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SIMULATION OF TRANSPARENT SPIN EXPERIMENT IN RHIC*

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Abstract

The transparent spin mode has been proposed as a new technique for preservation and control of the spin polarization of ion beams in a synchrotron. The ion rings of the proposed Jefferson Lab Electron-Ion Collider (JLEIC) adopted this technique in their figure-8 design. The transparent spin mode can also be setup in a racetrack with two identical Siberian snakes. There is a proposal to test the predicted features of the spin transparent mode in Relativistic Heavy Ion Collider (RHIC), which already has all of the necessary hardware capabilities. We have earlier analytically estimated the setup parameters and developed a preliminary experimental plan. In this paper we describe simulation setup and benchmarking for the proposed experiment using a Zgoubi model of RHIC.

MOTIVATION

For Electron Ion Collider (EIC), the high electron and ion polarizations are some of the key requirements [1] that include high polarization (> 70%) of protons and light ions (d, $^3He^{++}$, and possibly $^6Li^{+++}$); It also requires both longitudinal and transverse polarization orientations available at all interaction points (IPs), a sufficiently long polarization lifetime, and spin flipping. As a novel technique, the transparent spin (TS) mode makes the ring lattice "invisible" to the spins and allows for polarization control by small magnetic fields just slightly breaking this spin motion degeneracy. In practice, TS mode offers unique opportunities for design of electron and ion polarization dynamics in JLEIC and electron polarization dynamics in Brookhaven's eRHIC [2-5].

In order to further develop the spin dynamics theory and verify TS experimentally, cconsidering all technical capabilities and investigating the current existing colliders, it was proposed to experimentally test in RHIC [5]. RHIC schematically shown in Fig. 1 is a perfect place for an experimental test of the TS mode because it requires no new hardware. Making the snake axes parallel at 0° will set RHIC in the spin transparency mode. This adjustment yields minimum field integral, minimum orbit excursion and requires no flip of the field sign and power supply polarities. The snake currents can be changed dynamically at 1 A/s [6]. The existing polarimeter can provide a fast polarization measurement. Only relative measurement is needed.

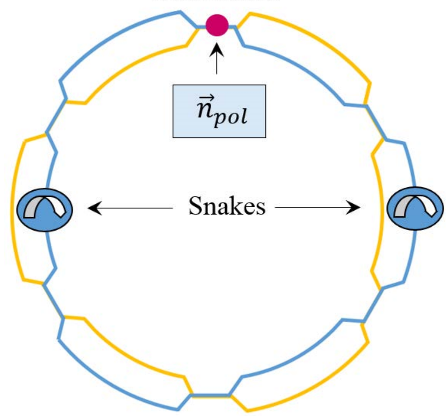

Figure 1: RHIC ring with two helical snakes.

MODEL OF TRANSPARENT SPIN MODE

The total TS resonance strength consists of the coherent and incoherent parts:

$$\omega = \omega_{coh} + \omega_{emitt}. \tag{1}$$

The spin stability criterion is that the spin tune induced by a spin rotator must significantly exceed the TS resonance strength. ω_{coh} can be estimated using a statistical model. Assuming independent random misalignments of machine elements, it is given by

$$|\omega_{coh}| = \sqrt{\frac{1}{4\pi^2} \sum_{elements} \frac{\overline{\Delta B_x^2 L_x^2}}{(B\rho)^2} |F|^2} \tag{2}$$

where $\overline{\Delta B_x^2}$ is the average of an element's error radial magnetic field squared, L_x is the element's length, $B\rho$ is the magnetic rigidity, and F is the spin response function $\overline{\Delta B_x^2 L_x^2}$ arises primarily [4] due to vertical quadrupole misalignments Δy

$$\overline{\Delta B_x^2 L_x^2} = \left(\frac{\partial B_x}{\partial y}\right)^2 \overline{\Delta y^2} L_x^2 \tag{3}$$

and dipole roll $\Delta\varphi$

$$\overline{\Delta B_x^2 L_x^2} = \theta^2\, \overline{\Delta\varphi^2}\, (B\rho)^2 \tag{4}$$

where θ is the dipole bending angle.

The rms vertical excursion of the closed orbit is

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$$\overline{y^2}(z) = \frac{\beta_y(z)}{8\sin^2(\pi\nu_y)} \sum_{elements} \frac{\overline{\Delta B_x^2} L_x^2}{(B\rho)^2} \beta_y(z_j) \tag{5}$$

For the expected closed orbit excursion, one can estimate $|\omega_{coh}|$. We find $|\omega_{coh}|$ for RHIC's injection lattice assuming an rms vertical closed orbit excursion of 0.2 mm. We then compare it to simulation results.

NUMERICAL SIMULATION AND RE-SULTS

We use Zgoubi to simulate some of the TS mode features in RHIC lattice [7, 8].

Case-1

In a principle scheme of RHIC snake (OPERA maps), two currents control the spin rotation angle and the spin rotation axis. By tracking three particles with orthogonal spins in Zgoubi, we determine the spin rotation angle and axis for a given set of snake currents. The snake currents are then varied using a fitting procedure [8] to adjust the snake axis to 0°.

The evolutions of the spin components along the helical trajectories are shown in Fig. 2. The simulation in Fig. 2 indicates a full snake with a longitudinal axis: the radial and vertical spins flip while the longitudinal spin remains longitudinal.

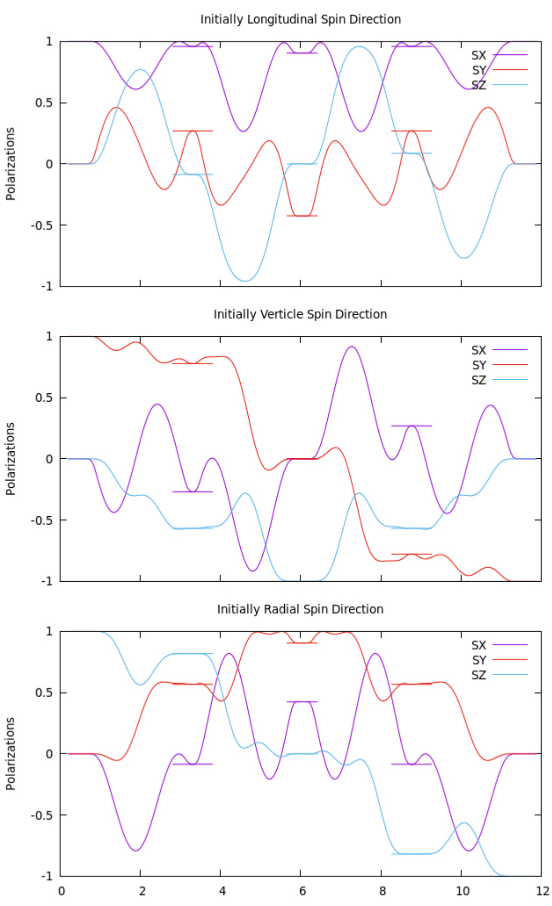

Figure 2: Tracking three initially orthogonal spins through a snake.

The closed orbits inside a snake for the 45° and 0° settings of its axis are shown in Fig. 3. Note the smaller closed orbit excursion for the 0° case.

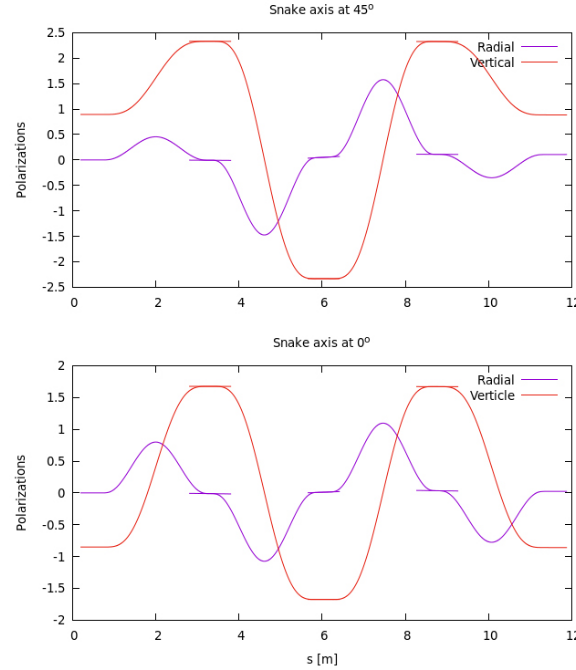

Figure 3. The closed orbits inside a snake: (top) 45° snake axis angle; (bottom) 0° snake axis angle.

Case-2

The spin motion is governed by a lattice design. As a sanity check, we first use an ideal lattice with the Siberian snakes modeled as thin spin rotators. When the snake axes are parallel, the spin tune is zero, which means the spin components do not change from turn to turn.

After precisely adjusting the total bending angle of all of the dipole magnets to sum up to 2π, we observe that the RHIC ring is spin transparent in a simulation: all of the spin components are constant from turn to turn with a good numerical precision as shown in Fig. 4.

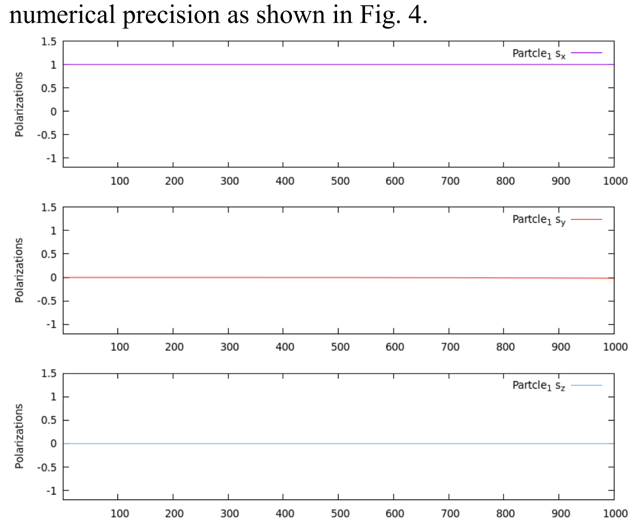

Figure 4: Spin components of a particle initially having $S_x = 1$ as a function of the turn number after the beam bending angle adjustment.

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Case-3

We next introduced random transverse quadrupole misalignments Δy and dipole roll $\Delta\varphi$ with rms magnitudes that provide 0.2 mm vertical closed orbit distortion ac-cording to a statistical model prediction. The radial y and vertical z closed orbit excursions for 10 different random seeds are shown in the Fig. 5. Averaging over all seeds gives a rms vertical closed orbit excursion of about 0.18~mm.

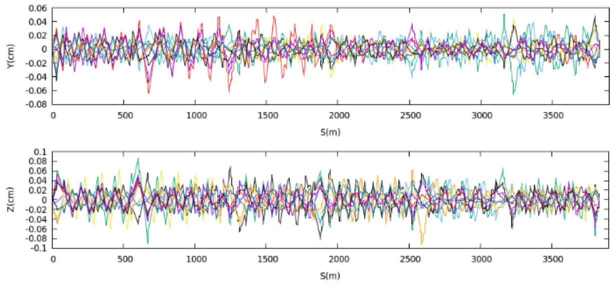

Figure 5: Trajectory: radial (top) and vertical (bottom) closed orbit excursions around RHIC for 10 different random seeds.

Case-4

After introducing the above rms Δy and Δφ we determine the spin resonance strength by tracking a particle with initially longitudinal spin for 2000 turns. The particle spin precesses about the spin field direction at a rate determined by the transparent spin resonance strength. An inverse of the number of turns it takes the spin to make one full oscillation is the resonance strength.

The spin field direction and the resonance strength are obtained by fitting the data in Fig. 6 to offset spin curves (sine waves).

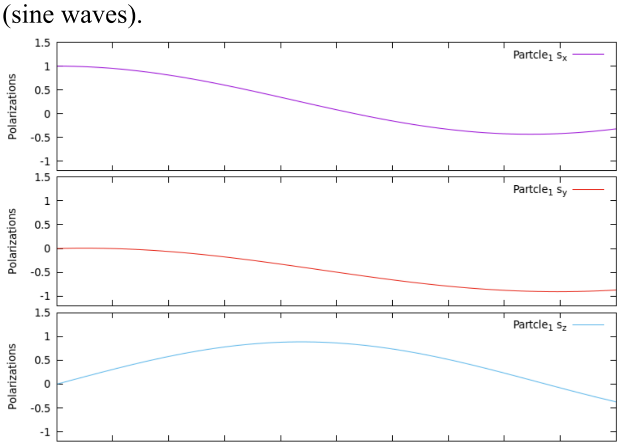

Figure 6: Spin components of a particle initially having $S_x = 1$ as a function of the turn number in a ring with random errors.

$$\begin{aligned}\vec{P}(N) = {} & \vec{P}_i \cos(2\pi\omega_{Coh}N) \\ & + (\vec{n}\times\vec{P}_i) sin(2\pi\omega_{Coh}N) \\ & + \vec{n}(\vec{n}\cdot\vec{P}_i)[1+\cos(2\pi\omega_{Coh}N)\end{aligned} \tag{6}$$

where, N is the turn number; $\vec{P}$ represents polarization and $\vec{P}_i$ is the initial polarization; the frequency of the sine wave gives the resonance strength and the offsets provide the spin field direction. The obtained resonance strength of $3.0\cdot10^{-4}$ is consistent with the theoretical prediction of $3.2\cdot10^{-4}$. The spin field $\vec{n} = (0.53,\ -0.84,\ 0.08)$ is nearly horizontal as expected.

CONCLUSION

The spin tracking validates the polarization control parameters for the transparent spin experiment in RHIC. We adjusted the snake axes and corrected their orbital effect. Thus, we obtained an accurate model of RHIC's ring with the snakes specified by field maps. Random quadrupole misalignments and dipole roll were introduced in RHIC's lattice. A closed orbit was determined and the transparent spin resonance strength was obtained by spin tracking. Both the rms closed orbit and resonance strength are consistent with the statistical model predictions reported earlier [3, 4].

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