

OVERVIEW OF MAGNETIC NONLINEAR BEAM DYNAMICS IN RHIC*

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Abstract

In this article we review our studies of nonlinear beam dynamics due to the nonlinear magnetic field errors in the Relativistic Heavy Ion Collider (RHIC). Nonlinear magnetic field errors, including magnetic field errors in interaction regions (IRs), chromatic sextupoles, and sextupole components from arc main dipoles are discussed. Their effects on beam dynamics and beam dynamic aperture are evaluated. The online methods to measure and correct the IR nonlinear field errors, second order chromaticities, and horizontal third order resonance are presented. The overall strategy for nonlinear corrections in RHIC is discussed.

INTRODUCTION

To increase the luminosity in RHIC, we can further reduce β^* functions at the interaction points (IPs), increase the bunch intensity, and/or reduce the transverse beam emittance. In the 2007 d-Au and 2009 polarized proton (pp) runs, RHIC has already operated with $\beta^* = 0.7\text{m}$ at store. In the 2008 pp run, bunch intensities in the Blue ring have reached 1.7×10^{11} , giving a beam-beam parameter of -0.017 .

A low β^* lattice will require larger chromatic sextupole strengths and increase nonlinear chromaticities. Particles will sample large nonlinear magnetic field errors in the IRs. All of these effects will reduce the beam dynamic aperture [1, 2].

The working points in the RHIC polarized proton (pp) run are constrained between 2/3 and 7/10. The nominal non-colliding tunes for the two RHIC rings are (28.685, 29.695) and (28.695, 29.685). For beam-beam parameters larger than -0.02 , there is not enough space to hold the beam-beam tune spread [3]. As temporary mitigation, corrections of the $3Q_{x,y}$ resonance driving term (RDT) and the nonlinear chromaticities may provide more beam-beam tune space [4].

In this article we focus on the following nonlinear magnetic fields: the magnetic nonlinear field error in IR magnets, the chromatic sextupoles, and the sextupole components in the arc dipoles. They all contribute to the linear and nonlinear chromaticities and the third order RDTs.

We first review the sources of nonlinear fields in the RHIC rings and their effects. We then review the methods

to measure and correct IR nonlinear magnetic errors, second order chromaticities, and third order RDTs. Finally we discuss a strategy to separate corrections of second order chromaticities and the third order resonance with different sextupole corrector families.

SOURCES OF NONLINEAR FIELDS

IR Nonlinearities

Magnetic nonlinear field errors in the RHIC IRs play a significant role in the reduction to the beam dynamic aperture at the store energy. These IR nonlinearities come from the magnetic imperfections in the triplets Q1, Q2 and Q3, and in the separation dipoles D0 and DX. All of these magnets are superconducting magnets.

Due to a tight installation schedule, only 13/24 Q3 magnets, 10/24 D0 magnets, 7/12 DX magnets, and all Q1 and Q2 magnets were measured cold. Even where cold measurements are available, the geometric configuration of the leads was not the same as the final as-installed magnet assemblies. To build a nonlinear IR model [5, 6, 7], currents were scaled from magnet measurement current to the real operating current and warm to cold conversions were used.

Some nonlinear correcting spool pieces were integrated into these magnets during triplet manufacture. However, only the b_3 , a_3 and b_4 correctors in the IR6 and IR8 currently have independent power supplies.

A task force was set up in 2003 to investigate the effects of IR nonlinearities on the RHIC dynamic aperture. We searched the predominant multipole components for keys to dynamic aperture reduction, but found no single multipole that dominates RHIC dynamic aperture [5].

Chromatic Sextupoles

There are 144 chromatic sextupoles in each RHIC ring, distributed evenly through 6 arcs. Chromatic sextupoles introduce nonlinear chromaticities and contribute to the sextupole RDTs. Their roles turn out to be more important with low β^* lattices and polarized proton run [2, 8]. As an example, Table 1 shows the nonlinear chromaticities for the lattices proposed for the proposed 100 GeV pp run lattices. The second order chromaticities have to be corrected for the lattices with $\beta^* = 0.7\text{m}$ and 0.5m .

Before 2007, there were 12 chromatic sextupole power supplies in each ring. During the RHIC 2006 summer shutdown, the number of arc chromatic sextupole power sup-

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Table 1: Chromaticity Correction with the 2-Family Scheme for the Proposed 100 GeV pp Run Lattices

Lattice β^*	$(\xi_x^{(2)}, \xi_y^{(2)})$	$(\xi_x^{(3)}, \xi_y^{(3)})$
0.9m	(-2606, 2792)	(5.026e5, 2.849e4)
0.7m	(-3135, 3995)	(11.25e5, 11.04e4)
0.5m	(-3706, 6620)	(26.78e6, 32.14e4)

plies was doubled from 12 to 24 to allow corrections of second and higher order chromaticities. The SF and SD sextupoles are split into two SF and two SD sub-families in each arc [9].

Sextupole Component in the Arc Main Dipole

Sextupole components in the arc main dipoles are also important in RHIC [10]. They are not yet included in the RHIC online model and thus make it difficult to predict the linear chromaticities. They also contribute to nonlinear chromaticities and third order RDTs. Unfortunately only about 20% of 288 RHIC arc main dipoles were measured cold before installation. For RHIC, the main dipole sextupole components in the arc main dipoles produce a chromaticity split in the transverse planes.

MEASUREMENT AND CORRECTION

IR Nonlinearities

RHIC IR bumps have been used online for local IR nonlinear correction [11, 12]. This method routinely measures and minimizes the dependences of tune shifts on transverse bump amplitudes from the feed-down of multipole errors due to the orbit bump. For sextupole and octupole components, tune shifts from a local horizontal orbit bump are proportional to the bump amplitude and bump amplitude squared, respectively.

At present only sextupole and octupole correctors in IR6/8 have their independent power supplies. They are used to locally correct tune shifts from sextupole and octupole field errors. Nonlinear field errors are corrected order by order. This method is limited by the maximum bump amplitude and the resolution of tune measurement.

The IR bump method is equivalent to the compensation of corresponding nonlinear resonance driving terms [14]. Corrections of sextupole, skew-sextupole, and octupole errors in IR6/IR8 are part of routine RHIC operations. In 2005, measured tune shifts and offline model predications were compared, and identified D0 dipoles as major sources of RHIC IR sextupole components [12].

Second Order Chromaticities

RHIC second order chromaticities can be corrected in the RHIC online model using an implementation of the MAD8 HARMON module [13]. However, the RHIC online model is not accurate enough to rely solely on this

method. This method was successfully tested in the Yellow ring in the 2007 RHIC Au run.

The off-momentum tune response matrix was also used to correct linear and second order chromaticities [15]. The advantage of this method is that the off-momentum tunes are of the same order. The off-momentum tune response matrix is calculated from the optics model and directly measured with the beam, and optimized with singular value decomposition (SVD). Several iterations were usually needed to reduce correction strengths and straighten off-momentum tunes.

Recently we also corrected second order chromaticities by minimizing half-integer RDTs [16]. From perturbation theory, both second order chromaticity and first order off-momentum β -beat are related to the half-integer RDT. To correct second order chromaticities, we sorted 24 sub-chromatic sextupoles into 4 knobs. This 4-knob method was tested in 2007 RHIC beam experiments and implemented in the RHIC control system. This method does not change first order chromaticities, and works when the RHIC online model does not closely reproduce the machine. From numeric simulations, this 4-knob method levels correction strengths and avoids sextupole polarity reversals. Figure 1 shows an example of second order chromaticities with this method in the Yellow ring in the 2009 100 GeV run. The second chromaticities before and after correction are (-1216, 3412) and (-620, 131) respectively.

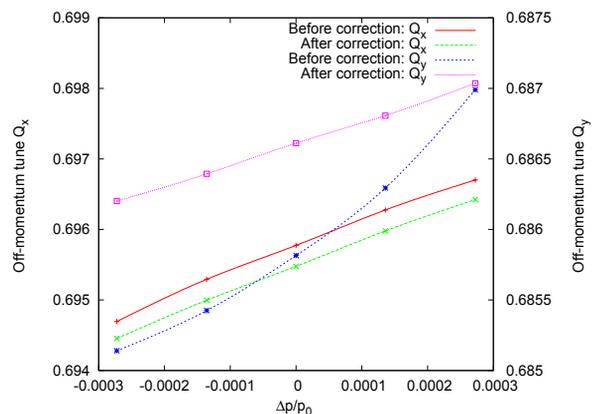


Figure 1: ξ^2 correction with 4-knob method.

Third Order Resonances

The third order resonance was measured and corrected in RHIC with several approaches. In 2004, third order RDTs were measured in the Blue ring with an AC dipole and the third order RDT was extracted from the spectrum of turn-by-turn normalized coordinates [17, 18]. Changes in the third order RDTs can be used to localize sextupole errors. Measured third order RDTs were compared to predictions from chromatic sextupoles.

The third order resonance was next corrected in 2006 during store conditions. A first attempt used 12 sub-sextupole families to correct the h_{30000} term while keeping

the first order chromaticities and other first order sextupole RDTs unchanged [20]. An AC dipole was used to measure these RDTs. The h_{30000} RDT was only measured close to Q3 in IR6, extracted from a spectrum of turn-by-turn action $J_x(N)$ [19]. A spectral peak at $3Q_x$ was observed with base tunes near $2/3$, but BPM and AC dipole problems precluded correction of h_{30000} . Figure 2 shows one example spectrum of $J_x(N)$.

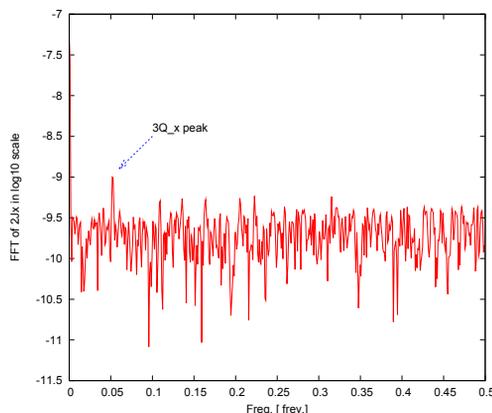


Figure 2: The spectrum of $J_x(N)$.

In 2006 we also tried to use local IR sextupole correctors to minimize the $3Q_x$ resonance stopband width [21]. Beam lifetime was used as the primary observable. Sextupole correctors were tuned to maximize beam lifetime while moving the Q_x as close to $2/3$ as possible. This improved beam lifetime out of collisions but did not improve beam lifetime in collisions. This approach ignored sextupole RDTs other than h_{30000} .

Sextupole Component in Arc Dipole

With known chromatic sextupole settings and measured linear chromaticities, the horizontal/vertical chromaticity split due to arc dipole sextupole components can be measured and modeled [10]. For offline analysis we inserted a thin sextupole at the center of each main dipole. With 144 main dipoles in each ring, linear chromaticity effects are dominated by the average strength of these sextupole components. The average sextupole strength was then used in a single-parameter fit to the measured chromaticity split.

In the 2007 Au run, we measured 20 units of linear chromaticity split in the Blue ring at injection and 3.5 units at store. From this we fitted the main dipole average sextupole component strength to -0.0505m^{-2} at injection and 0.0095m^{-2} at store. Substituting these average strengths back into the online model, we successfully reproduced measured linear and second order chromaticities.

DISCUSSION

As shown above, both second order chromaticities and third order RDTs can be corrected with RHIC chromatic sextupole families. However, simultaneous correction of

linear and nonlinear chromaticities and sextupole RDTs with 24 chromatic sextupole families is still challenging. Solutions often require unusually large sextupole strengths [22], indicating that the system is not well-constrained. From RHIC design, IR dispersion is usually smaller than that in the arcs. Second order chromaticities are driven mostly by chromatic sextupoles and main dipole sextupole components.

From simulation we verified that the second order chromaticities with the chromatic sextupoles do not significantly change the first order sextupole resonance driving terms, while the corrections of IR nonlinearities and the third order resonance driving with local IR sextupole correctors do not significantly affect the second order chromaticities. Therefore in the RHIC operation, we can first correct the second order chromaticity with the chromatic sextupoles. Then we correct the $3Q_x$ resonance driving term h_{30000} with the sextupole correctors in the IR6 and IR8. To fully control all first order sextupole driving terms, all 12 IR sextupole correctors should be used.

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