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FIRST POLARIZED PROTON COLLISIONS AT A BEAM ENERGY of 250 GeV IN RHIC*

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Abstract

After providing collisions of polarized protons at a beam energy of 100 GeV since 2001, the Relativistic Heavy Ion Collider (RHIC) at BNL had its first opportunity to collide polarized protons at its maximum beam energy of 250 GeV in the 2009 polarized proton operations. Equipped with two full Siberian snakes [1] in each ring, RHIC preserves polarization during acceleration from injection to 100 GeV with precise control of the betatron tunes and vertical orbit distortions. However, the strong intrinsic spin resonances beyond 100 GeV are more than two times stronger than those below 100 GeV, requiring much tighter tolerances on vertical orbit distortions and betatron tunes. With the currently achieved orbit correction and tune control, average polarizations of $\simeq 42\%$ at top energy and average polarizations of $\simeq 55\%$ at injection energy were achieved. Polarization measurements as a function of beam energy also indicated all polarization losses occurred around three strong intrinsic resonances at 136 GeV, 199.3 GeV and 220.8 GeV. Peak luminosity of $122 \times 10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ was also demonstrated. This paper presents the performance of the first RHIC 250 GeV operation and discusses the depolarization issues encountered during the run.

INTRODUCTION

As the world's first high energy polarized proton collider to study proton spin structure, the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory has been providing polarized proton collisions at a beam energy of 100 GeV since 2001. To preserve the beam polarization through acceleration, two pairs of Siberian snakes [2] in each of the two RHIC rings are employed to avoid intrinsic and imperfection spin depolarizing resonances at $G\gamma = kP \pm Q_y$ and $G\gamma = kP$, respectively [3]. Here, $G \simeq 1.793$ is the proton anomalous $g-$factor, k is an integer, P is the periodicity of an accelerator, and Q_y is the vertical betatron tune.

The two Siberian snakes in each of the RHIC rings are located 180° apart with their axes, around which the spin vector rotates, perpendicular to each other. This configuration keeps the spin precession tune $Q_s = \frac{1}{2}$ (the spin precession frequency in units of orbital revolution frequency) independent of energy, ensuring that none of the imperfection resonances are crossed. Since accelerators have to be operated with betatron tunes far away from 0.5 to keep the beam stable, a spin tune of 0.5 also avoids all the intrinsic spin resonances. However, due to vertical betatron oscillations, perturbations from the horizontal focusing fields on the spin motion can still add up coherently to drive snake resonances and lead to depolarization [3, 4] when

$$mQ_y = Q_s + k. \tag{1}$$

Here, m and k are integers and m is the order of the snake resonance [3]. This was experimentally first observed at IUCF [5]. Depending on whether m is even or odd, snake resonances are categorized into even order resonances and odd order resonances, respectively. With no closed orbit distortion and the two snakes located on the opposite side of the accelerator, all even order snake resonances are suppressed. However, even order snake resonances re-appear 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 [3, 6]. All of this greatly reduces the available betatron tune space where polarization is preserved.

RHIC has successfully accelerated polarized protons up to 100 GeV with no polarization losses by carefully controlling the betatron tunes and the vertical orbit distortion [7, 8]. However, between 100 GeV and 250 GeV, there are three much stronger intrinsic spin resonances located at $G\gamma = 3 \times 81 + (Q_y - 12) \simeq 260.7$ ($\simeq 136.38$ GeV), $G\gamma = 5 \times 81 - (Q_y - 6) \simeq 381.3$ ($\simeq 199.48$ GeV) and

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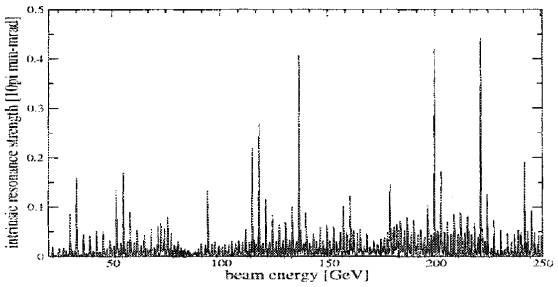

Figure 1: RHIC intrinsic spin resonance strength as a function of beam energy. This is calculated with a 0.7 m β^* at STAR and PHENIX, and 7.5 m β^* at all the other interaction points.

$G\gamma = 5 \times 81 + (Q_y - 12) \simeq 422.7$ ($\simeq$ 221.13 GeV) as shown in Fig. 1. Since stronger intrinsic resonances lead to stronger derived snake resonances, tolerances on betatron tunes and betatron tune spread as well as nearby imperfection resonances (the vertical closed orbit distortion) are much tighter. Numerical simulation shows that the imperfection resonance strength should be below 0.075 to avoid depolarization at these three strong intrinsic resonances [2]. This corresponds to a closed orbit distortion of 0.3 mm rms.

During the 2009 RHIC run, polarized protons were brought into collision at the maximum beam energy of 250 GeV for the first time. This was done for the two experiments at STAR and PHENIX to commission their detectors, and to take data for their first glimpse at W production. Both polarization and luminosity performances with the current tune and orbit control are presented in the following section. The spin rotators around the two detectors were also turned on to provide collisions with longitudinal polarization. Polarization deterioration during a long store was observed with certain rotator settings. Due to the limit of space, this paper only focuses on the depolarization during the acceleration from 100 GeV to 250 GeV, i.e. polarizations quoted in this paper are without rotators.

PERFORMANCE

RHIC 250 GeV polarized proton operation was set up with $\beta = 7.5$ m at all interaction points in both planes at injection. βs were kept constant for the acceleration except at the interaction points for STAR and PHENIX, where they were continuously squeezed down to 0.7 m from injection to 250 GeV. Collisions of 109 bunches with $1.2-1.3\times10^{11}$ protons per bunch were achieved in routine operation. A peak luminosity of $1.22 \times 10^{32}\text{cm}^{-2}\text{s}^{-1}$ was achieved. Fig. 2 shows the delivered average luminosity for 250 GeV operations as well as achieved peak luminosity. At the end of the 250 GeV run, collisions of 56 bunches in each rings with 1.8×10^{11} protons per bunch was also demonstrated.

The working point for acceleration to 250 GeV was chosen to be below 0.7 to avoid the snake resonance at $Q_y = \frac{7}{10} = 0.7$. Other than a high order resonances

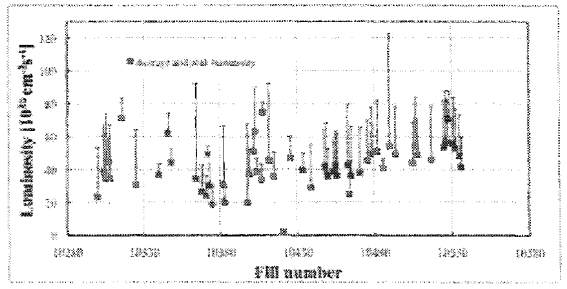

Figure 2: The red squares in the plot are the average luminosity for each fill and the size of the upper bar is the difference of the peak luminosity and average luminosity.

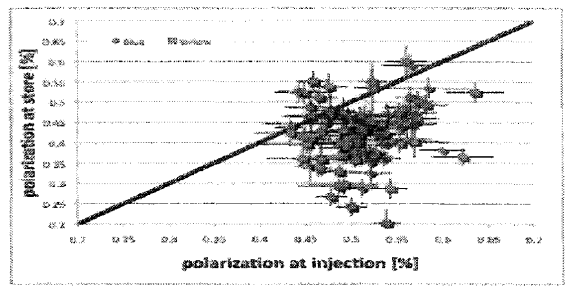

Figure 3: The plot is the polarization measured at store versus the polarization measured at injection using CNI polarimeter #1. Blue and Yellow are the two accelerators of RHIC. All the polarization measurements were done with profile-by-sweep mode, sweeping the target across the beam.

at $Q_y = \frac{11}{16} = 0.6875$, all other higher order snake resonances between $0.67 < Q_y < 0.7$ are benign to beam polarization based on numerical simulations. Beam polarization in RHIC was measured several times per store by a relative carbon polarimeter (CNI polarimeter) based on the Coulomb-nuclear interaction effect [9, 10]. Beam polarization is obtained from measuring the left and right asymmetry normalized by an analyzing power. In general, the analyzing power is a function of beam energy. The RHIC CNI polarimeter analyzing power at 100 GeV was calibrated by the RHIC absolute polarimeter using an H jet target [11].

Average polarization of 42% was achieved at 250 GeV. Fig. 3 shows the polarization measured at injection and at store, and the store polarizations are evidently lower than the polarizations at injection. The analyzing power at 100 GeV was used for these measurements. Preliminary analysis of the RHIC absolute polarimeter using the H jet target indicates that the analyzing power at 250 GeV is very similar to the value at 100 GeV. A number of polarization measurements as a function of beam energy were carried out to identify the location of polarization losses. Fig. 4 shows the polarization measurement as a function of the beam energy. The polarization measurements at injection in Fig. 4 were scaled with the injection analyzing power. All other polarization measurements during the ramp were

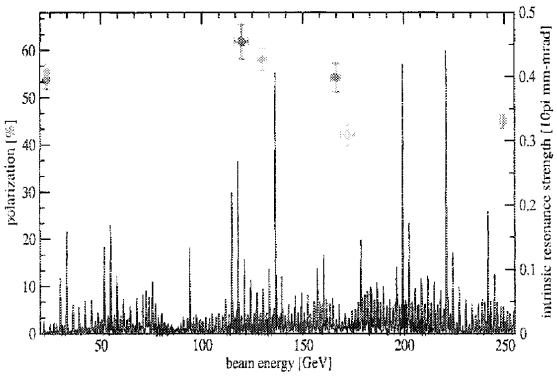

Figure 4: The solid blue circles and yellow diamonds are the measured polarizations of beam in the RHIC Blue ring and Yellow ring. The polarization measurements as function of beam energy are laid on top of the RHIC intrinsic depolarizing resonance strength as shown in Fig. 1 to guide eyes.

calculated with the analyzing power calibrated at 100 GeV. Since the analyzing power of the CNI polarimeter only changes slightly with the beam energy [12], the step-down of polarization around the beam energy of 136 GeV suggests depolarization there. Even though it is difficult to take a polarization measurement between $G\gamma = 381$ and $G\gamma = 422$ due to CNI polarimeter limitations, the polarization step-down between store and before $G\gamma = 381$ shows polarization losses when crossing these two resonances. Fig. 4 also confirms that there is no polarization loss from injection to 100 GeV.

A detailed polarization transmission efficiency of the acceleration as function of vertical betatron tune was carried out to explore the snake resonances as shown in Fig. 5. The snake resonance at $Q_y = 0.7$ is evident for both accelerators. Since the polarization transmission efficiency is between 250 GeV and RHIC injection energy, the $\frac{7}{10}$ resonance in this data represents the combination of the $\frac{7}{10}$ resonance at all the intrinsic resonances. Within the statistics of the polarization measurements, the data from Yellow beam seem to indicate the existence of a snake resonance at $\frac{11}{16}$. The data also show that close to 100% polarization transmission efficiency can be achieved by moving the vertical betatron tune to 0.67. Unfortunately, this can not be achieved due to a very strong orbital resonance at $3Q_y = 2$.

CONCLUSION

After providing polarized proton collisions at a beam energy of 100 GeV for over seven years, polarized protons were first brought into collisions at the maximum beam energy of 250 GeV in 2009. An average beam polarization of 42% was measured at the top energy. A peak luminosity of $122 \times 10^{30}\text{cm}^{-2}\text{s}^{-1}$ was also demonstrated. The polarization measurement as function of beam energy confirmed a

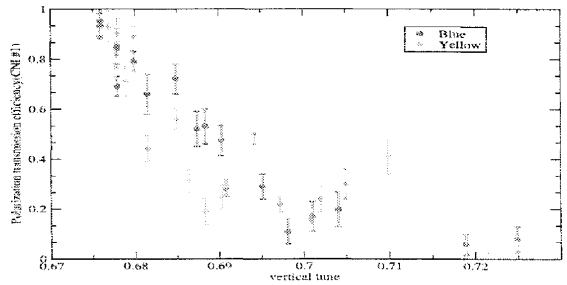

Figure 5: The polarization transmission efficiency in this plot is defined as the ratio of the polarization measured at store to the polarization measured at injection. For these measurements, only the vertical tune from 100 GeV up to 250 GeV was varied. The vertical tune below 100 GeV was kept around 0.68.

partial polarization loss due to the snake resonances around the three strong intrinsic spin depolarizing resonances from 100 GeV to 250 GeV. A detailed scan of polarization transmission efficiency as function of the vertical betatron tune shows that the RHIC operating vertical tune is still too close to the snake resonance at $Q_y = 0.7$. The measurement also suggests that polarization can be preserved if the vertical tune could be placed at 0.675 or below.

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