First Test of a Partial Siberian Snake During Polarized Beam Acceleration

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We recently studied the first acceleration of a spin-polarized beam through a depolarizing resonance using a partial Siberian snake. We accelerated polarized protons from 95 to 140 MeV while ramping a 10% partial Siberian snake along with the acceleration cycle. The 10% partial snake suppressed all observable depolarization due to the $G\gamma = 2$ imperfection depolarizing resonance which occurred near 108 MeV during acceleration. However, 20% and 30% partial Siberian snakes apparently moved the $G\gamma = 7 - \nu_y$ intrinsic depolarizing resonance from near 177 MeV into our energy range; this caused some interesting but not-yet-fully understood depolarization.

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Many spin-depolarizing resonances occur during the acceleration of a polarized proton beam in a high energy circular accelerator. The individual resonance correction technique used at the ZGS [1], Saturne [2], KEK [3], and the Brookhaven AGS [4] becomes impractical above about 20 GeV. Recent experiments at the Indiana University Cyclotron Facility (IUCF) Cooler Ring [5–8] suggested that a full Siberian snake [9] should simultaneously overcome all depolarizing resonances. A full Siberian snake forces all depolarizing effects to cancel themselves by rotating each proton's spin by 180° on each pass through the snake. A partial Siberian snake of strength s, which rotates each proton's spin by only $s \times 180°$, can still overcome many depolarizing effects. These spin rotations can be produced by using either a solenoid with a longitudinal magnetic field or several transverse dipole magnets, which distort the beam orbit only inside the snake itself. A full transverse Siberian snake is especially effective at high energies, while a longitudinal solenoid snake works best at low energies.

The orbit distortion problem [10], caused by a full transverse Siberian snake near injection, is especially serious in medium energy accelerators such as the Fermilab 8 GeV Booster [11], and the Brookhaven AGS [12]. In such accelerators, partial Siberian snakes might overcome the many imperfection depolarizing resonances, while modest pulsed quadrupoles could jump through the few weak intrinsic depolarizing resonances.

We studied a partial Siberian snake's ability to overcome depolarizing resonances during beam acceleration, by placing two rampable warm solenoid magnets symmetrically around our existing superconducting solenoid. This combination of three magnets allowed us to maintain a fixed partial Siberian snake strength of 10%, 20%, or 30% during acceleration; we could then study a partial snake's ability to overcome the $G\gamma = 2$ imperfection depolarizing resonance at 108 MeV during acceleration.

With no Siberian snake, each proton's spin precesses around the ring's vertical magnetic field; however, any horizontal magnetic fields can depolarize the beam. This depolarization occurs when the spin precession frequency, f_s, satisfies the depolarizing resonance condition

$$f_s = f_c \nu_s = f_c(n + m\nu_y), \tag{1}$$

where n and m are integers; f_c is the protons' circulation frequency; the vertical betatron tune, ν_y, is the number of vertical betatron oscillations during each turn around the ring; and the spin tune, ν_s, is the number of spin precessions during each turn around the ring. The imperfection resonances occur when $m = 0$, while the first-order intrinsic resonances occur when $m = \pm 1$.

During acceleration with no Siberian snake, the spin tune is proportional to the proton's energy

$$\nu_s = G\gamma, \tag{2}$$

where γ is the Lorentz energy factor and $G = 1.792\,847$ is the proton's anomalous magnetic moment. A recent experiment [7] confirmed that, in a ring containing a partial Siberian snake of strength s, the spin tune obeys the equation

$$\cos(\pi\nu_s) = \cos(\pi G\gamma)\cos\left(\frac{\pi s}{2}\right), \tag{3}$$

where $s = 1$ corresponds to a full snake, which rotates the spin by 180°. Note that for a full Siberian snake, the spin tune is equal to a half integer at all energies.

To create a Siberian snake of variable $\int B\,d\ell$, we recently built two rampable warm 0.2 T m solenoids of 1026 turns each. These warm solenoids then bracketed our 2 T m superconducting solenoid as shown in Fig. 1. The superconducting solenoid, the polarimeter, and the Cooler Ring's operation with polarized protons were discussed earlier [5–8,13–15]. The snake strength, s, for a solenoid magnet of NI ampere turns is given by

$$s = \frac{\mu_0(1 + G)}{10.479p} NI\,, \tag{4}$$

where $\mu_0 = 4\pi\ 10^{-7}\ \mathrm{T\,m\,A^{-1}}$ and p is the proton's momentum in GeV/c. At 8.4 A, the superconducting solenoid was about a 6.2% snake at 95 MeV, according to the earlier calibration [15].

The polarized proton beam was then injected into the Cooler Ring at 95 MeV, which is well below the $G\gamma = 2$ imperfection depolarizing resonance [5] near 108 MeV. The beam was then accelerated to 140 MeV, which is well above the $G\gamma = 2$ resonance, but still below 177 MeV, which is the normal energy of the $G\gamma = 7 - \nu_y$ intrinsic depolarizing resonance [6].

We first studied the depolarization during this acceleration from 95 to 140 MeV with the Siberian snake turned off. In a second study, the three solenoids were run together to maintain a 10% partial Siberian snake during the acceleration from 95 to 140 MeV. The superconducting solenoid current was held fixed at 8.4 A; thus during this acceleration it decreased from being about 6.2% snake at 95 MeV to about a 5% snake at 140 MeV. The two warm solenoid magnets were varied together from about 24 A to about 39 A each. This variation kept the total snake strength of the three solenoids fixed at about 10% during acceleration from 95 to 140 MeV. In each study we measured the beam polarization for different values of the imperfection $\int B\,d\ell$, which was produced by the correction solenoid magnets in the Ring's cooling section shown in Fig. 1.

The transverse beam polarization, $P_t = \sqrt{P_v^2 + P_r^2}$, after acceleration from 95 to 140 MeV, is plotted against the imperfection $\int B\,d\ell$ in Fig. 2 [16]. Note that the spin direction was flipped both with and without the partial Siberian snake. With a 0% snake, there is a significant decrease in P_t for nonzero $\int B\,d\ell$ due to the $G\gamma = 2$ imperfection depolarizing resonance. Since the beam accelerated through the resonance with $\langle d\gamma/dt\rangle = 0.061\ \mathrm{s^{-1}}$, this P_t curve is flatter than the 104 MeV fixed-energy data [5]; nevertheless, with no snake, the $G\gamma = 2$ resonance clearly depolarized the accelerated beam or rotated its spin into the unmeasurable longitudinal direction.

However, with a 10% partial Siberian snake, the beam polarization measured after acceleration to 140 MeV was almost independent of the imperfection $\int B\,d\ell$ within our precision of about 2%. Note that there may be a slight negative slope to the data; the dashed line is a constant polarization fit to these 10% snake data. These 0% and 10% data clearly demonstrate that a weak partial Siberian snake can overcome an imperfection depolarizing resonance during acceleration.

We also studied the effect of stronger partial Siberian snakes. In Fig. 3, the transverse beam polarization [16], $P_t = \sqrt{P_v^2 + P_r^2}$, after acceleration from 95 to 140 MeV is plotted against the imperfection $\int B\,d\ell$ for partial Siberian snakes of 0%, 10%, 20%, and 30%. Note the unexpected behavior in the 20% and 30% snake data; the polarization rapidly decreases at higher $\int B\,d\ell$; the change is especially sharp in the 20% data. This depolarization probably occurred because the stronger partial snakes moved the $G\gamma = 7 - \nu_y$ intrinsic depolarizing resonance into our energy region. The partial Siberian snake

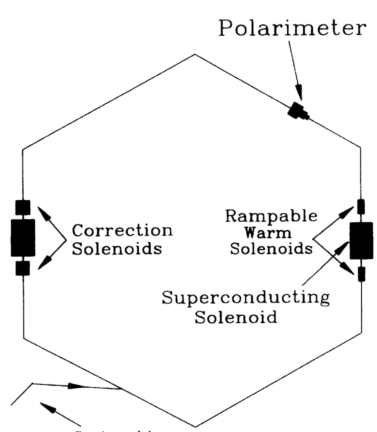

FIG. 1. Location of the two warm rampable solenoids, the superconducting solenoid, and other relevant hardware in the IUCF Cooler Ring.

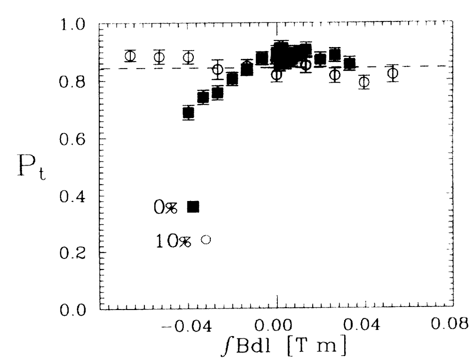

FIG. 2. The measured [16] transverse polarization, $P_t = \sqrt{P_v^2 + P_r^2}$, at 140 MeV is plotted against the imperfection $\int B\,d\ell$ with no snake and with 10% partial Siberian snake. The dashed line is the best constant polarization fit to the snake-on data. The beam was accelerated from 95 to 140 MeV.

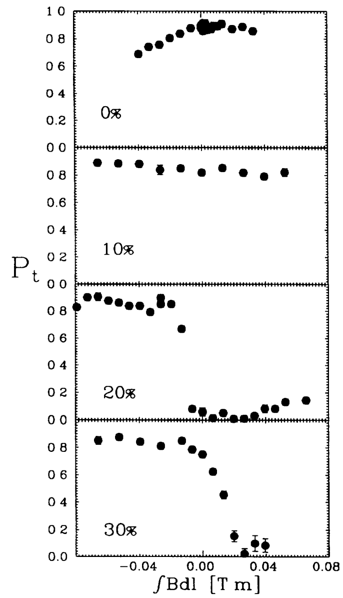

FIG. 3. The measured [16] transverse polarization, $P_t = \sqrt{P_v^2 + P_r^2}$, at 140 MeV is plotted against the imperfection $\int B\, d\ell$ for a partial Siberian snake of strength 0%, 10%, 20%, and 30%. The beam was accelerated from 95 to 140 MeV.

probably shifted the spin tune according to Eq. (3); this shift moved the intrinsic resonance energy. Moreover, the snake's strong solenoid focusing probably shifted the vertical betatron tune, ν_y, which also moved the intrinsic resonance energy. The Cooler Ring solenoids, which created the imperfection $\int B\, d\ell$, could also move the intrinsic resonance by shifting ν_s and ν_y [17]. All these shifts may have caused the unexpected polarization drop in the 20% and 30% data of Fig. 3; however, we do not yet have detailed explanation for this behavior. Note that the 20% data drops very sharply.

Thus, the $G\gamma = 7 - \nu_y$ intrinsic depolarizing resonance, which normally occurs near 177 MeV in the Cooler Ring, is apparently shifted by a 20% or 30% partial Siberian snake into our 95 to 140 MeV energy range. However, with a 10% partial snake, this intrinsic resonance apparently stays well outside the 95 to 140 MeV acceleration range; the 10% snake easily overcame the $G\gamma = 2$ imperfection resonance as shown in Fig. 2.

To summarize, the 10% snake data support the conjecture that a weak partial Siberian snake can maintain full beam polarization during acceleration through a weak imperfection depolarizing resonance. Therefore, partial Siberian snakes might allow the acceleration of a polarized proton beam at medium-energy accelerators such as the Fermilab 8 GeV Booster [11] or the Brookhaven AGS [12] by simultaneously using modest pulsed quadrupoles to jump quickly through the few weak intrinsic resonances. However, the apparently complex behavior of partial Siberian snakes, near intrinsic depolarizing resonances, highlights the need to further study their interaction.

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[16] In Figs. 2 and 3, there is a normalization uncertainty of about 15% which fortunately does not affect the shape of the curves. This first attempt to interpolate to 140 MeV data at nearby energies clearly gave too low an A in our polarimeter's angular range. Certainly the Cooler Ring polarization cannot be larger than the injected polarization which was about 75%.
[17] The vertical betatron tune ν_y, measured by the IUCF staff, was typically constant within ±0.01 during acceleration. Even this small $\Delta\nu_y = 0.01$ shifts the intrinsic resonance energy by about 5.2 MeV.