ACCELERATING POLARIZED PROTONS TO HIGH ENERGY*

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Abstract

High energy polarized proton beams are desired for exploring the proton spin structure as well as other spin dependent measurements. However, depolarizing mechanisms due to the interaction between the spin motion and the magnetic fields challenges accelerating polarized protons to high energy in circular accelerators. Several decades of efforts in developing techniques to preserve polarization to high energy have finally led to the success of the polarized proton program at the Brookhaven Relativistic Heavy Ion Collider (RHIC). Designed to provide polarized proton collisions up to 250GeV, RHIC is equipped with two Siberian snakes to avoid both intrinsic and imperfection depolarizing resonances. Currently, polarization has been preserved up to 100 GeV at RHIC with precise control of orbit and betatron tunes. The polarized protons were first brought into collisions at 250GeV in RHIC in 2009, and depolarizations were observed between 100 GeV to 250 GeV. This presentation reports the progress of RHIC polarized proton program. Strategies of how to preserve the polarization through the RHIC injectors are also presented.

INTRODUCTION

High energy polarized protons are needed for studying proton spin structure as well as other spin dependent physics. However, accelerating polarized protons to high energy is challenged by depolarizing mechanisms in an accelerator. In a circular accelerator, the spin motion is governed by the Thomas-BMT equation [1]

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

where $\vec{S}$ is the spin vector in the particle's rest frame, e and m are, respectively, the electric charge and rest mass of the particle, γ is the Lorentz factor, $G = 1.793$ is the proton anomalous g-factor, $\vec{B}_\perp$ and $\vec{B}_\parallel$ are the transverse and longitudinal components of the magnetic fields in the laboratory frame with respect to the particle's velocity $\vec{\beta}c$, and γ is the relativistic Lorentz factor. Here, Eq. 1 shows that in a perfect planar circular accelerator, the spin vector precesses $G\gamma$ times in one orbital revolution. $Q_s = G\gamma$ is then defined as spin tune.

Equation 1 also shows that the presence of non-vertical magnetic fields due to magnetic field errors, quadrupole misalignments or vertical betatron oscillations kick the spin vector away from vertical direction. When the frequency of the perturbation on the spin motion coincides with the spin precession frequency, the kicks on the spin vector can be coherently added and result in polarization loss, i.e. a depolarizing spin resonance [2].

In general, depending on the source of the spin perturbing magnetic fields, there are two types of spin depolarization resonances. The imperfection spin resonances at $G\gamma = k$ are due to dipole errors and quadrupole misalignments. Here k is an integer. The strength of this resonance is proportional to the size of the vertical closed orbit distortion. The intrinsic spin resonances at $G\gamma = kP \pm Q_y$, on the other hand, are driven by vertical betatron oscillation. Here, P is the super-periodicity of the machine and Q_y is the vertical betatron tune. The stronger the betatron oscillation, the stronger the intrinsic spin resonance.

Figure 1 shows the strength of intrinsic resonances and imperfection resonances as a function of energy in RHIC [3]. A total of 423 imperfection resonances lies between the RHIC injection energy and its designed store energy at 250 GeV, and the higher the beam energy, the stronger the imperfection resonance. The strong intrinsic spin resonances in RHIC are located at $81 \pm (Q_y - 12)$, $81 + (Q_y - 6)$, $2 * 81 + (Q_y - 12)$, $3 * 81 - (Q_y - 12)$ and $5 * 81 \pm (Q_y - 12)$. Clearly, no beam polarization can survive through all these depolarizing resonances.

CHALLENGES IN ACCELERATING POLARIZED PROTONS TO HIGH ENERGY

The polarization change after crossing a resonance depends on the resonance strength as well as how fast the resonance is crossed. For an isolated resonance, the ratio of the polarization after crossing through the resonance P_f to the initial polarization P_i is given by the Froissart-Stora formula [4]

$$P_f = P_i(2e^{-\frac{\pi\epsilon^2}{2\alpha}} - 1) \qquad (2)$$

where $\alpha = \frac{dQ_s}{d\theta}$ is the resonance crossing rate and ϵ is the strength of the spin resonance. Equation 2 shows that for $|\frac{P_f}{P_i}| = 1$, one can either make the resonance strength to zero or cross a resonance very quickly.

Overcome Imperfection Spin Resonance and Intrinsic Spin Resonance

Equation 2 shows that imperfection resonances and intrinsic resonances can be overcome by correcting the closed orbit distortion and fast jumping betatron tune at $G\gamma = kP \pm Q_y$ [2], respectively. Both techniques were

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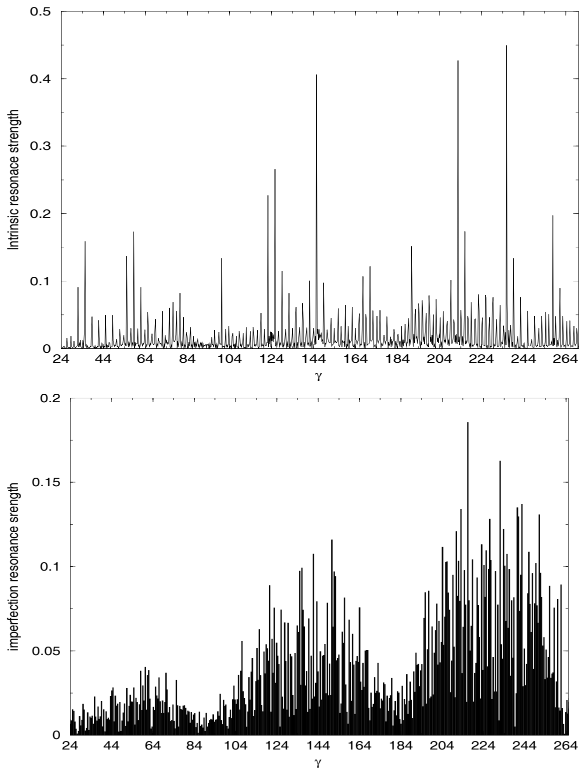

Figure 1: Strength of intrinsic and imperfection spin resonances from injection energy to 250 GeV in RHIC. These are calculated from a RHIC lattice without snakes and spin rotators. The intrinsic spin resonance strength is calculated with a single particle at an emittance of 10π mm-mrad. The imperfection spin resonance strength is calculated with an vertical orbit distortion of 1 mm.

first developed at the ZGS (Zero Gradient Synchrotron) [5], and were also applied to the AGS at BNL. With six fast tune jump quadrupoles and harmonic orbit corrections, polarized protons were accelerated to 22 GeV with 40% polarization in the AGS [6]. However, to achieve this, months of dedicated beam time were required [7].

Hence, new techniques of overcoming depolarizing resonances were required to simplify polarized protons setup. The technique of using a partial Siberian snake [8] to avoid imperfection resonances was first developed at the BNL AGS [9]. This device rotates spin vector around an axis in the horizontal plane by an angle of $\psi < 180^o$. In an accelerator with a partial snake, the spin tune then becomes

$$\cos(\pi \mathrm{Q_s}) = \cos(\mathrm{G}\gamma\pi)\cos(\frac{\psi}{2}) \qquad (3)$$

Equation 3 shows that spin tune, as a function of beam energy, becomes discontinuous at each integer. Hence, all imperfection resonances are avoided. A 5% solenoid snake was installed in the AGS in the mid 1990s to overcome all the imperfection resonances [10].

To overcome strong intrinsic spin resonance, a novel technique of using an RF dipole to induce full spin flip was successfully developed at the AGS [11]. By operating the RF dipole close to the beam betatron oscillation frequency, a coherent betatron oscillation with large amplitude can be excited which forces all particles sample stronger focusing field. This effectively enhances the intrinsic resonance strength and results in full spin flip with regular resonance crossing rate. The advantage of this technique is that the beam emittance can be preserved by energizing the RF dipole adiabatically [12]. After applying this technique in the AGS to obtain full spin flip at the four strong intrinsic resonances $G\gamma = 0 + Q_y$, $G\gamma = 12 + Q_y$ and $G\gamma = 36 \pm Q_y$ together with the 5% snake in the AGS, polarized protons at 24 GeV with 50% polarization was achieved during the RHIC polarized proton operation between 2000 and 2005.

In order to avoid the depolarization due to the weak resonances in the AGS, a dual partial snake scheme was developed in 2006. A 5.9% room temperature helical snake plus a super-conducting helical snake which can provide an maximum strength of 20% at the AGS extraction energy were installed located $\frac{1}{3}$ of the ring apart. With this configuration, spin tune then becomes [13]

$$\cos\pi \mathrm{Q_s} = \cos\mathrm{G}\gamma\pi\cos\frac{\psi_\mathrm{c}}{2}\cos\frac{\psi_\mathrm{w}}{2} - \cos\mathrm{G}\gamma\frac{\pi}{3}\sin\frac{\psi_\mathrm{c}}{2}\sin\frac{\psi_\mathrm{w}}{2}. \qquad (4)$$

Here, ψ_c and ψ_w are the amount of spin rotations of strong super-conducting snake and the 5.9% snake, respectively. Equation 4 implies that not only the spin tune is forbidden in a gap around each integer but also that the width of the gap is modulated at an integer multiple of 3. The gap reaches its maximum width at each integer multiple of 3 where the two snakes are coherently added and otherwise reaches its minimum width when the two snakes are subtracted. Since the AGS has a super-periodicity of 12, all the strong intrinsic resonances are located at the integer multiple of 3 where the spin tune forbidden gap reaches its maximum. Hence, by placing the vertical betatron tune inside the spin tune forbidden gap, neither the imperfection nor the intrinsic spin resonances are crossed during the AGS acceleration. Currently, polarized protons in the AGS reach polarization of 60% with a bunch intensity of 1.5×10^{11} at the AGS extraction energy of 24 GeV [14].

To reach even higher energy polarized protons, it is operationally impossible to individually overcome each depolarizing resonance due to the amount of spin depolarizing resonances during the acceleration. Thanks to the invention of the Siberian snake by Derbenev and Kondratenko in 1976 [15], the polarized proton acceleration to high energies became practical. The Siberian snake is a special device which rotates the spin vector by $180°$ around an axis in the horizontal plane. With this the spin tune becomes energy independent and both imperfection resonances and intrinsic resonances are avoided [15]. In RHIC, two full Siberian snakes [3] located at 180^o apart from each other are used. Each snake rotates the spin vector by 180^o around an axis in the horizontal plane. The spin precession tune Q_s

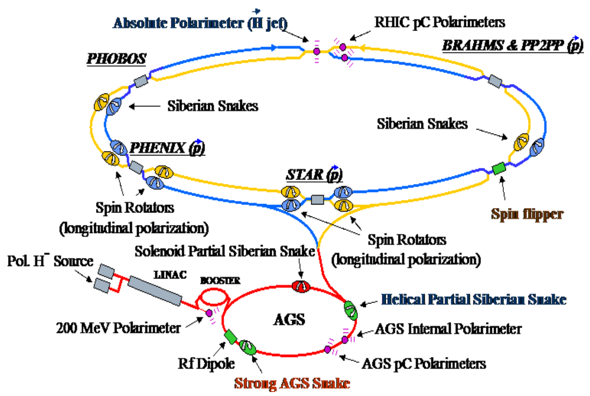

Figure 2: Polarized proton acceleration complex at Brookhaven National Laboratory

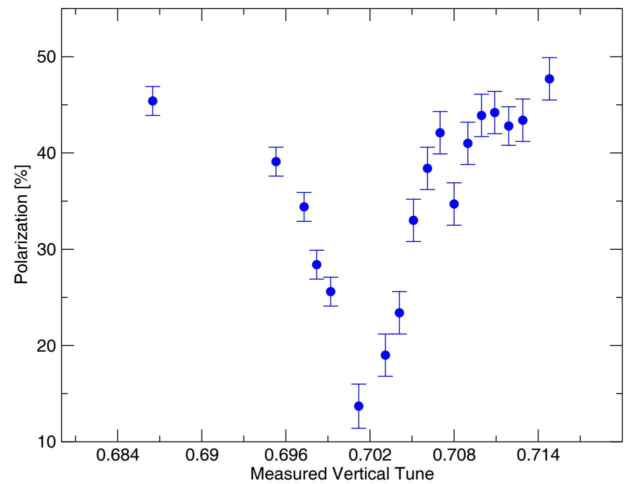

Figure 3: This plot shows the beam polarization as a function of the vertical tune when beam was stored at an energy of $G\gamma = 63$. The data points with vertical betatron tune above 0.7 were taken in the RHIC 2005 operation and the rest of data points were taken during the latest RHIC operation in 2006.

in RHIC is then given by

$$Q_s = \frac{1}{\pi}\Delta\phi \tag{5}$$

where $\Delta\phi$ is the angle between the axes of the two snakes. With the axes of the two snakes perpendicular to each other, the spin precession tune is $\frac{1}{2}$.

Figure 2 is the schematic layout of RHIC polarized proton complex. The collider consists of two circular synchrotrons (Blue ring and Yellow ring). Polarized H^- ion beam from the Optically Pumped Polarized Ion Source (OPPIS) is accelerated to 200 MeV through the linear accelerator (LINAC) and then strip-injected in the Booster where the polarized proton beam is accelerated to a kinetic energy of 1.42 GeV. At the end of each Booster acceleration cycle, the polarized proton beam is injected into the AGS and accelerated to a beam energy of 24 GeV. The local spin rotators at the entrance/exit of the two large detectors (STAR and PHENIX) are to provide longitudinally oriented spin polarized proton beams for the experiments [3].

Snake Resonance

However, even with full snakes, significant polarization can still be lost if the following condition is met near a strong intrinsic spin resonance

$$mQ_y = Q_s + k. \tag{6}$$

Here, m, k are integers, Q_y is the vertical betatron tune and Q_s is the spin precession tune. These are the so called snake resonances [2] and have been experimentally observed at RHIC. Fig. 3 shows the measured beam polarization as a function of beam vertical tune in the Blue ring. The data were taken with beam stored at an energy corresponding to $G\gamma = 63$. The snake resonance at $Q_y = \frac{7}{10}$ is evident.

For RHIC with two full snakes, only the snake resonances at $(2m+1)Q_y = Q_s + k$ exist if the closed orbit is fully corrected. However, both snake errors and imperfections resonances can shift the spin precession tune away from half integer. This in turn not only excites the even order snake resonances at $2mQ_y = Q_s + k$ but also causes each snake resonance to split [2, 18]. This then shrinks the available space for the betatron tune during the acceleration. Hence, precise control of betatron tune to stay away from any snake resonances and minimizing closed orbit distortion are critical in avoiding polarization loss.

Other than the precise control of the betatron tune and closed orbit distortion, it is also very critical to keep the spin tune as close to half integer as possible. In RHIC, there are two sources of spin tune shift. One is error in the angle between the axes of the two snakes, and one is from the horizontal orbital angle at the two snakes [19]. The total spin tune shift away from $\frac{1}{2}$ ΔQ_s is given by

$$\Delta Q_s = \frac{|\Delta\phi|}{\pi} + (1+G\gamma)\frac{Delta\theta}{\pi} \tag{7}$$

For RHIC polarized proton operation, the snake current settings are optimized at RHIC injection by maximizing the beam polarization with betatron tune at 0.745 [20]. The horizontal orbital angle between two snakes in each ring is also corrected to 0.1mrad during acceleration. Currently, RHIC polarized protons reached 100 GeV with negligible polarization loss with the help of tune/coupling feedback [16, 17].

The latest RHIC polarized proton collision at 250 GeV experienced significant depolarization between 100 GeV and 250 GeV due to the strong depolarizing resonances at $G\gamma = 3*81 + Q_y - 12$ and $G\gamma = 5*81 \pm (Q_y - 12)$ which are more than a factor of two stronger than the strong intrinsic spin resonances below 100 GeV. Figure 4 shows the measured asymmetry as a function of beam energy. It clearly shows the depolarization after 100 GeV.

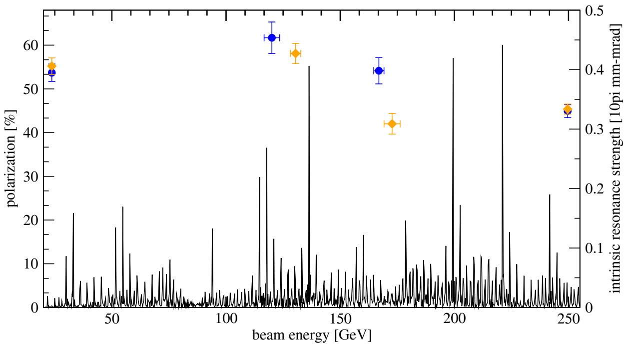

Figure 4: This plot shows the polarization measured as a function of beam energy. Both data consistently show significant polarization losses after 100 GeV. All polarizations were measured with the two relative CNI polarimeters [22]. These two polarimeters were calibrated by the absolute polarimeter in RHIC using a polarized hydrogen target [21] at 100 GeV. The polarization at injection was obtained with the analyzing power obtained at the AGS extraction energy. And the 100 GeV analyzing power was used for all the polarizations beyond injection energy.

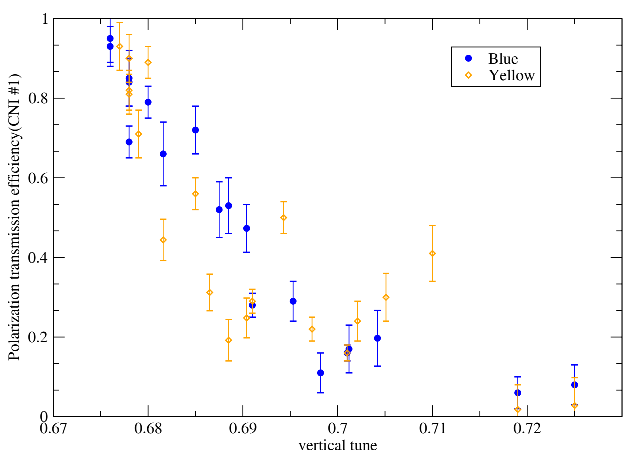

Figure 5: This plot shows the ratio of polarization measured at 250 GeV vs. the polarization at injection, i.e. polarization transmission efficiency, as a function of vertical betatron tune in both rings. The vertical tune was kept constant between 100 GeV to 250 GeV, while the horizontal betatron tune in both rings was set at Fig. 4, all polarizations were measured with the two relative CNI polarimeters.

Figure 5 shows the measured polarization polarization transmission efficiency, i.e. the ratio of polarization at 250 GeV vs. polarization at injection. The depolarization snake resonance at $Q_y = \frac{7}{10}$ is evident. The data in Fig. 5 also shows that the lower the vertical betatron tune away from 0.7, the less polarization loss. 90% polarization can be achieved with vertical betatron tune at 0.675 or lower. Due to the hardware issues, the vertical tune had to be set around 0.68 between 100 GeV and 250 GeV for Physics data taking during the latest RHIC polarized proton operation in 2009. significant polarization deterioration during a typical 8 hour store was also observed with spin rotators on. As a result, polarized proton collisions at 250 GeV with an average polarization of 35% was achieved for the RHIC spin physics program in 2009 [23].

CONCLUSION

Accelerating polarized protons to high energy is challenged by various depolarizing mechanisms driven by magnetic fields from manufacturing errors, misalignments, betatron oscillation and etc. Motivated by the need of having high energy polarized protons to study proton spin structure as well as other spin dependent physics, continuous efforts over the past couple of decades were made in seeking ways to overcome spin depolarizing resonances and preserve polarization to high energy. The early development of overcoming each imperfection resonance by harmonic orbit correction and each intrinsic resonance by fast tune jump quadrupoles in the ZGS led to the first successful acceleration of polarized proton to multi-GeV. Various novel techniques like partial snake for overcoming all imperfection resonances and RF dipole for overcoming strong intrinsic resonances were successfully developed in the AGS. Currently, the AGS employs two partial snakes to avoid all imperfection resonances and intrinsic resonances by placing the vertical tune close to an integer.

The invention of full Siberian snake made it possible to dream for high energy polarized proton colliders like RHIC. With the help of the two Siberian snakes in each of the two accelerators, polarized protons were accelerated to the highest energy of 250 GeV at Relativistic Heavy Ion Collider of BNL. By keeping betatron tunes away from snake resonances as well as precise control of closed orbit distortion, polarization was preserved up to 100 GeV in RHIC. Significant polarization was lost due to the snake resonance at $Q_y = 0.7$ when crossing three strongest intrinsic resonances between 100 GeV and 250 GeV. To preserve the polarization to 250 GeV, RHIC plans to accelerate the polarized protons at vertical betatron tune close to $\frac{2}{3}$ resonance. With further improvement of the AGS dual snake technique to avoid the depolarization from horizontal resonances, RHIC is looking forward to provide higher luminosity polarized proton collisions with a polarization of 70% or greater.

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