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LHC 2023 ION OPTICS COMMISSIONING

V. Ferrentino*, A. B. Carazo, F. S. Carlier, J. Dilly, E. Fol, A. Gilardi, M. Hofer, S. J. Horney, J. Keintzel, M. Le Garrec, E. H. Maclean, T. Nissinen, T. Persson, F. Soubelet, R. Tomás Garcia, W. Van Goethem, A. Wegscheider, CERN, Meyrin, Switzerland,
J. Cardona, UNAL, Bogota D.C, Colombia
P. Arpaia, University of Naples Federico II, Naples, Italy

Abstract

In 2023, about 2 months of LHC operation were devoted to Heavy Ion physics. In this paper, results of the 2023 ion optics commissioning are reported. Local corrections in Interaction Points (IP) 1 and 5 were reused from the earlier proton commissioning. The optics measurements, however, revealed an energy offset at the level of 10^{-4} for both beams, correction of which helped reduce the residual optics errors in IP1 and IP5. Optics measurements also showed the need for new local corrections in IP2. This, together with global corrections at top energy, allowed a β-beating of about 5% to be reached for the collision optics. Dedicated measurements during the energy ramp also later revealed a large β-beating, consistent with an energy mismatch.

INTRODUCTION

Following the LHC Long Shutdown 2 (2019–2022), the Heavy Ion physics program was restarted in 2023. The ion optics is significantly different from the proton optics. In particular, the β^* at IP2 (ALICE) is reduced from 10 m to 50 cm. This motivates a full recommissioning of the LHC optics, to bring optics errors within machine protection tolerances and minimize luminosity imbalance between the experiments. Optics measurements were carried out at at flat-top energy (6.8 TeV proton equivalent energy, per beam) with $\beta^* = 50$ cm in IP1, IP2 and IP5, and 1.5 m in IP8. To correct the optics, local corrections are applied to quadrupoles in the experimental Interaction Regions (IRs, where low-β^* operation generates large optics perturbations), followed by global corrections distributed around the ring to minimize residual optics errors [1, 2].

2023 IP2 LOCAL CORRECTIONS

For the 2023 LHC Ion commissioning, local corrections in IP1 and IP5 (ATLAS/CMS) were reused from the 2023 Proton Commissioning [3–5], but the resulting high β-beating showed the need for new local corrections in IP2.

Initial optics measurements were carried out without IP2 local corrections. To measure the local optics errors and β-beating, the Segment-by-Segment (SbS) [6, 7] and analytical N-BPM [8, 9] techniques were used, respectively. The orange curve in Fig. 1 represents the measured phase advance error (computed via SbS) without IP2 local corrections. A large phase-error is seen, which corresponds to the large peak of 20% β-beating, reported in orange in Fig. 2.

* Also with University of Naples Federico II, Naples, Italy; email: vittorio.ferrentino@cern.ch

To locally correct the IP2 optics, the magnets considered were the triplet magnets left and right of IP2. The possibility of using the IP2 local corrections from the LHC Run 2, computed in 2018 and reported in Table 1, was evaluated. The blue curve in Fig. 1 shows the simulated impact of using 2018 corrections on the phase advance, which did not work for the 2023 ion commissioning as they did not match with the measurements without corrections (in orange). The sign appears swapped for Beam 1 (B1) in the horizontal plane, but this was not the case and simply swapping the correction sign would spoil B1 vertical, not correct the optics. Since 2018 corrections did not work, new IP2 local corrections were computed to minimize the phase advance error on both beams and planes. The IP2 local corrections found for the 2023 LHC ion commissioning are reported in Table 1. The phase advance in IR2, including the 2023 IP2 local corrections, was simulated and it is reported in red in Fig. 1. It can be observed that the predicted phase advance follows very well the measured phase advance without IP2 local corrections (orange curve).

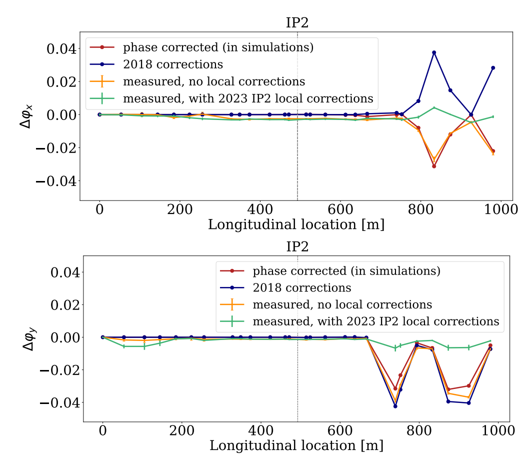

Figure 1: Phase advance error in IR2 from SbS for Beam 1 horizontal (top) and vertical (bottom). Very similar results were obtained for Beam 2.

MEASUREMENTS WITH LOCAL AND GLOBAL CORRECTIONS

After computing the new IP2 local corrections and testing them in simulation, new optics measurements were carried out. The positive impact of the new corrections can be observed in the green curve in Fig. 1, representing the measured

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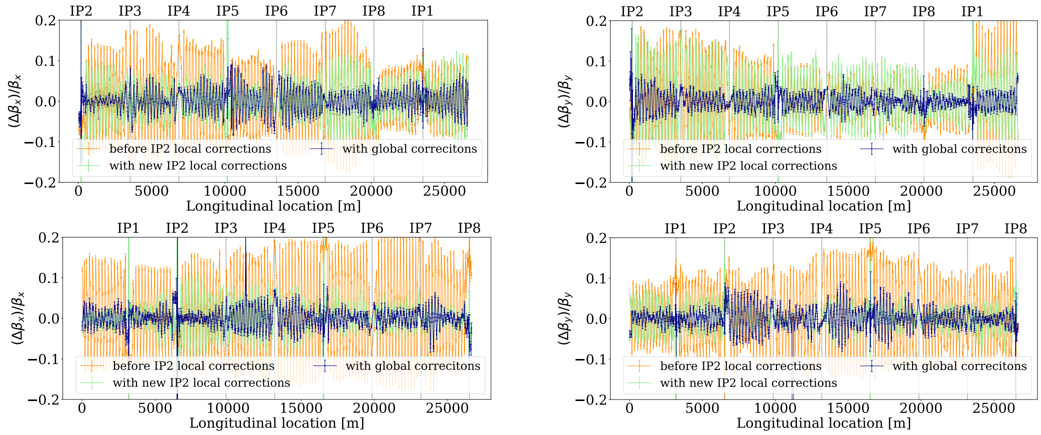

Figure 2: β-beating for Beam 1 (top row) and Beam 2 (bottom row) without IP2 local corrections (in orange), with IP2 local corrections (in green) and with global and local corrections (in blue).

Table 1: 2018 and 2023 Local Corrections in IP2

Magnet	2018	2023
MQXA1.L2 [1/m^2]	$2.275{\cdot}10^{-5}$	$-1.155{\cdot}10^{-5}$
MQXA1.R2 [1/m^2]	$3.410{\cdot}10^{-5}$	$-2.910{\cdot}10^{-5}$
MQXB2.L2 [1/m^2]	$2.732{\cdot}10^{-7}$	$-3.100{\cdot}10^{-6}$
MQXB2.R2 [1/m^2]	$-9.248{\cdot}10^{-6}$	$1.900{\cdot}10^{-5}$
MQXA3.L2 [1/m^2]	$-2.505{\cdot}10^{-5}$	$-2.000{\cdot}10^{-5}$
MQXA3.R2 [1/m^2]	$1.313{\cdot}10^{-5}$	$1.100{\cdot}10^{-5}$

Table 2: Summary of the Final Optics

	B1$_x$	B1$_y$	B2$_x$	B2$_y$
$(\Delta\beta/\beta)_{\rm rms}$	9.1%	7.2%	7.7%	8.5%
$(\Delta\beta/\beta)_{\rm rms}$	3.0%	2.2%	2.4%	2.6%
IP1 β^* [m]	0.50	0.50	0.49	0.51
IP2 β^* [m]	0.50	0.50	0.52	0.50
IP5 β^* [m]	0.48	0.50	0.51	0.50

phase advance error in IR2 with the new local corrections. It shows that the corrections worked well as the phase advance error is significantly reduced compared to measurements without IP2 local corrections.

The β-beating with the new IP2 local corrections is reported in green in Fig. 2. It shows a considerable improvement with respect to the measurements without IP2 local corrections (orange), but the residual β-beating is larger than normally targeted for LHC operation (typically, within the range of $\pm$10%). This led to considering the introduction of global corrections to decrease further the β-beating. Global corrections were calculated using a response matrix approach (generated from a MAD-X model) for all available quadrupoles in the ring. This aims to constrain β^* and the global optics errors, based on on/off-momentum optics measurements (via AC-dipole) and K-modulation [10, 11] data in IP1, IP2 and IP5. With global corrections, the resulting β-beating, reported in blue in Fig. 2, was within the range of $\pm$10%, well within machine protection constraints. Table 2 reports the summary of the final optics.

ENERGY CORRECTION

As described in the section above, local corrections in IP1 and IP5 from proton commissioning were reused. However, the initial SbS revealed a small, remaining phase-advance error that was not present in the proton commissioning. In previous commissionings, beam energy deviations were identified from analysis of systematic orbit corrector (COD) strengths, which created large local optics errors in IR1 and IR5, due to the high β function at the neighbouring triplets.

It was found, through optics simulation, that the SbS phase advance error could be explained with an energy error, which was then confirmed from analysis of the COD strengths. Thus, energy corrections of $1.6 \cdot 10^{-4}$ for Beam 1 and 10^{-4} for Beam 2 were applied in parallel with the new IP2 local corrections. This improved the SbS phase advance error in IR1 and IR5, even though there were no new corrections implemented at those locations. As an example for Beam 1, the SbS phase advance errors are shown in Fig. 3 in IP1 (top) and IP5 (bottom), before and after the energy trim. The difference in terms of phase advance is only due to the energy change. Results reported in the previous sections already included these energy trims. This was the first time optics measurements (as opposed to analysis of the COD settings) had been used to identify energy errors in the LHC.

MEASUREMENTS ON THE RAMP

Once ion operation was underway, additional optics measurements were performed to check the evolution of the β-beating during the energy ramp, by performing multiple AC-dipole kicks throughout. Figure 4 reports the rms β-beating during the ramp for Beam 1 (top) and Beam 2 (bottom). From injection to 5.4 TeV, the β-beating was within the $\pm$10% range. However, an unexpected enhancement of the β-beating was observed from 5.4 TeV up to 6.3 TeV, where the rms β-beating was the largest. Figures 5 and 6 report the β-beating measured around the ring for Beam 1 and Beam 2,

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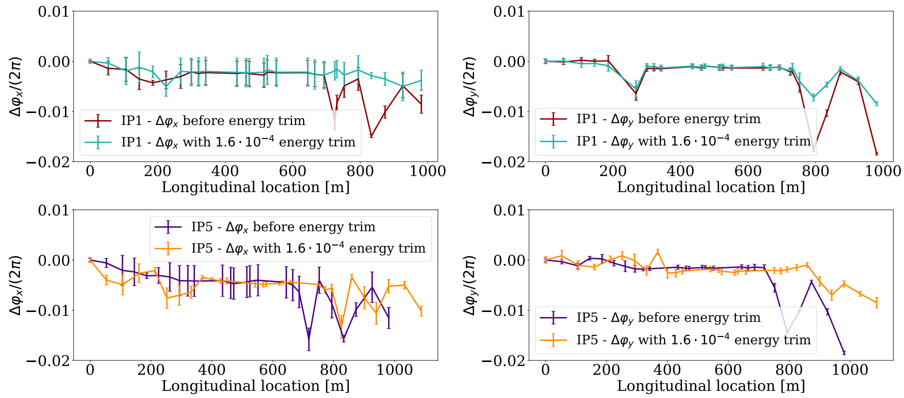

Figure 3: Effect of energy trim on the phase advance in IR1 (top) and IR5 (bottom) for Beam 1.

respectively, at 5.4 TeV (in dark blue), 5.8 TeV (in orange) and 6.3 TeV (in light blue). They show that a β-beating peak of 20 % was observed at 6.3 TeV, which is still within machine protection constraints, but significantly worse than the typical target quality. This optics error was also concluded to be consistent with an energy error during this portion of the ramp. No corrections were, however, implemented as the ion physics program was already underway.

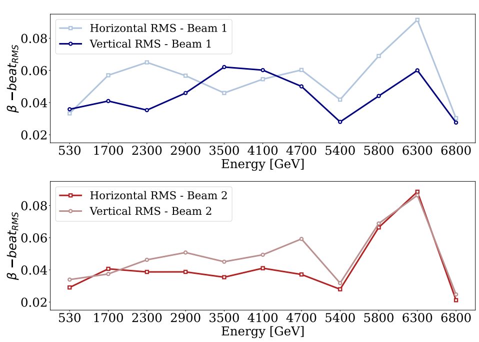

Figure 4: RMS β-beating during the ramp.

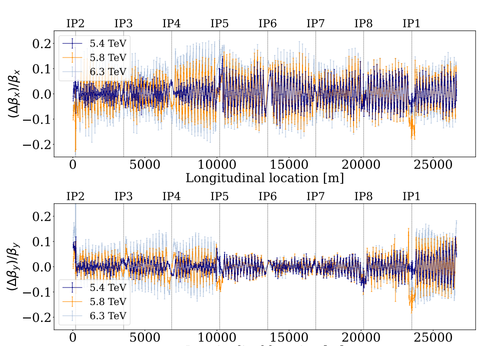

Figure 5: β-beating around the ring at 5.4 GeV, 5.8 GeV and 6.3 GeV - Beam 1.

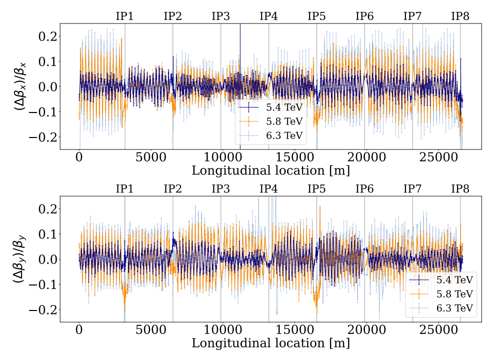

Figure 6: β-beating around the ring at 5.4 GeV, 5.8 GeV and 6.3 GeV - Beam 2.

sufficient to ensure a low β-beating. Old IP2 local corrections from 2018 Run 2 did not help to compensate the phase advance error in IP2. For this reason, new IP2 local corrections were computed. Optics measurements were carried out trimming in the new IP2 local corrections and while a decrease of the β-beating was observed, it was sill high with respect to the typical ±10% target for the LHC.

Therefore, global corrections were computed and trimmed into the machine. This led to a significant improvement of the β-beating to below 10%. For the first time, optics measurements identified an energy error through the SbS phase advance error, which was later confirmed by the operation team. A subsequent energy decrease of $1.6 \cdot 10^{-4}$ for Beam 1 and 10^{-4} for Beam 2 allowed the phase advance error in IR1 and IR5 to be improved. Optics measurements on the ramp showed a clear increase of the β-beating from 5.4 TeV, while for lower energies the optics was similar to the one at flat-top, with a β-beating below the 10% target.

CONCLUSION

In preparation of the LHC 2023 Ions Run, a dedicated optics commissioning was carried out. The local corrections in IP1 and IP5 used for the proton commissioning were not

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