PROCEDURES AND ACCURACY ESTIMATES FOR BETA-BEAT CORRECTION IN THE LHC *

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Abstract

The LHC aperture imposes a tight tolerance of 20% on the maximum acceptable beta-beat in the machine. An accurate knowledge of the transfer functions for the individually powered insertion quadrupoles and techniques to compensate beta-beat are key prerequisites for successful operation with high intensity beams. We perform realistic simulations to identify quadrupole errors in LHC and explore possible ways of correction to minimize beta-beat below the 20% level.

INTRODUCTION

The field quality of a significant number of LHC magnets has already been measured [1]. The location of most of these magnets has been assigned based on a variety of sorting algorithms [2, 3]. A computer code [4] incorporates all this information to construct a realistic MADX model of the LHC.

This paper aims to establish a procedure for the beta-beat correction as well as validate it through simulations using the most realistic LHC model. To be on the pessimistic side the correction is performed without assuming any knowledge of the systematic errors. The final goal is to ensure that the on-momentum beta-beating at injection will be lower than the tight tolerances of 14% and 16%, for the horizontal and vertical planes respectively [5]. On the other hand the consideration of installation faults, like mispowering of quadrupoles, is left for future studies.

β-BEATING CORRECTION

The β measurement techniques around the ring usually rely on the good calibration of the BPMs [6, 7] and/or a good knowledge of the focusing properties of some sections of the machine [8, 9]. Neither of these assumptions hold during the LHC commissioning. On the other hand the measurement of the phase advance between nearby BPMs is not affected by BPM calibration or tilt errors, and it is model independent. The phase is measured by exciting the beam motion and analysing the BPM data using either the FFT [10] or the SVD [7]. For these reasons we choose the phase-beating between consecutive BPMs as the observable to minimize, given by

$$\Delta\phi_{n+1} = \phi_{n+1}^{meas} - \phi_{n}^{meas} - (\phi_{n+1}^{mod} - \phi_{n}^{mod}) , \quad (1)$$

where the subscript refers to the BPM index and the superscript to either measurement or model. In Fig. 1 (bottom) the precise relation between the rms phase-beating and β-beating is shown for 100 error seeds of the LHC. This plot

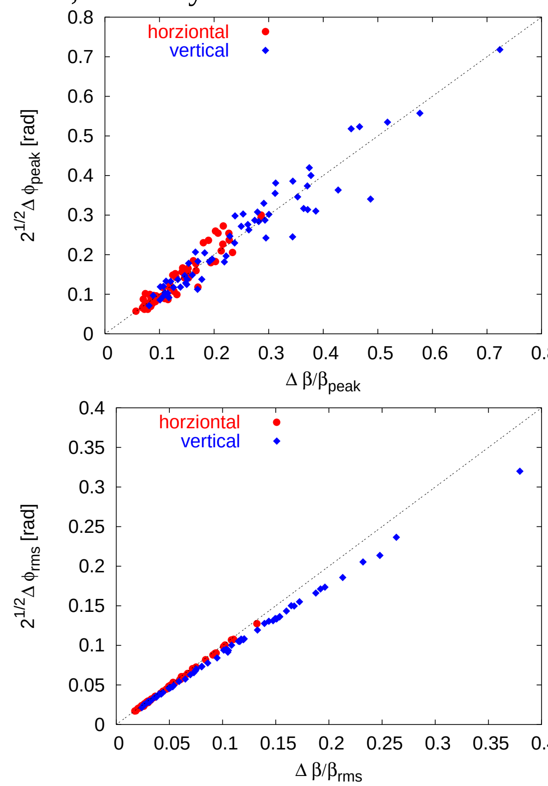

Figure 1: Phase-beating versus β-beating. Top: peak values. Bottom: rms values.

confirms that the correction of the phase-beating is equivalent to the correction of β-beating.

From the ideal model we compute the response matrix, $\mathbf{R}$, that relates the phase-beating, dispersion-beating and tune errors $(\Delta\vec{\phi}, \Delta\vec{D}, \Delta Q_x, \Delta Q_y)$ with the strengths of all quadrupole circuits, $\vec{k_1}$ (by quadrupole circuit we understand a set of quadrupoles powered in series) as

$$(\Delta\vec{\phi}, \Delta\vec{D}, \Delta Q_x, \Delta Q_y) = \mathbf{R}\Delta\vec{k_1} \quad (2)$$

The required correction strength is computed from the measured errors as

$$\Delta\vec{k_1} = -\mathbf{R}^{-1}(w_\phi\Delta\vec{\phi}, w_D\Delta\vec{D}, \Delta Q_x, \Delta Q_y) \quad (3)$$

where $\mathbf{R}^{-1}$ represents the generalized inverse of the non-square matrix $\mathbf{R}$ and $w_{\phi,D}$ are weights used to choose between beta-beating and dispersion correction. The correction is not guaranteed by this expression since it depends on the particular configuration of errors and quadrupole circuits. Therefore the applicability of the presented correction method needs to be proven by realistic numerical simulations.

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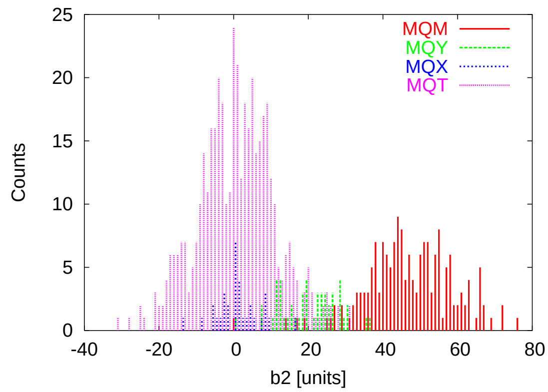

Figure 2: b2 distribution of selected magnet types.

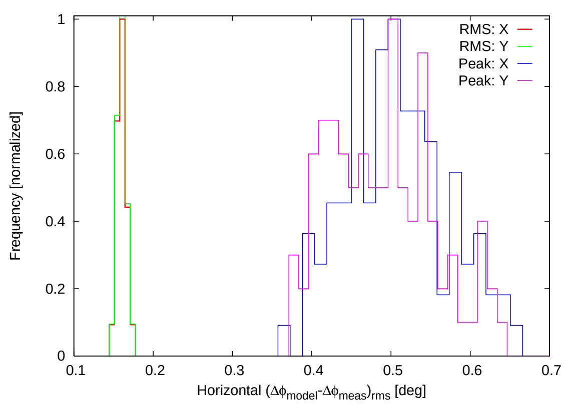

Figure 3: Phase error histogram.

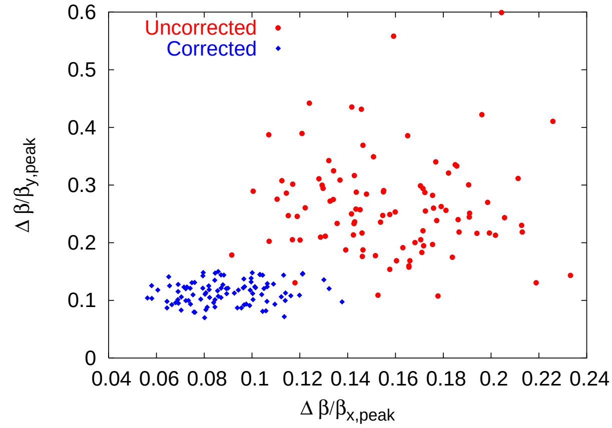

Figure 4: Beta-beating before and after β-beat correction.

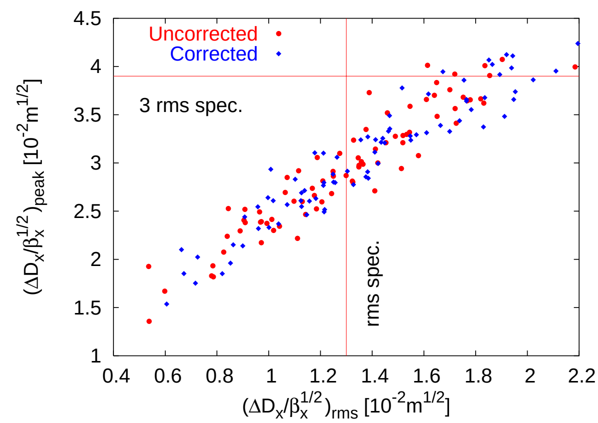

Figure 5: Dispersion beating before and after correction.

SIMULATIONS

The LHC is equipped with 210 quadrupole circuits (16 in the arcs and 194 in the IRs) and about 500 double plane BPMs. The matrix $\mathbf{R}$ is numerically computed using the ideal MADX LHC model by individually varying the different quadrupole circuits and recording the *beating* vector $(\Delta\vec{\phi}, \Delta\vec{D}, \Delta Q_x, \Delta Q_y)$. This matrix is computed once and it is stored for use during the simulations.

A realistic LHC model is obtained from the above mentioned code containing all errors from magnetic measurements. Examples of b_2 error distributions of selected quadrupole types are shown in Fig. 2 and more details can be found in [4]. The uncertainty of the magnetic measurements of b_2 is accounted for by adding a Gaussian noise with a sigma of 5 units to all quadrupoles. The effect of the closed orbit in LHC is taken into account by introducing a random displacement of the chromaticity sextupoles with a sigma corresponding to the expected closed orbit rms (2 mm during commissioning). The sextupolar spool pieces are also displaced by 0.5 mm rms to account for the relative misalignment between spool pieces and dipoles. The resolution of the measurement of the phase-beating is taken into account by adding Gaussian noise to the phase-beating provided by MADX. This resolution is computed from tracking simulations assuming 400 turns of undecohered motion, 4 mm kick and 200 μm of BPM noise. Pessimistically an error on the phase measurement of 0.25° is assumed, about 50% larger than the simulated error.

With all the above ingredients we proceed to correct the phase-beating of 100 seeds (w_D is set to zero). The results after, at most, 5 correction iterations are shown in Fig 4. The fact that there is a larger vertical beating is due to the misalignment of the chromaticity sextupoles. The dispersion beating before and after correction is shown in Fig. 5. The correction of the β-beating ($w_D = 0, w_\phi = 1$) does not spoil the dispersion-beating. Note that the peak specification for the dispersion-beating [5] is met for almost all seeds but this is not the case for the rms specification, where about half of the seeds are out of specification.

The relative variation of the strength of the power supplies with respect to their nominal setting at injection is shown in Fig. 6. The mostly used quadrupoles are the MQTs followed by the standalone IR quads from Q4 to Q10. The strength variation in the rest of the circuits is very low. To verify that β-beating can be corrected in the LHC it remains to check that the power supplies are within their limits. The specification is that the standalone quadrupoles (with the exception of MQTs) should be always above 3% of their setting at collision optics. Fig. 7 shows the relative variation of the strength of the power supplies with respect to their nominal setting at collision.

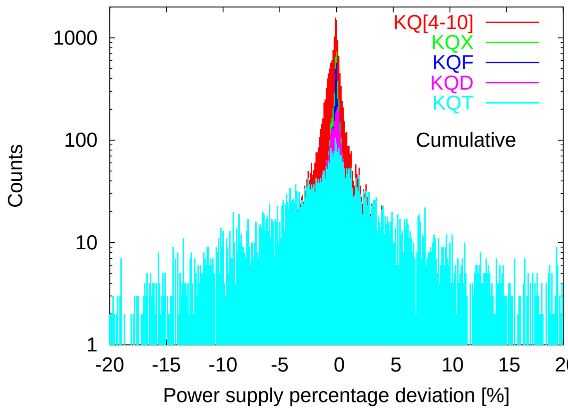

Figure 6: Relative variation of power supplies strength with respect to injection settings for 100 seeds.

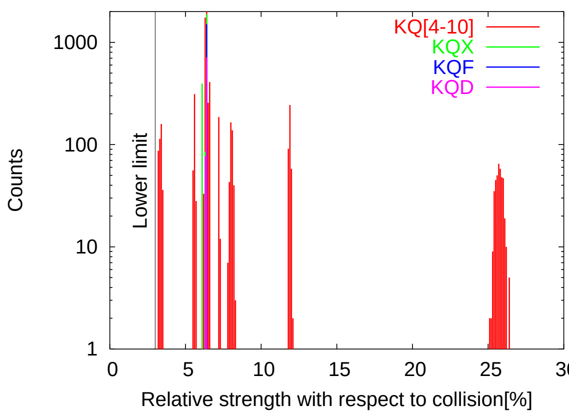

Figure 7: Relative power supply strengths with respect to collision nominal settings.

Dispersion correction should be equivalently achieved by setting $w_\phi = 0$. As Fig. 8 shows, the dispersion-beating cannot be corrected for some seeds. The reason is not understood. We suspect that this problem is related to the spurious dispersion in the IR quadrupoles (from Q7 to Q7). These quadrupoles will not be used in future dispersion corrections to clarify this problem.

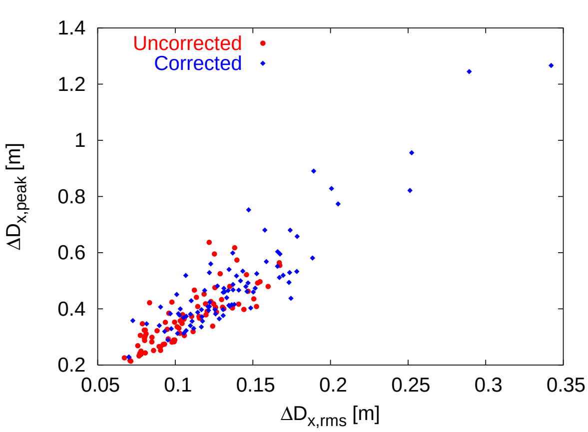

Figure 8: Dispersion beating correction.

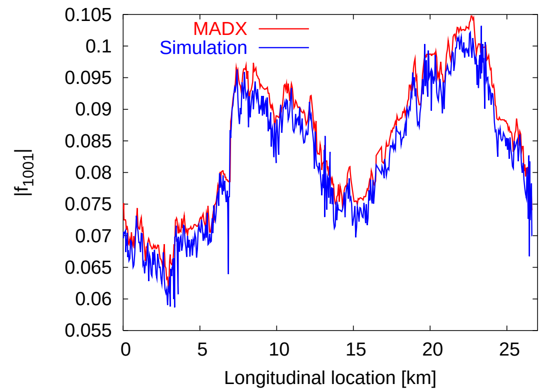

Figure 9: Local coupling measurement.

LOCAL COUPLING CORRECTION

One advantage of correcting the β-beating through the spectral analysis of kicked BPM data is that the local coupling information can also be inferred from the secondary spectral lines [12, 13]. A tracking simulation has been performed with random tilt and alignment errors plus a large quadrupole tilt (15 mrad) at about 6 km in the LHC ring. 400 turns of undecohered motion, 200 μm as BPM noise and 2 mrad BPM tilt have been assumed. Fig. 9 shows the comparison between the measurement simulation and the model prediction of the coupling term $|f_{1001}|$. The large tilt is clearly identified at 6 km as an abrupt jump of this term. The real and imaginary parts of this coupling term are also measured since all BPMs provide horizontal and vertical measurements. Using this information the coupling can be corrected either by skew correctors or by realignment of the identified sources.

ACKNOWLEDGMENTS

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