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EIC HADRON SPIN ROTATORS*

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Abstract

The Electron-Ion Collider in BNL will collide polarized electrons with polarized protons or polarized ^{3}He ions. Spin rotators will be used to create the longitudinal beam polarization at a location of the EIC experimental detector. Helical spin rotators utilized for polarized proton operation in present RHIC will be reused in the EIC Hadron Storage Ring. However, due to a significant difference of EIC and RHIC interaction region layouts, the EIC spin rotator arrangement has several challenges. Turning on the EIC spin rotators may lead to a significant spin tune shift. To prevent beam depolarization during the spin rotator turn-on, Siberian Snakes have to be tuned simultaneously with rotators. The EIC spin rotators must be able to operate in a wide energy range for polarized protons and polarized ^{3}He ions. The paper presents the challenges of spin rotator usage in the EIC and remedies assuring the successful operation with the rotators.

INTRODUCTION

The scientists and engineers of Brookhaven National Laboratory (BNL) and Tomas Jefferson National Accelerator Laboratory (TJNAF) are continuing design developments of Electron-Ion Collider (EIC) which shall be built in BNL. Essential feature of this collider is the use of highly polarized beams of electrons, protons and ^{3}He ions. Spin rotators are used in both electron storage ring (ESR) and hadron storage ring (HSR) of the EIC to produce longitudinal beam polarization orientation in the collision point where an experimental detector is located. In this paper we revise how the spin rotators in the HSR are used for controlling polarization direction of polarized protons and polarized ^{3}He ions. The EIC HSR will re-use much of the hardware of existing RHIC rings [1]. This includes the RHIC spin rotators which have been very successfully used over many years in RHIC polarized protons runs. The Siberian Snakes used in RHIC for proton beam polarization preservation on acceleration ramp and at the store, will be also re-used in the HSR, but the number of the Snakes in the storage ring will be increased to six [2]. Both Siberian Snakes and spin rotators have a similar basic structure, based on a sequence of four helical dipole magnets [3, 4]. The magnets of Siberian Snakes can be tuned, if needed, to select an appropriate orientation of Snake axis, which allows adjusting the spin tune. By adjusting helical magnets of the spin rotator one can convert the vertical spin to arbitrary direction in the horizontal plane (with some limits discussed later in this paper). This is needed since in both RHIC and HSR the lattice contains bending magnets between rotators and the interaction point, giving requirements for polarization orientation after rotator varying with the beam energy.

SPIN ROTATOR LAYOUT IN HSR

The layout of the EIC interaction region differ drastically from the RHIC IR layout. The EIC IR is more complex than the RHIC one. It must provide collisions of electrons and hadrons in wide beam energy range, integrating forward acceptance detector elements into accelerator structure, arranging fast beam separation and crab-crossing scheme, and managing electron synchrotron radiation. The positioning of spin rotators in the EIC HSR is also very different from RHIC.

The Figure 1 shows the schematics of RHIC IR with the rotators. Each rotator consists of four helical dipole modules, with each module being one helical period long. The letters L and R in Fig. 1 denote the helical magnet helicity (left-handed or right-handed). And plus and minus signs characterize the sign of horizontal magnetic field at the entrance of each helical magnet. The first and last rotator magnets have the same field (B_1), and second and third magnets have the same field (B_2). The rotators are located at 60 meters distance and 3.7 mrad bending angle from the RHIC interaction point. It is important to note that the net bending between the spin rotators in RHIC is zero and, therefore, the second rotator just realizes inverse spin transformation as compared with first rotator. The spin transformation from the entrance of first rotator to the exit of the second one is unit transformation. Hence, the RHIC rotator system is completely spin transparent.

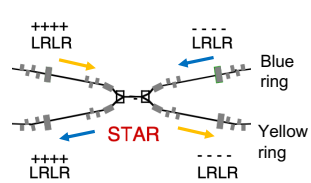

Figure 1: The spin rotators in the RHIC interaction region. There is a pair rotators in both Blue and Yellow rings of RHIC.

The Figure 2 shows the schematics of the EIC IR with HSR spin rotators. The vicinity of the interaction point is crowded with magnets, detector elements and crab-cavities. Thus, the spin rotators have to be pushed further away from the IP, both in terms of distance and bending angles. Also, the spin rotators in the HSR can not be placed symmetrically with respect to the IP. The Table 1 summarizes the location information for the RHIC and HSR spin rotators. The sign of bending angle is defined following the beam trajectory. One can note that there is a considerable left-right asymmetry in bending angle distances of HSR rotators. As a

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consequence, the net bending angle between spin rotators is non-zero. Thus, the spin rotator layout in the HSR is more complicated than in RHIC. It creates several issues that have to be considered in the accelerator design work.

Table 1: The Rotator Locations in RHIC and EIC HSR

	Distance from IP	Bending angle from IP
RHIC Rotator 1	61.4 m	3.675 mrad
RHIC Rotator 2	61.4 m	-3.675 mrad
HSR Rotator 1	97.8 m	-17 mrad
HSR Rotator 2	103.8 m	61.35 mrad

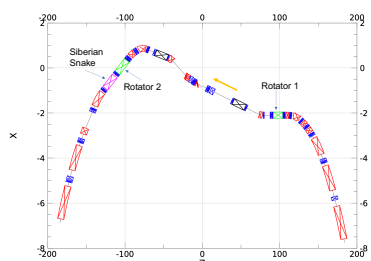

Figure 2: The layout of HSR interaction region area. The spin rotators are plotted as green boxes. The Siberian Snake is shown as a pink box.

ENERGY RANGE COVERAGE

The first issue is related with the energy range coverage of the spin rotators. The EIC requirements state that the HSR needs to provide polarized beams at following energies:

1. protons: 41 GeV, 100-275 GeV
2. ^{3}He ions: 41 GeV, 100-183 GeV/u

Are spin rotators capable to produce the longitudinal polarization at all required energies? To answer this question one needs to start with the characteristic plot of the spin rotator based on four helical magnets (Fig. 3). This plot relates the fields of rotator helical magnets with spin orientation in the horizontal plane after the rotators (for vertical spin at the rotator entrance). It also takes into account 4 T field limit of actual RHIC spin rotator magnets. Due to this field limit there is some range of polarization orientations in the horizontal plane which can not be produced. Combining this information with the bending angle data in Table 1 one can convert the data for polarization orientation into the data for beam energy. One should take into account that both longitudinal spin orientations (either +1 or -1) at the IP are acceptable. The conversion has to be done individually for the rotators on left and right side of the IP, and then results have to be combined. The final results of this conversion are summarized in Table 2 where the beam energy ranges at which the longitudinal polarization of proton can not be achieved are listed. While having small not-accessible energy ranges between 250 and 257 GeV should not be a big problem, for the second rotator configuration used in RHIC (L,R,L,R) not having perfect longitudinal polarization at 41 GeV is a serious issue not acceptable for EIC physics experiments. Fortunately, a simple solution exist. Changing the sequence of helical magnets in second rotator from (L,R,L,R) to (R,L,R,L) leads to the not-accessible energy ranges listed in bottom row of the Table 2. At this rotator configuration the longitudinal polarization at 41 GeV can be provided. The change of magnet sequence can be simply done by rotating the whole rotator by 180 degree around vertical axis, which should be realized during the HSR installation.

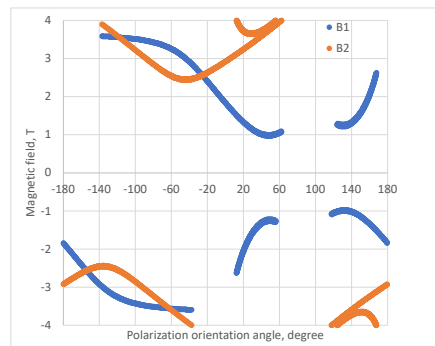

Figure 3: The characteristic plot shows relations between rotator fields and the spin orientation after the rotator for protons. The spin orientation angle is counted from the longitudinal axis.

Table 2: The Proton Beam Energies Where the Longitudinal Polarization Can Not Be Realized

2nd rotator helicity configuration	Energies (GeV)
(L,R,L,R)	36-44, 250-257
(R,L,R,L)	143-151, 226-232

The characteristic plot of the spin rotator for ^{3}He beam is shown in Fig. 4. All polarization orientations can be created by the spin rotator. Thus, the longitudinal polarization can be created at all energies of ^{3}He . Also, multiple sets of magnetic fields of rotator magnets for a particular longitudinal orientation exist, simplifying operational choices, for instance allowing to minimize the orbit excursion inside the rotators.

TURNING ON SPIN ROTATORS

Due to significant orbit excursion happening inside the rotator at the injection energy the spin rotators are turned on at the store energy. Since the net bending angle between the rotators in the HSR is non-zero the spin tune can be affected by the rotator turn on. The spin tune can be obtained from one-turn spin transformation matrix. The transformation matrix calculation should include six Siberian Snakes which will be used in the HSR, one in each sextant. When the

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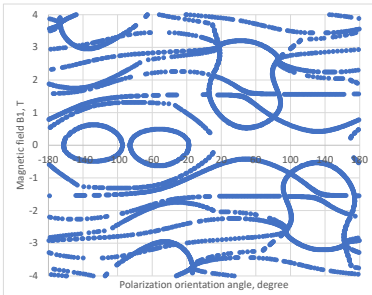

Figure 4: The characteristic plot shows relation between rotator field B_1 and the spin orientation after the rotator for ^{3}He ions. The spin orientation angle is counted from the longitudinal axis.

rotators are off the spin tune is defined by orientations of the rotation axes of the Siberian Snakes (called Snake axes):

$$\nu_{sp} = \frac{1}{\pi}\sum_{i=1}^{3}(\alpha_{s,2i} - \alpha_{s,2i-1}) \tag{1}$$

where $\alpha_{s,i}$ are Snake axes angles in the horizontal plane, accounted from the longitudinal direction.The Snake axes are normally oriented at ± 45 deg giving the fractional spin tune equal to one half, independently on the energy.

When the rotators are turned on the formula for the spin tune becomes more complex, but spin tune dependence on the Snake axis angles remains. The Fig. 5 shows what happens with the fractional spin tune at the proton beam energy of 275 GeV when the spin rotators are ramped up from zero field to the helical field values required for longitudinal polarization. At the end of the spin rotator ramp, the spin tune shift is as large as 0.4. Such tune shift will lead to depolarization due to crossing spin resonances with orbital betatron motion. To counteract the spin tune shift one has to vary Snakes axes, by adjusting magnetic fields of the Snakes concurrently with rotator ramping. The example is shown in Fig. 6 where the Snake axis angles are linearly adjusted on the second half of the spin rotator ramp, as shown in Fig. 7. It allows dramatically reduce the spin tune shift excursion, to less than 0.1.

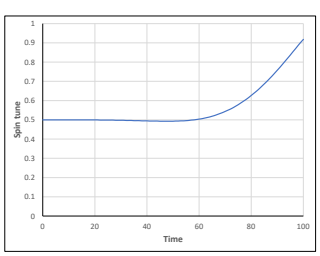

Figure 5: The spin tune change during the spin rotator ramp. The horizontal axis presents arbitrary time unit. As the time changes from 0 to 100, the spin rotator fields are linearly ramped to their required values at 275 GeV.

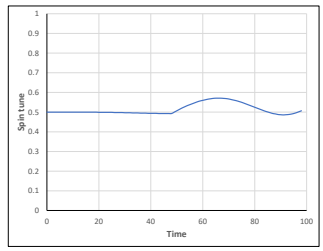

Figure 6: The spin tune shift during the rotator ramp, with applying the snake axis angle change in the Siberian Snakes shown in Fig. 7.

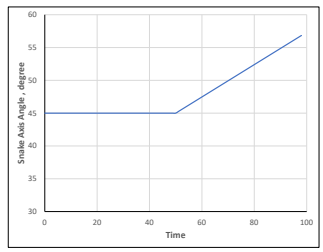

Figure 7: The Snake axis angle change applied on the spin rotator ramp to compensate the spin tune excursion.

CONCLUSION

The spin rotators used presently in RHIC will be re-used in the EIC Hadron Storage Ring. But, since the locations of the spin rotators in the HSR differ considerably from their RHIC locations several issues arise in the HSR. First, the longitudinal polarization can not be achieved at some beam energies for protons. Changing the order of magnets in second rotator ensures the longitudinal polarization at 41, 100 and 275 GeV, which are energies of most interest for physics experiments. Second, the turning on spin rotators at 275 GeV produces significant spin tune shift. This spin tune shift can be compensated by tuning Snake axis angles of six Snakes used in the HSR during the spin rotator field ramp.

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REFERENCES

[1] C. Liu *et al.*, "Reconfiguration of RHIC Straight Sections for the EIC", presented at the IPAC'22, Bangkok, Thailand, Jun. 2022, paper WEPOPT034, this conference.

[2] "EIC Conceptual Design Report", sections 5.4, 5,5, 2021. https://www.bnl.gov/ec/files/eic_cdr_final.pdf/.

[3] V. Ptitsyn and Yu. M. Shatunov, "Helical spin rotators and snakes", *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 398, p. 126, 1997. doi:10.1016/S0168-9002(97)00683-9

[4] RHIC Polarized Proton Manual, Ch.4, 2006. https://www.bnl.gov/cad/accelerator/docs/pdf/rhicppcman.pdf/.