EXPLORE THE POSSIBILITY OF ACCELERATING POLARIZED He-3 BEAM IN RHIC*

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Abstract

As the world'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 up quarks and down quarks to the proton spin structure, collisions of high energy polarized neutron beams are required. Polarized He-3 beams offer an effective way to provide polarized neutron beams. In this paper, we present studies of accelerating polarized He-3 in RHIC with the current dual snake configuration. Possibilities of adding two more pairs of snakes for accelerating polarized He-3 were explored. Results of six snake configuration in RHIC are also reported in the paper

INTRODUCTION

The spin physics program at RHIC is designed to explore the spin structure of protons as well as neutrons. An effective way of obtaining polarized neutron collisions at high energy is to accelerate heavier nuclei He-3 as neutron carriers. Just like accelerating polarized protons, accelerating a polarized He-3 beam to high energy also faces the challenge of preserving polarization through various depolarizing mechanisms [1], a resonant condition when the frequency of perturbation on the spin motion matches the frequency of spin precession.

In a circular accelerator with no special spin manipulations, the spin tune Q_s, i.e. the number of spin precessions in one orbital revolution, is given by $G\gamma$. Here, γ is the Lorentz factor and G is the anomalous $g-$factor and $G = 1.793$ for the proton, and $G = -4.191$ for He-3. Evidently, at higher energy, the spin precesses faster. To first order, there are two types of depolarizing resonances: imperfection spin resonances from closed orbit distortions due to machine imperfections such as dipole errors and quadrupole misalignment and intrinsic spin resonances driven by the horizontal magnetic field due to vertical betatron oscillations [1]. The imperfection spin resonances are located at $G\gamma = k$ and the intrinsic spin resonances are located at $G\gamma = kP \pm Q_y$. Here, k is any integer, P is the super-periodicity of the machine and Q_y is the vertical betatron tune. The amount of depolarization depends on the strength of the resonance and the resonance crossing speed. In general, the strength ϵ_k of a imperfection or intrinsic depolarizing resonance at $G\gamma = K$ is given by [1]

$$\epsilon_k = \frac{1}{2\pi}\int[(1+G\gamma)\Delta B_x]e^{iK\theta}ds. \qquad (1)$$

Here, ΔB_x is the radial magnetic field. For imperfection resonances, the resonance strength is proportional to the amplitude of the closed orbit distortion, and for intrinsic resonances, the strength is proportional to the amplitude of the betatron oscillation. And in both cases, the resonance strength is proportional to beam energy as well as the G factor. Fig. 1 shows the calculated intrinsic resonance strength for He-3 as well as for protons [4] at a vertical emittance of 10πmm-mrad. Similarly, for the same closed orbit distortion, imperfection resonances of polarized He-3 are about twice stronger than the imperfection resonances of polarized protons. It also shows that He-3 acceleration

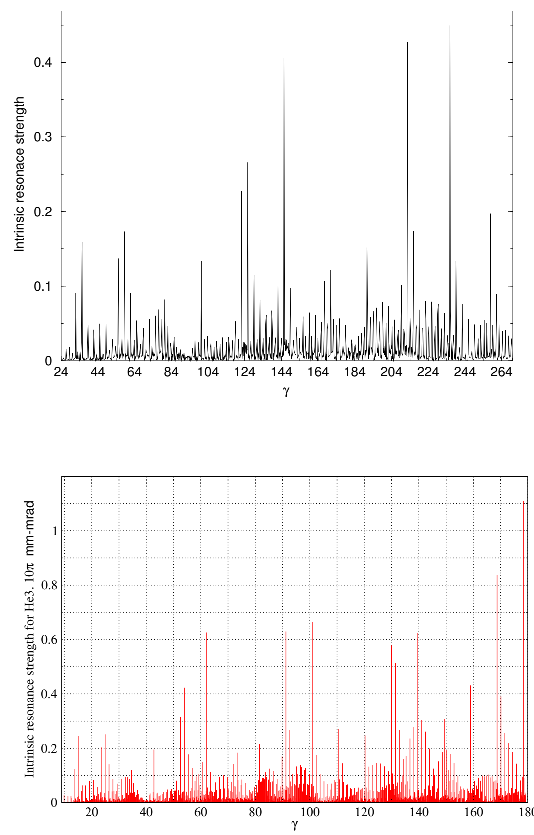

Figure 1: The top and bottom plots are the intrinsic depolarizing resonance strengths for proton and He-3 as a function of Lorentz factor γ, respectively.

has more intrinsic resonances than polarized proton acceleration.

To preserve the polarization of polarized protons, RHIC employs two Siberian snakes [2] per accelerator [3]. A Siberian snake [2] is a magnetic device to rotate the spin vector by 180° around an axis in the horizontal plane. The

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two snakes in each of the two RHIC accelerators are located 180° apart from each other with the spin rotation axis of one snake perpendicular to the axis of the other. In this configuration, the spin precession tune becomes a constant of half-integer, which not only avoids all the imperfection resonances but also all intrinsic resonances since a half integer is different from stable betatron tunes. However, it was discovered by Lee and Tepikian [5] that the perturbations on the spin motion can still add coherently and depolarization can still occur even in the presence of snake(s) when

$$mQ_y = Q_s + k. \quad (2)$$

Here, m and k are integers. m is the order of the resonance [1]. In this paper, both Q_y and Q_s in Eq. 2 are the fractional betatron tune and spin tune, respectively. This is called a snake resonance. An odd integer of m means an odd order snake resonance and a even integer of m corresponds to an even order snake resonance. This was also experimentally observed at IUCF and RHIC [6, 7]. Hence, the challenge of accelerating high energy polarized beams is to keep the betatron tune within the betatron tune areas free of snake resonances, particularly at beam energies where the intrinsic resonance without snakes would be strong.

POSSIBILITY OF ACCELERATING POLARIZED HE-3 IN RHIC

Similar to polarized protons, accelerating polarized He-3 also requires Siberian snakes. Due to the fact that the He-3 G factor is about twice of the proton's G factor, only a fraction of current RHIC Siberian snake magnetic field is needed for a full Siberian snake for He-3 [8].

However, accelerating polarized He-3 faces more and stronger spin depolarizing resonances. This means that the snake resonances encountered when accelerating He-3 are stronger and denser. In addition, the overlap of imperfection resonances due to closed orbit distortion and intrinsic resonances excites also even order snake resonances, which otherwise disappears with the dual snake configuration. Other sources for even order snake resonance include errors in snake settings. The overlap of an intrinsic resonance with an imperfection resonance also splits the existing odd order resonances [1, 9].

Fig. 2 shows the snake resonance spectrum for He-3 with the current dual snake configuration in RHIC. This calculation was done by tracking spin motion only, i.e. computing the evolution of the 2-component spinor for each orbital revolution with both snakes. In this lattice free spin tracking, the two snakes are placed 180° apart from each other and their spin rotation axis are perpendicular. In between the snakes, the intrinsic spin resonance is included by rotating the spinor into the resonance frame. The intrinsic resonance strength is chosen based on the beam emittance. Clearly, the He-3 snake resonance spectrum is very dense and the available tune space for accelerating the He-3 beam is quite limited, which means much less tolerance for

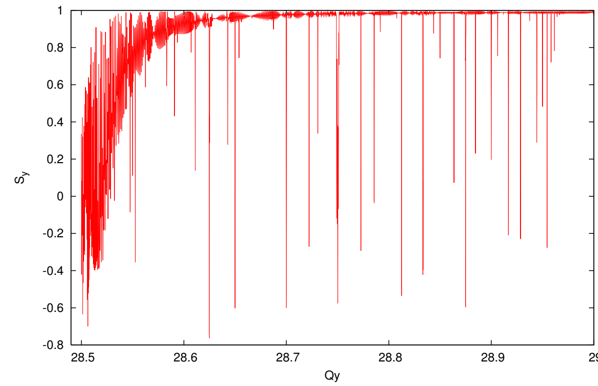

Figure 2: The plot shows the calculated snake resonance spectrum for He-3 in a dual snake configuration.

the snake configurations, closed orbit, tunes, chromaticities and other beam parameters for He-3 acceleration.

Careful studies show that to accelerate polarized protons with an rms normalized emittance of 3.33mm mrad, the imperfection resonance strength should be below 0.075 to avoid polarization loss at the strong intrinsic resonances around 136 GeV, 203 GeV and 221 GeV [3]. Hence, a closed orbit with $\sigma_{y,rms} \leq 0.3$mm is needed to keep the imperfection resonances below 0.075 at all energies in RHIC [3, 10].

Table 1 shows the required as well as achieved errors of beam parameters at RHIC with the dual snake configuration. Here, y_{rms} is the vertical rms closed orbit distortion,

Table 1: Errors of beam parameters for polarized beam acceleration in RHIC

species	$\mathbf{y}_{rms}$ **required**	$\mathbf{y}_{rms}$ **achieved**	$\Delta\mathbf{Q}_y$ **required**	$\Delta\mathbf{Q}_y$ **achieved**
proton	0.5mm	0.1mm	0.003	0.005
He-3	0.15mm	N/A	0.001	N/A

ΔQ_y is the vertical betatron tune spread. Evidently, the errors for the He-3 beam parameters are very difficult to achieve.

Fig. 1 shows that the strong intrinsic resonance strengths for He-3 reach as high as $\epsilon_k = 1$. This means more snakes are needed for accelerating polarized He-3 beam to cancel the perturbation on the spin motion. As a rule of thumb, the number of snakes scales with the depolarizing spin strength, i.e.

$$N_{snk} > 4\epsilon_{k,max} \quad (3)$$

where N_{snk} is number of snakes [1]. For He-3 in RHIC, $\epsilon_{k,max} \sim 1$, and a total of four more snakes are needed for the He-3 beam ring. Together with the existing two snakes, these six snakes should be distributed evenly through out the ring. The spin rotation axis of each snake alternates between 45 degrees and -45 degrees with respect to beam direction for all six snakes. Fig 3 is the schematic layout of the six snake configuration for RHIC. The spin tune is

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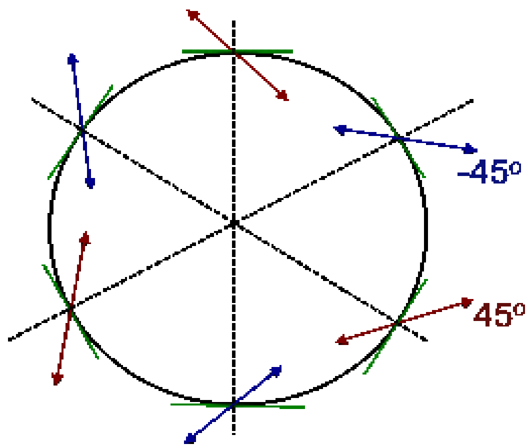

Figure 3: This plot is a schematic layout of six full Siberian snakes in RHIC. Along the ring, the distance between any adjacent snakes is an azimuthal angle of 60 degrees. The double arrowed line stands for the spin rotation axis of each snake. The axis angle alternates between 45 degrees and -45 degrees with respect to beam direction from snake to snake.

given by

$$Q_s = \frac{1}{\pi}\sum_{k=1}^{N_{snk}}(-1)^k\phi_k \quad (4)$$

where ϕ_k is the angle of the spin rotation axis relative to the beam direction. For the configuration in Fig. 3, the spin tune is independent of beam energy. The other important feature of this configuration is that the spin tune in the presence of a single isolated resonance is also independent of betatron amplitude [12, 13]. Fig. 4 shows the calculated snake resonance spectrum for the proposed six snake configuration. In comparison to the He-3 snake resonance spectrum of the current RHIC dual snake configuration in Fig. 2, it is clear that this six snake configuration has many fewer snake resonances, which means that there is more betatron tune space for acceleration as well as during the store for producing collisions.

CONCLUSION

We explored the possibility of accelerating polarized He-3 beam to high energy at RHIC. Even though the current RHIC Siberian snakes are fully capable of being a full snake for He-3, the more and stronger depolarizing resonances for He-3 beam pushes the tolerance of beam parameter errors, i.e. closed orbit distortion, space for betatron tune, etc to an unprecedented level. An alternative is to employ six snakes per accelerator to reduce the amount of snake resonances, and relax the tolerance on orbit distortions and opens up the available betatron tune space. Detailed spin numerical simulation with six snakes are in progress.

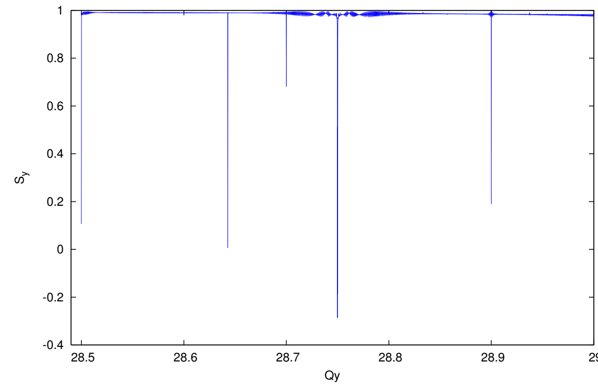

Figure 4: The plot shows the calculated snake resonance spectrum for He-3 in a six snake configuration as shown in Fig. 3.

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