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SEXTUPOLE RDTS IN THE LHC AT INJECTION AND IN THE RAMP

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Abstract

During 2023, examination of the action dependence of sextupolar resonance driving terms (RDT) in the LHC at injection, as measured with an AC-dipole, demonstrated that a robust measurement of the RDTs could still be achieved even with very small amplitude kicks, typically used for linear optics studies. Consequently, analysis of optics measurements from 2022 to 2024 during the LHC energy ramp allowed a first measurement of the sextupole resonance evolution. A large asymmetry was observed between the two LHC beams, with the clockwise circulating beam (LHCB1) being significantly worse than the counter-clockwise circulating beam (LHCB2), and a clear increase in the RDT strength during the ramp was observed. During 2024 commissioning, a first attempt was made to correct the f_{1020} RDT of LHCB1 at injection. Results are presented in this report.

SEXTUPOLAR RDTS

Resonances, $(j-k)Q_x+(l-m)Q_y$, are quantified by the strength of their respective resonance driving terms (RDTs), f_{jklm}. These can be measured by analysing Turn-by-Turn (TbT) beam position monitor (BPM) data with [1] or without AC-dipole (ACD) excitation [2–4]. The resonance lines appear as peaks in the tune-spectra.

For the normal sextupolar $Q_x + 2Q_y$ resonance, characterised by the f_{1020} RDT, a spectral line in the horizontal spectrum is expected at $-2Q_y$ and at $-Q_x-Q_y$ in the vertical spectrum. An example of a horizontal spectrum is shown in Fig. 1, with the main normal sextupolar resonances labelled in green, and the driven ACD tunes highlighted in red.

The significance of this resonance $(Q_x + 2Q_y)$ is that a strong f_{1020} line is seen clearly, even in measurements of linear optics where the kick amplitude is small (as seen in Fig. 1).

Typically, to obtain reliable RDT measurements, large ACD excitations are needed. An analysis of the f_{1020} vs. action demonstrated that, as expected, the RDT did not vary with action. This can be seen in Fig. 2, where the lowest action excitations are typical amplitudes for linear optics measurements. It was therefore concluded that even f_{1020} measurements from the linear optics studies were reliable. Interestingly, it was discovered that there was a consistently greater amplitude of f_{1020} in LHCB1 than in LHCB2.

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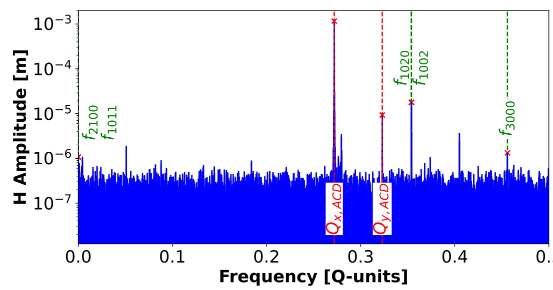

Figure 1: Example of a typical horizontal turn-by-turn spectrum from low AC dipole excitations.

During the LHC commissioning, it is normal to check the linear optics during the ramp [5] from injection (450 GeV) to top energy (6.8 TeV). Given the aforementioned results, a first non-linear analysis of the sextupole RDT during the LHC ramp was performed in 2023. These measurements, presented in Fig. 3, revealed some reduction of the f_{1020} just above the injection energy and then a growth of the RDT during the ramp, with again a consistently larger amplitude for LHCB1 compared to LHCB2. Re-analysis of 2022 data, as well as subsequent measurements in 2024, showed the same trends.

The prominence of the f_{1020} RDT was also surprising given that the $Q_x + 2Q_y$ resonance is relatively far from the nominal working point ($Q_x = 0.28$, $Q_y = 0.313$) as seen in the tune diagram featured in Fig. 4.

Thus, there was a strong motivation to correct this RDT, specifically to reduce LHCB1 f_{1020} RDT to LHCB2 level and see if there is improvement in lifetime or other operational aspects. First attempts at a correction were carried out during 2024 commissioning at injection energy.

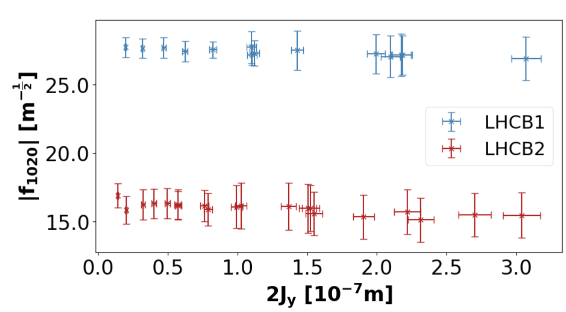

Figure 2: Strength of f_{1020} RDT quantified by the mean amplitude of the RDT around the ring vs. action at injection.

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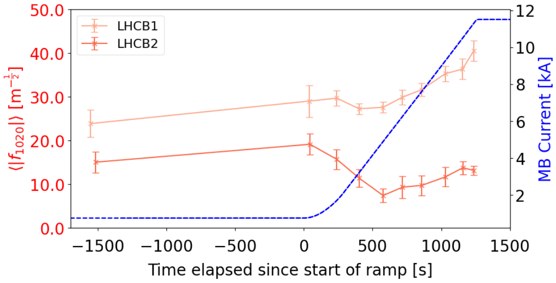

Figure 3: 2023 measurement of $|f_{1020}|$ in the ramp.

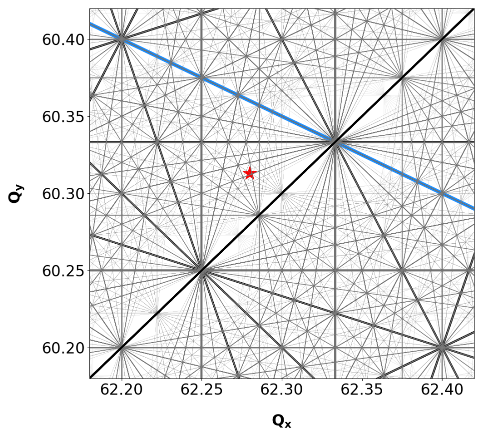

Figure 4: LHC tune diagram, with the nominal working point highlighted in red and the f_{1020} resonance in blue.

Simulation for the Correction

A model of the injection optics was created in MAD-X [6], where both the amplitude (Fig. 5) and phase of the f_{1020} RDT were found to globally match rather well with the measurements, especially compared with studies of other resonances in the LHC [7].

From the model, it was discovered that the majority of the RDT was driven by the main sextupole magnets (MS) used for chromaticity correction. In particular, models with the MS being the only sextupole sources displayed consistent amplitude and phase of f_{1020} with the measurements, and only a comparatively small shift to the RDT was obtained through inclusion of the b_3 error model and MCS sextupole correctors. Hence, a simple MAD-NG [8] simulation was created (chosen due to its powerful RDT matching capability) to explore the possible corrections to minimise the f_{1020}, by varying only the MS. This method would avoid changing the betatron-phase which had previously been optimised to suppress RDTs generated by the Landau octupoles [7].

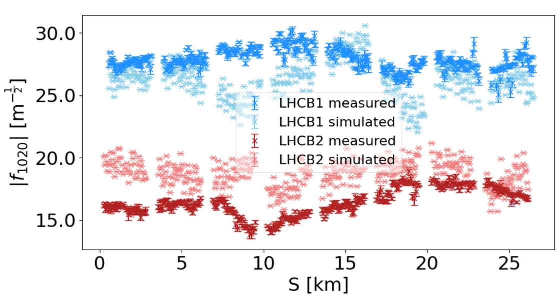

Figure 5: Amplitude of forced f_{1020} vs. distance along LHC circumference for MAD-X simulation and measurement.

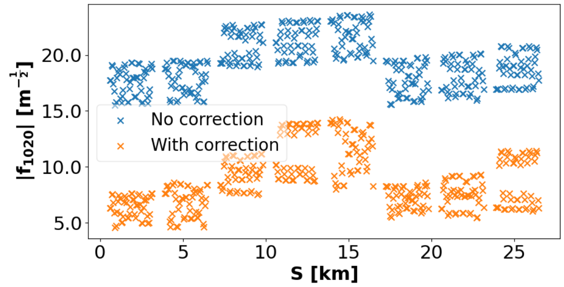

Figure 6: MAD-NG simulated amplitude of free f_{1020} around the LHC ring for LHCB1 with and without correction.

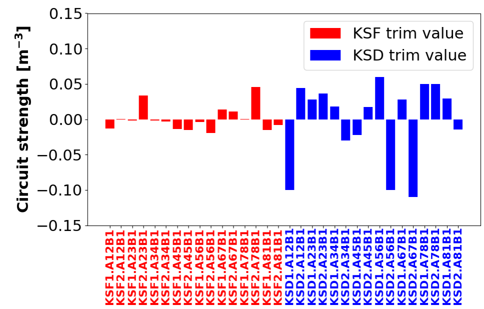

Figure 7: Normalised sextupolar gradient strengths used for the trim added to the nominal MS strengths

In the LHC, the MS are divided into families near the focussing quadrupoles (MSF) and defocussing quadrupoles (MSD). These are then further divided into 2 families per arc (MSF1,2 and MSD1,2).

The setup for the simulations used a basic model of the 2024 injection optics, with the MS powered nominally and uniformly to compensate the natural chromaticity ($Q' = 0$). The RDT was matched to a reduced value, by independently varying the 32 MS circuits, whilst constraining the Q' to be unchanged, limiting the range of the MS trims, and not significantly degrading any other sextupole RDTs. The capability in simulation was there to match RDT to zero, however it was found that in doing so, an unacceptably large chromatic beta-beating [9] was generated. Therefore, chromatic beta-beating was considered in the optimisation process. In practice, a compromise had to be made between reducing the RDT and minimising chromatic beta-beat. In the end, a partial correction was found which was predicted to significantly reduce the RDT, as presented in Fig. 6, and be acceptable in general operation. This correction was selected to be tested in the machine. Figure 7 shows the final trims of the MS for the corrections added to the initial circuit powerings.

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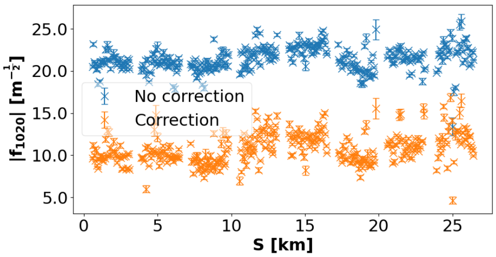

Figure 8: Measured amplitude of f_{1020} around the LHC ring for LHCB1 from the vertical kicks.

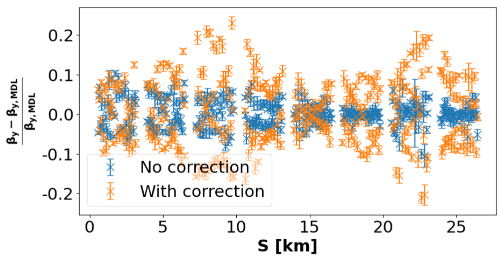

Figure 9: Vertical beta-beating with and without the f_{1020} correction at $\Delta p/p_0$ = 1.43×10^{-3}.

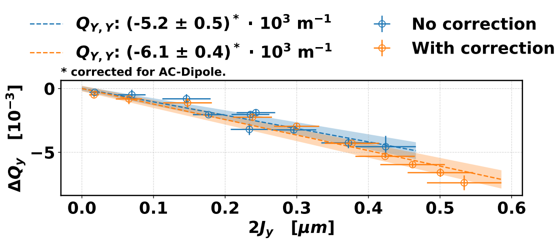

Figure 10: Change in tune as a function of action with and without the correction.

Implementation of Correction in the LHC

In March 2024, during the annual commissioning of the LHC, measurements were performed with and without the aforementioned correction applied. In Fig. 8, the measured f_{1020} amplitude is seen to be reduced by half with the correction implemented, roughly consistent with the expectation from the model.

Chromatic beta-beating was measured at the largest $\Delta p/p_0$ offset of interest to machine protection studies such as [10] (corresponding to $\Delta p/p_0$=1.43×10^{-3}). Figure 9 shows that the vertical beta-beat was below 22% at this frequency, both with and without the correction applied. The increased chromatic beta-beat was consistent with expectation from the model and was not deemed to be a problem for operation. The horizontal beta-beat was lower than this.

Tune and chromaticity were unaffected by the correction within measurement reproducibility. Amplitude detuning measurements [11] also showed no change due to the correction (see Fig. 10).

During these measurements (Fig. 10), it was found that with the RDT correction applied it was possible to excite to higher ACD amplitudes without being limited by beam-losses. This suggested the forced dynamic aperture [12] was improved by the correction. This effect can likewise be observed in Fig. 11, where the surviving fractional intensity vs. excitation amplitude is depicted, and a significant reduction in losses when the correction is applied can be seen.

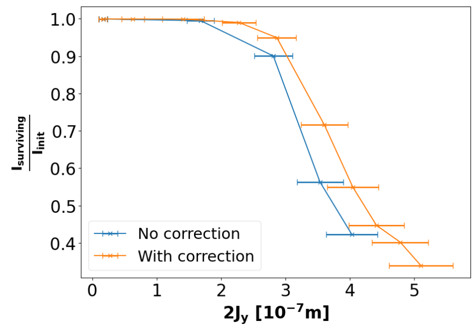

Figure 11: The fraction of beam intensity surviving vs. action for the vertical kicks with and without the f_{1020} correction.

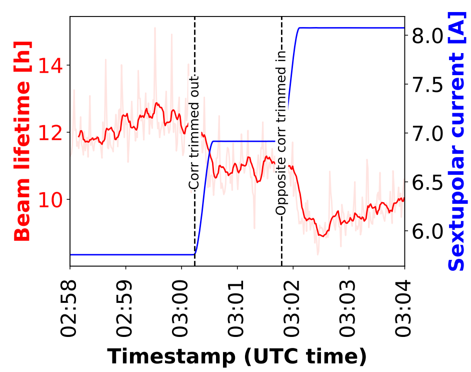

Figure 12: The effect of the correction on the lifetime averaged with a rolling window, with the raw signal shown in pale red, and the corresponding sextupolar currents vs. time

A lifetime test was made as well, with freshly injected pilot beams and the MO powering at 40A depicted in Fig. 12. This found that the removal of the f_{1020} correction decreased the lifetime, and that it was further reduced by applying the inverse of the correction to degrade the RDT. Turning off the f_{1020} correction degraded the lifetime on the same scale as turning on the MO in this case.

CONCLUSION

It was revealed that even in linear optics measurements, phase space deformations from the Q_x+2Q_y resonance were visible. This motivated studies to correct this resonance. MS strengths were computed to minimise $|f_{1020}|$ in LHCB1 with MAD-NG. The correction was verified experimentally to improve beam lifetime and forced DA. Hence, it is now implemented in nominal LHC operation. Future studies will explore correcting the RDT further, at high energy, and for both beams.

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