Preservation of Proton Polarization by a Partial Siberian Snake

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Abstract

A 9° solenoidal spin rotator or 5% partial Siberian snake was used to successfully accelerate polarized protons for the first time to 10.8 GeV kinetic energy in the Brookhaven AGS without using harmonic orbit correctors. It was found that a 5% partial snake can effectively overcome 18 imperfection resonances in this energy range. We also observed an interference between the spin flip induced by an intrinsic resonance and linear coupling due to the solenoid field of the partial snake.

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The acceleration of polarized beams in circular accelerators is complicated by the presence of numerous depolarizing resonances. During acceleration, a depolarizing resonance is crossed whenever the spin precession frequency equals the frequency with which spin-perturbing magnetic fields are encountered. There are two main types of depolarizing resonances corresponding to the possible sources of such fields: imperfection resonances, which are driven by magnet errors and misalignments, and intrinsic resonances, driven by the focusing fields.

The resonance conditions are usually expressed in terms of the spin tune ν_s , which is defined as the number of spin precessions per revolution. For an ideal planar accelerator, where orbiting particles experience only the vertical guide field, the spin tune is equal to $G\gamma$ [1], where $G = 1.7928$ is the anomalous magnetic moment of the proton and γ is the relativistic Lorentz factor. The resonance condition for imperfection depolarizing resonances arises when $\nu_s = G\gamma = n$, where n is an integer. Imperfection resonances are therefore separated by only 523 MeV energy steps. The condition for intrinsic resonances is $\nu_s = G\gamma = kP \pm \nu_v$, where k is an integer, ν_v is the vertical betatron tune and P is the superperiodicity. For the AGS, $P = 12$ and $\nu_v \approx 8.8$. For most of the time during the acceleration cycle, the precession direction, or stable spin direction, coincides with the vertical axis. Close to a resonance, the stable spin direction is perturbed away from the vertical direction by the resonance driving fields. When a polarized beam is accelerated through an isolated resonance, the final polarization can be calculated analytically [2] and is given by

$$\frac{P_f}{P_i} = 2e^{-\frac{\pi|\epsilon|^2}{2\alpha}} - 1, \quad (1)$$

where P_i and P_f are the polarizations before and after the resonance crossing, respectively, ϵ is the resonance strength obtained from the spin rotation of the driving fields, and α is the change of the spin tune per radian of the orbit angle. When the beam is slowly ($\alpha \ll |\epsilon|^2$) accelerated through the resonance, the spin vector will adiabatically follow the stable spin direction resulting in spin flip. However, for a faster acceleration rate partial depolarization or partial spin flip will occur. Traditionally, the intrinsic resonances are overcome by using a betatron tune jump, which effectively makes α large, and the imperfection resonances are overcome with the harmonic corrections of the vertical orbit to reduce the resonance strength ϵ [3,4]. At high energy, these traditional methods become difficult and tedious.

By introducing a 'Siberian Snake' [5], which is a 180° spin rotator about a horizontal axis, the stable spin direction remains unperturbed at all times as long as the spin rotation from the Siberian Snake is much larger than the spin rotation due to the resonance driving fields. Therefore the beam polarization is preserved during acceleration. Such a spin rotator can be constructed by using either solenoidal magnets or a sequence of interleaved horizontal and vertical dipole magnets producing only local orbit distortions. Since the orbit distortion is inversely proportional to the momentum of the particle, such a dipole snake is particularly effective for high-energy accelerators, e.g. energies above about 30 GeV. For lower-energy synchrotrons, such as the Fermilab booster and the Brookhaven AGS with weaker depolarizing resonances, a partial snake [6], which rotates the spin by less than 180°, is sufficient to keep the stable spin direction unperturbed at the imperfection resonances. This paper reports the first test of the partial snake concept crossing 18 imperfection resonances.

There have been several snake experiments performed at the low-energy Indiana University Cyclotron Facility (IUCF) Cooler Ring [7], where the effect of a full and partial snake

on the stable spin direction has been demonstrated in great detail. In these experiments, the acceleration rate was so low that the imperfection resonance always induced complete spin flip and no loss of polarization could be observed without a snake. Thus, a partial snake experiment at an accelerator such as the Brookhaven AGS, where numerous imperfection resonances lead to complete depolarization, was necessary to confirm the applicability of the partial snake.

The accelerator complex of the Brookhaven AGS, and the Relativistic Heavy Ion Collider (RHIC), presently being constructed, is shown schematically in Fig. 1. The solenoid, installed in an AGS 3-meter straight section, has an effective length of $\ell = 2.286\text{ m}$ with total number of turns $N = 402$, and inner diameter 16.51 cm . The snake can be ramped to 4.7 Tm in about 0.6 s at a 33% duty cycle and is capable of achieving a 5% snake strength up to $G\gamma = 48$, or 25 GeV kinetic energy. The spin rotation ϕ in the solenoid is given by

$$\phi = \frac{e(1+G)\mu_0 NI}{cp}, \quad (2)$$

where p is the momentum of the proton, μ_0 is the permeability of vacuum, and NI the ampere-turns. The effective snake strength s of the partial snake is $s = \phi/\pi$. The linear betatron coupling strength due to the 5% snake solenoid is $C_- \approx 0.30\text{ s } e^{-0.91i}$ or $|C_-| \approx 0.015$. The betatron tune shift due to the focusing effect of the solenoid is $\Delta\nu \approx 0.16s^2 \approx +0.0004$. Except in those cases where the horizontal and the vertical betatron tunes are close to each other, the solenoid causes little perturbation to the orbital motion.

The polarized beam from the atomic source [8] was accelerated through a radio frequency quadrupole (RFQ) and the 200 MeV LINAC. The beam polarization at 200 MeV was measured with elastic scattering from a carbon fiber target [4]. This measurement was made in a separate branch of the injection line and the polarization was checked periodically. The beam polarization was quite stable and was $80 \pm 5\%$. The beam was then injected and accelerated in the AGS Booster up to 1.56 GeV or $G\gamma = 4.77$. The vertical betatron tune of the AGS booster was chosen to be 4.88 in order to avoid crossing the intrinsic resonance $G\gamma = \nu_y$ in the booster. The imperfection resonance at $G\gamma = 4$, which caused about 5% depolarization, was corrected by harmonic orbit correctors. The measured polarization when injected into the AGS was $77 \pm 5\%$. The beam intensity in the AGS was typically 5×10^9 polarized protons per pulse. The normalized emittance was measured with an ionization profile monitor to be about $25\pi\text{ mm mrad}$. The polarized beam in the AGS was accelerated up to $G\gamma = 22.5$ or 10.8 GeV kinetic energy passing through eighteen imperfection resonances and three intrinsic resonances at $G\gamma = \nu_y$, $24 - \nu_y$, and $12 + \nu_y$.

The beam polarization in the AGS was measured by scattering the polarized protons from a $100\mu\text{m}$ diameter nylon string. The string was spooled through the beam at about 0.3 m/s to avoid melting and excessive radiation damage. The recoil protons were detected in left and right detector arms at an average angle of 77.25° with respect to the beam direction. The detector consisted of two initial scintillation counters, a scintillation hodoscope, an aluminum absorber wedge, a thick scintillation counter to stop the recoil protons, and a final veto counter to suppress pions. The beam polarization P was obtained from

$$P = \frac{1}{A} \left(\frac{\sqrt{L_\uparrow R_\downarrow} - \sqrt{L_\downarrow R_\uparrow}}{\sqrt{L_\uparrow R_\downarrow} + \sqrt{L_\downarrow R_\uparrow}} \right), \quad (3)$$

where A is the effective analyzing power for the nylon target, and L and R are the number of events in the left and right detectors, respectively. The polarization of the beam was switched between up and down (denoted by the subscripts $\uparrow$ and $\downarrow$) on alternate pulses. At $G\gamma = 10.5$ the left-right asymmetry was measured with both the nylon target and also with a target made from 35 individual $8\ \mu\text{m}$ diameter carbon fibers. This allowed the determination of the quasi-elastic background to the elastic scattering from the free hydrogen in the nylon. The measured background was less than 10% and had an analyzing power about 40% lower than that for elastic scattering. Using the analyzing power measurements from ref. [9] the effective analyzing power, and therefore, the absolute beam polarization, was determined with a systematic error of about 10%. For other beam energies, the analyzing power was scaled according to the measured values for elastic scattering in ref. [9].

The polarization measurement with the AGS polarimeter was accomplished by creating a flat top of 100 ms in the AGS cycle at the desired energy. The value of $G\gamma$ changed by less than 0.2 units over this time.

In the presence of a snake with strength s and for small imperfection resonance strength, the spin tune ν_s obeys the relation

$$\cos(\pi\nu_s) = \cos(\pi G\gamma) \cos\left(\frac{\pi s}{2}\right). \quad (4)$$

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 is shifted away from the integer value by $\pm \frac{s}{2}$. Thus, the partial snake creates a gap at all integers in the spin tune, and 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 gap created by the partial snake. The radial, vertical, and longitudinal components of stable spin direction under these conditions become

$$\begin{aligned} n_{\text{radial}} &= -\frac{1}{N} \sin((\pi - \theta) G\gamma) \sin\left(\frac{\pi s}{2}\right) \\ n_{\text{vertical}} &= \frac{1}{N} \sin(\pi G\gamma) \cos\left(\frac{\pi s}{2}\right) \\ n_{\text{long.}} &= \frac{1}{N} \cos((\pi - \theta) G\gamma) \sin\left(\frac{\pi s}{2}\right) \end{aligned}, \quad (5)$$

where θ is the beam deflection between the solenoid snake and the observation point, and $N = \sqrt{1 - \cos^2(\pi G\gamma) \cos^2\left(\frac{\pi s}{2}\right)}$. When passing through an imperfection resonance condition with a snake on, the stable spin direction moves slowly from up to down. For a 5% partial snake and the AGS acceleration rate $\alpha \approx 1.1 \times 10^{-5}$, the change in the stable spin direction is always adiabatic.

Figure 2 shows the measured polarization as a function of $G\gamma$ for a 10% snake. The polarization was observed to follow the predicted spin flip in passing through each imperfection resonance without loss of polarization. Without the snake, shown as open circles, there was some depolarization at $G\gamma = 8$. The increased depolarization when $G\gamma$ is slightly larger than an integer, particularly noticeable for $G\gamma = 8$, is due to the reduced acceleration rate just before the polarization measuring flat top.

Figure 3 shows the absolute value of the vertical polarization with a 5% snake measured at every half-integer value of $G\gamma$ between 6.5 and 22.5. As shown in Figure 2 the sign of the polarization is actually changing at every integer value of $G\gamma$. Without the partial

snake, the beam was completely depolarized after passing through the resonances at $G\gamma = 8, 9, 10$, and ν_y . Figure 3 also shows that the depolarization resulted only from the three intrinsic resonances, located at $G\gamma = \nu_y, 24 - \nu_y$, and $12 + \nu_y$, which the 5% partial snake can not overcome. The observed level of depolarization at the intrinsic resonances were -65%, 63%, and -49%, respectively. The partial spin flips at $G\gamma = \nu_y$ and $12 + \nu_y$ are in agreement with the prediction for a Gaussian beam with a 25π mm-mrad normalized emittance. Efforts to understand the unexpectedly high depolarization at $G\gamma = 24 - \nu_y$, which accidentally coincided with the AGS transition energy, are underway. Although it had been demonstrated earlier that the intrinsic resonances can successfully be overcome with the fast betatron tune jump [4], which was not available during this experiment, it seems feasible from these measurements that complete spin flip could be induced by slowing the acceleration rate or increasing the intrinsic resonance strength with coherent betatron oscillations [10]. Such schemes are made possible by the partial snake since it stabilizes the polarization against depolarization from nearby imperfection resonances.

The sizable linear betatron coupling introduced by the solenoid caused significant additional depolarization when $\nu_y \approx \nu_x$. Figure 4 shows the beam polarization measured at $G\gamma = 10.5$, after passing through the $G\gamma = \nu_y$ resonance, as a function of the vertical betatron tune ν_y for $\nu_x = 8.67, 8.75$, and 8.80 , respectively. The adiabatic 65% spin flip for the $G\gamma = \nu_y$ intrinsic resonance was diminished by the linear betatron coupling. We also observed less spin flip as ν_y approaches 8.5. We know of no depolarization mechanism that could account for this phenomenon. Further studies to understand in detail the depolarization mechanism are needed.

In conclusion, we have demonstrated for the first time that a 5% partial snake can effectively overcome 18 imperfection resonances without noticeable depolarization. The polarized beam in the AGS was accelerated to 10.8 GeV kinetic energy without using harmonic orbit correctors. This fact gives great optimism for the possibility of accelerating polarized proton beams to very high energies to study spin effects in polarized proton colliders. With the recent progress made in the polarized ion source performance and planned polarized beam accumulation using the AGS booster, luminosities with polarized protons equal to that of unpolarized protons should be achieved in RHIC.

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FIGURES

FIG. 1. The Brookhaven hadron facility complex, which includes the AGS booster, the AGS, and RHIC. The solenoidal partial snake is installed in a 3-meter straight section in the AGS. The RHIC spin project will install two snakes per ring with four spin rotators per detector for achieving helicity-spin experiments.

FIG. 2. The measured vertical polarization as a function of the spin tune $G\gamma$ for a 10% snake is shown with and without a snake. Note here that partial depolarization at $G\gamma = 8$ is avoided by using a 10% snake. The error bars only represent the statistical errors. The solid line is the result of eq. 5.

FIG. 3. The measured absolute value of the vertical polarization at $G\gamma = n + \frac{1}{2}$ up to $G\gamma = 22.5$ (solid points). Note here that partial depolarization is due to intrinsic spin resonances at $G\gamma = \nu_y$, $24 - \nu_y$, and $12 + \nu_y$. The open circles show the measured polarization without snake. The error bars only represent the statistical errors.

FIG. 4. Polarization measured at $G\gamma = 10.5$ as a function of the vertical betatron tune for 5% snake with nominal horizontal tune $\nu_x = 8.67, 8.75$, and 8.8 , respectively. Depolarization was observed at $\nu_y \approx \nu_x$ in all cases. The lines are drawn to guide the eye.

Fig. 1

Polarized Proton Collisions at BNL

Fig. 2

Fig. 3

Fig. 4