Polarized Proton Collisions at 205 GeV at RHIC

M. Bai,[1] T. Roser,[1] L. Ahrens,[1] I. G. Alekseev,[2] J. Alessi,[1] J. Beebe-Wang,[1] M. Blaskiewicz,[1] A. Bravar,[1] J. M. Brennan,[1] D. Bruno,[1] G. Bunce,[1,6] E. Courant,[1] A. Drees,[1] W. Fischer,[1] C. Gardner,[1] R. Gill,[1] J. Glenn,[1] W. Haeberli,[3] H. Huang,[1] O. Jinnouchi,[6] J. Kewisch,[1] A. Luccio,[1] Y. Luo,[1] I. Nakagawa,[7] H. Okada,[5,7] F. Pilat,[1] W. W. MacKay,[1] Y. Makdisi,[1] C. Montag,[1] V. Ptitsyn,[1] T. Satogata,[1] E. Stephenson,[4] D. Svirida,[2] S. Tepikian,[1] D. Trbojevic,[1] N. Tsoupas,[1] T. Wise,[3] A. Zelenski,[1] K. Zeno,[1] and S. Y. Zhang[1]

[1]*Brookhaven National Laboratory, Upton, New York 11973, USA*
[2]*Institute of Theoretical and Experimental Physics, Moscow, Russia*
[3]*University of Wisconsin, Madison, Wisconsin, USA*
[4]*Indiana University Cyclotron Facility, Bloomington, Indiana, USA*
[5]*Kyoto University, Kyoto, Japan*
[6]*RIKEN BNL Research Center, Upton, New York 11973, USA*
[7]*RIKEN, Wako, Saitama 351-0198, Japan*

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The Brookhaven Relativistic Heavy Ion Collider (RHIC) has been providing collisions of polarized protons at a beam energy of 100 GeV since 2001. Equipped with two full Siberian snakes in each ring, polarization is preserved during acceleration from injection to 100 GeV. However, the intrinsic spin resonances beyond 100 GeV are about a factor of 2 stronger than those below 100 GeV making it important to examine the impact of these strong intrinsic spin resonances on polarization survival and the tolerance for vertical orbit distortions. Polarized protons were first accelerated to the record energy of 205 GeV in RHIC with a significant polarization measured at top energy in 2005. This Letter presents the results and discusses the sensitivity of the polarization survival to orbit distortions.

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Introduction.—The Relativistic Heavy Ion Collider (RHIC) was designed to provide collisions of polarized protons at a maximum beam energy of 250 GeV to study proton spin structure [1,2]. Beam polarization during acceleration can be compromised by depolarization mechanisms driven by magnetic fields which perturb the spin motion away from its precession around the guiding dipole field. This can be illustrated by the Thomas-BMT equation [3] which describes the evolution of the spin vector $\vec{S}$

$$\frac{d\vec{S}}{dt} = \frac{e}{\gamma m}\vec{S} \times [(1 + G\gamma)\vec{B}_\perp + (1 + G)\vec{B}_\parallel]. \quad (1)$$

Here γ is the Lorentz factor and $G = 1.793$ is the proton anomalous g factor. $\vec{B}_\perp$ and $\vec{B}_\parallel$ are the magnetic fields perpendicular and parallel to the beam direction, respectively. Equation (1) also shows that in a perfect accelerator with only the guiding dipole field, the spin vector precesses $G\gamma$ times per orbital revolution. The spin tune Q_s is then equal to $G\gamma$.

In practice, spin perturbing magnetic fields from either magnet manufacturing and installation imperfections or vertical betatron oscillation are present. When the frequency of the perturbation on the spin precession coincides with the spin precession frequency, the spin vector is continuously kicked away from the vertical direction and a spin resonance occurs [4]. Machine imperfections such as dipole errors and quadrupole misalignments result in vertical closed orbit distortions and induce imperfection spin resonances at $G\gamma = k$ where k is an integer. The vertical betatron oscillations, in addition, force particles to sample the horizontally oriented focusing fields and drive intrinsic spin resonances at $G\gamma = kP \pm Q_y$. Here, P is the superperiodicity of the machine and Q_y is the vertical betatron tune. Depending on the strength of the resonance and the resonance crossing rate, the amount of depolarization can vary. For an isolated resonance, the ratio of the polarization after crossing through the resonance P_f, compared to the initial polarization P_i, is given by the Froissart-Stora formula [5]

$$P_f = P_i(2e^{-\pi|\epsilon|^2/2\alpha} - 1), \quad (2)$$

where $\alpha = \frac{dQ_s}{d\theta}$ is the resonance crossing rate, θ is the azimuthal angle around the accelerator, and ϵ is the strength of the spin resonance [4]. Equation (2) shows that for $\frac{P_f}{P_i} = 1$, one can either minimize the resonance strength to zero or cross a resonance very quickly. For imperfection resonances, the resonance strength is proportional to the size of the closed orbit distortion, and can be significantly reduced with a particular setting of the dipole corrector magnets. For intrinsic resonances, the strength is proportional to the size of the betatron oscillation and the resonance can be overcome by a fast jump of the betatron tune.

The techniques of using vertical harmonic orbit correction to overcome imperfection resonances and using tune jumps to cross intrinsic resonances were developed during the course of polarized proton development at the Zero Gradient Synchrotron (ZGS) where the polarized proton beam was first accelerated to multi-GeV [6]. When the two techniques were applied to the polarized proton acceleration in the Brookhaven Alternating Gradient Synchrotron (AGS), it was technically challenging because the strong focusing AGS has much stronger spin resonances. Achieving accurate orbit correction for each of the 39 imperfection resonances was a technical feat [7] but was difficult to maintain operationally. The application of using a partial Siberian snake made the polarized proton acceleration in the AGS much simpler [8,9]. The partial snake bends the spin vector away from the vertical direction by a fraction of 180° to move the spin tune away from any integer for all energies. Nevertheless, it is not strong enough to avoid polarization losses for higher energy accelerators like RHIC.

In 1976, Derbenev and Kondratenko proposed a special device which rotates the spin vector 180° around an axis in the horizontal plane every time the particle passes through it. The spin tune then becomes independent of beam energy [10]. This special device was soon named "Siberian snake" to honor its Siberian-based inventors. The first Siberian snake was successfully tested in the Indiana Cooler Ring at Indiana University Cyclotron Facility (IUCF) [11]. The success with the first Siberian snake opened the possibility of accelerating polarized protons in high energy accelerators. For polarized proton acceleration in RHIC, a configuration of two Siberian snakes in each ring was chosen to overcome both imperfection and intrinsic resonances. The two snakes are placed on opposite sides of the ring with their spin precession axes perpendicular to yield an energy independent spin tune [1].

Even in a perfect accelerator, which has no magnetic field errors, with snakes, the spin perturbations can still add coherently and result in significant polarization loss at certain tune values. For a single snake case, the accumulated spin perturbations cannot be perfectly canceled out if

$$mQ_y = Q_s + k. \tag{3}$$

Here, m and k are integers. These are called snake resonances [12] and m is the order of the snake resonance [4]. This was also experimentally observed at IUCF [13]. Adding the second snake at the opposite side of the ring to the first snake provides additional cancellation when m is an even number. Hence, with two snakes, all the even order snake resonances disappear. However, the even order snake resonances reappear if the intrinsic resonance overlaps an imperfection resonance. The overlap of an intrinsic resonance with an imperfection resonance also splits the existing odd order resonances [4,14]. All of this greatly reduces the available betatron tune space to avoid polarization loss. Hence, careful control of tunes and vertical closed orbit distortions are necessary for any high energy accelerator.

Polarized protons in RHIC have been successfully accelerated to 100 GeV with minimum or no polarization loss with careful control of the betatron tunes and the vertical orbit distortions. Figure 1 shows the achieved polarization at store and at injection in RHIC during the 2005 polarized proton operation [15] for the two independent RHIC accelerators, referred to as Blue and Yellow rings.

On average the data show that polarization was preserved in the Blue ring during the acceleration and beta squeeze, and some depolarization is evident in the Yellow ring. The difference of polarization transmission efficiency between Blue and Yellow is still under investigation. The energy of 205 GeV instead of the maximum design energy of 250 GeV was chosen for this first test of acceleration beyond 100 GeV because the PHOBOS experiment at RHIC requested a physics measurement with proton beams near a beam energy of 200 GeV.

Accelerating to 205 GeV.—Even with the success of accelerating polarized protons to 100 GeV, it was still uncertain whether the polarization would survive the acceleration from 100 GeV to 250 GeV with the precision of tune and orbit control currently achieved at RHIC. Figure 2 shows the calculated intrinsic spin resonance strengths of the RHIC lattice without snakes [16]. It shows that the strong intrinsic spin resonances at higher energy are expected to be over a factor of 2 stronger than those below 100 GeV. In general, because the closed orbit distortions are dominated by the harmonics around the betatron tune, imperfection resonances near strong intrinsic spin resonances are also stronger, and the tolerance on the machine imperfection around strong intrinsic spin resonances is

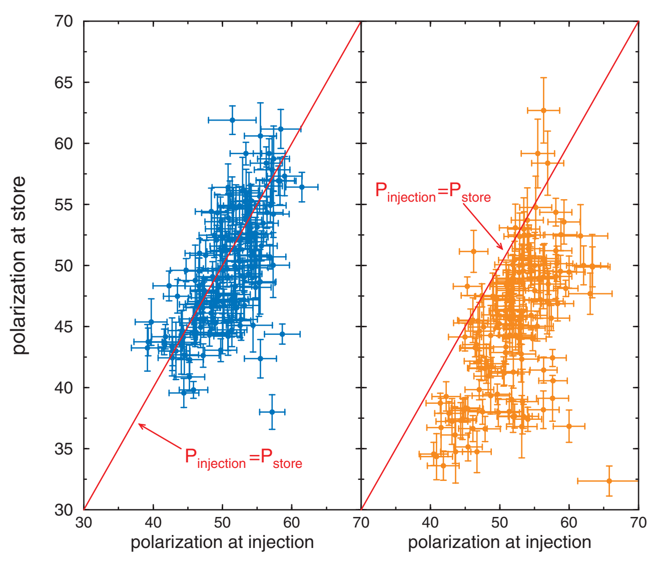

FIG. 1 (color). Achieved beam polarization at RHIC store (100.2 GeV) as a function of the beam polarization measured at injection (24.3 GeV) during the RHIC polarized proton 2005 run. The left plot shows the beam polarization in the Blue ring and the right plot is the achieved beam polarization in the Yellow ring.

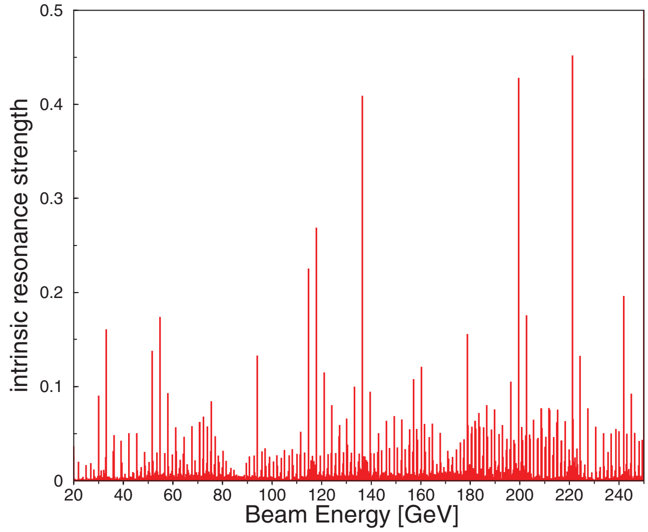

FIG. 2 (color). RHIC intrinsic spin resonance strength as a function of beam energy. This is calculated with a 2 m β^* at STAR and PHENIX, 3 m β^* at Brahms, 10 m β^* at PHOBOS, and 5 m β^* at the RHIC absolute polarimeter [18].

predicted to be proportionally tighter [17]. To accelerate polarized protons with a 95% normalized emittance of 20π mm-mrad, the simulation shows that the imperfection resonance strength should be below 0.075 to avoid polarization loss at the strong intrinsic resonances around 136 GeV, 203 GeV, and 221 GeV [1]. The imperfection resonance strength $\epsilon_{\rm imp}$ calculation [16] yields that the RHIC imperfection resonance strength is bounded by

$$\epsilon_{\rm imp} = 0.25\frac{\gamma}{250}\sigma_y. \quad (4)$$

Here, γ is the Lorentz factor of the beam and σ_y is the rms value of the vertical closed orbit distortion in mm. Hence, a closed orbit with $\sigma_{y,\rm rms} \leq 0.3$ mm is needed to keep the imperfection resonances below 0.075 at all energies in RHIC. This was also confirmed with numerical simulations [1,17].

A total of three polarimeters based on the Coulomb-Nuclear Interference effect, two fast relative ones plus an absolute one, were installed in RHIC to measure the beam polarization. The absolute polarimeter using a polarized hydrogen jet target (H jet polarimeter) is located at one of the RHIC interaction points [18], and measures the asymmetry of recoil protons from the elastic collisions off the polarized hydrogen jet target with a polarization of 0.924 ± 0.018. The two relative carbon polarimeters (one for Blue beam and one for Yellow beam) use carbon targets and measure the asymmetry of the recoil carbon [19,20]. The beam polarization is obtained from the measured asymmetry normalized by the analyzing power. The analyzing power of the carbon polarimeter was first measured at the AGS [20]. Its analyzing power at 100 GeV was calibrated with the H jet polarimeter in RHIC and was also applied to 205 GeV. In general, the change in analyzing power through the RHIC energy range is expected to be small [21]. The results presented here are from online measurements and have a typical statistical uncertainty of $\Delta P = \pm 0.03$ and an estimated scale uncertainty of $\frac{\Delta P}{P} = \pm 0.22$, from the knowledge of the polarimeter analyzing power. The estimate includes a 10% uncertainty, added in quadrature, from the expected weak dependence on the beam energy of the polarimeter analyzing power for the extrapolation from 100 GeV to 205 GeV [21]. In the following, only the statistical uncertainties are indicated.

For the acceleration to 205 GeV, the β^* at the two RHIC experiments STAR and PHENIX was set to 10 m at injection, continuously squeezed to 2 m during the ramp from injection to 100 GeV and then held constant to 205 GeV. Figure 3 shows the first polarization measurements at the store energy of 205 GeV as well as the polarization transmission efficiency defined as the ratio of polarization measured at the end of the ramp and polarization at injection. The highest polarizations achieved at 205 GeV are $-39.5 \pm 3.4\%$ in Blue and $-48.6 \pm 3.2\%$ in Yellow. The depolarization is evident. Detailed studies also show that the spread of polarization transmission efficiency is mainly due to the variations of the vertical orbit distortion.

In order to explore the sensitivity of depolarization to orbit distortions in RHIC at the energies close to the strong intrinsic spin resonances, two sets of polarization measurements along the ramp with different orbit distortion rms values were conducted. Figure 4 shows the polarization measurements made during two consecutive RHIC ramps. In each case, three polarization measurements were taken at around 40 GeV, 102 GeV, and 197 GeV. The horizontal bars in the plot represent the measuring time. Both ramp

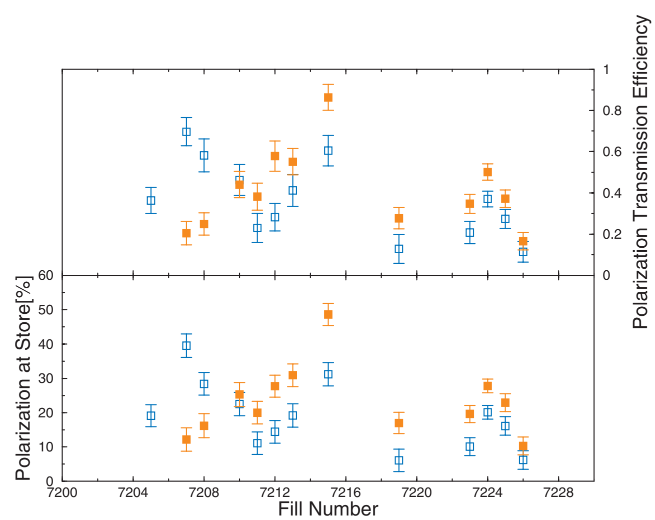

FIG. 3 (color). The bottom plot shows the first polarization measurements at store in Blue (blue open squares) and in Yellow (yellow solid squares). The top shows the polarization transmission efficiency (ratio of polarization measured at the end of the ramp to polarization at injection) for each fill for each ring.

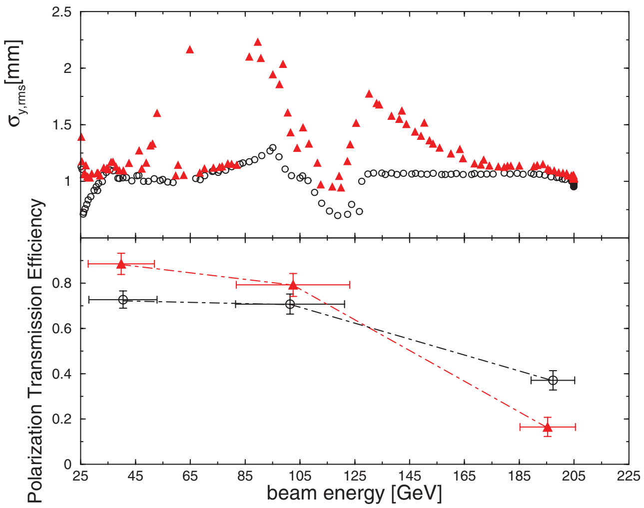

FIG. 4 (color). The bottom plot shows the polarization transmission efficiency in the Yellow ring during two consecutive ramps. The open black circles correspond to Fill 7225 and the red triangles to Fill 7226. The dot-dashed lines are for guiding the eye. The only difference between the two ramps above 100 GeV is that the vertical orbit rms distortion was increased by 0.5 mm at 135 GeV in Fill 7226. The top plot shows the measured vertical orbit distortion rms value along the ramp for Fill 7225 (black open circle) and for Fill 7226 (red triangle).

measurements show the polarization loss occurred between 128 GeV and 205 GeV where the strong intrinsic resonances around 136 GeV and 203 GeV are located. An increase of 0.5 mm rms orbit distortion around 136 GeV reduced the polarization transmission efficiency by 55%.

Conclusions.—Polarized protons were accelerated to a new record energy of 205 GeV and brought into collision. Significant beam polarization was measured at the top energy, after successfully crossing through strong spin resonances between 100 GeV and 205 GeV. Depolarization between 128 GeV and 205 GeV was confirmed by the polarization measurements along the energy ramp. The polarization measurements along the energy ramp with different vertical orbit distortion are consistent with the expectation that with Siberian snakes, significant depolarization can occur when strong intrinsic resonances overlap even relatively weak imperfection spin resonances. It is therefore critical to minimize the vertical orbit distortion to avoid the polarization loss during the acceleration.

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