STATUS OF PROTON POLARIZATION IN RHIC AND AGS*

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A fundamental aspect of particle physics is the spin of the particles. With polarized beams, the internal structure of the proton may be probed in ways that are unattainable with unpolarized beams. The Relativistic Heavy Ion Collider (RHIC) has collided protons with both transverse and longitudinal polarization at center-of-mass energy of 200 GeV. Future running will extend this to 500 GeV. This paper describes the methods used to accelerate and manipulate polarized proton beams in RHIC and its injectors. Special techniques include the use of a partial Siberian snake and an ac dipole in the AGS. In RHIC we use superconducting helical Siberian snakes for acceleration, and eight superconducting helical rotators for independent control of polarization directions at two interaction regions. The present status and future plans for the polarized proton program will be reviewed.

*Work performed under the auspices of the U. S. DOE (contract # de-ac02-98ch10886) and RIKEN of Japan.

1. Introduction

RHIC has been described in detail elsewhere[1], but it is worth noting (see Fig.1) the particular components used for spin control.

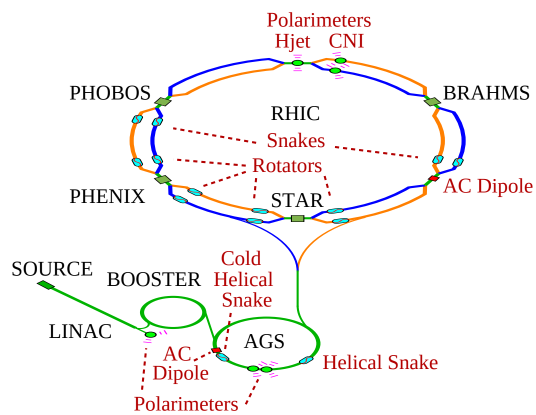

Figure 1. The accelerator complex for polarized protons. The beam in the RHIC Blue (dark) ring goes clockwise and in the Yellow ring (light) counterclockwise.

First an H^- beam with polarized protons is produced by the optically pumped polarized ion source[2], and then accelerated in the RFQ and linac to a kinetic energy of 200 MeV ($\gamma = 1.21$). The beam is then stripped on injection into the Booster and accelerated to 2.46 GeV ($\gamma = 2.62$). Acceleration continues in the AGS up to 24.3 GeV ($\gamma = 25.94$) followed by transfer into either of the RHIC rings. There are several polarimeters to measure the polarization at various stages: one at the source, another at the end of the linac, three p+C CNI (Coulomb Nuclear Interference) polarimeters in the AGS and and each RHIC ring, as well as local polarimeters at the STAR and PHENIX detectors. There is a partial Siberian snake in the AGS and a pair of full Siberian snakes in each of the RHIC ring. Around each of the STAR and PHENIX detectors are four rotators as shown to manipulate the polarization direction through the experiment. There is an rf dipole magnet in the AGS to aid in spin resonance crossing. RHIC has an additional ac dipole which will be used for spin flipping. A hydrogen jet polarimeter[12,13,14,15] to provide an absolute calibration of the CNI polarimeters in RHIC was installed and commissioned during the latest run.

2. Spin Dynamics

In the local rest frame of the proton, the spin precession of the proton obeys the Thomas-Frenkel (BMT) equation[4]

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

where the magnetic fields and time are expressed in the lab coordinates and electric fields have been ignored. Here $G = (g - 2)/2 = 1.792847$ for the proton. A comparison with the Lorentz force equation:

$$\frac{d\vec{p}}{dt} = \frac{g}{\gamma m}\vec{S} \times \Big[\qquad \vec{p} \qquad\qquad \Big] \tag{2}$$

shows that for a proton orbiting in planar ring with no vertical oscillations and a vertical bend field, the horizontal components of spin will precess a factor of $1 + G\gamma$ faster than the orbit in a fixed lab system. In the rotating coordinate system moving with the beam, any horizontal spin components will precess $\nu_{\mathrm{s}} = G\gamma$ times in one turn. The number of precessions ν_{s} per turn, called the spin tune, is proportional to the energy of the proton.

A radial field component causing a vertical deflection of the particle by an angle α will cause the spin to precess about the radial direction by an angle $(1+G\gamma)\alpha$. Since rotations about different axes do not commute, such vertical excursions can modify the amount of precession and hence also the spin tune. In addition the local axes about which the spins precess may move away from the vertical.

Integer (imperfection) resonances which are caused by misalignments of magnets can be quite strong and may flip the direction of polarization as the energy is ramped. For protons the energy separation of the imperfection resonances is 523 MeV.

The deflections of the vertical betatron oscillation also cause radial precessions which can build up when the spin tune matches the vertical betatron tune Q_{v}. This type of resonance is called an intrinsic resonance. For the most common resonances (intrinsic and imperfection) the resonance condition may be written as

$$\nu_{\mathrm{s}} = N + N_{\mathrm{v}} Q_{\mathrm{v}}, \tag{3}$$

where N and N_{v} are integers. With horizontal-vertical coupling from rotated quadrupoles or solenoids, there may be an additional term $N_{\mathrm{h}} Q_{\mathrm{h}}$.

As the energy increases with vertical angle oscillations of a constant amplitude, the radial precessions are amplified, so that the resonance strengths increase with energy (see Fig. 2). The resonance strength ϵ is the angle of

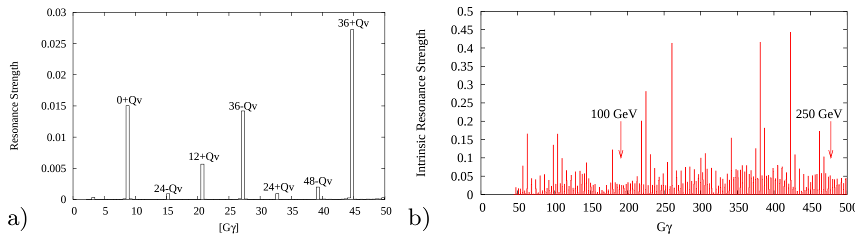

Figure 2. a) Calculated relative strengths of imperfection resonances in the AGS with no snake. It should be noted that there are 12 superperiods in the AGS, so the strongest intrinsic resonances occur with N being a multiple of 12 and $N_\mathrm{v} = \pm 1$. b) Relative strengths of intrinsic resonances in RHIC with no snakes. These resonance spectra were calculated for a protons on vertical emittance ellipses of $\pi\epsilon = 10\pi$ μm $Qv = 8.7$ in the AGS and $Q_\mathrm{v} = 29.219$ in RHIC.

rotation away from the vertical divided by 2π that a proton right on resonance would experience in one turn. The Froissart-Stora formula[20] gives the ratio of final to initial polarization for an isolated resonance crossing:

$$\frac{P_\mathrm{f}}{P_\mathrm{i}} = 2\exp\left(-\frac{\pi|\epsilon|^2}{2\alpha}\right) - 1, \qquad (4)$$

where $\alpha = d(G\gamma)/d\theta$ is the ramp rate in units of $G\gamma$ per radian of bend around the ring. For a large resonance strength, the spin can essentially completely flip over. Relative intrinsic resonance strengths for the AGS and RHIC are shown in Fig. 2.

3. The real machines

The linac provides a beam with about 70% polarization. In the Booster ($G\gamma$ from 2.18 to 4.5), we cross two imperfection resonances with harmonic orbit corrections to cancel any depolarization at the integers 3 and 4. The beam gets extracted at $G\gamma = 4.5$ below the first intrinsic resonance ($\nu_\mathrm{s} = Q_\mathrm{v} = 4.9$).

In the AGS with a more complicated resonance structure, the acceleration goes from $G\gamma = 4.5$ up to 46.5. Here we use a partial snake to cause a larger lattice disturbance with a rotation of the spin about the longitudinal axis and enhance spin flipping at the imperfection resonances. A single partial snake in the ring will open up stop bands in the spin tune at the integer as shown in Fig. 4a. If $G\gamma$ is equal to an integer plus one half, then the stable spin direction is tilted away from the vertical by half of the snake-rotation angle; at integer values of $G\gamma$ the closed-orbit stable spin direction is in the horizontal plane.

An ac dipole can be made to vertically shake the beam near the betatron tune line, so that large amplitude oscillations will enhance the spin resonance thus inducing more spin flip at the corresponding intrinsic resonance. We use the ac dipole to enhance spin flipping at four intrinsic resonances: $\nu_s = 0 + Q_v$, $12 + Q_v$, $36 - Q_v$, and $36 + Q_v$. Due to a lack of strength of the ac dipole we expect a loss of polarization at the $36+Q_v$ with a decrease by a factor of about 0.85 at this resonance.

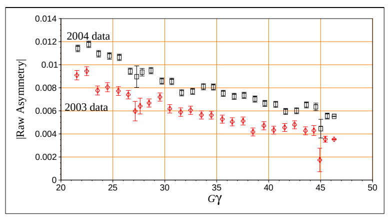

Figure 3. Absolute value of polarization asymmetry in AGS on ramp for runs in 2003 and 2004. At extraction ($G\gamma = 46.5$) the asymmetries corresponds to polarizations of 28% in 2003 and 42% in 2004.

In previous years the partial snake was a solenoid which introduced a large amount of horizontal-vertical coupling – particularly at low energy. For the latest run, we replaced the solenoid with a warm helically twisted dipole in order to reduce the contribution from coupling depolarizing resonances. Figure 3 shows the absolute value of the polarization asymmetry along the AGS ramp during the last two runs, in 2003 with the solenoidal snake and in 2004 with the helical snake.[8] Most of the increase was due to the new helical snake with smaller coupling; a few percent was due to improved performance of the polarized source.

With a single full snake in a ring the fractional part of ν_s will be an integer plus a half, and the imperfection resonances go away, since we never operate with Q_v at an integer plus a half. With a single full snake, the stable spin direction is in the horizontal plane which makes it difficult to match polarization from one ring to the next. There are however still some hybrid snake resonances.[7,20] As we increase energy, more precessions happen in the space between snake crossings, and the deleterious effects still build up, so that at RHIC energies up to 250 GeV ($G\gamma = 478$) a single snake would not be enough to maintain a reasonable amount of polarization. Higher energies require more snakes. In RHIC we inject and ramp with two full snakes on opposite sides of the rings (see Fig. 4b).

A snake is an insertion device which rotates the spin about an axis in

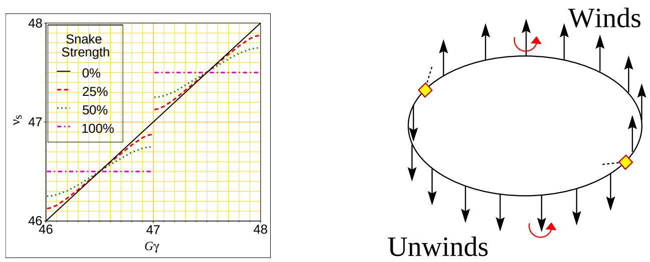

Figure 4. a) A single partial snake in a ring opens up stop bands for the spin tune. The percentage refers to the amount of spin rotation from the snake: 100% corresponds to 180° of rotation. b) With two full snakes on opposite sides of the ring that have rotation axes perpendicular to each other, the stable direction spin will be vertically up in one half of the ring and down in the other half, and the spin tune will be 0.5.

the horizontal plane. The simplest type of snake is a solenoid which rotates the spin around the longitudinal axis. As can be seen from Eq. 1 the amount rotation from a longitudinal field decreases with energy, so a solenoid becomes less effective for higher energy machines. Another drawback of solenoids is orbital coupling. In order to maintain a spin tune of 0.5 with two snakes on opposite sides of the ring, the rotation axes of the two snakes must be kept perpendicular. If the axes were parallel, the spin tune would be zero – a bad situation for maintaining polarization.

The RHIC snakes are constructed of four helical superconducting dipoles with right-handed pitch and fields. In contrast with the solenoidal snake, in a helical snake spin rotation is primarily due to the transverse fields so that the rotation is essentially independent of energy. Each snake is powered by two power supplies: The outer pair of helices are connected in series with opposite polarity to one supply, and the inner pair are likewise connected in series with opposite polarity to the second supply. This orientation of fields guarantees that the snake will act as an insertion device with minimal impact on the orbit outside the snake.

The spin rotators for longitudinal polarization are made of four helical superconducting dipoles. In this case we alternate the handedness of the pitch rather than polarity. Moving clockwise around both rings the pattern at each rotator is: right-left-right-left. For a rotator the field at the end of each helix is horizontal. Each pair (inner and outer) of helices within a rotator is again connected in series to a different power supply. The rotation axis of this kind of rotator lies in the plane perpendicular to the beam and not necessarily in the horizontal plane as in a snake. The rotators are laid out around one of the experiments as indicated in Fig. 5

As with the snakes the amount of rotation is essentially independent of energy. However due to the net horizontal bend between the rotator and interaction region there is an energy dependent precession which must be compensated to achieve a longitudinal polarization at the collision point.

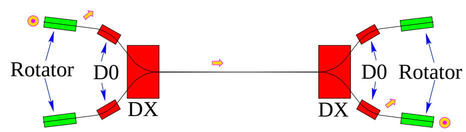

Figure 5. There are two rotators in each ring on either side of both the STAR and PHENIX detectors. Between the rotators and experiment are four dipoles (D0 and DX) to steer the beams into head-on collisions. The final-focus triplets (not indicated) are located between the rotators and and D0 magnets. For each ring the incoming rotator and outgoing rotator are parallel. There is a net bend angle of ±3.675 mrad from the rotator to the collision point.

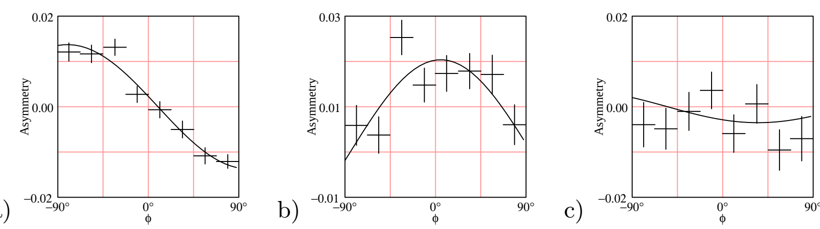

Figure 6. Transverse polarization asymmetry at PHENIX with a) rotators off, b) rotators with wrong polarity, c) rotators with correct polarity.

Figures 6a,b,c show transverse polarization asymmetries measured by the PHENIX experiment with three rotator settings.[19] The asymmetry is plotted as the left-right asymmetry tilted by an angle ϕ. In Fig. 6a we see a vertical polarization with the rotators turned off. With the currents accidentally reversed (Fig. 6b) the polarization was essentially radial, and with the correct polarity (Fig. 6c) the measured asymmetry was essentially zero with no appreciable loss of polarization measured by the CNI polarimeter outside the rotator region.

4. Status and future plans

To date we have achieved a peak polarization of 50–55% in the AGS at extraction with a bunch intensity of 1×10^{11}. We changed to a new betatron tune working point in RHIC to reduce beam loss from the beam-beam interaction and improve the luminosity – details are given in Ref. 6. At $\sqrt{s} = 200$ GeV in RHIC we have collided beams with an average luminosity of 4×10^{30} cm^{-2}s^{-1} and an average polarization of about $40 \pm 5\%$. Preliminary results[15] from the H-jet polarimeter give an A_N consistent with theory without hadron spin-flip as well as with the FNAL E704 experiment[16].

For the next run we will upgrade the solenoid for the OPPIS source, and expect to increase the polarization from the source from around 80% to 85%. In the AGS we will also be adding a superconducting helical partial snake[9] which can reach a 25% strength. We plan to commission this new snake during the next run in a mode which uses both the existing warm helical snake as well as the new superconducting snake. By placing the second snake one third of the way around the ring from the other, the snakes can be made to add in strength at spin tunes of multiples of three where the worst imperfection resonances lie, and subtract at spin tunes 1.5 units away where we inject ($G\gamma = 4.5$) and extract ($G\gamma = 46.5$). (See Ref. 10.) The addition of this superconducting partial snake should allow us to extract 2×10^{11} protons per bunch with $> 70\%$ polarization from the AGS.

To date we have only accelerated polarized protons up to an energy of 100 GeV, although a top energy of 250 GeV is possible. Since the rate of spin precession about transverse fields is proportional to energy we can expect more stringent requirements on the orbit flatness as we increase the energy. In the next run we plan to spend a fraction of the time developing acceleration to higher energies in RHIC. This summer we realigned quadrupoles in the vicinity of the north interaction area (location of Hjet in Fig. 1). We are planning a complete realignment of the ring next summer. The electronics for our beam position monitors is being upgraded to have fewer radiation induced glitches, and we removed some microwave switches which caused serious drift problems in the reported beam positions. With the quadrupole realignments and more reliable position readback, we expect to achieve a much flatter orbit thus reducing the size of depolarizing resonances.

We are installing NEG-coated beam pipes in the warm sections of RHIC to increase vacuum pumping as well as reduce secondary emission of electrons; at present we are about half completed and will finish adding the NEG coated pipes during the next summer shutdown. This NEG-coated pipe should help minimize the vacuum problems which are limiting beam intensity and thus luminosity.

Over the next few years we are aiming to reach an enhanced luminosity of 1.5×10^{32} cm^{-2}s^{-1} with a polarization of at least 70% at 250 GeV ($\sqrt{s} = 500$ GeV).

Other development plans in RHIC include commissioning the ac dipole as a spin flipper and calibrating the snakes for the correct spin rotation. We plan to calibrate the beam energy by tilting the spin away from the vertical direction with one of the PHENIX rotators and measuring the oscillation of the radial component of spin at the CNI polarimeters as a function of energy.

In the long term, we are designing an electron ring (or possibly a linac) to collide with heavy ions and polarized protons in at least one interaction area. For the ring design the electron beam will be polarized as discussed in Ref. 17. An overview of the eRHIC plan was presented in the final plenary talk by Abhay Deshpande[18].

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