IMPACT OF THE INNER TRIPLET POLARITY ON THE OPTICS COMMISSIONING OF THE LHC IN 2024 AND 2025

J. Dilly*, Y. Angelis, A. Calia, F. Carlier, R. De Maria, S. Fartoukh, V. Ferrentino, E. Fol,
J. M. Gray, S. J. Horney, M. Hostettler, D. Jacquet, U. Kar, J. Keintzel, E. Kravishvili,
M. Le Garrec, E. H. Maclean, D. Mirarchi, K. Paraschou, T. Persson, K. Skoufaris, F. Soubelet,
M. Stefanelli, R. Tomás, G. Trad, W. Van Goethem, J. Wenninger, CERN, Meyrin, Switzerland
J. Cardona, Universidad Nacional de Colombia, Bogotá, Colombia

Abstract

To mitigate the risk of radiation damage induced failure while operating the LHC beyond its initial integrated luminosity target, changes to the triplet polarity and crossing angles have been applied in the two main experimental interaction regions of the LHC. This allows for a more distributed radiation deposition in the insertion region magnets, which should allow their survival until they are replaced as part of the High Luminosity LHC upgrade from 2026 - 2030. These changes in the optics during 2024 and 2025 came with important challenges regarding machine commissioning and optics correction. In this paper, we discuss our experience of linear optics correction for the various triplet polarity configurations and review the implications for nonlinear optics corrections.

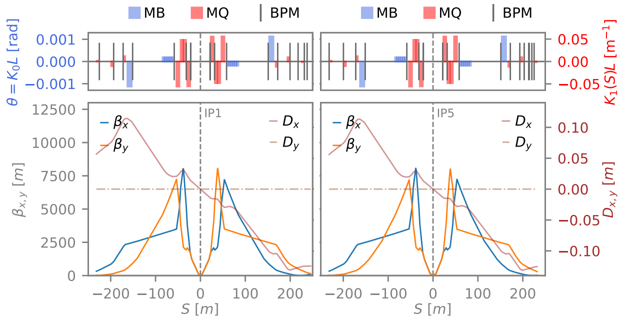
INTRODUCTION

Between 2023 and 2025, the Large Hadron Collider (LHC) optics underwent significant modifications, primarily in the main experimental interaction regions (IRs) at Interaction Point (IP) 1 (ATLAS) and IP5 (CMS). These changes aimed to mitigate radiation damage to IR magnets by distributing synchrotron radiation [1, 2]. Figures 1a to 1c illustrate these modifications. In IP1, the final focusing quadrupole (triplet) polarity was reversed between 2023-2024 and again for 2025, with the crossing plane changing from vertical to horizontal. In IP5, triplet polarity was reversed for 2025, accompanied by a crossing plane change from horizontal to vertical.

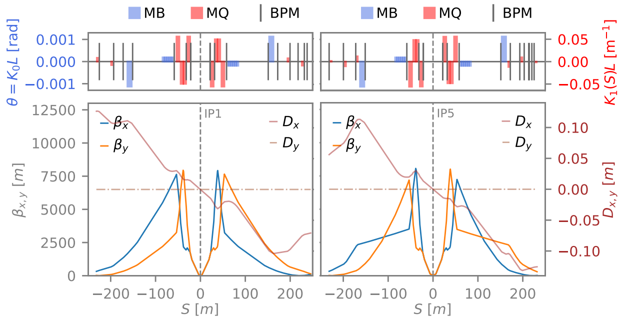
Furthermore, 2025 saw the operational deployment of "flat-optics" ($\beta^*_{\times/\parallel} = 60\,\text{cm}/18\,\text{cm}$) [3]. This configuration, characterized by increased β-functions in the surrounding IR (see Fig. 1c) and thus heightened sensitivity to local errors, was fully commissioned for the first time, following earlier tests [4, 5]. Consequently, full optics re-commissioning was necessary in both 2024 and 2025. A critical machine safety issue, the breakage of collimation hierarchy when squeezing beyond $\beta^* = 35$ cm, emerged in 2024 and required resolution.

LOCAL CORRECTIONS

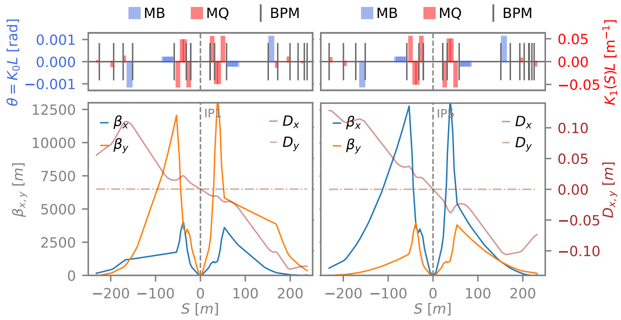
Efficient commissioning was achieved by extrapolating local corrections in IP1 and IP5 from previous years, changing the sign of corrections according to polarity. This method proved effective, even for the 2025 flat-optics, suggesting stable, optics-independent local errors in the IRs. Figure 2 displays the phase advance difference ($\Delta\phi$) between measurements and the ideal model, analyzed via segment-by-segment [6–8]. Notably, around IP5 (bottom plot), large pre-correction phase deviations were significantly reduced by using the 2022 IR5 local corrections with swapped signs. These deviations initially corresponded to a horizontal β-



(a) 2023: $\beta^* = 30$ cm



(b) 2024: $\beta^* = 30$ cm



(c) 2025: $\beta^*_{\times/\parallel} = 60/18$cm

Figure 1: Beam 1 optics around IP1 (left) and IP5 (right) for the operational squeezed optics in 2023 - 2025.

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* joschua.dilly@cern.ch

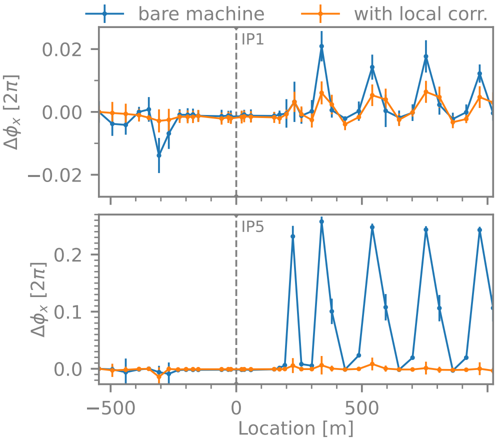

Figure 2: Measured phase-advance deviation from model ($\Delta\phi$) in Beam 1 horizontal at $\beta^*_{\times/\parallel} = 60/18$cm around IP1 (top) and IP5 (bottom), pre- (blue) and post- (orange) local corrections.

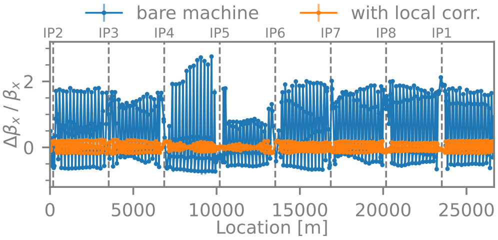

Figure 3: Beam 1 horizontal β-beating at $\beta^*_{\times/\parallel} = 60/18$cm pre- (blue) and post- (orange) local corrections in IP1 and IP5.

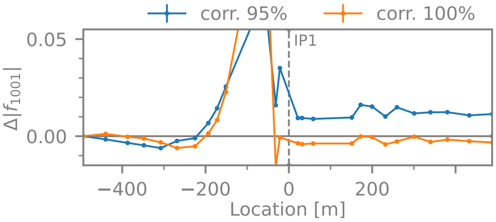

Figure 4: Deviation of the measured coupling RDT f_{1001} amplitude from model in Beam 1 at $\beta^*_{\times/\parallel} = 60/18$cm around IP1 with correction at 95 % (blue) and 100 % (orange) of nominal strength.

beating in Beam 1 up to ≈ 250 % (Fig. 3), which local corrections alone reduced to < 20 %.

Coupling Similarly, adapted local coupling corrections from 2022 were successfully validated for the 2025 optics. Figure 4 illustrates the deviation of the amplitude of the measured coupling Resonance Driving Term (RDT) f_{1001} from the model around IP1. At 95 % of its nominal strength, the correction showed a clear asymmetry across the IP, indicating an uncompensated coupling source. This asymmetry was resolved with the correction at its full design value (100 %).

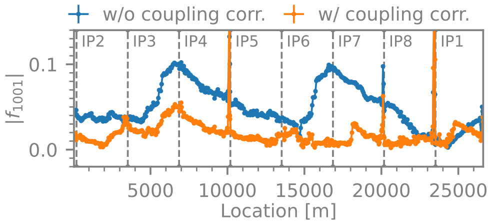

Figure 5: Measured coupling RDT $|f_{1001}|$ in Beam 1 at $\beta^*_{\times/\parallel} = 60/18$cm without (blue) and with (orange) arc-by-arc and global corrections.

Beyond local IR corrections, arc-by-arc and global corrections target broader optics imperfections [9, 10]. These are “effective” corrections, optimizing the targeted parameter with correctors from anywhere around the machine. Their validity is therefore limited to optics with similar β-scaling, necessitating iterative updates and annual revisions. Figure 5 demonstrates the combined efficacy of such corrections on the coupling RDT f_{1001} for the $\beta^*_{\times/\parallel} = 60/18$cm optics. Arc-by-arc corrections using skew quadrupole (MQS) families mitigated large coupling structures in specific arc sections (34-45-56 and 67-78-81), effectively reducing local variations in f_{1001}. Subsequent global coupling corrections, targeting the global $|C^-|$ [11], further decreased its mean amplitude across the machine.

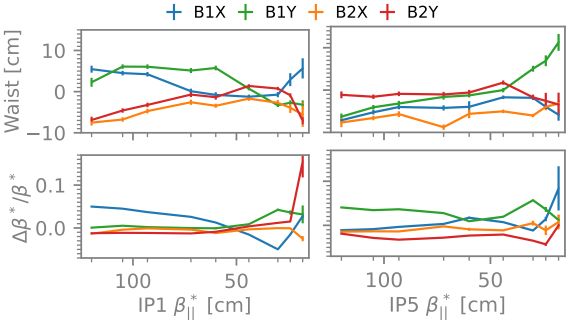

Figure 6: Measured waist (top) and β^*-beating (bottom) at IP1 and IP5 during squeeze to $\beta^*_{\times/\parallel} = 60/18$cm. Minor ticks indicate exact β^* match points.

β^* and Waist K-modulation measurements [12] were performed throughout the 2025 squeeze from $\beta^* = 120$ cm to $\beta^*_{\times/\parallel} = 60/18$cm to validate IP parameters critical for luminosity balance. At the minimum β^*, significant deviations were observed (Fig. 6): a waist shift of ≈ 10 cm (IP5, B1V) and β^*-beating exceeding 10 % (IP1 B2V; IP5 B1H). Correcting these proved challenging within the demanding optics and remains under investigation. Nevertheless, stable beams were achieved with these optics in 2025.

NONLINEAR CORRECTIONS

Nonlinear correction strategies evolved for 2025. While 2024 corrections primarily targeted feed-down to tune, 2025 saw the successful application of new beam-based measurement schemes to suppress higher-order resonances [8, 13–18]. Notably, novel a_4 (skew octupole) corrections were implemented, addressing not only skew octupolar resonances

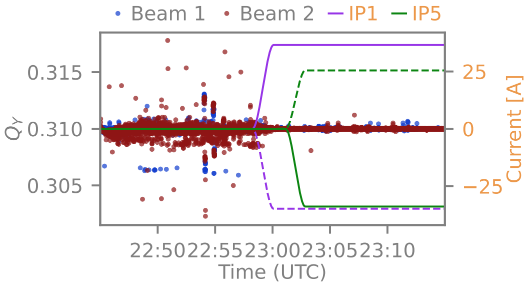

Figure 7: Improved tune measurement (BBQ) clarity after powering b_4 correctors near IP1 and IP5.

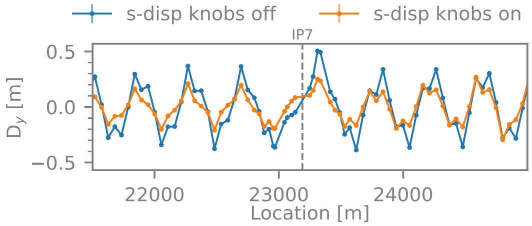

Figure 8: Vertical dispersion (D_y) around IP7 without (blue) and with (orange) spurious dispersion (s-disp) correction knobs (2025 commissioning).

but also compensating feed-down effects contributing to the $3Q_y$ resonance (see below).

K-modulation, essential for IP β-function determination, was again hampered by noisy base-band tune (BBQ) data in 2024 and 2025. Consistent with past experience, the application of b_4 (normal octupole) corrections effectively resolved these impediments. The resulting improvement in BBQ data quality (Fig. 7) is also vital for compensating tune drifts during extended measurements like amplitude detuning [19].

Collimation Hierarchy Breaking

A critical issue with the 2024 optics was the breaking of collimation hierarchy: Beam 2 particles were intercepted by secondary collimators in IR7 instead of the primaries [20]. This was eventually traced to vertical off-momentum halo particles, but identifying the multiple contributing factors and implementing mitigation was a lengthy process.

Dispersion Vertical dispersion was identified as a key contributor to the breakage. Enhancing existing dispersion suppression bumps in IR1, together with the correction of $3Q_y$ (below), successfully restored collimation hierarchy [21, 22]. For 2025, dedicated "spurious dispersion" suppression knobs, creating orbit bumps through arc sextupoles between IP2 and IP8, were implemented. Figure 8 demonstrates their effectiveness in reducing vertical dispersion around IP7.

$3Q_y$ Resonance Beam-beam interactions were implicated as the hierarchy breaking occurred only with bunch trains in both beams. Specialized measurements with specific bunch patterns were employed to study these effects [23, 24]. The $3Q_y$ resonance, exacerbated by skew sextupole errors and feed-down from octupole errors [13], was identified as the primary cause, distorting phase space and driving halo particles into the aperture [25]. During the 2025 commissioning, this resonance was actively monitored and suppressed using skew sextupole and skew octupole correctors [13–15]. Figure 9 exemplifies the $3Q_y$ reduction due to a_4 corrections in IR1 mitigating skew octupole error feed-down.

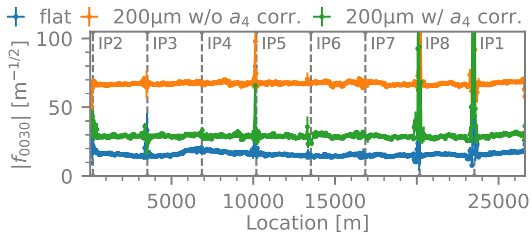

Figure 9: Amplitude of the $3Q_y$ resonance at flat orbit (blue) and at 200 µm horizontal crossing in IP1, pre- (orange) and post- (green) a_4 corrections.

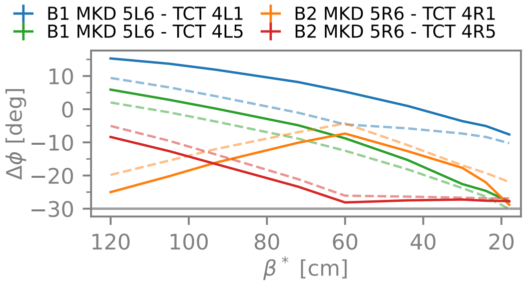

Figure 10: MKD-TCT phase advances for both beams at IP1 and IP5 during squeeze to $\beta^*_{\times/\parallel} = 60/18$cm. Measured (solid lines) vs. model (dashed lines).

MKD Phase Advance Machine protection requires specific phase advances (ϕ) between the dump kickers (MKD) and tertiary collimators (TCTs) protecting IP1 and IP5, with $\phi \in (-30°, 30°) \cup (150°, 210°)$. Figure 10 confirms these conditions were met for both beams and IPs throughout the squeeze at all measured match points, consistent with model predictions (dashed lines).

CONCLUSION AND OUTLOOK

The 2024 and 2025 LHC commissioning campaigns successfully addressed the challenges posed by the significant optics modifications, enabling continued high-performance operation and extending the expected magnet lifetime. While these campaigns required more time (13 shifts, ≈ 104 h, in 2024; 15 shifts in 2025) compared to the 6 shifts for revalidating 2022 optics in 2023, this was a significant improvement over the 27 shifts needed for the 2022 commissioning. This efficiency gain was achieved by extrapolating previous corrections and leveraging enhanced measurement and correction tools [8], which proved capable of tackling high-order nonlinear errors in demanding optics configurations [13].

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