

# HIGH PRECISION TUNE AND COUPLING FEEDBACK AND BEAM TRANSFER FUNCTION MEASUREMENTS IN RHIC\*

M. Minty<sup>#</sup>, A. Curcio, C. Dawson, C. Degen, Y. Luo, G. Marr, B. Martin, A. Marusic, K. Mernick, P. Oddo, T. Russo, V. Schoefer, R. Schroeder, C. Schultheiss, M. Wilinski, BNL, Upton, NY, U.S.A.

## Abstract

Precision measurement and control of the betatron tunes and betatron coupling in the Relativistic Heavy Ion Collider (RHIC) are required for establishing and maintaining both good operating conditions and, particularly during the ramp to high beam energies, high proton beam polarization. While the proof-of-principle for simultaneous tune and coupling feedback was successfully demonstrated earlier, routine application of these systems has only become possible recently. Following numerous modifications for improved measurement resolution and feedback control, the time required to establish full-energy beams with the betatron tunes and coupling regulated by feedback was reduced from several weeks to a few hours. A summary of these improvements, select measurements benefitting from the improved resolution and a review of system performance are the subject of this report.

## INTRODUCTION

The successful demonstration of simultaneous tune and coupling feedback in RHIC [1] during Run-6 was realized using direct-diode detection [2] for precision tune measurements (also referred to as BBQ, an acronym for base-band Q, or tune, measurements) and eigenmode projection [3-5] for direct measurement and hence control of the eigenmodes of the betatron oscillations. Since these very successful tests, routine use of tune and coupling feedback has been hampered by interferences from mains harmonics and complications with near-zero chromaticity [6], from rich spectral content at injection energy when accelerating ion beams [6,7], and from practicalities such as loss of lock of the phase lock loop used in determining the betatron frequencies [7,8]. Prior to and during initial system commissioning for Run-9, numerous hardware and software modifications [9,10] were implemented which significantly improved the measurement resolution and eliminated multiple sources of systematic errors. As a result, all the above difficulties have been overcome.

In addition to establishing for the first time routine implementation of tune and coupling feedback, the improved measurement resolution has allowed for detection and characterization of several interesting phenomena including significant tune modulations experienced by both beams in both planes of appreciable magnitude compared to the total beam-beam parameter. High-resolution beam transfer function measurements

revealed not only strong coherent modes induced by the beam-beam interaction but also a clear measure of significant structure between these modes.

## TUNE MEASUREMENTS

Shown in Fig. 1 is an example of the measured frequency response, converted to tune units by division by the nominal revolution frequency ( $\sim 78$  kHz), obtained using a variable frequency resonator used to simulate the beam response. The resolution given by the root-mean-square (rms) of the residuals between the measured data and linear fit is  $(1.9 \pm 0.1) \times 10^{-6}$ . With beam the measured tunes often evidenced significant modulations believed to result from feed-down in higher-order multipoles sampled via the dipole deflection generated by vibrating triplet magnets [11]. Shown in Fig. 2 are the measured horizontal ( $Q_x$ ) and vertical ( $Q_y$ ) tunes obtained under store conditions in both transverse planes.

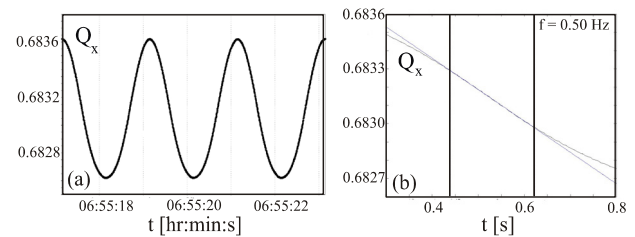


Figure 1: Measured instrumental resolution.

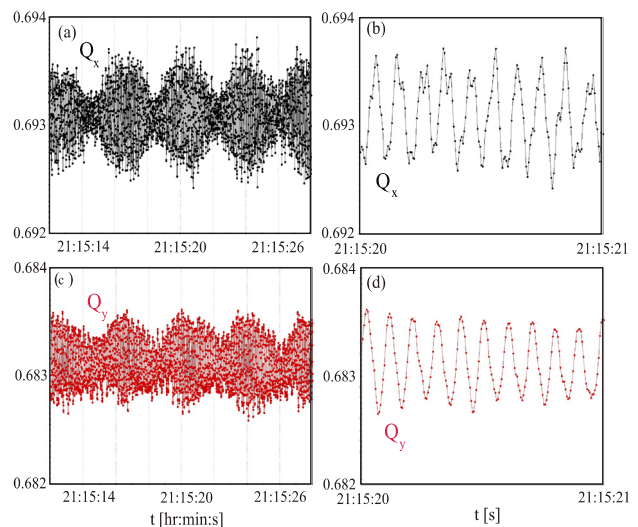


Figure 2: Measured tunes at 250 GeV evidencing modulations. Plotted are the horizontal (a) and vertical (c) tunes and the same with expanded time scale on the right (b,d).

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<sup>#</sup>minty@bnl.gov

### COUPLING MEASUREMENTS

In Run-9, prior to initial ramp development with tune and coupling feedback, the global betatron coupling of each beam was minimized at injection energy using tune measurements acquired while modulating the coupling angle [12]. Example data are shown in Fig. 3 (top two plots, Run-9; bottom two plots, Run-8) where the magnitude of the required correction strengths,  $\kappa_1$  and  $\kappa_2$ , inferred directly from measurements of the betatron tunes are given as a function of time (see [12]). Perfect decoupling was achieved when modulation of one family of skew quadrupoles had no effect on the data acquired in the orthogonal plane. Note the increased sensitivity and the factor of  $>2.5$  decrease in the vertical scale between data sets. Taking as a measure of coupling control the rms of the signal strength in the orthogonal plane, the precision on the control of the decoupling was reduced from  $\pm 0.0414$  in Run-8 to  $\pm 0.0035$  in Run-9.

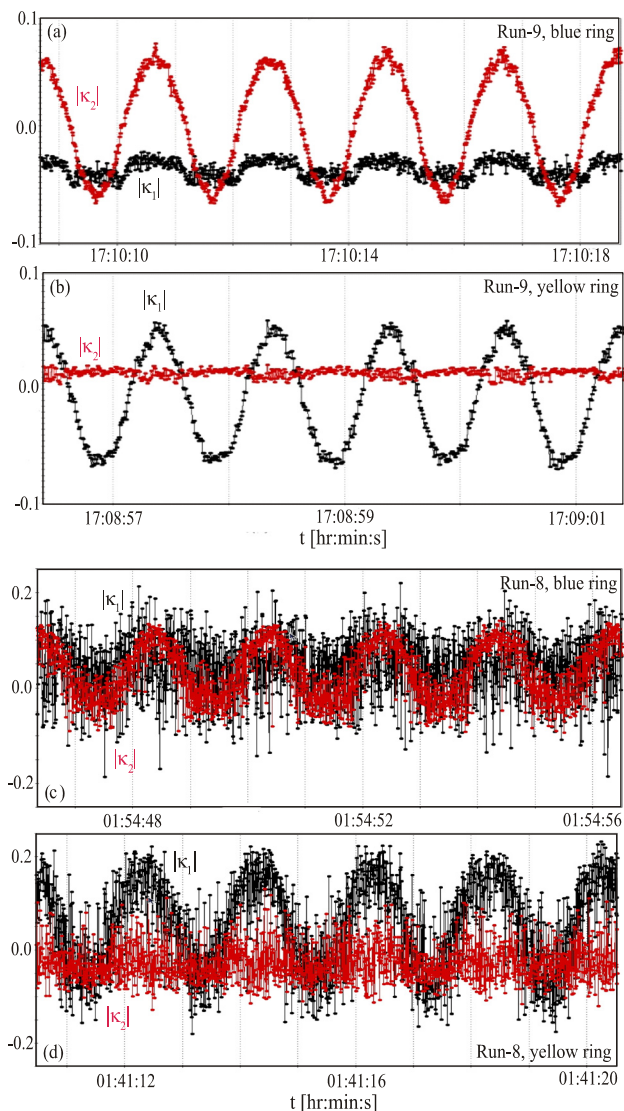


Figure 3: Measured coupling coefficients in run-9 (top) and run-8 (bottom) as measured at injection with applied modulation of coupling angles.

### TUNE AND COUPLING FEEDBACK

Tune and coupling feedback were successfully executed from the onset of ramp development for Run-9 beginning with record minimum times of one shift per ring, as commissioned consecutively based on accelerator availability, to accelerate proton beams to their full energies of 250 GeV. Starting from the beginning of Run-9, the execution of tune and coupling feedback was fully automated requiring no human interventions as was needed previously (controlling kicker amplitudes, the phasing of the I/Q demodulator inputs, tune scan ranges for the phase locked loop, closed-loop gain parameters, etc.) during execution. The possibility of human error during ramp development with tune/coupling feedback was therefore substantially reduced.

During Run-9 detailed analyses were made to determine the cause of any ramp with tune and coupling feedback which did not result in a complete record of quadrupole and skew quadrupole currents suitable for feed-forward on a subsequent ramp. Of note are that it was possible to diagnose each and every failed ramp and that the leading cause for failure was due to uncontrolled orbit excursions. These were easily diagnosed using logged parameters which showed increasing rms orbit amplitude followed by beam loss which in turn was followed by loss of tune regulation when the beam current became less than the measurement sensitivity of about  $1.5 \times 10^{11}$  particles corresponding to approximately  $1/8^{\text{th}}$  of the initial beam intensity used in ramp development. This is a considerable improvement over past years where “loss of lock” of the phase lock loop was considered and might possibly have been the dominant source for failed ramps.

### BEAM TRANSFER FUNCTIONS

Beam transfer function (BTF) measurements at RHIC [13] are presently made using the same experimental hardware as for the tune measurements with the exception that excitation frequency is independently controlled. Under test conditions using a fixed frequency resonator to simulate the beam, the measured amplitude and phase response through the detection system is shown in Fig. 4.

Shown in Fig. 5 are two consecutive beam transfer function measurements obtained with 250 GeV proton beams before and immediately after the beams were brought into collision. Before collisions the betatron tunes were similar in the two rings: in the blue ring (BR):  $Q_x=0.6942$ ,  $Q_y=0.6860$ ; in the yellow ring (YR):  $Q_x=0.6965$ ,  $Q_y=0.6870$  or  $|\Delta Q_x|=0.0023$  and  $|\Delta Q_y|=0.0010$  with total intensities of  $1.30 \times 10^{12}$  and  $1.20 \times 10^{12}$  protons in the BR and YR, respectively, with 12 bunches per ring. The beam spectra are shown in Figs. 5a and 5b acquired with 1 colliding bunch and 11 non-colliding bunches. The beams were brought into collision by adjusting the relative phase of the radiofrequency (rf) systems between the two accelerators yielding the spectra shown in Figs. 5c and 5d with 1 non-colliding and 11 colliding bunches and  $1.22 \times 10^{12}$  and  $1.16 \times 10^{12}$  protons in the BR and YR, respectively. Comparing the

beam spectra obtained before and after colliding the beams we note: (1) the appearance of strong coherent pi-mode signals in the vertical plane of both beams, (2) strikingly, in the vertical planes a broad range of frequencies between the coherent sigma and pi modes, and (3) a downward shift in the horizontal tune of both beams accompanied by a significant spreading of the tune peaks particularly in the direction of lower betatron tune.

The nature of the observed structure between the observed sigma and pi modes of coherent oscillation is intriguing: while theoretically expected for multiple reasons, to our knowledge the data shown in Fig. 5 are the first ever to evidence this structure. Possible explanations include multiple modes due to collision schedules, multiple interaction points, long-range interactions, and/or the continuum of incoherent modes.

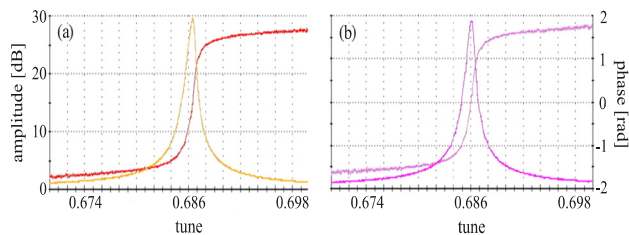


Figure 4: BTFs measured versus excitation frequency converted to tune units obtained with a fixed frequency resonator in the horizontal (a) and vertical (b) planes.

## SUMMARY

Following the many modifications in hardware and in the data processing algorithms, the time required to establish full-energy beams with the betatron tunes and coupling regulated by feedback was reduced from several weeks to a few hours. Experimental data were presented demonstrating the improved resolution of the tune and coupling measurements which were essential for this achievement. Numerous improvements in the data acquisition and processing have additionally been implemented for measurements of the beam transfer functions.

Improved measurement resolution has allowed for detection of beam properties not previously observed including significant externally driven tune modulations. With textbook clarity, experimental data were also presented showing the presence and location of strong beam-beam induced coherent modes as well as significant structure between these modes.

The externally driven tune modulations (and not the resolution) presently limit the precision of the tune and coupling measurements. The tune modulations have been shown [11] to have identical frequency content as the measured orbit oscillations indicating a common source. While efforts for eliminating these perturbations to the beam orbit and optics are being pursued with renewed vigour [14,15], applications identified to be free of other systematic errors have been modified [16] to input tune measurements averaged over the driven excitations for precision determination of beam optics parameters.

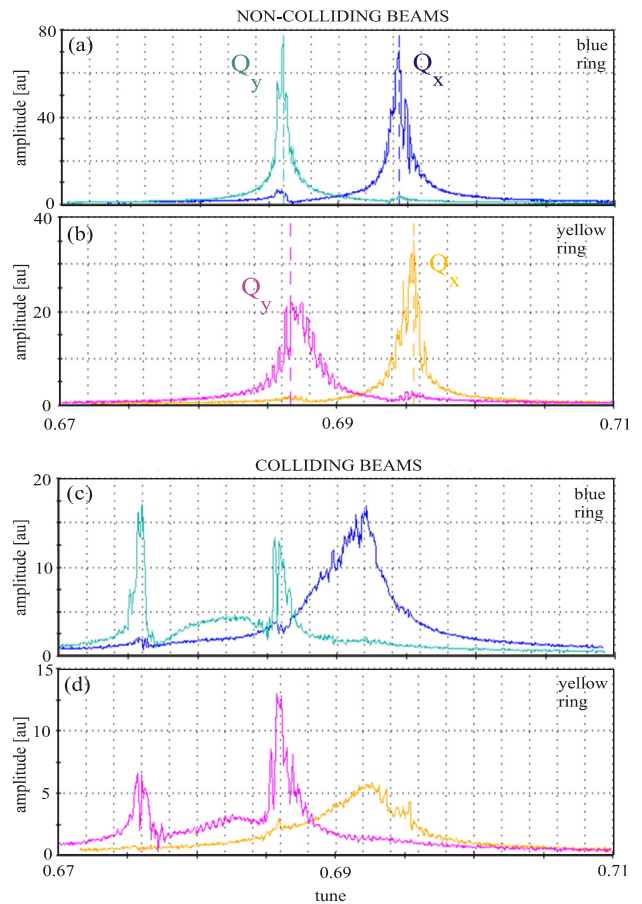


Figure 5: Measured BTFs with beams in and out of collision evidencing strong coherent beam-beam modes.

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