The Partial Siberian Snake Experiment at the Brookhaven AGS*

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Abstract

We are building a 4.7 Tesla-meter room temperature solenoid to be installed in a 10-foot long AGS straight section. This experiment will test the idea of using a partial snake to correct all depolarizing imperfection resonances and also test the feasibility of betatron tune jump in correcting intrinsic resonances in the presence of a partial snake.

1 INTRODUCTION

The spin equation of motion for a moving particle in a static magnetic field is given by[1]

$$\frac{d\vec{S}}{dt} = \frac{e}{\gamma m}\vec{S} \times [(1+G\gamma)\vec{B}_\perp + (1+G)\vec{B}_\|]. \quad (1)$$

where $\vec{B}_\perp$ and $\vec{B}_\|$ are the transverse and longitudinal components of the magnetic fields respectively. G is the anomalous gyromagnetic g-factor and γmc^2 is the energy of the moving particle.

Eq. (1) indicates that the transverse vertical dipole guide field in an accelerator, gives rise to a spin precession around the vertical direction by $G\gamma$ per turn around the ring. On the other hand, the transverse horizontal and the longitudinal fields kick the beam spin away from the vertical polarization direction. Normally, there is no longitudinal field in the accelerator except the solenoidal snake in the present proposal. The transverse horizontal fields could arise from: (1) vertical orbital motion away from the center of quadrupoles and/or (2) dipole rotation error. Given the repetitive nature of circular accelerators, these depolarization kicks can be Fourier analyzed to obtain the resonance frequency, or resonance tune per revolution. The intrinsic resonance occurs at a resonance tune $K_j = k \cdot P \pm \nu_y$ and the imperfection resonance occurs at $K_j = n$. The corresponding Fourier amplitudes are called resonance strengths, ϵ_j. Intrinsic resonances arise from the vertical betatron motion of particles, and imperfection resonances arise from the vertical closed orbit distortion.

As γ increases during acceleration, the intrinsic resonance condition can be avoided by appropriately shifting the vertical betatron tune. Imperfection depolarizing resonances due to the vertical closed orbit motion occur at $\nu_s = G\gamma = n$. They have been overcome by using the methods of harmonic correction[2] and adiabatic spin flip[3]. For example, at the AGS the method of harmonic correction is applied by utilizing 95 correction dipoles.

The above mentioned correction schemes are, however, of limited applicability when accelerating polarized protons to very high energies. The harmonic correction method is tedious, time consuming and depends on the closed orbit of the accelerator, which may drift with time and change between running periods.[2] At high energies, where the resonances are overlapping, the method of adiabatic spin flip fails, as does the method of tune jump which is stopband limited.

An arrangement of magnets, called a Siberian snake, was proposed[4] to simultaneously overcome all depolarizing resonances. A snake rotates the spin of each proton by 180 degrees about an axis in the horizontal plane on each turn around the ring without affecting the orbital closed orbit outside of the snake. Similarly, a partial snake rotates the spin of each proton by an angle $\delta < 180°$. The behavior of a partial snake is most easily understood from the point of view that the spin tune ν_s of a spin particle is given by the following equation,

$$\cos \pi\nu_s = \cos(\pi G\gamma) \cos \frac{\delta}{2}. \quad (2)$$

For a 100% snake, $\delta = 180°$, we have $\nu_s = 1/2$. Neither resonance condition discussed above is therefore ever satisfied regardless of the beam energy. For a partial snake, $\delta < 180°$, the spin tune ν_s obtained from Eq. (2) will deviate from an integer value by a distance of $\frac{\delta}{2\pi}$. Thus the imperfection resonance condition will not occur. The vertical stable spin direction will however flip sign in passing through every integer $G\gamma$ value. The situation for intrinsic resonances is more complicated, and in general a partial snake will not be able to overcome the intrinsic depolarization resonances. Thus the vertical tune jump method has to be used.

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Recently, snake experiments[5] have been performed at the Indiana University Cyclotron Facility. These experiments demonstrated that a Siberian snake can indeed overcome a single depolarizing resonance. More importantly, a partial snake is found to be capable of correcting imperfection resonances. However these tests were partially static and only corrected an individual resonance during the acceleration cycle. A very slight depolarization on each of many resonances could be troublesome. Although absent in ideal theoretical simulation,[6] we should determine that this does not occur in a real machine. An AGS test would be a direct demonstration of a partial snake correcting many resonances during acceleration.

The accelerator physics experiment at the AGS is intended to study (1) the effect of a partial snake[6] on the spin motion in the presence of imperfection and intrinsic resonances, (2) adiabatic turn on/off of the snake[7], and (3) betatron tune jump in the presence of the partial snake.

2 ACCELERATOR PHYSICS ISSUES

2.1 *Emittance Growth due to Tune Jump*

Intrinsic resonances in the presence of a 5% partial snake, can be overcome with the vertical betatron tune jump, where 10 laminated ferrite quadrupoles are pulsed primarily to change the vertical betatron tune (the horizontal tune is also changed by the ratio of β_x/β_z) with rise and fall times of 3 μsec and 3 $m$sec respectively. These pulsed quadrupole fields create a betatron amplitude mismatch. The emittance growth is estimated to be 10% with $\Delta\nu_z = 0.3$.

During the tune jump, the horizontal and vertical betatron tunes will cross each other. Thus the linear betatron coupling is enhanced in the presence of a solenoidal snake. Since the resonance strength is proportional to the square root of the vertical emittance, $\sqrt{\varepsilon_z}$, the emittance growth must be minimized. This process has been studied with a numerical simulation.

2.2 *Effect of Solenoid on Emittance*

A transport matrix is used to track the particle motion in the AGS ring with a solenoid. The transport matrix, M_{total}, a 4 x 4 matrix, is given by

$$M_{total} = M_{sol} \cdot M_{ring}. \qquad (3)$$

The maximum tolerable tune jump is $\Delta\nu = 0.3$, so the time for ν_z to return to its normal value is $\Delta t = \Delta\nu/G\dot{\gamma} = 3.3ms(\dot{\gamma}{=}50\ \text{s}^{-1}$ for the AGS). Since the revolution frequency is 2.7μs, the vertical tune ν_z is restored in about 1200 turns after the jump. For a solenoid with length l=2.5m, θ=kl=4.7/Bρ=0.057, we obtain the coupling strength k=0.0226 m^{-1}.

In the present simulation, we use $\Delta\nu_z = 0.2$,i.e., ν_z increases linearly from 8.6 to 8.8 in 1200 turns for $\Delta\nu_z$=0.2, ν_x decreases linearly from 8.7 to 8.6 in 1200 turns. Then ν_x and ν_z are kept as constants as the particle travels upto 1700 turns. The simulation has been done for two cases:

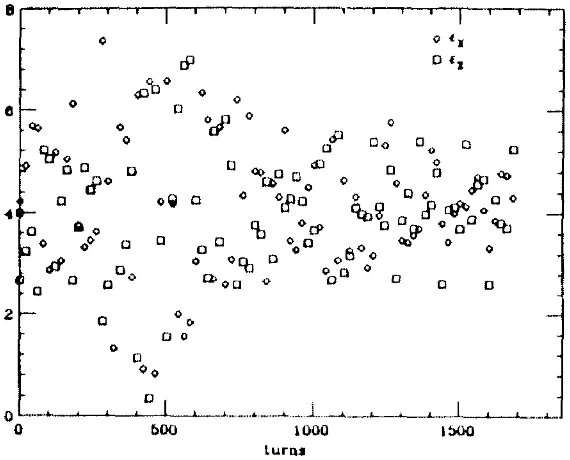

Figure 1: The initial position of the particle is x=z=7 mm. ε_x=ε_z=4π mm-mrad.

1) The two initial transverse emittances are unequal. The simulation results show that the two emittances oscillate around the original values. Since ν_x and ν_z cross at 400 turns, the amplitude oscillation is more drastic around 400 turns. At the same time, ε_z and ε_x are exchanged. The emittance exchange gives rise to emittance growth. The simulation has been done for several different initial phase space coordinates, all results show the emittance exchange. It seems that the emittance exchange is inevitable for unequal initial emittances.

2) The two initial transverse emittances are equal. The simulation shows that the trend does not change: ε_x and ε_z oscillate around the initial values and oscillate drastically when near 400 turns. The differences between ε_x and ε_z are smaller, since the starting emittances are the same. Which of ε_x and ε_z is larger depends on the initial phase space coordinates. No emittance growth is observed in this case(see Fig.1). Emittance measurement during the tune jump[2] shows similar behavior.

2.3 *Spin Flip due to Large Betatron Amplitude*

The beam bunch is made of particles with different transverse action. The rms emittance ε_0 of the beam is defined as

$$\varepsilon_0 = \frac{{\sigma_z}^2}{\beta_z}$$

The Gaussian distribution of the beam is given by

$$\rho(\varepsilon) = \frac{1}{2\varepsilon_0} e^{-\frac{\varepsilon}{2\varepsilon_0}}$$

The intrinsic depolarizing resonance strength of a spin particle is given by

$$\epsilon = \epsilon_0 \sqrt{\frac{\varepsilon}{\varepsilon_0}}$$

where ϵ_0 is the resonance strength for particle with rms emittance ε_0. Applying the Froissart-Stora Formula to each particle, the effective polarization after passing through resonance becomes,

$$\frac{\langle P\rangle}{P_0} = \int_0^\infty \rho(\varepsilon)[2e^{\frac{-\pi|\epsilon|^2}{2\alpha}} - 1]d\varepsilon = \frac{1-\frac{\pi|\epsilon_0|^2}{\alpha}}{1+\frac{\pi|\epsilon_0|^2}{\alpha}}.$$

For the AGS, $\alpha \equiv \frac{dG\gamma}{d\theta} \simeq 4 \times 10^{-5}$. It is necessary to have a rms resonance strength, $\epsilon_0, 0.016$ to obtain 90% spin flip; i.e., $\langle P\rangle/P = -0.90$. On the other hand, a single particle spin flip occurs at a resonance strength $\epsilon = 1.2 \times 10^{-2}$. The coresponding rms emittance of the particle to achieve 99% spin flip is about $\varepsilon = 2\pi$ mm-mrad at $\gamma = 4.8$. Let us assume that the normalized rms emittance is $\varepsilon_N = 2\pi$ mm-mrad, The required kick emittance will be about 2.5 π mm-mrad at $\gamma = 4.8$. The kicked bunch will execute a betatron oscillation at a maximum amplitude of $\sqrt{2.5 \times 22} \simeq 7.5$ mm. A problem related to such a scheme is that the beam decoheres in the betatron phase space and leads to bunch dilution or emittance growth. Amplitude dependent tune is given by

$$\nu_z = \nu_{z0} + \frac{\alpha_{zz}}{\beta_z} a_z^2$$

with $\alpha_{zz} \simeq 30[\frac{1}{\pi m}]$. When the bunch is kicked, the tune spread of the bunch is given by

$$\Delta\nu_z = 2\frac{\alpha_{zz}}{\beta_z} \cdot a_z \cdot \Delta a_z \simeq 7.5 \times 10^{-5}.$$

Thus the bunch will completely decohere in about 34 *ms*. Thus the scheme is indeed possible. Assuming that 5 *ms* is needed in passing through a resonance, the emittance growth will be about $\frac{5}{34} \simeq 15\%$. Thus the scheme is limited by its applicability due to bunch decoherence.

2.4 *Is a 5 % Partial Snake Enough for the AGS?*

A partial snake introduces an effective resonance strength $\frac{\delta}{2\pi}$ on each integer spin precession frequency. The polarization is given by Froissart-Stora Formula,

$$\frac{P_f}{P_i} = 2e^{-\frac{\pi}{2\alpha}|\frac{\delta}{2\pi}+\epsilon|^2} - 1$$

For the partial snake to dominate the spin depolarization process, $|\epsilon|$ should be less than 0.012.

The resonance strength at $G\gamma = 45$ is estimated to be 0.018 based on 1988 measured magnet survey data. It is thus interesting to study the interference between the longitudinal and transverse field errors at $G\gamma = 45$.

2.5 *Specification and Design of the 4.7 Tm Solenoid*

The experiment calls for the construction of a 4.7 Tm solenoid with length 90 inches, 3.8 million ampere turns and 1.5MW power supply. The magnet is ramped to peak field in 0.6 sec to match the AGS cycle with 33 % duty cycle. The present design uses six layers 68 turns solenoid with current 9.5 KA. A schematic drawing of the conceptal design[8] is shown in Fig.2.

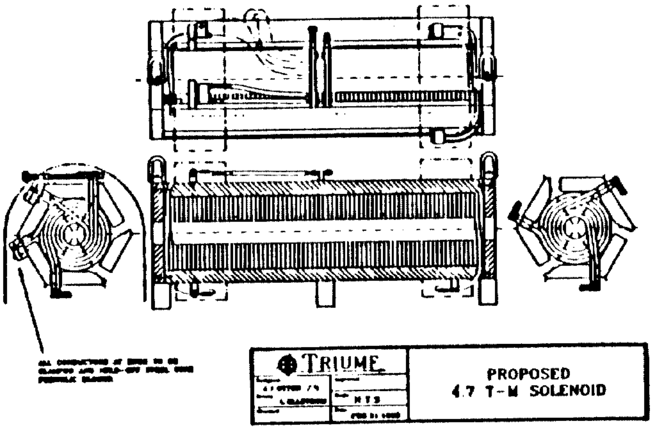

Figure 2: A schematic drawing of the solenoidal partial snake for the AGS.

3 CONCLUSION

The partial snake experiments at the AGS are of fundamental importance to the accelerator physics study of spin motion in the synchrotron and to polarized proton collision experiments in the high energy colliders[9], such as RHIC, Tevatron and the SSC. The experiment is approved and is likely to take place in late 1993 or early 1994.

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