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OPTICS CORRECTION STRATEGY FOR RUN 3 OF THE LHC

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Abstract

After more than 3 years of shutdown the LHC is again operational in 2022. Experience from the previous Long Shutdown (LS) has shown that the local errors in the triplet quadrupoles changed significantly between Run 1 and Run 2, and first measurements in 2022 unveil further changes. In the LHC, feed-down from the Interaction Region (IR) non-linear corrections to linear errors requires an iterative approach between the two types of corrections. In this article we describe the key measurements and corrections performed in 2021 and 2022 until the write-up of this report.

INTRODUCTION

The Run 3 presents a new set of challenges for the optics commissioning. Run 2 was started with a moderate β^* of 80 cm and it was then reduced in yearly steps [1, 2]. This gave time to optimize the corrections iteratively as well as focusing on the linear optics in the first 2 years, shifting the focus to the nonlinear IR contributions in the rest of the run. Another challenge is the increase of the range in the operational β^* for physics [3], requiring accurate corrections for a larger number of optics. Run 3 optics features the largest telescopic squeeze factor [4] used in operation so far, implying the largest arc β functions and the consequent enhancement of arc optics errors. The Run 3 energy has been increased from 6.5 TeV in Run 2 to 6.8 TeV which could have some consequences for the magnetic field quality.

In 2021 a dedicated beam test took place at injection energy. This period allowed to measure and correct the optics at injection. In this article we outline the linear measurements at injection and give a snapshot of the status of the LHC commissioning to date. A full picture is unfortunately not available since the LHC commissioning is still ongoing.

INJECTION

The first measurement of the injection optics, during the beam test, revealed a surprisingly large β-beating compared to what was measured in Run 2. This triggered some investigations and the optics error was localised using the Segment-by-Segment (SbS) technique [5] to come from the RQTL7.R3 quadrupole. Its Beam 1 and Beam 2 powering was swapped as also found in 2008 [5]. This swap was accidentally re-introduced during the Long Shutdown 2. A change on the software side fixed the issue within hours restoring global β-beating to the same level as in Run 2. A global optics correction reduced peak β-beating to about 10% which is well within the requirements for machine protection. The measured β-beating before and after correction is shown in Fig. 1.

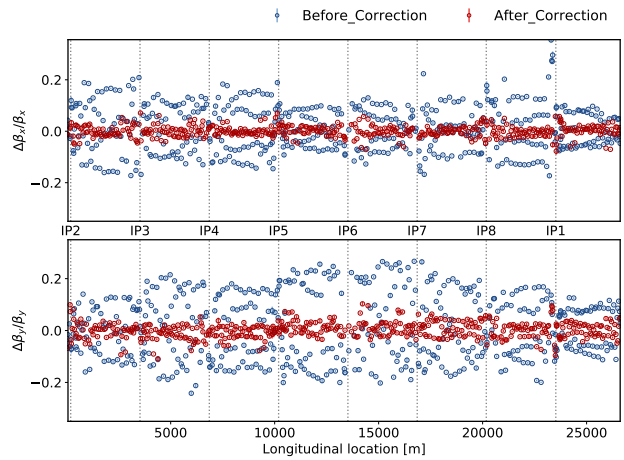

Figure 1: β-beating at injection before and after global corrections for the LHC Beam 1 in the 2021 beam test.

The optics was also re-measured in 2022 with the same global corrections and even though a small degradation of a few percent was observed in the peak β-beating it was still acceptable for operation.

FIRST OPTICS MEASUREMENTS AT 6.8 TEV

In order to determine the Interaction Region local corrections the optics was squeezed down to $\beta^* = 30$ cm without any optics corrections. This is the smallest β^* ever reached in the LHC without triplet corrections. The measurement revealed a peak β-beating of around 150% which is also the highest ever measured in the LHC. The usual procedure to compute local IR corrections was followed. It consists of taking turn-by-turn data with the AC-dipole [6] and performing K-modulation for the most inner quadrupole (Q1) left and right of IP1 and IP5 [7]. The local corrections calculated in Run 2 were all based on the SbS technique [5, 8]. In Run 3 two additional methods based on Action-Phase-Jump (APJ) [9–12] and Machine Learning (ML) [13–15] were used. The SbS and APJ techniques are using both the AC-dipole turn-by-turn data and the results from the K-modulation while the ML currently only uses the Turn-by-Turn (TbT) data. The three different methods performed well but the ML was less local in the correction and therefore the choice was then between the SbS and APJ. Even though the corrections are different in strength, see Tab. 1, they had almost identical impact on both the phase and the

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Table 1: Local correction strengths for end of proton Run 2 compared values calculated using APJ and SbS in Run 3. The polarity indicates the sign of the K-value of the magnet.

	Circuit	$\Delta k\,(10^{-5}\mathrm{m}^{-2})$			Polarity
		Run 2	APJ	SbS	LSA
IR1	**ktqx1.l1**	1.23	0	1.23	-
	ktqx1.r1	−1.23	0	−1.23	+
	ktqx2.l1	0.65	1.15	0.41	+
	ktqx2.r1	−1.0	−0.87	−0.70	-
	ktqx3.l1	1.22	1.94	1.22	-
	ktqx3.r1	−1.22	−2.88	−1.22	+
IR5	**ktqx1.l5**	2.0	0	2.25	-
	ktqx1.r5	−2.0	0	−2.10	+
	ktqx2.l5	0.26	0.38	0.16	+
	ktqx2.r5	1.48	0.93	1.35	-
	ktqx3.l5	1.49	3.40	2.25	-
	ktqx3.r5	−1.49	−2.46	−2.10	+

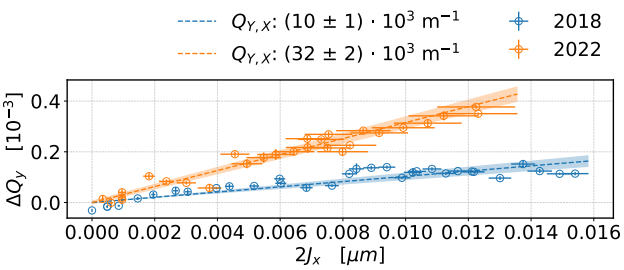

Figure 2: Amplitude detuning measured in 2018 and in 2022 for Beam 1 with the same IR octupolar corrections.

β-functions, as seen in Fig. 3. We can also observe that the corrections calculated in Run 2 were not fully compatible with what was measured in Run 3 [1]. The difference of the local phase beating between Run 2 and Run 3 is smaller than what was observed between Run 1 and Run 2 [16].

Both the APJ and the SbS corrections were tested in the machine and the resulting β-beating was very similar between the two sets of corrections. In Fig. 4 the β-beating before and after corrections is shown. The corrections used for IP1 were calculated with APJ while for IR5 they were calculated using SbS. The reason for this was that K-modulation in this configuration gave results slightly closer to the model. Local corrections at IP2 and IP8 were also implemented, based on SbS, but they have a much smaller impact on the overall β-beating due to the larger β^* and hence smaller β-function in the triplet magnet.

COUPLING CORRECTION

The local IR coupling corrections were first calculated during the injection beam test and then reiterated after the optics was squeezed to $\beta^* = 30$ cm, hence enhancing the effect of local errors. The coupling corrections are found very close to Run 2 with a slightly weaker correction in IR1 [18]. The method that has been used is based on matching the change in the coupling Resonance Driving Terms (RDTs) f_{1001} and f_{1010} close to the IP [5]. However, there is still the uncertainty in how to balance the skew quadrupoles left and right of the β^* IPs. In order to find the best balance, which has an impact on the IP beam size [19], a new method is being used in this run. This method breaks the symmetry of the IR optics by creating a rigid betatron waist shift for both beams and planes at the IP. In this way the local coupling error at the IP causes a change of the global coupling, which is significantly easier to measure [20, 21].

However, even with the local corrections optimized there are also coupling sources coming from the arcs. These are corrected with the global coupling knobs that use dedicated skew quadrupolar families located in the arcs with two degrees of freedom. The measurement is either performed with the ADT-AC dipole or with the AC-dipole [22, 23]. However, when there is a significant variation of the coupling along the machine a dedicated correction is needed that freely utilizes the skew quadrupoles in all the arcs in order to flatten $|f_{1001}|$. Figure 5 shows $|f_{1001}|$ and $|f_{1010}|$ before and after the arc-by-arc correction was applied for Beam 1.

CONCLUSION AND OUTLOOK

The optics commissioning in the LHC has been off to a good start. The incorporation of the local corrections in the triplet region brought down the β-beating from 150% to below 20% at $\beta^* = 30$ cm and we are for the first time using corrections based on the APJ method. The coupling has been corrected to a low level thanks to local corrections and the arc-by-arc and global coupling approaches. However, there is still a long way to finalize the optics commissioning. Arcs have to be scrutinized to decide if optics corrections with orbit bumps at sextupoles are needed as in Run 2 experiments [8]. Global optics corrections still need to be applied once the reference orbit with crossing angle is established, followed by fine tuning of the IP β^* and coupling aberrations using novel measurement techniques, as the rigid waist shift or resorting to scans monitoring luminosity. Non-linear IR corrections need to be re-computed as first measurements point towards a larger amplitude detuning than in Run 2, as shown in Fig. 2. These require orbit scans to determine local sextupolar and octupolar corrections. For the first time it has been planned to implement dodecapolar corrections in the IRs [24]. Non-linear corrections in Run 2 demonstrated to be instrumental in the control of Landau damping, minimizing feed-down to the linear optics and improving the quality of optics measurements [2].

[1] The compared corrections are from the proton-proton run. A small correction was also applied for the Ion Run in 2018 [17]

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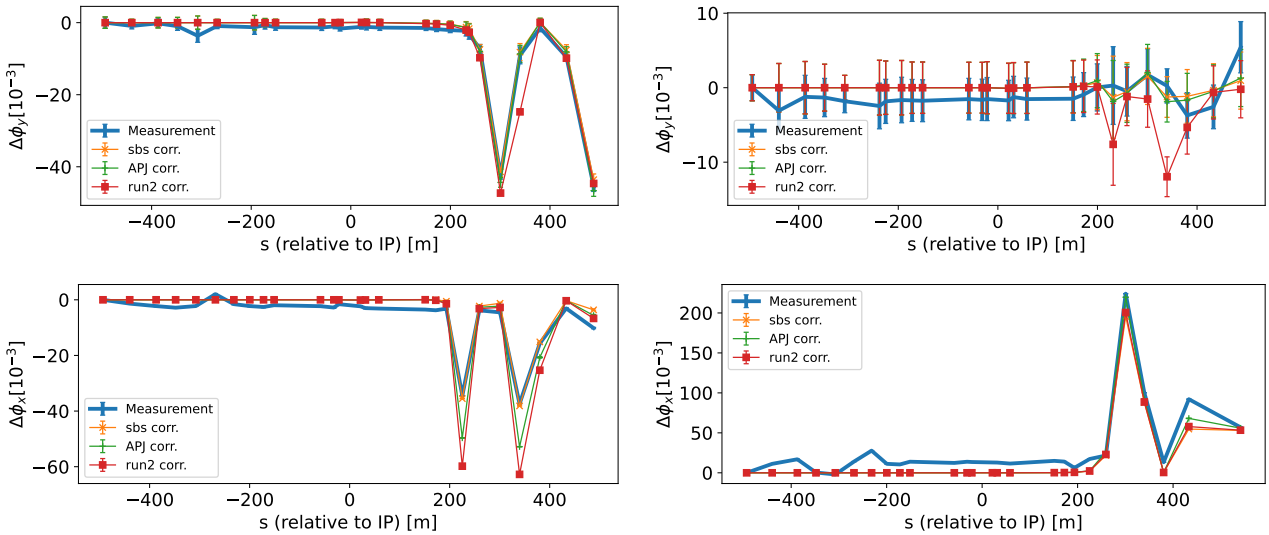

Figure 3: IR1 Vertical (top) and IR5 Horizontal (bottom) phase deviation between measurement and model run as a segment, or from a model with Run 2 corrections (with opposite sign to mimic errors). Left plots are for Beam 1 and right plots for Beam 2.

Table 2: The measured β^* before and after the Local Corrections were trimmed in for the $\beta^* = 30$ cm optics.

	IP 1 β^* [cm]				IP 5 β^* [cm]			
	Beam 1		Beam 2		Beam 1		Beam 2	
	H	V	H	V	H	V	H	V
Virgin	66.6 ± 1.2	46.6 ± 0.5	40.2 ± 0.7	129.5 ± 2.3	69.1 ± 1.3	49.6 ± 1.1	34.8 ± 0.5	52.9 ± 1.0
After Local	32.4 ± 0.3	30.5 ± 0.3	31.6 ± 0.4	28.3 ± 0.1	32.4 ± 0.4	31.2 ± 0.2	28.7 ± 0.3	31.2 ± 0.2

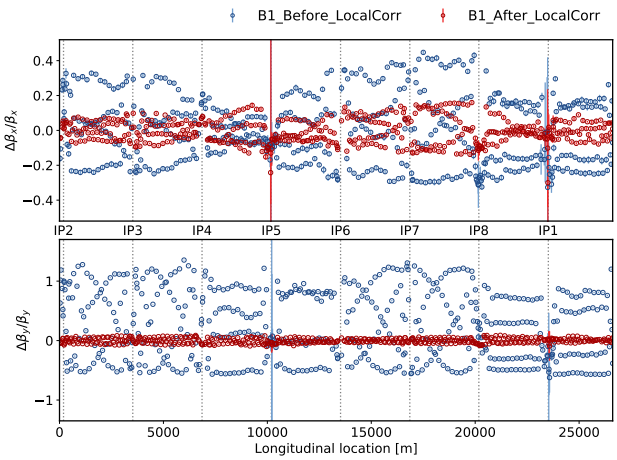

Figure 4: The measured β-beating at β^*=30 cm before and after local corrections for Beam 1.

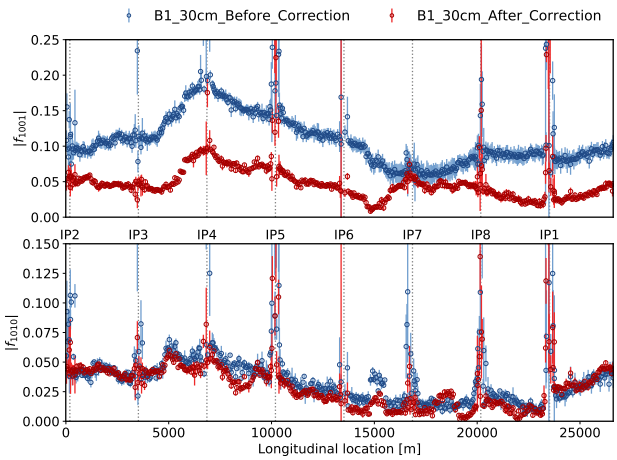

Figure 5: The Beam 1 $|f_{1001}|$ and $|f_{1010}|$ before and after the arc-by-arc coupling correction, measured at $\beta^* = 30$ cm.

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