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STRATEGY FOR PROTON POLARIZATION IN THE ELECTRON ION COLLIDER*

H. Huang†, K. Hock, F. Meot, V. Ptitsy, V. Ranjbar, V. Schoefer
Brookhaven National Laboratory, Upton, NY, USA
V. Morozov, Oak Ridge National laboratory, Oak Ridge, TN, USA

Abstract

The polarization of 60% at 255 GeV has been delivered to experiments with 1.8×10^{11} bunch intensity at top energy of RHIC. To preserve polarization through numerous depolarizing resonances over the whole RHIC hadron accelerator chain, harmonic orbit correction, partial snakes, horizontal tune jump system and full snakes have been used. In addition, close attentions have been paid to betatron tune control, orbit control and beam line alignment. For the EIC era, the beam brightness has to be maintained to reach the desired luminosity. To improve the polarization transmission efficiency and higher beam brightness, electron cooling at injection of EIC hadron storage ring will be used. To further improve the polarization transmission efficiency in the AGS, a new scheme using skew quadrupoles to compensate horizontal intrinsic resonances is under development. Since there is only one hadron ring in the EIC era, existing spin rotator and snakes can be converted to six snake configuration for one hadron ring. The number of snakes can be increased. With properly arranged snakes in EIC and reduction of emittance, the polarization can reach 70% at 275 GeV. The general strategy of polarization preservation scheme in the injectors and hadron ring of the EIC is described in this paper.

INTRODUCTION

Relativistic Heavy Ion Collider (RHIC) has provided polarized proton beams over an energy range from 31 GeV to 255 GeV during the past decade. To preserve polarization through numerous depolarizing resonances over the whole accelerator chain, harmonic orbit correction, partial and full Siberian Snakes, and a horizontal tune jump system have been used. In addition, close attention has been paid to betatron tune control, orbit control and magnet alignment. A polarization of 60% at 255 GeV has been delivered to experiments with an intensity of 1.8×10^{11} protons per bunch. For the newly proposed Electron Ion Collider (EIC), part of the RHIC rings will be used as hadron ring. The EIC requires polarized proton beams with 70% polarization and 3×10^{11} protons/bunch out of the Alternative Gradient Synchrotron (AGS). the beam brightness has to be maintained to reach the desired luminosity. Since the EIC will only use RHICs counter clockwise ring(yellow), The spin rotators and snakes from the clockwise ring (Blue) can be converted into additional Siberian Snakes for the EIC hadron ring. With a proper arrangement of six snakes in the hadron ring and additional reduction of emittance growth in the AGS, the polarization is expected to reach 70% at 275 GeV beam energy.

The current proton acceleration chain is as follows. High intensity, high polarization H^- is produced at the polarized proton source. The H^- beam polarization is measured at the end of the 200 MeV linac as 80-82%. The beam is then strip-injected into the AGS Booster. The Booster vertical tune is set high enough so that the intrinsic resonance in the Booster at $0 + Q_y$ is avoided. Two imperfection resonances in Booster are corrected by harmonic orbit correction. In the AGS, two partial Siberian Snakes separated by 1/3 of the ring circumference are used to overcome the imperfection and vertical intrinsic resonances [1]. The vertical tune Q_y on the energy ramp is mostly above 8.98, so that it is in the spin tune gap and away from the high order snake resonances. To avoid the horizontal intrinsic resonances driven by the partial snakes, a pair of pulsed quadrupoles is employed to jump the tune across the many weak horizontal intrinsic resonances on the ramp [2]. Two full Siberian Snakes are used in each of the two present RHIC rings to maintain polarization [3]. The betatron tune, coupling and orbit feedback on the energy ramp are crucial for polarization preservation.

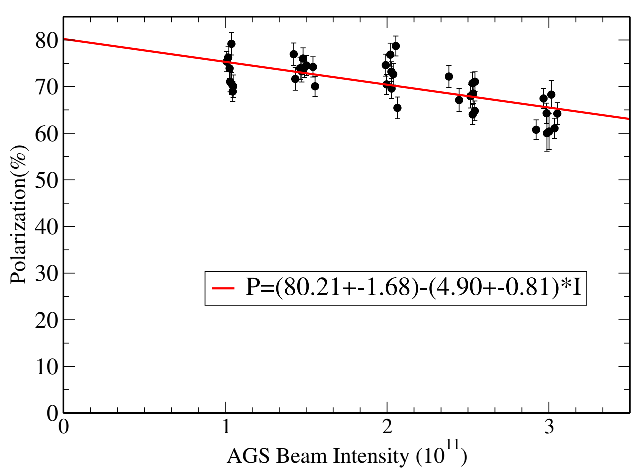

Figure 1: AGS polarization at extraction as function of bunch intensity. The polarized proton source can deliver an intensity of 9×10^{11} at the Booster input. Booster scraping (both horizontal and vertical) is used to reduce the beam emittance for AGS injection. The intensity in this figure is changed by varying the Booster scraping level.

The polarization measured at AGS extraction is shown in Fig. 1 as function of beam intensity. The intensity was reduced by Booster scraping. The polarization dependence

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† huanghai@bnl.gov

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on intensity is in fact a dependence on emittance. As higher intensity is always associated with larger emittance, and consequently greater depolarizing resonance strength, lower polarization is expected for higher intensity. As shown in Figure 1, the polarization at 3×10^{11} is about 65%.

At 3×10^{11} protons/bunch, the rms normalized vertical emittance at AGS extraction is about 2.6 μm and the rms normalized horizontal emittance is about 2.4 μm. These are the emittances we are going to deal with in the injectors. A new scheme by using skew quadrupoles to overcome the horizontal intrinsic resonance is under study to improve the AGS polarization transmission efficiency [4]. This should improve the polarization out of AGS from 70% to near 80%. As the experience at RHIC shows, the polarization transmission efficiency up to 100 GeV is close to 100% but only about 92% for 250 GeV at 1.8×10^{11} bunch intensity due to stronger intrinsic resonances. The vertical emittance is about 2.3-2.5 μm. The highest resonance strength, calculated by DEPOL [5], for a particle with 10 μm normalized emittance invariant is about 0.18 below 100 GeV and about 0.45 beyond 100 GeV. As the intrinsic resonance strength is proportional to the square root of vertical emittance, the resonance strength (assuming 2.5 μm) seen in RHIC is 0.09 below 100 GeV and 0.225 beyond 100 GeV. This implies that the two snakes can preserve polarization for intrinsic resonance strength 0.09 but not for 0.225. The resonance strength threshold for 100% polarization transmission efficiency with two snakes may therefore lie somewhere between 0.09 and 0.225. In current EIC design, The vertical emittance of ion beams will be pre-cooled at the injection of Hadron Storage Ring (HSR) down to 0.5-1 μm [6]. Take the middle value of 0.75 μm, the corresponding strongest resonance strength is around 0.09. This implies that two snakes may work. On the other hand, the resonance strength for ^{3}He is stronger and six snakes are expected to be needed. Since six snakes are needed, the simulation study was done with six snakes configuration.

In the EIC, only one hadron storage ring (HSR) is needed for ion beam acceleration and storage. In this case, the spin manipulating devices from the RHIC "Blue" ring can be used in the EIC hadron storage ring. A configuration with six Siberian Snakes will be created by moving the two existing RHIC "Blue" snakes into the appropriate locations in the Hadron Storage Ring, and constructing two more snakes using the helical dipoles of the RHIC "Blue" spin rotators.

As a rule of thumb, the resonance strength threshold should increase by the same factor as the number of snakes. Since the real resonance threshold is unknown, simulations are needed to determine how far polarization preservation is improved in a configuration with six snakes.

SPIN SIMULATIONS IN HSR

Since ^{3}He resonance strengths are much stronger than those of protons, the spin simulations were done with ^{3}He. To estimate the polarization transmission efficiency on the ramp, spin tracking was done for crossing a pair of strongest depolarizing resonances at $735 - Q_y$, and $717 + Q_y$ using the Zgoubi code [7]. The RHIC lattice is used for the simulations. The tracking was done for 1000 particles with normalized rms emittance $\varepsilon = 1$ μm in both planes. To speed up the tracking, the acceleration rate in the model is 5 times of the actual acceleration rate for protons. It should be noted that in the presence of a Siberian Snake, the polarization loss is not sensitive to resonance crossing speed.

For an energy independent spin tune with multiple snakes, the simplest snake arrangement is for all snakes to be equally spaced azimuthally. The snake axis angles are $\phi = \pm 45°$ from the longitudinal axis in the local Serret-Frenet frame, ensuring, respectively, a spin tune of $Q_{\rm spin} = 3/2$, following

$$Q_{\rm spin} = \frac{1}{\pi}\left|\sum_{k=1}^{N_s=6}(-1)^k\phi_k\right|. \tag{1}$$

where $N_s = 6$ is the number of snakes. Due to the injection region constraint, the snake near IP6 cannot be put in the symmetric position. As such, the snake near IP12 needs to be moved. The proposed snake locations are as following with counting starting at IP12: snake1 = ϕ, snake2=$\pi/3 - \phi$, snake3 = $2\pi/3 - \phi$, snake4 =$\pi + \phi$, snake5 = $4\pi/3 - \phi$, snake6 = $5\pi/3 - \phi$, where $\phi = 0.0435$rad. In this arrangement, only snakes 1 and 4 are not in ideal locations. Ideal locations for them would be snake1 =$-\phi$, snake4 =$\pi - \phi$. Then all snakes will be separated by $\pi/3$ bending angle. Spin simulations were done for ideal snake locations and a pair of snakes with offset in RHIC lattice. As Fig. 2 shows, the polarization is preserved for the pre-cooled beam sizes with one pair of snakes offset.

The HSR lattice design is finished recently. The symmetry of the HSR is less than that of RHIC. Overall, the strong resonances are weaker in HSR, but non-systematic resonances are stronger. The spin simulations with the HSR lattice is ongoing.

SPACE CHARGE EFFECT

With cooled ion beam and other beam parameters, the space charge tune shift at injection (25 GeV) is 0.1 and at the low collision energy 41 GeV is 0.05. On one hand, the depolarizing resonance strengths are weaker at lower energies and the available betatron tune space should be larger. On the other hand, the space charge tune shift at lower energies are larger. The space charge effects need to be addressed.

The space charge effect is studied in the HSR with two snakes for both 25 GeV and 41 GeV as the worst case. The polarization lifetime was simulated with lattice independent model [8]. The polarization loss rate is scanned as function of vertical betatron tune for various vertical emittance. The vertical emittance at 25 GeV before cooling is 2.5 μm. The results show that, with two snakes in the HSR ring, the polarization decay rate is flat as 0.0%/hr in the vertical tune range 29.16 to 29.30 even for the particles at 10 μm emittance ellipse. There is no polarization loss with the relative weak resonance strength. With the 0.1 space charge tune

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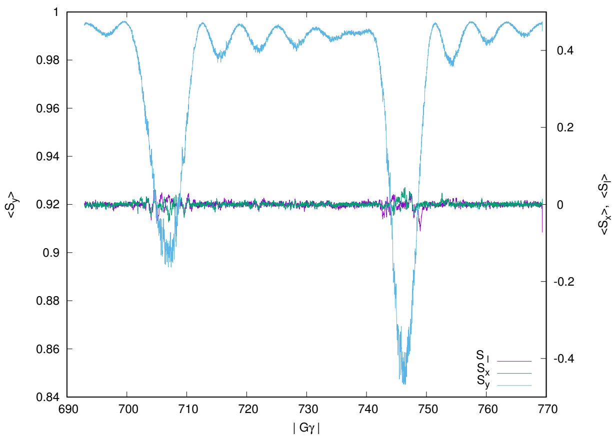

Figure 2: Simulation results of three spin components (< S_y >, < S_x > and < S_l >) for 6 snakes, with one pair of snake offset by ϕ=0.0435rad and snake axes at ±45° through the strongest depolarizing resonances for ^{3}He at $735-Q_y$ and $717+Q_y$. The simulation was done for 1000 particles with Gaussian distributions in 6D phase space. The acceleration rate is about five times that of the proton acceleration rate in operation. The betatron tunes are $Q_y = 28.685$ and $Q_x = 29.673$. The rms normalized emittance is $\varepsilon = 1$ µm in both planes.

shift considered, the polarization lifetime is not a problem. At 41 GeV, the vertical emittance after cooling is 0.75 µm. Similarly, the polarization loss rate is also small in the wide range of vertical tune space, due to the relative weak resonance strength. It is in general also near zero for the vertical tune range of 29.16 to 29.30. The expected space charge tune shifts of 0.05 and 0.1 do not pose a threat to the polarization lifetime.

SPIN ROTATOR SETTINGS

EIC will use existing RHIC spin rotators based on helical dipole magnets in order to transform the vertical beam polarization in the arcs into the longitudinal one in the interaction point. Outer helical modules as well as inner helical modules have the same magnetic field, thus the rotator is characterized only by two magnetic field values.

The configuration of EIC interaction region is very different from the interaction region of RHIC. As a consequence the field setting of spin rotators at various proton energies will be different from the field settings for RHIC. In RHIC the spin rotators are placed symmetrically from the interaction point, with the bending angle +3.675 mrad between first rotator and the IP and the bending angle -3.675 mrad between the IP and second rotator. In the EIC interaction region, the bending angle is -17 mrad between the upstream rotator and the IP and the bending angle is +61.35 mrad between the IP and the downstream rotator. Thus, the rotators in EIC are placed much further away from the IP in terms of bending angles, and polarization vector may rotate more than one full turn between the rotator and the IP, depending on the beam energy. The simulations have shown that it is possible by adjusting both snake and rotator together to get longitudinal polarization at IP while maintaining the spin vertical spin outside the region.

With the original sequence of spin rotator helicity settings, namely (L,R,L,R), the energy range coverage of the spin rotators will have some gaps where the longitudinal polarization cannot be realized. These ranges are 36-44 GeV and 250-257 GeV. On the other hand, the EIC requires HSR to provide polarized protons at following energies: 41 GeV and 100-275 GeV. Note that the 41 GeV is excluded from the above settings. By changing the sequence of helical magnets in the second spin rotator from (L,R,L,R) to (R,L,R,L), The longitudinal polarization can be reached at all three important collision energies of 41, 100 and 275 GeV [9]. Longitudinal polarization cannot be reached at the energy ranges of 143-151 and 226-232 GeV, which is acceptable.

SUMMARY

Currently, the RHIC proton ring is able to deliver 60% polarization at 250 GeV for collisions with 1.8×10^{11} bunch intensity [10]. AGS can deliver 65% polarization with 3×10^{11}. The additional gains in polarization comes from three parts. First, skew quads compensation scheme in the AGS will further reduce polarization loss in the AGS. Second, cooling at RHIC injection will reduce the resonance strength in the HSR. Third, six snakes in the HSR will preserve polarization through acceleration. All of these lead to higher polarization required for EIC. The space charge effect on polarization at lower energies (injection energy and collision at 41 GeV) are also studied and the results show that the space charge does not pose threat to the polarization lifetime. The positions of spin rotators relative to IP are different from RHIC. The configuration has been analyzed and the needed longitudinal polarization can be provided. The simulation tool has been constructed for polarization lifetime due to IBS and cooling section. The detailed simulations with EIC HSR lattice are underway.

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