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Accelerating Polarized Protons to High Energy

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Abstract. The Relativistic Heavy Ion Collider (RHIC) is designed to provide collisions of high energy polarized protons for the quest of understanding the proton spin structure. Polarized proton collisions at a beam energy of 100 GeV have been achieved in RHIC since 2001. Recently, polarized proton beam was accelerated to 250 GeV in RHIC for the first time. Unlike accelerating unpolarized protons, the challenge for achieving high energy polarized protons is to fight the various mechanisms in an accelerator that can lead to partial or total polarization loss due to the interaction of the spin vector with the magnetic fields. We report on the progress of the RHIC polarized proton program. We also present the strategies of how to preserve the polarization through the entire acceleration chain, i.e. a 200 MeV linear accelerator, the Booster, the AGS and RHIC.

Keywords: polarized protons, acceleration, spin
PACS: 41.75.Ak, 07.77.+p, 29.27.Bd, 29.27.Hj

INTRODUCTION

In the quest to understand the proton spin structure, experiments desire to investigate the collisions of polarized protons. In addition to all the issues that any high energy collider has to face in order to achieve high luminosity, the challenge for polarized proton collisions is to maintain the beam polarization throughout the acceleration and during collision. In general, the depolarization in an accelerator is caused by the perturbation from the magnetic field errors on the spin precession around the guiding magnetic field. In a circular accelerator, the spin motion is governed by the Thomas-BMT equation [1]

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

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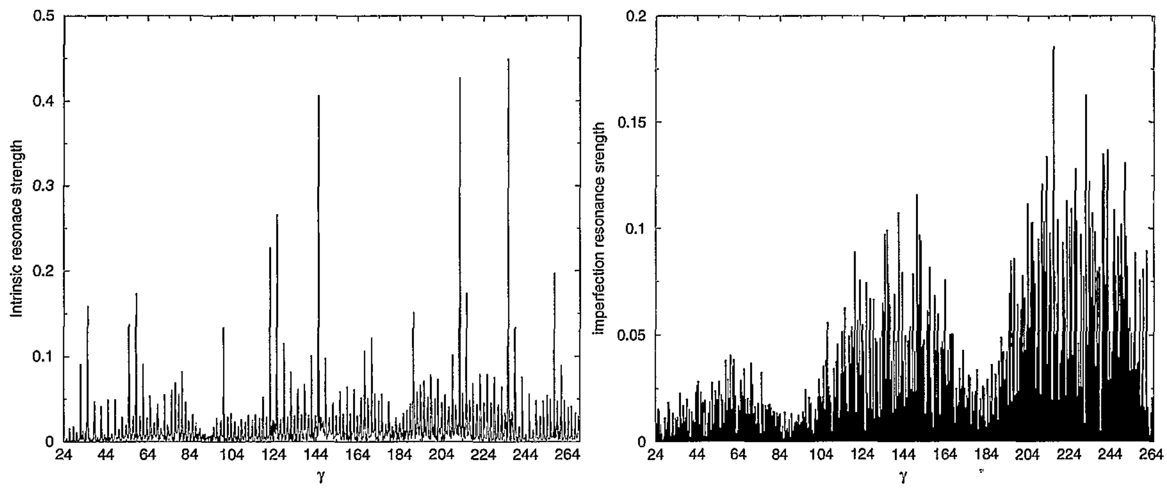

FIGURE 1. Strength of intrinsic and imperfection spin resonances from injection energy to 250 GeV. These are calculated from a RHIC lattice without snakes and spin rotators. The intrinsic spin resonance strength is calculated with a single particle at an emittance of 10π mm-mrad. The imperfection spin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

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 an accelerator with only the guiding dipole field, the spin vector precesses $G\gamma$ times in one orbital revolution. $Q_s = G\gamma$ is then defined as spin tune.

In reality, because of magnetic field errors, quadrupole misalignments and vertical betatron oscillations, the spin precession is perturbed. When the frequency of the perturbation on the spin motion coincides with the spin precession frequency, the spin vector gets resonantly kicked away from vertical direction and a spin resonance occurs [2].

In general, depending on the source of the spin perturbing magnetic fields, there are two types of spin depolarization resonances. Machine imperfections like 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 oscillation, on the other hand, makes particles to sample the horizontally oriented focusing fields and drives 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. Fig. 1 shows the strengths of intrinsic resonances and imperfection resonances as a function of energy in RHIC, the higher the energy, the stronger the spin depolarization resonance.

The amount of depolarization after crossing a resonance is a function of the resonance strength as well as the speed of resonance crossing. 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 [3]

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

where $\alpha = \frac{dQ_s}{d\theta}$ is the resonance crossing rate and ε is the strength of the spin resonance. Eq. 2 clearly shows that for $|\frac{P_f}{P_i}| = 1$, one can either make the resonance strength to zero or cross a resonance very quickly. For imperfection resonances, the resonance strength is proportional to the amplitude of the closed orbit distortion, and can be significantly reduced with a particular setting of dipole correctors magnets. For intrinsic resonances, the strength is proportional to the amplitude of the betatron oscillation and the resonance can be overcome by a fast jump of the betatron tune.

Both, the technique of using vertical harmonic orbit correction to overcome imperfection resonances and the technique of using tune-jumps to cross intrinsic spin resonances have been first developed at the ZGS (Zero Gradient Synchrotron) [4]. New techniques of using a 5% partial Siberian snake to avoid imperfection resonances and using an rf dipole to induce adiabatic full spin flip at a strong intrinsic spin resonance were also successfully developed at the AGS [5, 6, 7, 8]. However, it is still operationally impractical to apply these techniques to high energy polarized proton accelerators like RHIC due to the amount of spin depolarizing resonances during the acceleration [9]. Thanks to the invention of the Siberian snake by Derbenev and Kondratenko in 1976, 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 [10].

POLARIZED PROTON ACCELERATION IN RHIC AND ITS INJECTORS

The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory 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 [11].

TABLE 1. RHIC design parameters for polarized proton operation

injection energy (GeV)	24.3	beta* (m)	1.0
store energy (GeV)	250	average luminosity ($cm^{-2}s^{-1}$)	150×10^{30}
protons per bunch	2×10^{11}	average polarization	70%
bunches per ring	111	normalized emittance (mm-mrad)	20π

The collider consists of two circular synchrotrons (Blue ring and Yellow ring) laying side by side as shown in Fig. 2. 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

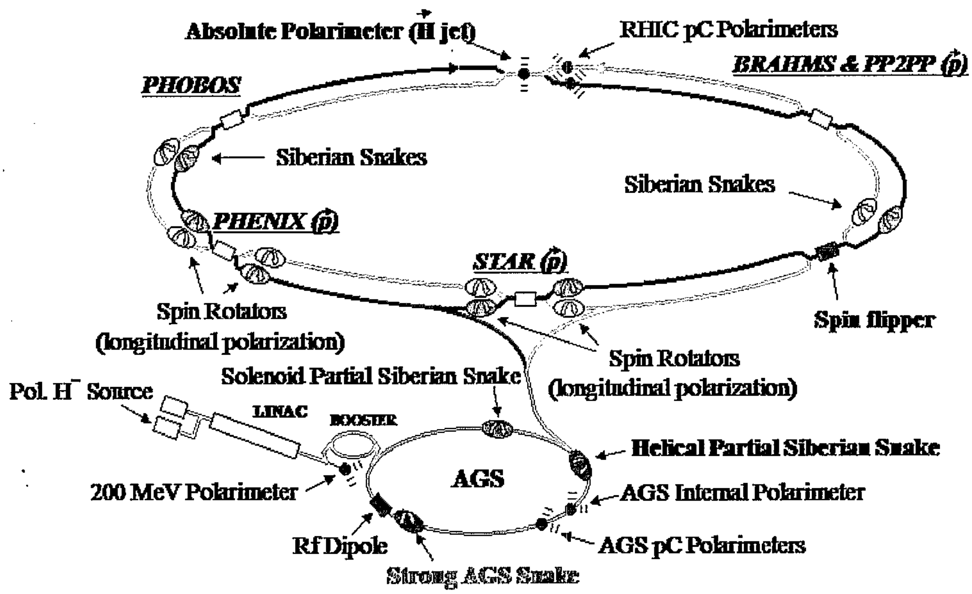

FIGURE 2. Polarized proton acceleration complex at Brookhaven National Laboratory

cycle, the polarized proton beam is injected into the AGS and accelerated to a kinetic energy of 23 GeV.

The acceleration of polarized H^- ion beam in LINAC is spin transparent. Special setups are needed for the polarized proton acceleration in the chain of circular accelerators like the Booster, the AGS and RHIC.

Booster polarization setup

As a low energy machine, the spin resonances in the Booster are in general weak. The intrinsic spin resonance in Booster is avoided by setting its vertical betatron tune at 4.7, higher than the beam extraction energy ($G\gamma = 4.5$). The only spin depolarizing resonances the polarized proton beam sees are the two imperfection spin resonances at $G\gamma = 3$ and 4. These two imperfection spin resonances in the Booster can be fully corrected by using the vertical harmonic correctors [12], and then the Booster becomes spin transparent.

AGS polarization setup

The polarized proton beam in the AGS on the other hand encounters a total of over 40 imperfection spin resonances during the acceleration. Since the AGS has a superperiodicity of 12, there are only seven intrinsic spin resonances. Four of them are strong resonances which can cause full polarization loss or partial spin flip with the regular AGS polarized proton ramp rate [12]. Before 2006, the AGS employed a 5% partial snake to preserve the beam polarization through all the imperfection spin resonances [12] plus an rf dipole, which drives the beam at the neighborhood of the betatron frequency, to induce a full spin flip at the four strongest intrinsic spin resonances [8]. 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 was around 76%. During the RHIC 2006 run, AGS used 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 to overcome all the imperfection and intrinsic spin resonances. The two snakes are located $\frac{1}{3}$ of the ring apart and yield a spin tune as [13]

$$\cos\pi Q_s = \cos G\gamma\pi\cos\frac{\psi_c}{2}\cos\frac{\psi_w}{2} - \cos G\gamma\frac{\pi}{3}\sin\frac{\psi_c}{2}\sin\frac{\psi_w}{2}. \qquad (3)$$

Here, ψ_c and ψ_w are the amount of spin rotations the strong super-conducting snake and the 5.9% snake provides, respectively. Eq. 3 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. During the latest RHIC polarized proton operation in 2006, the setup of running the cold snake at a strength of 10% plus the 5.9% warm snake yielded a polarization of 65% with a bunch intensity of 1.5×10^{11} at the AGS extraction energy. The vertical betatron tune was set to 8.98 and higher [14].

RHIC polarization setup

In RHIC, in order to preserve the polarization during the acceleration, two full Siberian snakes [11] 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 is defined as

$$Q_s = \frac{1}{\pi}\Delta\phi \qquad (4)$$

where $\Delta\phi$ is the angle difference between the precession axes of the two snakes. With the axes of the two snakes perpendicular to 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:

$$mQ_y = Q_s + k. \qquad (5)$$

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

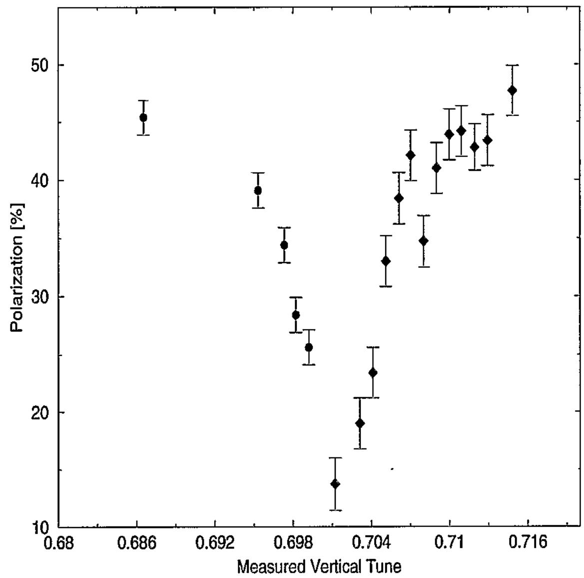

FIGURE 3. This plot shows the beam polarization as a function of the vertical tune when beam was stored at an energy of $G\gamma = 63$. The data points with vertical betatron tune above 0.7 are taken in the RHIC 2005 operation and the rest of data points are taken during the latest RHIC operation in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

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 visible.

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, 16]. This then shrinks the available space for the betatron tune during the acceleration. Hence, precise control of tune and orbit distortion are critical.

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.

A total of three polarimeters using the Coulomb-Nuclear Interference effect 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 [17], and measures the asymmetry of recoil protons from the elastic collisions off the polarized hydrogen jet target with a polarization of $92.4 \pm 1.8\%$. 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 [18]. The beam polarization is obtained from the measured asymmetry normalized by the analyzing power. The carbon polarimeter analyzing power at 100 GeV was calibrated with the H jet polarimeter in RHIC in 2004.

RHIC POLARIZED PROTON PERFORMANCE

From the RHIC injection energy to its current store energy (100 GeV), there are four strong intrinsic spin resonances 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 reduces the available tune space. Thus, good control of the work point and vertical orbit is very critical for the RHIC operation.

Currently, RHIC polarized protons are accelerated to the stored energy at the working point of (0.73,0.72) to avoid the snake resonances at $Q_y = \frac{3}{2} \times \frac{1}{2}$ and $Q_y = \frac{7}{5} \times \frac{1}{2}$. The working point is then swung down to (0.695,068) favored for the luminosity lifetime as well as the polarization lifetime [19]. This working point swing is necessary because it is difficult to inject beam with the working point due to the 3^{rd} order resonance driven by the sextupole component in the main dipoles [19].

Table. 2 lists the achieved RHIC performance from 2002 to 2006.

TABLE 2. RHIC achieved performance

Year	collision points	β^* [m]	number of bunches	bunch intensity $\times 10^{11}$	peak lumi- -nosity $\times 10^{30}$ $cm^{-2}s^{-1}$	average polarization at store[%]
2002	4	3	55	0.70	2.0	15
2003	4	1	55	0.70	6.0	35
2004	4	1	56	0.70	6.0	46
2005	3	1	106	0.90	10.0	47
2006	2	1	111	1.35	35.0	65

The significant increase of polarization and luminosity from 2005 to 2006 is mainly due to the success of the dual partial snake scheme in the AGS. This technique not only improved the polarization transmission efficiency but also allowed higher bunch intensities without compromising the beam polarization [14].

Other than the precise control of the betatron tune and closed orbit distortion for the polarized proton acceleration in RHIC [15], it is also very critical to optimize the snake current settings to make the spin precession tune as close to the half integer as possible. Any deviation of the spin tune from the half integer results in a reduction of the available window for the betatron tune to avoid snake resonances [20].

During the 2006 polarized proton run, the polarized protons were also accelerated to the maximum design energy of 250 GeV for the first time to explore the depolarizing resonances between 100 GeV and 250 GeV during which the three predominant intrinsic spin resonances at $G\gamma = 243 + Q_y - 12$, $G\gamma = 405 - Q_y + 12$ and $G\gamma = 405 + Q_y - 12$ are more than a factor of two stronger than the strong intrinsic spin resonances below 100 GeV. Fig. 4 shows the measured polarization at 250 GeV using the 100 GeV analyzing power. The beam polarization at injection was around 65% and the polarization at store averaged around 45%. Some depolarization is evident.

The polarization was measured as function of beam energy during the acceleration

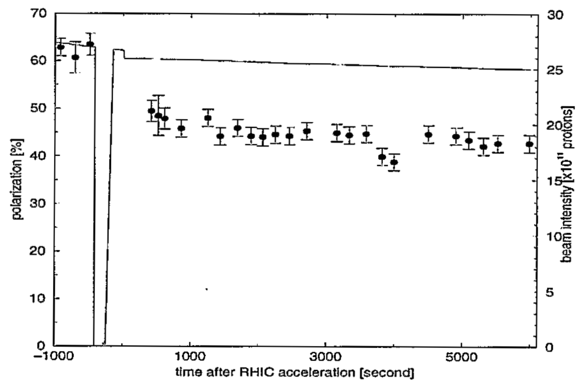

FIGURE 4. This plot shows the beam polarization at injection as well as at store in the Blue ring. A total of 6 bunches of polarized protons were accelerated in the Blue ring. The beam was stored at 250 GeV for the polarization measurement as a function of betatron tunes. The solid line is the total beam intensity as a function of time from the beginning of the ramp. The solid dots are the measured beam polarization.

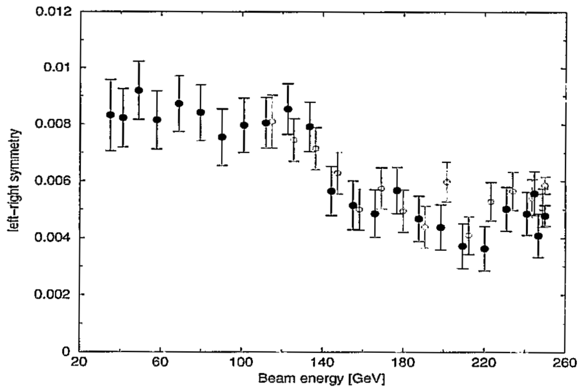

FIGURE 5. This plot shows the polarization measurement as a function of beam energy in the Blue ring for two consecutive ramps. Both data consistently show the depolarization around 136.5 GeV.

to identify the location of depolarization. Fig. 5 shows the measured asymmetry as a function of beam energy. It clearly shows the depolarization occurs at the sharp step around 136.5 GeV, the first strong intrinsic resonance at $G\gamma = 243 + Q_y - 12$ after 100 GeV.

CONCLUSION

Accelerating polarized protons to high energies provides an unique opportunity to study the details of the proton spin structure. As the world's first and only high energy polarized proton collider, the Relativistic Heavy Ion Collider at Brookhaven National Laboratory has achieved 65% beam polarization at 100 GeV with a peak luminosity of $35 \times 10^{30} cm^{-2} s^{-1}$. With further improvement of the AGS dual snake technique to avoid the depolarization from horizontal resonances, RHIC is looking forward to provide higher 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. 1 shows that the intrinsic spin resonance strength is a factor of two stronger than those below 100 GeV. Precise orbit control as well as betatron tune control will be very critical for staying away from the snake resonances. Currently, RHIC luminosity is limited by beam-beam effects [21, 22]. At its current working point for store (0.69, 0.685), it was found that the third order betatron resonance at $3Q_x = k$ limits the beam and luminosity lifetime. Here, k is integer. For further luminosity improvements, a resonance correction is investigated together with the correction of non-linear chromaticity.

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REFERENCES

1. L. H. Thomas, Phil. Mag. 3, 1 (1927); V. Bargmann, L. Michel, V. L. Telegdi, Phys, Rev. Lett. 2, 435 (1959).
2. S. Y. Lee, *Spin Dynamics and Snakes in Synchrotrons*, World Scientific, Singapore, 1997.
3. M. Froissart and R. Stora, Nucl. Instrum. Methods Phys. Res. 7, 297 (1960).
4. D. L. Adams *et al.*, Phys. Lett. B276, 531 (1992).
5. Ya. S. Derbenev *et al.*, Particle Accelertors, Vol. 8, pp-115-118, (1978).
6. T.Roser, *Partial Siberian Snake Test at the Brookhaven AGS*, in High Energy Spin Physics: 10th International Symposium, ed. T.Hasegawa, et al., Nagoya, Japan, 1992, (Univesal Academic Press, Inc.,1992), p.429.
7. H. Huang, *et al.*, *Preservation of Proton Polarization by a Partial Siberian Snake*, Physical Review Letters 73, 2982(1994).
8. M. Bai *et al.*, *Overcoming Intrinsic Spin Resonances with an rf Dipole*, Physical Review Letters 80, 4673(1998).
9. F. Z. Khiari *et al.*, *Acceleration of polarized protons to 22GeV/c and the measurement of spin-spin effects in PP PP, Phys. Rev. D 39, 45-85*, (1989).
10. Ya. S. Derbenev, A. M. Kondratenko, Sov. Phys. Dokl. 20, 562 (1976).
11. I. Alexseev *et al.*, *Design Manual - Polarized Proton Collider at RHIC*, 1997.
12. H.Huang, *et al.*, *Polarized Proton Beam in the AGS*, 13th International Symposium on High Energy Spin Physics, Protvino, (September,1998).
13. T. Roser, *et al.*, *Acceleration of polarized beams using multiple strong partial siberian snakes*, proceedings of Spin2004, Trieste, Italy, 2004.
14. H. Huang, *et al.*, *Polarized Proton Acceleration in the AGS with Two Helical Partial Snakes*, proceedings of Spin2006, Kyoto, Japan, 2006.
15. V. Ptitsyn, *et al.*, *RHIC Performance with Polarized Protons in Run-6*, proceedings of Spin2006, Kyoto, Japan, 2006.
16. S. R. Mane, *A critical analysis of the conventional theory of spin resonances in storage rings*, 677-706, Nuclear Instruments and Methods in Physics Research A 528 (2004).
17. H. Okada *et al.*, Phys. Lett. B 638 (2006).
18. D. N. Svirida *et al.*, proceedings of Spin2004, Trieste, Italy, 2004.
19. R. Tomas, *et al.*, *Quest for a New Working Point in RHIC*, proceedings of EPAC04, Lucern, Switzerland, 2004.

20. M. Bai *et al.*, *Observation of Snake Resonance in RHIC*, proceedings of PAC05, Knoxville, Tennessee, 2005.
21. W. Fischer *et al.*, *Observation of Strong-Strong and Other Beam-Beam Effects in RHIC*, Proceedings of the 2003 Particle Accelerator Conference, Portland, Oregon (2003).
22. V. Ptitsyn, *et al.*, *RHIC Performance as Polarized Proton Collider in Run-6*, proceedings of EPAC06, Edinburgh, Scotland, 2006.