AC DIPOLE BASED OPTICS MEASUREMENT AND CORRECTION AT RHIC*

X. Shen†, S. Y. Lee, Indiana University of Bloomington, IN, 47405, USA
M. Bai, S. White, G. Robert-Domolaize, Y. Luo, A. Marusic, BNL, Upton, NY, 11973, USA
R. Tomás, CERN, CH1211 Geneva 23, Switzerland

Abstract

Independent component analysis (ICA) was applied to the AC dipole based optics measurement at RHIC to extract beta functions as well as phase advances at each BPM. Existence of excessive beta-beat was observed in both rings of RHIC at polarized proton store energy. A unique global optics correction scheme was then developed and tested successfully during the RHIC polarized proton run in 2013. The feasibility of using horizontal closed orbit bump at sextupole for arc beta-beat correction was also demonstrated.

INTRODUCTION

Accurate optics measurement and efficient optics correction schemes are highly demanded to provide more precise optics manipulation for further improvement of RHIC luminosity as well as its polarization performance.

ICA FOR AC DIPOLE BASED OPTICS MEASUREMENT

At RHIC, AC dipole has been routinely used to excite sustained coherent beam motion with large amplitude and preservation of beam emittance to facilitate acquisition of 1024 turn by turn beam position data at the beam position monitors (BPMs) [1]. Optical functions can then be extracted from the recorded BPM data by the technique of independent component analysis (ICA). ICA is more efficient than principle component analysis (PCA) because, in addition to correlations of data from all BPMs, it takes advantage of the time correlation between independent components to extract source signals with non-overlapping spectra [2]. From the spatial functions of source signals corresponding to AC dipole driven oscillation, one may extracted the modified betatron amplitude function β_d and phase advance ψ_d, which are related to the optical functions β_f and ψ_f of free betatron oscillation as [3]:

$$\beta_d = \frac{1+\lambda^2 - 2\lambda\cos[2(\psi_f - \pi\nu)]}{1-\lambda^2}\beta_f, \tag{1}$$

$$\tan(\psi_d - \pi\nu_d) = \frac{1+\lambda}{1-\lambda}\tan(\psi_f - \pi\nu_f), \tag{2}$$

where $\lambda = \sin[\pi(\nu_d - \nu_f)]/\sin[\pi(\nu_d + \nu_f)]$, ν_d is the driving tune of the AC dipole, and ν_f is the betatron tune of free oscillation. In Eq. (1) and (2), the reference point for phase advance is at the location of the AC dipole. In order to reconstruct the β_f and ψ_f, an accurate and efficient method was developed for routine operation. This method averages optical functions from two measurements in which ν_d is set on either side of ν_f with a distance of 0.01 to minimize the systematic errors from AC dipole driven oscillation. Details about the robustness of this averaging method against BPM errors can be found in Ref. [4].

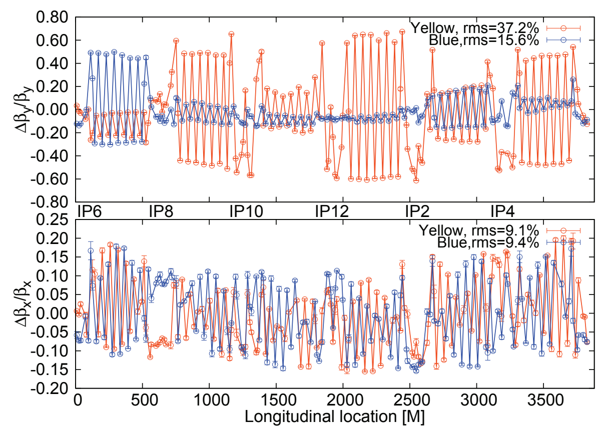

Figure 1: Measured beta-beat with error bars in the horizontal (bottom) and vertical (top) plane for both rings at RHIC. 15% peak beta-beat was observed in the horizontal plane for both rings. A 30% vertical peak beta-beat was found in the Blue ring and 60% in the Yellow ring

Figure 1 shows the beta-beat for the 255 GeV polarized proton beams in the Blue and Yellow rings during RHIC operation in 2013. In both rings, the horizontal peak beta-beat is approximately 15%. In the vertical plane, the peak beta-beat reaches 30% in the Blue ring and 60% in the Yellow ring. The excessively large beta-beat requires efficient correction to be explored.

BETA-BEAT RESPONSE MATRIX CORRECTION METHOD

The problem of beta-beat correction can be described by the following model:

$$\mathbf{WB} = \mathbf{WRK}, \tag{3}$$

where $\mathbf{B}^T = (\frac{\Delta\vec{\beta}_x}{\beta_x}, \frac{\Delta\vec{\beta}_y}{\beta_y}, \Delta\nu_x, \Delta\nu_y)$ is composed of the beta-beat vectors and tune variations, $\mathbf{K}^T = (\Delta K1L_1, \Delta K1L_2, \ldots, \Delta K1L_N)$ represents the change of integrated strength of N quadrupoles, and the superscript T means a transpose. $\mathbf{R}$ is the $M \times N$ beta-beat

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† xiaoshen@indiana.edu

response matrix. $\mathbf{W}$ is a diagonal matrix containing the weighting factors w_i $(i = 1, \ldots, M)$. To avoid beam loss and polarization loss, the tune variations receive high weights to be minimized. Beta-beat from noisy BPMs are assigned low weights. In reality, the number of independently powered quadrupoles is often very limited, i.e., $M \gg N$, such that Eq. (3) describes an overdetermined system in which the weighted measured beta-beat is minimized with the constraint of zero tune shifts. The required correction strength $\mathbf{K}_{\text{cor}}$ is computed by using the generalized inverse $(\mathbf{WR})^\dagger$ of the weighted response matrix from singular value decomposition (SVD) as:

$$\mathbf{K}_{\text{cor}} = -(\mathbf{WR})^\dagger \mathbf{WB}. \tag{4}$$

Since the response matrix $\mathbf{R}$ is calculated from the ideal model, multiple iterations of correction based on Eq. (4) are necessary in the event of large beta-beat.

Based on the method discussed above, systematic computations were carried out to determine optimum correction for both rings of RHIC, in which a total of 72 triplet and trim quadrupoles in the interaction regions (IRs) with independent power supply are used as beta-beat correctors and two families of arc quadrupoles are included for tune compensation.

Figure 2 shows the relative correction strength for the Blue ring. All relative changes are below the maximum capability of power supplies. The large changes in trim quadrupoles are because the trim quadrupoles are initially set at a low field. Figure 3 shows the measured beta-beat with and without correction. The horizontal peak beta-beat was successfully reduced from 15% to 8%, while the vertical peak beta-beat was reduced from 40% to 14%. The experimental results were in good agreement with predictions.

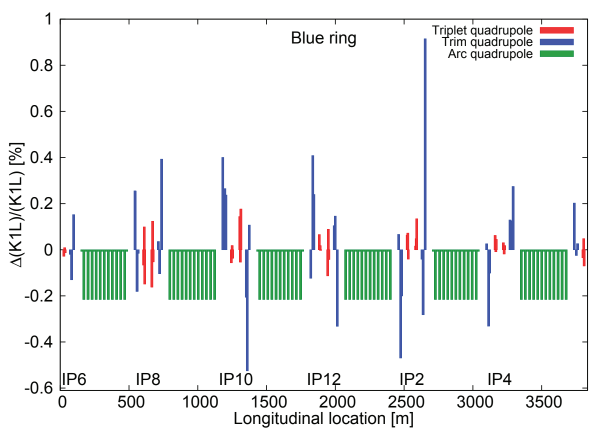

Figure 2: Relative changes of quadrupole integrated strength as a function of quadrupole locations in the Blue ring.

Due to the excessively large beta-beat in the vertical plane of the Yellow ring, two iterations of correction were implemented within the limited beam time. Figure 4 shows the computed relative corrections for the Yellow ring for the first and second iteration. Figures 5 and 6 show the measured horizontal and vertical beta-beat in the Yellow ring with and without corrections ,respectively. After the first iteration, the horizontal peak beta-beat was reduced to 12% which is consistent with the prediction, while the vertical peak beta-beat was reduced to 20% which still deviates quite much from the computation. Good agreement between experiment and prediction was found after the second iteration and peak beta-beat in both planes were reduced to 10%.

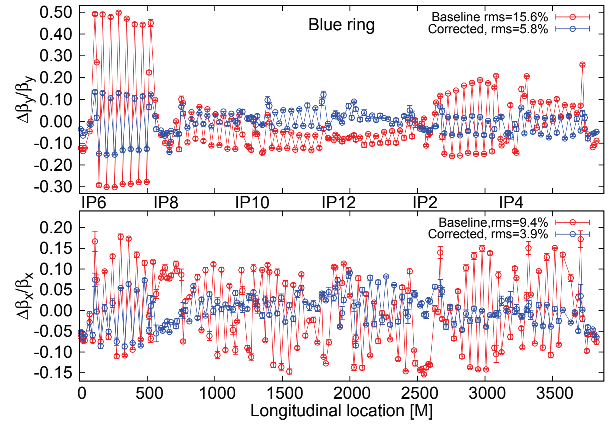

Figure 3: Baseline and corrected horizontal (bottom) and vertical (top) beta-beat with error bars for the Blue ring. Horizontal peak beta-beat was corrected from 15% to 8%, while vertical peak beta-beat from 40% to 14%.

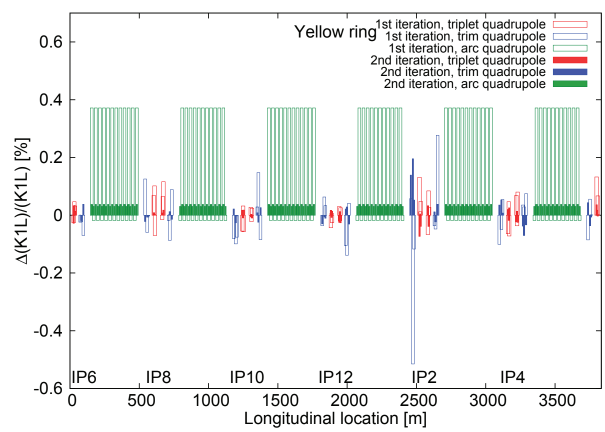

Figure 4: Relative changes of quadrupole integrated strength as a function of quadrupole locations in the Yellow ring for the first iteration (hollow bars) and second iteration (solid bars), respectively.

ARC BETA-BEAT CORRECTION USING CLOSED ORBIT BUMP AND SEXTUPOLE

In RHIC, there are no independently powered quadrupoles in the arcs such that gradient errors in these regions cannot be effectively corrected. However, feed-down normal quadrupole field from horizontal closed orbit bump at sextupole can be included as additional correctors to reduce beta-beat in these regions. This technique also provides capabilities of more precise optics

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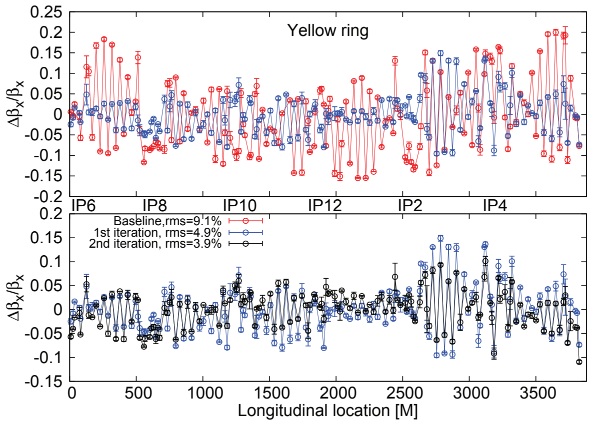

Figure 5: Baseline and corrected horizontal beta-beat with error bars for the Yellow ring. The peak beta-beat was reduced from 15% to 12% after the first iteration of correction, and further reduced to 10% after the second iteration.

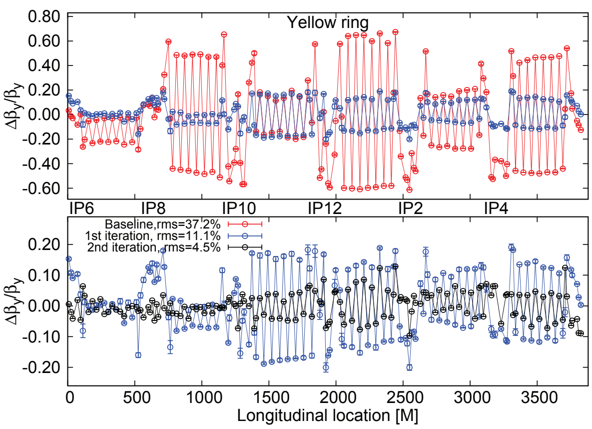

Figure 6: Baseline and corrected vertical beta-beat with error bars for the Yellow ring. The peak beta-beat was reduced from 60% to 20% after the first iteration of correction, and further reduced to 10% after the second iteration.

control to facilitate demanding optics manipulations. A proof-of-principle experiment of this technique was successfully carried out during the 2013 RHIC polarized proton operation.

Figure 7 shows the computed horizontal closed orbit required for arc beta-beat correction as well as the measured horizontal closed orbit. The computed and measured closed orbit are well matched in the arcs. The mismatches at around the interaction points (IPs) do not affect the correction performance because there are no sextupoles in these regions. The correction results are shown in Fig. 8. In the horizontal plane, beta-beat reduction was seen clearly in the arc between IP10 and IP12 as well as the arc between IP4 and IP6. In the vertical plane, significant beta-beat reduction was observed in the four arcs between IP10 and IP4. Overall, the peak beta-beat was reduced to 7%.

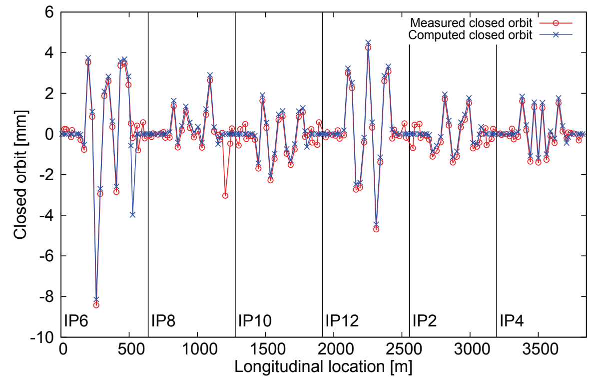

Figure 7: Measured and computed horizontal closed orbit for correction of arc beta-beat in the Yellow ring.

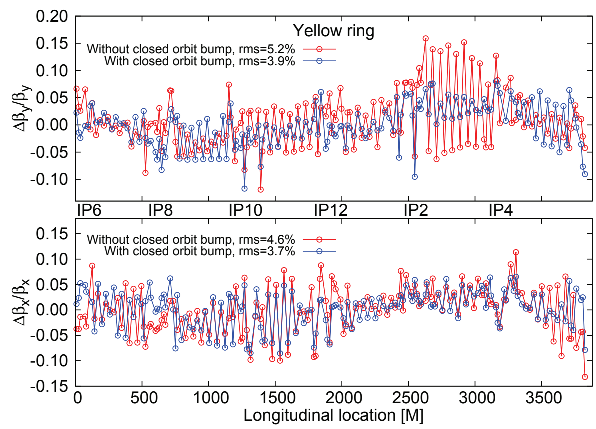

Figure 8: Horizontal (bottom) and vertical (top) residual beta-beat with and without the horizontal closed orbit bump displayed in Fig. 7 for the Yellow ring. Peak beta-beat was reduced to 7% for both planes with the closed orbit bump.

CONCLUSION

ICA was by the first time applied to RHIC to accurately extract optical functions from turn by turn BPM data of AC dipole driven betatron oscillation. With limited number of quadrupole correctors, a global correction scheme using beta-beat response matrix method was experimentally demonstrated to reduce the peak beta-beat to 10%. Peak beta-beat was further reduced to 7% during a proof-of-principle experiment of arc beta-beat correction using horizontal closed orbit bumps at sextupoles.

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