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REACHING THE SUB PER MIL LEVEL COUPLING CORRECTIONS IN THE LHC

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Abstract

The High Luminosity LHC (HL-LHC) is requiring sub per mil coupling correction, as defined by the closest tune approach. In this article, the current coupling correction strategy is analyzed in order to understand if it can robustly correct to these very low levels. The impact of realistic errors on the coupling correction is investigated with MAD-X simulations, including the influence of local coupling on the global coupling correction. Through simulations and measurements in the LHC, the effect of BPM noise on the coupling correction is analyzed.

INTRODUCTION

Minimizing the closest tune approach (ΔQ_{min}) is important for the operation of the LHC. ΔQ_{min} is a measure of the global coupling in an accelerator, which equals how close the horizontal and vertical tune can approach each other. In fact, ΔQ_{min} equals the absolute value of the coupling coefficient C^-, which is a complex quantity that can be estimated using perturbation theory [1]. Left uncorrected, coupling can impact Landau damping and thereby deteriorate beam stability in the LHC [2, 3]. Additionally, coupling disturbs the tune control and can reduce the dynamic aperture [4].

During LHC commissioning, both global and local coupling are corrected. Local coupling errors near the interaction regions (IRs) are corrected with the two skew quadrupoles in the vicinity of the triplet [5]. Distributed coupling sources are corrected, if needed, using response matrix inversion with all the arc skew quadrupole correctors. However, coupling as estimated through ΔQ_{min} has been observed to drift during operation [6]. This drift is also corrected using response matrix inversion, but only using two orthogonal knobs designed to control the real and imaginary parts of the C^- coefficient [7].

The correction of the ΔQ_{min} to the sub per mil level has been achieved in the LHC only once [8]. This article investigates if this level of correction can be reached robustly, in order to meet the requirements of the High-Luminosity LHC (HL-LHC) [3]. The efficacy of the matrix response correction is demonstrated using MAD-X [9] simulations. First, the arc-by-arc response correction is tested by correcting a distributed coupling error. Second, the coupling knob response correction is shown to successfully correct realistic operational coupling errors. Finally, the impact of noise in the turn-by-turn (TbT) data is analyzed, both for simulations and measured data.

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RESPONSE CORRECTION

The resonance driving terms (RDTs) f_{1001} and f_{1010} are local properties that relate to the transverse coupling in an accelerator. Assuming that the tune is close to the difference coupling resonance and that $|f_{1001}| >> |f_{1010}|$, the closest tune approach can be related to the resonance driving term f_{1001} with the following expression [10]

$$\Delta Q_{min} = |C^-| \approx 4\Delta \frac{1}{N} \sum_{i}^{N} |f_{1001,i}| \ , \quad (1)$$

where N is the number of beam position monitors (BPMs) and Δ is the fractional tune split. The minimisation of ΔQ_{min} can therefore be achieved by minimizing the average amplitude of the f_{1001} RDT. Assuming that the f_{1001} is sufficiently small, this can be done by response matrix inversion [6]. The response matrix R, which is relating the change in the f_{1001} to the change in the strength of the skew quadrupoles, is constructed with MAD-X

$$R\Delta\vec{K}_{cor} = (Re\{\vec{f}_{1001}\}, Im\{\vec{f}_{1001}\}) \ . \quad (2)$$

Then taking the pseudoinverse R^{-1} and applying it to the measured f_{1001}, the magnets strengths that minimize the measured $|f_{1001}|$ are recovered

$$\Delta\vec{K}_{cor} = -R^{-1}(Re\{\vec{f}_{1001}\}, Im\{\vec{f}_{1001}\}) \ . \quad (3)$$

When correcting distributed coupling sources during commissioning, $\Delta\vec{K}_{cor}$ contains all the independent skew quadrupoles. During operation of the machine, $\Delta\vec{K}_{cor}$ is restricted to two orthogonal knobs designed to control the real and imaginary part of the C^-. The knobs are designed to utilize the smallest skew quadrupole strength possible [7].

Simulations

The response correction is tested using MAD-X simulations. The simulations are done with the LHC lattice, using collision optics with $\beta^* = 30$ cm. In order to simulate a coupling error similar to what was encountered during commissioning [11, 12], all the b_3 spool pieces are vertically misaligned by 0.4 mm. This distributed coupling error causes the $|f_{1001}|$ to vary around the ring, making correction with the coupling knobs ineffective. However, Fig. 1 shows that the coupling error can be corrected by iteratively applying the arc-by-arc response correction. After correcting the distributed coupling error, realistic skew quadrupole errors are added in order to simulate coupling errors encountered during operation. Figure 2 shows the closest tune approach before and after correcting these errors with the coupling

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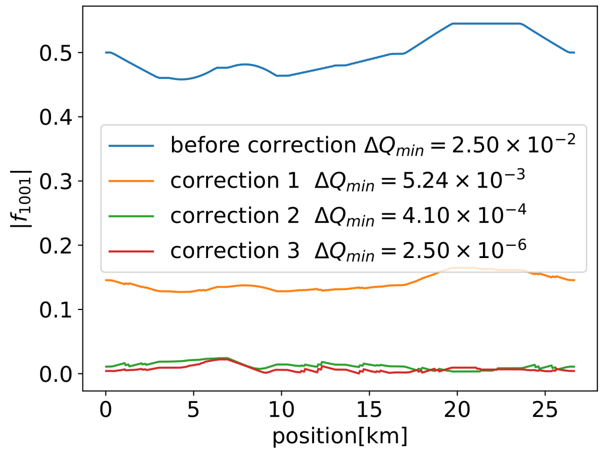

Figure 1: Arc-by-arc response correction of global coupling caused by b_3 spool piece misalignment. $|f_{1001}|$ plotted around the ring before and after correction.

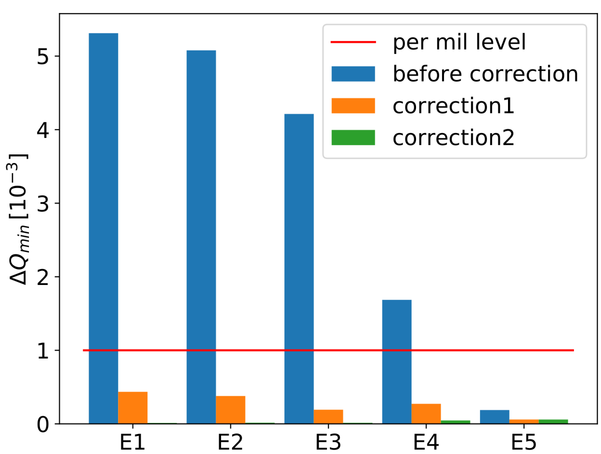

Figure 2: ΔQ_{min} before and after response correction with the coupling knobs for skew quadrupole errors. E1: one local skew source, E2: two local skew sources, E3: random skew component in all quadrupoles, E4: Tilt in the three quadrupoles (triplet) to the right of IP1 and E5: closed bump at IP1. Note that E4 being smaller than E1-3 is not inherent to the type of error, but due to the strength chosen.

knobs. The simulation shows that the coupling knobs can correct to the sub per mil level.

Quadrupole focusing errors are identified as having a negative impact on the coupling correction. Focusing errors cause β-beating, creating a mismatch between the machine and the underlying model, on which the response is based. Figure 3 shows the correction of the coupling errors considered in Fig. 1, with a constant quadrupole error added to the sector 56 quadrupoles. By applying the response correction iteratively, the ΔQ_{min} can be well corrected under the influence of focusing errors.

Strong local coupling at the IRs has been observed in the LHC [5]. Assuming that the local coupling at the IRs has been corrected up to a degeneracy between the left and right corrector, the $|f_{1001}|$ will only be different from zero within the left and right triplets. This closed f_{1001} bump is emulated in MAD-X by adding opposite strengths to the corrector skew quadrupoles at either side of interaction point 1 (IP1). The effect on the ΔQ_{min} is negligible, as shown in column E5 of Fig. 2.

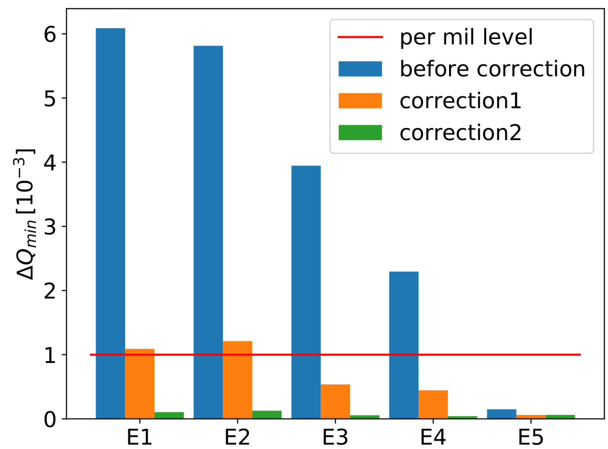

Figure 3: ΔQ_{min} before and after response correction with the coupling knobs for skew quadrupole errors given in Fig. 2, with focusing error leading to 4.3% rms β-beating.

IMPACT OF BPM NOISE

When measuring the f_{1001}, coherent motion is excited using forced oscillations. TbT data is gathered using the BPMs, and cleaned using singular value decomposition [13]. The f_{1001} is then inferred from the spectrum of the TbT data. Noise at the BPMs will spoil the accuracy of the f_{1001} measurement and, thereby, the ability to correct the ΔQ_{min}. During commissioning, the motion is driven using the AC-dipole [14], which enables a good signal-to-noise ratio. During operation, it is unsafe to drive the beam using the AC-dipole, and therefore a single bunch is excited using the transverse feedback (ADT) [15], which can drive the beam like the AC-dipole. The ADT drives at a lower amplitude, making the effect of noise more important. Typically, the AC-dipole has noise of less than 10% of the excited amplitude, while the ADT can have over 50% noise.

Through the excitation of the AC-dipole or ADT, the beam is undergoing a forced oscillation. An algorithm has been implemented that analytically compensates the effect of the forced oscillations giving the free f_{1001} [16, 17]. The algorithm uses measurements from a few BPMs close to the AC-dipole to determine the compensation, making it sensitive to noise. The free f_{1001} can also be approximated as a constant scaling of the driven f_{1001}. This compensation is theoretically less accurate, but avoids sensitive dependence on selected BPMs.

Simulations

Using MAD-X tracking, the effect of noise on the coupling knob response correction is investigated. The simula-

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tion is performed using collision optics with nominal tunes $Q_x = 62.31$ and $Q_y = 60.32$. The BPM noise in the real machine is not perfectly uncorrelated and Gaussian, making the SVD cleaning less effective. Therefore, not cleaning the TbT data in simulations gives more realistic results.

A random skew quadrupole component is added to all quadrupoles, resulting in a coupling coefficient $|C^-| = 5.8 \times 10^{-3}$. The TbT data is then acquired with MAD-X using AC-dipole tracking for 8600 turns with a 2000 turn ramp, with the AC-dipole frequencies $Q_x^{ac} = 62.30$ and $Q_y^{ac} = 62.332$. Gaussian noise is added to the TbT data and the f_{1001} is calculated for both the analytic and scaled compensation. The correction resulting from the measured f_{1001} is then calculated using Eq. (3). In Fig. 4, the $|C^-|$ after applying the corrections is plotted against the noise level. The simulation is run 25 times at each noise level, and the standard deviations are used as error bars. At high noise, the plot shows that the analytic compensation provides a much worse correction of the $|C^-|$, as compared to the scaled compensation. The analytic compensation both increases the error in the average $|C^-|$ and its variance. In Fig. 5, Gaussian noise is added to all the BPMs, except for the three BPMs responsible for the compensation. In this case, the analytic compensation is greatly improved with respect to Fig. 4, showing that most of the difference between the compensation methods is explained by the noise in the BPMs used for the compensation.

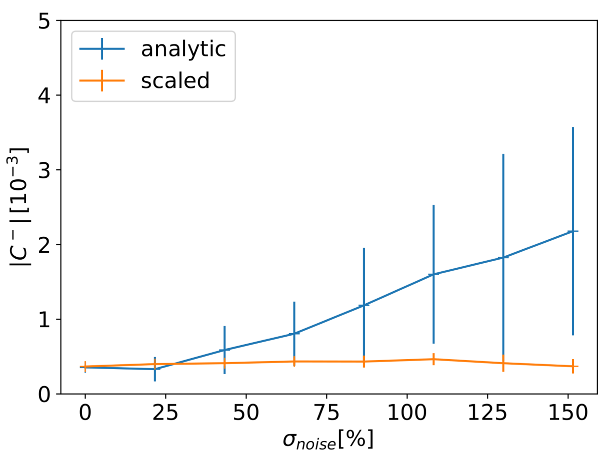

Figure 4: $|C^-|$ estimated with Eq. (1) after correction plotted against standard deviation of added Gaussian noise, given as percentage of excited amplitude at BPM with $\beta_x = 170.3$ m.

Measured Data

During August 2018, the coupling measured with the ADT was observed to vary in time. The measured $|C^-|$ changed on the per mil scale, between measurements that were less than a minute apart. This variation is inconsistent with more precise measurements of the coupling using the AC-dipole [18]. In Fig. 6, the data is reanalyzed with both analytic and scaled compensation. The figure shows that the knob settings calculated with the scaled compensation are more stable in time.

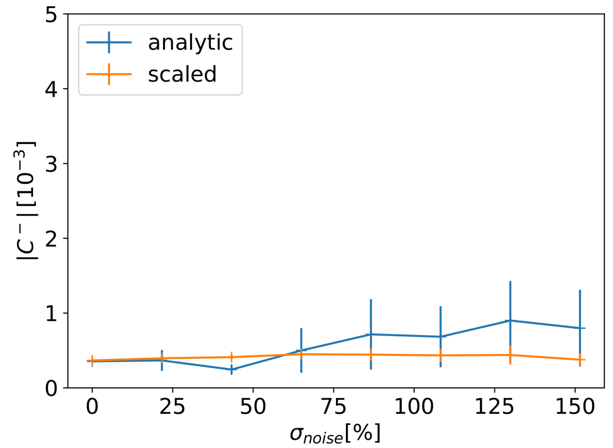

Figure 5: $|C^-|$ estimated with Eq. (1) after correction plotted against standard deviation of added Gaussian noise, given as percentage of excited amplitude at BPM with $\beta_x = 170.3$ m. Noise removed at BPMs used for compensation.

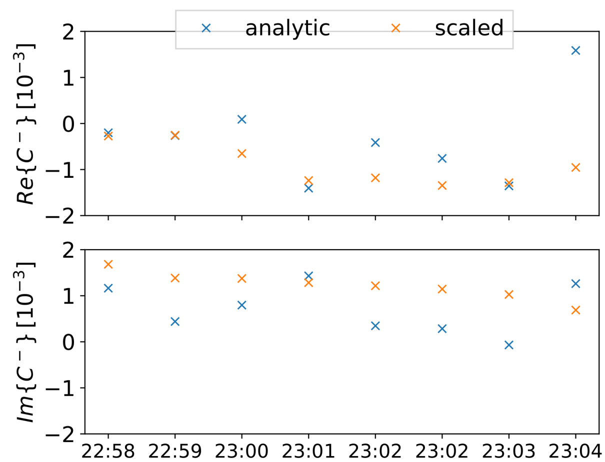

Figure 6: Setting of the coupling knobs calculated with Eq. (3) for analytic and scaled compensation. Calculated for LHC data measured on August 6th 2018. Measurement was performed on beam 1 and cleaned using 12 singular values.

This result shows that the choice of compensation method has significant impact and provides evidence that the scaled compensation is better for measurements with high noise.

CONCLUSION

Assuming perfect measurement of the f_{1001} around the ring, sub per mil ΔQ_{min} can be achieved using the response correction using the coupling knobs. The main limitations for the global coupling correction are therefore machine stability and measurement quality. At high noise levels, the measurement quality is shown to be improved by using the scaled compensation, both with MAD-X simulations and with measured LHC data.

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