HIGH INTENSITY BEAM DYNAMICS CHALLENGES FOR HL-LHC

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Abstract

The High Luminosity (HL-LHC) project aims to increase the integrated luminosity of CERN's Large Hadron Collider (LHC) by an order of magnitude compared to its initial design. This requires a large increase in bunch intensity and beam brightness compared to the first LHC runs, and hence poses serious collective-effects challenges, related in particular to electron cloud, instabilities from beam-coupling impedance, and beam-beam effects. Here we present the associated constraints and the proposed mitigation measures to achieve the baseline performance of the upgraded LHC machine. We also discuss the interplay of these mitigation measures with other aspects of the accelerator, such as the physical and dynamic aperture, machine protection, magnet imperfections, optics, and the collimation system.

INTRODUCTION

HL-LHC relies on a levelled luminosity reaching $5 \cdot 10^{34}\,\mathrm{cm^{-2}\,s^{-1}}$ [1, 2] to be able to integrate $250\,\mathrm{fb^{-1}}$ per year of proton-proton luminosity in ATLAS and CMS [2]. In terms of beam properties, the luminosity $\mathcal{L} \propto \frac{n_b N^2}{\varepsilon_n}$ depends mainly on the number of colliding bunches n_b, the intensity per bunch N, and the normalised transverse emittance ε_n [1].

A high brightness N/ε_n for the initially injected beam, and its preservation through the machine cycle, are obviously critical ingredients to maximise luminosity. In view of HL-LHC, the entire LHC injector chain has undergone a campaign of improvements through the LHC Injectors Upgrade (LIU) project [3]. LIU was designed to provide HL-LHC with $N = 2.3 \cdot 10^{11}$ protons per bunch (p^+/b) within an emittance of 2.1 µm. Currently, nominal trains with up to $2.2 \cdot 10^{11}$ p^+/b within about 2 µm have been accelerated to 450 GeV/c in the CERN Super Proton Synchrotron (SPS), i.e. just before extraction into the LHC [4, 5]. Brightness preservation in HL-LHC is a subject in itself and will not be specifically considered in this article – we simply note that based on past experience, from injection to collision, losses are assumed to remain below 5% and an emittance blow-up of 20% is assumed (i.e., $\varepsilon_n = 2.5$ µm is foreseen at the start of collisions, as a conservative estimate that takes into account some blow-up at injection, when ramping the energy, and when the separation between the two beams is collapsed).

The main focus of this paper will be on two crucial beam-dependent parameters that drive the machine performance, namely the bunch intensity and the number of bunches per beam. We will first discuss the limitations arising from electron-cloud (or e-cloud) effects, in particular, in terms of number of bunches, as well as their mitigation measures. Then we will focus on transverse impedance and stability, detailing the constraints imposed by the collimation system, the crab cavities and the dynamic aperture, as well as possible mitigation measures, before providing the global picture about beam stability. A few additional considerations with impact on intensity reach will then be listed, and our conclusion will follow.

THE ELECTRON-CLOUD CHALLENGE

Since the first LHC runs, the electron-cloud effect was found to significantly affect machine performance [6–9], essentially through its impact to the heat load on the magnet beam screens, which have to be maintained at a temperature of 20 K through an active cooling system whose capacity is limited. In addition, the electron cloud may also be responsible for emittance blow-up and instabilities.

The e-cloud is generally a self-healing phenomenon, i.e. it is gradually mitigated through a progressive conditioning of the inner surface of the vacuum pipe (or that of the beam screens, in the case of the superconducting magnets). Surface conditioning occurs during operation or in dedicated runs in the presence of e-cloud. This beam-induced scrubbing process effectively reduces the secondary electron emission yield (SEY), quickly at its beginning but then slowing down in an asymptotic way. It stops at a level that may depend on the surface properties and/or on the beam parameters. Unfortunately, the conditioning in the LHC became less and less effective for several sectors after being vented during successive long shutdowns. The reason has been identified in the degradation of the copper-plated surface of the beam screens, related to the unwanted formation of CuO oxide on conditioned surfaces exposed to air [10, 11]. This oxide increases the effective SEY value obtained after reconditioning compared to that of pure copper. As a consequence, the strong heat load in the most affected sector 78 [9, 12] has been limiting the number of bunches in LHC during Run 3. The degradation of the heat load from Run 2 to Run 3, for sector 78, is illustrated in Fig. 1.

For HL-LHC, several options are being studied to prevent the formation of an electron cloud, involving amorphous carbon coating (performed in situ), possibly after CuO reduction through surface treatment [14]. While these could be partially implemented already during long shutdown 3 (LS3, 2026–2029), it is likely that the first run of HL-LHC (Run 4) will still be limited by electron-cloud-induced effects, in particular the heat load, as in Run 3, and possibly

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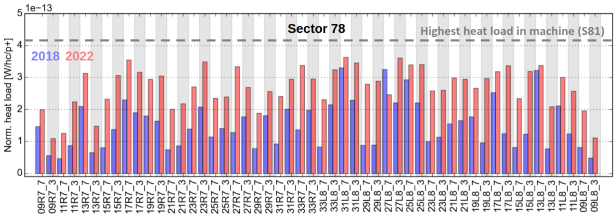

Figure 1: Evolution of the heat load along all half-cells of sector 78, between the end of Run 2 (2018) and the beginning of Run 3 (2022), with similar beam parameters) [13].

also by instabilities. Therefore, three options can be considered [13, 15] – they are summarised in Table 1 with their consequences in terms of the filling scheme. These range from the absence of limitation (case of an e-cloud sufficiently mitigated through beam screens coating) to a strongly degraded situation where the SEY has intolerably increased in so many cells that the e-cloud must be limited through additional means. This can be achieved thanks to the use of an "8b4e" filling scheme [16, 17], made of short trains of eight bunches with 25 ns bunch spacing separated by four empty slots (see Fig. 2), whose structure is able to strongly decrease electron multipacting and hence e-cloud effects, at the cost of a reduction in the number of bunches by almost 30 %. In-between these two extremes, hybrid schemes (containing 8b4e units and standard 25 ns trains) are envisaged for intermediate situations, such as moderate degradation during LS3, moderate degradation with a partial coating of the beam screens, or status quo with respect to Run 3. Only the latter case is considered here.

These schemes are tailored to make the heat load comply with the hard limit given by the cooling capacity of the cryogenic system. On top of that, vertical instabilities during collisions also need to be considered [18] – these are related to a degradation of the stability situation, triggered on one side by the decrease of the Landau damping from the beam-beam head-on tune spread, consequence of the burn-off, and on the other side by an instability maximum occurring for bunch intensities just below 10^{11} p$^+$/b. In 2022, these actually proved to be worse than in previous runs [19] and were not fully suppressed by conditioning, as in Run 2. This means that in the cases where the e-cloud is not strongly mitigated (by using the full 8b4e scheme), chromaticity will have to be maintained high during collisions ($Q' > 15$) to avoid such instabilities, although this has consequences on the dynamic aperture (see below).

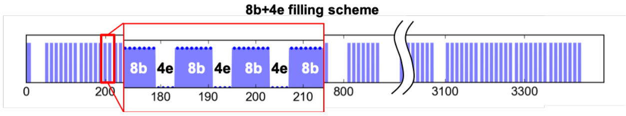

Figure 2: Schematic representation of the 8b4e filling scheme [13].

In injectors, the pure 8b4e scheme is currently being tested, and a bunch intensity of $2.15 \cdot 10^{11}$ p$^+$/b within an emittance of 2.1 µm has already been reached in the SPS at top energy [20].

Table 1: Several filling scheme options considered to mitigate the heat load from e-cloud effects, with the corresponding limitation in number of bunches per beam [15], and the requirement in terms of chromaticity during collisions (Q'). In all cases, a bunch intensity of $2.3 \cdot 10^{11}$ p$^+$/b is assumed. A possibility to go beyond this number in the 8b4e case, is currently being explored.

Scheme	**8b4e ratio**	**Number of bunches**	Q'	**Assumption on beam screens**
Baseline	0 %	2748	>15	Surface treatment
Hybrid	47 %	2320	>15	No further degradation w.r.t Run 3
8b4e	100 %	1972	-	Strongly degraded

In the above considerations, only the limitations from heat load and beam instabilities in collisions are considered. In principle, additional issues could arise at injection, such as instabilities and emittance growth, which are under scrutiny; for the latter a mitigation with new optics was implemented during the 2023 operation [21, 22].

TRANSVERSE IMPEDANCE

The transverse impedance is one of the main sources of bunch intensity limitations in the current LHC machine at top energy [19, 23], its dominant contribution being the collimation system. In HL-LHC, crab cavities are also potentially high contributors that need to be carefully assessed. On top of these, dynamic aperture (DA) is a subject of concern as it can significantly limit the octupole current used to stabilise the beam at flat top before collisions are established. In this section we shall hence describe the parameter space available for each of these factors, before assessing the transverse stability.

Collimation System

In the LHC, the collimation system protects the magnets and other sensitive elements of the machine from halo particles. Primary (TCP) and secondary (TCS) collimators were originally made of poorly conducting carbon-reinforced carbon (CFC), which represents a trade-off between robustness and impedance considerations. To decrease the large impedance of these collimators, an upgrade programme has been launched for HL-LHC to decrease their contribution. In particular, four TCS per beam in insertion region 7 (IR7) were replaced during long shutdown 2 (LS2) by low-impedance counterparts (TCSPM) in molybdenum graphite (MoGr) coated with 5 µm of molybdenum metal [24–26]. Furthermore, two TCPs per beam were replaced by higher conductivity MoGr ones (TCPPM) [26]. In addition, during LS3, five other secondary collimators in CFC will be exchanged with even lower-impedance ones featuring copper-coated isostatic graphite jaws and taperings [27].

For the IR7 collimators, two sets of settings are currently being considered at top energy: tight and relaxed [28]. While the tight settings are slightly larger than the ones successfully deployed in runs 2 and 3, the relaxed ones were introduced to decrease the transverse impedance [29, 30] at the cost of reducing the margins for the β^* reach and cleaning efficiency. Both configurations are summarised in Table 2, for two possible end-of-levelling β^*. The aperture of the tertiary collimators (TCT) at interaction points (IP) 1 and 5 is also given, as it drives the cold-protected aperture (1σ larger than the TCT gaps). To respect the collimator hierarchy, the TCT gaps must be opened at least by 1σ more than the secondary collimators, and they must be larger than those of the single-jaw absorbers (TCDQ) in the dump region (IR6) that protects from asynchronous beam dump failures [31, 32]. Aperture bottlenecks in the triplet region of HL-LHC are also given as an interval ranging from the ideal configuration to the worst-case scenario, assuming mechanical, alignment, and optical imperfections.

Table 2: Collimator settings [28] (in σ units, with ε_n =2.5 µm), in IR6, IR7 and for the TCT close to ATLAS and CMS, for two different β^*, together with protected aperture in the triplets and aperture bottleneck (all in σ) [32].

	Relaxed		**Tight**	
IP1/5 β^* [cm]	15	20	15	20
TCP IR7	8.5		6.7	
TCS IR7	10.1		9.1	
TCLA IR7	13.7		12.7	
TCDQ/TCS IR6	11.1		10.1	
TCT 1/5	11.4	13.2	10.4	12.0
Protected aperture 1/5	12.4	14.2	11.4	13.0
Aperture bottleneck 1/5	13.1–16.6	15.2–19.2	13.1–16.6	15.2–19.2

Even in the worst-case scenario and for relaxed settings, the triplets are well within the protected aperture. Note that for flat optics, i.e. smaller β^* in the separation plane than in the crossing plane, the situation is less clear and more studies are needed (in particular for $\beta^* = 7.5$ cm in the separation plane [32]).

In addition to aperture protection, collimator settings are driven by considerations of cleaning efficiency, and tight settings are clearly beneficial in that respect. On the other hand, a highly populated halo could damage collimators in case of fast failures. For this aspect, the relaxed settings could be favorable [33], especially without the hollow electron lens (HEL) which has been descoped from the project.

Finally, studies are ongoing to reduce the impedance of IR7 and IR3 collimators even more through optics changes [34, 35] together with global phase-advance optimisation [36].

Crab Cavities

The crab cavities (CC) are an essential improvement for HL-LHC [2], their goal being to increase the geometric reduction factor of the luminosity induced by the crossing angle (see chap. 4 in [1]). However, they are detrimental to transverse impedance and stability, as a result of their numerous narrow-band resonant modes and the high β functions in the crabbing plane at the location of the CC. Although high-order modes (HOMs) are well under control [37, 38], the impedance from the fundamental mode was only recently deemed very significant [39–42], leading to a dramatic increase of the octupole current required to stabilise the beam through Landau damping before collisions are established at top energy [43]. Several mitigations are considered:

1. Switch off the cavities and detune the resonant frequency between unstable betatron lines (and switch them back on only when collisions are established). This option needs further evaluation, especially after observation during dedicated machine development (MD) studies in the SPS of transient effects when cavities and RF feedbacks are switched on with circulating high-intensity beam [44].

2. Use a standard RF feedback [45] that will broaden and reduce the height of the peak from the fundamental mode. The gain from such feedback is nevertheless limited [46, slide 4]. This could be complemented by moving to flat optics, with a higher β^* in the crossing plane than in the separation plane (e.g. 2.8 m vs. 0.7 m at flat top [36]). This would lower β at the crab cavity in the crabbing plane, hence the impedance of the fundamental mode [42].

3. Use RF feedback together with a betatron comb filter to reduce impedance specifically at betatron frequencies, similar to what is done for RF cavities to mitigate their longitudinal fundamental mode [47, 48]. Nevertheless, a large uncertainty remains in the case of the betatron comb filter: as the betatron lines are offset by the tune, one needs to make sure the tune remains within a given bandwidth. Hence, tune jitter or bunch-by-bunch tune variations (from collective effects) are a matter of concern and are under study.

Currently, the third option (betatron comb filter) appears to be the most promising mitigation of the fundamental mode impedance, as it decreases the additonal octupole current needed by 80 %, vs 60 % for the second option [42].

Dynamic Aperture Considerations

The LHC octupoles are used to damp instabilities through the Landau damping mechanism, and can be set to a current as large as 570 A [23]. In HL-LHC, such a high octupole current may become a limiting factor to reach the DA target, in particular in the critical phase when beams are brought into collisions – few beam dumps related to losses have already been observed in this phase during Run 3 [49, slide

39]. Indeed, at that point of the cycle the octupoles are strongly powered because they are needed in the preceding phase (flat top), where they are the main source of Landau damping, and at the same time, the beam-beam head-on tune spread will increase rapidly, while the separation is reduced towards zero. In HL-LHC, DA issues during collisions are enhanced with respect to the LHC, as a consequence of beam-beam effects due to a higher brightness. In addition, the interplay between magnet imperfections and a large crossing angle should be considered carefully.

In this phase, with as much as 460 A in the octupoles, $\beta^* = 1$ m, $N = 2.3 \cdot 10^{11}$ p$^+$/b and $\varepsilon_n = 2$ µm (anticipating a very good emittance preservation), a DA marginally above 6σ can be found for a few working points [29, Fig. 4], with the baseline filling scheme (see Table 1). The DA situation is better with negative octupole current, with the 8b4e scheme [50], or with a smaller chromaticity (e.g. $Q' = 5$ instead of 15) [51]. On the other hand, DA is degraded with flat optics [50] but a direct comparison is not straightforward, as a telescopic index (see [52] for a definition) is then introduced, which is beneficial for stability, hence leading to a smaller octupole current required – studies are ongoing on this aspect.

Transverse Stability Limits

The transverse stability situation, in terms of the minimum octupole current needed to stabilise the beam at flat top (before collisions), is summarised in Fig. 3, where we explore the most relevant options described above, in terms of collimator settings and mitigation of the fundamental mode of crab cavities. Positive octupole polarity is assumed, and a wide chromaticity range is explored due to the uncertainty on Q'. Note that contrary to past estimates [29], transverse Gaussian tails are taken into account, following the descoping of the HEL and studies in the injectors during Run 3 indicating that beams sent to LHC have indeed significant tails. This decreases the threshold by up to 20 % [53]. In addition, latency effects [54] are taken into account.

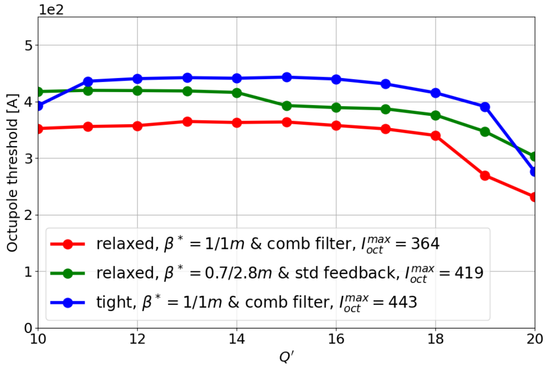

Figure 3: Single-beam octupole threshold (positive polarity) needed for stability at flat top (round or flat optics), for a 25-ns full beam (4σ bunch length 1 ns, $\varepsilon_n = 2$ µm, Gaussian in all planes, $N = 2.3 \cdot 10^{11}$ p$^+$/b, bunch-by-bunch feedback with 100 turns damping time).

The octupole threshold with the RF comb filter at the most unstable chromaticity in the range $10 < Q' < 20$ is 364 A and 443 A for relaxed and tight collimator settings, respectively. With relaxed settings, standard RF feedback and flat optics, it is 419 A[1]. Therefore, all cases are compatible with DA (see above), although the tight settings do not provide much margin.

Note that the transverse mode coupling instability (TMCI) threshold is not an issue for HL-LHC: the latest estimates put it around $6 \cdot 10^{11}$ p$^+$/b (in single bunch) [26]; moreover TMCI is strongly attenuated by transverse feedback [55] and thus does not have to be considered as a hard limit.

The octupole thresholds presented in Fig. 3 are computed for an energy of 7 TeV. The option to go to 7.5 TeV would a priori increase the threshold by ~7 % as long as the collimator settings remain unchanged in mm, as assumed in [56].

ADDITIONAL CONSIDERATIONS

Local Heating in Sensitive Devices

Heat load is systematically checked for any new device added to the machine, but non-conformities may be present. In particular, after an incident on a RF vacuum module (A4L1) in 2023, several two-beam RF vacuum modules have been found to be nonconforming and will be replaced [57]; intensity has been limited to $1.6 \cdot 10^{11}$ p$^+$/b, and studies are ongoing to pin down the role of impedance in the problem [58].

Limitations on the RF Power

New high-efficiency klystrons are needed to achieve HL-LHC baseline and hybrid filling schemes, to cope with the strong injection transients and high average power required, which is beyond the capability of the present system [59].

Beam-beam Wire Compensation

The wire could be used to gain margin on DA during collisions, in particular if the TCTs can be moved to maintain a constant gap in σ during the luminosity levelling [60], as done in 2023. On the other hand, before collisions β^* is much higher, which reduces the potential gain in DA.

CONCLUSIONS

The limitations in number of bunches and bunch intensity have been reviewed, in particular those stemming from electron-cloud and impedance effects. Depending on the state of the beam screen surface after LS3, three options in terms of number of bunches are envisaged, from baseline to 8b4e, via an intermediate hybrid scheme. In terms of the bunch intensity limit, the baseline is achievable, but the octupole currents, and hence the dynamic aperture and lifetime during the separation collapse, will ultimately depend on the collimator settings chosen and the mitigation strategy used to reduce the impedance contribution of the crab cavities.

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[1] In the flat optics case, octupoles have been rescaled to a telescopic index of one for comparison purposes, as these optics would otherwise induce a telescopic index that strongly lowers the octupole threshold.

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