ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPL034

HIGH LUMINOSITY LHC OPTICS SCENARIOS FOR RUN 4*

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Abstract

Run 4 will be the first operational run of the LHC, with full deployment of the upgrades from the High Luminosity (HL-LHC) project planned for installation in 2026-2028 (Long Shutdown 3). The commissioning goals for the first run were defined to approach steadily the design beam parameters and configuration, while already fulfilling significant luminosity goals. Despite extensive operational experience already gained, the intensity limitations due to electron cloud and/or impedance might require to use pushed β^* values to reach the integrated luminosity goal. The paper presents the main machine parameters and main optics aspects that are considered to prepare Run4 optics scenarios.

INTRODUCTION

The HL-LHC project [1] aims at upgrading part of the ring and ancillary systems for integrating over 3000 fb^{-1} proton-proton luminosity in ATLAS and CMS in ten years (including the integrated luminosity collected during previous runs), providing collisions to the ALICE and LHCb experiments, while maintaining the ion programme (see Fig. 1) each year.

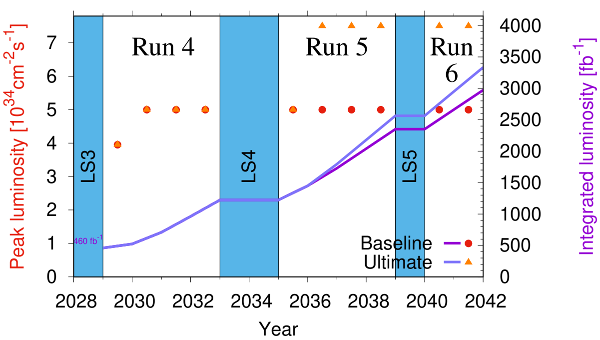

Figure 1: HL-LHC schedule and projection of the peak and integrated luminosities for ATLAS and CMS. The blue boxes represent the long shutdowns (LS). The integrated luminosity projection assumes a baseline configuration not exceeding $5 \cdot 10^{34}$cm^{-2}s^{-1} levelled luminosity and an ultimate scenario, obtained using all engineering margins, that assumes a levelled luminosity up to $7.5 \cdot 10^{34}$cm^{-2}s^{-1}. These scenarios assume 15 week of yearly technical stops.

Run 4 is the first run with the new HL-LHC hardware, notably Nb_3Sn triplet magnets, crab cavities (CC), full remote alignment system, new collimation system and additional cryogenic plants. The first year is expected to be mostly dedicated to commissioning activities, with luminosity production reaching the yearly integrated luminosity target of 260 fb^{-1} by the end of Run 4, while integrating a substantial amount of luminosity (750 fb^{-1}) in the first 4 years [2–4].

BASELINE BEAM PARAMETERS

Table 1 shows the main beam parameters for HL-LHC compared to LHC. The large increase in virtual luminosity[1] is obtained mainly from the increase in bunch charge, the decrease in β^* and the crab cavities, while the gain in integrated luminosity stems mostly from the increase of levelled luminosity and the bunch charge. As of 2022, the LHC already exceeded all nominal parameters, except the beam energy and number of bunches. The number of bunches is currently limited by electron-cloud effects [5]. A surface treatment project has been launched to address this potential major limitation, but, due to the uncertainty of the chemical processes underlying the loss of secondary emission yield conditioning (SEY) and the scale of interventions, Run 4 is being prepared assuming that the number of bunches will be limited between 1972 and 2320 [4]. Furthermore, for HL-LHC, reaching 7 TeV will be challenging, as the maximum energy is limited by the time and associated risk required to train all main dipole magnets [6].

Although Run 4 is being prepared with conservative parameters due to the need to commission several new equipment, the e-cloud issue triggered a review of the assumptions to compensate for the integrated luminosity losses. In particular, the updated Run 4 scenarios will rely on three main pillars. (i) Experiments could operate at the design pile-up (200) instead of the baseline (140) pile-up for Run 4 if computing capabilities could be procured on time. This allows increasing the luminosity per bunch beyond nominal to compensate for fewer bunches, as the cryogenic system in the triplets will be limited only by the total luminosity. (ii) The 8b-4e injector production scheme [7] allows injecting bunch trains generating reduced e-cloud heat load, thereby increasing the number of colliding bunches as compared to nominal trains of 72-bunches. Furthermore, using only 8b-4e trains could free margins that could allow a larger bunch population, up to $2.5 \cdot 10^{11}$ ppb, and therefore increase the virtual luminosity, but also the duration of the levelled luminosity. (iii) Virtual luminosity could also be increased by reducing β^* to the minimum allowed by the triplet aperture, earlier than anticipated. In particular, flat optics ($\beta^*_x \neq \beta^*_y$, proposed in conjunction with crab-cavities [8]) yield larger virtual luminosity compared to equal β^* for comparable aperture in the triplets at the cost of increased sensitivity to field imperfections in triplets and arcs.

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[1] The virtual luminosity is defined using the smallest β^* and the maximum bunch charge.

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Table 1: Main beam parameters for the LHC as designed, the best parameters obtained in 2022 [9], nominal HL-LHC and those currently considered for HL-LHC in Run 4. The table shows the range of potential parameters for Run 4. The integrated luminosity estimates [10] assume an optimum fill duration with a turn-around time of 2.5 h, an R.M.S. bunch length of 7.55 cm and a crabbing angle of ±190 μrad for HL-LHC scenarios.

Parameter	LHC Nominal	LHC 2022	HL-LHC Nominal	HL-LHC Run 4
Beam energy in collision [TeV]	7	6.8	7	6.8 – 7
Particles per bunch, N_{ppb} [10^{11}]	1.15	1.4	2.2	2.2
Number of bunches per beam	2808	2462	2760	1972–2320
Number of collisions in IP1 and IP5	2808	2450	2748	1960–2308
Crossing angle in IP1 and IP5 [μrad]	285	320	500	500
Minimum β^*[cm]	55	30	15	20 – 7.5
Normalized emittance ε_n[μrad]	3.75	2.0	2.5	2.5
Virtual luminosity L_{virtual} [10^{34}cm^{-2}s^{-1}]	1	3.1	17	9.5-17
Levelled luminosity [10^{34}cm^{-2}s^{-1}]	-	1.9	5.0	3.6–6.4
Maximum events per crossing	26	48	131	140-200
Integrated luminosity [pb^{-1}/h]	22	56	136	97-151

OPTICS DESIGN

Achromatic Telescopic Squeezing (ATS) optics schemes [11] give large flexibility in the β^* reach in ATLAS and CMS. In fact, without using the ATS scheme, β^* is limited to 50 cm due to the Q7 quadrupole strength at Points 1 and 5 and sextupole strength in the arcs to correct for the off-momentum β-beating and crossing-angle-induced dispersion [12]. In contrast, by allowing a β-beating wave in the arcs surrounding ATLAS and CMS (telescopic squeeze), it is possible to reduce β^* in IP1 and IP5 as low as 7.5 cm, however limited by: the physical aperture in the triplets and in the arcs; the ability to preserve a phase advance ($\Delta\mu$) below to 20 degrees between the dump kicker (MKD) and the tertiary collimators (TCTs); the dynamic aperture (DA) reduction due to beam-beam effects, Landau octupoles, large chromaticity, and field imperfections in the interaction region from Q1 to D2; the ability to correct optics imperfections[13]; the orbit jitter at the IP. Table 2 shows the main steps of the p-p cycles with their associated β^* and optimisation criteria.

Optics Aspects

Although telescopic squeeze is now routinely used in LHC [14], the large telescopic squeeze factors (up to 6.6) required for HL-LHC flat optics have not yet been tested [15]. A machine development programme is being elaborated for 2024-2025 to prepare for Run 4. Optics can also be optimised at the beginning of levelling to mitigate possible RF control and related instability issues from crab cavities under maximum beam loading conditions [16]. This can be achieved by reducing the β-function at the location of the crab cavity by using flat optics β^* with the ATS or by a change of the local optics. In the second case, the optimal condition for crabbing angle should be restored shortly after collisions. Furthermore, the criticality of crab cavity failure modes could be reduced by optimising phase advance between crab cavities and primary collimators (TCPs) [17].

Table 2: Optics steps (and corresponding $\beta*$ in IP1/5) under consideration for Run 4 with their optimisation criteria.

Step in the cycle	β^* [cm]	Optimisation criteria
Injection	600	aperture in the arcs, octupole Resonance Driving Terms (RDT)
Flat top	200-50	β_{crab}, octupole RDT
Separation collapse	200-50	octupole RDT
Start of levelling	200-50	octupole RDT, $\Delta\mu_{x,\text{CC1}-\text{TCPH}}$, $\Delta\mu_{y,\text{CC5}-\text{TCPV}}$
End of levelling	20-7.5	aperture in the triplets, field quality, $\Delta\mu_{x,\text{MKD}-\text{TCT1,5}}$, $\Delta\mu_{x,\text{CC1}-\text{TCPH}}$, $\Delta\mu_{y,\text{CC5}-\text{TCPV}}$

Aperture Aspects

The protected aperture for the HL-LHC [18] is 12.6σ at injection for all cold apertures. Table 3 shows the protected aperture at flat top. The tertiary collimator (TCT) gaps must be opened at least by 1σ more than the secondary collimator (TCS) gap. Moreover, in the horizontal plane, the TCT gaps have to be larger than that of the TCDQ, which is a collimator that protects from asynchronous beam dump failures, by an amount that depends on the phase advance between the dump kicker (MKD) and the TCT. The cold aperture protected by the TCT should be 1σ larger than the TCT gaps. The other cold aperture needs to be further away to avoid intercepting debris in the case of such a dump failure.

Table 4 shows the expected aperture in the arcs and triplets. Optimisation of the phase advance between MKD and TCT

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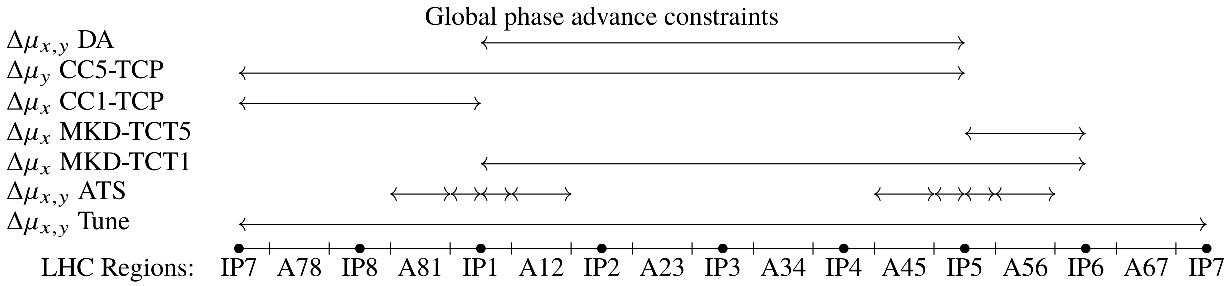

Figure 2: Phase-advance constraints considered during optics design for physics. The LHC has the flexibility to change the phase advance in the 8 arcs and 16 half-straight sections around the IP. While tune and ATS are strict constraints, the others could be fulfilled with some flexibility, which allows for some optimisation.

Table 3: Protected aperture for two different aperture types and collimator scenarios (tight and relaxed) at flat top energy in units of nominal beam size ($\varepsilon_n = 2.5\,\mu\text{m}\,\text{rad}$).

Aperture H/V	TCP at 6.7σ	TCP at 8.5σ
Cold TCT-protected	11.2-14.6/11.2	12.2-15.6/12.2
Cold general	19.4	20.4

is critical to the β^* reach, and it is particularly challenging given the global phase advance constraints (see Fig. 2) and the local constraints in the dump region, named Insertion Region (IR) 6 [19]. A more thorough statistical analysis of the aperture is underway, based on updated tolerance estimates [20]. The values obtained are compatible with the tight collimator scenario, even in the worst case. Relaxed collimator scenario, interesting to mitigate the impedance of the collimators at flat top, loss spikes from tails and crab cavity failures, are incompatible to the most pushed flat optics (7.5/18) in the worst case. At the same time, the impedance could be addressed with specially crafted optics [21] in the collimator region (IR7) and the most critical failure cases of the crab cavities with the phase advance crab to TCP [17].

Table 4: Expected aperture bottlenecks for different parts of the machine in units of nominal beam size ($\varepsilon_n = 2.5\,\mu\text{m}\,\text{rad}$). The values range from the ideal case to the worst-case scenario, assuming mechanical, alignment, and optics imperfections. In case of aperture issues, it is always possible to step back in β^* with small impact on the integrated luminosity.

β^*_{sep} [cm]	$\beta^*_{\text{crossing}}$ [cm]	Triplets [σ]	Arcs [σ]
20	20	15.2-19.2	24.9-32.9
15	15	13.1-16.6	21.7-28.8
9	18	13.5-16.7	21.7-27.5
7.5	18	12.4-15.3	19.8-25.1

DA Optimisation

The DA of the HL-LHC is strongly impacted by the need for high chromaticity. First operational data after the second long shutdown, i.e. after further degradation of the beam-screen surface conditioning, suggest that 15 to 25 units might be needed to cope with the strong electron cloud effects, even at flat top. Landau octupoles needed to stabilise the beams significantly reduce the dynamic aperture, too.

DA can be optimised by several means. Long-range beam-beam effects (BBLR) are reduced by setting the largest crossing angle compatible with the aperture (at injection and at the end of levelling) and the orbit corrector strength (at flat top). Field imperfections are carefully measured and corrected when possible [22–25]. Recent efforts have focused on reducing the RDTs generated by the Landau octupoles at flat top (before collapse) [26] and more recently at injection [27]. The octupole RDTs are created in the arcs and their complex sum can be minimised by a careful choice of their amplitude and phase, while providing the required detuning with amplitude (direct and indirect terms). In addition, the BBLR effects also generate RDTs that play a role in both detuning and DA reduction. When they are strong (in particular towards the end of levelling [28]), the phase advance between IP1 and IP5 has been shown (see Fig. 2) to be an effective parameter to optimise DA [25, 26], but being particularly challenging considering the other global phase constraints. Other means, such as wire BBLR [29] compensation (not part of the HL-LHC baseline) and octupole sign reversal [28], will also be considered in the optimization.

CONCLUSIONS

Run 4 is planned to mark the first LHC operations with the new hardware installed by the HL-LHC project. Potential e-cloud limitations expected in Run 4 require pushing the pile-up and β^* to reach the nominal integrated luminosity goals. As a result, the Run 4 optics scenarios need a global revision to be compatible with the new parameters and additional constraints. A machine development programme is being prepared to validate most of the Run 4 optics during the last years of Run 3.

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