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MITIGATION OF PERSISTENT CURRENT EFFECTS IN THE RHIC SUPERCONDUCTING MAGNETS

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Abstract

Persistent currents in superconducting magnet introduce errors in the magnetic fields especially at low operating currents. In addition, their decay cause magnetic field variations therefore drifts of beam orbits, tunes and chromaticities. To reduce field errors and suppress magnetic field variations, new magnetic cycles were proposed for low energy beam operation at RHIC. The new magnetic cycle has been demonstrated experimentally to reduce field errors and the amplitude of magnetic field variations significantly and is essential for the ongoing RHIC Beam Energy Scan II (BES-II) program. This article will present beam-based experimental studies of the persistent current effects with the new magnetic cycle.

INTRODUCTION

These persistent current effects are especially strong for the Beam Energy Scan II (BES-II) physics program at RHIC [1, 2], where gold beam energy drops to as low as 3.85 GeV/nucleon (only 1/26 of the top beam energy). To compensate the sextupole field errors induced by persistent currents, the polarities of some sextupole magnets had to be reversed during past operation at low energy [3]. In addition, significant time was spent for the magnetic field to reach a steady state for beam operation.

To combat these persistent current effects, we proposed a new demagnetization magnet cycle [4] on all RHIC superconducting dipoles and quadrupoles. The magnet current oscillates around the operating current with diminishing amplitude a few times in the demagnetization cycle, similar to a “degaussing cycle” [5] tested on LHC magnets. Beam-based studies demonstrated that the new cycle reduced the sextupole field error and its decay amplitude significantly at the RHIC injection energy.

HYSTERESIS CYCLE AND DECAY OF PERSISTENT CURRENTS IN SUPERCONDUCTING MAGNETS

The persistent currents cause hysteresis effects in superconducting magnets because the polarity of the currents reverses with increasing and decreasing main field [6]. The magnetic field of superconducting magnets decay because of persistent currents and coupling currents decay once the external main field stops ramping [7]. Flux creep [8] induces a decrease of the critical current density and produces a logarithmic decay. Inter-filament and inter-strand coupling currents develop when the external field changes, and decay when the external field stays constant. Boundary induced coupling currents result in different currents in strands, the redistribution of which can affect the magnetization due to changes of the local field [9].

EXPERIMENTAL STUDIES ON PERSISTENT CURRENTS WITH A DEMAGNETIZATION CYCLE AT INJECTION ENERGY

Experiment Overview

The new demagnetization cycle for RHIC dipoles and quadrupoles, with the currents oscillating a few times with a diminishing amplitude before settling at the operating current, is shown in Fig. 1. For comparison, the conventional magnet cycle, with the current going to high amplitude then back down to park current and up to operating current, is shown in Fig. 2. The operating current in this study was for the nominal gold beam injection energy of 9.8 GeV/nucleon.

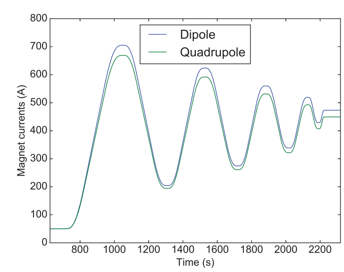

Figure 1: Demagnetization magnetic cycle: RHIC superconducting dipole and quadrupole currents are ramped up and down several times, with intermediate current points at [50, 700, 200, 625, 275, 560, 340, 520, 430 A], before being held constant at operating currents for beam injection.

The magnets (RHIC dipoles and quadrupoles) were ramped through the demagnetization cycle twice. After the first magnet cycle, the dipole, quadrupole and the sextupole current were adjusted to compensate the difference introduced by the demagnetization cycle. After the second magnet cycle, the variation of magnetic fields were measured by monitoring the drift of beam orbit, tunes and chromaticities.

Change of Magnetic Fields Induced by the Demagnetization Cycle

In this subsection, we observe and analyze first the change of high-order magnetic field errors, which have potential

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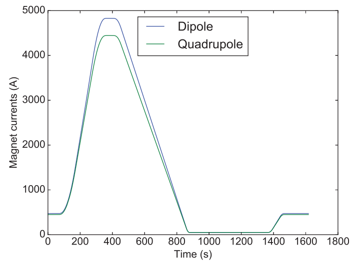

Figure 2: Conventional magnetic cycle: RHIC superconducting dipole and quadrupole currents are ramped up to currents for top energy, back down to park current at 50 A, then up to operating currents for beam injection.

detrimental effects on beam dynamic aperture; then the change of low-order magnetic components. The high-order magnetic field errors of concern are sextupole (b_3) and decapole (b_5) components from RHIC superconducting dipoles, octupole (b_4) component from superconducting quadrupoles. These components are monitored based on first, second and third order chromaticities respectively. The low-order magnetic field of concern are the change of dipole and quadrupole transfer functions. These changes were monitored based on beam average orbit in dispersive arc sections and relative errors of $\beta-$functions ($\beta-$beat) respectively.

Reduction of sextupole field errors in dipole magnets The change of sextupole components in superconducting dipoles introduced by the demagnetization cycle will be deduced first. At injection energy (9.8 GeV/nucleon) which is below transition energy (~24 GeV/nucleon), beam chromaticities are set to be ~-5 for stability with compensation of sextupole magnets. The contributions to beam chromaticities consist of sextupole component in dipoles, natural chromaticity from quadrupoles and compensation from sextupole magnets.

$$k * b_3 + Q_{natural} + Q_c = -5, \qquad (1)$$

where b_3 is the average sextupole component in RHIC superconducting dipoles, $k = 4.6$ is the scale factor for converting sextupole component to beam chromaticity unit [10], $Q_{natural}$ is the natural chromaticity from the quadrupoles and Q_c is the compensation from sextupole magnets. The sextupole component (b3) was measured to be -5.39 with the conventional hysteresis cycle.

After the demagnetization cycle, the sextupole compensation was lowered by 20 unit in the horizontal plane (adjustment in the vertical plane is approximately equal and opposite) to keep the measured chromaticity at ~-5. As will be shown in , the change of quadrupole transfer function was not significant, therefore, the natural chromaticities are considered as unchanged after the demagnetization cycle.

$$k * b_{3,n} + Q_{natural} + (Q_c - 20) = -5, \qquad (2)$$

Combining Eq. 1 and 2, one finds the sextupole component after the demagnetization cycle is -1.04. Therefore, the sextupole component from RHIC superconducting dipoles was reduced from -5.39 with the conventional magnetic cycle to -1.04 with the demagnetization cycle.

Reduction of the second and third order chromaticities The demagnetization cycle was proven to reduce the high-order errors by roughly the same order of magnitude (~10) based on the comparison of the absolute value of Q'' and Q'''. The second and third order chromaticities, measured with the demagnetization cycle, are compared to the ones measured with the conventional magnetic cycle in Table 1.

Table 1: Comparison of the Second and Third Order Chromaticities Measured with the Conventional and the Demagnetization Cycles

Cycle	Q''_h	Q''_v	Q'''_h	Q'''_v
Conventional	459±806	-478±815	4.7E6±6.7E6	-1.5E6±3.5E6
Demagnetization	58±345	31±188	-1.9E6±3.6E6	-1.5E5±3.0E5

The octupole correctors in RHIC were powered but not used for compensation at injection energy for either the conventional or the demagnetization cycle. The decapole correctors were not even powered. Therefore, the measurement of Q'' and Q''' are the direct reflection of the high-order field errors in the dipole and quadrupole magnets.

Change of dipole and quadrupole main fields The change of dipole and quadrupole magnet transfer functions introduce the change of beam orbit, betatron tunes and Twiss parameters. These changes were compensated by adjusting the dipole and quadrupole magnet currents. Here we examine the magnitude of the changes of beam average orbit and $\beta-$beat.

The horizontal orbit after the demagnetization cycle shifted inwards by ~2 mm (Fig. 3) in the ring with respect to the otherwise centered orbit after a conventional magnetic cycle. The orbit shift was due to the expected difference of RHIC dipole transfer function with the demagnetization cycle. It took a relative adjustment of RHIC dipole strength of -4.48E-4 to center the beam orbit.

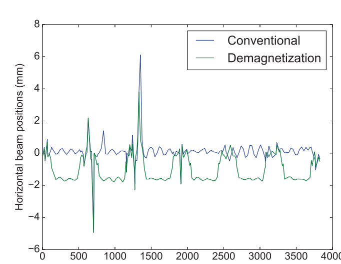

Figure 3: The horizontal orbit shifted inwards by 1.8 mm in the ring due to expected difference of RHIC dipole transfer function with the demagnetization cycle.

The $\beta-$beat, measured with the demagnetization cycle, is shown in Fig. 4. The magnitude of the $\beta-$beat is comparable

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to the ones measured with the conventional magnetic cycle therefore no compensation was applied.

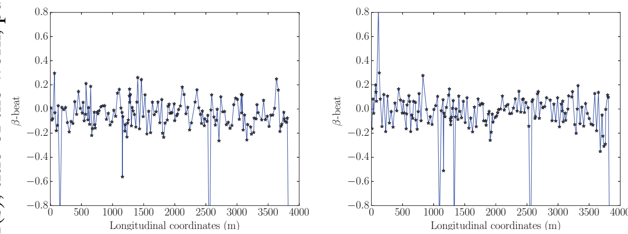

Figure 4: The measured relative errors of $\beta-$functions, the horizontal plane on the left and the vertical plane on the right, with the demagnetization cycle.

Beam-Based Measurement of Drifts of the Magnetic Fields

The drifts of the dipole main field cause the drift of the average beam position in the dispersive arc section. The magnitude of the drifts are compared in Fig. 5 for the conventional and demagnetization cycles. The drift of the average beam position was reduced by a factor of ~10 with the demagnetization cycle.

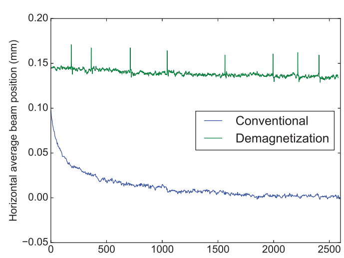

Figure 5: Comparison of the horizontal average beam position drifts, due to persistent currents decay in superconducting dipoles, with the conventional cycle (the blue curve) and the demagnetization cycle (the green curve).

The drifts of the quadrupole main field causes the drift of the betatron tunes. The magnitude of the drifts are compared in Fig. 6 for the conventional and demagnetization cycles. The drift of betatron tunes were reduced by a factor of ~8 with the demagnetization cycle.

The drifts of the sextupole field causes the drift of beam chromaticities. The drift of beam chromaticities are shown in Fig. 7 for the demagnetization cycle. Unlike the logarithmic drift measured previously at RHIC (see Fig. 3 in Ref. [11]), the beam chromaticities stayed almost constant with the demagnetization cycle.

SUMMARY

A demagnetization magnet cycle, with magnet current oscillating a few times with deminishing amplitude around the operating current before settling, was proposed at RHIC

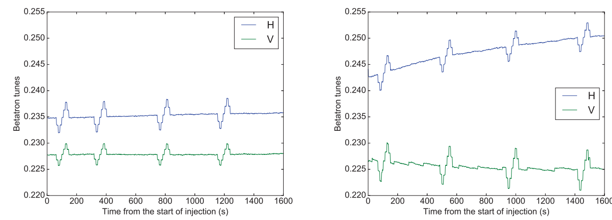

Figure 6: The left plot shows the drift of the horizontal and vertical betatron tunes after the demagnetization cycle. The right plot shows the drift of the horizontal and vertical betatron tunes after the conventional cycle. The excursion of the betatron tunes were due to change of RF frequency for chromaticity measurements.

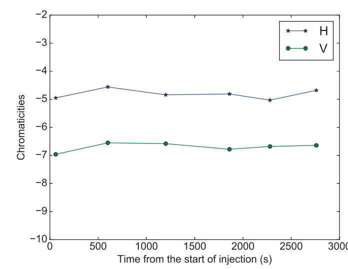

Figure 7: The measured beam chromaticities after the demagnetization cycle.

to combat the persistent current effects in superconducting magnets. Beam-based studies demonstrated substantial reduction of persistent current induced magnetic field errors and their decay. The sextupole component in dipoles from persistent current was significantly reduced. The second and third order chromaticities are measured to be smaller with the demagnetization cycle than those with the conventional cycle. The change of dipole field, which is measured by orbit shift, was compensated by adjusting the main field. The change of quadrupole field, which is measured by $\beta-$beat, were observed to be non-substantial. The drift of the dipole field, which is measured by drift of the average beam position, was reduced by a factor of ~10 with the demagnetization cycle. The drift of quadrupole field, which is measured by the drift of betatron tunes, were reduced by a factor of ~8 with the demagnetization cycle. The drift of sextupole component, which was measured by drift of chromaticities, were mostly constant compared to a logarithmic decay with the conventional cycle.

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