POLARIZED PROTON ACCELERATION AT THE BROOKHAVEN AGS AND RHIC*

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Abstract

Polarized proton beam has been accelerated and stored at 100GeV in Relativistic Heavy Ion Collider (RHIC) to study spin effects in the hadronic reactions. The essential equipment includes four Siberian snakes and eight spin rotators in two RHIC rings, a partial snake in the AGS, fast relative polarimeters, and ac dipoles in the AGS and RHIC. This paper summarizes the performance of RHIC as a polarized proton collider and of AGS as the injector to RHIC.

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

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

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[2]

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

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. In the AGS, a few weak intrinsic resonances were not corrected with any scheme. The final polarization were affected by the value of α.

* Work performed under Contract Number DE-AC02-98CH10886 with the auspicies of the US Deparment of Energy.

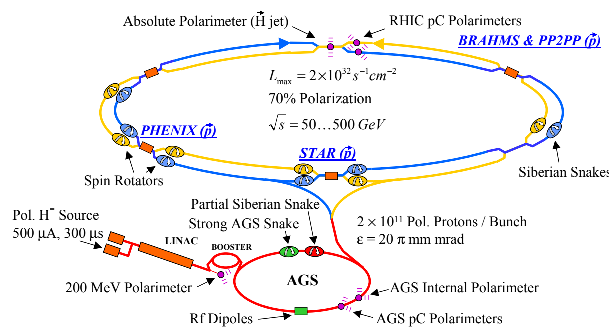

Figure 1: The Brookhaven polarized proton facility complex, which includes the OPPIS source, 200 MeV LINAC, the AGS Booster, the AGS, and RHIC.

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

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

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 and energy independent. Thus, all imperfection, intrinsic and coupling resonance conditions can be avoided. 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.

POLARIZED PROTONS IN THE AGS

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

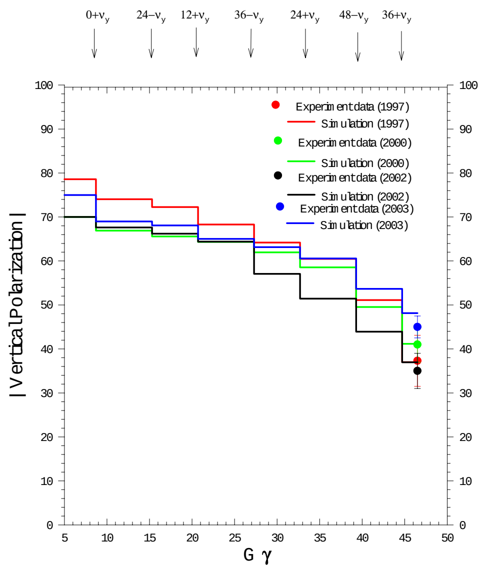

Figure 2: Measured AGS polarization vs. simulation for various years.

70-75% polarization. The beam was then strip-injected and accelerated in the AGS Booster up to 2.5 GeV or $G\gamma = 4.7$.

At the AGS, a 5% partial Siberian snake that rotates the spin by 9° is sufficient to avoid depolarization from imperfection resonances up to the required RHIC transfer energy [4]. Full spin flip at the four strong intrinsic resonances can be achieved with a strong artificial rf spin resonance excited coherently for the whole beam by firing an ac dipole [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. Since the intrinsic and coupling resonance strength is dependent on transverse emittance, it is very important to maintain emittance as small as possible. The beam was scraped in three dimension in the Booster: both transverse dimensions and longitudinal dimension. The longitudinal scraping is to meet the RHIC requirement of 0.5 eV-s longitudinal emittance. 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 40-45%. A future, much stronger partial snake should eliminate depolarization in the AGS [6].

A new polarimeter based on proton carbon elastic scattering in the Coulomb Nuclear Interference (CNI) region has been installed in AGS to measure polarization fast and reliably. The polarimeter consists of ultra-thin carbon targets(5 μg/cm^2 and 600 μm wide) and two silicon detectors. Fig. 3 shows the layout of the AGS CNI polarimeter. The electronics has to be designed and installed carefully to live with the noisy environment of AGS ring. One advantage of this new polarimeter is to measure polarization during acceleration. Fig. 4 shows such a ramp measurement compared with expected polarization. The analyzing power for CNI process is expected to be largely independent of energy for energy above a few GeV. These data show that other process might have mixed in and analyzing power is not a constant in this energy region.

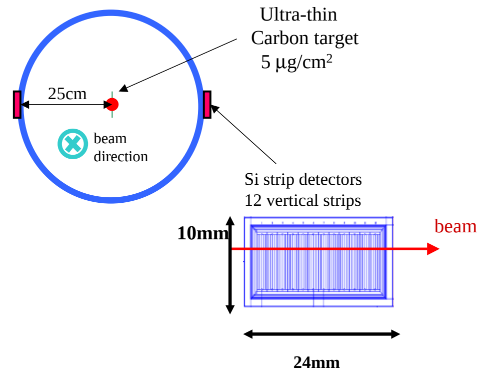

Figure 3: The layout of the AGS CNI polarimeter. The two Si strip detectors measure left-right asymmetry of recoil carbons at 90 degree recoil angle.

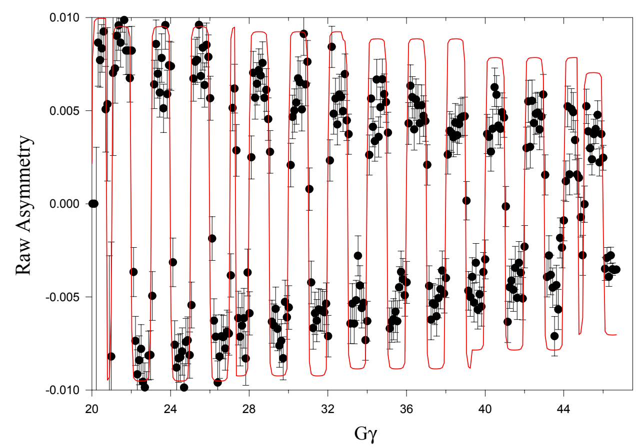

Figure 4: The measured asymmetry between $G\gamma = 20$ to 46.5. The 5% partial snake flips spin at every integer of $G\gamma$.

POLARIZED PROTONS IN RHIC

The basic construction unit for RHIC snake is a superconducting helical magnet producing a 4T dipole filed that rotates 360° in a length of 2.4 meters. These magnets are assembled in group 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 second RHIC polarized proton run of nine weeks are still going on. Spin Rotators are required at the IRs used by PHENIX and STAR to allow measurements of spin effects with longitudinally 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 have

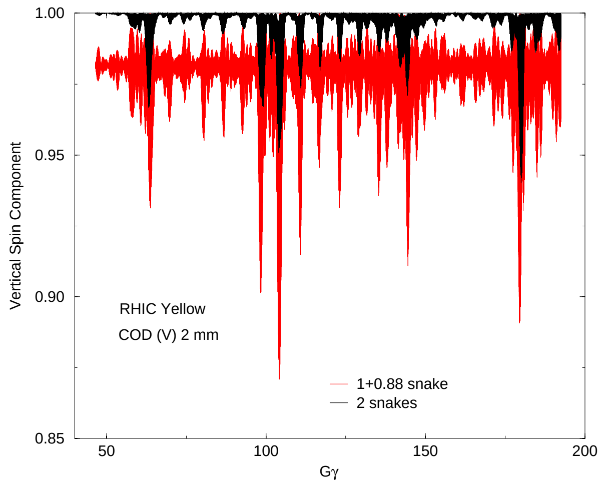

Figure 5: A single particle spin tracking for Yellow ring with two snakes and 1.88 snake scenarios. For the 1.88 snake case, the stable spin direction is not vertical.

been installed in the RHIC after last run. 60 bunches pattern was used in each ring (55 filled, 5 empty for an abort gap). The beam emittance was about 12 π mm-mrad in both transverse planes. The beam was injected into RHIC with 10 m β^* lattice and accelerated up to 100 GeV without beta-squeeze. β^* was then squeezed down to 1 m and 3 m at various IRs. A separate rotator ramp brings spin to longitudinal at IR 8 [7]. The set at IR 6 will be commissioned soon. The total intensity of 3.3×10^{12} and peak luminosity of about 4.5×10^{30} cm^{-2}s^{-1} have been achieved.

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 3/14 snake resonance. Close attention was also paid to the orbit, since the imperfection resonance strength is proportional to the rms orbit error.

In the middle of operation, one helical magnet unit failed due to defects of coils. With the rest units, we decided to run this snake as a 88% partial snake while keeping the angles between the two snakes as 90°. The polarization in Yellow was recovered with the new configuration although it is more sensitive to tune value and orbit errors. Simulation shown in Fig. 5 confirms this. In general, the polarization level was not as good as Blue ring.

Although the analyzing power at 100 GeV for the RHIC polarimeter is unknown, it is expected to be similar at injection energy. Under this assumption the polarization measured at store was typically about 30-35%, while injection polarization is consistently about 40%. One example is shown in Fig.6. The loss of polarization is likely in the beta squeeze part of the ramp.

CHALLENGES AHEAD

The real time tune control system has been tested successfully for a few RHIC fills along the up ramp. But it

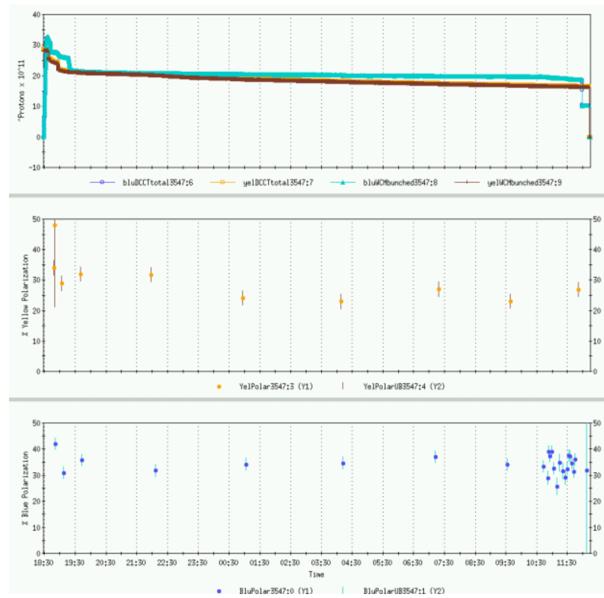

Figure 6: Beam intensity (top) and measured polarization in the Blue (bottom) and Yellow (middle) rings for a typical store.

needs work to be operational. It is essential to have the tune control system operational to control betatron tunes along the ramp. In RHIC the primary source of coupling comes from quadrupole rolls in the triplet quadrupoles at the six interaction regions. In addition, a small longitudinal field is introduced by each helical dipole snake. The decoupling was done fairly well at injection and flattop. However, problems during the ramp persisted since a dynamic correction technique has yet to be implemented.

There are also intensity limitation due to vacuum pressure rise for 110 bunch of 10^{11}. Some beam study has been done to fight this problem [8]. Another limitation we are facing is beam-beam tune shift limit [9]. The beam-beam tune shift is about 0.012 for four IRs. We have to live with operation close to the beam-beam tune shift limit.

To reach the desired 70% polarization in RHIC, a new strong partial snake in the AGS, higher polarization from the source, and good control of RHIC orbit and tunes are needed.

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