ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB007

PROSPECT FOR INTERACTION REGION LOCAL COUPLING CORRECTION IN THE LHC RUN 3 *

F. Soubelet†‡, CERN, Meyrin, Switzerland; University of Liverpool, Liverpool, UK
T. H. B. Persson, R. Tomás, CERN, Meyrin, Switzerland
O. Apsimon, C. P. Welsch, University of Liverpool, Liverpool, UK

Abstract

Successful operation of large scale particle accelerators depends on the precise correction of unavoidable magnet field or alignment errors present in the machine. During the LHC Run 2, local linear coupling in the Interaction Regions (IR) has been proven to have a severe impact on beam size and reduce the luminosity by up to a 50% , making its proper handling a necessity for Run 3 and High Luminosity LHC (HL-LHC). However, current measurement methods are not optimised for local IR coupling. In this contribution, an approach to accurately minimise IR local coupling based on correlated external variables such as the $|C^-|$ is proposed. The validity of the method is demonstrated through simulations and benchmarked against theoretical values, such as Resonance Driving Terms (RDTs) and Ripken parameters.

INTRODUCTION

The Large Hadron Collider (LHC) is currently in the last year of the Long Shutdown 2 (LS2), and Run 3 commissioning is scheduled for 2022 [1]. During the Run 2 ion run, local linear coupling errors in the IR have been identified to deteriorate the luminosity delivered to the ALICE experiment, due to an increase in beam size [2–4].

The approach to coupling correction used in previous LHC runs has been to measure the RDTs in the vicinity of the Interaction Point (IP) and use the dedicated skew quadrupole correctors left and right of the IP to correct the local linear coupling. The IR around Point 1 is shown in Fig. 1, with the position of the dedicated correctors highlighted in green. Due to the phase advances in the IRs, a local coupling bump has little to no effect outside the region. Furthermore, the phase advances between Beam Position Monitors (BPMs) in the IRs also make it difficult to get a good measurement of the coupling RDTs, which has made finding the balance of left and right corrector settings challenging.

In preparation of Run 3 and to minimize the luminosity imbalance between the two main LHC experiments [5], a new method for local coupling correction is being developed which relies on breaking the symmetry of the IR setup. The underlying concepts and first simulation results are presented in this paper.

* This research is supported by the LIV.DAT Center for Doctoral Training, STFC and the European Organization for Nuclear Research.
† felix.soubelet@cern.ch
‡ orcid id: 0000-0001-8012-1440

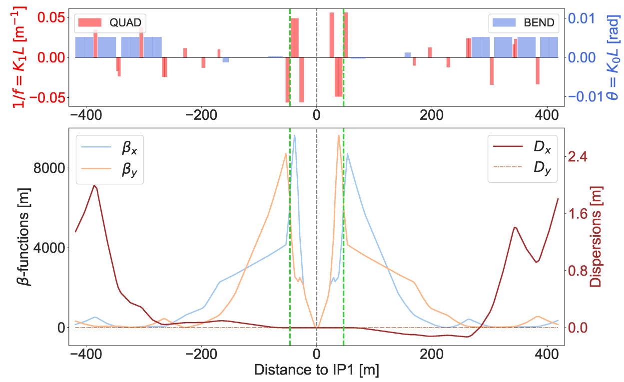

Figure 1: LHC IR1 for a round optics configuration at 7 TeV and $\beta^* = 25$ cm. The upper plot shows the machine layout with dipoles in blue and quadrupoles in red. The lower plot shows β and dispersion functions for both transverse planes. The vertical green lines highlight the location of the skew quadrupole correctors used for corrections.

LOCAL IR LINEAR COUPLING

During the 2018 ion run, the strengths of the skew quadrupole correctors located left and right of IR2 were swapped by mistake, causing a local coupling bump across the IR. This caused a luminosity loss of about 50%, which was observed by scanning a knob already generated for studies with flat optics [6]. More importantly, the incident revealed that even after fixing the swap, the existing correction would still not correct the beam size to the nominal [3].

Figure 2 shows the relative beam size increase versus the strength of such a coupling bump for IP2 at $\beta^* = 50$ cm in the LHC, and for IP1 or IP5 at $\beta^* = 15$ cm in the HL-LHC. In the case of the HL-LHC, the beam size increase and consequent luminosity loss are even greater due to the larger β-functions in the triplet. Therefore, local coupling control will need to be about a factor four more accurate than in the LHC. The definition of the colinearity knob is described in Table 1.

Table 1: Definition of One Unit of the Colinearity Knob, a Powering Setting of the IR Skew Quadrupole Correctors

Magnet	K_{1S} [m^{-2}]
MQXS.3R[IP] → K_{1S}	$+10^{-4}$
MQXS.3L[IP] → K_{1S}	-10^{-4}

Additionally, it is shown analytically that K-modulation measurements are weakly affected by the presence of local coupling [7], preventing the possibility of directly measuring the β^* variation at an IP from local coupling. This behavior

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB007

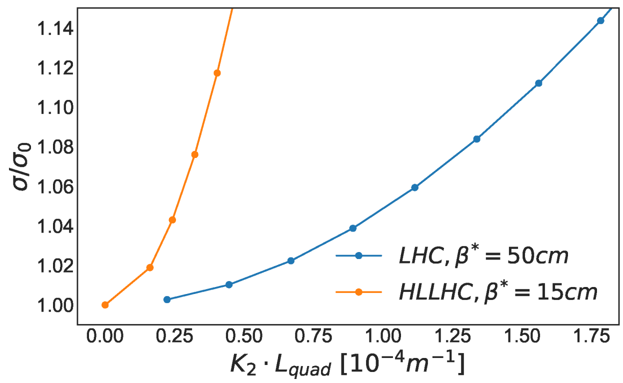

Figure 2: Relative increase in beam size at the IP from different settings of the colinearity knob for LHC and HL-LHC, creating a closed local coupling bump.

has been demonstrated in a dedicated Machine Development (MD) experiment in the LHC in 2018 [8].

In operation, a luminosity scan could be performed to find the optimal settings of the skew quadrupole correctors. However, this requires nominal bunches as well as a collimation setup, which only could be done in a later stage of the commissioning. It is therefore desirable to come up with a new method to find the optimal local linear coupling correction during the initial optics commissioning stage with low bunch intensity.

RELATING LOCAL COUPLING TO EXTERNAL MEASURABLE QUANTITIES

In order to circumvent the issues related to measuring the local coupling, it is necessary to find a way to relate its evolution to other measurable quantities. The idea is to apply a rigid waist shift to the beam - meaning all four betatron waists moving simultaneously - in order to break the symmetry of the optics in the IR. This is done by unbalancing the strength of the triplet quadrupoles on either side of the IP. Making away with the symmetry allows to break the locality of the coupling bump, making the impact of the IR coupling errors measurable everywhere.

Figure 3 shows the linear coupling RDTs from a closed coupling bump created through the colinearity knob (see the green lines) in the presence and absence of a rigid waist shift. When applying the waist shift and breaking the optics symmetry in the IR, one can observe a leakage of the RDTs outside of the limits of the coupling bump. These RDTs will then have a residual presence in the machine, and can be reconstructed from turn-by-turn data from BPMs with more suitable phase advances.

As a consequence, under a rigid waist shift a local coupling bump will have a direct impact on the global coupling, measured as the $|C^-|$ [9, 10]. This is showcased in Fig. 4, where changes in the setting of the colinearity knob now have a strong effect on the $|C^-|$. The behavior seen in Fig. 4 has been verified in the machine during an MD [8].

However, the rigid waist shift has an effect on the β-beating across the machine and will change the impact of

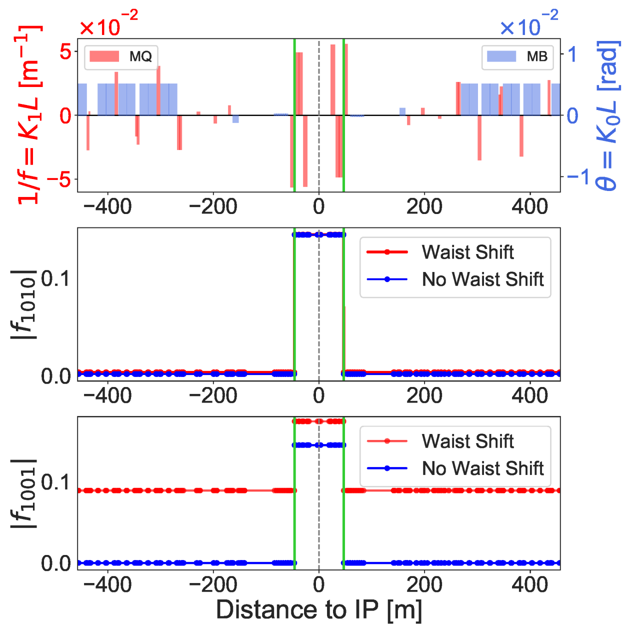

Figure 3: Linear coupling RDTs in the vicinity of IP1 under a coupling bump, with and without a rigid waist shift. The vertical green lines represent the positions of the skew quadrupoles (MQSX.3[RL]1) used to implement the coupling bump. A colinearity knob setting of 10 and a rigidity waist shift knob setting of 1 were used, which results in a 0.5% change in the triplet powering knob.

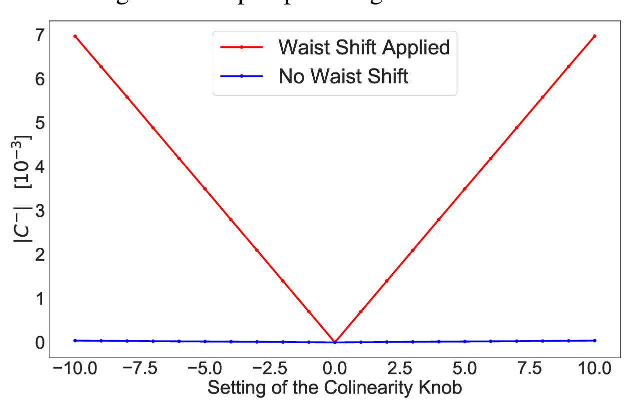

Figure 4: Impact of the colinearity knob on the global $|C^-|$ with and without applying a rigid waist shift.

errors, namely the skew quadrupolar impact on the $|C^-|$. For instance, simulations show that applying a rigid waist shift knob setting of 1 causes a 15% deviation from the achieved $|C^-|$ to the target value set through the coupling knob.

In order to limit this impact of the rigid waist shift on the optics, a new knob has been developed that also makes use of the individually powered quadrupoles Q4 to Q10 (included) to tune the optics functions. As shown in Fig. 5, the new knob has less impact on the optics.

LOCAL COUPLING MINIMIZATION

Simulations have been done with the MAD-X [11] code to investigate the feasibility of minimizing local coupling using the aforementioned method. For the conducted studies, the

ISBN: 978-3-95450-214-1   ISSN: 2673-5490   doi:10.18429/JACoW-IPAC2021-MOPAB007

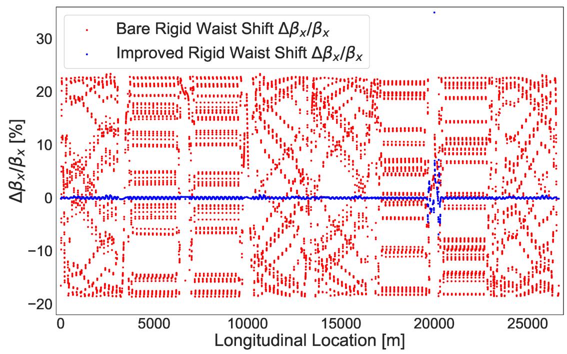

Figure 5: Resulting horizontal β-beating across the machine for the simple and improved implementations of the rigid waist shift.

LHC lattice was used and the IR around LHC Point 1 was considered. A local coupling bump was created in the IR by introducing a tilt error in the last triplet quadrupoles Q3 - thus giving a skew quadrupolar component - and compensation was done by acting on the setting of the colinearity knob. Figure 6 shows the resulting beam size increase as a ratio to the nominal beam size across the parameter space, highlighting that minimization of the growth is possible but a wrong setting would enhance the said growth.

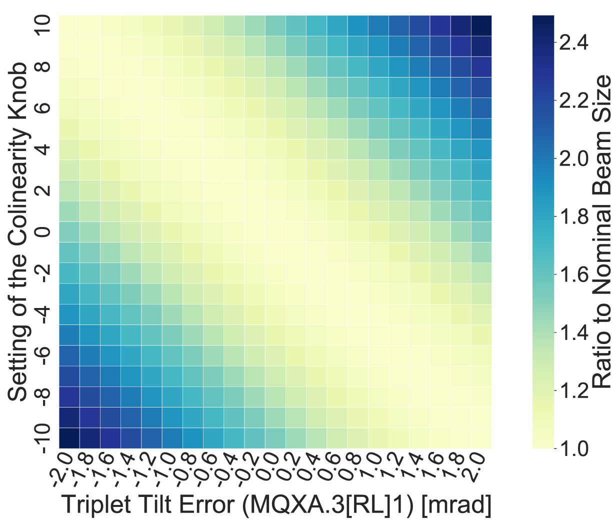

Figure 6: Resulting beam size increase for various combinations of tilt error and colinearity knob settings.

In this study, the beam size was calculated through the formalism of Ripken parameters [12, 13], according to the following formula developed by Lebedev and Bogacz [14]:

$$\langle z \rangle = \sqrt{\epsilon_1 \beta_{1z} + \epsilon_2 \beta_{2z}} \ , \qquad (1)$$

where z can be one of x, y, ϵ_1 and ϵ_2 are respectively the horizontal and vertical emittances. The Ripken parameters are output directly from MAD-X. The evolution of both the $|C^-|$ and the beam size at IP for a given value of the quadrupole tilt error can be seen in Fig. 7.

It can be observed that settings minimizing the measured $|C^-|$ under a rigid waist shift will then minimize the local coupling and beam size when removing that rigid waist shift.

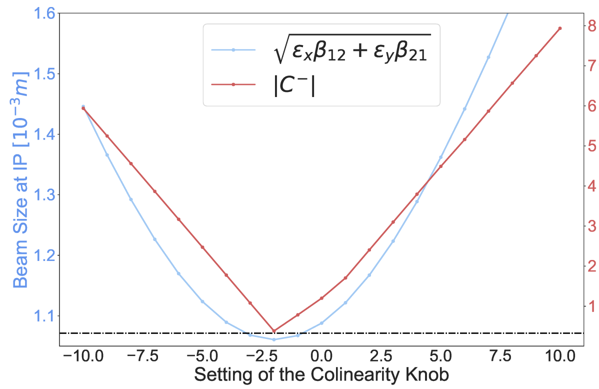

Figure 7: Resulting $|C^-|$ and IP1 beam size, according to Eq. (1), for various powering of the skew quadrupole correctors, after introducing a 0.4 mrad tilt error on the Q3s left and right of IP1. The black dotted line represents the threshold of a 1% beam size increase from the nominal scenario.

Across the parameter space of the study, one computes a 0.96 Pearson correlation coefficient between those two quantities.

CONCLUSIONS AND OUTLOOK

A good correction of the local linear coupling is essential to ensure the correct beam size at IPs and deliver the planned luminosity to the experiments. After Run 2 has uncovered challenges, Run 3 should be used to develop a new technique for local coupling correction.

The currently envisioned technique and early simulation results have been presented in this paper. With this method, the foreseen procedure for local linear coupling correction would be made of three steps. Firstly, calculating and applying a correction of any coupling leaking outside the IR based on RDTs from turn-by-turn measurements. Secondly, breaking the optics symmetry between the right and left-hand side of the IP and minimizing the global coupling. Finally, and if a collimation setup is possible, performing a scan of the colinearity knob settings while observing the luminosity in order to validate the correction.

It is worth noting that due to the proximity of the correctors to the skew quadrupolar source in the above results, the scenario is close to ideal. Further studies will look into the minimization of coupling coming from other sources in the IR, which may not be as easily minimized.

ACKNOWLEDGEMENTS

This work was supported by the STFC Liverpool Centre for Doctoral Training on Data Intensive Science (LIV.DAT) under grant agreement ST/P006752/1. The authors would like to thank the OMC team members for their continued valuable feedback and fruitful discussions. The authors would also like to give credit to the following Python packages used in these studies: cpymad [15], matplotlib [16], numpy [17], pandas [18], seaborn [19], pyhdtoolkit [20], omc3 [21], optics_functions [22] and PyLHC [23].

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB007

REFERENCES

[1] LHC Long Term Schedule, `https://lhc-commissioning.web.cern.ch/schedule/LHC-long-term.htm`

[2] J. Jowett *et al.*, "The 2018 Heavy-Ion Run of the LHC", in *Proc. 10th Int. Particle Accelerator Conf. (IPAC'19)*, Melbourne, Australia, May 2019, pp. 2258-2261. `doi:10.18429/JACOW-IPAC2019-WEYYPLM2`

[3] T. Persson *et al.*, "LHC Optics Corrections in Run 2", in *Proc. 9th LHC Operations Evian Workshop*, Evian Les Bains, France, Jan.-Feb. 2019, pp. 59-66.

[4] R. Tomás *et al.*, "LHC Run 2 Optics Commissioning Experience in View of HL-LHC", in *Proc. 10th Int. Particle Accelerator Conf. (IPAC'19)*, Melbourne, Australia, May 2019, pp. 508-511. `doi:10.18429/JACoW-IPAC2019-MOPMP033`

[5] E. Meschi, "ATLAS and CMS Luminosity", presented at 129th LHC Machine Committee Meeting, CERN, Geneva, Switzerland, Apr. 2012, unpublished.

[6] S. Fartoukh *et al.*, "LHC Beam experiments with telescopic flat optics in 2018", submitted for publication.

[7] M. Hofer and R. Tomás, "Effect of Local Linear Coupling on Linear and Nonlinear Observables in Circular Accelerators", *Physical Review Accelerators and Beams*, vol. 23, p. 094001, 2020. `doi:10.1103/PhysRevAccelBeams.23.094001`

[8] T. H. B. Persson, F. S. Carlier, M. Hofer, E. H. Maclean, R. T. Garcia, and A. G.-T. Valdivieso, "MD4944: Local linear coupling measurement at the ips", CERN, Geneva, Switzerland, Rep. CERN-ACC-NOTE-2020-0013, Jan. 2020.

[9] T. Persson and R. Tomás, "Improved Control of the Beta-tron Coupling in the Large Hadron Collider", *Physical Review Accelerators and Beams*, vol. 17, p. 051004, 2014. `doi:10.1103/PhysRevSTAB.17.051004`

[10] F. Carlier and R. Tomás, "Accuracy and feasibility of the * measurement for LHC and High Luminosity LHC using k modulation", *Physical Review Accelerators and Beams*, vol. 20, p. 011005, 2017. `doi:10.1103/PhysRevAccelBeams.20.011005`

[11] *The MAD-X Program (Methodical Accelerator Design), Version 5.06.01 - User's Reference Manual*, CERN, Geneva, Switzerland, Sep. 2020, `http://mad.web.cern.ch/mad/releases/5.06.01/madxuguide.pdf`

[12] I. Borchardt, E. Karantzoulis, H. Mais, and G. Ripken, "Calculation of beam envelopes in storage rings and transport systems in the presence of transverse space charge effects and coupling", *Zeitschrift für Physik C Particles and Fields*, vol. 39, pp. 339–349, 1988. `doi:10.1007/BF01548283`

[13] F. Willeke and G. Ripken, "Methods of beam optics", *AIP Conference Proceedings*, vol. 184, p. 758, 1989. `doi:10.1063/1.38050`

[14] V. A. Lebedev and S. A. Bogacz, "Betatron Motion with Coupling of Horizontal and Vertical Degrees of Freedom", *Journal of Instrumentation*, vol. 5, p. P10010, 2010. `doi:10.1088/1748-0221/5/10/p10010`

[15] T. Gläßle, R. D. Maria, Y. Levinsen, and K. Fuchsberger, Cpymad 2021, `https://zenodo.org/record/4724857#.YOykpbuSkdU`

[16] J. D. Hunter, "Matplotlib: A 2D graphics environment", *Computing in Science and Engineering*, vol. 9, pp. 90–95, 2007. `doi:10.1109/MCSE.2007.55`

[17] C. R. Harris *et al.*, "Array programming with NumPy", *Nature*, vol. 585, pp. 357–362, 2020. `doi:10.1038/s41586-020-2649-2`

[18] Pandas-dev/pandas: "Pandas 1.3.0", 2021, `https://zenodo.org/record/5060318#.YOymMLuSkdU`

[19] M. Waskom *et al.*, "Seaborn: statistical data visualization", 2021, `https://zenodo.org/record/4645478#.YOynIbuSkdU`

[20] PyhDToolkit: Release 0.8.4, `https://zenodo.org/record/4583205#.YOyn0buSkdU`

[21] Omc3: Python 3 codes for beam optics measurements and corrections in circular particle accelerators, `https://github.com/pylhc/omc3`

[22] J. Dilly, R. T. Garcia, and T. Persson, "Optics functions version 0.1.0", 2021, `https://zenodo.org/record/4518969#.YOyo6ruSkdU` `doi:10.5281/zenodo.4518969`

[23] PyLHC: Additional tools for particle accelerator data analysis and machine information, `https://github.com/pylhc/PyLHC`