DESIGN CHALLENGES AND SOLUTIONS FOR FLAT OPTICS IN HL-LHC

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Abstract

The High-Luminosity LHC (HL-LHC) upgrade imposes stringent requirements on optics design and correction to achieve its performance goals while maintaining beam stability, sufficient aperture margins, and controlled sensitivity to alignment and field imperfections. Among the explored configurations, flat optics—featuring asymmetric β-functions at the interaction points—has been proposed as an alternative to the conventional round-optics scheme, including scenarios where crab cavities (CC) are not fully deployed. This configuration can be implemented early in the squeeze cycle and offers several advantages, such as reduced impedance, a modified beam–beam interaction pattern, and potential performance improvements. Focusing on the optics at the end of luminosity leveling for the HL-LHC version 1.9, this paper discusses the phase-advance constraints for machine protection, one of the main design challenges, and presents the achieved flat-optics configurations. Research supported by the HL-LHC project.

INTRODUCTION

The High-Luminosity LHC (HL-LHC) project aims to deliver an integrated luminosity of at least 250 fb^{-1} [1–4] per year by upgrading interaction regions (IR1 and IR5) with Nb$_3$Sn triplet magnets and crab cavities (CC). While the baseline scenario focuses on “round” optics with equal β^* in both transverse planes, alternative configurations like “flat” optics are critical for performance optimization [5,7,8].

Flat optics, characterized by asymmetric β-functions at the Interaction Points (IPs), offer a strategic alternative when crab cavities are not fully deployed or to mitigate intensity limitations such as electron cloud and impedance. By using a larger β^* in the crossing plane and a smaller β^* in the orthogonal plane, the impact of the geometric luminosity reduction factor is minimized, potentially increasing virtual luminosity beyond what is achievable with round optics at comparable triplet apertures.

In the HL-LHC, an asynchronous beam dump occurs when the extraction kickers (MKD) fire out of sync with the “abort gap” in the beam. This causes the kicker field to rise while particles are still passing, resulting in bunches being deflected at intermediate angles rather than being safely sent down the extraction tunnel. To protect the machine during such a failure, the phase advance ($\Delta\mu$) between the extraction kickers (MKD) and the tertiary collimators (TCT) is a critical design parameter. As the HL-LHC uses much higher beam intensities and smaller “squeeze” factors (β^*) than the LHC, the TCT-MKD phase advance is among the most important restrictions that must be respected and well-controlled to push collider performance further. The optimization for a set of different flat optics is presented in this work.

HL-LHC OPTICS

The HL-LHC optics V1.9 was used for these studies; although the V2.0 is expected to be released soon, it remains a valid baseline for this analysis. For Run 4 and beyond, it is planned to reach $\beta^* = 0.15$ m for round beams at the end of luminosity leveling, and $\beta^*_{\parallel/\times} = 0.075 - 0.09/0.18$ m if flat optics are used. Such strong focusing is made possible by the Achromatic Telescopic Squeezing (ATS) scheme [11] utilized for optics below 50 cm.

Flat Optics

Flat optics in the HL-LHC [6–8] are configurations where the horizontal and vertical beta functions at the IP are unequal ($\beta^*_x \neq \beta^*_y$). This leads to different beam sizes in the two transverse planes, providing an alternative to round optics for optimizing luminosity under aperture constraints. By using a larger β^* in the crossing plane and a smaller β^* in the parallel plane, flat optics can increase virtual luminosity compared to round optics with similar aperture limitations while reducing geometric reduction effects.

This scheme can be combined with crab cavities, which reduce the effective crossing angle and allow for stronger focusing. It can also help optimize optics conditions, such as lowering the β-function at the crab cavity locations to mitigate impedance issues. Specifically, it can compensate for luminosity loss in scenarios where crab cavities do not reach nominal performance and still provide an additional luminosity gain (on the order of a few percent) in nominal conditions. Additionally, with ideal phases for machine protection, the flat VH (vertical crossing in IP1 and horizontal in IP5) have better aperture than corresponding round also flat optics can contribute to reducing the head-on beam-beam interaction and also makes it easy to correct some resonances related to long-range interaction supporting performance goals for future upgrades.

LHC operated with flat optics for the first time in 2025, reaching $\beta^*_{\parallel/\times} = 0.18/0.60$ m, increasing virtual luminosity and, hence, leveling time. In 2026 LHC reached $\beta^*_{\parallel/\times} = 0.15/0.50$ m further improving performance [9, 10]. This optics could be a good target for the first year of Run 4 to reproduce achieved performances.

However, these advantages come with limitations: flat optics increase sensitivity to field imperfections in the triplets due to stronger focusing in the parallel plane, and require better control of beam size, orbit, coupling, and mechanical tolerances. Due to a lack of extensive tests with high telescopic indices and high intensity, the operational flexibility

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could be reduced by higher required magnet strengths, or the configuration could become incompatible with certain settings, such as relaxed collimator scenarios in case of not ideal TCT-MKD phases, thereby limiting the achievable minimum β^*. While these factors do not preclude the use of flat optics, they indicate that further optimization—specifically regarding phase advance control and RDT compensation—is required to fully realize their benefits.

Machine Protection Limitations

The HL-LHC performances are also directly related to machine protection limitations [12–14], such as the tertiary collimator (TCT) gaps at IR1 and IR5. Based on studies in [14], the TCT gap can be at least equal to the TCDQ gap if the phase advance between the TCT and the extraction kickers (MKD) is $\leq 20^\circ \pmod{180^\circ}$ where the TCDQ is located in IR6 serving as a protection layer for quadrupole Q4 and all downstream elements (Q5 and the dispersion suppressor) in the event of an asynchronous beam dump, as illustrated in Fig. 1. If the phase advance limitation is not respected, the TCT opening must be larger than the TCDQ opening, which prevents pushing β^* to smaller values for performance improvement.

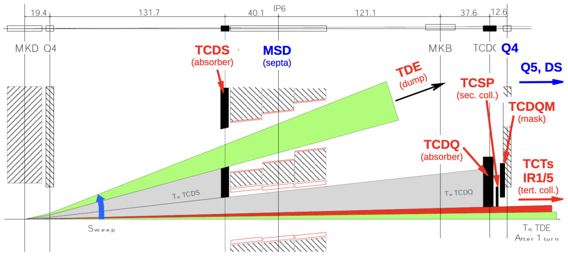


Figure 1: Schematic representation of the collimator and absorber function in the case of an MKD failure during an asynchronous dump.

With the new Beam Energy Tracking System (BETS) [15], the TCDQ opening in σ_x is fixed, but β_x can change during the squeeze (whereas previously both TCDQ opening and optics were fixed). Specifically, for tight settings, the TCDQ gap should be at least 3 mm plus 1 mm for margins, resulting in a 10.1 σ_x opening. This collimator is not planned to be replaced for the HL-LHC era; therefore, the 10.1 σ_x limit results from the radiation limitation of 2.7 kJ/g for a bunch intensity of 2.2×10^{11} ppb. However, at the end of luminosity leveling, the bunch intensity is below 1.8×10^{11} ppb. Thus, the TCDQ opening could potentially be reduced to 2.5 mm plus 1 mm for margins without violating the 2.7 kJ/g limitation. Based on this, two β_x values at the TCDQ are studied: one at 470 m (10.1 σ_x = 4 mm gap) and a more aggressive one at 430 m (10.1 σ_x = 3.83 mm gap). The scope of this work is to discover how beneficial this β_x reduction can be for the TCT-MKD phase advance.

CONCLUDED OPTICS

As discussed, the goal of this study is to reduce the horizontal phase advance between the TCT and MKD ($\Delta\mu_x$(TCT-MKD) latter noted as ddtct) as much as possible. The absolute goal for maximum β^* squeeze is to achieve a phase equal to or below $20^\circ \pmod{180^\circ}$. This should be done for TCTs at both IP1 and IP5 and for both Beam 1 (ddtct1b1, ddtct5b1a) and Beam 2 (ddtct1b2a, ddtct5b2a). Given the machine layout and beam direction, the most difficult phase to achieve is for Beam 2 at the IP5 TCT (ddtct5b2a), since only the heavily constrained ATS IR6 and Arc 56 can be used. For the other phases, the non-ATS arcs 23, 34, 67, and 78 are available.

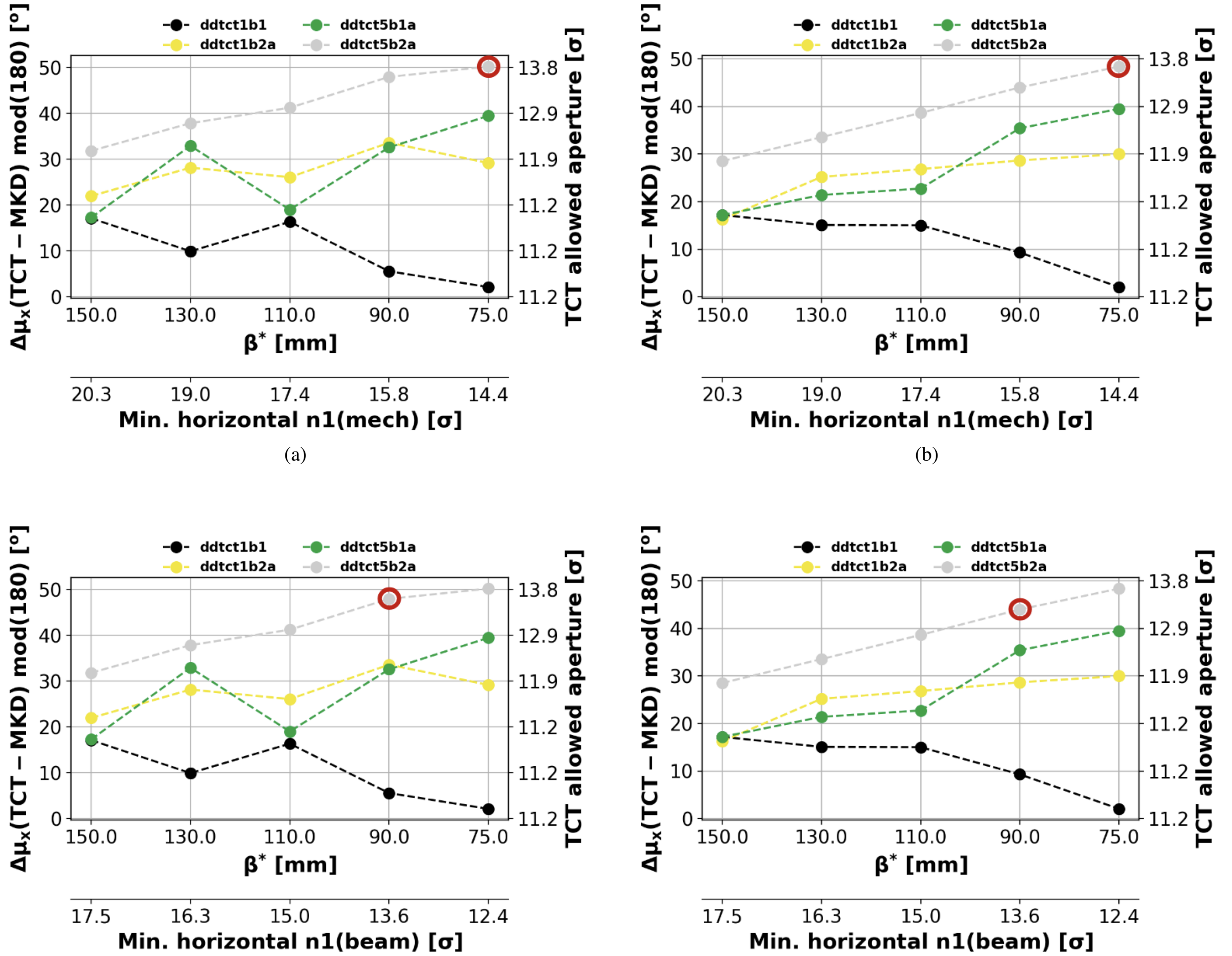
If $\Delta\mu_x$(TCT-MKD) $\leq 20^\circ$, the TCT gap can be equal to the TCDQ gap; otherwise, the TCT allowed aperture must be larger, as shown in [14]. Simultaneously, the allowed aperture for the TCTs must remain smaller than the protected aperture (n_1). The calculation of n_1 depends on various imperfection scenarios: the realistic one is labeled *mech*, while the more pessimistic one is labeled *beam*.

The results of the $\Delta\mu_x$(TCT-MKD) optimization are shown in Fig. 2, where the most aggressive scenario (smallest β^*) achieved is indicated with a red circle. The first column (Figs. 2a, 2c) shows results with β_x = 470 m at the TCDQ, while the second column (Figs. 2b, 2d) uses β_x = 430 m. In the first row (Figs. 2a, 2b), the bottom x-axis shows n_1 for the *mech* scenario; for both TCDQ β_x cases, β^* can go down to 75 mm. In the second row (Figs. 2c, 2d), the bottom x-axis shows n_1 for the *beam* scenario, where both β_x cases allow a reduction down to β^* = 90 mm.

In addition to these restrictions, the final optics must respect TCLM radiation limits. Assuming their gap (in σ) can match the resulting TCT after removing the extra 1σ margin ($\mathrm{TCT_{sep}} = \mathrm{TCT} - 1\sigma$), the resulting gap in mm is shown in Table 1. In general, the TCLM4 gap is less than 27.5 mm, which is close to the acceptable limit [3, 16] for nominal pile-up (PU = 170) although the current 75 mm optics configuration is at the limit and could surpass the radiation limits. Future optimization should consider TCL limitations in advance.

CONCLUSIONS

This study demonstrates that optimizing the horizontal phase advance between the TCT and MKD is essential for maximizing the performance of flat optics in the HL-LHC. By reducing the β_x at the TCDQ from 470 m to 430 m, additional flexibility is gained in meeting the $\leq 20^\circ \pmod{180^\circ}$ phase constraint, particularly for the highly restricted Beam 2 at IP5. The results indicate that a β^* as low as 75 mm is achievable under realistic machine imperfection scenarios (*mech*), while a more conservative limit of 90 mm is required for the pessimistic *beam* scenario. While these configurations satisfy current machine protection requirements and TCDQ radiation limits, the proximity of the TCL gaps to their operational limits suggests that future optics developments must integrate TCL-related constraints early in the design process to ensure robust operation at nominal pile-up levels.



(a)

(b)

(c)

(d)

Figure 2: TCT-MKD phase advance and allowed aperture for different β^* values in the parallel plane for 470 m β_x at TCDQ (a, c) and 430 m β_x at TCDQ (b, d). The bottom x-axis represents the protected aperture under different imperfection scenarios (*mech* for top row, *beam* for bottom row). The TCT allowed aperture must be smaller than the protected one; red circles indicate the most performance-oriented optics achieved.

Table 1: TCLM4 Gap in mm for the Different Scenarios Studied

n1 scenario	**TCDQ:** $\beta_x \geq 470\,\mathrm{m}$	**TCDQ:** $\beta_x \geq 430\,\mathrm{m}$
mech	TCLM4 ($\beta^* = 75$ mm; $\mathrm{TCT_{sep}} = 12.8\sigma$) = 27.5 mm	TCLM4 ($\beta^* = 75$ mm; $\mathrm{TCT_{sep}} = 12.7\sigma$) = 27.3 mm
beam	TCLM4 ($\beta^* = 90$ mm; $\mathrm{TCT_{sep}} = 12.6\sigma$) = 24.7 mm	TCLM4 ($\beta^* = 90$ mm; $\mathrm{TCT_{sep}} = 12.3\sigma$) = 24.1 mm

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