

*Observation of snake resonances at Relativistic
Heavy Ion Collider*

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Observation of snake resonances at Relativistic Heavy Ion Collider

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Abstract. The Siberian snakes are powerful tools in preserving polarization in high energy accelerators has been demonstrated at the Brookhaven Relativistic Heavy Ion Collider (RHIC). Equipped with two full Siberian snakes in each ring, polarization is preserved during acceleration from injection to 100 GeV. However, the Siberian snakes also introduce a new set of depolarization resonances, i.e. snake resonances as first discovered by Lee and Tepikian [1]. The intrinsic spin resonances above 100 GeV are about a factor of two stronger than those below 100 GeV which raises the challenge to preserve the polarization up to 250 GeV. In 2009, polarized protons collided for the first time at the RHIC design store energy of 250 GeV. This paper presents the experimental measurements of snake resonances at RHIC. The plan for avoiding these resonances is also presented.

1. Introduction

In a circular accelerator, the motion of a particle's spin vector \vec{S} is governed by the Thomas-BMT equation [2], i.e.

$$\frac{d\vec{S}}{dt} = \frac{e}{\gamma m} \vec{S} \times [(1 + G\gamma)\vec{B}_\perp + (1 + G)\vec{B}_\parallel]. \quad (1)$$

Here γ is the Lorentz factor and G is the anomalous g -factor and $G = 1.793$ for proton. \vec{B}_\perp and \vec{B}_\parallel are the magnetic fields perpendicular and parallel to the beam direction, respectively. Eq. 1 shows that in a perfect planar accelerator with only vertical dipole field, the spin vector precesses $G\gamma$ times per orbital revolution. The spin tune Q_s is then equal to $G\gamma$.

Eq. 1 also shows that the beam polarization, the average of the spin vectors of all the particles in the beam, can be compromised by the depolarization mechanisms from non-vertically oriented magnetic fields. In general, there are two types of first order spin resonances, i.e. imperfection spin resonances from closed orbit distortions due to machine imperfections such as dipole errors and quadrupole misalignments, and intrinsic spin resonances driven by the horizontal magnetic field due to vertical betatron oscillations [3]. 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. 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.

For high energy accelerators like RHIC, the technique of preserving polarization is to employ Siberian snakes [4], a magnetic device to rotate the spin vector by 180° around an axis in the horizontal plane. In this way, the spin precession tune becomes a half-integer constant, which not only avoids all the imperfection resonances but also intrinsic resonances since half integer is different from stable betatron tunes. However, it was discovered by Lee and Tepikian [1] 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 [3]. In this paper, both Q_y and Q_s in Eq. 2 are 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 an even integer of m corresponds to an even order snake resonance. This was also experimentally observed at IUCF [6]. 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.

Recently, Mane showed that in the case of a single intrinsic resonance, the spin motion in the neighborhood of snake resonance can be analytical calculated by a set of special functions [7]. Unfortunately, no analytic solution is available for cases when overlapping spin resonances are involved, i.e. when the intrinsic resonance overlaps with a strong imperfection resonance. In this case, the snake resonance structure can only be studied with numerical simulations.

2. Accelerating polarized protons in RHIC

In RHIC, two Siberian snakes are placed on opposite sides of the ring, and the spin tune Q_s is $\frac{|\Delta\phi|}{\pi}$. Here, $\Delta\phi$ is the angle between the spin rotation axes of the two snakes. With the axes of the two snakes perpendicular to each other, the spin tune becomes $\frac{1}{2}$ [8]. For an accelerator without closed orbit distortions, the dual snake configuration makes the stable spin direction stay vertical and cancels all the even order snake resonances in Eq. 2. This helps to make more tune space available for acceleration as well as storage. However, the even order snake resonances can still reappear if the intrinsic resonance overlaps an imperfection resonance, or if the snakes are not set properly and the spin tune deviates from 0.5. The overlap of an intrinsic resonance with an imperfection resonance also splits the existing odd order resonances [3, 7]. Hence, to preserve the polarization in RHIC requires careful control of tunes and vertical closed orbit distortions as well as the snake precession axis and spin rotation.

Careful studies show that to accelerate polarized protons with an rms normalized emittance of 3.33 mm 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 [8]. 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 [8, 10].

Polarized protons in RHIC have been successfully accelerated to 100 GeV with minimum or no polarization loss by carefully controlling the betatron tunes and vertical orbit distortions [11]. However, polarized protons accelerated to 250 GeV in 2009 suffered significant polarization losses due to the much stronger intrinsic resonances around 136 GeV, 203 GeV and 221 GeV [8, 11].

Figure 1 shows the measured polarization as a function of beam energy. The polarization losses occurred beyond 100 GeV. The polarization as function of beam energy was measured by the

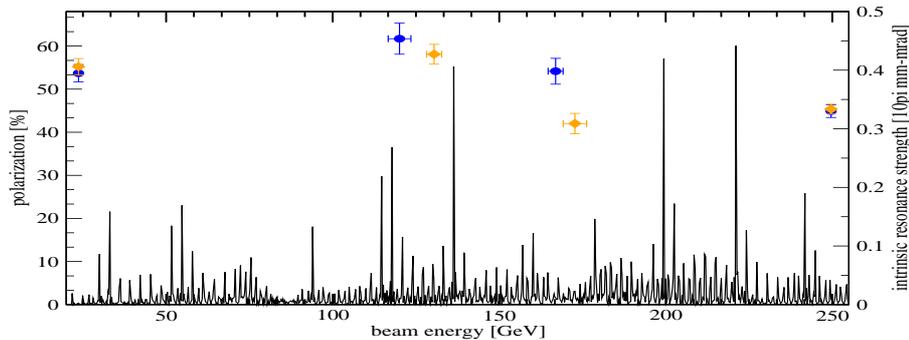


Figure 1. Measured polarization in the Blue and Yellow rings as a function of beam energy. The blue dots correspond to the Blue ring, and the Yellow diamonds are for Yellow ring. The intrinsic resonance strength as function of beam energy is also plotted as the black lines.

Coulomb-Nuclear Interference polarimeter (See section III) at the four energies during the ramp. In order to have enough statistics for each data point, a total of 5 ramps were executed. In each case, four polarization measurements were taken at around injection energy, 128 GeV, 175 GeV and 250 GeV. The horizontal bars in the plot represent the energy uncertainty due to the measurement duration. The ramp measurements show the polarization loss occurred between 128 GeV and 205 GeV where strong intrinsic resonances are located.

3. Experimental observation of snake resonances at RHIC

The polarization measurement at RHIC is primarily carried out by two relative polarimeters based on the Coulomb-Nuclear Interference effect of elastic proton-carbon scattering in each ring (CNI polarimeter). An absolute polarimeter using a polarized hydrogen jet target (H jet polarimeter) located at one of the RHIC interaction points [13] is used to calibrate the two relative carbon polarimeters. The results presented here are from online measurements and have a typical statistical uncertainty of 0.03 and systematic uncertainty of 0.1. In the following, only the statistical uncertainties are indicated.

High order snake resonances were first observed at RHIC parasitically during RHIC polarized proton operation in 2002 [17]. The even order resonance $2Q_y = Q_s$ was then observed at RHIC injection. Figure 2 shows the measured polarization as function of vertical betatron tune at injection. The even order snake resonance at $Q_y = 0.25$ is evident. Polarization was lost in both rings when the vertical betatron tune was pushed towards 0.25. The fact that the location of $2Q_y = Q_s$ snake resonance deviated from $Q_y = 0.25$ indicates that the spin tune in Yellow was not exactly 0.5. This was improved by changing the snake current as shown in the blue dot data set. To observe the fifth order snake resonance $5Q_y = Q_s + k$ at $Q_y = \frac{7}{10}$ beam in the Blue ring of RHIC was accelerated to $G\gamma = 63$ the location of the first strong intrinsic resonance. The proton beam was first accelerated to this energy with its vertical betatron tune about 0.02 either above or below 0.7. Polarization was then measured as a function of the vertical betatron tune while beam was stored as shown in Fig. 3. It is evident that the polarization became less and less as the vertical tune got closer and closer to 0.7.

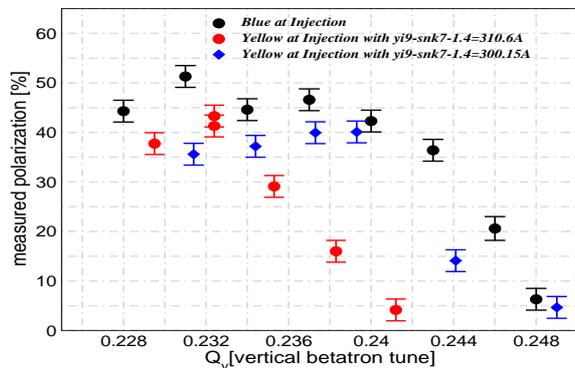


Figure 2. Measured polarization as a function of vertical betatron tune at RHIC injection energy of $G\gamma = 46.5$ in 2003. The black dot data set is from Blue ring. The red dot data set is from the Yellow ring with the initial snake current.

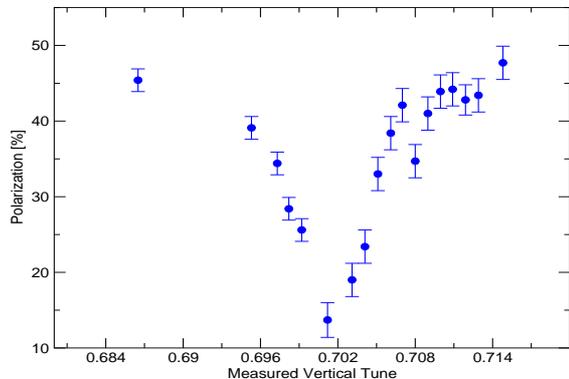


Figure 3. Measured polarization as a function of the vertical betatron tune. The data were taken in Blue ring with beam accelerated from $G\gamma = 45.4$ to $G\gamma = 63$, an energy where a strong intrinsic spin resonance is located.

In order to explore the sensitivity of depolarization to vertical betatron tunes at the three strong intrinsic resonance around 136 GeV, 203 GeV and 221 GeV in RHIC, a detailed polarization measurement as a function of the vertical tune from 100 GeV to 250 GeV were conducted. Currently, with the help of the tune feedback system [14], the betatron tunes can be well controlled during acceleration in RHIC. For a typical RHIC polarized proton ramp to 250 GeV, the betatron tunes were set to be flat at $Q_x = 0.69$ and $Q_y = 0.68$ for the whole acceleration. A total of 21 ramps were carried out with the vertical tune between 100 GeV and 250 GeV varied from ramp to ramp. For each case, polarizations in both rings were measured with the CNI polarimeters at injection as well as at store. Figure 4 shows the polarization transmission efficiency (ratio of polarization at 250 GeV and polarization at injection) as function of the vertical tune. The snake resonance $5Q_y = Q_s + 3$ can be clearly seen. For lower vertical tune below 0.7, the polarization transmission increases towards 100%. The lower polarization transmission efficiency with vertical tune above 0.7 is due to the snake resonance at $2Q_y = Q_s + 1$. There are also hints of higher order snake resonances of $8Q_y = Q_s + 5$ and $11Q_y = Q_s + 7$ in the Yellow ring. In the latest RHIC polarized proton 250 GeV run in 2009, the vertical tune had to stay at 0.68 due to an intermittent power supply glitch, which caused the vertical tune to jump cross the 3rd order resonance and aborted beam.

4. Conclusions

Siberian snakes have been proven to be a very powerful tool for preserving polarization when accelerating beams to high energy. However, depolarization can still occur because of snake resonances. This depolarizing mechanism has been observed at RHIC. The success of preserving polarization losses up to 100 GeV at RHIC also shows that careful selection of betatron tune as well as precise betatron tune control and orbit control are needed to avoid snake resonances.

The main challenge of preserving polarization when accelerating polarized proton beams to 250 GeV in RHIC is to avoid the polarization losses due to snake resonances around the three intrinsic resonances beyond 100 GeV. A polarization transmission efficiency scan with respect to the vertical betatron tune shows that the polarization transmission efficiency favors a tune close to 0.67. Options of accelerating polarized proton beams at a vertical tune close to 0.67

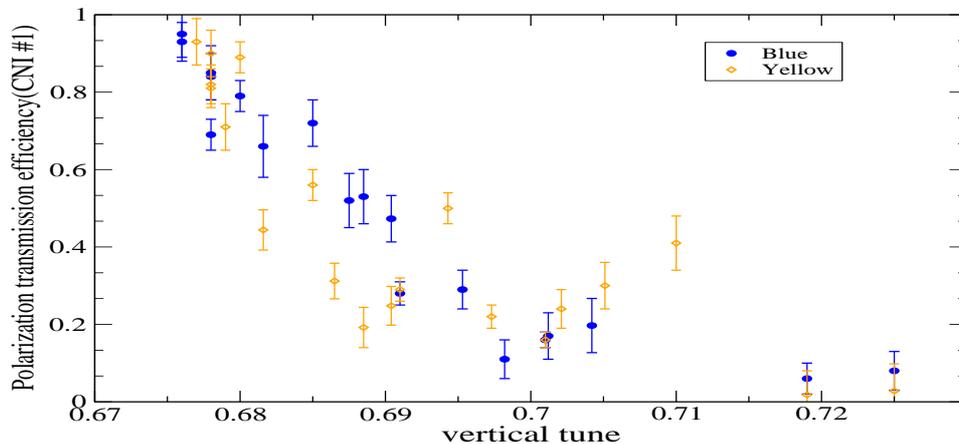


Figure 4. Measured polarization transmission efficiency as a function of the vertical betatron tune during the acceleration between 100 GeV and 250 GeV. The data were taken in Blue ring. Each data point corresponds to one complete RHIC acceleration from injection to 250 GeV.

will be explored during RHIC polarized proton operation in 2011.

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