PROBING THE ULTIMATE β^* REACH OF THE LHC

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Abstract

In 2026, the Large Hadron Collider concludes its final run, before being upgraded to the High-Luminosity Large Hadron Collider. Originally conceived with a nominal β^* of 0.55 m in both planes, its optics design has been steadily pushed beyond those initial goals, with round optics down to 0.25 m (2018), and flat optics down to 0.5 m/0.15 m (2026) used in operation. In 2025, dedicated beam-studies were performed to test the viability of controlling β^* waist errors at such low-β, and to explore the viability of squeezing and commissioning the optics even further. Possible operational scenarios down to 0.4 m/0.12 m were tested, and optics measurements down to a minimum β of 0.075 m achieved, the outcome of which are presented.

LOW-β COMMISSIONING

Collider operation at very low-β^* suffers from strong sensitivity to magnetic errors in the experimental IRs, leading in the LHC's case to large increases in β-beating through the squeeze unless dedicated beam-based corrections are applied [1–3]. In 2025 the LHC operational configuration was pushed to a flat $\beta^* = 0.6\,\mathrm{m}/0.18\,\mathrm{m}$ configuration [4, 5], with the low-β plane alternating between the ATLAS and CMS experiments. This led to a peak β-beat of 275 %. To successfully run the LHC in this configuration the optics quality must therefore be improved by about 2 orders-of-magnitude. This was successfully achieved during the 2025 LHC commissioning [6–8], as seen in Fig. 1.

Later in 2025, machine development tests were performed to try and squeeze further. The design β^* in the ATLAS and CMS insertions was reduced in two steps: to $\beta^* = 0.5\,\mathrm{m}/0.15\,\mathrm{m}$, then $\beta^* = 0.4\,\mathrm{m}/0.12\,\mathrm{m}$, with optics measurements performed at each step. The optics corrections commissioned previously for the operational 0.18 m configuration were maintained constant during the additional squeeze. Examples of the resulting optics quality at 0.15 and 0.12 m are shown in Figs. 2-3.

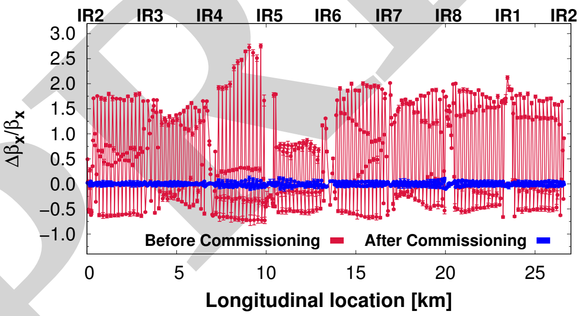

Figure 1: Example of measured β-beat (Beam 1) at $\beta^* = 0.18\,\mathrm{m}$ in 2025, before/after optics commissioning.

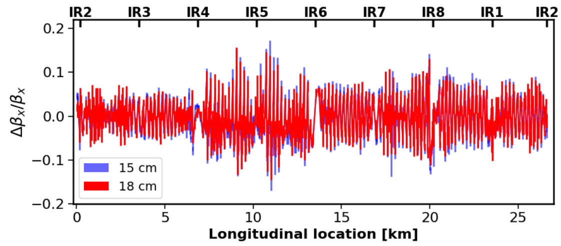

Figure 2: Example of measured β-beat (Beam 1 horizontal) at $\beta^* = 0.15\,\mathrm{m}$, compared to $\beta^* = 0.18\,\mathrm{m}$.

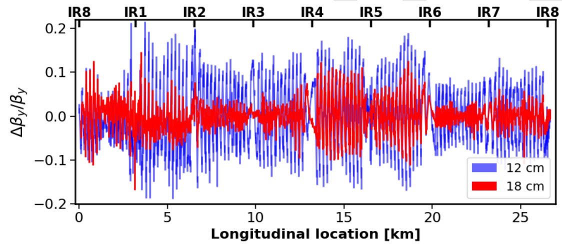

Figure 3: Example of measured β-beat (Beam 2 vertical) at $\beta^* = 0.12\,\mathrm{m}$, compared to $\beta^* = 0.18\,\mathrm{m}$.

The additional squeeze to $\beta^* = 0.15\,\mathrm{m}$ was found to be approximately transparent in terms of optics quality, with negligible degradation compared to the operational scenario. Even when squeezing to a $\beta^* = 0.12\,\mathrm{m}$ only a moderate degradation was found, reflecting the high-quality of local optics corrections in the experimental IR achieved over many years. It is also notable that even in this strongly pushed configuration, well beyond the LHC's original design, there was sufficient dynamic aperture and beam-lifetime to remain at low-β for many hours and perform extensive optics measurements via AC-dipole kicks, which further reflects the good control of nonlinear optics achieved in the LHC. Ultimately, the additional squeeze to $\beta^* = 0.15\,\mathrm{m}$ was selected for inclusion in 2026 operation.

OPTICS STABILITY AT LOW-β

A particular issue for low-β collider operation is optics stability, since even small changes to magnetic errors and alignments in the IRs can result in large optics perturbations. This concern also holds true for future HL-LHC operation. While the LHC has generally exhibited good year-to-year stability at high-β^* [6], regular updates to the low-β operational scenario mean very limited year-to-year comparisons are available. During LHC commissioning in February 2026 however, the optics at $\beta^* = 0.15\,\mathrm{m}$ could be directly compared with the $\beta^* = 0.15\,\mathrm{m}$ machine development study in November 2025 [7, 9].

Between 2025 and 2026 a clear degradation to the optics quality was observed, growing through the squeeze. This was most severe in the horizontal plane of Beam 2, where the peak β-beat exceeded 20 % at 0.15 m (Fig. 4), and machine protection constraints were violated from 0.18 m onwards. The degradation was primarily caused by a change in the optics errors of the CMS insertion (identified via segment-by-segment analysis of the optics measurements [9]) however smaller degradations were also seen in the ALTAS IR, and in Beam 1, where changes to the β-beat at the level of 5 % were observed between these two years.

A new local correction of a single quadrupole ($\Delta K = -3 \times 10^{-5}\,\mathrm{m}^{-2}$ applied to Q5 right of the CMS insertion) corrected the Beam 2 horizontal β-beat, allowing low-β operation to proceed. Note however, that while this trim effectively compensated the β-beat, this does not a priori imply it was the source of the degradation, as large degeneracy can exist in local correction schemes [1].

While 2026 experience reinforces expectations that HL-LHC cannot assume a year-to-year stability of its optics commissioning, arguably a greater concern is optics stability within a given year. In most cases where data is available, good stability has been observed throughout the LHC cycle [6], however exceptions exists at low-β. Notably, an optics shift was observed between April and June 2024 at $\beta^* = 0.3$ m, where a 5 % degradation was observed (Fig. 5). This was again identified as originating from a change to the optics errors in the insertions. In 2024 the degradation was small enough that operation could continue, but ex-

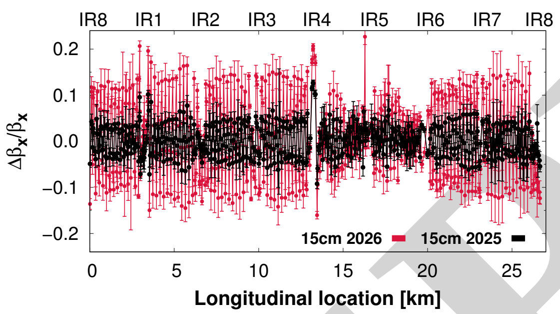

Figure 4: Degradation of β-beat at $\beta^* = 0.15$ m between the 2025 MD and the 2026 LHC run (Beam 2 horizontal).

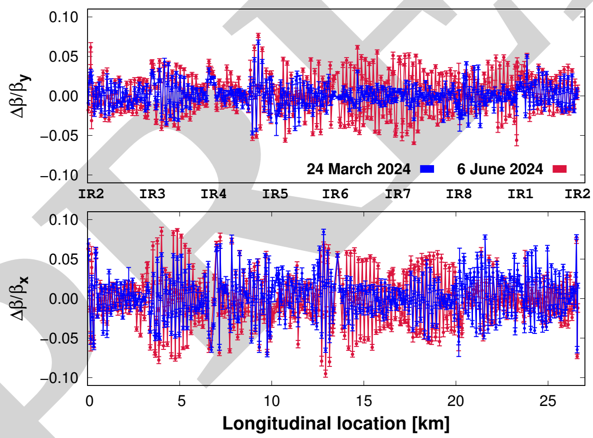

Figure 5: Change in β-beat observed at $\beta^* = 0.3$ m part way through the 2024 run (Beam 1).

trapolating to the lower β^* in the HL-LHC era, such shifts to the errors could pose a challenge to machine protection. Fortunately experience at $\beta^* = 0.18$ m in 2025 showed an excellent stability between March commissioning and the November MD (within 2 % reproducibility).

β-WAIST CONTROL

Table 1: β^* and Waist Errors in the low-β planes of ATLAS and CMS after 2025 commissioning (positive waist implies a shift toward the innermost focusing triplet).

	ATLAS vertical		CMS horizontal	
	B1 [cm]	B2 [cm]	B1 [cm]	B2 [cm]
β^*_{design}	18.0	18.0	18.0	18.0
β^*	18.7 ± 0.3	20.5 ± 0.9	19.6 ± 0.7	18.1 ± 0.2
β_W	18.1 ± 0.05	18.1 ± 0.05	17.7 ± 0.05	17.6 ± 0.05
waist	-3.3 ± 0.8	-6 ± 1	-5.5 ± 1	-3.0 ± 0.8

2025 experience highlighted another key challenge at low-β: control of β-waist errors. These are longitudinal offsets of the minimum beta (β_W) from the design location, resulting in an increase to β in the experiments (β^*) and loss of aperture margins. For moderately squeezed optics large waist errors can be accommodated without significant impact, but for LHC scenarios in 2025-26, and planned for HL-LHC, even small waists quickly become a significant source of luminosity loss or imbalance between the detectors. β^* and waist errors are measured during commissioning via K-modulation, and have previously been compensated (alongside residual β-beat and dispersion) via a response matrix approach [2]. While this was sufficient in previous years, at the low-β employed in 2025 the residual β^* and waist errors which remained in the low-β plane after commissioning were found to have a non-negligible influence on luminosity at the end-of-squeeze. The measured errors in the low-β planes of ATLAS and CMS are detailed in Table 1.

When aggregated, the β^* errors over all beams/planes cause an optics-related luminosity loss at end-of-squeeze of 5 ± 1% and 2.5 ± 1% in ATLAS and CMS respectively, and a Luminosity imbalance of 2.5 ± 1 %. This impact on luminosity is dominated by two roughly 6 cm waist errors in low-β^* planes (ATLAS B2-V and CMS B1-H).

For LHC operation in Run 3 most luminosity is produced during β^*-levelling, thus the impact on integrated luminosity is small. In HL-LHC a high proportion of luminosity is delivered in unlevelled operation at end-of-squeeze, and control of waist errors becomes a significant concern. Consequently, two correction strategies were studied during dedicated tests in 2025, focusing on the most lumi-impacting waist (a 6 cm offset of the ATLAS LHCB2-V plane).

The first approach attempted a local waist correction: five quads in the IR were used to create an optics shift through the IR which linearly displaces the waist, while minimizing leakage. When applied in the real machine, K-modulation measurements showed the expected correction to the waist and β^* (Tab 2). The knob was applied during a dedicated

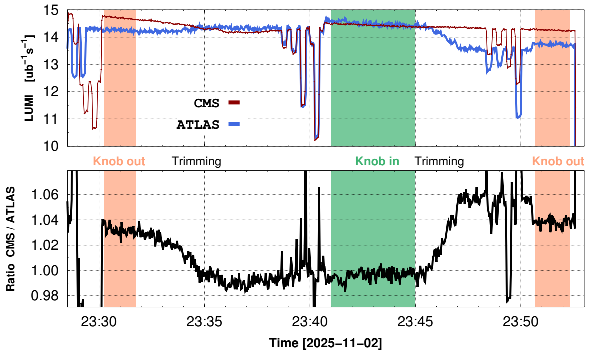

Figure 6: Measured luminosity and lumi-imbalance during application/removal of the local waist correction.

Table 2: β^* and Waist errors (Beam 2 vertical, ATLAS IR) before/after the local waist correction.

[cm]	β^*_{design}	β^*	β_W	waist
Before corr	18.0	20.3 ± 0.1	18.2 ± 0.05	-6.2 ± 0.3
After corr	18.0	18.1 ± 0.05	18.0 ± 0.05	$+1.3 \pm 0.3$

Table 3: β^* and Waist errors (Beam 2 vertical, ATLAS IR) before/after the ATS waist correction.

[cm]	β^*_{design}	β^*	β_W	waist
Before corr	12.0	16.6 ± 0.4	12.8 ± 0.1	-7.0 ± 0.4
After corr	12.0	9.3 ± 0.1	9.3 ± 0.1	0.4 ± 0.5

test with colliding beams, where the expected increase to ATLAS luminosity and reduction in ATLAS/CMS luminosity imbalance was observed (Fig. 6).

It is not possible when matching this correction using only magnets in the ATLAS insertion to perfectly isolate a single IR and plane, thus the 'local' approach benefits from flat-optics as leakage to the high-β^* planes has a negligible impact on performance. Waist correction in round optics is even more challenging. An alternative 'ATS' approach was also tested during the $\beta^* = 0.12$ m MD. In this case β-waves generated in the IR and arc either side of low-β IR propagate through to perturb the optics at the experiment. In principle this allows matching of individual corrections independently controlling waist and β^* of each plane, though knobs no-longer have a linear response.

Figure 7 shows the β-beat from this waist correction, at 0.12 m. K-modulation measurements before/after correction are shown in Table 3. This approach also successfully reduced the waist error, though β_W was undesirably perturbed.

7 CM LHC OPTICS

While the waist correction tested at 0.12 m worked as expected, it was originally part of a combined correction targeting both the waist and β_W. This combined correction did not function as expected. A 100 % β-beat was generated in the arcs either side of the ATLAS experiment (Fig. 8). While highlighting the necessity for beam-based validation of new optics corrections, this was of particular interest as

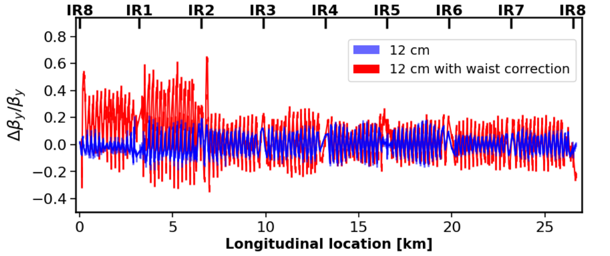

Figure 7: Vertical β-beat generated in Beam 2 by the ALTAS ATS waist correction.

the β-beat was actually found to generate a further squeeze of the β^* in ATLAS. K-modulation results with the combined trims are shown in Table 4, showing that a record low β_W of 7.5 cm was achieved! The β_W seen in K-modulation was independently validated using the kicked beam data and a segment-by-segment analysis [10]. This is remarkable since this LHC configuration exceeds HL-LHC design targets (for the single plane in question) and is comparable to values more commonly achieved in lepton colliders, notably LEP2, yet once again sufficient lifetime, dynamic- and geometric-aperture remained available to allow extensive optics measurements with kicked beams.

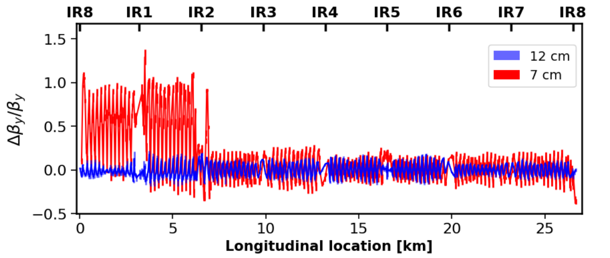

Figure 8: Vertical β-beat generated in Beam 2 by the combined ATS waist and β_W correction in ATLAS.

Table 4: β^* and Waist errors (Beam 2 vertical, ATLAS IR) at 0.12 m optics with the combined ATS IR correction.

[cm]	β^*_{design}	β^*	β_W	waist
Combined corr	0.12	7.7 ± 0.7	7.5 ± 0.05	1 ± 1

CONCLUSION

LHC operation has been pushed to significantly lower β^* than originally envisaged. High-quality local optics corrections achieved at flat $\beta^* = 0.6/0.18$ m in 2025 allowed even further squeeze steps to be implemented in 2026. Experience at such low-β has highlighted particular challenges relating to optics stability and control of β-waists which will be pertinent to future HL-LHC operation, while during dedicated tests a minimum β of 7.5 cm was even achieved in one plane, a configuration which exceeded even HL-LHC baseline targets.

ACKNOWLEDGEMENTS

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REFERENCES

[1] R. Tomás *et al.*, "Record low β beating in the lhc", *Phys. Rev. ST Accel. Beams*, vol. 15, no. 9, p. 091001, Sep. 2012. doi:10.1103/PhysRevSTAB.15.091001

[2] T. Persson *et al.*, "LHC optics commissioning: A journey towards 1% optics control", *Phys. Rev. Accel. Beams*, vol. 20, no. 6, p. 061002, Jun. 2017. doi:10.1103/PhysRevAccelBeams.20.061002

[3] E. H. Maclean *et al.*, "New approach to lhc optics commissioning for the nonlinear era", *Phys. Rev. Accel. Beams*, vol. 22, no. 6, p. 061004, Jun. 2019. doi:10.1103/PhysRevAccelBeams.22.061004

[4] S. Fartoukh and F. Cerutti, "RP optics options for 2024 and beyond", Joint Accelerator Performance Workshop 2023, Montreux, Switzerland, 5-7 December 2023, https://indico.cern.ch/event/1337597,

[5] S. Fartoukh, F. Cerutti, and S. Kostoglou, "Flat optics proposal for the 2025-26 run", 499th LHC Machine Committee meeting, 2024, https://indico.cern.ch/event/1484357/,

[6] E. Maclean *et al.*, "Review of linear and nonlinear optics measurements in the cern lhc", in *Proc. IPAC'25*, Taipei, Taiwan, Jun. 2025, pp. 3250–3255. doi:10.18429/JACoW-IPAC2025-FRYD2

[7] E.H. Maclean, "OMC and Optics Commissioning in 2025 and 2026", LHC Machine Committee (LMC 523), https://indico.cern.ch/event/1661349/,

[8] E.H. Maclean, "OMC studies", CERN Injectors and LHC MD days 2025, https://indico.cern.ch/event/1584331/contributions/6750633/,

[9] E.H. Maclean, "OMC commissioning summary", LHC Beam Operation Committee meeting 191, 24 March 2026, https://indico.cern.ch/event/1664034/,

[10] M. Stefanelli, Y. Angelis, J. Dilly, J. Gray, E. Maclean, and F. Soubelet, "Extrapolated optics measurement from BPM to instrumentation in LHC commissioning", paper WEP5072, unpublished.