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LHC RUN 3 OPTICS CORRECTIONS

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Abstract

The first year of Run 3 of the Large Hadron Collider (LHC) revealed significant changes in both linear and nonlinear optics errors with respect to Run 2. Several iterations of optics corrections were required to successfully bring the linear optics within operational tolerances. This paper presents the current status of optics corrections in the LHC and the challenges experienced in commissioning the optics to a β^* of 30 cm in a single commissioning year after the Long Shutdown.

INTRODUCTION

The first year of Run 3 of the Large Hadron Collider (LHC) posed a significant challenge for the ambitious optics commissioning programme [1, 2]. The aim was to carry out a full linear and nonlinear optics commissioning campaign on a virgin machine to reach Run 2 optics quality, as well as commissioning several special optics such as the Van der Meer optics [3], a new 60° optics [4], and ballistic optics [5]. A step-wise correction strategy was used to achieve Run 2 equivalent linear optics quality in 2022, of which the first commissioning results were presented in [2, 4, 6–9]. This paper reports on the final adjustments to the optics corrections implemented and presents the final optics achieved in 2022. Further studies on nonlinear optics at injection [10, 11], k-modulation [12], and optics to minimize losses at the injection dump (TDIS) [13] are presented in the dedicated contributions.

OPTICS REPRODUCIBILITY DURING COMMISSIONING

In the middle of the LHC commissioning, a one week break was taken to install equipment and repairs to the RF-system. Following this pause, it was observed that the β-beating had changed by up to 10%. Different hypotheses, such as the impact of the hysteresis and RF configuration were tested and could be ruled out as the main cause. It was observed that the corrector magnets used to correct the orbit in the machine had different settings. While it is normal that these drift over time it was observed that their average value had shifted. An average kick changes the average magnetic field and hence shifts the beam energy since the RF system keeps the path length constant. The relative energy change from this corrector shift was estimated to be 10^{-4} for Beam 2 and around half that for Beam 1. In

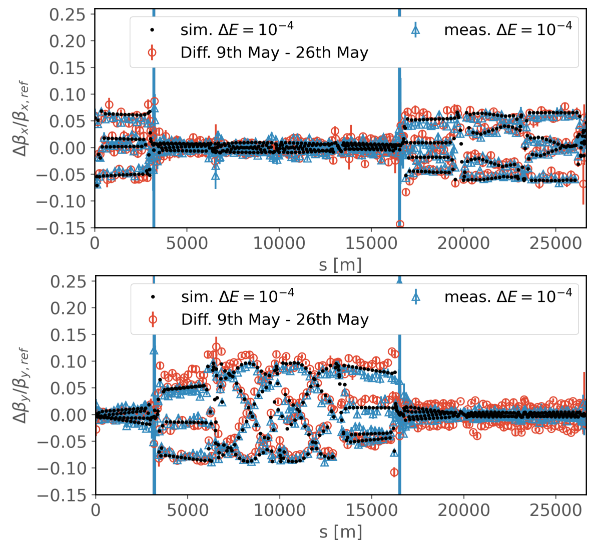

Figure 1: Comparison of β-beating for three different cases; (black) simulation with energy offset of $\Delta E = 10^{-4}$, (blue) difference between two different optics measurements during commissioning, (orange) measurement with energy offset of $\Delta E = 10^{-4}$.

Fig. 1 the change in β-beating before and after the stop is shown, together with the simulated effect in MAD-X and a dedicated test that was done later to demonstrate that this was indeed the cause. Simulations show that this effect is only significant for the small β^* where the β-functions are large in the triplet magnets in IR1 and IR5. It should be emphasised that a change of the average value of the corrector magnets is never done at top energy in normal operation and that the orbit feedback is designed in such a way as to prevent this from happening. However, during commissioning, there are manual setups to optimize the orbit where this is not the case. In order to prevent this in the future, optics corrections will only be performed after the final orbit setup. To mitigate the β-beating from the energy change in 2022, an additional optics correction was introduced for Beam 2 using the Q4 magnets around Interaction Points (IPs) 1 and 5, as presented in Table 1.

Table 1: Correction used to cancel the β-beating from the relative energy shift of 10^{-4} in Beam 2.

Corrector	$\Delta K1$ [m^{-2}]	Corrector	$\Delta K1$ [m^{-2}]
RQ4.L1	-1.3·10^{-5}	RQ4.R1	1.3·10^{-5}
RQ4.L5	-1.75·10^{-5}	RQ4.R5	1.75·10^{-5}

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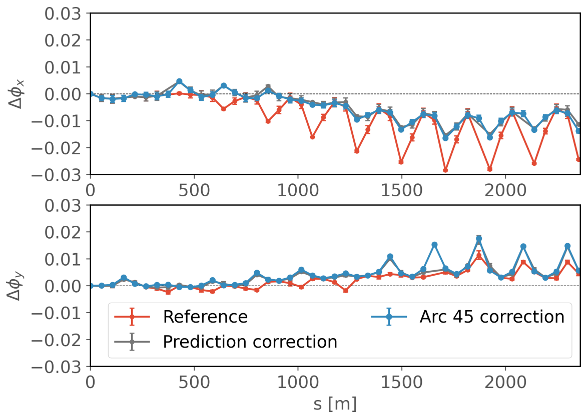

Figure 2: Measured reference and corrected phase beating in arc45 using the segment-by-segment method.

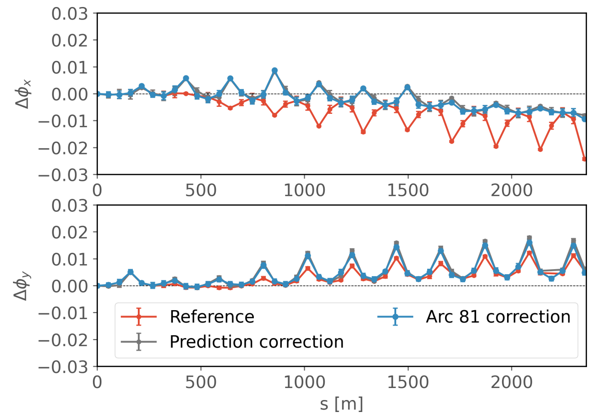

Figure 3: Measured reference and corrected phase beating in arc81 using the segment-by-segment method.

FIRST LOCAL CORRECTIONS IN LHC ARCS

The Achromatic Telescopic Squeeze (ATS) [14] optics scheme used during Run 3 significantly increases the β-functions in the LHC arcs around IP1 and IP5, enhancing the effect of magnetic errors and misalignments in those arcs on the global optics quality. Indeed, significant contributions from the ATS arcs to the global β-beating were observed in 2017 [15].

The segment-by-segment method is used to study local optics errors by propagating the difference between the measured phase advance and the model phase advance from the starting point of a machine segment till the end of the segment. Measurements were taken in 2022 to test the local arc corrections in Beam 1, and the above method was used in the LHC arcs around IP1 and IP5 to identify possible strong sources in the ATS arcs. Figures 2 and 3 show the measured phase deviation (in red) for the arc45 and arc81 respectively. The segments range from BPM.12R4.B1 to BPM.12L5.B1 in arc45, and BPM.12R8.B1 to BPM.12L1.B1 in arc81. A slowly accumulating phase error is observed in both arcs. Such errors have been observed in arc45 in 2017 during the MD on flat optics with ATS scheme [15], and a correction was determined using local horizontal orbit bumps in arc sextupoles in conjunction with a single quadrupole trim. The predicted effect of the correction on 2022 measurements is shown in both Figs. 2 and 3 in grey. The correction for arc81 is identical to that of arc45, but only transposed to arc81. The corrections predict a significant improvement in the horizontal phase error while slightly degrading the vertical phase error.

The results from the segment-by-segment analysis of measurements with arc corrections are presented in Fig. 2 for arc45 and in Fig. 3 for arc81. In both cases the measured phase deviation with respect to the model agrees very well with the predictions: an improvement is observed in the horizontal phase error.

The implemented corrections further translate into a direct improvement of measured global β-beating in Beam 1 in both planes, as shown in Fig. 4. The improvements are most

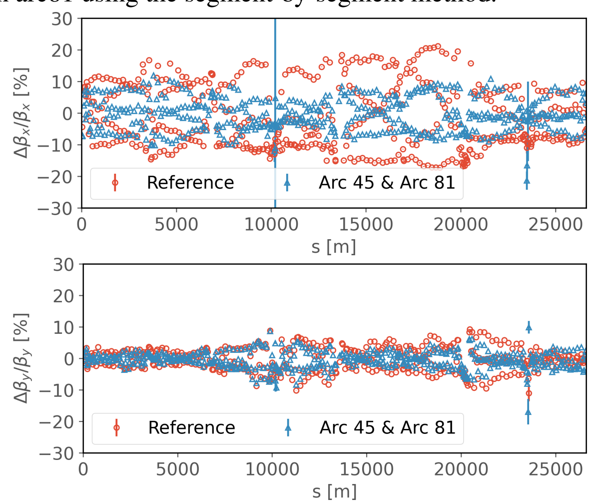

Figure 4: Comparison of measured β-beating for the LHC Beam 1 with (blue) and without (red) the local arc bump corrections for the horizontal plane (top plot) and vertical plane (bottom plot).

notable in the horizontal plane where the peak β-beating is improved from 20% to 10% with the application of both arc45 and arc81 corrections. The slight deterioration of the vertical phase deviation observed in the segment-by-segment analysis does not deteriorate the β-beating. This further motivates a detailed study of optics errors in the ATS arcs. The successful implementation of the local arc corrections using horizontal bumps in sextupoles greatly facilitated the search for global corrections to finalize the 2022 optics corrections.

BEAM 2 IP5 WAIST CORRECTION

k-modulation measurements were performed in 2022 to measure the IP optics functions and showed a significant longitudinal offset of the location of the minimum β-function at IP5, which is often referred to as the waist [12,16–20]. Since large waist offsets significantly increase the uncertainty of k-modulation measurements [17], an optics knob was created to correct the waist back to zero. The magnetic strengths of the knob are given in Table 2. While the implemented waist shift offers a minor improvement in the waist location

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Table 2: Magnetic strengths of the quadrupoles left and right of IP 5 used to correct the vertical waist shift in IP 5 of Beam 2.

Corrector	Left $\Delta K1$ [m^{-2}]	Right $\Delta K1$ [m^{-2}]
RQ10	0.013	-0.118
RQ4	3.654	-1.809
RQ5	-5.239	3.271
RQ7	-1.098	-2.264
RQ8	-2.486	0.327
RQ9	0.178	1.500
RQT12	-1.023	1.955
RQT13	-0.002	-0.217
RQTL11	-0.223	0.156

Table 3: Values of the waist and β^* before and after the waist shift in IP 5 of Beam 2.

	Before [cm]	After [cm]
w_x	-5.7 ± 2.9	-6.4 ± 0.2
w_y	-9.4 ± 3.8	-7.5 ± 0.2
β_x	31.1 ± 1.2	30.6 ± 0.1
β_y	33.1 ± 2.4	30.6 ± 0.1

(see Table 3), this improvement increases the accuracy of the k-modulation measurements. This demonstrates that a good control of the waist is needed for accurate k-modulation measurements when moving to small β^* values.

FINAL LHC OPTICS QUALITY 2022

To conclude the 2022 linear optics commissioning, a final global optics correction was implemented. The resulting optics at the end of squeeze ($\beta^* = 30\,\text{cm}$) after the implementation of all corrections for both beams and both planes are presented in Fig. 5. The resulting global β-beating is well within machine tolerances, with the maximum RMS β-beating of 2.1% in the vertical plane of Beam 2. With these results the optics commissioning campaign successfully achieved its main target of correcting the linear optics to reach an optics quality similar to the end of Run 2. The horizontal and vertical dispersion deviations are presented in Fig. 6. While the quality of the dispersion measurement in Beam 2 is poor, the results are well within machine tolerances.

CONCLUSION

Starting from the post-LS2 virgin machine, the nominal physics optics were successfully commissioned, as well as the Van der Meer optics, ballistic optics, and a special 60° optics. To achieve the successful commissioning of the nominal optics, several new corrections were implemented.

A relative energy change of 10^{-4} in Beam 2 resulted in a significant optics perturbation, and was successfully compensated using the Q4 quadrupole circuits left and right of IP1 and IP5. Optics errors in the ATS arcs are now becoming more important and corrections were applied in the form of horizontal orbit bumps in arc sextupoles, for both arc45

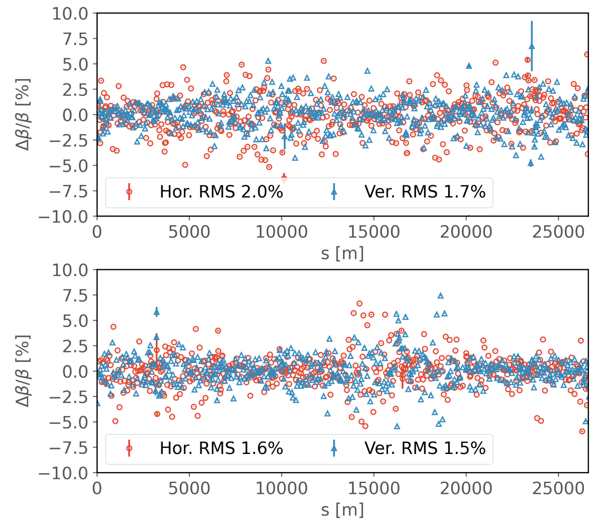

Figure 5: The final measured β-beating for the LHC Beam 1 (top) and Beam 2 (bottom) for the horizontal plane in red and vertical plane in blue.

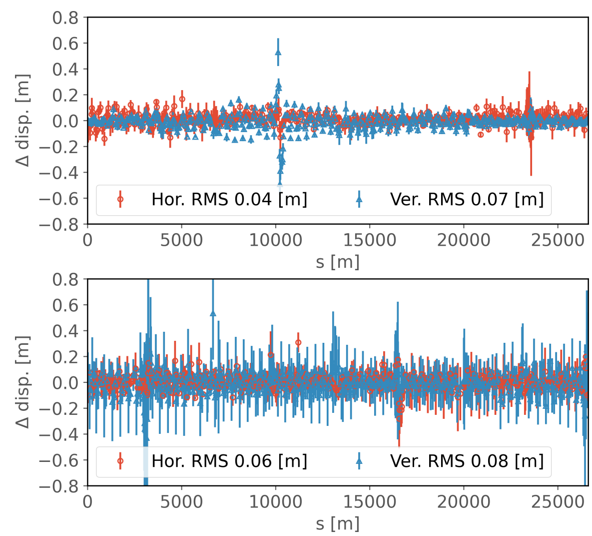

Figure 6: The final measured dispersion deviation w.r.t. nominal for the LHC Beam 1 (top) and Beam 2 (bottom) for the horizontal plane in red and vertical plane in blue.

and arc81 of Beam 1. These corrections resulted in a reduction of the peak horizontal β-beating by 10%. Final global corrections were calculated and implemented, thus further improving the optics quality. At $\beta^* = 0.3\,\text{m}$, the maximum *rms*-$\Delta\beta/\beta$ is 2.0%, while the peak β-beating is 7%, thus confirming that the LHC is well within tolerances.

However, the broad diversity of linear corrections applied clearly illustrates the need for a continued effort in understanding the LHC optics in view of the HL-LHC.

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