Spin flipping a stored polarized proton beam with an rf dipole

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We recently studied the spin flipping of a 202.7 MeV vertically polarized proton beam stored in the Indiana University Cyclotron Facility cooler ring during the first polarized run with its new cooler injector synchrotron and its new cooler injector polarized ion source. We first set the vertical betatron tune to avoid the measured ν_y value of the $G\gamma = 7 - \nu_y$ intrinsic depolarizing resonance in the cooler ring. We then flipped the spin by ramping the frequency of an rf dipole through an rf-induced depolarizing resonance. After optimizing the rf dipole's frequency ramp parameters, we used multiple spin flips to measure a maximum spin-flip efficiency of $97.5 \pm 1\%$.

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There is a growing interest in polarized beam experiments in storage rings such as the Indiana University Cyclotron Facility (IUCF) cooler ring [1], the MIT-Bates storage ring [2], the Brookhaven relativistic heavy ion collider (RHIC) [3], and HERA at DESY [4]. Frequent reversals of the beam polarization direction can significantly reduce the systematic errors in an experiment's spin asymmetry measurements. An rf solenoid was used earlier [5] to spin flip a vertically polarized proton beam stored in the cooler ring with no Siberian snake [6]. Since a solenoid's spin rotation decreases linearly with energy, a solenoid is impractical for spin flipping in high energy rings. However, a dipole's spin rotation is energy independent. Therefore, we recently used an rf dipole to spin flip a 202.7 MeV vertically polarized proton beam stored in the IUCF cooler ring with no Siberian snake.

In any flat circular accelerator or storage ring with no horizontal magnetic fields, each proton's spin precesses around the vertical fields of the ring's dipole magnets. The spin tune ν_s, which is the number of spin precessions during one turn around the ring, is proportional to the proton's energy

$$\nu_s = G\gamma, \tag{1}$$

where $G = (g - 2)/2 = 1.792\,847$ is the proton's gyromagnetic anomaly and γ is its Lorentz energy factor.

This vertical spin precession can be perturbed by the horizontal rf magnetic field from either an rf solenoid or an rf dipole. This perturbation can induce an rf depolarizing resonance, which can be used to flip the spin direction of the ring's stored polarized protons [5,7]. The frequency f_r, at which an rf-induced depolarizing resonance occurs, is given by

$$f_r = f_c(k \pm G\gamma), \tag{2}$$

where f_c is the proton's circulation frequency and k is an integer. Sweeping the rf magnet's frequency through f_r can flip the spin. The Froissart-Stora equation [8] relates the beam's polarization after crossing the resonance P_f to its initial polarization P_i,

$$P_f = P_i \left\{ 2\exp\left[\frac{-(\pi\varepsilon f_c)^2}{\Delta f / \Delta t} \right] - 1 \right\}, \tag{3}$$

where ε is the resonance strength and $\Delta f / \Delta t$ is the resonance crossing rate, while Δf is the frequency range during the ramp time Δt.

The apparatus used for this experiment, including the rf dipole [9], the IUCF cooler ring, and the polarimeter, were discussed earlier [5,10–22] and are shown in Fig. 1. The 202.7 MeV vertically polarized proton beam in the cooler ring was obtained using the new cooler injector polarized ion source (CIPIOS) [23] and the new cooler injection synchrotron (CIS) [24]. For this first polarized run with CIS and CIPIOS, the beam polarization was $75 \pm 2\%$ after the 7 MeV linac. However, the cooler ring's measured beam polarization was only about 20% because the $G\gamma = 2$ imperfection resonance in CIS was not yet corrected [25].

The spin tune ν_s in the cooler ring was almost [12] equal to $G\gamma$, which is 2.180 17 at 202.7 MeV; the beam circulation frequency f_c was 1.965 80 MHz. Thus, there should be an rf depolarizing resonance with its frequency near

$$f_r = f_c(3 - \nu_s) = 1.6080 \text{ MHz}. \tag{4}$$

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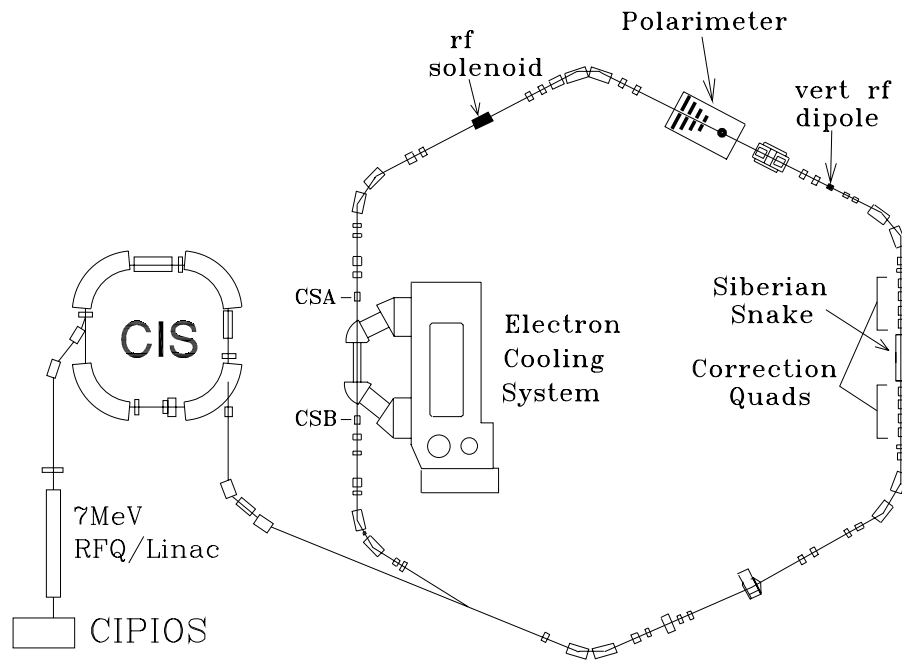[†]Also at: Portland Physics Institute, Portland, OR 97201.

FIG. 1.   Layout of the IUCF cooler ring with its new CIS and its new CIPIOS polarized ion source.   Also shown in the cooler ring are the rf dipole, the polarimeter, and the Siberian snake which was off.

We excited this rf depolarizing resonance by operating the rf solenoid or the rf dipole near 1.6080 MHz. An intrinsic depolarizing resonance can also occur if the vertical betatron tune ν_y is set near the resonance value

$$\nu_y = 7 - \nu_s = 4.818. \qquad (5)$$

We first varied the vertical betatron tune to determine the location of the $7 - \nu_y$ intrinsic depolarizing resonance. The measured vertical beam polarization is plotted against the betatron tune in Fig. 2. As expected [11], the depolarization dip was observed near $\nu_y = 4.817$.

For the rf-dipole-resonance spin-flipping studies, we set the vertical betatron tune at 4.791, which was well away from the intrinsic resonance. The rf dipole's input voltage was set at 47 V rms, corresponding to an $\int B\,dl$ amplitude of 0.06 T mm. The vertical polarization was then measured at different dipole frequencies; this measured vertical polarization is plotted against the rf dipole's frequency in Fig. 3. The curve is a second-order Lorentzian fit to the data with a resonance frequency f_r of $1\,607\,600 \pm 55$ Hz and a width w of 1630 ± 100 Hz.

To study spin flipping, we crossed this rf-induced resonance by linearly ramping the rf dipole's frequency, through the measured f_r, from $f_r - 2$ to $f_r + 2$ kHz, with various ramp times Δt, while measuring the beam polarization after each frequency ramp. The measured vertical polarization is plotted against the ramp time in Fig. 4. Note that, after a very rapid increase, the polarization's magnitude seems to decrease slightly for ramp times above 100 msec. By comparing the measured polarization of $17.9 \pm 1.2\%$ at $\Delta t = 0$ with the value of $16.4 \pm 1.0\%$, which is the average of the three data

points in the Δt range of 100 to 150 msec, we obtained a $92 \pm 8\%$ spin-flip efficiency.

To further optimize the spin-flipping efficiency, we next varied the rf dipole's frequency range Δf with its ramp time Δt set at 80 msec, its amplitude set at 0.06 T mm, and its range centered around 1607.7 kHz. The data indicated that the spin-flip efficiency had a maximum near $\Delta f = 6$ kHz.

After setting Δt and Δf to optimize the spin-flip efficiency, we more precisely determined this efficiency by
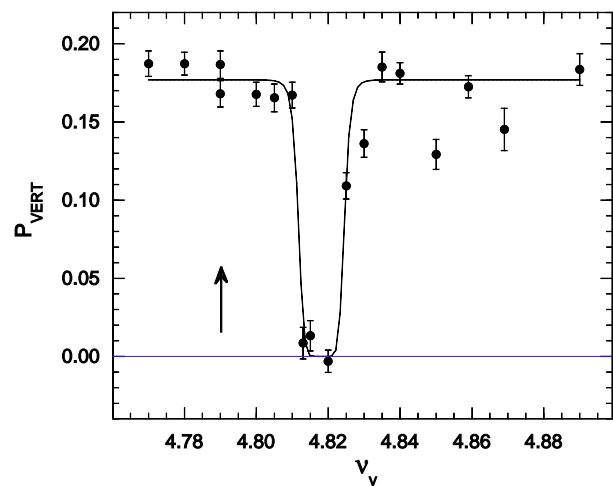

FIG. 2. (Color) The measured vertical proton polarization at 202.7 MeV is plotted against the vertical betatron tune. The curve is hand drawn to guide the eye. For the later studies, we set ν_y at the arrow value of 4.791, which is well away from the $\nu_s = 7 - \nu_y$ resonance value.
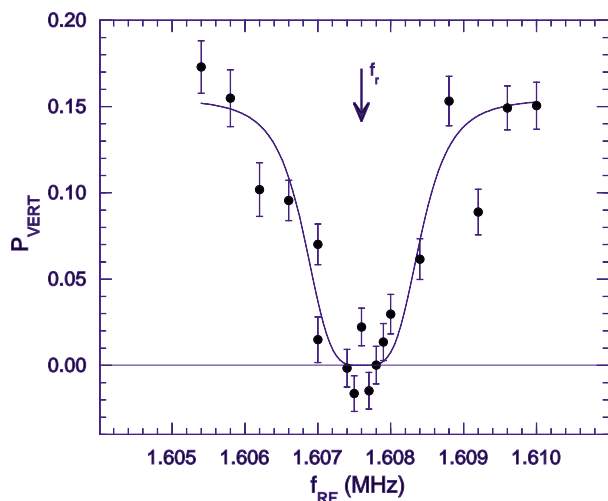
FIG. 3. (Color) The measured vertical proton polarization at 202.7 MeV is plotted against the rf dipole's frequency. The rf dipole's $\int B\,dl$ was 0.06 T mm. The curve is a fit using a second-order Lorentzian.

measuring the vertical polarization after many spin flips. We varied the number of spin flips while keeping, for each spin flip, the ramp time, the frequency range, and the rf voltage all fixed. The vertical polarization is plotted against the number of spin flips in Fig. 5. We fit this data using

$$P = P_0 \epsilon^n, \tag{6}$$

where P_0 is the initial polarization, ϵ is the spin-flip efficiency, and n is the number of spin flips. The best fit to the optimized spin-flip efficiency is $97.5 \pm 1\%$.

In summary, we used an rf dipole to spin flip a stored 202.7 MeV vertically polarized proton beam with no Siberian snake in the IUCF cooler ring. We reached
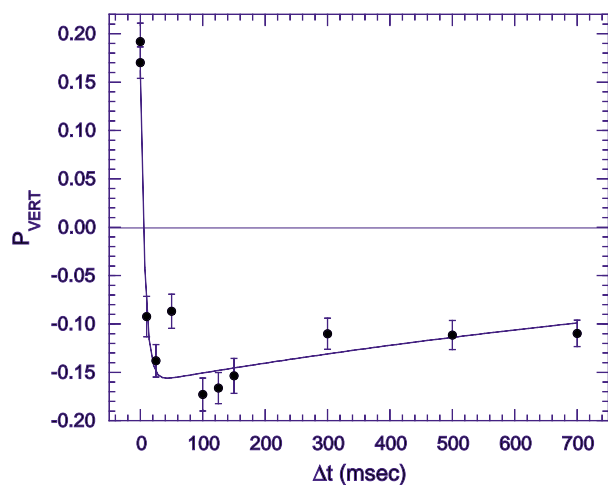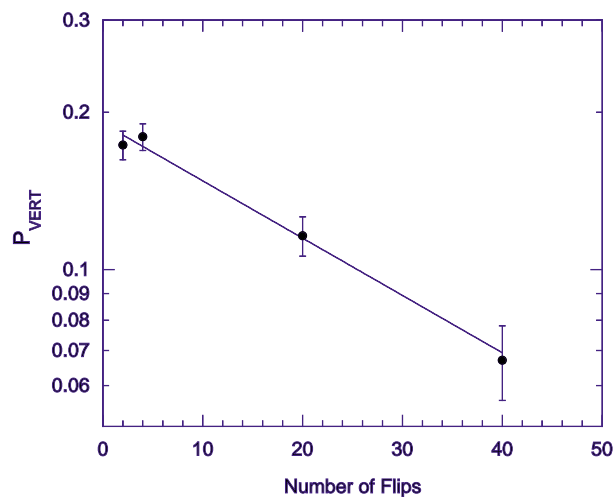
FIG. 5. (Color) The measured vertical proton polarization at 202.7 MeV is plotted against the number of spin flips. The rf dipole's ramp time Δt was 80 msec, its frequency range Δf was 6 kHz, and its $\int B\,dl$ was 0.06 T mm. The curve is a fit to the data using Eq. (6).

a measured spin-flip efficiency of $97.5 \pm 1\%$; it may have been reduced by possible nearby weak higher-order resonances [20]. Our future plans include increasing the spin-flip efficiency with both an rf dipole and an rf solenoid, both with and without a Siberian snake in the ring, developing a spin-flipping technique for an exactly 100% Siberian snake, and further studying higher-order snake resonances.

FIG. 4. (Color) The measured vertical proton polarization at 202.7 MeV is plotted against the rf dipole ramp time Δt. The frequency range Δf was 4 kHz and the rf dipole's $\int B\,dl$ was 0.06 T mm. The curve is hand drawn to guide the eye.

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