Hadron polarization control at integer spin resonances in synchrotrons using a spin navigator

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We consider the capability of flexible spin-transparent polarization control and manipulation in conventional synchrotrons at integer spin resonances by means of spin navigators. The latter are designed as a couple of small solenoids separated by a constant beam bend. We formulate the requirements to the navigator design considering the criteria for stability of the spin motion in the presence of synchrotron energy oscillations. We propose the design of a novel spin-flipping system free of resonant beam depolarization based on such a spin navigator. We discuss the possibilities of testing spin-flipping systems at an integer spin resonance with protons in the Nuclotron ring at JINR in Dubna, Russia, and with deuterons in the RHIC rings at BNL in Upton, New York. The results are relevant to the existing and future facilities where the spin transparency mode can be applied for polarization control.

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I. INTRODUCTION

Polarized beam experiments are an essential part of the scientific programs at the future colliders including the accelerator complex NICA (Nuclotron-based Ion Collider Facility) [1] in Russia and the Electron Ion Collider (EIC) [2] in the USA. In these projects, the capabilities of polarized beam experiments can be significantly expanded using an advanced technique for polarization control called a spin transparency (ST) [3].

The general definition of an ST control of a polarized beam includes two principal properties: (1) the spin tune ν on the design orbit is zero i.e., any spin orientation repeats every orbital turn and the spin motion is degenerate; (2) the degeneracy is then removed by introducing a spin navigator (SN). An SN is a device composed of compact insertions of weak fields giving a certain stable periodic polarization direction $\vec{n}$ on the closed orbit and a small tune ν_N of the spin precession about $\vec{n}$ [4,5]. The effect of such a navigator on the spin should significantly exceed the influence of perturbing fields due to errors of beam transport lattice and beam emittances. An important advantage of this method is its high flexibility and efficiency in manipulating the stable spin including frequent spin flips at a constant ν during beam operation. This avoids resonant depolarization when manipulating the orientation of the beam polarization [6].

Birth and formation of the ST concept was stimulated by inception of the figure-8 booster and collider rings in the EIC design version proposed by Thomas Jefferson National Accelerator Facility [7,8]. On a flat figure-8 orbit, the spin tune is zero regardless of the particle energy. Spin degeneration is removed by insertion of a small solenoid [9]. This avoids the resonance depolarization problem during acceleration and maintenance of the polarized hadron beams. This property makes the figure-8 configuration a universal ST booster and collider ring for all polarized ion beam species. In particular, it arrives as a unique ST collider ring to harbor high-energy polarized deuterons, for which Siberian snakes are not practical.

The next crucial step in forming the ST concept was replacement of a single solenoid with a more flexible device, a spin navigator, which would be able to not only control the spin tune but to also manipulate the direction $\vec{n}$ of the stable polarization. This has naturally led to a scheme with two small solenoids separated by a fixed orbital bend [10]. Such an expansion of the spin control concept allows one to adjust the beam polarization to any desired orientation at any point along the orbit. This adjustment can be done not only as a static setting but also in real time during collider operation.

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The ST concept as a whole was next expanded for use in racetrack collider rings. The ST features can be implemented there by introducing a system of Siberian snakes resulting in a zero spin tune design. For example, two solenoidal snakes allow the NICA collider ring to work in the ST regime with polarized protons and deuterons in its entire energy range of up to 13.5 GeV/c [11]. One or more pairs of snakes are able to provide the ST regime for a polarized proton or ^{3}He beam in the RHIC rings of BNL in the energy range of up to 275 GeV. It has been proposed to experimentally verify this regime with protons in RHIC [12].

The ST approach can be expanded for application in future high-energy hadron colliders. Note that, at high energies, an SN can be designed more efficiently using transverse fields rather than solenoids. In addition, one can employ the spin *response function* [13–16] technique to develop an SN with transverse fields, which perturb the entire closed orbit of an ST synchrotron in a particular way. This special perturbation results in amplification of the navigator strength through the spin response of the ring lattice.

The ST concept in combination with the flexible SN technique thus simultaneously can provide solutions for the main aspects of spin control in polarized hadron beam facilities: acceleration, maintenance and manipulation of the coherent spin.

With certain limitations, the ST method of spin manipulation can also be expanded to stationary situations in the vicinity of resonance energies in racetracks without snakes when

$$\nu = \gamma G = k, \tag{1}$$

where γ is the relativistic Lorentz factor, G is the anomalous part of the gyromagnetic ratio, and k is an integer.

The limitations are in general due to the presence of the spin tune spread caused by the energy spread:

$$\Delta\nu = G\Delta\gamma = \gamma G(\Delta\gamma/\gamma). \tag{2}$$

In practice, the relative energy spread can be maintained small through acceleration and storage while the absolute spread $\Delta\gamma$ grows with energy. With synchrotron oscillations of $\Delta\gamma$ in a conventional racetrack without Siberian snakes, there is a growing probability of depolarization by the satellite spin resonances:

$$\bar{\nu} \equiv \bar{\gamma} G = k + m_s \nu_s, \qquad \gamma = \bar{\gamma} + \Delta\gamma, \tag{3}$$

where ν_s is the synchrotron tune, $\bar{\gamma}$ is the relativistic factor averaged over the synchrotron oscillations, and m_s is the satellite spin resonance number.

This paper specifies the requirements on the SN design for conventional racetracks associated with synchrotron oscillations. It then describes a spin-flipping system allowing one to eliminate resonant depolarization during spin reversals. The paper next considers the possibility of testing a proton polarization control system in the ST mode at integer resonances in Nuclotron, which is a polarized proton injector of the NICA collider [17,18]. We also discuss the possibility of testing a spin navigator for deuterons in RHIC when use of helical snakes is not practical.

II. SPIN NAVIGATOR IN A CONVENTIONAL RACETRACK

A. Requirements on the spin navigator fields

Let us consider the limitation on the spin navigator design when operating in the ST mode at integer spin resonances in conventional racetrack rings. First of all, the spin tune ν_N induced by the SN must significantly exceed the ST-resonance strength ω [3]

$$\nu_N \gg \omega. \tag{4}$$

The ST-resonance strength is the magnitude of the average spin field $\vec{\omega}$ determined by the deviation of the trajectory from the design orbit. This deviation is caused by construction and alignment errors of magnetic elements and the beam emittances. In the absence of a navigator, the spin rotates by an angle $2\pi\omega$ about the $\vec{\omega}$ direction in one orbital turn along the closed orbit. The spin completes its full rotation about $\vec{\omega}$ in $1/\omega$ orbital turns around the ring. The ST-resonance strength consists of two parts: a coherent part arising due to additional transverse and longitudinal fields on a trajectory deviating from the design orbit and an incoherent part associated with the particles' betatron and synchrotron oscillations (beam emittances):

$$\vec{\omega} = \vec{\omega}_{\mathrm{coh}} + \vec{\omega}_{\mathrm{emitt}}. \tag{5}$$

The literature traditionally calls the coherent part of the ST-resonance strength the "imperfection resonance strength." However, the incoherent part of the ST resonance strength does not vanish even in an ideal collider structure where the imperfection resonance strength is zero.

With increase in energy, the coherent part ω_{coh} dominates over the incoherent one ω_{emitt}. In a stationary situation, the coherent part does not cause beam depolarization and only results in a coherent rotation of the polarization about the spin field determined by the strength and alignment errors of the collider elements. In principle, the direction and magnitude of the coherent part of the resonance strength can be measured and taken into account for polarization control. To preserve the polarization, it is then sufficient to satisfy a weaker condition:

$$\nu_N \gg \omega_{\mathrm{emitt}}. \tag{6}$$

When a conventional collider without snakes is in the ST mode at an integer resonance, the spin tune is proportional to energy. One must then consider the constraints imposed on the navigator fields by synchrotron oscillations, which lead to satellite resonances. The strengths of the satellite resonances decrease sharply, when their numbers $m_s \gg \Delta\nu/\nu_s$. Therefore, implementation of the additional condition,

$$\nu_N \gg \max(\Delta\nu, \nu_s), \tag{7}$$

excludes the effect of satellite resonances on the spin dynamics [19].

B. Adiabatic capture of the polarization by a SN

When operating in the ST mode with a beam at an integer spin resonance, one must ensure alignment of the polarization orientation with the spin field direction induced by the SN. Away from the integer spin resonance, the stable polarization axis (the $\vec{n}$ axis) is determined by the arc dipoles and points vertically. At the resonance point, the $\vec{n}$ axis is determined by the spin field of the SN and lies in the synchrotron's plane. The aforementioned matching is automatically attained in the case of an adiabatic entrance into the ST resonance region.

When the condition of Eq. (7) is satisfied, one can adiabatically arrive at an ST resonance by ramping the average energy $\bar{\gamma}mc^2$ at a rate meeting an additional condition:

$$\frac{d\bar{\gamma}}{dt} \ll \frac{\Omega_0}{G}\nu_N^2, \tag{8}$$

where Ω_0 is the particle revolution frequency in the collider. In this case, the spin oriented vertically far from the resonance adiabatically tilts into the synchrotron plane until it lies along the spin field induced by the SN. During an adiabatic (slow) approach to the spin resonance point, the beam polarization degree is preserved to a high accuracy. In another limiting case, when the resonance is reached quickly, the particle spins have no time to change their orientation and remain vertical, i.e., transverse to the SN field, at the ST resonance point. As a result, when sitting after that at the ST resonance point, the polarization is lost due to the spin tune spread.

In the described process, the beam polarization is adiabatically captured into a stable state where it precesses about the SN axis $\vec{n}_N$ with the tune ν_N. It can be viewed as a "half" of the process of adiabatic crossing of an imperfection spin resonance using partial snakes widely used in practice. For example, solenoidal and helical partial snakes are used in the Alternating Gradient Synchrotron (AGS) at BNL to cross these resonances without polarization loss [20,21].

C. Spin navigators and partial Siberian snakes

A spin navigator and a partial Siberian snake have different design criteria and application areas.

The original intention and use of partial Siberian snakes is to overcome depolarization at imperfection resonances during acceleration when full Siberian snakes cannot be implemented or are not necessary. Partial snakes create gaps in the spin tune around integer points [22]. Typically, these gaps are made as large as possible to detune from the imperfection resonance as far as possible and to allow for adjustment of the betatron tunes so that the main intrinsic resonances can be placed in the spin tune gap as well. The field of a partial snake does not change in the short time of crossing a resonance region. The spin tune does change during the process of resonance crossing. It is important that this change occurs adiabatically while polarization orientation at the moment of resonance crossing does not matter.

In contrast to a partial snake, the purpose of a spin navigator is not to overcome the integer resonance but to provide polarization control and the capability to manipulate it in real time when operating in the ST regime at a fixed energy. To keep the polarization stable over the long course of an experiment, manipulation of the spin orientation must be performed at a fixed spin tune. This prevents resonant depolarization discussed below in Sec. IV. Manipulation of the spin direction and control of the spin tune are accomplished by appropriately combining the spin effects of the navigator solenoids. Their fields are set and dynamically varied accounting for the spin phase advance between them.

The necessary strength of the spin navigator is determined by the requirement to provide polarization stability against spin effects due to ring imperfections, beam emittances and synchrotron motion as discussed above. At the same time, it should not be so large as to approach main intrinsic spin resonances in a stationary state.

III. SPIN NAVIGATOR BASED ON SOLENOIDS

Spin navigators can be technically realized in different ways using longitudinal and transverse fields [4,5]. At low and medium energies, it is most adequate to use weak solenoids, which have no effect on the closed orbit.

A single solenoid stabilizes the longitudinal polarization direction at its location. One can set any polarization direction in the horizontal plane (xz) at the detector by introducing one more solenoid into the ring lattice.

Figure 1 shows a schematic of such a spin navigator [3]. Its two solenoids separated by an arc section rotate the spins by small angles φ_{z1} and φ_{z2}. The navigator solenoids with the longitudinal fields B_{z1} and B_{z2} are indicated in orange. The black arrows indicate the field directions of the solenoids. The arc dipoles located between the solenoids rotate the spins by an angle φ_y.

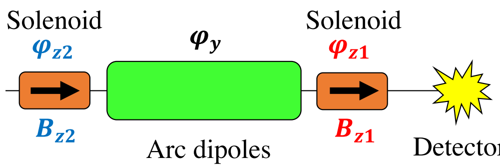

FIG. 1. Schematic of a spin navigator for control of the ion polarization direction in the ring plane.

The required longitudinal field integrals of the navigator solenoids are

$$B_{z1}L_{\text{sol}} = \frac{\varphi_{z1}}{1+G}B\rho, \qquad B_{z2}L_{\text{sol}} = \frac{\varphi_{z2}}{1+G}B\rho, \quad (9)$$

where $B\rho$ is the magnetic rigidity.

Figure 2 shows a vector diagram of the navigator field allowing one to calculate the polarization direction $\vec{n}$ in the detector and the spin tune $\nu_N \ll 1$ induced by the navigator:

$$\vec{n} = \frac{B_{z2}\sin\varphi_y\vec{e}_x + (B_{z1} + B_{z2}\cos\varphi_y)\vec{e}_z}{\sqrt{B_{z1}^2 + B_{z2}^2 + 2B_{z1}B_{z2}\cos\varphi_y}}, \quad (10)$$

$$\nu_N = \frac{(1+G)L_{\text{sol}}}{2\pi B\rho}\sqrt{B_{z1}^2 + B_{z2}^2 + 2B_{z1}B_{z2}\cos\varphi_y}, \quad (11)$$

where $\vec{e}_x$ and $\vec{e}_z$ are the radial and longitudinal unit vectors, respectively. These equations show that one can set any polarization orientation in the ring plane for any values of φ_y except for integer multiples of π where $\sin\varphi_y = 0$ and polarization becomes longitudinal for any field strengths of the navigator solenoids. In this case, the spin fields $\vec{\varphi}_{z1}$ and $\vec{\varphi}_{z2}$ are collinear and the navigator effect is equivalent to that of a single solenoid.

The conditions for stabilization of the coherent spin specified by Eqs. (4) and (7) are determined by magnetic lattice imperfections and beam emittances as well as by effect of synchrotron energy oscillations. They define the navigator field requirements.

The presented scheme of polarization control in the ST mode using two weak solenoids was first proposed for deuteron and proton polarization control in a figure-8 collider [10] and then extended to proton and deuteron

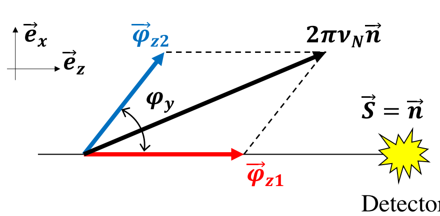

FIG. 2. Vector diagram of the navigator field in the detector. The red and blue arrows correspond to the spin fields $\vec{\varphi}_{z1}$ and $\vec{\varphi}_{z2}$ induced in the detector by the first and second navigator solenoids, respectively.

polarization control in the NICA collider [5]. In these colliders, the spin tune is zero at any energy. Therefore, there are practically no additional limitations on the navigator fields due to synchrotron oscillations.

IV. SPIN-FLIPPING SYSTEM

The spin-flipping schemes that have been experimentally demonstrated to this date are based on adiabatically sweeping an rf magnet's frequency through an induced spin resonance [23]. This technique is used in RHIC for spin flipping polarized protons with a high efficiency of 97% in an energy range of 24 to 255 GeV [24]. However, each crossing of an rf resonance causes some polarization loss that can significantly limit the admissible number of spin flips during an experiment.

The proposed spin navigator provides a capability for adiabatic spin flipping using quasistationary solenoids when the beam depolarization associated with resonance crossing is eliminated. Manipulation of the spin direction (n-axis) during an experiment, such as a spin flip, requires the change of the navigator fields to be adiabatic:

$$\left|\frac{\partial\vec{n}}{\partial B_{z1}}\left(\frac{dB_{z1}}{dt}\right)\right| \ll \nu\Omega_0, \qquad \left|\frac{\partial\vec{n}}{\partial B_{z2}}\left(\frac{dB_{z2}}{dt}\right)\right| \ll \nu\Omega_0. \quad (12)$$

Let us consider, for example, a flip of the longitudinal polarization at the detector. According to Eq. (10), when setting the longitudinal spin direction, only the field of the first solenoid is turned on while $B_{z2} = 0$. The spin direction along or against the particle velocity is defined by the sign of B_{z1}. The fulfillment of the adiabaticity condition depends on how we change the navigator fields from their initial configuration (B_{z1}, B_{z2}) to the final one. If B_{z1} is changed slowly while $B_{z2} = 0$ the adiabaticity condition is violated at the point ($B_{z1} = 0$, $B_{z2} = 0$) where the navigator spin tune becomes zero. However, one can achieve the final configuration while maintaining the adiabaticity condition by getting around the resonance point with no change in the spin tune at all. This requires moving along an ellipse in the (B_{z1}, B_{z2}) parameter space:

$$(B_{z1}^2 + B_{z2}^2 + 2B_{z1}B_{z2}\cos\varphi_y)L_{\text{sol}}^2 = \left(\frac{2\pi\nu_N B\rho}{1+G}\right)^2 = \text{const}. \quad (13)$$

This avoids beam depolarization due to the spin resonance crossing.

When $\cos\varphi_y = \pm 1$, the ellipse equation reduces to a straight line:

$$|B_{z1} \pm B_{z2}|L_{\text{sol}} = \frac{2\pi\nu_N B\rho}{1+G}. \quad (14)$$

In this case, as noted earlier, one can stabilize only the longitudinal polarization. The polarization can only be flipped by changing the signs of the solenoid fields, which leads to variation of the spin tune and subsequently crossing of the ST resonance.

V. ST MODE IN NUCLOTRON FOR PROTONS OF UP TO 3.5 GeV/c

Nuclotron is a conventional strong-focusing synchrotron with an eightfold symmetry [25]. Navigator solenoids are placed in two adjacent superperiods and are separated by a section of arc magnets bending the orbit by an angle of $\pi/4$. With the betatron tunes of $\nu_x = 7.40$ and $\nu_y = 7.56$, there is no problem with preservation of the proton polarization during beam acceleration in the Nuclotron momentum range of up to 3.5 GeV/c, since there are no strong intrinsic resonances [18].

To determine the required field strengths of the navigator solenoids, let us provide a calculation of the resonance strengths using the response functions for the ST mode [13]. The contribution of the perturbing fields ΔB_x, ΔB_y, and ΔB_z to the spin field of the ST resonance is given by

$$\vec{\omega} = \frac{1}{2\pi}\int_0^L \left(\frac{\Delta B_x}{B\rho}\vec{F}_x + \frac{\Delta B_y}{B\rho}\vec{F}_y + \frac{\Delta B_z}{B\rho}\vec{F}_z\right)dz, \quad (15)$$

where L is the Nuclotron's circumference, z is the coordinate along the orbit, and $\vec{F}_x$, $\vec{F}_y$, and $\vec{F}_z$ are the radial, vertical, and longitudinal periodic spin response functions determined by Nuclotron's lattice.

In Nuclotron, vertical perturbing fields ΔB_y have no effect on the spin dynamics in the linear approximation in particle deviations, since $\vec{F}_y = 0$. The magnitude of $\vec{F}_x$ grows with energy as shown in Fig. 3 while the magnitude of $\vec{F}_z$ is independent of energy: $|\vec{F}_z| = 1 + G$.

The rms value of the coherent part of the ST resonance strength ω_{rms} is obtained using the statistical model allowing one to account for random perturbations of the magnet fields [13]:

$$\omega_{\text{rms}}^2 = \frac{\sum_{\text{elem}}(\overline{\Delta B_x^2}|\vec{F}_x|^2 + \overline{\Delta B_z^2}|\vec{F}_z|^2)L_{\text{el}}^2}{4\pi^2(B\rho)^2}, \quad (16)$$

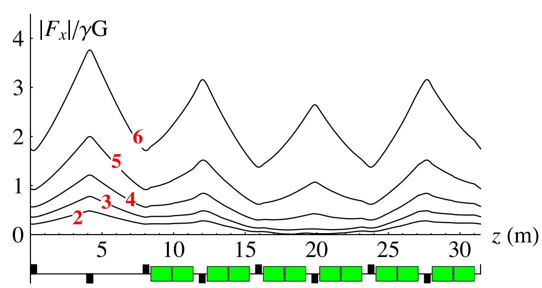

FIG. 3. Magnitude of the radial response function $|F_x|$ in units of γG as a function of z in a single superperiod of Nuclotron for $\gamma G = 2, 3, 4, 5, 6$. The green boxes indicate arc dipoles while the black bars show quadrupoles.

where $(\overline{\Delta B_x^2})^{1/2}$ and $(\overline{\Delta B_z^2})^{1/2}$ are the rms values of random perturbations of the radial and longitudinal magnetic fields due to lattice imperfections and L_{el} is the length of each element. Distortion of the radial magnetic field ΔB_x in Nuclotron can be caused by random quadrupole misalignments in the vertical direction Δy_q and dipole roll $\Delta\alpha_z$ about the longitudinal direction. Perturbation of the longitudinal field ΔB_z occurs due to random dipole pitch $\Delta\alpha_x$ about the radial direction.

The magnitude of the incoherent part of the spin field ω_{emitt} caused by the betatron oscillations is not zero only in the second order approximation in the particle oscillation amplitude and is proportional to the betatron beam emittances [3]. The incoherent part of the resonance strength is numerically obtained using a spin-tracking code, ZGOUBI [26]. A particle is launched with a longitudinal spin and a given betatron amplitude and is tracked over multiple turns. A graph of the longitudinal spin component versus the turn number is used to determine the number of orbital turns it takes the spin to return to the longitudinal direction.

Table I lists the rms values of the coherent ω_{rms} and incoherent ω_{emitt} parts of the integer spin resonances in Nuclotron. The calculations assume Δy_q of ∼0.1 mm, $\Delta\alpha_z$ of ∼0.1 mrad, $\Delta\alpha_x$ of ∼0.03 mrad and the radial and vertical normalized betatron emittances of 4.5π mm mrad. With these errors, the rms vertical closed orbit distortion in Nuclotron is about 1 mm.

The value of the navigator tune for Nuclotron is primarily limited by synchrotron oscillation parameters. In the indicated energy range, the synchrotron tune ν_s and the spin tune spread $\Delta\nu$ do not exceed 10^{-3}. Therefore, a navigator tune value of $\nu_N = 0.01$ is sufficient to control the proton polarization.

Table II provides the maximum field integrals of the navigator solenoids giving the spin tune value of $\nu_N = 0.01$.

For the $\gamma G = 4$ resonance, $\varphi_y = \pi$ and the navigator allows one to stabilize only the longitudinal polarization $\vec{n} = \pm\vec{e}_z$. For the other resonances, the navigator can provide "any" orientation of the polarization in the plane of the Nuclotron ring. The polarization can be flipped by

TABLE I. Proton integer spin resonance strengths in Nuclotron.

$\gamma G = k$	2	3	4	5	6
ω_{rms}, 10^{-4}	0.24	0.57	1.27	2.81	6.88
ω_{emitt}, 10^{-4}	0.36	0.26	0.35	0.55	1.07

TABLE II. Maximum field integrals of the navigator solenoids for control of the proton polarization in Nuclotron.

$\gamma G = k$	2	3	4	5	6
pc, GeV	0.46	1.26	1.87	2.44	3.00
$\vec{n}$ direction	Any	Any	$\pm\vec{e}_z$	Any	Any
$\lvert B_{zi}L\rvert_{\text{max}}$, Tm	0.035	0.13	0.07	0.26	0.23

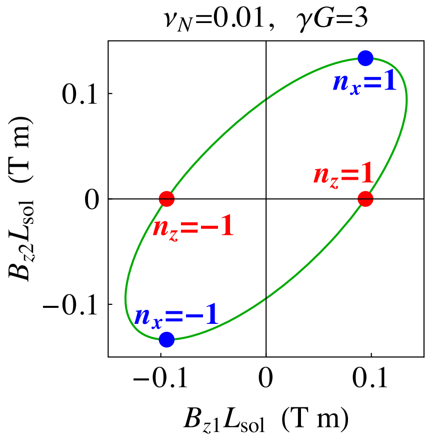

FIG. 4. Change of the solenoid field integrals that keeps ν_N constant while setting the required proton polarization direction.

adiabatically adjusting the proton polarization direction in the Nuclotron plane. The spin tune must be kept constant during the entire reversal process to avoid resonance crossing and associated polarization loss.

Figure 4 shows the relation between the field integrals $(B_{z1}L_{\rm sol})$ and $(B_{z2}L_{\rm sol})$ of the navigator solenoids at $\gamma G = 3$ that maintains the spin tune at a constant value of $\nu_N = 0.01$ as the polarization orientation changes. The red dots indicate the solenoid field integrals when the polarization is oriented along the particle's velocity $n_z = \pm 1$. The blue dots mark the solenoid field integrals when the polarization is radial $n_x = \pm 1$.

To preserve the polarization, the rate of change of the polarization direction must satisfy the adiabaticity condition that can be written in terms of the spin-flipping time τ as

$$\tau \gg \frac{T}{\nu_N}, \tag{17}$$

where T is the particle revolution period in Nuclotron. This condition gives a proton spin-flipping time of 1 ms.

VI. ST MODE FOR DEUTERONS IN THE EIC

Deuteron beams with adjustable polarization orientation may complement ^{3}He beams as a source of high-energy polarized neutrons in the EIC [27]. Due to the small anomalous magnetic moment of a deuteron, spin rotators are not practical as means of deuteron polarization control.

Since one of the RHIC rings will serve as the ion collider ring of the EIC, adjustment of the longitudinal deuteron polarization at integer spin resonances in RHIC has been considered in paper [28]. It analyzed the possibility of preserving the deuteron polarization during acceleration over the entire energy range of the EIC using two detector solenoids. They are located in adjacent superperiods of RHIC and are separated by arc dipoles bending the orbit by an angle of $\pi/3$. The paper notes that, when using the two solenoids, the polarization is longitudinal in both detectors at $\gamma G = 3k$ resonances. However, according to Eq. (10), control of the polarization orientation is not possible at these points.

Assuming successful acceleration of a polarized deuteron beam to the integer spin resonance energy [28], the two detector solenoids can be used as a spin navigator described in Sec. III of this paper. It allows one to adjust the deuteron polarization in any direction in the horizontal plane of the EIC. It can also provide multiple spin flips of the beam without resonant depolarization at $\gamma G \neq 3k$ resonances.

Paper [28] provides information about the strengths of imperfection resonances and parameters of the synchrotron motion. On its basis, the limit on the navigator solenoids at RHIC's low and medium energies, as in Nuclotron, is mainly related to the synchrotron energy modulation. A navigator tune of $\nu_N = 0.01$ is sufficient to control the deuteron polarization.

Table III lists the maximum field integrals of the navigator solenoids providing a deuteron spin tune of $\nu_N = 0.01$ for the first five resonances at the low to medium energies of RHIC. At the $\gamma G = -3$ and $\gamma G = -6$ resonances, the spin rotation angles accumulated in the arc between the solenoids are $\varphi_y = \pi$ and $\varphi_y = 2\pi$, respectively. The navigator can only stabilize the longitudinal polarization $\vec{n} = \pm\vec{e}_z$. The spin cannot be flipped at these resonances using the navigator (detector) solenoids without violation of the adiabaticity condition given by Eq. (12). Its violation results in resonant depolarization. At the other resonances with $\gamma G \neq 3k$, the navigator can provide any polarization direction in RHIC's orbital plane. In this case, the navigator solenoids allow one to go adiabatically around the resonance point without any change in the navigator tune.

Figure 5 shows the relation between the field integrals $(B_{z1}L_{\rm sol})$ and $(B_{z2}L_{\rm sol})$ of the navigator solenoids allowing for a spin flip at $\gamma G = -2$. The polarization direction is adjusted in the RHIC ring plane at a constant deuteron navigator tune of $\nu_N = 0.01$. The red and blue dots correspond to the longitudinal and radial deuteron polarizations, respectively.

It is important to note that, for deuterons in the ST mode at integer resonances, the main constraint on the navigator solenoid strengths comes from the energy dependence of

TABLE III. Maximum field integrals of the navigator solenoids for deuteron polarization control in RHIC.

$\vert\gamma G\vert = k$	2	3	4	5	6
pc, GeV	26.2	39.4	52.6	65.8	78.9
$\vec{n}$ direction	Any	$\pm\vec{e}_z$	Any	Any	$\pm\vec{e}_z$
$\vert B_{zi}L\vert_{\max}$, Tm	7.4	4.8	14.8	18.6	9.6

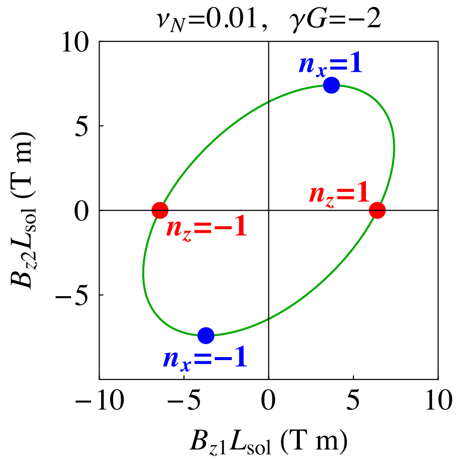

FIG. 5. Change of the solenoid field integrals that keeps ν_N constant while setting the required deuteron polarization direction.

the spin tune. In a figure-8 collider where the spin tune is zero at any energy, the limitation of the navigator solenoid strengths is determined only by the ST resonance strength [29]. Deuteron polarization control then requires significantly lower field integrals of the navigator solenoids. For example, a navigator tune of $\nu_N \sim \omega_{coh} \sim 10^{-4}$ is sufficient to control the deuteron polarization in the momentum range of up to 100 GeV/c. With an optimal placement of two navigator solenoids, this requires a field integral of 0.25 Tm of each solenoid.

Finally, let us note that two solenoids located in available straight sections of RHIC can be used to set up a proton spin-flipping system in RHIC in the ST mode with two identical snakes. As in a figure-8 collider, the proton spin tune in this case is energy independent. The requirements on the detector (navigator) solenoids are then determined mainly by the coherent part of the ST resonance strength $\nu_N \sim \omega_{coh}$, which is of the order of $10^{-3} - 10^{-2}$ in a wide energy range [30]. Note that spin flipping in the ST mode does not have the problem of the mirror spin resonance occurring when RHIC operates in its regular mode at a half-integer spin tune [24]. Instead of using rf fields as in RHIC's regular mode, quasistatic fields of an SN can be used to coherently reverse the spins in the ST mode with identical snakes.

VII. CONCLUSIONS

Our study demonstrates the feasibility and proposes an experimental verification of a new SN-based polarization control system for synchrotrons operated in the ST mode. We analyzed the possibilities of applying such systems with protons in the Nuclotron ring and with deuterons in one of the RHIC rings. The ST mode is implemented at discrete values of the beam energy corresponding to integer spin resonances. Use of the ST mode presents a unique opportunity to control the deuteron polarization in RHIC where application of full Siberian snakes and strong spin rotators is not practical.

The proposed navigator based on two weak solenoids allows one to realize a spin-flipping system avoiding depolarization associated with spin resonance crossing.

The limitation on the navigator solenoid strengths in the aforementioned rings is mainly determined by the synchrotron energy modulation. It is most convenient to conduct initial testing at low energies where the spin tune spread is minimal and there are no issues with preserving the beam polarization during acceleration to the experimental energy.

The proposed spin navigator is universal and can be used to control the polarizations of deuteron, proton and helium-3 beams in the ST modes of the existing and future machines such as NICA, EIC, EicC [31] in China, and COSY [32] in Germany.

An experimental verification of the spin transparency concept will provide new opportunities for high-precision experiments with polarized beams and will expand the toolkit of polarization control techniques for colliders.

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[1] V. Kekelidze, A. Kovalenko, R. Lednicky, V. Matveev, I. Meshkov, A. Sorin, and G. Trubnikov, The NICA project at JINR Dubna, ICNFP 2013, EPJ Web Conf. **71**, 00127 (2014).

[2] A. Accardi *et al.*, Electron-Ion Collider: The next QCD frontier, Eur. Phys. J. A **52**, 268 (2016).

[3] Y. N. Filatov, A. M. Kondratenko, M. A. Kondratenko, Y. S. Derbenev, and V. S. Morozov, Transparent Spin Method for Spin Control of Hadron Beams in Colliders, Phys. Rev. Lett. **124**, 194801 (2020).

[4] V. S. Morozov, S. Derbenev, F. Lin, Y. Zhang, A. Kondratenko, M. Kondratenko, and Y. Filatov, Ion polarization control in MEIC rings using small magnetic fields integrals, Proc. Sci., (PSTP 2013) (**2014**) 026.

[5] A. D. Kovalenko, A. V. Butenko, V. D. Kekelidze, V. A. Mikhaylov, Y. Filatov, A. M. Kondratenko, and M. A. Kondratenko, Ion polarization control in the MPD and SPD detectors of the NICA collider, in *Proceedings of IPAC'15, Richmond, VA* (JACoW, Geneva, Switzerland, 2015), p. 2031, https://doi.org/10.18429/JACoW-IPAC2015-TUPTY017.

[6] V. S. Morozov *et al.*, Spin flipping system in the JLEIC collider ring, in *Proceedings of NAPAC'16, Chicago, IL*

(JACoW, Geneva, Switzerland, 2016), TUPOB30, p. 558, https://doi.org/10.18429/JACoW-NAPAC2016-TUPOB30.

[7] Ya. S. Derbenev, The twisted spin synchrotron, University of Michigan Report No. UM HE 96-05, 1996.

[8] A. M. Kondratenko, M. A. Kondratenko, Yu. N. Filatov, Ya. S. Derbenev, F. Lin, V. S. Morozov, and Y. Zhang, Ion polarization scheme for MEIC, arXiv:1604.05632.

[9] V. S. Morozov, Ya. S. Derbenev, Y. Zhang, P. Chevtsov, A. M. Kondratenko, M. A. Kondratenko, and Yu. N. Filatov, Ion polarization in the MEIC figure-8 ion collider ring, in *Proceedings of the 3rd International Particle Accelerator Conference, New Orleans, LA, 2012* (IEEE, Piscataway, NJ, 2012), pp. 2014–2016.

[10] A. M. Kondratenko, Ya. S. Derbenev, Yu. N. Filatov, F. Lin, V. S. Morozov, M. A. Kondratenko, and Y. Zhang, Preservation and control of the proton and deuteron polarizations in the proposed electron-ion collider at Jefferson Lab, Phys. Part. Nucl. **45**, 323 (2014).

[11] Yu. N. Filatov, A. D. Kovalenko, A. V. Butenko, E. M. Syresin, V. A. Mikhailov, S. S. Shimanskiy, A. M. Kondratenko, and M. A. Kondratenko, Spin transparency mode in the NICA collider, EPJ Web Conf. **204**, 10014 (2019).

[12] V. S. Morozov, P. Adams, Y. S. Derbenev, Y. Filatov, H. Huang, A. M. Kondratenko *et al.*, Experimental verification of transparent spin mode in RHIC, in *Proceedings of IPAC'19, Melbourne, Australia* (JACoW Publishing, Geneva, Switzerland, 2019), p. 2783, https://doi.org/10.18429/JACoW-IPAC2019-WEPGW122.

[13] Yu. N. Filatov, A. M. Kondratenko, M. A. Kondratenko, Ya. S. Derbenev, V. S. Morozov, and A. D. Kovalenko, Spin response function technique in spin-transparent synchrotrons, Eur. Phys. J. C **80**, 778 (2020).

[14] V. I. Ptitsyn, Yu. M. Shatunov, and S. R. Mane, Spin response formalism in circular accelerators, Nucl. Instrum. Methods Phys. Res., Sect. A **608**, 225 (2009).

[15] Yu. M. Shatunov and S. R. Mane, Calculations of spin response functions in rings with Siberian snakes and spin rotators, Phys. Rev. ST Accel. Beams **12**, 024001 (2009).

[16] V. S. Morozov, Y. S. Derbenev, F. Lin, Y. Zhang, Y. Filatov, A. M. Kondratenko, and M. A. Kondratenko, Analysis of spin response function at beam interaction point in JLEIC, in *Proceedings of IPAC'18, Vancouver, BC, 2018* (JACoW Publishing, Geneva, Switzerland, 2018), p. 400, https://doi.org/10.18429/JACoW-IPAC2018-MOPML007.

[17] N. I. Golubeva, I. B. Issinskii, A. M. Kondratenko, M. A. Kondratenko, V. A. Mikhailov, and E. A. Strokovskii, Study of depolarization of deuteron and proton beams in the nuclotron rings, Report No. P92002-289.

[18] Y. Filatov, A. V. Butenko, A. M. Kondratenko, M. A. Kondratenko, A. D. Kovalenko, and V. A. Mikhaylov, Acceleration of polarized proton and deuteron beams in Nuclotron at JINR, in *Proceedings of IPAC2017, Copenhagen, Denmark* (JACoW, Geneva, Switzerland, 2017), p. 2349, https://doi.org/10.18429/JACoW-IPAC2017-TUPVA112.

[19] Y. S. Derbenev, A. M. Kondratenko, and A. N. Skrinskii, Dynamics of particle polarization near spin resonances, Zh. Eksp. Teor. Fiz. **60**, 1216 (1971) [Sov. Phys. JETP **33**, 658 (1971)], http://www.jetp.ac.ru/cgi-bin/dn/e_033_04_0658.pdf.

[20] H. Huang *et al.*, Preservation of Proton Polarization by a Partial Siberian Snake, Phys. Rev. Lett. **73**, 2982 (1994).

[21] H. Huang *et al.*, Overcoming Depolarizing Resonances with Dual Helical Partial Siberian Snakes, Phys. Rev. Lett. **99**, 154801 (2007).

[22] H. Huang *et al.*, Overcoming an intrinsic depolarizing resonance with a partial Siberian snake, Phys. Rev. Accel. Beams **7**, 071001 (2004).

[23] V. S. Morozov, Z. B. Etienne, M. C. Kandes, A. D. Krisch, M. A. Leonova, D. W. Sivers, V. K. Wong, K. Yonehara, V. A. Anferov, H. O. Meyer, P. Schwandt, E. J. Stephenson, and B. von Przewoski, First Spin Flipping of a Stored Spin-1 Polarized Beam, Phys. Rev. Lett. **91**, 214801 (2003).

[24] H. Huang, J. Kewisch, C. Liu, A. Marusic, W. Meng, F. Méot, P. Oddo, V. Ptitsyn, V. Ranjbar, and T. Roser, High Spin-Flip Efficiency at 255 GeV for Polarized Protons in a Ring with Two Full Siberian Snakes, Phys. Rev. Lett. **120**, 264804 (2018).

[25] A. M. Baldin and A. D. Kovalenko, The status of the Dubna relativistic heavy ion accelerator facility, CERN Report No. 14/93, no. 4, 1993.

[26] F. Méot, The ray-tracing code ZGOUBI, Nucl. Instrum. Methods Phys. Res., Sect. A **427**, 353 (1999).

[27] W. Cosyn, V. Guzey, D. W. Higinbotham, C. Hyde, S. Kuhn, P. Nadel-Turonski, K. Park, M. Sargsian, M. Strikman, and C. Weiss, Neutron spin structure with polarized deuterons and spectator proton tagging at EIC, J. Phys. Conf. Ser. **543**, 012007 (2014).

[28] H. Huang, F. Méot, V. Ptitsyn, V. Ranjbar, and T. Roser, Polarization preservation of polarized deuteron beams in the electron ion collider at Brookhaven National Laboratory, Phys. Rev. Accel. Beams **23**, 021001 (2020).

[29] V. S. Morozov, Y. S. Derbenev, F. Lin, Y. Zhang, Y. Filatov, A. M. Kondratenko, and M. A. Kondratenko, Baseline scheme for polarization preservation and control in the MEIC ion complex, in *Proceedings of IPAC'15, Richmond, VA* (JACoW, Geneva, Switzerland, 2015), pp. 2301–2303, https://doi.org/10.18429/JACoW-IPAC2015-TUPWI029.

[30] V. S. Morozov, P. Adams, Y. S. Derbenev, Y. Filatov, H. Huang, A. M. Kondratenko, M. A. Kondratenko, F. Lin, F. Mot, V. Ptitsyn, W. B. Schmidke, and Y. Zhang, Spin response function for spin transparency mode of RHIC, in *Proceedings of IPAC'19, Melbourne, Australia* (JACoW Publishing, Geneva, Switzerland, 2019), pp. 2791–2793, https://doi.org/10.18429/JACoW-IPAC2019-WEPGW124.

[31] X. Chen, A plan for EIC in China, arXiv:1809.00448.

[32] A. Lehrach, U. Bechstedt, J. Dietrich, R. Gebel, B. Lorentz, R. Maier, D. Prasuhn, A. Schnase, H. Schneider, R. Stassen, H. Stockhorst, and R. Tolle, Acceleration of polarized protons and deuterons at COSY, AIP Conf. Proc. **675**, 153 (2003).