# OPTICS CYCLES FOR MAXIMUM INTEGRATED LUMINOSITY IN THE HL-LHC

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## *Abstract*

We present an update of the optics cycles foreseen during physics operation in the High-Luminosity LHC (HL-LHC) era. New optics around the upgraded ATLAS and CMS experiments are needed due to the new quadrupole layout and lower $\beta^*$. In addition, thanks to numerous studies and lessons learned during Run 3, the entire machine's optics will be modified to improve key aspects such as machine protection, beam-lifetime optimisation, and $\beta^*$ minimisation. This is achieved by integrating the optimisation of octupole-induced resonances, phase advances between collimators and crab cavities, new collimation optics, control of dispersion, and flat-optics options. This paper presents a proposal for the $\beta^*$ steps during Run 4 and Run 5 with the aim of maximising integrated luminosity. These new cycles will also be used in the Inner Triplet (IT) string operational validation programme and in future collimation studies.

## INTRODUCTION

The HL-LHC upgrade baseline is documented in the technical design report [1]. The first LHC upgrade optics studies started in the 2004–2007 period, with an emphasis on the triplet design and a target of $\beta^* = 25\,\mathrm{cm}$ at the high-luminosity experiments [2, 3]. Subsequently, an even lower $\beta^* = 15\,\mathrm{cm}$ was chosen for the HL-LHC upgrade, exploiting the Achromatic Telescopic Scheme (ATS) [4]. Complete optics solutions based on the ATS scheme were developed, along with a flat optics options with and without crab cavities [5–8]. Recent studies motivated a review of the baseline optics based on the following reasons. Machine protection [9] and background studies [10] motivated the search for optimised phase advances at the flat top [11]. Incoherent effects from the electron cloud motivated a change in phase advances at injection [12, 13]. Machine studies demonstrated that optimised flat-top optics for betatron collimation provide better cleaning and lower impedance [14]. An updated version of the machine layout is now being finalised for installation during the Long Shutdown 3 (LS3), starting in June 2026, in which the nominal magnetic lengths of the new Inner Triplet magnets have been refined and frozen to provide stable installation references. This requires small adjustments to the previous optics solutions. The most recent HL-LHC optics cycle incorporates new features derived from recent beam dynamics studies and will provide a comprehensive new baseline for HL-LHC studies and for operation in Run 4 [15, 16].

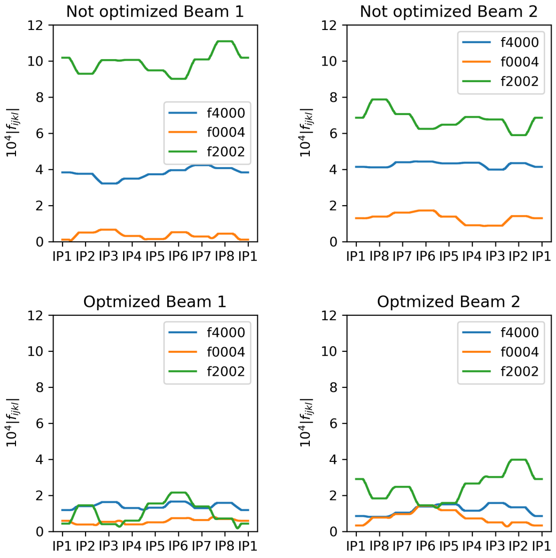

Figure 1: Optimisation of the octupolar resonance driving term at injection for Beam 1 and Beam 2. The plots show the amplitude of the first-order octupolar resonance driving terms (for the definition refer to [17]) in the lattice for the previous HL-LHC baseline injection optics and the newly proposed injection optics. The reduction of the perturbation is significant for both beams.

## INJECTION OPTICS

Electron-cloud effects require operation with very large chromaticity ($Q' = 25$) and strong octupole currents ($I_{\mathrm{MO}} = 40$ A) to suppress coherent beam instabilities. The e-cloud octupolar nonlinearities are significant, especially the associated resonance $2Q_x - 2Q_y$ [12]. The phase advance can be adjusted arc by arc to reduce the resonance driving terms (RDTs) for the 3 main octupolar resonances ($2Q_x - 2Q_y$, $4Q_x$, and $4Q_y$), while preserving the existing amplitude detuning [13]. The phase advance modifications are implemented by rephasing the arcs and, unlike in the Run 3 optics, also by rematching the insertions; see Fig. 1. This strategy avoids introducing unnecessary beta-beating (up to 15% locally), which would reduce the available aperture. A change in the arc phase advances had to be implemented in 2025 to mitigate a collimator hierarchy breakage that appeared with the change of octupole polarity [16], which reduced the measured $4Q_x$ resonance. Incidentally, the new phase configuration also reduced the $3Q_y$ resonance [13] which is also beneficial for lifetime and for the choice of the working point.

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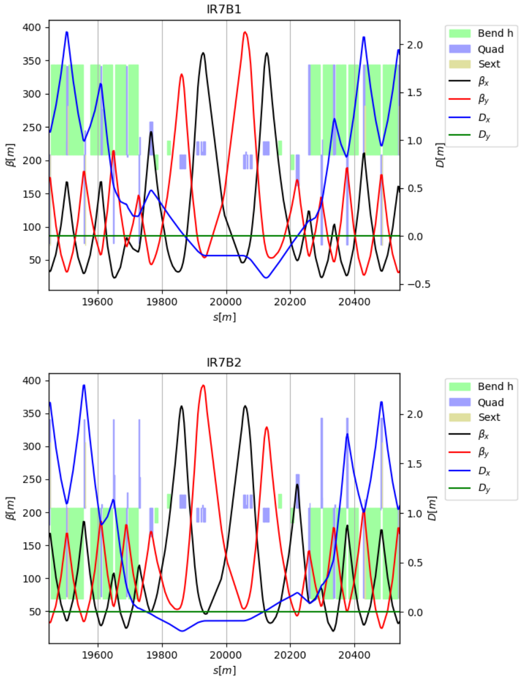

Figure 2: Reference collimation insertion optics for Beam 1 and Beam 2. The plots show the Twiss parameters and dispersion in the area together with the position and strengths of the the main magnets, shown without units.

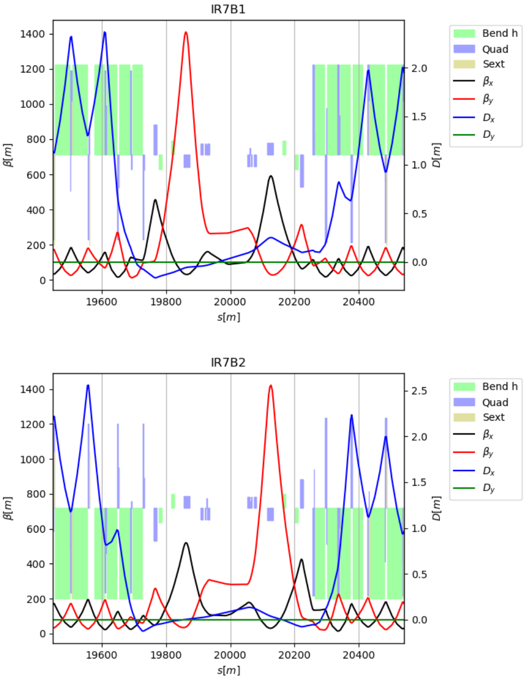

Figure 3: Optimised collimation insertion optics for Beam 1 and Beam 2. Compared with the reference optics, the large $\beta$-functions are not compatible with the aperture at injection energy; therefore, an optics transition is needed.

## NEW BETATRON COLLIMATION OPTICS

During Run 3 machine studies, a new optics configuration was studied for the collimation region (IR7) to improve collimation efficiency and reduce impedance [14]. This optics configuration exploits the additional flexibility from the reduced beam size at higher energy and the presence of individually powered quadrupoles, which allow the optics to change dynamically from injection to collision. Integrating this optics is challenging because it changes the relative phase advance between the primary collimators (TCPs) and the insertion boundaries. In addition, the limited number of individually powered quadrupoles, together with the presence of a few non-conforming quadrupoles, does not allow these optical changes to be easily absorbed at the boundaries while maintaining proper matching; see Figs. 2 and 3. Global phase advance optimisation needs to take these challenges into account, as discussed in the following section.

## FLAT TOP PHASE ADVANCE OPTIMISATION

As LHC optics are increasingly optimised, global phase advances play a significant role in machine performance.

The ATS scheme already significantly constrains the freedom to choose phase advances [4]. Arcs 81, 12, 45, 56 have strict 90°-FODO cells such that sextupoles in selected families can produce strong chromatic beta-beating and dispersion when orbit bumps are added. The phase advance from sextupoles relative to the IP (about 90°) cancels the chromatic beating and dispersion generated in the triplets close to the IP. The phase advance from the beam dump kicker (MKD) to the tertiary collimators near to the experiments (TCTs) must be kept far from 90° to prevent hardware damage in the case of asynchronous beam dumps [18, 19]. The main crab-cavity failure scenario [9] is mitigated by choosing the phase advance between the crab cavities and the primary collimators (TCP) to be close to 0 in the plane of the crossing angle in Point 1 (ATLAS) and Point 5 (CMS). Part of the background seen by the experiments originates from particles scattered in the TCPs that are not intercepted by the secondary collimators (TCS) and are then further scattered by the tertiary collimators: the ideal phase advances between TCPs and TCTs are close to 0°or ±90° (see [10] for details). In general, non-optimal values imply that the TCP gaps need to increase in the case of CC–TCP phase advances, TCT gaps need to increase to avoid damage in the case of the MKD–TCT phase advance, or to limit the background in the case of the TCP–TCT phase advance. Increasing TCP gaps reduces cleaning efficiency, and increasing TCT gaps translates into a larger $\beta^*$ at the experiments, thus reducing integrated luminosity.

Optics solutions approaching these ideal cases have been found in the past [11] and need to be integrated into the baseline, while taking into account additional constraints, such as the new collimation insertions and dynamic-aperture optimisation [20], with ideal values for Points 1 and 5, see Table 1. Point 8 is not critical since $\beta^*$ reach is not limiting the performance of the LHCb experiment in Run 4.

Table 1: Baseline Phase Advances

| CC–TCP | B1 L | B1 R | B2 L | B2 R |
|---|---|---|---|---|
| CC1 H | 16.11 | 14.65 | 14.19 | 15.55 |
| CC1 V | 7.74 | 6.27 | 6.63 | 7.98 |
| **MKD–TCT** | **B1 A** | **B1 O** | **B2 A** | **B2 O** |
| TCTH1 | -4.21 | 1.74 | -18.84 | -14.71 |
| TCTH5 | -29.23 | -23.28 | -31.10 | -26.98 |
| TCTH8 | 4.70 | 10.66 | 48.42 | 52.54 |
| **TCP–TCT** | **B1 H** | **B1 V** | **B2 H** | **B2 V** |
| TCT1 | -84.15 | -68.26 | -83.64 | -76.26 |
| TCT5 | 70.83 | -72.24 | 84.09 | -72.53 |
| TCT8 | -75.24 | -89.20 | -16.39 | 50.66 |

The baseline phase advances are organised in Table 1 by class: a) crab cavities (CC) to primary collimators (TCP), relevant for CC failure; b) beam dump kicker (MKD) to tertiary collimators (TCT), relevant for MKD failure; c) TCP to TCT, relevant for background. Green indicates optimal values, orange near-optimal values, and red non-optimal values. The values are expressed in degrees mod 180.

The integration of the new collimation optics results in less-than-ideal TCP-TCT phase advances, particularly Beam 2 H in Point 1 and V in Point 5 (see Table 2). Beam 2 background is expected to worsen compared to the previous baseline. In Run 4, round optics (i.e., equal $\beta^*$ in both planes as opposed to flat optics), and the choice of the crossing planes imply that the aperture bottleneck will be in the horizontal plane at Point 1 and in the vertical plane at Point 5. Ongoing collimation beam and simulation studies will confirm whether additional phase optimisation is needed.

Table 2: Optimised Phase Advances with New Collimation Insertion

| CC–TCP | B1 L | B1 R | B2 L | B2 R |
|---|---|---|---|---|
| CC1 H | 11.04 | 9.57 | -22.64 | -21.28 |
| CC1 V | 13.26 | 11.80 | -17.04 | -15.69 |
| **MKD–TCT** | **B1 A** | **B1 O** | **B2 A** | **B2 O** |
| TCTH1 | 1.10 | 7.05 | -23.71 | -19.58 |
| TCTH5 | -30.07 | -24.11 | -31.89 | -27.76 |
| TCTH8 | 11.40 | 17.36 | 37.10 | 4.23 |
| **TCP–TCT** | **B1 H** | **B1 V** | **B2 H** | **B2 V** |
| TCT1 | -79.08 | 65.40 | -46.81 | 76.00 |
| TCT5 | 69.75 | -77.77 | -55.00 | -48.87 |
| TCT8 | -68.78 | 43.26 | 13.99 | 25.65 |

## CYCLE AND NEXT STEPS

At the time of writing, a set of optics configurations for injection and for the end of levelling has been produced, and HL-LHC teams are validating this set of optics with respect to collimation performance and dynamic aperture. At the same time, we are completing the optics cycles (see Fig. 4) by implementing smooth optics transitions [21] using new operational methods developed for the HL-LHC [22] and first deployed in 2025. Beam energy for Run 4 will be 6.8 TeV as in Run 3 to reduce the risk and duration of the long shutdown, potentially reaching 7 TeV for Run 5. Given the exceptionally low $\beta^*_{\parallel/\times} = 15/50$ cm and large bunch intensity of $1.8 \times 10^{11}$ ppb achieved in Run 3, we are studying alternative commissioning paths to achieve maximum performance for HL-LHC using flat optics; see [23] and references therein. We also plan to introduce best-knowledge models (including measured magnet imperfections) for matching the HL-LHC optics to reduce commissioning time (see [24] and references therein).

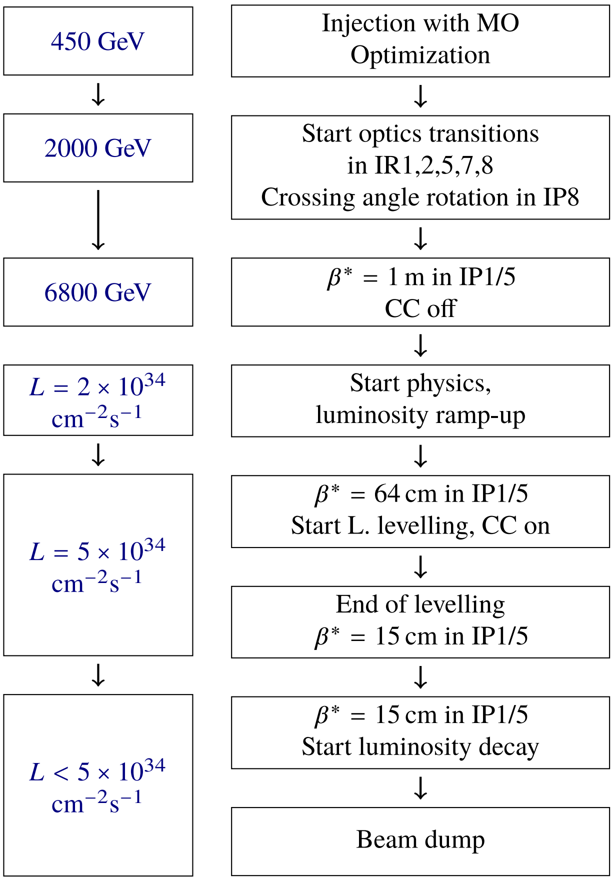

Figure 4: Main steps of the nominal HL-LHC cycle.

## CONCLUSION

We have presented the status of the HL-LHC optics baseline just before the start of the long shutdown, marking the beginning of HL-LHC construction. The new cycles integrate the lessons learned from HL-LHC studies and Run 3. Simulation campaigns, in particular collimation studies, have begun to validate the performance of the new optics. Specifically, background studies will be critical to identifying needs for further optimisation. At the time of writing, we are completing the full set of optics for the HL-LHC cycles so that they are ready for testing in the accelerator controls infrastructure.

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