this problem is to install warm collimators close to high dispersion points. This can be achieved by replacing an existing LHC dipole with two higher-field 11 T dipoles, in order to free enough space to install a collimator. The 15 m long unit consisting of 2 new dipoles and 1 collimator is shown in Fig. 1. In IR7, two such units improve the cleaning performance by about a factor 10 according to tracking and energy deposition simulations [7, 8] and reduce losses around the ring for the HL-LHC optics baseline [9]. In IR2 for ion operation, the gain is larger than a factor 50 (as presented in [10]).

Our present strategy for DS collimation follows the recommendations of an international collimation project review organized in May 2013 [10]. According to the present understanding of extrapolations of quench limits and collimation losses to higher energy, and limited by the availability of 11 T dipole units, we plan to equip IR2 with one collimator per beam in LS2 to remove limitations during ion operation. Collimation losses around IR3 and IR7 during Run II are expected to be below quench limits, also thanks to larger margins than foreseen in the superconducting magnets [11]. Clearly, this conclusion will have to be confirmed by operational experience at higher energy.

For the HL-LHC era, two units per beam will definitely be installed around IR7. The need of DS collimation around IR1 and IR5 is expected for ion operation if ATLAS and CMS require the same luminosity as IR2. The optics in this IRs is however different than in IR2. Simulations are ongoing to verify the performance with and without TCLD collimators. Likely, DS collimation will not be needed for proton operation, also thanks to the physics debris collimation solution discussed below. All together, up to 10 collimators, i.e. 20 11 T dipoles, might be needed for installation in LS3.

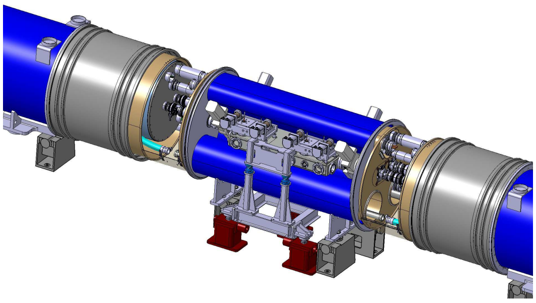


Figure 2: Preliminary layout of the TCLD integration in the by-pass cryostat between two 11 T dipoles. *Courtesy of D. Duarte Ramos.*

The collimator to be installed between 11 T dipoles (TCLD) demands a new design to fit in the tight space between cold magnets. The latest status of integration studies of the cryo by-pass and the TCLD collimator is shown in Fig. 2. The active jaw length of 80 cm initially foreseen is now being reviewed and might be slightly reduced in light of recent updated design of the cold-to-warm transitions (see presentations at the 2014 review of the 11 T dipole study [12]). The TCLD collimator will only have one motor per jaw and is based on conventional materials such as tungsten heavy alloys. We plan to start the construction of a prototype in 2015.

Low-impedance and High-robustness Collimators

The present estimates of LHC impedance indicate that the HL-LHC beams will not be stable unless the collimator impedance is significantly reduced [13]. This problem can be satisfactorily addressed by replacing the present secondary collimators made of Carbon-Fibre Composites (CFC) with a low-impedance design, as they are responsible for the largest contribution to the LHC impedance at top energy. Impedance reduction should not be achieved at the expenses of collimator robustness. The present baseline upgrade design is based on Molybdenum-Graphite (MoGR) composite, possibly coated with pure Mo. This is predicted to reduce to about 10 % the individual collimator contributions bringing the total collimation impedance within safe limits [13]. The option without coating might be used for higher-robustness tertiary collimators by gaining a factor up to 1000 compared to the tungsten heavy alloy. This change is beneficial for the β^* reach as it will al-

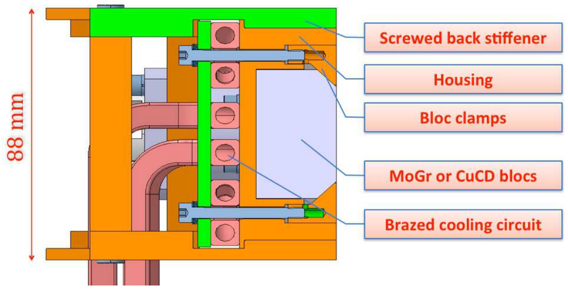


Figure 3: Cross section of the upgraded secondary collimator jaw. Inserts of different materals can be mounted without changing the jaw design. The present baseline relies on MoGR coated with pure Mo. Beam tests are planned at LHC and HiRadMat to confirm the material choice. *Courtesy of F. Carra for the MME team.*

low to reduce further protection margins between dumping system and tertiary collimators [14]. The impact on protection levels from the reduced Z of MoGR is being evaluated.

Production and installation of new secondary collimators must be done for HL-LHC but a partial installation can be envisaged already for LS2, depending on the limitations observed during the LHC Run II and the planned beam parameters for Run III. The jaw design of the new collimator is shown in Fig. 3. Inserts of different materials can be clamped against the cooling plates as shown in figure. This design will be validated by HiRadMat tests as described below. Simulations are ongoing to understand the cleaning performance and the radiation doses in IR7 with the new materials.

Note that the present CFC-based primary and secondary collimators are robust against full train injection failures with the nominal LHC parameters of 288 bunches of 1.15e11 protons with a 3.5 μm emittances. We are presently reviewing the equivalent scenarios for the HL-LHC injection case in order to understand if these collimators will also have to be changed in LS3.

HiRadMat Tests and Prototyping for HL-LHC

The beam-based validation of new collimator designs is crucial to ensure the compatibility with the extreme LHC beam conditions. In particular, the verification of the robustness against fast beam losses calls for a qualification with beam. The complexity of the simulations of full-jaw geometry in case of beam impacts, and the absence of detailed information of equations of state for novel materials, make it difficult to predict accurately the collimator response for the relevant failure cases. The HiRadMat facility at CERN provides a unique opportunity to perform such validations in a controlled way [15].

Two collimator tests were already successfully performed at HiRadMat in 2012 [16, 17] where material samples (see also Fig. 4) and a full tertiary collimator were tested against beam impacts equivalent to and beyond the expected LHC loss cases. Similar tests are now planned for the new designs. In particular, we proposed (1) an integral validation of the robustness of three complete jaws: the present CFC jaw with BPM's and two jaws based made of MoGR and Copper Carbon-Diamond (CuCD); this will be done with the apparatus in Fig. 5 that enables testing 3 jaws in a vertical setup in the same experiment, see 6; (2) the characterization of new material composites and the final grades foreseen for the LHC. Details of these collimation experiments were presented at a recent HiRadMat scientific board meeting [18].

The immediate goals these tests is to enable the finalization of the design of a low-impedance, high-robustness secondary collimator prototype that we would like to install in the LHC during the 2015 Christmas. Collimator slots and cabling have been prepared in LS1 for a quick installation. The needs of MD time to validate this new design are also

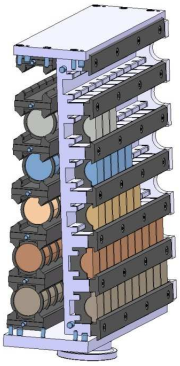


Figure 4: Sample holder housing up to 12 materials as build for the HRM-14 collimator material experiment [16]. *Courtesy of A. Bertarelli.*

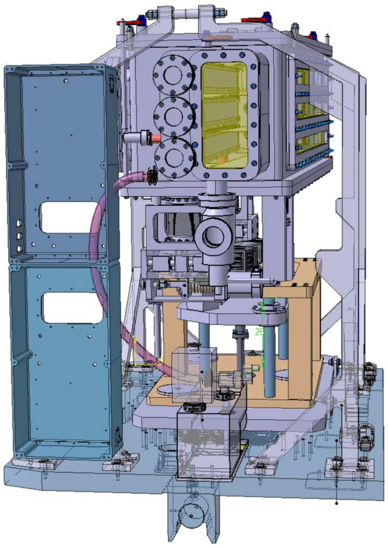


Figure 5: Design of the setup for the full jaw-test at HiRadMat in 2015, HRNT-23 experiment, featuring three jaws in a vertical setup for multiple designs tests. *Courtesy of L. Gentini.*

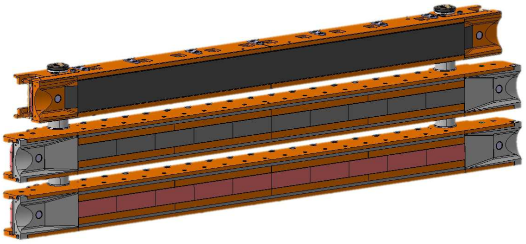


Figure 6: Present baseline for the full-jaw test at HiRadMat foresees to test a CFC jaw with integrated BPMs (top), a MoGR-base jaw (middle) and a CuCD jaw (bottom). *Courtesy of L. Gentini*.

discussed in [19].

Hollow e-lenses for Active Halo Control

Even if the present assumptions on quench limits at 7 TeV were confirmed and betatron losses were below, controlling operational beam loads on the collimation system would remain of paramount importance. For a perfect Gaussian transverse profiles, at HL-LHC beams some 2 MJ are found above 3 σ. Tail measurements performed so far with LHC beams [20, 21] actually indicate that tails might be significantly over populated, as also confirmed by the analysis of operational beam losses in 2012 [22].

A means to mitigate the problems of losses during standard operation, which already during Run I affected significantly the operation efficiency [23], is to actively control the beam halo diffusion and the tail population. This would mitigate transient loss spikes, e.g. from fast orbit jitters, and ease MP aspects of the operation of crab-cavities when fast failures become more critical in presence of overpopulated tails. Our baseline proposal for HL-LHC is to use hollow electron lenses for this purpose. Following a detailed conceptual design of LHC e-lenses [24], a preliminary design of a device for the LHC, which could be installed in point 4, was produced, see Fig. 7. If the present loss assumptions are confirmed, HL-LHC might need 1 electron lens per beam. In case of severe problems with losses, one could envisage a deployment already in LS2. Otherwise, the installation can be planned for LS3. We are presently evaluating the possibility to prototype this technique with LHC beams by installing one device in LS2.

Alternative methods of halo excitation are also being studies with higher priority, see for example recent discussion [25] and the MD plans for 2015. We expect that until 2016 enough operational experience should be accumulated to decide on the optimum strategy for active halo control at the LHC.

Crystal Collimation Studies

Crystal collimation is considered as a means to improve collimation cleaning by exploiting the coherent deflection of large-amplitude halo particles through the usage of high-purity bent crystals. The usage of less collimators than for the present system, achievable thanks to larger deflection angles that ideally require one single absorber instead of several secondary collimators, might also mitigate the collimation impedance issue. A test setup for crystal collimation studies has been installed in the LHC point 7 for prototyping beam tests with LHC beam conditions, see [26] and references therein. The scope of this first implementation in the LHC is to assess if improvements of collimation cleaning with respect to the present system are possible. This will be done with safe beam intensities only. If crystal collimation is proved successful, confirming at the LHC what has been concluded from SPS beam tests [26], this technique could be considered as an alternative to the DS collimation based on the 11 T dipoles. Note that crystals cannot be used to collimate the physics debris products around experiments because out-scattered protons are still within the main beam due to the small dispersion function in the matching sections.

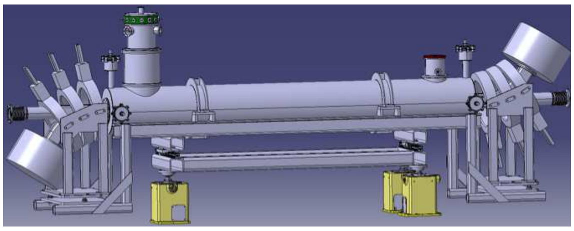


Figure 7: Present design of the LHC hollow e-lens for an integration in P4. *Courtesy of D. Perini*.

Other Ongoing Studies and Tests

Present works within the collimation project also address new advanced collimator designs for various purposes. Figure 8 shows, for example, the cross section of a jaw with an integrated wire for long-range beam-beam compensation (LRBBC) studies. Four collimators based on this design will be produced in 2015 and installed in IR1 and/or IR5 in the 2015-16 LHC shutdown, replacing existing collimators in these insertions. The wire embedded in the tungsten blocks of the jaws can be powered up to about 300 A. An MD program is foreseen [19] to benchmark the simulation tools that indicate that such a technique can be used to compensate the effect of the long-range interactions with the opposite beam. From the collimation project side, work is ongoing to demonstrate that the proposed design can replace without loss of performance the existing collimators, see for example [27]: collimators with wires shall replace devices that are needed for the LHC high-intensity operation so changes must be transparent. For the moment, no show-stoppers have been found in the proposed design.

In Dec. 2013, CERN received from SLAC a full-scale prototype of the rotatable collimator [28] that is based on a “consumable collimator jaw” concept. Two cylindrical jaws with 20 flat facets can be rotated in case of jaw damage from beam losses, offering a new collimating surface without need to replace the collimator as it would be re-

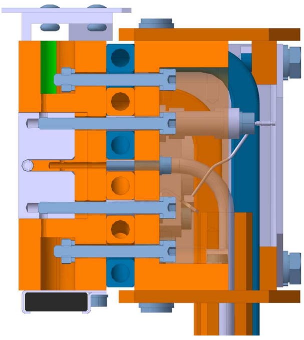


Figure 8: Cross-section of a tungsten-based collimator jaw integrating a wire for long-range beam-beam compensation (LRBBC) studies. Four collimators based on this design will be produced in 2015 and installed in the LHC, replacing existing TCT and TCL collimators, to test the LRBBC schemes in IR1 and IR5. *Courtesy of F.Carra*.

quired for the standard flat-jaw design. The validation of this design without beam has been completed. We plan to test this device in the SPS in 2015 to demonstrate that this design is suitable for operation with circulating beams. It is then planned to test it in the HiRadMat facility (see [18]) in order to demonstrate that the delicate rotation mechanisms continue working as designed after severe beam impacts that damage a facet.

COLLIMATION IN THE INTERACTION REGIONS

The ongoing collimation layout studies in the different IRs have recently been discussed at the 4$^{\text{th}}$ Annual HiLumi Meeting [29]. In particular, recent results on collimation layout studies are available in [30]. The present layouts in IR1/5 is shown in Fig. 9 [31].

Incoming Beam Collimation

The main roles of the incoming beam collimation are: (1) keeping all heat deposition into magnets well below their quench limits in standard operation; (2) protecting the relevant aperture restrictions in case of fast beam failures; (3) optimising the halo-driven background to experiments. For the present LHC layout, these roles are provided satisfactorily by a pair of tertiary collimators located in cell 4, at positions at nearly zero betatron phase difference upstream from the triplet magnets (i.e. located between the D2 and the TAN). This collimator will be maintained for HL-LHC at the same functional position, i.e. at a shifted longitudinal position compared to the present LHC, in order to be compatible with the overall layout changes of the magnetic elements. For the HL-LHC, standard aperture calculations show that potentially critical aperture bottlenecks could be introduced upstream of the triplet. Therefore, we foresee to install a additional pair of horizontal and vertical tertiary collimators in cell 5 in front of Q5. Detailed studies are ongoing to estimate the performance reach of the proposed layouts in case of standard operational losses and abnormal losses in case of failures [30].

Outgoing Beam Collimation

Collimation of the outgoing beams at the high-luminosity experiments is designed to keep the heat deposition into superconducting magnets of matching sections and of dispersion suppressors safely below quench limits, protecting them from the products of physics debris. Concentrating losses on the collimators also reduces the effect of total radiation doses to critical components.

The baseline layout for HL-LHC, inherited from the present LHC, is based on 3 horizontal physics debris absorbers placed in cells 4, 5 and 6 (3 movable collimators per beam per side of IR1 and IR5). The HL-LHC challenges require in addition up to 4 fixed masks on the IP-side of D2, Q4, Q5 and Q6. As can be seen from Fig. 9, the TCLs in cells 4 and 5 have been shifted longitudinally in the HL-LHC layout as a consequence of the general layout changes. We are presently working on the detailed design of the new collimators that might have to be changed compared to the present one, in particular in the region between the D2 and the TAN, in order to address some integration issues revealed by the first implementation in the present optics version and to simplify the design of the new TAN for HL-LHC (see below).

Injection Protection in IR2/IR8

The injection protection system protects the LHC elements in case of injection failures and specifically failures in time or amplitude of the injection kickers MKI. A schematic view of the key injection elements is shown in Fig. 10. The protection system consists of several absorbers which need to be upgraded following the HL-LHC requirements. The upgrade of the LHC injection absorbers is part of the HL work package 14 [32]. As the main changes in the injector chain, as part of the LIU project, are taking place in LS2, it is proposed to upgrade the LHC injection protection systems following the same timeline.

The main injection absorber taking most of the beam load in case of an MKI failure is the two-sided collimator TDI. It now consists of a single tank per IP and will be replaced by three individual, shorter modules called TDIS's. The jaw materials will need to be replaced. However, for the small BCMS beams under grazing impact, the survival of even the new TDIS absorber materials is not guaranteed [33]. The protection of the D1 will need to be achieved by either a reduction of the transverse aperture of the TCDD mask or a displacement of the TCDD closer to the D1. An alternative presently being studied is to install a mask directly around the beam pipe inside the D1 cryostat [34]. Simulations show that only little beam is to impact on the auxiliary collimators TCLIA and TCLIAB. However, the TCLIA in Point 2 will most likely need to be replaced because of aperture requirements of the ALICE ZDC.

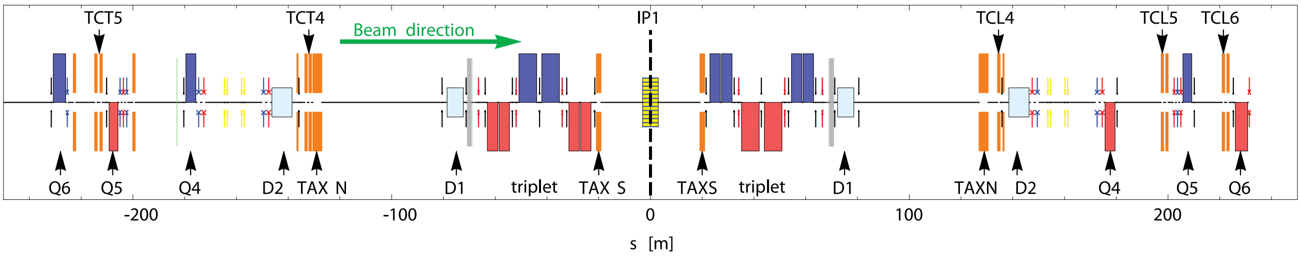


Figure 9: Collimation layout for incoming and outgoing beams in IR1. The IR5 layout is equivalent.

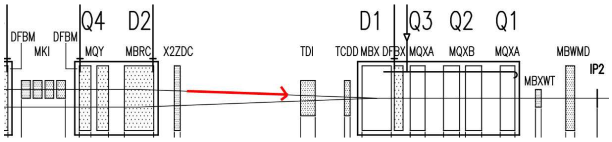


Figure 10: Schematic view of the LHC Point 2 showing the B1 injection region, the injection kickers MKI and absorbers TDI and TCDD. The auxiliary absorbers TCLIA and TCLIB are at the other side of the IP.

The spare TDI absorbers for Run II are equipped with interferometric measurement of the collimator gap. This new gap measurement is to be used as a redundant interlock by the Beam Energy Tracking System (BETS) [35]. In addition, the hBN absorber blocks will be coated with a few microns of copper to reduce the resistive heating. Vacuum and functional tests of the spares are presently ongoing. The plan is to install the spare TDIs in Point 2 and Point 8 during the short 2015/2016 shutdown. If the operation with beam of the interferometric gap measurement is successful, it will be applied for the series TDIS to be installed in LS2.

TAXN for HL-LHC

New beam neutral absorbers (TAXN) will be installed for HL-LHC operation around the high-luminosity experiments at IP1 and IP5. The new TAXN will follow the same design principles as the existing ones for LHC, however upgraded to meet the increased energy deposition and resulting radiation. The TAXN contains the transition from a single to twin vacuum pipes and is designed primarily to absorb the flux of forward high-energy neutral particles coming out from the interaction region. The aperture of the vacuum pipes will is designed to allow sufficient clearance for all beam optics. With respect to the existing TAN, the TAXN is moved by approximately 4m towards the IP following layouts changes foresee on HL-LHC [1].

Although in the present HL baseline scenario the beam optics for the high-luminosity areas is based on the crab cavities with the so called "round beam optics", alternative optics configurations with "flat optics", i.e. with unequal β^* values in the horizontal and vertical planes at the IP, are considered. The requirements for the TAXN aperture design to cope with round and flat options are quite distinct. For the round optics a larger crossing angle is envisaged that requires larger aperture, while for the flat optics smaller crossing angles pose more challenges in the protection of downstream elements. The present baseline foresees that (1) The TAXN will be designed with a fixed aperture optimized to provide the necessary clearance and maximum protection for the neutral particles. (2) A special design of the TCL collimator in cell 4 will be produced to provide the needed protection to the D2 bend and downstream quadrupoles. We are presently considering the possibility to enlarge transversally the jaw width to make this collimator more efficient [36].

The exact layout configuration and arrangement of the TAXN and the TCL collimator will be defined taking into account all installed materials and collimators in the region. Recent studies using a tungsten for the TAXN instead of copper showed that adequate efficiency could be maintained with a reduction in length that alleviates some layout issues [36]. In terms of schedule, the TAXN design needs to be finalized by end of 2017, which leaves sufficient time to perform all the optimization studies and optimize the designs and energy deposition to the magnets.

CONCLUSIONS

Upgrading the LHC collimation is crucial for the HL-LHC project. The ongoing studies of collimation solutions that address potential limitations to the present system have been described. A solid upgrade baseline has been established based on in-depth analyses of various aspects of the Run I operational experience. On the other hand, a crucial milestone for collimation will be the confirmation of present assumptions on the Run II operation at higher energies. This will solve present uncertainties on cleaning performance, quench limits, beam losses and collimation impedance etc. The upgrade strategy will be updated and re-tuned, if needed, once sufficient operational experience has been accumulated, i.e. not before the second half of 2015. At the same time we expect also to have at hand the results of important prototyping tests without and with beam, e.g. on new collimator designs and materials (both for the cleaning system and for the protection devices). We believe that we are on a good track to deploy important collimation upgrades starting already in LS2, if required, and that all the potential issues are being addressed.

ACKNOWLEDGMENTS

This contribution was prepared on behalf of the members of the collimation team as well as of the WP8 and WP14 teams. They are kindly acknowledged for their contributions to this work.

REFERENCES

[1] `http://hilumilhc.web.cern.ch/`

[2] R. Assmann *et al.*, "Collimators and beam absorbers for cleaning and machine protection," LHC Project Workshop Chamonix XIV, pages 261-267 (2005).

[3] `http://lhc-collimation-project.web.cern.ch/lhc-collimation-project/LS1/default.php`

[4] B. Salvachua *et al.*. "Collimation system post-LS1: status and commissioning," in the proceedings of Evian 2014.

[5] `https://indico.cern.ch/event/304154/`

[6] `http://www.cern.ch/lhc-collimation`

[7] R. Bruce *et al.*, "Cleaning performance with 11 T dipoles and local dispersion suppressor collimation at the LHC," in the proceedings of IPAC2014.

[8] A. Lechner *et al.*, "Power deposition in LHC magnets with and without dispersion suppressor collimators downstream of the betatron cleaning insertion," in the proceedings of IPAC2014.

[9] A. Marsili *et al.*, "Collimation cleaning for HL-LHC optics scenarios with error models," in the proceedings of IPAC2014.

[10] `https://indico.cern.ch/event/251588/`

[11] B. Auchmann *et al.* "BLM threshold strategy versus UFOs and quenches," in these proceedings.

[12] `https://indico.cern.ch/event/354499`

[13] E. Métral *et al.*, "Machine settings and operational scenario from stability considerations for HL-LHC," presentation at the 4th Annual Meeting of HL-LHC.

[14] R. Bruce *et al.*, "Baseline machine parameters and Configuration for 2015," in these proceedings.

[15] I. Efthymiopoulos *et al.*, "HiRadMat: a new irradiation facility for material testing at CERN," in the proceedings of IPAC2011.

[16] A. Bertarelli *et al.*, "First results of an experiment on advanced collimator materials at CERN HiRadMat facility," CERN-ACC-2013-0268.

[17] M. Cauchi *et al.*, "High energy beam impact tests on a LHC tertiary collimator at the CERN high-radiation to materials facility," Phys. Rev. ST Accel. Beams **17**, 021004.

[18] `http://indico.cern.ch/event/303890/`

[19] G. Arduini, "Down selection criteria and MDs prior to LS3," in these proceedings.

[20] G. Valentino *et al.*, "Beam diffusion measurements using collimator scans in the LHC," Phys. Rev. ST Accel. Beams **16**, 021003

[21] F. Burkart *et al.*, "Experience with high-intensity beam scraping and tail populations at the Large Hadon Collider," in the proceedings of IPAC2013.

[22] S. Redaelli *et al.*, "Experience with beam scraping and tail population at the Large Hadron Collider," in the proceedings of IPAC2013.

[23] B. Salvachua *et al.*, "LHC collimation cleaning and operation outlook," Evian 2012.

[24] G. Stancari (FNAL) *et ad.*, "Conceptual design of hollow electron lenses for beam halo control in the Large Hadron Collider," ATS Report CERN-ACC-2014-0248.

[25] Minutes of the 197th LHC Machine Committee held on 3rd Dec. 2014.

[26] Presentation by W. Scandale at, and minutes of the 173rd LHC Machine Committee held on 5th Feb. 2014.

[27] Presentation at the 181st Collimation Working Group meeting of 18th Oct. 2014.

[28] `http://lhc-collimation-project.web.cern.ch/lhc-collimation-project/slac_collimator.php`

[29] `https://indico.cern.ch/event/326148`

[30] `https://cds.cern.ch/record/1972595/files/CERN-ACC-2014-0293.pdf`

[31] R. Bruce *et al.*, "Collimation status and layout for IR1 and IR5,", presentation at the 4th Annual Meeting of HL-LHC.

[32] J. Uythoven *et al.*, "HL-WP14 overview." presentation at the HL-LHC Annual Meeting at KEK, 17-21 November 2014.

[33] V. Kain *et al.*, "Concerns with low emittance beams operation," in these proceedings.

[34] A. Lechner *et al.*, "Protection of superconducting elements in the case of injection failures." presentation at the HL-LHC Annual Meeting at KEK, 17-21 November 2014.

[35] N. Magnin, "LBDS: status and plans," in the proceedings of Evian 2014.

[36] F. Cerutti *et al.*, presentation at the HL-LHC Annual Meeting at KEK, 17-21 November 2014.

Proceedings of Chamonix 2014 Workshop on LHC Performance

DOWN SELECTION CRITERIA AND MDs PRIOR TO LS3

G. Arduini, CERN, Geneva, Switzerland

Abstract

The operation of the LHC and the machine studies conducted during run I have provided important input for the validation of some of the choices that are at the base of the HL-LHC upgrade scenario but it has evidenced also some potential limitations. Progress has been done in their understanding but some open points remain that need to be further studied to consolidate the operational scenario and performance (e.g. stability during the squeeze and collision process, electron cloud effects with 25 ns beams). Some of the solution proposed for the HL-LHC nominal scheme like the operation of crab cavities has not been tested in hadron machines so far and possible alternative solutions have been proposed (e.g. the implementation of long range wire compensators). The required validation studies and the possible criteria for the validation and down-selection of these options will be outlined.

HL-LHC CHALLENGES

The High Luminosity LHC (HL-LHC) will push the performance of the LHC well beyond the presently explored range [1,2], which has already exceeded the nominal parameters in some cases.

Some of the challenges underlying the HL-LHC performance are listed below:

- operation with low β* optics with well-behaved chromatic properties;
- electron cloud effects with 25 ns beams;
- large crossing angle and crab crossing to minimize the geometric reduction factor and pile-up density;
- β* levelling as a means to limit the event pile-up at the experiments;
- large beam-beam tune spreads resulting from head-on and long range effects;
- beam halo measurement and control, particularly to cope with possible crab cavities failure scenarios;
- minimization of impedance and beam stability;
- operation at higher stored beam energies.

Some of the main studies and machine experiments (in LHC and SPS) that are required to validate the main choices in terms of operational settings and scenarios or hardware are presented in the following.

ATS Optics

The Achromatic Telescopic Squeezing (ATS) is the solution selected to reduce the β function at the interaction point both for “round” (equal β functions in the horizontal and vertical planes) or “flat” (different β functions in the horizontal and vertical planes) optics configurations down to unprecedented values for a hadron collider (e.g. 15 cm for round optics or 7.5 / 30 cm for flat optics) while controlling the induced chromatic aberrations [3]. Machine Development studies performed in 2011-2012 have demonstrated the pre-squeeze/achromatic telescopic squeezing down to 10 cm, the feasibility of correcting beta beating in the LHC with this optics configuration and have confirmed the excellent chromatic properties of such optics solution [4-8].

This optics is mature to become operational and its implementation in operation, possibly in the second half of 2015 or 2016, is one important milestone for HL-LHC. In preparation of that, machine studies are required for the validation of collimation efficiency and machine protection aspects during the 2015 run [9].

Operation with 25 ns Bunch Spacing

Operation with 25 ns bunch spacing is mandatory in order to reach the goal integrated luminosity of 250 fb^{-1}/y while maintaining the event pile-up level within a range acceptable by the detectors of the high luminosity experiments in the Interaction Points (IP) 1 and 5. Important electron cloud effects have been observed during machine experiments conducted during Run I in the arcs and interaction regions [10]. Signs of reduction of the Secondary Electron Yield (SEY), responsible for the electron cloud build-up, have been observed in the LHC dipoles during dedicated “scrubbing runs”. Beams with a bunch time structure (“doublet beams”) [11] aimed at enhancing the electron-cloud build-up have been conceived and tested in the SPS with the aim of enhancing the electron dose and consequently the speed of the scrubbing process to reach SEY values lower than 1.3 in the LHC beam screens. That would allow suppressing the electron cloud build-up at least in the main dipoles for the LHC beams with 25 ns spacing. The threshold value of the SEY above which multipacting is expected in the quadrupoles and in particular in the common regions where both counter-rotating beams are sharing the same vacuum chamber is too low (~1.1) to be considered within reach during the scrubbing runs. The present estimates of the available cooling power for the beam screens indicate that this is sufficient to allow operation even in the presence of electron cloud in the arc quadrupoles even for the HL-LHC beam parameters [12, 13].

For the HL-LHC parameters the heat load in the beam screens in the single aperture magnets (triplet quadrupoles and D1 recombination dipoles) will exceed the available cooling power and no suppression of the electron cloud is expected for SEY values of 1.3 that could be reasonably achieved after scrubbing, for that reason it is planned to coat the triplet and D1 beam screens in all interaction points with amorphous carbon that have shown SEY<1 at room temperature.

Laboratory tests are ongoing to characterize the properties of these coatings at cryogenic temperatures and a coated beam screen maintained at cryogenics temperatures has been installed (see Fig. 1) in a test area in the SPS ring (COLDEX) to validate the behaviour at cryogenics temperatures with beam during the SPS scrubbing run in 2014. Irradiation tests are foreseen in order to evaluate possible ageing effects that could have an impact on the properties of these surfaces with respect to SEY.

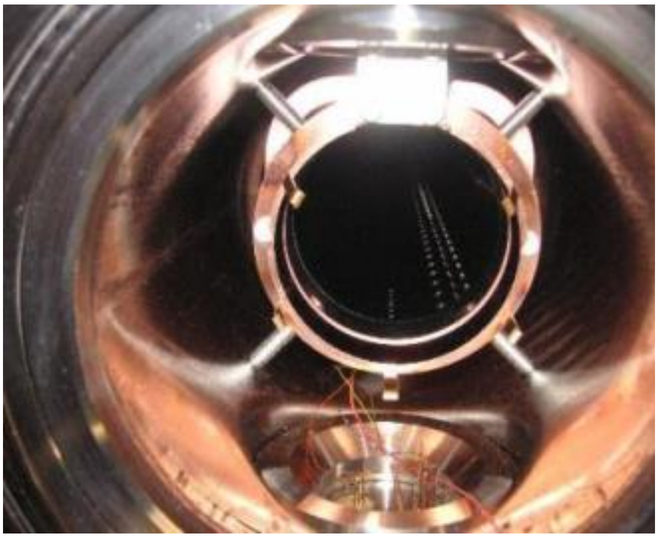


Figure 1: Coated beam screen installed in the SPS ring (COLDEX). Courtesy of P. Chiggiato and M. Taborelli.

The design of low impedance clearing electrodes (tested successfully at DAϕNE – INFN/Frascati [14]), is also being considered as a possible back-up solution, though it would require a specific design to be fitted in a cryogenic environment with limited space available.

Crab Crossing

Crab crossing by means of crab cavities has been considered as a baseline HL-LHC scenario to suppress the luminosity geometric reduction factor due to the large crossing angle required to minimize the effect of beam-beam long range encounters. In this way, the virtual luminosity (i.e. the peak luminosity that could be delivered to the experiments if no limit in the event pile-up rate would exist) is increased without increasing the event pile-up density. Crab cavities can also be used to act on the event pile-up longitudinal or temporal distribution (e.g. with the so-called "crab-kissing" scheme [15]).

Crab cavities have never been installed in high intensity proton machines and several aspects related to their operation in these conditions need to be studied, in particular:

- Impedance effects like transverse instabilities and High Order Mode power;
- Validation of operation modes and cavity control during the various mode of operation and in case of a failure;
- Effect of phase and amplitude noise on beam quality and in particular on transverse blow-up and halo generation.

For that reason a module with two crab cavities (see Fig. 2) will be installed in the SPS to conduct tests with the LHC beams during the 2017-2018 runs. Measurements will include:

- beam induced heat load,
- emittance blow-up,
- beam stability

for different operating modes.

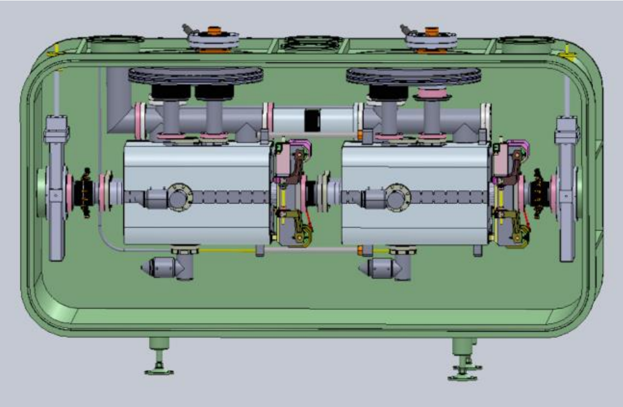


Figure 2: Layout of the cryo-module with two crab cavities to be installed in the SPS for the crab cavity test. Courtesy of R. Calaga and A. MacPherson.

Alternative scenarios have been devised and would imply a reduction of the crossing angle by using flat optics (with larger β* in the crossing plane) and possibly implementing beam-beam long range compensators to control the tune spread resulting from long-range parasitic encounters [16].

β levelling/Collide and Squeeze*

The proposed scheme for levelling the luminosity compatibly with the event pile-up rate that can be accepted by the detectors is based on the so-called β* levelling. According to this scheme the β function at the IP (β*) is reduced progressively during the physics fill down to its minimum value so to maintain the luminosity constant at the desired value (smaller than the virtual peak luminosity) until the minimum value of β* is reached from that time onwards the luminosity will decay following the reduction of the beam population due to luminosity burn-off or other effects and following the evolution of the transverse emittance ε. Such a scheme has the advantage of providing a larger normalized long range beam-beam separation ($\propto \theta\sqrt{\frac{\beta^*}{\varepsilon}}$ for a constant crossing angle θ) at the beginning of the fill when the bunch population is larger. A similar scheme could be used to provide a strong Landau damping during the squeeze by performing that process with the beams in collision and profiting of the large tune spread provided by head-on beam-beam interaction. That might be required to stabilize the beams at high energy, during the squeeze, when:

- the impedance due to the collimators is maximized as their gap is reduced to protect the triplets that would otherwise become the aperture bottleneck during this process;
- the effects of the impedance of the crab cavities increase with the corresponding increase of the β function at their location.

The feasibility of such scheme has been demonstrated at low intensity in three dedicated experiments in 2012 [17-19]. Figure 3 shows the relative evolution of the luminosity (normalized to the value at the end of the squeeze) during the reduction of the β^* in IP1 and 5 and compares it with the expected evolution in the absence of unexpected sources of emittance blow-up. The observed blow-up is small.

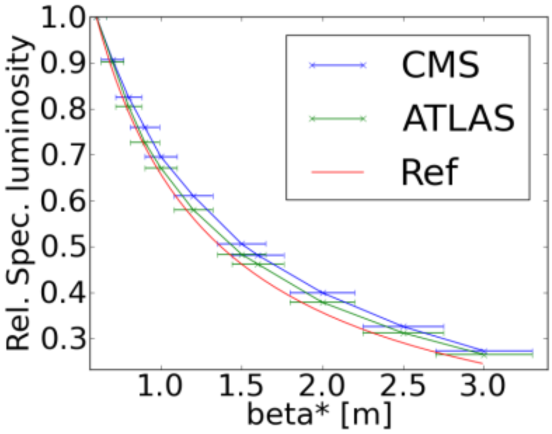


Figure 3: Evolution of the ATLAS and CMS luminosity during the β* levelling experiment as compared to the expected evolution.

In spite of the positive results it must be stressed that these tests have been performed at low intensity and no experience could be gathered on the reproducibility of the orbit on a cycle-by-cycle basis. In particular instabilities might occur when operating at high intensity if the beams separate during the squeeze process. Instabilities have been observed during physics when the beams were separated by approximately 1.5 σ (see for example [20]). Systematic studies of this phenomenon should be performed with controlled machine settings (e.g. chromaticity, octupole polarity, and damper gains). If confirmed this phenomenon would be even more critical for HL-LHC due to the smaller beam size at the IP as compared to that available in 2012 in the LHC at 4 TeV.

The possibility of applying β* levelling as an alternative to levelling by beam separation (used in operation 2011 and 2012) in IP8 is still under discussion. While the first option would allow to profit of the additional Landau damping provided by this additional head-on collision it must be noted that the correspondingly larger tune spread could result in poorer dynamic aperture.

Machine studies are required to develop and test the tools required for β* levelling, among others a feed-forward/feedback system allowing to keep the beams in collision during the β* levelling process. It is worth noting that luminosity levelling might be required even before the HL-LHC upgrade in case of operation with low β* (40 cm) and with high brightness BCMS (Batch Compression Merging and Splittings) beams [21].

In case of difficulties in the implementation of β* levelling in operation, levelling by separation at the IP remains a possible alternative. Although that is operationally simpler it would imply operating with minimum long-range normalized separation from the beginning of the fill when the bunch population is maximum.

Beam-beam Effects

The HL-LHC will operate at unprecedented beam-beam parameters with head-on beam-beam tune spreads larger than 0.01/IP possibly on 3 IPs (if β* levelling is implemented in ATLAS, CMS and LHCb) and the additional contribution of beam-beam long-range effects. This might have an impact on dynamic aperture and emittance blow-up and therefore on the luminosity integrated performance, for that reason the validation of this mode of operation is mandatory with simulations and experiments to confirm the criteria used for the definition of the operational scenarios and of the corresponding performance. At present the same criteria that have guided the LHC design are used with a minimum dynamic aperture of 6 beam sigma from simulations considered to be acceptable [22].

Experiments have been performed to study the machine performance with large beam-beam head-on tune spread (but with a small number of bunches) and values as large as ~0.017/IP have been achieved in two IPs but in the absence of long range effects [23-27].

Long range effects and their scaling with beam and machine parameters have been studied with 50 ns beams and, although only preliminarily, with 25 ns beams with the aim of benchmarking simulations and provide additional experimental evidence for the design criteria above mentioned [28].

It will be vital to complete the studies on the scaling of long-range effects with 25 ns beams and with energy (e.g. for the possible effect of radiation damping) during Run 2.

Possible alternative scenarios in case of limitations due to the beam-beam head on tune spread or to beam-beam long-range effects include the levelling by separation in IP8 and the implementation of a Beam-Beam Long Range (BBLR) compensation scheme, respectively. The second scheme has been proposed initially in [29] and possible tests in the LHC will be discussed later in this paper.

Dynamic Aperture

The evaluation of the impact of field quality on machine performance and its steering during the design and construction phase has been one of the reasons of LHC excellent performance (the unprecedented beam-beam tune shifts achieved is likely one of the results of that). The impact of field quality has been so far evaluated in terms of dynamic aperture that is the region in phase space where stable motion occurs, at least for a given amount of machine turns (typically 10^5 to 10^6 turns). During the LHC design the limited experimental data available and the limitations in computing power led to the decision of considering an important (approximately a factor 2) safety margin between the dynamic aperture and the mechanical aperture defined by the collimators [30]. With the LHC start-up, efforts have been done to correlate measurable quantities (e.g. losses) with the expected asymptotic value of the simulated dynamic aperture for an increasing number of turns [31][32] and experiments have shown that the estimated accuracy of the dynamic aperture simulations is 20 to 30% at injection (see Fig. 4).

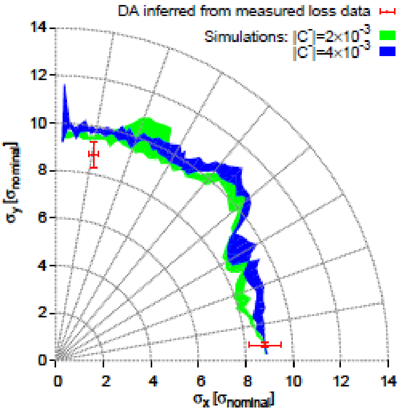


Figure 4: Comparison of dynamic aperture data from simulations (green and blue) with those inferred form measured loss data (red) in one of the machine studies conducted in the LHC at injection [32].

Although in general there is an excellent agreement between the LHC optics linear and non-linear model and the measurements some discrepancies still persist that need to be addressed during Run 2 together with the performance of the correction algorithms. This will be extremely important for the operation at low β* and of the correction of the non-linearities of the triplet magnetic field during HL-LHC operations.

Collimation

Pushing the collimation efficiency compatibly with impedance will be crucial for high- intensity/high brightness operation at the HL-LHC. A reduction of the impedance of the collimators is required in order to operate the LHC with the brighter beams required during the HL-LHC era. Low impedance collimators (Mo-graphite with Molybdenum coating of 5 μm) remain the baseline solution (a prototype could be installed in the LHC in 2016). Furthermore dispersion suppression collimators might be required in the dispersion suppressors around point 7 depending on the observed quench limits and beam loss rates at high energy [33].

The collimation studies are strongly coupled with the performance of the LHC during Run 2 and Run 3 and therefore the required MD time should be planned taking this synergy into account.

Halo Control

Operation at high intensity and large beam stored energy demands for a tight control (both measurement and reduction) of the beam halo to avoid loss spikes that might result, for example, from:

- orbit drifts at collimators (as already observed in 2012);
- transients in case of crab cavity failure.

Halo measurements techniques are being studied together with possible techniques to clean the beam halo at amplitudes below the aperture of the primary collimators. Among them two active excitation mechanisms [34] are being considered:

- one based on the modulation of quadrupole gradient by a controlled ripple (in frequency and amplitude) that will induce side-bands in the beam tune spectrum and therefore will follow any tune variation;
- the second based on a narrow-band dipolar excitation with the transverse feedback

While the latter will not generate sidebands of the tune and will not follow any tune variation (unless programmed) it could be in principle modulated within the bunch train to account for tune variations inside the train due to collective effects like beam-beam and impedance.

Another possible scheme considered as future development, although more demanding in terms of the hardware, is the use of an electron hollow lens that could have synergies with the effort for a long range beam-beam compensator based on an electron beam [35].

For all these techniques the effectiveness in terms of halo cleaning and impact on beam core blow-up needs to be carefully studied in simulations and experiments.

VARIANTS AND OPTIONS

Possible variants and options have been conceived as alternative solutions in case of issues with some of the challenges above mentioned [15,16,36,37].

Flat Optics

Flat optics (i.e. an optics providing $\beta^*_{xing} > \beta^*_{sep}$ where β^*_{xing} and β^*_{sep} are the β functions at the interaction point in the crossing and separation planes, respectively) [16] promises to operate with smaller crossing angle at constant normalized beam-beam separation and with constant if not larger virtual luminosity thanks to the reduction of the crossing angle in absolute terms. This would offer the advantage of reducing the requirements on the crab cavities voltage (in case of limitations in their performance with beam or for the purpose of implementing the "crab kissing" scheme [15]) and would reduce the event pile-up longitudinal density.

Beam-beam simulation indicate nevertheless that larger normalized beam-beam separation are required for flat optics configurations as compared to round optics at constant dynamic aperture due to the partial compensation of long range effects in IP1/5 even for alternating crossing. Beam-beam experiments would provide valuable input to benchmark simulations and scaling laws. The ATS optics can easily provide flat configurations that could be of interest for the LHC operation even during Run 2.

Beam-beam Long Range Compensation

As mentioned earlier beam-beam long range compensation schemes based on wires or electron beams could in principle mitigate beam-beam long range effects and/or allow reducing the crossing angle in particular when combined with the implementation of a flat optics. The latter configuration would allow:

- providing margin for the "crab kissing" scheme [15];
- mitigating performance limitations from crab cavities (e.g. max. achievable voltage, noise, etc.);
- providing flexibility for the crossing angle orientation in IP1/5 otherwise bounded to the choice of alternating crossing plane to compensate tune and chromaticity shifts due to long range effects;
- reducing the energy deposition on the D2 recombination dipoles with the choice of vertical crossing in both IP1 and IP5.

Although very promising (see [38] for an overview of the experimental tests in the SPS) limited experience exists for the use of a beam-beam long range compensator in a hadron collider [39-41] and an experimental programme has been launched to benchmark simulations and validate scenarios that are compatible with machine protection. For this purpose it is planned to install wire beam-beam demonstrators embedded in tertiary collimators around IP1 and IP5 during the winter stop 2015-16.

In order to obtain meaningful information for the HL-LHC implementation additional simulation tools and diagnostics are required [42-45].

A beam-beam compensator based on an electron beam is also being considered [46], this would allow moving the electron beam closer to the circulating beam providing ideal conditions for the long range compensation, although with a significant investment in hardware.

800 MHz System

An 800 MHz system [47] (double harmonic of the main LHC RF system operating at 400 MHz) has been proposed as a means to modify the longitudinal distribution to reduce the peak longitudinal density (flat bunches) by operating it in bunch lengthening mode for the purpose of:

- enhancing the reduction of the event pile-up longitudinal density in the crab kissing scheme [16];
- reduce beam induced heating.

It must be noted that the mode of operation in bunch lengthening mode would require the installation of at least 8 to 10 RF cavities [47] and might reduce longitudinal stability while the impact on transverse stability needs to be further studied.

Flat longitudinal distributions could be obtained without any hardware changes by applying RF phase modulation at frequencies close to the synchrotron frequency as shown already during machine studies performed in the LHC [48] although bunch length modulation has been observed along the bunch trains. The long term behaviour of the longitudinal distribution in the presence of Intra-Beam Scattering (IBS) and synchrotron radiation needs to be studied during machine experiments at 6.5 TeV during Run II. The impact of such a modified bunch longitudinal distribution on transverse and longitudinal stability has still to be studied.

Crystal Collimation

The use of crystals for enhancing collimation efficiency is being investigated as an alternative configuration to the installation of the dispersion suppressor collimation scheme based on 11 T dipoles around the collimation cleaning insertions [33]. This solution relies on the extrapolation to high energy of SPS experiments and simulations and for that reason a crystal-assisted collimation test set-up has been installed in the LHC [49] with the aim of demonstrating that crystals can indeed improve the cleaning efficiency with respect to the present system in realistic LHC beam conditions. Benchmarking the simulations and verifying the operational tolerance of such concept to dynamic changes occurring during the whole machine cycle will require a solid experimental programme.

SUMMARY

The HL-LHC beam and machine parameters are challenging and the solution proposed for the baseline scenario are relying on innovative scheme that, although based on excellent results obtained during LHC run I are not always fully proven. Some of the machine experiments and studies required in order to validate the main choices have been presented together with the possible alternative configurations that can be envisaged to overcome potential issues that might be encountered in the implementation of the baseline scenario.

Some of the Machine Studies and solutions proposed for HL-LHC could have an impact on the LHC performance even during Run 2 or 3.

ACKNOWLEDGEMENTS

I would like to warmly thank the Task Leaders of the Hi-Lumi Work Package 2 (O. Brüning, M. Giovannozzi, E. Métral, A. Valishev), as well as R. Calaga, R. De Maria, S. Fartoukh, G. Iadarola, I. Papaphilippou, T. Pieloni, S. Redaelli, G. Rumolo and R. Tomás for their invaluable contribution in the preparation of this presentation.

The HiLumi LHC Design Study is included in the High Luminosity LHC project and is partly funded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404.

REFERENCES

[1] O. Brüning, L. Rossi, eds., “High Luminosity LHC”, special issue of International Journal of Modern Physics A, to be published.

[2] G. Apollinari, I. Béjar Alonso, O. Brüning, M. Lamont, L. Rossi eds., “HL–LHC Preliminary Design Report”, to be published

[3] S. Fartoukh, “Achromatic telescopic squeezing scheme and application to the LHC and its luminosity upgrade”, Phys. Rev. Spec. Top. Accel. Beams 16 (2013) 111002 and references therein.

[4] S. Fartoukh, G. Vanbavinckhove, M. C. Alabau Pons, R. Alemany Fernandez, R. Assmann, A. Butterworth, M. Giovannozzi, B. Goddard, P. Hagen, W. Höfle, D. Jacquet, R. de Maria, R. Miyamoto, G. Müller, S. Redaelli, R. Steinhagen, M. Strzelczyk, R. Suykerbuyk, E. Todesco, R. Tomás, W. Venturini, J. Wenninger, F. Zimmermann, “The Achromatic Telescopic Squeezing (ATS) MD part I”, CERN-ATS-Note-2011-033 MD, 2011.

[5] S. Fartoukh, M. Lamont, R. De Maria, R. Miyamoto, G. Müller, L. Ponce, S. Redaelli, M. Strzelczyk, R. Tomás, G. Vanbavinckhove, J. Wenninger, M. Albert, R. Giachino, M. Giovannozzi, B. Goddard, P. Hagen, W. Höfle, V. Kain, A. Macpherson, L. Normann, G. Papotti, R. Steinhagen, D. Valuch, D. Wollman, “The Achromatic Telescopic Squeezing (ATS) MD part II”, CERN-ATS-Note-2011-060 MD, 2011.

[6] S. Fartoukh, R. Tomás, B. Goddard, W. Höfle, D. Jacquet, G. Kruk, M. Lamont, R. de Maria, R. Miyamoto, G. Müller, M. Pojer, L. Ponce, S. Redaelli, N. Ryckx, R. Steinhagen, M. Strzelczyk, G. Vanbavinckhove, J. Wenninger, “The Achromatic Telescopic Squeezing (ATS) MD part III”, CERN-ATS-Note-2011-132 MD, 2011.

[7] S. Fartoukh, V. Kain, Y. Levinsen, E. Maclean, R. de Maria, T. Persson, M. Pojer, L. Ponce, P. Skowronski, M. Solfaroli, R. Tomás, J. Wenninger, “The 10 cm beta* ATS MD”, CERN-ATS-Note-2013-004 MD, 2013.

[8] S. Fartoukh, “ATS MD experience for run I and perspective for run II”, LHC Studies Working Group Day, CERN, 2nd September 2014, https://indico.cern.ch/event/331020/contribution/1/material/slides/0.pptx

[9] Summary of the 188th LMC Meeting held on 3rd September 2014, https://espace.cern.ch/lhc-machine-committee/Minutes/1/lmc_188.pdf

[10] G. Iadarola, “Scrubbing: Expectations and Strategy, Long Range Perspective”, these Proceedings.

[11] G. Iadarola, “Electron Cloud and Scrubbing”, 5th Evian Workshop on LHC operation, Evian (France), 2-4 June 2014, https://indico.cern.ch/event/310353/session/3/contribution/11/material/paper/0.pdf

[12] G. Iadarola, “Electron cloud effects and expected limitations in the HL-LHC era (stability, heat load in existing and new components, countermeasures)”, 3rd Joint Hi-Lumi LHC-LARP Annual Meeting, Daresbury, 11-15 November 2013, https://indico.cern.ch/event/257368/session/11/contribution/32/material/slides/10.pptx

[13] E. Métral, “Beam intensity limitations”, CERN-ACC-2014-0297.

[14] M. Zobov, D. Alesini, A. Drago, A. Gallo, S. Guiducci, C. Milardi, A. Stella, S. De Santis, T. Demma, P. Raimondi, “Operating Experience with Electron Cloud Clearing Electrodes at DAΦNE”, Proceedings of the Joint INFN-CERN-EuCARD-AccNet Workshop on Electron-Cloud Effects, La Biodola, Isola d’Elba, Italy, 5 - 9 Jun 2012, CERN-2013-002, pp. 259-265.

[15] S. Fartoukh, “Pile up management at the High Luminosity LHC and introduction to the crab-kissing concept”, CERN-ACC-2014-0076, (2014).

[16] S. Fartoukh, “Towards the LHC Upgrade using the LHC well-characterized technology”, CERN-sLHC-PROJECT-Report-0049, 2010.

[17] X. Buffat, W. Herr, M. Lamont, T. Pieloni, S. Redaelli, J. Wenninger (2012), “Results of β* luminosity levelling”, CERN-ATS-Note-2012-071 MD

[18] X. Buffat, W. Herr, M. Lamont, T. Pieloni, L. Ponce, S. Redaelli, J. Wenninger (2013), “MD on squeeze with colliding beams”, CERN-ATS-Note-2013-002 MD.

[19] X. Buffat, W. Herr, M. Lamont, T. Pieloni, S. Redaelli, J. Wenninger (2013), Colliding during the squeeze and β levelling in the LHC, TUPFI033 in IPAC13 proceedings.

[20] J. Uythoven, “Progress with beam”, 133rd LMC Meeting held on 16 May 2012, https://espace.cern.ch/lhc-machine-committee/Presentations/1/lmc_133/lmc_133a.pdf

[21] H. Damerau, “Performance Potential of the Injectors after LS1”, Proc. of LHC Performance Workshop (Chamonix 2012), February 2012, p.268.

[22] Y. Luo and F. Schmidt, “Dynamic Aperture Studies for LHC Optics Version 6.2 at Collision”, LHC Project Note 310 (2003).

[23] R. Alemany, X. Buffat, R. Calaga, K. Cornelis, M. Fitterer, R. Giachino, W. Herr, A. McPherson, R. Miyamoto, G. Papotti, T. Pieloni, S. Redaelli, F. Roncarolo, M. Schaumann, R. Suykerbuyk, G. Trad, S. Paret, “Head-on beam-beam tune shifts with high brightness beams in the LHC”, CERN-ATS-Note-2011-029 MD

[24] M. Albert, R. Alemany, R. Assmann, X. Buffat, R. Calaga, K. Cornelis, M. Fitterer, R. Giachino, W. Herr, R. Miyamoto, L. Norman, G. Papotti, T. Pieloni, L. Ponce, S. Redaelli, M. Schaumann, G. Trad, D. Wollmann, “Head-on beam-beam collisions with high intensities and long range beam-beam studies in the LHC”, CERN-ATS-Note-2011-058 MD

[25] G. Trad, R. Alemany, X. Buffat, R. Calaga, K. Cornelis, G. Crockford, R. Giachino, W. Herr, G. Papotti, M. Pojer, M. Schaumann, “Beam parameters observations during a high pile-up collisions fill”, CERN-ATS-Note-2011-105 MD

[26] R. Alemany, R. Assmann, X. Buffat, R. Calaga, M. Fitterer, R. Giachino, G.H. Hemelsoet, W. Herr, G. Papotti, T. Pieloni, M. Pojer, M. Schaumann, G. Trad, D. Wollmann, “Results of long range beam-beam studies and observations during operation in the LHC”, CERN-ATS-Note-2011-120 MD

[27] G. Trad, R. Alemany, X. Buffat, R. Calaga, K. Cornelis, W. Herr, D. Jacquet, G. Papotti, M. Schaumann, W. Venturini Delsolaro, “Beam parameters observations during the second high pile-up collisions fill in 2011”, CERN-ATS-Note-2012-010 MD

[28] R. Assmann, R. Bruce, X. Buffat, R. Calaga, R. Giachino, W. Herr, E. Metral, G. Papotti, T. Pieloni, G. Roy, G. Trad, D. Kaltchev, “Results of long-range beam-beam studies - scaling with beam separation and intensity”, CERN-ATS-Note-2012-070 MD

[29] J.-P. Koutchouk, “Principle of a Correction of the Long-Range Beam-Beam Effect in LHC using Electromagnetic Lenses”, LHC Project Note 223, 2000.

[30] J.-P. Koutchouk, “The LHC Dynamic Aperture”, Proceedings of the 1999 Particle Accelerator Conference, New York, 1999, p. 372-376.

[31] M. Giovannozzi, “Dynamic Aperture: Simulations vs. Experiments and first DA results in the LHC”, 14th HiLumi WP2 Task Leader Meeting, 27 August 2013, https://indico.cern.ch/getFile.py/access?contribId=2&resId=0&materialId=slides&confId=267840

[32] E. H. Maclean, R. Tomás, F. Schmidt, and T. H. B. Persson, "Measurement of nonlinear observables in the Large Hadron Collider using kicked beams", Phys. Rev. ST Accel. Beams 17, 081002, (2014).

[33] S. Redaelli, “Collimation and MP Roadmap”, these Proceedings.

[34] R. Bruce, “Status and plan for alternative halo control methods”, 3rd Joint Hi-Lumi LHC–22nd LARP Collaboration Meeting May 7-8, 2014, BNL, USA, https://indico.bnl.gov/getFile.py/access?contribId=40&sessionId=33&resId=0&materialId=slides&confId=730

[35] G. Stancari, V. Previtali, A. Valishev, R. Bruce, S. Redaelli, A. Rossi, B. Salvachua Ferrando, “Conceptual design of hollow electron lenses for beam halo control in the Large Hadron Collider”, CERN-ACC-2014-0248.

[36] R. Tomás, O. Dominguez and S. White, “HL-LHC: Exploring alternative ideas”, Review of LHC and Injector Upgrade Plans Workshop (RLIUP), Archamps, France, 29-31 October 2013.

[37] R. Tomás, “HL-LHC alternative scenarios, parameters and lay-out”, these Proceedings.

[38] F. Zimmermann, “10 Years of wire excitation experiments in the CERN SPS”, Proceedings of the ICFA Mini-Workshop on Beam-Beam Effects in Hadron Colliders, CERN, Geneva, Switzerland, 18 - 22 Mar 2013, W. Herr and G. Papotti Eds., CERN-2014-004, pp.153-166.

[39] H. J. Kim, T. Sen, “Long-Range Beam-Beam Compensation in RHIC”, Proceedings of IPAC’10, Kyoto, Japan, p. 2072-2074.

[40] W. Fischer, Y. Luo, N. Abreu, R. Calaga, C. Montag, G. Robert-Demolaize, U. Dorda, J.-P. Koutchouk, G. Sterbini, F. Zimmermann, H.-J. Kim, T. Sen, V. Shiltsev, A. Valishev, J. Qiang, A. Kabel, “Long-range and head-on beam-beam compensation studies in RHIC with lessons for the LHC”, CARE-HHH working meeting - LHC beam-beam effects and beam-beam compensation, http://www.osti.gov/scitech/servlets/purl/948476

[41] H. J. Kim, T. Sen, N. P. Abreu, W. Fischer, “Simulations of beam-beam and beam-wire interactions in RHIC”, PRST-AB 12, 031001 (2009)

[42] Y. Papaphilippou, “BBLR test: present ideas on set-up, beam conditions and measurements”, 31st Hi-Lumi WP2 Task Leader Meeting, 4th July 2014, https://indico.cern.ch/event/323861/contribution/2/material/slides/0.pdf

[43] R. Steinhagen, “Status of the BBLR design with emphasis on MD, accelerator physics questions and possible HW issues”, 3rd Joint Hi-Lumi LHC-LARP Annual Meeting, Daresbury, 11-15 November 2013, https://indico.cern.ch/event/257368/session/11/contribution/52/material/slides/0.pdf

[44] T. Rijoff, “Beam-beam Long range compensation studies with wires”, LHC and HL-LHC Beam-Beam Studies Working Group Meeting, 20th March 2014, https://indico.cern.ch/event/308480/contribution/0/material/slides/3.pptx

[45] S. Redaelli, “Collimation constraints”, LHC and HL-LHC Beam-Beam Studies Working Group Meeting, 20th March 2014, https://indico.cern.ch/event/308480/contribution/1/material/slides/0.pdf

[46] A. Valishev, G. Stancari, “Electron Lens as Beam-Beam Wire Compensator in HL-LHC”, arXiv:1312.1660, FERMILAB-TM-2571-APC - 2013.

[47] R. Calaga, “HL-LHC RF Roadmap”, these Proceedings.

[48] E. Shaposhnikova, T. Argyropoulos, P. Baudrenghien, J. Esteban Muller, T. Mastoridis, G. Papotti, B. Salvant, H. Timko, C. Bhat, A. Burov, “Flat Bunches in the LHC”, Proceedings of IPAC2014, Dresden, Germany, p. 1413-1415.

[49] D. Mirarchi, S. Montesano, S. Redaelli, W. Scandale, A.M. Taratin, F. Galluccio, “Final layout and expected cleaning for the first crystal-assisted collimation test at the LHC”, CERN-ACC-2014-0136, Proceedings of the 5th International Particle Accelerator Conference, Dresden, Germany, 15 - 20 Jun 2014, pp.882.

ACCELERATORS AND NON LHC EXPERIMENT AREAS CONSOLIDATION UP TO LS3 - LINACS

R. Scrivens, CERN, Geneva, Switzerland

Abstract

The consolidation requests for Linacs 2 and 3 will be summarised and prioritised, as well as the requests for the transfer line between Linac2 and the PSB which will be reused for Linac4 beams in the future.

INTRODUCTION

Consolidation of the equipment of CERN particle accelerators is vital to keep them operating reliably. Accelerator equipment needs consolidation because of wear and tear to systems, loss of key knowledge, unmaintainability due to subsystems going out of production. In order to reduce the number of technologies to maintain, there has also been a large amount of rationalisation of the types of technology, sometimes meaning otherwise fit-for-purpose equipment is replaced by other technology choices used elsewhere at CERN.

CERN’s three primary hadron beam accelerators are the topic of this paper’s review of the consolidation requests. They consist of

- Linac2 - 50MeV proton linear accelerator, to remain in service up to 2018 (LS1).
- Linac3 - 4.2MeV/u ion linear accelerator, to remain the future source of ions.
- Linac4 - 160MeV H- linear accelerator, to become the supplier of hydrogen ions from LS1.

Linac3 was constructed through a collaborative effort in the early 1990’s and has left a lot of unique equipment.

Linac4 is itself a new facility, but will reuse part of the transfer line presently from Linac2 to the PSB. There are consolidation requests for equipment in this line.

Within this report the main requests for consolidation at these facilities will be summarised, and priorities given from an operational point of view. The operational priorities reflect items that stop the beam production, are single points of failure that cannot easily be overcome, or require a lot of operational support. These priorities are possibly different from those expressed from the equipment group concerned, but both views must be balanced in the prioritization of funding.

Priority 1 is the highest. If no priority is given the task is understood to already be funded by the consolidation project. The date given indicates the best time for the system to be installed on the accelerator or beam line, if this is relevant.

Linac2

The consolidation requests for Linac2 can be found in Table 1. The very few requests reflect the short time left as part of the injector chain.

Transfer Line

Part of the LT and LTB transfer lines will continue to be part of the LHC injection chain with Linac4.

All the requests are fully justified, and the prioritisation reflects the importance and benefit to operation of having these tasks completed.

The exact combination of magnets and power convertors is not fully finalised, and might lead to additional consolidation proposals.

Although not part of the transfer line, EN-ICE request funds to software support for the low energy emittance meter as part of their continuous software update programme.

Linac3

The Linac3 accelerator was built on a tight budget in the early 1990’s, and used in kind contributions from many institutes. Although now fully supported by CERN’s equipment groups, much equipment is now more than 20 years old, and some equipment was recovered from Linac1. Furthermore, institutes often provided unique solutions to requirements (which was divided into machine regions), which in particular for magnets and power convertors lead to a large number of system varieties that are difficult to support and maintain spares for, even if they work reliably today.

Generic PS Requests that Affect Linacs

Several requests are generic for equipment used at CERN and in the PS complex. Amongst these a request from BE-CO to replace the TTL-Blocking timing repeat units is a priority, these systems fail several times a year in the PS complex, and they have no inbuilt diagnostics meaning the cause of faults is often difficult to diagnose.

Table 1: Linac2 consolidation requests

Item	Priority	Group	When	Approx Cost / Approved
Tank Quadrupole Failure Mitigation EN/MME are not confident on the procedure to make a drift tube. Remake drawings and build a prototype (of a presently leaking DT). Useful only if approved now and finished end 2015.	2	BE/ABP EN/MME + others	-	No
Spare RFQ amplifier. Increases difficulty of repair.	-	BE/RF	-	-

Table 2: LT-LTB-BI Linac to PSB transfer line consolidation requests

Item	Priority	Group	When	Approved
Replacement magnets (spares, and operational) (Some convertors are replaced under LIU)	-	TE-MSC	LS2	>1300 kCHF Yes
Power Convertor Controls to FGC3 for ~100 convertors Would eradicate MIL1553 from Linac4 up to PSB injection Decreased maintenance diversity for EPC. Improves ion LBS measurements post LS2 = higher operational priority.	2	TE-EPC	LS2	800 kCHF No
Turbo Pumps Not active – used for pre-pumping, leak detection. If failing these pumps are inaccessible – leading to longer downtime. VSC would prioritise these in their consolidation.	1	TE-VSC	LS2	540 kCHF No
BCTs – exchange of 40yo to Linac4 standard on the LT and LTB line.	-	BE-BI	EYETS	350 kCHF Yes
Emittance meter scanner software – Maintenance of code with new base software versions (e.g. Labview) Maintains development and qualification of Linac4 sources in the test stand.	1	EN-ICE	N/A	0.5FTE ~35 kCHF No
Renovate the HVAC in building 363, for powering of Linac4 to PSB equipment.	2	EN-CV	LS2	270 kCHF No
Warm Magnet Interlock Many magnets are completely unprotected. They have to run at <2xI for Linac4. Would be best coupled with EPC FGC and any magnet installation.	1	TE-MPE	LS2 – with convertor control	150 kCHF (part of 1800 kCHF for full PS complex) No

Table 3a: Linac3 consolidation requests.

Item	Priority	Group	When	Approved
HVAC replacement Must include a major asbestos clean up – not budgeted. Cooling has been a persistent operational issue for Linac3. Post LS1 we will increase typical rep rate from 2 -> 3.6Hz – MD showed little margin for this. Increased operational workload, beam downtime and performance restrictions in summer, to become worse post LS2 if not consolidated.	1	EN-CV GS-SE	LS2	1300 kCHF No
Replace many power convertors in Linac3, including controls. Remove multiple design types, increasing maintainability. Air heat load should not be increased. Some PCs lack spares – they should be prioritized more highly.	2	TE-EPC		900 kCHF No
LBS Line – consolidate for ions. Also requested to LIU-Ions – Negotiation needed. Renovation is best in LS2 when zone is modified for LBE line anyway (easing access).	2	BE-ABP	LS2	1000 kCHF No
Linac3 Triplet Drift tubes There are spares – but possible recurring water leak issue on brazing – Replacement takes ~8-10 weeks. Priority to be modified if one fails.	2	BE-ABP	-	500 kCHF No
The LLRF, upgrade to the Linac4 standard. ABP ops are happy with the present system which fulfils specs and is easy to use.	2	BE-RF	2017	350 kCHF No
Spare magnets and coils. Menagerie of different magnet types, without spares.	-	TE-MSC	Spares	335 kCHF Yes
Turbo pump group renovation High gas loads from the source, even for Pb with O_2. Higher operational downtime. Adds remote control.	1	TE-VSC	LS2	315 kCHF No
101 MHz amplifiers (Bertronix) Change driver tubes to solid state (the tubes are out of production and spares are finite), Replace Step5 control and interlocks, some amplifier parts reaching end of life.	1	BE-RF	LS2	250 kCHF No
Replace Thompson 14GHz Generator Can delay this until the Thompson generator fails. But that would mean 1 year without a spare.	2	BE-ABP	Wait for failure	150 kCHF No
Replace Critical Source spares when used	-	BE-ABP	2014-2018	150 kCHF Yes
BCT hardware consolidation Replace 40yo BCT on ITH transfer line	-	BE-BI	2014	50 kCHF Yes
Stripper Mechanism – Old, unmaintained design with no spare bellow. Almost complete.	-	EN-STI	2015	106 kCHF Yes
Low energy beam bending chamber Missing spare for this complex rectangular chamber, suffering from beam damage. Being financed from operation money, which leads to holes elsewhere.	1	TE-VSC	Now	100 kCHF No

Table 3b: Linac3 consolidation requests.

Item	Priority	Group	When	Approved
The driver amplifiers for bunchers, debuncher and ramping cavity; Missing spare amplifier for ramping cavity. All three systems are becoming obsolete.	1	BE-RF	LS2	60 kCHF No
Ion Pumps damaged after Ar run Poor vacuum degrades Pb beam performance.	1	TE-VSC	2015	30 kCHF No
The Frank James amplifiers. Replacement of small parts.	1	BE-RF	2016	25 kCHF No
Critical cavity spares (tuners, couplers) for RFQ, IH, bunchers etc. Includes potentially critical items without spares.	1	BE-RF	?	?

.

PSB AND PS CONSOLIDATION FOR LS2 AND BEYOND

S. Gilardoni, K. Hanke, D. Hay, S. Mataguez, B. Mikulec, R. Steerenberg,

CERN, Geneva, Switzerland

Abstract

The consolidation activities proposed for the PSB and PS until the end of LS2 will be revised. Particular attention is given to the activities with direct impact on machine operation and machine performances. The analysis on the interventions and priorities proposed will be done by system (e.g. injection, extraction, RF, beam instrumentation, etc..), with the goal of verifying that the consolidation activities of a specific item is consistently taken into account by the different groups.

INTRODUCTION

The consolidation activities proposed for the PSB and PS are revised with the goal of verifying that the consolidation activities of specific items are consistently taken into account by the different groups and considering activities with direct impact on machine operation and machine performances.

Activities are categorized according to the following families:

- Activities Not Approved but needed to operate the machine effectively (NA).
- Activities Approved and Needed to operate the machine effectively (AN).
- Activities Approved or Not Approved but Not Urgent to operate effectively the machine (NU).
- Activity in LIU because PICS and/or upgrade (PICS= PERFORMANCE IMPROVING CONSOLIDATION) (LIU).

The analysis was done on the different activities considering only the ones impacting directly on PS-PSB operation and machine performances. As example, the asbestos removal from buildings or cooling pipes is considered as an important intervention but without a direct impact on machine performances. The same for the AUG (Systèmes d’arrêts d’urgence généraux), which are fundamental in case of an accident requiring a prompt cut of the electrical network, but have no impact on machine operation (if properly maintained). Both topics are not subject of this work.

Concerning the general infrastructure, even if it might look like less impacting the daily operations, one has to consider that if there are no good cables or good cranes, keeping the machine running with high reliability can become an issue. Still, this will not be a subject of a detailed analysis.

Last but not least, consolidation activities related to radioprotection (RP) are not included because are not part of the accelerator consolidation project, but profit from a dedicated one.

The paper is based on the information provided by the different equipment groups and presented in the different IEFC meetings (see BIBLIOGRAPHY section).

PSB INJECTION

H$^-$ Injection Operational after LS2 (LIU)

The PSB injection will be completely rebuilt during LS2 to allow for the connection of the Linac4. The main elements related to the 50 MeV proton injection are going to be replaced by the ones of the 160 MeV H$^-$ injection.

Injection line magnets to be consolidated (AN)

The consolidation of the LT-LTB(-BI) that will remain in operation even during the L4 era has been approved.

PS INJECTION CONSOLIDATION

New Injection Elements for 2 GeV Operation (LIU)

The main injection elements of the PS currently in use for the 1.4 GeV operation (septum and bumpers plus their power converters) are not compatible with the future 2 GeV operation and they are going to be replaced during LS2. Until then, the usual maintenance will be sufficient to maintain the current machine reliability.

KFA45 Tank (AN)

The vacuum tank of the injection kicker is considered as a single point of failure, with no spare available in case of need for an urgent replacement. The construction of a spare has been approved and should be ready by LS2.

PSB LATTICE SYSTEMS

As “lattice systems” are intended all the magnetic ring elements used during the accelerating cycle.

Spare Coils for Multipole Stacks (AN)

Multipoles, up to skew octupoles, are heavily present in the PSB lattice since its construction. In total there are 112 units currently installed. They were originally conceived for chromaticity control and resonance compensation. The approved proposal foresees the production of 2 spare units for each of the 4 families currently not covered by spares, for a total of 8 new units.

Cooling Circuit Main Magnets (LIU)

The cooling circuit of the main magnets is going to be renovated in view of the 2 GeV operation planned after LS2.

Spare Coils for Main Bends (AN)

Spare coils for the main bends will be made available in view of the 2 GeV operation, requiring larger magnetic field and thus larger currents, which is more demanding for the 40 years old coils.

PS LATTICE SYSTEMS

As for the PSB, the "lattice systems" identify all the magnetic ring elements used during the accelerating cycle.

Main Magnet Units Renovation (NA)

In the last few years since 2005, ~55 main magnet units were renovated by replacing the main coils and the pole-face windings by newly produced ones. The renovated units were chosen on the basis of the radiation damage and the risk of breakdown due to bad insulation.

It is proposed to partially renovate all the remaining ~45 units during LS2 by replacing only the pole-face windings for which signs of degradation of the insulation have been observed. In fact, in case of multiple magnet failures during a run, there is a certain risk of long down time since only one magnet unit per magnet type is available.

The intervention implies the removal of the ~45 magnets from the tunnel and the dismantling of their vacuum chambers. The replacement of the chamber enameled flanges, consumed by the repeated opening of the vacuum during the last decades, could be carried out during the same period.

Considering the fact that this intervention would consist of the removal of more than 45% of the machine elements, a staged approach could be considered.

Magnets/Power Converters for Low Energy Correctors (LIU)

Some of the existing correctors used at low energy are no longer compatible with the future 2 GeV operation. For this reason, the vertical and the skew correctors are going to be replaced. The low energy quadrupole magnets and the back-leg windings will remain un-touched.

All the power converters of the correctors are going to be replaced by new ones with increased maximum current before LS2.

PSB RF SYSTEMS

Replacement of C02, C04 Systems (LIU)

The C02 and C04 RF systems, both based on ferrite loaded cavities, should be replaced by a single broad-band system based on the Finemet© technology. After a first series of tests, a degradation of the final amplifiers once exposed for a long time to a significant amount of radiation was observed. The final decision on the new system installation will be taken in 2016. In case it would not be possible to install the new Finemet© system, the C02 and C04 are going to be consolidated such that they will also be compatible with the future LIU beam parameters.

C16 Renovation (AN)

The C16 RF system will be renovated.

A Modern Interlock and Control Interface (AN)

The old G64 interface is going to be replaced by a more modern one.

PS RF SYSTEMS

10 MHz Power System (LIU)

The power amplifiers of the 10 MHz main accelerating cavities are going to be renovated by LS2 to cope with the future LIU intensities.

In the same framework, a new gap relay development is ongoing, since a unique company produces the existing gap relays and CERN is the only customer for this device.

40/80 MHz Power Converters (AN)

The existing power converters of the 40 and 80 MHz cavities used for the production of the LHC-type beams are now reaching their end of life. The Inverpower 150 kVA power converters are showing a reduced reliability and are clearly limiting the 40 MHz system performances. The new power converters will be able to deliver up to three times more current than the existing ones.

A Modern Interlock and Control Interface (AN)

The old interlock system and its G64 interface is going to be replaced by a more modern one. This also to avoid a failure of one of the 40 MHz cavities, due to an undetected malfunctioning of the cooling system.

PSB EXTRACTION

Extraction and Recombination Kickers and Septa (LIU)

The renovation of the extraction and recombination kickers and septa is part of LIU in view of the 2 GeV future operation.

Switch Magnet BT-BTP (BT.BHZ10) (LIU)

The magnet BT.BHZ10 directs the beam extracted from the PSB either to the PS via the BTP line or to the external PSB dump or ISOLDE via the BTM line. The magnet is going to be replaced in view of the future 2 GeV operation.

PS EXTRACTION

Spare KFA71-79 Modules (AN)

The extraction kicker KFA71 is composed of 12 independent modules located respectively, 9 in straight section (SS) 71 and 3 in SS79. Spare modules are going to be built, since the production of the LHC beams depends on the availability of the kicker.

New oil circuits, as for the other kickers of the CPS complex, are going to be installed.

Additional Spare Magnetic SMH16 + 57 (AN)

The magnetic septum located in SS16 is used to deliver the beams to the SPS whereas the magnetic septum in SS57 is used for the slow extracted beams towards the EAST Area. Both need new spares for potential replacements of the operational ones.

BEAM DIAGNOSTICS SYSTEM

Wire Scanners (LIU)

A new generation of wire scanners should replace the existing ones by the end of LS2. The activity is part of the LIU project.

TV Beam Observation System (BTV) (NA)

The BTV system is considered fundamental for the daily operation of the CPS complex. There are also lines like the ones of the EAST Area where the beam can be steered and brought to the experimental zones exclusively by using the BTVs. Currently the electronics, the cameras and control systems for video distributions need consolidation that was not approved. This is should be considered a high priority task.

PSB Beam Loss Monitors and Fast PS/PSB Loss Monitors (LIU)

The PSB ACEM beam loss monitors in the ring are going to be replaced by LHC-type ionization chambers. Additional ionization chamber beam loss monitors with a flat geometry more adapted to the tight space available between the different PSB rings will be added to increase the coverage. Moreover LHC-type beam loss monitors will replace the ACEMs installed in all the PSB injection and transfer lines.

A series of diamond-type detectors are going to be installed in the PS and PSB to monitor fast losses in specific locations, like the injection and the extraction regions.

PS Beam Loss Monitors (NU)

The PS ACEM beam loss monitors, as for the PSB case, could be replaced by LHC-type ionization chambers, in view of having a common technology in all the injector complex, but also to eradicate the now 30 years old ACEM detectors. The number of available spares is decreasing and the calibration procedure is not compliant with the ALARA (‘As Low As Reasonably Achievable’) principle. For the moment, only the budget to renovate the acquisition electronics is secured.

PROTECTION SYSTEMS AND DEVICES

WIC – Warm Magnet Interlock Controller (NU)

Almost all the machines of the LHC injector complex are protected by a dedicated WIC, whose role is for example to protect the warm magnets from overheating. The only exceptions are the transfer lines between the PSB and the PS, the PS ring and TT2. Whereas the existing interlock system might be maintained, a new WIC would be more meaningful with respect to the rest of CERN. LS2 would also probably be the best moment to implement the new WIC, considering that during LS2 a big cabling campaign will take place and about 75% of the WIC implementation constitutes cabling activities.

BIS – Beam Interlock System (NU)

The BIS is used to protect the accelerators to inhibit beam operation if a subsystem indicates that it is not ready for safe beam production. Whereas it is clearly a necessary system for the LHC, the SPS and the future operation of the PSB with the Linac4, the necessity of a BIS in the PS is less clear. In any case, a future BIS in the PS should be considered as a new project, and not part of the consolidation, since there are no similar systems currently implemented.

Beam Stoppers (NA)

The current situation of the numerous beam stoppers of the PSB and PS could not be evaluated yet, so there is no clear consolidation request yet.

BEAM DUMPS

PSB External Beam Dumps (AN)

The PSB external dump was renovated during LS2 due to its ageing, but also to be compatible with the future 2 GeV operation.

PS Internal Beam Dumps (LIU)

The PS internal beam dumps are not any longer adequate for a safe operation with the existing LHC-type beams in case of a failure of the cooling system and their use is not possible with the future LIU-type beams.

A new design of the internal dumps is progressing within the LIU project, together with the consolidation of their control system.

VACUUM SYSTEMS

PSB Vacuum Systems (NU)

The vacuum of the PSB is considered of very good quality, and the PSB is going to produce, also in the future, exclusively protons. For this reason, the replacement of the TMP (turbo molecular pumps) and the old ion pump groups is not considered a high priority. The two activities are considered important, but in view of the optimization of limited resources less urgent than other interventions.

PS Vacuum Systems (NA)

The success of the ion run in the PS is also the result of the high vacuum quality maintained during the years. For this reason, the consolidation of vacuum pumps, gauges and valves and TMP pumping groups should continue without any loss of continuity. An additional argument for renovation is also the evidence of corrosion found on some of the vacuum systems that might degrade significantly the vacuum and thus the beam quality during future ion runs.

CV ACTIVITIES

PSB

For the Cooling and Ventilation of the PSB there are two main activities, which are considered as high priority to secure beam operation, but that were not approved for consolidation:

- *Replacement of the ventilation system (NA).*
- *Refurbishment of the demineralized water-cooling plant (NA).*

PS

Considering the PS activities, two main interventions will take place by the end of LS2, i.e.:

- *Conclude works started in 2000 on the chilled water pipes (removal of asbestos) (AN).*
- *Consolidation of the Cooling stations (AN).*

Two other activities, instead, which have a direct impact on the machine operation have not been approved yet, i.e.:

- *Consolidation of the PS central building cooling station (RF building) (NA)*
- *Consolidation of the warm water network in the PS area (NA).*

POWER SYSTEM

Electrical Distribution (NA)

A new SVC (Static Var Compensator) is needed with a new sub-station ME59, and requested for LS2.

Main Power Converters

The PS is currently running on the new POPS (Power for the PS) capacitor-based main power converter. After the identification of some degradation of the capacitor banks, their status and an eventual replacement is still under investigation.

During a recent campaign of high-voltage tests for the PS main unit bus bars, it was found that there are no spare parts for the machine-to-power generator bus bars. *Their procurement is considered a high-priority task (NA).*

The existing PSB main power converter is not going to be consolidated since a new one, based on the same POPS technology, will be built by LS2 to allow operation at 2 GeV (LIU).

Auxiliary Power Converters

About 20% of the auxiliary power converters of the PSB and the PS are planned to be renovated (AN).

The BT.BHZ10 will receive a new power converter compatible with 2 GeV operation (LIU). The details of the interaction with the access system for enhanced safety (2 power converters) are still under discussion.

A new generation of high precision current digital control loop has been already deployed in the PSB and for some PS equipments. *This FGC (Function Generator Controller) based control* should be deployed almost everywhere by the end of LS2 *(NA).*

CIVIL ENGINEERING

The civil engineering interventions related to consolidation could not be defined in detail, since depending on cabling, CV and other group activities, which are also not sufficiently well defined yet to determine now the priorities, except for:

- *Work for chilled water upgrade of PS/PSB to be concluded during LS2 (AN).*
- *The work related to the cable campaigns (clean-up or installations), whose details are not yet defined (NA).*
- *Flushing of PS tunnel drains (AN).* This activity should not be underestimated, since in 2014 the PS had to stop for nearly 1 day because of a water leak in the EAST zone that could not be properly evacuated due to dirty drains.

GENERAL CONTROL SYSTEM

OASIS - Open Analogue Signal Information System (AN)

The OASIS system provides to the CCC the acquisition and display of analogue signals of the different machine equipments and it is an indispensable tool for machine monitoring during daily operation.
OASIS is a VXI-based system with multiplexers and a triggering system that must be maintained operational and consolidated on a regular basis.

Operational Databases Upgrade (NA)

The consolidation of the operational database includes the upgrade of the disk controllers, servers and network switches. In particular, the IT maintenance policy requires the replacement of the hardware no longer covered by warranty. By definition, the operation of the machines needs a consolidated operational database, storing all the machine settings for the different physics users.

CompactPCI FECs (NU)

The consolidation of the Intel Single board computers (CPU boards) used for the local front-ends is required because after 2017 it could be impossible to install new LINUX operating systems for OASIS, RF and ABT systems and thus could introduce IT security issues.

PLS-SU Receivers (NA)

The PLS receivers, about 100 in the entire complex, are local electronic boards generating a specific cycle timing for selected users. These receivers are located for example in the local control rooms or in the equipment rooms.

Their unavailability can significantly hamper the diagnostics possibilities, for example for the RF/BI experts, and their replacement is considered pretty urgent.

TTL-Blocking Converters (NA)

The timing pulse distribution in the injector complex is mostly done using Blocking logic levels (24V), for a total of 400 TTL-Blocking systems, designed and manufactured in the 1980's, which now are becoming obsolete. A new system, already proposed, can offer remote monitoring and failure detection. The replacement of the converters is considered a high priority.

Septa and Kicker Controls

The septa and kicker controls are outdated with respect to more modern systems used elsewhere in the LHC and the injector complex. A harmonization of the system is planned by the end of LS2.

CABLES

PS Licker/Septa Cables

There is going to be *a renovation of new electrostatic septa HV cables (AN)*, which in many places are considered as consumable items due to the fast decay of the material properties induced by radiation.

The renovation of the 80 kV kicker HV cables (AN) is going to take place, partially in collaboration with LIU.

The PFL RG220 cables in B.359 (NU) are reaching their end-of-life, but their replacement is not considered an urgent activity.

Cable Clean-up Campaign (NA)

The PSB and PS complex is suffering from, now endemic, missing space for new cables due to the cumulative installation of new cables done in the past without a parallel clean-up of existing, obsolete, and un-used ones. A clean-up campaign should take place as soon as possible, in particular to allow the installation of new equipment foreseen for LS2, but also to assure the correct functioning of the existing devices. During LS1, a campaign to identify un-used cables was extensively carried out in the PSB and the PS, with the goal of removing the kilometres of unused cables between now and LS2.

Particularly crowded and thus critical regions have been identified:

- Bld. 360-361 (under the Booster), BCER, BOR, BAT
- Bld. 354, room CCR et MNR, gallery 815
- Gallery TP9 between Bld. 354 and Bld. 361
- Bld. 353 (ring center) and tunnel of PS Bld. 350.

TRANSPORT

The renovation of transport elements is necessary to assure fast and effective interventions during normal machine operation. Currently, the budget for the remaining main activities in the PSB and the PS, i.e. the crane *PS (B151) – PR3 (40t) and the PSB table (AN)* are both approved. Possibly interventions should be concluded before LS2, when important activities will take place in the PSB/PS.

ELECTRICAL NETWORKS

LV Distribution Network Consolidation (NA)

The obsolete elements of the Low Voltage distribution network must be replaced in many systems, but instead of proceeding for a 1-for-1 exchange, a more detailed analysis will be done with upgrade programs to identify the new and critical installations.

Consolidation of Meyrin HT Infrastructure

The consolidation of the HT infrastructure of Meyrin will not impact specifically on machine operation, with the only exception of a minor *PSB-related part already included in LIU (LIU).*

TT2

Power Converter Consolidation (AN)

The consolidation of the power converters of TT2 has been approved for LS2 and a functional specification document has already been approved in preparation of the power converter family design.

Magnet Renovation (NA)

The magnets of TT2 clearly show signs of degradation due to their ageing and numerous cycles. In total, 36 more magnets, together with their cooling circuit, should be refurbished during LS2.

Beam Loss Monitors (NU)

As for the PS ring, the replacement of the ACEM monitors would bring more modern and maintainable detectors also in TT2.

CONCLUSIONS

The consolidation activities mentioned in the paper are of fundamental importance to keep high machine availability and performance for the PSB, now more than 40 years old, and the PS, more than 50 years old.

The presented vision is from only one perspective, i.e. from the point of view of the activities proposed for consolidation that seem to impact directly on machine operation, and the presented list is most probably not exhaustive.

It is considered vital that consolidation activities with direct impact on injector upgrades will continue to be budgeted and executed according to LIU time lines. This is particular important for the PSB, as reported in EDMS 1082646 v.3 (see sec. 20.2.17).

BIBLIOGRAPHY

[1] Chamonix IEFC Session: Beam Instrumentation Consolidation, R. Jones, L. Søby, 18th June 2014, 104th IEFC, https://indico.cern.ch/event/325142/

[2] Chamonix IEFC Session: BE-CO Consolidation, S. Deghaye, 29th August 2014, 112th IEFC, https://indico.cern.ch/event/337432/

[3] Chamonix IEFC session: BE-RF Consolidation, C. Rossi, 11th July 2014, 106th IEFC, https://indico.cern.ch/event/329923/

[4] Chamonix IEFC Session: DGS-RP Consolidation, D. Perrin, 18th July 2014, 107th IEFC, https://indico.cern.ch/event/331195/

[5] Chamonix IEFC Session: EN-CV Consolidation, S. Deleval, 1st August 2014, 108th IEFC, https://indico.cern.ch/event/333383/

[6] Chamonix IEFC Session: EN-EL Consolidation, D. Bozzini, 5th September 2014, 113th IEFC, https://indico.cern.ch/event/338872/

[7] Chamonix IEFC Session: EN-HE Consolidation, I. Rühl, 22nd August 2014, 111th IEFC, https://indico.cern.ch/event/335579/

[8] Chamonix IEFC Session: Beam Intercepting Devices Consolidation, R. Losito, 18th June 2014, 104th IEFC, https://indico.cern.ch/event/325142/

[9] Chamonix IEFC Session: GS-ASE Consolidation, P. Ninin, 29th August 2014, 112th IEFC, https://indico.cern.ch/event/337432/

[10] Chamonix IEFC Session: GS-SE Consolidation, L. Scibile, 29th August 2014, 112th IEFC, https://indico.cern.ch/event/337432/

[11] Chamonix IEFC session: TE-ABT Consolidation, B. Goddard, 11th July 2014, 106th IEFC, https://indico.cern.ch/event/329923/

[12] Chamonix IEFC Session: Power Converters Consolidation, J-P. Burnet, 6th June 2014, 103rd IEFC, https://indico.cern.ch/event/321213/

[13] Chamonix IEFC Session: TE-MPE Consolidation, B. Puccio, 8th August 2014, 109th IEFC, https://indico.cern.ch/event/334158/

[14] Chamonix IEFC Session: Magnets Consolidation, D. Tommasini, 18th June 2014, 104th IEFC, https://indico.cern.ch/event/325142/

[15] Chamonix IEFC Session: TE-VSC Consolidation, J. Ferreira Somoza, 22nd August 2014, 111th IEFC, https://indico.cern.ch/event/335579/

SPS CONSOLIDATION FOR LS2 AND BEYOND

J. Ridewood, CERN, Geneva, Switzerland

Abstract

As a major part of the LHC injector chain and with its own dedicated physics program it is essential that the SPS remains capable of reliably providing high quality beams.

This presentation will give an overview of the consolidation plans concerning the SPS and its transfer lines as provided by each of the equipment groups to the IEFC committee. The overview will be presented from a perspective of machine operation.

These consolidation plans will be reviewed focusing principally on the impact on operation with beam and will endeavour to highlight any of the works that are of particular interest or represent a particular concern for operations.

This presentation will not focus on LIU or other project work unless there is a direct consequence of one upon the other.

INTRODUCTION

A brief overview of each equipment group’s main consolidation plans, as presented to the IEFC, was shown detailing a brief explanation of the works and the reasons behind their necessity also some detail, where available, of budget and approximate dates of execution.

Each consolidation project was then considered by SPS operations as to its importance to be able to effectively operate the SPS complex. The following rating system was used

- Activities not approved but needed to operate the machine effectively.
- Activities approved and needed to operate the machine effectively.
- Activities approved and needed to operate the machine effectively
- Activity partially covered by LIU or depends upon LIU

It was felt that this grading system did not allow the possibility to establish a level of priority amongst those works which were deemed as needed to effectively operate the machine therefore we added a further prioritisation: High, Medium and Low with a brief explanation as to why the prioritisation was given.

The activities highlighted in red were deemed necessary to operate the machine however this grading is not always simple to apply as the systems currently in place could be considered as functioning correctly and not causing significant machine downtime but their upgrade could be necessary to provide newly required functionality or as part of a longer term view towards reliability.

Also for those groups whose equipment does not have a direct impact on operation with beam they are often evaluated as having a low priority from an operations standpoint but their correct functioning may indeed have a secondary impact on operations or impact other factors important to the safe operation of the beam.

During the presentation the consolidation plans were considered alphabetically by group.

BE-BI – L. SØBY AND R. JONES [1]

Installation of TT10 Beam Loss Monitors (BLM)

At the present time there are no BLMs installed in TT10 however this is the only beam line in the SPS complex which is not equipped with BLMs and is therefore considered as part of a coherent strategy to renew all systems from LINAC4 to SPS with the same system. They estimate the cost to be 150kCHF in electronics and 500kCHF in cabling during LS2. SPS operations consider this to be of medium importance as this does not hinder machine operation but BLMs could be of use particularly during periods of setting up and to identify injection trajectory issues more quickly and therefore potentially reduce doses to those having to work in the line.

SPS Ring BLM Electronics Renovation

This project was originally intended as part of LIU but due to manpower constraints it cannot be executed until after LS2. BE-BI propose to install new, radiation hard ASICs (Application Specific Integrated Circuit) devices connected via the new BE-BI fibre optic network due for commissioning during LS2). They estimate a cost of 900kCHF and would intend its installation to take place from 2019-2024. SPS operations consider this to be an important upgrade as this should allow us to read the beam loss rate throughout the cycle and not simply the integral, which is currently the case. This would allow us to apply what we call “sunglasses” meaning that we can hide the losses which we consider “normal” such as injection, scraping or dumping losses so that any abnormal losses are more easily identified. For this reason SPS operations consider it a high priority.

Mechanical Spares for Critical Injector Complex Monitors

A number of BE-BI’s spares for critical injector complex monitors are more than 20 years old and therefore no longer compliant with modern vacuum requirements. SPS operations has already evaluated the importance of each instrument and its effect on operations as part of the BI BOSS workshop and the overall outcome was that the majority of beam instrumentation is essential for the efficient functioning of the SPS complex. It is for this reason and the fact that the unavailability of spares could potentially increase machine downtimes that SPS operations evaluated this as a high priority. They estimated a cost of 300kCHF from 2015-2017

SPS & Transfer Line BCT Renovation

BE-BI propose to renovate both the LSS4 DCCT, sensor and electronics due to a reliance on an external company whose future may not be certain. They also propose the upgrade of the 6 transfer line fast BCTs to LHC standards. They estimate a cost of 200kCHF from 2016 to 2018. SPS operations evaluated this as a medium priority as the current systems are working but it's important that we are not left with unsupported equipment in the longer term.

BE-CO – S. DEGHAYE [2]

Upgrade of OASIS VXI, Multiplexers and Triggering System

This is an approved project to upgrade obsolete hardware and software for the OASIS digital scope system. The replacement of this legacy equipment is intended to provide greater reliability and performance to meet operation's needs. The cost is 1100kCHF from 2014-2016 shared between the SPS and PS (3 systems in SPS and 10 in PS).

Operational Database Hardware Consolidation

The current database hardware is approaching the end of its five-year warranty period and after will no longer be supported. They estimate costs of 230kCHF in 2016 and 365kCHF in 2018. SPS operations evaluated this as a high priority as these databases are essential for systems needed to operate the machine (laser alarms, diamond, data logging, etc.).

Removal of the SPS Intercom

BE-CO propose the removal of the old SPS intercom system due to ageing equipment and soon to be disappearing expertise. They estimate 200kCHF in 2016 for the removal of equipment and cables. The opinion of SPS operations is that this is a low priority because, although old, the intercom system is regularly used and is an important means of communication and has on several occasions proved essential for diffusing important messages to those working in the tunnel. GS-ASE will propose a new public address system and SPS operations requests that the old BE-CO system not be decommissioned until a replacement is operational. It is also noted that the removal of intercom cables could be integrated into the EN-EL campaigns to remove obsolete cabling in the SPS.

Consolidation of Intel Single Board Computers (CPU Boards)

The currently installed boards are not compatible with 64 bit Linux and the end of support for 32 bit SLC5 is announced for 2017. They estimate a cost of 75kCHF in 2015 which covers the SPS and PS. SPS operations considers this a high priority as these machines are required for essential systems (RF, ABT and OASIS).

Replacement of Obsolete Analogue BTV Video Systems

BE-CO propose to replace the obsolete analogue system for BTVs by the new systems developed for LHC. They estimate costs of 400kCHF from 2015-2106. SPS operations considers this to be a medium priority as the majority of the SPS has already been converted to the new digitised system with only TT20 remaining on the obsolete analogue equipment. TT20 should however be updated as soon as possible as BTVs are one of the primary means of re-commissioning this complex extraction channel and transfer line.

BE-RF – C. ROSSI [3]

Renovation of 18kV Power Converters

The RF power converters date from the 80's and have a life expectancy of 20-30 years and over recent years have been showing signs of deterioration. The main part of the consolidation works which consist of replacing HV transformers, capacitors and cabling will be executed by TE-EPC who will take responsibility of this equipment once the consolidation is complete. The cost will be shared with 500kCHF for BE-RF from 2018-2019 and 3MCHF for TE-EPC from 2016-2019. SPS operations consider this a high priority as it will improve the reliability and safety of this essential equipment.

Replacement of the 40 year old Cooling Pipework

To be consolidated for reasons of reliability and personal safety. Costs are estimated at 500kCHF in 2018. SPS operations considers this a medium priority as it is currently functioning satisfactorily but for the safety and reliability of this essential equipment these issues should be addressed soon.

YL Tube Replacement

An approved consolidation plan which is currently underway and entails the replacement of YL tubes due to the original manufacturer ceasing production. BE-RF are currently transferring to a pin for pin replacement provided by Thales costing 2.7MCHF from 2014-2018.

DGS-RP & DGS-SEE – D. PERRIN [4]

Radioprotection Monitoring

The SPS currently uses the ARCON (ARea CONtroller) radiation monitoring system and there is an approved project: GROAC (General Renewal Of Area Controller) to extend its life until the full arrival of RAMSES (RAdiation Monitoring System for the Environment and Safety) in LS2.

Site Gate Monitors and Hand Foot Monitors

DGS-RP propose to consolidate the site gate monitors (700kCHF 2016-2017) and the hand foot monitors (340kCHF 2016-2017). SPS operations consider this a low priority as there is no immediate impact upon operations.

EN-CV – S. DELEVAL [5]

Replacement of the Control System for Chilled Water Systems

This entails the replacement of an obsolete TRANE^{TM} system with the current LHC standard at a cost of 300kCHF from 2015 to 2018. The works are intended to take place during the year-end technical stops.

Upgrade Input/Output Cards of Cooling Control Systems

Upgrade to a full Siemens S7 infrastructure at a cost of 100kCHF from 2015-2017. EN-CV currently has a mix of S5 and S7 generation equipment which is proving unreliable. SPS operations considers this a relatively low priority as up to now this does not appear to have incurred any significant machine downtime.

Replacement of The Control And Power Cubicles, Sensors and Actuators for BA Ventilation

EN-CV propose to replace the control and power cubicles along with sensors and actuators for BA surface building ventilation costing 2060kCHF from 2015-2019. SPS operations consider this to be a low priority as it was clarified that these works will not affect the tunnel ventilation however certain surface building equipment may be indirectly affected e.g. Faraday cage, RF power equipment, power supplies, kicker systems, etc.

Renovation of the SPS Sumps

The SPS sumps level switches and pumps are ageing and starting to become unreliable. EN-CV estimate costs of 350kCHF from 2015 to 2018. SPS operations consider this to be a medium priority as although it has no direct impact on operations with beam it is essential for the evacuation of infiltration and floodwater during periods of prolonged heavy rain.

SPS Cooling Towers Upgrade

The SPS cooling towers require upgrade by the addition of a fifth cooling cell during LS2. This upgrade is primarily to cover the increased power needs coming from LIU and AWAKE however the cooling towers are already working at or above their limit. EN-CV explained that they currently have a derogation from HSE to be able to purge a minimal amount of warm water to the local river system during periods of high load. This is a situation which obviously should not exist in the longer term. Discussions are on-going as to the budget split between LIU and consolidation. SPS operations consider this a high priority as the system is already working at its limit and must be able to cope with future needs.

EN-CV concluded by stating that the technical needs exceed by far the possibilities and that a reduction of operational performance has to be taken into account. They also said that the works foreseen for LS2 are already double what was planned for LS1.

EN-EL – D. BOZZINI [6]

Consolidation of SPS Substations Switchgear

EN-EL has approved plans to consolidate the switchgear at each BA as a continuation of the 18kV cabling works executed during LS1. This is to cost 12.1MCHF from 2014-2018.

Consolidation of SPS HV and LV (BA4 and BA5) Secured Network

EN-EL also propose to consolidate the SPS HV and LV secured network supplying BA4, BB4, BA5 and BB5 which is currently fed from a single, 40 year old infrastructure. They estimate the cost at 1.45MCHF from 2016-2017. The current configuration allows no discrimination in the event of a fault and would therefore trip all four areas should there be a fault on any one. The secured network provides power to certain systems needed for personnel safety such as lifts and smoke extraction and therefore SPS operation. SPS operations have given this a high priority because of its importance for those having to intervene in the tunnel and its inevitable impact on operations.

Clean up of Obsolete Cables

EN-EL have highlighted a massive overcrowding of the SPS cable trays with obsolete cables all around the SPS but particularly in BA5. They propose, as part of a campaign, to begin removing those cables which are no longer used. Cable tray space will be required with future upgrades and unused cables represent a fire risk as they are one of the main sources of combustible material in the machine. They estimate the cost at 5.2MCHF in LS2. SPS operations consider this a low priority from an operations point of view but feel it needs to be addressed urgently for future upgrades and for fire prevention.

Irradiated Cable Campaigns

EN-EL proposes to continue the on-going irradiated cable campaigns in the SPS during LS2 with the next location likely to be either TS6- or TS4+. These campaigns are to ensure that cables are replaced ideally before they show signs of deterioration due to radiation. The cost is estimated at 3.2MCHF during LS2. SPS operations consider this to be a high priority as cable breakdowns can cause potentially long stops and are often not trivial to repair without damaging other delicate cables.

LV Distribution Network Consolidation

EN-EL has highlighted problems with the LV distribution network in that the equipment dates from the 70's and approximately 20% are now deemed dangerous. They also state that there are almost no remaining spares and soon the equipment will become unmaintainable. EN-EL propose to consolidate the 20% which are considered dangerous and any others that are required by LIU and suggest a complete revision taking into account both current needs and those of the foreseeable future to strengthen the electrical integrity and in turn reduce downtime and improve safety for EN-EL operations. They estimate the cost at 2MCHF over the next 5 years. SPS operations consider this a high priority because of its inevitable consequences on operations and its impact on personal safety.

48V DC System Consolidation

For very similar reasons EN-EL propose the consolidation of the 48V dc system. This is again equipment dating from the birth of the SPS and consequently there are almost no spares remaining. The 48V dc system provides, amongst others, power for the tunnel emergency lighting. EN-EL indicate that the current system has no redundancy and therefore intend to upgrade the system so that it is fully independent and redundant thus greatly reducing downtime and facilitating maintenance. The cost is estimated at 2.1MCHF for the SPS from 2015-2019 with the majority focused around LS2. SPS operations consider this a medium priority from an operations point of view but suggest it should be addressed urgently due to its impact on personnel safety.

EN-HE – I. RÜHL [7]

Crane Consolidation

EN-HE proposes the consolidation of three large cranes in the SPS:

- BB5 75t PR565
- ECA4 40t PR570
- ECX5 40t rotational PR567

EN-HE also propose the replacement of two smaller cranes in BB3:

- BB3 7.5t PR554
- BB3 7.5t PR555

This work was originally planned for LS2 but they propose to advance to 2015-2016 so that the equipment can be ready and available for use in LS2. The cost would be 750kCHF. SPS operations consider this to be a low priority as there is no direct impact on operation however this could have an indirect impact through delayed return to service.

Goods Lifts Consolidation

EN-HE also state that if major works such as removal and coating of a large number of SPS magnets be undertaken for LIU then the goods lifts would then need consolidation.

EN-STI – R. LOSITO [8]

TIDVG Consolidation

Until recently EN-STI had little consolidation work foreseen in the SPS however with the recent discovery of damage to the TIDVG they have had to consolidate with new core internals blocks costing 250kCHF, which is perhaps a conservative estimate. They also say they have 4 outer shells available in case of a need of replacement, however three of the shells require a cooling circuit modification, the one which does not is the one which was removed from the tunnel this August and is therefore the hottest. Hardware interlocks will be put in place to prevent similar issues reoccurring. SPS considers this to be a medium priority as to reduce any extended downtime in the event of another problem.

As the TEDs have a very similar construction they may also be susceptible to the same issues however their different conditions of use and separate vacuum suggest that consequences would perhaps be slightly less critical.

Beam Intercepting Devices Consolidation Studies

For the reasons mentioned above and due to the fact many of these BIDs (Beam Intercepting Devices) are inherited equipment from other groups, EN-STI propose to initiate consolidation studies for BIDs across the entire injector complex to reconstitute full documentation and ensure compatibility of the currently installed designs with present and future beams. For this they estimate 1640kCHF from 2014-2018.

GS-ASE – P. NININ [9]

Replacement of SPS Access System

GS-ASE has an approved consolidation project to replace the SPS access system bringing it up to the standard now installed in the LHC and PS. This is due to take place from 2014 to LS2 with the majority of installation taking place during LS2 at a cost of 14.5MCHF.

BIW (Beam Imminent Warning) and Evacuation Alarm Upgrade

GS-ASE also propose to consolidate the BIW (Beam Imminent Warning) system in the SPS in parallel with the access system upgrade at a cost of 1.1-1.3MCHF from 2016 to LS2. SPS operations consider this to be a high priority as there have been inconsistencies noted between the access system and BIW system sectorisation which must be addressed.

Renewal of SPS Smoke Detection Pipework

GS-ASE requests the renewal of around 20km of PVC air sampling pipework for smoke detection costing

600kCHF during LS2. SPS operations consider this a low priority due to it not having a direct impact on operations but feel that it should be addressed in conjunction with other fire prevention upgrades.

Installation of SPS Public Address System

GS-ASE has also proposed a public address system as a replacement to the BE-CO intercom system, which is approaching end of life. The investigations are still at an early stage so budget and planning are yet to be established however first estimations indicate a cost of around 250kCHF. At the present time a public address system is the only efficient means of evacuating the tunnel therefore SPS operations consider this a high priority and recommends that the BE-CO intercom not be decommissioned until the new GS-ASE system is operational.

SPS Fire Safety Improvements

GS-ASE in conjunction with HSE and GS-FB have been considering general fire safety improvements to the SPS including modified sectorisation, advanced fire alarms and auto extinguish systems, amongst others. Discussions are still in the early stages but the outcome of recent presentations to the SPS CSAP suggest that a full study of improvements relating to fire safety should be requested. These improvements should comply with external standards for insurance and the safety of external fire fighters. SPS operations consider this a low priority from the point of view of machine operation but recognises that the SPS requires urgent attention in terms of fire safety and it has the full backing of the SPS CSAP.

GS-SE – L. SCIBILE [10]

Monitoring of Sensitive Tunnel Sections

The main component of GS-ASE’s consolidation work is in the monitoring of the SPS tunnel infrastructure. Phase one being the installation of fibre optic monitoring of the recently consolidated TT10 tunnel to gain experience and phase 2 being the extension of this and other monitoring techniques such as photogrammetry and geo-radar to other potentially sensitive tunnel areas. They estimate the cost to be 500kCHF from 2015 to 2018. SPS operations considers this to be a low priority as there is very little chance this would have an impact on operations however we need to know if there are serious structural issues in the tunnel infrastructure.

SPS Technical Ducts Consolidation

The recent failure of an SPS technical duct at the tunnel entrance at BA4 during the transport of the TIDVG due to degraded concrete coupled with an insufficient design highlighted that these ducts were no longer capable of withstanding the necessary transport loads. A temporary solution is in place with a permanent repair for BA4 planned during the Christmas 2014/2015 technical stop and a permanent repair in all other BAs by LS2 or before. It is understood that these works are covered under an approved budget for SPS studies and works underground. SPS operations consider this a high priority as this poses a serious risk to the transport of potentially radioactive equipment.

TE-ABT – B. GODDARD [11]

Assemble MKDH Spare

TE-ABT propose to assemble a spare horizontal dump kicker magnet (MKDH) as currently there is no spare available. The cost is estimated at 160kCHF in 2018. SPS operations considers this to be a medium priority as TE-ABT say that the risk of an MKDH failure is relatively slim and in most cases the return to service would be largely dictated by its reconditioning.

Upgrade MKP Thyratron Switches

TE-ABT has an approved project to replace the thyratron switches for the MKP in an effort to reduce the number of different types and therefore increase spare availability costing 200kCHF in 2017.

Construct New Septum Yokes

TE-ABT has another approved project to construct new septum yokes for MSE and MST magnet spares costing 200kCHF in 2015

Radiation-hard Potentiometers for Septa

Another approved project is the procurement of new radiation resistant potentiometers for septa girder position measurement.

Replace ZS HV Generator

TE-ABT propose also to replace the Electrostatic septum (ZS) HV generator at a cost of 230KCHF however due to a fault it has recently been refurbished and its replacement has been postponed until 2021 Therefore SPS operations consider this a low priority.

Renew Kicker Timing and MS Controls

Another approved consolidation project for TE-ABT is the renewal of kicker timing and magnetic septa control electronics costing 210kCHF in 2017.

Upgrade Fast Thyratron Interlocking

TE-ABT propose to upgrade the fast thyratron interlocking system as it is still using LEP era electronics. Estimated to cost 250kCHF in 2018 SPS operations consider this to be of medium priority as this would hopefully help reduce the frequency of damaged switches and therefore reduce downtime.

Modernise Kicker/Septa Controls

TE-ABT also intend to modernise the kicker and septa controls to current standards and to standardise the control electronics across installations and machines. This is estimated to cost 1460kCHF in 2018 for both the PS and SPS with the SPS representing approximately 30%. SPS operations evaluate this to be a low priority as the current systems function adequately and the new system does not appear to offer significant operational advantages.

New MKDV Generators and Controls

This is motivated by the replacement of the mercury ignitron switches by solid state switches both for reasons of safety and reliability. It will also include the reconfiguration of the MKDV so that the risk of damaging one of the MKDV magnets is reduced. This work will cost 800kCHF in 2019 and will also be partially covered under LIU with the eventual budget split still to be decided. SPS operations consider this to be of medium priority as it will reduce the risk of damaging MKDV magnets.

New Electrostatic Septa Cables

An approved project exists to replace the ageing cable that descends the vertical access shaft in BA2 costing 240kCHF and scheduled for 2017

Renew MKP RG200 Cables

This entails the replacement of injection kicker (MKP) cables due to normal HV cable degradation which is exacerbated by radiation. SPS operations considers this to be a low priority as these cables have been recently replaced during the LSS1 irradiated cable campaign and TE-ABT have said they would have some spare stock available from the new PS injection kicker installation should a breakdown occur. For these reasons SPS operations consider this a low priority for the foreseeable future.

Upgrade Thermal Interlocks

This is an approved project to upgrade the thermal interlocks to ensure their reliability and safety. The cost is 110kCHF in 2017.

Kicker Oil System Fire Prevention

To bring deficient kicker system areas up to the current standard as installed in LSS4 by means of firewall partitioning, fire detection etc. Cost is estimated to be 290kCHF in 2016. SPS operations consider this a low priority from an operations standpoint however it remains important from the need to improve SPS general fire prevention measures.

Kicker Discharge and Earthing Switches

To install automatic capacitor discharging and earthing systems as it is currently a partially manual system with a small risk of human error. Estimated to cost 180kCHF and scheduled for 2016. SPS operations consider this to be a low priority for operations but important for personnel safety.

Consolidation of SPS LSS4 Extraction Kicker Configuration

To reconfigure the extraction kickers in LSS4 now that the fast rise times required by CNGS are no longer needed. They propose to have the same configuration as in LSS6, which is effectively five times less complex. The removal of pulse forming networks (PFN), switches and magnets would mean greater reliability due to fewer components, better spares availability and removal of unnecessary impedance. Cost and schedule are still to be confirmed. SPS operations for the reasons indicated above consider this to be a medium priority.

TE-ABT explained that manpower is their main limiting factor for consolidation and requested that consolidation budget be used for manpower.

TE-EPC - J-P. BURNET [12]

Replacement of SVC BEQ1

This is the approved replacement of the end of life of the BEQ1 static var compensator costing 10.2MCHF during LS2

Replacement of Electronics for Main Dipole and Main Quadrupole Power Supplies

As a follow up to the LS1 converter and transformer consolidation the main dipole and quadrupole electronics are to be consolidated at a cost of 400kCHF in 2017

Replacement of MUGEF by FGC Converter Controls

TE-EPC propose to convert SPS converter controls to FGC in a move to standardise systems across machines and to replace the ageing 70's MUGEF system at a cost of 2MCHF from 2016-2019. TE-EPC also propose to advance the replacement of COD (Orbit Corrector Dipole) power supplies including their upgrade to FGC from LS3 to LS2 at a cost of 3MCHF thus transferring the entirety of the SPS, with the exception of TT20, to FGC controls. TT20 would be upgraded in conjunction with the north area in LS3. SPS operations consider this to be a medium priority as it would allow greater reliability, versatility and flexibility.

Renovation of 18kV Power Converters for RF Power

As previously detailed as part of BE-RF consolidation. TE-EPC will be heavily involved in its consolidation and will take responsibility once complete.

TE-MPE – B. PUCCIO [13]

Installation of WIC in TT10 and TT20

TT10 and TT20 are the only lines remaining in the SPS that are not covered by the WIC (Warm magnet Interlock Controller). TT10 is therefore the missing link in the injector chain. TE-MPE propose to install TT10 in 2017-2018 in conjunction with TE-EPC converter upgrades at a cost of 400kCHF and TT20 after LS2 at a cost of 900kCHF in conjunction with north area upgrades. TE-EPC point out that approximately 75% of these cost are for cabling. SPS operations consider this to be a low priority as the currently installed system, although ageing, functions satisfactorily.

Installation of BIS System in TT10

To install the Beam Interlock System in the TT10 transfer line. TT10 and TT20 are the only lines not yet covered by the BIS meaning TT10 is again the missing link in the LHC injector chain. Costs are not yet fully established but are estimated in the region of 200-400kCHF with execution to take place during LS2. SPS operations consider this to be a medium priority as future higher energy and intensity injected beams will require greater protection.

Replacement of SPS Ring Magnet Interconnection Boxes "Trèfles"

The "Trèfles" are local magnet over temperature indicators that are designed to latch at a predetermined temperature to indicate magnet or cooling circuit issues. With age these mechanical devices are starting to become unreliable, not always latching as they should. Their replacement is estimated to cost 100kCHF in 2018. SPS operations consider this to be a low priority as to date this has not caused any significant delay to the diagnosis of magnet issues.

Increased WIC Granularity for SPS

The WIC currently identifies problems by demi sextant. TE-MPE proposes to upgrade the system to be able to identify issues by individual or small groups of magnets at a cost of 600kCHF from 2020-2022. SPS operations consider this to be a low priority as this would represent only a relatively small improvement to the speed of magnet fault diagnosis.

TE-MSC - D. TOMMASINI [14]

Procurement of New SPS Magnet Coils

TE-MSC have an approved consolidation project to procure three new magnet coils to ensure spare availability. One TT10 quadrupole coil (SPQI_NWP) at a cost of 30kCHF, 30 of which are installed in the SPS. One SPLSFN_FWP type and one SPLSDN_FWP SPS ring sextupole coils of which there are 54 of each installed in the SPS. Each sextupole coil will cost 50kCHF.

Manufacture of 10 MBB Dipole Coils

In an effort to return stock to original levels TE-MSC propose to manufacture 10 MBB dipole magnet coils. The MBB magnet coils are susceptible to inter turn short circuits which are not repairable and 10 of the original 22 magnets have been used for this reason. Since 2011 capacitive discharge testing has been used as a means to identify weak magnets before the physics run commences. SPS operations consider this to be a high priority as although it has no immediate impact on operations it is essential for the long term future of the SPS. There are, as yet, insufficient statistics to determine if the rate of failure is increasing and potentially long lead times need to be taken into account.

New Vertical Bumpers MPLV and MPLV

With current stock levels at 2 spares for 3 MPLV type magnets in service and 1 spare for 10 MPSV type magnets in service TE-MSC propose, in conjunction with LIU, to fabricate a new vertical bumper compatible both with the proposed new LIU scraping scheme and the replacement of MPLV and MPSV magnets at a cost of 330kCHF 70% of which to be covered by LIU and 30% by consolidation. If the new LIU scraping scheme does not go ahead TE-MSC propose to manufacture an MPSV type magnet to existing specification. SPS operations consider this to be a medium priority to ensure sufficient spares for operation.

TE-VSC – J. FERREIRA SOMOZA [15]

Replacement of 850 Obsolete Ion Pump Controllers

Ageing ion pump controllers and their associated power supplies are outdated and require replacement to reduce failure rates, reduce downtime and generally improve vacuum performance along with improvements in safety standards. Estimated to cost 3.1MCHF from 2017-2019. SPS considers this to be a medium priority as reliable pumps will be needed for future beams and faster recovery after interventions affecting vacuum.

Installation of RXVA in BA2, BA5, BA6

RXVA are connection boxes local to the ion pumps that, when disconnected, isolate the 6kV power supply. These boxes are not yet implemented in BA2, BA5 or BA6 TE-VSC propose to install these during LS2 at a cost of 180kCHF. SPS operations considers this a low priority for operations but important for the safety of those working in the tunnel, particularly TE-VSC personnel.

Replacement of 1000 VPIA Ion Pumps

To be executed as part of the LIU carbon coating upgrade should it go ahead. To replace ageing vacuum pumps which are working at a reduced capacity meaning degraded vacuum performance and slower recovery. If not executed as part of the LIU coating upgrade then one additional industrial support staff would be required. Costing 2.5MCHF from 2016-2018 with installation taking place during LS2. SPS operations consider this to be a medium priority as good vacuum performance is essential for good beam performance and fast recovery.

Replacement of Ageing Vacuum Valves

TE-VSC propose to replace several of the ageing SPS vacuum valves at a cost of 300kCHF during LS2 as the risk of valve blockage is increasing. A valve blocked closed is an obvious interruption for operations but a valve blocked open can also pose a risk to sensitive, conditioned equipment. It is for the above reasons that SPS operations consider this to be a medium priority.

Re-establishment of Regularly Used Spares

Following LS1 and in preparation for LS2 TE-VSC propose to restock the regularly used spares such as enamelled flanges, damper resistors and chambers needed for maintaining the correct SPS grounding scheme at a cost of 200kCHF from 2015-2016. SPS operations consider this to be a medium priority as, in conjunction with TE-VSC, we have recently been aiming to re-establish correct vacuum grounding to avoid earth loops.

Industrial Support – Manpower

TE-VSC requires additional manpower to be able to meet their consolidation commitments. They estimate that approximately 80% of their LS1 work was support for other groups. Currently only 3 technicians take care of the SPS and as a result they are all approaching their annual dose limits. They request 1 industrial support staff per year with another during LS2 at a cost of 150kCHF per IS per year.

TE-VSC also explained that they are in the process of reviewing their consolidation needs in an effort to reduce costs.

CONCLUSIONS

Many of the consolidation plans depend upon or are awaiting LIU decisions.

Recent events, not detailed in this presentation, indicate that the responsibility for cables between magnets and power supplies needs to be clarified. Since the presentation the responsibility of these cables has officially been assigned to EN-EL.

Consolidation for safety reasons is a recurring theme for several equipment groups in the SPS. Many of the systems in the SPS date form the 70's and have the associated safety standards.

It was also highlighted that once consolidation was approved details of the works should be communicated to EN-MEF for proper planning and integration if not already done.

ACKNOWLEDGMENT

I would like to thank Karel Cornelis especially for his advice in evaluating the priority of each consolidation task.

REFERENCES

[1] Chamonix IEFC Session: Beam Instrumentation Consolidation, R. Jones, L. Søby, 18th June 2014, 104th IEFC, https://indico.cern.ch/event/325142/

[2] Chamonix IEFC Session: BE-CO Consolidation, S. Deghaye, 29th August 2014, 112th IEFC, https://indico.cern.ch/event/337432/

[3] Chamonix IEFC session: BE-RF Consolidation, C. Rossi, 11th July 2014, 106th IEFC, https://indico.cern.ch/event/329923/

[4] Chamonix IEFC Session: DGS-RP Consolidation, D. Perrin, 18th July 2014, 107th IEFC, https://indico.cern.ch/event/331195/

[5] Chamonix IEFC Session: EN-CV Consolidation, S. Deleval, 1st August 2014, 108th IEFC, https://indico.cern.ch/event/333383/

[6] Chamonix IEFC Session: EN-EL Consolidation, D. Bozzini, 5th September 2014, 113th IEFC, https://indico.cern.ch/event/338872/

[7] Chamonix IEFC Session: EN-HE Consolidation, I. Rühl, 22nd August 2014, 111th IEFC, https://indico.cern.ch/event/335579/

[8] Chamonix IEFC Session: Beam Intercepting Devices Consolidation, R. Losito, 18th June 2014, 104th IEFC, https://indico.cern.ch/event/325142/

[9] Chamonix IEFC Session: GS-ASE Consolidation, P. Ninin, 29th August 2014, 112th IEFC, https://indico.cern.ch/event/337432/

[10] Chamonix IEFC Session: GS-SE Consolidation, L. Scibile, 29th August 2014, 112th IEFC, https://indico.cern.ch/event/337432/

[11] Chamonix IEFC session: TE-ABT Consolidation, B. Goddard, 11th July 2014, 106th IEFC, https://indico.cern.ch/event/329923/

[12] Chamonix IEFC Session: Power Converters Consolidation, J-P. Burnet, 6th June 2014, 103rd IEFC, https://indico.cern.ch/event/321213/

[13] Chamonix IEFC Session: TE-MPE Consolidation, B. Puccio, 8th August 2014, 109th IEFC, https://indico.cern.ch/event/334158/

[14] Chamonix IEFC Session: Magnets Consolidation, D. Tommasini, 18th June 2014, 104th IEFC, https://indico.cern.ch/event/325142/

[15] Chamonix IEFC Session: TE-VSC Consolidation, J. Ferreira Somoza, 22nd August 2014, 111th IEFC, https://indico.cern.ch/event/335579/

AD AND LEIR CONSOLIDATION

T.Eriksson, M.-E. Angoletta, L.Arnaudon, J.Baillie, M.Calviani, F.Caspers, M.Cattin, A.Fowler,
L.Joergensen, G.Le Godec, R.Louwerse, M.Ludwig, D.Manglunki, A.Newborough, C.Oliveira,
S.Pasinelli, A.Sinturel, G.Tranquille, CERN, Geneva, Switzerland

Abstract

As the AD programme now faces a renewed lease of life following the start of the ELENA project, it is essential to ensure best possible reliability and performance for the next 20 years or so. The AD machine, which was started in 1999, is based on the Antiproton Collector (AC) ring of the Antiproton Accumulator Complex (AAC) which in turn was constructed in the mid-80:ies. Since most of the major AD components were retained from the AC, we now have a significant amount of 30-year old equipment to deal with.

LEIR is in a similar situation having started life in the 80s, supplying antiproton beams at various energies for the PS physics programme. After having been transformed into a heavy ion accumulator in 2004 and subsequently used in operation, some consolidation needs have become apparent. LEIR is expected to keep delivering heavy ions to the North Area and to the LHC until 2035, and possibly light ions to a new biology research facility in the South Hall.

A consolidation programme is underway for both machines and here we will discuss the main aspects of ongoing and planned activities from an operational point of view.

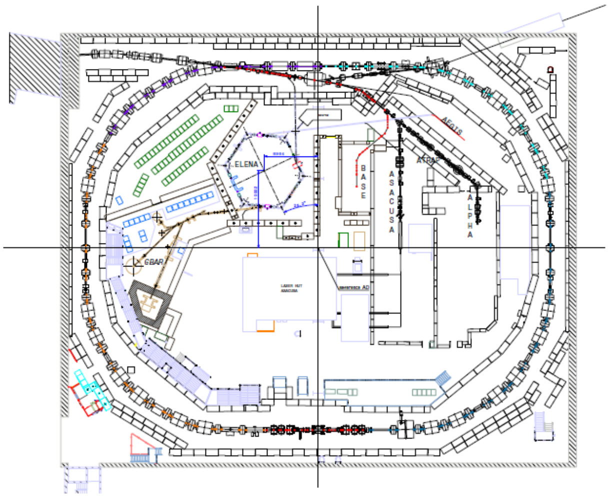


Figure 1: Layout of AD, ELENA and experimental areas.

INTRODUCTION

During more than ten years of regular operation, CERN's Antiproton Decelerator (AD) has supplied the successful physics program with low-energy antiproton beams at 5.3 MeV kinetic energy. The approved Extra Low Energy Antiprotons (ELENA) project will greatly increase the ejected beam density and intensity thereby increasing the number of trapped antiprotons at the experiments by up to two orders of magnitude. ELENA will deliver antiprotons at 100 keV to the experiments as of 2017. For the AD machine itself, an extensive consolidation program has been worked out. To reliably produce antiprotons and deliver them to ELENA for the next 10–20 years, all AD sub-systems have to be renovated or renewed. In total, a budget of some 23.8 MCHF has been allocated for AD consolidation during the period 2014 to 2020.

Layout of AD, ELENA and the experimental areas can be seen in Fig.1.

LEIR (Low Energy Ion Ring) is based on LEAR which was used for antiprotons starting in 1983. No general consolidation plan has yet been defined but a number of consolidation requests have been issued.

AD PRODUCTION TARGET AREA

The AD target area (see Figure 2) is undergoing important consolidation activities which will continue in the next years during the "ELENA era" of the AD machine exploitation. An initial and limited program took place during LS1 treating the most urgent items. A serious breakdown of the Magnetic Horn assembly was discovered in LS1 and repaired just in time for the start-up. This indicates the need for urgent and in-depth consolidation of the whole target area and associated systems. In case of further failures between LS2 and LS3, a significant impact on the AD physics program can be expected as well as increased contamination levels and radiological risks.

The main activities about to start are:

- Studies for a new target design with modified cooling.
- Production of spare Targets and Horns including stripline and junction box.
- Renewal of Target and Horn chariots
- Renovation of cooling and ventilation systems.
- Renovation of surface buildings.
- Additional monitors for beam intensity and position.

A budget totalling some 5.5 MCHF has been requested for the work packages which are spread over various groups/departments. Activities need to start as soon as possible in order to be ready for installation during LS2.

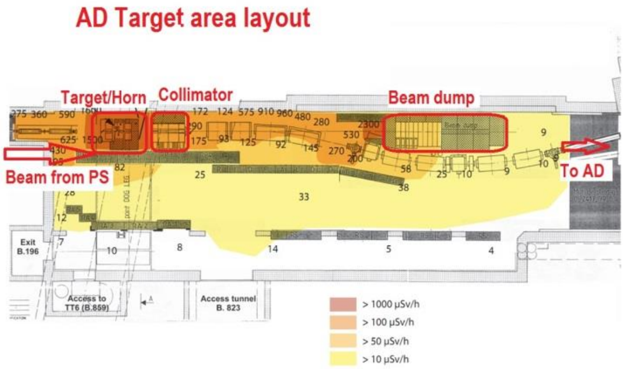


Figure 2: Layout of the production target area

AD MAGNETS

Degradation of the coil shimming has been observed in several of the 24 AD ring bending magnets as movement of the coils in relation to the yokes has gradually increased over the last few years. Renovation of the first unit (DR.BHN06) during LS1 showed that the coil shimming was severely degraded. The coils themselves were in good state and thus re-installed. Regular measurements of the coil movement of the dipoles will determine the order of renovation of the remaining units during the years to come. Procurement of some types of spare coils is about to be completed in order to have a complete set available.

For the ring quadrupoles, no specific needs have been identified as these 57 units underwent a re-shimming campaign a few years ago.

A general consolidation of the target area magnets is also planned. Apart from renovation of spare units, which can be difficult due to high activation levels, a re-design of the two quadrupoles immediately upstream of the target is under study. This was prompted by lack of knowledge about state, manipulation and connections.

As part of the ELENA project, all ejection line magnets will be replaced by electrostatic elements in a few years effectively eliminating consolidation needs here.

A total of 1.67 MCHF has been foreseen for magnet consolidation.

AD POWER CONVERTERS

A general consolidation program with the aim of standardizing the magnet power converters has been launched for the period 2015 – 2020 at a cost of 2.2 MCHF. The aim is to reduce the number of converter types. Included is upgrade of main ring converters, renewal of orbit corrector converters with standard Cancun units, replace the pulsed injection line converters with Megadiscap units and also replace thyristor converters with commercially available units.

AD VACUUM SYSTEM

A general consolidation of the vacuum system is underway since 2013 with the aim of completion by 2018. Cost is estimated at 2.2 MCHF. Completed or near-completion: Renewal of control system, Cryo-system, Sublimation pump filaments, 6000-line primary pumps, turbo-pump groups, previdage valves and Pirani/Penning gauges. Ongoing: renewal of bakeout equipment and Ion pumps, installation of Ion pump HV-feedthrough heaters and also integration of the BASE beamline vacuum equipment. To be started in 2015 is: Fabrication of spare vacuum chambers, Standardization of straight sections, procurement of spare Cryo compressors and renewal of the gas injection system as well as the fast valve electronics.

AD BEAM TRANSFER EQUIPMENT

A total budget of 950 kCHF is planned for beam transfer consolidation.

Prompted by the ELENA installation, the injection and ejection kicker pulse generators will have to be re-located into the new building B393. At the same time a renewal of the sub-systems will take place including controls and electronics renewal and consolidation of dump and main switches. This is to be operational for the 2015 start-up.

Other equipment that will be addressed includes:

- Renewal of septa electronics and controls
- Replacement of the Horn pulser HV supply
- Phase-out of the mercury switches for the Horn pulser ignitrons
- Installation of a test bench in B195 for testing Magnetic Horns

AD STOCHASTIC COOLING

A significant part of the consolidation was finished in time for the 2014 start-up.

Modern switch mode power supplies along with a modern PLC system for control, acquisition and interlock handling has replaced the old power supplies for the 48 RF power amplifiers.

Dynamic and static delay and attenuator control (“Platform Fritz”) have been upgraded with PLC control. The notch filter delay line of the longitudinal system has been re-located to make space for ELENA. To further gain space in the AD hall, investigations will be done for the possible use of optical delay lines instead of the present coaxial cable. Both delay lines could initially be operational simultaneously in order to compare performance and reliability.

The pick-up and kicker tanks motor control has been modernized with up-to-date HW.

The 48 RF power amplifiers are equipped with obsolete semiconductors. Replacement using a new design or upgrade of the present design are under consideration. Estimated cost for a new design is 1 MCHF. Some prototype work will be done as a first step while carefully monitoring the failure rate of the operational amplifiers.

Life expectancy and mechanical integrity of the pickup and kicker tanks and their associated equipment is not very well known. A consolidation strategy has not yet been defined at this stage.

AD ELECTRON COOLING

The current electron cooler at the AD was recycled from the previous ICE and LEAR machines at CERN and is now close to 40 years old. No spares for the magnetic system exist. It has been decided to build a new electron cooler for the AD incorporating all the advances in electron cooling from the intervening period such as e.g. adiabatic expansion, variable density electron beam and electrostatic deflector plates for efficient collection of the electron beam. The preliminary design studies for the new electron cooler are being launched with an aim to install it at the AD during LS2 scheduled for 2018. Estimated cost is around 2.5 MCHF.

AD RF SYSTEMS

After replacement and relocation of the C02 (2 MHz) cavity tuning and HV power supplies with modern and more compact devices, next step is to migrate the low-level system to the Digital LLLRF (DLLRF) family [1] currently under development for all circular machines in CERN's Meyrin site. This is expected to take place between 2016 and 2018.

This new DLLRF family is an evolution of the system successfully operational in LEIR since 2006 [2]. The main benefits of the DLLRF approach are its remote controllability, built-in diagnostics and extensive signal observation capabilities. Its digital nature grants an excellent repeatability as well as the implementation of extensive archiving capabilities; this will allow recalling previously-validated sets of control parameters.

Regarding the 2 C10 (10 MHz) systems used for bunch rotation at injection, a solution has to be found for renewal of the final power stages where obsolete TH116 triode tubes are used. Only a few spares are available at this moment and a complete re-design of the system at a cost of some 4 MCHF might be necessary to ensure continued operation.

AD INSTRUMENTATION

In order to measure tunes during the deceleration ramps, a “BBQ” system, already used elsewhere in the LHC injector chain [3], and connected to the 5.7 MHz Schottky pickup has been installed and is ready to be commissioned for operation.

A new orbit system using individual ADC:s for each pickup is being developed with installation planned for 2015. This will allow orbit measurements also during the ramps.

To measure the low intensity of the circulating beam, a new technique will be tried at AD, also in view of possible use in ELENA. A ccc (cryogenic current comparator) will be installed in 2014-2015 and subsequently evaluated. A precise and continuous read-out during the AD cycle is expected, this will greatly improve and simplify monitoring of machine performance.

The ionisation profile monitors, which non-destructively measure the circulating beam profile throughout the deceleration cycle, will be upgraded to a strip read-out system similar to what has been implemented on LEIR [4]. The two monitors will be installed in vacuum sector 42 and will share a common gas injection system.

Further Instrumentation consolidation includes renewal of 2 BCT:s, addition of 1 BCT and 1 BPM in the target area and integration of the Schottky based DSP system into the new RF Low-level system.

Total consolidation cost for instrumentation during the period is around 900 kCHF.

AD CONTROL SYSTEM

A major upgrade was performed during LS1 with upgrades of the timing and cycle generation systems. Furthermore, the front-end computer upgrade and FESA/JAVA/InCA migration is nearly completed. No further consolidation needs are foreseen for the moment.

AD INFRASTRUCTURE

Requests have been made for a complete cooling/ventilation upgrade in B193 and B195 during LS2 at a cost of 5.9 MCHF. Upgrade of the overhead cranes in B193 is also requested for LS2 at a cost of 750 kCHF.

An upgrade of the present system for distribution of liquid Cryo-gases is planned for 2015/16 at a cost of 750 kCHF.

LEIR CONSOLIDATION

LEIR was transformed into a heavy Ion accumulator ten years ago. No general consolidation plan has been worked out as of now and only a few consolidation requests have been made.

LEIR MAGNETS

Main bending spare coils (190 kCHF): Production is in progress at SigmaPhi (FR) and prototypes are currently being validated.

Main quadrupoles spare coils and spare magnet (110 kCHF): produced and currently undergoing geometrical inspection at Danfysik (DK)

Ring extraction bumper & corrector, transfer line magnets: Spare magnets and coil sets are needed but this has a lower priority.

LEIR POWER CONVERTERS

Transfer line Danfysik converters: There are some reliability issues with the twenty operational units. A study is needed since these are not compatible with standard CERN converters. Estimated replacement cost is 600 kCHF.

Septum ER.SMH11 converter: Old non-standard unit with reliability issues. To be replaced with commercial unit at a price of 100 kCHF.

Furthermore a study is needed to investigate compatibility with 10Hz operation.

LEIR INSTRUMENTATION

The present Schottky analysis system is based on Agilent spectrum analyzers. Practical remote operation from CCC is not possible and the Windows operating system is no longer supported by CERN's IT Department. A new system needs to be developed in–house.

A system based on the ELENA orbit measurement system will be used at LEIR. It is proposed to implement this in the second half of 2016 at the same time as the upgrade of the digital RF system.

LEIR CONSOLIDATION, OTHER

Low-level RF: It is planned to upgrade to the same hardware and software as recently deployed and commissioned in PSB. This will probably happen in 2015, depending on the manpower available in BE/RF. After 2015 some parts of the existing system will no longer be supported by BE/CO. Also, some issues related to the real-time part of the FESA class have started to appear this year. This is not yet understood.

Electron cooler: renewal or spare part procurement for the collector.

REFERENCES

[1] M.E. Angoletta et al., “CERN’s LEIR Digital LLRF: System Overview and Operational Experience”, IPAC ‘10, Kyoto, Japan, May 2010, p. 1464.

[2] M. E. Angoletta et al. “CERN’s PS Booster LLRF Renovation: Plans and Initial Beam Tests”, IPAC ‘10, Kyoto, Japan, May 2010, p. 1461.

[3] M. Gasior, R. Jones: “The principle and first results of betatron tune measurements by direct diode detection”, LHC-project report 853, CERN.

[4] First Results from the LEIR Ionization Profile Monitors, C. Bal, V. Prieto, R. Sautier, G. Tranquille, DIPAC’07, 20-23 May 2007, Venice.

NORTH AREA AND EAST AREA CONSOLIDATION

I. Efthymiopoulos, A. Fabich, L. Gatignon, M. Wilhelmsson, CERN, Geneva, Switzerland

Abstract

The PS East Area and the SPS North Area are world-wide unique facilities of CERN that provide secondary beams to numerous different experiments every year, doing research covering fundamental particle physics, detector prototype testing for LHC, space experiments and medical applications. They represent a core activity of the laboratory, complementary to the LHC. The size of the installations is large, in terms of km of tunnels, number and diversity of installed equipment, infrastructure needs, comparable to that of the SPS accelerator. The relevant consolidation items identified by the groups as presented in the IEFC sessions are summarised.

INTRODUCTION

CERN has a unique set of high-energy general-purpose experimental areas that can provide a wide spectrum of particle beams from the injector complex for experiments and R&D projects. This paper covers the consolidation program for the PS East Area (EA) and the SPS North Area (NA).

Over the years the East Area has served, in addition to the DIRAC and CLOUD experiments and an ad-hoc irradiation facility, a multitude of test beam users (**Error! Reference source not found.**). Recently the T10 beam line was mostly used by the ALICE collaboration, whereas T9 served many different users: the SPS or LHC experiments, also linear collider community, space experiments, and R&D projects from all over the world.

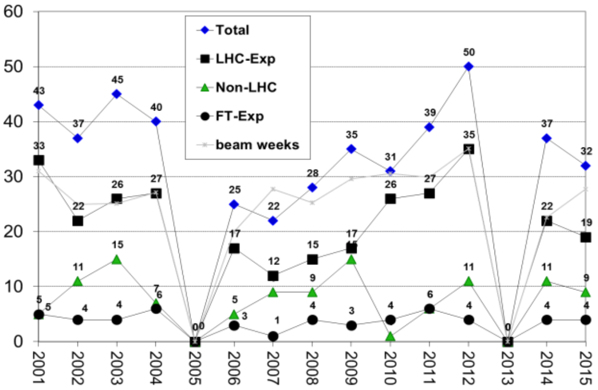


Figure 1: The evolution of the beam time user requests and the available beam time (weeks) in the PS East Area beam line complex over the last 15 years.

The East Area test beams are suitable for users that need beam momenta below the lower limit of the North Area test beams (typically limited to ≧ 10 GeV/c). Some experiments prepare their set-up in the East Area before running in the North Area. Also some users that prefer the North Area beams accept running in the East Area, as the North Area beam lines are increasingly over-booked. Recently users are more willing to come to the East Area since we have added some minimal beam instrumentation (a scintillator and a delay wire chamber) at the end of each beam line.

The SPS North Area has a long history of experiments and R&D tests. With the decline of the big Fixed Targets experiments, the beam lines were and are used for R&D tests of detector components initially for LEP and recently for LHC detectors. The yearly available beam time in the NA beams is nowadays completely booked, and several tests are often scheduled in parallel in a configuration of main and parasitic user mode with several experiments coexisting in the same experimental zone or spread over the several zones in the same beam line (Figure 2). The test beam experiments are typically short-term installations with variable set of beam tunes, while the remaining Fixed Targets experiments operate with continuous data-taking with constant beam conditions and gradual upgrades of their apparatus.

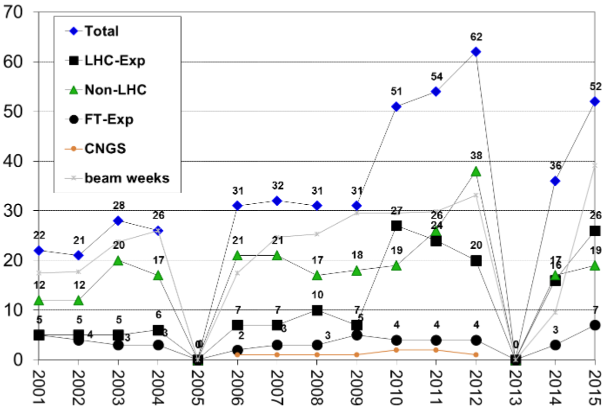


Figure 2: The evolution of the beam time user requests and the available beam time (weeks) in the SPS North Area beam line complex over the last 15 years.

This need for beam time in the Secondary Beam Areas is expected to continue in the forthcoming years, and could even further increase with respect to a possible R&D program for future projects, like FCC or a linear collider. In addition, future projects for new installations and experimental facilities in the North Area premises are being discussed in the scientific community, and/or are in the process of approval, which would substantially change the landscape of the installations.

For those reasons, both the EA and the NA will have to continue operation for many years to come. Whereas the past strategy in the EA was to perform minimum maintenance (in view of replacing the PS with a new ring), the NA benefited from a solid exploitation plan. Beam instrumentation, magnets, power supplies, controls, survey, cooling and ventilation, handling, and many others, the installations were correctly maintained over the years, which prevented major breakdowns and loss of beam time for the experiments. In this framework, the TAX blocks downstream the primary targets in the NA were renovated between 2000 and 2004, as well as the beam instrumentation and regular cable exchange campaigns were performed in the high-radioactive areas of the NA.

However, today the installations also in the NA show their age with an increase of the frequency of failures on major components that are hard to cover in a yearly maintenance scenario. A dedicated effort, e.g. in the framework of the discussed consolidation and with the confirmed availability of personnel resources, is required. In addition, the installed equipment of several systems is now obsolete, making it hard to find replacement parts, and not anymore compliant to today's safety standards and practices.

Therefore to assure the proper operation of both EA and NA beam facilities a consolidation project needs to be established.

RISK ASSESSMENT

The consolidation/renovation activities concern groups in EN, TE, BE and GS Departments as described in a series of presentations in the IEFC Committee and summarized in this paper. The activities are identified in terms of risk and impact to operations and classified accordingly, including a projection of upgrades and needs arising from new projects and usage of the facilities within the knowledge of the authors.

For the risk analysis, the following factors are identified:

- Probability of failure (P, 1-4)
- Impact on CERN scientific objectives (I_o, 1-4)
- Impact on CERN's reputation (I_r, (1-3)
- Financial impact of failure (I_f, (1-5)
- Safety impact in case of failure (I_s, (1-5)

For each activity the combined risk score (R_s) is calculated as the probability of failure (P) multiplied by the maximum of I_f and I_s. As the North Area beam lines have a strong, direct service goal to users, for each activity the combined priority score (P_s) is calculated as P multiplied by the maximum of the I_o and I_r.

Further, the analysis distinguishes between the following scenarios:

- Baseline - including the high priority actions to be carried out immediately to prevent any imminent damage that would lead to harm of personnel or material damage and that would therefore jeopardize near-term operation;
- Preservation scenario - a consolidation plan, compliant with planned operations until 2030, taking into account foreseen LHC and injector maintenance periods and actions and operation phases;
- Value-added scenario - activities, which in addition to the preservation scenario will accommodate new infrastructures or significant upgrades.

Figure 3 summarizes the budget needed with respect to the different scenarios and with respect to timeline, not taking into account the availability of CERN personnel resources, which strongly depends on priority defined by CERN management.

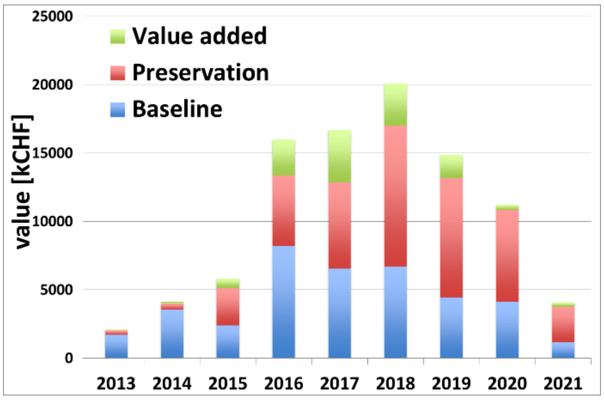


Figure 3: Possible budget for the NA consolidation activities

CONSOLIDATION ITEMS

A Product Breakdown Structure of the consolidation activities for the East and the North Area has been established. A detailed list of the about 200 work units, which have been identified, with their risk assessment has been presented to the consolidation project team ([2-3] for the East Area, [4] for the North Area).

The consolidation of the power converters and magnets is a key item for both areas. Inter-relations of the activities should also be taken into account in the final definition of the Work Packages. For instance, the renovation of the power supplies is strongly related to the ones of the magnets, the electrical network and the cooling system. Furthermore, in the value added scenario a replacement towards energy saving investments could be considered. As an example, as both the East and the North Area are partially equipped with magnets with non-laminated yoke, therefore operated in DC mode, a consolidation of such magnets could cover a change to laminated yokes, where the additional investment costs could be counter-balanced with the reduced operational costs in the coming years. The additional gain of the environmental impact and on CERN's reputation cannot be quantified in terms of money. The spare policy for magnets, especially the ones in the high radiation areas of targets, should be reviewed. A break-down of such a magnet could cause the stoppage from weeks to months of several beam lines at once as spares are not available and an in-situ repair would cause large collective dose even after a dedicated cool-down period.

The renovation plan for the electric power network of the North Area can be split into two main subjects [5]:

- To identify the most worn-out low voltage installations (48V) for which a systematic replacement must be done assuring a reliable and safe network.
- To identify components in the electric pulsed network, that is the power system “upstream” the power converters, which must be replaced for a long term reliability of the system. It contains high and low voltage switchboards as well as transformers; much which dates to installation of the north area. The dimensioning of the new power system depends mainly on the ratings chosen for the new power converters.
-

A very urgent item of the consolidation concerned the elements in target switchyard of the NA in TDC2/TCC2. In this area the installed elements are exposed to high radiation levels limiting their lifetime and further the high induced activity constraints maintenance interventions. The central position in operating the North Area makes it indispensable and a break-down of one element could dramatically reduce the operability of larger parts of the North Area complex. Being a high-priority item, the consolidation of this area including the renovation of the target stations, and a refurbishment of the TAX motorizations as well as infrastructure improvements around the splitter region was scheduled and completed during LS1.

For the Civil Engineering of the buildings, the major concern is the state of the roofs for the big experimental halls, in particular for EHN1 that has the highest occupancy of users during beam operation, and of BA81 building that houses a large number of power supplies for the beam lines. This is considered as a baseline must, where the wish for a dedicated users’ building with offices etc. is clearly a value-added scenario.

The upgrade of the gas detection system responding to the increased need, also given by the EHN1 extension, is not necessarily a part of the consolidation. However, the consolidation item of replacing PVC cabling is obsolete if the new detection system relies on a bus system.

The alarm system for electrical power, relating input from an AUL or the GS/ASE systems for cutting the power, relies on an outdated PLC system. These PLCs show more and more failures, but spare parts/replacements are no more available from the industrial supplier. With this opportunity all active alarm systems of the general infrastructure in the Secondary Beam Areas were reviewed and a common approach proposed [6]. The today’s needs for the safety systems is included in the preservation scenario.

FUTURE PROJECTS AND RELATED IMPROVEMENTS

Not being part of the consolidation program, it is most important tackling any consolidation item in view of on-going or future projects optimizing the long-term perspectives and resources.

In the autumn of 2012 it was decided to stop and dismantle the DIRAC experiment and to install a proton irradiation facility IRRAD and a mixed field facility CHARM [7] in its location. This allowed suppressing the T7 secondary beam and the old irradiation facility. It also relieves significantly the pressure on proton cycles, as the DIRAC cycles no longer needed. However, due to the huge workload involved, the LS1 shutdown had to be almost entirely dedicated to the dismantling of DIRAC and the design and installation of the upgraded irradiation facilities. The work on the primary beam line and test beams had to be postponed to LS2, with all the risks this implies for reliable operation of the test beams and CLOUD.

In the NA within the framework of the CERN Neutrino Platform, the future extension of EHN1 [8] in the North Area will host detector tests for neutrino R&D. The CE works started in January 2015, where the building and the infrastructure will be available for the detector installation from early 2017 onwards, with several large detectors foreseen (WA104, WA105, LBNF/DUNE, NESSiE and others). Due to this extension, the need to consolidate and bring to today’s standards the installations in the whole EHN1 building comes as an increased priority.

Also currently reviewed by the SPSC, the SHiP proposal [9] is considered for installation in the SPS North Area. If realized, would also increase the infrastructure needs in the NA and would call for an upgrade in the TT20 beam line installations. Also the close vicinity to existing installations urges considering common infrastructure, where upgrades should be included in the planning phase of the consolidation project.

CONCLUSIONS

A number of equipment failures have marked the recent operation the Secondary Beam Areas, where the equipment dates largely from its initial installation in the 1970’s. In the East Area, the magnet system is identified as key consolidation item as there are many different types of magnets. Without spares and with respect to the radiological environment, the repairs are costly in time and in radiation dose to personnel. In the North Area, the consolidation of the power converters is the key item to ease operations, improve the beam quality and avoid maintenance overhead. Today the regular failure of power supplies hampers the daily exploitation of the secondary beam lines. In view of their age the situation is expected to further worsen significantly in the coming years. General infrastructure needs of the large experimental halls require immediate consolidation actions, as well as the electrical network distribution that needs to be upgraded in order to comply with today's safety standards.

This overview shows the consolidation needs for the East and the North Area in total of about 100 MCHF, where high priority items are defined. The consolidation timeline will be discussed in the CERN wide framework evaluating the available personnel resources.

REFERENCES

[1] A. Fabich, NA and EA Consolidation, Chamonix 2014, Indico 315665

[2] L. Gatignon, The East Area upgrade – specifications and cost estimate, EDMS 1471844

[3] L. Gatignon, Proposed spending profile for East Area consolidation, EDMS 1474943

[4] I. Efthymiopoulos et al., The SPS North Area Consolidation Program. EDMS 1456636

[5] Y. Gaillard et al., EN-EL Consolidation needs for the North Area EL-NET2025, EDMS 1312090

[6] A. Fabich, E. Gschwendtner, "Requirements for Active Safety Systems of the General Infrastructure in the Secondary Beam Areas" EDMS No. 1365914, Under Approval

[7] http://cern.ch/ps-irrad/

[8] I. Efthymiopoulos, EHN1 Hall Extension for Neutrino Detector R&D Experiments, EDMS 1350076

[9] W. Bonivento et al., Proposal to Search for Heavy Neutral Leptons at the SPS, arXiv:1310.1762[hep-ex]

Proceedings of Chamonix 2014 Workshop on LHC Performance

ISOLDE AND N_TOF CONSOLIDATION

R. Catherall, CERN, Geneva, Switzerland

Abstract

The ISOLDE Facility [1] resumed operation in July 2014 providing low energy radioactive ion beams (RIB) to a physics community of over 500 collaborators. While progress continues on the upgrade of the REX-ISOLDE post-accelerator within the HIE-ISOLDE project [2], assuring the production of RIB for an approved and demanding physics program will require extensive maintenance of the existing facility. The consolidation requests include; the replacement of the ISOLDE target stations, more commonly known as Frontends, renovation of the Resonant Laser Ionization (RILIS) equipment and operation of the REXEBIS and REXTRAP - the low energy systems of the REX-ISOLDE post-accelerator.

However, the radiation protection issues associated with the present performance of ISOLDE and the potential consequences associated with a possible increase in p-beam power should be considered [3]. Consequently, consolidation of the overall shielding of the ISOLDE target area is presented along with the need to replace the ISOLDE beam dumps, both crucial to the exploitation of ISOLDE after the commissioning of Linac 4.

The n_TOF Facility [4, 5] also successfully started its physics program in July 2014 making more efficient use of the neutron flux following the commissioning of EAR2, the second experimental area above the n_TOF target. Further consolidation requirements include the dismantling of the first n_TOF target cooling station and the replacement of the power converter and controls of the sweeping magnet in EAR1.

INTRODUCTION

The performance of ISOLDE and n_TOF has always been maintained largely due to regular winter shutdown periods defined by the CERN accelerator complex schedule. The change in CERN's schedule, brought upon by the operation of the LHC, now provides longer shutdown periods giving the possibility to execute major consolidation projects required for both maintaining the performance of the existing facility and to accommodate any future projects impacting operations. In 2014, ISOLDE celebrates 50 years of providing radioactive ion beams, 22 of which have been at the Proton Synchrotron Booster (PSB). Although various upgrades have been made, consolidation has been relatively minor. The consolidation requests described in this paper are driven by the need to maintain performance of the facility, to overcome issues due to aging, the difficulty in repairing due to high radiation dose rates and the commitment to improve safety standards, notably in radiation protection.

However, with the arrival of Linac 4 and the potential increase in proton beam intensity as well as the possible upgrade of the PSB to 2GeV, the longer shutdown periods provide a unique opportunity to improve on the existing infrastructure in order to accommodate these changes.

n_TOF on the other hand has been taking data since 2002 and the major consolidation request is to replace the second spallation target. After installation in 2007, this target has an expected lifetime of around 10 years yet in 2014, observations have already revealed signs of external corrosion. Once again, expected high dose rates and the time required for a target change make the LS2 period an ideal moment for the replacement of the n_TOF target #2.

ISOLDE

In this section, a brief description and justification of the consolidation requests for the ISOLDE Facility over the next 6 years are highlighted individually.

Frontends

Essential to the operation of ISOLDE, this equipment – also known as a target station - is at the heart of providing RIBs. They accommodate the vacuum, acceleration voltage, target power supply connections, cooling, beam diagnostics and focussing elements required for the production of the unseparated ion beams. There are two Frontends at ISOLDE; the HRS and the GPS installed in 2010 and 2011 respectively. Based on previous experience, the estimated lifetime of a Frontend is approximately 7 years. Should one Frontend fail during the operational period, its replacement can only be done during a shutdown period due to the high dose rates involved. Consequently, the ISOLDE physics program would be cut by 50% during the downtime of one Frontend. A change of Frontend also provides an opportunity to make substantial upgrades, often in line with safety requirements. Potential upgrades are being addressed in the HIE-ISOLDE Design Study due to be published by the end of 2014[6]

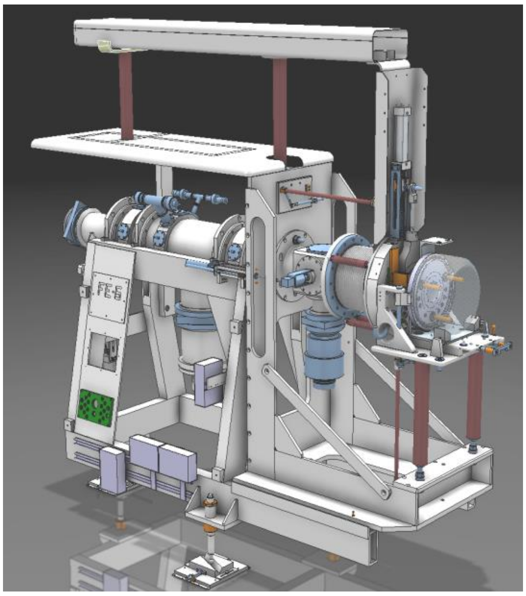


Figure 1. The ISOLDE Frontend

Vacuum

First beam line chamber. Situated directly behind the Frontend, this vacuum chamber was partly responsible for the delayed start-up of the HRS separator after the LS1 period. Corrosion issues are at the heart of the failure and since their initial installation in 1992, these chambers have never been replaced. A further option on this equipment would be to remove the wire grid and install it on the Frontend reducing the need to access for maintenance and assuring a regular replacement every 7 years.

Exhaust gas tanks. All vacuum exhaust gases from the Frontend and separator vacuum vessels are stored in two tanks where the volatile radioactive species are allowed to decay before being released to the atmosphere. As an environmental safety measure, when both tanks are full, the vacuum systems at ISOLDE are stopped. The addition of a third tank would both increase storage capacity and provide more decay time prior to release.

Beam line turbo pumps. This request is driven by the need to replace the aging beam line turbo pumps throughout the entire low energy part of the facility.

Beam dumps

Based on the little known characteristics of the existing ISOLDE beam dumps, calculations have shown that they are operating at their limits in terms of compressive and thermal stresses and that these limits are exceeded for certain primary proton-beam conditions. Replacement of the beam dumps during the LS2 period would not only ensure safe operation for existing primary proton-beam conditions but modifications would also allow for an increase in proton beam intensity and energy. Two options have been identified for the consolidation of the beam dumps, both of which imply the installation of a water-cooled copper alloy block with its associated disadvantages in terms of the cooling system maintenance and activated water..

Option 1: insertion of a water-cooled PSB-like beam dump in front of the existing beam dumps.

Based on a known design and probably the cheaper version, this option would be relatively easy to install. But, placing a copper alloy block in front of the original dump reduces the collimator effect of the existing beam dump shielding and would lead to an increase of activated air during operation and possibly a decrease in performance with regards to the air ionization and the pulsed high-voltage recovery time. Installation of the beam dump would also require spending an unacceptable amount of time in a highly radioactive environment.

Option 2: Complete replacement of the beam dumps.

The main advantages of this option include; replacing an unknown device with a well-specified beam dump, an overall lower collective dose compared to option 1 and the possibility to improve the beam dump shielding. The main disadvantages however, are both the cost and issues associated with the handling of over 3500m^3 of shielding earth. Above the HRS beam dump, recent sampling down to 4.5 meters of the 9 meter thick layer of soil has revealed unnaturally high levels of specific radioisotopes which only add to the difficulties of excavation work.

Shielding

There are two aspects to the consolidation of the shielding. The first is the impact on the environment during operation and the ambient dose equivalent rate measured external to the ISOLDE shielding. During the operation of thick targets with 2μA of primary proton-beam on the HRS target, measurements of up to 18μSvh^{-1} have been recorded directly above the target station. This area has been fenced off but attention must be paid to the contribution of future ISOLDE operation to the ambient dose equivalent rates in the non-designated and low occupancy areas – 0.5μSvh^{-1} and 2.5μSvh^{-1} respectively – in the vicinity. This includes the future laser laboratory above building 179 and building 199. At present, the contribution by ISOLDE to any prompt ambient dose equivalent rate beyond the ISOLDE perimeter has not been determined.

The second issue is air activation. In order to maintain an under-pressure in the target area, the ISOLDE ventilation system extracts 2900 m^{3}h^{-1} of activated air with an average count rate of 500 kBqm^{-3}. While every effort is being made to reduce the air extraction, the alternative is to improve the shielding especially around the beam dumps; the main source of air activation.

Off-line Separator

In compliance with quality assurance, all targets, with the exception of actinide targets, are tested under nominal operational conditions on an off-line separator prior to irradiation on-line. Full testing of the actinide targets is not done due to the absence of an off-line separator in the Class A laboratories. Since the commissioning of the

Class A laboratories in building 179, all handling of open radioactive sources, including the actinide target material, is confined to these laboratories alone therefore prohibiting the transport of actinide targets to building 3 for off-line testing. Over the years, the versatile uranium carbide targets now represent up to 60% of target production at ISOLDE; generating a shortfall in quality assurance. The consequences of a non-performing actinide target on-line can amount to a two week loss in the physics program and incalculable losses in time, resources and preparation.

REX-ISOLDE

The low energy part of REX cools, bunches (REXTRAP) and ionizes to a multi-charged state (REXEBIS) the singly-charged ion beams from ISOLDE before injecting into the REX-Linac for post-acceleration up to 3MeV/u. REX_ISOLDE provides up to 200 x 8 hour shifts per year of physics to the ISOLDE community and a failure in the low energy part would not only jeopardize the physics program but also undermine the effort being put into the upgrade in energy of the REX-Linac within the HIE-ISOLDE project.

Consolidation implies the replacement of critical components for the REXTRAP and REXEBIS, however, this may be off-set should funding be made available to replace the REXEBIS with an upgraded version currently being investigated within the HIE-ISOLDE Design Study.

RILIS

The Resonant Ionization Laser Ion Source contributes up to ~3000 hours of operation at ISOLDE with 70% of beam requests asking for this highly selective and efficient ionization technique. Consolidation requests for RILIS are for the provision of spare laser systems to assure operation in the event of a failure as well as the replacement of laser systems every 15000 hours; the typical lifetime of laser equipment.

Magnets

Any failure of the ISOLDE or REX-ISOLDE magnets would result in a 50% loss in the yearly physics schedule and this may increase significantly depending on when the failure occurred and the need to order spare parts. At present, there are no spare coils or magnets available for the ISOLDE Facility and with more than 20 years of operation, the TE-MSC group at CERN have identified the importance of providing adequate spares.

High Voltage

The present high voltage power supplies purchased from Astec in the early nineties our now approaching the end of their lifetime with failure rates becoming more and more frequent. Fortunately, the TE-ABT group have already identified this issue and have been allocated funding for their replacement in 2015. In parallel to the procurement of new power supplies, the development of a new compatible modulator system is progressing well within the HIE-ISOLDE Design Study. The specifications of both power supply and modulators take into account the potential increase in primary proton-beam intensity and energy associated with the arrival of Linac 4 and the upgrade of the PSB.

Cooling and Ventilation

The coupling of the Class A laboratory ventilation system to that of the target area is far from optimal in terms of activated air release. While efforts have been made to propose a new solution, modifications will be implemented sooner than expected thanks to the approval and construction of the MEDICIS project [7]. The MEDICIS laboratory is adjacent to the Class A laboratory in building 179 and, after being physically connected during the 2014-2015 shutdown period, they will have their own dedicated ventilation system. During the same period, the Class A laboratory ventilation system will be decoupled from that of the target area.

While funding for adjoining the two laboratories has been approved within the MEDICIS project, funding for the modification or replacement of the obsolete target area ventilation controls has yet to be assured. Furthermore, the completion of the latter is of paramount importance for the start-up of ISOLDE operations in April 2015.

Safety

Any consolidation or modification of the ISOLDE infrastructure will require a detailed risk analysis at the design stage. Furthermore, detailed installation planning, testing and preparation of Work and Dose rate Planning (WDP) will be important for all interventions taking place within a highly radioactive environment. This will be complemented by detailed documentation on feedback and intervention reporting.

Consolidation Budget Request for ISOLDE

The 6 year consolidation budget request for each topic is presented in Table 1. Contributions have been provided by the equipment groups who will drive the consolidation work package should funding be made available. Depending on decisions taken, further research is required for the unknown costs.

Table 1. Consolidation budget requests for ISOLDE

WU/kCHF	2015	2016	2017	2018	2019	2020	Groups
Frontends x 2		300	300		50		EN-STI-RBS
Spare FE						300	
Beam dumps Option 1				1000			EN-STI-TCD
Option 2				?	?		
Shielding				?	?		GS-SE
Off-line separator	400	400					EN-STI-RBS
REX-ISOLDE		100	100	100			BE-ABP
RILIS	325					435	EN-STI-LP
Magnets	200	300	300				TE-MSC
Vacuum		70	60	160	60	60	TE-VSC
High Voltage	93	100					TE-ABT
CV controls	?						EN-CV
Safety	120	120	120	120	120	120	EN-STI

n_TOF

Three topics have been highlighted for consolidation at n_TOF and although the work will be done during the LS2 period, preparations will be started as early as 2015.

Target #2

Target #2 is the result of a major upgrade of the original n_TOF target #1 following issues related to damage, oxidation and the migration of spallation products into the cooling water system. However, installed in 2007 and with a projected lifetime of approximately 10 years, the present n_TOF neutron spallation target is already showing initial signs of surface corrosion. The monolithic Pb block along with its cooling system cannot be repaired due to both its design and expected dose rate after removal and will therefore have to be replaced during the LS2 period to ensure reliable physics after LS2. It is worth noting that a target change at n-TOF is a lengthy process and would jeopardize the physics program for at least 1 year if done in during the physic's period.

Target #1 Cooling Station

After being removed from the service gallery in 2013, the original n-TOF target is now under preparation for shipment to PSI, Villigen for final storage as radioactive waste. However, the original target cooling station remains in the FTN transfer tunnel between TT2 and the n_TOF target area. Plans are now under way for the decommissioning and conditioning of the cooling station during the LS2 period.

Figure 2. Initial signs of corrosion at the target neutron window

Sweeping Magnet Power Converter

Situated in the EAR1 experimental hall, the sweeping magnet is essential to assuring the physics program in that it prevents high-energy charged particles from entering the target area and saturating the sensitive detectors during operation. While the magnet itself is sound, consolidation requests are for a replacement of its associated power converter and control system; both of which are obsolete and are currently maintained on a best effort basis.

Consolidation Budget Request for n_TOF

The budget request for the consolidation of n_TOF over the next 4 years is given in table 2.

Table 2. Consolidation budget request for n_TOF

WU/kCHF	**2015**	**2016**	**2017**	**2018**	**Total**
Design and construction of a new neutron spallation target	250	500	350	200	1300
Dismantling of the target #1 cooling station	0	0	0	200	200
Consolidation of EAR1 sweeping magnet power supply	0	0	100	100	200
Total/year	250	500	450	500	1700

CONCLUSION

To exploit the long LS2 shutdown period and to benefit from the inherent extended radioactive cooling, both ISOLDE and n_TOF have made provisional requests for major consolidation projects. Most of these requests assure the operation and performance of both facilities beyond the LS2 period and in the case of ISOLDE, will allow for any upgrade in intensity and energy of the primary proton beam.

ACKNOWLEDGEMENTS

The author would like to express his gratitude for the contributions from the machine specialist groups with special thanks to Marco Calviani for his contributions on the n_TOF facility.

REFERENCES

[1] A. Herlert, The ISOLDE Facility, Nuclear Physics News, Vol 20, No. 4, 2010
[2] http://hie-isolde.web.cern.ch/hie-isolde/
[3] Evaluation du blindage de la zone cible ISOLDE. CERN-DGS-2010-006-RP-SN. https://edms.cern.ch/document/1142606/1
[4] n_TOF Collaboration. Performance of the neutron time-of-flight facility n_TOF at CERN, Eur. Phys. J. A (2013) **49**: 27
[5] https://ntof-exp.web.cern.ch/ntof-exp/
[6] R. Catherall et al, An Overview of the HIE-ISOLDE Design Study, EMIS 2012 Proc. NIMB D-13-00320
[7] CERN-MEDICIS (MEDical Isotopes Collected from ISOLDE): A new facility**.** CERN-ACC-NOTE-2014-0019

SCOPE OF THE LONG SHUTDOWN 2 (OPTIMISATION OF THE PERIOD 2015-2018)

J.M. Jimenez, Geneva, Switzerland

Abstract

During this talk, the scope and mandate of the Long Shutdown 2 (LS2) has been introduced, emphasising on the major differences with respect to LS1.

The flexibility to use the winter shutdown to advance part of the works initially planned for LS2 will be considered in the frame of the LS2 discussions, the reporting line has been presented.

Finally, the main dates for the LS2 preparation have been presented and will be followed carefully in order to ensure a smooth preparation of the LS2 shutdown.

PROJECT SCOPE & MANDATE OF LS2 COORDINATOR

The project scope covers all activities carried out and resources needed in the context of Long Shutdown 2 over the whole CERN accelerator facilities.

The mandate of the project coordinator includes the period of preparation before the LS2, the definition of a resource loaded master schedule, the coordination and follow-up of activities and the flexibility to use periods before and after LS2 to decrease the working load or coactivity problems.

More specifically:

- Prior to the start of the LS2, the definition of main works to be achieved over the LS2 and of potential options based on priorities given to activities. This study shall highlight in particular LS2 duration and resources needed for each option and be presented to the Directorate by mid-2016 for final decision;
- The definition of a CERN-wide “resource-loaded planning”, ensuring the compatibility of resources and planning across the LHC Machine and LHC Experiments;
- The preparation, coordination and follow-up till completion of all LS2 activities in the frame of the LIU, HL-LHC Projects and other CERN approved projects. Work packages will define the work absolutely essential to achieve the LS2 objectives (activities which will bear a priority 1), which execution will be closely followed up by the LS2 coordinator. It is essential to also identify works which can be postponed to the LS3 (activities which will bear a priority 2), which impact on LS3 will be assessed by the LS2 coordinator.

The flexibility to use the end-of-year technical stops before and after the LS2 to decrease the load of the LS2 is left at the discretion of the LS2 coordinator and is also part of the scope of the project.

REPORTING LINE & COLLECTING INFORMATION

Reporting Line

The LS2 coordinator will report on a strategic level to the CERN Director for Accelerators and Technology. At the technical level and when needed, LS2 Coordinator will report to the LMC and IEFC respectively for the LHC and Injectors.

The LS2 progress will get reviewed regularly at an executive level, as done for the LS1, in the LS2 Committee (LSC).

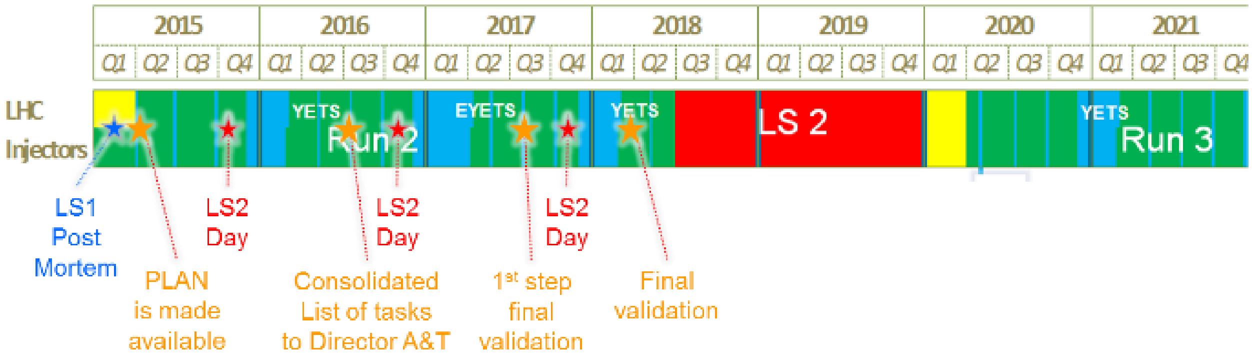


Figure 1: Main dates and milestones.

Collecting Information

Collecting the relevant information is the challenge of the preparatory phase. As done for LS1, this will be initiated by Groups which will enter their requests and then followed by bi(multi)lateral meetings with Experiments, Groups, Teams and Projects to tune the information.

Indeed, the extensive use of PLAN tool during LS1 has been positively values by all actors. Important improvements have getting implemented following the feedback received. In particular, a PLAN Quality Assurance Manager has been assigned to check and homogenise the information available.

To ensure the proper preparation of the LS2 and give time for discussions and arbitration, the Coordination Team has set important milestones (Fig.1):

- LS1 Post-Mortem to take place during the 1st trimester'15: The objective of the meeting will be to address the topics relevant for LS2 and for which, feedback is considered important for its preparation. Learning from LS1 experience is mandatory.

- The "PLAN" tool will be introduced during the LS1 Post-Mortem meeting with its new features. It will be, within a month, get introduced to the Groups' member in charge of uploading the tasks. The objective is to have most of the activities declared by end'15 for both Injectors and LHC, including Experimental Areas.
    - By mid'16, are expected the definition of activities for EYETS 2016 and for LS2.
    - The preliminary "final" validation will take place by mid'17.

- The LS2 kick-of day will take place end of 3rd trimester'15, and an LS2 day will take place once per year in the same period of the year, to provide relevant feedback to Chamonix workshop scheduled in January every year.

- The LS2 shutdown (personnel accessing underground accelerator tunnels) will:
    - Start the 1st July 2018, and
    - End after the Christmas Stop of 2019, for a total
    - Duration of 18 months (end'19).

ACKNOWLEDGMENTS

Many thanks to all contributors from all CERN Groups and also to the LHC Experiment Technical Coordinators for their helpful feedback.

WHAT HAS BEEN LEARNED FROM LS1

K. Foraz, J. Coupard, M. Bernardini, CERN, Geneva, Switzerland

Summary

The Long Shutdown 1, which started in February 2013, is almost finished. A huge number of activities have been performed, and the machine is now being cooled-down and power tested. As part of the preparation for Long Shutdown 2, the talk will review the process of the coordination of LS1 from the preparatory phase to the testing phase.

The preparatory phase is a very important process: an accurate view of what is to be done, and what can be done is essential. But reality is always different, the differences between what was planned and what was done will be presented.

Daily coordination is essential for the good progress of the works. The talk will recall the coordination and reporting processes, highlighting points of success and points to be improved in terms of general coordination, in-situ coordination, safety coordination (including safety rules), logistics…

INTRODUCTION

After 18 months of intense activities, the first long shutdown of the LHC and its injectors is ending. Beam is circulating in the LHC injector complex, while LHC is being cooled-down and power tested. Following interviews of group leaders involved the author will highlight the points of success and points to be improved in terms of general organization.

PREPARATION PHASE

The Long Shutdown 1 was, first, triggered by the need to consolidate the magnet interconnections to allow the LHC to operate at 14TeV in the centre-of- mass, in 2009. It became a major shutdown which in addition includes repairs, consolidation, upgrades across the whole accelerator complex, as well as maintenance.

Main Activities

After more than three years of operation, the accelerator complex needed a full maintenance of all the systems. Major consolidation and upgrade activities were added [1]:

PS & PS Booster: new access system, new ventilation system in PS, RF upgrades, radiation shielding around PS, vacuum control system, dump renovation…

SPS: vacuum coating of 16 dipoles to test e-cloud mitigation, kicker systems upgrade (impedance), RF system upgrade, cooling and ventilation upgrade, 18kV transformers replacement, replacement of irradiated cables, new optic fibre systems…

LHC: Superconducting Magnets and Circuits Consolidation, Radiation to Electronics, upgrade and consolidation of beam instrumentation, pumping stations…

Prioritization

The preparation phase started just after the decision to resume the LHC operation at 7TeV centre-of-mass. The detailed program was defined according to the following priorities:

- P0 -All activities needed for a safe operation
- P1 -All activities needed to operate at 14TeV
- P2 -All activities needed to ensure a reliable operation
- P3 -CERN approved projects
- P4 -CERN non approved projects

In order to avoid conflicts or overloads, the project leader team set up a tool “Plan” to gather and approve the activities. Groups were requested to declare the activities they intend to perform, and to detail the support they needed from other groups. This unique repository, with a simple approval process, eased the communication, helped the support groups to have a clearer picture of the support to be given. The resources availability declared by all the stakeholders facilitated the prioritization and acceptance process for the LS1 team, focusing only on discordance points. As reported by the different group leaders, “Plan” is an essential tool to prepare major shutdowns, but it should have been put in place earlier during the preparation phase. In addition, as reported by the support groups, not all the activities were declared in “Plan”, which caused punctual overloads. In the future they recommend using “Plan”, and reviewing the program regularly. Moreover the tool will be adapted to better fit our needs (redundancy with APT, granularity of items...)

LS1 Day

In June 2012, the LS1 project leader organized the LS1 day with the aim to announce the results of the survey and analysis of which activities will be performed during the first long shutdown (LS1), which activities might be performed subject to the availability of resources (call for extra manpower), and which activities will be postponed. The LS1 day provided, also, the latest update on LHC & injector planning. The support groups presented their activities and organization during LS1. According to the main stakeholders, this meeting was essential to crosscheck the requests from other groups and experiments, and to avoid omissions and misunderstandings.

Preparation Methods

During four years, prior to the start of LS1, a massive and solid preparation has taken place:

- The project's objectives were detailed into tasks. Stakeholders were identified. Furthermore, the resources (human, surface areas, materials), the project required, were identified. Coordination and management arrangements as well as monitoring and evaluation methods were defined.
- Coordination teams organized work package analysis meetings to review, for each activity, conditions prior to start, schedule, perimeter of worksites, storage areas, logistics aspects, risks and compensatory measures, and ALARA plans. During these meetings, gathering the different stakeholders, a lot of points were clarified.
- In parallel, groups and project leaders, established contracts and collaboration with external institutes, in order to fit their activities within the agreed time window.
- The good quality of documentation edited during the 4 years of groundwork indicates the good level of preparation: procedures, Engineering Change Requests needed for intervention.
- Fruitful external reviews were organized for the SMACC project.

This high level of preparation contributed largely to the success of LS1.

When to Start?

It took 4 years of intense preparation from the definition of global objectives to the start: to subdivide objectives to activities, activities to tasks, to ensure that the appropriate human resources were allocated and trained, to review the technical issues and mitigated actions, to prepare the interventions in supervised areas…

Group leaders underlined the importance of defining technical details in due time, in order to get contracts in due time. Moreover they highlighted the fact that additional staff, needed for a major shutdown, have to be employed around 2 years prior to start; this, considering the training of personnel to the accelerator complex specificities and the preparation time of the different projects.

IMPLEMENTATION PHASE

Coordination

Coordination meetings were important events through LS1, as they guided operational partners and other stakeholders through a process, which stimulated cooperation between them.

During these regular meetings, held by technical coordination teams and project leaders, progress of activities and readiness of equipment were reviewed, technical aspects were presented and discussed, as well as logistics, and safety matters. As mentioned by Group leaders, these forums were very useful as it facilitated the information flow and enhanced team spirit.

The need of seven coordination meetings in the injectors complex was challenged, as this was time consuming for the groups.

Schedules

Once the time windows of the shutdown of each machine were defined and the compliance between them was checked (especially in terms of resources), a baseline schedule was approved by the groups.

The schedules were reviewed on a weekly basis, thanks to the feedback given from the field and during coordination meetings. Ad-hoc meetings were held with groups/projects discovering unexpected issues or delays, in order to find technical solutions and to adapt the global plan, and additional activities were added, in the shadow of the others. The readiness of beam instrumentation and some of vacuum equipment, produced or tested on surface on CERN premises was one of the issues which was reported during LS1. The coordination team reacted promptly organizing the surface schedule from one service to another, up to the transport of the equipment in the machines. This schedule was weekly updated, synchronizing the surface and underground plans. In the future, this process shall be defined prior to the start of a shutdown.

Moreover, planners from coordination team were part of the SMACC and R2E projects. This eased the whole coordination process, and the information flow (crosscheck of information).

With respect to ALARA (As Low As Reasonably Achievable) principles, the activities in supervised areas were scheduled as late as possible in order to decrease as much as possible the level of radiation. These activities were thus on the critical path. This generated a lot of stress to the team involved, especially when unexpected events occurred. In the future, one will have to compromise between cooling period and reasonable margins.

Documentation

The configuration management is maintaining consistency of the machines functional and physical attributes through their life cycle:

- The hardware baseline is kept up to date thanks to Engineering Specifications, Hardware procedures, Tests procedures… and Engineer Change Requests. So far, around one hundred ECRs were treated for the LHC machine, and around sixty for the injectors complex. As shown in figure 1 below, around 20% of ECRs were released at the start of LS1, and around 10% have just been edited are being processed.

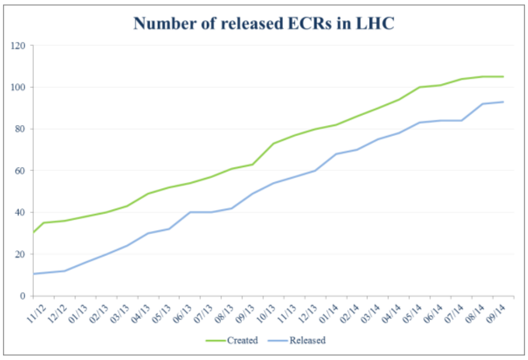


Figure 1 – Number of ECRs realised with respect to time

- Once Engineering Change requests and Engineering specifications are released, the layout database and the MAD/Y files are updated.
- The machine drawings with release notes are then edited.

The Group Leaders acknowledged the regular presentations of the ECRs progress in the different committees (LMC, IEFC, LSC) as it was most important to maintain the database of the machines up to date.

Daily Management

The LS1 involved around 1600 persons [1]. The preparation of logistics, induced by a massive arrival of personnel, has been well treated as no major issues appeared. The access in the machines were filtered thanks to the IMPACT system [2]. Moreover, the DIMR (Demande d'Intervention en Milieu Radioactif) was inserted in the IMPACT tool, and connected to the RAISIN database.

It is important, at this stage, to mention that most of the main stakeholders were the same as during the installation of LHC. This eased considerably the coordination processes, as each one knew the others and the procedures to follow.

The daily personnel access was fluid. Lift breakdown occurred, but solutions were put in place from the coordination side to reduce the effect of such inconveniences. The plan for the lift exchange (aging from LEP installation) is in the pipeline.

The material logistics was well organized. The material exiting the machines and experiments were processed through the TREC systems (Traceability of Radioactive Equipment at CERN) [2] installed at the exit of the machines. The lack of TREC buffer zones next to production and tests premises was reported by the stakeholders.

Information Exchange

Effective communication is a key determinant of any project success, and certainly for LS1. As already mentioned it is important to keep a good ratio between experts and new personnel in order to capitalize the experience of a shutdown. The communication channels were well defined, for the configuration management, but also for reporting progress of works (machine coordinators and project leaders reported regularly to the main committees); the dashboard of LS1 was weekly updated and available for public.

Some points of improvement have been mentioned during the interviews of Group and Project Leaders:

Coordination teams notice that information has sometimes difficulties to go down to the worksites. Fortunately, it was mitigated thanks to the very good follow-up on field.

Stakeholders encountered sometimes difficulties to find information on a specific project as each project uses different storage systems (edms, Sharepoint, indico).

"Notes de coupure" were prepared in due time and distributed largely. But one has to pay attention to give clear messages for non-experts. Moreover, it would be interesting to draw a repository of services unavailability and their impacts on the other systems.

Safety

Safety, top priority of LS1, has been carefully studied, and respected through the duration of LS1. The statistics, up to September 2014 show low rate for Frequency (7.3) and Severity (0.7), despite the enormous number of working hours (1.5 millions). This is largely due to the efforts of work supervisors and safety coordinators. Coordination teams mentioned the need to train the new work supervisors with respect to safety organization and specificities of CERN environment.

As underlined by Group Leaders, the safety courses for LS1 arrived very lately, and did not facilitate the arrival and training of the newcomers. Moreover, the implementation of new safety rules and procedures during the course of LS1 perturbed the activities leading to a lot of discussions.

Resources

As already mentioned, around 1600 persons intervened in the different machines of the accelerator complex. It is important to recruit our staff in due time. The specific case of work supervisors was already mentioned: 2 years prior to the start are needed to prepare both projects and personnel training. The non-LHC facilities suffered from the lack of resources, as part of the existing teams were redeployed from SMACC project. The major efforts made to redirect internal resources to LS1 activities paid, but it is important to involve them during the preparation phase, and to avoid partial detachment to increase effectiveness.

Group Leaders also reported the difficulties of maintenance contractors to find the adequate personnel needed to keep the tight schedule. The framework contracts were overloaded during the whole period of LS1 and additional works led to difficult negotiation both on financial and deadlines aspects.

Discrepancies between Baseline and Reality

This part will be detailed during the LS1 post-mortem day. All baseline activities were performed. Additional activities were included in the plan. For instance, the consolidation of unexpected defaults (QRL compensator, 15%->30% of splices), as well as the non-announced ones. These last ones were disorganizing the support group activities, inducing more work for already overloaded groups. This specific point should be followed systematically during the future shutdowns.

CONCLUSIONS

Despite the points of improvement mentioned in this paper, and as reported by the CMAC (CERN Machines Advice Committee), “the tremendous work scope of LS1 is being successfully completed with only minor delays”, thanks to the management process set up for LS1 and the strong commitment of our staff.

ACKNOWLEDGEMENTS

The author would like to thank the Group and Project Leaders who took time to report on LS1 organization, and to thank all the stakeholders of LS1 for their support and collaboration.

REFERENCES

[1] F. Bordry, S. Baird, K. Foraz, A.-L. Perrot, R. Saban, J.Ph. Tock, “The First Long Shutdown (LS1) for the LHC” CERN-ATS-2013-0084

[2] K. Foraz and al. “Reliability and Intervention Management for the LHC”, CERN-ATS-2012-252

RADIATION PROTECTION ASPECTS

D. Forkel-Wirth, P. Carbonez, A. Goehring-Crinon, D. Perrin, S. Roesler,
H. Vincke, L. Ulrici, CERN, Geneva, Switzerland

Abstract

The paper describes CERN's approach to radiation protection during LS1. It addresses the regulatory and operational landscape before and during LS1. The lessons learnt from LS1 will be used to define the roadmap towards LS2. Despite the large amount of maintenance and repair work in all radiation areas, CERN succeeded in keeping the collective dose to personnel at a reasonable level. Moreover, CERN's objective of keeping individual doses below 3 mSv in 2013 was largely achieved; only two experts slightly exceeded the dose objective. In addition, no radiological incident or accident had to be reported.

INTRODUCTION

The long shutdown LS1 proved a challenge to CERN's Radiation Protection Group. It was the first time that the Radiation Protection Group had been faced with such an amount of maintenance and repair work in CERN's radiation areas. They represent about 45 km of accelerator tunnels; several target areas, experimental areas including the specific LHC experiments and facilities like ISOLDE and n-TOF. Moreover, changes in the radiation protection regulations had to be communicated and implemented – just before the beginning of LS1. Overall, the experience from LS1 was largely positive and the lessons learnt will be applied to LS2.

REGULATORY LANDSCAPE OF CERN'S RADIATION PROTECTION

As an intergovernmental organisation, CERN has the right to establish its own internal legislation as necessary for its functioning. CERN's Safety rules, including radiation protection rules, are based on International and European Standards and Directives as well as on the relevant legislation in CERN's Host States, France and Switzerland.

On an international level, the International Commission of Radiation Protection (ICRP) issues recommendations, which are then converted into Safety Standards and Guidelines by the International Atomic Energy Agency (IAEA). Although the IAEA recommendations are normally not binding, the European Union considers them as binding with respect to the European regulations. The European Union issues legally binding Directives in matters of radiation protection, which define the minimum requirements in the field and which then have to be introduced into national laws by all EU Member States. Although Switzerland is not a member State of the EU it normally follows EU Directives. EU member States can define stricter requirements than the European Directives concerned.

CERN's legislation in matters of radiation protection is currently laid down in Safety Code F "Radiation Protection" and its underlying rules and guidelines. All is tailored to the needs of a large, international High Energy Accelerator Laboratory.

Safety Code F mainly follows the Swiss Radiation Protection Ordinance, which has the international reputation of being one of the most pragmatic radiation protection regulations. Furthermore, Switzerland was the first European country to transpose the ICRP recommendation from 1990 into national law. Indeed, in 1994, Switzerland lowered the annual exposure limit for radiation workers from 50 mSv to 20 mSv and the limit for the public from 5 mSv to 1 mSv – as recommended by the ICRP. CERN's Safety Code F issued in 1996 followed the ICRP and the Swiss Ordinance. The EU adopted the ICRP recommendation from 1990 only in 1996 with the European Council Directive 96/29/EURATOM and it took the EU member States still some years to implement the Directive (e.g. Germany in 2002 and France in 2003). However, when the Safety Code F was revised in 2006 the concept of type A and B workers* defined in the 96/29/EURATOM Directive was introduced at CERN.

As it is a political sensitive subject, radiation protection has also been the subject of several agreements between CERN and its Host States. In the past, radiation protection was covered by several bilateral agreements between CERN and each Host State. This implied different rules and procedures applying to the French and the Swiss part of the CERN site, in particular when the so-called "INB convention" between France and CERN, signed in 2000, was in effect. On 15th November 2010, France, Switzerland and CERN signed a tripartite agreement on radiation protection and radiation safety that replaced all previous bilateral agreements. This agreement defines a framework for CERN and its two Host States to discuss matters of radiation protection and radiation safety in a collaborative way and on equal footing.

CERN further participated in a working group where the Host States' Safety Authorities, ASN and OFSP, but also the French work inspectorate, the French unions and employers, as well as the Swiss SUVA (accident insurance) were represented. The aim of the working group was to reassure the French unions, in particular as to CERN's compliance with French radiation protection standards. The result of the discussions was that CERN does indeed comply with French standards but that the French contractors did not comply with their obligations

---

* A worker: annual dose limit is 20 mSv
B worker: annual dose limit is 6 mSv

regarding the dose monitoring of their personnel. CERN thus clarified the contractors' responsibilities in this respect, imposing independent dose monitoring for all contractors. CERN further agreed to support its contractors by designing a radiation protection course adapted to the risks at CERN.

Naturally, the communication and implementation of these measures shortly before the beginning of LS1 was quite challenging.

As was the case for LS1, LS2 will also have to adapt to regulatory changes, namely to Council Directive 2013/59/Euratom that should be implemented by all EU member States by 6th February 2018. Once again, Switzerland will most probably be the first European country to follow this EU Directive with its new Ordinance in matters of radiation protection foreseen to enter into force in 2016. As a consequence, the exemption limits for radioactive material will be lowered by a factor of 10 to 100 for common radionuclides produced in CERN's radioactive material.

Table 1: Exemption limits applicable in LS1 and LS2 for selected isotopes typical at CERN

Isotope	**LS1**	**LS2**
22Na	3 Bq/g	0.1 Bq/g
54Mn	10 Bq/g	0.1 Bq/g
60Co	1 Bq/g	0.1 Bq/g

The Operational Landscape of LS1 and LS2

CERN's radiation areas comprise of about 45 km of accelerator tunnels, the LHC experiments and five fixed target facilities for the production of secondary beams to be sent to several big experimental areas. The fixed target facilities include the radioactive ion beam facility ISOLDE and the neutron beam facility n-TOF. Both ISOLDE and n-TOF are equipped with type A and C laboratories.

LHC in LS1: the LHC and its experiments are areas of relatively low radiation risk, the major part of the LHC and the experiments are classified as Supervised Radiation Areas. The collimator region in Point 3 and the injection areas of CMS and ATLAS are Simple Controlled Radiation Areas, the collimator region in Point 7 and the beam dump caverns are Limited Stay Areas.

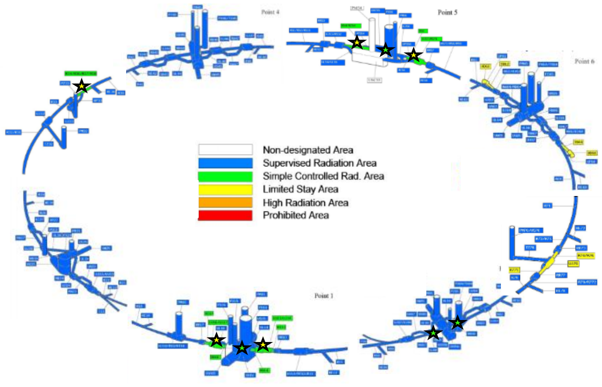


Figure 1: Radiological classification of LHC in LS1.

LHC in LS2: the radiation levels in LHC will increase due to increased beam intensity, beam energy and luminosity. FLUKA calculations based on the presently known scenarios for LHC operation until LS2 predict a dose rate increase by a factor of 3 to 4 in the collimator regions, the injection regions of CMS and ATLAS and the beam dumps. All these areas will have to be classified as Limited Stay Areas; whereas the rest of the accelerator remains quite clean meaning it should be possible to classify it as a Supervised Radiation Area.

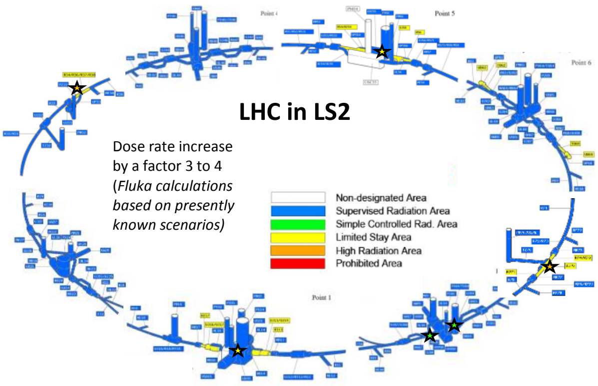
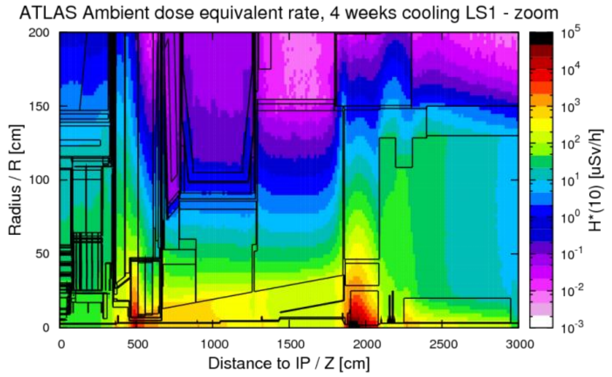


Figure 2: Radiological classification of LHC in LS2

Whereas for LHCb and ALICE no change in the radiological area classification is expected for LS2, the dose rates in CMS and ATLAS will increase by a factor of two to three. However, in some areas the dose rate will decrease as during LS1 the experiments replaced steel components by aluminium components. The major part of the CMS and ATLAS cavern will remain a Supervised Radiation Area, whereas the Forward Shielding and the Inner Detector will be classified as a Limited Stay Area.

ATLAS in LS1



ATLAS in LS2

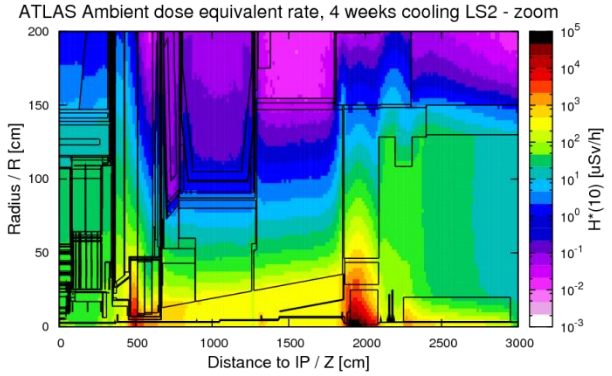


Figure 3: Radiological situation of ATLAS in LS1 and LS2

The dose rate levels in the LHC injectors and the target areas for the fixed target program will not change much from LS1 to LS2 as the activation of these facilities is already more or less in saturation. The LINACs are mainly Simple Controlled Radiation Areas whereas the rest of the injector chain is classified as a Limited Stay Area or High Radiation Area. The target areas are High Radiation Areas.

The experimental areas like the East or North Area are classified as Supervised Radiation Areas. In LS2 irradiation facilities like CHARM might need to be classified as Simple Controlled Radiation Areas or Limited Stay Radiation Areas.

The Preparatory Phase of LS1

During the preparatory phase of LS1, CERN's Radiation Protection Group faced the considerable challenge to provide high quality, sustainable and efficient radiation protection training without knowing either the exact number or the arrival dates of the participants.

CERN's Radiation Protection Group developed a new, radiation risk based training concept that fulfilled these requirements and that was endorsed by the Host States' authorities competent in matters of radiation protection and radiation safety. Whereas in the past all radiation workers had to follow a half-day, face-to-face theoretical training course, the new scheme introduced an e-learning based radiation protection course for all workers intervening in Supervised Radiation Areas and a full day face-to-face radiation protection training course for all workers intervening in Controlled Radiation Areas. The course for workers in Controlled Radiation Areas consists of half a day theoretical training and half a day practical training. A dedicated training room was acquired and installed close to the LHC mock-up on CERN's premises in Prévessin to allow for an integral radiation protection and radiation safety training. The training content for both types of RP courses is subject to continuous updates, integrating relevant changes in radiation protection procedures as soon as they become applicable. Due to this approach, no additional resources are required to prepare the content of the LS2 radiation protection training.

In total 4,767 persons successfully passed the e-learning course for Supervised Radiation Areas and 2,224 persons were trained in the one day face-to-face RP training course for Controlled Radiation Areas (1401 workers by the company SOFRANEXT since September 2012, 823 workers by CERN since March 2013).

With respect to operational radiation protection in LS1, several preparatory actions had been taken:

1) in his New Year's Speech 2013, the Director General announced an annual CERN dose objective of 3 mSv for radiation workers
2) in collaboration with the computer specialists of the HSE unit, CERN's Radiation Protection Group developed the data base RAISIN which lists all CERN's radiation areas (about 1000) and the corresponding radiological classifications. All persons with a NICE password have access to this database to find out the type of RP training required and to gain prior knowledge of the radiological situation of the workplace
3) CERN's Radiation Protection Group implemented a new operational dosimetry system which allows the immediate follow-up of operational doses. The system has been operational since March 2013
4) the new operational dosimetry system was integrated into the IMPACT work planning tool, a tool which now provides outstanding efficiency with respect to assigning doses to jobs and to dose follow-up
5) integration of RP's Work and Dose Planning (WDP) tool into the IMPACT tool which allowed the immediate comparison of the measured operational dose with the estimated dose.

The first ALARA committees for jobs costly in individual and collective doses or with increased radiological risks had already been held before the beginning of LS1. About 10 ALARA committees approved 11 jobs, with a total estimated collective dose of 423 man·mSv.

Radiation Protection during LS1 – Some Key Figures (status July/August 2014)

During the period from 1st March 2013 until 31st July 2014 the individual doses added up to a collective dose of 1,129 man.mSv. Two workers received an individual dose of more than 3 mSv/12 months (3.1 mSv and 3.4 mSv) and one worker received 4.2 mSv during the entire period mentioned above. In total, the CERN dosimetry service performed 13345 assignments of an individual dosimeter (DIS) to a radiation worker. The Associated Members of Personnel (MPA) represented the largest group, receiving 47% of the collective dose. CERN staff received about 22% and contractors' personnel 31% of the collective dose. In total 1,500 operational dosimeters were distributed for specific jobs in Supervised and Simple Controlled Radiation Areas (e.g. PS ventilation refurbishment) and for all jobs in Limited Stay and High Radiation Areas.

The Radiation Protection Group performed radiation surveys at several stages of the LS1, the first one at the very beginning of the shut-down. The resources for all surveys accumulated to 34 man·weeks, 2 for the PS complex and 16 each for the SPS complex and the LHC. The Radiation Protection Group validated 3,597 IMPACTs in total, including those with job and dose planning. More than 34,000 radiological checks of components had been performed and in total more than 2,982 tons of material measured. 2,302 tons had been found to be radioactive and 680 tons of the radioactive material were declared as radioactive waste.

In total 2,410 separate internal radioactive transports were performed by CERN's transport service. 1,145 transports departed from CERN/Meyrin, 527 from Prévessin and 738 from the various SPS and LHC points.

Radioactive goods were imported (36 packages) and exported (50 packages). The analytic laboratory performed 2,729 γ-spectrometry measurements and 7,318 measurements of alpha- and beta-contamination.

The calibration service calibrated 420 monitors from the ARCON/RAMSES system and 12,734 DIS dosimeters. Additionally, 163 new monitoring channels were added to RAMSES during LS1.

The Radiation Protection Group received 680 tons or 1,677 m^3 of radioactive waste in total. Unfortunately, the numerous non-conformities of the radioactive waste received caused additional costs in terms of resources (personnel, time and space). For example, about 1,800 bags of so-called burnable waste were received but 600 needed to be re-sorted as they contained metal pieces – which is not in compliance with the procedure for waste sorting at the source.

During checks on conventional waste, 56 radioactive items had been found in conventional waste bins, 8 in the recuperation centre for conventional waste and 16 were found during radiological checks on trucks by the gate monitor in Prévessin.

The GS Department, which manages the storage of radioactive material, could accommodate all requests during LS1 (2,450 m^3 for TE, 13 m^3 for EN, 30 m^3 for CMS, 12 euro palettes for BE). Even highly radioactive material like 7 septas, 16 magnets and 4 quadrupoles could be stored. However, today there is no more storage space available for heavy material and rack space is available for only a few euro palettes. GS Department proposes the extension of building 954 to overcome this critical space shortage.

Roadmap Towards LS2

The storage of both radioactive material and radioactive waste requires decent planning to ensure the availability of space, in particular in view of the LS2. Whilst a forecast for the production of radioactive waste for the next years including LS2 already exists in the form of the waste study, a similar survey has to be conducted for the storage of radioactive material. These forecasts have to be updated on a regular basis, preferably annually or at least bi-annually. As a lesson learnt from LS1: the forecast for radioactive waste for LS1 was performed at the beginning of 2013 and concurred with the amount delivered until the end of 2013. However, in 2014 about 2.5 times more than forecast was received. Finding a solution for the missing storage space should be considered as high priority – not only for LS2 but already for the shut-downs during the second LHC physics run.

Some regulatory changes have to be taken into account for LS2. CERN inter-site radioactive transports will have to be performed according to the international transport rules (ADR). Although the EN Department and the HSE Unit already acquired the necessary transport containers, some practical issues still need to be solved as loading and unloading the containers does not always conform to the ALARA principle. In addition, administrative issues still need to be discussed within the Tripartite to keep the "paperwork" at a reasonable level.

As already mentioned earlier, the exemption limits for some CERN specific radionuclides will decrease by a factor 10 to 100, representing a challenge to the measurement techniques applied by the Radiation Protection Group.

The responsibility of employers in matters of radiation protection has been clarified unambiguously for contractors, but not yet for associated members of the personnel (MPA). This subject is presently under discussion.

The lessons learnt from LS1 for LS2 are:

1. Communication throughout the preparatory phase and the entire shut-down period is essential. Well defined communication channels between the Departments and the Radiation Protection Group need to be established to avoid misunderstandings, frictions and delays.
2. Departments and the Radiation Protection Group need to ensure collaboration at an early stage for

all relevant technical specifications to avoid frictions, delays and extra costs.

3. The RP training for LS2 is continuously updated and does not require any specific modification for LS2.
4. The Dosimetry Service demonstrated its capacity to handle large amounts of radiation workers and to follow-up individual doses.
5. The operational dosimetry system is adequate for LS2; however the use of pool dosimeters will be promoted. A group of workers who are not frequently in radiation areas are asked to share dosimeters.
6. Forecasts for dose rates in LS2 are available, for LHC by Monte Carlo calculations, for injectors and auxiliaries via long-standing experience.
7. CERN's approach to ALARA is adequate; today it is an essential and natural part of CERN's culture.
8. Worksite planning and management needs further improvement. Excellent examples of planning and coordination from a radiation protection point of view had been the AD strip line repair, the Booster Beam Dump exchange and SMACC. Other worksites gave rise to concerns such as, for example:
    a. language problems between radiation protection personnel and contractors
    b. inadequate information flow between contractors' foremen and workers
    c. technically unskilled workers causing additional doses
    d. unsatisfying cleaning of the worksite
    e. end of shut-down cleaning was left to the Technical Coordinator and the Radiation Protection team.
9. The radiological characterization of potentially radioactive material and waste represents a challenge for the Radiation Protection Group.
10. Transport rules and procedures need to be finalized by RP and EN and agreed by the competent Host States authorities.
11. The needs for radioactive workshops need to be identified for LS2. In LS1 all requests were fulfilled.
12. The forecast for storage needs for radioactive material and waste has to be done for accelerators and experiments. First actions have already been taken by RSOs, RP and GS.
13. The forecast for radioactive waste exists, but the capacity for waste storage depends on the operation of the Radioactive Waste Treatment Centre:
    a. CMS still occupies space in ISR3 and building 184 but is ready to move out
    b. the agreement on project support by GS-SE is still pending.

CONCLUSIONS

Although LS1 was the first experience of a long shut-down in all CERN's radiation areas (including LHC), the results in terms of radiation protection were satisfactory. The new radiation protection training scheme allowed all radiation workers to be trained in time and according to the risks present. Thanks to an efficient shut-down planning by the EN planning team and the implementation of organizational and technical means such as IMPACT and the operational dosimetry system, the strong commitment of CERN's management to the ALARA approach finally resulted in a satisfying dose record. There were no radiological accidents to report and the collective dose was 1,129 man.mSv since 1st March 2013. Only two workers slightly exceeded the CERN dose objective of 3 mSv in 2013.

All radioactive material and waste is stored by GS and RP, respectively. However, additional storage space for the future has to be identified.

The roadmap towards LS2 has been identified - thanks to the "dry-run" LS1. However, it has to be followed rigorously to face and overcome the challenges of the next long shut-down.

ACKNOWLEDGEMENTS

The authors highly acknowledge the contribution of:

Y. Algoet
L. Bruno
N. Conan
A. Day
Y. Donjoux
A. Dorsival
G. Dumont
J. Germa
A. Herve
J. Madden
M. Magistris
R. Michaud
Y. Pira
Ch. Tromel
M. Widorski

LIU PLANNED ACTIVITIES

E. Chapochnikova, S. Chemli, J. Coupard, R. Garoby, S. Gilardoni, B. Goddard, K. Hanke, D. Hay,
B. Holzer, A. Lombardi, D. Manglunki, D. Mcfarlane, M. Meddahi, S. Mataguez, B. Mikulec,
Y. Muttoni, G. Rumolo, M. Vretenar, CERN, Geneva, Switzerland

Abstract

The baseline LIU installation activities corresponding to both ion and proton upgrades will be described for the whole injector chain. The additional possible installation activities linked to the pending options on which decision will be made during 2015 will also be reviewed. It will be examined whether any of these activities can be anticipated to earlier shutdowns or postponed beyond LS2, emphasising the consequences on beam operation and the preparation and performance reach of the LIU beams for HL-LHC. The corresponding support needed from the various CERN groups together with the required technical expertise will be estimated. Finally, a preliminary LIU installation master schedule will be presented.

INTRODUCTION

The list of LIU installation activities for the machines of the injector chain [1] is well defined. Some upgrades are still being studied and decisions will be taken in 2015. The lengths of the upgrades of the PSB, PS and SPS were studied in 2013 for the Review of LHC and Injector Upgrade Plans Workshop “RLIUP” [2] and are updated to the current Long Shutdown 2 “LS2” time window defined from 2018-2019.

PLANNING AND INSTALLATION

A new working group named “Planning and Installation Coordination” has been included in the LIU Project organization [3] in summer 2014. The main elements of the mandate [4] are to:

- Generate the detailed schedule of the hardware works relative to the LIU project within the assigned time constraints;
- Plan the necessary manpower and coordinate the different teams in order to set up the logistics and permit the smooth execution of the works;
- Ensure that the defined time and manpower planning does not clash with other activities potentially involving access to the same zones and/or the same teams;
- Manage and follow-up the scheduled work during shutdowns and technical stops.

To ensure those functions, the schedule responsible of each machine will work closely in collaboration with the configuration management and layout section, the integration studies and the safety coordination units.

The planning and installation meeting will centralize the common information for all the machines (Linacs, LEIR, PSB, PS, SPS) through the relative documents (Space reservation, Engineering Change Request, Functional Specification, Engineering Specification, Installation Procedure, Tests Procedure,etc.).

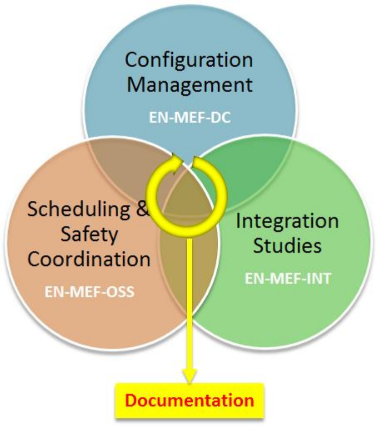
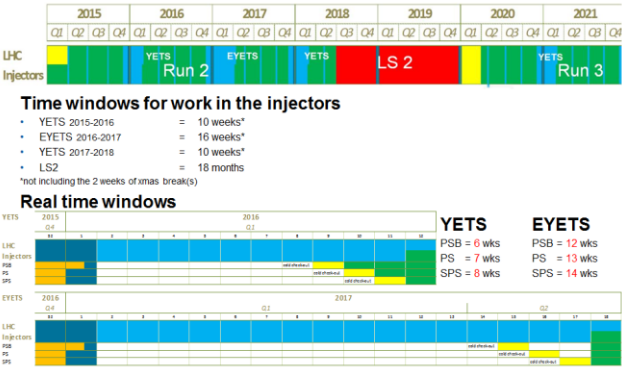


Figure 1: EN-MEF sections involved in the coordination of work

It will be very important during the coming years to have the documents prepared and approved in due time.

TIME WINDOWS

Eighteen months are dedicated for the LHC injector chain upgrade during the LS2, from mid-2018 till the end of 2019. It could be possible to anticipate some preparatory work to the Year End Technical Stops “YETS” and the Extended YETS “EYETS” but the real time windows for each machine are shorter than announced in the general schedule [5]. An optimization by stopping the ion run just before the two weeks of Christmas break would avoid losing time of Radiation Protection “RP” cooling. The time of access in the PSB, PS and SPS could be extended by one to one week and a half.



Time windows for work in the injectors

- YETS 2015-2016 = 10 weeks*
- EYETS 2016-2017 = 16 weeks*
- YETS 2017-2018 = 10 weeks*
- LS2 = 18 months

*not including the 2 weeks of xmas break(s)

Real time windows

YETS
PSB = 6 wks
PS = 7 wks
SPS = 8 wks

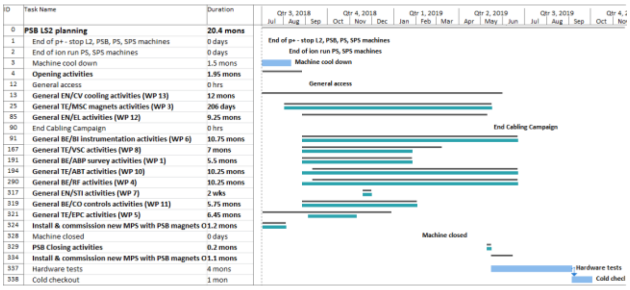
EYETS
PSB = 12 wks
PS = 13 wks
SPS = 14 wks

Figure 2: Time window for stops from LS1 to LS2

PSB PLANNED ACTIVITIES

As described in the Technical Design Review "TDR" [6], the LIU-PSB project can be divided in two upgrade projects, which could either be implemented simultaneously or in two phases: the modification of the Booster injection (BI) line and injection region for 160 MeV H- injection, and the energy upgrade of the Booster rings and extraction including the transfer line to the PS to 2 GeV.

The modifications of the injection region cover the part of the Linac4-PSB transfer line downstream of the concrete wall which separates the Linac and PSB access zones (downstream of BI.QNO20). The part of the transfer line upstream of this wall falls into the Linac4 project. The LIU-PSB project therefore comprises the modifications of most of the BI line as well as the modifications in the injection period of the PSB (periods 1/16). This includes the beam separation scheme (distributor and vertical septum), as well as the stripping foil and painting hardware and other modifications associated with this.



ID	Task Name	Duration
0	**PSB LS2 planning**	**20.4 mons**
1	End of p+ - stop L2, PSB, PS, SPS machines	0 days
2	End of ion run PS, SPS machines	0 days
3	Machine cool down	1.5 mons
4	**Opening activities**	**1.95 mons**
12	General access	0 hrs
13	**General EN/CV cooling activities (WP 13)**	**12 mons**
25	**General TE/MSC magnets activities (WP 3)**	**206 days**
85	**General EN/EL activities (WP 12)**	**9.25 mons**
90	End Cabling Campaign	0 hrs
91	**General BE/BI instrumentation activities (WP 6)**	**10.75 mons**
167	**General TE/VSC activities (WP 8)**	**7 mons**
191	**General BE/ABP survey activities (WP 1)**	**5.5 mons**
194	**General TE/ABT activities (WP 10)**	**10.25 mons**
290	**General BE/RF activities (WP 4)**	**10.25 mons**
317	**General EN/STI activities (WP 7)**	**2 wks**
319	**General BE/CO controls activities (WP 11)**	**5.75 mons**
321	**General TE/EPC activities (WP 5)**	**6.45 mons**
324	**Install & commsission new MPS with PSB magnets O**	**1.2 mons**
328	Machine closed	0 days
329	**PSB Closing activities**	**0.2 mons**
334	**Install & commsission new MPS with PSB magnets O**	**1.1 mons**
337	Hardware tests	4 mons
338	Cold checkout	1 mon

Figure 3: PSB draft schedule for LIU Project during LS2

One month and a half are needed for RP cooling before going underground. Fifteen months of work are estimated, taking into account three shifts for more than nine months of cabling activities, and hardware commissioning.

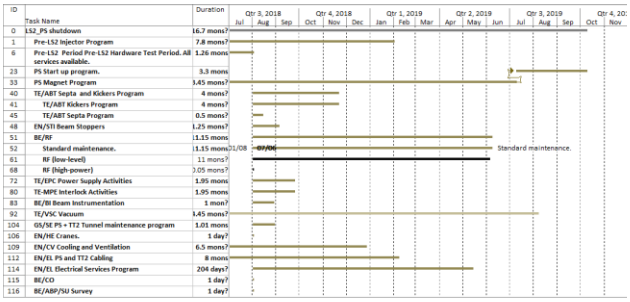
There will be three months of beam commissioning of the PSB, after the complete modification of the machine.

Half Sector Test

According to the Linac4 Master plan [7] reviewed in August 2014, the half sector test will be performed in 2016. The end of those tests is foreseen for August 2016.

PS PLANNED ACTIVITIES

The role of the PS in the production of the beams for the LHC, as defined in the TDR [6], is to preserve at maximum the transverse emittances defined by its injector, the PS Booster (PSB), and to manipulate the longitudinal phase-space to define the bunch spacing required by the collider. For the production of the future HL-LHC type beam, major upgrades are needed to eliminate the existing limitations, in particular related to space-charge and longitudinal instabilities.



ID	Task Name	Duration
0	LS2_PS shutdown	16.7 mons?
1	Pre-LS2 Injector Program	7.8 mons?
6	Pre-LS2 Period Pre-LS2 Hardware Test Period. All services available.	1.26 mons
23	PS Start up program.	3.3 mons
33	PS Magnet Program	3.45 mons?
40	TE/ABT Septa and Kickers Program	4 mons?
41	TE/ABT Kickers Program	4 mons?
45	TE/ABT Septa Program	0.5 mons?
48	EN/STI Beam Stoppers	1.25 mons?
51	BE/RF	11.15 mons
52	Standard maintenance.	11.15 mons
61	RF (low-level)	11 mons?
68	RF (high-power)	0.05 mons?
72	TE/EPC Power Supply Activities	1.95 mons
80	TE-MPE Interlock Activities	1.95 mons
83	BE/BI Beam Instrumentation	1 mon?
92	TE/VSC Vacuum	1.45 mons?
104	GS/SE PS + TT2 Tunnel maintenance program	1.01 mons
106	EN/HE Cranes.	1 day?
109	EN/CV Cooling and Ventilation	6.5 mons?
112	EN/EL PS and TT2 Cabling	8 mons
114	EN/EL Electrical Services Program	204 days?
115	BE/CO	1 day?
116	BE/ABP/SU Survey	1 day?

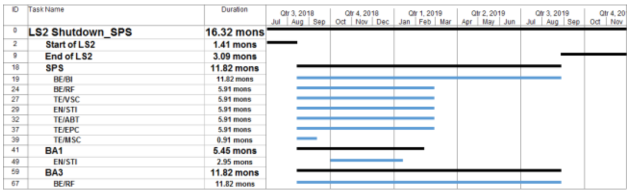
Figure 4: PS draft schedule for LIU Project during LS2

The RP cooling time before accessing into the PS is shorter than for the PSB. The underground will stay closed during one month and thirteen months are then needed for the upgrade and consolidation of the magnets, which is not part of the LIU Project.

One month and a half will be added for the hardware commissioning and cold check-out, before finishing with one month and a half of beam commissioning.

SPS PLANNED ACTIVITIES

The TDR [6] mentions that for the SPS, the main limitations come from the beam-loading at very high beam intensity, which reduces the RF voltage available; longitudinal instabilities linked to the longitudinal impedance; the electron cloud effect, which at 25 ns can make operation impossible through high vacuum or instabilities; and the high stored beam energy which requires significant upgrades of all beam intercepting protection devices in the ring and transfer lines. The instrumentation requires major changes to be able to reliably characterise the very bright beams, and changes to other systems like the magnet interlocking and vacuum sectorisation are designed to improve availability.



ID	Task Name	Duration
0	**LS2 Shutdown_SPS**	**16.32 mons**
2	**Start of LS2**	**1.41 mons**
9	**End of LS2**	**3.09 mons**
18	**SPS**	**11.82 mons**
19	BE/BI	11.82 mons
24	BE/RF	5.91 mons
27	TE/VSC	5.91 mons
29	EN/STI	5.91 mons
32	TE/ABT	5.91 mons
37	TE/EPC	5.91 mons
39	TE/MSC	0.91 mons
41	**BA1**	**5.45 mons**
49	EN/STI	2.95 mons
59	**BA3**	**11.82 mons**
67	BE/RF	11.82 mons

Figure 5: SPS draft schedule for LIU Project during LS2

Some of the upgrade activities have been done during the LS1. The remaining interventions request at least ten months of work and two months and a half for the hardware commissioning.

The beam commissioning of the SPS is estimated to one month and a half.

ION ACTIVITIES

In order to increase the peak luminosity requested by the ALICE experiment for the HL-LHC era, it has been decided, as explained in the TDR [6], to increase the number of bunches in the collider. So that, the following upgrades are planned:

- Implementing new optics in the Low Energy Beam Transport (LEBT)
- Increasing the repetition rate of Linac3 to 10 Hz (“100 ms operation”)
- Lifting or mitigating the LEIR intensity limitation
- Reintroducing the bunch splitting in the PS
- Installing a new ion injection system in the SPS, with a 100 ns rise time
- SPS momentum slip stacking

The upgrades are located inside the machine Linac3, LEIR and the SPS. No more than six months are needed for all modifications. The major work concerns the 100 ns rise time kickers in the SPS and the modification of the LBS measurement line.

CONNECTION OF THE LINAC4

The Linac4 will be operated for reliability run from 2016. The major works to be carried out for the connection of the Linac4 to the transfer line going to the PSB are

- The dismantling of the HST
- Completion of the transfer line with installation of the debuncher
- Change of the BHZ20
- Modification of civil engineering and access
- Modification of the LBE measurement line

Three months of intervention will be needed for the connection. These activities must be done at the appropriate time, in order to fit with the workload and resource levelling in the other machines.

MASTER SCHEDULE

The preliminary master schedule of the LIU Project compiles all draft schedules of the machines of the injector chain. The phases are identified as RP cooling, underground activities, hardware commissioning and beam commissioning.

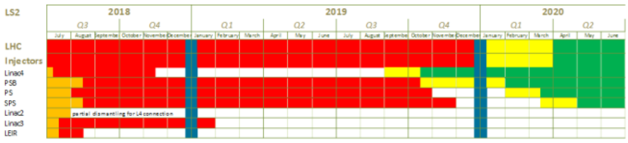


Figure 6: Master schedule of the LIU Project

The PSB upgrade and the commissioning of the whole injector chain are clearly on the critical path. The work organization and resource levelling will be challenging for LS2.

CONCLUSIONS

All work activities listed in the scope of the LIU fit in the LS2 time window defined for the injector chain but the schedules are very tight. There are no contingency and the cabling activities are already foreseen to be carried out in shifts for the PSB.

The decisions on non-priority consolidation works have to take into account the LIU activities.

To complete the schedule analysis and organization of the work, additional studies have to be done:

- All new cabling requests (DIC) need to be made as early as possible in order to estimate the EN/EL workload and integration.
- Evaluation of manpower usage in all CERN complex (Injectors, LHC, Experiments), mainly for contributing groups: EN/MME, EN/HE, EN/CV, EN/EL, EN/MEF-SU, GS/SE, TE/VSC
- Design and production plan to be defined in order to match the installation schedule
- Integration studies to be completed (3D models of infrastructures, general services)
- Definition of all works that can be anticipated in YETS and EYETS in order to reduce the workload for LS2 (i.e. dismantling, de-cabling)

REFERENCES

[1] LIU Upgrade work activities, LIU-PM-NOT-0013, EDMS 1296785

[2] Review of LHC and Injector Upgrade Plans Workshop (RLIUP), 29th – 31st October 2013, https://indico.cern.ch/event/260492/overview

[3] LIU Project organization chart, LIU-PM-PP-0030, EDMS 1403771

[4] Technical Coordinator of the LHC Injectors Upgrade Project Mandate, LIU-PM-QA-0011, EDMS 1410283

[5] LHC schedule beyond the LS1, EDMS 1342322

[6] Technical Design Review of the LIU-Project

[7] Linac4 Master Plan, EDMS 1419460

HL-LHC PLANNED ACTIVITIES DURING LS2- ACCELERATOR

I. Béjar Alonso, CERN, Geneva, Switzerland

Abstract

The HL-LHC schedule aims at the installation of the main HL-LHC hardware during the Long Shutdown 3 (LS3), together with the final upgrade of the experimental detectors (so-called upgrade Phase-II). However, a few items like the new cryogenic plant for P4, the 11 T dipole for the Dispersion suppressors (DS) collimation in P2 (for ions), the Superconducting (SC) links in P7 and several prototypes for the collimation, beam instrumentation and injection and beam dump systems are already foreseen for the Long Shutdown 2 (LS2). This paper describes the main activities that the project plans to carry out during LS2

HL-LHC BASELINE

The first HL-LHC Baseline was presented in July 2014 [1] to the LHC Machine Committee. Together with the baseline a series of options were presented with the objective of mitigating some of the risks already identified for the operation of LHC and in case of late delivery/failure of one of the baseline components. The complete description of the systems belonging to the baseline and to the options can be found in the HL-LHC conceptual specification (CS) series [2]. The CSs provide the scope, benefit for the machine performance and equipment performance objective for all mayor equipment/systems (hereafter components) of HL-LHC. The CSs also contain their preliminary technical parameters, configuration and installation constrains, interface parameters and schedule.

The project is structured in Work Packages (WPs). Each WP integrates components of the same nature. There are presently 17 WPs of which three are WPs giving global support to the component driven WPs (See Fig1).

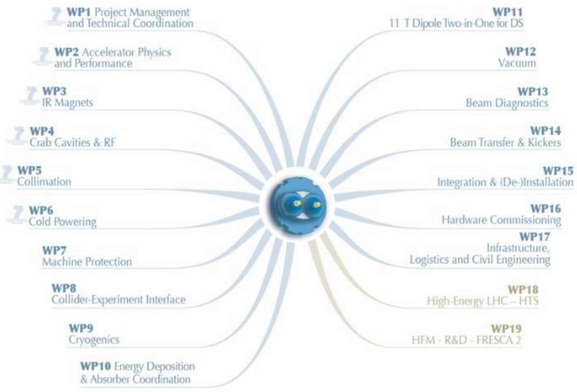


Figure 1: HL-LHC Work Packages

SCHEDULING STRATEGY

The activities of the HL-LHC follow the HL-LHC life cycle (See Fig 2) [3]. The first draft Master Schedule was prepared using the schedules prepared by the WP Leaders (WPL) during the preparation of the CSs to which was added the different constrains indicated in the CSs and on the System Architecture and interface identification documents [4].

The draft Master Schedule was after completed with other variables such as those linked to the other operation and consolidation works already known and to the machine constrains such as the timing of the yearly technical stops (YETS) and the LSs.

It was also taken in consideration the ALARA principle to minimize the doses to be taken by workers during the desinstallation/installation tasks.

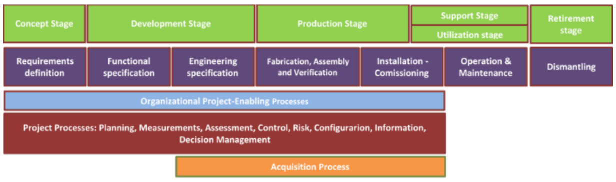


Figure 2: HL-LHC Life cycle processes.

The combination of the draft Master Schedule with the different constrains provided the first Installation and Commissioning schedule for the HL-LHC components during LS2.

Even though the objective of the HL-LHC Project is to distribute as homogenously as possible the different tasks so to decrease the pick requests during LS3 of certain support services, in no case HL-LHC will jeopardize resources required for the completion of the LHC Injectors Upgrade (LIU) or consolidation Projects.

POTENTIAL INSTALLATION ACTIVITIES DURING LS2

Installation activities for 10 of the 17 HL-LHC WPs during LS2 have been identified. Below we will describe the different activities by WP.

WP3 Insertion Magnets

WP3 main scope is the insertion region magnets (while the 11T dipoles required in the DS region is described in WP11).

The Achromatic Telescopic Squeezing (ATS) is the baseline optics for HL-LHC The ATS optics can be fully exploited in the LHC by an additional lattice sextupole in Q10 (MS10) of IR1-IR5 and a stronger Q5 in IR6 in order to keep a balanced β* reach in ATLAS and CMS.

The additional MS in Q10 is needed to bring the β* reach at 7 TeV of the pre-squeeze optics to 44 cm at 7 TeV instead of 48 cm already taking counting on the lattice sextupoles at 600A and to compensate the geometric aberrations of the MS14 that are enhanced by the blow-up in the arc [5].

IR6 optics are very rigid due to the position of the quadrupoles and internal phase advances. While there are still several options under study, among them the possibility to double the MQY (See Fig. 3), it is clear that to fully exploit the ATS optics the Q5 in P6 will have to be replaced by a stronger Q5.

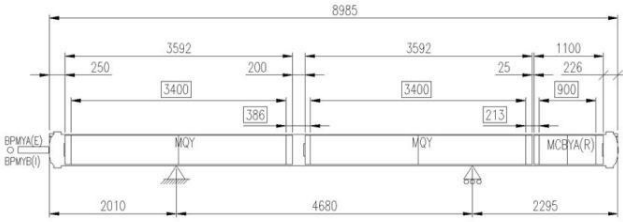


Figure 3: Q5 cold mass Proposal for HL-LHC

To reduce the overload on CERN teams the present baseline is to replace the Q5 during LS2. This will also allow synergies with the other works on P6.

WP4 Radio Frequency Systems

Until this moment no specific works have been identified for LS2 for the LHC crab cavities (CC) but it is important to underline that it is foreseen to test, in the SPS, two types of crab cavities before LS2. The validation run requires dedicated SPS MD time. Failure to test the CC with an SPS beam before LS2 or a non-conclusive/negative result could imply a delay or impossibility to install the CCs during LS3.

WP5 Collimation System

The present collimation system is operating according to design. LHC Run 2 will show if its impedance has to be reduced in case of beam instabilities at nominal intensity. While it can be discussed if the future modifications can be considered as part of the LHC consolidation or being part of the HL-LHC, it is clear that we should get prepared testing prototypes of new collimators or collimation systems capable to protected components during the large change of the collision beam parameters or just from the beam halo.

Together with the test of prototypes, WP5 will have to provide the new collimators in the DS region of P2 where leakage of off-momentum particles into the first and second main superconducting dipoles has already been identified as a possible LHC performance limitation for ion collisions.

Run 2 will show also if it might also be needed to implement the same solution in the DS around IP7 during LS2, which at present does not seem required.

During LS2 it is foreseen to continue the installation of the new secondary collimators (TCSPM) and tertiary collimators (TCTPM) prototypes based on advanced robust and low-impedance materials It is also planned the installation of the Target Collimator Long Dispersion suppressor (TCLD) in P2 together with the 2 11T dipoles that will replace a main dipole in the DS region.

The Hollow Electron Beam system is presently under evaluation for controlling the beam halo. In case of approval its installation during LS2 could be considered.

WP6 Cold Powering

The purpose of the Cold Powering Work Package is to remove to radiation free areas sensitive power converters and Distribution Feed Boxes (DFBs) to improve availability, reduce radiation dose to personnel intervening on such equipment and free space in the tunnel. This requires the use of Superconducting links containing tens of High Temperature (HTS) cables feeding different circuits and transferring all together up to about 150 kA.

At P7 it is proposed to move the power converters and current leads to the TZ76 gallery. This will imply two superconducting links going up to RR73 and RR77.

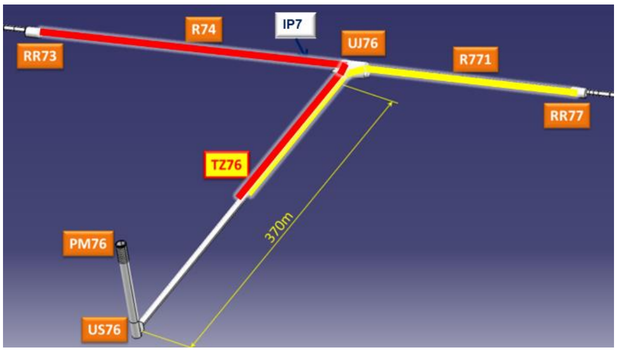


Figure 4: P7 Superconducting link routing

The deployment of the system was foreseen for LS2 but a recent evaluation of the powering in P7 has shown that other alternative scenarios will be more convenient for HL-LHC. Therefore, the SC links will not be installed in P7 in LS2 and most probably neither in LS3.

WP7 Machine Protection

No works are foreseen during LS2 for the Machine protection, interlocks and availability WP.

WP8 Experiments-Collider Interface

The ALICE and LHCb experiments will be upgraded during LS2. The luminosity increase requested by LHCb does not require any change to the magnet layout but should be accompanied by an improved shielding (Passive absorber for neutrals – TAN) on both sides of the experiment. The new TAN has been renamed mini TAXN and will have to be installed during LS2, according to the upgrade of the experiment.

WP9 Cryogenics

The upgrade of the cryogenic system for HL-LHC includes among others the design and installation of a new 4.2 K cryogenic plant at Point 4 (P4) for the Superconducting Radio Frequency (RF) cryo-modules and other future possible cryogenic equipment (e-lens, RF harmonic system). Fig. 6 shows the baseline architecture of the upgraded cryogenic system in P4. The installation is foreseen during LS2. Presently other scenarios are under evaluation, too. The alternative scenario would consist of an upgrade of one of the existing refrigerator of Point 4 to fulfil the required cooling capacity of existing SRF modules with sufficient margin, while keeping the baseline new distribution scenario. This modular and staged approach would allow the installation at a later stage of a new and dedicated refrigerator adapted to the loads presently under definition.

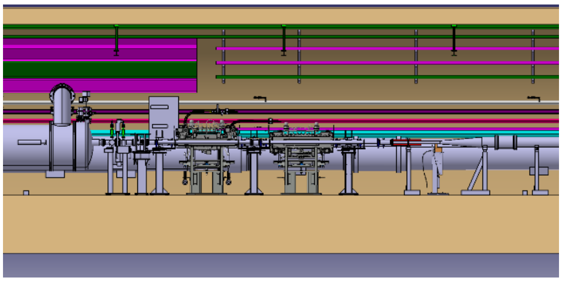


Figure 5: Integration of mini TAXN in PC4L8

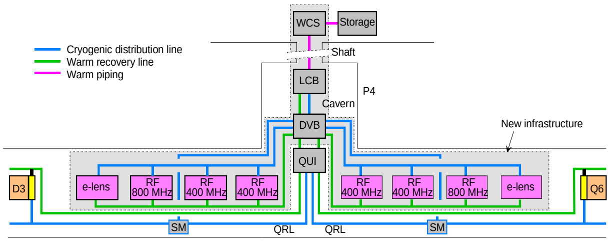


Figure 6: New Cryogenics P4

WP11 11T Dipole for the DS Collimators

As indicated in the description of the work belonging to WP5 two 11 T dipoles will replace some of the main dipoles (MB) in the dispersion suppressor (DS) regions of LHC to create space for additional collimators, which are necessary to cope with losses (off-momentum particles) not foreseen in the nominal LHC design (See Fig.7).

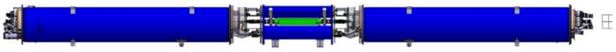


Figure 7: 11T Dipoles with DS collimator

The full assembly will house two 6.252 m long 11T dipole, plus a by-pass cryostat installed in-between. The by-pass cryostat ensures the continuity of the cryogenic and electrical circuits and comprises cold to warm transitions on the beam lines in order to create a room temperature vacuum sector for the collimator.

For LS2, the present plan is to replace 2 main dipoles MB.A10L2 and MB.A10R2 in P2 with 4 11 T magnets and 2 by-pass cryostats. The installation in LS2 will concerns LSS2 only, to cope with the upgrade of the ion beams. Here the uncertainty is given by the readiness of the 11 T dipole itself, to be proved in 2015.

WP12 Vacuum system

The HL-LHC beam vacuum system must be designed to ensure the required performance when beams with HL-LHC nominal parameters circulate. The different components to be installed during LS2 shall be compliant with the vacuum requirements expressed by the WP on their CS.

During LS2 will be actively supporting the equipment groups for their vacuum elements such as beam pipes and beam screens.

Recent evaluations of the electron cloud show that will be also necessary to coat the IR regions on P2 and P8. This work has still to be precisely planned, however there are good reasons (including ALARA) to consider to be done during LS2.

WP13 Beam Instrumentation and Long-Range Beam-Beam Compensation

The extensive array of beam instrumentation with which the LHC is equipped, has played a major role in its commissioning, rapid intensity ramp-up, and safe and reliable operation. HL-LHC brings a number of new challenges in terms of instrumentation. The Beam Loss system will need a significant upgrade. In particular cryogenic beam loss monitors are under investigation for the new inner triplet magnets. Radiation tolerant integrated circuits are also under development to allow the front-end electronics to sit much closer to the detector. The use of crab cavities also requires the development of new diagnostics equipment.

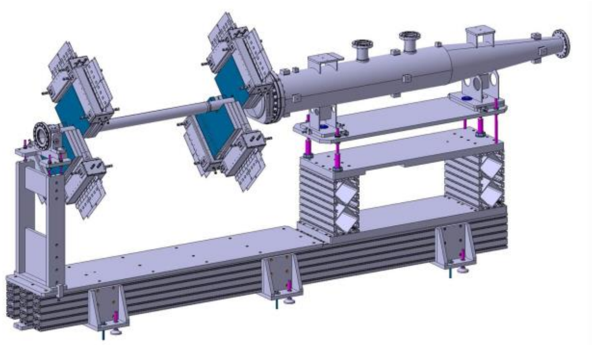


Figure 8: Beam Gas Vertex detector (BGV)

During LS2 there will be an intensive campaign in which certain prototypes will be tested such for the Fast Wire Scanners, the Interlock abort monitor and halo diagnostic systems. It will also be installed a second BGV on the right side of IP4

WP14 Injection and Dumping Systems

Several changes are under study for the different LHC beam transfer systems. Among them, those for LS2 include a new injection absorber (TDIS) that is foreseen to comprise shorter absorbers accommodated in separate tanks, two auxiliary collimators (TCLIA and TCLIB) (its need is under evaluation) and an injection protection mask (TCDD). It is also foreseen to install a new prototype for the Injection kicker magnet (MKI)

WP17 Infrastructure

Several minor civil engineering works would be needed to host the new cryogenic plant in P4. The installation of most part of the new equipment would require the intervention of several service groups such alignment or electricity.

The study of the different alternative installation for the P1 and P5 cryogenics, warm powering and crab cavities shows that some of them will require heavy civil engineering during LS2. Only during 2015 will the correct planning of these works become clear.

ACKNOWLEDGMENTS

This paper was prepared thanks to the contributions of the HL-LHC WP Leaders.

REFERENCES

[1] L. Rossi, “HL-LHC Baseline”,LMC 184, CERN, July 2014, https://espace.cern.ch/lhc-machine-committee/default.aspx.
[2] HL-LHC Project., “Scope Management” https://edms.cern.ch/nav/P:CERN-0000096404:V0/P:CERN-0000096368:V0.
[3] I. Bejar Alonso, “HL-LHC Life Cycle Processes”; https://edms.cern.ch/document/1346952
[4] HL-LHC “WPs Architecture” https://edms.cern.ch/nav/P:CERN-0000096404:V0/P:CERN-0000096398:V0.,
[5] R. De Maria, S. Fartoukh, 64th LMC 2010, sLHC PR.50, sLHC PR.55.
[6] LMC199 http://indico.cern.ch/event/358569/

Proceedings of Chamonix 2014 Workshop on LHC Performance

LHC EXPERIMENTS UPGRADE AND MAINTENANCE

W. Riegler, CERN, Geneva, Switzerland

Abstract

The LHC experiments have planned significant maintenance and upgrade efforts for LS2. ALICE and LHCb will implement major upgrades with important changes to the entire apparatus, while ATLAS and CMS will perform their major detector upgrades only during LS3. However, the overall scale of the LS2 operations is quite similar for all experiments. The presentation will review the LS2 plans of the experiments and focus on aspects related to support needed from the technical sector.

INTRODUCTION

A very first assessment of the needed support for the LS2 plans of ATLAS, CMS, ALICE and LHCb has been performed. The plans will of course be refined during the coming years, so some flexibility and close involvement in the LS2 planning are important. Standard maintenance of equipment by EN-EL, EN-CV, TE-VAC as well as access to the EN-MEF cabling and scaffolding contract are assumed to be implicit and are therefore not detailed in the specific experiment needs.

ALICE and LHCb install massive amounts of fibers (10k/17k) to ship all data in a “triggerless” fashion from the cavern to the counting rooms. ATLAS and CMS will also need additional fibers for their upgrades. It has to be ensured that the EN-EL frame contract for fibres is competitive and properly adapted.

Advancing the installation of the new TAS from LS3 to LS2 for ATLAS and CMS is unfortunately not feasible but many other preparatory changes must be performed in LS2 in order to follow ALARA principles and ensure that the upgrades can be implemented in the foreseen time frame. ALICE and LHCb have an extremely tight planning for the LS2 upgrade implementation, which is partially already organised in shifts. Availability of sufficient survey personnel and safety coordination are therefore very important. In general, support from the technical sector will be required already well before LS2.

The LS2/LS3 upgrades of the LHC experiments are usually referred to as Phase1/Phase2 upgrades.

ATLAS

ATLAS has implemented many upgrades and medium term consolidation items for Run2+Run3 already during LS1. A new central beam pipe and an additional layer of Pixel detectors, the insertable B-Layer (IBL), were installed during LS1. New service panels for the Pixel detector as well as a new thermosiphon cooling system were implemented as well. The experimental beam pipes made from Fe were changed to Beryllium and Aluminium for reasons of background and activation (ALARA).

The planned PHASE1 upgrade for ATLAS is detailed in 4 technical design reports and refer to the New Small Wheel, the Fast TracKer, the Liquid Argon Calorimeter and the TDAQ system. Beyond the standard maintenance there are at this moment no major foreseen implications on the technical department.

CMS

The CMS Phase1 upgrade is distributed between the 2015-2018 YETS and LS2 and is detailed in 3 technical design reports. They refer to the upgrade of the Level-1 trigger (ready for 2016 data taking), the new pixel detector (implemented in the 2016/2017 EYETS) and the HCAL photo-detectors and electronics upgrade of the HCAL (HF 2015/16 YETS, HB/HE LS2).

The central beam pipe was changed in LS1, the forward experimental beam pipes will be changed to Al in LS2. The 4+1 500kVA UPS system will be upgraded to 7+1 500kVA and the electrical infrastructure has to be upgraded. A possible re-siting of battery banks is discussed.

The control room is being revised and a UPS unit will have to be moved. An increase of chilled water production (+1.5MW) and a dry gas (air/N2) system upgrade for Phase2 detectors will be implemented as well. A multi-purpose extension of the surface assembly hall (1000m2) will need support from the technical departments.

The refurbishment of the magnet control and safety system and a freewheel thyristor for immunity from power converter glitches are planned.

The installation of a second UXC crane with suspended cage for personnel access and replacement of the elevator will also be done during LS2.

Since the detector will be completely opened, the upgrades and detector maintenance efforts are on the same scale as LS1, so transport, rigging, survey & FSU support on same scale as LS1 are needed.

ALICE

The Phase1 upgrade of ALICE will see major changes to the entire apparatus in order to be able to read the full 50kHz of Pb-Pb collisions in trigger-less mode. This upgrade is detailed in 5 technical design reports referring to the Inner Tracking System (ITS), the readout and trigger system, the Time Projection Chamber (TPC), the Muon Forward Tracker (MFT) and the Online-Offline System.

Since the computing farm will need a massive extension it has to be studied whether the available space and electrical infrastructure are sufficient.

A new central beam pipe as well as mobile bake-out equipment have to be developed. A modification of Miniframe beam-pipe, the displacement of the central gauge as well as the implementation of an ion pump in Aluminium are foreseen. 10k fibres have to be installed in ALICE, and the possibility of installation during the EYETS 2016/2017 are studied. A new cooling plant is needed for the new ITS detector and a possible new dry air ventilation system is studied. The change of the elevator to the UX cavern, that dates from LEP times, is essential at the earliest possible time.

Vacuum consolidation in the LSS around ALICE in order to arrive at the lowest possible vacuum pressure and therefore the lowest possible level of beam-gas background are essential. As part of this effort, a new TDI to limit high vacuum pressure from outgassing is foreseen. To allow maximum Pb-Pb luminosity, collimators in dispersion suppressor region need to be implemented. From the machine side, the infrastructure for increase of Pb-Pb luminosity to more than of 6x1e27 must be implemented.

LHCb

The Phase1 upgrade of LHCb foresees major changes to the apparatus. All frontends are upgraded to read events at the full 40MHz collision rate into the online farm and several detector systems are exchanged in order to cope with much higher readout frequency. The upgrade is detailed in four technical design reports referring to the Vertex Locator (Velo), the Tracker, the Particle Identification (PID) and the Trigger and Online system.

A large new computing farm (2MW) will have to be housed in a new surface building or a dedicated container. The strategy for cooling and operational temperature as well as possible UPS needs are being worked out. All beam pipes in the cavern must be removed and then reinstalled during LS2, but no new beam pipes are planned. Probably a TAN will have to be installed around LHCb. 17k optical fibres have to be installed from the experimental hall up to the surface, possibly already in EYETS 2016/2017. The new Scintillating Fibre Tracker (SciFi) cooling plant (-40C monophase Freon for SiPMs) has to be developed and the present OT/PS/SPD cooling plant has to be adapted for the SciFi electronics cooling. The planned changes of elevator and crane have to be properly scheduled.

For integration of cables, cable trays, cooling lines, access platforms as well as supervision of the service installation activities LHCb relies on EN-MEF.

LONG SHUTDOWN 2 @ LHC

M. Bernardini, K. Foraz, CERN, Geneva, Switzerland

Abstract

After a second period of operation of more than three years, the accelerator complex will be stopped for about 18 months, from July 2018. The main purpose of the Long Shutdown 2 (LS2) is the LHC injectors upgrade (LIU). Nevertheless LHC will profit from this period to perform full maintenance of all the equipment, to consolidate part of the machine and to anticipate activities, where possible, of the LHC High Luminosity (HL-LHC) project. During LS2 activities across LHC, Injectors and LHC Experiments will be performed. This paper reviews all the major LS2 activities (maintenance, consolidation and HL-LHC), identifying those which are on the critical path, those which can be anticipated during End of Year Technical Stops, and those which will have to be postponed to Long Shutdown 3. The support needed from infrastructure services and logistics will be highlighted, as well as those requiring technical expertise from the Accelerator and Technology sector. A preliminary LS2 schedule is proposed, including the driving activities and the critical path.

INTRODUCTION

Long Shutdown 2 is scheduled to start in July 2018 and its duration is 18 months. This long shutdown will be mainly dedicated to Injectors, nevertheless important activities as maintenance and consolidation will be performed in the LHC machine. Moreover the Accelerator Consolidation Project and the HL-LHC will also implement important modifications during LS2.

METHODOLOGY USED TO SELECT THE ACTIVITIES TO BE PERFORMED

To identify the activities to be performed during LS2, a systematic approach was used. The Group Leaders of TE, EN and some Group Leaders of IT and GS have been interviewed and some recurrent questions have been submitted. Part of the information around the activities related to LS2 is already available, part is related to the performances of Run 2, and will be disclosed only during 2017. In addition, some exchanges went on with the Project Leader of the accelerator consolidation project and the Technical Coordinator of the HL-LHC project.

The typical set of questions was around the following areas:

- Description of activities foreseen during LS2 in the LHC; including the indication if the activities are related to safety, reliability, improvement or RP issues and the impact if they are not realised.
- Maintenance to be performed, impact on the machine and preliminary durations.
- Announcement of the activities: to identify if the activities are already declared in Impact, Plan or in different Workshops.
- Resources needed to realise the activities: human and material;
- Support needed from other groups;
- Need of surface & production areas at CERN;
- First duration of the announced activities.

Concerning the projects, the same set of questions has been asked, focusing on activities foreseen during LS2.

Following the information from the Group Leaders, Project Leaders and Coordinators, the activities have been analysed and three main areas of intervention have been identified. Activities related to: Projects, Maintenance and Consolidation. A detailed description of the activities corresponding to each area is given below.

PROJECTS

The two main projects which foresee activities during LS2, are:

- Accelerator consolidation project;
- HL-LHC project.

Concerning the accelerators consolidation, the baseline around the LHC activities is being reviewed and in September 2014 the official baseline is not yet available.

Concerning the HL-LHC project, the activities are around the following areas:

- Point 2: the replacement of the 8T Dipole, with two 11T Dipoles and a warm collimator, in the dispersion suppressor regions;
- Point 4: the debottlenecking of the cold power and the increasing of the cryogenic redundancy; a first approximate duration is 8 months of work and 3 months for commissioning;
- Point 7: the displacement of the power converters and DFB in the TZ76, the installation of the superconducting link from TZ76 to the tunnel. This part of the project will include also the modification of cryogenics related to the installation of the superconducting link.
- Point 2 and Point 8:
    - Replacement of the TDI with new TDIS consisting of several tanks and new absorber materials to cope with intense LIU beam;
    - Replacement of TCDD and possible TCLIA and TCLIB to provide sufficient protection of superconducting elements in the case of injection failures.

MAINTENANCE

The maintenance activities are specific to each group and listed below.

Technology Department:

Cryogenics: the main maintenance of compressors and rotating machines will be performed with duration between 8 and 12 months; this activity is certainly on the critical path of LS2.

Vacuum: maintenance will be done around all the vacuum pumps, valves and instrumentation; the beam gas injection system in LSS4; the remote reconditioning of NEG cartridge across the ring; the exchange of ion pumps at MKBs; the corrective maintenance on defective PIMs; and other activities not related to maintenance, but to the test phase, as the leak tests on the whole LHC machine.

Power Converters: in this area, corrective and preventive maintenance will be performed according to the performance of Run 2; as baseline, all equipment will be maintained and the PCs situated in the RR will be replaced.

Machine Protection equipment: all the systems will be maintained during LS2, such as Energy Extraction System, QPS, etc.; moreover ELQA tests will be performed at the beginning and at the end of LS2, in the test period phase.

Engineering Department:

Cooling and Ventilation: regular maintenance of the ventilation system, on the surface and underground; including the special maintenance of UW, SU and SF; the maintenance of rotating machines as engines of pumps, ventilators, fans, etc…; replacement of valves, cleaning of heat exchangers and piping, replacement of defective equipment, cleaning of piping, etc…

Electrical: maintenance of 400kV and 66 kV, with duration of about 8 weeks and a maximum consumption during this period of 60 MW. Moreover corrective and preventive maintenance will be performed on all the LHC points with duration of 1 week per point.

Sources, Targets and Interactions: the maintenance or replacement of collimators in LHC will be done according to the performance during Run 2; moreover the dismounting of some collimators will be necessary to ease operation and co-activities in the collimation points, according to the requests from other groups. For the STI Group LS2 is a good opportunity to prepare activities to be performed during LS3, in particular the establishment of ALARA procedures.

Information Technology Department:

Communication Systems: to prevent the deterioration of the internal insulation, it is foreseen to replace the present radiating cable on the whole LHC machine; this activity will generate some safety constraints, due to the fact that Tetra network is transmitted with the radiating cable. The replacement of the routers in the computing centre will be performed and will impact the technical and general services networks.

General Infrastructure Services Department:

Access, Safety and Engineering tools: the maintenance of the fire detection systems, ODH, access system and evacuation is foreseen on the surface and underground, followed by a series of tests on the whole machine.

Other civil engineering work will be carried out, most probably related to projects and consolidation activities. For the time being these activities are unknown, but will be defined in a second stage.

In September 2014 only part of the maintenance activities are known; the other will be disclosed during Run 2. Activities related to maintenance around RF, Kickers, Beam Instrumentation, Controls will be also realised.

CONSOLIDATION

The consolidation activities are specific to each group; part of these activities will be included in the LHC Consolidation Project, but in September 2014 this is not yet defined.

Technology Department:

Cryogenics: it is necessary, during LS2, to proceed to the mechanical consolidation of the support of the quench line, which will be used in case of major quench. The redundancy of the LHC warm compressors will be implemented, so to decrease the mean time to repair from one week to one day. Moreover, to reduce the storage of Helium from 90t to 30t, it is foreseen to equip the existing storage tanks with a small liquifier.

A subject to be discussed between the Cryogenics and Magnet Groups, is the need to replace the heat exchanger of the Inner Triplets at Points 1 and 5. According the cryogenics group, there is a need to increase the capability of heat extraction due to the increased beam parameters during Run 2.

For the consolidation of the QRL bellows, it is not expected to discover non-conformities during LS2; only minor replacements are expected compared to LS1.

Vacuum: the consolidation activities of the vacuum group are around the turbo pumps. In the LSS the turbo pumps will be replaced; in the arcs and QRL the control system of the turbo pumps will be moved to the REs, and this implies a major cabling campaign in the arcs. Other consolidation activities concern all the vacuum equipment around the LHC ring, for insulation and beam vacuum: valves, pressure gauges, pumping systems, ... An action plan should be defined around the Elastomer joints (o-rings) situated on the W bellows and on magnet feet; the reliability of the joints vs the radiation doses should be assessed.

Magnet: during LS2 it is foreseen to replace about 15 magnets. For the moment, the need to replace 4 magnets in sector 34 (3 SSS and 1 Dipole) is identified, but the final number of magnets to replace, will be assessed during run 2. Concerning the warm magnets, the screens to protect the coil from radiation, should be installed on about 35 units situated in Point 1 and Point 7. An important work for TE-MSC, is the preparation, of LS3 to ease dismantling and installation of Inner Triplets.

Machine Protection Equipment: TE-MPE group foresees the replacement and upgrade of all the DYPQ racks, to increase their reliability and reduce the downtime; to perform this activity, the support of the transport group is needed, as well as a surface storage. The obsolete electronics of the beam interlock system will be replaced; the activities will be performed mostly on the surface; nevertheless the upgrade involves 17 controllers between LHC and Experiments, and it is expected to have heavy commissioning and starting phase.

Engineering Department:

Cooling and Ventilation: several renewal and relocation activities will be realised during LS2. The interventions will be around the compressed air plant, the HVAC warm water for the underground ventilation, the firefighting water pipeline for surface Points, the air handling units of the TU and the cooling towers. During the consolidations and the maintenance the related networks will be out of service.

Sources, Targets and Interactions: in the frame of the consolidation activities, the Collimation project is on-going in collaboration with BE-ABP. The project includes activities for the replacement of secondary collimators in Point 7 and for the improvement of tertiary collimators at Points 1 and 5; the support of TE-VSC, EN-EL, EN-CV and EN-MME is fundamental to reach the expected results. Moreover STI foresees the replacement of 12 TCDIs in the transfer lines, to increase their robustness and attenuation for the use with LIU beams. For STI, LS2 is a good opportunity, to develop ALARA procedures to apply during LS3.

The Electrical Group has a huge and heavy plan around consolidation. It is a long term plan, which will be implemented step by step during YETS, EYETS and Run 2. The plan has major activities also in the frame of LS2, as the consolidation of the Jura station, with a duration of 6 months minimum, the creation of an additional CERN station 400/66 kV near Bois Tollot [CERN 2 400 kV _220 MVA], the installation of the new compensation on the Meyrin Machine network (TE/EPC), the consolidation of the automation of control and regulation for the LHC Diesels. Moreover, the partial replacement of the 18 kV protection relays and 48 V DC systems on the surface is foreseen. EN-EL group has a very tight and busy schedule, which will be on the critical path of LS2. The group is analysing the possibility to optimise the activity, anticipating as much as possible the interventions before LS2. For the cabling, the activity of replacement of water cooled cables will be completed during LS2; 45% of these cables need to be replaced. Some optical fibres for LHCb will also be installed. EN-EL-CF outlines the need to receive the requests for copper cabling at least 1 year before LS2, and to be informed of any project requiring cabling, as early as possible.

Engineering Handling: It is foreseen to replace all the LHC lifts (machine and experiments) between 2015 and the end of LS2. During LS2 it is forseen to work on the replacement of PM15, PM25, PZ33, PZ45, PM56, PM65 and PM76; the duration of replacement is 3 months per lift. At Point 1 a temporary lift (Alimack) will be installed during the replacement of PM15, but the capacity is under investigation.

Information Technology Department:

Communication Systems: the installation of a second radiating cable is foreseen on the whole LHC machine; this will allow to increase the transmission rate with 4G+ and to download up to 100 Mbps. During LS2 no Wi-Fi will be available in the machine, but only the 4G+; therefore is it important for the users to validate the compatibility of the user’s device, before LS2.

General Infrastructure Services Department:

Access, Safety and Engineering tools: the alarm transmission system will be consolidated during LS2, with the installation of an anti-fire cable; moreover the access system will be upgraded and the access point in SZ6 (PZ65) will be refurbished to support the replacement of PM65 Lift. In addition, the recommendation of the Helium spill working group about the ODH detectors will be implemented during LS2.

In conclusion, already in September 2014, a lot of consolidation activities are declared, to be performed during LS2; nevertheless, the activities to be performed in the frame of the Accelerator Consolidation project, for LHC should be finalised.

PRELIMINARY SCHEDULE

The preliminary schedule of LS2 is composed of three main parts:

- The warm up and test phase: the duration is about 3 months for the whole machine, nevertheless the first sector will be “released for activities” after about one month, from the beginning of the warm up. The access to LSS7, is related to its radiological cool down, which is estimated to be 6 months.
- The maintenance and activities phase: this includes all activities related to maintenance, consolidation and projects. The critical path of this phase is related to the cryogenics maintenance in all the cryogenics points, and to the implementations of HL-LHC project in Points 2, 4 and 7.
- The cool down, tests and hardware commissioning phase: the duration of this phase is about 6 months, nevertheless, as for warm up; the sectors will be cooled down in sequence.

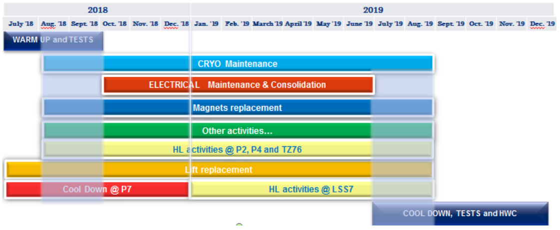


Figure 1: Snapshots of LS1-LHC dashboard

In conclusion, depending on the cool down and warm up sequence, the period available for maintenance and consolidation activities is between 9 and 13 months.

CONCLUSIONS

Long Shutdown 2 is mainly dedicated to the Injectors; nevertheless in the LHC and its Experiments, the Maintenance and Consolidation activities are important. Also for the projects, such as HL-LHC, LS2 is a good opportunity to prepare for LS3, when all the modifications will be implemented. In addition, LS2 is a good opportunity for all the groups to study and implement ALARA procedures, to be applied during LS3.

During LS2, the support groups will have to manage a large amount of activities and the shutdown will be a challenge. The same will be true for for the coordination teams of the LHC and Experiments. Due to the large involvement of all the groups during LS2, it is important that this will not compromise the preparation of LS3. The resource optimisation across the Accelerators and Experiments will be one of the main challenges of LS2.

ACKNOWLEDGEMENTS

The coordination team would like to thank all the Group Leaders, Project Leaders and Technical Coordinators for their collaboration, support and reactivity.

REFERENCES

[1] Accelerator Consolidation Workshop, Sept 12th, 2013, CERN
[2] LHC Performance Workshop (Chamonix 2014), Collimation and MP Roadmap. S.Redaelli;
[3] LHC Performance Workshop (Chamonix 2014), What has been learnt from LS1, K. Foraz;
[4] LHC Performance Workshop (Chamonix 2014), LIU Planned Activities, J. Coupard;
[5] LHC Performance Workshop (Chamonix 2014), HL-LHC Planned activities – Accelerator, I. Bejar Alonso.

Author Index: