ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-WEPOPT007

Content from this work may be used under the terms of the CC BY 4.0 licence (© 2022). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI

FIRST INTERACTION REGION LOCAL COUPLING CORRECTIONS IN THE LHC RUN 3*

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

Abstract

The successful operation of large scale particle accelerators depends on the precise correction of unavoidable magnetic field or magnet alignment errors present in the machine. During the LHC Run 2, local linear coupling in the Interaction Regions (IRs) was shown to have a significant impact on the beam size, making its proper handling a necessity for Run 3 and the High Luminosity LHC (HL-LHC). A new approach to accurately minimise the local IR linear coupling based on correlated external variables such as the $|C^-|$ had been proposed, which relies on the application of a rigid waist shift in order to create an asymmetry in the IR optics. In this contribution, preliminary corrections from the 2021 beam test and the early 2022 commissioning are presented, as well as first results of the new method's experimental configuration tests in the LHC Run 3 commissioning.

INTRODUCTION

The approach to local coupling correction in the LHC has been to use the segment-by-segment technique [1] to calculate adequate powering of the MQSX magnets, the skew quadrupole correctors left and right of the Interaction Point (IP). The Interaction Region (IR) for point 1 is shown in Fig. 1, where the position of the dedicated correctors is highlighted in green.

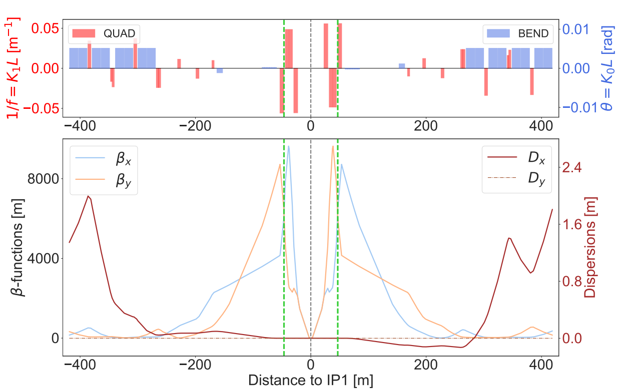

Figure 1: LHC IR1 for a round optics configuration at 7 TeV and $\beta^* = 25$ cm. The upper plot shows the machine layout with dipoles in blue and quadrupoles in red. The lower plot shows β and dispersion functions for both transverse planes. The vertical green lines highlight the location of the skew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

* This research is supported by the LIV.DAT Center for Doctoral Training, STFC and the European Organization for Nuclear Research.
† felix.soubelet@cern.ch

The coupling corrections calculated with the segment-by-segment technique are essential to reach low β^* with good optics control: at $\beta^* = 30$ cm the local errors compensated in Run 2 would contribute to the $|C^-|$ by the amount of 0.33 - too high for the arc correctors to handle. However, due to unfavorable phase advances in between Beam Position Monitors (BPMs) in the IRs, it is difficult to get a good measurement of the coupling Resonance Driving Terms (RDTs) in these regions. In turn, this means the method can hardly give a correction of coupling at the IP location, which is of importance to guarantee beam size and luminosity performance. A new method was developed which relies on breaking the symmetry of the IRs, and would allow to relate the coupling at IP to other external observables [2]. The first preliminary local coupling corrections of Run 3 and first implementation test of the new method in the LHC are presented in this paper.

SEGMENT-BY-SEGMENT CORRECTIONS

The segment-by-segment technique treats a segment of the accelerator as an independent line and propagates measured optics properties through this segment using the MAD-X code [3]. One then tries to find correction settings - powering changes of selected magnets - that would best reproduce the propagated optics. Thereby, inverting these settings and applying the inverted values in the machine corrects the measured errors.

In October 2021, a week of beam tests was done in the LHC at injection energy. From the measurements at 450 GeV a first set of local coupling corrections were calculated for each of the four main IRs using the segment-by-segment technique. Figure 2 shows the segment-by-segment results for the absolute value of the f_{1001} RDT in IR5, from the 12th BPM left to right of IP5. The vertical grey line indicates the location of the IP in the segment. Due to the skew quadrupole correctors in the IRs being single aperture magnets, one needs to find a single powering setting that works for both beams. As most of the error to be corrected derives from the triplets, which are also single aperture, this compromise is usually found. One can see that the determined correction in IR5 matches the propagated measurement within the tolerance of the error bars at the edges of the segment.

During the LHC Run 3 commissioning, local coupling corrections determined during the previous year beam test were trimmed in the machine from the start. After reaching the $\beta^* = 30$ cm optics, where the machine is more sensitive to local errors, a noticeable deviation around IP1 was observed

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-WEPOPT007

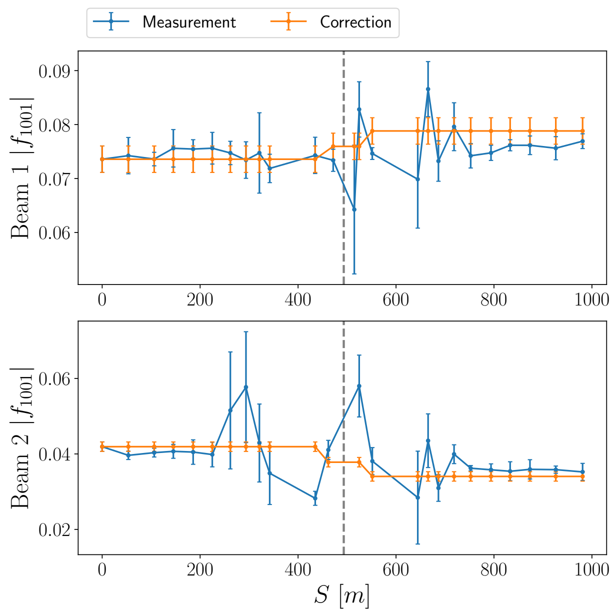

Figure 2: Propagation of the measured $|f_{1001}|$ around IP5 and of the reconstructed values from the determined correction, measured at 450 GeV and $\beta^* = 11$ m.

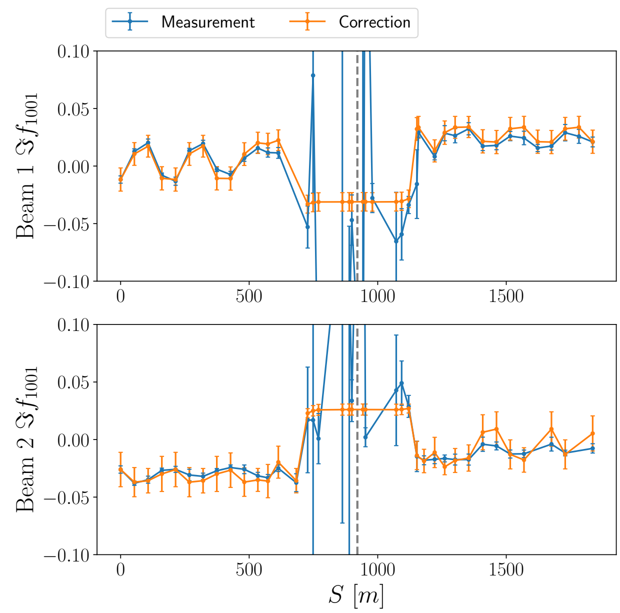

Figure 4: Propagation of the measured $\Im f_{1001}$ around IP1 and the reconstructed values from the determined correction, measured at 6.8 TeV and $\beta^* = 30$ cm.

and a refinement of the correction was calculated. Figures 3 and 4 show the effect of the new correction on the real and imaginary parts of the f_{1001} RDT in the segment.The beating observed from the old correction was re-matched thanks to a new corrector setting where the IR1 right-hand side corrector's powering was changed by 10^{-4}m^{-2}.

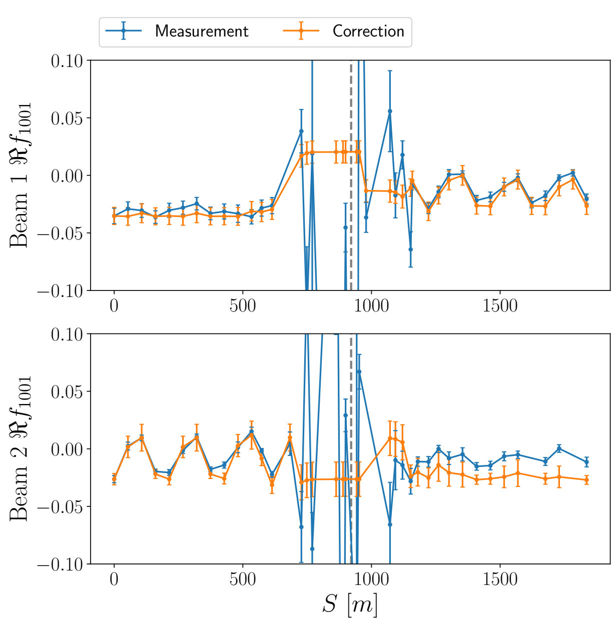

Figure 3: Propagation of the measured $\Re f_{1001}$ around IP1 and the reconstructed values from the determined correction, measured at 6.8 TeV and $\beta^* = 30$ cm.

The correction settings determined with the segment-by-segment technique and trimmed in the machine at the four main IRs can be found in Table 1, as well as their counterpart values from Run 2.

Table 1: Corrections Determined with Segment-by-Segment in 2022 and Run 2

Circuit	Δk [10^{-4}**m**$^{-2}$]	
	2016-2018 [4]	**2022**
RQXS.3L1	11	8
RQXS.3R1	7	7
RQXS.3L2	−14	−14
RQXS.3R2	−14	−14
RQXS.3L5	7	6
RQXS.3R5	7	6
RQXS.3L8	−5	−5
RQXS.3R8	−5	−5

One can notice however that this method gives little information on the actual coupling at the IP location due to the very high error bars, which prevents finding the optimal powering balance between the right and left MQSX.

THE RIGID WAIST SHIFT APPROACH

To circumvent the difficulty of measuring coupling RDTs at the IP, a new method was developed to relate coupling and beam size at the IP location to the $|C^-|$, a reliable observable external to the IR [2]. The method relies on breaking the optics symmetry of the IR by unbalancing the powering of the left and right triplet quadrupoles. Figure 5 shows

Content from this work may be used under the terms of the CC BY 4.0 licence (© 2022). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-WEPOPT007
Content from this work may be used under the terms of the CC BY 4.0 licence (© 2022). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI

the simulated linear coupling RDTs from a closed coupling bump in IR1 created through the MQSX magnets (located at the vertical green lines) in the presence and absence of a rigid waist shift.

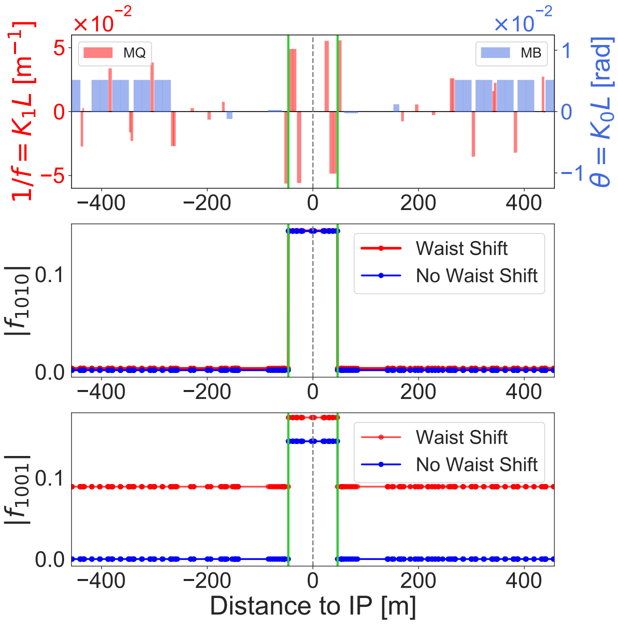

Figure 5: Linear coupling RDTs in the vicinity of IP1 under a coupling bump, with and without a rigid waist shift. The vertical green lines represent the positions of the skew quadrupoles (MQSX.3[RL]1) used to implement the coupling bump. A rigid waist shift setting of 1 was used, which results in a 0.5 % change in the triplet powering; and the MQSX magnets were powered with $\pm$ 10^{-3} m^{-2}.

By breaking the optics symmetry in the IR, the rigid waist shift forces a leakage of the RDTs outside of the limits of the coupling bump, ensuring that local sources have an impact outside of the region. The residual presence of these RDTs in the machine can be reconstructed from turn-by-turn data from BPMs with more suitable phase advances, and directly linked to the $|C^-|$, helping to determine an optimal correction by doing scans of the colinearity knob - a powering setting convention of the left and right skew quadrupole correctors.

The implementation of a rigid waist shift however has an effect on the β-beating across the machine, and will change the impact of errors - namely the skew quadrupolar impact on the $|C^-|$. In order to limit this impact and guarantee good measurements, a knob can be created that also makes use of the individually powered quadrupoles Q4 to Q10 to re-match the optics. A new software was developed to create these experimental configurations for a given IP in the machine [5], for any optics and strength of the rigid waist shift knob.

Early in the Run 3 commissioning, some beam time was allocated to the testing of the experimental setup for the rigid waist shift, which was implemented in one IR only at 6.8 TeV and β^* = 30 cm. Figure 6 shows the β-beating across the machine for Beam 1 with the rigid waist shift applied in IR5, before and after the application of the optics re-matching knob.

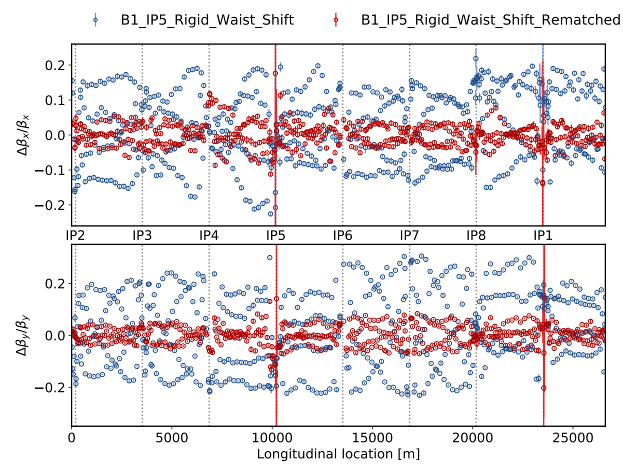

Figure 6: β-beating observed in the machine from the implementation of the rigid waist shift in IR5 at 6.8 TeV and β^* = 30 cm, before and after the trim of the optics re-matching knob. Prior to the application of any knob β-beating was kept around 5 % throughout the machine by applied corrections, which is also achieved by the re-matching knob.

The measured impact is very close to what could be expected from earlier simulations, where the application of the rigid waist shift leads to a 20-30 % increase in β-beating in the machine [2]; while the re-matching knob brought it back to about 5 %, depending on the observed beam and plane. Considering the state of the machine at the time of these tests, where the β-beating was kept at 5 % thanks to existing corrections, the optics re-matching after the application of the rigid waist shift shows great efficiency.

CONCLUSIONS AND OUTLOOK

During the LHC 2021 beam tests and early Run 3 commissioning, preliminary local coupling corrections have been calculated with the segment-by-segment technique and implemented in the machine, helping to reach low β^* and calculate global corrections. The segment-by-segment technique is, however, sub-optimal for minimizing the local coupling at the IP. To do so a new method was developed that relies on the application of a rigid waist shift and a necessary re-matching of the optics. Early in the Run 3 commissioning, the experimental configuration for the new method has been tested, showing good control of the machine optics in agreement with previous simulations. As the experimental setup has been validated, in the near future beam time will be used for colinearity knob scans from which final local coupling corrections will be determined.

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.

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-WEPOPT007

REFERENCES

[1] R. Tomás *et al.*, "CERN Large Hadron Collider optics model, measurements, and corrections," *Physical Review Special Topics - Accelerators and Beams*, 2010, doi:10.1103/PhysRevSTAB.13.121004

[2] F. Soubelet, O. Apsimon, T. H. B. Persson, R. T. García, and C. P. Welsch, "Prospect for Interaction Region Local Coupling Correction in the LHC Run 3," in *Proc. IPAC'21*, Campinas, Brazil, May 2021, pp. 61–64, doi:10.18429/JACoW-IPAC2021-MOPAB007

[3] H. Grote and F. C. Iselin, "The MAD Program," CERN, Tech. Rep., 2016.

[4] T. Persson *et al.*, "LHC Optics Corrections in Run 2," in *9th LHC Operations Evian Workshop*, 2019, https://indico.cern.ch/event/751857/contributions/3259376/attachments/1781875/3033022/optics_corrections_run2.pdf

[5] F. Soubelet, *Pyrws*, version 0.2.0, 2022, doi:10.5281/zenodo.6517668

Content from this work may be used under the terms of the CC BY 4.0 licence (© 2022). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI