OPTICS CORRECTION IN THE LHC *

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Abstract

Optics correction in the LHC is challenged by the tight aperture constrains and the demand of a highly performing BPM system. To guarantee that the LHC optics remains within a maximum allowable beta-beating of 20% several methods are being investigated through computer simulations and experiments at existing hadron machines. A software package to consolidate the implementation of the various techniques during LHC operation is underway (or nearing completion).

INTRODUCTION

In [1, 2] it was demonstrated through simulation that the correction of the β-beating and dispersion beating with measured magnetic errors [3] in the LHC is achievable by using the phase advance and normalized dispersion as calibration independent observables. Two techniques can be reliably used to measure the phase advance: the standard FFT and the Closed Orbit Distortion (COD), latter of which was successfully implemented in KEK-B [4]. β-functions can be infered from the measured phase advances and the model transfer matrix.

Dedicated measurements to test the $\beta-$beating correction were carried out at the Relativistic Heavy Ion Collider (RHIC). This paper describes the above techniques and the results from the RHIC experiments including the noise characterization of the phase measurement and the localization of $\beta-$beating errors.

β MEASUREMENT FROM PHASE

The beta function in the LHC will be inferred by measuring betatron phases between BPMs as done in LEP [5], using the following equation,

$$\beta_1 = \frac{\frac{1}{\tan\phi_{12}} - \frac{1}{\tan\phi_{13}}}{\frac{m_{11}}{m_{12}} - \frac{n_{11}}{n_{12}}} \tag{1}$$

where ϕ_{ij} are the phase advances from BPM i to j, m and n are the elements of transfer matrices between BPM 1 to 2, and between BPM 1 to 3. The design transfer matrices are employed as an approximation. In the LHC arcs, the phase advance between neighboring BPMs is about 45 degree, therefore very appropriate for this measurement.

The measurement error is checked via simulations of 100 LHC machines. Fig. 1 shows the maximum error of the β measurement in the arcs. The maximum error does not exceed 5% in arcs and shows a roughly linear dependence on the model β-beating since we assumed the design transfer

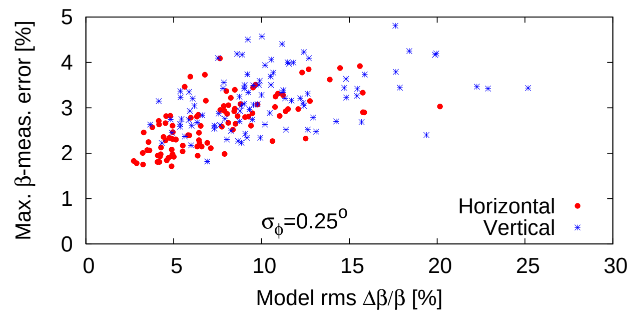

Figure 1: Maximum error in arc β measurement vs. r.m.s. model beta-beating. Phase error is assumed $\sigma_\phi = 0.25^o$.

matrices to find the beta function. The measurement error reaches few 10% in the IRs due to the phase advances between BPMs. The large errors are, however, detectable and reducible in two ways: 1.-by computing the error bars from Eq.1 and 2.-measuring β_2 and β_3 with similar equations to Eq.1 for five successive BPMs will give three different measurement results for one location, thus averaging three results, the measurement erros are again assesseed and effectively reduced.

CLOSED ORBIT BASED MEASUREMENT

The analysis tool for both beta-function and betatron phase based on the closed orbit response of single dipole kick are transplanted from the KEKB project. This method [4] is based on the analytic formula of the first-order perturbation theory:

$$\triangle\chi(s) = \frac{\sqrt{\beta_\chi(s)}}{2\sin\pi\nu_\chi}\triangle\theta_\chi\sqrt{\beta_\chi(s_{\rm kick})} \cos\left(|\phi_\chi(s) - \phi_\chi(s_{\rm kick})| - \pi\nu_\chi\right). \tag{2}$$

If the given dipole kicks are small enough to conserve the optics functions, the unknown variables $\beta_\chi(s)$ and $\phi_\chi(s)$ could be determined by fitting the set of the closed orbit response $\triangle\chi(s)$ using the different dipole magnets.

In order to estimate the error of the reconstructed beta-function and betatron phase advance, the benchmark test is achieved on the SAD [6] simulation model. In this benchmark, the closed-orbit responses are generated from the LHCB2 injection optics . As the error source of the closed-orbit measurement, both the $\pm 4\%$ uniform random calibration error of the BPM response gain and the Gaussian random sampling error of the closed-orbit measurement due to the BPM resolution are assumed. The $\pm 4\%$ calibration error makes about $\pm 8\%$ reconstruction error of the beta-function, because $\sqrt{\beta_\chi(s)}$ in Eq.2 follows the scaling con-

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version of $\triangle\chi(s)$. On the other hand, the reconstruction error of the betatron phase shown in Fig.2 does not depend with the BPM calibration. In the tested region, the maximum error of the betatron phase depends on the BPM resolution linearly.

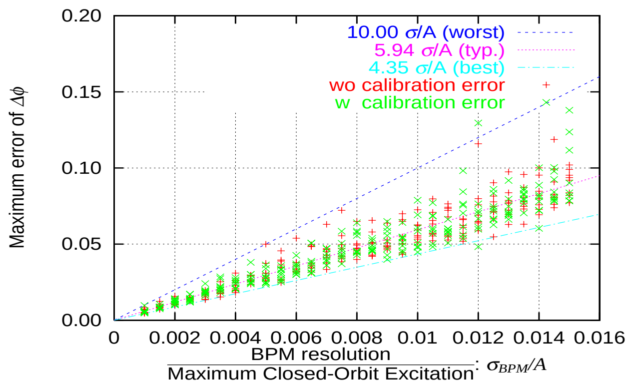

Figure 2: BPM resolution dependency of the betatron phase reconstruction error. The red and green points correspond to the simulation results with and without $\pm4\%$ BPM calibration error.

DISPERSION MEASUREMENT

The error in the dispersion measurement using closed orbit changes with momentum deviation ($\delta p/p$) can be upto a few percent due to BPM calibration error [9]. To avoid this we measure the normalized dispersion $ND = D/\sqrt{\beta}$. Calibration errors cancel if both D and $\sqrt{\beta}$ inferred from amplitudes of the BPM signals. A "global factor" for momentum deviation in dispersion measurement and kick amplitude for $\sqrt{\beta}$ measurement, common to all BPMs, is defined as

$$G = \frac{1}{\langle ND_M \rangle} \left\langle \frac{\Delta x}{C_\beta} \right\rangle \tag{3}$$

where Δx is the closed orbit shift, C_β is the largest coefficient of FFT analysis of BPM turn-by-turn data, $\langle ND_M\rangle$ is the average $D/\sqrt{\beta}$ in the model. Assuming that $\langle ND_M\rangle$ remains unchanged with optics errors [2] the global factor is inferred. ND at each BPM is given by

$$ND = \frac{\Delta x}{C_\beta G}. \tag{4}$$

The measurement of ND is simulated to confirm the global factor as shown in Fig 3. The maximum error shows no dependence on r.m.s. β-beating and hence can be assumed to be model independent measurement.

RHIC EXPERIMENTS

Dedicated RHIC expriments were performed with a goal to demonstrate an online measurement and correction of the magnetic optics using the same tools developed for the LHC. The procedure of measurement and correction is detailed in ref [2] which mainly consists using turn-by-turn

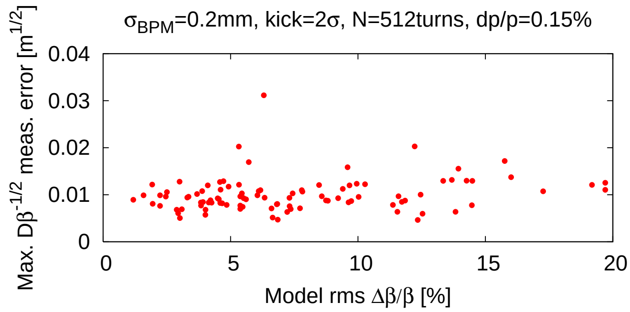

Figure 3: Maximum error in ND measurement vs. rms β-beating (simulation) for a 100 of LHC machines with errors.

BPM data to calculate phase advance and apply a linear RM type correction with the available quadrupole circuits. The normalized dispersion is always included in the RM to either keep the dispersion unchanged or perform a dispersion correction simultaneously. The effect of chromaticity and tunes on the measurement of the phase advances were also detailed in [2]. Two experiments were performed using manually induced quadrupole errors to have a controlled set of data and evaluate the impact of BPM noise. Due to bad quality of the baseline data (without induced quadrupole error), two data sets with two different set of 3 quadrupole error settings were used to compute the phase beat. This phase beat eliminates residual errors already existing in the lattice as compared to the model, thus providing a clean source for comparison.

The two sets of three quadrupoles are {bi8-tq4, bo7-tq5, bo11-tq4} and {bi8-tq6, bo3-tq6, bo11-tq6} by amounts of $\pm0.005\,\mathrm{m}^{-1}$. The measured phase advance between BPMs is shown in Fig. 4 together with the model.

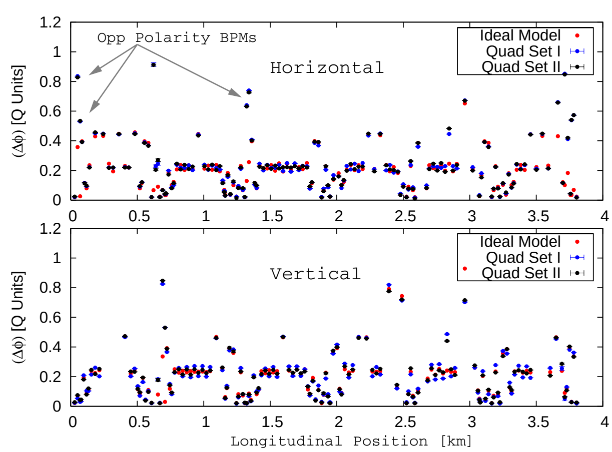

Figure 4: Measured phase advance between RHIC BPMs after trimming 1^{st} set of three quadrupoles (blue) and the 2^{nd} set (black) compared to the ideal model (red). Vertical error bars are statistical deviation between three consequetive data sets with the same condition

The phase beat induced by the net change of six quadrupoles can be obtained from the difference between the two sets which is shown in Fig. 5. The reconstructed phase beat from the model RM inversion onto the measured phase beat is also plotted.

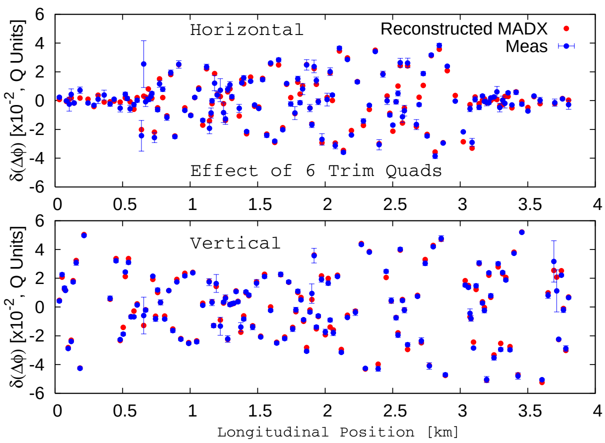

Figure 5: Measured phase beat between RHIC BPMs after trimming six quadrupoles by $\pm 0.005\ \mathrm{m}^{-1}$ randomly.

The resulting quadrupole trims predicted by the inversion of the RM to reconstruct the observed phase beat is shown in Fig. 6. A similar experiment was performed with a single quadrupole error while using an ac dipole instead a impulse kick which has an inherent advantage due to resonant excitation. It therefore induces coherent betatron oscillations, only limited by data acquisition capacity [7]. Although, it has superior signal to noise ratio, the system is a driven oscillator which is different from the natural betatron frequency. Fig. 6 shows the detection of the single quadrupole error via RM inversion and ac dipole induced coherent oscillation.

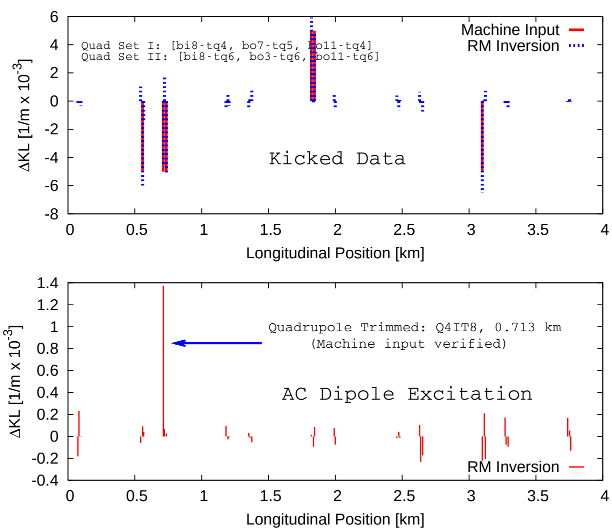

Figure 6: Top: Quadrupole trims predicted by RM inversion onto the measured phase beat from kicked data compared to the input trims into the machine. Bottom: Quadrupole trim predicted by RM inversion onto measured phase beat using an ac dipole excitation.

NOISE

BPM noise studies in simulations have indicated an upper limit of 1.0° in rms phase noise (σ_ϕ) and 10-15% percent BPM failure to ensure a effective β-beat correction below the 20% level in the LHC [2]. Robust techniques are also in place to identify and remove faulty BPMs from the data analysis [8]. shows a histogram of phase noise from several data sets acquired with RHIC BPMs both for kicked data and via an ac dipole which indicate that σ_ϕ is a factor of 4 less with the low chromaticity.

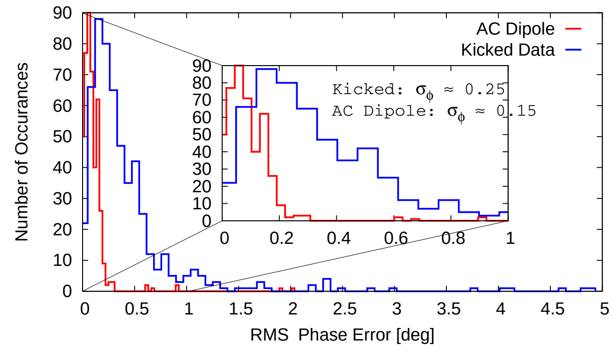

Figure 7: Histogram of the rms phase noise from the all the BPMs from several data sets both from kicked data and ac dipole excited data.

However, RHIC measurements also indicate that higher chromaticity can dramatically increase σ_ϕ to several degrees [2]. This effect will also be verified in the SPS. Optics correction is anticipated to be be performed at low intensities and small chromaticties. If higher chromaticities are required for beam stability, ac dipole can aid in improving the optics measurement and correction.

CONCLUSIONS

Phase beat induced via dedicated experiments at RHIC have been successfully measured and the error sources are clearly identified using RM techniques developed for the LHC. Experiments using ac dipole excited data show promising results and can aid in overcoming deterioation of phase measurement due to larger chromaticity. A software application to automate the beta-beating correction in the LHC is currently being tested in the SPS.

ACKNOWLEDGMENTS

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