

HIGH LUMINOSITY POLARIZED PROTON COLLISIONS AT RHIC*

T. Roser, BNL, Upton, NY 11973, USA

Abstract

The Brookhaven Relativistic Heavy Ion Collider (RHIC) provides the unique opportunity to collide polarized proton beams at a center-of-mass energy of up to 500 GeV and luminosities of up to $2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$. Such high luminosity and high energy polarized proton collisions will open up the possibility of studying spin effects in hard processes. However, the acceleration of polarized beams in circular accelerators is complicated by the numerous depolarizing spin resonances. Using a partial Siberian snake and a rf dipole that ensure stable adiabatic spin motion during acceleration has made it possible to accelerate polarized protons to 25 GeV at the Brookhaven AGS. After successful operation of RHIC with gold beams polarized protons from the AGS have been successfully injected into RHIC and accelerated using a full Siberian snakes built from four superconducting helical dipoles. A new high energy proton polarimeter was also successfully commissioned. Operation with two snakes per RHIC ring is planned for next year.

1 INTRODUCTION

Polarized proton colliders will open up the completely unique physics opportunities of studying spin effects in hard processes at high luminosity, high energy proton-proton collisions. It will allow to study the spin structure of the proton, in particular the degree of polarization of the gluons and antiquarks, and also to verify the many well documented expectations of spin effects in perturbative QCD and parity violation in W and Z production.

The Brookhaven Relativistic Heavy Ion Collider (RHIC) is the first hadron accelerator and collider consisting of two independent rings. It is designed to operate at high collision luminosity over a wide range of beam energies and with particle species ranging from polarized protons to heavy ions. A center-of-mass energy range of 200 to 500 GeV, as achievable at RHIC[1], is ideal in the sense that it is high enough for perturbative QCD to be applicable and low enough so that the typical momentum fraction of the valence quarks is about 0.1 or larger which guarantees significant levels of parton polarization.

Initial operation with gold beams has already delivered a peak luminosity of $3.3 \times 10^{25} \text{ cm}^{-2} \text{ s}^{-1}$ for the collision of Gold ions. In terms of collisions of nucleons this corresponds to a luminosity of about $10^{30} \text{ cm}^{-2} \text{ s}^{-1}$ demonstrating RHIC's promise of high luminosity. The first operation with Gold beams was followed by a highly successful commissioning run of polarized proton acceleration in one of

the two RHIC rings.

2 SPIN DYNAMICS, RESONANCES AND SIBERIAN SNAKES

Accelerating polarized beams requires the control of both the orbital motion and spin motion. Whereas the effect of the spin on the orbit is negligible the effect of the orbit on the spin is usually very strong. The evolution of the spin direction of a beam of polarized protons in external magnetic fields such as exist in a circular accelerator is governed by the Thomas-BMT equation [2],

$$\frac{d\vec{P}}{dt} = - \left(\frac{e}{\gamma m} \right) \left[G\gamma \vec{B}_\perp + (1 + G) \vec{B}_\parallel \right] \times \vec{P}$$

where the polarization vector P is expressed in the frame that moves and rotates with the particle's velocity. This simple precession equation is very similar to the Lorentz force equation which governs the evolution of the orbital motion in an external magnetic field:

$$\frac{d\vec{v}}{dt} = - \left(\frac{e}{\gamma m} \right) \left[\vec{B}_\perp \right] \times \vec{v}.$$

From comparing these two equations it can readily be seen that, in a pure vertical field, the spin rotates $G\gamma$ times faster than the orbital motion. Here $G = 1.7928$ is the anomalous magnetic moment of the proton and $\gamma = E/m$. In this case the factor $G\gamma$ then gives the number of full spin precessions for every full revolution, a number which is also called the spin tune ν_{sp} . At top RHIC energies this number reaches about 400. The Thomas-BMT equation also shows that at low energies ($\gamma \approx 1$) longitudinal fields \vec{B}_\parallel can be quite effective in manipulating the spin motion, but at high energies transverse fields \vec{B}_\perp need to be used to have any effect beyond the always present vertical holding field.

The acceleration of polarized beams in circular accelerators is complicated by the presence of numerous depolarizing spin resonances. During acceleration, a spin resonance is crossed whenever the spin precession frequency equals the frequency with which spin-perturbing magnetic fields are encountered. There are two main types of spin resonances corresponding to the possible sources of such fields: imperfection resonances, which are driven by magnet errors and misalignments, and intrinsic resonances, driven by the focusing fields.

The resonance conditions are usually expressed in terms of the spin tune ν_{sp} . For an ideal planar accelerator, where orbiting particles experience only the vertical guide field, the spin tune is equal to $G\gamma$, as stated earlier. The resonance condition for imperfection depolarizing resonances

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arise when $\nu_{sp} = G\gamma = n$, where n is an integer. Imperfection resonances are therefore separated by only 523 MeV energy steps. The condition for intrinsic resonances is $\nu_{sp} = G\gamma = kP \pm \nu_y$, where k is an integer, ν_y is the vertical betatron tune and P is the superperiodicity. For example at the AGS, $P = 12$ and $\nu_y \approx 8.8$.

Close to a spin resonance the spin tune deviates away from its value of $G\gamma$ of the ideal flat machine. For a resonance with strength ϵ , which is the total spin rotation due to the resonance driving fields, the new spin tune is given by the equation

$$\cos(\pi\nu_{sp}) = \cos(\pi G\gamma) \cos(\pi\epsilon).$$

A similar calculation can be done for the effective precession direction or, as it is now often called, the stable spin direction. The stable spin direction describes those polarization components that are repeated every turn. Note that both the stable spin direction and the spin tune are completely determined by the magnetic structure of the accelerator and the beam energy. The magnitude and sign of the beam polarization, however, depends on the beam polarization at injection and the history of the acceleration process.

The spin tune and stable spin direction calculations apply only to a time-independent static situation or if parameters are changed adiabatically. Far from the resonance the stable spin direction coincides with the main vertical magnetic field. Close to the resonance, the stable spin direction is perturbed away from the vertical direction by the resonance driving fields. When a polarized beam is accelerated through an isolated resonance at arbitrary speed, the final polarization can be calculated analytically [3] and is given by

$$P_f/P_i = 2e^{-\frac{\pi|\epsilon|^2}{2\alpha}} - 1,$$

where P_i and P_f are the polarizations before and after the resonance crossing, respectively, and α is the change of the spin tune per radian of the orbit angle. When the beam is slowly ($\alpha \ll |\epsilon|^2$) accelerated through the resonance, the spin vector will adiabatically follow the stable spin direction resulting in complete spin flip. However, for a faster acceleration rate partial depolarization or partial spin flip will occur.

Over the last ten years new techniques to cross both imperfection and intrinsic resonances adiabatically have been developed. A localized spin rotator or 'partial Siberian snake' can make all the imperfection resonance strengths large and cause complete adiabatic spin flip at every imperfection resonance [4], as shown in Fig. 1. A single vertical rf dipole magnet can create a strong artificial spin resonance by driving large coherent betatron oscillations, overpowering the effect of the intrinsic resonances.

At higher energies a 'full Siberian snake' [5], which is a 180° spin rotator of the spin about a horizontal axis, will keep the stable spin direction unperturbed at all times as long as the spin rotation from the Siberian snake is much larger than the spin rotation due to the resonance driving

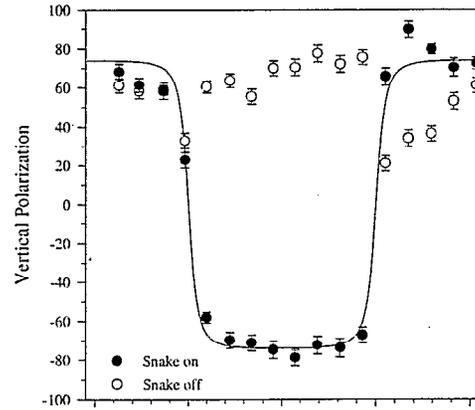


Figure 1: The measured vertical polarization as a function of $G\gamma$ for a 10% snake is shown with and without a snake. The solid line is the predicted energy dependence of the polarization.

fields. Therefore the beam polarization is preserved during acceleration. An alternative way to describe the effect of the Siberian snake comes from the observation that the spin tune with the snake is a half-integer and energy independent. Therefore, neither imperfection nor intrinsic resonance conditions can ever be met as long as the betatron tune is different from a half-integer.

A local spin rotator can be constructed by using either a solenoid at lower energies or at high energy by a sequence of interleaved horizontal and vertical dipole magnets producing only a local orbit distortion. Since the orbit distortion is inversely proportional to the momentum of the particle, such a dipole snake is particularly effective for high-energy accelerators, e.g. energies above about 30 GeV.

3 ACCELERATING POLARIZED PROTONS IN AGS AND RHIC

Fig. 2 shows the lay-out of the Brookhaven accelerator complex highlighting the components required for polarized beam acceleration. A new polarized source using the 'Optically Pumped Polarized Ion Source' (OPPIS) technique, assembled at TRIUMF using components of the KEK OPPIS, was recently installed at BNL[6]. The new source produced 10^{12} polarized protons per pulse. A single source pulse is captured into a single bunch and accelerated in the Booster and AGS for 'box-car' injection into RHIC. This is ample beam intensity to reach the nominal bunch intensity of 2×10^{11} polarized protons.

Polarized proton beam experiments at the AGS have demonstrated that a 5% partial snake, that rotates the spin by 9 degrees, is sufficient to avoid depolarization from imperfection resonances up to the required RHIC transfer energy of about 25 GeV[7]. More recently a novel scheme of overcoming strong intrinsic resonances using a rf dipole magnet was successfully tested [8]. Full spin flip can be achieved with a strong artificial rf spin resonance excited

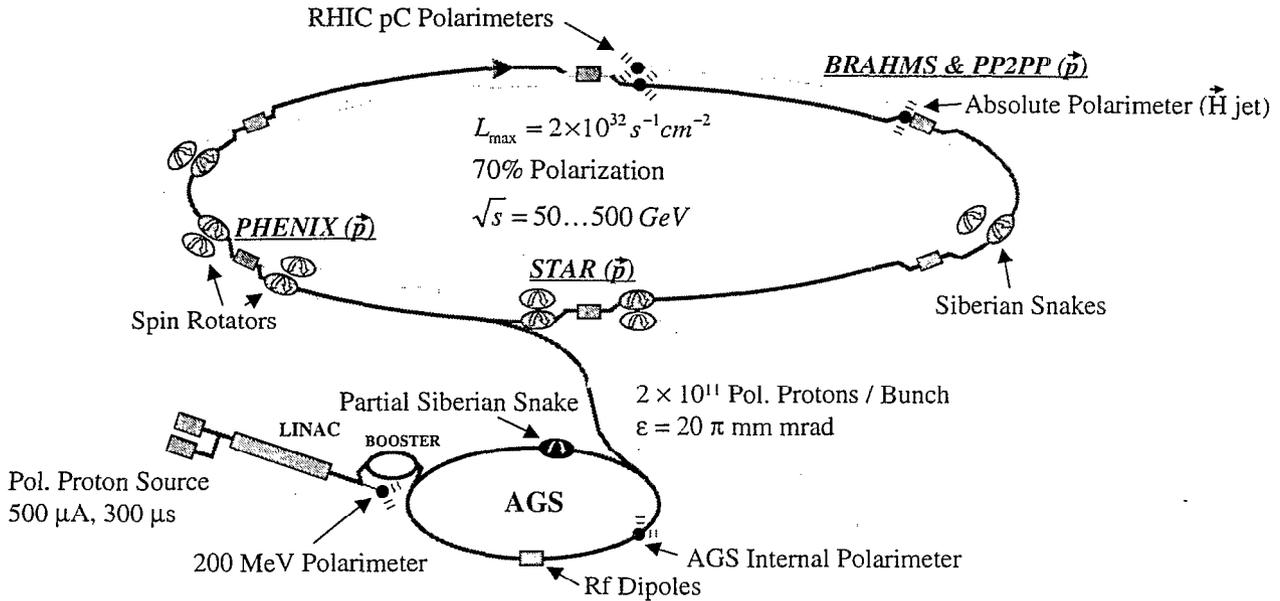


Figure 2: The Brookhaven hadron facility complex, which includes the AGS Booster, the AGS, and RHIC. The RHIC spin project will install two snakes per ring with four spin rotators per detector for achieving helicity-spin experiments.

coherently for the whole beam by driving large coherent vertical betatron oscillations. The rf dipole was used to completely flip the spin at the four strong intrinsic resonances $0 + \nu_y$, $12 + \nu_y$, $36 - \nu_y$, and $36 + \nu_y$. During the recent commissioning run beam polarization of about 40% was maintained at the AGS extraction energy of 25 GeV. Most of the 30 % polarization loss during acceleration in the AGS is caused by coupling resonances and weak intrinsic resonances. New betatron tune working points in the AGS should reduce the effect of these weak resonances in the future.

With full snakes in RHIC all depolarizing resonances should be avoided since the spin tune is a half-integer independent of energy. However, if the spin disturbance from small horizontal fields is adding up sufficiently between the snakes depolarization can still occur. This is most pronounced when the spin rotation from all the focusing fields add up coherently which is the case at the strongest intrinsic resonances. A simplistic rule of thumb would then suggest that as long as the total spin rotation of all the Siberian snakes is much larger than the total spin rotation per turn caused by the strongest spin resonance the polarization should be preserved during acceleration. This rule holds for the AGS partial Siberian snake with regard to the imperfection resonances. It would also predict that for a beam with a normalized 95% emittance of $20 \pi \text{ mm mrad}$ at least two snakes are needed for RHIC.

Of particular interest is the design of the Siberian snakes (two for each ring) and the spin rotators (four for each collider experiment) for RHIC. Each snake or spin rotator consists of four 2.4 m long, 4 T helical dipole magnet modules each having a full 360 degree helical twist [9]. Using he-

lical magnets minimizes orbit excursions within the extend of the snake or spin rotator which is most important at injection energy. Nevertheless the bore of the helical magnets has to be 10 cm in diameter to accommodate the 3 cm orbit excursions. The superconducting helical dipoles are being constructed at BNL using thin cable placed into helical grooves that have been milled into a thick-walled aluminum cylinder. A schematic picture of the helical dipole magnet is shown in Fig. 3. For a snake or spin rotator four full length helical dipole magnets are assembled into a single cryostat with the length of a regular RHIC dipole[10].

Only a single Siberian snake in one of the two RHIC rings was available for the first polarized proton commissioning in RHIC. This meant that vertically polarized protons needed to be injected without the snake powered, the snake was then turned on, which rotates the spin into the horizontal plane, and then finally the beam was accelerated. Even under this more complicated scenario polarized protons were successfully accelerated to about 30 GeV,

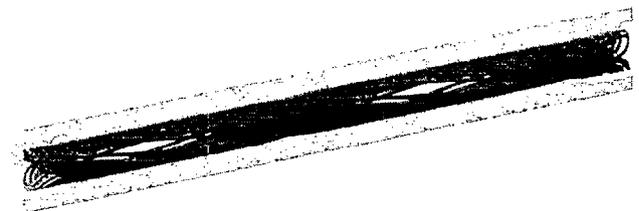


Figure 3: Schematic picture of the superconducting helical dipole shows the 16 helical current blocks and half of the iron yoke

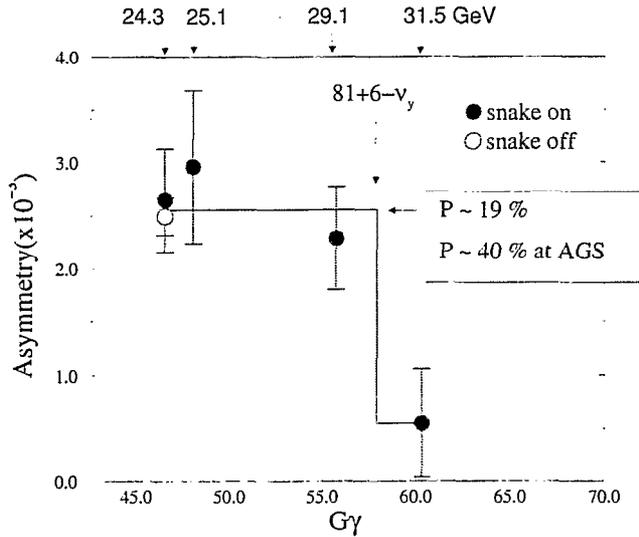


Figure 4: Measured polarization of the first polarized proton beam in RHIC at injection without Siberian snake (open circle) and accelerated with snake (filled circles). The graph shows the asymmetry measured with the RHIC proton-carbon polarimeter. The polarization values given were obtained from calibration measurements performed previously in the AGS.

the highest energy accelerated polarized proton beam ever achieved. Fig. 4 shows the beam polarization measured in RHIC during this first commissioning run. More than 20 years after Y. Derbenev and A. Kodratenko made their proposal to use local spin rotators to stabilize polarized beams in high energy rings it has now been demonstrated that their concept is working flawlessly even in the presence of strong spin resonances at high energy. It also confirms the initial tests of the Siberian snake concept at low energy that were performed at IUCF. Significant polarization was lost at injection when the snake was off and at the first very strong spin resonance. Spin tracking[11] confirmed that this latter loss is due to an improper betatron tune setting and the large uncorrected closed orbit distortions.

Extensive spin tracking also confirms that with two Siberian snakes and a well corrected closed orbit and a well controlled betatron tune no polarization should be lost up to the full RHIC energy of 250 GeV. The acceleration through the energy region of the strongest resonance was simulated in great detail including a 1 mm rms misalignment of the quadrupoles, and sextupoles as well as the corrector dipoles used to correct the closed orbit. The result is shown in Fig. 5 for a beam with a normalized 95% emittance of $20 \pi \text{ mm mrad}$. The upper and lower curve show the result for the full beam and the particles at the edge of the beam, respectively. Although there is a significant decrease of the polarization at the energy of the resonance at $G\gamma = 5 \times 81 + (\nu_y - 12) = 422.18$, the polarization of the full beam is restored after accelerating completely through

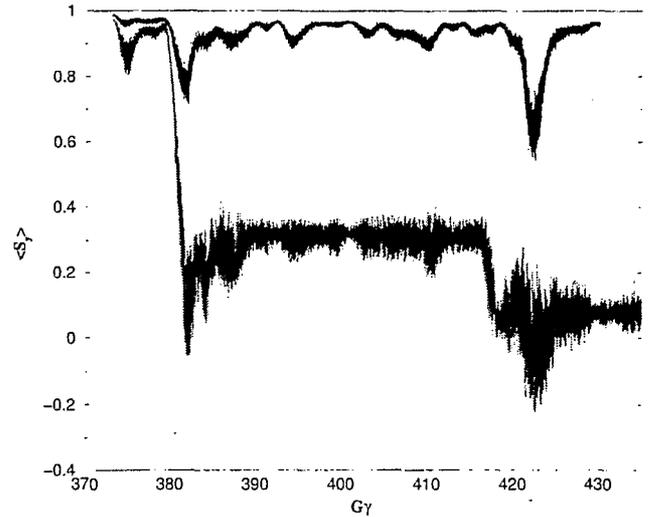


Figure 5: Result of spin tracking through the region of the strongest resonance in RHIC. The closed orbit was corrected with residuals of less than 0.2 mm.

the resonance region. The simulation also shows that there is significant polarization loss at the edge of the beam. This fact highlights the need for a polarimeter that can measure polarization profiles.

In addition to maintaining polarization the fast, accurate, and reliable measurement of the beam polarization is of great importance. The analyzing power of only very few reactions has been measured at high energies and the magnitudes are typically rather small. Polarization sensitive interaction with an external electromagnetic field is also much smaller than for the much lighter electron for which Compton back scattering is typically used for high energy polarization measurement. Very small angle elastic scattering in the Coulomb-Nuclear interference region offers the possibility for an analyzing reaction with a high figure-of-merit which is not expected to be strongly energy dependent[12]. For polarized beam commissioning in RHIC an ultra thin carbon ribbon was used as an internal target and the recoil carbon were detected to measure both vertical and radial polarization component. The detection of the recoil carbon with silicon detectors using both energy and time-of-flight information showed excellent particle identification. It was demonstrated that this polarimeter can be used to monitor polarization of high energy proton beams in a almost non-destructive manner and that the carbon fiber target could be scanned through the circulating beam to measure polarization profiles.

4 COMMISSIONING PLANS AND SCHEDULE

For the upcoming polarized proton run it is planned to install all four Snakes as well as the proton-carbon polarimeter in the second ring. This should allow for acceleration to the full RHIC energy of 250 GeV. Collisions are planned

Table 1: Beam and lattice parameters for RHIC proton-proton design and upgrade possibilities.

	RHIC Spin design	RHIC II	Future Upgrade
Emittance(95%), ϵ [$\pi \mu m$]	20	12	12
Beta function at IR, β^* , [m]	1	1	0.3
Number of bunches, M	120	120	360
Bunch population, N , [10^{11}]	2	2	2
Beam-beam parameter per IR, ξ	0.0073	0.012	0.012
Angular beam size at IR, σ'^* , [μrad]	112	86	157
RMS beam size at IR, σ^* , [μm]	112	86	47
Luminosity, L , [$10^{32} cm^{-2} s^{-1}$]	2.4	4.0	40

at 100 GeV on 100 GeV at which energy one of the two snakes per ring can be turned off to produce longitudinal polarization at the detectors. The luminosity is expected to be about $5 \times 10^{30} cm^{-2} s^{-1}$.

All spin rotators will be installed for the following run with the possibility to go to full collision energy of $\sqrt{s} = 500 GeV$ with longitudinal polarization at STAR and PHENIX. Finally a polarized gas jet will be installed as an internal target for small angle proton-proton scattering which will allow the absolute calibration of the beam polarization to better than 5 %.

5 LUMINOSITY UPGRADES FOR POLARIZED PROTON OPERATION

The present RHIC spin physics program is based on colliding polarized proton beams at a center-of-mass energy of up to 500 GeV and a luminosity of up to $2 \times 10^{32} cm^{-2} s^{-1}$. Although the physics potential of this capability still needs to be exploited there are upgrades to RHIC that can significantly extend the physics reach of this program since spin physics relies on high precision measurements.

The proton beam intensity can be increased, or the beam emittance be decreased until the beam-beam limit is reached which corresponds to a luminosity of about $4 \times 10^{32} cm^{-2} s^{-1}$. The RHIC electron cooler proposed for heavy ion operation could be used at injection energy to achieve this reduction of the proton beam emittance. Alternatively the bunch intensity could be increased to 3×10^{11} protons. The machine parameters for the RHIC Spin design and the luminosity at the beam-beam limit (column "RHIC II") are listed in Table 1.

It also seems possible to install in one or two interaction regions an additional pair of high field focusing triplets that would reduce beta-star to about 30 cm increasing the luminosity by an additional factor of 3. Finally, the number of bunches in each ring could be increased from 120 to 360 increasing the luminosity by another factor of 3. The latter two upgrade options, shown in the last column in Table 1, would also require upgrades to the detectors. Taken together these upgrades would allow for a polarized proton luminosity at 500 GeV of up to $4 \times 10^{33} cm^{-2} s^{-1}$, a 20-fold increase over the present luminosity goal.

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