ADVANCES IN HIGH-ORDER INTERACTION REGION NONLINEAR OPTICS CORRECTION AT RHIC

C. Zimmer*, S. Binello, M. Minty, Brookhaven National Laboratory, Upton, NY 11973, U.S.A.
F. Pilat, Jefferson Laboratory, Newport News, VA 23606, U.S.A

Abstract

A method to measure and deterministically correct the higher order magnetic errors of the final focusing magnets in the Relativistic Heavy Ion Collider has been in place for several years at BNL. This method yields control over the effects of multi-pole errors through application of closed orbit bumps followed by analysis and correction of the resulting betatron tune shifts using multi-pole correctors. The process has recently been automated in order to provide more efficient and effective corrections. The tune resolution and the reliability of measurements has also been improved significantly due to advances/upgrades in the betatron tune measurement system employed at RHIC (BBQ). Here we describe the foundation of the IR bump method, followed by recent improvements along with experimental data.

INTRODUCTION

For a hadron collider, the beam lifetime and dynamic aperture are typically determined by a few key factors which include the well-known beam-beam effect and the operational β* values. Interaction region (IR) nonlinear magnetic errors in the low-β* sections, however, also have a significant and deleterious effect on beam lifetime/dynamic aperture. Therefore, it is critical to recognize and correct these effects.

The IR Bump correction method has been developed over several years as a primary tool to correct local errors in the interaction regions of RHIC. This method affords compensation for the sextupole/skew sextupole/octupole errors that are unavoidably present in collider magnets (triplet quadrupoles and crossover dipoles). Decapole and dodecapole field components are currently corrected in a less deterministic manner which involves scanning corrector magnet setpoints in order to optimize baseline beam decay. This method is used because the bump amplitude and tune resolution required to correct these higher order (10+12 pole) errors in a deterministic manner would be problematic at best. Therefore, this paper will focus on the deterministic correction of sextupole, skew sextupole and octupole field components.

CORRECTION METHOD

In principle, the method is quite simple. A continuously changing closed orbit bump (the amplitude function mimics a sine wave) is applied to the beam through the IR. Beam traveling off-axis through the final focusing/bending magnets will encounter higher order (sextupole, skew sextupole, octupole etc.) nonlinear fields and a tune shift will necessarily ensue. These measured tune shifts manifest themselves as a result of either the feed-down to the normal gradient or from the repelling effect of linear coupling. The plane of the bump, the parity of the multi-pole order and whether the multi-pole is normal or skew all dictate if the feed-down from a given multi-pole affects the normal gradient or the linear coupling, as summarized in table 1.

* czimmer@bnl.gov

Work supported by Brookhaven Science Associates

Table 1: Measurable Quantities for each Non-Linear Multipole. b_2 is Normal Sextupole, a_2 is Skew Sextupole etc.

Bump	b_2	a_2	b_3	a_3	b_4	a_4	b_5
H	ΔQ	Δc	ΔQ	Δc	ΔQ	Δc	ΔQ
V	Δc	ΔQ	ΔQ	Δc	Δc	ΔQ	ΔQ

As the table suggests, one must use certain bumps to produce a meaningful tune shift as an indication of the necessary type and magnitude of multipole correction. A horizontal bump is used to correct for normal sextupole fields, a vertical bump for skew sextupole fields, and a bump in both planes for normal octupole fields.

The tune shifts resulting from these bumps are subsequently measured to observe the shifts in both planes as a function of bump amplitude. Finally, multi-pole corrector magnets purposefully positioned nearby (at positions with relatively large beta functions) are utilized in an attempt to null out the tune dependence on beam position. This tune shift cancellation is equivalent to correcting for the multipole field errors and has been shown to be effective for bumps up to and including 10mm in both planes.

It is worth detailing the corrector package layout for one of the IRs. The layout in other IRs is equivalent. Figure 1 details the IR correction system layout for IR8 where the PHENIX experiment is located.

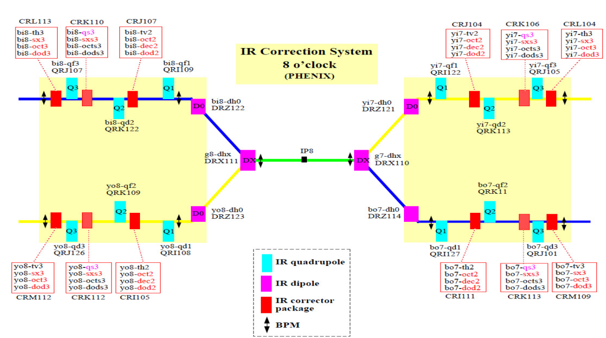

Figure 1: Nonlinear corrector layout for IR8. Conventions: sx=normal sextupole, sxs= skew sextupole and oct= normal octupole.

The conditions during each measurement need to be such that the tune shifts produced by coupling are negligible in comparison with the tune shifts from the normal gradient change. The residual coupling in the machine must be well corrected for this to be valid, and the tunes in both planes have to be well separated. The amount of coupling compensation and the tune separation must satisfy the relation:

$$\frac{|C_0 + \Delta c|^2}{4\Delta Q_{xy}} << \Delta Q$$

where C_0 is the residual component of the coupling and $\Delta Q_{xy} = |Q_x - Q_y|$ is the separation between the horizontal and vertical betatron tunes. The summation of conditions to be satisfied before the initiation of measurements is as follows:

- Both rings must be de-coupled, with coupling corrected to a minimum tune separation of $\Delta Q_{min} < 0.002$.
- The horizontal and vertical fractional tunes are separated before the measurements by 0.01-0.012 to further minimize coupling effects.
- Both rings must be anti-cogged (longitudinally separated) by at least three RF buckets.
- Measurements are performed as soon as possible after the ramp. The generally smaller beam size allows for larger bump amplitudes and smaller losses.
- Dedicated ramps of 6-12 bunches are typically used in contrast to the 109 bunches used for normal physics-based operation.
- Good overall orbit correction.
- Good centering of the orbit through the IR magnets.

The measured tune shift becomes negligible after implementation of the corrections, and several important improvements necessarily result. The correction has been shown to decrease beam decay for a 10mm bump by up to a factor of 20. The baseline beam decay is also lowered by several percentage points with this correction in place. As expected, the operability of the machine increases along with the integrated luminosity.

RECENT DEVELOPMENTS

Recent progress has been critical for improving the process of correction implementation. There have been substantial improvements to the reliability of measurements and the betatron tune resolution exhibited by the base band tune measurement system employed at RHIC. Upgrades have enabled the tune to be accurately measured to a level of ~1×10^{-6} [2]. This resolution along with the improved stability has allowed for extremely accurate and reliable measurements, which gives us a powerful tool that has enabled more efficient and accurate corrections.

Algorithms have also been developed to automate the process of sextupole/skew sextupole/octupole correction. The automation has been implemented into the existing IRBump application that is currently used to manually correct interaction region magnetic errors. Replicating the process currently undertaken by system experts, the program looks at the tune shifts caused by continuously changing bumps in different planes and adjusts relevant power supplies while using the tune shift as a figure of merit. This iterative process terminates when there is no longer any improvement. Each algorithm works in the following manner:

- Activate a bump of the proper amplitude.
- Record the observed tune shift.
- Adjust the relevant corrector(s).
- Create another bump and record the new tune shift.
- Compare the tune shift and adjust the relevant corrector(s) in the proper direction.
- Continue this process until the tune shift has been minimized.

The sextupole and skew sextupole algorithms seem to be effective (although testing time has been sparse, at best, due to ever present time constraints for machine development). Some erratic behavior was observed while briefly testing the octupole algorithm in 2010. It is believed that the problem has been identified, and modifications have been made for future testing.

SEXTUPOLE/SKEW SEXTUPOLE FIELD CORRECTION

Sextupole correction has proven to be effective at greatly reducing the horizontal and vertical tune shifts due to a 5mm bump in the horizontal plane. Figure 2 and 3 demonstrate the effect on beam loss and fractional tunes.

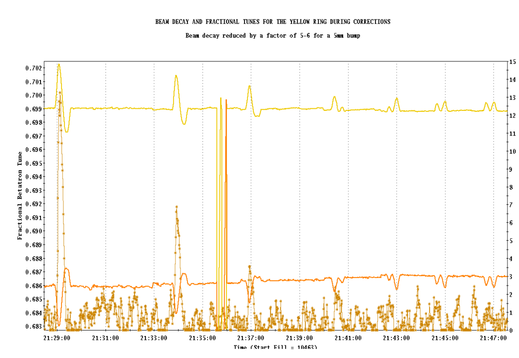

Figure 2: Horizontal/vertical tunes and beam decay for successive 5mm horizontal bumps accompanied by iterative corrections.

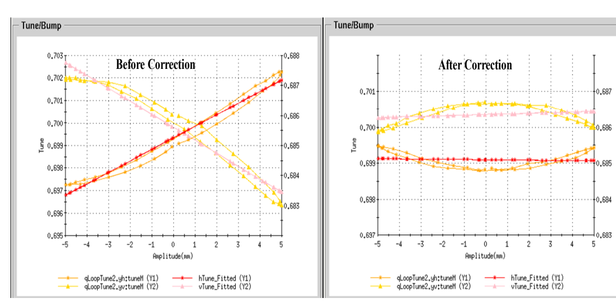

Figure 3: Tune vs. bump amplitude before and after sextupole correction in the yellow ring.

Not only does this correction decrease the beam decay from a given bump; it also significantly affects the baseline beam decay. Figure 4 and figure 5 show the effect of removing and installing (respectively) sextupole/skew sextupole correction settings.

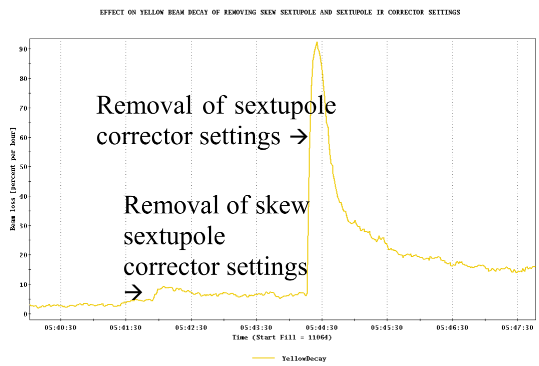

Figure 4: Removing skew sextupole and then sextupole correction has a clear effect on baseline beam decay.

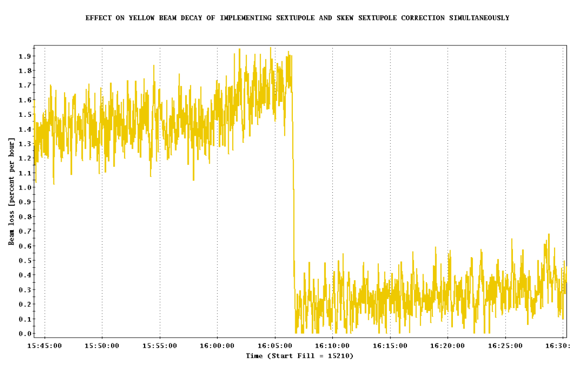

Figure 5: Simultaneous implementation of both skew sextupole and sextupole correction settings lowers beam decay.

EFFECT ON TUNE MODULATION

Several years ago, horizontal beam jitter at a frequency of approximately 10 Hz was observed at all beam position monitors. For bpms near the crossover dipoles, the amplitude of oscillations was measured to be roughly 1.5mm. It has been speculated that helium flow to the superconducting magnets is causing a mechanical vibration of the triplets. Although RHIC now employs an effective 10 Hz feedback system [3], it was previously observed that nonlinear corrections reduced the tune modulation due to this phenomenon, as shown in figure 6.

OCTUPOLE FIELD CORRECTION

In the case of octupole correction, the effect on baseline beam decay is less pronounced and still under investigation. Regardless, the correction affords a much improved situation when the orbit is altered. Figure 7 demonstrates the effect of progressive adjustments to octupole correctors using 10mm bumps.

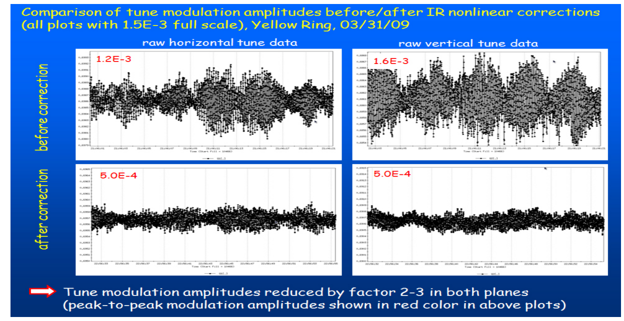

Figure 6: 10Hz tune modulation was observed to be reduced by a factor of 2-3 after IR nonlinear corrections (using sextupole/skew sextupole correctors).

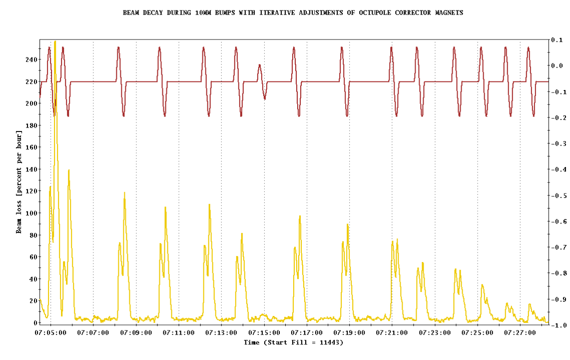

Figure 7: Successive 10mm bumps correlate with a decrease in yellow beam decay as the quadratic tune shifts from octupole fields are progressively corrected.

SUMMARY

Nonlinear optics correction in the interaction regions of the Relativistic Heavy Ion Collider using a tune shift-based method has proven to be effective at providing compensation for the intrinsically present higher-order multipole fields generated by collider focusing and bending magnets. It has been shown to have a significant and beneficial effect on beam losses, tune stability and the dynamic aperture of a hadron collider. Recent improvements, such as increased tune resolution/stability and the automation of corrections, have significantly increased the effectiveness and efficiency of these corrections.

REFERENCES

[1] F. Pilat, Y. Luo, N. Malitsky, V. Ptitsyn, “Beam-Based Non-Linear Optics Corrections”, BNL C-AD AP Note 202, 2005.

[2] M. Wilinski et al., “Improvements for Operational Baseband Tune and Coupling Measurements and Feedback At RHIC”, Beam Instrumentation Workshop, 2010.

[3] R. Michnoff et al., "RHIC 10 Hz Global Orbit Feedback System", Particle Accelerator Conference, 2011.