

Polarized Proton Collisions at RHIC*

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Abstract

The Relativistic Heavy Ion Collider (RHIC) provides not only collisions of ions but also collisions of polarized protons. In a circular accelerator, the polarization of polarized proton beam can be partially or fully lost when a spin depolarizing resonance is encountered. To preserve the beam polarization during acceleration, two full Siberian snakes were employed in RHIC. In 2002, polarized proton beams were first accelerated to 100 GeV and collided in RHIC. Beams were brought into collisions with longitudinal polarization at the experiments STAR and PHENIX by using spin rotators. Optimizing polarization transmission efficiency and improving luminosity performance are significant challenges. Currently, the luminosity lifetime in RHIC is limited by the beam-beam effect. The current state of RHIC polarized proton program, including its dedicated physics run in 2005 and efforts to optimize luminosity production in beam-beam limited conditions are reported.

INTRODUCTION

In the 1980s, the deep elastic scattering experiments at SLAC and CERN showed that the sum of the three quarks' spin is much smaller than the total proton spin of $\frac{1}{2}$ [1, 2]. This then stimulated efforts to measure the contribution of gluons on the proton spin and study the details of proton spin structure which requires collisions of high energy polarized protons. The Relativistic Heavy Ion Collider (RHIC) is a high energy collider designed to provide not only collisions of heavy ions but also of polarized protons at a maximum energy of 250 GeV. Table 1 lists the design parameters for the polarized proton collisions in RHIC [3].

The polarized proton injector chain for RHIC consists of a polarized H^- ion source, a 200 MeV Linear acceleration

Table 1: RHIC design parameters for polarized proton operation

injection energy (GeV)	24.3
store energy (GeV)	250
protons per bunch	2×10^{11}
bunches per ring	111
normalized emittance (mm-mrad)	20π
beta* (m)	1.0
peak luminosity ($\text{cm}^{-2}\text{s}^{-1}$)	1.5×10^{31}
average polarization	70%

tor (LINAC), a Booster and the Alternating Gradient Synchrotron (AGS). Fig. 1 is the layout of the polarized proton acceleration complex at Brookhaven National Laboratory. The polarized H^- beam from the Optically Pumped Polarized H^- Ion Source (OPPIS) first gets accelerated to 200 MeV by the LINAC. The H^- beam is then stripped and injected into Booster, a fast cycling synchrotron. At the end of each Booster acceleration cycle, the polarized proton beam is injected into the AGS at an energy of 2.35 GeV and accelerated to 24.3 GeV.

RHIC also employs local spin rotators at the entrance/exit of the two large detectors (STAR and PHENIX) to provide longitudinally spin oriented polarized proton beams for the experiments. At the entrance of the detector, a spin rotator rotates the spin vector by 90 degrees into the longitudinal direction and then rotates the spin vector back to vertical at the exit of the experiment. The polarization in RHIC is measured on-line by the Coulomb Nuclear Interaction (CNI) polarimeter [4]. The H^- jet polarimeter was installed in 2004 to calibrate the CNI polarimeter [5].

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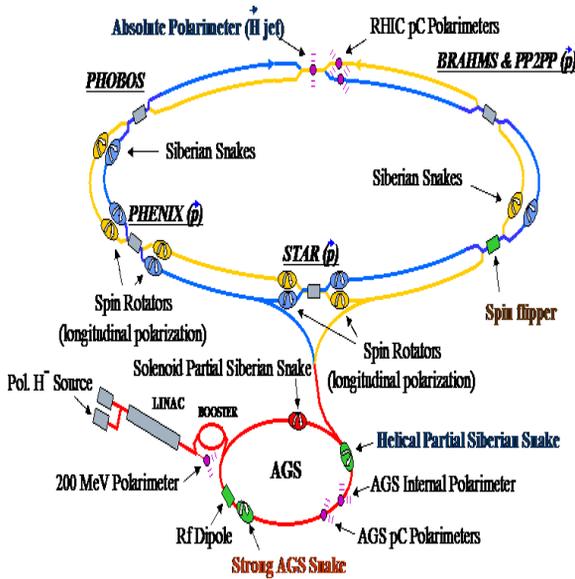


Figure 1: Polarized proton acceleration complex at Brookhaven National Laboratory

POLARIZED PROTON SETUP IN RHIC AND ITS INJECTORS

Spin dynamics

During the entire journey from OPPIS to the final store energy of RHIC, polarized proton beam is accelerated in three circular synchrotrons. In general, the spin motion in a circular accelerator is governed by the Thomas-BMT equation [6]

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

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, \vec{B}_\perp and \vec{B}_\parallel are the transverse and longitudinal components of the magnetic field in the laboratory frame with respect to the particle's velocity βc , and γ is the relativistic Lorentz factor. In a perfect circular accelerator, the spin vector precesses around the guiding magnetic field direction at a tune of $G\gamma$. The spin precession tune is defined as the number of precessions per one orbital revolution. In reality, because of magnetic field errors, quadrupole misalignments, and horizontal magnetic field from quadrupoles due to betatron oscillations, the spin precession is perturbed and can be kicked away from vertical direction if the perturbation of the spin motion resonates with the spin precession tune.

In general, there are two types of spin depolarization resonances, imperfection resonances at $G\gamma = k$ and intrinsic spin resonances at $G\gamma = Q_y \pm kP$. Here, Q_y is the vertical betatron tune, k is an integer and P is the super-periodicity of the machine. The imperfection spin resonance is driven by the vertical close orbit distortion. The intrinsic spin resonance arises from the betatron oscillation and the strength

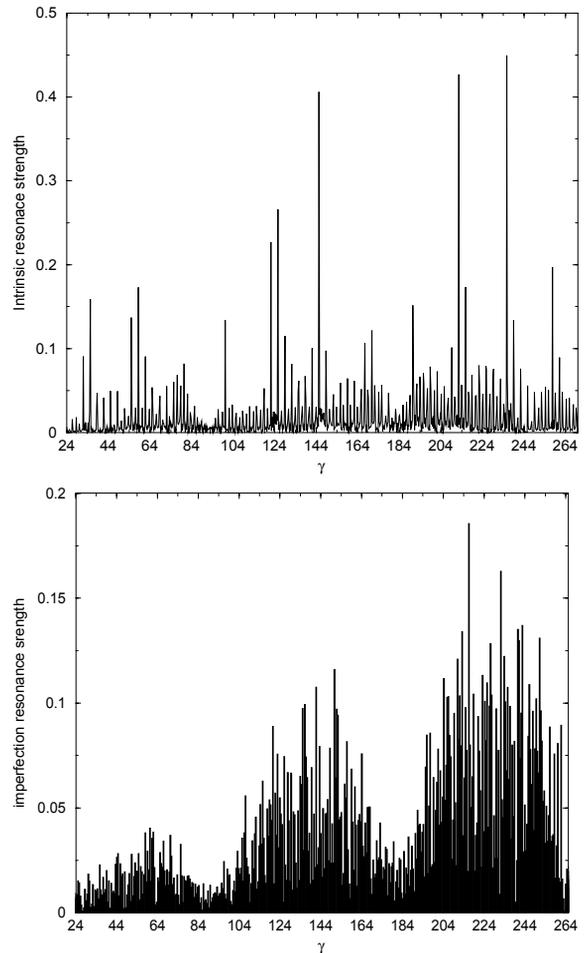


Figure 2: strength of intrinsic and imperfection spin resonance strength from injection energy to 250 GeV. They are the calculations of RHIC lattice without snakes and spin rotators. The intrinsic spin resonance strength is calculated with a single particle at an emittance of 10π mm-mrad. The imperfection spin resonance strength is calculated with an rms vertical orbit distortion of 1mm.

is linearly proportional to the size of the betatron oscillation amplitude. Fig. 2 shows the strength of intrinsic resonance and imperfection resonance as a function of energy in RHIC. It is clear that the higher energy, the stronger the spin depolarization resonance.

Polarized proton setup in injectors

In Booster, the vertical betatron tune is set above the beam extraction energy, and the only spin depolarized resonances the polarized proton beam sees are the two imperfection spin resonances at $G\gamma = 3$ and 4. The imperfection spin resonances in the Booster are not strong and can all be fully corrected by using the vertical harmonic correctors [7]. Hence, Booster is spin transparent.

The acceleration of the polarized proton beam in the AGS on the other hand encounters a total of 42 imperfection spin resonances. Since the AGS has a super-periodicity

of 12, there are only seven intrinsic spin resonances before the extraction energy. Four of them are strong resonances which can cause full polarization loss or partial spin flip with the regular AGS polarized proton ramp rate [7]. Currently, a 5% partial snake is employed to preserve the beam polarization through all the imperfection spin resonances [8, 9]. An rf dipole, which drives the beam at the neighborhood of the betatron frequency, is used to induce a full spin flip at the four strongest intrinsic spin resonances [10]. However, because the three weak resonances are not corrected and imperfection of spin flipping with the rf dipole due to the lack of its strength, the best polarization transmission efficiency in the AGS is around 80%.

Polarized proton setup in RHIC

In RHIC, in order to preserve the polarization during the acceleration, two full Siberian snakes [3] located at 180° apart from each other are used. Each snake rotates the spin vector by 180° around an axis in the horizontal plane. The spin precession tune Q_s is defined as

$$Q_s = \frac{1}{\pi} \Delta\phi \quad (2)$$

where $\Delta\phi$ is the angle difference between the precession axes of the two snakes. With the axes of the two snakes perpendicular with each other, the spin precession tune is $\frac{1}{2}$. However, even with full snakes, significant polarization can still be lost if the following condition is met near a strong intrinsic spin resonance:

$$mQ_y = Q_s + k. \quad (3)$$

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 resonance [6]. 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 imperfection 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. This then shrinks the available space for the betatron tune during the acceleration. Hence, precise control of tune and orbit distortion are very critical to the polarized proton operation in RHIC.

RHIC POLARIZED PROTON PERFORMANCE

Luminosity performance

RHIC started to provide polarized proton collisions at 100 GeV for experiments since 2002. The first RHIC polarized proton run in 2002 achieved a peak luminosity of $2 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$ with collisions at four experiments. The experience of 2003 run showed that beam-beam interactions was the limiting factor on the luminosity performance [11]. Since the beam-beam driven non-linear

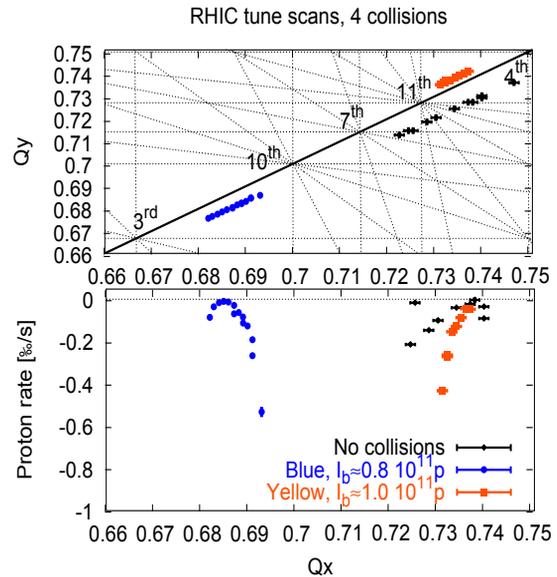


Figure 3: RHIC tune scans in the presence of four collisions. The top plot shows the working points with the location of the orbital resonance marked. The bottom plot shows the measured lifetime as a function of the working point.

resonances are very sensitive to the working point, a detailed study after the run found either working point of (0.735, 0.73) or (0.69, 0.685) should provide wider tune space with beam-beam than the 2003 run working point of (0.235, 0.225) [12].

Both working points were studied in detail during the RHIC polarized proton engineering run in 2004. Fig 3 shows the beam lifetime at the neighborhood of the two working points. Both show a similar tune width in the presence of beam-beam. Table 2 lists the results of the working points which were studied. RHIC polarized proton run in

Table 2: RHIC working points

operation year	β^* (m)	Q_x, Q_y	available tune space with beam-beam	peak luminosity [$\text{cm}^{-2} \text{s}^{-1}$]
2002	3.0	0.235, 0.225	0.005	2×10^{30}
2003	1.0	0.235, 0.225	0.005	6×10^{30}
2004	1.0	0.735, 0.730	0.007	10×10^{30}
2005	1.0	0.690, 0.685	0.007	10×10^{30}

2005 is setup with the working point at (0.73, 0.72) during the acceleration and (0.69, 0.685) at store and a peak luminosity of $10 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$ has been achieved as well.

Fig. 4 shows a typical polarized proton store. The luminosity lifetime is 18 hours and average polarization over the store is above 45%.

Polarization performance

From the RHIC injection energy to its current store energy (100 GeV), there are four strong intrinsic spin reso-

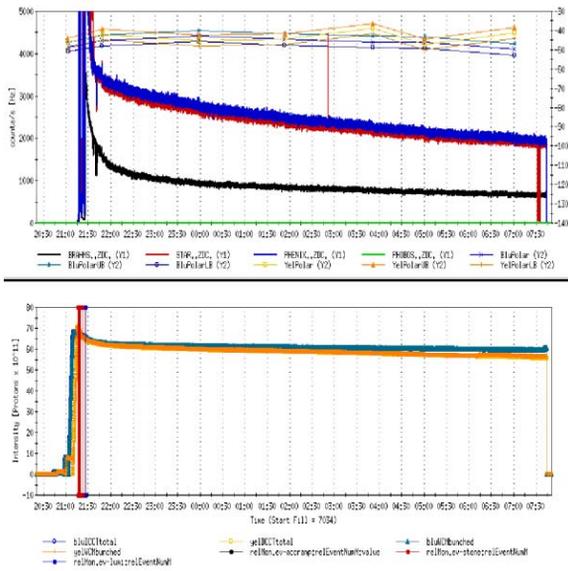


Figure 4: A typical store of polarized protons during the RHIC operation in 2005. The luminosity lifetime is 18 hours. The bottom plot shows the beam current across the store. The top plot shows the luminosity and polarization through the store.

nances at $93 - Q_y$, $69 + Q_y$, $75 + Q_y$ and $150 + Q_y$. To avoid polarization loss, it is required to place the RHIC working point in a window free of snake resonance. Even with two full snakes, an imperfection resonance due to the vertical closed orbit distortion can overlap with an intrinsic resonance and induce even order snake resonance which narrows down the available tune space. Thus, good control of the work point and vertical orbit is very critical for the RHIC operation.

The 2003 working point (0.23,0.22) was chosen to avoid the snake resonances at $Q_y = \frac{1}{2} \times \frac{1}{2}$ and $Q_y = \frac{3}{7} \times \frac{1}{2}$. The working point (0.73,0.72) in 2004 and 2005 was chosen to avoid the snake resonances at $Q_y = \frac{3}{2} \times \frac{1}{2}$ and $Q_y = \frac{7}{5} \times \frac{1}{2}$ [13]. Fig. 5 shows a typical plot of the RHIC tune in Blue ring along the ramp. The swing from working point (0.73,0.72) down to below 0.7 during the ramp is because the polarized proton run in 2004 showed that the working point at (0.695,0.68) improved polarization lifetime at store significantly. However, it is impossible to inject beam into RHIC with this working point because of the 3rd order resonance driven by the sextupole component in the main dipoles.

Table. 3 lists the achieved polarization at RHIC injection and at RHIC store for the operation in 2003, 2004 and 2005. All the RHIC polarization measurements at injection were done with the analyzing power measured using extracted AGS polarized proton beam at 22 GeV/c [?]. The same analyzing power was applied to all the RHIC store polarization measurements except the measurements in 2005. The polarization measurements at store in 2005 use the analyzing power calibrated by the H Jet target in 2004 [5].

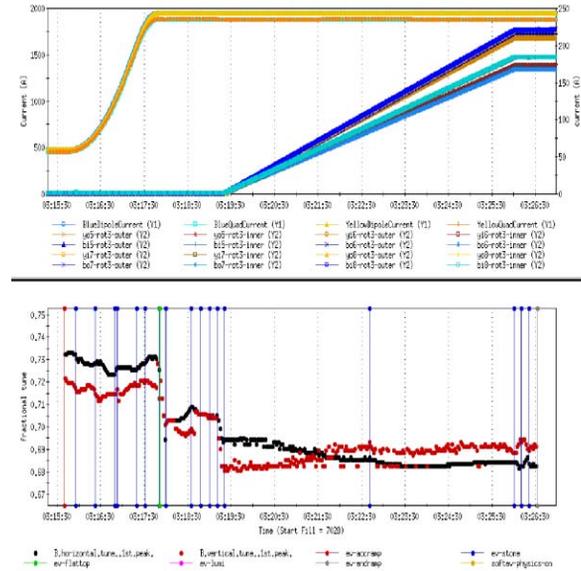


Figure 5: The top plot shows the RHIC main dipole and quadrupole current as well as the rotator current during the ramp. The lower plot shows the horizontal and vertical betatron tune during the ramp.

Table 3: RHIC achieved polarization

Year	Q_x, Q_y	injection polarization	average store polarization	bunch intensity $\times 10^{11}$	polarization direction at STAR, PHENIX
2002	0.23,0.22	30%	25%	0.7	Transverse
2003	0.23,0.22	40%	30%	0.7	Longitudinal
2004	0.73,0.72	50%	45%	0.7	Longitudinal
2005	0.73,0.72	55%	50%	1.0	Longitudinal

In reality, the available tune window can be significantly smaller because the spin precession tune deviates from half integer. Hence, during the RHIC polarized proton operation in 2003, 2004 and 2005, snake current scans were done to make the spin precession tune as close to the half integer as possible [13]

The increase of the polarization at injection from 2003 to 2004 is contributed to the increase of the achieved polarization in the AGS. The increase was due to the warm partial snake which significantly reduced the amount of polarization losses at the coupling spin resonances due to the linear coupling of horizontal and vertical betatron oscillations.

CONCLUSION

The Relativistic Heavy Ion Collider at Brookhaven National Laboratory is the first high energy polarized proton collider. It provides polarized proton collisions with an average polarization of 45% or greater. This provides an opportunity to study the details of the proton structures. With the commissioning of the AGS cold snake, RHIC is looking forward to provide high peak luminosity polarized proton collisions with a polarization of 70% or greater.

The challenge for future polarized proton collisions at RHIC lies in two aspects. The first is to preserve the polarization beyond 100 GeV. Fig. 2 shows that the intrinsic spin resonance strength is a factor of 3 higher than below 100 GeV. Precise orbit control as well as betatron tune control will be very critical for keeping away from the snake resonances. Besides beam-beam effects which limits the bunch intensity, RHIC luminosity is currently also limited by dynamic pressure rises [14]. To mitigate the pressure rise effects, a number of counter measures are pursued. All bakable elements are baked, and most of the warm beam pipes are replaced with NEG coated pipes. In the cold regions, more pumps are installed to reduce the pressure before the cool-down begins, resulting in a smaller number of molecular layers under cold conditions. Since 2004, optimized bunch patterns were used to allow arbitrary number of bunches that are distributed close to uniformly around the circumference.

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