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EXPERIMENTAL VERIFICATION OF TRANSPARENT SPIN MODE IN RHIC*

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Abstract

High electron and ion polarizations are some of the key design requirements of a future Electron Ion Collider (EIC). The transparent spin mode, a concept inspired by the figure 8 ring design of JLEIC, is a novel technique for preservation and control of electron and ion spin polarizations in a collider or storage ring. 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 the beam's orbital characteristics. It offers unique opportunities for polarization maintenance and control in Jefferson Lab's JLEIC and in BNL's eRHIC. The transparent spin mode has been demonstrated in simulations and we now plan to test it experimentally. We present a design of an experiment using a polarized proton beam stored in one of the RHIC rings. In the experiment, one of the RHIC rings is configured in the transparent spin mode by aligning the axes of its two Siberian snakes. The experiment goals, procedures, hardware requirements and expected results are presented.

INTRODUCTION

A particle moving on a closed orbit in a ring has a unique "distinct" periodic spin precession axis $\vec{n}$ [1] 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 a particle turn, i.e., the collider becomes "transparent" to the spin. Thus, rings can operate 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 [2].

Polarized rings has traditionally operated in the DS mode [3]. In general, the difficulties with preserving the ion beam polarization are associated with crossing of spin resonances [4]. 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 [5] by stabilizing the spin tune in the whole energy range at $\nu = 1/2$ in the DS mode and at $\nu = 0$ 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 [6]. 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 $1\ \mathrm{T \cdot m}$ is sufficient to preserve the polarizations of both protons and deuterons during accelerator to 100 GeV [7]. To stabilize the spin tune during acceleration, the solenoid field should change proportionally to the beam momentum.

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.

For polarization stability in the TS mode, the spin tune induced by the weak control fields must significantly exceed the resonance strength, which consists of two parts: a coherent part ω_{coh} arising due to spin perturbing transverse and longitudinal fields on the distorted closed orbit and an incoherent part ω_{emitt} associated with the beam emittances. In practice, the coherent part significantly exceeds the incoherent one: $\omega_{coh} \gg \omega_{emitt}$ [8].

The TS concept along with some of its benefits can be extended to a racetrack ring by setting its spin tune to zero. This can be done using a couple of symmetrically located identical Siberian snakes.

TS MODE IN JLEIC

A natural example of a collider transparent to the spin is the proposed Jefferson Lab Electron Ion Collider (JLEIC)

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with figure-8 shaped rings [9]. In such a collider, effect of one arc on the spin is compensated by the other arc. As an example, Fig. 1 shows a scheme for setting the longitudinal polarization in the experimental straight section of JLEIC by activating a weak solenoid of a universal 3D spin rotator [10]. Since the effect of the whole ring on the polarization over one particle turn is reduced to zero, the spin motion is stabilized by the solenoid, which "forces" the longitudinal polarization direction at the solenoid location. The subsequent polarization dynamics along the collider ring is determined by strong arc fields, which rotate the spins in the collider's plane returning them to the longitudinal polarization after a full particle turn.

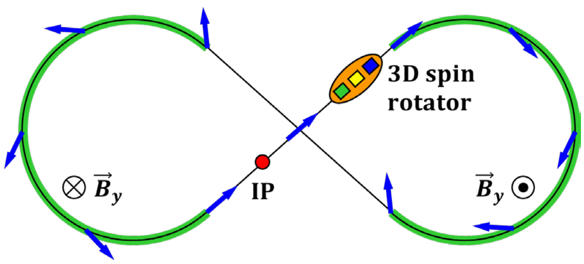

Figure 1: Schematic of polarization dynamics in JLEIC.

To obtain any polarization direction at the collision point for any particle species including deuterons, the universal 3D spin rotator includes three modules, which can rotate the spin about three orthogonal axes (n_x, n_y, n_z). They are built using weak solenoids and stabilize a given polarization direction $\vec{P} = \vec{n}$. The 3D rotator can flip the polarization by adiabatically reversing $\vec{n}$ while keeping the spin tune constant.

The JLEIC electron collider ring also relies on the TS mode of operation. While nuclear physics experiments require longitudinal polarization at the interaction points, the spin dynamics necessitates vertical electron polarization in the collider arcs to avoid the spin diffusion due to spin orbit coupling. There are spin rotators at the ends of each arc to rotate the vertical polarization to the longitudinal direction. However, the spin motion in the JLEIC electron ring is organized in the ST mode. It provides (a) identical evolution of the opposite spin states avoiding systematic asymmetries due to the Sokolov-Ternov effect, (b) absence of synchrotron side-band resonances due to energy independence of the spin tune and therefore improved polarization lifetime, and (c) simplified spin matching of the electron spin rotators by their solenoids cancelling each other's effect thus improving the polarization lifetime.

TS MODE IN RHIC AND ERHIC

As illustrated in Fig. 2, polarization in each ring of RHIC is controlled using two helical snakes rotating the spin about the axes at $+45°$ and $-45°$ with respect to the beam direction. In this case, RHIC operates in the DS mode, the spin tune equals $1/2$ and the stable polarization orientation is unique and is vertical in the collider's arcs. Any other polarization direction lying in the collider's plane rotates by 180° every orbit turn and, due to the spin tune spread, vanishes in a few thousand turns.

The existing snakes can also be used for operation of RHIC in the TS mode. The spin rotation axes of the helical snakes lie in the collider's plane and are set by the snakes' magnetic fields [11]. The spin tune is determined by the angle φ between the snake axes and the stable polarization in the collider's arcs is vertical:

$$\nu = \frac{\varphi}{\pi}, \qquad \vec{n}_{arc} = \pm\vec{e}_y. \tag{1}$$

The spin tune equals one half (RHIC's regular mode of operation) if the angle between the snake axes is $\pi/2$. To convert RHIC to the TS mode, when the spin tune is zero (or one), the angle between the snake axes must be set to zero (or π), i.e. the snakes must be identical. The effect of the strong fields in the arcs and snakes on the spin reduces to zero over one orbit turn, any polarization direction repeats after each orbit turn.

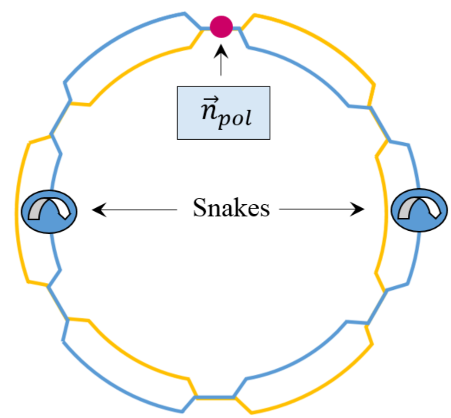

Figure 2: RHIC ring with two helical snakes.

Thus, two identical snakes convert RHIC to the TS mode and, from the spin dynamics point of view, it becomes equivalent to a figure-8 collider. While geometrically obviously still different, the two kinds of rings have identical topologies of the spin motion. The two snakes located opposite to each other in a circular ring divide the ring into two 180° arcs. Due to the action of the snakes, the spin sees opposite fields in the two arcs in exactly the same way as it happens in a figure-8 ring. JINR (Dubna, Russia) develops the NICA collider project with two solenoidal snakes set in the TS mode [12].

Note that the axes' orientation of the identical snakes can be arbitrary in the orbital plane, which can be used for additional optimization of the beam's transverse deviation from the design orbit at the proton injection energy.

Although not included in the present eRHIC design [13], the TS mode can be arranged in the eRHIC ion and electron collider rings by appropriately configuring snakes and spin rotators. The benefits of such a configuration could be similar to those of the JLEIC ion and electron figure-8 rings discussed above. This option needs further analysis.

SPIN CONTROL IN TS MODE IN RHIC

In the regular DS mode of operation, the longitudinal polarization at the collision point is provided using a pair of

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radial rotators, which first turn the polarization direction to be along the beam moving direction and then restore the vertical polarization back before the beam enters the collider's arc. The radial rotators do not change the spin tune leaving it equal to one half.

In the TS mode, to control the polarization at the collider's collision point or polarimeter, one must use a 3D spin rotator with small control fields. 3D spin rotators can be realized in different ways. For example, one can use the existing snakes [14]. Polarization direction at the polarimeter $\vec{n}_{pol} = (n_x, n_y, n_z)$ can be controlled by adjusting a small angle $\delta\alpha$ between the snake axes and small offsets $\delta\mu_1$ and $\delta\mu_2$ of the snakes' spin rotation angles from π:

$$\nu_x = \frac{\delta\mu_1 - \delta\mu_2}{2\pi}\sin\left(\frac{\gamma G\pi}{2}\right), \qquad \nu_y = \frac{\delta\alpha}{\pi},$$
$$\nu_z = -\frac{\delta\mu_1 + \delta\mu_2}{2\pi}\cos\left(\frac{\gamma G\pi}{2}\right), \tag{2}$$
$$\nu = \sqrt{\nu_x^2 + \nu_y^2 + \nu_z^2}\,, \qquad \vec{n}_{pol} = \frac{(\nu_x, \nu_y, \nu_z)}{\nu}$$

where ν is the spin tune induced by the snake 3D spin rotator. Equation (2) assumes that both snake axes are longitudinal.

The described rotator allows one to set any 3D polarization direction at the polarimeter by small variation of the snake currents. Exceptions are $\gamma G = k$ points where the snake rotators allows one to set any 2D polarization orientation in the (yz) plane for even k and in the (yx) plane for odd k.

EXPERIMENTAL SCENARIOS

Vertically polarized protons are injected from the AGS into a collider ring. To match the injected polarization direction, the 3D spin rotator must provide vertical polarization in the collider's arcs. To meet this requirement, the spin rotation angle offsets $\delta\mu_1 = \delta\mu_2 = 0$ and the angle between the snake axes should be of the order of 10°, which provides a spin tune value:

$$\nu = \nu_y \approx 0.05 \quad (\nu_z = 0,\ \vec{n}_{pol} = \vec{e}_y). \tag{3}$$

To preserve the polarization, one must avoid crossing of spin resonances during acceleration. To accomplish this, it is sufficient to maintain a constant spin tune (angle between the snake axes).

Proton polarization control can be demonstrated by an example of reversing the vertical polarization component at the polarimeter. The polarization reversal is produced by a small variation of the angle between the snake axes with the spin rotation angle offsets $\delta\mu_1 = \delta\mu_2$ fixed ($\gamma G \neq k$). The vertical polarization component at the polarimeter is

$$\left(n_{pol}\right)_y = \frac{\nu_y}{\sqrt{\nu_y^2 + \nu_z^2}}. \tag{4}$$

The dependencies of the vertical polarization component at the polarimeter and of the spin tune on the angle between the snake axes at fixed $\delta\mu_1 = \delta\mu_2$ are shown in Fig. 3. An adiabatic change of the angle between the snake axes from $-10°$ to $+10°$ causes polarization flip. The spin rotators set the minimum value of the spin tune and eliminate the possibility of crossing the zero-integer spin resonance. In an experiment, one can use the following parameters of the 3D spin rotator:

$$\nu_z \sim 0.01 = const\,, \qquad -0.05 < \nu_y < 0.05 \tag{5}$$

In principle, such an experiment with $\delta\mu_1 = \delta\mu_2 = 0$ allows one to measure the strength of the zero-integer spin resonance through the characteristic width of the polarization reversal region. In that case,

$$\left(n_{pol}\right)_y = \frac{\nu_y}{\sqrt{\nu_y^2 + \omega^2}}, \qquad \nu_{min} = \omega. \tag{6}$$

The polarization measurement will be done with RHIC polarimeters. There are two polarimeters in each ring, and they are located near 12 o'clock IP. The polarimeters can provide polarization measurement with 2% statistical error in one minute for a fully loaded ring (110 bunches and $2 \cdot 10^{11}$ bunch intensity). If needed, these polarimeters can also provide turn-by-turn polarization evolution with special operation mode.

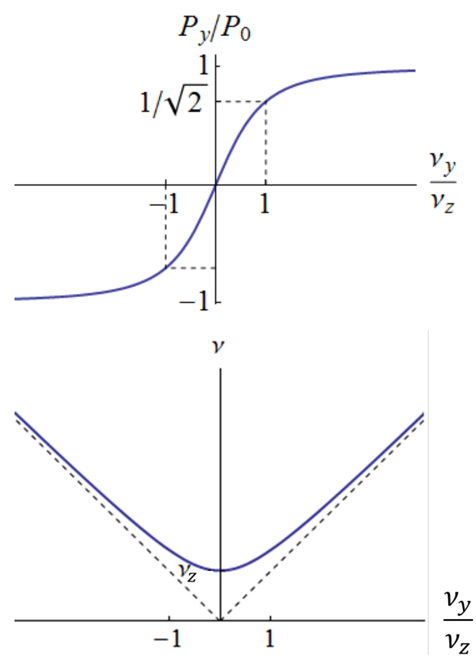

Figure 3: Dependencies of the vertical polarization component (top) and spin tune (bottom) on the angle between the snake axes at fixed $\delta\mu_1 = \delta\mu_2$.

CONCLUSION

A new mode of RHIC operation with a polarized proton beam, a transparent spin mode, has been proposed. It offers new opportunities for manipulation of the proton polarization at any location in the collider. BNL's RHIC has all of the necessary components for an experimental test of the new mode. Potential experimental scenarios have been presented. Experimental parameters are being developed [15]. The experiment will validate the TS concept as a new tool for polarization preservation and control in the existing and future synchrotrons.

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