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ENERGY SENSITIVITY OF THE HIGH LUMINOSITY LHC OPTICS AT THE END OF THE β^* SQUEEZE

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Abstract

During 2022 and 2023 LHC optics commissioning, it was observed that, at low-β^*, small changes in the beam-energy could generate substantial perturbations of the linear beam optics, requiring re-commissioning of local corrections in the experimental insertions. This issue may become even more significant at the very low β^* anticipated for operation in the High Luminosity LHC (HL-LHC). Furthermore, energy drifts, for example due to the terrestrial tides, have generally been ignored during LHC optics commissioning, with no regular corrections applied during the duration of a specific measurement campaign. This paper examines the anticipated sensitivity of HL-LHC optics corrections to energy errors at the end of the β^* squeeze.

MOTIVATION

In 2022, there was a sudden optics shift identified part way through the LHC commissioning. Specifically, a change to the measured β functions around the ring was observed at end-of-squeeze ($\beta^* = 0.3\,\text{m}$), when remeasuring the exact same machine configuration after a 2.5 week period. The magnitude of the shift was non-negligible, around 10% [1]. Figure 1 shows an example of the relative optics shift measured for this period. The necessary beam-time to diagnose and re-correct the optics following this shift led to a non-negligible increase in the total optics commissioning time for 2022.

The optics deviation was ultimately attributed to an energy error ($\Delta p/p \approx 10^{-4}$) caused by the set-up of the nominal closed orbit. This final orbit set-up is performed with nominal intensity bunches after the initial phase of optics commissioning, which must be performed with pilot beams. In establishing the nominal orbit, there was a change in the average strength of horizontal closed orbit corrector magnets, leading to an energy shift. An energy shift on the reference orbit causes an optics shift due to the effective change in the beam rigidity and hence the quadrupole focusing. This becomes particularly significant at low-β^* due to the strong influence of the triplet magnets. In the years since 2022, similar energy-induced optics shifts during LHC commissioning, requiring repeated iterations of optics corrections have occurred on numerous occasions.

IMPACT OF ENERGY SHIFTS IN HL-LHC

Following the end of the LHC's third operational run in 2026, the accelerator will be upgraded to High-Luminosity LHC (HL-LHC) [2]. A key feature of the upgrade are significant reductions to the minimum β^* at end-of-squeeze (to $\beta^* = 0.15\,\text{m}$ with round optics, and possibly down to $\beta^* = 0.075\,\text{m}$ for a flat-optics option, it should be noted that a more likely option will be 18/11cm). After the HL-LHC upgrade, the impact of energy-induced optics shifts will therefore be exacerbated as the β^* will be squeezed further.

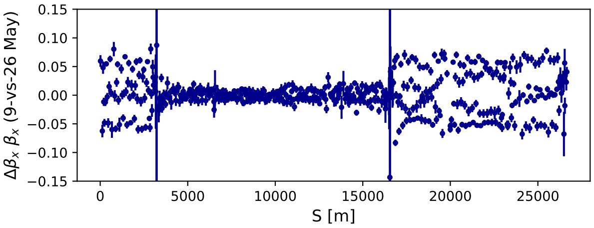

Figure 1: Measured relative optics shift for LHC beam 1 (LHCB1) between 9 and 26 May 2022 for same machine configuration at β^* 30cm [1].

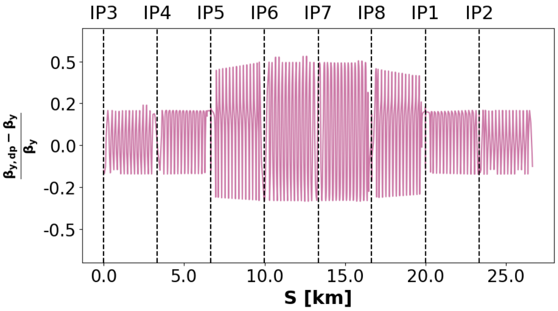

Figure 2: Vertical β-beating for HL-LHCB1 corresponding to an $\Delta p/p$ offset of $\approx 2\times10^{-4}$ using round optics.

To assess the implications for HL-LHC, typical energy errors representative of experience during LHC commissioning in Run 3 were simulated for HL-LHC models.

To model the impact of an energy offset while maintaining the same reference orbit, a systematic change in quadrupole strength was applied to the HL-LHC sequence. Following introduction of the systematic quadrupole strength error, the tune was re-matched to the previous reference using the specific quadrupole knobs used for this operation. This approach has previously proved effective in reproducing the observed β-beat in 2022 [1]. This was simulated for HL-LHC round optics at the end-of-squeeze ($\beta^* = 15\,\text{cm}$). A 2×10^{-4} energy shift ($\Delta p/p$) was considered, being representative of the worst-case energy shifts regularly experienced during LHC commissioning between 2022 and 2025. When applied to the HL-LHC simulations, this corresponded to

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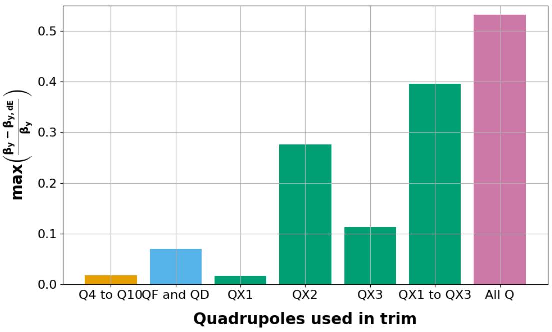

Figure 3: Maximum vertical β-beating for HL-LHCB1 for an $\Delta p/p$ offset of $\approx 2\times10^{-4}$, assessed for various quadrupole types in the HL-LHC.

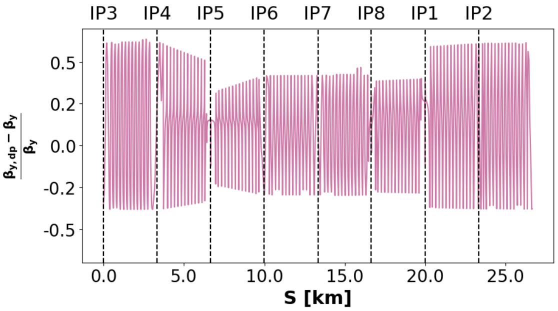

Figure 4: Vertical β-beating for HL-LHCB1 corresponding to an $\Delta p/p$ offset of $\approx 2\times10^{-4}$ using flat optics.

a peak β-beat of around 50%, which can be seen in Fig. 2 (only vertical is shown since it was a similar magnitude for horizontal β-beat). To put this into perspective, LHC optics corrections achieve around the 7% level regularly [3].

The main quadrupolar source of the β-beating was investigated by applying the quadrupole strength shifts individually to different magnet classes. Figure 3 shows the peak β-beat generated in the vertical plane of HL-LHCB1 by the IR and arc magnets. As expected the dominant contribution came from the IR triplet magnets (QX, Fig. 3 green), specifically those in QX2, however the main arc quadrupoles (QF and QD, Fig. 3 blue) also had a non-negligible effect. Quadrupoles in the matching section consistently showed a minimal impact for both beams and both planes.

Other operational backup scenarios for HL-LHC include the use of flat-optics [2], where one plane is squeezed further at the IP (down to a β^* configuration of 30/7.5cm). The flat optics produced notably larger β-beating than round optics (see Fig. 4), reaching $>60\%$ at $\Delta p/p$=2×10^{-4}.

Given the typical scale of energy error experienced during LHC commissioning in Run 3, induced by orbit set-up, if such issues persist in the HL-LHC era, a dramatic impact on optics variability through the commissioning period would be anticipated. This would pose a significant challenge to optics commissioning. In view to better control this variability in future runs, there are ongoing studies in order to automatically identify energy shifts directly from optics measurements [4]. In addition, for 2025 commissioning, the operations team will be attempting to better regulate the average orbit corrector strength during the orbit set-up process to minimise such energy shifts in the future.

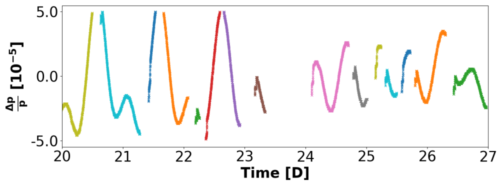

Figure 5: $\Delta p/p$ calculated from the LHCB1 RF frequency data; the different colours signify separation of shifts.

IMPACT OF TERRESTRIAL TIDES ON HL-LHC OPTICS

Given the extreme sensitivity of the HL-LHC scenarios to energy offsets, the implications of additional sources of energy drift were considered. One of the most prominent sources of energy drifts in the LHC are the Terrestrial tides, which change the beam energy through the gravitational deformation of the accelerator. This changes the path length of each particle, and the resultant mismatch between RF frequency and the new circumference leads to energy drifts [5]. Extensive studies of the terrestrial tide effect on beam-energy were performed for the Large Electron-Positron Collider (LEP) [6], the tides being a particular concern during LEP operation in the context of measurements of the Z boson. By contrast, with proton-proton operation in the LHC, tidal impacts on energy are a lesser concern, and during regular operation energy drifts due to the tides are well controlled by the LHC orbit, energy, and radial feed-back systems [7]. This modulates the RF frequency, adjusting the path length to account for any source of change in the accelerator's circumference.

During optics commissioning however, energy drifts due to the tides have never been a meaningful concern. Typically, optics commissioning is performed in shifts of 8-16 hours, and in many cases, individual measurements can persist for multiple hours at a time. During such periods, it is not uncommon that energy and orbit feed-backs may be left off for extended periods, in order not to interfere with regular beam-excitations for optics measurements [8]. It was therefore interesting to study whether tides and optics sensitivity of HL-LHC at very low β^* could cause meaningful β-beat shifts on the time-scale of typical optics measurements. In Fig. 5, the $\Delta p/p$ variation expected from a reconstruction from the radial loop feed-back at flat-top is shown.

From the graph, it can be seen that the peak-to-peak energy swing is around 10^{-4}. The rate of change of $\Delta p/p$ on typical timescales relevant to optics commissioning was calculated from radial loop measurements and from simulated tidal shifts, via the LHC steering programme YASP [9]. Simulated and measured data agree well. Figure 6 shows the predicted rate of $\Delta p/p$ change per hour, simulated over a several month period. A cyclical trend is clearly visible, with the highest rates correlated to spring tides. Figure 7 shows

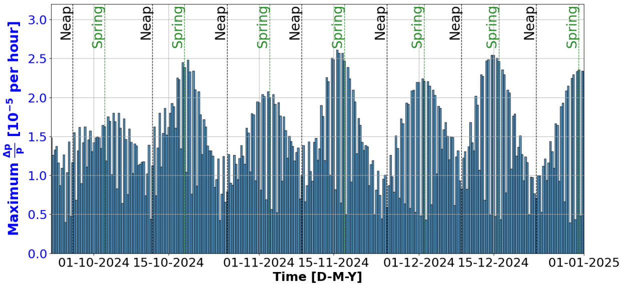

Figure 6: Maximum change in YASP-predicted $\Delta p/p$ over an hour. Spring (green) and neap (black) tide times taken from [10].

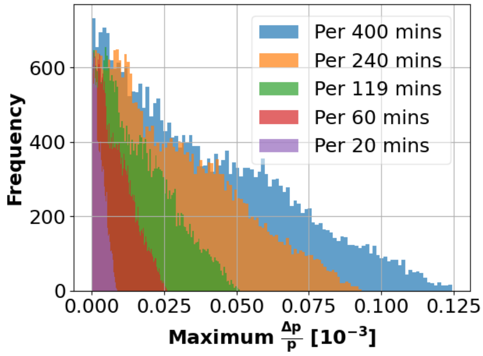

Figure 7: Distribution of tidal change in $\Delta p/p$, predicted on several time intervals relevant to optics commissioning.

the distribution of expected change in $\Delta p/p$ due to simulated tidal shifts over a 200 day period, for several time-scales relevant to commissioning.

In regard to the tides, the case shown before in Fig. 4 may be too pessimistic. Modelling an energy shift on the reference orbit (as appropriate for the orbit set-up induced shifts) does not induce any sextupolar contribution. A clearer picture relevant to the tides can be that of an off-momentum orbit in a different lattice (i.e. different lengths of lattice) resulting in chromatic β-beat (see Fig. 8) being the most appropriate description. In this case, sextupoles help reduce the maximum off-momentum β-beat, which is also more localised around the experimental IRs. Nonetheless, during optics commissioning, local corrections in the IR are a vital concern, meaning errors in these regions are still significant.

Figure 9 shows the change to peak off-momentum β-beating vs $\Delta p/p$ for flat and round HL-LHC optics. Using this chromatic β-beating and Fig. 7 to estimate tide-induced peak-optics shifts returns a sizeable distribution on timescales relevant to optics commissioning, as seen in Fig. 10.

Moving forward, with a view to HL-LHC commissioning, greater care should be taken during optics measurements to control radial drifts due to the tides.

CONCLUSION

Repeated observations of optics shifts during LHC commissioning, caused by energy errors induced via closed-orbit setup, has sparked concern for the HL-LHC operational era, where the smaller β^* will amplify the effect. When energy shifts, typical for the LHC, were simulated for HL-LHC end-of-squeeze optics the β-beating induced was dramatic. Better control of these orbit induced energy errors will be necessary in HL-LHC, studies for which are ongoing. Given the sensitivity of HL-LHC optics to energy errors, the potential impact of energy shifts from terrestrial tides (which are typically uncontrolled during optics commissioning) was studied. The resultant shifts in β-beat can become significant on timescales relevant to optics measurements.

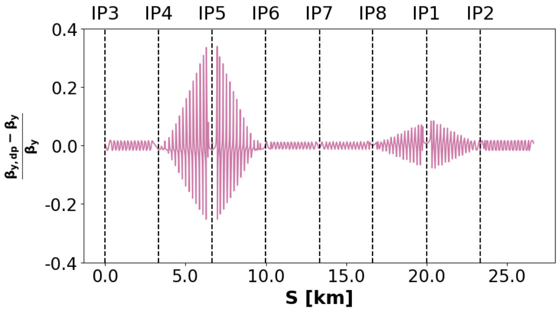

Figure 8: Vertical off-momentum β-beating for HL-LHCB1 corresponding to a $\Delta p/p$ offset of $\approx 2\times10^{-4}$ using flat optics.

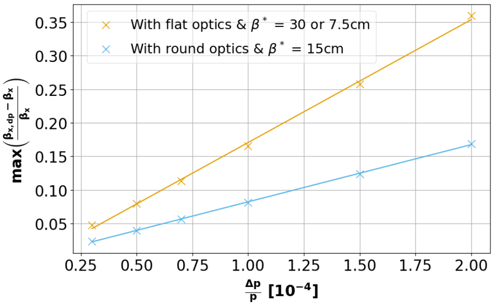

Figure 9: Predicted maximum Δchrom β_x/β_x for HL-LHCB1 as a function of $\Delta p/p$.

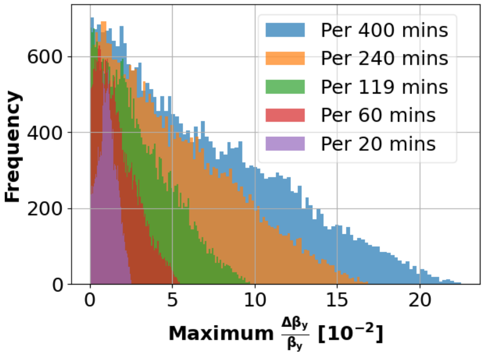

Figure 10: Maximum change in Δchrom β_y/β_y for HL-LHCB1 flat optics over several different time intervals.

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