MITIGATION OF COHERENT BEAM INSTABILITIES (MCBI) FOR CERN LIU AND HL-LHC

G. Rumolo*, CERN, CH-1211 Geneva 23, Switzerland

Abstract

The High Luminosity upgrade of the Large Hadron Collider (HL-LHC) will meet its future yearly integrated luminosity target by means of performance improving upgrades of the LHC itself as well as by receiving significantly higher beam current and brightness from its injectors. The implications of the pushed beam parameters are twofold. On one side, all the accelerators of the LHC injection chain will have to be upgraded to produce the desired beam parameters. For this purpose, the LHC Injectors Upgrade (LIU) program has been established to implement all the needed modifications for meeting the required beam specifications. These upgrades will target the mitigation of coherent beam instabilities and space charge in the injectors, which will allow lifting their existing intensity and brightness limitations to the desired extent. On the other side, the LHC will have to be able to accept the new beam parameters and exploit them at best to produce the integrated luminosity target. This will mainly require control of impedance driven instabilities, beam-beam effects and electron cloud in the LHC itself. In this paper, we will focus on proton beams by describing the identified performance limitations of the LHC and its injectors, as well as the actions envisioned to overcome them.

INTRODUCTION

The LHC Injectors Upgrade (LIU) project [1, 2] aims at increasing the intensity and brightness of the beams in the injectors in order to match the beam requirements set out by the High Luminosity LHC (HL-LHC) project [3], while ensuring high availability and reliable operation of the injector complex well into the HL-LHC era (up to about 2037) in synergy with the Consolidation (CONS) project [4]. For the upgrade of the LHC injector proton chain, LIU includes the following principal items:

- The replacement of Linac2, which accelerates protons to 50 MeV, with Linac4, providing 160 MeV H^- ions;
- Proton Synchrotron Booster (PSB): New 160 MeV H^- charge exchange injection, acceleration to 2 GeV from current 1.4 GeV with new power supply and RF system;
- Proton Synchrotron (PS): New 2 GeV injection, broadband longitudinal feedback;
- Super Proton Synchrotron (SPS): Upgrade of the 200 MHz RF system, impedance reduction and e-cloud mitigation, new beam dump and protection devices.

All these upgrades will lead to the production of beams with the challenging HL-LHC parameters and they are currently being implemented during the Long Shutdown 2 (LS2) in 2019-20.

To extend its discovery potential, the LHC will undergo a major upgrade during Long Shutdown 3 (LS3) in 2024-25 under the HL-LHC project. The goal will be to increase the rate of collisions by a factor of 5-7.5 beyond the original LHC design value, leading to a target integrated luminosity of 3000-4000 fb^{-1} over the full HL-LHC run (2026-2037). The new configuration will rely on the replacement of the final focusing quadrupoles at the high luminosity Interaction Points (IPs), which host ATLAS and CMS, with new and more powerful magnets based on the Nb_3Sn technology, as well as a number of key innovations that push accelerator technology beyond its present limits while enabling, or even broadening, the future desired performance reach. Among these are the cutting-edge 11 T superconducting Nb_3Sn-based dipoles, the new superconducting link technology with MgB_2, compact superconducting cavities for transverse beam tilting along the longitudinal axis to compensate for the crossing angle at collision (crab cavities), the upgrade of the cryogenic system and general infrastructure, new technology and material for collimators, hollow electron lenses for beam halo cleaning.

The beam dynamics aspects of the LIU and HL-LHC projects are challenging, because during the HL-LHC era:

- The LHC injectors will have to be able to routinely produce, stably control and safely handle beams with unprecedented intensity and brightness;
- The LHC will have to be able to run with the future beams, preserve their stability and make them available for collisions all along the calculated optimum fill length with the desired levelling scheme, ensuring as little as possible beam quality degradation.

Addressing the beam intensity limitations of the LHC and its injectors and illustrating the envisaged strategies to cope with them will be the subject of the next sections.

BEAM PERFORMANCE LIMITATIONS IN THE LHC INJECTORS AND GOALS

In this section we will first present a general overview on the present LHC beam performance of the injectors and the beam requirements for the LIU project. We will only focus on the so called 'standard LHC beam', which is baseline for the projects and produced as follows:

- Two subsequent injections of 4+2 bunches from the four PSB rings into the PS at E_{kin}=1.4 GeV;
- In the PS, triple splitting of the injected bunches at 2.5 GeV, then acceleration to 25 GeV and two consecutive double splittings of all 18 bunches at 25 GeV;
- Four subsequent injections of trains of 72 bunches spaced by 25 ns into the SPS (train spacing 200 ns) at 25 GeV and acceleration to 450 GeV.

---

* Giovanni.Rumolo@cern.ch

Then, we will describe the actions that the LIU project has (planned to) put in place to overcome the intensity/brightness limitations in the various accelerators of the injector chain.

Present performance of the LHC injector chain

An upper limit for the brightness of standard LHC beam is determined at the PSB injection, because of the efficiency of the multi-turn injection process as well as the effects of space charge during injection. The normalised transverse emittance has been measured as a function of intensity at the PSB extraction after optimization of the injection settings and for a longitudinal emittance of 1.2 eVs at extraction [5]. The relation is found to be linear and the resulting line defines the "PSB brightness" line. The longitudinal emittance at extraction can be made in principle as high as 2.8 eVs via longitudinal emittance blow up along the PSB cycle [6] compatibly with other constraints coming from the transfer to the PS and further longitudinal beam manipulation in the PS ring. This is believed to be beneficial in terms of space charge in the PS since it would allow injecting longer bunches with larger momentum spreads. The PSB does not have an intensity limitation for the LHC beams, as it already nowadays successfully accelerates to 1.4 GeV beams up to 7 times more intense than the current LHC beams, which are used for fixed target experiments at the ISOLDE facility. However, it is well-known that a horizontal instability is excited in the PSB at 160 MeV and few other defined energy values, due to the impedance associated to the external circuits of the extraction kickers [7]. In pre-LIU operation, this instability was successfully suppressed by means of a horizontal feedback system over the whole intensity range accelerated in the PSB.

Combining the experience accumulated with operational beams with the outcomes of several dedicated space charge Machine Development (MD) studies conducted throughout 2012 – 2017, it can be assumed that the maximum values of space charge vertical tune spread, ΔQ_y, compatible with the beam loss and emittance blow up budgets reported below, are 0.31 and 0.21 at the PS and SPS injection, respectively. Besides, prior to the LIU upgrade program, due to longitudinal dipolar coupled bunch instabilities on the ramp and at top energy, the PS was not able to produce 25 ns beams with more than 1.8e11 p/b within the longitudinal emittance of 0.35 eVs, which is currently the optmised value to limit capture losses and keep the beam longitudinally stable in the SPS. Finally, due to RF power constraints on the main SPS RF system (200 MHz) and longitudinal coupled bunch instabilities along the cycle, beams with more than 1.3e11 p/b could not be extracted from the SPS with the desired bunch length of 1.6 ns for a basically lossless injection into LHC. E-cloud has been also affecting 25 ns beams in the SPS, but currently the SPS has undergone sufficient beam induced scrubbing to produce beams with 1.3e11 p/b transversely stable and without the characteristic pattern imprinted by e-cloud on the bunch intensities and emittances along the trains. Finally, the onset of the vertical Transverse Mode Coupling Instability (TMCI) limited in the past the bunch intensity to 1.6e11 p/b [8], but this limitation was lifted in 2012 by commissioning a new optics with γ_t lower by 4 units, which increases the TMCI threshold by a factor 2.5 [9].

After including some predefined budgets for emittance blow up and beam loss (5% in the PSB and PS for both, and 10% in the SPS) we can represent in the plane emittance vs. intensity per bunch at the SPS extraction the curves corresponding to PSB brightness, PS and SPS space charge limits, and intensity limitations of the PS and SPS. The regions of inaccessible parameter ranges are shaded. The outcome of this exercise is displayed in Fig. 1, from which we deduce that presently the best standard LHC beam produced by the injectors has 1.3e11 p/b within about 2.7 μm transverse emittance. All the points measured at LHC injection over the years 2015 – 2018, displayed in green, fully confirm this analysis.

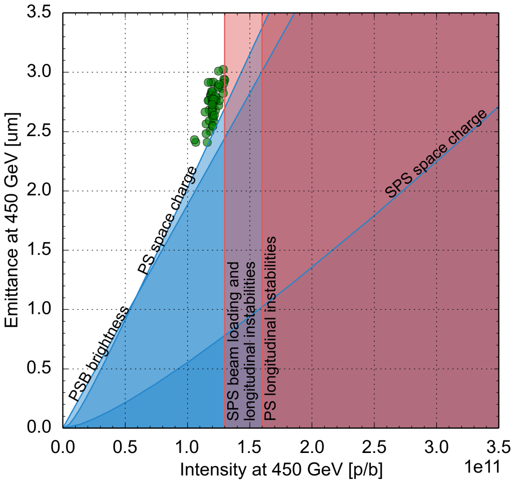

Figure 1: Limitation diagram for the standard LHC beam in the present injectors' chain.

Other methods of LHC beam production exist, which can lead to brighter bunches at the expense of the length of the trains transferred from the PS to the SPS at each cycle. For example, by transferring trains of 48 bunches instead of 72, obtained through a different sequence of batch compression and bunch merging/splitting actions at 2.5 GeV in the PS, the beam brightness can be almost doubled with respect to the scheme discussed above. The beam obtained in this way has been preferred for physics production in the LHC for most of the current run and has been routinely employed since the beginning of 2018. More details about alternative LHC beam production schemes can be found in [10–12].

HL-LHC beam requirements

The HL-LHC upgrade aims at accumulating an integrated luminosity of 250 fb^{-1}/year at the high luminosity IPs. Assuming 50% HL-LHC performance efficiency, this goal can be achieved assuming a standard LHC beam with bunch intensity of 2.3e11 p/b and a transverse emittance of 2.1 μm injected from the SPS. In order not to exceed a pile up of 140 events/crossing, the luminosity is levelled at 5e34 cm^{-2}s^{-1}

by gradually lowering the beta functions at the IPs (β^*) down to 15 cm while partially compensating for the crossing angle with the crab cavities. An ultimate goal of 320 fb^{-1}/year is also set assuming levelling at 7.5e34 cm^{-2}s^{-1}, allowing for a pile up of 200 events/crossing. Table 1 shows achieved and HL-LHC specified beam parameters at the SPS exit.

Table 1: Current and HL-LHC beam parameters out of SPS

	N$_b$ (10^{11} p/b)	**$\epsilon_{x,y}$ (μm)**
Achieved	1.3	2.7
HL-LHC target	2.3	2.1

It is clear that both intensity and brightness of the LHC beams will need to be roughly doubled in the HL-LHC era. Looking back at Fig. 1, HL-LHC is basically targeting a point right in the middle of the currently inaccessible region.

LIU CHALLENGES TO REACH THE HL-LHC BEAM PARAMETERS

Figure 1 directly suggests the path to reach the challenging beam parameters specified in the second row of Table 1. We will discuss first how to achieve the desired brightness and we will focus later on the intensity reach.

Achieving the future brightness relies on two main pillars:

- Reduction of the slope of the PSB brightness line by at least a factor two;
- Mitigation of the space charge effect in the PS.

The space charge in the SPS does not seem to limit the performance even for the future beams, as its limitation curve clearly lies below the HL-HLC target point. The two goals listed above will be realised within the LIU project by means of the following actions. Firstly, the PSB brightness line with half slope will be made possible by using Linac4 with H$^-$ charge exchange injection into the PSB at 160 MeV. It has been simulated that if Linac4 provides 40 mA within 0.4 μm, the future LHC beams can be injected in about 20 turns and the desired transverse emittance is compatible with the blow up due to space charge at the new injection energy (as was expected from a naive $\beta^2\gamma$ scaling) [13]. If the current from Linac4 is lower (compatibly with the goal set for the future fixed target beams), the number of injected turns will have to be correspondingly increased. Secondly, the injection energy into the PS will be raised to 2 GeV, which alone guarantees a 63% intensity increase for a fixed transverse emittance while keeping the space charge tune spread the same as nowadays. Besides, the longitudinal beam parameters at the PSB-PS transfer will have to be optimised to further reduce the tune spread at PS injection and ensure that the PS space charge curve in the limitation diagram ends up in the shadow of the PSB brightness line. The longitudinal emittance will be blown up along the PSB cycle to provide longer bunches at the PS injection, while the larger momentum spread will also further reduce the space charge tune spread due to the increase of the average beam horizontal size through dispersion. The longitudinal emittance blow up can be reproducibly applied in the PSB via either phase modulation of a higher harmonic or injection of band limited phase noise on the main harmonic, as has been demonstrated in MDs in 2017 [6] and 2018.

The achievement of the future intensity relies on:

- Longitudinal stabilisation of the beam along the PS accelerating ramp and at top energy;
- Increase of the available power of the 200 MHz RF system in the SPS in combination with a program of longitudinal impedance reduction;
- E-cloud mitigation in the SPS.

The main longitudinal limitation for LHC-type beams in the PS are dipolar coupled-bunch instabilities. A dedicated broad-band feedback system using a Finemet cavity as a longitudinal kicker has been installed and commissioned in the PS. Extensive tests with beam have been performed since 2016 to explore the intensity reach with this system. The maximum intensity with nominal longitudinal emittance at PS extraction has been measured to be above 2.0e11 p/b [14]. Due to quadrupolar instabilities and incoherent longitudinal emittance growth, it is not yet clear whether a higher harmonic system will be required eventually to keep the beam longitudinally stable with the desired longitudinal emittance at the design intensity for HL-LHC reported in table 1.

The LIU baseline for the SPS includes an upgrade of the low-level RF and a major upgrade of the 200 MHz RF system [15]. The low-level RF upgrade will allow pulsing the RF amplifiers with the revolution frequency (the LHC beam occupies less than half of the SPS circumference) leading to an increase of the available RF power from the existing power plant up to about 1.05 MW per cavity. The main upgrade consists of the re-arrangement 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 overall increase of the available RF voltage and a reduction of the peak beam coupling impedance at the fundamental frequency. With all this massive upgrade in place, the SPS will be able to provide LHC beams with up to about 2e11 p/b, still limited by coupled bunch longitudinal instabilities on the ramp and at top energy [16]. To achieve 2.3e11 p/b it is necessary to reduce the SPS longitudinal impedance. LIU has foreseen shielding of the vacuum flanges between the focusing quadrupoles and the adjacent straight sections as well as installation of High Order Mode (HOM) couplers to improve the damping of the HOMs of the 200 MHz cavities. Numerical simulations have shown that these two measures will allow matching the HL-LHC beam requirement [17]. Finally, the e-cloud in the SPS is a potential limiting factor for operation with higher intensity. Accelerating the present LHC beam without significant degradation from the e-cloud has required an integrated time of several days of dedicated scrubbing distributed over several years. Scrubbing is preserved from year to year in the SPS regions not exposed to air during the stop, while it is partially lost, but usually quickly recovered, where there has been air exposure. Studies of e-cloud build up in the different SPS chambers have revealed that the Secondary Electron Yield (SEY) thresholds will not change significantly when going to the HL-LHC intensity for most cases [18]. Although instability simulations showed that the beam becomes more sensitive to the e-cloud in the dipoles when increasing the beam intensity, it is believed that scrubbing will work also up to the HL-LHC bunch intensity. The Run 2 experience with beams with 2e11 p/b already injected into the SPS has indeed revealed that scrubbing can be efficiently carried out over few days and results in a clear reduction of the e-cloud induced indicators [19]. Coating with amorphous carbon (a-C) [20] is currently being applied to the chambers of the focusing quadrupoles (QF) and adjacent drift chambers during LS2 in synergy with the impedance reduction campaign, which will also gain an extra margin on the instability threshold. Recent machine development studies (2017-18) with intensities above 1.8e11 p/b have revealed the onset of a horizontal coupled bunch instability in this intensity range. Simulation studies have clearly pinned down the source, which is a combination of resistive wall and narrow band horizontal impedances, whose effect is further enhanced by the destabilizing action of the kicker broadband impedance reduction [21]. PyHEADTAIL simulations can reproduce to a very high degree of accuracy the behaviour of this instability as a function of the horizontal chromaticity and octupole settings, as shown in Fig. 2. As this will need to be operationally stabilized in future operation with chromaticity and/or amplitude detuning, a tradeoff of beam stability with beam lifetime and emittance growth might have to be found when pushing the current toward the LIU values. Another option that is being considered, should the stabilisation be unachievable through operational knobs, is the deployment of a horizontal wide band feedback system, whose proof of principle has been demonstrated at the SPS against TMCI in the vertical plane [22].

Putting together all the points discussed in this section, we can draw the new brightness and intensity curves representing the projected limitations after the implementation of the LIU upgrades or actions, obtaining the limitation diagram in Fig. 3. The HL-LHC required point from Table 1 is also shown in yellow, demonstrating that the LIU upgrades are indeed compliant with the achievement of this final goal.

HL-LHC CHALLENGES

The HL-LHC layout is based on the nominal LHC ring configuration, in which about 1.2 km of beam line will be changed. The nominal configuration is designed for a realistic, cost-efficient and achromatic implementation of the low β^* collision optics, based on the deployment of the Achromatic Telescopic Squeeze (ATS) scheme [23]. The installation of triplet quadrupoles of larger aperture is needed to safely accommodate the beams, which reach large dimensions (peak beta functions >20 km), and the shielding to limit the energy deposition and radiation in the SC coils and cold mass [3]. Single particle stability in HL-LHC is challenged by the large beta functions in the triplets and in the adjacent arcs, which enhance the effect of linear and non-linear errors in those regions leading to potentially low Dynamic Aperture (DA) in absence of correction. Even to allow for basic optics measurements pre-computed corrections based on accurate magnetic measurements will have

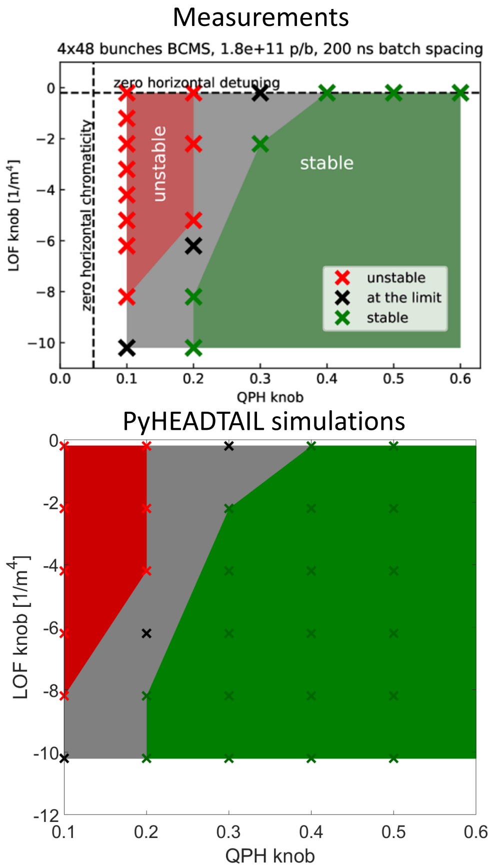

Figure 2: Stability map of the 4 trains of 48 bunches with a current of 1.8e11 p/b and train spacing of 200 ns: Experimental (top) and simulations (bottom). Courtesy of H. Bartosik and C. Zannini

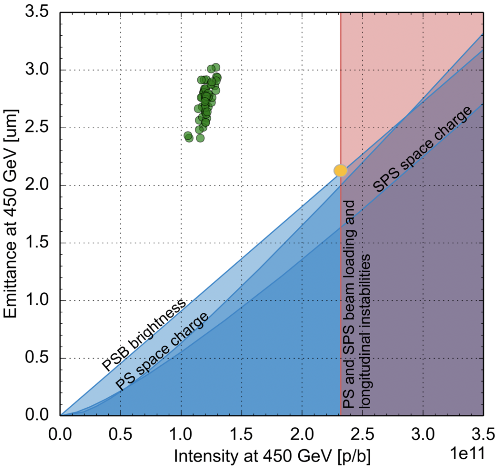

Figure 3: Limitation diagram for the standard LHC beam in the injectors' chain after the LIU upgrades.

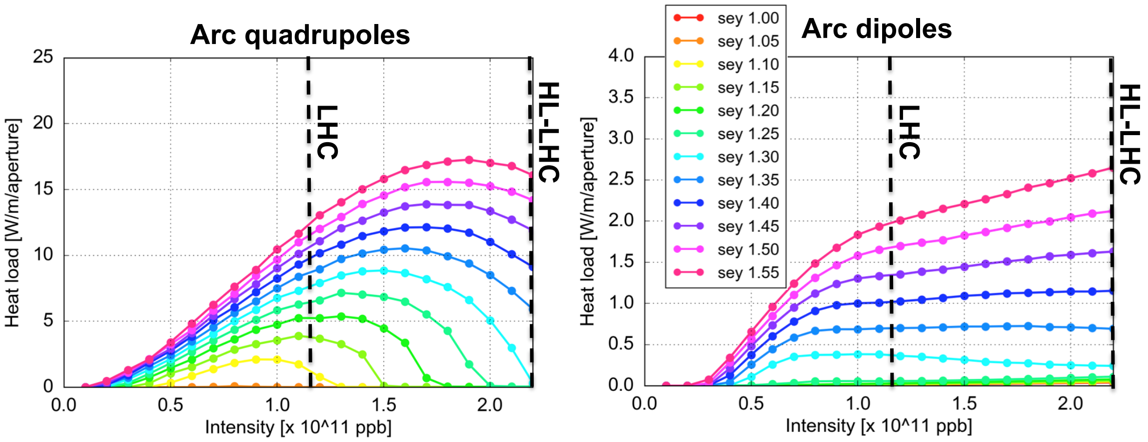

Figure 4: E-cloud generated heat load as a function of bunch intensity in LHC arc dipoles (left) and quadrupoles (right) for different SEYs, as labeled. Courtesy of G. Iadarola and G. Skripka.

to be used. Besides, the β^* levelling during many hours of operation at constant luminosity will require the commissioning of a large number of optical configurations. This further challenges the efficiency of the optics measurement and correction tools, needed to fulfil the tight tolerances coming from DA or coherent stability constraints [24].

In terms of effects related to the collective beam dynamics, running HL-LHC with double intensity and brightness will pose notable challenges, such as beam stability, beam induced heat loads in the cold regions and beam-beam [25]. (1) Transverse instabilities have been observed in the LHC with different types of beams and during different machine processes, and have required operation with quite extreme settings, e.g. with Q'=+15, octupole strength close to the maximum, as well as with maximum gain and maximum bandwidth of the transverse feedback (50 turns and 20 MHz, respectively) at high energy. The instabilities observed at injection energy (450 GeV), which are also cured by high chromaticity and octupole strength, are ascribed to e-cloud. Due to some features (such as symmetry between the transverse planes, heat load measurements on single magnets, simulated electron distributions with different magnetic fields), the e-cloud forming in the quadrupoles is likely to be the main culprit. Combined e-cloud build up and instability simulations show that the electron density in quadrupoles decreases for higher bunch currents and therefore these instabilities should become less critical for HL-LHC intensities. The underlying assumption is of course that all beam chambers will scrub for the higher HL-LHC beam intensities at least as much as they have for the present intensity. To gain margin in the octupole strength needed for suppressing instabilities driven at least partly by impedance, impedance reduction will be applied to the main existing contributors (i.e. the collimators) and to new elements in high beta regions (e.g. crab cavities). In particular, all secondary betatron collimators will be replaced with new ones based on a low-impedance design. The present baseline foresees using Mo-Graphite jaws coated with a 5μm Mo layer. This material exhibits comparable robustness as the present carbon-based secondary collimators, but has an electrical resistivity 5 (uncoated) to 100 times (coated) lower [26]. Through an iterative process between the RF and the impedance teams, the HL-LHC crab cavities have been already designed with attention to minimise the impact of HOMs on beam stability. (2) Within HL-LHC, the SEY in the insertion regions will be actively reduced by surface treatments (a-C coating [20] or laser treatment [27]), with an expected reduction of the heat load due to e-cloud in these regions. However, no intervention is foreseen on the beam screen of the arcs, which cover more than two thirds of the whole machine. When operating with 25 ns beams, the measured heat loads in the arcs have been consistently much larger than those expected from impedance and synchrotron radiation and they exhibited a still unexplained spread between arcs, being very close to the nominal cryogenics limits in the "hottest" arcs [28]. In future operation, we will be faced with two main issues. First, when moving to HL-LHC intensities and 7 TeV, the contribution of impedance and synchrotron radiation will become three-fold, which roughly halves the available margin of the cryogenic system for additional heat loads. Second, the scaling with intensity of the observed additional heat loads is quite uncertain. Making the educated assumption that e-cloud is the most plausible source of these heat loads (since it is compatible with a number of observations), we can however predict the heat load in the new parameter regime, as displayed in Fig. 4. For SEYs in the 1.2-1.4 range, as inferred from the present excess heat load in the various sectors, e-cloud build up simulations foresee a relatively mild change of e-cloud generated heat load when increasing the bunch intensity to HL-LHC values. This scaling needs to be validated experimentally after LS2 (when LIU will make higher intensity beams available from the injectors [29]). When summing up all the heat load contributions from the e-cloud in the different regions and those from impedance and synchrotron radiation, one finds out that, while the heat load in low-load sectors would be below 8 kW/arc and thus compatible with HL-LHC, the heat load in high-load sectors exceeds the maximum value by at least 20%. If this is confirmed, a back-up filling scheme featuring several 125 ns gaps within the bunch trains will be used for keeping the heat load in the high-load sectors within the capacity of the cryogenic plant. This will be at the expense of a 10-30% lower number of bunches in LHC.

(3) The beam-beam interaction introduces additional strong nonlinearities in the particle motion and leads to resonance excitation as well as a large tune spread, potentially resulting in a significant restriction of the DA and thus beam degradation. Operational experience and machine studies have proven that the present LHC has surpassed the head-on beam-beam tune shift limit, which was assumed based on experience from past colliders [30, 31]. However, the HL-LHC represents yet another jump into an unexplored parameter range, furthermore with a baseline configuration of luminosity β^* levelling and crossing angle compensation with crab cavities. The beam-beam studies for HL-LHC are performed by tracking the particles over a few million turns under the weak-strong approximation for the beam-beam interaction and for HL-LHC baseline parameters. The DA is calculated and compared with the target value of 6σ over 1e6 turns. Simulations seem to confirm so far that the target DA is comfortably achieved during the whole levelling process and including the chromaticity and octupole settings necessary for beam stability. This gives room to crossing angle adjustments during the levelling process to reduce the pile-up density and the radiation on the inner triplets [32]. A global exploration of the impact on DA of all the related parameters, including possible compensation of the long-range beam-beam effects with wires or electron lenses, is underway to refine operational scenarios and optimise the projected HL-LHC performance.

ACKNOWLEDGEMENTS

This paper summarises the enormous and excellent work carried out by the LIU and HL-LHC beam dynamics teams. Special thanks to H. Bartosik, G. Iadarola, R. Tomás and C. Zannini. Then, I would also like to thank S. Albright, R. Alemany, S. Antipov, F. Antoniou, G. Arduini, M. Beck, E. Benedetto, R. Bruce, O. Brüning, X. Buffat, M. Carlà, H. Damerau, G.P. Di Giovanni, R. Di Maria, S. Fartoukh, V. Forte, M. Fraser, B. Goddard, K. Hanke, A. Huschauer, V. Kain, E. Koukovini-Platia, A. Lasheen, K. Li, M. Meddahi, L. Mether, E. Métral, B. Mikulec, Y. Papaphilippou, T. Pieloni, D. Quartullo, S. Redaelli, J. Repond, A. Romano, L. Rossi, B. Salvant, M. Schenk, R. Scrivens, E. Shaposhnikova, G. Skripka, F. Velotti.

REFERENCES

[1] J. Coupard *et al.*, "LIU Technical Design Report - Volume I: Protons", CERN, Geneva, Switzerland, Rep. CERN-ACC-2014-0337, Dec. 2014.

[2] J. Coupard *et al.*, "LIU Technical Design Report - Volume II: Ions", CERN, Geneva, Switzerland, Rep. CERN-ACC-2016-0041, April 2016.

[3] G. Apollinari, I. Béjar Alonso, O. Brüning, P. Fessia, M. Lamont, L. Rossi, and L. Tavian, "High-Luminosity Large Hadron Collider (HL-LHC): Technical Design Report V. 0.1", CERN, Geneva, Switzerland, CERN Yellow Reports: Monographs, Rep. CERN-2017-007-M, April 2017, `doi:10.23731/CYRM-2017-004`

[4] M. Benedikt *et al.*, "Summary of Session 7: Accelerators and non LHC Experiment Areas Consolidation up to LS3", in *Proc. Chamonix 2014 Workshop*, Chamonix, France, Sept. 2014, CERN-ATS-2015-002, pp. 31-32.

[5] G. Rumolo *et al.*, "Expected Performance in the Injectors at 25 ns Without and With Linac4"', in *Proc. Review of LHC and Injector Upgrade Plans (RLIUP) Workshop*, Archamps, France, Oct. 2013, CERN-2014-006, pp. 17-24.

[6] S. Albright, E. Shaposhnikova and D. Quartullo, "Longitudinal emittance blow up and production of future LHC beams", in *Proc. Injector MD days 2017*, Geneva, Switzerland, March 2017, CERN-Proceedings-2017-002.23, pp. 23-26.

[7] E. Koukovini-Platia, M. J. Barnes, H. Bartosik, G. Rumolo, L. Sermeus, and C. Zannini, Phys. Rev. Accel. Beams, vol. 22, p. 124201, December 2019.

[8] G. Arduini *et al.*, "Fast vertical single-bunch instability at injection in the CERN SPS - an update", in *Proc. PAC07*, Albuquerque, New Mexico, US, June 2007, paper FRPMN065, pp. 4162-4164.

[9] H. Bartosik, "Beam dynamics and optics studies for the LHC injectors upgrade", CERN, Geneva, Switzerland, Ph.D. thesis CERN-THESIS-2013-257, Nov. 2013.

[10] R. Garoby, *IEEE Transactions on Nuclear Science*, vol. 32, no. 5, pp. 2332 - 2334, Oct. 1985, `doi:10.1109/TNS.1985.4333903`

[11] H. Damerau *et al.*, "LIU: Exploring alternative ideas", in *Proc. Review of LHC and Injector Upgrade Plans (RLIUP) Workshop*, Archamps, France, Oct. 2013, CERN-2014-006, pp. 127-138.

[12] H. Bartosik and G. Rumolo, "Beams in the injectors", in *Proc. 5th Evian Workshop on LHC beam operation*, Evian-les-Bains, France, June 2014, CERN-ACC-2014-0319, pp. 93-98.

[13] E. Benedetto *et al.*, "Space charge effects and mitigation in the CERN PS-Booster, in view of the upgrade", in *Proc. HB2016*, Malmö, Sweden, July 2016, paper THPM9X01, pp. 517-522.

[14] H. Damerau and L. Ventura, "Longitudinal coupled-bunch instability studies in the PS", in *Proc. Injector MD days 2017*, Geneva, Switzerland, March 2017, CERN-Proceedings-2017-002.59, pp. 59-62.

[15] E.Shaposhnikova, E. Chapala and E. Montesinos, "Upgrade of the 200 MHz RF System in the CERN SPS", CERN, Geneva, Switzerland, Rep. CERN-ATS-2011-042, Aug. 2011.

[16] M. Meddahi *et al.*, "LHC Injectors Upgrade (LIU) project at CERN", in *Proc. IPAC15*, Richmond, VA, USA, May 2015, paper THPF093, pp. 3915-3918.

[17] E. Shaposhnikova *et al.*, "Identification and reduction of the SPS impedance", in *Proc. HB2016*, Malmö, Sweden, July 2016, paper TUAM3X01, pp. 260-265.

[18] G. Iadarola and G. Rumolo, “Electron cloud in the CERN accelerators (PS, SPS, LHC)”, in *Proc. ECLOUD’12*, Elba island, Italy, June 2012, CERN-2013-002, pp. 19-26.

[19] G. Rumolo *et al.*, “Electron cloud effects at the CERN accelerators”, in *Proc. ECLOUD’18*, Elba island, Italy, June 2018, in course of publication.

[20] C. Yin Vallgren *et al.*, “Amorphous carbon coatings for the mitigation of electron cloud in the CERN Super Proton Synchrotron”, vol. 14, p. 071001, July 2011, `doi:10.1103/PhysRevSTAB.14.071001`

[21] C. Zannini *et al.*, “Low-impedance design with example of kickers”, elsewhere in these proceedings.

[22] K. Li *et al.*, “Concept and simulations of unconventional damping devices: wideband damper and RFQ”, presented at ICFA Mini-Workshop on Impedances and Beam Instabilities in Particle Accelerators, Benevento, Italy, Sept. 2017, unpublished.

[23] S. Fartoukh, “Achromatic telescopic squeezing scheme and application to the LHC and its luminosity upgrade”, *Phys. Rev. ST Accel. Beams*, vol. 16, p. 111002, Nov. 2013, `doi:10.1103/PhysRevSTAB.16.111002`.

[24] F. Carlier *et al.*, “Optics Measurement and Correction Challenges for the HL-LHC”, CERN, Geneva, Switzerland, Rep. CERN-ACC-2017-0088, Nov. 2017.

[25] G. Arduini *et al.*, *JINST* vol. 11, p. C12081, Dec. 2016, `doi:10.1088/1748-0221/11/12/C12081`.

[26] E. Quaranta *et al.*, “Towards optimum material choices for the HL-LHC collimator upgrade”, CERN., Geneva, Switzerland, Rep. CERN-ACC-2016-0062, May 2016.

[27] R. Valizadeh *et al.*, “Low secondary electron yield of laser treated surfaces of copper, aluminum and stainless steel”, in *Proc. IPAC 2016*, Busan, Korea, June 2016, paper TUOCB02, pp 1089-1092.

[28] G. Iadarola, G. Rumolo, P Dijkstal, and L. Mether “Analysis of the beam induced heat loads on the LHC arc beam screens during Run 2”, CERN, Geneva, Switzerland, Rep. CERN-ACC-Note-2017-0066, Dec. 2017.

[29] G. Rumolo *et al.*, “Update on the HiLumi/LIU parameters and performance ramp up after LS2”, presented at HiLumi Collaboration meeting, Madrid, Spain, Nov. 2017, unpublished.

[30] W. Herr *et al.*, “Observations of beam-beam effects in the LHC in 2011”, in *Proc. Chamonix Workshop 2012 on LHC Performance*, Chamonix, France, Jan. 2012, CERN-2012-006, pp. 99-104.

[31] T. Pieloni *et al.*, “Colliding high brightness beams in the LHC”, in *Proc. HB2012*, Beijing, China, Sept. 2012, paper MOP250, pp. 180-182.

[32] Y. Papaphilippou *et al.*, “Long Range Beam-Beam effects for HL-LHC”, presented at LHC Performance Workshop (Chamonix 2018), Chamonix, France, Jan. 2018, unpublished.