DOWN SELECTION CRITERIA AND MDs PRIOR TO LS3

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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.

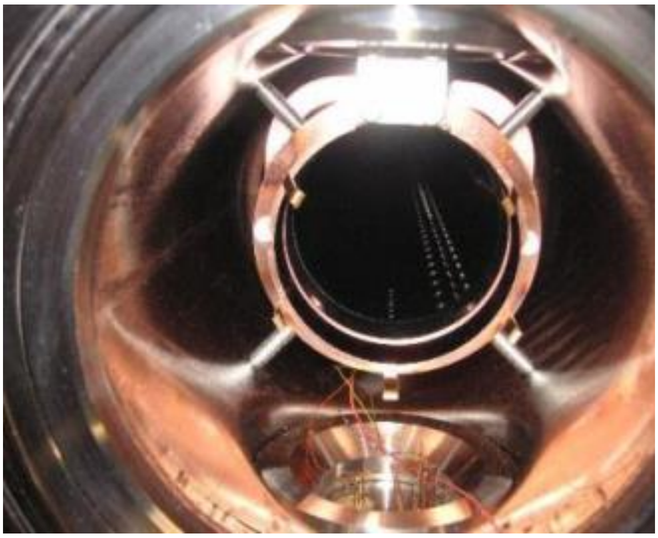

Figure 1: Coated beam screen installed in the SPS ring (COLDEX). Courtesy of P. Chiggiato and M. Taborelli.

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.

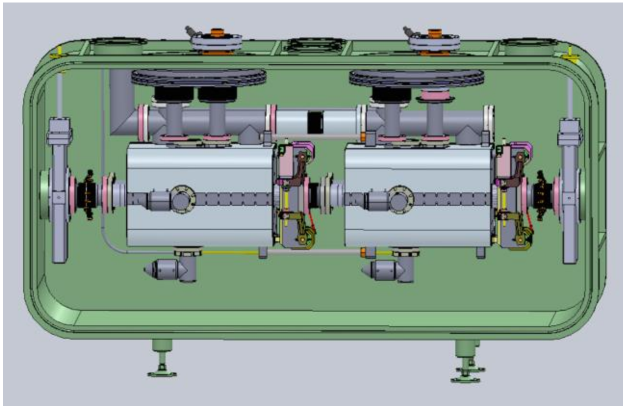

Figure 2: Layout of the cryo-module with two crab cavities to be installed in the SPS for the crab cavity test. Courtesy of R. Calaga and A. MacPherson.

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.

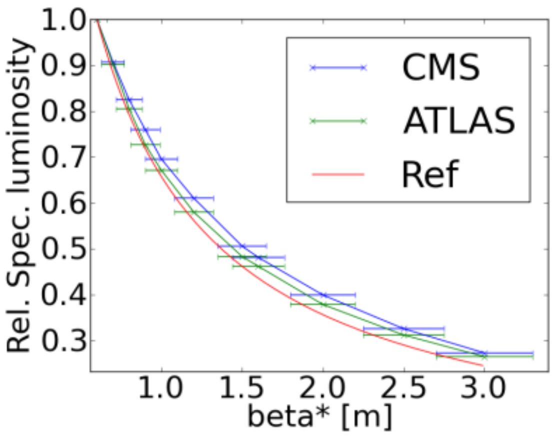

Figure 3: Evolution of the ATLAS and CMS luminosity during the β* levelling experiment as compared to the expected evolution.

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).

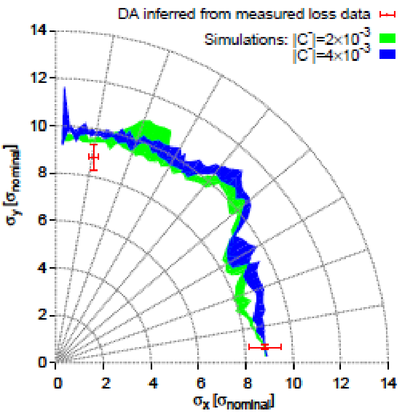

Figure 4: Comparison of dynamic aperture data from simulations (green and blue) with those inferred form measured loss data (red) in one of the machine studies conducted in the LHC at injection [32].

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.

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