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OPTICS MEASUREMENTS AND CORRECTION PLANS FOR THE HL-LHC

T. Persson, X. Buffat, F. Carlier, J. Coello, R. De Maria, J. Dilly, E. Fol, D. Gamba, H. García Morales, A. García-Tabares, M. Giovannozzi, M. Hofer, E. Jaccheri Høydalsvik, J. Keintzel, M. Le Garrec, E. H. Maclean, L. Malina, P. Skowronski, F. Soubelet, R. Tomás, F. Van der Veken, L. Van Riesen-Haupt, A. Wegscheider, D. W. Wolf, CERN, Geneva, Switzerland

Abstract

The High Luminosity LHC (HL-LHC) will require stringent optics correction to operate safely and deliver the design luminosity to the experiments. In order to achieve this, several new methods for optics correction have been developed. In this article, we outline some of these methods and we describe the envisioned strategy of how to use them in order to reach the challenging requirements of the HL-LHC physics program.

INTRODUCTION

The replacement of the triplet magnets in the ATLAS and CMS Interaction Regions (IRs) will enable to reach a β^* of 15 cm for round optics and 7.5 cm for flat optics [1]. The machine layout and β-functions around the interaction point (IP) 1 are shown in Fig. 1. The large β-functions in the triplet magnets will require that both linear and nonlinear errors are well corrected, to be able to safely operate the machine and to deliver the design luminosity to both ATLAS and CMS.

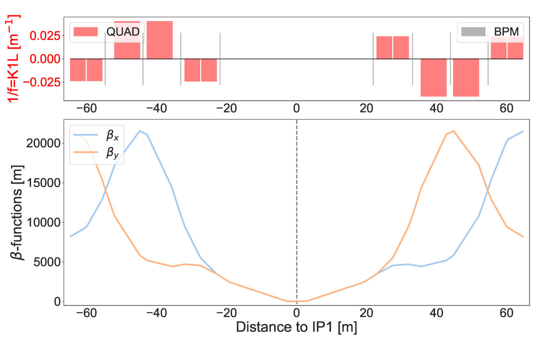

Figure 1: The layout and the β-functions close to IP1 for round optics, with a β^* of 15 cm.

In order to understand the background of the development of the methods described in this article, some of the key requirements are listed below:

- In order to guarantee safe machine conditions, the peak β-beating should be below 20% at all locations.
- The β^*-beating (the relative deviation of the β-function at the IP) should be below 2.5% for ATLAS and CMS.
- The $\Delta Q_{min} = |C^-|$, the closest the transverse tunes can approach each other, should be kept below 10^{-3} [2].
- The residual local linear coupling at the IP should result in a luminosity reduction of not more than 1%.
- The octupolar errors in the triplet should be locally corrected to keep the generated amplitude detuning within design tolerances for Landau damping [2].
- The corrections of the nonlinear multipolar components should be within 30% of the ideal ones in order not to significantly impact the dynamic aperture [3].

MEASURING AND CORRECTING β^*

During the LHC Run 1, the local optics corrections close to the IRs were only based on the phase advance measurements [4]. In Run 2, the correction method was extended to include the information from K-modulation of the Q1 magnets left and right of the IPs [5]. This significantly improved the IR-corrections and resulted in an improved control of the β^*. In the HL-LHC, the K-modulation will remain a key method to determine the β^* and to constrain the local optics corrections [6, 7]. However, it is predicted that at β^*=15 cm the uncertainty of the β^* will be around 4%, which is higher than the target [8] and is mainly due to the tune jitter. It is therefore desirable to have alternative methods to measure the β^*. One such method consists in directly obtaining the β functions at the BPM locations in the IR. The standard method used in the LHC is to reconstruct the β-functions from the phase advance, obtained from turn-by-turn data, but due to the unfavorable phase advance and magnetic errors in the IRs, it is not precise enough. It is also possible to reconstruct the β-functions directly from the amplitude of the oscillations. The main uncertainty in this method comes from the calibration factors of the BPMs. In order to overcome this, a special calibration optics has been designed, where the quadrupoles Q1-Q4 are switched off [9], making the region in between them a plain drift space, thus allowing a calibration factor to be calculated from the ratio of the β-function obtained from the amplitude and from the phase measurements [10]. Assuming less than 1.6% BPM calibration error, and using the described beam-based calibration method, the β-function at the waist can be measured to below 2.3% [11]. In order to optimize the location of the waist, dedicated knobs that move the longitudinal position of the waist can be applied while optimizing the luminosity [12].

Another possible approach is to find the local errors and estimate the β^* by using supervised machine learning (ML) techniques [13, 14]. The method is to first simulate with MAD-X thousands of seeds with different distributions of gradient errors and to use these simulations for supervised training. To find the local errors, the ML model is trained

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using phase advance, normalized dispersion, and β-function at the closest BPMs to the IP as input features and corresponding errors as output. An example of such a simulation is shown in Fig. 2, where the difference between the predicted error and the true error is plotted versus the true error for the Q2 magnets in IR5. The mean absolute value for the true errors is 7.0×10^{-4} and the mean absolute value for the true minus predicted error is 2.9×10^{-4}.

The estimation of β^* is achieved by training the ML model using phase advances at every BPM as input data and the β^* at the IPs as output targets.

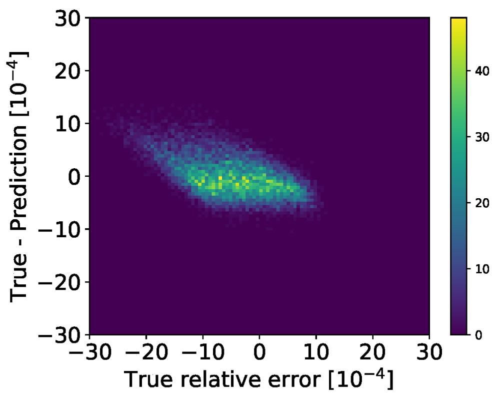

Figure 2: Heat map of the true minus predicted errors versus the true errors for the IR5 Q2 magnets. The prediction is from the ML model.

GLOBAL β-BEAT CORRECTIONS

The correction of the global β-beating in the LHC has been based on phase advance measurement between BPMs, β^* from K-modulation, and the normalized dispersion. Using MAD-X, a response matrix has been created which was used as the basis for calculating an optics correction. This method has been demonstrated to work very well, but as the β-function increases in the arc with the higher telescopic index, the impact of magnetic errors becomes larger. These errors are in general not possible to correct locally with quadrupoles, due to the lack of individually-powered magnets in the arcs. An alternative approach to correct these effects is to introduce an orbit bump through the main sextupoles [15, 16] to generate quadrupolar feed-down effects. An example of such an orbit bump through a sextupole is shown in Fig. 3. A new observable that only depends on the quadrupolar errors in a given segment might help us to localize the errors [17].

Traditionally, the beam has been excited using the AC-dipole in the transverse planes [18]. A newly developed method allows to excite in the longitudinal plane simultaneously with the transverse plane [19, 20]. From these 3D excitations, we can then obtain both the normalized dispersion and β-functions without dedicated off-momentum measurements. This would help reducing the commissioning time and, more importantly, it would enable to measure normalized dispersion during the energy ramp, something that previously would have required several dedicated ramps. A comparison of the normalized dispersion measured with the traditional method based on dedicated off-momentum measurements and the new one based on 3D excitations can be seen in Fig. 4, where a good agreement is clearly visible.

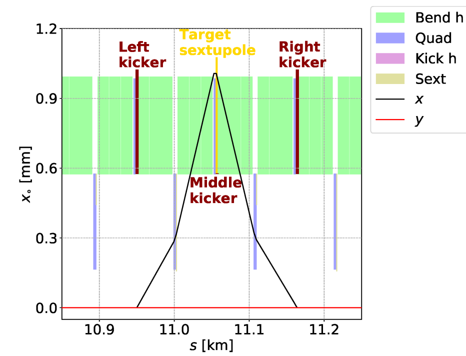

Figure 3: The layout of a region with a sextupole where the feed-down can be used to correct the β-beating.

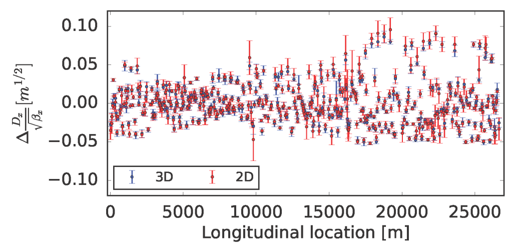

Figure 4: Comparison of normalized dispersion with 3D excitation (in blue) to the traditional method (in red) where the momentum is changed in steps before the excitation [19].

LOCAL COUPLING CORRECTIONS

The linear coupling originating from the IRs has been seen to deteriorate both the global coupling and the luminosity if left uncorrected. A fitting method based on the amplitude and phase of the coupling Resonance Driving Terms (RDTs) has been developed [15], which allows for a good correction of the coupling leaking outside of the IRs. There is, however, a strong degeneracy on how to distribute the coupling correction between the left and right sides of the IR. In order to correct this closed-coupling bump, a new method that introduces an imbalance in the left and right triplet strengths is being investigated [21]. After introducing this imbalance, a local coupling bump is no longer closed, and any local coupling error will leak out of the IR, making it detectable through the easier measurable global $|C^-|$, as shown in Fig. 5. A final validation of the correction might be done by adjusting the strength of the closed-coupling bump while maximizing the luminosity.

GLOBAL COUPLING CORRECTIONS

The dynamic aperture has been found to be best when the horizontal and vertical tunes are close to the diagonal [22].

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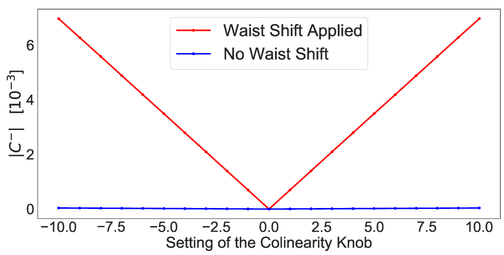

Figure 5: The impact of the colinearity knob on the global $|C^-|$ with and without applying a rigid waist shift. One unit in the colinearity knob changes the strengths of the right and left skew quadrupoles in the IR by $\pm 10^{-4}\mathrm{m}^{-2}$, respectively.

When the tunes are separated by 5×10^{-3} the $|C^-|$ needs be corrected to below 10^{-3} in order not to alter the Landau damping, which is crucial for preventing beam instabilities [23]. In order to keep the coupling below this target we will need to apply corrections both during commissioning and throughout the normal run, since the coupling has been observed to vary by $2 - 3 \times 10^{-3}$ when measured a few months apart [24].

In Run 2 the transverse damper was modified to be able to excite the beam in a similar way as the AC-dipole [25, 26] to be able to measure coupling. Using this in operation, it was observed that bunches with different Beam-Beam Long Range (BBLR) interactions experienced different transverse coupling. The observed difference is consistent with a roll of the crossing angle plane by 5-10 deg [27]. It is currently proposed to have a fill every 2 weeks where a few bunches are not experiencing any BBLR interactions [28] and these bunches can then be used to monitor and, when needed, correct the transverse coupling.

NONLINEAR CORRECTIONS

In the end of Run 2, multipoles up to normal and skew octupoles errors were compensated for using beam-based correction methods [29, 30]. It has been observed that the feed-down from sextupole errors to quadrupoles has a significant impact on the β-beating, and the correction of the octupolar error significantly improved the quality of the tune measurement, also improving the quality of other measurements. The most often used method to obtain the beam-based corrections for the IR-correctors has been to change the crossing angle and measure the feed-down to tune and transverse linear coupling. The skew octupolar errors have also been corrected using driven RDTs. In HL-LHC, the correction of the decapole and dodecapoles will also be of significant importance, as, e.g. an uncorrected b_6 (dodecapole) has been shown to deteriorate the dynamic aperture by 25%. This would be an unacceptable reduction and it is therefore essential to have beam-based methods to measure these nonlinearities. The dodecapoles generate a quadratic tune variation with action, and through feed-down they generate an octupole component that is quadratically proportional to the horizontal or vertical orbit. However, the decapole component does not, to first order, cause any detuning, but normal decapole feed-down linearly to normal octupoles in case of a horizontal offset and the skew decapole component feed-down to normal octupole with a vertical offset. It was demonstrated during an MD where the dodecapole correctors were increased in order to replicate the HL-LHC conditions that the second order tune dependence on the excitation amplitude was measurable. This is however a global approach and hence it is not possible to separate the contributions from the different IRs. In order to do so, an alternative approach is being developed, based on measuring the amplitude detuning as a function of the crossing angle and then fit the first- and second-order detuning. An example of such a simulated scan is shown in Fig. 6. The simulated measurement points include uncertainties of the crossing angle of σ_{xing} =10 µrad and an uncertainty of the amplitude detuning measurement based on previous measurements in the LHC [31]. Additional methods under investigation to measure the nonlinearites are based on driven RDTs [30], direct dynamic aperture measurement [32], and short-term dynamic aperture measurement using the AC-dipole [33].

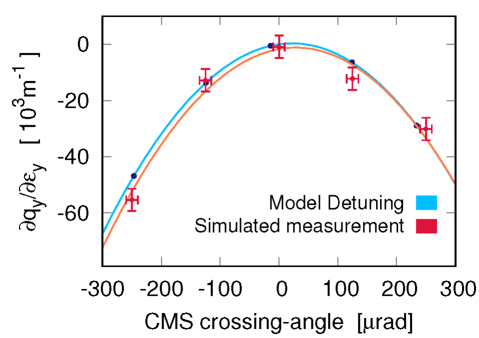

Figure 6: An example of a simulated scan compared to the detuning obtained from the model. Each red point corresponds to a simulated measurement of the amplitude detuning [31].

CONCLUSION

The HL-LHC sets increasingly stringent requirements on the linear and nonlinear optics corrections. In order to meet them, a number of new and refined methods have been developed. They will be tested, to a large extent, in the LHC during the Run 3, where the experience gained will be crucial in order to reach the objectives.

REFERENCES

[1] I. Béjar Alonso and L. Rossi, "HiLumi LHC Technical Design Report: Deliverable: D1.10", CERN, Geneva, Switzerland, Rep. CERN-ACC-2015-0140, Nov. 2015.

[2] X. Buffat *et al.*, "Update on the operational scenario taking into account of the constraints on coupling and non-linear optics corrections", presented at the 159th HiLumi WP2 Meeting, CERN, Geneva, Switzerland, Sep. 2019, unpublished.

[3] R. De Maria *et al.*, "HL-LHC IR non-linear correction and options", presented at the 77th HiLumi WP2 Meeting, CERN, Geneva, Switzerland, Sep. 2016, unpublished.

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-WEPAB026

[4] R. Tomás *et al.*, "Record low β beating in the LHC", *Phys. Rev. ST Accel. Beams*, vol. 15, p. 091001, Sep. 2012. doi:10.1103/PhysRevSTAB.15.091001

[5] T. Persson *et al.*, "LHC optics commissioning: A journey towards 1% optics control", *Phys. Rev. Accel. Beams*, vol. 20, p. 061002, 2017. doi:10.1103/PhysRevAccelBeams.20.061002

[6] F. Carlier and R. Tomás, "Accuracy and feasibility of the β^* measurement for HL-LHC using K-modulation", *Phys. Rev. Accel. Beams*, vol. 20, p. 011005, 2017. doi:10.1103/PhysRevAccelBeams.20.011005

[7] M. Hofer *et al.* , "K-Modulation for future High energy colliders", in *Proc. 10th Int. Particle Accelerator Conf. (IPAC'19)*, Melbourne, Australia, May 2019, pp. 476–479. doi:10.18429/JACoW-IPAC2019-MOPMP022

[8] X. Buffat *et al.*, "Optics measurement and correction strategies for HL-LHC", unpublished.

[9] J. Coello *et al.*, "MD Test of a Ballistic Optics", CERN, Geneva, Switzerland, Rep. CERN-ACC-NOTE-2016-0008, Jan. 2016.

[10] A. García-Tabarés Valdivieso and R. Tomás, "Optics-measurement-based beam position monitor calibrations in the LHC insertion regions", *Phys. Rev. Accel. Beams*, vol. 23, p. 042801, 2020. doi:10.1103/PhysRevAccelBeams.23.042801

[11] L. Malina *et al.*, "LHC experience and HL-LHC requirements for BPMs", presented at the 157th HiLumi WP2 Meeting, CERN, Geneva, Switzerland, Sep. 2019, unpublished.

[12] J. Coello *et al.*, "MD3287: Luminosity scans with waist shifts", CERN, Geneva, Switzerland, Rep. CERN-ACC-NOTE-2020-0048, Jul. 2020.
et al.

[13] E. Fol *et al.*, "Supervised learning-based reconstruction of magnet errors in circular accelerators", *Eur. Phys. J. Plus*, vol. 136, p. 365, 2021. doi:10.1140/epjp/s13360-021-01348-5

[14] H. Garcia Morales and J. Cardona R. Tomas, "HL-LHC Local Linear Correction at the Interaction Regions", presented at the 12th Int. Particle Accelerator Conf., Campinas, SP, Brazil, May 2021, paper MOPAB185, this conference.

[15] J. Coello *et al.*, "New local optics measurements and correction techniques for the LHC and its luminosity upgrade", *Phys. Rev. Accel. Beams*, vol. 23, p. 041001, 2020. doi:10.1103/PhysRevAccelBeams.23.041001

[16] D. Wolf, "Local beating corrections with orbit bumps in the LHC", Master thesis, University of Heidelberg, Heidelberg, Germany, 2021.

[17] A. Wegscheider and R. Tomás, "Applications of the local observable in future optics measurements", presented at the 12th Int. Particle Accelerator Conf., Campinas, SP, Brazil, May 2021, paper WEPAB399, this conference.

[18] R. Tomás *et al.*, "Reliable Operation of the AC Dipole in the LHC", CERN, Geneva, Switzerland, Rep. CERN-LHC-PROJECT-Report-1095, Aug. 2008.

[19] L. Malina and J. Coello de Portugal,"Optics measurements in storage rings based on simultaneous 3-dimensional beam excitation", in *Proc. IPAC'18*, Vancouver, BC, Canada, May 2018, paper THPAF046, pp. 3068-3071.

[20] L. Malina *et al.*, "Driven 3D beam oscillations for optics measurements in synchrotrons",presented at the 12th Int. Particle Accelerator Conf., Campinas, SP, Brazil, May 2021, paper THXA07, this conference.

[21] F. Soubelet *et al.*, "Prospect for Interaction Region Local Coupling Correction in the LHC Run 3", presented at the 12th Int. Particle Accelerator Conf., Campinas, SP, Brazil, May 2021, paper MOPAB007 this conference.

[22] N. Karastathis *et al.*, "Refining the HL-LHC Operational Settings with Inputs From Dynamic Aperture Simulations: A Progress Report", in *proc IPAC 2018*, Vancouver, BC, Canada, pp. 188-191. doi:10.18429/JACoW-IPAC2018-MOPMF041.

[23] L. R. Carver *et al.*, "Transverse beam instabilities in the presence of linear coupling in the Large Hadron Collider", *Phys. Rev. Beams*, vol. 17, p. 044401, 2018. doi:10.1103/PhysRevAccelBeams.21.044401

[24] T. Persson, "Transverse Coupling", presented at the OMC-OP Workshop, CERN, Geneva, Switzerland, Oct. 2019, unpublished.

[25] A. Calia, *et al.*, "Online coupling measurement and correction throughout the LHC Cycle", in *Proc. ICALEPCS'17*, Barcelona, Spain, October 2017, paper TUPHA119, pp. 686-691.

[26] T. Persson and R. Tomás, "Improved control of the betatron coupling in the Large Hadron Collider", *Phys. Rev. ST Accel. Beams*, vol. 17, p. 051004, 2014. doi:10.1103/PhysRevSTAB.17.051004

[27] J. Wenninger *et al.*, "LHC MD2877: Beam-beam long range impact on coupling measurements", CERN, Geneva, Switzerland, Rep. CERN-ACC-NOTE-2018-0026, Mar. 2018.

[28] G. Iadarola, "HL-LHC filling schemes", presented at the 172nd HiLumi WP2 Meeting, CERN, Geneva, Switzerland, Apr. 2020, unpublished.

[29] E. H. Maclean *et al.*, "A new approach to the LHC optics commissioning for the nonlinear era", *Phys. Rev. Accel. Beams* vol. 22, p. 061004, 2019. doi:10.1103/PhysRevAccelBeams.22.061004

[30] F. S. Carlier *et al.*, "Measurement and Correction of Resonance Driving Terms in the Large Hadron Collider", *Phys. Rev. Accel. Beams*, to be published.

[31] J. W. Dilly *et al.*, "Report and Analysis from LHC MD 3311: Amplitude detuning at end-of-squeeze", CERN, Geneva, Switzerland, Rep. CERN-ACC-NOTE-2019-0042, Mar. 2019.

[32] E. H. Maclean *et al.*, "Innovative method to measure the extent of the stable phase-space region of proton synchrotrons", *Phys. Rev. Accel. Beams*, vol. 22, p. 034002, 2019. doi:10.1103/PhysRevAccelBeams.22.034002

[33] F. S. Carlier *et al.*, "First Demonstration of Dynamic Aperture Measurements with an AC-dipole", *Phys. Rev. Accel. Beams* vol. 22, p. 031002, 2019. doi:10.1103/PhysRevAccelBeams.22.031002