OBSERVATIONS OF SNAKE RESONANCE IN RHIC *

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Abstract

Siberian snakes now become essential in the polarized proton acceleration. With proper configuration of Siberian snakes, the spin precession tune of the beam becomes $\frac{1}{2}$ which avoids all the spin depolarizing resonance. However, the enhancement of the perturbations on the spin motion can still occur when the spin precession tune is near some low order fractional numbers, called snake resonances, and the beam can be depolarized when passing through the resonance. The snake resonances have been confirmed in the spin tracking calculations, and observed in RHIC with polarized proton beam. Equipped with two full Siberian snakes in each ring, RHIC provides us a perfect facility for snake resonance studies. This paper presents latest experimental results. New insights are also discussed.

INTRODUCTION

In high energy accelerator, the unperturbed spin precession tune is $G\gamma$ where G is the anomalous $g-$factor and γ is the Lorentz factor. In order to avoid significant polarization loss due to the two types of first order spin resonances, imperfection spin resonance at $G\gamma = k$ and intrinsic spin resonance at $G\gamma = kP + Q_y$ [1], Siberian snake(s) [2] is often employed to make the spin precession tune energy independent by kicking the spin vector by 180^o every time the beam passes through. In general, the imperfection spin resonance arises from the vertical closed orbit distortion, and the intrinsic spin resonance is the result of vertical betatron oscillation. Here, k is an integer, P is the periodicity of the lattice and Q_y is the vertical betatron tune.

However, at the location of a strong intrinsic spin resonance, the perturbations on the spin precession can still be coherently added up when

$$mQ_y = Q_s + k, \tag{1}$$

and polarization can get lost. Here, Q_s is spin precession tune , m and k are integers. This is the so called snake resonances which were first discovered during the simulations by S. Y. Lee and S. Tepikian [3], and has been observed in RHIC [4]

Depending on whether m is an even number or odd number, a snake resonance is either an even order resonance or an odd order resonance. For an accelerator with one full snake, the intrinsic spin resonance drives both even order and odd order snake resonances. For an accelerator with two full Siberian snakes located 180^o apart from each other, the intrinsic spin resonance can only drive odd order resonances because the perturbations on the spin motion during one turn can be perfectly canceled out with the perturbations from the next turn when m is an even number. Fig. 1 shows the simulation results by tracking the spin one turn map for the cases of a machine with a single snake with two snakes. The two snake case certainly provides much wider tune space free of snake resonance than the one snake case. Since the higher the beam energy, the stronger the spin depolarization resonance, two or even more snakes are needed to avoid polarization losses.

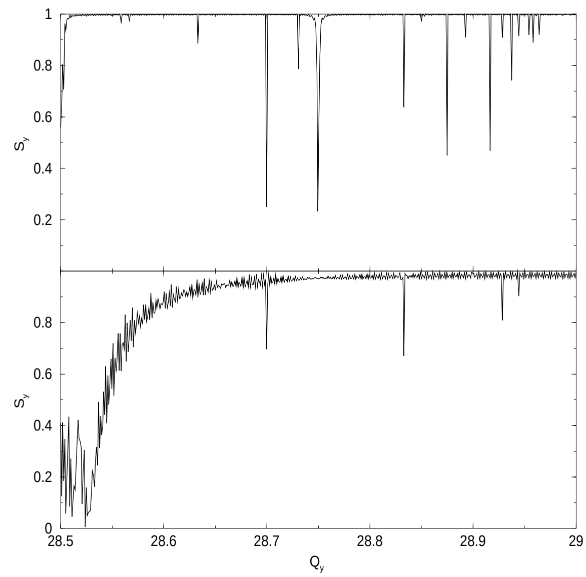

Figure 1: The top plot is the snake resonance spectrum for a machine with only one snake. The bottom plot shows the spectrum with two full snakes.

In an real accelerator even with two full snakes, the overlap an intrinsic spin resonance with an imperfection resonance can drive the even order snake resonances at $2mQ_y = Q_s + k$ and significantly shrink the resonance free tune space. The spin precession tune can also be shifted away from half integer due to the errors of snake. This then splits each snake resonance into two according to Eq. 1 and further tights up the available tune space free of snake resonance. Fig. 2 shows the snake resonance spectrum with and without imperfection spin resonance. The spin precession tune in both cases is set to 0.49 by moving the spin precession axis of one snake by making the angle between the two snakes' axes at 88.2^o instead of 90^o. Clearly, the

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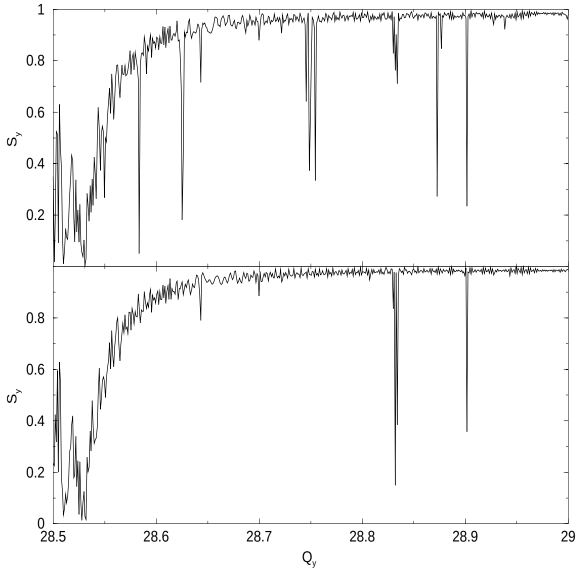

Figure 2: The top plot shows the snake resonance spectrum with non-zero imperfection resonance. The bottom plot shows the resonance spectrum with no imperfection resonance. The spin tune was placed at 0.49 in both cases.

even order snake resonances show up with non-zero imperfection resonance and each snake resonance is split due to the spin tune deviation from half integer.

RHIC POLARIZED PROTON SETUP

In RHIC, there are four strong intrinsic spin resonances between its injection energy at $G\gamma = 46.5$ and current store energy at $G\gamma = 191.5$ [5]. The strength of the strongest imperfection resonance is 0.05 for an rms closed orbit distortion of 1mm [5]. Two full helical Siberian snakes per ring were employed in RHIC to avoid the polarization loss at imperfection and intrinsic resonances [6]. The two snakes are 180^o apart. The spin precession axis of both snakes are lying in the horizontal plane and the spin precession tune Q_s is given by

$$Q_s = \frac{1}{\pi}\Delta\phi \tag{2}$$

Where $\Delta\phi$ is the angle between the precession axis of the two snakes. With their axis perpendicular with each other, the spin precession tune $Q_s = \frac{1}{2}$.

To avoid polarization loss, the RHIC working point are chosen to be in a snake resonance free window. The 2003 working point (0.23,0.22) was chosen to avoid a second order snake resonances at $Q_y = k + \frac{1}{2} \times \frac{1}{2}$ and a seventh order snake resonance at $Q_y = k + \frac{3}{7} \times \frac{1}{2}$. The working point (0.73,0.72) in 2004 and 2005 was chosen to avoid the second order snake resonances at $Q_y = k + \frac{3}{2} \times \frac{1}{2}$ and the fifth order snake resonance at $Q_y = k + \frac{7}{5} \times \frac{1}{2}$.

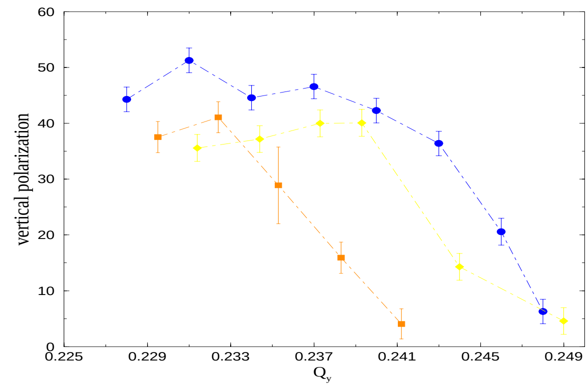

Figure 3: Polarization scan as a function of vertical betatron tune in run 2003. The blue circles are the polarization measurements in the blue ring with the designed snake current settings. The brown squares are the polarization measurement in the yellow ring with also the designed snake current settings. The yellow circles are the polarization measurements in the yellow ring with the snake current in the inner helix 10 Amps less than its design value.

EXPERIMENTAL OBSERVATION

The second order snake resonances were observed experimentally in RHIC at its injection energy by placing the vertical betatron tune very close to 0.25 or 0.75. Fig. 3 shows the observation of the second order snake resonance at 0.25 during RHIC polarized proton operation in 2003 when one of the four helices of one yellow snake was broke. Special arrangement was made to reconfigure the snake as an 88% partial snake. Hence, it is very critical to confirm the corresponding spin precession tune is at 0.5. Scans of beam polarization as a function of betatron tune at injection energy in both rings were done to measure the spin precession tune. It is evident that when the vertical betatron tune approaches 0.25, beam then gets partially depolarized. The width of second order resonance at 0.25 in yellow with a snake inner current at 310 Amp is significantly wider than the one in blue. This shows that the yellow spin precession tune was much further away from 0.5. A scan of current setting of the inner helix in the yellow partial snake showed the optimized current should be around 300 Amp. With this current, the measured width of the second order snake resonance then becomes comparable with the width of the snake resonance width in blue.

Even with two full snakes, the spin tune can be significantly shifted from half integer due to the snake errors. Eq. 3 is the amount of spin precession tune shift from $\frac{1}{2}$ as a function of the snake errors.

$$\Delta Q_s = -\frac{\delta\phi}{\pi} + \frac{(\delta\mu)^2}{4\pi}\cos G\gamma\pi. \tag{3}$$

Here, $\delta\phi$ is the deviation of the angle between the two snake precession axes away from 90^o, and $\delta\mu$ is the error of the snake precession angle. Eq. 3 also shows that the spin precession tune is more sensitive to the angle between

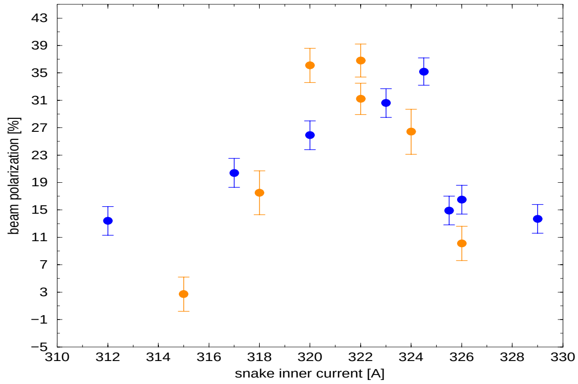

Figure 4: The blue dots are the scans of the blue snake inner current. The orange dots are the scans of the yellow snake inner current. The preferred current for the yellow snake is at 322 Amp while the optimized blue snake current is around 326 Amp.

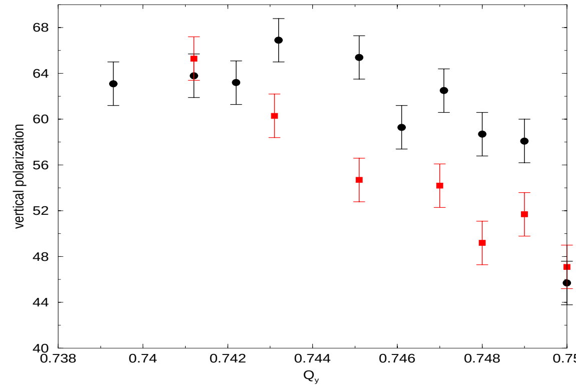

Figure 5: The beam polarization scan as a function of betatron tune at injection in the yellow ring. The black dots are the data with the nominal well corrected orbit at injection. The red squares are the data with the orbit of enhanced imperfection spin resonance, and shows a wider width of the second order snake resonance.

the two snakes' precession axis. Fig. 4 shows the scans of the snake inner current in both blue and yellow to find the optimized snake current settings corresponding to 0.5 spin tune. During the current scans, the vertical tune was placed at 0.745 close to the second order snake resonance at $\frac{3}{4}$. The yellow snake scans show the optimized current setting is around 322 Amp and the optimized current in blue is around 326 Amp. The fact that the blue snake scan is wider than the yellow snake scan also indicates that this second order snake resonance in blue is weaker than the corresponding resonance in yellow.

The effect of imperfection resonance on the second order snake resonance was also studied during the RHIC polarized proton operation in 2005. The beam polarization was measured at injection as a function of vertical betatron tune with two sets of different vertical orbit. One is the well corrected orbit and one is the orbit with four 15 mm vertical bumps in the arc to enhance the imperfection resonance at injection to a strength of 0.06. Fig. 5 shows the width of the second order resonance at 0.75 with the orbit of enhanced imperfection spin resonance is wider than the width with the nominal well corrected orbit at injection.

The fifth order snake resonance at $\frac{7}{10}$ was also explored at injection by measuring the beam polarization with respect to difference vertical betatron tunes in the neighborhood of 0.7. However, no significant depolarization was seen yet. This could be because the intrinsic resonance at $G\gamma = 46.7$ is too weak to be seen.

CONCLUSION

Siberian snakes are introduced in high energy accelerators to overcome first order spin resonances during the acceleration. However, the perturbation on the spin motion due to the betatron oscillation can still be coherently added up when the spin precession tune is the of the betatron tune. This new type of spin resonances was first experimentally observed at RHIC during its polarized proton operations. The snake resonance at $\frac{1}{4}$ or $\frac{3}{4}$ are very evident at injection. Shifting the spin tune by changing the snake current also moved the location of the $\frac{3}{4}$ resonance. Further studies on the other snake resonances are currently carried out in RHIC during the FY05 polarized proton operation.

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