SIMULATION STUDIES OF ACCELERATING POLARIZED LIGHT IONS AT RHIC AND AGS*

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Abstract

As the worlds's first high energy polarized proton collider, RHIC has made significant progresses in measuring the proton spin structure in the past decade. In order to have better understanding of the contribution of u quark and d quark to the proton spin structure, collisions of high energy polarized neutron beams are required. In this paper, we discuss the perspectives of accelerating polarized light ions, like deuteron, Helium-3 and tritium. We also represent simulation studies of accelerating polarized Helium-3 in RHIC.

INTRODUCTION

Physics Motivation

The quest of understanding the proton spin structure has enabled an exciting physics program at the Relativistic Heavy Ion Collider (RHIC) of Brookhaven National Laboratory. After having provided polarized proton collision at a beam energy of 100 GeV for close to a decade, RHIC has been colliding polarized protons at a beam energy of 250 GeV in the past two years. However, to further distinguish the contribution of up quark and down quark to the proton spin structure, the collisions of polarized neutrons are required. To obtain high energy polarized neutrons, polarized ion beams, like deuterons, helium-3, tritium, need to be accelearted as neutron carriers.

Introduction of Spin Dynamics

Same as accelerating polarized protons, the challenge of accelerating polarized ions to high energy is to overcome depolarizing resonances driven by the perturbation on the spin motion from the magnetic fields that particles encounter in an accelerator [1]. In a perfect planar circular accelerator, free of spin rotators, a spin vector precesses $G\gamma$ times in one orbital revolution, i.e. spin tune $Q_s = G\gamma$. Here, $G = \frac{g-2}{2}$ is the anomolous g factor and γ is the Lorentz factor. Spin rotators is an apparatus which can change the direction of the spin vector by rotating it around certain axis [2].

In a circular accelerator, imperfection spin resonance and intrinsic spin resonance are the two primary spin depolarizing resonances. Driven by dipole errors and quadrupole mis-alignments, imperfection spin resonances are located at every integer of $G\gamma$, i.e. $G\gamma = k$. Intrinsic resonance, on the other hand, is excited by the horizontal magnetic field due to vertical betatron oscillation and is located at $G\gamma = kP \pm Q_y$. Here, P is the periodicity of the lattice and Q_y is the vertical betatron tune. The strength of each depolarizing resonance ϵ_k is defined as

$$\epsilon_k = \frac{1}{2\pi}\oint [G\gamma\frac{B_x L}{B\rho} + (1+G)\frac{B_{//}L}{B\rho}]e^{-ik\theta}d\theta \qquad (1)$$

where $B\rho$ is the beam rigidity, or momentum per unit of charge. $B_x L$ and $B_{//}L$ are the horizontal magetic field and longitudinal magnetic field, respectively. Eq. 1 shows that for the same horizontal magnetic field and same beam rigidity, the larger the particle's G factor, the stronger the depolarizing spin resonance. Fig. 1 is the calculated intrinsic depolarizing resonance strength for He-3 and deuteron using depol [3]. Both calculations were done with a particle at normalized 10π mm-mmrad betatron amplitude for RHIC lattice with 1 m beta⋆ at IP6 and IP8, 7.5 m beta⋆ at all the other IPs. It is evident that the intrinsic resonances

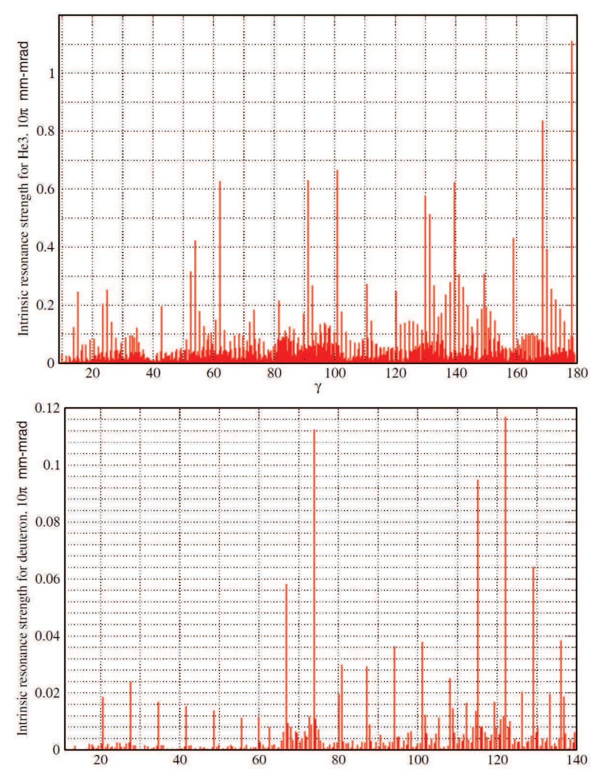

Figure 1: The top plot shows the intrinsic spin resonance of He-3 particle and the bottom plot shows the intrinsic spin resonance strength of deuteron partcile.

for polarized He-3 beams are much denser and stronger than those for deuteron beams. Since tritium has similar $\frac{A}{ZG}$ ratio, its intrinsic resonances are similar to those for He-3. Here, A is the atomic number and Z is the charge number.

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Table 1: Light Nuclei Including Proton Parameter List

Nucleus	A	Z	Spin	G	BL[T-m]
p	1	1	$\frac{1}{2}$	1.793	5.484
d	2	1	1	-0.143	137.915
He-3	3	2	$\frac{1}{2}$	-4.191	3.519
tritium	3	1	$\frac{1}{2}$	7.937	3.716

Clearly, acceleration of light ions to high energy also requires full Siberian snakes [2] to overcome strong depolarizing resonances. A Siberian snake is a device which rotates the spin vector by $180°$ around an axis in the horizontal plane. This makes the spin tune become independent of beam energy. And with proper setup of the snakes, one can then get $Q_s = \frac{1}{2}$. Since beta tune at half integer is not stable for orbital motion, this avoids not only imperfection depolarizing resonances but also intrinsic depolarizing resonances. This was demonstrated again with the success of polarized proton acceleration at the BNL Relativstic Heavy Ion Collider where two full Siberian snakes were employeed to preserve the polarization during the acceleration and collision [4].

For high energy polarized beams, generally magnets with transverse magnetic field are used to manipulate the spin motion. For a full Siberian snake for high energy polarized beams, the required magnetic field $B_{snk}L$ to rotate a spin vector by $180°$ is

$$B_{snk}L = \pi\frac{B\rho}{G\gamma} = 9.8323\frac{A}{Z}\frac{1}{G}, \qquad (2)$$

The feasibility of accelerating polarized He-3 and deuteron beam were first examed by E. Courant [3]. Table 1 shows the spin resonance strength and required magnet strength for a full snake for all three ions. Proton case was also listed for comparison. Evidentally, it is very difficult to accelerate polarized deuterons to full energy due to the exceptionally high field required for a full Siberian snake. However, it is still feasible to accelerate polarized deuteron beam up to 30 GeV in RHIC with transverse polarization at each collision point. Longitudinal polarization at collision point is also very difficult to obtain due to the same reason for deuteron beam.

Acceleration of He-3 and tritium, on the other hand, both benefit from the larger G factor. So, only about 65% strength of the current RHIC Siberian snakes are needed to get a full snake. Since tritium has similar $\frac{A}{ZG}$ ratio as He-3, this paper focus on the simulation studies for the He-3 beam.

Snake Resonances

Equipped with the two full Siberian snakes per accelerator, the depolarizing in RHIC is dominated by snake resonances [5]

$$mQ_y = Q_s + k, \qquad (3)$$

where m and k are integers, Q_y and Q_s are vertical betatron tune and spin precession tune, respectively. This phenomina was first discovered by S. Y. Lee and S. Tepikian during RHIC spin tracking studies, and then observed during the RHIC polarized proton operations [5]. The snake resonances associated with odd number m are primarily driven by the intrinsic spin resonances, while the even order snake resonances with even number m also requires the presence of both imperfection spin resonance and intrinsic spin resonance.

For an odd order snake resonance, in general, the stronger the intrinsic resonance, the snake resonance is. For a given lattice, the intrinsic spin resonance strength is fixed and the only way to avoid this type resonance is to make sure the betatron tunes of the polarized particles stay away from the snake resonance location. For even order snake resonances, they can be mitigated by minimizing the closed orbit distortion.

In addition to the precise control of closed orbit and optics, it is also very critical to minimize the errors in the snake configurations to ensure the spin tune stays at $\frac{1}{2}$ [6, 7]. The deviation of the spin tune will split each snake resonance in two which reduces the available tune space for beam operation. The experience of RHIC polarized proton operation has demonstrated that precise orbit and optics controls are critical in preserving beam polarization up to high energy.

SIMULATION OF ACCELERATION OF POLARIZED HELIUM-3 AND TRITIUM

Even with the success of RHIC polarized protons, Since He-3 has a larger G factor, the depolarizing resonance strength is also about a factor of 2.5 stronger. It is necessary to explore whether the current polarized proton configuration is still adequate for accelerating polarized He-3. Even though the odd order snake resonance can be analytically solvable [8], there is no analytical model for the snake resonances due to the overlap of imperfection and intrinsic resonance and numerical simulation is necessary.

A series of spin tracking were carried out with a ideal RHIC lattice of 1 m beta* at two interaction points and 7.5 m beta* at all other interaction points. These simulation studies were carried out with numerical tracking code zgoubi [9], which calculates the spin motion element by element by numerically solving the Thomas-BMT equation [10], the differential equation governs the spin dynamics in a circular accelerator. A zero length element which rotates the spin vector by certain angle around an axis in the horizontal plane was added to the original code to simulate an artificial snake.

Fig. 2 shows spin tracking results of accelerating an on momentum He-3 particle with different vertical emittance through one of the strong intrinsic resonances around $G\gamma = 168$. For both cases, the spin vector was aligned vertically initially and the plot shows the spin vector vertical component as a function of beam energy. It is evident that the resonance strength is quite sensitive to the betatron amplitude of the particle. Nevertheless, it is very comfortable to see that the two snakes are able to bring the spin vector back to vertical direction after passing the resonance for both cases.

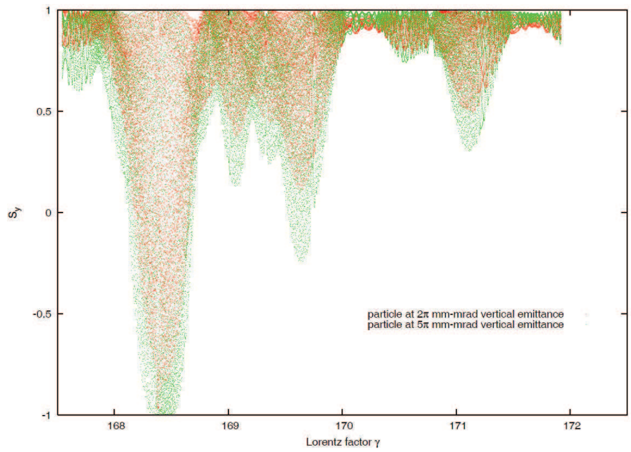

Figure 2: This shows the vertical component of the spin vector as a function of the beam energy for He-3 for an on momentum particle with different vertical emittances. The red dot data set is for a particle at 2π mm-mrad emittance and green dot data set corresponds to 5π mm-mrad emittance.

Fig. 3 on the other hand compares the spin tracking results of accelerating an on momentum particle and an off momentum particle through the same intrinsic spin resonance. Both particles were launched on a vertical betatron emittance of 2π mm-mrad. The red dot data set corresponds to the on-momentum particle, while the green dot data set is for the off momentume particle with $\frac{dp}{p} = 0.0005$ momentum deviation. Compared with Fig. 2 results, the

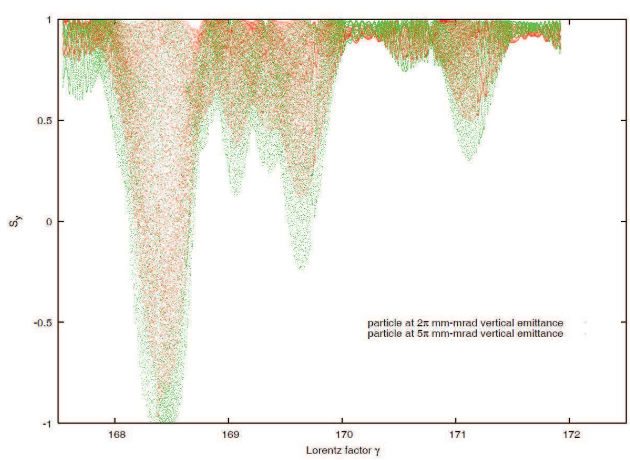

Figure 3: This plot compares the vertical component of the spin vector as a function of the beam energy of a on momentum particle with an off momentum particle with $\frac{dp}{p} = 0.0005$ momentum deviation. The vertical emittance was set to 2π mm-mrad for both spin trackings.

resonance strength is much less sensitive to the momentum deviation.

CONCLUSION

Feasibility of accelerating polarized light ion beams like deuteron, He-3 and tritium were examined. Preliminary spin trackings were carried out to study the acceleration of polarized He-3 in RHIC. The results of preliminary spin tracking are encouraging and show that it is feasible to accelerate He-3 beam to high energy in RHIC with its current dual Siberian snake setup. Further detailed spin trackings are necessary to explore the sensitivity of various beam parameters, like orbit distortion, betatron tune etc on polarization losses.

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