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FEASIBILITY OF POLARIZED DEUTERON BEAM IN THE EIC*

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Abstract

The physics program in the EIC calls for polarized neutron beam at high energies. The best neutron carriers are 3He nuclei and deuterons. Both neutron carriers are expected to be used by spin physics program in the EIC. Due to the small magnetic moment anomaly of deuteron particles, much higher magnetic fields are required for spin rotation, so full Siberian snake is not feasible. However, the resonance strength is in general weak and the number of resonances is also small. It is possible to deal with individual resonances with conventional methods, such as betatron tune jump for intrinsic depolarizing resonances; and a weak partial snake for imperfection resonances. The study shows that accelerating polarized deuteron beyond 100 GeV is possible in the EIC.

INTRODUCTION

The collision of polarized proton beams has been an essential component of the Relativistic Heavy Ion Collider (RHIC) operations in the past two decades [1]. To preserve the proton polarization, a pair of Siberian snakes [2] have been used in each of the two rings. The deuteron is on the list of species to be collided in the future Electron Ion Collider (EIC) [3], so that the spin properties of the neutron can be studied relative to those of the proton. The EIC is under design at Brookhaven National Laboratory (BNL), and will utilize one of the existing RHIC rings as an ion ring. As there is no easy method of accelerating polarized neutrons to high energies, a polarized deuteron beam provides an alternative solution. A deuteron consists of a proton and a neutron. One important feature of the deuteron is its very small anomalous magnetic g-factor of $G = -0.1426$. This has a profound effect on the manipulation of its spin in a synchrotron. The Siberian snake scheme employed in RHIC does not work for a polarized deuteron. Owing to the small value of G, a considerably higher magnetic field is required for spin rotation. The required magnetic field is so high that Siberian snakes are not feasible. On the other hand, with the small value of G the resonance strengths are expected to be weaker and the energy separation between resonances is expected to be wider than in the proton case.

OVERCOMING IMPERFECTION SPIN RESONANCES

Since the $|G|$ value is very small, deuteron beam does not encounter any meaningful depolarizing resonance in the injectors. The challenge of polarization preservation occurs in the ion ring of the BNL EIC, where the deuteron energy range is from 10 GeV to 137.5 GeV, or $|G\gamma|$ from 1.5 to 20.9, with total of 19 imperfection resonances. An energy of 137.5 GeV corresponds to $B\rho$ of the proton at an energy of 275 GeV. The nominal ramp rate for unpolarized deuteron operation in RHIC is dγ/dt=90/220, which corresponds to a resonance crossing rate of $\alpha = 1.2 \times 10^{-7}$, where α is defined as $\frac{dG\gamma}{d\theta}$ and θ is the orbit angle. This only represents approximately one fifth of the rate assumed in previous studies. The imperfection resonance strengths for deuterons have been calculated using DEPOL [4] for several standard RHIC lattices with random orbit errors. From beam–beam analysis and previous experience of RHIC operation, three possible vertical tunes are considered as 0.175, 0.224, and 0.673. With an rms orbit error of 0.3 mm, the strongest resonance strength is less than 0.0015.

As the resonance strengths are generally weak, a partial snake can overcome these resonances. The required partial snake strength can be estimated from the Froissart–Stora formula [5]. The localized spin rotation by a partial snake with a strength of χ is $\chi\delta(\theta - \theta_0)$ and the strength of the generated resonance is the Fourier amplitude $\frac{\chi}{2\pi}e^{in\theta_0}$, for all integers n. Here, θ_0 is the relative phase of the resonance. In the presence of an imperfection resonance and a partial snake, the Froissart–Stora formula [5] can be rewritten as

$$\frac{P_\mathrm{f}}{P_\mathrm{i}} = 2\exp(-\frac{\pi}{2\alpha}|\epsilon + \frac{\chi}{2\pi}e^{in\theta_0}|^2) - 1, \qquad (1)$$

where P_i and P_f are the polarization before and after crossing the resonance, respectively; ϵ is the resonance strength; and $\alpha = \frac{d(G\gamma)}{d\theta}$ is the resonance crossing rate. A complete spin-flip occurs if

$$\chi \gg 2\pi|\epsilon| + \sqrt{8\pi\alpha}. \qquad (2)$$

Using the strongest resonance strength of 0.0015 and the given resonance crossing speed $\alpha = 1.2 \times 10^{-7}$, for a spin flip of over 99%, the partial snake strength χ/π must be greater than 0.00355. A strength of 0.0045, or a 0.45% partial snake, would satisfy this requirement.

The strengths of existing Siberian snakes for the deuteron have been calculated by tracking particles through the four helical modules with various currents. The strongest strength of an existing snake is 0.015%. This is too weak to be utilized for the deuteron. A solenoid can be added to preserve the polarization through these imperfection resonances. A solenoid of a given strength $B_\mathrm{s}L$ rotates the spins of particles by an angle

$$\chi = (1 + G)B_\mathrm{s}L/B\rho \qquad (3)$$

and produces an integral of resonance strength

$$\epsilon_\mathrm{sol} = \chi/2\pi \qquad (4)$$

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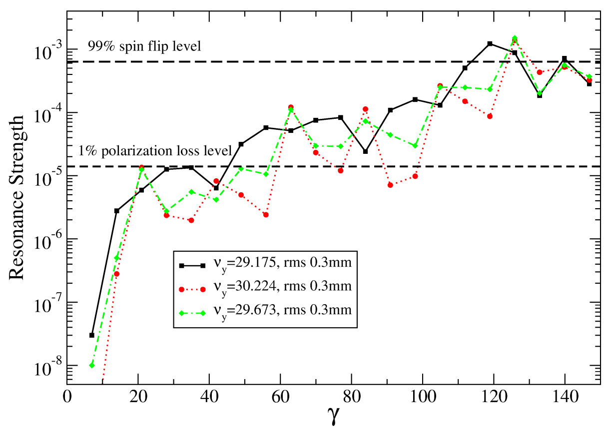

Figure 1: The imperfection resonance strength with three ion-ring lattices. The partial snake resonance strengths for single and dual detector solenoids are shown. From Eq. (4), the partial snake strength decreases as the energy increases for a constant solenoid field. The lines between points are only drawn to guide the eye. The resonance strengths between the two straight lines cause a polarization loss of over 1% with the nominal ramp rate.

at all integer values of $G\gamma$. In the above two equations, B_s is the solenoid magnetic field, L is the effective length of the solenoid, and $B\rho$ is the magnetic rigidity of the beam. When the beam energy increases, the corresponding resonance strength decreases for a constant solenoid field. At the energy of the highest imperfection resonance at $|G\gamma| = 20$, the required 0.45% solenoidal partial snake corresponds to a 15 T m solenoid field. Indeed, in the current design, the detector solenoid strength is 15 T m.

With the detector solenoid as partial snake, the spin-tune and stable spin direction are given as :

$$\cos\pi\nu_s = \cos\frac{\chi_1}{2}\cos G\gamma\pi, \tag{5}$$

$$\begin{aligned} \cos\alpha_1 &= \frac{-1}{\sin\pi\nu_s}[\sin\frac{\chi_1}{2}\sin G\gamma(\pi-\theta)], \\ \cos\alpha_2 &= \frac{1}{\sin\pi\nu_s}[\sin\frac{\chi_1}{2}\cos G\gamma(\pi-\theta)], \\ \cos\alpha_3 &= \frac{1}{\sin\pi\nu_s}[\cos\frac{\chi_1}{2}\sin G\gamma\pi] \end{aligned} \tag{6}$$

It can be observed from Eq. (6) that with $\theta = 0$ (at the detector location) and $|G\gamma|$=integer, the spin is in the longitudinal direction. The resonance strength of detector 1 is plotted in Fig. 1. The detector acts as one partial snake, and is sufficiently strong.

LONGITUDINAL POLARIZATION

Physics experiments require polarization along the longitudinal direction at the detectors. For protons, this is achieved by using spin rotators to rotate the vertical spin into and out of the longitudinal direction in the interaction region (IR). In the BNL EIC ion ring, the stable-spin direction of the deuteron beam is nearly vertical except when $G\gamma$ is near an integer. In general, it is impossible to build spin rotators to rotate the spin from vertical to longitudinal, owing to the small G value. However, at $G\gamma$=integer, the stable-spin direction will precess in the horizontal plane. For certain energies, polarization is naturally in the longitudinal direction at the experimental IRs. For a single-detector operation scenario, as shown in Eq. (6), the vertical ($\cos\alpha_3$) and horizontal ($\cos\alpha_1$) components are both zero when $G\gamma$ is an integer. Therefore, experiments with longitudinal spin are possible at the discrete energies with $|G\gamma|$=integer, or approximately every 6.58 GeV.

OVERCOMING INTRINSIC SPIN RESONANCES

The intrinsic resonance strength can also be calculated from DEPOL [4]. Based on previous unpolarized deuteron beam operations in RHIC, a 2 µm normalized rms beam emittance is expected. Figure 2 depicts the resonance strengths with a rms emittance of 2 µm for a few lattices. The three-fold symmetry means that the stronger resonances occur at $G\gamma = 3n \pm \nu_y$. However, owing to the slow ramp rate, other resonances can also cause polarization losses, which were not included in previous studies. The strongest resonance is at $G\gamma = 12 - \nu_y$, where the strength is approximately 3.5×10^{-3} for a 2 µm emittance beam. This resonance can fully flip the spin with the nominal ramp rate.

A vertical tune jump can be utilized to provide a fast resonance crossing speed. From experience with the AGS, it is not necessary to jump the betatron tune in one turn to maintain the polarization over a strong intrinsic resonance. A benign horizontal tune jump scheme [6] in the AGS has also been implemented in recent operations to overcome the horizontal intrinsic resonances [7] induced by the partial Siberian snakes [8]. The final polarization after crossing an isolated depolarizing resonance is given by the Froissart–Stora formula [5]. In the case of a tune jump, the resonance crossing rate is

$$\alpha = \frac{d(G\gamma)}{d\theta} \pm \frac{d\nu_y}{d\theta} \tag{7}$$

To overcome the resonance strength shown in Fig. 2 and achieve over 99% polarization preservation for each resonance, the required resonance crossing speed should be approximately 9.5×10^{-5}, or about 800 times the value of the regular ramp rate. Considered the spin tune spread, the tune jump amplitude needs to be 0.03. For the required crossing speed, this corresponds to 50 orbit turns.

The required quadrupole strength and power supply can be estimated. The intrinsic resonance with the highest rigidity is at $|G\gamma| = -9 + \nu_y = 20.673$ or $\gamma = 135.6$, where $B\rho = 904$ T m. Considering the three-fold symmetry of RHIC ion ring, three quadrupoles are used. To correct this resonance, a tune jump of $\Delta\nu_y = 0.01$ in 50 turns is required for each of the three quadrupoles. The required quadrupole

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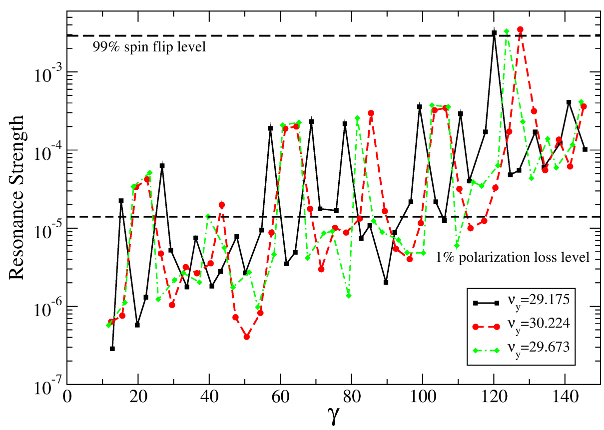

Figure 2: The intrinsic resonances for a few lattices calculated by DEPOL. The two dashed lines are calculated with a Gaussian beam of 2 µm rms emittance. The resonance strengths between the two lines cause polarization losses of over 1% with the nominal ramp rate. The lines between points are only drawn to guide the eye.

strength is

$$B'l = \frac{4\pi\Delta\nu_y}{\beta}B\rho = 2.27T, \tag{8}$$

where $\beta = 50$ m, $\Delta\nu_y = 0.01$, and $l = 0.8$ m for each quadrupole. This yields $B' = 2.84$ T/m. For the beam pipe radius R=0.04 m, the required current becomes

$$NI = \frac{B'R^2}{2\mu_0} = 1809\text{A} - \text{turns}, \tag{9}$$

Using a two-turn coil gives a required current of 905 A. This is similar to the design of the AGS horizontal tune-jump system. The inductance for such a quadrupole is 57 µH, based on the standard inductance formula. In EIC, 50 turns require approximately 640 µs. The required voltage is

$$V = L\frac{dI}{dt} \approx 81V, \tag{10}$$

where $L = 57$ µH and 640 µs are used. Thus a tune-jump system consisting of three quads and three power supplies of 1000 A and 100 V, respectively, should be effective.

The polarizations after each intrinsic resonance are illustrated in Fig. 3, where the results of the nominal ramp with and without a tune-jump system are presented. The tune-jump system can correct all the intrinsic spin resonances except for $|G\gamma| = \nu_y - 12$, which will induce a full spin flip at the nominal ramp, without the need for the tune-jump quadrupoles. The overall efficiency for the tune-jump method plus a normal ramp across $|G\gamma| = \nu_y - 12$ is 95%.

CONCLUSION

The possibility of accelerating polarized deuterons in the BNL EIC has been explored in detail. The resonance

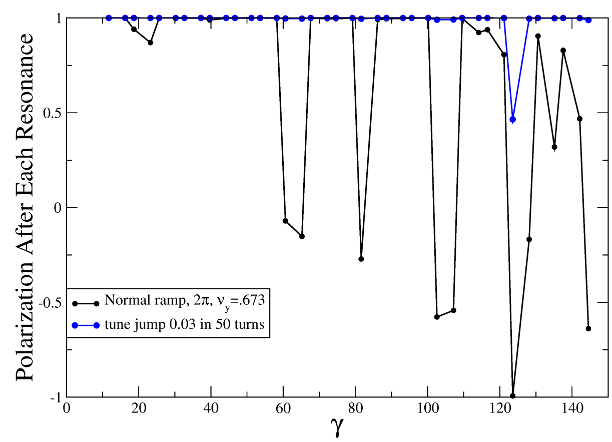

Figure 3: The polarization after each intrinsic resonance with 2 µm normalized rms emittance. Each data point represents the polarization value after crossing an intrinsic resonance. The lines between points are drawn to guide the eye.

strengths have been calculated for various RHIC lattices. Furthermore, several possible schemes to overcome these resonances have been analyzed. We found that the imperfection spin resonances can be overcome by using the detector solenoid as partial snake. This has the additional benefit of ensuring longitudinal polarization at $|G\gamma|$=integer. Intrinsic spin resonances can be handled using a modest tune-jump system.

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