BEAM DYNAMICS CHALLENGES FOR THE LHC AND INJECTOR UPGRADES

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Abstract

The High Luminosity upgrade of the Large Hadron Collider (HL-LHC) will rely on significantly higher bunch current and brightness to meet the future yearly integrated luminosity target. The implications 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 lead to the lifting of the main intensity and brightness limitations in the injectors, linked to beam instabilities driven by impedance or electron cloud (e-cloud), and space charge. On the other side, the LHC will have to be able to swallow the new beam parameters. This will mainly require control of impedance driven instabilities and beam-beam effects, and e-cloud mitigation. 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, if not already installed, they will for the most part be 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

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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 Nb₃Sn 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 Nb₃Sn-based dipoles, the new superconducting link technology with MgB₂, 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, the optional use of 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.

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.

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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. Although this is believed to be beneficial in terms of space charge in the PS since it would allow the transfer of longer bunches with larger momentum spreads, the experimental proof is to date still missing – probably due to other issues related to the transfer of bunches with large momentum spread. 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 6 times more intense than the current LHC beams, which are used for fixed target experiments at the ISOLDE facility.

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 [7], 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 [8].

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 publisher, 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 work, injectors has 1.3e11 p/b within about 2.7 μ m transverse emitbution of this work must maintain attribution to the author(s), title of the tance. All the points measured at LHC injection over the years 2015 – 2018 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 [9–11].

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 μ m injected from the SPS. In order not to exceed a pile up of 140 events/crossing, the luminosity is levelled at $5e34 \text{ cm}^{-2}\text{s}^{-1}$ 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 $\text{cm}^{-2}\text{s}^{-1}$, allowing for a pile up of 200 events/crossing. Table 1 shows achieved and HL-LHC specified beam parameters at the SPS exit.

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.

Table 1: Current and HL-LHC Beam Parameters Out of SPS

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

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.

maintain attribution to the author(s), title of the work, publisher, and 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 must goals listed above will be realised within the LIU project by work means of the following actions. Firstly, the PSB brightness line with half slope will be made possible by using Linac4 $\frac{1}{2}$ with H⁻ charge exchange injection into the PSB at 160 MeV. ъ It has been simulated that if Linac4 provides 40 mA within Anv distribution 0.4 μ m, 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) [12]. If the current from Linac4 is lower (compatibly with the goal 8) set for the future fixed target beams), the number of injected 201 turns will have to be correspondingly increased. Secondly, the injection energy into the PS will be raised to 2 GeV, O which alone guarantees a 63% intensity increase for a fixed licence transverse emittance while keeping the space charge tune spread the same as nowadays. Besides, the longitudinal 3.0 beam parameters at the PSB-PS transfer will have to be d optimised to further reduce the tune spread at PS injection 0 and ensure that the PS space charge curve in the limitation the diagram ends up in the shadow of the PSB brightness line. The longitudinal emittance will be blown up along the PSB of terms cycle to provide longer bunches at the PS injection, while the larger momentum spread will also further reduce the the i space charge tune spread due to the increase of the average under beam horizontal size through dispersion. The longitudinal emittance blow up can be reproducibly applied in the PSB used via either phase modulation of a higher harmonic or injection of band limited phase noise on the main harmonic, as has þ been demonstrated in MDs in 2017 [6] and 2018. Content from this work may

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.

÷: 10 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 [13]. 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 [14]. 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 [15]. 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 [16]. 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 [17]. 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. Recent 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 emittance growth

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(see Fig. 2). Coating with amorphous carbon (a-C) [18] will be 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.



Figure 2: Evolution of emittance growth in SPS during high intensity run. Courtesy of H. Bartosik and M. Carlà.

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.



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

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 [19]. The inpublisher, stallation 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 work, and cold mass [3]. Single particle stability in HL-LHC is he challenged by the large beta functions in the triplets and in the adjacent arcs, which enhance the effect of linear and of attribution to the author(s), title 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 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 [20].

maintain 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 must 1 induced heat loads in the cold regions and beam-beam [21]. work (1) Transverse instabilities have been observed in the LHC with different types of beams and during different machine his processes, and have required operation with quite extreme of settings, e.g. with Q'=+15, octupole strength close to the bution 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 in-Any distr jection 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 8. planes, heat load measurements on single magnets, simu-201 lated electron distributions with different magnetic fields), 0 icence 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 3.0 decreases for higher bunch currents and therefore these insta-BY bilities should become less critical for HL-LHC intensities. S The underlying assumption is of course that all beam chamthe bers will scrub for the higher HL-LHC beam intensities at of least as much as they have for the present intensity. To gain terms margin in the octupole strength needed for suppressing instabilities driven at least partly by impedance, impedance under the 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 é Mo-Graphite jaws coated with a 5μ m Mo layer. This matemay rial exhibits comparable robustness as the present carbonwork based secondary collimators, but has an electrical resistivity 5 (uncoated) to 100 times (coated) lower [22]. Through an from this 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. Content (2) Within HL-LHC, the SEY in the insertion regions will

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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.

attribution to the author(s), title of the work, publisher, and DOI be actively reduced by surface treatments (a-C coating [18] or laser treatment [23]), with an expected reduction of the maintain heat load due to e-cloud in these regions. However, no intervention is foreseen on the beam screen of the arcs, which must cover more than two thirds of the whole machine. When operating with 25 ns beams, the measured heat loads in the arcs work have been consistently much larger than those expected from impedance and synchrotron radiation and they exhibited a of this still unexplained spread between arcs, being very close to the nominal cryogenics limits in the "hottest" arcs [24]. In fudistribution ture 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 N three-fold, which roughly halves the available margin of the cryogenic system for additional heat loads. Second, the scal-8 ing with intensity of the observed additional heat loads is 20 quite uncertain. Making the educated assumption that elicence (© 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, 3.0 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 sec-В tors, e-cloud build up simulations foresee a relatively mild change of e-cloud generated heat load when increasing the the bunch intensity to HL-LHC values. This scaling needs to terms of be validated experimentally after LS2 (when LIU will make higher intensity beams available from the injectors [25]). When summing up all the heat load contributions from the under 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 used compatible with HL-LHC, the heat load in high-load secþ tors exceeds the maximum value by at least 20%. If this is nav confirmed, a back-up filling scheme featuring several 125 ns gaps within the bunch trains will be used for keeping the work heat load in the high-load sectors within the capacity of the cryogenic plant. This will be at the expense of a 10-30% from t 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 headon beam-beam tune shift limit, which was assumed based on experience from past colliders [26, 27]. 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 [28]. A global exploration of the impact on DA of all the related parameters, including possible compensation of the longrange beam-beam effects with wires or electron lenses, is underway to refine operational scenarios and optimise the projected HL-LHC performance.

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