BPM CALIBRATION INDEPENDENT LHC OPTICS CORRECTION *

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Abstract

The tight mechanical aperture for the LHC imposes severe constraints on both the beta and dispersion beating. Robust techniques to compensate these errors are critical for operation of high intensity beams in the LHC. We present simulations using realistic errors from magnet measurements and alignment tolerances in the presence of BPM noise. Correction reveals that the use of BPM calibration and model independent observables are key ingredients to accomplish optics correction. Experiments at RHIC to verify the algorithms for optics correction are also presented.

INTRODUCTION

In [1] it was demonstrated through simulation that the correction of the beta-beating with magnetic measurement errors [2] in the LHC is achievable by using the phase advance between BPMs as the calibration independent observable. However the dispersion beating remained uncorrectable at that time. This paper shows how a calibration independent observable for the dispersion enables beta and dispersion beating correction simultaneously. Limitations of the method due to signal quality and faulty BPMs are also addressed. Finally the experience of applying this method to the Relativistic Heavy Ion Collider (RHIC) is reported.

DISPERSION BEATING CORRECTION

Looking for new observables for the dispersion correction, the quantity $D_x/\sqrt{\beta_x}$ appears very interesting since it can be measured independently of the BPM calibration. D_x is measured by momentum modulation and the $\sqrt{\beta_x}$ is measured by Fourier analysis of excited data. This guarantees that both observables are proportional to the BPM calibration. Therefore this calibration factor cancels out in the ratio $D_x/\sqrt{\beta_x}$. It has been also checked that the normalized dispersion $D_x/\sqrt{\beta_x}$ behaves linearly over a longer range of quadrupolar perturbations than D_x.

Fig. 1 shows the machine averages of $D_x/\sqrt{\beta_x}$, β_x and D_x normalized to the ideal values versus the rms beta-beating for many machines with random errors. The maximum deviation of $\langle D_x/\sqrt{\beta_x}\rangle$ from the design value is below the 1% level. Therefore it allows to accurately restore unknown global factors in the measurements of D_x and $\sqrt{\beta_x}$, like the calibration of the momentum and the transverse actions $\sqrt{I_{x,y}}$. Note that the machine average normalized dispersion has the smallest standard deviation of all three observables, supporting this choice.

Proceeding as in [1], the response matrix is computed using the ideal model. The $\mathbf{R}$-matrix relates the phase-beating, dispersion-beating and tune errors $(\Delta\vec{\phi}, \Delta\frac{\vec{D_x}}{\sqrt{\beta_x}}, \Delta Q_x, \Delta Q_y)$ with the strengths of all quadrupole circuits, $\vec{k_1}$ (by quadrupole circuit we understand a set of quadrupoles powered in series) as

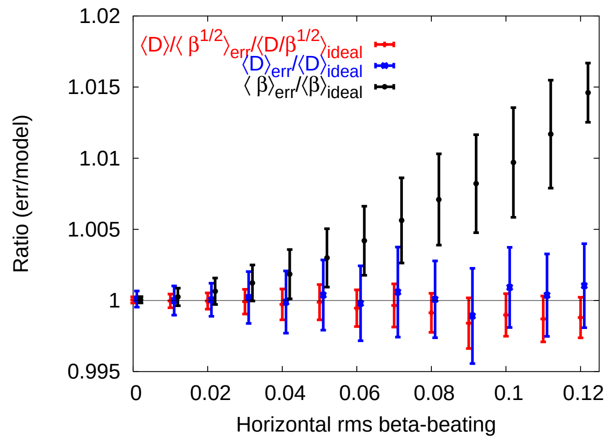

Figure 1: Average of the observables $D_x/\sqrt{\beta_x}$, β_x and D_x, for the LHC lattice.

$$(\Delta\vec{\phi}, \Delta\frac{\vec{D_x}}{\sqrt{\beta_x}}, \Delta Q_x, \Delta Q_y) = \mathbf{R}\Delta\vec{k_1} \quad (1)$$

The required correction strength is computed from the measured errors as

$$\Delta\vec{k_1} = -\mathbf{R}^{-1}(w_\phi\Delta\vec{\phi}, w_D\Delta\frac{\vec{D_x}}{\sqrt{\beta_x}}, \Delta Q_x, \Delta Q_y) \quad (2)$$

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 proved by realistic numerical simulations.

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 $(\Delta\vec{\phi}, \Delta\frac{\vec{D_x}}{\sqrt{\beta_x}}, \Delta Q_x, \Delta Q_y)$. This matrix is computed once and it is stored for use during the simulations.

A realistic LHC model is obtained by including all errors from magnetic measurements [3, 4]. In Fig. 2 the successful correction of beta-beating and dispersion beating is

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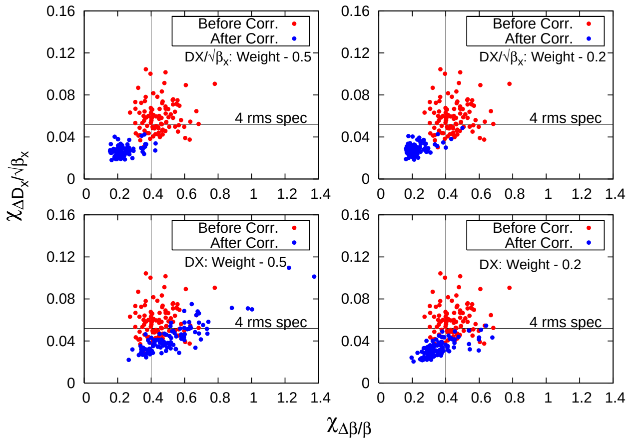

Figure 2: The top plots show the successful correction when using the normalized dispersion as observable for LHC. The bottom plots show the correction failure when using just dispersion for LHC.

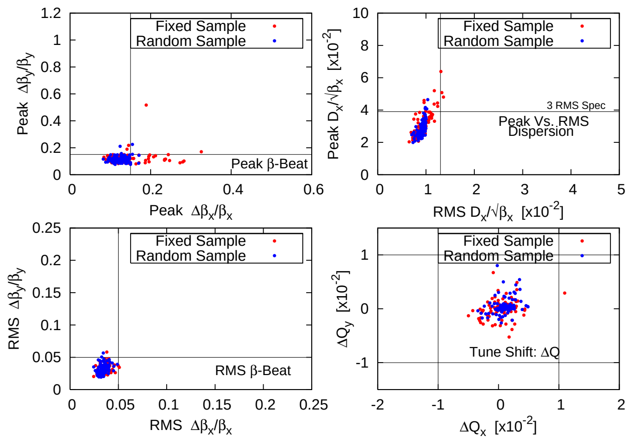

Figure 4: Distribution of seeds after correction having 10% BPM failure and for two cases: fixed distribution of failing BPMs through iterations and changing distribution of failing BPMs through iterations for LHC.

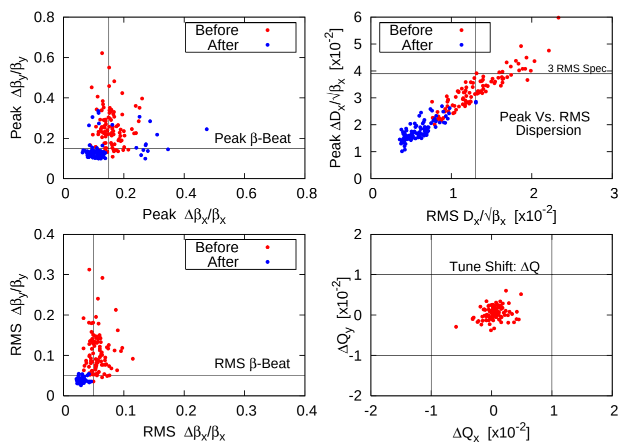

Figure 3: Some seeds fail correction when the error in the measurement of the rms BPM phase is considered to be 1° for LHC.

shown in the top two plots by using the $\frac{D_x}{\sqrt{\beta_x}}$ observable. The bottom plots show the failure to correct the dispersion beating if the normalized dispersion is not used, as was the case for [1]. All the ingredients of the simulation are the same as in [1]. One of the critical parameters is the accuracy of the measurement of the phase advance between BPMs. Initially an rms error on the phase measurement of 0.25° was assumed. Simulations were done in order to assess the maximum acceptable phase error. It has been found that at about 1° rms error some seeds start failing the correction, Fig. 3.

A critical problem for the optics correction is the existence of failing BPMs. Several mechanisms to identify those BPMs giving a non-physical signal have been proposed and applied in real machines [5]. Once the faulty BPMs are identified they are discarded from the analysis. Different percentages of failing BPMs were simulated just by removing them. Two scenarios were considered: -the set of faulty BPMs is fixed during the correction and -the set of faulty BPMs varies randomly between iterations. The most pessimistic case is clearly when the set of faulty BPMs is fixed and a threshold of about 10% missing BPMs in order to achieve correction is found, Fig. 4.

RHIC EXPERIENCE

A big effort has been done to develop a Python package to correct the RHIC optics on-line. This package is substantially equivalent to that to be used in the LHC. The steps follow:

- Data acquisition: Few sets of 1000 turns are recorded at all BPMs having applied simultaneous horizontal and vertical kicks to the beam.
- Data cleaning: Different filters are run to spot and remove the faulty BPMs.
- Data analysis: A refined Fourier Transform is ran to obtain the phase at all the BPMs.
- Computation of correction: Based on the phase-beat and a precomputed response matrix the correction is calculated in terms of the selected quadrupole circuits.

Different studies were done prior to correction attempts. The deterioration of the signal quality with chromaticity was assessed by recording various sets of data at different chromaticities. A histogram of the random errors of the phase advance between BPMs is shown in Fig. 5. There is very good resolution for the baseline measurement with a peak right below 0.2°. This is much better than the one required for LHC correction and confirms the feasibility of the measurement. However increasing the chromaticity by 2 units causes some BPMs to report with very large phase

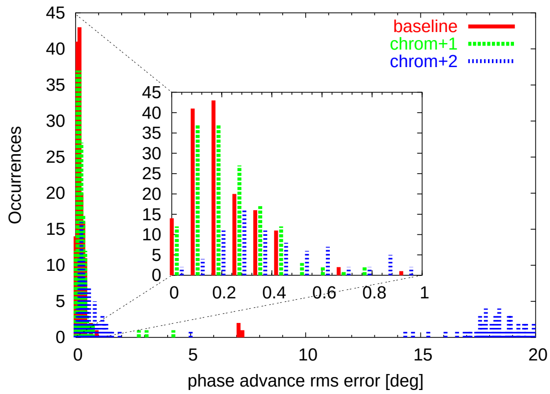

Figure 5: Histogram of random error of phase advance between RHIC BPMs for three data sets with increasing chromaticity in steps of 1 unit.

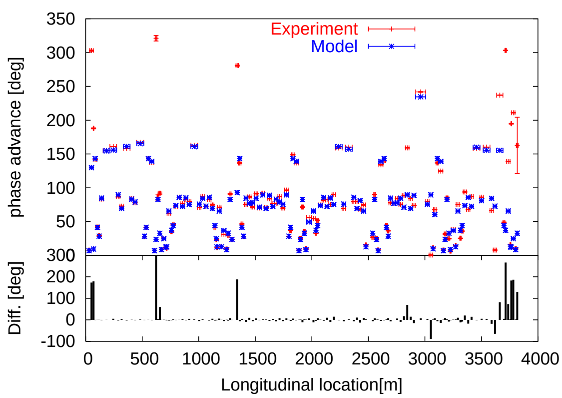

Figure 6: Measured phase advance between RHIC BPMs for the baseline together with a prediction from the model. Horizontal error bars correspond to the separation between the BPMs.

errors (>15°). This effect is not clear and has the drawback of having to reject these BPMs from the analysis. Regular BPMs seem to simply report with a slightly larger error for larger chromaticities as shown in the central plot of Fig. 5.

Fig. 6 compares the measured RHIC phase advance between adjacent BPMs to the phase advance of the existing RHIC model. Severe discrepancies exist after 2.7km and at a few other locations. The reason for this disagreement is under investigation. Although unlikely, one reason could be the wrong polarity of the BPM. A simple test was performed during a RHIC experiment by changing the strengths of three quadrupoles: [bi8-tq4, bo7-tq5, bo11-tq4], by the amounts 0.005, 0.005 and -0.005 m $^{-1}$, respectively. The measured change in the phase advance between adjacent BPMs is shown in Fig. 7 (bottom) together with a prediction from the model. Again the discrepancies are more severe after 2.7km. However even before 2.7km the agreement is only qualitative. A simplex algorithm was used to yield a better convergence of the model to the measured using just the three trim quadrupoles. As seen in Fig 7 (top), the agreement is better but not exact. Also the final trim values are [-0.015,-0.025,-0.002] which are far from the values used in the experiment. These dis-

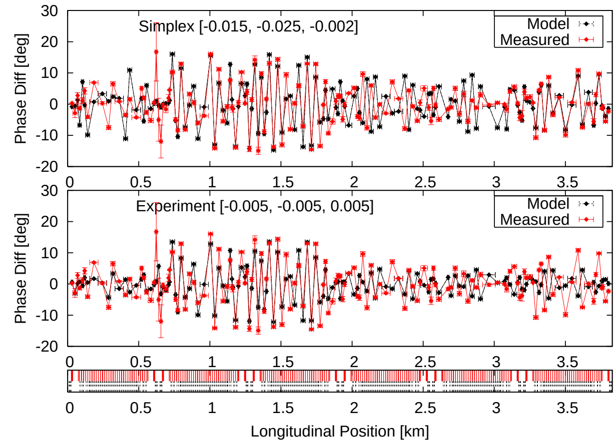

Figure 7: Measured phase shift between RHIC BPMs after trimming three quadrupoles together with a prediction from the model (bottom). A simplex fit of model to measured using the three trim quadrupoles (top). Horizontal error bars correspond to the separation between the BPMs.

crepancies would certainly impair any optics correction and are under investigation.

CONCLUSIONS

The use of BPM calibration independent observables is crucial to succesfully correct the LHC optics. These observables are: phase advances between BPMs, the normalized dispersion and the tunes. Furthermore, to guarantee correction some other constraints have to be fulfilled:

- The phase measurement must have an rms error $<1^\circ$
- The number of faulty BPMs must be below 10%

It was observed in RHIC that the BPM signals are abruptly deteriorated with small changes in chromaticity. This problem needs more understanding and maybe dedicated studies in other accelerators like the SPS.

From RHIC experiments, it was observed that the experimental phase response to the change of three quadrupoles had discrepancies with the model.

ACKNOWLEDGMENTS

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