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# LHC OPTICS COMMISSIONING IN 2023 AND 2024

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*Abstract*

The LHC machine configuration was changed in 2023 compared to previous years, requiring a new set of optics configurations to be measured and corrected. A telescopic optics was deployed in the energy ramp for the first time, which gave rise to a $\beta$-beat of up to 25%. This was corrected using a global correction approach which reduced the $\beta$-beat down to below 10%. A change in the phase advance at injection was also applied to mitigate the negative effect of the main octupoles used to stabilize the beam. These measurements and corrections, coupled with the results from the 2024 commissioning, will be presented in this paper.

## INTRODUCTION

After the successful restart of the LHC in 2022 [1, 2] it was decided to increase the beam intensity in 2023. To avoid reaching a too high pile-up in the two main experiments, the range of the $\beta^*$ in collisions was increased from 60 cm-30 cm to 120 cm–30 cm [3]. In terms of optics corrections, this meant that the corrections in the segment 60 cm-30 cm could be kept from 2022 but there was the need for new optics corrections from 120 cm to 60 cm in 2023. The measurements at 2 m and 1.2 m revealed a peak $\beta$-beat of 25%, significantly above tolerance. This was mainly linked to the new telescopic factor at the end of the ramp, which in 2022 was 1 while in 2023 it was 0.5 [4].

In 2024 the polarity of the Interaction Region 1 (IR1) triplet was reversed to distribute the radiation coming from the collisions more equally, leading to a better expected lifetime of the magnets in the triplet region [5].

## INJECTION

In 2023 a new optics with optimized phase advance between arcs was deployed. This was done to reduce the negative impact from the main octupoles needed at injection to stabilise the beam, described in detail in [6]. The analysis showed a positive impact on the beam lifetime and the same phase advance was used in 2024. This configuration requires a tight control of the global phase advance that called for beam-based corrections in 2023 and 2024.

The new optics deployed in 2024 with opposite triplet polarity in IR1 showed significant differences at injection with respect to previous years. In Fig. 1 a comparison of the uncorrected optics at injection is shown between standard and reversed polarity. The $\beta$ functions are reconstructed based on the measurement of the phase-advance and the local model [7, 8].

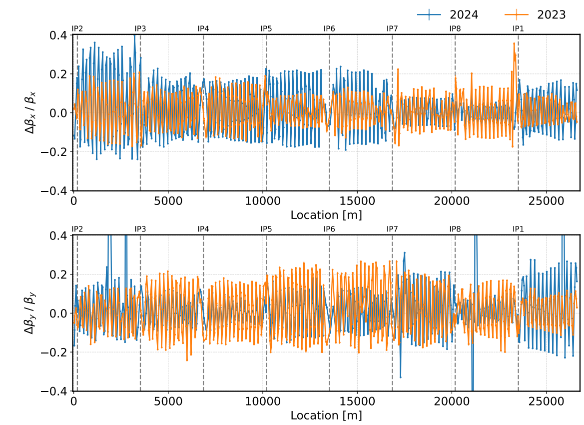


Figure 1: $\beta$-beat for Beam 1 without any optics corrections in 2022 and in 2024 (reverse polarity IR1).

We can observe that the $\beta$-beat is larger with the reversed polarity. The increase of $\beta$-beat is most likely linked to how the errors add up. It is also worth noting that the IR1 optics have changed beyond the triplet polarity inversion, meaning that the impact of other IR magnets also plays a role. This increase does not cause any issues and using individually powered magnets, the optics was corrected to the same levels as in 2023.

In 2023 and 2024 the first correction of the $3Q_y$ resonance using the IR skew sextupoles [9, 10] was performed. The motivation for this was coming from the fact that the $3Q_y$ resonance together with e-cloud is expected to have a negative impact on lifetime [11].

The Resonance Driving Term (RDT) $f_{1020}$ was also corrected in 2024 for the first time in the LHC [12]. A test at injection indicated that it had a positive impact on the lifetime. The decapole spool-pieces were used at injection in 2023 and 2024 to correct the higher-order chromaticity [13].

## LOCAL CORRECTIONS

The local corrections for the IRs calculated in 2022 could also be used in 2023. The correction in IR1 was based on Action Phase Jump (APJ) [14–16] but when the polarity was changed in 2024 it was unclear if a simple sign swap on the corrections would give the desired results. The usual procedure to compute local IR corrections was followed, using turn-by-turn data with AC-dipole [17, 18] excitation and performing K-modulation for the innermost quadrupole (Q1) left and right of IP1 and IP5 [19, 20]. However, after measuring without any correction in IR1 it was clear that a

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Table 1: The global corrections used for the different years and different parts of the cycle for the normal proton cycle starting at the end of the ramp.

| $\beta^*$ | 2022 | 2023 | 2024 |
|---|---|---|---|
| 2 m-60 cm[1] | - | new | same |
| 60 cm-30 cm | new | same | new |
| 30 cm-22 cm | - | - | new |

simple swap of the polarity would yield a good correction. The correction was not perfect and a small trim of the Q5 magnets was needed for Beam 1. In Fig. 2 we can see a comparison of the impact of the phase correction, together with the measurement for the two polarities. We observe that the phase error measured fits the correction for both triplet polarities and the residual error in Beam 1 was adjusted with the Q5.

The 2024 optics commissioning again demonstrated the importance of controlling the relative beam energy to the $10^{-4}$ level for the lower $\beta^*$ [1]. This was first noticed in the 2022 optics commissioning but a strategy to deal with this was first used in the ion commissioning in 2023 [21].

## GLOBAL CORRECTIONS FROM END OF RAMP TO $\beta^*$ = 22 CM

It was observed in 2023 that the $\beta$-beat was around 25% for the 2 m $\beta^*$ optics, at the end of the energy ramp. The $\beta$-beat was particularly significant for Beam 1 and an attempt was made to use an orbit bump in the arc and use the feed-down of the sextupoles to correct the $\beta$-beat in a similar way as done at the lower $\beta^*$ with higher ATS factor [1]. This approach was unsuccessful, but after applying a global correction, the $\beta$-beat was reduced to a peak value of 7% as seen in Fig. 3.

In 2024 it was observed that the errors after implementing the local corrections were very similar to those of 2023 at 1.2 m. This is expected since the optics in most of the machine stayed constant and the residual errors coming from the IR1 are small when the $\beta^*$ is in this range. This allowed to the global corrections from 2023 to be re-used in 2024. This was not the case for the lower $\beta^*$ and new corrections needed to be calculated. In 2024 all of the global corrections were calculated with the new Orbit Measurement and Corerection (OMC) software package [22]. Table 1 shows the global corrections calculated for a given year and $\beta^*$.

In 2024 there is the proposal to go below the lowest-ever operational $\beta^*$ of 25 cm [23] down to 22 cm. The first exploratory measurement and correction were performed during the beam commissioning in 2024. The results from the global corrections can be seen in Fig. 4. We see that a good global correction of the optics is possible, but a remaining validation with crossing angle is needed because of the strong feed-down from the sextupolar errors in the IRs [23]. The motivation to go to a lower $\beta^*$ of 22 cm is to

[1] Note that end of ramp was 1.33m in 2022.

Table 2: The strength of the skew quadrupoles used for the local corrections in IR1 for 2023 and 2024.

| Magnet | 2023 | 2024 |
|---|---|---|
| MQSX.R1 | $3.5 \times 10^{-4}\,\mathrm{m}^{-2}$ | $-4.5 \times 10^{-4}\,\mathrm{m}^{-2}$ |
| MQSX.L1 | $1.15 \times 10^{-3}\,\mathrm{m}^{-2}$ | $-1.05 \times 10^{-3}\,\mathrm{m}^{-2}$ |

Table 3: Normal octupole corrector strength in IR1 for 2023 and 2024.

| Magnet | 2023 | 2024 |
|---|---|---|
| MCOX3.L1 | $+0.811\,\mathrm{m}^{-4}$ | $-0.887\,\mathrm{m}^{-4}$ |
| MCOX3.R1 | $-1.049\,\mathrm{m}^{-4}$ | $+0.846\,\mathrm{m}^{-4}$ |

produce more integrated luminosity, partially mitigating the intensity limitation currently in place to limit the risk of another failure of a vacuum chamber transition module [24,25]. Additionally, running at this lower $\beta^*$ and higher tele-index could provide valuable insight in view of the High Luminosity LHC where these parameters will be pushed even further [26].

## LOCAL COUPLING CORRECTION

In 2022 we used a new method based on a rigid waist shift to determine the balance of the local coupling corrections [27]. These settings were validated with luminosity and could be used in 2023. In 2024 when the polarity of the triplet was reversed in IR1 the guess was that the sign of the correction would be opposite to the previous corrections. As we see in Table 2 this is indeed what was observed for the correction found in 2024 with the small differences either due to some drift during the winter shutdown or because the correction is not only deriving from the errors in the triplet but also partially from other magnets in the IR.

## NONLINEAR CORRECTIONS IN THE IRS

Both the normal and skew sextupolar and octupolar correctors were used at the end of Run 2. In Run 3, in addition to these components, the dodecapolar component was corrected for the first time [28]. Normal octupolar corrections in IR1 were recomputed for 2024, via minimization of second-order feed-down to tune as a function of the crossing-angle, as seen in Fig. 5. The octupole corrector strength showed an approximate sign inversion with respect to previous years, see Table 3, which is consistent with the relative $b_4$ error being unchanged by the triplet polarity inversion. Skew octupole and normal dodecapole corrections were not implemented for IR1 in 2024 due to the limited commissioning time and challenges in achieving high-quality measurements of the relevant observables. Normal and skew sextupole corrections did not show simple sign inversions, but these are dominated by feed-down from the higher-order corrections rather than by the relative geometric errors in the triplets, and as such, a simple scaling would not be expected. It is also worth noting that the crossing angle sign was inverted between 2023 and 2024 in IR1.

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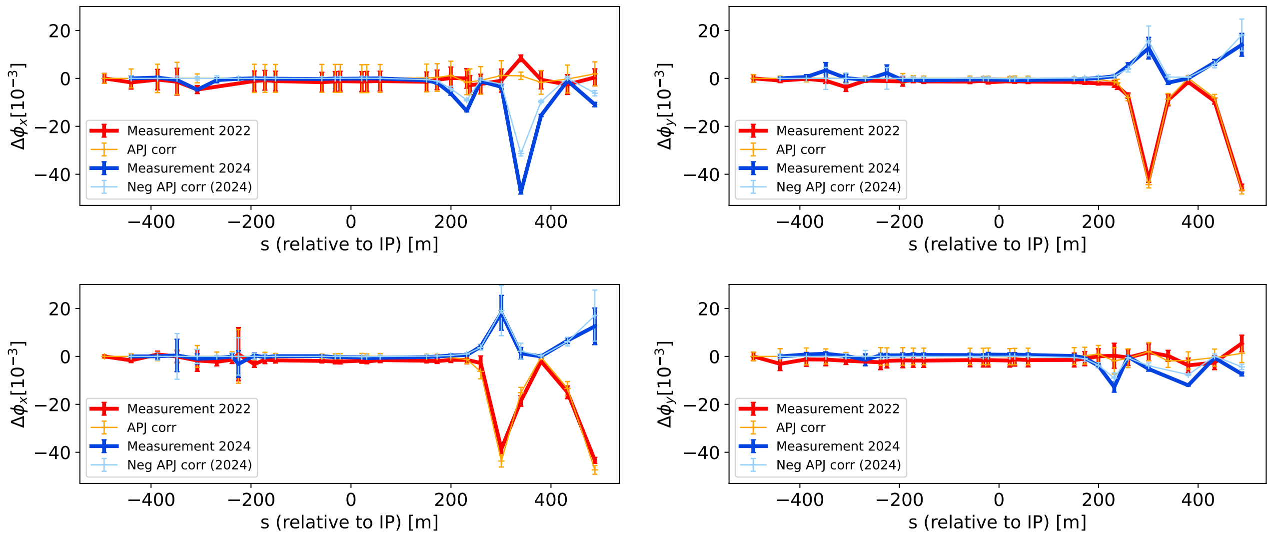


Figure 2: A comparison of the measured phase deviation, before local corrections for IR1, compared to a model including the calculated correction for IR1. Top left is Beam 1 Horizontal, top right is Beam 1 vertical, bottom left is Beam 2 Horizontal and bottom right is Beam 2 vertical.

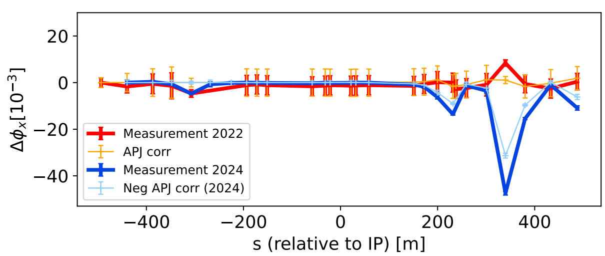


Figure 3: $\beta$-beat before and after correction at $\beta^*$ of 2 m.

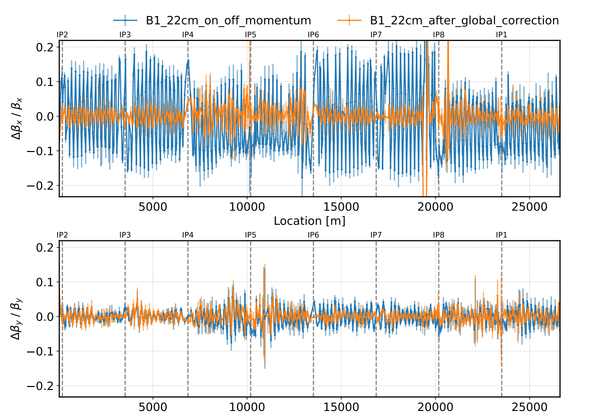


Figure 4: $\beta$-beat before and after global correction at a $\beta^*$ of 22 cm.

## CONCLUSION AND OUTLOOK

The LHC proton optics keeps evolving with optimized phase advance at injection to mitigate octupolar resonances since 2023 and with a reversed triplet polarity to mitigate radiation damage in 2024. The commissioning of these optics was successful with the $\beta$-beat corrected to within tolerances all along the cycle. Additionally, corrections at injection targeting different non-linearities have been implemented and are presently used in operation. In 2023 all nonlinear correctors available in the IRs were used to compensate for higher-order effects. The optics with the smallest ever LHC $\beta^*$ of 22 cm has been measured and corrected with the aim of using it in operation later in 2024.

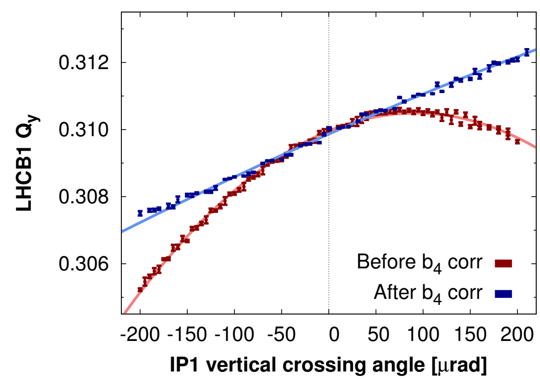


Figure 5: The impact of feed-down on the vertical tune of Beam 1 as a function of the vertical crossing angle in IP1, before and after $b_4$ correction. Similar results were obtained for $Q_{x,y}$ of both beams.

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