Experimental study of the persistent current in RHIC superconducting dipole

C. Liu

Collider Accelerator Department

Brookhaven National Laboratory

U.S. Department of Energy

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C. Liu, D. Bruno, A. Marusic, P. Thieberger

Motivation

The first goal [1] of this study is to reduce the high order magnetic component (mostly sextupole component) generated by persistent current in RHIC superconducting dipoles [2]. For Beam Energy Scan Phase II (BES-II) [3,4], reduction of lattice non-linearity is desirable for better beam control and beam lifetime. The sextupole component from RHIC dipole persistent current was too strong to be compensated at low operating current. The store length demonstrated in 2010 low energy operation at 3.85 GeV [5] was 10 minutes partially due to the lattice non-linearity. The measurement and compensation of lattice non-linearity were very difficult with such a short lifetime.

The second goal [1] is to study the persistent current decay with a new magnetic cycle. Less persistent current decay would help improve machine reproducibility. Low energy beams are more susceptible to persistent current decay because of low rigidity. RHIC magnet persistent current decay time constant is about 10s minutes. The current of the magnets was kept at the operating value for days in the past operation so persistent current will not decay during physics stores. However, the magnets will switch from one current to another for different beam energies to take physics data and commissioning electron cooling in the coming years.

Experiment overview

A new magnet cycle for RHIC dipoles and quadrupoles is designed such that the current would oscillate a few times with a diminishing amplitude before settling at the working current (Fig. 2), in contrast to the current going to high amplitude then back down to 50 A and up to operating current in the conventional magnet cycle (Fig. 1). The operating current in this study was for nominal beam injection energy at 9.8 GeV. After the new magnet cycle, beam was injected and tuned. Beam-based measurement of lattice non-linearity and the persistent current drift was performed and compared with those with the conventional magnet cycle.

RHIC dipoles (and quads) were ramped twice through the new magnet cycle (Fig. 3). After the first ramp, the dipole trim, quadrupole current and the sextupole current were adjusted to compensate the difference in b1, b2 and b3; beam-based measurement of the drift of b1, b2 and b3, which present themselves as drift of orbit, tunes and chromaticities, were performed after the second ramp.
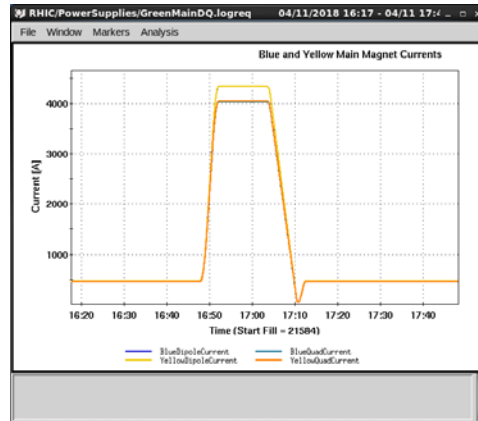
Figure 1: RHIC dipoles (and quads) were ramped to 4334 A, back down to 50 A, then up to 473.3 A for beam injection in the regular hysteresis cycle.
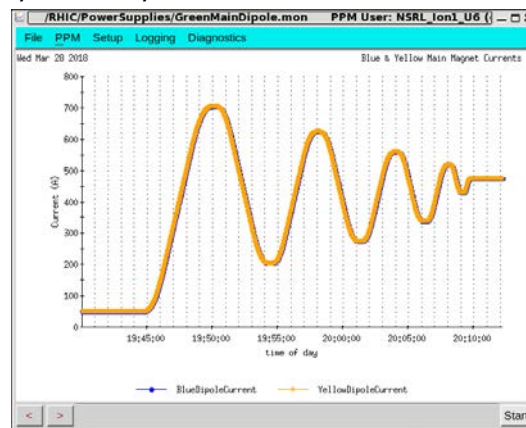

Figure 2: RHIC dipoles (and quads) were ramped up and down several times, with intermediate current points at [50, 700, 200, 625, 275, 560, 340, 520, 430] A, before being held constant at 473.3 A for beam injection in the new magnet cycle.
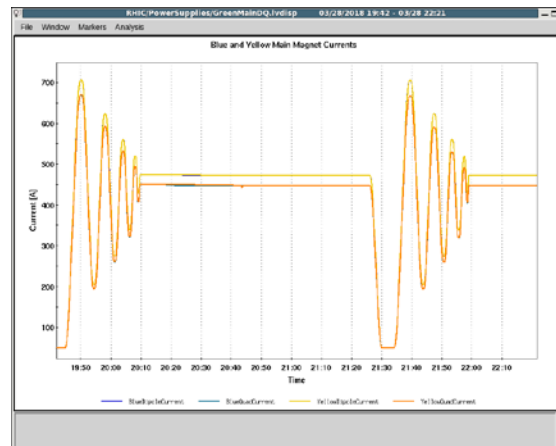

Figure 3: RHIC dipoles (and quads) were ramped twice through the new magnet cycle.

Beam-based compensation study

The transfer function of RHIC dipole and quadrupole, and the sextupole component from RHIC dipole persistent current are all expected to deviate from the nominal values with the conventional magnet

cycle. These differences will be shown in the beam horizontal closed orbit, beam betatron tune and chromaticities.

The horizontal orbit shifted inwards by ~2 mm (Fig. 4) in the ring due to expected difference of RHIC dipole transfer function with the new magnet cycle. The relative adjustment of RHIC dipole strength was -4.48E-4 to center the beam orbit.

Figure 4: The horizontal orbit shifted inwards by ~2 mm in the ring due to expected difference of RHIC dipole transfer function with the new magnet cycle.

The adjustment of quadrupole current for compensation of b2 component is more complicated due to contribution from multiple sources, therefore it will not be discussed here.

The b3 contribution from RHIC dipole was reduced from -5.38 to -0.87. For both regular hysteresis cycle and the new magnet cycle, sextupole magnets were adjusted to compensate RHIC dipole b3 component so that the beam chromaticity were kept around -5 (1 unit of b3 is equivalent to 4.6 unit of chromaticity [6]). For regular hysteresis, beam chromaticity (horizontal, neglecting natural chrom and compensation) is: -5.38*4.6 (b3 contribution) + 19 (sextupole compensation) = -5. For the new magnet cycle, beam chromaticity is: b3*4.6 + 19 (sextupole compensation) -20 (sextupole adjustment after new magnet cycle) = -5, therefore b3 = -0.87.

Beam-based persistent current decay study

The horizontal average orbit (Fig. 5), the betatron tunes (Fig. 6) and the chromaticities (left plot in Fig. 7) were measured over a period of ~ 1 hr to characterize the persistent current decay. The peaks in Fig. 5 and 6 are due to change of RF frequency during chromaticity measurements. The drift of orbit and beta tunes are less than those with drift compensation after conventional magnet cycle. The chromaticities with the new magnet cycle (left plot in Fig. 7) did not show a drift behavior as measured previously with a conventional magnet cycle (right plot in Fig. 7) [7]. The measurement of Blue horizontal chromaticity was contaminated by the interlock of tune measurements.
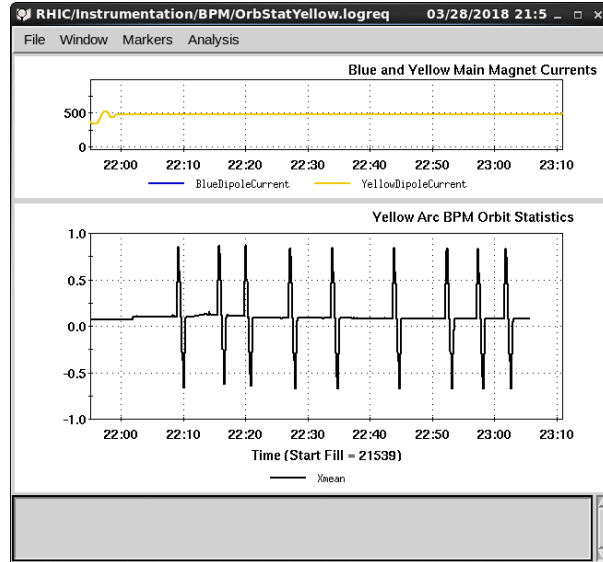
Figure 5: The lower plot shows the average of horizontal orbit, which would drift if dipole field decays, over a period of ~1 hr after the second ramp.
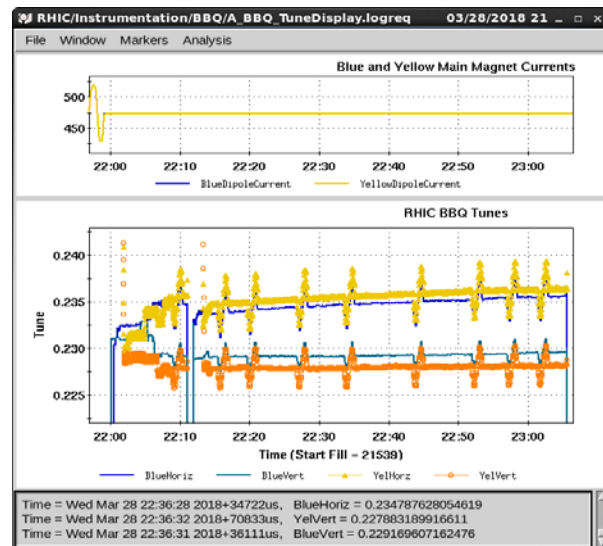

Figure 6: The lower plot shows the horizontal and vertical tunes of both beams, which would drift if b2 component decays, over a period of ~1 hr after the second ramp. The drift was 0.001 in the horizontal plane, and negligible in the vertical plane (for regular hysteresis cycle, the drift is ~0.02 in the horizontal, 0.002 in the vertical plane). The peaks were tune changes due to change of RF frequency during chromaticity measurements.
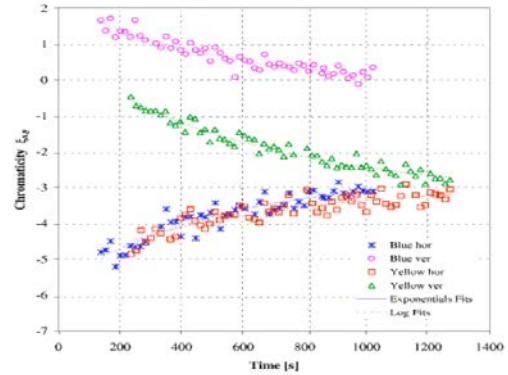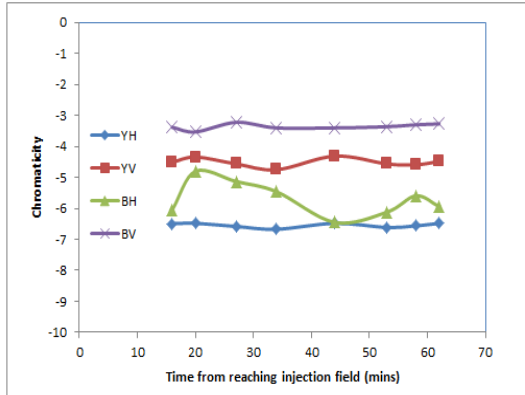
FIG. 3. (Color) Measured chromaticity in the two RHIC rings on a linear time scale.

Figure 7: the left plot shows the beam chromaticities in both planes for both beams, which would drift if b3 component decays, over a period of ~1 hr after the second ramp. The drifts of the chromaticities are negligible. The right plot shows the drift of the chromaticity measured over a period of ~20 minutes after a regular hysteresis cycle.

Simulation

Simulation of static persistent current in RHIC superconducting dipole [8] has been started before the experimental study. The model can calculate the magnetic components with custom designed magnet cycle, however, not the persistent current decay behavior. The comparison of simulation with experimental results is ongoing.

Summary

A new magnet cycle with oscillating current was demonstrated at RHIC to substantially reduce the lattice non-linearity, especially the sextupole contribution, and the persistent current decay in the superconducting dipole.

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