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RHIC BLUE SNAKE BLUES*

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Abstract

Two helical full snakes are used in both Blue and Yellow rings of RHIC collider, in order to preserve beam polarization during acceleration to collision energy and polarization lifetime at store. A snake in RHIC is comprised of four 2.4 m long modules, powered by pair. During the startup of RHIC Run 22 in December 2021, two successive power dips have caused the 9 o'clock RHIC Blue ring snake to loose two of its four modules. In spite of this regrettable loss, it has been possible to maintain near 180° snake precession, by proper powering of the remaining two modules, as well as, by retuning the 3 o'clock sister snake, vertical spin precession axis around the ring and spin tune ½. Determining these new settings, in order to salvage polarization with the handicapped Blue snake pair, has required series of numerical simulations, a brief overview is given here.

INTRODUCTION

Two power supply dips at RHIC Run 22 startup in December 2021 caused RHIC Blue ring 9 o'clock snake to lose two of its four coils. Detailed spin dynamics simulations, using the OPERA field maps of the snakes, were undertaken to help determine new settings of RHIC Blue ring snake pair, accounting for the handicapped 9 o'clock snake [1]. Full polarization at store was eventually recovered, essentially as good as in earlier polarized proton RHIC runs, Fig. 1.

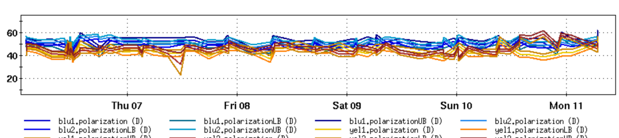

Figure 1: Sample polarization in Blue and Yellow rings during RHIC Run 22, over the period 4/6-11/2022.

RHIC snakes Blue and Yellow RHIC rings each house two helical snakes, Fig. 2 [2]. . A snake is a series of 4 right-handed helix modules (Fig. 3) with alternating field signs. A module is 2.4 m long, bore 10 cm (this matters regarding local closed orbit bump excursion), modules are spaced 0.212/0.448/0.212 m hence an overall length of 10.472 m.

Module currents are normally 100/-322/322/-100 Amp (R+R-R+R- series) and -100/322/-322/100 Amp (R-R+R-R+ series). The helical orbit requires centering along the snake, as part of the local closed orbit bump design during RHIC operation (Fig. 4 top row), with some tolerance as the magnetic field along the orbit, and thus spin motion, is

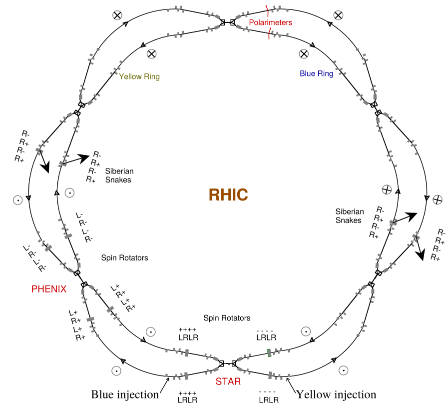

Figure 2: Location of snake series R+R-R+R- and R-R+R-R+ in Blue and Yellow rings, at 9 o'clock and 3 o'clock. Beam goes clockwise in Blue, counter-clockwise in Yellow.

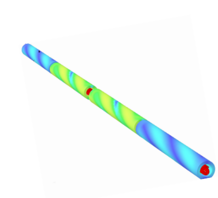

Figure 3: OPERA model of RHIC four helical module snake.

mostly independent of possible mis-centering (Fig. 4 top row, right),

Following the power supply dips, the 9 o'clock Blue snake was left with its sole coils 1 and 3, eventually operated in series in the 300$^+$ A region. Local closed orbit bump matching includes helix centering in this 2-coil R-0R+0 series (Fig. 4 bottom row).

Expected perturbation Given these new settings, RHIC Blue 9 o'clock snake is operated as ≈164° partial snake, a $\delta\approx 16°$ defect compared to full snake. This causes a $\delta/2\approx 8°$ off-vertical tilt of the stable spin precession direction $\vec{n}_0(s)$ around a half of the ring - in particular $\vec{n}_0 = \left(\frac{\sqrt{2}}{2}\sin\frac{\delta}{2}, \frac{\sqrt{2}}{2}\sin\frac{\delta}{2}, \cos\frac{\delta}{2} \approx 1 - \frac{\delta^2}{8}\right)$ at 9 o'clock snake [1]. An additional adjustment of 3 o'clock snake to a similar value - as results from optimal settings, see below - doubles the defect. With vertical $\vec{n}_0$ at injection this would mean an expected polarization loss, other things being equal, of up to $1 - \cos 16° \approx 4\%$. To the first order in δ spin tune remains unchanged, $\nu_{sp} = 1/2$.

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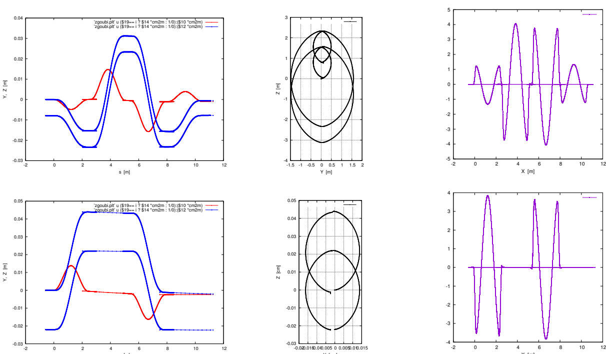

Figure 4: Top row: Helical orbit through the R+R-R+R- series, before and after helix centering in the snake. Left: Y(s), Z(s); middle: (Y,Z) projected helix; right: field $B_Z(s)$, largely independent of possible mis-centering of the helix. Bottom row: same, for the R+0R-0 series at 300 A.

POLARIZATION IN RHIC BLUE

The simulations detailed here have pointed toward the following optimal settings of the sister snakes: (i) 9 o'clock: 320 A in the coil pair; (ii) 3 o'clock: 130 A in outer coils (30 A more than normal operation), 322 A in inner two coils.

The resulting individual spin matrices and snake angles at injection ($G\gamma = 45.5$) and store ($G\gamma = 487$) are as follows (with "Precession axis" given in a reference frame *(longitudinal, radial, vertical)*):

9 o'clock snake spin matrix:

```
Ggamma=45.5

-0.187104  -0.959915   0.208696
-0.959952   0.223764   0.168588
-0.208529  -0.168795  -0.963340

spin precession =164.4378555494 deg
Precession axis :
    (-0.6288,  0.7776, -0.0001)
```

```
Ggamma=487

-0.177465  -0.960952   0.212315
-0.960997   0.215711   0.173068
-0.212109  -0.173320  -0.961754

spin precession =164.1025567575 deg
Precession axis :
    (-0.6323,  0.7747, -0.0001)
```

3 o'clock snake spin matrix:

```
Ggamma=45.5

 0.184654   0.966157   0.180121
 0.966090  -0.144784  -0.213795
-0.180481   0.213491  -0.960129

spin precession =163.7662874059 deg
Precession axis:
    ( 0.7642,  0.6450, -0.0001)
```

```
Ggamma=487

 0.192468   0.965082   0.177688
 0.965050  -0.153333  -0.212525
-0.177859   0.212382  -0.960864

spin precession =163.9175969339 deg
Precession axis:
    ( 0.7669,  0.6417, -0.0001)
```

Importantly, these settings preserve $129 - 40 \approx 90°$ angle between the snake precession axes, so ensuring $\nu_{sp} = 1/2$.

Optics and Spin at Injection

Blue closed orbit and optical functions with 9 o'clock 320 A and 3 o'clock 130/322 A settings are given in Fig. 5.

Figure 6 shows details of the orbits in the snake region. As a consequence of its 2-module operation, the vertical orbit downstream of 9 o'clock snake is strongly kicked off-axis by the next QF quadrupole (Fig. 6-middle); to mitigate the effect and maintain an excursion < 3 cm, the vertical orbit is given a non-zero incoming angle at entrance of the snake.

In the absence of rotators (spin essentially vertical all around), RHIC 1-turn spin matrix at $G\gamma = 45.5$, at STAR detector, is:

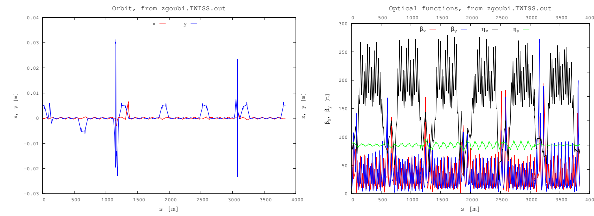

Figure 5: Blue orbit (left) and optics (right) at injection. The 9 and 3 o'clock local snake bumps are apparent, to the left of respectively the IP8 and IP4 vertical separation bumps.

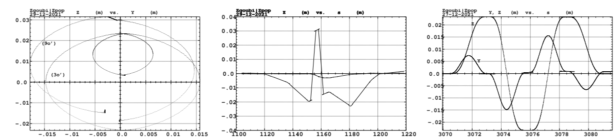

Figure 6: Left: transverse projection of helical orbits in 9 o'clock/320A and 3 o'clock/130A/322A snakes. Middle: 90 m extent H and V closed orbit bumps in 9 o'clock snake region (the 10 m snake is located at $s \approx 1155$ m). Right: H and V closed orbit bumps across the 3 o'clock snake.

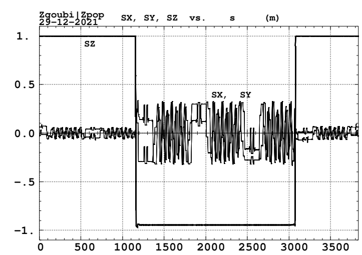

Figure 7: Components of the periodic spin vector around RHIC Blue. Origin s=0 is at STAR.

```
-0.992041     1.7514E-02    0.124688
-2.449E-02   -0.998204     -5.4669E-02
0.123506     -5.7288E-02    0.990689
```

yielding
- Spin precession : $178.79°$,
- Precession axis : $(-0.0622, 0.0281, -0.9977)$,
- $n_{0,Z} = \pm 0.9977$ at STAR, spin tune $= 0.4966$.

which confirms a marginal vertical tilt of $\vec{n}_0$. Transporting $\vec{n}_0$ around the ring yields Fig. 7 and Table 1, showing $\approx 18°$ tilt of $\vec{n}_0$ at the H-Jet and pC polarimeters, close to the aforementioned $\delta \approx 16°$ estimate.

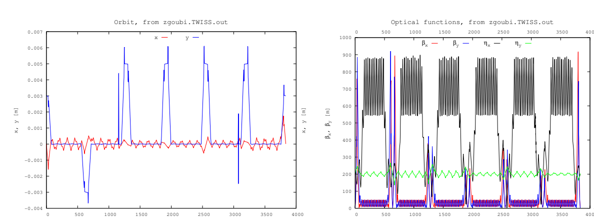

Figure 8: Blue orbit (left) and optics (right) at injection.

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Table 1: Spin $\vec{n}_0$ at STAR detector, H-Jet and pC-polarimeter; $G\gamma = 45.5$

s (m)	S_X (long.)	S_Y (radial)	S_Z (vertical)	
0.	6.2141E-02	-2.8111E-02	9.9766E-01	STAR
1917	7.4926E-02	3.1395E-01	-9.4647E-01	H-JET
1988	1.2231E-01	2.9709E-01	-9.4698E-01	pC-Pol

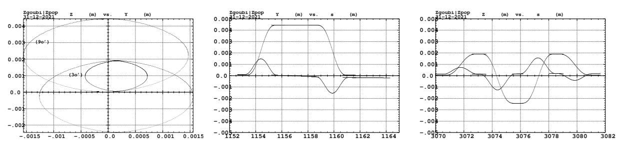

Figure 9: Y-Z projection of helical orbits in 9 o'clock/320A and 3 o'clock/130A/322A snakes, at 255 GeV. H and V bumps at 9 (top) and 3 o'clock (bottom) snakes.

Optics and Spin at Store

Blue closed orbit and optical functions are displayed in Fig. 8. Figure 9 shows the orbit bumps, much reduced at 255 GeV, and optical functions in collision optics. Figure 10 details spin motion through the snakes, Fig. 11 shows $\vec{n}_0(s)$ components around Blue. Table 2 gives sample $\vec{n}_0(s)$ values at $G\gamma = 485.74$ where $\vec{n}_0$ is vertical at STAR.

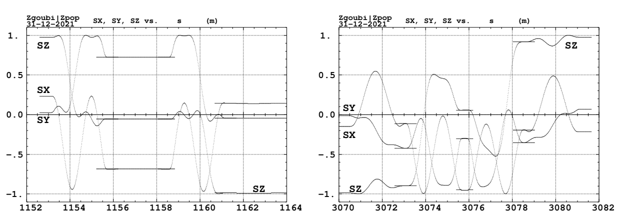

Figure 10: Spin $\vec{n}_0$ components across 9 (left) and 3 o'clock (right) snake, at 255 GeV.

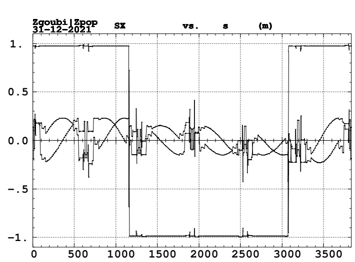

Figure 11: $\vec{n}_0$ components around RHIC Blue. 255 GeV.

Energy Dependence of $\vec{n}_0$

As part of the optimization, $G\gamma$ scans of $\vec{n}_0$ components, at STAR, H-Jet and pC-Polarimeter, in the 255 GeV region, have been performed. Samples are displayed in Fig. 12. Vertical $\vec{n}_0$ at STAR for instance occurs, all other things equal, at $G\gamma = 485.74$.

Preservation of Polarization During Ramp

Finally, 2-coil 9 o'clock snake operation had to further stand the crossing of the three strong snake resonances met

Table 2: Spin $\vec{n}_0$ and tilt angles, at $G\gamma = 485.74$

s (m)	n_X (long.)	n_Y (radial)	n_Z (vertical)	$\vec{n}_0$ to Z ang. [deg]
STAR	8.14732E-03	6.22673E-02	9.98026E-01	3.60
H-Jet	-6.73281E-03	-2.67909E-01	-9.63420E-01	164.46
pC-pol	-3.09843E-01	5.99222E-02	-9.48897E-01	161.60

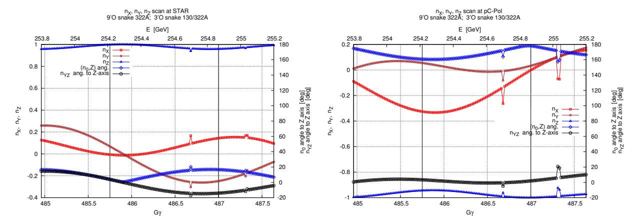

Figure 12: $G\gamma$ scans of $\vec{n}_0$ components and angle to Z-axis at STAR (left) and pC-polarimeter (right). $\vec{n}_{YZ}$ is the projection of $\vec{n}_0$ in the (Y,Z) plane, a quantity measured at pC-polarimeter.

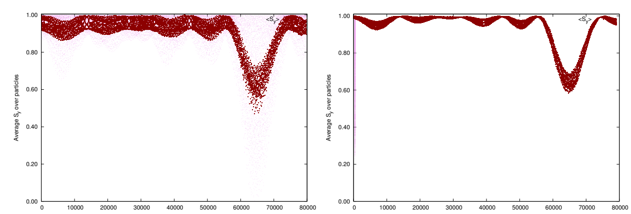

Figure 13: Crossing of $393 + {}_Z$, with 9 O'clock snake 88% (left) or 100% (right). Red curve: $\langle S_Z \rangle$ (turn) average over 3 particles; blue: the 3 individual motions.

on the way from $G\gamma = 45.5$ to top energy. Simulation-wise this proves to be the case. Sample tracking outcomes are given in Fig. 13, crossing of the strongest resonance, located at $393 + {}_Z$; they use 3 different particles on $\sigma = 2.5\ \mu$m normalized invariant, with different initial betatron phases.

SUMMARY

Simulations indicate that operation of RHIC Blue with a 2-coil partial snake allows nominal polarization, comparable to the past runs, main drawbacks appearing to be, referring to RHIC Run 22 operation, (i) geometrical acceptance issues in the 2-coil snake region, which would require local optics counter-measures, and (ii) contribution to spin $\vec{n}_0$ tilt, which can be locally mitigated using spin rotators.

REFERENCES

[1] F. Méot *et al.*, "RHIC Run 22, 9 o'clock, a Snake in the Blue". BNL C-AD Tech Note C-A/AP-661, May 2022.

[2] F. Méot, R. Gupta, H. Huang, V. Ranjbar, and G. Robert-Demolaize, "Re-visiting RHIC snakes: OPERA fields, $\vec{n}_0$ dance". BNL C-AD Tech Note C-A/AP-590, Sep. 2017. `https://technotes.bnl.gov/PDF?publicationId=42159`