PRECISION BEAM INSTRUMENTATION AND FEEDBACK-BASED BEAM CONTROL AT RHIC*

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Abstract

In this report we present advances in beam instrumentation required for feedback-based beam control at the Relativistic Heavy Ion Collider (RHIC). Improved resolution has contributed to enabling now routine acceleration with multiple feedback loops. Better measurement and control of the beam's properties have allowed acceleration at a new working point and have facilitated challenging experimental studies.

INTRODUCTION

Beam properties at RHIC are now measured with unprecedented precision. This has made possible simultaneous orbit, tune, and coupling feedback [1] now routinely applied during beam acceleration. Also, a new "10-Hz" feedback [2] designed to suppress orbit distortions due to triplet quadrupole vibrations was applied during the energy ramp. This feedback enabled even more precise measurement of the beam's parameters.

These achievements have culminated in a conversion of beam control from being setpoint based (pre-programmed and subject to external influences, such as persistent current decay or thermal variations) to being based on measurement of the beam's properties and continually corrected through the use of feedback.

In this report we review briefly the present resolution of the beam position, tune and coupling measurements. We then show experimental data illustrating the effect of the 10 Hz feedback system on measurement precision. Next we describe changes which allowed routine implementation of simultaneous orbit, energy, tune, and coupling feedback on all ramps during run-11. We motivate and illustrate the impact of these results on overall RHIC performance and present experimental data acquired under extreme conditions; namely, near-resonance acceleration, used during normal operations, and acceleration/deceleration for dedicated studies.

BEAM POSITION MONITORS (BPM)

A factor of ~50 improvement in the resolution of the measured average orbit was achieved [3] by implementation of an IIR filter to effectively average over predominantly ~10 Hz closed orbit distortions. A difference orbit obtained during a BPM polarity check procedure is shown in Fig. 1. The resolution of the BPMs used for orbit feedback is now < 5 μm.

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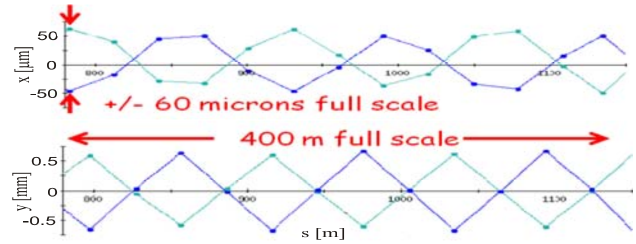

Figure 1: Horizontal (x, top) and vertical (y, bottom) difference orbit measurements in a RHIC arc.

TUNE AND COUPLING

The resolution of the tune and coupling measurements was greatly improved by (1) numerous hardware modifications, (2) detection and avoidance of data corruption by interfering processes, and (3) by using all available data, averaging, and delivering at the same rate as previously [4]. The resolution of tune measurements is now <2E-6 (factor 100 improvement) and the coupling parameters, κ and Δ, defined in Ref. [5], <1E-3 (factor >10 improvement). Recent measurements acquired at store (100 GeV, Au beam) without feedback close to the coupling resonance are shown in Fig. 2. Residual oscillations due to triplet motion now dominate the measurements.

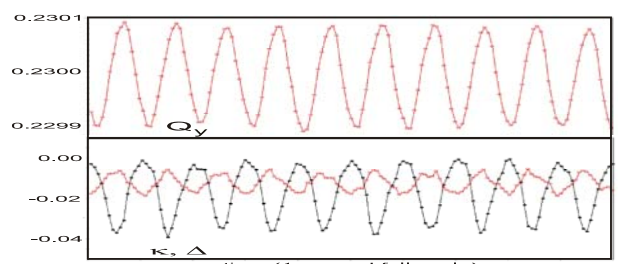

Figure 2: Vertical tune (Q_y, top) and coupling coefficients (κ and Δ, bottom) measured at store without feedback.

EFFECT OF 10 HZ FEEDBACK

Correction of orbit distortions by 10 Hz feedback [2] reduced also the amplitude of residual tune modulations generated by feeddown in the ring sextupoles [6]. This is illustrated in Fig. 3 which shows horizontal tune measurements Q_x obtained at the same time during two consecutive ramps one with and one without 10 Hz feedback (and with normal orbit, energy, tune and coupling feedback). Shown in Fig. 4 are the measured beam transfer functions in the blue and yellow rings measured approximately after ½ hour of collisions with and without the 10 Hz feedback. Without feedback the spectra, yellow horizontal (b) in particular, were influenced by the triplet vibrations.

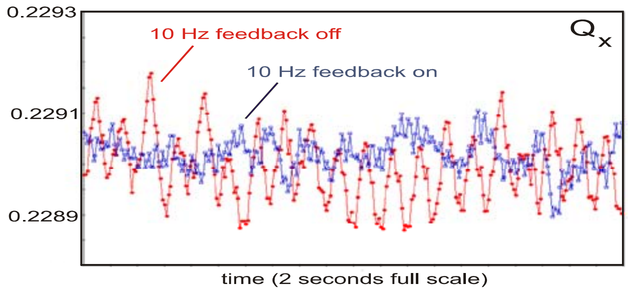

Figure 3: Measured horizontal tunes during the energy ramp with (blue) and without (red) 10 Hz orbit feedback.

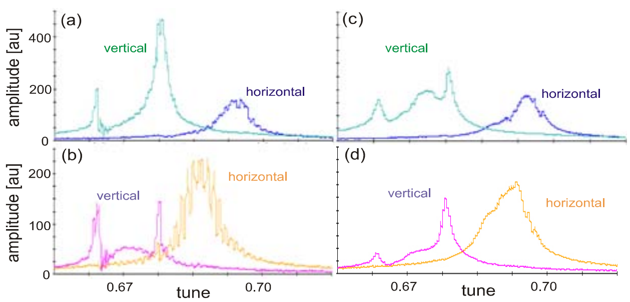

Figure 4: Measured beam transfer functions without (a,b) and with (c,d) 10 Hz feedback in the blue (a,c) and yellow (b,d) rings.

ORBIT AND ENERGY FEEDBACK

In run-11 orbit [7] and energy feedback were added together with existing tune and coupling feedback and used routinely during all energy ramps including those for physics stores. Key to this effort was an extension of the existing orbit correction method to force the average horizontal corrector strength to zero. Additionally precision measurements (using all arc BPMs) of the radial beam offsets were generated and delivered to the low-level rf system to adjust the rf frequency to horizontally center the beams*.

IMPACT ON RHIC OPERATIONS

A major portion of the RHIC physics program involves high energy polarized protons collisions. During the previous 250 GeV polarized proton run [run-9, ref. 8], the polarization at store was lower than estimated A detailed study [8], reproduced in Fig. 5, indicated a very strong dependence on the vertical tune Q_y during the energy ramp. In particular the snake resonance at Q_y=7/10 and orbit resonance at Q_y=3/4 were inexplicably wide.

During run-11 the vertical tune could be lowered towards the dangerous 2/3 resonance during the critical portion (100 to 250 GeV or from 100 to 250 seconds) of the energy ramp. The measured tunes (Q_x, horizontal and Q_y, vertical) are shown versus time in Fig. 6. With orbit, tune and coupling feedback applied on all energy ramps, tune deviations of up to 0.018 [9] without feedback were eliminated. This allowed the vertical tune to be reduced from 0.678 (run-9) to 0.673 (run-11). Additionally imperfection depolarizing resonance strengths were likely reduced and diurnal variations [7] were eliminated. Based on Fig. 5, an estimated (20-25)% higher relative polarization was achieved which is significant as the figure of merit for systematic errors for the physics programs at RHIC scale with the fourth power of the polarization.

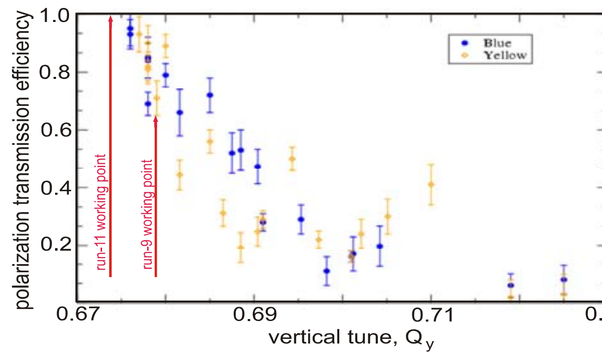

Figure 5: Polarization transfer efficiencies in the blue and yellow rings versus vertical tune setting during the 100 to 250 GeV portion of the energy ramp.

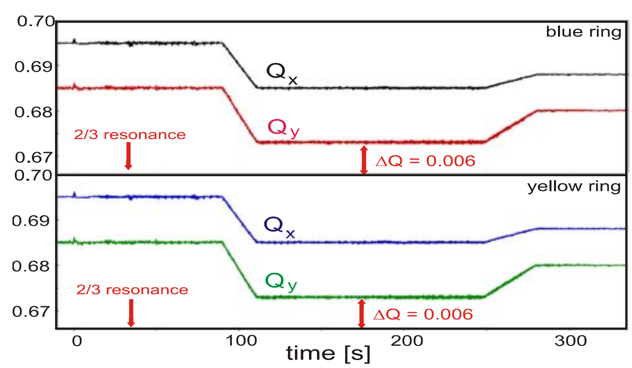

Figure 6: Tunes in RHIC during the energy ramp.

ACCELERATION / DECELERATION

Dedicated studies [10] were performed to measure the polarization asymmetry measured before acceleration and after identical deceleration ("up-and-down" ramps). For this experiment, orbit, tune, coupling and chromaticity [11] feedback were applied. Shown in Fig. 7 are the beam intensities and main dipole currents during three consecutive ramps used for this study.

Measurements of the orbit parameters (mean horizontal/vertical, x_{mean}/y_{mean} and arc BPM rms values, x_{rms}/y_{rms} in the blue ring (a), the yellow ring (b) and the tunes in both rings (c) are shown in Fig. 8 during one of the two full-current ramps. The rms orbits were controlled to ~20 μm and the tunes to <2E-4 (rms) during acceleration and deceleration.

* This superceded previously implemented "radial feedback", which used the energy offset derived from two fast sampling BPMs and is referred to at RHIC now as "xmean feedback".

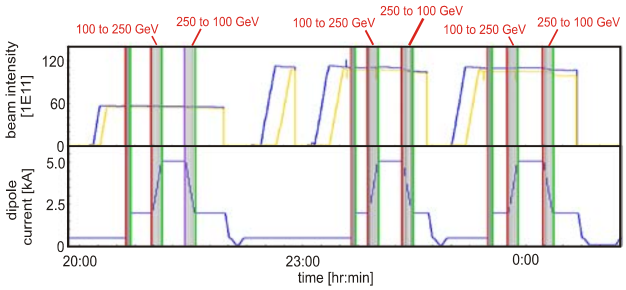

Figure 7: Beam intensities (top) and dipole current (bottom) during 3 consecutive up-and-down ramps.

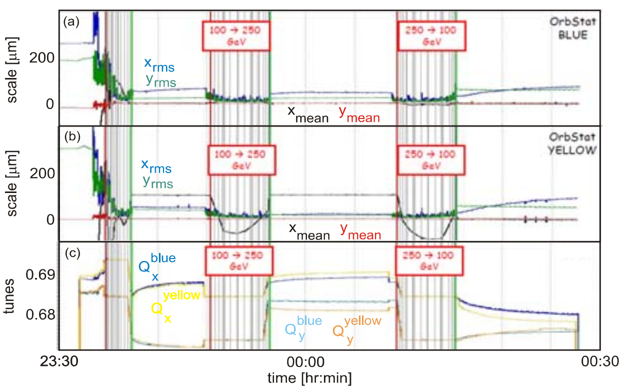

Figure 8: Beam orbit parameters (a,b) and tunes (c) during an up-and-down ramp with full beam intensities.

The actions (amount of correction) of the tune, coupling, and chromaticity feedbacks are shown during the up-and-down ramps in Fig. 9. Table 1 compares the actions from both rings showing the particularly strong tune, coupling and chromaticity corrections made by feedback for the down ramps. Given the absence of an accelerator model with predictive power for the down ramps, these studies were successful exclusively through application of feedback.

SUMMARY

Improved measurement precision has contributed directly to improved control of the beam's properties and to the successful application of routine orbit, energy, tune, and coupling feedback.

Overall, ramp development efficiency (the time required to establish beams to full energies with a new optic and/or change in particle species at RHIC has been reduced from several days (<2009), to one 8 hour shift (2009) down to 1 ramp or about 2 hours (2011). The need for dedicated optimization efforts (post maintenance or after extended down periods) has been eliminated.

Precision control of the beam's parameters has expanded the parameter space accessible during acceleration resulting in a (20-25)% relative increase in each of the two proton beam's polarization at 250 GeV. Orbit, tune, coupling, and chromaticity feedback were essential for realization of acceleration/deceleration ramps.

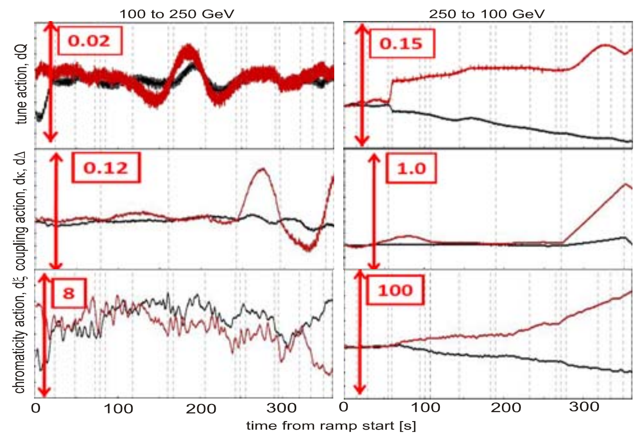

Figure 9: Action of the tune (top), coupling (middle) and chromaticity (bottom) feedback loops in the yellow ring.

Table 1: Action of the feedback loops during the up and down ramps in the horizontal (x) and vertical (y) planes.

		100 to 250 GeV	250 to 100 GeV
BLUE	orbit	< 0.04 mrad (x,y)	< 0.04 mrad (x,y)
	tune	< 0.015 (x) < 0.020 (y)	< 0.04 (x) < 0.10 (y)
	coupling	< 0.04 (x,y)	(< 0.7 (x)), < 0.25 (y)
	chromaticity	~ 7 (x,y)	~ 12 (x) ~ 10 (y)
YELLOW	orbit	< 0.02 mrad (x) < 0.01 mrad (y)	< 0.05 mrad (x) < 0.02 mrad (y)
	tune	< 0.01 (x) < 0.01 (y)	< 0.04 (x) < 0.07(y)
	coupling	< 0.01 (x,y)	< 0.1 (x), < 0.5 (y)
	chromaticity	~ 5 (x,y)	~ 20 (x) ~ 40 (y)

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