

INVESTIGATION OF OCTUPOLAR RESONANCES IN THE LHC

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Abstract

During operation for luminosity production, the LHC runs with very strong Landau octupoles to ensure the collective stability of the beams. A disadvantage of this is that these octupoles can drive resonances which can be detrimental to beam lifetime. Recently, a special optics configuration has been utilised to reduce the impact of the main octupoles on lifetime. This design relies on correctly modelling the resonance driving term (RDT) response to changes in these magnetic circuits. This paper presents beam-based studies comparing the RDT response to simulations where large discrepancies were found. To try and understand the source of this, several approaches were taken. Various methods including individual circuit measurements, studies of other circuits, and tests at different energy were employed but it remained challenging to localise the source of the discrepancy around the ring. This paper presents an attempt to apply and extend a segment-by-segment method, that has been very effective at identifying local linear optics errors, to non-linear errors through analysis of RDTs.

MOTIVATION

At injection energy in the LHC, one of the main drivers of normal octupole resonances are the Landau Octupoles (MO), which are powered strongly ($K_4 = 18\text{m}^{-4}$) to introduce tune spread for the purpose of Landau damping [1].

Figure 1 shows the Q-spread (in red) generated by the MO at injection energy (450 GeV). The key resonances of interest, driven by normal octupoles, are highlighted in blue.

Unfortunately, the beneficial (in regard to Landau damping) tune spread caused by the MO can lead to particles crossing resonances, potentially resulting in emittance growth, or particle loss. Thus, Landau damping must be balanced with optimisation of dynamic aperture.

In 2023, a new optics configuration was deployed in the LHC, aiming to reduce the impact of the MO on lifetime with minimal change to the detuning [2]. This design relies on the accuracy of modelling the resonance driving term (RDT) response to changes in these magnetic circuits. Hence, it was a priority to attempt to measure the MO RDTs for the first time, to test the effectiveness of this new optics configuration. Beam-based studies were thus performed to compare the response with simulations.

MO RESPONSE WITH THE NEW OPTICS

First octupolar RDT measurements are shown in Figs. 2 and 3, where the normal octupole RDT f_{2002} (driving the $2Q_x - 2Q_y$ resonance) measured (blue) before and after the

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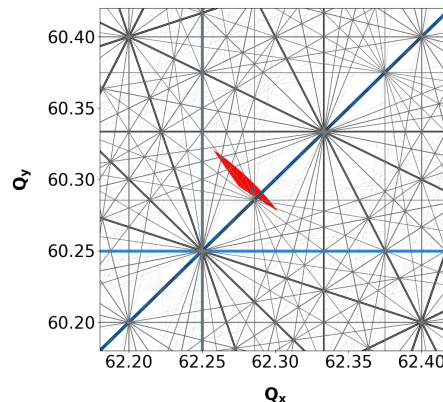


Figure 1: Tune diagram where blue denotes resonances $4Q_x$, $4Q_y$, and $2Q_x - 2Q_y$, and the red area is the tune footprint caused by the MO at injection tunes at 6σ .

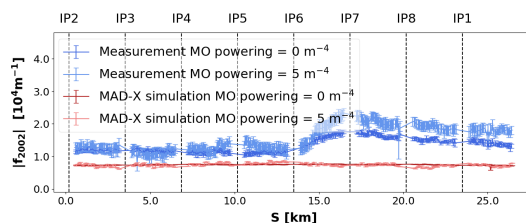


Figure 2: Measured vs. simulated amplitude of f_{2002} RDT with and without MO powered for LHC B1.

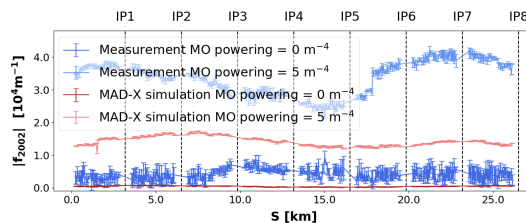


Figure 3: Measured vs. simulated amplitude of f_{2002} RDT with and without MO powered for LHC B2.

MO was powered on to $K_4 = +5\text{m}^{-4}$. The prediction for the new 2023 optics is shown in red.

The new injection optics was supposed to suppress the RDT generated by MO, however in Fig. 3, the RDT generated by the MO for LHC B2 is clearly worse than expected from simulation. Initially in Fig. 2, the shift in amplitude of the LHC B1 RDT looks similar in simulation to measurement. On the other hand, when comparing the real and imaginary parts of the RDT (as depicted for the imaginary parts in Figs. 4 and 5), it was found that in reality there was an even larger discrepancy for LHC B1 than LHC B2. This occurs because the amplitude does not take into account any change

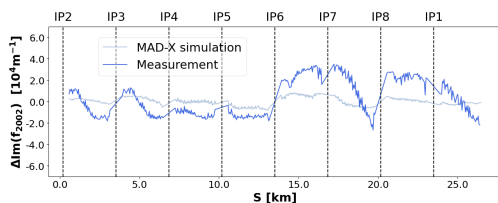


Figure 4: f_{2002} imaginary part shift caused by all MO powered at 5 m^{-4} for LHC B1 in simulation and measurement.

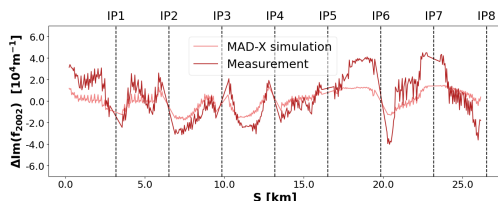


Figure 5: f_{2002} imaginary part shift caused by all MO powered at 5 m^{-4} for LHC B2 in simulation and measurement.

in phase of the RDT. As a consequence, this study focuses on the shift to the real and imaginary parts of the RDT, rather than the shift of their amplitudes.

This inconsistency was found reproducibly over several measurements in 2023 and 2024. Many beam-dynamics studies rely on accurate modelling of the MO circuits. Therefore, it was crucial to find the reason for this disparity.

TESTING MEASUREMENT PROCEDURES

Given the significance of the MO to LHC operation, it was vital to confirm that the observed discrepancy reflected a real problem with the MO response, and not simply an issue with the measurement procedure or analysis tools.

To assess the analysis tool performance, directly calculated RDT strengths obtained from the MAD-NG code were benchmarked against tracking simulations performed in MAD-X and analysed with OMC analysis tools [3]. Both methods of RDT determination were found to be consistent.

Further validation of the measurement procedure was undertaken by testing the response of a different octupole circuit at top energy. Dedicated measurements of the RDT response of the octupole correctors in the experimental insertions were performed (MCOX). The MCOX was powered in IP1 (ATLAS) and IP5 (CMS) in such a way that amplitude detuning was unaffected, but strongly shifting the RDT. The inverse of the trim was also measured. Figure 6 shows the shift to the imaginary part of the RDT measured during the test. Forward and reverse trims cause opposite shifts to the RDT, as expected. Figure 7 compares the measured shifts to the imaginary part of f_{2002} to model predictions. There was a good correspondence between simulation and measurement, suggesting the measurement procedure is robust.

Another potential cause of the problem could have been RDT measurements being perturbed by amplitude detuning induced by the MO themselves. Alternative arrangements of MO powering were measured at injection, with alternating

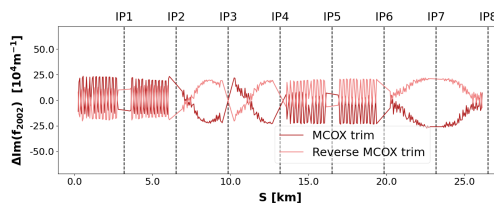


Figure 6: Comparison of measured shift to imaginary part of the f_{2002} RDT caused by the MCOX trim and its reverse.

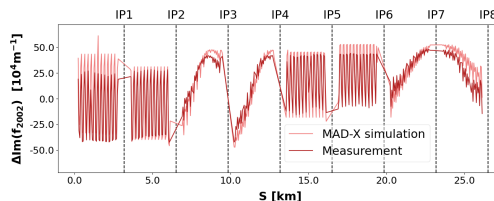


Figure 7: Comparison of simulation and measurement for shift to imaginary part of f_{2002} RDT caused by MCOX trim.

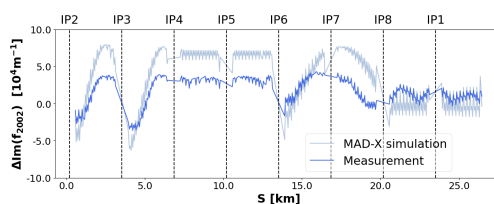


Figure 8: Shift to the imaginary part of f_{2002} caused by all the MO being powered at 5 m^{-4} for LHC B1 in simulation and measurement for 2022 optics.

positive and negative strengths to induce negligible detuning. However, the discrepancy remained. Given these confirmations, the observed discrepancy in RDT response appeared to relate to a real problem in the machine, rather than any issue with the measurement procedure.

OLD OPTICS MO RESPONSE

It was necessary to establish if this problem was caused by the MO or simply the introduction of the new optics. In order to test this, the new injection optics was reverted to the state of 2022 during dedicated beam-tests. A large discrepancy is still seen in the example Fig. 8 although the impact of MO was now less than predicted. This establishes that the issue was not a consequence of the new injection optics but with the MO.

MO RESPONSE IN DIFFERENT CONFIGURATIONS

The next step was to determine if the RDT response reflected an issue with all, or only some, MO circuits. To this end, measurements were completed with two different circuit arcs powered individually to compare with a MAD-X simulation. As shown in Figs. 9, and 10, by powering only single focusing MO circuits in Arc12 or only Arc56, the shift agreed well in simulation compared to measurement. This shows the response discrepancy does not arise from a

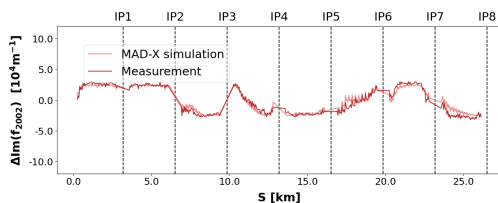


Figure 9: Shift to the imaginary part of measured and simulated f_{2002} caused by the MO in arc12 being powered at 10 m^{-4} for LHC B2.

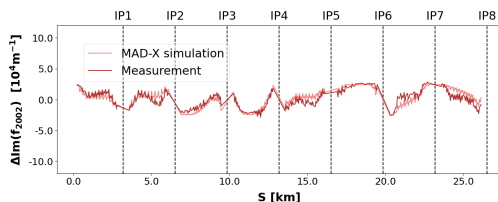


Figure 10: Shift to the imaginary part of measured and simulated f_{2002} caused by the MO in arc56 being powered at 10 m^{-4} for LHC B2.

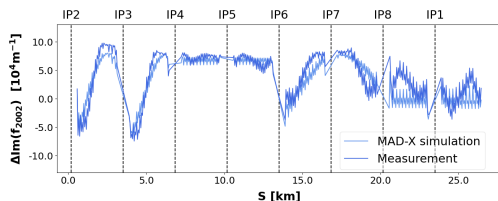


Figure 11: Comparison of simulation and measurement for the difference in the imaginary part of the f_{2002} RDT caused by all MO being powered at 5 m^{-4} for LHC B1.

uniform non-conformity of the MO circuits, however testing each individual circuit represents a substantial draw on LHC beam-time, and has not yet been performed.

Before carrying out this long task, it was decided to conduct some tests during a proton-proton reference run (PP Ref), to see if the discrepancy between model and measurement could be the result of a different issue. During the PP Ref run beam energy is about 2.6 TeV, allowing the measurement with the same K_4 strength, but with higher currents. Figures 11, and 12 show a much better alignment between simulation and measurement than at injection.

This has resulted in a new hypothesis that the model does not include some large component of hysteresis in the octupoles (with a current of $\approx 11 \text{ A}$ for $K_4=5 \text{ m}^{-4}$) that is significant at injection.

SEGMENT-BY-SEGMENT STUDIES

One of the challenges highlighted by this study is the difficulty in localizing the source of non-linear errors. This can be very time-consuming, requiring a systematic check of each arc individually.

A method that is very successful at identifying locations of local errors in the linear regime is the Segment-by-Segment

approach (SbS) [4]. A preliminary study was carried out to

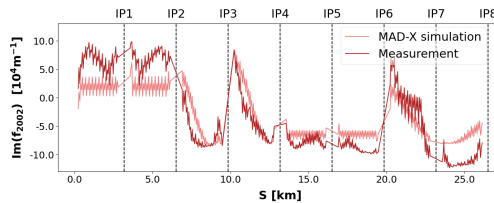


Figure 12: Comparison of simulation and measurement for the difference in the imaginary part of the f_{2002} RDT caused by all MO being powered at 5 m^{-4} for LHC B2.

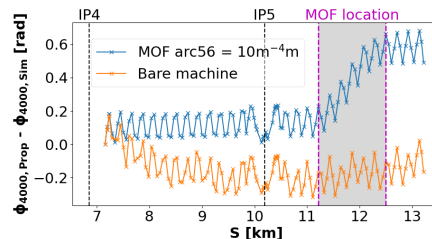


Figure 13: Comparison of the difference between simulation and propagated f_{4000} phase for the bare machine and MOF in arc56 powered at 10 m^{-4} for LHC B1.

test if a similar procedure could also be effective for non-linear errors. Simulation studies were conducted in MAD-X, via tracking simulations with the AC-Dipole included. These tracking simulations were analysed with OMC3 tools, and the measured RDT phase advance from an initial BPM was compared to an analytical prediction of the RDT propagation (see Eq. (3) in [5]).

Figure 13 shows the difference between the propagated and simulated phase of the f_{4000} RDT for the machine without any MO powered, compared with a simulation including a mispowering of the MOF in arc56. It can be seen that there is a shift in phase difference in the section where the MOF are located, i.e. where the “error” is introduced. Although representing a simple test case, this demonstrates the potential of a non-linear SbS method to help identify local non-linear errors.

CONCLUSION

The MO RDT response was studied for the first time and a large discrepancy was found. Various tests of measurement procedure led to the conclusion that this was a real issue which was not related to optics but to MO hardware. It appears to be a hysteresis issue that is only significant at injection energy. The challenge now is to localise the specific circuits. To this end, the study of the SbS method applied for non-linear errors was explored. The preliminary simulation results showed that this is a promising method to use.

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