CORRECTION OF LONG-RANGE BEAM-BEAM DRIVEN OPTICS PERTURBATIONS FOR THE LHC

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Abstract

Optics measurements in the LHC are usually performed with low-intensity, non-colliding pilot beams in the interest of machine safety. However, long-range beam-beam (LRBB) interactions can drive substantial optics perturbations. In 2024, a weak-strong measurement scheme was developed that probes the weak beam while leaving the strong beam unaffected, and machine tests validated this method. In 2025, a reported luminosity discrepancy between ATLAS and CMS motivated further study of the LRBB-induced β-beat in the new 18 cm flat-optics configuration. A large β-beat was observed, reaching typical LHC machine-protection limits. Correction strategies using magnets in the experimental insertions were demonstrated successfully, and, for the first time, non-linear corrections addressing sextupolar and octupolar resonance driving terms were also successfully demonstrated for example the measurement of the $3Q_y$ correction.

MOTIVATION

Long-range beam-beam (LRBB) interactions impact key performance parameters, including dynamic aperture, beam lifetime, and luminosity, and has been extensively studied in accelerators such as Tevatron [1] and the LHC [2], using a combination of simulations and measurements of some of these observables.

Direct optics measurements including LRBB effects have historically been lacking, primarily due to the difficulty of performing measurements under such conditions. LHC optics commissioning and measurements have typically been conducted using low-intensity, non-colliding bunches. In 2024, a novel method for optics measurements in the presence of LRBB effects was developed [3].

In 2025, a luminosity imbalance between the CMS and ATLAS experiments was reported [4], motivating detailed investigations into its origin. This new approach was exploited to measure the β-beating in the presence of LRBB. The peak β-beat was found to reach approximately 20%, corresponding to the machine-protection limit. The horizontal β-beating for LHCB1, with a β^*=18/60 cm, is shown in Fig. 1. These conditions correspond to a crossing angle of 160 µrad and a strong-beam intensity of 1.5×10^{11} ppb. The usual operational scenario at end-of-squeeze is an intensity of around 1.1×10^{11} ppb but even at those intensities the β-beat would be substantial.

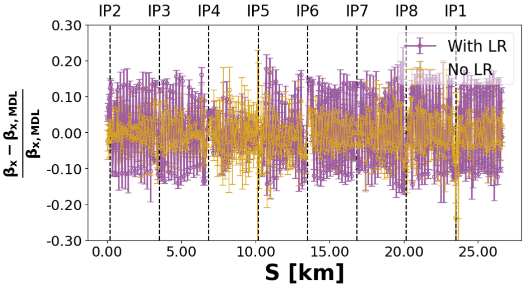

Figure 1: Horizontal β-beating vs s with and without LR effects for LHCB1, crossing angle = 160 µrad.

When the crossing angle was reduced to 120 µrad, the peak β-beating increased further, as shown in Fig. 2.

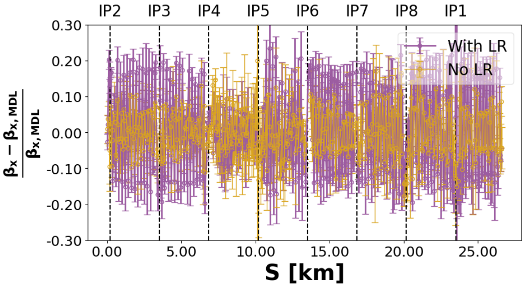

Figure 2: Horizontal β-beating vs s with and without LR effects for LHCB1, crossing angle = 120 µrad.

Maintaining low β-beating is essential to preserve an operational margin against optics drifts, accommodate additional optics trims and corrections [5], and to ensure compliance with machine-protection constraints.

The increase in β-beating between the two crossing angles exhibits a correlation of comparable magnitude with the corresponding increase in luminosity imbalance reported.

To assess whether the observed luminosity imbalance could be reproduced in simulation, an Xsuite model including LRBB effects was employed. The resulting luminosity imbalance, summarised in Table 1, was also found to be consistent with the values reported by the experiments.

Table 1: Simulated luminosity imbalance from LRBB for an intensity of 1.1×10^{11} ppb for each crossing angle.

Crossing angle [µrad]	**Luminosity imbalance in favour of CMS** [%]
160	4.5
120	7.4

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CORRECTION CREATION

Two complementary approaches were investigated for the correction of LRBB-driven β-beating. The first approach is simulation-based, where the tune was re-matched to its initial value following the inclusion of LRBB elements, first in IR1 and subsequently in IR5. This was performed using the inner-most individually powered quadrupoles for each beam and interaction region. The simulation was configured with a bunch intensity of 1.5×10^{11} ppb and a crossing angle of 160 µrad, corresponding to a typical MD setup. This approach achieved a significant reduction in LRBB-induced β-beating in simulation, as shown in Fig. 3.

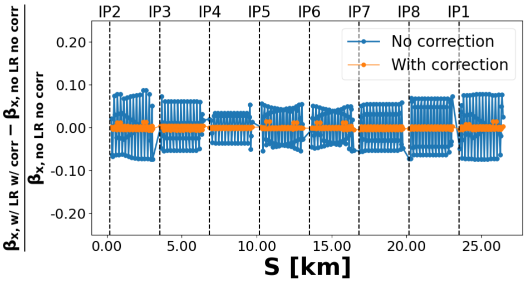

Figure 3: Horizontal β-beating vs s with and without the Xsuite correction for LHCB1, crossing angle = 160 µrad.

These simulation studies further indicated that the local β-beating correction, optimised only for a crossing angle of 160 µrad and an intensity of $1{\times}10^{11}$ ppb hence the lesser reduction for a crossing angle of 120 µrad, reduces the luminosity imbalance in favour of CMS, as summarised in Table 2. The correction can be readily re-calculated for different crossing angles and or intensities. These results suggests that the proposed correction provides a viable means of addressing the observed imbalance.

Table 2: Simulated luminosity imbalance for an intensity of $1.1{\times}10^{11}$ ppb for each crossing angle.

Correction	**Crossing angle** [µrad]	**Luminosity imbalance in favour of CMS** [%]
No correction	160	4.5
With correction	160	0.1
No correction	120	7.5
With correction	120	3.3

The second approach employed standard β-function correction techniques conventionally used for LHC optics commissioning [6, 7]. In this case, the correction was derived using the bunch experiencing all long-range interactions, rather than the non-colliding bunch typically used in standard commissioning procedures. Consequently, the correction is optimised for the majority of luminosity-producing bunches, while the performance of other bunches, such as bunches with fewer LRBB encounters, will be degraded.

CORRECTION TESTING

A dedicated MD session was allocated to test these corrections in the machine. The measurements were found to be reproducible after a four month period, as demonstrated by comparison of Figs. 1 and 4.

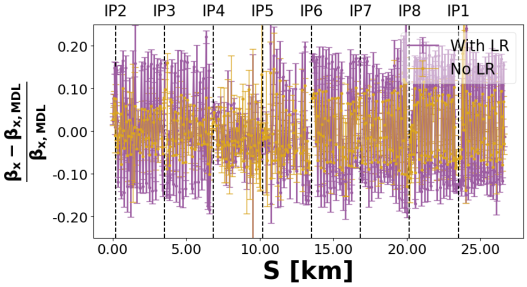

Figure 4: Horizontal β-beating vs s with and without LR effects for LHCB1, crossing angle = 160 µrad.

To enable direct comparison between simulation and measurement, and to quantify the β-beating induced by the applied correction, a modified definition of β-beating was introduced, defined as the difference between the β-function with LR effects and correction and that without LR effects or correction, normalised to the model β-function.

Using this definition, approximate agreement in both amplitude and phase of the β-beating between simulation and measurement was observed for LHCB1, as shown in Fig. 5. The measurement uncertainties were, however, relatively large, likely due to the limited excitation amplitudes achievable.

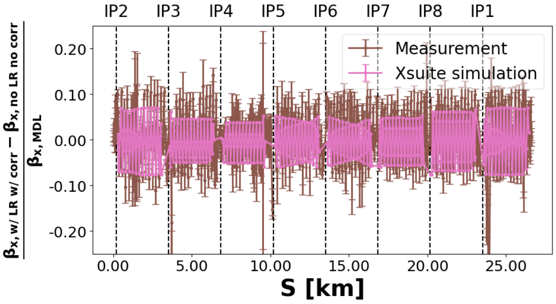

Figure 5: Horizontal β-beating vs s for simulation and measurement for LHCB1 with full LR effects.

The application of the model-based correction resulted in a substantial reduction of the conventional β-beating for the LRBB bunches, as shown in Fig. 6.

For LHCB2, the benchmarking between simulation and measurement did not exhibit the same level of agreement, as illustrated, for example, in Fig. 7. Notably, between IP1 and IP3, the measured β-beating was more significant than in simulation.

The LRBB model-based correction achieved a reduction of the peak of the conventional β-beat in LHCB2 (Fig. 8), addressing the primary machine protection concern. However, it introduced mostly a degradation in the horizontal plane. Fortunately though this yielded a more balanced distribution between the planes, which is operationally preferable.

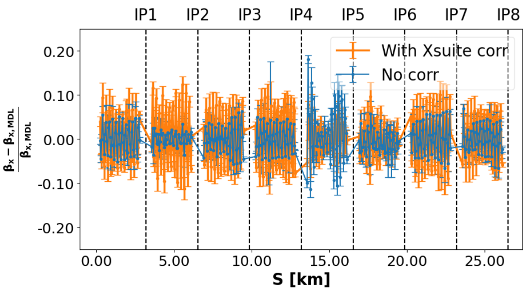

Figure 6: Measured horizontal β-beating vs s with and without Xsuite correction for LHCB1 with full LR effects.

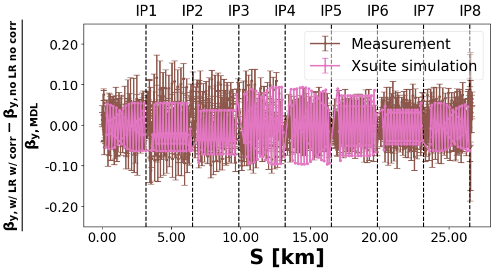

Figure 7: Vertical β-beating vs s for simulation and measurement for LHCB2 with full LR effects.

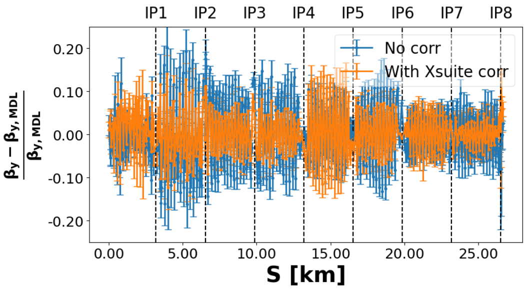

Figure 8: Measured vertical β-beating vs s with and without Xsuite correction for LHCB2 with full LR effects.

To assess potential improvements to the model-based correction, a beam-based correction [8] was also applied to LHCB2. This approach provided a solution in which both planes could be reduced. Figure 9 shows that the GUI-based correction was more effective than the simulation-based approach; however, a comparable level of correction was achieved for the vertical β-beating in both cases, as shown in Fig. 10.

These results demonstrate that a simultaneous correction for both beams is, in principle, achievable.

NON-LINEAR CORRECTION

Using the same novel optics measurement procedure for bunches in the presence of LRBB, there was also a successful demonstration of a simulation-based, LRBB-driven non-linear resonance correction, as described in [9–11]. An example of the measured reduction in the amplitude of the resonance driving term associated with the $3Q_y$ resonance is shown in Fig. 11.

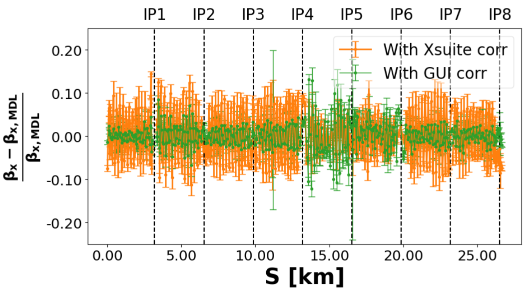

Figure 9: Measured horizontal β-beating vs s with the Xsuite correction and the GUI-based correction for LHCB2 with full LR effects.

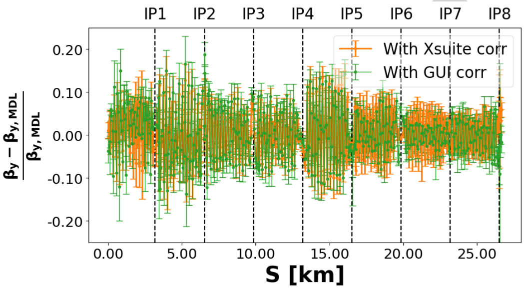

Figure 10: Measured vertical β-beating vs s with the Xsuite correction and the GUI-based correction for LHCB2 with full LR effects.

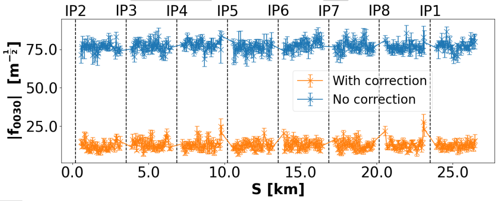

Figure 11: Measured resonance driving term amplitude corresponding to the $3Q_y$ resonance vs s for LHCB1 with and without correction.

CONCLUSION

A reported luminosity imbalance between the CMS and ATLAS experiments motivated an investigation of the β-beating under the same experimental conditions. Dedicated tests provided a first demonstration that linear optics perturbations induced by LRBB can be both measured and corrected with magnets. There was also a successful correction in the non-linear regime using the same measurement method. This opens the possibility of extending optics commissioning beyond the single-particle regime, enabling LRBB-driven optics corrections to be considered operationally during LHC or HL-LHC commissioning. These results further validate the robustness of the measurement framework and emphasise the requirement for reliable optics measurements in this configuration.

ACKNOWLEDGEMENTS

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REFERENCES

[1] V. Shiltsev *et al.*, “Beam-beam effects in the Tevatron”, *Phys. Rev. Spec. Top. Accel. Beams*, vol. 8, no. 10, p. 101001, Oct. 2005. doi:10.1103/PhysRevSTAB.8.101001

[2] D. Kaltchev and W. Herr, “Analysis of long-range studies in the LHC - Comparison with the model”, in *ICFA Mini-workshop on Beam-Beam in Hadron Colliders 2013*, pp. 93–100, 2014. doi:10.5170/CERN-2014-004.93

[3] T. H. B. Persson *et al.*, “LHC MD #12263 - Weak-Strong investigation of Long-Range Beam-beam”, CERN, Rep. CERN-ACC-NOTE-2025-0011, 2025. `https://cds.cern.ch/record/2930597`

[4] D. Mirarchi, M. Hostettler, G. Ripellino, K. Monig, and D. Stickland, “LHC Luminosity Calibration and Monitoring Working Group 4 August 2025”, `https://indico.cern.ch/event/1584331/contributions/6750633/attachments/3191192/5679450/2025-12-12_MDdays.pdf`,

[5] E. Maclean, OMC team, and OP team, “LHC OMC MDs – takeaway from 2025”, Injectors & LHC MD days 2025, Dec. 2025, `https://indico.cern.ch/event/1584331/contributions/6750633/attachments/3191192/5679450/2025-12-12_MDdays.pdf`,

[6] M. Aiba *et al.*, “First β-beating measurement and optics analysis for the CERN Large Hadron Collider”, *Phys. Rev. Spec. Top. Accel. Beams*, vol. 12, no. 8, p. 081002, Aug. 2009. doi:10.1103/PhysRevSTAB.12.081002

[7] R. Tomás *et al.*, “Record low β beating in the LHC”, *Phys. Rev. Spec. Top. Accel. Beams*, vol. 15, no. 9, p. 091001, Sep. 2012. doi:10.1103/PhysRevSTAB.15.091001

[8] J. W. Dilly, L. Malina, and R. Tomás Garcia, “An Updated Global Optics Correction Scheme”, CERN, Rep. CERN-ACC-NOTE-2018-0056, 2018. `https://cds.cern.ch/record/2632945`

[9] S. J. Horney *et al.*, “Correction of Long-Range Beam-Beam Driven Normal Sextupolar Resonance Driving Terms”, in *Proc. IPAC’25*, Taipei, Taiwan, pp. 322–325, Nov. 2025. doi:10.18429/JACoW-IPAC2025-MOPM019

[10] S. Horney, E. Maclean, T. Persson, OMC team, and OP team, “Using the IT corrector package for long range beam-beam mitigation”, 15th HL-LHC Collaboration Meeting, Sep. 2025, `https://indico.cern.ch/event/1559978/contributions/6664806/attachments/3146048/5585263/Using_the_IT_corrector_package_for_long_range_beam_beam_mitigation-2.pdf`,

[11] S. Horney, “Improvement of optics control in the Large Hadron Collider with forced Resonance Driving Terms”, Ph.D. thesis, Submitted April 2026.