SPIN TRANSPORT FROM AGS TO RHIC WITH TWO PARTIAL SNAKES IN AGS*

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Abstract

The stable spin direction in the RHIC rings is vertical. With one or two partial helical Siberian snakes in the AGS, the stable spin direction at extraction is not vertical. Interleaved vertical and horizontal bends in the transport line between AGS and the RHIC rings also tend to tip the spin away from the vertical. In order to maximize polarization in RHIC, we examined several options to improve the matching of the stable spin direction during beam transfer from the AGS to each of the RHIC rings. While the matching is not perfect, the most economical method appears to be a lowering of the injection energy by one unit of $G\gamma$ from 46.5 to 45.5.

INTRODUCTION

Ideally in a flat ring without snakes, we should expect the stable spin direction $\vec{n}_0$ of the closed orbit to be vertical (except at spin resonances). The collider accelerator complex[1] at BNL consists of a polarized proton source followed by a linac, the Booster ring, the AGS ring and the two collider rings, not to mention the connecting transport lines. At injection ($G\gamma = 2.18$) and extraction ($G\gamma = 4.5$) in the Booster ring, the stable spin direction is vertical. At present the AGS has two helical partial Siberian snakes[2, 3] (a warm iron snake and a second stronger superconducting snake) which rotate the stable direction away from the vertical direction. When a single partial snake in the AGS is operated with a 5.9% rotation (5.9% of $180° = 10.6°$), the stable spin direction is tilted $5.3°$ away from the vertical at extraction ($G\gamma = 45.5$). The second stronger superconducting helical has been added to the AGS to increase the spin-tune stop bands around the imperfection (integer $G\gamma$) resonances. This stronger snake (up to 25%) can rotate the spin by as much as $45°$ which could produce a tilt away from the vertical of $22.5°$.

Each of the collider rings has a pair of full ($180°$-rotation) superconducting helical Siberian snakes to fix the spin tune exactly at 0.5, independent of beam energy. With the snakes the injection points of the collider rings have stable spin directions which are vertical.

Injection and extraction in the Booster and AGS rings happen in horizontal plane, but for RHIC we inject vertically. The AGS is about 1.7 m higher than the RHIC rings, so in the AGS-to-RHIC transfer line (ATR) there are vertical bends interspersed with the normal horizontal bends.

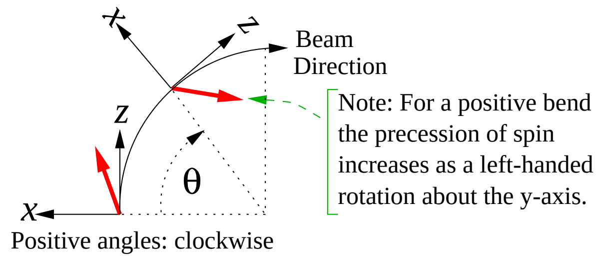

Figure 1: For the local coordinate system traveling with the beam, the z-axis points along the direction of the beam, y-axis points vertically (out of the page), and the x-axis points to the left thus forming a right-handed system. Clockwise bends (to the right) have a positive bend angle. The projection of the polarization in the horizontal plane is measured relative to the local z-axis.

Due to the partial snakes in the AGS and the vertical bends in the ATR, spin matching from the AGS into RHIC is not perfect.

We define our coordinates with positive angles for clockwise bends as shown in Figure 1. The Pauli matrices for the three directions are defined as

$$\sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \ \sigma_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \ \sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}, \quad (1)$$

so that a left-handed spin rotation about an axis $\hat{n}$ by an angle θ is then given by the 2×2 spinor rotation matrix

$$\begin{aligned} \mathbf{R}_{\hat{n}}(\theta) &= e^{i\hat{n}\cdot\vec{\sigma}\theta/2} = \mathbf{I}\cos\tfrac{\theta}{2} + i\hat{n}\cdot\vec{\sigma}\sin\tfrac{\theta}{2} \\ &= \begin{pmatrix} \cos\frac{\theta}{2} + in_z\sin\frac{\theta}{2} & (n_y + in_x)\sin\frac{\theta}{2} \\ (-n_y + in_x)\sin\frac{\theta}{2} & \cos\frac{\theta}{2} - in_z\sin\frac{\theta}{2} \end{pmatrix}. \quad (2) \end{aligned}$$

In the AGS and Yellow ring with counterclockwise beams, we have $+x$ pointing toward the center of the rings. In the Booster and Blue ring the beam rotates clockwise so $+x$ points away from the center of the rings.

AGS WITH TWO PARTIAL SNAKES

Both helical snakes in the AGS have a right-handed helical twist of the dipole component of field which produce left-handed rotators of the spin vector about the longitudinal axis.

The AGS lattice has a superperiodicity of 12 with 24 long straight sections equally spaced in azimuthal angle. There are 20 gradient dipole bend magnets in each of the superperiods. The beam is injected after the L20 dipole,

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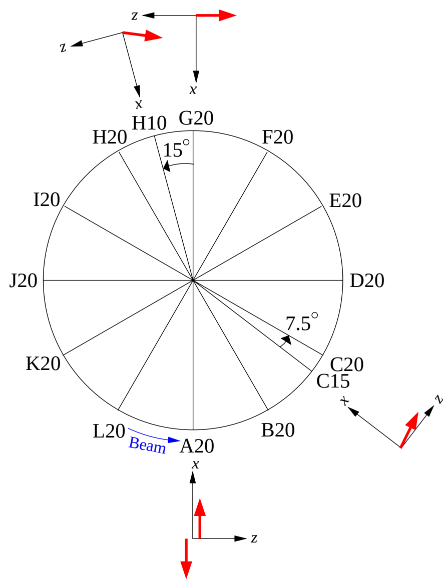

Figure 2: Basic geometry of the AGS spin precession with a 15% partial snake in the A20 straight section at extraction energy ($G\gamma = 46.5$). For the superconducting helical snake, the snake's rotation axis is longitudinal as in a solenoid. is a left-handed rotation of $27°$ about the longitudinal axis from a tilt of $13.5°$ radially outward to $13.5°$ radially inward if the spin is predominantly vertical. Opposite the snake at G20, the horizontal component of spin points backwards to the direction of motion. At the H10 extraction point, the stable spin direction is predominantly vertical with a horizontal component $22.5°$ away from the backwards direction as indicated in the figure.

(See Figure 2.) and extracted just after the H10 dipole. The strong cold snake and weaker warm snake are located just after A20 and E20 dipoles, respectively. There is an internal polarimeter located just after the C15 dipole.

Figure 2 outlines the spin precession in the AGS for a single strong snake in the A20 straight section. The heavy (red) arrows in the figure indicate the direction of the horizontal component of $\hat{n}_0$ at a few locations around the AGS for $G\gamma = 46.5$.

For two snakes we define the precession angles about the vertical axis in terms of azimuthal angles θ_j between snake and observation points as

$$\eta_1 = G\gamma\theta_1, \quad \eta_2 = G\gamma\theta_2, \quad \text{and} \quad \eta_3 = G\gamma\theta_3, \qquad (3)$$

with the precession angles in the two snakes as η_c for the A20 cold snake and η_w for the E20 warm snake. The 1-turn spin rotation matrix at H10 becomes

$$\mathbf{M} = \mathbf{R}_y(\eta_3)\,\mathbf{R}_z(\eta_w)\,\mathbf{R}_y(\eta_2)\,\mathbf{R}_z(\eta_c)\,\mathbf{R}_y(\eta_1) \qquad (4)$$

The closed orbit stable spin direction is then

$$\hat{n}_0(\mathrm{H10}) = \left(\frac{\Im(M_{12})}{\sin\pi\nu_{\rm sp}}, \frac{\Re(M_{12})}{\sin\pi\nu_{\rm sp}}, \frac{\Im(M_{11})}{\sin\pi\nu_{\rm sp}}\right), \qquad (5)$$

where $\cos\pi\nu_{\rm sp} = \Re(M_{11})$.

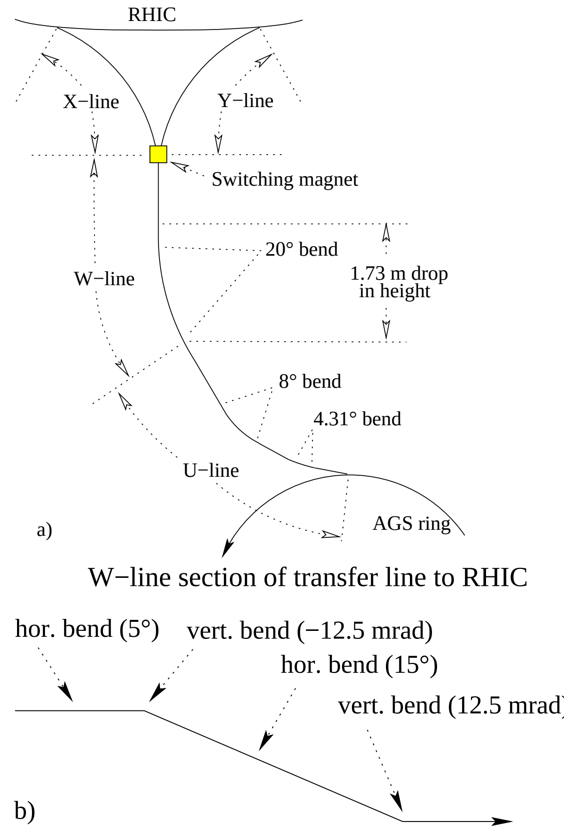

Figure 3: Layout of the AGS to RHIC transfer lines (ATR). a) Horizontal layout of the ATR. b) Layout of vertical bends for 1.73 m drop to the AGS. c) Vertical layout of injection to RHIC. This figure was drawn for the Yellow ring injection; the horizontal bends of 38 mrad and -38.92 mrad should reverse sign for injection into the Blue ring.

TRANSFER LINE FROM AGS TO RHIC

Due to interleaved horizontal and vertical bends from the AGS extraction to the RHIC injection points, the value of the $\vec{n}_0$ of the injected beam at the RHIC injection point will vary both with energy and AGS snake setting, and may differ for each of the Blue and Yellow rings. Since the RHIC rings each have two full snakes, the nominal $\vec{n}_0$-direction for the circulating beam at the injection point is vertical. The transfer lines are divided into four sections (See Figure 3a.): first, the U-line has two horizontal bends of $4.31°$ and $8°$; next, the W-line provides a horizontal bend of $20°$ to orient the beam to the switching magnet along a mirror symmetry axis for the RHIC rings; finally, two large arcs bend the beam in the X-line for injection into the clockwise Blue ring and the Y-line for injection into the counterclockwise Yellow ring. Since the planes of the AGS and RHIC rings have a 1.73 m difference in height, there are a pair of vertical bends in the W-line as shown in Figure 3b. The lattice was designed to have a full period of betatron phase advance between the two bends in order to minimize vertical dispersion for injection. Beams are injected into RHIC through vertical septum (Lambertson) magnets. The nom-

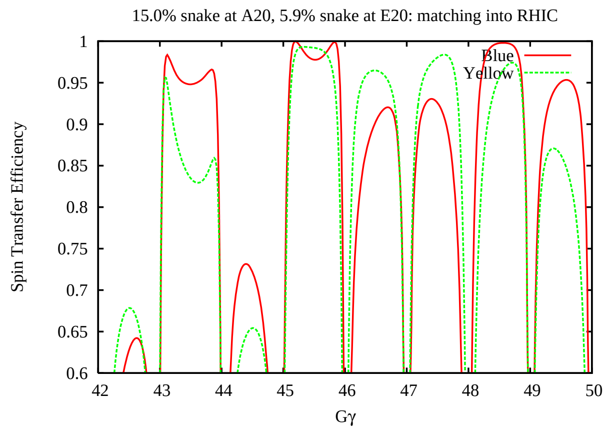

Figure 4: Spin injection efficiency from AGS to both rings of RHIC at $G\gamma = 45.5$ with 15% and 5.9% snakes at A20 and E20, respectively.

inal vertical bends from steering magnets upstream of the septum magnet, two ring quadrupoles downstream of the septum, and the injection kicker magnets (4 modules) are interleaved with horizontal bends as shown in Figure 3c.

Figure 4 shows how the spin matching varies with energy AGS snakes of 15% and 5.9%. At $G\gamma = 45.5$ the spin transfer efficiency (Blue: 97.8%, Yellow: 99.1%). is better than the old injection energy at 46.5 (Blue: 90.4%, Yellow: 96.5%). The matching to the Blue ring is not quite as good as to the Yellow. However for an A20 snake strength of 18.9%, the matching to both rings becomes equal at 98.9%, and for higher A20 snakes strengths the matching to the Yellow ring becomes worse.

It should be noted that the helical snakes at injection in the AGS require a large aperture (ID of 0.3 m) and perturb the lattice with strong focusing in both transverse planes. While we have added quadrupoles and bumps for compensating the optics, pushing the A20 snake above 15% may not be possible. For operations, we have been setting the A20 snake to only 10%. In this case the spin transfer efficiency is 95.8% for Blue and 99.1% for Yellow.

OTHER METHODS OF MATCHING

Previous compensation schemes[4, 7] have looked at modification of the ATR to match the spin transfer with a single solenoid snake in the I10 straight section of the AGS.

We examined three new solutions for matching with two AGS snake:

1. Detuning the snakes in the Blue and Yellow rings at injection to tilt the stable spin vector in RHIC to match the incoming vector requires too large a shift in spin-tune to be attractive. This could provide partial compensation, but has the drawback of slow snake ramps.

2. Ramping a the old I10 snake[8] in the AGS at extraction could help matching. Both the new helical snakes are dc magnets; however, the old solenoid snake was actually ramped every AGS cycle in the old days to minimize coupling at AGS injection.

3. Adding one or two partial snakes to the ATR around the horizontal dipole (WD2) just upstream of the first vertical bend magnet in the ATR could provide considerable tunability to $\hat{n}_0$ for RHIC injection. At $G\gamma = 45.5$ the stronger of the two solenoids would require a strength of 1 T over 6 m to raise the transfer efficiency to 100% for both rings. This could in addition provide compensation for future running with polarized $^3\mathrm{He}^{+2}$ ions.

CONCLUSIONS

We have considered a number of methods to improve the spin transfer efficiency for polarized proton injection from the AGS into both RHIC rings with two strong partial snakes. Lowering the RHIC injection energy by one unit of $G\gamma$ to 45.5 has considerably improved the efficiency for both the Blue and Yellow rings. An efficiency of 100% can be realized by adding two partial snakes to the common part of the transfer lines between the AGS and RHIC.

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REFERENCES

[1] I. Alekseev et al., Nucl. Inst. and Meth. **A 499**, 392 (2003).

[2] J. Takano et al., Proc. of EPAC 2004, 2116 (2004).

[3] E. Willen et al., Proc. of PAC05, 2935(2005).

[4] W. W. MacKay and N. Tsoupas, AIP Conf. Proc. 667, 84, (2003).

[5] T. Roser et al., Acceleration of Polarized Beams using Multiple Strong Partial Siberian Snakes, EPAC04, 1577 (2004).

[6] H. Huang et al., "Acceleration of Polarized Protons in the AGS with Two Helical Partial Snakes", Proc. of PAC05, 1404 (2005).

[7] N. Tsoupas, M. Bai, H. Huang, and T. Roser, "Transferring Polarized Proton Beam from AGS to RHIC at Energies below the Spin Resonance $G\gamma = 36 + \nu_y$", C-A/AP/1 (1999).

[8] J. Takano et al., "Stable Spin Direction in the AGS with Three Partial Snakes", These Proceedings.