ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPL003

POLARIZED PROTON OPERATION AT RHIC WITH PARTIAL SNAKES*

V. Schoefer†, H. Huang, C. Liu, F. Méot, V. Ptitsyn, V. Ranjbar, G. Robert-Demolaize, T. Shrey
Brookhaven National Laboratory, Upton, NY, USA

Abstract

A series of power outages during setup for RHIC Run 23 damaged two of the four helical dipole modules that comprised one of the full Siberian Snakes in RHIC's Blue ring. The remaining two helical dipoles were reconfigured as a "partial" snake, one which rotates the spin by an angle less than 180 degrees. This partial snake configuration has a rotation angle and axis which both deviate from the ideal. We describe the compensatory measures taken to address the effects of these deviations. These include reconfiguring the other Blue snake to rematch the stable spin direction at injection and a change of the nominal store energy from 255 GeV to 254.2 GeV to improve the stable spin direction condition at store. Polarization transmission through RHIC acceleration was as good as with full snakes and we present some analytical and tracking results that corroborate the observed robustness with respect to deviations from ideal snakes.

INTRODUCTION

Preservation of proton beam polarization during acceleration in RHIC from 23 GeV to 255 GeV is accomplished largely by use of a pair of helical dipole Siberian snakes in each ring. Each snake provides a 180° rotation about an axis in the horizontal direction. With two snakes placed azimuthally diametrically opposite in the accelerator ring, if the rotation axes are chosen to be orthogonal (at RHIC at ±45° with respect to the longitudinal axis), then the spin tune is fixed at 1/2 and the stable spin direction fixed to be vertical, independent of the energy, which allows avoidance of all first order depolarizing resonances [1, 2].

These snakes each consist of four separate helical dipole coils ("modules") labeled #1-#4 along the beamline. The modules are usually wired together in series in pairs, with #1 in series with #4 and #2 with #3. Power failures early in Run 23 operation caused failures of modules #2 and #4. Both modules developed resistance consistent with an open circuit inside the cryostat.

The remaining two modules #1 and #3 were wired in series with the polarity of module #1 reversed from nominal. The resulting spin rotation angle is less than 180° resulting in a so-called partial snake. In the following we discuss the effects of this change on both the proton trajectory and the spin rotation.

TRAJECTORY IN PARTIAL SNAKE

The maximum current at which the partial snake could be operated was set by the available physical aperture. Inside a helical dipole magnet the protons execute a helical orbit which has a radius that is largest at the injection rigidity (79.4 T m for typical proton operation). Shown in Fig. 1 are the trajectories and 6σ beam envelopes in a nominal full RHIC snake and a partial snake for proton beams at injection with a normalized rms transverse emittances of 2.5 µm in each plane, plotted with the vacuum pipe apertures. A normal RHIC full snake requires 100 A in the two "outer" modules (#1, #4) and 323 A in the "inner" modules (#2,#3). The trajectory in the partial snake as shown is for a current of 320 A in modules #1,#3, which was the current used in operation.

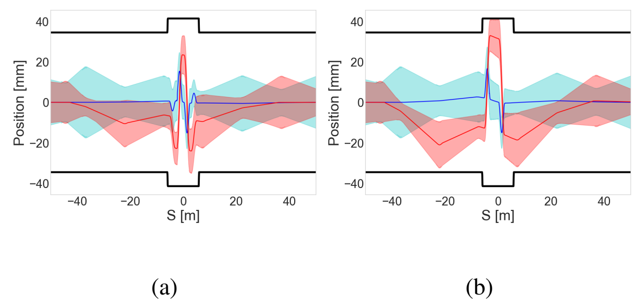


Figure 1: Trajectories and beam envelopes (horizontal in blue and vertical in red) in and near a RHIC helical dipole. The circular aperture is indicated with black lines. The aperture is slightly larger inside the 10.56 m long snakes. The s-coordinate is relative to the center of the helical dipole. (a) is a normal, full snake. (b) is a partial snake with only the first and third modules powered. In the partial snake, the aperture is just barely 6σ inside the snake body.

The trajectories in Fig. 1 are calculated using a zgoubi model [3] with field maps representing each of the helical dipole modules. A four corrector bump is used to fit the trajectory to BPM measurements made during operation. At a current of 320 A, the 6σ vertical envelope of the circulating beam envelope just impinges the available aperture in the snake(for the full snake the aperture is 9.5σ). Since this is the trajectory at injection energy, injection oscillations (typically of order 0.5-1σ also contribute to the effective beam size and lead to losses on the snake magnet while filling for RHIC stores. Figure 2 shows a comparison of loss rates in Runs 17 and 22 as measured by a beam loss monitor (BLM) near the 9 o'clock snake for typical fills. For fills of similar intensity, the loss rates are highly elevated in the partial snake case, consistent with the significantly limited aperture. A typical threshold for this BLM is a rate of 300 rad/h, above which the beam is aborted to prevent beam-induced quenches of the superconducting snake helices. This aperture restriction set the maximum operational current at 320 A.

* Work supported by Brookhaven Science Associates, LLC under Contract No. DE-SC0012704 with the U.S. Department of Energy.
† schoefer@bnl.gov

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPL003

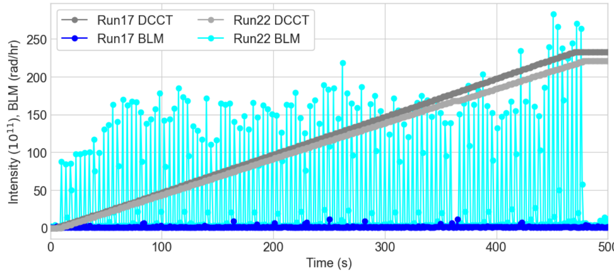


Figure 2: Radiation measured at a loss monitor adjacent to the RHIC blue ring snake in the 9 o'clock position from Runs 17 (with a full snake) and Run 22 (partial snake) during injection for fills of similar intensity. Loss rates are highly elevated in the partial snake configuration.

SPIN EFFECTS OF PARTIAL SNAKE

Without two full snakes, the spin tune, ν_s, and stable spin direction $\vec{n}_0$ are in general not fixed at 1/2 and vertical respectively and are functions of the energy. For a pair of diametrically opposed snakes with correct rotation axes, but errors in their rotation angles away from 180° of $d\mu_1$, $d\mu_2$ we have for the ν_s and stable spin direction vertical component n_z

$$\nu_s = \frac{1}{\pi}\cos^{-1}\left[\cos\left(G\gamma\pi\right)\sin\left(\frac{d\mu_1}{2}\right)\sin\left(\frac{d\mu_2}{2}\right)\right], \quad (1)$$

$$n_z = \cos\left(\frac{d\mu_1}{2}\right)\cos\left(\frac{d\mu_2}{2}\right) + \sin\left(G\gamma\pi\right)\sin\left(\frac{d\mu_1}{2}\right)\sin\left(\frac{d\mu_2}{2}\right), \quad (2)$$

where the subscripts label each of the two snakes. Similarly if the rotation angles are both exactly 180°, but there are errors in the rotation axis such that the axes are still in the horizontal plane, but deviate from ±45° by $d\theta_1$ and $d\theta_2$, we have for ν_s and n_z

$$\nu_s = \frac{1}{\pi}\cos^{-1}\left[\sin\left(d\theta_2 - d\theta_1\right)\right], \quad (3)$$

$$n_z = 1. \quad (4)$$

It is interesting to note that Eq. (1) implies that so long as one snake has a rotation of angle of 180°, the spin tune remains fixed at 1/2 and n_z, while not 1, remains energy independent. With a rotation angle defect in both snakes, the spin tune shift is second order in $d\mu$. These conclusions are verified by comparison with spin tunes derived from the one turn spin transfer map of a Zgoubi simulation of the RHIC ring with varying snake strengths as shown in Fig. 3.

Since changes in the spin dynamics depend only on a difference between the rotation axis angles, a known error in one snake axis is straightforwardly compensated using the second snake. We performed a tracking study to determine the sensitivity of the polarization loss due to a strong intrinsic resonance with respect to the rotation angle errors $d\mu_i$, which are not as easily compensated. Particles are launched at an energy corresponding to $G\gamma$=420.5 and accelerated through the intrinsic resonance at $G\gamma$=422.675 (with resonance strength 0.4 for a particle on a vertical 10π mm·mrad invariant ellipse [1]). Ten particles are accelerated on a vertical phases space ellipse corresponding to a normalized emittance of 2.5 µm with zero horizontal or longitudinal deviation from the design trajectory from an ideal (flat) vertical closed orbit. The acceleration rate is 20 times the nominal acceleration rate in RHIC to keep simulation time tractable.

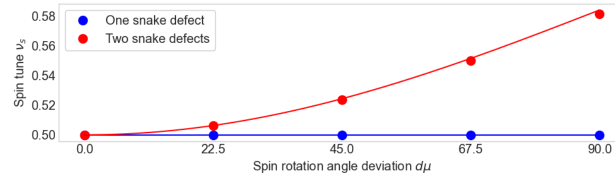
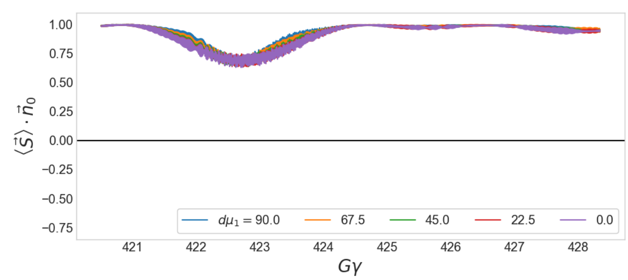
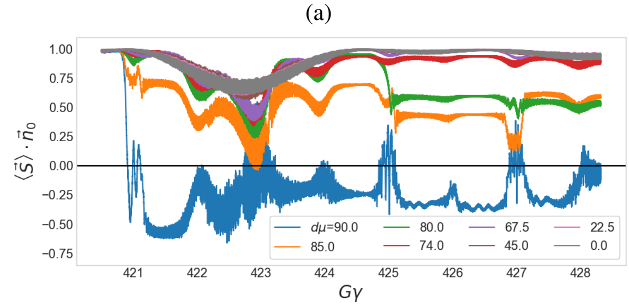


Figure 3: Spin tune calculated for cases where there is a change in rotation angle away from 180° in one or both RHIC snakes. Markers indication calculations from a Zgoubi model, lines are theoretical calculations from Eq. (1).



(a)



(b)

Figure 4: Projection onto the stable spin direction during acceleration through the $G\gamma$=422.675 resonance with a rotation error in (a) one snake, (b) both snakes.

The resulting projection of the average spins onto the stable spin direction is shown in Fig. 4. The snake rotation angle errors are scanned over a range between 0° and 90° in two scenarios: one where the deviation from 180° occurs in only one of the two snakes (Fig.4a) and in the second where an equal error occur in both snakes (Fig.4b). Figure 5 shows the polarization transmission as a function of the snake angle deviation for both cases. One can see that even for very large single snake errors, there is good transmission. Since the primary effect of a snake angle rotation angle deviation is to drive an imperfection resonance (at all integer values of $G\gamma$), this is consistent with the ability of the snakes to compensate for even large imperfection driving terms [2].

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPL003

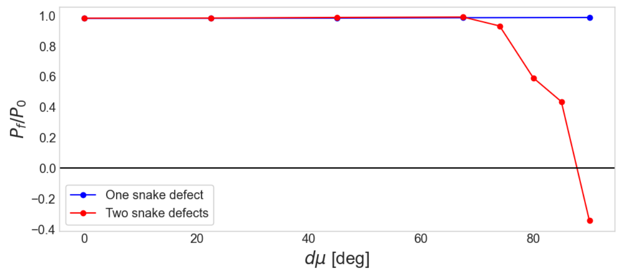


Figure 5: Polarization transmission through the resonance $G\gamma$=422.675 with snake rotation angle errors in one (red) or both snakes (blue).

The two snake error case begins to show deterioration above an angle deviation of about 70°. The polarization loss occurs where the spin tune shift and the snake resonance tune shift cause a snake resonance condition. In the one snake error case, where no spin tune shift occurs, there is no effect on polarization transmission.

Stable Spin Direction

The stable sin direction ($\vec{n}_0$) at the injection point needs to match the direction of the incoming beam from the injector in order to prevent depolarization. To achieve this, the second RHIC snake was adjusted to have a rotation axis orthogonal to the partial snake with rotation angle of 163.9°. This change in rotation causes a spin tune shift and modulation (Eq. (1)), but the spin tune remains between 0.499 and 0.497 (well within the tolerance implied by the tracking results).

At RHIC store energy the stable spin direction is more complicated to determine since nearby imperfection resonances have a strong influence in addition to the effects of the partial snake [4]. It is nevertheless important for $\vec{n}_0$ to be nearly vertical, especially at the collision points, where it influences the physics under study and at the polarimetry where it affects the measurement calibration. At the nominal store energy with the partial snake, $\vec{n}_0$ was strongly tilted away from vertical (12.5°). Measurements of the spin direction using the proton-Carbon polarimetry and the STAR detector at the collision point were made as a function of the energy (in both RHIC rings). The overall tilt away from

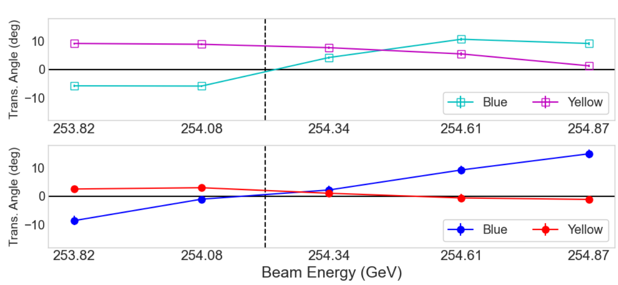


Figure 6: Angle of the projection of $\vec{n}_0$ onto the transverse plane with respet to the vertical axis. Measured at the proton-Carbon polarimetry (top) and using the STAR detector (bottom). The vertical line indicates the energy selected for operation that minimized the tilt in most planes.

vertical in both the Blue and Yellow rings was minimized at an energy of 254.2 GeV, so this energy was selected for operation (Fig. 6). Since both kinds of polarimetry can only measure the transverse components of $\vec{n}_0$, more dedicated invasive measurements are needed to observe the full three-dimensional vector. These measurements are described in Ref. [5].

CONCLUSIONS

Operation of RHIC with a partial snake due to failure of helical dipole coils ultimately delivered polarization in the Blue ring that was similar to that in the Yellow ring and to previous performance in Blue (Fig. 7). This was due largely to compensation of the spin tune shift using the other (functioning) snake. Zgoubi tracking results corroborate that resonance crossings can tolerate the residual error. Spin direction tilts at store were ameliorated by a change in energy which precessed the spin to an acceptable orientation at the collision point and the polarimetry.

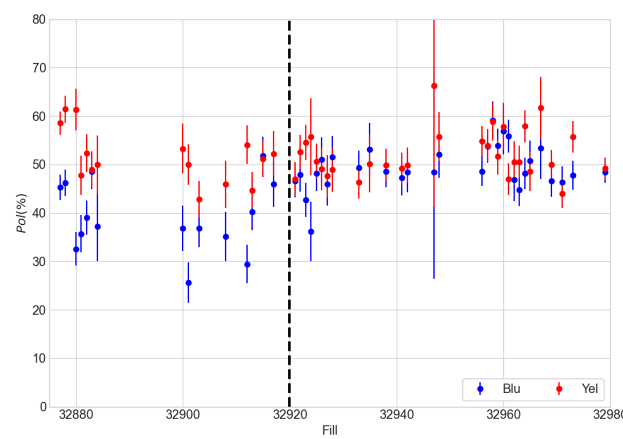


Figure 7: Beam polarization measured at store energy using a polarized hydrogen jet target in RHIC in the Blue and Yellow rings. The vertical dashed line indicates the onset of compensation of spin tune shifts from the partial snake using the second snake.

REFERENCES

[1] T. Roser *et al.*, "Configuration Manual: Polarized Proton Collider at RHIC," Brookhaven National Laboratory, Tech. Rep. BNL-73650-2005-IR, 2006. `doi:10.2172/15011215`

[2] S. Lee, *Spin dynamics and snakes in synchrotrons*. World Scientific, 1997.

[3] F. Mèot, *Zgoubi*. `http://sourceforge.net/projects/zgoubi/`

[4] V. H. Ranjbar, E. C. Aschenauer, H. Huang, A. Marusic, F. Méot, and V. Schoefer, "Modeling RHIC Spin Tilt as Lattice Imperfections," in *Proc. IPAC'22*, Bangkok, Thailand, 2022, pp. 1884–1885. `doi:10.18429/JACoW-IPAC2022-WEPOPT020`

[5] V. Schoefer, E. Aschenauer, H. Huang, V. Ptitsyn, F. Meot, and V. Ranjbar, "Stable Spin Direction Measurements at RHIC with Polarized Proton Beams," presented at IPAC'23, Venice, Italy, May 2023, paper MOPL004, this conference.