# ACCELERATION OF POLARIZED PROTONS IN THE AGS WITH TWO HELICAL PARTIAL SNAKES*

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*Abstract*

Acceleration of polarized protons in the energy range of 5 to 25 GeV is particularly difficult: the depolarizing resonances are strong enough to cause significant depolarization but full Siberian snakes cause intolerably large orbit excursions and are not feasible in the AGS since straight sections are too short. Recently, two helical partial snakes with double pitch design have been built and installed in the AGS. With careful setup of optics at injection and along the ramp, this combination can eliminate the intrinsic and imperfection depolarizing resonances encountered during acceleration. This paper presents the accelerator setup and preliminary results.

## INTRODUCTION

Acceleration of polarized proton beams in a circular synchrotron is complicated by the numerous depolarizing spin resonances. There are mainly two kinds of resonances: imperfection resonances due to magnet field errors and misalignments, and intrinsic resonances due to vertical betatron motion in quadrupoles. The imperfection resonance happens when $G\gamma = n$, where n is an integer, $G=(g-2)/2=1.7928$ is the anomalous factor of the magnetic moment and $\gamma$ is the Lorentz factor. $G\gamma$ gives the number of full spin precessions for every orbit revolution and is also called the spin tune $\nu_{sp}$. The intrinsic resonance strength is proportional to the square root of beam energy. The intrinsic resonance occurs when $\nu_{sp} = G\gamma=mP\pm \nu$, where m is an integer, P is the super-periodicity of the synchrotron and $\nu$ is the betatron tune. In the Brookhaven Alternating Gradient Synchrotron (AGS), P=12. When passing through a depolarizing resonance with constant crossing speed $\alpha$, the ratio of final polarization $P_f$ to initial polarization $P_i$ is given by the Froissart-Stora formula[1]. For intrinsic resonances and a beam with Gaussian transverse distribution:

$$\frac{P_f}{P_i} = \frac{1-\pi|\varepsilon|^2/\alpha}{1+\pi|\varepsilon|^2/\alpha}, \quad (1)$$

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where $\varepsilon$ is the spin resonance strength for the particle with the rms amplitude and $\alpha= d(G\gamma)/d\theta$. $\theta$ is the orbit angle in the synchrotron. For the AGS acceleration rate of $\alpha = 5\times10^{-5}$, a resonance strength of 0.004 leads to complete depolarization. Typical resonance strengths in the AGS for a beam with a normalized 95% emittance of 10 $\pi$ mm mrad are between 0.0001 and 0.01 and therefore most of the resonances cause significant depolarization.

## TWO PARTIAL SIBERIAN SNAKES

An arrangement of magnets as a local spin rotator, called a Siberian snake, can overcome both imperfection and intrinsic depolarizing resonances. For a ring with a partial snake (a local spin rotator) with strength s, the spin tune $n_s$ is given by

$$\cos\pi\nu_{sp} = \cos G\gamma\pi \cos s\pi/2, \quad (2)$$

where s=1 corresponds to a full snake, which rotates the spin by 180°. When s is small, the spin tune is nearly equal to $G\gamma$ except when $G\gamma$ equals an integer n, where the spin tune $\nu_{sp}$ is shifted away from the integer by ±s/2. Thus, the partial snake creates a gap in the spin tune at all integers. Since the spin tune never equals an integer, the imperfection resonance condition is never satisfied. Thus the partial snake can overcome all imperfection resonances, provided that the resonance strengths are much smaller than the spin tune gap created by the partial snake. Partial snake is particular interesting to medium energy synchrotrons such as the AGS, as a full snake is not practical due to the field strength required and lack of available straight sections. Over the past ten years, a 5% partial solenoidal Siberian Snake has been used successfully to overcome imperfection resonances in the AGS[2]. In addition, a coherent spin resonance excited by an ac dipole was used to overcome the four strong intrinsic spin resonances[3]. Since the depolarizing resonance strength is not very strong, a strong enough partial snake can generate a large enough spin tune gap to overcome both intrinsic and imperfection resonances, as long as the vertical tune is placed inside the gap. The challenge is to run the synchrotron with a tune close to an integer.

For a strong partial snake, however, polarization loss at injection and extraction is no longer negligible. A 20% ($36^{\circ}$ spin rotation) snake will lead to a 10% polarization loss due to this spin direction mismatch. A single additional partial snake located in the AGS can provide the spin direction matching at injection and extraction and also increase the effective partial snake strength if its position is chosen properly[4]. The locations of multiple partial Siberian snakes have to be chosen very carefully to maintain control of the spin tune in a similar way as is necessary for multiple full Siberian snakes. Separating the two partial snakes by one third of the ring is of particular interest since it will introduce a periodicity of three units in the spin tune dependence on Gγ. Since both the super-periodicity of the AGS (12) and the vertical betatron tune (~9) are divisible by three the spin tune will be the same at all intrinsic resonances, namely for Gγ = 3n. With both snakes at equal strength, the effective snake strength doubles at Gγ = 3n. At the injection and extraction energies, for which Gγ = 3n + 1.5, the two snakes cancel. The polarization direction in the AGS is therefore exactly vertical and no polarization is lost due to spin direction mismatch. Even in the case of different partial snake strength, the spin mismatch at injection and extraction is still minimized by choosing Gγ as half integer.

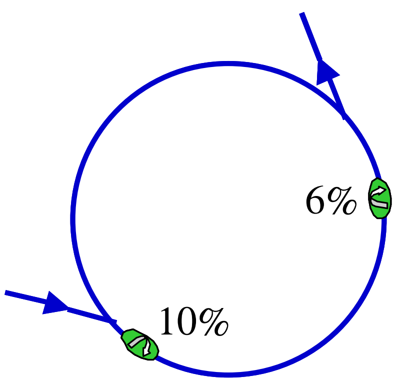


Figure 1: Locations of the partial Siberian snakes and the injection and extraction regions that give minimum polarization loss due to spin direction mismatch.

The 6% warm partial snake has been installed in 2004. The super-conducting (cold) partial snake has been installed in 2005 and is used for RHIC polarized proton operation for the first time this year. The cold snake is capable of being a 20% partial snake. Since spin matching at extraction and injection is much better with two properly arranged partial snakes, we run the two snakes together. The injection and extraction regions have to be located as shown in Fig. 1 relative to the location of partial Siberian snakes. In this case the polarization loss due to injection and extraction mismatch is only 3%.

In general, the intrinsic resonance is only associated with the vertical betatron tune $\nu_y$ for a vertical polarization, as the vertical spin can only be affected by the horizontal magnetic field. However, in the presence of a partial snake, the stable spin direction is not purely vertical. For the horizontal component of polarization, the vertical magnetic field can drive spin resonances. Therefore, the horizontal betatron motion also contributes to the polarization loss. To avoid these horizontal spin resonances, the horizontal betatron tune should also be put into the spin tune gap generated by the partial snakes. However, at present such optics are difficult to achieve in the AGS. This depolarizing effect of horizontal spin resonances is proportional to the partial snake strength. The total snake strength is then a compromise between overcoming vertical intrinsic resonances and minimizing the effect of horizontal resonances.

## HELICAL SNAKE OPERATION

The AGS injection and extraction energies are set to occur at Gγ = 4.5 and 45.5, respectively. The extraction energy is chosen such that the spin transmission between AGS and RHIC is optimized [5]. At low energies, the helical magnets cause significant lattice distortion. Four compensation quads are added for each of the two helical snake magnets. The vertical tune is ramped into the gap at slightly higher energy after Gγ=5. This low tune lattice is more stable and the experiment results proved that the resonances near Gγ=5 do not cause distinguishable polarization loss. A detailed plot of the vertical tune vs. Gγ and the spin tune gap generated by two partial snakes is shown in Fig. 2. With such a lattice, more than $2\times10^{11}$ protons can be injected and accelerated to the RHIC injection energy. Last run, without proper compensation quads for the warm snake, the lattice distortion reduced the dynamic aperture of AGS injection, and intensity in the AGS was limited to less than $1\times10^{11}$. Polarization at AGS extraction was 65% for an intensity of $1.5\times10^{11}$ per bunch with a 2T cold partial snake and 1.5T warm partial snake.

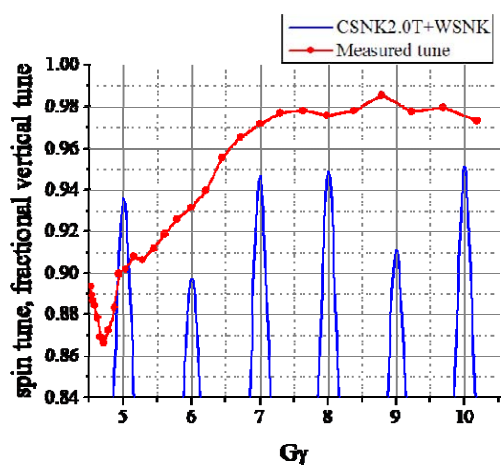


Figure 2: Spin tune for two partial snakes in AGS. The vertical betatron tune cannot be put into the spin tune gap at injection. But it moves up quickly into the spin tune gap generated by the two partial snakes.

To maintain polarization in the AGS, we have to put the vertical tunes along the energy ramp into the spin tune gap generated by the two partial snakes. Moreover, due to the so-called partial snake resonances, the available tune space is even reduced. The partial snake resonances happen when

$$\nu_{sp} = k + m\nu_y \qquad (2)$$

where $m$ and $k$ are integers. When $m$=1, these are the intrinsic resonances discussed earlier. In the presence of the snakes, the higher order resonances constrain the betatron tune space available. The strength of these snake resonances is proportional to the intrinsic resonance strength nearby. In general, the higher the resonance order, the weaker the resonance strength. The polarization measurements shown in Fig. 3 depict the effect of the snake resonances for two resonances with different resonance strength. As can be seen, there is no polarization dip when $\nu_y$>8.92 for 12+$\nu_y$, because this resonance strength is relatively weak. In contrast, there are two polarization dips for 0+$\nu_y$, where the intrinsic resonance is strong.

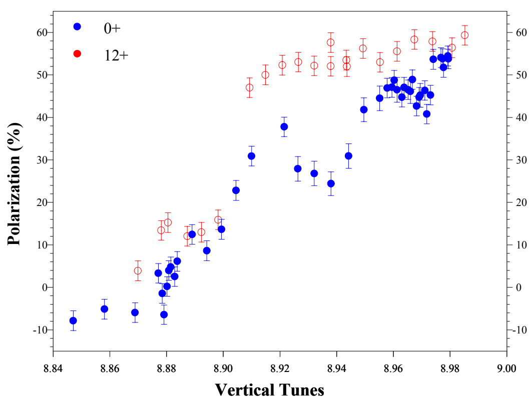


Figure 3: Polarization as function of vertical tunes at two intrinsic resonances with different resonance strength.

With two partial snakes installed, the imperfection resonances can still be important. As shown in Fig. 4, for a lattice with large orbit distortion, the imperfection resonance strength could be comparable to the partial snake strength. If they have opposite phase, the imperfection resonance just cancels the effect of the two partial snakes. In fact, we observed polarization loss with a large amplitude of one of the 9th harmonic equilibrium orbit distortion. An example of such a harmonic scan is shown in Fig. 5. There was not a similar effect for the 15% cold snake case since the partial snake is stronger and the phase between them may be different.

## CONCLUSIONS

Acceleration of 1.5x10$^{11}$ protons to 23 GeV with 65% polarization was achieved in the AGS using 6% and 10% helical partial snakes. The new partial Siberian snake design using helical dipoles with varying pitch make it possible to build such a compact partial snake. The two-snake scheme avoids depolarization from both imperfection and intrinsic spin resonances in medium energy accelerators and also maintains good matching to the vertical polarization in the injection and extraction beam lines.

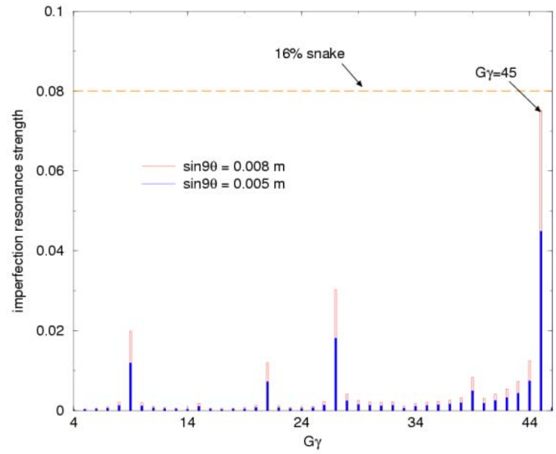


Figure 4: Estimated imperfection resonance strengths with large sin 9th harmonics. With 8mm 9th harmonic amplitude, the resonance strength is comparable to a 16% partial snake in the AGS and the snake effect can be canceled by the orbit distortion.

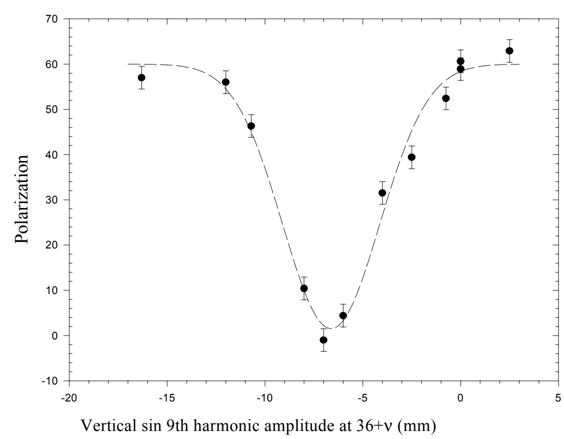


Figure 5: Measured polarization as function of the sine 9th harmonic amplitude at 36+$Q_y$. The dashed line is to guide the eyes. The location of the polarization dip agrees with model prediction as shown in Fig. 4.

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