# VALIDATION OF THE NEW HL–LHC BASELINE AND ALTERNATIVE OPERATIONAL SCENARIOS[*]

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## *Abstract*

The High Luminosity (HL–LHC) project aims to increase the integrated luminosity of CERN's Large Hadron Collider (LHC) up to 3 $\mathrm{ab}^{-1}$, and 4 $\mathrm{ab}^{-1}$, as Nominal and Ultimate goals, respectively, over the full lifetime of the facility. The large boost in bunch population and beam brightness, compared to the currently achieved beam parameters in the LHC and stemming from the LHC injector upgrade project deployed during the previous long shutdown 2, poses several beam dynamics challenges that must be addressed, including, for example, electron cloud, impedance-related stability, and beam lifetime. In addition, the increasing availability of measurements for the magnets to be installed in the ATLAS and CMS interaction regions also allows for a more precise determination and optimisation of the dynamic aperture. Recently, modifications of the HL–LHC operations baseline, including ion runs throughout the lifetime of the project, led to a tighter margin on the integrated luminosity goals. Therefore, we present here an update of the baseline scenario of HL–LHC, together with alternative proposals that could mitigate potential shortcomings.

## LHC ACHIEVEMENTS TOWARDS HL

The baseline scenario of HL–LHC foresees a six-fold increase in integrated luminosity in interaction points (IP) 1 and 5 with respect to LHC Runs 1–3. This is achieved by luminosity levelling at $5 \cdot 10^{34}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ with $\beta^*$ reaching 15 cm at the end of fills. This performance also requires 2760 bunches and $2.3 \cdot 10^{11}$ protons per bunch (ppb) with 2.5 µm of transverse emittance in both planes [1–6].

The current status of the experimental validation of these challenging parameters is summarised in Table 1. The LHC injectors have achieved their HL–LHC targets since 2024 [7–9]. Major milestones were achieved with the injection of 1152 high-intensity bunches in trains of 4 × 72 (HL–LHC baseline scheme) into the LHC [10], and the injection and ramp to 3 TeV of 1500 bunches of BCMS flavour (Batch Compression Merging and Splitting, i.e. 5 × 48 trains with low emittance) [11]. Bringing in collisions 8b4e [12], HL–LHC trains of 560 bunches marked another success in 2025, allowing to reach the HL–LHC beam-beam tune shifts [13].

Table 1: Key HL–LHC Design Parameters with their Current Experimental Demonstration [7–11, 13–18] (Green: Fully Validated; Orange: Partially Validated)

| **Parameter** | **Design** | **Achieved** |
|---|---|---|
| **# of bunches with $2.3 \times 10^{11}$ ppb** | | |
| SPS → LHC injection (Standard) | 4 × 72 | **4 × 72** |
| LHC injection energy (Standard) | 2760 | **1152** |
| SPS → LHC injection (BCMS) | 5 × 48 | **5 × 48** |
| LHC injection energy (BCMS) | 2748 | **1500** |
| SPS → LHC injection (8b4e) | 4 × 56 | **2** × 56 |
| **LHC collisions (8b4e)** | 1972 | **560** |
| **Emittance [µm] (at $2.3 \times 10^{11}$ ppb)** | | |
| SPS (Standard) | 2.1 | **2.1** |
| LHC injection (Standard) | 2.1 | **2.2** |
| SPS (BCMS) | 1.7 | **1.7** |
| LHC injection (BCMS) | 1.7 | **2.0** |
| SPS (8b4e) | 1.7 | **1.7** |
| LHC injection & flat top (8b4e) | 1.7 | **1.6** |
| **$\beta$ functions [m] (achieved in operation / MD $10^{10}$ ppb)** | | |
| Peak $\beta$ in the arcs | 600 | **600**/**1040** |
| Minimum $\beta^*$ at the IP | 0.15 | **0.15**/**0.077** |
| **Tune shift (8b4e at $2.3 \times 10^{11}$ ppb)** | | |
| Beam-beam head-on (2 IPs) | 0.020 | **0.020** |
| Beam-beam long-range [19] (1 IP) | 0.004 | **0.008** |

Finally, another major milestone was achieved when $\beta^* =$ 15 cm was reached in operation in 2026, thanks to flat optics with $\beta^*{}_{\times/\parallel} = 51/15$ cm [14–17]. Combined with the higher intensity of $1.8 \cdot 10^{11}$ ppb, this allowed a record levelling time of 12 h in physics with nominal pile-up (~ 65) [18].

Following the update of the HL–LHC project schedule, in particular its delayed start towards mid 2030 and the presence of an ion run every year until 2041, HL–LHC operational schedule and performance numbers were updated. The pile-up requirements had to be gradually increased (up to 150 at the end of Run 4 and 180 at the end of Run 5 — above the HL–LHC baseline) to ensure that the 3000 $\mathrm{fb}^{-1}$ goal is reached. The resulting operational scenario is shown in Table 2, with integrated luminosity provided for ATLAS/CMS (IP1/5) and LHCb (IP8), including the option of an LHCb phase II upgrade during long shutdown (LS) 4 [20].

Figure 1 shows the evolution of the peak and integrated luminosity over the years since the start of LHC. In the baseline scenario, the target of 3000 $\mathrm{fb}^{-1}$ is reached for IP1

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Table 2: Current HL–LHC schedule and parameters. The figures in parentheses indicate the impact of a potential LHCb upgrade II occurring in LS4, with round IP8 optics ($\beta^* = 1.5$ m in both planes) and an effective cross section of 110 mb

| **Year** | **E [TeV]** | **ppb [$10^{11}$]** | **$\beta^*$ [m] IP1&5** | **Pile-up IP1&5** | **Proton days*** | **Ion days†** | **Levelled luminosity for protons [$10^{34}$ cm$^{-2}$ s$^{-1}$] IP1&5** | **IP8** | **Integrated luminosity for protons [fb$^{-1}$] IP1&5** | **IP8** |
|---|---|---|---|---|---|---|---|---|---|---|
| 2030 | 6.8 | 1.8 | 30 | 101 | 74 | 0 | 3.8 | 0.2 | 56 | 3.4 |
| 2031 | 6.8 | 2.2 | 25 | 132 | 151 | 29 | 5 | 0.2 | 212 | 8.8 |
| 2032 | 6.8 | 2.2 | 20 | 150 | 164 | 29 | 5.7 | 0.2 | 259 | 9.7 |
| 2033 | 6.8 | 2.2 | 20 | 150 | 162 | 29 | 5.7 | 0.2 | 255 | 9.5 |
| 2036 | 7 | 2.2 | 15 | 150 | 138 | 29 | 5.7 | 0.2 (1) | 217 (214) | 7.9 (31.3) |
| 2037 | 7 | 2.2 | 15 | 170 | 176 | 29 | 6.4 | 0.2 (1) | 304 (299) | 10.1 (41) |
| 2038 | 7 | 2.2 | 15 | 170 | 179 | 29 | 6.4 | 0.2 (1) | 310 (305) | 10.3 (41.8) |
| 2039 | 7 | 2.2 | 15 | 170 | 179 | 29 | 6.4 | 0.2 (1) | 310 (305) | 10.3 (41.8) |
| 2040 | 7 | 2.2 | 15 | 180 | 135 | 29 | 6.8 | 0.2 (1) | 236 (233) | 7.5 (30.5) |
| 2041 | 7 | 2.2 | 15 | 180 | 184 | 29 | 6.8 | 0.2 (1) | 327 (322) | 10.5 (42.5) |
| Total HL–LHC | | | | | 1542 | 261 | | | 2485 (2458) | 88 (260) |
| **LHC Runs 1–3** | | | | | | | | | **540** | **40** |
| **Total** | | | | | | | | | **3025 (2998)** | **128 (300)** |

* Proton days include the intensity ramp-up (on both the number of protons per bunch and the number of bunches).

† Ion days include physics, commissioning, intensity ramp-up and possibly Machine Development (MD) studies with ions.

and 5, and almost 130 fb$^{-1}$ would be accumulated in IP8. The LHCb upgrade II would allow 300 fb$^{-1}$ to be reached in IP8, with a comparably small effect on the luminosity of ATLAS and CMS (−1%). These figures assume that the effective cross section remains unaffected by the additional collisions in LHCb, which is an open question.

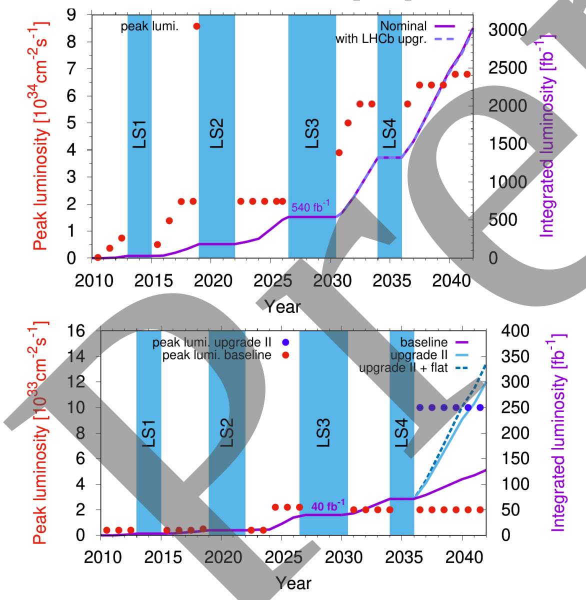

Figure 1: Peak and integrated luminosity in ATLAS and CMS (top), and in LHCb (bottom) during the LHC lifetime, with and without LHCb upgrade II during LS4. For LHCb, the impact of flat optics in IP8 (0.5/1.5 m) is also shown.

## CHALLENGES AND OPTIONS

### *Electron Cloud Effects and Mitigation Measures*

The number of bunches in the LHC is currently limited by the heating induced by the electron cloud formed in the magnet beam screens, at the limit of the available cooling capacity of the cryogenic system. During LS1 and LS2, the inner surface of the beam screens degraded upon venting, leading to an increase in secondary emission yield (SEY) in numerous arc cells. During LS3, the beam screen treatment (BST) campaign [21, 22] is foreseen to strongly reduce heat load in limiting sectors.

Nevertheless, some sectors will remain mostly uncoated and could suffer from further surface degradation during LS3 despite the measures taken to avoid it. Its impact could be mitigated with alternative filling schemes, such as short 36-bunch (or 24-bunch) trains, or 8b4e trains [12] mixed with 72-bunch trains (so-called "hybrid" schemes). These options lower the number of bunches compared to the baseline. Table 3 shows the performance reach for different degradation scenarios of LHC arcs (e.g. sector 45 or 56 degraded), as well as the Run 3 case (no BST nor further degradation). The impact on integrated luminosity in IP 1 & 5 ranges from -6 to -26%, with hybrid schemes performing better than $n \times 36$ (or $n \times 24$) schemes under equivalent conditions.

### *Dynamic Aperture*

The dynamic aperture (DA) will be reduced in HL–LHC because of the larger beam-beam parameter. However, the impact on the DA of magnet imperfections beyond acceptance criteria should be assessed during phases with separated beams (without beam-beam effects), or during beam commissioning phases, as in all these cases the field quality might have an impact on DA. Currently, the mitigation of magnet field quality is carried out through sorting [23–25].

Two phases are critical in terms of DA: 1) the end of collapse, when beams have just been brought into collisions, while octupoles and chromaticity are still at a large value to ensure coherent stability up to that time in the fill (see

Table 3: Filling scheme options considered in various LS3 degradation scenarios. BST in 120 cells is assumed except for the last scenario, and the bunch intensity is $2.3\times10^{11}$ ppb

| **Scenario** | **Scheme (8b4e ratio)** | **Max num. of bunches** | **Impact on int. luminosity** | |
|---|---|---|---|---|
| | | | **IP1&5** | **IP8** |
| Baseline | $4\times72$ (0%) | 2760 | Ref. | Ref. |
| Degr. S56 | Hybrid (13%) | 2580 | -6% | -10% |
| | $5\times36$ (0%) | 2496 | -9% | -12% |
| Degr. S45 | Hybrid (25%) | 2500 | -9% | -12% |
| | $4\times36$ (0%) | 2316 | -16% | -20% |
| No BST, no degr. | Hybrid (42%) | 2260 | -18% | -18% |
| | $6\times24$ (0%) | 2052 | -26% | -29% |

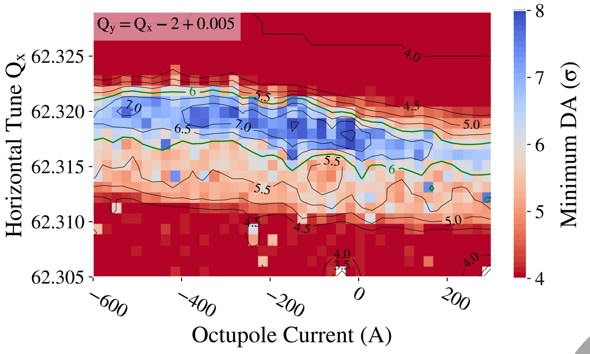

Figure 2: Minimum DA at the end of collapse as a function of $Q_x$ and octupole current, along $Q_y = Q_x - 2 + 0.005$, for round ($\beta_x^* = \beta_y^*$) HL–LHC optics (v1.6).

below); 2) the end of levelling, when the beams are squeezed to the minimum $\beta^*$ [26]. The latest DA results are shown in Fig. 2 for the end-of-collapse situation, showing that with negative octupoles the available DA remains very large up to a current of 600 A in absolute value [27]. Regarding the end of levelling, MDs with aggressive beam-beam parameters showed no lifetime issue despite a DA below $6\sigma$ [13]. Moreover, flat optics (see below) may help during this phase [26].

Dedicated DA studies for a pile-up that reaches 180 (as proposed in Table 2) have yet to be carried out, as well as to check the impact of a potential LHCb upgrade II.

### *Impedance*

Transverse impedance may lead to instabilities in the LHC, with its main contribution coming from the collimators [4]. A low-impedance upgrade of the collimation system was planned for HL–LHC, and has already been partially implemented and tested with beam [28–31]. Transverse coherent stability is also significantly affected by the fundamental mode of crab cavities (CC) [32], hence a dedicated mitigation, the betatron comb filter, is part of the baseline [33].

During the most critical phase of the HL–LHC cycle, i.e. at flat top before collisions are established, stability is ensured thanks to the transverse feedback system, high chromaticity ($Q' = 15$) and Landau octupoles [34]. Since 2025, the LHC operates with negative octupole polarity, which is now the baseline for HL–LHC [5]. It will allow to operate with less than 300 A of octupole current (in absolute value) [35], with relaxed collimator settings [2]. Given the DA available even for much higher octupole strengths (see Fig. 2), this provides a margin for a potential tightening of the collimators (+20%), or a reduced performance of the RF comb filter (+15%, assuming flat optics) [4]). Moreover, if necessary, several impedance mitigation measures can be considered: 1) increasing chromaticity to $Q' = 20$ before collisions, thus allowing a large decrease of the octupole current [4]; 2) optics optimisation, in IR7 and/or with flat optics to decrease the impact of CC impedance (see below).

The beam-beam tune spread ensures stability during collisions, except for the 12 bunches not colliding in IP1 & 5. These will feature a lower brightness for better stability.

In the longitudinal plane, the broadband impedance combined with the high-order modes of CCs may lead to coupled-bunch instabilities [36], but mitigations are currently being studied [37]. Localised beam-induced heating is also a concern, as a number of non-conformities were discovered in the LHC and led to heating, equipment damage, and downtime [38, 39]. To anticipate such issues before Run 4, a two-week high-intensity test is planned in June 2026 [10].

### *Transverse Emittance Growth*

In the LHC, transverse emittance blow-up arises from intra-beam scattering at injection, incoherent effects from e-cloud in the triplets, and partly unknown sources. In HL–LHC, IR1 and 5 will be coated with amorphous carbon, which will effectively remove one source of blow-up. Progress is currently being made on other sources [13,40,41], and the transverse emittance blow up will be probed with HL–LHC nominal beam intensities during the high-intensity test [10]. Finally, in the HL–LHC era, additional transverse blow-up will originate from CC RF noise [42,43], for which a mitigation approach has been proposed [44].

### *Optics Baseline and Alternative Options*

The development of the HL–LHC optics is relentless, aiming to maximise performance, aperture and machine protection, minimise impedance, and optimise phase advances between collimators, CCs and beam dump kickers. Round ($\beta_x^* = \beta_y^*$) optics v1.9 is currently being finalised [45]. Alternative optical options are also considered, in particular: 1) rematched IR7 optics, optimised for betatron collimation cleaning and impedance [46], already tested but challenging in terms of background and phase advances [45]; 2) flat optics ($\beta_x^* \neq \beta_y^*$) [47], used in physics since 2025, which increases integrated luminosity by +3.5% [48]) and allows impedance reduction of the CCs [4] and DA optimisation at the end of levelling [26]. However, these options remain to be fully validated in terms of phase advances, protected aperture, machine protection, cleaning efficiency, and DA [5].

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