Optics Studies and Corrections in the LHC

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Abstract

This report presents three optics studies conducted during an internship with the Optics Measurement and Correction team at CERN's Large Hadron Collider (LHC), aimed at improving machine performance and luminosity delivery. The first study involved commissioning of ion optics for the upcoming proton and oxygen collision cycles, using AC dipole–based measurements and global optics corrections to reduce β-beating. The second study examined waist shifts and β^*-beating at 18 cm optics following application of optics corrections during LHC commissioning, revealing significant discrepancies between measured and simulated optics at low β^*, which suggests limitations in current models. The third study investigated anomalies in 3Qy resonance driving term measurements, identifying strong evidence for systematic miscalibration of the beam position monitors as a potential cause. By combining LHC measurements with MAD-X and Xsuite simulations, these studies provide valuable insights relevant to both near-term runs and long-term upgrades, including the High Luminosity LHC.

Contents

1 Introduction

The Large Hadron Collider (LHC) is a highly complex accelerator whose performance depends on precise control of beam optics to sustain high luminosity at the four interaction points (IPs) holding the main experiments. Achieving this requires continuous measurement and correction of beam parameters, using a combination of experimental studies and simulations.

The Optics Measurement and Correction (OMC) team commissions the LHC optics for each operational cycle, which can involve different particle species with specific energy and β^* requirements. For the upcoming proton and oxygen cycles, dedicated corrections were required, following measurements of key observables such as β-beating, dispersion, and resonance driving terms (RDTs). The β-function describes the transverse beam envelope along the accelerator, with β-beating denoting its deviations from the design values. Dispersion quantifies the sensitivity of particle trajectories to momentum deviations, while RDTs characterize non-linear resonances induced by magnetic field imperfections.

This work focuses on three studies central to LHC performance: commissioning of ion optics for the proton and oxygen cycles, analysis of waist shifts and β^*-beating at $\beta^* = 18\,\mathrm{cm}$ optics (where β^* denotes the value of the β-function at the interaction point), and investigation of anomalies in 3Qy resonance measurements, likely linked to beam position monitor (BPM) calibration. These studies combined direct LHC measurements with simulations in MAD-X and Xsuite, providing results relevant both to immediate operation and to future upgrades, including the High Luminosity LHC (HL-LHC).

2 Ion Optics Commissioning

The commissioning of optics in the LHC involves measurements of the two beams, achieved by exciting them with an AC dipole [1]. This adiabatic excitation enables the repeated collection of accurate turn-by-turn beam position data from which spectral analysis can be performed, and key measurements, such as the β-beating [2] shown in

Eq. (1), can be extracted.

$$\frac{\Delta\beta}{\beta} = \frac{\beta_{measured} - \beta_{design}}{\beta_{design}} \tag{1}$$

β-beating exceeding 20% typically necessitates correction to meet machine protection constraints and minimize beam losses in areas where it could cause damage to components and degrade magnets. These corrections [3] are implemented through adjustments of quadrupole magnets around the accelerator ring to reduce β-beating (see Figure 1).

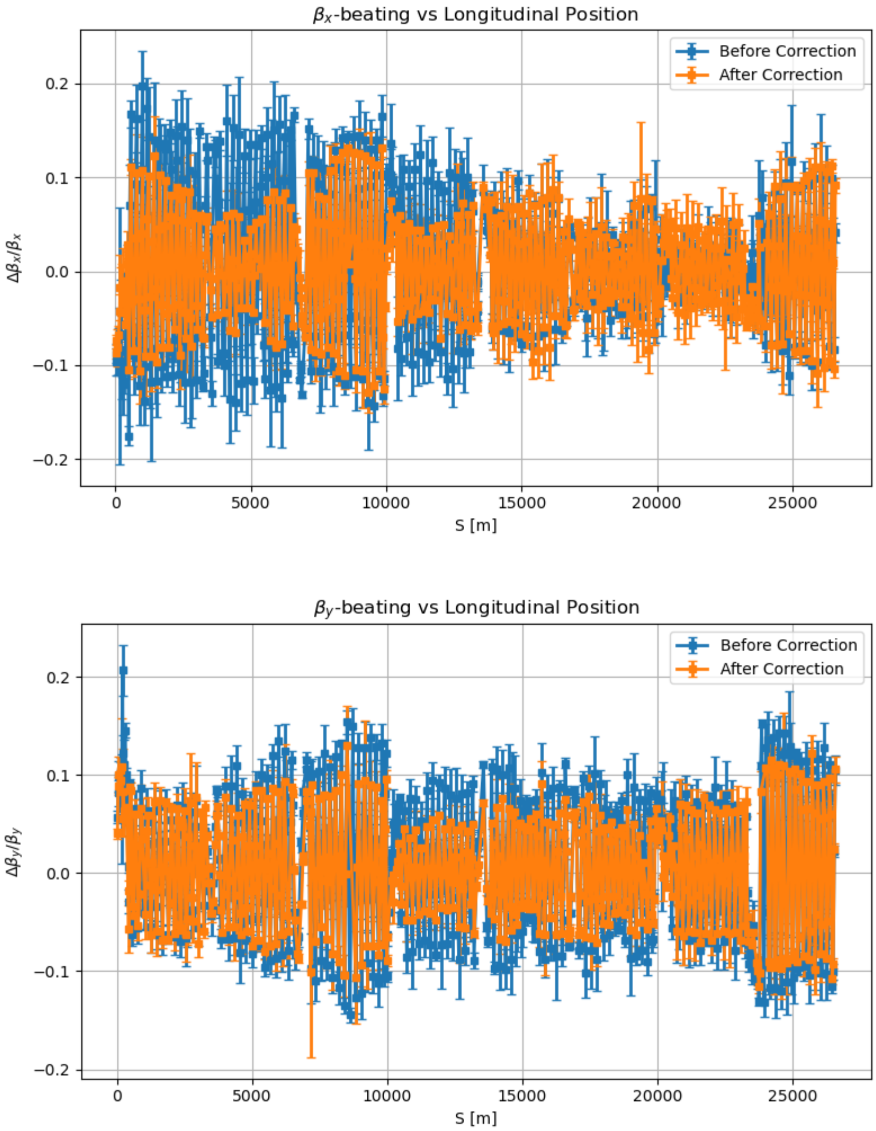


Figure 1: β-beating correction in the energy ramp at 6.3 TeV. Blue is before the correction and orange is after showing a successful reduction below 20%.

This study focused on applying global corrections to reduce β-beating, particularly around the interaction points (IPs), where optics deviations have the greatest impact on luminosity. To produce and implement corrections, first a model of the ideal optics is created using the OMC3 software tool [4] along with MAD-X [5], software used to simulate accelerators and beam dynamics. Then turn-by-turn data is measured from the AC dipole and analyzed using OMC3 to obtain important quantities such as the β-beating. Measurements usually deviate from the ideal optics, so quadrupole strengths are varied in simulation until the simulated β-beating matches the measured β-beating. The changes to the quadrupoles made in simulation can then be inverted and applied to the simulation (Figure 2) or the real machine (Figure 1), with the goal of reducing β-beating toward zero. These inverted quadrupole strength changes taken from simulation combined form the global correction.

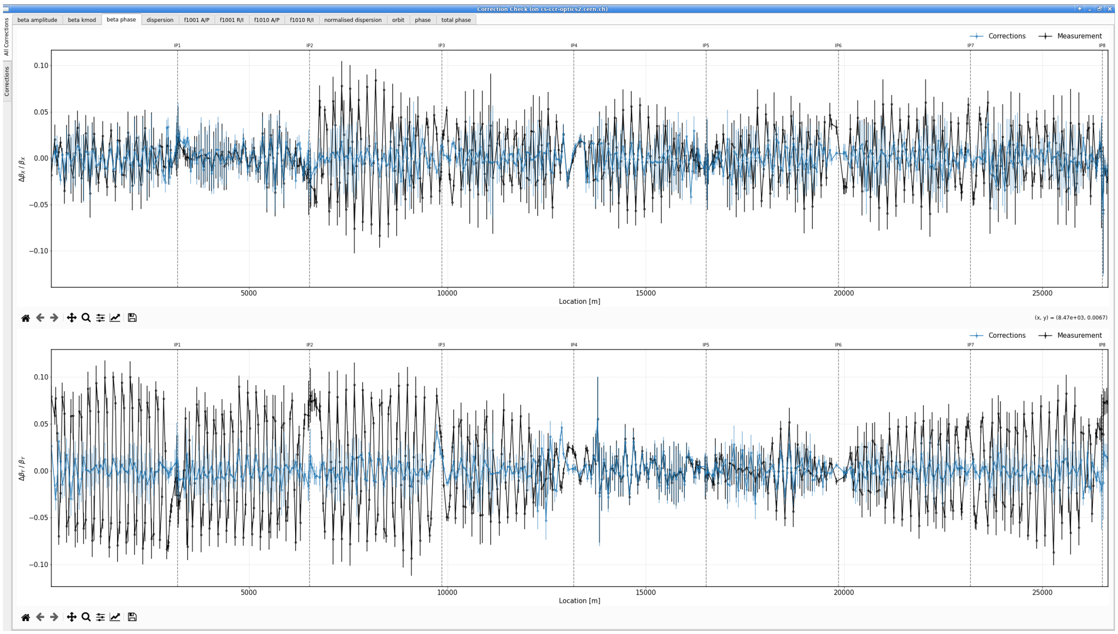


Figure 2: Simulated correction (Blue) of β-beating on measurement (Black) at flat top.

The LHC beam cycle comprises several distinct stages: injection, where bunches are transferred from the SPS at 450 GeV; ramp, during which the beam energy is increased to 6.8 TeV; flat top, where the beams stabilize at top energy; and squeeze of the β-functions at the IPs to maximize luminosity, by the end of which β^* reaches 18 cm in one plane while the other reaches 60 cm due to the use of flat optics [6]. A global correction was first found at the end of squeeze stage that brought the β-beating to satisfactory levels. This correction was then tested at other stages such as injection, flat top, and the energy ramp. Ideally, one correction will work for all stages, however, it was found this cycle that the ramp needed its own dedicated correction as the tested global correction did not bring the β-beating below the desired levels. After a new correction was calculated for the ramp (Figure 1), it was subsequently tested along with the previous correction applied in the other stages to verify that the entire LHC beam cycle maintained β-beating values below the desired threshold.

Uncorrected β-beating poses a limitation on beam intensity in the LHC due to machine protection constraints. Only a single pilot bunch of 10^{10} protons is allowed until the optics are fully commissioned, compared to the operational requirements of >1000 high intensity $1.6*10^{11}$ proton bunches for effective luminosity production. The corrections calculated during this commissioning cycle enabled both the proton and oxygen collision cycles to operate safely while satisfying all machine protection requirements.

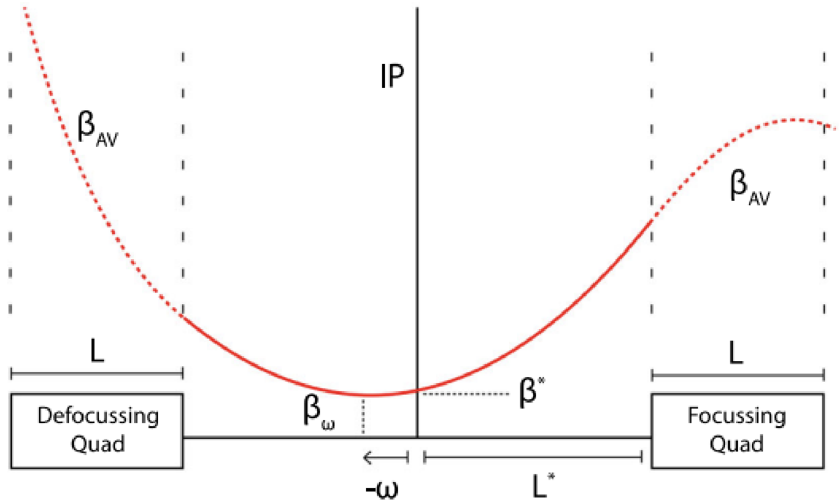


Figure 3: [7] A diagram showing the β function in the interaction region. The waist w corresponds to the minimum of the β function, but does not necessarily coincide with the IP.

3 Analysis of Waist Shifts and β^*-Beating at 18 cm Optics

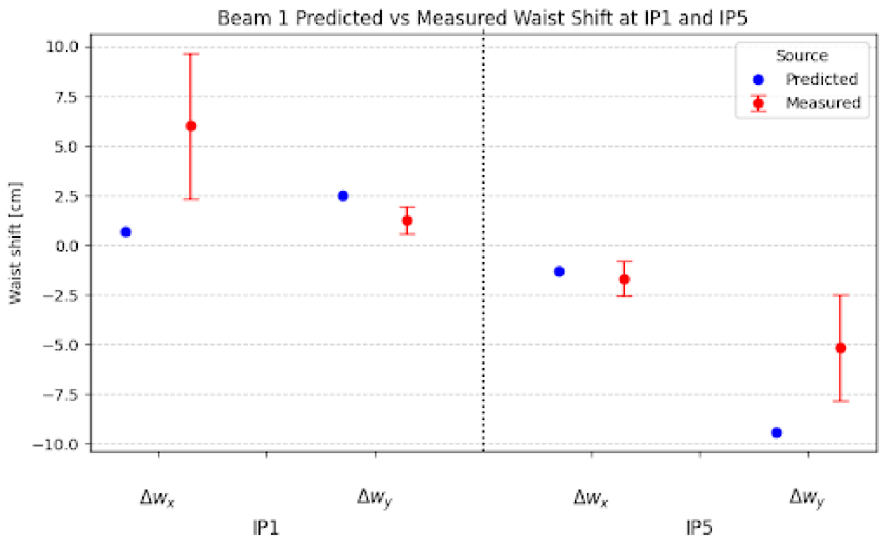
Although corrections are commonly applied to improve beam optics, it is frequently observed that adjustments benefiting one region may adversely affect another. This phenomenon was evident in the global corrections tested at 18 cm optics in April 2025, which aimed to mitigate waist shifts detected at IP1 and IP5. The waist of an interaction point corresponds to the location of the minimum β function (see Figure 3), and optimal luminosity is achieved when the waist coincides precisely with the IP.

The applied correction intended to move the waist closer to the IP instead caused a shift in other planes resulting in β-beating up to 20% in the 18 cm plane. The objective of this study was to evaluate, via simulations in MAD-X, whether induced waist shifts and β^*-beating could have been predicted prior to the implementation of the correction.

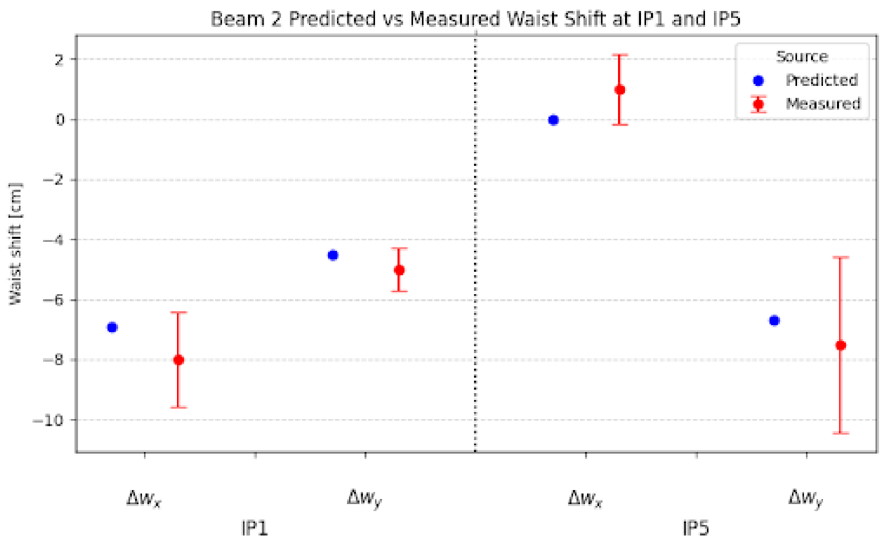
The results in Figure 4 and Figure 5 indicated that the simulations were unable to fully replicate the magnitude of β^*-beating observed experimentally at low β^* configurations, suggesting that current models may not be entirely accurate and may show deviations from measured correction outcomes.

3.1 Simulate Quadrupole β-Beating

A plausible explanation for the observed waist shifts and β^* beating at IP1 and IP5 is the presence of β-beating within the quadrupoles located immediately next to the interaction points. These magnets are used for the k-modulation [8] procedure to determine the trajectory of the β-function in the interaction area. To investigate these waist shifts,

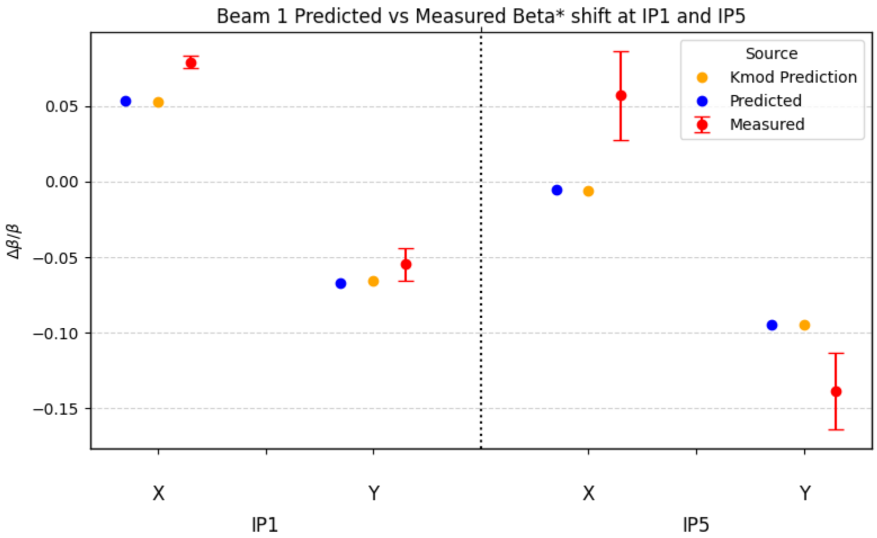


(a) Beam 1 waist shift in IP1 and IP5

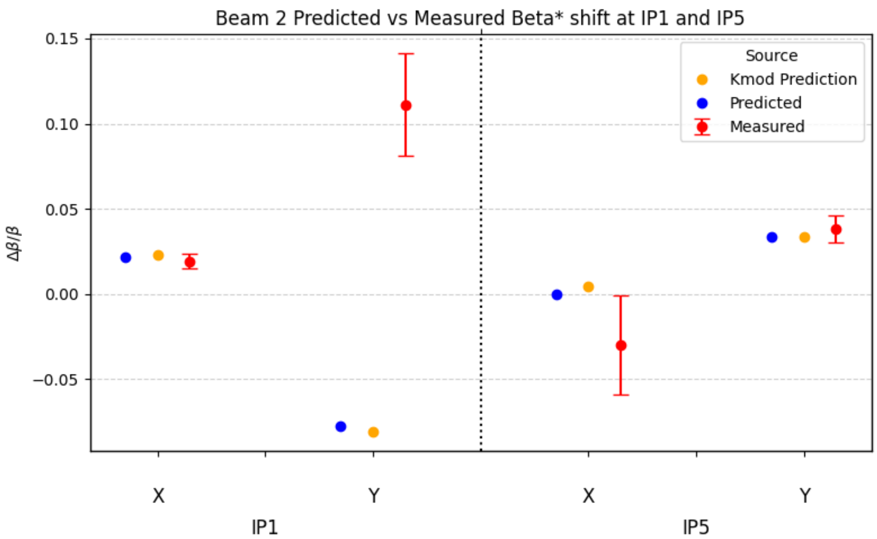


(b) Beam 2 waist shift in IP1 and IP5

Figure 4: Comparison of waist shift between simulation prediction (blue) and measurement (red) as well as prediction from simulations with kmod-data [8] from the OMC3 correction tool (orange). The waist shift simulation agrees with measurement as the simulated waist falls within the error of the measurement.

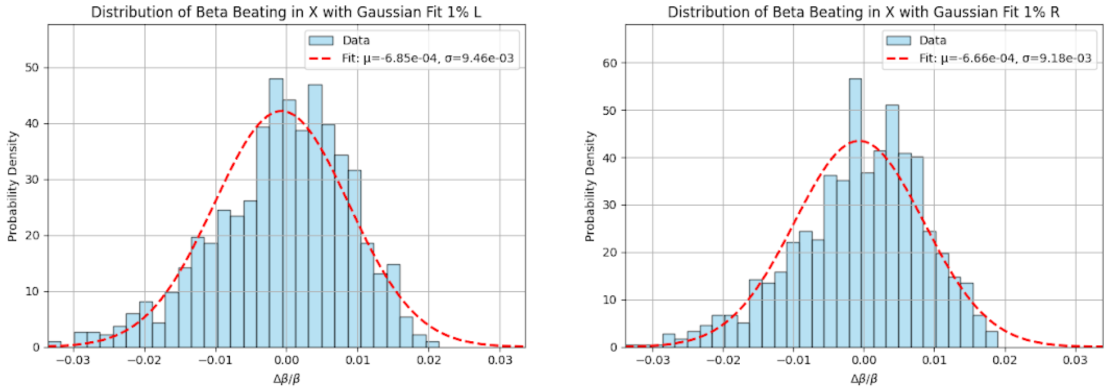


(a) Beam 1 β^*-beating in IP1 and IP5



(b) Beam 2 β^*-beating in IP1 and IP5

Figure 5: Comparison of β^*-beating between simulation prediction (blue) and measurement (red) as well as prediction from simulations with kmod-data [8] from the OMC3 correction tool (orange). Beam 1 IP5x and Beam 2 IP1y measured β^*-beating doesn't agree with simulation.

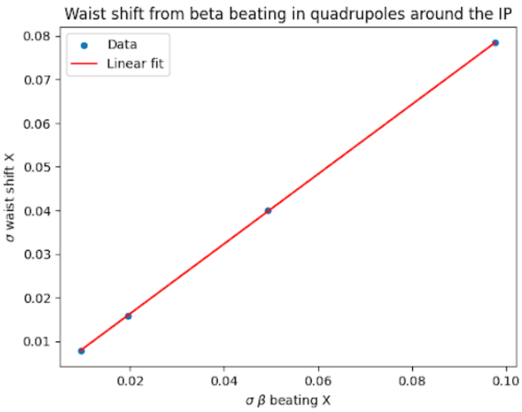


(a) Example β-beating in left quadrupole

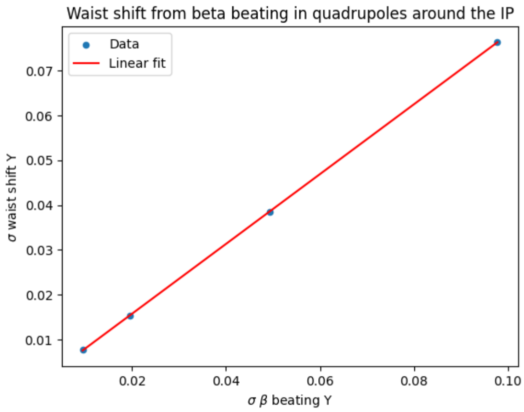
(b) Example β-beating in right quadrupole

Figure 6: Gaussian β-beating in quadrupoles to the left and right of the IP. Beating caused by changing quadrupole gradient k.

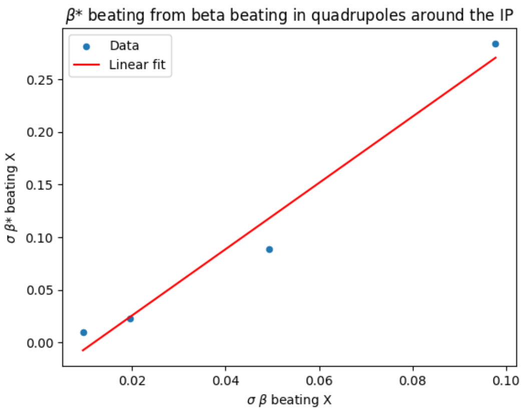
simulations were performed in which random perturbations, drawn from a Gaussian distribution, were applied to the quadrupole gradient k of these magnets. This procedure induces a β-beating pattern with a similar statistical distribution. The strength of the perturbations was varied to produce β-beating amplitudes in the range of 1% to 10%, and the corresponding waist shifts and β^* beating were calculated. An example of the induced beating is shown in Figure 6.



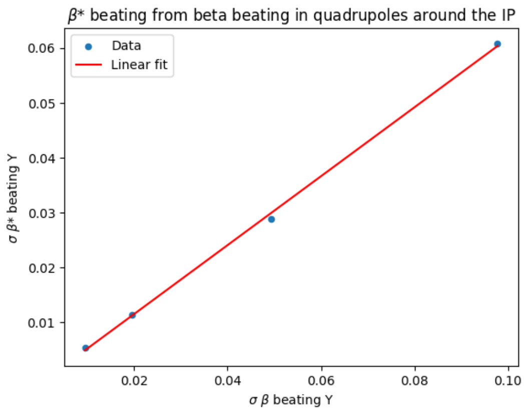
(a) Waist shift vs. β-beating in x plane



(b) Waist shift vs. β-beating in y plane



(c) β^*-beating vs. β-beating in x plane



(d) β^*-beating vs. β-beating in y plane

Figure 7: Dependence of both waist shifts and β^*-beating on the magnitude of β-beating in the quadrupoles. Both show a strong linear dependence.

The results shown in Figure 7 reveal a clear linear dependence of both waist shifts and β^*-beating on the magnitude of β-beating in the quadrupoles. For typical machine operation, the β-beating in these magnets is approximately 2%, which, according to the simulations, is insufficient to reproduce the effects observed experimentally. This mismatch between measurement and simulation implies that additional mechanisms are likely contributing to the observed discrepancies. For example, β^* calculations require detailed knowledge of the transfer map between the end of the closest quadrupole to the IP and the IP itself. Fringe fields from the triplet quadrupoles, which are missing from our model, could be causing the disagreement between the simulations and measurements, especially at low β^* where more subtle effects can make a bigger difference. Further investigation is needed to identify the exact source of the discrepancy, whether that be from fringe fields or some other missing effect.

4 3Qx and 3Qy Average Value from Non-Linear BPM Miscalibration

Resonance Driving Terms (RDTs) are measurable quantities in the LHC that characterize the strength of resonances affecting beam dynamics [9][10]. Resonances induce nonlinear particle motion, which can limit the dynamic aperture and cause significant beam losses, thereby reducing beam lifetime. Among these, the 3Qy RDT is of particular importance due to its substantial impact on beam lifetime seen in Figure 8.

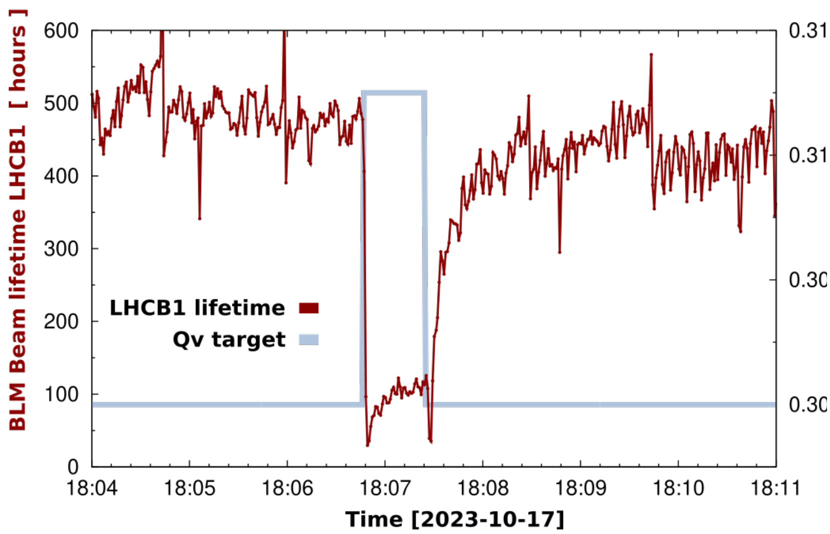


Figure 8: [11] A graph of the LHC beam 1 lifetime (red) during operation. The blue line represents the vertical tune (Qv) working point. The sharp jump in Qv at about 18:07 is a shift of the working point closer to the 3Qy resonance. While the shift in Qv was active, a significant drop in beam lifetime can be seen until Qv is brought away from the 3Qy resonance again.

The 3Qy resonance in the LHC primarily arises from skew sextupole field errors, coupling in normal sextupole magnets, feed-down effects from higher order magnets, and beam-beam effects [12]. Measurement of the 3Qy RDT is performed using an AC dipole to induce controlled oscillations at elevated amplitudes without emittance growth. Analysis of the long-term driven oscillations allows the 3Qy signal to be clearly distinguished above the noise floor in the Fourier spectrum, enabling more precise measurement of RDT. Long-term application of this technique has allowed detailed recording of the 3Qy behavior in the LHC.

Each RDT comprises of a real and imaginary component, both extracted experimentally by measuring the complex RDT. Recently, anomalous behavior was observed wherein the real and imaginary parts of the 3Qy RDT exhibited a non-zero average value around the ring, instead of oscillating about zero as expected. This is illustrated in the measurement data shown in Figure 9. Furthermore, this average value increased with the action of the excitation kick used for measurement. A summary of the analysis

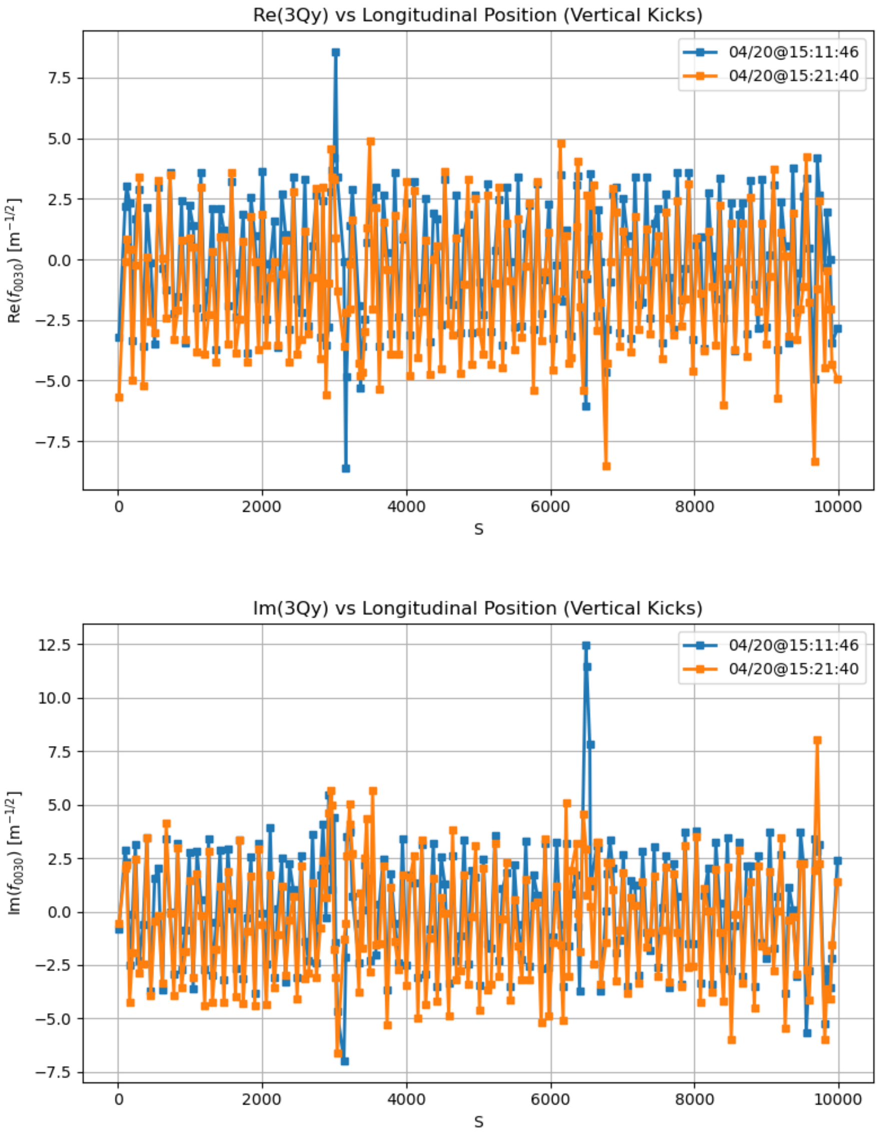
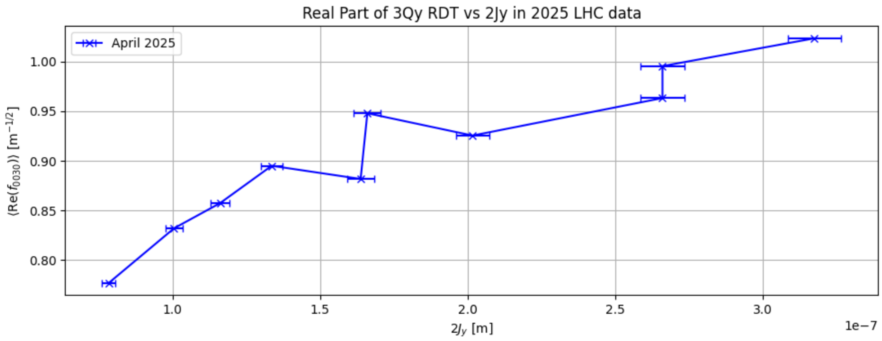
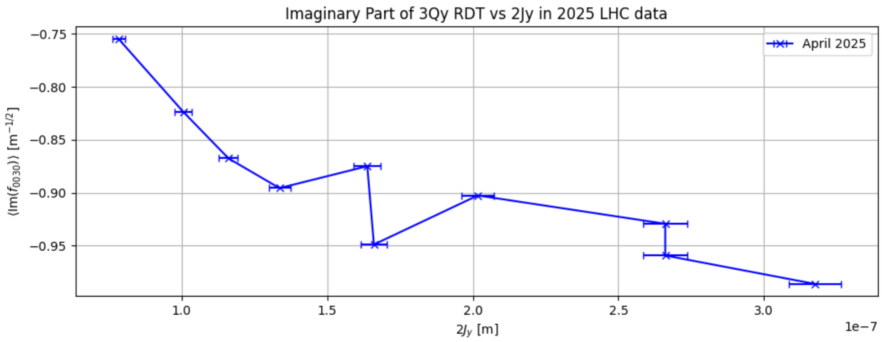


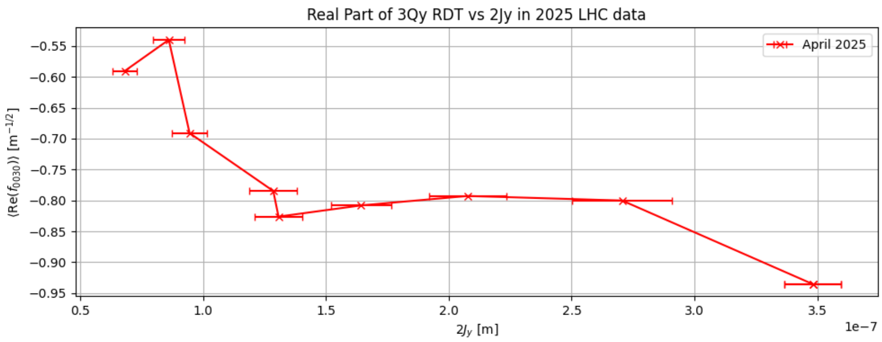
Figure 9: Real and imaginary parts of 3Qy RDT. Orange indicates a higher kick amplitude. A systematic shift in the average value can be seen in both parts from the higher kick amplitude.



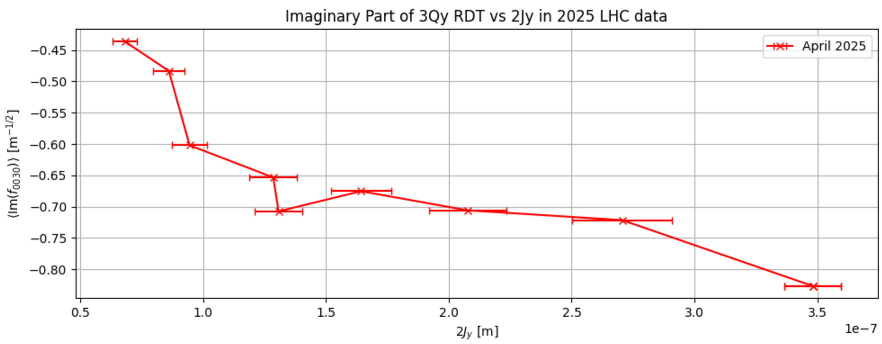
(a) Re(3Qy) average vs. Action in Beam 1



(b) Im(3Qy) average vs. Action in Beam 1

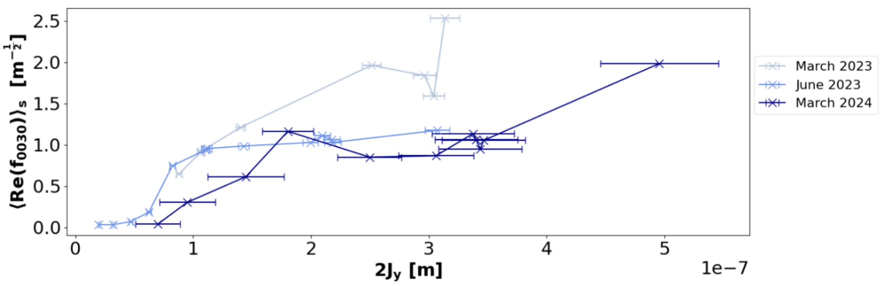


(c) Re(3Qy) average vs. Action in Beam 2

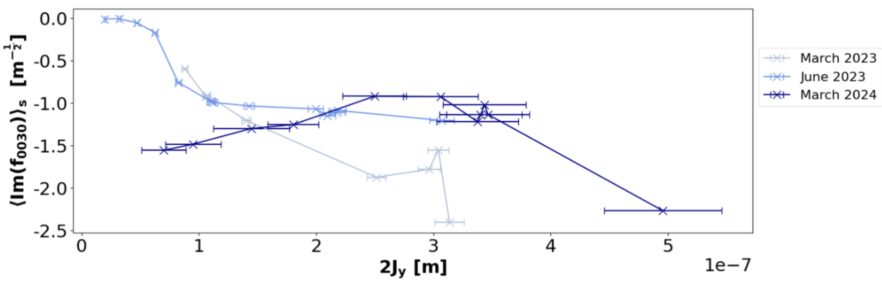


(d) Im(3Qy) average vs. Action in Beam 2

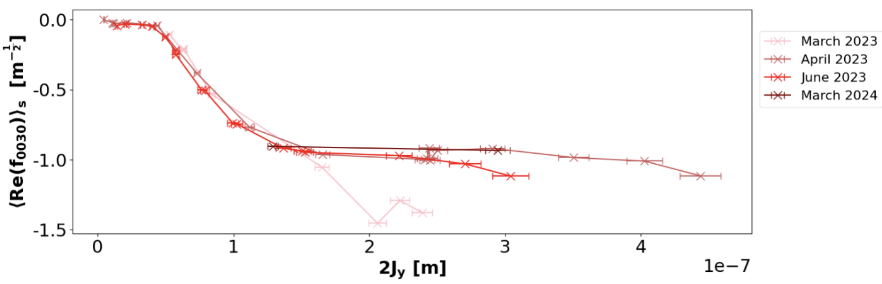
Figure 10: Average value of the 3Qy real and imaginary parts in Beam 1 and Beam 2 dependence on the action from data taken in April 2025. The magnitude of the average value increases as the action increases in both Beam 1 and Beam 2.



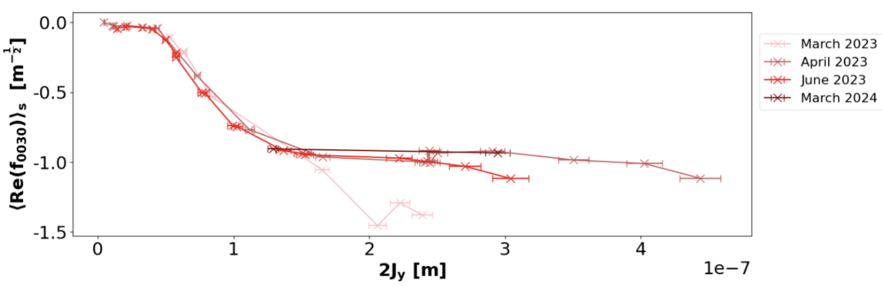
(a) Re(3Qy) average vs. Action in Beam 1



(b) Im(3Qy) average vs. Action in Beam 1



(c) Re(3Qy) average vs. Action in Beam 2



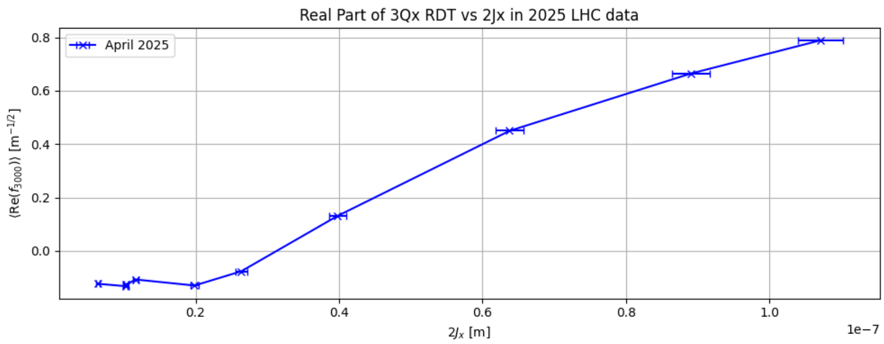
(d) Im(3Qy) average vs. Action in Beam 2

Figure 11: [13] Average value of the 3Qy real and imaginary parts in Beam 1 and Beam 2 dependence on the action from previous years. The April 2025 analysis in Figure 10 matches these earlier results.

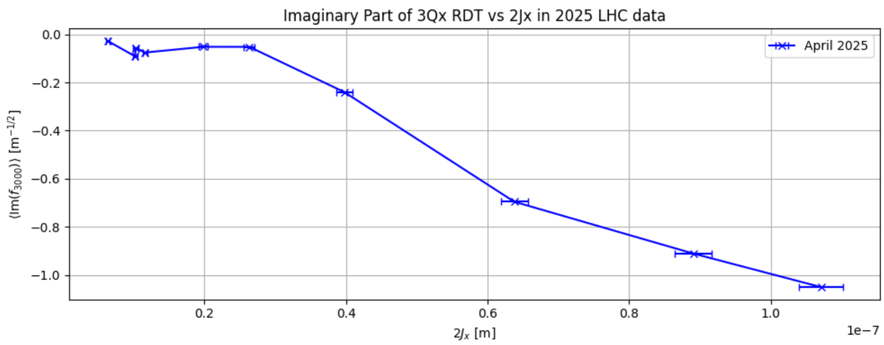
I did on the data from April 2025 can be seen in Figure 10. The same behavior can be seen dating back to 2023 in Figure 11. Measurement of the 3Qx RDT has not been done in previous years, but my analysis of the data from 2025 shows a similar effect as seen in Figure 12. The similar behavior in both 3Qx and 3Qy suggests a systematic effect within the measurement apparatus, with BPM calibration errors being a possible suspect.

BPMs require polynomial scaling corrections to convert raw electrical signals into accurate beam positions [14]. These scaling factors are periodically recalibrated using detailed BPM simulations. However, some effects may be unaccounted for, or coefficients could be miscalculated. The objective of this study was to see if observed measurement anomalies could be reproduced by simulating systematic BPM miscalibration within LHC tracking data using Xsuite.

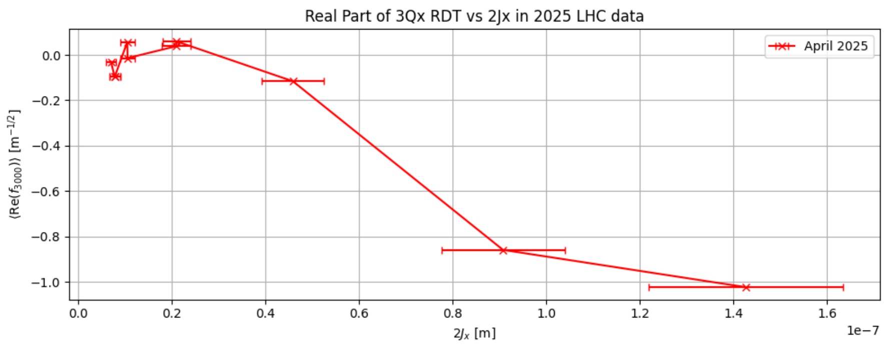
The hypothesized miscalibration involved a quadratic term in the vertical BPM data of the form $y \to y + \alpha y^2$, corresponding to an effective y^2 contribution due to the beam position relation $y \sim \sqrt{2J_y\beta_y}$. This gives the simulated measurement an additional linear action dependence, as we would expect to see theoretically from the 3Qy RDT line [15]. Alternative miscalibrations were tested but failed to reproduce the observed 3Qy anomalies. To simulate the 3Qy source, either a single skew sextupole was powered or coupling knobs activating multiple skew quadrupoles simultaneously were employed. Both approaches generated an average offset in the real and imaginary components of 3Qy, however, the coupling knobs simulation exhibited an action dependence most consistent with measurements, albeit with discrepancies in the detailed shape and sign. In both scenarios, an α was found to best match the simulation to the measurements.



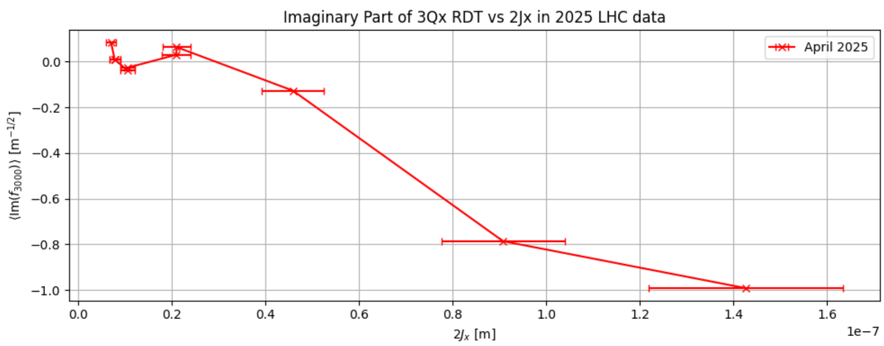
(a) Re(3Qx) average vs. Action in Beam 1



(b) Im(3Qx) average vs. Action in Beam 1



(c) Re(3Qx) average vs. Action in Beam 2



(d) Im(3Qx) average vs. Action in Beam 2

Figure 12: Average value of the 3Qx real and imaginary parts in Beam 1 and Beam 2 dependence on the action from data taken in April 2025. The magnitude of the average value increases as the action increases in both Beam 1 and Beam 2.

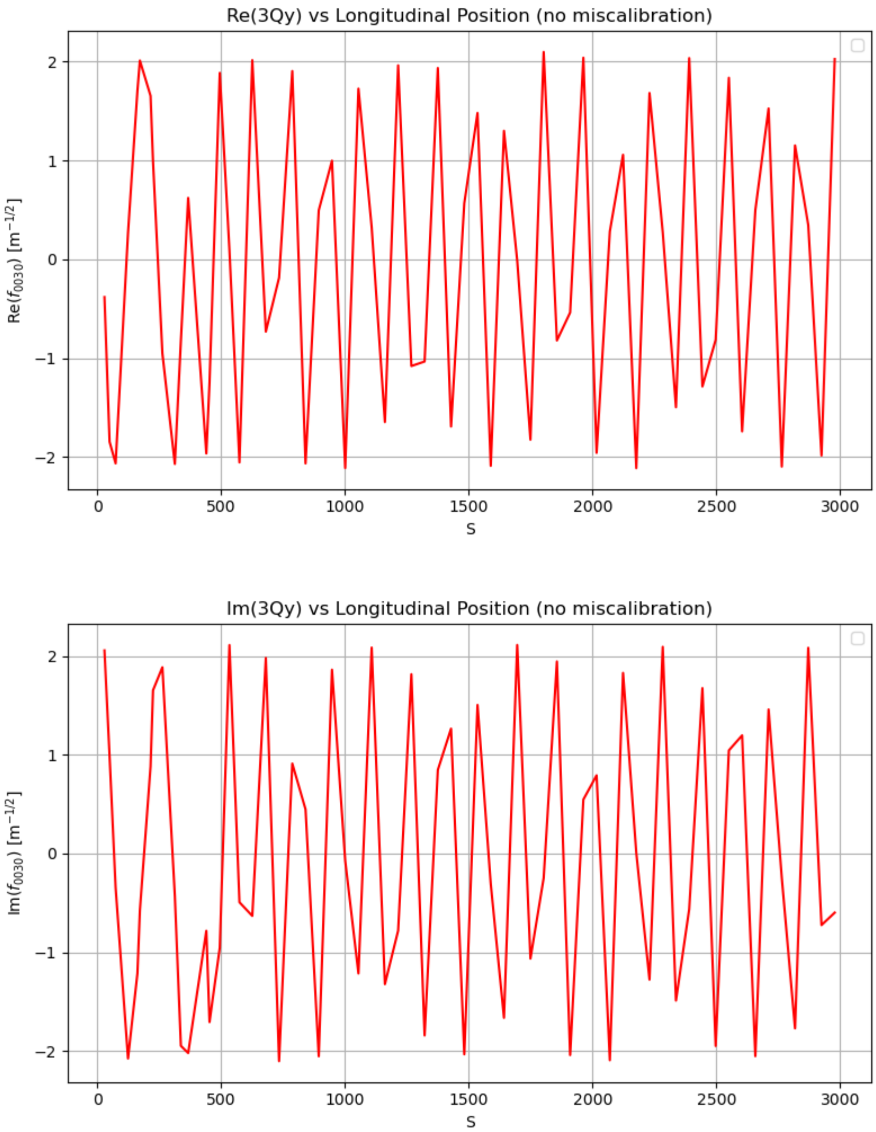
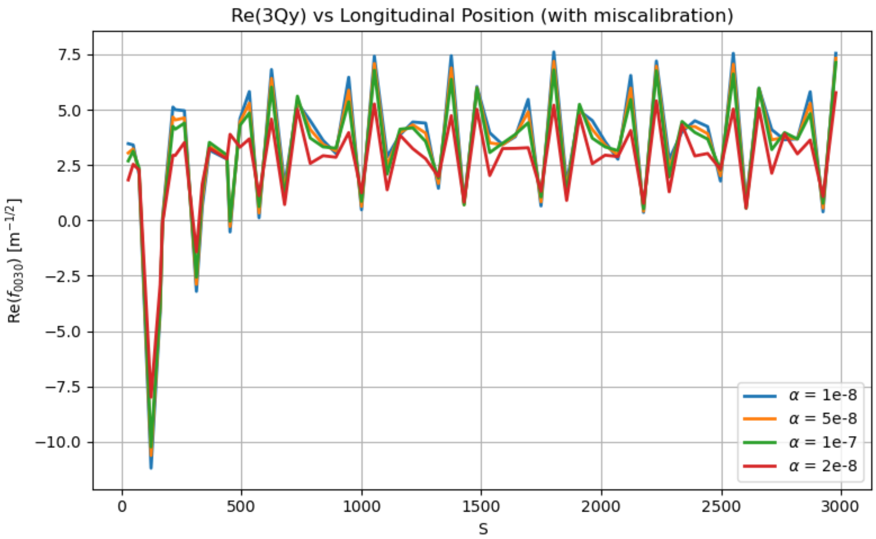


Figure 13: A graph of the average value of the real and imaginary parts of the 3Qy RDT in simulation with no added miscalibration.



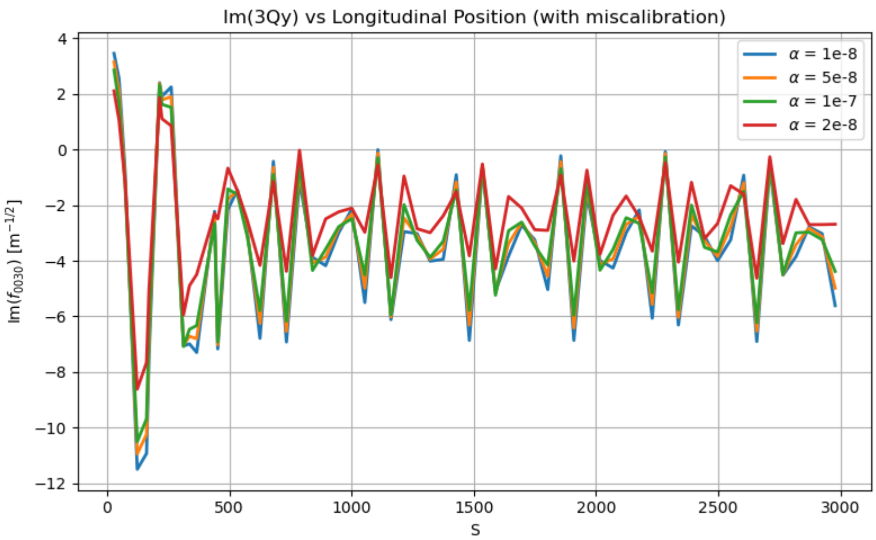
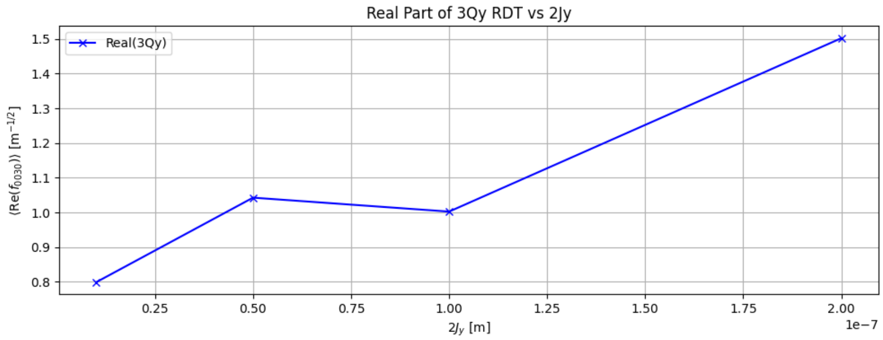
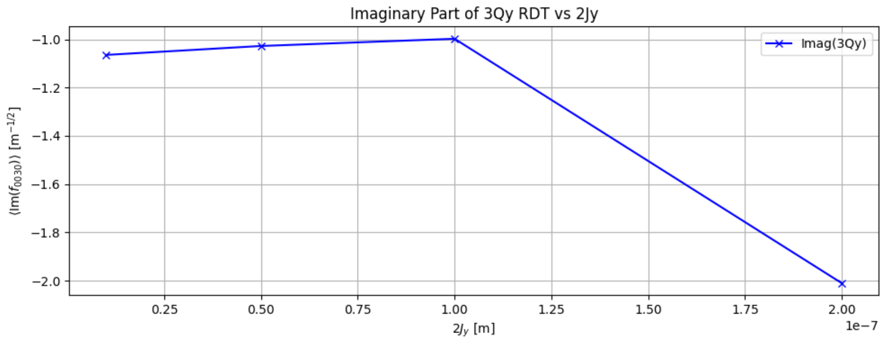


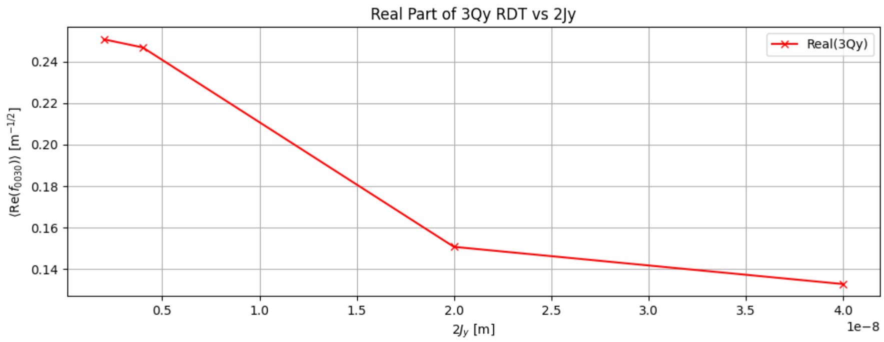
Figure 14: A graph of the average value of the real and imaginary parts of the 3Qy RDT in simulation with added miscalibration and various scale factors.



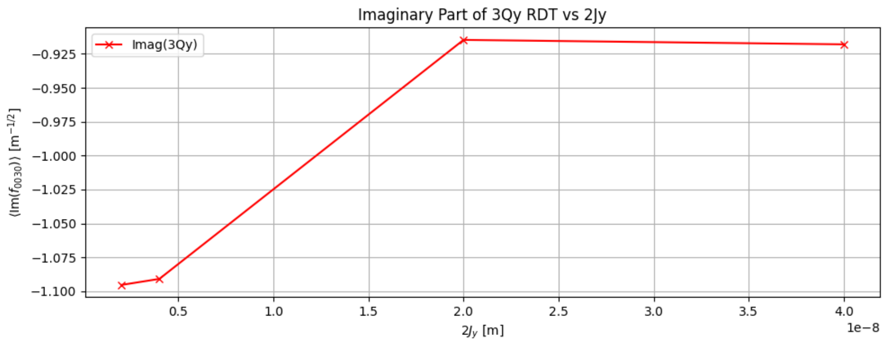
(a) Simulated Re(3Qy) average vs. Action in Beam 1



(b) Simulated Im(3Qy) average vs. Action in Beam 1



(c) Simulated Re(3Qy) average vs. Action in Beam 2



(d) Simulated Im(3Qy) average vs. Action in Beam 2

Figure 15: Average value of the Simulated 3Qy real and imaginary parts in Beam 1 and Beam 2 dependence on the action. The coupling knobs provide the source for the 3Qy with $\alpha = -3.2[\mathrm{m}^{-1}]$, providing the best match for the measurement data.

Although the simulation results shown in Figure 15 do not perfectly match experimental data, they enable estimation of a potential systematic BPM misalignment. Such a misalignment would cause an x^3 term in the BPM scaling polynomial to produce an effective x^2 term. This allows back-calculation of the misalignment from the simulated data. Figure 16 provides the coefficients used for BPM scaling in the LHC during 2025. Using this, we can do our calculation for the misalignment.

#		Poly type	A (x^5)	B (x^3)	C (x^1)	D (x^3y^2)	E (x^1y^4)	F (x^1y^2)
7	BPM	1D	3.5215	3.2087	13.0402	0	0	0
		2D (2014)	3.0268	3.4651	13.0207	-1.8265	2.0741	0.5032
		2D (2025)	3.3196	2.9523	12.7018	1.0800	2.7487	1.3592

Figure 16: Table of polynomial scaling coefficients for BPMs in the LHC. [16]

First we expand the Bx^3 term with the misallignment.

$$B(x+\Delta x)^3 = Bx^3 + 3\Delta x B x^2 + 3(\Delta x)^2 Bx + B(\Delta x)^3 \tag{2}$$
$$\tag{3}$$

The $3\Delta x B x^2$ term is proportional to x^2, so its coefficient should be equal to the α from simulation.

$$3\Delta x B = \alpha \tag{4}$$
$$\Delta x = \frac{\alpha}{3B} \tag{5}$$

Using the best alpha found from simulation, $\alpha = -3.2[\mathrm{m}^{-1}]$, we get:

$$\Delta x = -0.36\ \mu\mathrm{m} \tag{6}$$

The inferred misalignment magnitude is too small to solely explain the measurement anomaly and would require a uniform misalignment across all BPMs in the ring, which is improbable. It is plausible that a combination of misalignment and residual errors in polynomial scaling contribute to the effect, or that more comprehensive studies are necessary to fully capture what has been seen in measurements. Either way, this study provides compelling evidence implicating BPM miscalibration in the observed 3Qy measurement anomalies while highlighting the need for further investigation.

5 Conclusions

This project addressed three optics studies important for LHC performance: ion commissioning for the upcoming oxygen cycle, analysis of waist shifts and β^*-beating at 18 cm optics, and investigation of anomalies in 3Qy resonance measurements. By combining LHC measurements with simulations in MAD-X and Xsuite, these studies improve confidence in future runs and provide valuable insights for upcoming machine operation, including the High Luminosity LHC upgrade.

References

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