Chapter 4

Snakes and Spin Rotators in RHIC

To fit within existing straight sections in RHIC, it is important to find the most compact design for Siberian Snakes and Spin Rotators which could produce the desired spin rotation in the shortest space. A particularly elegant solution was proposed by V. Ptitsin and Y. Shatunov.[27] Their solution is based on helical dipole magnet modules, each having a complete 360° twist. Using helical dipole magnets minimizes orbit excursions which is most severe at injection energy. This allowed for a more modular design, where similar superconducting helical magnets could be used for both Snakes as well as Spin Rotators near the interaction points in RHIC.

4.1 General Layout

Two full Siberian Snakes on opposite sides of each of the two RHIC rings serve to avoid depolarization from imperfection and intrinsic depolarizing resonances up to the top energy of 250 GeV. In addition, Spin Rotators are required at the intersection points used by PHENIX and STAR to allow for measurements of spin effects with longitudinally polarized protons. The Spin Rotators rotate the polarization from the vertical direction into the horizontal plane on one side of the interaction region and restore it to the vertical direction on the other side.

The Siberian Snakes introduce a 180° spin rotation without generating a net orbit distortion. The Spin Rotators placed around the experiments rotate the spin by 90° to provide longitudinal polarization at the interaction region again without generating net orbit distortions. In both cases the spin rotation is accomplished with a sequence of constant field, superconducting helical dipole magnets.

Each Snake rotates the spin by 180° around a horizontal axis and the two axes of the two Snakes of each ring have to be perpendicular to each other. We are planning to use pairs of Siberian Snakes with one Snake rotating the spin around an axis that points 45° to the outside and the other Snake rotating around an axis that points 45° to the inside of the ring. In this case all Snakes can be constructed in the same way. Also, the two Snakes of each ring have to be installed on opposite sides of the ring. In fact, the beam direction in one Snake has to be exactly opposite to the beam direction in the other Snake to within

0.3 mrad. The following is a summary for the locations and construction of the Siberian Snakes and the Spin Rotators (see Fig. 1.2):

- Two pairs of full Siberian Snakes, one pair in each ring, are installed in the 3 o'clock and 9 o'clock sections of RHIC as shown in Fig. 1.2. These Snakes rotate the spin around axes that point 45° to the inside or outside of the ring. We are planning to install the Siberian Snakes in the 13 m long, cold straight sections between Q7 and Q8.

- The two pairs of Spin Rotators, one set for PHENIX at the 8 o'clock region and another set for STAR at the 6 o'clock region, are installed in the 40 m long straight sections between Q3 and Q4 on either side of the interaction region. The beam direction in the straight sections is different from the direction in the collision area by 3.67 mrad which introduces a spin rotation that is larger by a factor of $G\gamma$. This means that the Spin Rotators have to prepare a horizontal polarization direction such that after this spin rotation the desired longitudinal polarization direction is obtained at the interaction point.

4.2 Siberian Snake and Spin Rotator Design

For both the Siberian Snakes and the Spin Rotators we are planning to use four helical magnets[27]. Helical field magnets have some distinctive advantages over more conventional transverse Snakes or rotators: (i) the maximum orbit excursion is smaller, (ii) orbit excursion is independent from the separation between adjacent magnets, and (iii) they allow an easier control of the spin rotation and the orientation of the spin precession axis.

In an ideal helical dipole magnet to be used for our purposes, the central dipole field should rotate through a complete 360° from one end of the magnet to the other. In a real magnet, of course, the fields at the ends of the magnet will also contribute to the particle dynamics. The plan is to design a magnet in which the field integrals $\int B_x d\ell$ and $\int B_y d\ell$ are both equal to zero (for some particular energy). The maximum body field will thus rotate through an angle less than 360° along the axis of the magnet. Moreover, in order to simplify the construction of the Snakes/Rotators, a solution has been found with all magnetic modules identical in both devices. The only variation is that the helix of some magnets is right-handed and others left-handed.

Snake parameters are listed in Table 4.1. The parameters are a result of an optimization using an orbit and spin tracking program that includes the effects of fringe fields[28], [29]. The integration is performed by interpolation through the magnetic field numerically calculated and mapped on a 3-dimensional grid. The result of the orbit and spin tracking is shown in Fig. 4.1. To produce these results, it was found that the central body field of the helical magnets should rotate through approximately 340°, with the ends contributing the necessary remaining field. Naturally, the exact amount of rotation depends upon the

Number of helical magnets				4
Total length				10.56 m
Magnet bore				100 mm
Helical Magnets				
	Length (effective)	Field helicity	Field orientation at entrance/exit	Field strength
1	2.40 m	right-handed	Vertical	1.3 T
2	2.40 m	right-handed	Vertical	-4.0 T
3	2.40 m	right-handed	Vertical	4.0 T
4	2.40 m	right-handed	Vertical	-1.3 T
Max. orbit excursion (hor./ver.)			(25 GeV)	15 mm / 33 mm
Total field integral				24 T-m
Orbit lengthening			(25 GeV)	2 mm

Table 4.1: Parameters for the Siberian Snake magnets. All helical magnets are right-handed, and begin and end with vertical fields. The central field strengths were optimized to include end effects of the magnets.

model used to describe the ends, and final magnet parameters will be a result of actual magnet tests and measurements.

All helical magnets may be powered by separate power supplies. This allows for an adjustment of the spin tune to 1/2 and of the direction of the rotation axis to compensate for the effect of the detector solenoids. This is shown in Fig. 4.2.

Spin Rotator parameters are listed in Table 4.2. The result of the orbit and spin tracking is shown in Fig. 4.3. Since in RHIC the direction of the Spin Rotator beam line is at a horizontal angle $\theta = 3.674$ mrad with the direction of the adjacent insertion, the spin should emerge from the rotator in the horizontal plane and at an angle $G\gamma\theta$ with the rotator axis in order to obtain a longitudinal polarization through the insertion region. The needed rotation is therefore dependent on the beam energy. The values of the field needed to provide a longitudinal polarization at different energies are shown in Fig. 4.4.

4.3 Effects on RHIC Operation

Calculations of the changes to the RHIC lattice parameters generated by the helical dipole magnets show minimal effects on the RHIC lattice parameters. Because of the spiral trajectory within the magnets, the Snakes and rotators introduce coupling into the RHIC accelerators. Both computer modeling and analytical calculations have shown that this effect is also small, with a minimum tune separation due to coupling of $\Delta\nu = 0.004$ with two Snakes and 4 Spin Rotators present at RHIC injection.[30],[31]

The effects on RHIC operation of helical dipole magnet error fields and misalignments have also been studied.[32] In contrast to a "regular" dipole magnet error which can be thought of as producing a kink in the slope of the particle trajectory at the source of the error, a "helical dipole" error will introduce a step in the trajectory. To keep the vertical orbit distortions under control, the helical dipole field errors

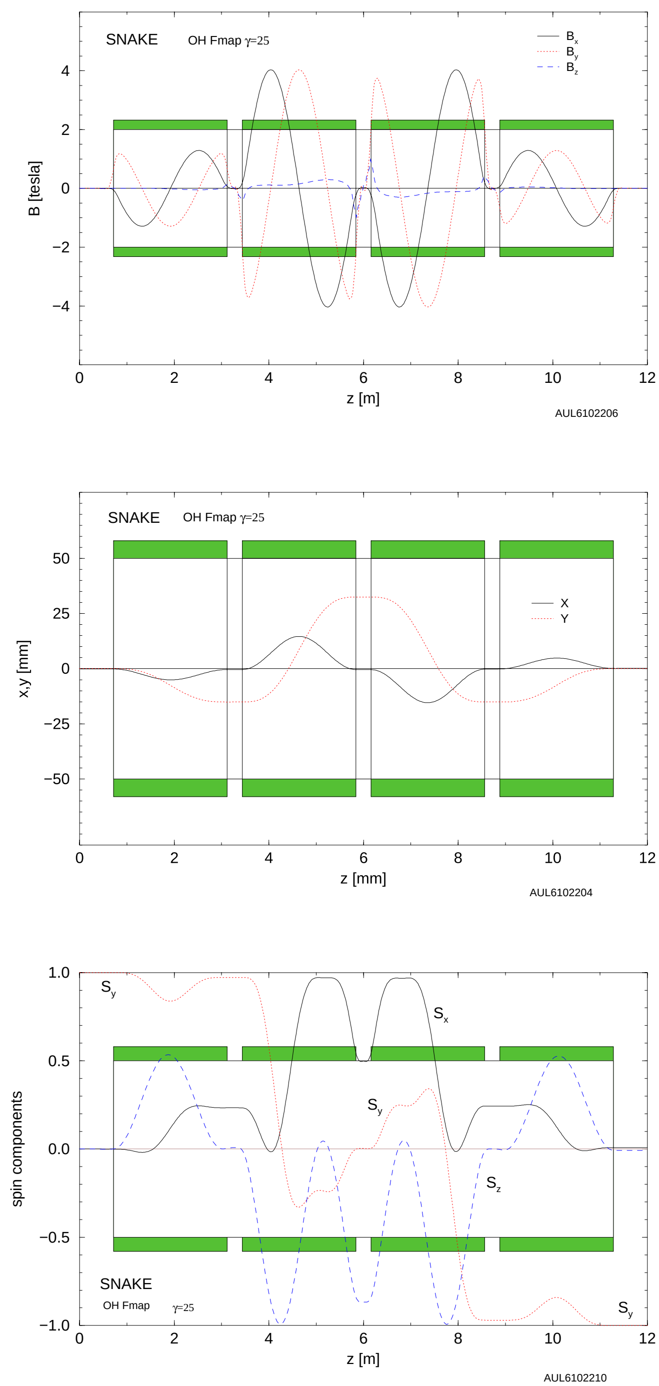

Figure 4.1: Field, orbit, and spin tracking through the four helical magnets of a Siberian Snake at $\gamma = 25$. The spin tracking shows the reversal of the vertical polarization.

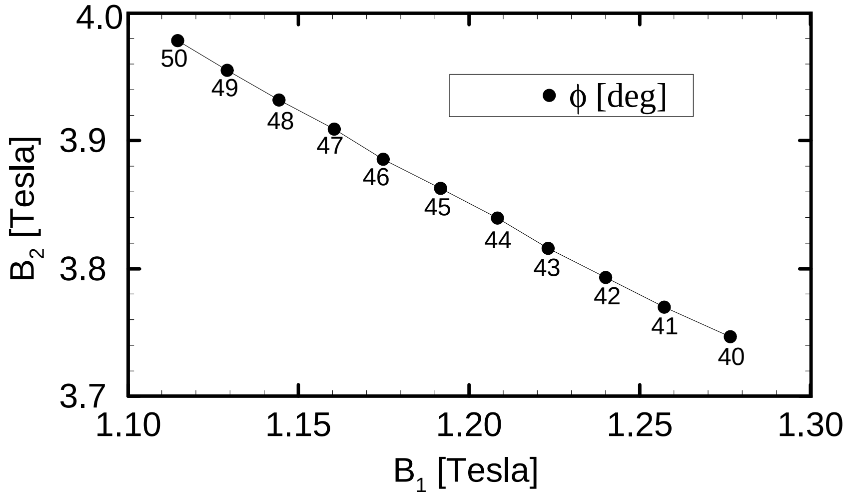

Figure 4.2: Change of the direction of the Snake rotation axis as a function of magnet excitation. This calculation uses an analytical expression for the Snake magnetic field.

Number of helical magnets				4	
Total length				10.56 m	
Magnet bore				100 mm	
Helical Magnets					
	Length (effective)	Field helicity	Field orientation at entrance/exit	Field (25 GeV)	Field (250 GeV)
1	2.40 m	right-handed	Horizontal	2.1 T	3.5 T
2	2.40 m	left-handed	Horizontal	2.8 T	3.1 T
3	2.40 m	right-handed	Horizontal	2.8 T	3.1 T
4	2.40 m	left-handed	Horizontal	2.1 T	3.5 T
Max. orbit excursion (hor./ver.)			(25 GeV)	25 mm / 10 mm	
Total field integral				23 T-m	
Orbit lengthening			(25 GeV)	1.4 mm	

Table 4.2: Parameters for the Spin Rotator magnets. Helical magnets alternate right-handed and left-handed, and all begin and end with horizontal fields. The central field strengths were optimized to include end effects of the magnets, and are calculated for longitudinal polarization at the beam collision point.

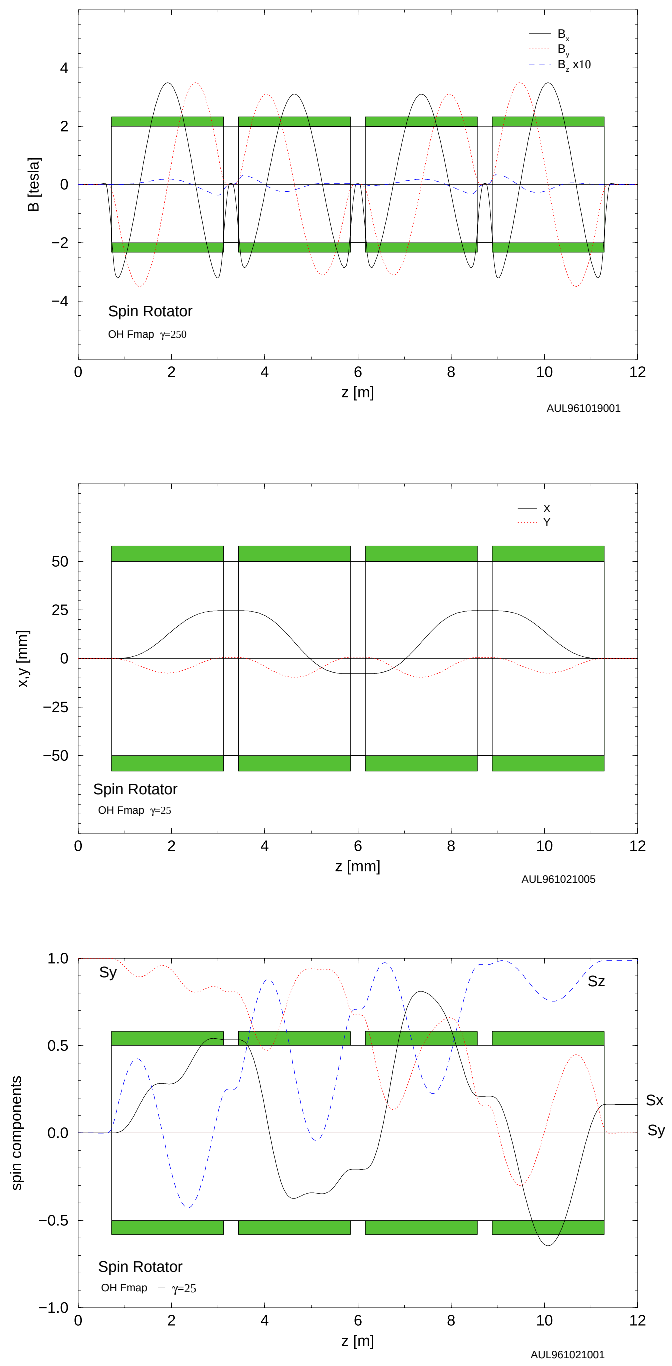

Figure 4.3: Field, orbit, and spin tracking through the four helical magnets of a Spin Rotator at $\gamma = 25$. In this example, the spin tracking shows how the polarization is brought from vertical to horizontal.

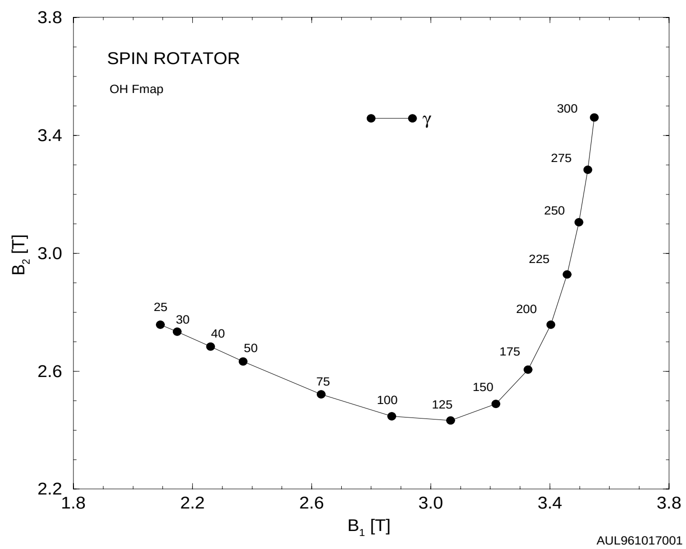

Figure 4.4: Excitation of the two pairs of helical magnets in the rotator to achieve longitudinal polarization in the insertion of RHIC, for various beam energies.

$\Delta(B\ell)/(B\ell)$ should be kept reasonably below 1%, and rotational misalignments should be less than about 10 mrad. The more important parameter will be the total integrated field strength ($\int B_x ds$, $\int B_y ds$) which should be zero, or equivalently the total equivalent integrated twist of the magnet should be 360°. This last requirement is especially sensitive in the case of the Rotator magnets (horizontal fields at the entrance and exit of the magnets). The Rotators, however, are only used at storage energy, where their effects on the orbit are smaller. With two Snakes on throughout injection and acceleration, the orbit distortions generated by their twist errors can easily be corrected using standard RHIC dipole correctors. The total twist angle and its tolerance are $360° \pm 2°$.[33] The ends of the magnets have been carefully designed to obtain not only the desired integrated field strength but also the desired total field twist well within this tolerance.[34], [35]

Field quality is also an issue for the helical magnets, though not as central an issue as for the normal bending magnets in the accelerator. The intrinsic helical nature of the field will itself produce nonlinear terms in the field expansion. In particular, Maxwell's equations dictate that the helical dipole field will be of the form

$$B_x \approx -B_0 \left\{ [1 + \frac{k^2}{8}(3x^2 + y^2)] \sin kz - \frac{k^2}{4} xy \cos kz \right\} \quad (4.1)$$

$$B_y \approx B_0 \left\{ [1 + \frac{k^2}{8}(x^2 + 3y^2)] \cos kz - \frac{k^2}{4} xy \sin kz \right\} \quad (4.2)$$

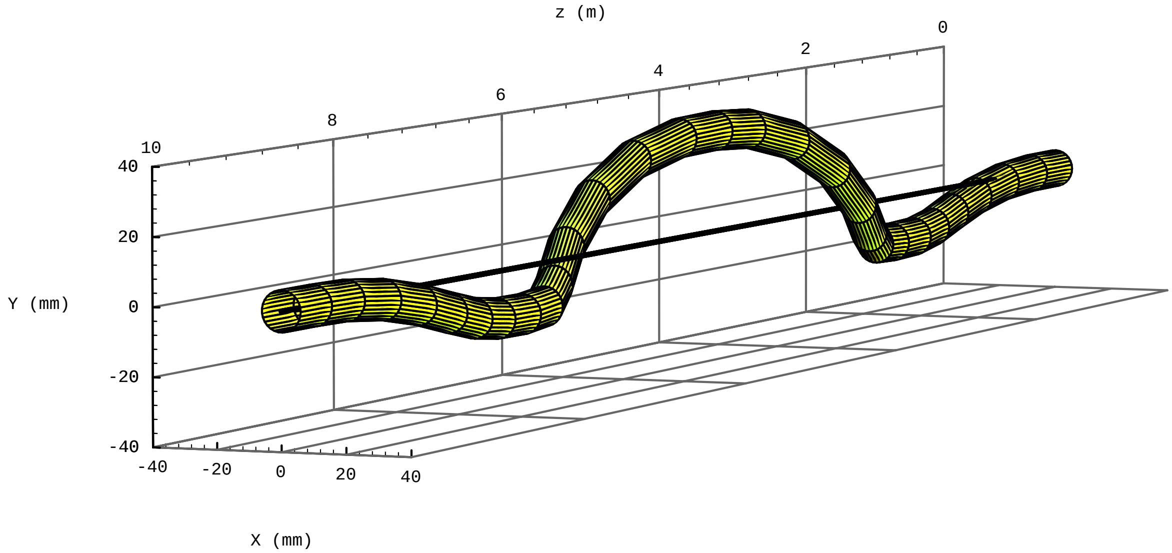

Figure 4.5: Three dimensional view of the trajectory through a RHIC Snake.

$$B_z \approx -B_0 k \left\{1 + \frac{k^2}{8}(x^2+y^2)\right\} [x \cos kz + y \sin kz] \tag{4.3}$$

where the repeat period of the helical field is $\lambda = 2\pi/|k|$. In the above, we have assumed a field which is "vertical" (i.e., positive y direction) at the entrance to the magnet. The sign of k determines the handedness of the field. To first order, the transverse fields are just $B_y = B_0 \cos kz$, $B_x = -B_0 \sin kz$ as desired. However, we see that for significant displacements, there are nonlinear terms which will contribute to the particle motion.

In addition to this intrinsic nonlinear feature, magnet design and construction errors will add nonlinearities to the field as well. While the nonlinear field components tend to average to zero over the length of the helical dipole, the protons follow a trajectory which is not centered within the magnet. (This is illustrated in Fig. 4.5, in which the choice of the name "Snake" is readily apparent.) Thus, one expects to see feed-down effects due to this trajectory. For example, a sextupole component in the magnet will generate a tune shift due to the off-centered orbit. Analytical estimates indicate that the intrinsic tune shift at 25 GeV due to two Snakes in RHIC is on the order of $\Delta\nu \approx 0.015$, and that a sextupole component in the magnet design of strength $b_2 \approx 2 \times 10^{-4}/\text{cm}^2$ (or, approximately 20 "units" measured at 3.1 cm) will give approximately the same tune shift.[36],[37] Particle tracking results are in qualitative agreement with these estimates.[38] The magnet design has a much smaller b_2 component, and so should not pose a problem in this regard.

4.4 Compensation for Detector Solenoids

The STAR and PHENIX detectors use solenoid magnets as spectrometers. With transverse polarization at the collision point the solenoid contributes to the imperfection resonance strength,

$$\epsilon_{imp,sol} = \frac{1+G}{2\pi}\frac{\int B_{\parallel} d\ell}{B\rho}$$

For a 5 Tesla-meter integrated solenoid field strength, the resulting spin resonance strength is about 0.02 at the injection energy and 0.003 at 250 GeV/c.

With longitudinal polarization at the collision point the longitudinal field rotates the polarization around its axis and thus changes the spin tune. The spin tune is changed by 0.03 to 0.003 at 25 GeV and 250 GeV, respectively, by a 5 T-m solenoid. This can be compensated by adjusting the direction of the axes around which the Snakes rotate the spin. By adjusting up to $\pm 5^{\circ}$ the spin tune can be adjusted for energies down to 25 GeV.