CHROMATICITY FEEDBACK AT RHIC*

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Abstract

Chromaticity feedback during the ramp to high beam energies has been demonstrated in the Relativistic Heavy Ion Collider (RHIC). In this report we review the feedback design and measurement technique. Commissioning experiences including interaction with existing tune and coupling feedback are presented together with supporting experimental data.

INTRODUCTION

The physics program at RHIC often requires changes in particle species (protons, various heavy ions) and beam energies [1]. New accelerator optics are frequently implemented either in support of these various programs or to maximize luminosity by configurations changes for tighter transverse focussing at the interaction points for example. In the interest of providing more stable, reproducible, and optimal beam conditions as well as to improve ramp development efficiencies, precision measurement and control of beam properties are essential.

The ability to derive chromaticities [2] from measurements of the betatron tunes [3] during the energy ramp with applied modulation of the radiofrequency (rf) of the accelerating cavities was demonstrated during early commissioning of RHIC. Controls were also developed [4] for implementation of tune feedback using quadrupole magnets for control of the betatron tunes and, as duplicated later, skew quadrupoles for coupling control and sextupoles for chromaticity control.

A new system, now commonly referred to as the BBQ system [5], was subsequently developed for measurements of the tunes and, particularly, the betatron coupling [6-8]. With this system tune and coupling feedback during the energy ramp were successfully demonstrated at RHIC [8]. Implementation of chromaticity feedback and routine operation of tune coupling feedback however remained elusive due to problems with tune peak identification, tune tracking in the presence of mains harmonics [9, 10], an anomalous betatron resonance shape at injection energies [11] which produced multiple peaks in the beam frequency spectrum, and 'tune scalloping' [11] which caused non-constant measured betatron tunes despite constant quadrupole settings.

Following numerous changes for improved measurement and feedback control of the betatron tunes and coupling [12], these difficulties have been overcome and the measurement precision and control of these parameters have been substantially improved. In consequence other subtleties necessary for realizing chromaticity feedback were revealed. In this report we describe the development of chromaticity feedback with experimental data obtained recently at RHIC.

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CHROMATICITY ALGORITHM

To measure the chromaticity, the momentum is varied by modulating (at a 0.5 Hz rate) the frequency f of the rf cavities. In the limit of small variations, the offset in radius R is given by$\Delta R\sin(\omega t)$ with $\omega = 2\pi f$. The tune, Q, can be modelled as

$$Q(t) = A\sin(\omega t) + Bt + C \quad (1)$$

and the chromaticity ξ is given by $\xi = \frac{\alpha R}{\Delta R}A$, where α is the momentum compaction. Minimizing

$$\chi^2 = \sum_{k=1}^{N}[Q_k - A\sin(\omega t_k) - Bt_k - C]^2 \quad (2)$$

with respect to the coefficients A, B, and C (where N is the number of measurements used for the computation), the coefficients are calculated by solving the equation of the k^{th} tune measurement Q_k (t_k): $\vec{Q} = M\,(ABC)^T$. With implicit sums over $k = 1$ to N and $S_k = \sin(\omega t_k)$

$$\begin{pmatrix} Q_k S_k \\ Q_k t_k \\ Q_k \end{pmatrix} = \begin{pmatrix} {S_k}^2 & t_k S_k & S_k \\ t_k S_k & {t_k}^2 & t_k \\ S_k & t_k & 1 \end{pmatrix} \begin{pmatrix} A \\ B \\ C \end{pmatrix}. \quad (3)$$

CHROMATICITY FEEDBACK

Chromaticity feedback adjusts the sextupole (both focusing and defocusing) magnet currents to keep the chromaticities equal to the desired values. The difference between the measured and desired chromaticity is converted to energy-independent field strength corrections using a two-by-two matrix of elements specifying the derivatives of the required field strengths per unit change in chromaticity as given by the accelerator optical model. The correction strengths are then added to the nominal operating strengths and then converted to currents for the power supplies powering the sextupole magnets. The closed-loop response of the chromaticity loop is regulated using a PI controller.

INTERACTION WITH TUNE AND COUPLING FEEDBACK

When tune and coupling feedbacks are engaged, the tune modulations are reduced depending on the gain of these feedback loops. The corrections sent to the quadrupole magnets, the so-called filtered tunes, are used as input for the chromaticity measurement (in Eqs. 2-3 above) as opposed to using the measured tune directly.

MEASUREMENT VALIDATION

In the past, chromaticity measurements during the energy ramp contained sign flips presumed to be caused by poor quality of the tune measurements. Shown in Fig. 1 are the measured horizontal (Q_x) and vertical (Q_y) tunes and chromaticities (ξ_x and ξ_y) obtained towards the end of run-9 with improved [12] resolution of the tune measurements. The sign flips were found to be attributable to a cumulative numerical precision error which was then corrected.

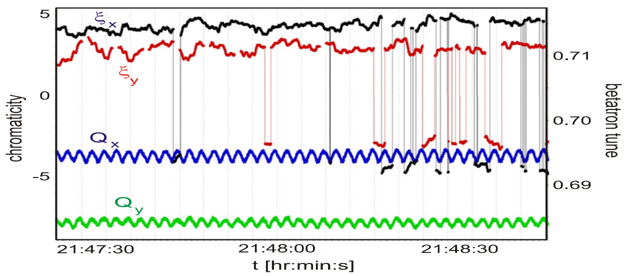

Figure 1: Measured chromaticities and betatron tunes (run-9: 250 GeV, protons) revealing numerical sign flips.

Another systematic error was found to result from a non-constant betatron tune during the energy ramp. Shown in Fig. 2 are the measured betatron tune and chromaticity, derived with two methods, as a function of time along the energy ramp. In this mode of operation from run-9, the desired betatron tune was intentionally changed during the ramp. This caused unacceptably large variations in the chromaticity during the tune swing when derived using an FFT-based algorithm (black curve). Using the algorithm given above, taking into account the intended change in tune, this sensitivity was removed as shown by the red curve.

While non-deterministic tune variations (due for example to externally driven tune modulations [12]) will affect the precision of the measured chromaticities, with simultaneous tune, coupling and chromaticity feedback this systematic error is significantly reduced.

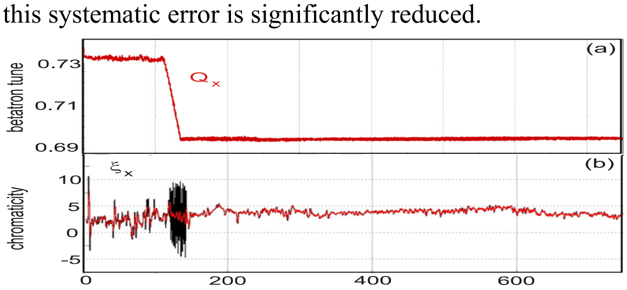

Figure 2: Measured betatron tune (a) and chromaticity (b) during the energy ramp (run-9: 100 GeV, protons) which revealed a sensitivity to non-constant tune.

FEEDBACK COMMISSIONING

A number of small difficulties were encountered and corrected in the process of engaging chromaticity feedback at injection energy. Initial tests invoking large changes in chromaticity to test feedback convergence caused the betatron frequencies to probe spurious 120 Hz harmonics thus complicating initial data interpretation. The magnitudes of the requested changes were found to exceed the 23-bit limit of the RHIC real-time data link which is used to communicate the requested changes in strength to the magnet waveform generators (WFG). This was avoided by rescaling all WFGs which affected also the existing drift compensation (which corrects for persistent current decay at injection energy). Lastly a modest code change was required to eliminate the start-up transient and smoothly engage the chromatic corrections.

Shown in Fig. 3 are the chromaticities measured at injection energy as chromaticity feedback was engaged (subsequent to already controlling the tunes and coupling with tune/coupling feedback) demonstrating convergence to the target values.

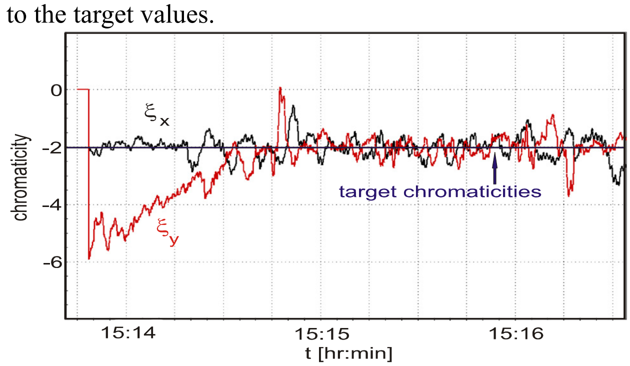

Figure 3: Measured chromaticities at injection energy as chromaticity feedback was engaged.

For the energy ramp, the sequence of events used was as follows: tune and coupling feedback were engaged, the rf frequency modulation was initiated, the measured chromaticities were obtained (with a ~1.5 s delay to ensure sufficient statistics in the S_k of Eq. 3), and then the chromaticity corrections were applied.

TUNE, COUPLING, AND CHROMATICITY FEEDBACK

During the very first ramp to 19.5 GeV/beam in run-10 orbit, tune, coupling, and chromaticity feedback were successfully exercised and used to ramp the beams to top energies. Unfortunately the initial sextupole settings at certain times during the ramp caused a large discrepancy between measured and desired chromaticity so the feedback could not completely correct for the errors due to administratively set power supply ramp rate limits. After correcting these aberrant settings, and feed-forwarding 50% of the chromaticity correction, the beams were ramped successfully with near 100% transmission efficiency to full energies. In Fig. 4 are shown the data from both accelerators (labelled "blue" and "yellow") recorded during this ramp.

Subsequent accelerator studies aimed towards demonstrating viability of ramping with vertical betatron tunes in proximity of the third-order resonance, used tune, coupling, and chromaticity feedback to accelerate beams through transition energy to 100 GeV. The measurements obtained during this exercise are shown in Fig. 5. For stability reasons the target chromaticity was negative below and positive above transition energy. Deviations from target chromaticities were observed in the vicinity of snapback (t<50s) and after transition crossing (again due to administrative sextupole ramp rate limits). The small residual oscillation seen in Fig. 5c has since been shown to result from a phase error between the applied rf modulation frequency and the filtered tune as input to the chromaticity derivations.

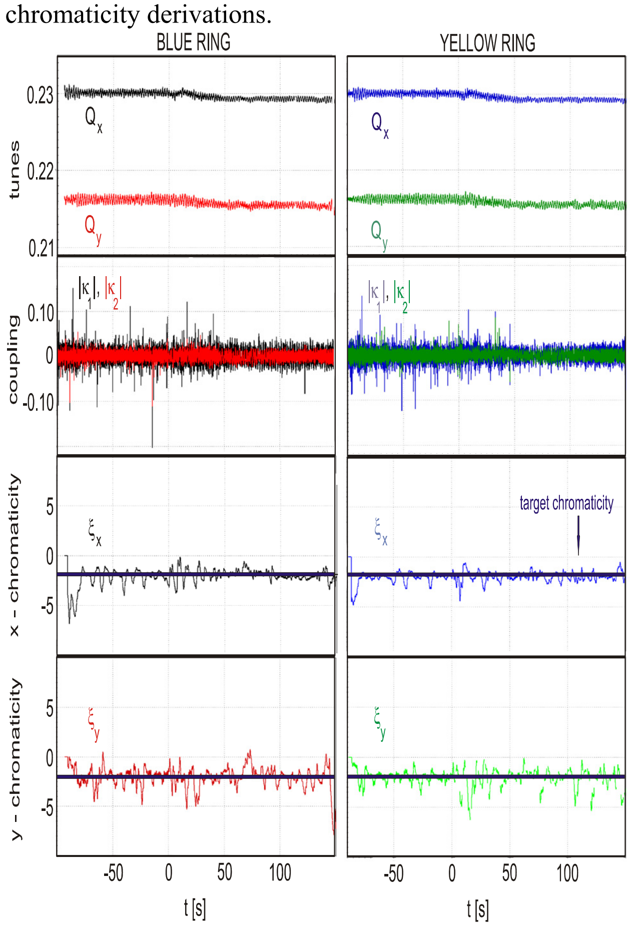

Figure 4: Betatron tunes, coupling strengths, and chromaticities with simultaneous orbit, tune, coupling, and chromaticity feedback during the energy ramp to 19.5 GeV (t=0 at the start of the ramp).

SUMMARY

Chromaticity feedback, used together with tune and coupling feedback, has been demonstrated for the first time during run-10 at RHIC. Ramps without transition energy crossing (low energy ions) were executed with control of the chromaticities to within ~5 units. With transition crossing (high energy ions), chromaticity feedback with feed-forward was likewise successful, however has as yet not been consequently applied (due to limited availability of these conditions). In the latter case chromaticity control was limited by administratively set power supply limits which may be overcome by iterative application of feedback and feed-forward.

In run-11 chromaticity feedback will be used for ramp developments including acceleration of protons to 250 GeV which in run-9 without chromaticity feedback evidenced variations in the chromaticities by up to 10-15 units. It is anticipated that past experiences of occasional failed ramps (those which caused excessive beam loss) due to large amplitude oscillations resulting from improper values of the chromaticities will be avoided by feedback control of the chromaticities thus significantly improving overall development efficiency.

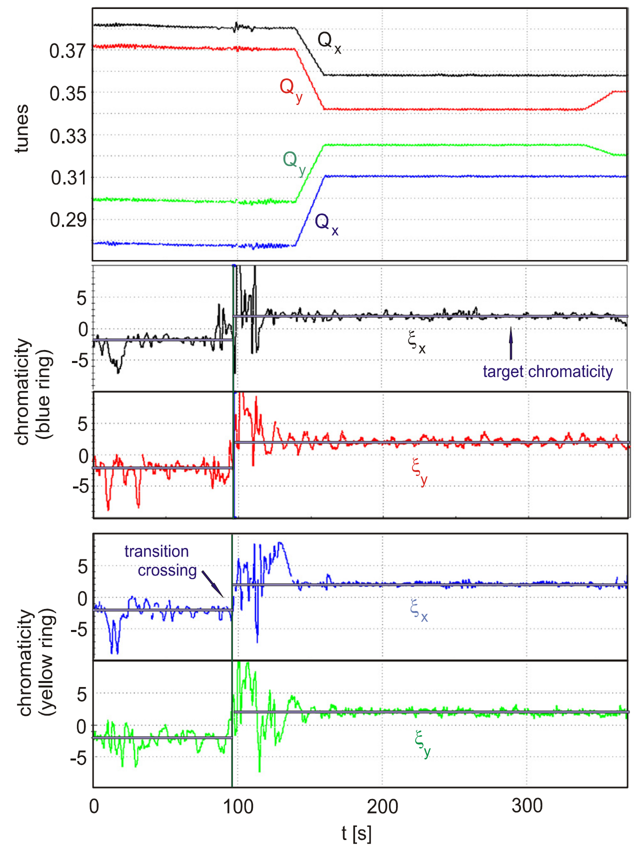

Figure 5: Betatron tunes and chromaticities as a function of time during the ramp to 100 GeV with tune, coupling, and chromaticity feedback. Transition energy was crossed at t~100s as shown by the vertical lines.

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