Spin Flipping a Stored Polarized Proton Beam

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We recently studied the spin flipping of a vertically polarized, stored 139-MeV proton beam. To flip the spin, we induced an rf depolarizing resonance by sweeping our rf solenoid magnet's frequency through the resonance frequency. With multiple spin flips, we found a polarization loss of 0.0000 ± 0.0005 per spin flip under the best conditions; this loss increased significantly for small changes in the conditions. Minimizing the depolarization during each spin flip is especially important because frequent spin flipping could significantly reduce the systematic errors in stored polarized-beam experiments.

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There is a growing interest in spin-polarized beam experiments in storage rings such as the Indiana University Cyclotron Facility (IUCF) Cooler Ring [1], Hadron Electron Ring Accelerator (HERA) [2], Relativistic Heavy Ion Collider (RHIC) [3], and the Tevatron [4]. These experiments require frequent reversals of the beam polarization direction to reduce systematic errors in the measured asymmetry. This growing interest has highlighted the need to minimize the depolarization during each spin reversal, since even a small polarization loss could cause significant depolarization during many reversals. Therefore, we recently studied ways to minimize the depolarization caused by spin flipping a stored polarized proton beam at the IUCF Cooler Ring.

In a circular accelerator ring with no Siberian snakes, each proton's spin precesses around the vertical magnetic field of the accelerator's dipole magnets; however, any horizontal magnetic fields can depolarize the beam. This depolarization occurs whenever the spin precession frequency f_s satisfies the resonance condition

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

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 $m = \pm 1$. With no Siberian snake, the spin tune is proportional to the protons' 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. From Eqs. (1) and (2), a depolarizing resonance occurs whenever

$$G\gamma = n + m\nu_y. \tag{3}$$

The spin direction can be flipped by slowly varying either $G\gamma$ or ν_y through some depolarizing resonance. At the Zero Gradient Synchrotron (ZGS) [5,6], Saturne [7,8], the National Laboratory for High Energy Physics (KEK) (Ibaraki, Japan) [9,10], and the Alternating Gradient Synchrotron (AGS) [11], the spin was flipped by increasing $G\gamma$ while accelerating through imperfection depolarizing resonances.

In a fixed energy storage ring, where $G\gamma$ is constant, one can instead flip the spin by installing rf solenoids or rf dipole magnets in the ring and then sweeping their frequency through an rf depolarizing resonance [12]. The resonance will occur when the rf magnet's frequency passes through the resonance frequency f_r, which satisfies the resonance equation

$$f_r = f_c(\pm G\gamma \pm n), \tag{4}$$

where n is an integer. Slowly sweeping the rf solenoid's frequency through f_r can flip the spin. The Froissart-Stora equation [13] gives the ratio of the vertical polarization P_v after the rf frequency sweep to the initial vertical polarization P_0,

$$P_v = P_0[2e^{\frac{-(\pi\delta)^2}{\Delta f/\Delta t}} - 1], \tag{5}$$

where δ is the resonance width in Hz, while Δf is the frequency range during the ramp time Δt. The exponent in Eq. (5) will be very large for either a slow frequency ramp rate $\Delta f/\Delta t$ or a large resonance width δ; then the spin will be completely flipped. Thus, the spin-flip efficiency should increase with increasing rf field strength and with decreasing frequency ramp rate.

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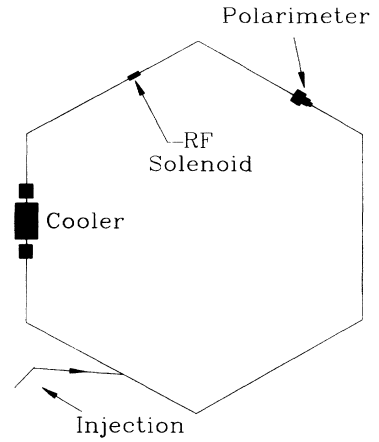

FIG. 1. Location of the rf solenoid and other relevant hardware in the IUCF Cooler Ring.

We recently tested this spin-flipping technique using our rf solenoid magnet at the IUCF Cooler Ring. The rf solenoid, the polarimeter, and the Cooler Ring's operation with polarized protons were discussed earlier [14–20]; the location of this rf solenoid is shown in Fig. 1 along with other relevant hardware.

We first studied the rf depolarizing resonance with a 139 MeV stored proton beam whose circulation frequency was $f_c = 1\,697\,300$ Hz; the injected vertical polarization was about 75%. The rf solenoid's amplitude was held fixed at about $\int B\,dl = 0.0014$ T m throughout the experiment. Using a previously described technique [17], we measured the resonance's frequency and width to be $f_r = 1\,800\,230 \pm 10$ Hz and $\delta = 227 \pm 9$ Hz HWHM.

We next studied the vertical polarization after the rf solenoid frequency was linearly varied from $f_r -$ 1.75 kHz to $f_r +$ 1.75 kHz with various ramp times Δt. This measured polarization is plotted against the rf frequency ramp time in Fig. 2. The curve is a fit by Eq. (5) using $\Delta f = 3.5$ kHz. The χ^2 is minimum for $\delta = 225 \pm 4$ Hz and $P_0 = 0.741 \pm 0.011$. Notice that this measured resonance width of 225 Hz is in good agreement with the 227 Hz obtained above. Moreover, note that complete spin flip occurs for ramp times of 20 msec or greater. These data clearly show that one can efficiently spin flip a stored vertically polarized proton beam by sweeping an rf solenoid's frequency through an rf resonance.

However, since the exponent in Eq. (5) is never infinite, some small polarization loss will always occur each time the spin is flipped. Even a small loss could cause significant depolarization in a storage ring when the spin is flipped many times. If p is the fractional polarization remaining after one spin flip, then the fractional polarization remaining after n spin flips is p^n.

To maximize p, we studied multiple spin flipping. We first measured the beam polarization after sweeping the rf solenoid frequency many times, back and forth, through f_r. We chose a 160 ms frequency ramp time with a 40 ms constant-frequency interval between each 3.5 kHz frequency ramp. The measured vertical polarization is plotted against the number of rf frequency ramps in Fig. 3. We also plotted the best fit to the curve

$$P_v = P_0 p^n. \tag{6}$$

Note that n was always an even number of flips. The best fit obtained by minimizing χ^2 gives $P_0 = 0.74 \pm 0.03$ and $p = 0.996 \pm 0.001$; therefore, with these conditions, we lost 0.004 ± 0.001 fractional polarization per spin flip.

We then tried to further minimize the polarization loss per spin flip by varying the rf frequency ramp time, while flipping the spin 50 times; this large number of spin flips greatly increased our sensitivity to small polarization losses. We used the same 3.5 kHz rf frequency range and 0.0014 T m rf magnetic field. The vertical polarization measured after 50 ramps is plotted against the rf ramp time Δt in Fig. 4. Notice that the polarization increased with increasing ramp time up to about 60 ms and then it slowly decreased. The spin flip efficiency peaks at some optimum ramp time that we do not yet fully understand; apparently the ramp time must be long enough for full spin flip, but not long enough for other depolarizing effects to occur [21].

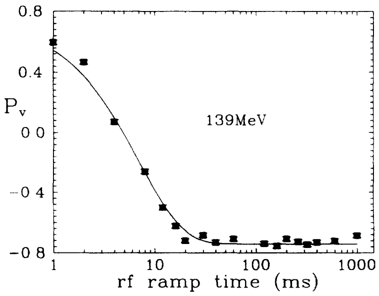

FIG. 2. The vertical polarization P_v after a single rf frequency ramp at 139 MeV is plotted against the rf ramp time; the frequency was varied through a 3.5 kHz range around the rf resonance. The curve is a fit by Eq. (5).

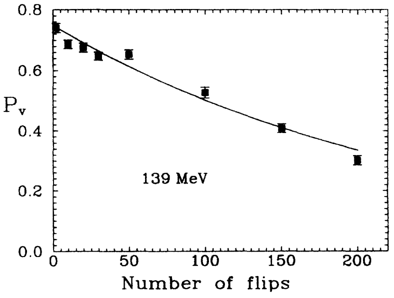

FIG. 3. The vertical polarization P_v at 139 MeV is plotted against the number n of rf frequency ramps through a 3.5 kHz range around the rf resonance. The ramp time was 160 msec. The curve is a fit by Eq. (6).

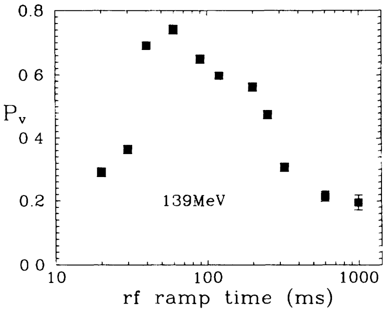

FIG. 4. The vertical polarization P_v at 139 MeV is plotted against the rf ramp time through a 3.5 kHz range around the rf resonance. The rf frequency was ramped 50 times.

The measured vertical polarization after 50 spin flips reached a peak value of $P_v = 0.742 \pm 0.014$ at 60 ms. To eliminate some relative systematic errors, we used for P_0 the polarization measured after one spin flip in Fig. 2, which was $P_0 = 0.741 \pm 0.011$. Therefore, the measured polarization ratio reached a peak value of $P_v/P_0 = 1.0013 \pm 0.0240$ for $n = 50$ spin flips. Thus, from Eq. (6), the fractional polarization remaining after one spin flip was $p = 1.0000 \pm 0.0005$; the corresponding fractional polarization loss per spin flip was 0.0000 ± 0.0005.

These data clearly demonstrate that, in the absence of Siberian snakes, one can spin flip a vertically polarized stored beam many times with very little loss in polarization. This frequent spin flipping should significantly reduce the systematic errors in scattering experiments using a stored polarized beam. We plan to further study spin flipping to better understand any possible remaining depolarization. This understanding may further reduce any depolarization and may help spin flipping to become a practical and simple tool for stored polarized beam experiments.

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[21] This small polarization loss might be caused by the beam's synchrotron oscillations; the 139 MeV beam had a 4.1 kHz energy oscillation. With a slow rf solenoid frequency ramp, the rf resonance frequency f_r may occur many times, since the energy oscillations make f_r oscillate. Similar synchrontron oscillations were studied by S. Hiramatsu *et al.*, in *Proceedings of the 8th International Symposium on High Energy Spin Physics* (Ref. [10]), p. 1436.