# SPIN TRANSPARENCY EXPERIMENT TEST IN RHIC[*]

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## Abstract

A novel technique, called spin transparency mode, for preservation and control of electron and ion spin polarizations in colliders and storage rings has been proposed. The beam polarization can then be fully controlled by small adjustments of the snake axis orientations and snake strengths. An experiment has been carried out recently to test the concept. One of the RHIC rings is set to be transparent to the spin by making the axes of its two Siberian snakes nearly parallel. The polarization was rotated from vertical to radial and from up to down by varying the snake currents. This paper summarizes the recent experiment results and discusses the comparison with simulations.

## INTRODUCTION

For periodical accelerator structure, the spin motion is also periodic, which results in spin tune concept. Spin tune $\nu_s$ is defined as number of spin precessions per orbit turn. For a perfect planar synchrotron, it is given as $\nu_{sp} = G\gamma$, where $G$ is the gyromagnetic anomaly and $\gamma$ is the Lorentz factor. Because of the periodic property, the spin motion can experience resonant motion. These resonances can be divided into a few categories: imperfection resonances, intrinsic resonances, synchrotron side band resonances, etc. The resonance strength is a function of energy ($G\gamma$), the lattice used (betatron tune, beta functions), the magnitude of field error, and orbit error. Spin transparency mode was proposed initially as a way to deal with depolarizing resonances in the low and medium energy synchrotrons. It is also useful to overcome depolarizing resonances in polarized deuteron [1] in future Electron Ion Collider(EIC) [2].

A particle moving on a closed orbit in a ring has a unique distinct periodic spin precession axis $\vec{n}$ [3] except when it is in an integer spin resonance. In an integer spin resonance, the direction of the periodic spin precession axis $\vec{n}$ is degenerate. Any spin direction repeats after an orbit turn, i.e., the synchrotron becomes transparent to the spin. In general, synchrotrons can be operated in two polarized beam modes, namely, Distinct Spin (DS) mode and Transparent Spin (TS) mode. In the DS mode, the periodic spin motion along the closed orbit is unique, i.e. the static magnetic lattice determines a single stable orientation of the beam polarization. In the TS mode, the spin direction is stabilized by introducing small-integral static magnetic fields [4].

Polarized rings have traditionally operated in the DS mode such as in Relativistic Heavy Ion Collider(RHIC) [5]. In general, the difficulties with preserving the ion beam polarization are associated with crossing of spin resonances [6]. In a conventional ring without spin control devices, the stable polarization is vertical and the spin tune is proportional to energy that unavoidably leads to crossing of spin resonances. Polarization can be preserved in the DS and TS modes using Siberian snakes [7] by stabilizing the spin tune in the whole energy range at $\nu_s = 1/2$ in the DS mode and at $\nu_s = 0$ in the TS mode. The energy independence of the spin tune eliminates crossing of spin resonances during beam acceleration. However, at medium energies, solenoidal snakes are not sufficiently efficient while transverse- field snakes cause a large orbit excursion and strong focusing. Moreover, full Siberian snakes are not practical for deuterons due to their small anomalous magnetic moment. An elegant solution for acceleration of any polarized ions including deuterons is to use a figure-8-shaped accelerator operating in the TS mode [8] . The spin tune of an ideal figure-8 accelerator is zero for any beam energy, i.e. the particles are in the region of an integer spin resonance. To stabilize the polarization direction, instead of strong snake fields, it is now sufficient to introduce a weak field to overcome the effect of the integer spin resonance strength. For example, a longitudinal field integral of about 1 T-m is sufficient to preserve the polarizations of both protons and deuterons during acceleration to 100 GeV [9]. The main difference between the DS and TS modes is in how the polarization direction is manipulated in each of the two modes. Polarization control in the DS mode is done locally (in a detector) using high-field-integral spin rotators, which affect the orbital motion. In the TS mode, stabilization of the desired spin direction at any orbital location for particles of any kind is done using small-integral quasi-static magnetic fields. This provides a lot of flexibility when designing injection, polarimetry and spin-flipping systems.

A spin transparency mode of operation of RHIC would allow preservation and control of ion spin polarization at store [10]- [11]. It makes the ring lattice invisible to the spin and allows for polarization control by small quasi-static magnetic fields with practically no effect on beam orbital parameters.

The goal of the proposed study is experimental verification of this novel technique. One of the RHIC rings is set to be transparent to the spin by making the axes of its two Siberian snakes nearly parallel (see Fig. 1). The beam polarization can then be fully controlled by small adjustments of the snake axis orientations (a few degrees) and snake strengths
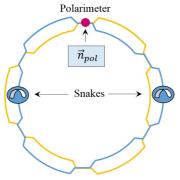
Figure 1: RHIC snake can be configured to be spin tune=0 for the TS mode operation.

(a few percent). One can adjust any polarization at the IP without spin rotators and adiabatically flip the spin with 100% efficiency not using rf magnets. The spin transparency mode has been demonstrated in simulations. This study would provide experimental data to validate the simulation results.

With the spin transparency mode, the spin can be manipulated by small magnetic fields. For example, The two snake strengths can be tuned away from $\pi$ by the amount $\delta\mu_1$ and $\delta\mu_2$ respectively. This will provide spin rotation about the axes with longitudinal and radial components:

$$\nu_x = (\delta\mu_1 - \delta\mu_2)\sin(\gamma G\pi/2)/2\pi \qquad (1)$$
$$\nu_z = -(\delta\mu_1 + \delta\mu_2)\cos(\gamma G\pi/2)/2\pi \qquad (2)$$

On the other hand, small angle $\delta\alpha$ between the two snake axes provides rotation about the vertical axis:

$$\nu_y = (\delta\alpha)/\pi \qquad (3)$$

The polarization direction is given by $\vec{n} = \vec{\nu}/|\nu|$.

Demonstration of the spin transparency concept would benefit both current polarized proton RHIC operation and the future EIC. It provides the capability of adjusting any polarization direction at the interaction point without spin rotators by only small adjustments of the snake settings that have essentially no impact on the beam dynamics and can even be done during an experiment. The beam polarization can be adiabatically flipped without using rf magnets with no polarization loss. The spin transparency mode allows for longitudinal polarization of the deuteron beam. It may also benefit the electron beam of the EIC by equalizing the lifetimes of the two spin states and simplifying electron spin matching.

## EXPERIMENT RESULTS

The experiment was designed as following. It is optimal to adjust the snake axes to 0° with regards to the longitudinal direction. It comes with minimum field integral and consequently minimum orbit excursion. One additional practical advantage is that there is no change in field and power supply

polarities. The stable vertical polarization with a spin tune of about 0.05 is set in RHIC by adjusting the angle between the snake axes to 10°. The strengths of both snakes are set to 180°, while the snake axes are set to -10° and 0° with respect to the beam direction, respectively. Then vertically polarized beam was injected into Yellow ring of RHIC. The polarization in the ring is measured using RHIC polarimeter [12]. Two spin rotations were performed. The first one is to rotate the spin from vertical to radial by changing the four snake helix currents. The second one is to rotate the spin from vertical up to vertical down, or flip the spin.

For the radial rotation experiment, ZGOUBI code [13] was used to design the snake current paths [14]. Fig. 2 shows that the spin tune is more or less a constant (around 0.06) and spin direction changes from mostly vertical to radial. The longitudinal component does not change between the initial and final states. The snake currents of four helix magnets are changed linearly during this time.
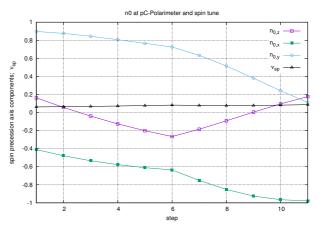


Figure 2: Simulated spin direction and spin tune as functions of the ten steps in the radial spin rotation.

Proper orbit bumps around snakes are used to run snakes at the new configuration with spin tune near zero [15]. The polarimeter can measure the vertical and radial components of the polarization. The polarization amplitudes are shown in Fig. 3. Four snake currents should reach the final state at the same time. On the other hand, even with the not perfect ramp, the spin did rotate from vertical to radial. The polarization directions measured at the initial state does not have much radial component as simulations showed. The final state angle matches the expectation. Polarization was measured multiple times at initial and final states. The average polarization at the two states are listed in Table 1. Snake currents were ramped continuously from the initial to final states. During the ramp, polarization were also measured twice and are given in Table 1 with larger error bars. All the polarization measurements show a gradual change of spin direction from vertical to radial. The initial test showed that the spin manipulation (rotating from vertical to radial) with changing snake currents works. From the simulations, the longitudinal polarization component is similar in the two states.
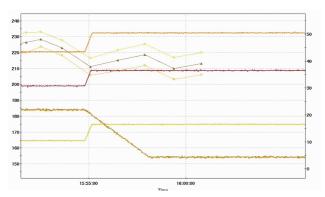
Figure 3: Polarization measurements with error bars and the four snake currents during the radial spin rotation path.

Table 1: The Polarization In One Step

| Step | Polarization | Angle (°) | Polarization ratio |
|------|-------------|-----------|-------------------|
| initial | 46.6$\pm$1.7 | 2.0$\pm$3.2 | |
| mid 1 | 37.9$\pm$3.2 | -22.0$\pm$6.2 | 0.81$\pm$0.07 |
| mid 2 | 40.3$\pm$3.8 | -67.6$\pm$3.8 | 1.06$\pm$0.13 |
| final | 39.6$\pm$2.3 | -94.0$\pm$2.3 | 0.98$\pm$0.11 |

The two measurements during snake current ramp showed continued rotation of the spin from vertical to radial. Another set of polarization measurements at each of the ten intermediate steps were taken and the data set is shown in Table 2. Again, the polarization shows the expected rotation from vertical to radial. The average polarization loss per step is similar to the total polarization loss in one step, at about 15%.

Several different snake current paths were tested, including the synchronized snake current ramping and constant spin tune in addition to the synchronization. The best final to initial polarization ratio was with the unsynchronized snake ramp. It was 85.0$\pm$6.0%. For the two cases of using constant spin tune as 0.056 (65.9$\pm$6.0%) and just synchronized (69.8$\pm$4.3%), the polarization transmission ratio is similar but lower than the unsynchronized case. Simulations were carried out for these conditions. The results showed that near perfect spin rotation efficiency is expected for all these cases.

The second part of the experiment was to flip spin from vertical up to vertical down, namely, change the angle from 0° to 180°. For this process, constant spin tune in the process is important. In the first attempt with spin tune varying from 0.064 initial state to 0.035 at middle point, polarization was lost in the flipping process. Using the snake current path with constant spin tune as 0.056, the spin flip is achieved with 59.6$\pm$4.4% spin flip efficiency. The simulated spin rotation is shown in Fig. 4. With a factor of 2 slower snake ramp, the spin flip polarization ratio is not changed: 59.1$\pm$4.8%. With spin tune as 0.03, the flip efficiency (polarization ratio) is comparable to the case of 0.056: 62.1$\pm$5.0%.

Table 2: The Polarization In Ten Steps

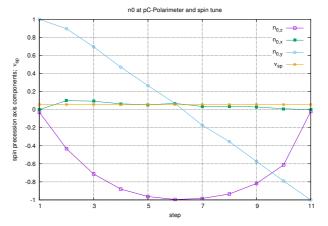| Step | Polarization | Angle (°) | Polarization ratio |
|------|-------------|-----------|-------------------|
| initial | 35.9 $\pm$0.9 | -2.1$\pm$2.2 | |
| 2 | 30.5$\pm$ 0.9 | -7.6$\pm$ 2.6 | .85 $\pm$.03 |
| 3 | 26.3$\pm$ 1.0 | -15.9$\pm$ 2.9 | .86 $\pm$ .04 |
| 4 | 26.3$\pm$ 1.0 | -19.4 $\pm$ 2.8 | 1.00$\pm$ .05 |
| 5 | 22.8$\pm$ 1.2 | -30.1$\pm$ 3.2 | .86$\pm$ .05 |
| 6 | 17.1$\pm$ 1.3 | -37.5$\pm$ 4.2 | .75 $\pm$.07 |
| 7 | 14.7$\pm$ 1.3 | -40.7 $\pm$ 4.7 | .86 $\pm$.10 |
| 8 | 12.6$\pm$ 1.5 | -62.8 $\pm$ 4.7 | .85$\pm$ .12 |
| 9 | 11.3$\pm$ 1.5 | -64.4$\pm$ 4.9 | .90$\pm$ .16 |
| 10 | 7.7$\pm$ 1.6 | -78.9$\pm$ 7.3 | .69$\pm$ .16 |
| final | 7.3$\pm$ 1.4 | -84.0 $\pm$ 6.9 | .95$\pm$ .26 |



Figure 4: Simulated spin direction and spin tune as functions of the ten steps in the spin flip path.

## SUMMARY

After setting yellow ring of RHIC to spin transparency mode ($\nu_{sp} \sim 0$), the spin rotations were performed by varying the snake rotation angles and rotation axes. The spin did rotate as expected but polarization losses are also observed in the process. The results show that the constant spin tune is important while the ramping speed and the specific spin tune value do not matter. These two results are in agreement with simulations. There could be several reasons for the polarization losses. First, the calibration of the snake strengths and angles as function of helix currents could be off, which would result in some amount of spin tune error in the snake ramping path. Second, the power supply ripples during the ramping of helix magnets may not be smooth enough which could cause additional unwanted spin tune disturbance. To improve the efficiency of this novel scheme, more simulation studies and calibration of snake current will be done.

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