16th International Particle Accelerator Conference, Taipei, Taiwan JACoW Publishing
ISBN: 978-3-95450-248-6 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2025-MOPM019

CORRECTION OF LONG-RANGE BEAM-BEAM DRIVEN NORMAL SEXTUPOLAR RDTS

S. Horney*[1,2], E. Maclean[1], P. N. Burrows[2], J. Dilly[1], L. Deniau[1], T. Persson[1], R. Tomás[1]
[1]CERN, Geneva, Switzerland, [2]University of Oxford, Oxford, UK

Abstract

Beam-based studies at the LHC injection energy showed that compensation of a strongly driven sextupolar resonance, $Q_x + 2Q_y$, improved dynamic aperture and lifetime, even when far from the working point. Thus, a reduction of other strong normal sextupolar resonance sources was of interest. In 2024, first measurements of resonance driving terms with long-range beam-beam (LRBB) interactions were performed. These showed that LRBB was driving sextupole resonances strongly, in agreement with model predictions. A correction was found for the strongest normal sextupole resonance using the existing sextupole corrector magnets in the LHC, obeying the constraints on the chromatic coupling and the maximum magnet powering. In 2025, there was an extension to correct the $3Q_y$ resonances and some normal octupolar resonances.

MOTIVATION

In 2023, it was found that the normal sextupolar resonance driving term (RDT) f_{1020} (driving $Q_x + 2Q_y$) was significant at injection. A correction for this RDT was put into operation in 2024, which improved Dynamic Aperture (DA) and lifetime [1]. This success led to increased interest in the viability of such correction in the rest of the cycle.

Long-range beam-beam (LRBB) [2] interactions are expected to be one of the significant drivers of resonances at top energy. RDTs have recently been measured for the first time with low-intensity collisions in the LHC [3], paving the way to testing a correction in the machine. In Fig. 1, the f_{1020} RDT more than doubles with the inclusion of LR interactions in an Xsuite [4] simulation of the 2024 LHC optics at $\beta^* = 0.3$ m.

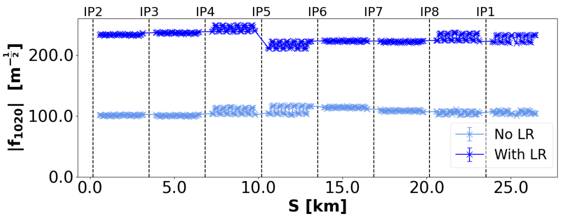

Figure 1: Amplitude of f_{1020} vs. s with and without LR for an Xsuite simulation of 2024 LHC optics at $\beta^* = 0.3$ m.

Historically, the approach considered for correcting LRBB in the LHC and HL-LHC has been via Beam-Beam-Wire Compensation [5]. In the case of unavailability of wire compensation, or of sub-optimal wire placement (LRBB wires tested in the LHC in 2024 for example [6], do not correct the sextupole resonances), a complementary strategy could be to correct using the non-linear corrector magnets located in the experimental insertions [7]. These magnets are common for both beams, increasing the difficulty of their utilisation and some corrections of this nature were already attempted in [8], without much promise however.

NORMAL SEXTUPOLE CORRECTION SCHEME WITH ROUND OPTICS

The viability of correction was studied in simulation for the f_{1020} RDT using the 2024 round LHC optics (with β^*=0.3 m), using the MCSX normal sextupole correctors. To calculate a correction, tracking simulations were performed in Xsuite with and without LRBB elements included. Analysis with the OMC tool-set [9] enabled the calculation of the RDT shifts generated by beam-beam. MAD-NG [10] (which offers powerful tools for rapid RDT calculation and matching) was then used to examine the response of f_{1020} to the MCSX correctors. Figure 2 shows the RDT response to the maximum powering of each individual MCSX.

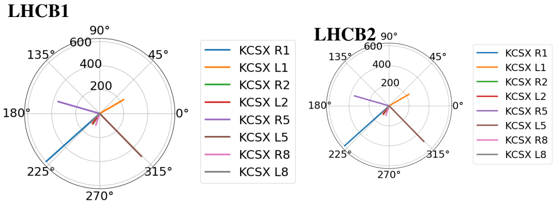

Figure 2: f_{1020} amplitude/phase from maximum powering of MCSX, for LHC beam 1 (LHCB1) and beam 2 (LHCB2).

One of the difficulties with this approach is that the MCSX are located in the common aperture region of the ring, so each individual magnet affects both beams. Despite this, by identifying a combination of MCSX in MAD-NG that were in phase with the real and imaginary parts of the RDT in the presence of LRBB, simultaneously for both LHCB1 and LHCB2, and applying the reverse of this circuit powering, a correction was devised.

The correction identified in MAD-NG was applied to Xsuite simulations, where it worked well, correcting for the RDT in both beams below the level present with just the lattice. The magnitude of the RDT was reduced by a factor of four as displayed in Fig. 3 and similarly for LHCB1.

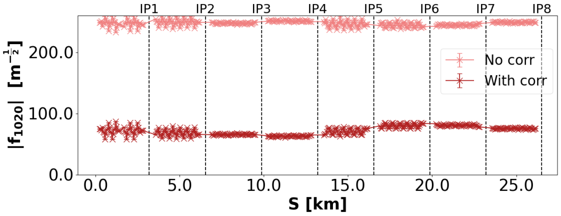

Figure 3: Simulated amplitude of f_{1020} with and without correction at top energy for LHCB2.

---

* sasha.jade.horney@cern.ch

ISBN: 978-3-95450-248-6 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2025-MOPM019

MACHINE PROTECTION CHECKS

Machine protection constraints in the LHC could not permit the identified corrections to be immediately applied during collision fills with high-intensity. Preliminary tests were required to first demonstrate that the knobs behaved as predicted in simulation with low-intensity, non-colliding beams. During these tests an interlock on the powering of one of the magnets limited the correction to 65% of the initially defined strengths (this is not expected to be an issue for corrections in future years).

The operational test of correction degraded the RDT (in Fig. 4), as expected with no LRBB effects present in the machine. The magnitude of this shift matched what was predicted. Similar results were obtained for both beams and both planes. The β-beating (in Fig. 5) was not impacted which was of importance for machine protection. The sextupole correction was initially planned to be tested in dedicated MDs during 2024. Unfortunately, time availability did not permit for a final validation with collisions.

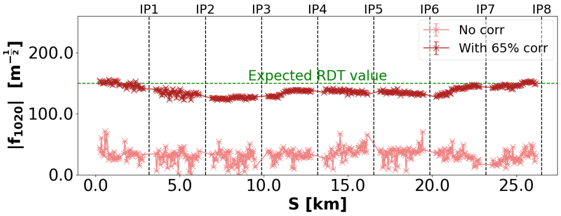

Figure 4: Measured amplitude of f_{1020} with and without correction at top energy for LHCB2 with non-colliding beams.

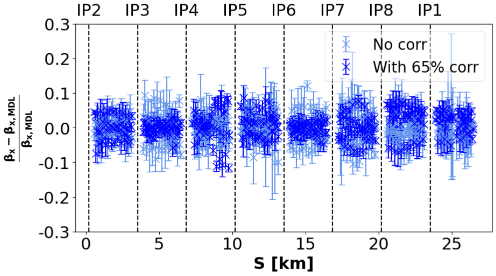

Figure 5: Horizontal β-beating resultant of the LR MCSX corrections.

SEXTUPOLE CORRECTION WITH 2025 FLAT-OPTICS

For 2025, LHC operation switched to "flat-optics" (where IPs are asymmetrically squeezed) which meant that new LRBB corrections had to be devised.

One of the features of the switch to flat-optics was that at the end-of-squeeze the sextupolar RDTs generated by LRBB are about a factor of 2 lower than with round-optics (Fig. 3), as can be seen when looking at the uncorrected RDT in Fig. 6, which shows the simulated f_{1020} for flat-optics with $\beta^* = 0.6/0.18$ m.

In spite of a change to flat-optics, a correction for the f_{1020} RDT was found successfully. The method was further extended to the skew-sextupolar $3Q_y$ resonance (f_{0030} RDT), using the MCSSX skew sextupole. Figures 6 and 7 show for LHCB2 that with a combined correction of the f_{1020} and f_{0030}, the strength of both resonances are substantially reduced. Even better results were obtained in LHCB1.

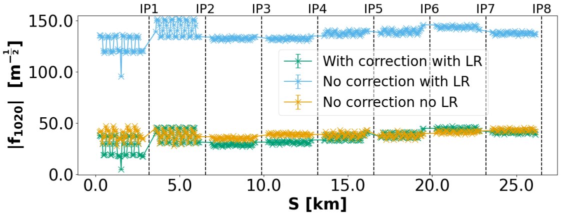

Figure 6: Simulated amplitude of f_{1020} with and without correction at top energy for LHCB2 including a base-line with no LR.

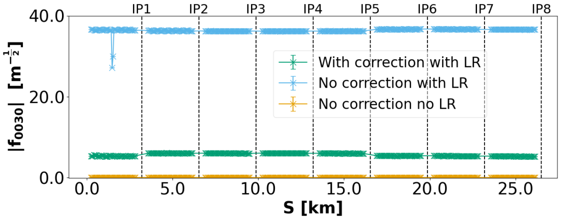

Figure 7: Simulated amplitude of f_{0030} with and without correction at top energy for LHCB2 including a base-line with no LR.

The correction used the MCSX left and right of the ATLAS insertion, and the MCSSX left and right of the CMS IP. Maximum current required was 26 A for a beam intensity of 1.8×10^{11} protons per bunch, at a crossing-angle of 150 μrad. For typical intensities at the LHC end-of-squeeze this would be further reduced. These strengths are well below the maximum powering of the correctors (100 A) hence no interlock issue (identified in the previous section) is encountered.

There was negligible coupling and chromatic β-beat predicted to be generated by the MCSX and MCSSX corrections, with small β-beat ($\approx 2\%$) on-momentum anticipated. Hence, it can be tested later this year.

EXTENSION TO OCTUPOLAR RDT CORRECTION

As an extension to the sextupolar RDT study, it was intriguing to see if the same methods could be applied with normal octupolar resonances driven by LRBB, using the equivalent IR octupole correctors (MCOX) left and right of the experimental insertions.

With flat-optics, the β^*s are squeezed asymmetrically, in IP1 to β_x^*=0.6 m and β_y^*=0.18 m, and vice versa in IP5. As a consequence, purely vertical perturbations from LRBB are overwhelmingly dominated by IP1, and in the horizontal near IP5, with mixed terms resulting from both.

Therefore, to define a correction, the method evaluates the amplitude detuning [11] generated locally in IP1 and IP5 by the LRBB to try to recreate it with the MCOX. By inverting the values found, it was possible in Xsuite simulations to correct the direct term ($\frac{\partial Q_{x,y}}{\partial J_{x,y}}$) triggered by LRBB, without degrading the cross-term detuning ($\frac{\partial Q_{y,x}}{\partial J_{x,y}}$). Since correction with MCOX is approximately local, reducing detuning also compensated the RDTs associated. From this, the $4Q_y$ and $4Q_x$ resonances (f_{0040} and f_{4000}) could be corrected, leaving the $2Q_x - 2Q_y$ resonance (f_{2002}) mostly unchanged.

Table 1 displays the values of the detuning terms ($\frac{\partial Q_y}{\partial 2J_x}$ indirect term was left out since similar to $\frac{\partial Q_x}{\partial 2J_y}$) for LHCB1 and LHCB2 calculated from some Xsuite simulations. It shows that with the correction, the direct detuning terms reduce almost to the level without LRBB and that the indirect terms are barely changed. Figure 8 shows an example of the direct amplitude detuning.

Table 1: Amplitude Detuning values for Direct and Indirect Terms for Different Configurations.

	[10^3 m^{-1}]	$\frac{\partial Q_x}{\partial 2J_x}$	$\frac{\partial Q_x}{\partial 2J_y}$	$\frac{\partial Q_y}{\partial 2J_y}$
LHCB1	Without LR	8	-13	7
	With LR no corr	590	-529	554
	With LR with corr	53	-545	208
LHCB2	Without LR	2	-9	7
	With LR no corr	577	-512	579
	With LR with corr	109	-525	167

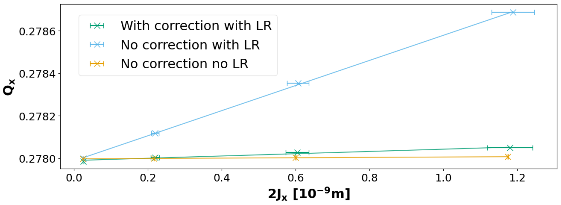

Figure 8: Simulated amplitude detuning with and without LR and a baseline of no LR for LHCB1.

A similar picture can be seen for both the f_{4000} and f_{0040} RDTs and the f_{2002} in Figs. 9, 10 and 11 respectively, which was similar to results obtained from LHCB1.

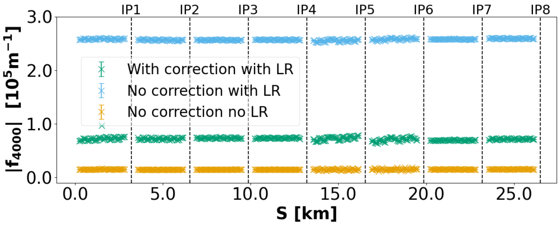

Figure 9: Simulated amplitude of f_{4000} with and without b_4 correction at top energy for LHCB2 including a base-line with no LR.

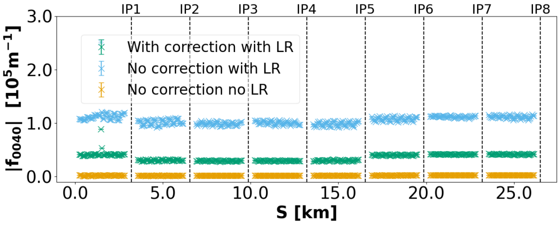

Figure 10: Simulated amplitude of f_{0040} with and without b_4 correction at top energy for LHCB2 including a base-line with no LR.

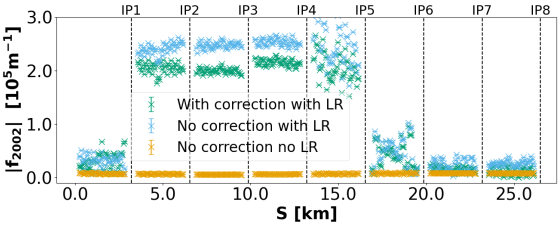

Figure 11: Simulated amplitude of f_{2002} with and without b_4 correction at top energy for LHCB2 including a base-line with no LR.

The required octupolar RDT corrections were strong in powering, utilising the full available strength of the MCOX correctors (after the lattice corrections were applied). This compensated the detuning in a simulation for beam-intensity of 1.8×10^{11} protons per bunch and a 150 μrad crossing-angle. In this scheme, feed-down effects were not problematic i.e. not impacting machine protection constraints.

A combined octupole and sextupole correction using all the circuit powerings listed was also determined to be effective in simulation. These corrections appear promising for operation and aim to be tested during 2025 commissioning and MDs.

CONCLUSION

The viability of the correction of LRBB-driven RDTs using non-linear corrector magnets at low-β insertions has been studied. A correction scheme for the normal sextupole resonance $Q_x + 2Q_y$ was identified for LHC round-optics. Tests of the circuit powerings with low intensity beams showed real impact in the machine aligning with expectation, and confirmed machine protection limits were preserved. Following the decision to operate LHC with flat-optics in 2025, and the resultant lowering in RDT aberrations and allowance for correction of more RDTs associated with the change (very relevant for HL-LHC), a revision of the correction was calculated with an extension to the skew-sextupolar resonance $3Q_y$. These appear promising for operation. The approach was extended to octupolar resonances where operational-feasible corrections for direct detuning was obtained without degradation of cross-term detuning. This translated to a reduction in the $4Q_x$ and $4Q_y$ resonance strengths whilst maintaining the average strength of $2Q_x - 2Q_y$ resonance around the ring. The correction represents an interesting option to support wire compensation or increase flexibility of wire placement in future colliders making this work very important for HL-LHC [12]. It now requires demonstration in the real machine, and there are simulation studies ongoing to confirm beneficial effect on Dynamic Aperture. Finally, there will be similar studies conducted on HL-LHC configurations in the future.

ACKNOWLEDGEMENTS

Many thanks to the LHC OP and OMC teams.

REFERENCES

[1] S. J. Horney *et al.*, "Sextupole RDTs in the LHC at injection and in the ramp", *JACoW IPAC*, vol. 2024, p. MOPC13, 2024. `doi:10.18429/JACoW-IPAC2024-MOPC13`

[2] W. Herr *et al.*, "Long Range Beam-beam Effects in the LHC", in *ICFA Mini-Workshop on Beam-Beam Effects in Hadron Colliders, BB 2013 - Proceedings*, pp. 87–92, 2014. `doi:10.5170/CERN-2014-004.87`

[3] E. Maclean, T. Persson, F. Burkhardt, S. Horney, and R. Tomás, "Beam-based beam-beam benchmarking (and correction)", *JACoW IPAC*, vol. 2025, p. WEPM010, 2025. `https://indico.jacow.org/event/81/contributions/8146/`

[4] G. Iadarola *et al.*, "Xsuite: an integrated beam physics simulation framework", *JACoW HB*, vol. 2023, p. TUA2I1, 2024. `doi:10.18429/JACoW-HB2023-TUA2I1`

[5] A. Rossi *et al.*, "Progress with Long-Range Beam-Beam Compensation Studies for High Luminosity LHC", in *8th International Particle Accelerator Conference*, 2017. `doi:10.18429/JACoW-IPAC2017-TUPVA115`

[6] G. Sterbini, "Status of the Beam-Beam Long-Range Wire Compensation Studies", 2024. `https://indico.global/event/9305/contributions/90650/attachments/41517/77771/ICFA_EPFL_2024-4.pdf`

[7] O. S. Brüning, S. D. Fartoukh, M. Giovannozzi, and T. Risselada, "Dynamic Aperture Studies for the LHC Separation Dipoles", CERN, Tech. Rep., 2004. `https://cds.cern.ch/record/742967`

[8] L. Medina Medrano, J. Barranco García, X. Buffat, T. Pieloni, and R. Tomás, "Assessment of Linear and Non-Linear Optics Errors due to Beam-Beam with Multipoles for the High Luminosity LHC", *JACoW IPAC*, p. THPAK135, 2018. `doi:10.18429/JACoW-IPAC2018-THPAK135`

[9] J. Dilly *et al.*, "Status of the CERN optics measurement and correction analysis tools".

[10] L. Deniau, *MAD-NG Reference Manual*, 2023. `https://madx.web.cern.ch/madx/releases/madng/html/index.html`

[11] S. White, E. Maclean, and R. Tomás, "Direct amplitude detuning measurement with ac dipole", *Phys. Rev. Accel. Beams*, vol. 16, no. 7, p. 071 002, 2013. `doi:10.1103/PhysRevSTAB.16.071002`

[12] A. Poyet, S. D. Fartoukh, N. Karastathis, Y. Papaphilippou, K. Skoufaris, and G. Sterbini, "Numerical Simulations of the DC Wire Prototypes in LHC for Enhancing the HL-LHC Performances", in *Proc. IPAC'19*, Melbourne, Australia, May 2019, pp. 566–569. `doi:10.18429/JACoW-IPAC2019-MOPMP052`