OBTAINING A RECORD LUMINOSITY PRODUCTION IN THE LARGE HADRON COLLIDER IN 2025

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Abstract

The Large Hadron Collider (LHC) run in 2025 was the last long production year of LHC Run 3 (2022 to 2026). To mitigate potential radiation damage to magnets installed in the low-beta sections due to the integrated radiation dose near the high luminosity experiments, a flat optics was used for the first time in beam operation, underlining the adaptability of the LHC. A record production of 125 fb^{-1} was achieved in 2025 despite vacuum component non-conformities leading to intensity limitations in one of the beams during part of the year. The integrated luminosity collected by each of the two high luminosity experiments since the startup of the LHC now exceeds 500 fb^{-1}. This paper presents the configuration, operational strategies and beam parameters of the LHC in 2025 which led to another record year.

INTRODUCTION

The LHC collider [1] serves four main experiments: the ATLAS and CMS high luminosity experiments located in interaction regions (IR) 1 and 5, the medium luminosity experiment LHCb in IR 8 and the low luminosity experiment ALICE in IR 2. ATLAS and CMS operate typically at peak luminosities above $2 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$, more than twice the design value, LHCb operates around $2 \times 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ and ALICE operates in the range $10^{31}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$. Forward physics experiments FASER and SND installed around ATLAS complete the picture.

The fourth Run 3 operation year of the LHC in 2025 was the last long production year before a short run in 2026 and the 4 years long shutdown LS3 to install the equipment for the HL-LHC project [2].

OPTICS CONFIGURATION

Due to the very high rate of proton collisions, all equipment in and close to the LHC low-beta quadrupoles (inner triplets, ITs) in IR 1 and IR 5 is heavily irradiated. The recommended dose limit is 30 MGy for the IT magnets (superconducting main quadrupoles), and 75 MGy in the normal-conducting separation dipole magnets [3]. To preserve the magnet lifetime, the dose can be distributed over different coils using various optics and crossing angle configurations.

The target luminosity of 300 fb^{-1} in Run 3 can only be achieved by pushed beam parameters and crossing angle, and the dose projections for the nominal focusing-defocusing-focusing (FDF) inner triplet optics exceed the recommended limit. To spread the dose more evenly over different magnets, and to reduce the overall dose, a reverse-polarity (DFD) optics and a crossing angle change [4, 5] have been used in IR 1 for the 2024 run. This solution led however to an increased background at the forward physics experiments FASER and SND. For this reason, in 2025, the nominal polarity in IR 1 was restored and the reverse polarity was implemented in IR 5.

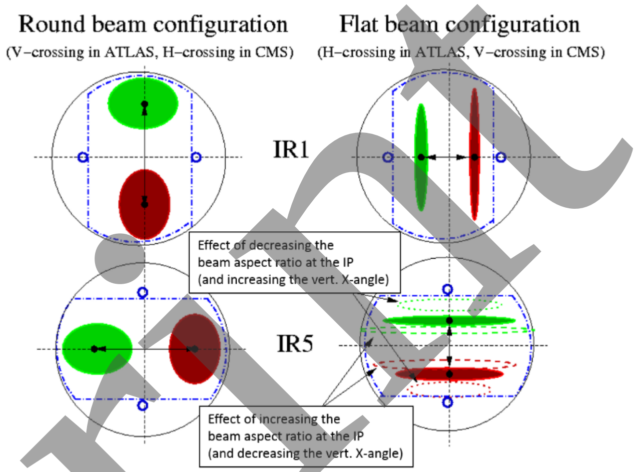

Figure 1: Beam envelopes in the low-beta quadrupoles around a high luminosity IP for round beam ($\beta^*_x = \beta^*_y$) and flat beam configuration ($\beta^*_x \neq \beta^*_y$).

At the same time the crossing angle planes were inverted, because the only change of triplet polarity in IR5 was not sufficient to mitigate appropriately the radiation dose expected in the IT of IR5 for the rest of Run 3. Due to the race-track shape of the beam-screens (see Fig. 1), this requires to flatten the optics ($\beta^*_x \neq \beta^*_y$) to preserve the machine performance, and actually even improve it in the end.

While in 2024 the LHC operated in physics conditions with round optics at a minimum β^* of 30 cm, in 2025 the lowest flat optics values were $\beta^*_x = 60$ cm and $\beta^*_y = 18$ cm in IR 1 with a horizontal crossing angle, the reverse configuration being used in IR 5 due to the orientation of the vacuum chamber beam screens and to the requirement of orthogonal crossing planes for long-range beam-beam compensation.

After being ramped to 6.8 TeV the beams are brought in collision with a round optics at β^* of 120 cm in ATLAS and CMS. The luminosity is leveled by β^* down to 60 cm with round optics. Then β^* in the plane of crossing is kept constant at 60 cm while β^* in the orthogonal plane is progressively lowered to 18 cm in flat optics configuration.

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INTENSITY LIMITATIONS AND ISSUES

Following the completion of the LHC Injector Upgrade project [6], the injector chain is now able to produce the nominal HL-LHC beams consisting of 72 bunch trains spaced by 25 ns at $I_b = 2.3 \times 10^{11}$ protons per bunch (ppb).

An important limitation of the LHC beam intensity arises from electron cloud induced heat load to the cryogenic system. In Run 3 electron clouds limit the bunch intensity I_b to $(1.7 - 1.8) \times 10^{11}$ ppb for bunch trains consisting of 36 bunches spaced by 25 ns and a maximum around 2500 bunches [7–10]. The intensity limitation will be lifted with the deployment of the HL-LHC upgrade.

In 2023 localized damage to the tension spring in a sliding contact radio-frequency finger module [11, 12] highlighted the important consequences of minor mechanical non-conformities of such modules, with around 100 units installed around the LHC. Following the failure of one module the bunch intensity has been limited to $I_b = (1.6 - 1.65) \times 10^{11}$ ppb [10]. To control the beam induced heating of components inside the vacuum chamber, the bunch length is also blown up during the ramp to counteract the natural emittance shrinkage and to ensure that at the physics energy of 6.8 TeV the bunch length is around 1.3 ns (39 cm), where the bunch length is defined as four times the rms length. The number of bunches is 2460.

At the start of the 2025 run, all critical sliding contact radio-frequency finger modules had been replaced with a more robust design, and the bunch intensity was planned to be pushed up to $I_b = 1.8 \times 10^{11}$ ppb.

However, in July a similar non-conformity in a specialized interconnection module in the ring 1 injection region led to a renewed limitation around $I_b \simeq 1.6 \times 10^{11}$ ppb [13, 14]. The situation degraded in October, forcing a reduction to $I_b \simeq 1.4 \times 10^{11}$ ppb in ring 1. No issues were encountered in ring 2 which was pushed to $I_b = 1.8 \times 10^{11}$ ppb. The increase on ring 2 compensated the loss in ring 1 and the luminosity performance was essentially unaffected compared to operation with both rings at $I_b \simeq 1.6 \times 10^{11}$ ppb. Figure 2 presents the evolution of the bunch intensity at the start of physics fills during Run 3. In 2025 LHC operated for the first time with asymmetric proton beam intensities.

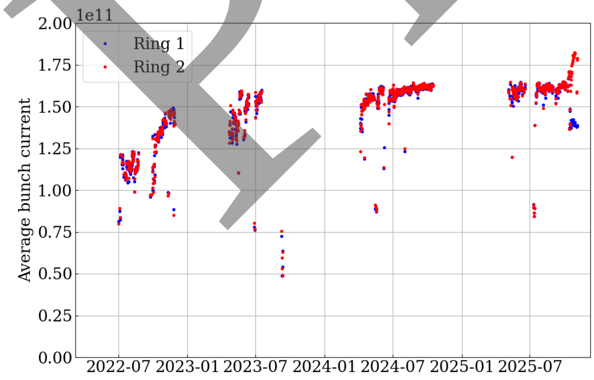

Figure 2: Evolution of the bunch intensity I_b over Run 3. After an initial intensity ramp-up in 2022, I_b was limited to $\simeq 1.6 \times 10^{11}$ ppb during most of Run 3.

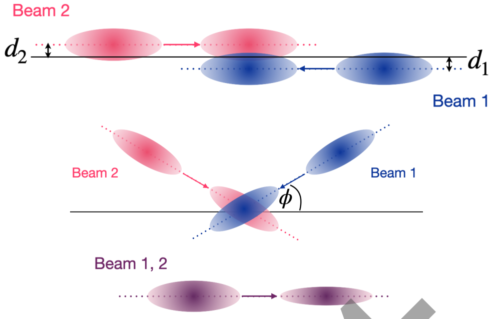

Figure 3: Luminosity leveling techniques used at the LHC: by transverse beam separation (top), by crossing angle (middle) and by β^* (bottom).

Vacuum leaks on flexible collimator bellows interrupted operation twice in 2025 [13, 14]. A first leak appeared on the bellow of an injection protection collimator which could be locked in an open position with varnish as a temporary repair because this collimator was not required for the current injection optics. A second issue affected a ring 2 horizontal secondary collimator of the betatron cleaning insertion. Thanks to the redundancy of the collimation system, operation could proceed with the collimator retracted and the vacuum leak tightened with varnish.

LUMINOSITY LEVELING

In the LHC, luminosity leveling is required due to cryogenic cooling limitations in the IT magnets, limiting the peak luminosity around 2.2×10^{34} $\mathrm{cm^{-2}s^{-1}}$, and to detector limitations which restrict the number of interactions per bunch crossing (pile-up).

Various luminosity leveling techniques are available [15]: beam separation, crossing angle adjustments, and dynamic β^* variation during collisions, see Fig. 3. Among these, leveling by β^* preserves head-on beam-beam interactions, maintaining amplitude detuning and Landau damping, which are essential for beam stability at high intensities [15]. However, modifying β^* requires optics changes, a delicate operation with colliding high-intensity beams and detectors in data-taking configuration.

A leveling technique combining β^* and separation leveling is utilized since 2024 [16]. This technique provides smooth leveling for ATLAS and CMS, while preserving sufficient landau damping from partial head-on overlap. The LHCb and ALICE experiments are leveled in parallel by separation. The luminosity control is better than 2.5%. The luminosity evolution in a 2025 physics fill is presented in Fig. 4. The leveling time exceeds 8 hours for $I_b \simeq 1.6 \times 10^{11}$ ppb at the start of the fill.

In 2025 quasi-continuous crossing-angle leveling was introduced at the end of β^* leveling, see Fig. 4. This reduced the luminosity decay at the end of the combined separation and β^* leveling period, extending the leveling time by another 1.5 h.

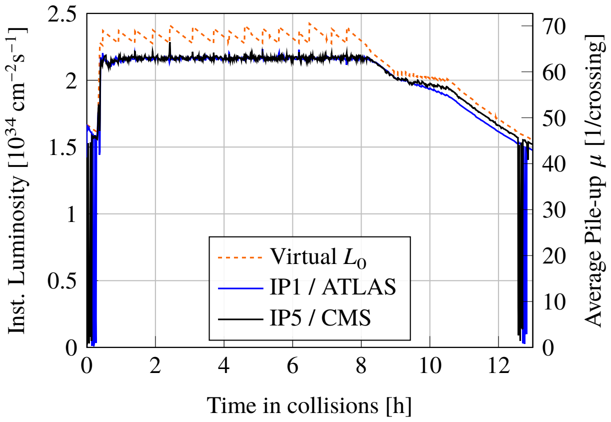

Figure 4: ATLAS and CMS luminosities recorded during LHC fill 10905, leveled within 1.5‰ of the experiments' targets by combined β^* and separation leveling. The virtual luminosity corresponds to the peak luminosity without separation leveling [16]. The decay of the luminosity after the end of β^* leveling is slowed down by crossing angle reduction starting after 9 h in collision.

With higher beam intensities, smaller β^* and higher peak luminosity compared to design parameters, a typical machine filling delivers now roughly 3 times more integrated luminosity than what the LHC had been designed for.

PERFORMANCE IN 2025

With an excellent machine availability of 70%, 55% of the operation time spent colliding beams for data-taking and the pushed leveling techniques, the LHC delivered a new yearly record of 125 fb^{-1} to both ATLAS and CMS in 2025.

The median turn-around time T$_{\text{ta}}$ from beam dump to the start of the next physics period was 3.6 h, while the most likely T$_{\text{ta}}$ value was 2.2 h, close to the achievable minimum of 1.8 h. The excellent reproducibility of the LHC played a central role for the efficient turn-around. The optimum length of the physics data taking corresponding to the mean T$_{\text{ta}}$ was around 13 to 14 hours, see the example fill in Fig. 4.

Figure 5 presents LHC peak luminosity between 2011 and 2025. In 2025 LHC operated reliably at 2.2×10^{34} cm^{-2}s^{-1}, slightly above previous years of Run 3. This corresponds to an average pile-up of ≈ 63. The stored energy in ring 2 reached 470 MJ for 2640 bunches of 1.8×10^{11} ppb.

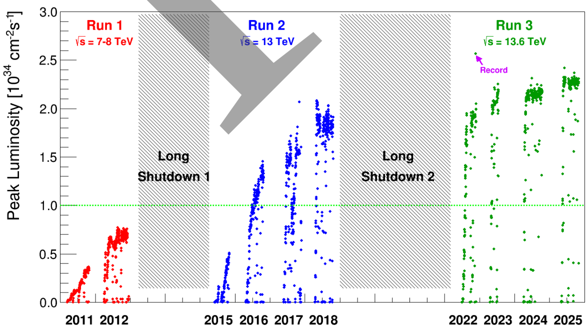

Figure 5: Peak luminosities of the ATLAS/CMS experiments over the three LHC runs.

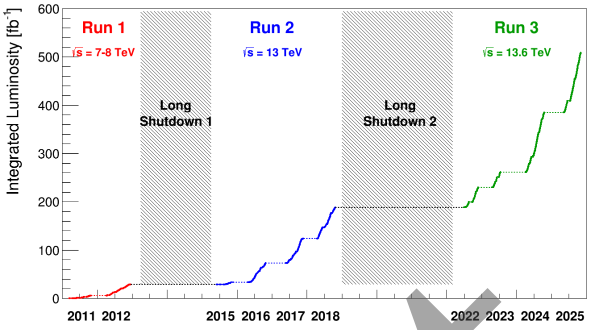

Figure 6: Cumulative integrated luminosity delivered over the three LHC runs to the the ATLAS and CMS experiments.

The cumulated integrated luminosity is presented in Fig. 6. The integrated luminosity delivered since the start of LHC to each of the two experiments exceeds now 500 fb^{-1}. Together more than 1 ab^{-1} was delivered by the LHC during its operation span.

The LHCb experiment, which is typically leveled at a pile-up around 6.5, also profited from the excellent machine availability of the LHC and collected more than 10 fb^{-1} in 2024 and in 2025. Figure 7 presents the integrated luminosity of LHCb between 2011 and 2025. In 2024 and 2025, LHCb collected more integrated luminosity than the total of runs 1 and 2.

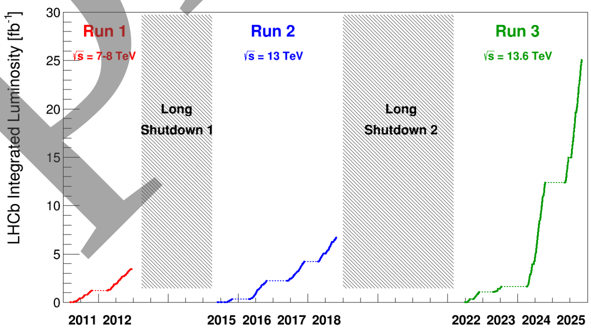

Figure 7: Integrated luminosity delivered to the LHCb experiment over 3 LHC runs. The peak luminosity was boosted in Run 3 thanks to the Phase I LHCb upgrade, during the first two years of Run 3 the luminosity was limited by detector issues.

CONCLUSIONS AND OUTLOOK

The luminosity production of the LHC has been pushed to the limits by squeezing out the last percent of performance thanks to exquisite beam control in collision mixing leveling techniques by beam separation, by crossing angle and by β^*. In 2025 LHC operated with a luminosity leveled for more than 8 hours at more than twice its design luminosity. The availability was excellent with up to 470 MJ of stored energy in one beam. The LHC leveling techniques prepare the ground for future HL-LHC operation at even higher pile-up and luminosity.

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