RHIC OPERATION WITH LONGITUDINALLY POLARIZED PROTONS*

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Abstract

Polarized proton beams have been accelerated, stored and collided at 100GeV per beam in the Relativistic Heavy Ion Collider (RHIC) with longitudinal polarization. The essential equipment includes four Siberian snakes, eight spin rotators and fast relative polarimeters in each of the two RHIC rings as well as local polarimeters at the STAR and PHENIX detectors. This paper summarizes the performance of RHIC as a polarized proton collider in the FY03 run with emphasis on polarization issues. Preliminary data from the FY04 run is also shown.

INTRODUCTION

In a perfect planar synchrotron with vertically oriented guiding magnetic field, the spin vector of a proton beam precesses around the vertical axis $G\gamma$ times per orbital revolution, where $G = (g-2)/2 = 1.7928$ is the gyromagnetic anomaly of the proton, and γ is the Lorentz factor. The number of precessions per revolution is called the spin tune ν_{sp} and is equal to $G\gamma$ in this case.

In general, a spin resonance is located at

$$\nu_{sp} = G\gamma = k \pm l\nu_y \pm m\nu_x \pm n\nu_{syn}, \quad (1)$$

where k, l, m and n are integers, ν_x and ν_y are horizontal and vertical betatron tunes, and ν_{syn} is the tune of the synchrotron oscillation. There are three main types of depolarizing resonances: imperfection resonances at $\nu_{sp} = k$, intrinsic resonances at $\nu_{sp} = l \pm \nu_y$ and coupling resonances at $\nu_{sp} = n \pm \nu_x$.

When a polarized beam is uniformly accelerated through an isolated spin resonance, the final polarization P_f is related to the initial polarization P_i by the Froissart-Stora formula[1]

$$P_f = (2e^{-\pi|\epsilon_k|^2/2\alpha} - 1)P_i, \quad (2)$$

where α is the rate of change of spin tune per radian of the orbit angle due to acceleration: $\alpha = \frac{d(G\gamma)}{d\theta}$, and θ is the orbital angle in the synchrotron.

For a ring with a partial snake with strength s, the spin tune ν_{sp} is given by

$$\cos \pi\nu_{sp} = \cos\frac{s\pi}{2}\cos G\gamma\pi, \quad (3)$$

where $s = 1$ would correspond to a full snake which rotates the spin by 180°. When s=1, the spin tune is always 1/2 independent of energy. Thus, all imperfection, intrinsic and coupling resonance conditions can be avoided [2]. However, when the spin resonance strength is large, a new class of spin-depolarizing resonance can occur. These resonances, due to coherent higher-order spin-perturbing kicks, are called snake resonances [3] and located at $\Delta\nu_y = \frac{k\pm\nu_{sp}}{n}$, where $\Delta\nu_y$ is the fractional part of vertical betatron tune, n and k are integers, and n is called the snake resonance order.

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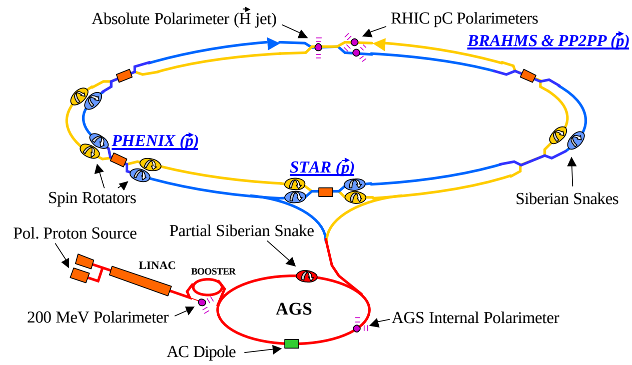

Figure 1: The Brookhaven polarized proton facility complex, which includes the OPPIS source, 200 MeV linac, the AGS Booster, the AGS, and RHIC.

ACCELERATION OF POLARIZED PROTONS

The Brookhaven polarized proton facility complex is shown schematically in Fig.1. The polarized H^- beam from the optically pumped polarized ion source (OPPIS) was accelerated through the 200 MeV linac. The OPPIS source produced 10^{12} polarized protons per pulse with 70-75% polarization. The beam was then strip-injected and accelerated in the Booster up to 2.5 GeV or $G\gamma = 4.7$.

The beam is then injected into Alternative Gradient Synchrotron (AGS), where a 5% partial Siberian snake is used to overcome imperfection resonances [4] and an ac dipole is used to overcome the four strong intrinsic resonances [5]. The remaining polarization loss in the AGS is caused by coupling resonances and weak resonances. The polarized proton beam was accelerated up to $G\gamma = 46.5$ or 24.3 GeV. The beam intensity varied between 0.5 -0.7$\times 10^{11}$ protons per fill. The polarization level at the AGS extraction energy was about 40%. In the future, two new partial snakes should eliminate depolarization in the AGS [6].

The basic construction unit for the RHIC snakes is a superconducting helical magnet producing a 4T dipole field that rotates 360° over a length of 2.4 meters [7]. These magnets are assembled in groups of four to build four Siberian snakes (two for each ring) for RHIC. With two snakes in each ring, the stable spin direction is vertical in RHIC and independent of beam energy.

The beam emittance was about 12 π mm-mrad in both transverse planes. A 60-bunch pattern was used in each ring (55 filled, 5 empty for an abort gap). The beam was injected into RHIC with $\beta^* = 10$m lattice and accelerated up to 100 GeV without a beta-squeeze; the β^* was then squeezed down to 1 m and 3 m at various IRs. A separate rotator ramp brings the spin to the longitudinal direction at IRs 6 and 8. A total intensity in both rings of 3.5×10^{12} and peak luminosity of 6×10^{30} cm^{-2}s^{-1} have been achieved. The integrated luminosity for STAR and PHENIX for the FY03 run was about 1.6 nb^{-1}.

The fractional betatron tune space ranged between 0.215 and 0.23 for the horizontal tune and between 0.225 to 0.24 for the vertical. The vertical betatron tune was chosen to avoid the 3/14 snake resonance. Close attention was also paid to the orbit, since the 1/4 snake resonance is driven by the orbit distortions.

In the middle of operation, one helical magnet unit failed due to coil defects. With the remaining units, we decided to run this snake as an 88% partial snake while keeping the angles between the two snakes at 90°. The polarization in the yellow ring was recovered with the new configuration, although it was more sensitive to tune value and orbit errors. In general, the polarization level was not as good as in the blue ring.

The separation of energy ramp and β-squeeze allowed a separate analysis of optics errors during the acceleration and the squeeze part of the ramp. Based on an analysis of measured tunes and chromaticities along the FY03 polarized proton ramp, quadrupole transfer-function changes were implemented for the FY04 Au and proton ramps, showing the improved model agreement for tunes, chromaticities along the ramp, and measured transverse phase advance at store [8].

POLARIZATION AT INJECTION AND STORE

Due to interleaved horizontal and vertical bends from AGS extraction to the RHIC injection points, the value of the vertical component of the stable spin direction varies with energy and the AGS snake setting, and may differ for the blue and yellow rings [9]. With the present 5% solenoid snake setting, the polarization ratio of blue ring vs. yellow ring at injection was 0.948. For the three weeks physics running period, the averaged ratio (blue vs. yellow) is 0.988 ± 0.019.

Although the analyzing power at 100 GeV for the RHIC polarimeter is unknown, it is expected to be similar to the values at injection energy [1]. Under this assumption the average polarization measured at store for the three weeks of physics running is 30% for blue and 25% for yellow. The averaged injection polarization is about 40% in both rings.

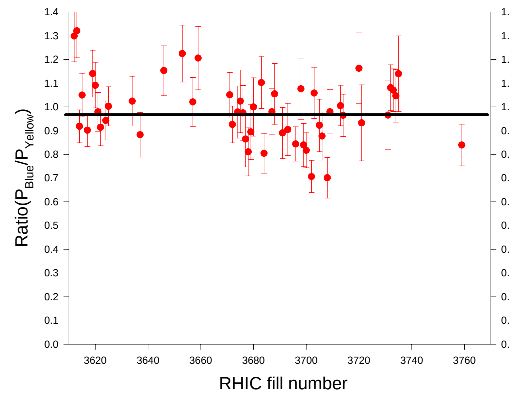

Figure 2: Ratio of injection polarization in blue vs. in yellow vs. RHIC fill number. The solid line marks the average of all data points. It is very close to the expected value.

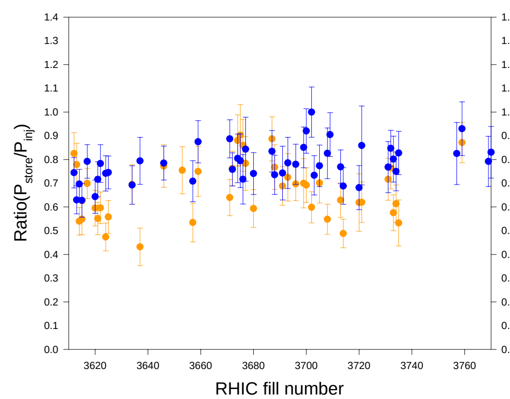

Figure 3: Ratio of polarization measured at store vs. measured at injection For both blue (blue or dark) and yellow (yellow or light) rings vs. RHIC fill number. The average ratio is 0.78 for blue ring and 0.67 for yellow ring.

The beam polarization was also measured during the ramp for a few ramps. This measurement showed some polarization loss when rf voltages changed before the energy ramp. This was later addressed in the FY04 run [10]. An example of one fill in FY04 is shown in Fig.4. Comparing the polarization level at store with and without the β^* squeeze, it also indicates some loss of polarization in the β^* squeeze part of the ramp, where decoupling and tune control are difficult. Polarization profiles in both horizontal and vertical planes were also measured at the end of a store. They showed no strong dependence of polarization on transverse position of the polarimeter target within the beam.

Spin rotators are required at the IRs used by PHENIX and STAR to allow measurements of spin effects with lon-

[1] A more precise value of the analyzing power will be determined by proton-proton scattering at small angle with a polarized jet target in the coming runs.

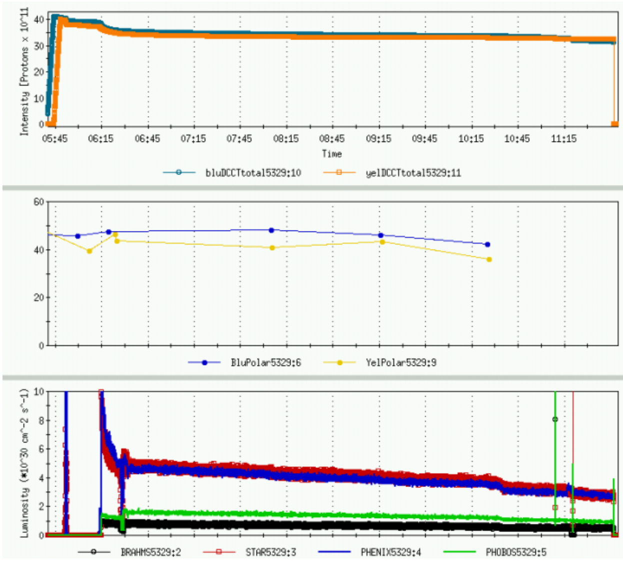

Figure 4: A typical store in FY04. Top: beam intensity in unit of 10^{11}. Middle: measured polarization in the blue and yellow rings. Bottom: luminosity in the unit of $10^{30}cm^{-2}s^{-1}$ for four experiments.

gitudinally polarized protons. The spin rotators rotate the polarization from the vertical direction into the horizontal plane on one side of the IR and restore it to the vertical direction on the other side. Eight spin rotators were installed in RHIC in 2002. These spin rotators cause significant orbit distortions, especially at low energies. For this reason, they are powered after the energy ramp. This took an additional seven minutes for each store. The spin rotators at PHENIX and STAR were commissioned separately and both worked well for the two experiments, as shown in Fig. 5. For most fills, the polarization in both rings was measured before and after the rotator ramps, showing no polarization loss during this ramp.

OUTLOOK

To reach the desired 70% polarization in RHIC, a new strong superconducting partial snake in the AGS, higher polarization from the source, and good control of RHIC orbit and tunes are needed. Beam induced pressure rise remains an intensity limit at RHIC for polarized proton operation. Beam study are underway to address this problem [11]. Another limitation we are facing is beam-beam tune shift limit. A new working point established in FY04 run is promising for both polarization preservation and reduce beam-beam tune shift [12].

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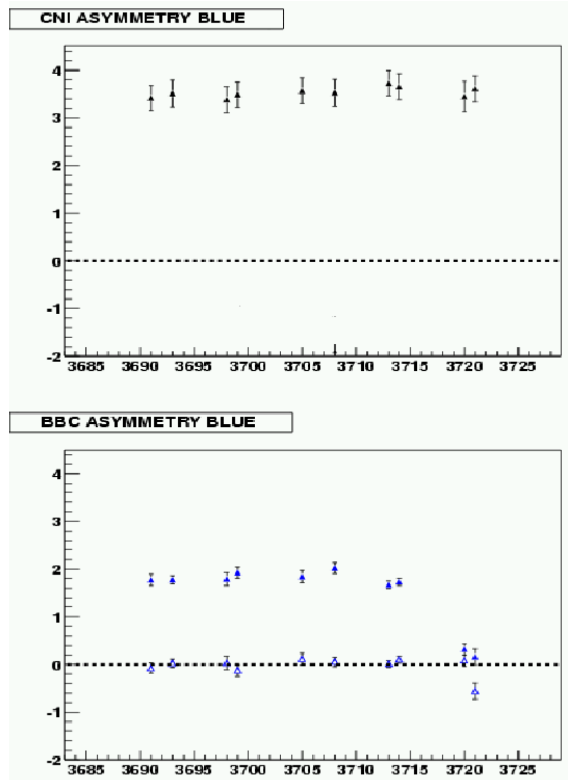

Figure 5: Measured asymmetry (in the unit of 10^{-3}) vs. RHIC fill numbers in blue ring. The solid triangles are vertical polarization and open triangles are radial polarization (bottom plot pnly). Top plot: RHIC CNI polarimeter near IP 12. Bottom plot: asymmetry measured at STAR experiment. Note the vertical component measured at STAR dropped to zero near fill 3720 (when rotators were on) while the CNI polarimeter maintained the vertical polarization level.

REFERENCES

[1] M. Froissart and R. Stora, Nucl. Instrum. Meth. **7**, 297(1960).

[2] Ya.S. Derbenev and A.M. Kondratenko, Part. Accel. **8**, 115 (1978).

[3] S.Y. Lee and S. Tepikian, Phys. Rev. Lett. **56**, 1635 (1986).

[4] H. Huang, *et al.*, Phys. Rev. Lett. **73**, 2982 (1994).

[5] M. Bai, *et al.*, Phys. Rev. Lett. **80**, 4673 (1998).

[6] T. Roser,*et al.*, these proceedings.

[7] V.I. Ptitsyn and Yu.M. Shatonov, Nucl. Instrum. Meth. **A398**, 126(1997).

[8] J. van Zeijts, these proceedings.

[9] W. MacKay, and N. Tsoupas, AIP Proceedings **667**, p84(2003).

[10] T. Satogata, these proceedings.

[11] S.Y Zhang, *et al.*, these proceedings.

[12] R. Tomas, *et al.*, these proceedings.