ACCELERATING POLARIZED PROTONS TO 250 GeV*

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Abstract

The Relativistic Heavy Ion Collider (RHIC) as the first high energy polarized proton collider was designed to provide polarized proton collisions at a maximum beam energy of 250 GeV. It has been providing collisions at a beam energy of 100 GeV since 2001. Equipped with two full Siberian snakes in each ring, polarization is preserved during the acceleration from injection to 100 GeV with careful control of the betatron tunes and the vertical orbit distortions. However, the intrinsic spin resonances beyond 100 GeV are about a factor of two 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 accelerated to the record energy of 250 GeV in RHIC with a polarization of 46% measured at top energy in 2006. The polarization measurement as a function of beam energy also shows some polarization loss around 136 GeV, the first strong intrinsic resonance above 100 GeV. This paper presents the results and discusses the sensitivity of the polarization survival to orbit distortions.

INTRODUCTION

As the world first high energy polarized proton collider, the Relativistic Heavy Ion Collider at Brookhaven has been successfully providing collisions of polarized protons at 100 GeV since 2001. Two pairs of Siberian snakes were employed in the two accelerators of RHIC to keep the spin precession tune Q_s, i.e. the spin precession frequency in unit of orbital revolution frequency, at $\frac{1}{2}$ and independent of beam energy. Hence, the imperfection spin resonances and intrinsic spin resonances are avoided during acceleration and at store [1]. However, due to the vertical betatron oscillation, perturbations from the horizontal focusing fields on the spin motion can still add up coherently and lead to depolarization. This is the mechanism of snake resonances [2, 3] given by

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

Here, m and k are integers and m is the order of the snake resonance [3]. This was also experimentally observed at IUCF [4]. Depending on whether m is an even number or an odd number, the snake resonances are categorized into even order resonances and odd order resonances, respectively. The two snakes in each of the two RHIC accelerators are separated by 180° which provide additional cancellation when m is an even number. Hence, all the even order snake resonances are absent. 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 [3, 5]. All of this greatly reduces the available betatron tune space where polarization can be preserved.

Since 2005, RHIC has successfully accelerated polarized protons up to 100 GeV with no polarization loss by carefully controlling the betatron tunes and the vertical orbit distortion. A record polarization of 65% was reached during the RHIC polarized proton operation in 2006 [6].

However, between 100 GeV and 250 GeV, there are three strong intrinsic spin resonances located at $G\gamma = 3 \times 81 + (Q_y - 12) \sim 260.7$, $G\gamma = 5 \times 81 - (Q_y - 6) \sim 381.3$

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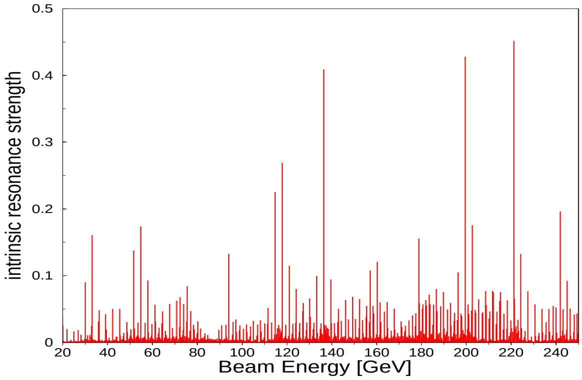

Figure 1: RHIC intrinsic spin resonance strength as a function of beam energy. This is calculated with a 2 m β^* at STAR and PHENIX, 3 m β^* at Brahms, 10 m β^* at PHOBOS and 5 m β^* at the RHIC absolute polarimeter [10].

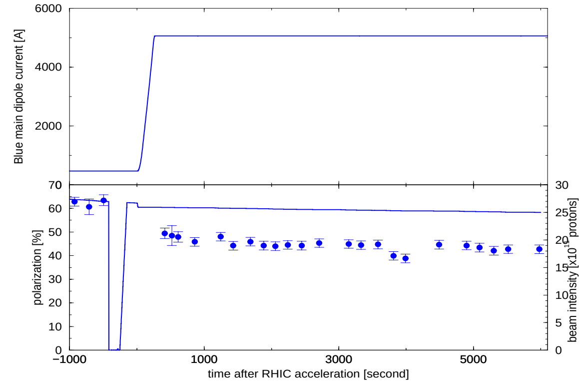

Figure 2: The top plot shows the beam energy in unit of $G\gamma$ as a function of the time from the beginning of the RHIC acceleration. The bottom plot shows the beam current and polarization measured in the Blue ring. The beam polarization at injection is around 65% and beam polarization at store is about 46%.

and $G\gamma = 5 \times 81 + (Q_y - 12) \sim 422.7$ as shown in Fig. 1. These resonances are more than a factor of two stronger than the strong spin resonances below 100 GeV. Since the stronger the intrinsic resonance, the stronger the derived snake resonances, the tolerance on the nearby imperfection resonance, i.e. the vertical closed orbit distortion, is tighter. The numerical simulation shows that the imperfection resonance strength should be below 0.075 to avoid depolarization at these three strong intrinsic resonances [1]. This corresponds to a closed orbit distortion of 0.3 mm rms value. Hence, it is necessary to explore 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.

ACCELERATING POLARIZED PROTONS TO 250 GEV IN RHIC

In 2006, RHIC had its first opportunity to accelerate the polarized protons up its designed store energy at 250 GeV to explore both the polarization issues beyond 100 GeV and luminosity aspect at 250 GeV. Even though the first test of accelerating polarized protons to 205 GeV in 2005 yielded significant polarization at 205 GeV [7], the last strong intrinsic resonance at $G\gamma = 5 \times 81 + (Q_y - 12) \sim 422.7$ was not explored due to the energy limit.

The polarized proton setup for the 250 GeV development is very similar to the setup for the 205 GeV development except that the betatron tunes were kept below 0.7 from injection to store energy during the 250 GeV. Since the Siberian snakes in RHIC are helical dipoles, the amount of spin rotation from the snakes is weakly dependent on the beam energy and the magnet current remains constant during acceleration and store. The beam polarization in RHIC was measured by the relative carbon polarimeter (CNI polarimeter) based on Coulomb-nuclear interaction effect [8, 9]. The beam polarization is obtained from measuring the left and right asymmetry normalized by the analyzing power. In general, the analyzing power is a function of beam energy and the RHIC CNI polarimeter analyzing power at 100 GeV was calibrated by the RHIC absolute polarimeter using H jet target polarimeter [10]. Since it is expected that the analyzing power variation is very small at high energy, the analyzing power at 100 GeV was also at 250 GeV as well as 205 GeV.

The polarized proton beam in one ring was accelerated to 250 GeV and an average 46% polarization was measured at the store energy. Fig. 2 shows the polarization measured at injection and at store.

It is very encouraging to see 46% beam polarization at 250 GeV. However, a depolarization of 30% is also evident. In order to locate where the polarization loss occurs, a polarization measurement as a function of beam energy was carried out. Fig. 3 shows the polarization measurement as a function of the beam energy. Since the analyzing power could change slightly as a function of beam energy, the data in Fig. 3 are presented as the measured raw asymmetry as a function of beam energy. However, it is still reasonable to assume that the analyzing power is a smooth curve of the beam energy [11]. Hence the sudden reduction of the measured asymmetry around beam energy of 136 GeV is evidence of where polarization got loss.

Fig. 3 also shows that there is no polarization loss at the other two spin resonances. As discussed earlier, the depolarization at a spin resonance should be associated with the closed orbit distortion as well as the betatron tune at that time during acceleration. A comparison of the orbit and betatron tune at the other two strong spin resonances seems to suggest the depolarization could be due to the fact that the horizontal betatron tune at this resonance is too close to 0.7, a snake resonance due to coupling [12] as shown in Fig. 4. Unfortunately, there wasn't any time left to explore the effect of orbit distortion as well as the betatron tunes on the beam polarization at this resonance. The discrepancy between the ratio of the polarization at store and at injection of 74.3% and the ratio of the raw asymmetry at store

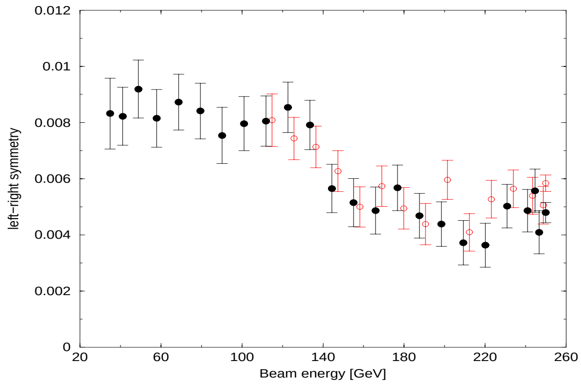

Figure 3: Both data sets in the plot are the polarization measurement as a function of beam energy from two consecutive ramps. Both show a step of left-right asymmetry reduction around 136 GeV where the first strong intrinsic spin resonance beyond 100 GeV at $G\gamma \sim 260.7$.

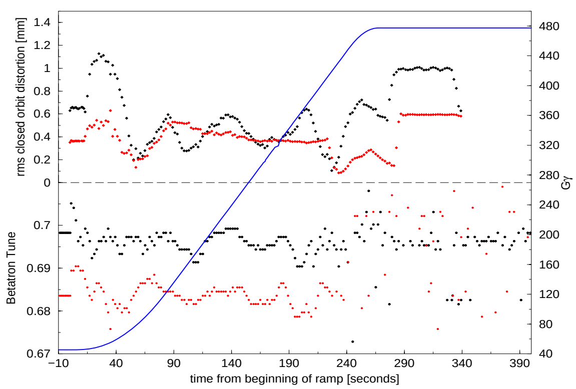

Figure 4: Closed orbit and betatron tune during the RHIC acceleration where the polarization was also measured as a function of beam energy. The three strong spin resonances at $G\gamma = 3 \times 81 + (Q_y - 12) \sim 260.7$, $G\gamma = 5 \times 81 - (Q_y - 6) \sim 381.3$ and $G\gamma = 5 \times 81 + (Q_y - 12) \sim 422.7$ are crossed at 150.7 seconds, 208.7 seconds and 228.7 seconds respectively. The top plot shows the closed orbit as a function of beam energy. The black diamonds are the horizontal closed orbit and red diamonds are the vertical closed orbit. The black dots in the bottom plot are the horizontal betatron tunes and red dots are the vertical betatron tune as a function of beam energy.

and at injection of 65.1% comes from the difference in analyzing power of the RHIC CNI polarimeter at 100 GeV and at injection.

CONCLUSION

Polarized protons were first accelerated to the design store energy of 250 GeV at the end of 2006 RHIC polarized proton operation. Using the 100 GeV analyzing power, an average beam polarization of 46% was measured at the top energy. Two successful polarization measurements as function of beam energy during acceleration were also taken to locate where the polarization was lost. The sudden reduction of raw asymmetry as a function of beam energy shows the depolarization occurs at spin resonance $G\gamma = 3 \times 81 + (Q_y - 12) \sim 260.7$, the first strong resonance after 100 GeV, and polarization was preserved through the rest of the acceleration cycle. A comparison of the closed orbit distortion and betatron tune along the acceleration suggests that the depolarization is due to the snake resonance at 0.7 due to coupling.

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