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OPTICS FOR LANDAU DAMPING WITH MINIMIZED OCTUPOLAR RESONANCES IN THE LHC

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Abstract

Operation of the Large Hadron Collider (LHC) requires strong octupolar magnetic fields to suppress coherent beam instabilities. The amplitude detuning that is generated by these octupolar magnetic fields brings the tune of individual particles close to harmful resonances, which are mostly driven by the octupolar fields themselves. In 2023, new optics were deployed in the LHC at injection with optimized betatronic phase advances to minimize the resonances from the octupolar fields without affecting the amplitude detuning. This paper reports on the optics design, commissioning and the lifetime measurements performed to validate the optics.

INTRODUCTION

In 2022 losses driven by the Landau octupoles and chromaticity were observed in the LHC at injection [1]. In addition, e-cloud simulations showed that the LHC Landau octupoles drive emittance growth that could be mitigated by reducing resonance driving terms [2]. These observations motivated the quest for a new injection optics in the LHC aiming to suppress the main resonances driven by the Landau octupoles via parametric optics matching in the LHC [3]. To minimize the changes between 2022 and 2023 only arc trim quadrupoles would be used in the optimization with the only constraints of keeping the same tunes and a β-beating below 5% in the Insertion Regions (IRs), with respect to the 2022 optics. Therefore, the phase advances between the different arcs are the key parameters in the optimization.

In the arc12 of Beam 1 there is a total of 21 octupoles, 13 of them are defocusing and are placed in 13 consecutive FODO cells with a phase advance of about $\pi/2$. The remaining 8 focusing octupoles are interleaved with the defocusing octupoles, extending over 10 consecutive FODO cells but skipping 2 cells. In arc23 the same structure is present but swapping the focusing and defocusing roles of the octupoles. These two structures alternate along the 8 arcs of both beams with the exception of arc56 in Beam 1, where instead of 13 defocusing octupoles there are only 10 available. Within one arc the focusing octupoles drive the $4Q_x$ resonance in-phase and the defocusing octupoles drive the $4Q_y$ resonance in-phase too. The resonance $2Q_x - 2Q_y$ is driven by all focusing and defocusing octupoles within one arc with similar phases. The resonance driving terms (RDTs) f_{2002}, f_{4000}, f_{0004} drive the resonances $2Q_x - 2Q_y$, $4Q_x$ and $4Q_y$, respectively.

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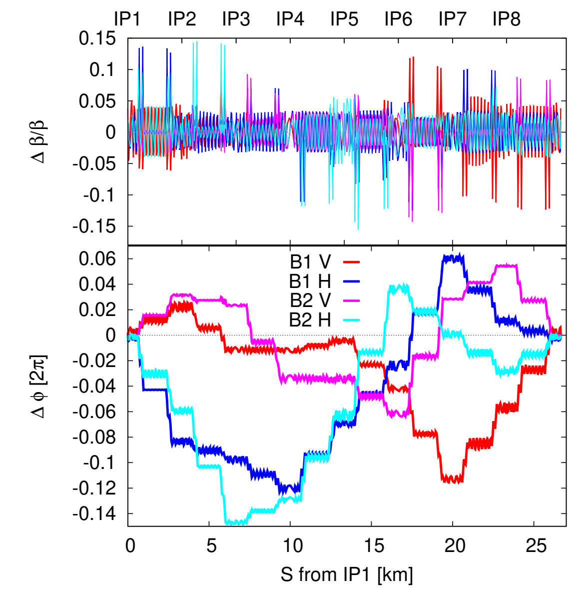

Figure 1: Relative β-function and phase advance deviations between the 2023 and 2022 optics at $Q_{x,y}$ = (62.270, 60.295).

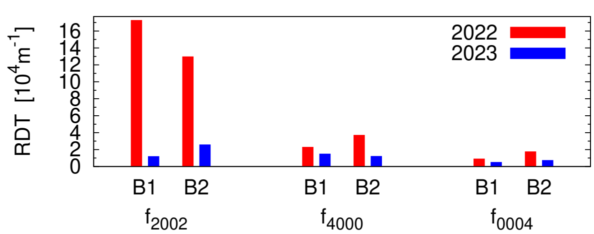

Figure 2: Average octupolar RDTs in the 2023 and 2022 optics at $Q_{x,y}$ = (62.270, 60.295) for both beams.

Figure 1 shows the resulting β-beating and phase advance shift between the 2023 and the 2022 design optics. A peak β-beating of about 5% is seen in the IRs with spikes of up to 15% at the location of the trim quadrupoles in the arcs. Phase advance shifts up to 50° are induced. Figure 2 shows a comparison between the RDTs in the two optics with Landau octupoles powered at 40 A and chromaticities of $Q'_{x,y}$ = 25. All RDTs are reduced between 2022 and 2023, achieving large factors above 5 for the $2Q_x - 2Q_y$ resonance in both beams. Dynamic aperture simulations show a remarkable improvement by more than 1σ for both beams, see Ref. [3].

OPTICS COMMISSIONING

Optics measurements and corrections are necessary in LHC to meet tolerances. During Run 1 optics corrections

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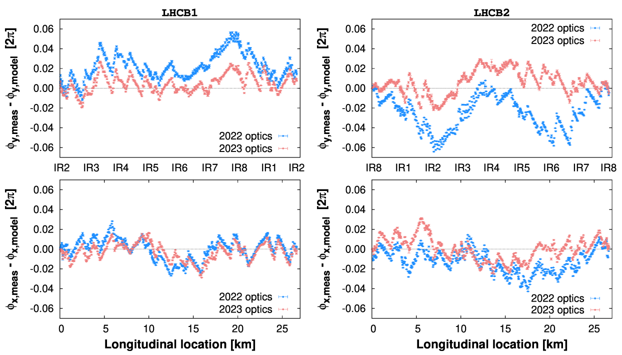

Figure 3: Deviation of measured phase advance to the corresponding model in 2022 and 2023.

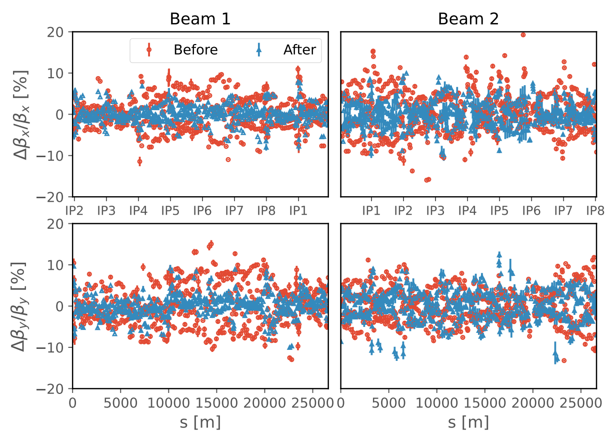

Figure 4: Measured β-beating before and after the 2023 global correction.

were required almost every year until β-beating reached the tolerance of about 16% at injection [4–6]. The injection optics commissioning in the start of Run 3, 2021-2022, is reported in [7]. In 2023 it was decided to start with the injection optics corrections used in 2022 and add corrections as required. Until 2022 no tolerances were set on phase advance errors at injection, leaving long-range phase deviations of up to 25° uncorrected [4, 7]. However, to ensure the mitigation of the octupolar RDTs dedicated phase advance corrections were performed in 2023, reducing the peak deviation to about 10°, as shown by the red points in Fig. 3. The quality of these corrections is limited by the low number of trim quadrupoles in the arcs and a reproducibility of about 5°. These long-range phase corrections were performed with the arc trim quadrupoles and two quadrupoles towards the left and right ends of every IR (Q12 and Q13). The maximum quadrupolar strength used by this correction is 30% of the maximum strength used to generate the new optics. Their impact on β-beating and dispersion beating was few % and few cm, respectively.

Following the long-range phase correction a regular global β-beating optics correction was performed, as shown in Fig. 4. The β functions are measured using the Analytical N-BPM method [8]. The resulting β-beating is comparable to those achieved in previous years with a peak of about 10%,

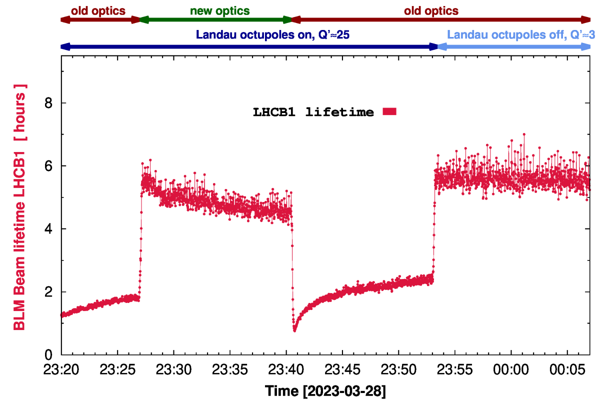

Figure 5: Measured lifetime for Beam 1 while switching between the 2022 and 2023 optics and powering on and off the Landau octupoles (MO) along with the high and low chromaticity (Q'=25 and Q'=3). Clear improvements above a factor of 2 are observed for the new optics with MO on. With MO off similar lifetimes are observed for both optics.

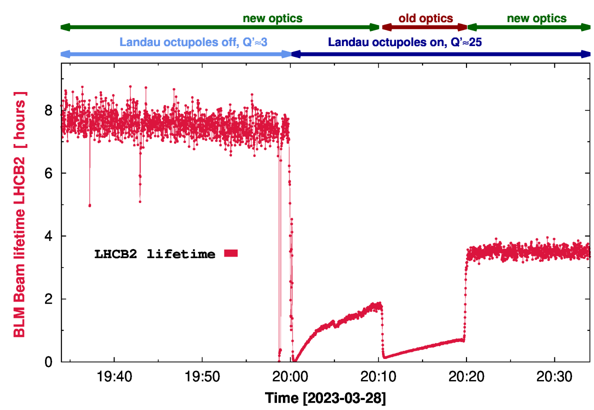

Figure 6: Measured lifetime for Beam 2 as in Fig. 5.

see [7]. This correction does not change the long-range phase advance significantly.

Concerning transverse betatron coupling, a shift in the ΔQ_{min} of 0.02 and 0.015 in Beam 1 and Beam 2, respectively, was observed when implementing the new optics. This significant change is due to the phase change at the coupling sources and was easily corrected with the global coupling knobs. It should be noted that there was no need to update the global coupling knobs in 2023 as they remained orthogonal with the new optics. Global coupling knobs are constructed as described in [9].

LIFETIME AND RDT MEASUREMENTS

To validate the new optics in the non-linear regime lifetime measurements were performed for both 2022 and 2023 optics in the same experimental session and with the same low intensity proton bunch. Figures 5 and 6 show the measured lifetimes while switching between both optics with and without powering the Landau octupoles (MO). Clear improvements above a factor of 2 are observed for the new optics with MO on. With MO off similar lifetimes are ob-

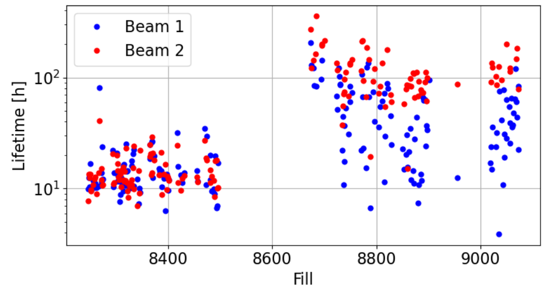

Figure 7: Measured beam lifetime at the end of the injection process during nominal operation in 2022 (fills below 8600) and 2023 (fills above 8600).

served for both optics in Beam 1. On- and off-momentum loss maps were also performed for both optics, yielding no significant differences between the two [10, 11]. The previous observations concluded on the beneficial effect of the new optics and, therefore, it was deployed for operation in 2023 at injection. The transition to the 2022 optics is implemented during the first six minutes of the energy ramp up to an energy of 1.7 TeV. During operation, a remarkable improvement in the lifetime at the end of the injection process was observed in 2023 in comparison to 2022 [12], see Fig. 7. The large spread in the Beam 1 lifetime needs to be investigated.

The 2023 optics optimization was performed targeting octupolar RDTs and using ideal LHC models without magnetic or alignment errors. Therefore, it is possible that the machine errors play a significant role in the excitation of resonances in the new optics. To address this an RDT measurement campaign took place to compare key resonances for both optics without Landau octupoles [13], as shown in Fig. 8. These measurements were performed with AC dipoles, which affect the RDTs and, hence, are referred to as forced RDTs [14–19]. The sextupolar RDT f_{1020} does not show a significant change while f_{0030}, driving the $3Q_y$ resonance, has improved by about a factor 2 in Beam 1 for the new optics. On the other hand, the octupolar term f_{2002} has increased by almost a factor of 2 in Beam 1 to 2×10^4 m^{-1}. Surprisingly, this is also twice larger than the expected value in the ideal 2023 optics with Landau octupoles, as shown in Fig. 2. Therefore the $2Q_x - 2Q_y$ resonance is now dominated by the unknown machine errors and requires further investigations. On the contrary the $4Q_x$ resonance is reduced for both beams in the new optics. For the $4Q_y$ resonance only a mild increase is seen in Beam 2. Lastly, for the decapolar term f_{1004}, driving the resonance $Q_x - 4Q_y$, a large increase is observed for both beams in the new optics. Dedicated decapolar corrections are being investigated [20, 21] to mitigate this unwanted effect of the new optics. $3Q_y$ corrections were already being investigated since 2022 [22, 23] but were compromised for requiring too large skew sextupole strengths. Thanks to the reduction of the f_{0030} term in the new optics, skew sextupolar corrections can be implemented in both beams.

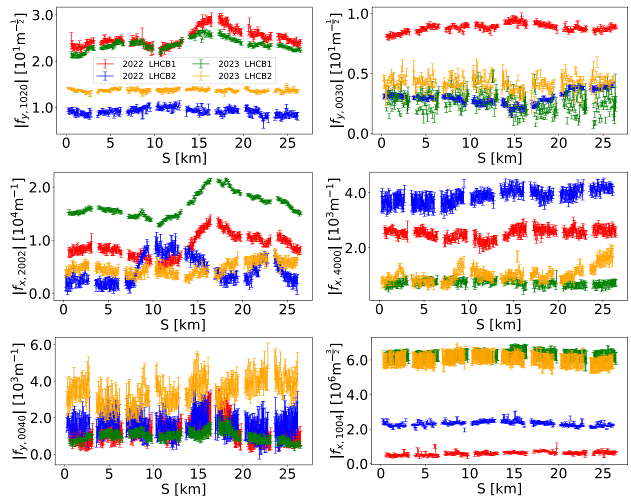

Figure 8: Measured forced RDTs for nominal machines in 2022 (red and blue for Beam 1 and Beam 2) and 2023 (green and yellow) with Landau octupoles off.

RDT measurements with nominal Landau octupoles using AC dipoles are impractical due to a too low forced dynamic aperture [24]. First RDT measurements with low Landau octupole strengths were performed, however results are not yet fully understood and need further investigations.

SUMMARY & OUTLOOK

A new LHC injection optics was conceived to minimize the main octupolar RDTs generated by the Landau octupoles, demonstrating larger DA in simulations and a longer lifetime in dedicated experiments and nominal operation. This also opens the door for operation with negative octupole polarity both for the LHC and the HL-LHC [25–27]. Further improvements require correcting the machine imperfections and understanding the RDT measurements in presence of the Landau octupoles.

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