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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 lifetime measurements performed to validate the optics.

Keywords: Accelerator modelling and simulations (multi-particle dynamics, single-particle dynamics); Beam dynamics; Beam Optics

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1 Introduction

LHC requires strong Landau octupoles to suppress coherent beam instabilities. In 2022 beam 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 octupolar Resonance Driving Terms (RDTs) [2]. These observations motivated the quest for new injection optics in the LHC aiming to suppress the main resonances driven by the Landau octupoles via parametric optics matching with MAD-NG [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, same amplitude detuning, 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.

2 New injection optics

The eight LHC arcs are equipped with trim quadrupoles to correct the systematic quadrupolar errors of the arc dipoles and to control the tunes. Four quadrupoles powered in series are placed in four consecutive FODO cells with a phase advance of about $\pi/2$ so that minimal β-beating or dispersion beating leaks outside of these four cells, inducing mostly a betatron phase shift. Four sets of these four quadrupoles are placed in each arc, two sets for the horizontal phase control and the other two for the vertical phase.

In the arc12 of Beam 1 there is a total of 21 Landau 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 RDTs f_{2002}, f_{4000}, f_{0004} drive the resonances $2Q_x - 2Q_y$, $4Q_x$ and $4Q_y$, respectively.

MAD-NG was used to minimize the aforementioned octupolar resonances using the arc trim quadrupoles, and keeping the tunes and the amplitude detuning constant while avoiding large deviations of the β-functions in the IRs. In general, it was sufficient to minimize the real and the imaginary parts of f_{2002}, f_{4000}, and f_{0004} altogether at one location to achieve a good global reduction along the machine. The MAD-NG optimization is based on a modified Newton-Raphson algorithm that requires the knowledge of the Jacobian between the targeted constraints (tunes, detuning, RDTs) and the optimized variables (quadrupole strengths), and calculated directly by the parametric differential maps to order 5 where the strengths kqt of the arc trim quadrupoles are the parameters, e.g. to obtain $\partial f_{2002}/\partial$kqtf.a12b1. Details of the minimization process and the MAD-NG implementation are given in [3]. Figure 1 shows the resulting relative β-function deviations and phase advance shifts between the 2022 and the 2023 design optics for both transverse planes and both beams. The relative β-function deviation features spikes of up to 15% at the locations of the trim quadrupoles in the arcs, as expected, as this is the region where the phase shift is induced. Nevertheless, the largest relative β-function deviation in the IRs (regions around the labeled IPs on the plot) is about 5%, which is defined as the maximum acceptable change. Phase advance shifts up to 0.14 2π radians (which is about 50°) are induced. Figure 2 shows a comparison between the simulated 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 figures 3 and 4.

3 Optics commissioning

Optics measurements and corrections are necessary in the LHC to meet tolerances. During Run 1 optics corrections 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 [8]. 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, 8]. However, to ensure the mitigation of the octupolar RDTs in the new 2023 optics dedicated beam-based phase advance corrections were performed in 2023, reducing the peak deviation to about 10°, as shown by the red points in figure 5. 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 were a few % and a few cm, respectively.

Following the long-range phase correction a regular global β-beating optics correction was performed, as shown in figure 6. The β functions are measured using the Analytical N-BPM method [7]. The resulting β-beating is comparable to those achieved in previous years with a peak of about 10%, see [8]. This correction does not change the long-range phase advance significantly.

The vertical dispersion beating after correction features very similar levels for the old and the new optics in both beams, as shown in figure 7. It is important to highlight that the vertical dispersion bump developing between IP5 and IP8 for Beam 2 is only mildly affected by the new phase advance. This might suggest that the sources of this dispersion beating are placed in this region and a robust correction could be computed using measurements from both optics.

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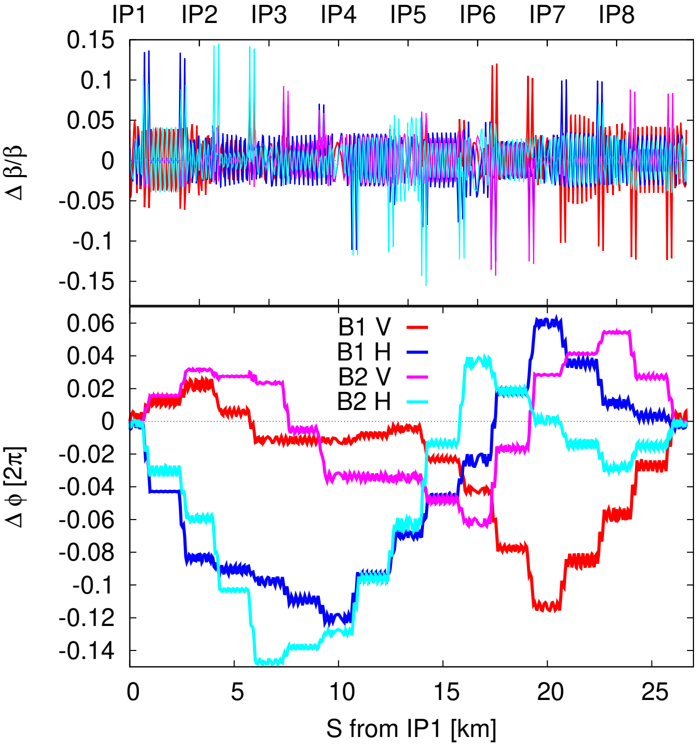

Figure 1. Relative β-function deviations and phase advance shifts between the 2023 and 2022 optics at $Q_{x,y}$ = (62.270, 60.295) for both transverse planes and beams. Red and blue lines stand for Beam 1 vertical and horizontal parameters, respectively. Magenta and cyan lines stand for Beam 2 vertical and horizontal parameters, respectively.

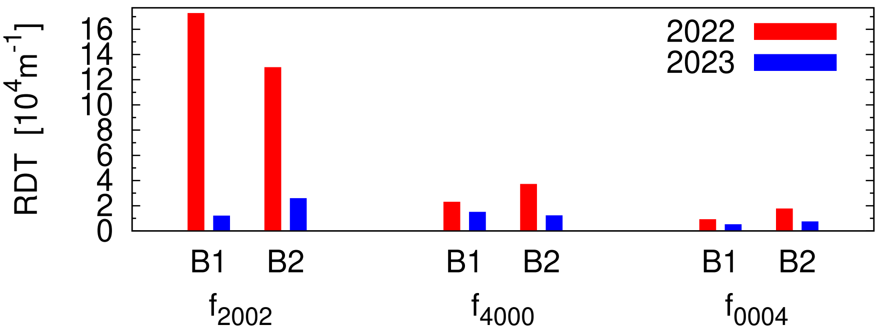

Figure 2. Average octupolar RDTs in the 2022 (red) and 2023 (blue) optics at $Q_{x,y}$ = (62.270, 60.295) for both beams.

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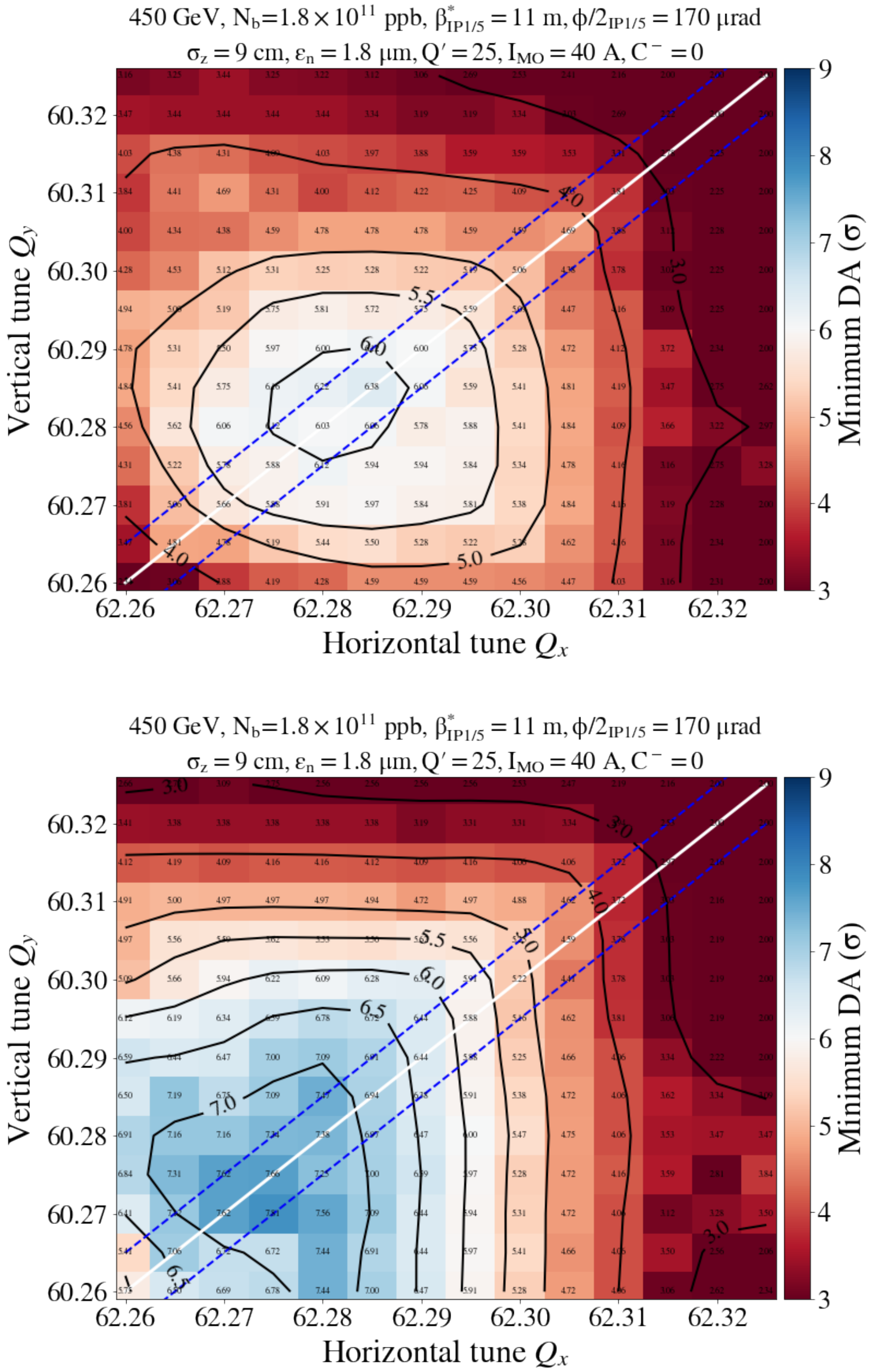

Figure 3. Dynamic aperture for Beam 1 versus horizontal and vertical tunes for the 2022 optics (top) and for the 2023 optics (bottom), showing an improvement above 1σ.

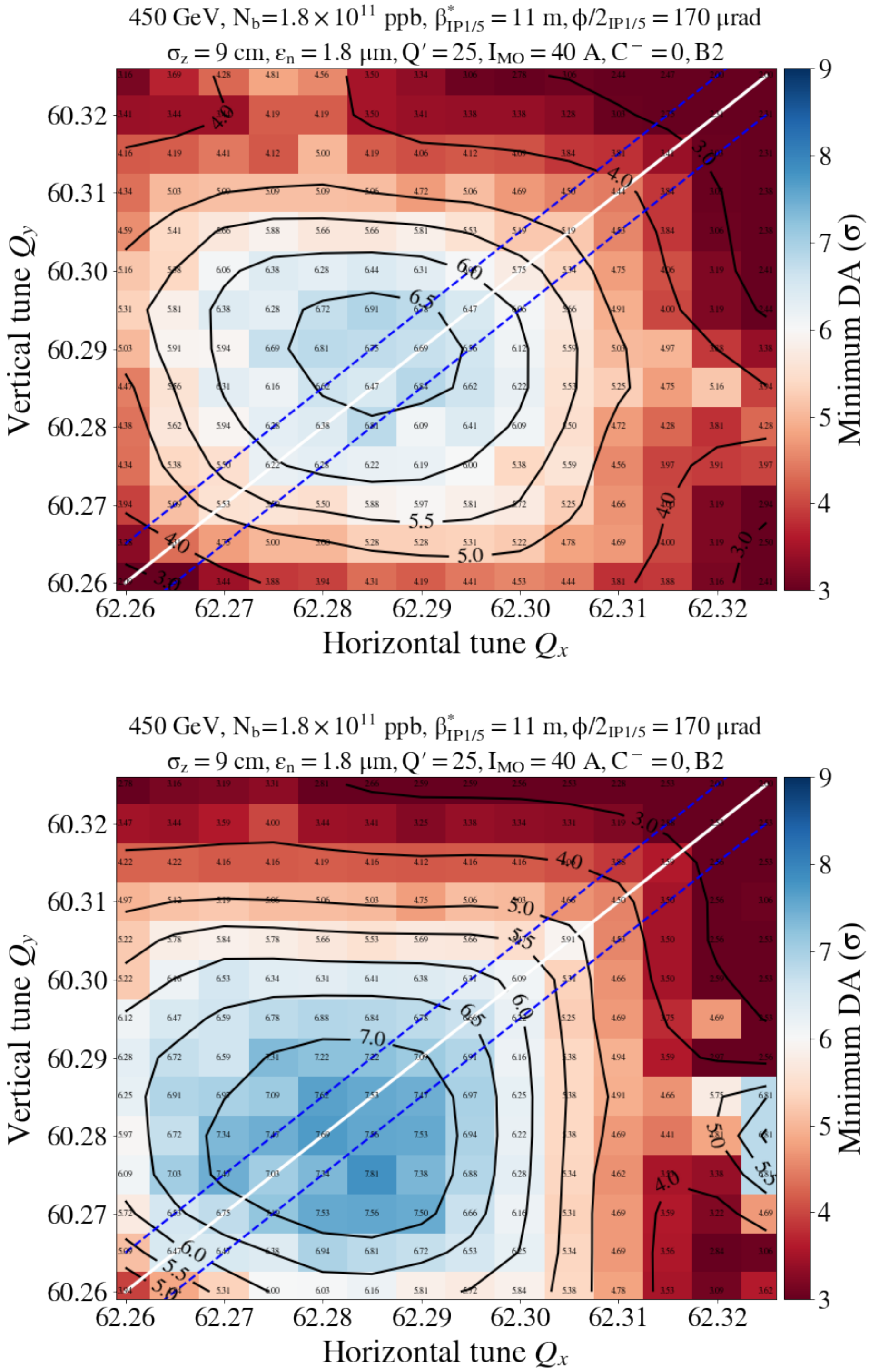

Figure 4. Dynamic aperture for Beam 2 versus horizontal and vertical tunes for the 2022 optics (top) and for the 2023 optics (bottom), showing an improvement above 1σ.

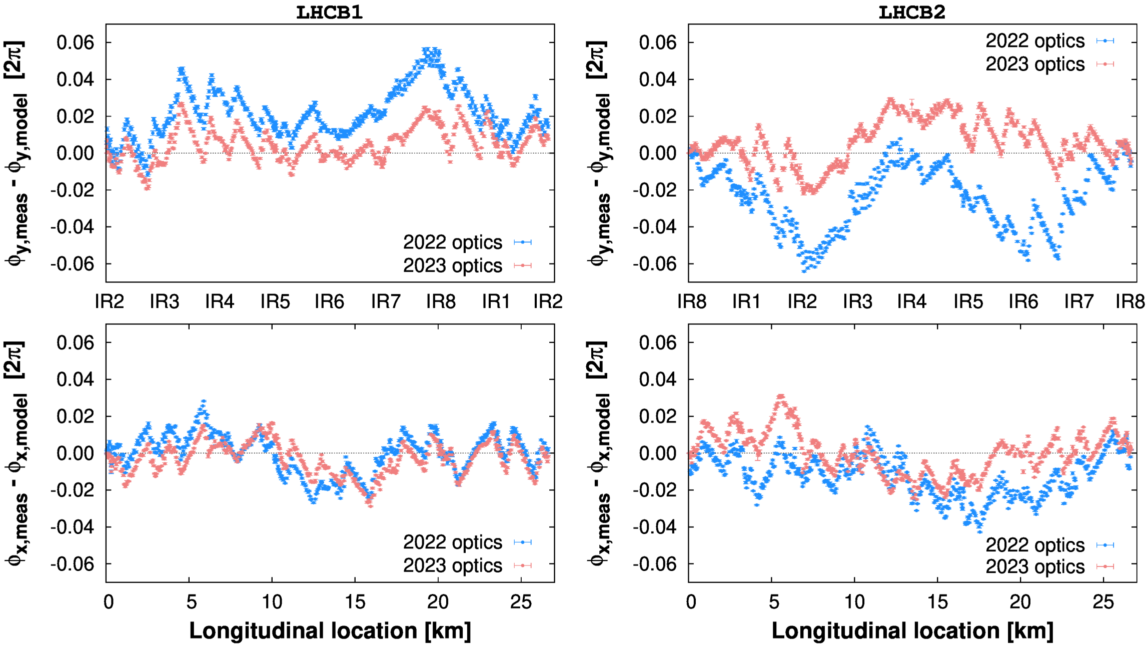

Figure 5. Deviation of measured phase advance to the corresponding model in 2022 and 2023.

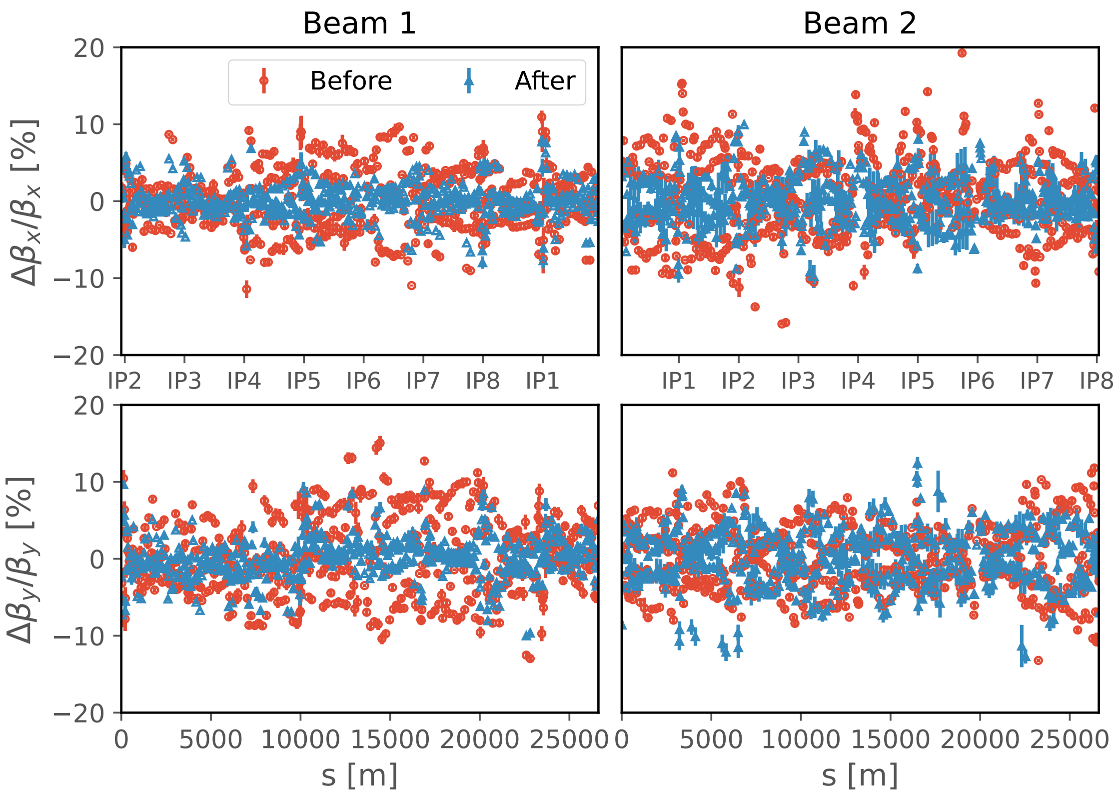

Figure 6. Measured β-beating before and after the 2023 global correction.

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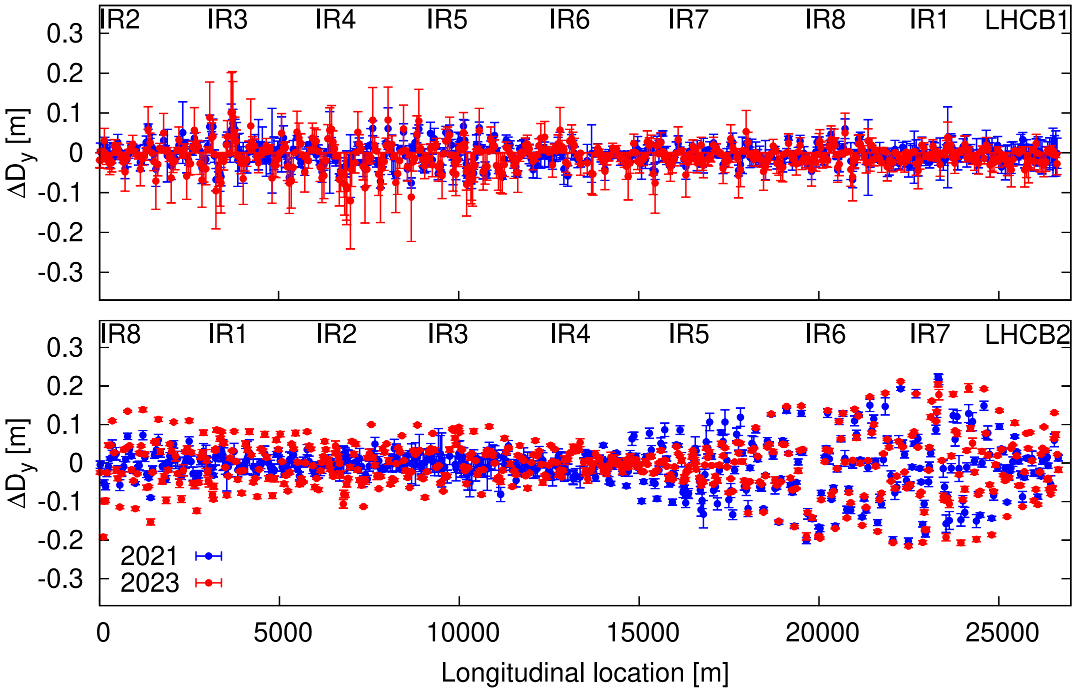

Figure 7. Measured vertical dispersion beating after optics corrections in 2021 (blue) and 2023 (red), for Beam 1 (top) and for Beam 2 (bottom).

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].

4 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 8 and 9 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 observed 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]. From these observations, it was concluded on the beneficial effect of the new optics and, therefore, it was deployed for operation in 2023 at injection. During the energy ramp, an optics transition is introduced to move from the new phase advances at injection to the previous configuration. This is performed 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 figure 10. The large spread in the Beam 1 lifetime needs to be investigated.

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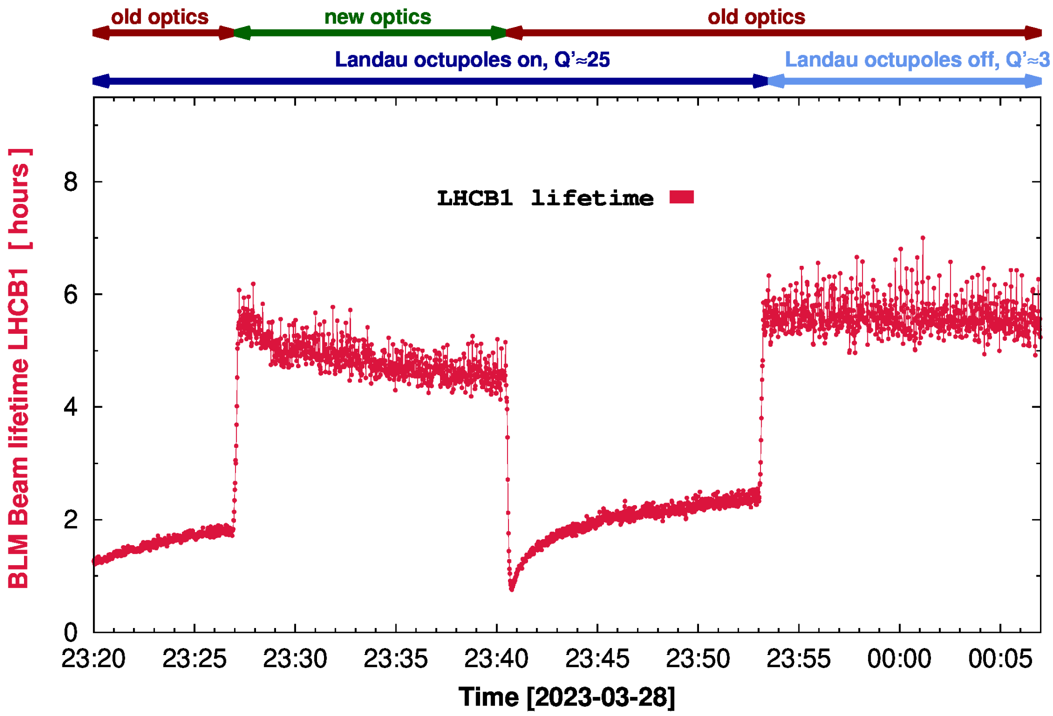

Figure 8. Measured lifetime for Beam 1 while switching between the 2022 and 2023 optics and powering on and off the Landau octupoles (MO) along with the high and low chromaticity (Q'=25 and Q'=3). Clear improvements above a factor of 2 are observed for the new optics with MO on. With MO off similar lifetimes are observed for both optics.

The 2023 optics optimization was performed targeting octupolar RDTs with Landau octupoles and using ideal LHC models without magnetic or alignment errors. Therefore, it is possible that machine errors play a significant role in the excitation of resonances in the new optics. To address this an RDT measurement and simulation campaign took place to compare key resonances for both optics without Landau octupoles [13], as shown in figure 11 for measurements and in figure 12 for simulations. These measurements and simulations are performed with AC dipoles, which affect the RDTs and, hence, are referred to as forced RDTs [14–19]. The models used in the simulations include magnetic multipolar components coming from magnetic measurements before installation [20] and only a small set of alignment errors, namely the misalignments of sextupolar, octupolar, and decapolar correctors placed next to the arc dipoles [21, 22]. An estimate of the hysteresis error in the octupolar correctors, based on magnetic measurements during construction, was also applied [23]. The models used do not include any matching to reproduce any measured quantity with the exception of the tunes.

The normal sextupolar RDT f_{1020}, driving the resonance $Q_x + 2Qy$ does not show a significant change in 2023, and simulations and measurements agree rather well, validating the normal sextupole model of the machine.

The skew sextupolar RDT f_{0030}, driving the $3Q_y$ resonance, has improved by about a factor 2 in Beam 1 for the new optics. Simulations do not explain the larger value for Beam 1 in 2022 while good agreement is observed for the other cases. This implies that the Beam 1 skew sextupolar model sources should be improved, probably requiring including magnet alignment errors or linear imperfections as β-beating and coupling [24].

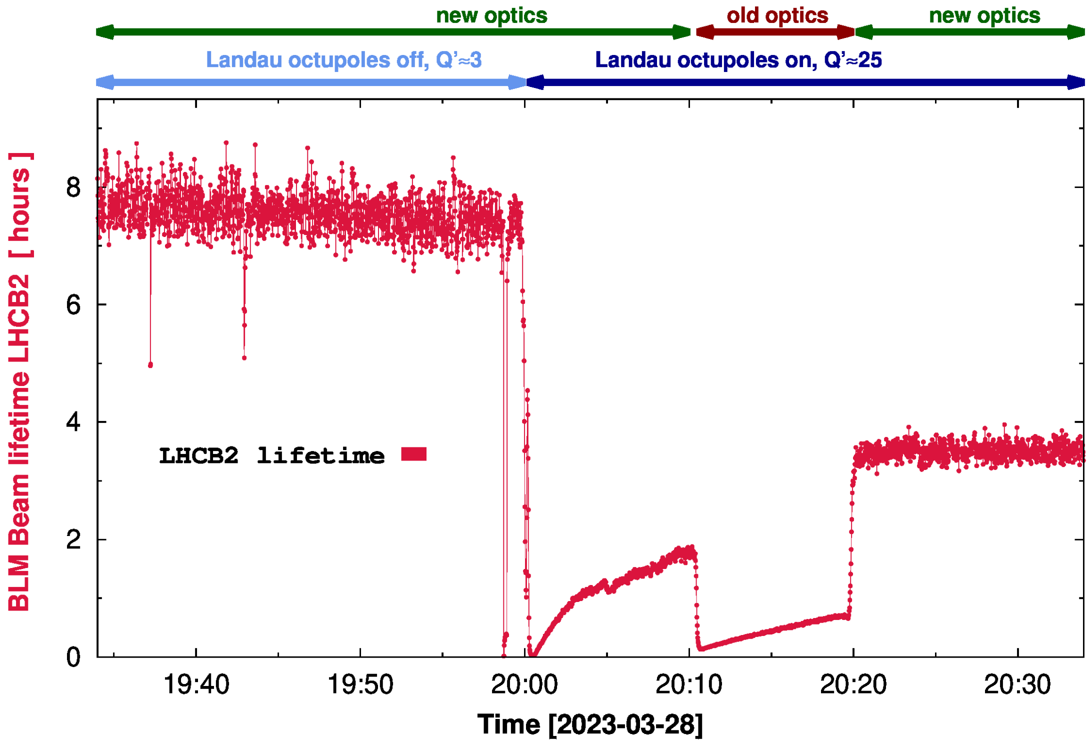

Figure 9. Measured lifetime for Beam 2 as in figure 8.

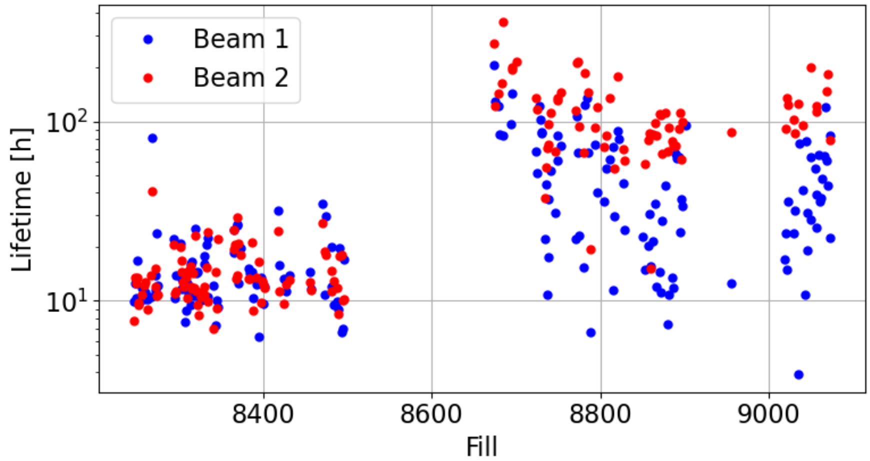

Figure 10. Measured beam lifetime at the end of the injection process during nominal operation in 2022 (fills below 8600) and 2023 (fills above 8600).

The measured octupolar term f_{2002}, driving the resonance $2Q_x - 2Q_y$, 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 figure 2. Beam 1 simulations show about a factor 2 lower f_{2002} than in measurements, implying that this octupolar resonance is not well modeled in the bare machine. Therefore the $2Q_x - 2Q_y$ resonance is now dominated by the unknown machine errors and requires further investigations.

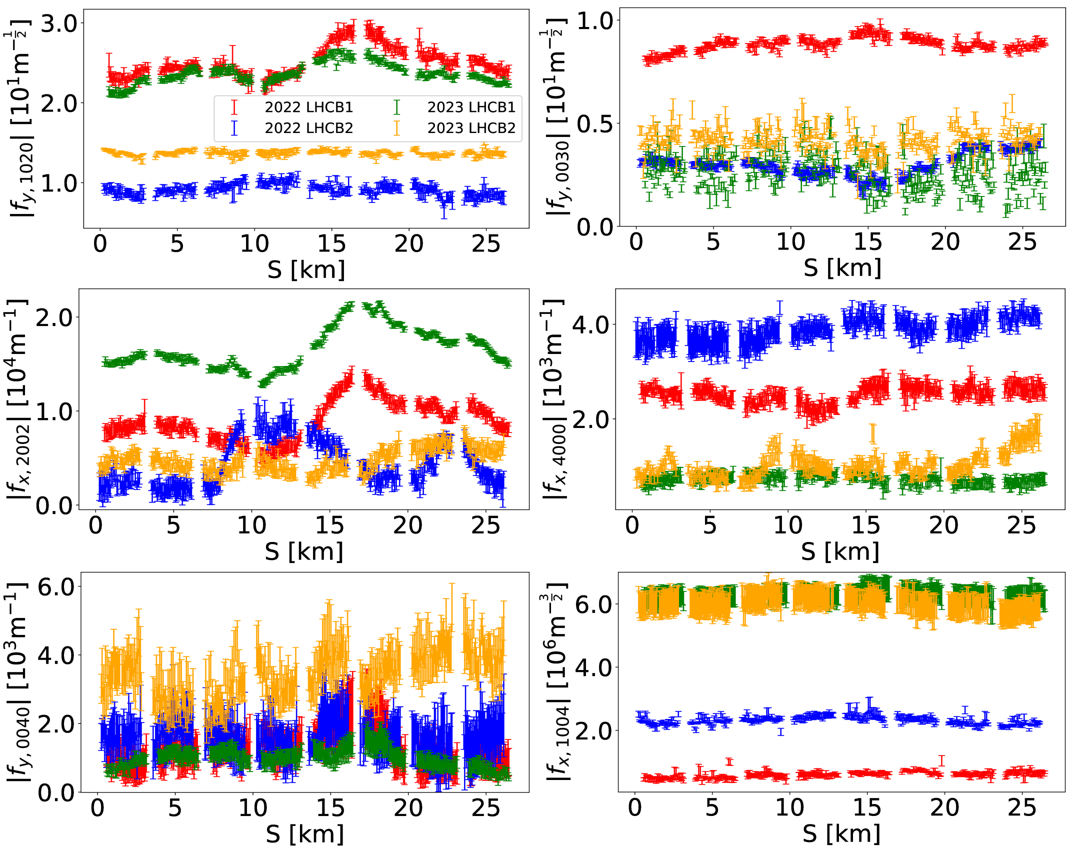

Figure 11. Measured forced RDTs for nominal machines in 2022 (red and blue for Beam 1 and Beam 2) and 2023 (green and yellow) with Landau octupoles off.

The measured octupolar RDT f_{4000}, driving the resonance $4Q_x$, is significantly reduced for both beams in the new 2023 optics. However, again, simulations do not predict the larger values of the 2022 optics, probably implying that some unknown octupole-like errors or linear imperfections are missing from the model.

For the measured octupolar RDT f_{0040}, driving the resonance $4Q_y$, only a mild increase is seen in Beam 2 for the new optics. The measurement features large relative error bars and the Beam 2 simulations predict, instead, a mild decrease of the RDT.

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 while simulations predict a reduction for both beams. Dedicated studies to understand this large discrepancy are being carried out along with potential decapolar corrections [25, 26] to mitigate this unwanted effect of the new optics.

$3Q_y$ corrections have been under investigation since 2022 [27, 28] but were compromised for requiring too large skew sextupole strengths. Thanks to the reduction of the f_{0030} term in the new optics, and the better control of the total phase errors implemented in 2023, skew sextupolar corrections can now be implemented in both beams.

RDT measurements with nominal Landau octupoles using AC dipoles are impractical due to a too low forced dynamic aperture [29]. First RDT measurements with low Landau octupole strengths were performed, however, results are not yet fully understood and need further investigations.

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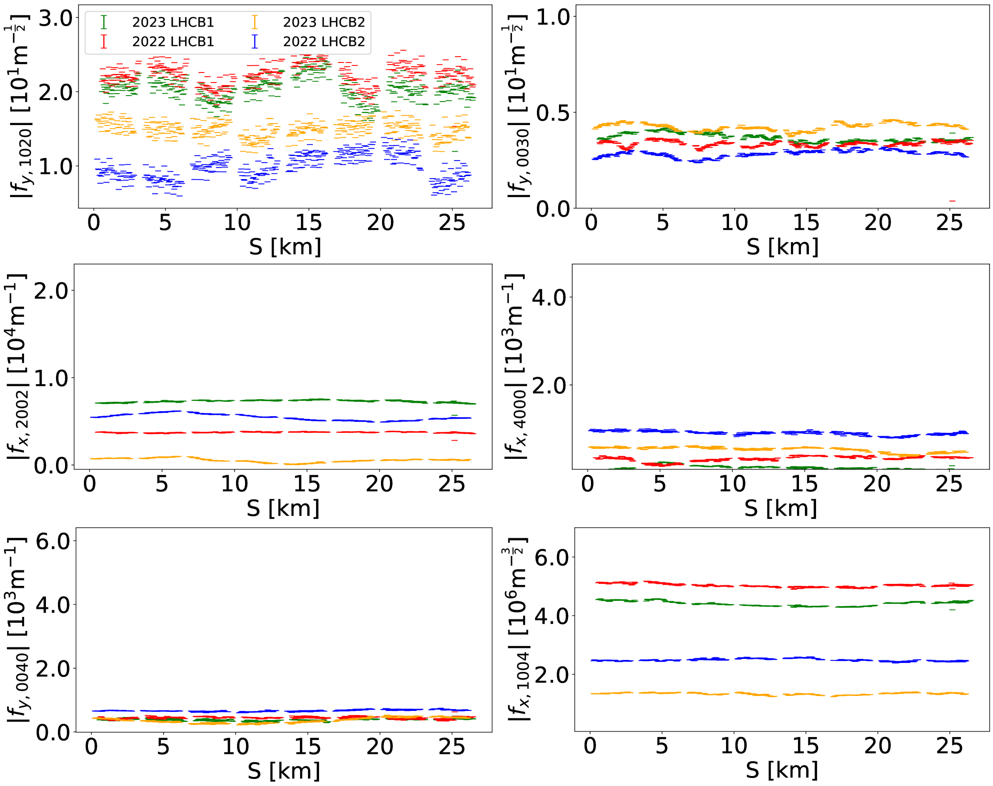

Figure 12. Simulated forced RDTs for nominal machines in 2022 (red and blue for Beam 1 and Beam 2) and 2023 (green and yellow) with Landau octupoles off.

5 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 during nominal operation. This also opens the door for operation with negative octupole polarity both for the LHC and the HL-LHC [30–32]. This new optics offers the possibility to study the machine errors in different phase configurations, which has highlighted a systematic vertical dispersion beating that could be corrected using both optics configurations. Comparing RDTs in both lattices is guiding new developments of the non-linear model of the bare machine. The largest discrepancies are seen for the decapolar order while normal sextupolar modeling shows the best agreement. This might indicate that the models need the implementation of more accurate magnetic models, misalignments or matching the linear imperfections as β-beating and transverse coupling. Incidentally, the new optics feature a weaker $3Q_y$ resonance in Beam 1 which allows for further corrections in both beams. Further improvements require correcting the machine imperfections and understanding the RDT measurements in presence of the Landau octupoles.

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