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LINEAR AND CHROMATIC OPTICS MEASUREMENTS AT RHIC *

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Abstract

Measurements of chromatic beta-beating were carried out for the first time in the RHIC accelerator during Run 2009. The analysis package developed for the LHC was used to extract the off-momentum optics for injection and top energy. Results from the beam experiments and compassion to the optics model are presented.

INTRODUCTION

The primary goal of the RHIC experiments were execute an on-line measurement of the optics using the tools developed for the LHC. Turn-by-turn BPM trajectories (typically 1000 turns) acquired immediately after an external dipole kick are numerically analyzed to determine the optical parameters at the location of the beam position monitors (BPMs). For chromatic optics, a similar analysis, but on a beam with finite momentum offset(s). Each optical measurement typically is calculated from multiple data sets to capture statistical variations and ensure reproducibility. The procedure of measurement and analysis is detailed in ref [1, 2]. Two dedicated experiments were performed at RHIC with protons during Run 2009. The first at injection energy and optics and the other at 250 GeV and squeezed optics. The basic RHIC parameters relevant for the two experiments are listed in Table 1.

Table 1: RHIC beam parameters for injection and top energy.

Quantity	Blue Ring	
	Injection	250 GeV
# of bunches	6×6	12×12
Bunch Intensity [10^{11}]	1.0	1.0
Max Beam loss [%/h]	150	100
Emittance, $\epsilon_{x,y}$ [μrad]	12/21	12/21
Tunes, $Q_{x,y}$	28.74, 29.72	28.69, 29.70
Chromaticity, (ξ_x, ξ_y)	2.6, 1.5	∼2.0
Quantity	**Yellow Ring**	
	Injection	250 GeV
# of bunches	-	12×12
Bunch Intensity [10^{11}]	1.0	1.0
Max Beam loss [%/h]	-	100
Emittances, $\epsilon_{x,y}$ [μrad]	-	10/-
Tunes, $Q_{x,y}$	28.72,29.74	28.69, 29.70
Chromaticity, (ξ_x, ξ_y)	∼2.0	∼2.0

LINEAR OPTICS

Deviations of lattice quadrupole strengths from the ideal lattice can generate a β wave (β-beat) around the ring. The limitation for the maximum allowable β-beat is typically due to the available machine aperture which could be restricted at the final focus triplets with decreasing β^*. These perturbations will also result in the change of betatron tune and result in the shrinking of dynamic aperture and beam losses during injection and nominal operation.

The perturbation of the β function due to N quadrupole errors at locations s_i is

$$\frac{\Delta\beta(s)}{\beta(s)} = \frac{1}{2\sin(2\pi Q)}\sum_{i=1}^{N}\Delta k\beta(s_i).\sin\left(2|\psi(s)-\psi(i)|-2\pi Q\right) \quad (1)$$

where Δk is the integrated quadrupole strength.

The measured β-functions and therefore the β-beating is calculated from the turn-by-turn data. Equivalently, phase-beating which independent of the BPM calibration is a more robust observable. The phase beating at injection and collision (250 GeV) optics for RHIC are shown in Fig. 1. Note the lattice is depicted at the bottom and the breaks in the regular pattern represent the IRs, with clockwise nomenclature. The large error bars at specific locations are

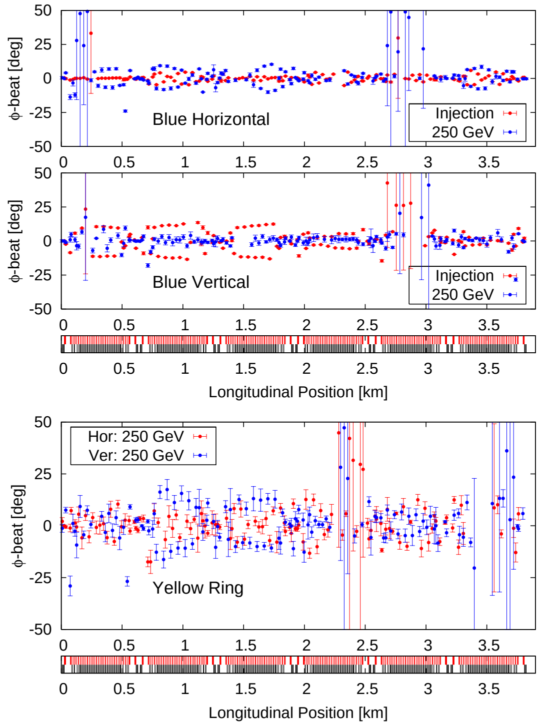

Figure 1: Phase beating measured in the Blue (top) and Yellow (bottom) rings at injection energy and 250 GeV.

due to incorrect BPM synchronization offsets at the time of the measurements. The phase beating is rather large

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in all measurements compared to measurements performed in past at RHIC [5]. Some quadrupolar errors are evident from the phase-beating pattern in IR_6 & IR_{12} at injection in the Blue ring and IR_6 & IR_8at 250 GeV in the Yellow ring. If this phase beat is reproducible for successive ramps, an optics correction can be either performed using all available quadrupole circuits or selective IR-by-IR [1].

RHIC operates close to the difference resonance to maximize the available tune space. The global coupling is typically corrected to $\Delta Q_{min} \leq 5 \times 10^{-3}$. It is important to identify the local sources of coupling and compensate them more effectively the with available skew quadrupoles. Some relevant coupling sources in RHIC include:

- IR Triplet and arc quadrupoles rolls (-$k_1\theta$), skew quadrupole errors in the interaction region (IR) (-k_1^s) and experimental solenoids
- Sextupole feed-down to skew quadrupole field at the chromaticity sextupoles and at all the dipoles due to vertical closed orbit offsets (-$k_2 y$)

The major sources of the coupling are expected from triplet rolls where the β functions are also the largest. Coupling is deduced from a complex Fourier spectrum of the turn-by-turn BPM data. The Fourier transform is constructed from normalized particle positions and momenta using technique of adjacent BPMs positions [4, 3]. The sum and difference resonance driving terms (RDT's) f_{1001} and f_{1010} are deduced from the secondary spectral lines [4, 6]. These terms are functions of the uncoupled lattice parameters at the location of both the coupling elements and the observation point s given by

$$f(s)_{\substack{1001\\1010}} = \frac{-1}{4(1-e^{2\pi i(Q_x \mp Q_y)})} \sum_l k_l \sqrt{\beta_x^l \beta_y^l} e^{i(\Delta\phi_x^{sl} \mp \Delta\phi_y^{sl})} \quad (2)$$

where k_l is the l^{th} integrated skew quadrupole strength, $\beta_{x,y}^l$ are the Twiss functions at the location of the l^{th} skew quadrupole, $\Delta\phi_{x,y}^{sl}$ are the phase advances between the observation point s and the l^{th} skew quadrupole and $Q_{x,y}$ are the horizontal and vertical tunes. Fig. 2 shows the amplitude of the coupling RDTs for the RHIC lattice at injection (Blue ring only) and 250 GeV optics.

CHROMATIC OPTICS

Knowledge of chromatic optics and deviations from the model is useful with decreasing β^* as the IR regions could pose an aperture limitation. The linear chromatic β-function, $\frac{1}{\beta}\frac{d\beta}{d\delta}$, can be computed from a linear fit of β-functions with respect to energy. The normalization with on-momentum β-function provides a BPM calibration independent observable.

A momentum offset scan with simultaneous turn-by-turn BPM trajectories synchronized with kicks to measure chromatic optics of RHIC was also carried out. The agreement of chromatic β-functions at injection in the Blue ring are very good with the model. Some deviations are observed in the vertical plane. The maximum chromatic beta-beat is measured to be ∼5% for a momentum deviation of $\delta = 1 \times 10^{-3}$.

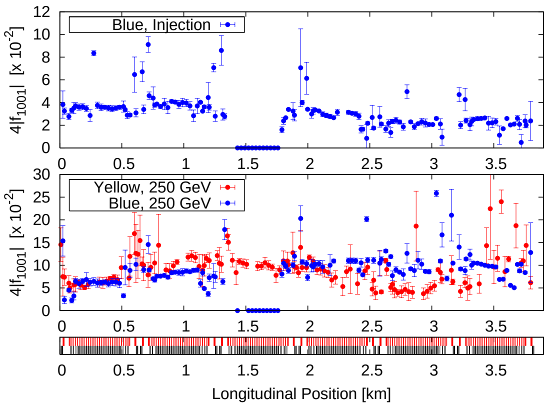

Figure 2: Amplitude of the coupling difference resonance driving term (f_{1001}) as a function of longitudinal position.

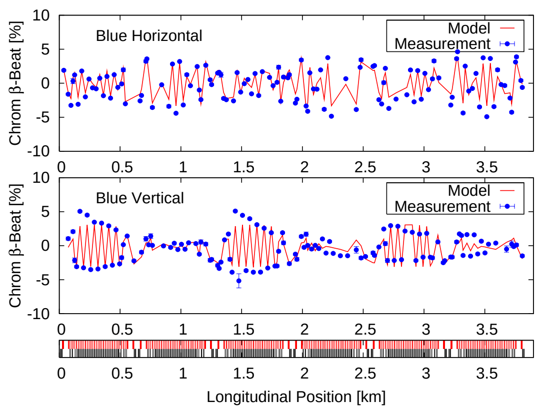

Figure 3: Phase beating measured in the Horizontal and vertical planes in the Blue ring at injection energy and optics.

At collision optics (0.7m at $IR_{6,8}$), there is already a difference in the model chromatic optics in Blue and Yellow ring as seen in Fig. 4. The measured chromatic beta-beat is in good agreement with the model with some deviation between the two low-beta IRs. The maximum chromatic beta-beat at collision optics is approximately ±40%. Some improvement in model chromatic beta-beat with adjusting arc phase advances and existing sextupole circuits could be beneficial from aperture considerations at collision optics.

The average orbits as a function of momentum offsets are automatically available from acquired data. Therefore, dispersion information is also available. To avoid BPM calibration errors, the normalized dispersion $(D_x/\sqrt{\beta_x})$ is typically measured. Fig. 5 shows the normalized dispersion for injection and collision optics. The measured normalized dispersion is required to have a simultaneous optics and dispersion correction.

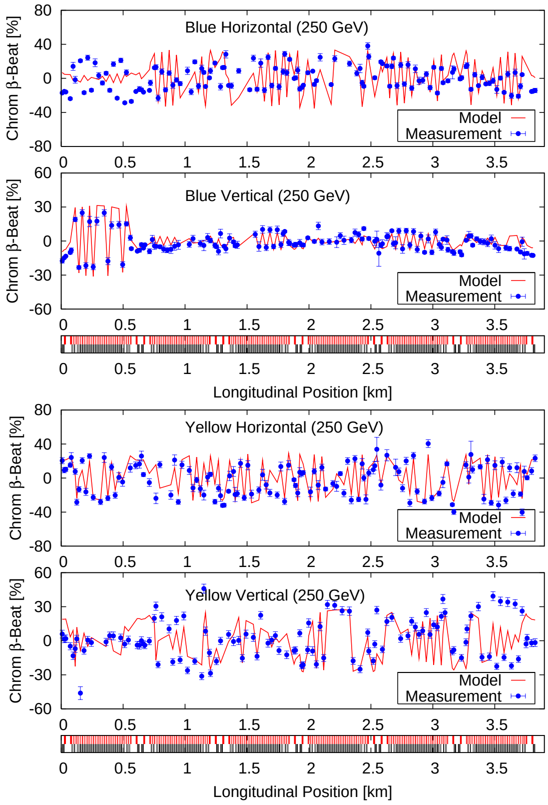

Figure 4: Phase beating measured in the Blue (top) and Yellow (bottom) rings at 250 GeV and collision optics.

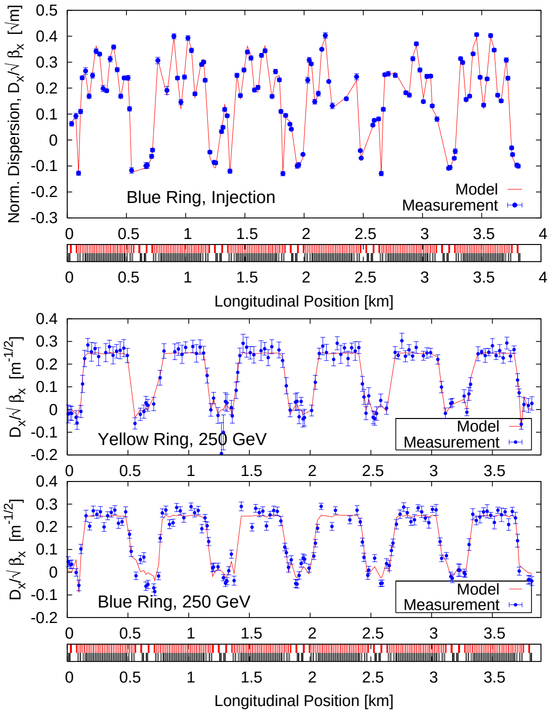

Figure 5: Normalized dispersion at injection energy (top, blue only) and at 250 GeV (bottom) as a function of longitudinal position.

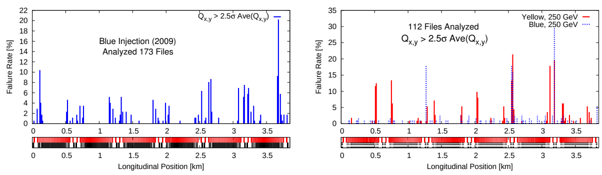

Figure 6: Statistics of BPMs failure in data sets acquired at injection energy and 250 GeV.

BPM NOISE STATISTICS

All data analysis is typically pre-conditioned to eliminate faulty BPMs. Robust numerical techniques have been developed and bench marked with data for identification of faulty BPM data [7]. An additional cut based on measured tune at each BPM is also incorporated to ensure data sanity. The data acquired for the two experiments were analyzed for the tune sanity check and fig. 6 shows the BPM failure rate as a function of the longitudinal position. The tune sanity cut was set at $< 2.5\sigma$ of average tune. As in the past measurements, the IR BPMs have a worse performance than the arcs by at least a factor of 5-10. However, the failure pattern is different at injection energy as compared to 250 GeV. Therefore, identification and mitigation of the individual BPM failures may not be trivial.

CONCLUSIONS

Measurements of linear and chromatic optics were carried during Run 2009 in RHIC and results from these experiments were presented. The on-momentum optics show larger than usual phase beating both at injection and collision optics than past measurements. The dispersion and the first chromatic beta-beating measurements show good agreement with the model. Improvements in the model chromatic optics at collision optics could prove beneficial to gain available apertures.

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