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SPIN TUNE DEPENDENCE ON CLOSED ORBIT IN RHIC*

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Abstract

Polarized proton beams are accelerated in RHIC to 250 GeV energy with the help of Siberian Snakes. The pair of Siberian Snakes in each RHIC ring holds the design spin tune at 1/2 to avoid polarization loss during acceleration. However, in the presence of closed orbit errors, the actual spin tune can be shifted away from the exact 1/2 value. It leads to a corresponding shift of locations of higher-order ("snake") resonances and limits the available betatron tune space. The largest closed orbit effect on the spin tune comes from the horizontal orbit angle between the two snakes. During RHIC Run in 2009 dedicated measurements with polarized proton beams were taken to verify the dependence of the spin tune on the local orbits at the Snakes. The experimental results are presented along with the comparison with analytical predictions.

INTRODUCTION

The polarization of proton beams during its acceleration in RHIC is preserved due to the application of special spin manipulating devices, Siberian Snakes [1,2]. Each of the two RHIC accelerator rings has two Siberian Snakes placed on opposite sides of the ring. Such a configuration provides the vertical orientation of the stable spin direction and the energy independent spin tune. In RHIC the configuration of the Snake spin rotation axes (45 degrees in one Snake and 135 degree in the other, with respect to the beam direction) have been chosen to provide the spin tune equal to 1/2 for the ideal machine without closed orbit errors.

Besides the Siberian Snakes, both RHIC rings incorporate spin rotator insertions, which are used to control the polarization orientation in the two experimental detectors (STAR and PHENIX).

In the RHIC polarized proton runs in 2008 and 2009 a substantial loss of beam polarization had been observed during the acceleration of the proton beam to 250 GeV. This stimulated work to revise different depolarizing factors originating from various kinds of machine errors and to reassess the control of important lattice parameters, such as the closed orbit and betatron tunes [3,4].

A possible shift of the spin tune away from 1/2 value has been investigated. The shift of the spin tune causes also the shift of the locations of high-order spin resonances ("snake" resonances) [5,6], so that the resonances can overlap with the betatron tunes and cause depolarization. In RHIC, the lattice used for the acceleration of polarized protons has fractional betatron tunes in the (0.68-0.695) region and the dangerous snake resonance is at $\nu_{sp} = 5 \cdot Q_\beta - k$. Here, Q_β is either vertical or horizontal betatron tune and k is an integer. While the resonance with the vertical

betatron tune is always present due to the vertical betatron motion, the resonance with the horizontal betatron tune may also occur if the betatron coupling is not well corrected.

The largest distortion of the spin tune is expected to come from snake imperfections and closed orbit imperfections. The most important effect generated by closed orbit is related with the orbit angles in the locations of the Snakes and rotators. The effect of the horizontal closed orbit angles in the Snakes on the spin tune was noted in [2,3]. We did dedicated measurement in order to confirm the spin tune dependence on the closed orbit angle at the Snakes. The results of the measurements helped us also to evaluate the possibility of beam depolarization due to a snake resonance shift on the acceleration ramp.

GENERAL FORMALISM

In this paper we evaluate the spin tune shift in first order of perturbation theory, which is adequate for the scale of the effect in RHIC. Since we will consider only the effect of perturbations periodical with a machine circumference C , the spin tune shift is:

$$\delta\nu_{sp} = \frac{1}{2\pi} \oint_C \mathbf{w} \mathbf{n}_0 ds \quad (1)$$

where the vector \mathbf{w} presents a perturbation of spin precession by various machine errors and orbit oscillations and the vector \mathbf{n}_0 is the stable spin direction on the design closed orbit. With two Siberian Snakes in RHIC the vector \mathbf{n}_0 is vertical and directed upward on one half of the ring and downward on another half. The arrangement of spin rotating devices in RHIC together with the vertical component of \mathbf{n}_0 is demonstrated in Figure 1. Throughout the paper z is used as a vertical coordinate and y as a longitudinal one.

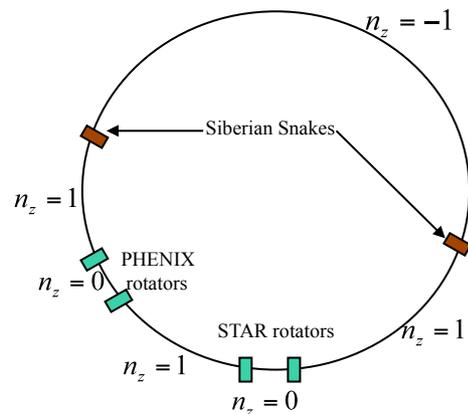


Figure 1: Schematics of the Siberian Snake and spin rotator location in a RHIC ring. The vertical component of the vector \mathbf{n}_0 is also shown. The horizontal and longitudinal components of \mathbf{n}_0 in PHENIX and STAR depend on the rotator settings.

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The components of the vector \mathbf{w} , related to perturbations caused by the closed orbit as well as beam mean energy errors, are following [7]:

$$\begin{aligned} w_x &= G\gamma z''; \quad w_y = -G\gamma K_z z' \\ w_z &= -G\gamma x'' + G\gamma K_z \frac{\Delta p}{p}; \quad K_z = B_z / (B\rho) \end{aligned} \quad (2)$$

Here γ is a relativistic factor, G is a magnetic moment anomaly ($G=1.793$ for proton). Only terms proportional to $G\gamma$ are kept, since these terms dominate at the beam energies of interest in RHIC.

HORIZONTAL ORBIT ANGLES

Using vertical component (w_z) of the precession perturbation and substituting the closed orbit x_{co} instead of x we get the expression for the spin tune shift:

$$\begin{aligned} \delta\nu_{sp} &= -\frac{1}{2\pi} \oint_C G\gamma x'' n_z ds = \frac{G\gamma}{2\pi} (\alpha_{rt-1} + \alpha_{rt-2} + 2\alpha_{sn}) \\ \alpha_{rt-i} &= x'_{co-l-i} - x'_{co-r-i}; \quad \alpha_{sn} = x'_{co-sn2} - x'_{co-sn1} \end{aligned} \quad (3)$$

where x'_{co-sn2} and x'_{co-sn1} are the orbit angles at the Snake locations, x'_{co-l-i} and x'_{co-r-i} are the orbit angles at locations of spin rotators on the left and right sides of an interaction region. α_{rt-1} and α_{rt-2} correspond, respectively, to the difference of orbit angles at the rotators around STAR and PHENIX experimental detectors. For instance, the spin tune shift due to a 100 μrad difference of the horizontal orbit angles at the Snakes (α_{sn}) is 1.54×10^{-2} at a 250 GeV beam energy. $\delta\nu_{sp}$ from the difference of orbit angles in a rotator pair is two times smaller than that from the Snakes, according to the expression (3). The full form of the expression (3) applies to the store energy, when both the Snakes and rotators are switched on. During the acceleration ramp the rotators are kept off, therefore the spin tune shift comes only from α_{sn} .

During RHIC Run-9 in 2009 dedicated measurements were made in order to verify the spin tune dependence on the horizontal orbit angle at the Snakes. One should take into account that the spin tune shift can be caused also by mistuned Siberian Snakes. This happens if the angle between the spin rotation axes of two Snakes deviates from 90 degrees. The combined spin tune shift due to mistuned Snake axes and horizontal orbit angles at the Snakes is:

$$\delta\nu_{sp} = \frac{\delta\phi_{sn}}{\pi} + \frac{G\gamma}{\pi} (\alpha_{snm} - \alpha_0) \quad (4)$$

where $\delta\phi_{sn}$ is a deviation of the angle between the spin rotation axes of two Snakes from $\pi/2$, α_{snm} is a *measured* difference of horizontal orbit angles in two Snakes and α_0 presents a possible systematic error of this orbit angle measurement, for instance, due to the Beam Position Monitor misalignments. In order to disentangle the orbit contribution to the spin tune shift from that caused by a Snake axis error, the measurements were taken at two different energies, 100 GeV and 250 GeV.

To observe the spin tune shift, the depolarization by a second order spin resonance, $\nu_{sp} = 2*Q_z - 59$, was used. When $\nu_{sp} = 1/2$, the resonance is located exactly at $Q_z = 29.75$. In the experiment we moved the vertical betatron tune sufficiently close to 29.75. For the measurement at 250 GeV, $Q_z \sim 29.73$ was used, while at 100 GeV $Q_z \sim 29.241$. After that, a gradual, controlled change of the snake orbit angle (in one or the two Snakes) caused the spin tune shift from $1/2$ and therefore the shift of spin resonance from 0.75. The depolarization was observed when the spin resonance shifted to the location of fractional part of Q_z . The polarization measurements were done using CNI polarimeter [8].

An example of the measurements done in the Blue RHIC ring at 250 GeV is shown in the Figure 2. The observed depolarization happens not symmetrically with respect to zero value of measured difference of snake orbit angles (α_{snm}), which indicates that either $\delta\phi_{sn}$ or α_0 , or both are not equal to 0.

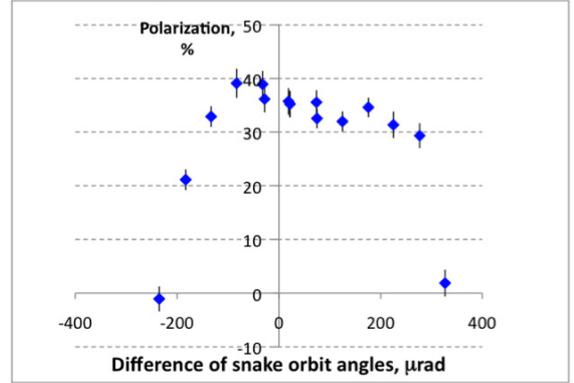


Figure 2: The dependence of measured beam polarization on the difference of the horizontal orbit angles at Snake locations at 250 GeV beam energy. The measurements were done with different beams on two consecutive fills.

Having the measurements done at two different energies, the values of $\delta\phi_{sn}$ and α_0 can be found from best fit for observed depolarization. Figure 3 shows results of the measurement done at 100 and 250 GeV, where α_{snm} was converted to the snake resonance location shift ($\delta\nu_{3/4}$) using the formula (4) and the relation: $\delta\nu_{3/4} = \delta\nu_{sp}/2$. Dashed lines correspond to the fractional part of the vertical betatron tune at the time of measurements. That is the locations where the depolarization is expected. The derived values of $\delta\phi_{sn}$ and α_0 , corresponding to the depolarization in the expected locations, are:

$$\begin{aligned} \delta\phi_{sn} / \pi &= 4.4 (+2.5) \cdot 10^{-3}, \\ \alpha_0 &= 17 (+15) \mu\text{rad} \end{aligned}$$

where the errors comes from a limited step size of the orbit angle change used during the measurements.

Using the found values of $\delta\phi_{sn}$ and α_0 and the expression (4), the spin tune shift as well as shifts of snake resonances during the acceleration can be evaluated, as shown in Figure 4. In Figure 4 the orbit at the snakes is assumed to be perfectly corrected, $\alpha_{snm} = 0$.

According to Figure 4, the snake resonance shift from 0.7 does not exceed 10^{-3} , thus the center of the resonance

remains away from the betatron tunes. For the depolarization to happen the snake resonance should be sufficiently wide, at least at some energies during the acceleration. The evaluation of the snake resonance strength, and effects which can enhance it, is underway using the spin simulations with UAL-SPINK code [9].

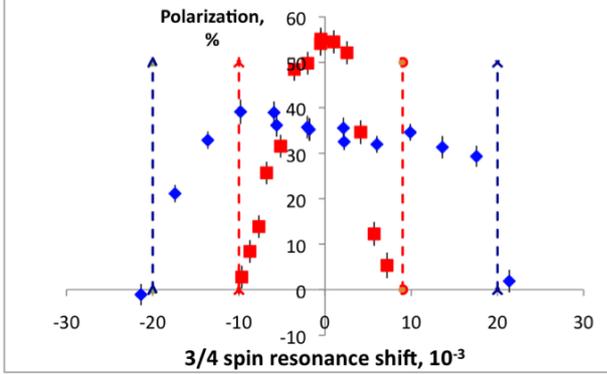


Figure 3: Measured $\frac{3}{4}$ spin resonance shift caused by the modification of the horizontal orbit angles at the Snakes at two energies: 100 GeV (red squares) and 250 GeV (Blue circles).

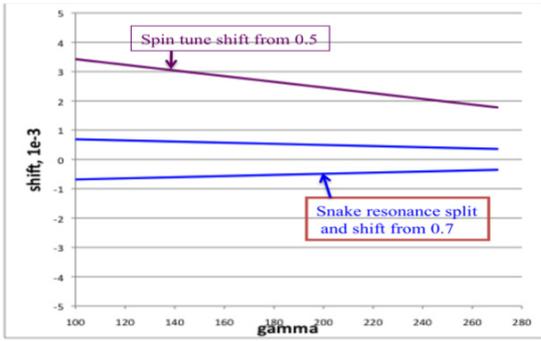


Figure 4: Spin tune shift and the snake resonance split and shift derived according to the $\delta\phi_{sn}$ and α_0 values from (6) and $\alpha_{snm}=0$.

MEAN MOMENTUM SHIFT

The mean momentum of the beam as well as the radial orbit offset (or the mean horizontal orbit) may be shifted due to a deviation of RF frequency from an optimal value or due to bending field errors. For instance, in RHIC the radial orbit offset can make excursions as large as 1mm on the acceleration ramp. By using w_z from (2) in the expression (1) where $D\Delta p/p$ should be substituted in place of x , and D is the horizontal dispersion function, after the integration one obtains:

$$\delta v_{sp} = \frac{G\gamma}{2\pi} (\Delta D'_{r1} + \Delta D'_{r2} + 2\Delta D'_{sn}) \frac{\Delta p}{p} \quad (5)$$

where $\Delta p/p$ presents the beam momentum shift and $\Delta D'_{iii}$ presents differences of the dispersion function angles at the Snakes and rotators similar to α'_{iii} defined in the expression (3) for the closed orbit. $\Delta D'$ are defined by the lattice. Considering the RHIC lattice and the beam energy of 250 GeV, for the momentum error $\Delta p/p = 5 \times 10^{-4}$ (radial offset ~ 0.8 mm) one gets $\delta v_{sp} = 4.2 \times 10^{-3}$ from the

dispersion angles at the Snakes and $\delta v_{sp} = 0.2 \times 10^{-3}$ from a rotator. Although the effect from the Snakes dominates, it is small enough to avoid depolarization problems during the acceleration.

VERTICAL ORBIT ANGLES

When the spin rotators are turned on the effect of vertical closed orbit should be considered. In order to evaluate corresponding spin tune shift one can apply again the expressions (1) and (2). Using intrinsic symmetry properties of RHIC interaction region and spin rotator insertions, we get the following expression for the spin tune shift from one interaction region:

$$\delta v_{sp} = \frac{G\gamma}{2\pi} \oint_C z' n_x ds = \frac{G\gamma}{2\pi} n_{x-tr} (z'_{lrt} - z'_{rrt}) \quad (6)$$

where n_{x-tr} is the horizontal component of the vector \mathbf{n}_0 in the IR triplets and z'_{lrb} , z'_{rrt} are vertical closed orbit angles at the locations of left and right spin rotators respectively. Largest effect, related with the vertical closed orbit, comes from separation bumps used in interaction regions to separate the beams and prevent the collisions. 3 mm vertical orbit bumps are used throughout STAR and PHENIX experimental regions when the spin rotators are being turned on. The calculation, using the expression (6), leads to the spin tune shift, combined from the two experimental regions, as large as 0.026 (at $n_{x-tr} = 1$) at 250 GeV beam energy. This tune shift should be taken into account during the rotator turn on.

SUMMARY

Various effects on the spin tune shift, originating from the closed orbit errors, have been evaluated. The control of the orbit angles in the locations of Siberian Snakes and spin rotators is important to prevent the spin tune shift. The measurements done in RHIC for horizontal orbit angle at the Snakes agree well with the theoretical predictions. Extracted from the measurements the shift of snake resonance on the acceleration ramp is sufficiently small.

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