Spin flipping a stored vertically polarized proton beam with an RF solenoid

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Abstract. A recent experiment in the IUCF cooler ring studied the spin flip of a stored vertically polarized 139 MeV proton beam. This spin flip was accomplished by using an RF solenoid to induce an artificial depolarizing resonance in the ring, and then varying the solenoid's frequency through this resonance value to induce spin flip. We found a polarization loss after multiple spin flips of about 0.00 ± 0.05% per flip and also losses for very long flip times. This device will be useful for reducing systematic errors in polarized beam-internal target scattering asymmetry experiments by enabling experimenters to perform frequent beam polarization reversals in the course of the experiment.

Interest is growing in polarized beam experiments in storage rings such as IUCF (1), RHIC (2), and the Tevatron (3). Any scattering asymmetry experiment which uses a polarized beam must perform frequent polarization reversals of the beam to reduce systematic errors in the measured asymmetry due to efficiency and acceptance mismatch of the detectors. In a storage ring one confronts the problem of how to reverse the polarization of a beam stored for long periods of time with a minimum of polarization loss from each reversal. In a circular accelerator ring with no Siberian Snakes, each proton's spin precesses around the vertical field of the accelerator's dipole magnets; however, any horizontal magnetic fields can depolarize the beam. This depolarization occurs when the spin precession frequency, f_s, satisfies the resonance condition

$$f_s \equiv f_c\nu_s = f_c(n + m\nu_y), \qquad (1)$$

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 = ±1.

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 $G = 1.792847$ is the proton's anomalous magnetic moment. Combining equations 1 and 2, one arrives at the resonance condition

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

Spin flip can be achieved by slowly varying one side of equation 3 so that the resonance condition is passed through at a slow enough rate with a strong enough non-vertical magnetic field. This has been accomplished in accelerators by passing through a strong imperfection depolarizing resonance (4–9). The resonance condition given in equation 3 is then passed through as $G\gamma$ is slowly increased. In a storage ring where the energy, and hence $G\gamma$, is constant, an alternative is to vary the rate at which the protons experience non-vertical fields by introducing an RF magnet with a non-vertical field, the resonance condition is then

$$G\gamma = n \pm f_{rf}/f_c, \tag{4}$$

where f_{rf} is the applied frequency, which is slowly varied through this resonance condition to flip the spin.

We installed an RF solenoid at the IUCF cooler ring to test this spin flipping technique. The RF solenoid, polarimeter and the Cooler Ring's operation with polarized protons were discussed earlier (10–14). Before spin flipping could be accomplished, we first found the depolarizing resonance frequency of the 139 MeV vertically polarized proton beam. This procedure is outlined in a previous paper (12). The resonance frequency was $f_{rf} = 1,800230 \pm 10$Hz with a half width half max resonance width δ of 227 ± 9Hz. The RF solenoid field amplitude was 0.0014 T·m and the beam kinetic energy was fixed at 139 MeV for all results reported here.

According to theory (15), if the applied frequency starts out very far to one side of the resonance frequency, and is changed linearly in time to go through the resonance very far to the other side, the beam polarization should be reversed with an efficiency which increases as the RF field strength is increased, or the rate of change of frequency is decreased. We tested this by injecting vertically polarized protons into the cooler ring, then turned on the RF magnetic field 1.75 kHz below the resonance frequency, and linearly ramped the frequency to 1.75 kHz above the resonance frequency. In each run, only the RF ramp time was changed. The ramp time was varied from 1 msec to 1 sec. Polarization was measured after the end of the frequency ramp. A plot of the vertical polarization after spin flip vs. ramp time is given in Fig. 1. It is seen that complete spin flip occurs for ramp times of 20 msec or greater. It should be noted that the injected beam polarization was about 75%. This data shows that spin flip of a stored vertically polarized beam is possible using this RF ramp technique.

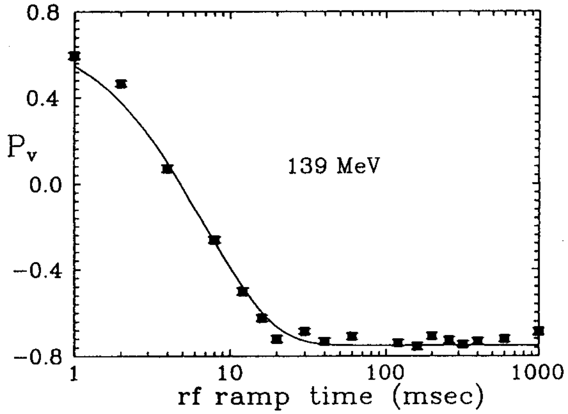

FIGURE 1. The vertical polarization P_v plotted against the time taken for the RF ramp through a 3.5 kHz range around the resonance for a single ramp.

The curve in Fig. 1 is a χ^2 fit of the Froissart-Stora formula (15), modified for the case when the energy is fixed and the resonance frequency is ramped. This formula for the vertical polarization P_v after the ramp in terms of the initial vertical polarization P_o, the resonance half width half max. δ, the frequency ramp interval Δf of 3.5 kHz and variable ramp time Δt is

$$P_v = P_o\Big\{2\exp[-(\pi\delta)^2\Delta t/\Delta f] - 1\Big\}. \tag{5}$$

Note from equation 5 that for a slow enough ramp rate $\Delta f/\Delta t$ or large enough resonance width, $P_v/P_o \rightarrow -1$, so the spin will be completely flipped. The fit parameters were $P_o = 0.741 \pm 0.011$ and $\delta = 225 \pm 4$Hz. Note that this width δ is in good agreement with the 227 Hz width obtained earlier when the depolarizing resonance frequency was found.

One expects a small loss of polarization each time the spin is flipped. In a storage ring where the spin will be flipped many times, these losses would compound from flip to flip. That is, if p is the fraction of polarization left after one flip, after n flips one would expect a polarization proportional to p^n. Note that flipping the spin many times before polarization measurement will allow for increased precision on the determination of p. We measured p for a specific ramp rate and strength. We ramped the RF many times up and down through the resonance at a fixed ramp time of 160 msec and the same 3.5 kHz frequency ramp as in the single flip case before measuring the beam polarization. Between each ramp there was a 40 msec period where the RF was fixed off resonance. A plot of the vertical polarization vs number of ramps is shown in Fig. 2, where the maximum number of flips was 200. The curve is a 2 parameter χ^2 fit of the form $P_v = P_o p^n$, where n is the number of flips, $P_o = 0.74 \pm 0.03$ is the injected polarization and the fractional surviving polarization per ramp $p = 0.996 \pm 0.001$. We therefore lost about 0.4% polarization per flip with this ramp time, resonance strength and frequency range.

Finally, we measured the polarization loss per flip as a function of the RF

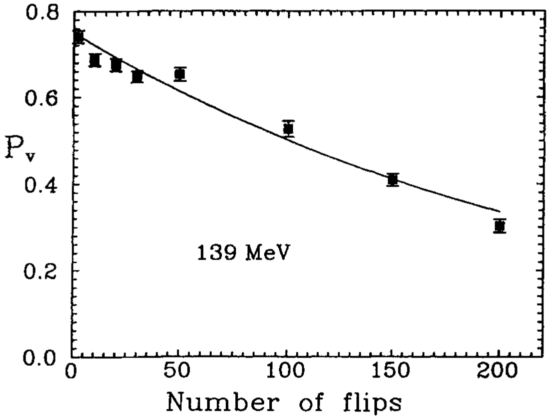

FIGURE 2. The vertical polarization P_v plotted against the number of times the RF ramped through a 3.5 kHz range around the resonance. The curve is a fit of the form $P_v = P_o p^n$ where n is the number of ramps.

ramp time by fixing the number of flips to be 50 and varying the ramp time. We again measured the polarization after the 50 flips were completed, and with the same 3.5 kHz ramp range, varied the ramp time up to 1000 msec per ramp. A plot of the vertical polarization vs the ramp time for one of the 50 ramps is shown in Fig. 3. The polarization increased as the ramp time increased for times up to 60 msec, and then started a slow decline with increasing ramp time. Analysis gives a value for p, the fraction of polarization surviving each flip, of 1.0000 ± 0.0005 for the 60 msec ramp rate. Hence to within our experimental uncertainty, no polarization was lost over 50 flips for this ramp rate. The loss for longer ramp times might be due to the synchrotron motion of the beam. The 139 MeV beam energy had a 4.1 kHz modulation. When one ramps the RF very slowly, the resonance is actually passed through many times since $G\gamma$, hence the RF resonance frequency, also has some modulation. This phenomenon has been studies for the case of passage through a depolarizing resonance by acceleration (16). The data indicates that there is an optimum ramp rate for spin flip, which is long enough to achieve full spin flip, but not so long that other depolarizing effects can occur.

This experimental data shows that spin flipping a vertically polarized beam can be accomplished with very little loss in polarization, making it a useful technique in machines where polarized beam is stored for long periods of time. It also shows that in the case of spin flipping a vertically polarized beam when no snakes are present, there is an optimum rate at which to vary the applied RF for the most efficient spin flip. This spin flip procedure will be essential to reduce the systematic errors in stored polarized proton beam scattering asymmetry experiments.

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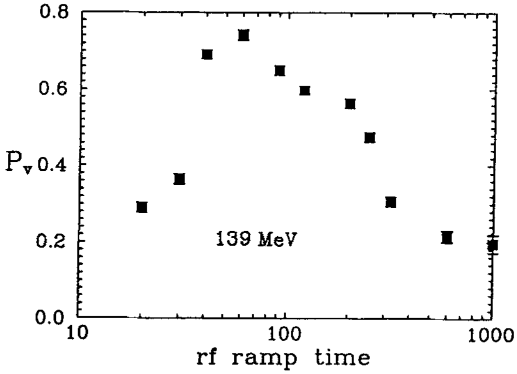

FIGURE 3. The vertical polarization P_v plotted against the RF ramp time through a 3.5 kHz range around the RF resonance for one of the 50 ramps performed.

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