Spin-flipping with an rf-dipole and a full Siberian snake[*]

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Abstract.
We recently used a vertical-field rf-dipole magnet to study the spin-flipping of a 120 MeV horizontally polarized proton beam stored in the presence of a nearly-full Siberian snake in the IUCF Cooler Ring. The spin was flipped by ramping the rf-dipole's frequency through an rf-induced depolarizing resonance. After optimizing the frequency ramp parameters, we used multiple spin-flips to measure a maximum spin-flip efficiency of 86.5±0.5% in April 2000, and 92.5±0.5% in June 2000. The spin-flip efficiency was apparently limited by the maximum achievable current in the rf-dipole. This result indicates that spin-flipping a stored polarized proton beam should be possible in high energy rings such as RHIC (and perhaps HERA in the future), where Siberian snakes are utilized and the dipole rf-flipper-magnets should be quite practical. During the June 2000 run, a new *faster* technique of locating the rf depolarizing resonance frequency was developed.

INTRODUCTION

Siberian snake experiments in the IUCF Cooler Ring have been instrumental in understanding the spin dynamics of a polarized proton beam in a storage ring. In this past year, we studied spin-flipping of a polarized proton beam at the Cooler Ring. Frequent reversals of the beam polarization direction should help to significantly reduce systematic errors in a scattering experiment's spin asymmetry measurements. We previously used an rf solenoid to spin-flip, with $97 \pm 1\%$ efficiency, a horizontally polarized proton beam stored in the Cooler Ring containing a Siberian snake. [1] However, a solenoid's spin rotation decreases linearly with energy because of the Lorentz contraction of its $\int B \cdot dl$; thus, a solenoid would be impractical for spin-flipping in high energy rings. On the other hand, a transverse rf dipole's spin rotation remains constant, independent of energy and thus should be more practical at high energies. As a first step, we earlier succeeded in spin-flipping efficiently with an rf-dipole in the absence of a Siberian snake. [2]

In a storage ring, each proton's spin precesses around the Stable Spin Direction (**SSD**) with a frequency of:

$$f_s = f_c \, \nu_s \; ; \tag{1}$$

where f_c is the circulation frequency, and ν_s is the **spin tune**, which is the number of spin precessions during one turn around the ring. With a Siberian snake in the ring, the spin tune is:

$$\nu_s = \frac{1}{\pi} cos^{-1} \left(cos(\pi G \gamma) cos(\pi s) \right) ; \tag{2}$$

where $G = (g - 2)/2 = 1.792847$ is the proton's anomalous magnetic moment, γ is its Lorentz energy factor, and s is the **snake strength**. For a full (100%) snake, $s = 1$, and then $\nu_s = \frac{1}{2}$, independent of energy.

Spin-flipping with a full Siberian snake

One can spin-flip a horizontally polarized proton beam in a ring with a Siberian snake using a depolarizing resonance induced by a vertical-field rf-dipole; similarly, a horizontal-field rf-dipole can spin-flip a vertically polarized beam. A resonance occurs when the rf magnetic field's frequency is synchronized with the spin tune and the circulation frequency according to:

$$f_r = f_c(k \pm \nu_s); \tag{3}$$

where k is an integer. This resonance condition allows *coherent* kicks to build up and rotate the spin about the vertical axis by 180° causing a **spin-flip**.

Spin-flipping parameters

The rf resonance strength ϵ is given by:

$$\epsilon = \frac{\theta_s}{\pi} = \frac{Ge \int B \cdot dl}{2\pi m_p v} \quad \text{for an rf dipole,} \tag{4}$$

where θ_s is the rf-dipole's spin rotation angle, m_p is the proton's mass and v is the proton's velocity. By varying the rf dipole frequency from below to above the resonance frequency f_r, one can *cross* the depolarizing resonance. After this crossing, the final beam polarization, P_f, is related to the initial beam polarization, P_i, by the **Froissart-Stora** form:

$$P_f = P_i \left\{ 2 \, exp \left[\frac{-(\pi \epsilon f_c)^2}{\Delta f / \Delta t} \right] - 1 \right\}, \tag{5}$$

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

Three distinct conditions for the frequency variation rate $\Delta f / \Delta t$ are:

Rate	Polarizations	Effect
Fast crossing:	$P_f \approx P_i$	Little or no depolarization
Medium crossing:	$P_i > P_f > -P_i$	Depolarization
Slow crossing (adiabatic):	$P_f \approx -P_i$	Spin-flip

The **spin-flip efficiency** is defined as:

$$\eta = \frac{-P_f}{P_i}. \tag{6}$$

To maximize the spin-flip efficiency, one must carefully choose $\epsilon, \Delta f$, and Δt.

For a description of the apparatus used in this experiment, including the rf-dipole, the IUCF Cooler Ring, the Siberian snake, and the polarimeter, the reader is referred to Ref. [3]. The 120 MeV horizontally polarized proton beam in the Cooler Ring was obtained using the new Cooler Injector Polarized Ion Source (CIPIOS) and the new Cooler Injection Synchrotron. The beam polarization was about $(50\text{-}60) \pm 2\%$ after the 7 MeV Linac. At 120 MeV, the circulation frequency in the Cooler Ring was $f_c = 1.59784$ MHz.

With a nearly-full Siberian snake in the Ring, from Eq. (2), the spin tune ν_s is very near but not exactly equal to $\frac{1}{2}$. Therefore, Eq. (3) implies that two closely spaced rf depolarizing resonances, f_r^- and f_r^+, exist:

	April 2000 run	June 2000 run
Center of 2 resonances	$1.5 f_c = 2.39676$ MHz	$0.5 f_c = 0.79892$ MHz
f_r^-	$f_c(2 - \nu_s)$	$f_c(1 - \nu_s)$
f_r^+	$f_c(1 + \nu_s)$	$f_c(0 + \nu_s)$

With a snake strength s of 1.01, ν_s was about 0.505; thus, the f_r^- resonance was:
slightly below $1.5 f_c$ for k = 2 for April 2000 run; and
slightly below $0.5 f_c$ for k = 1 for June 2000 run.

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In the April 2000 run, the f_r^- resonance was first located using the much stronger rf solenoid. Once found, this resonance was mapped out by the radial polarization response to varying the rf dipole's frequency, as shown in Fig 1.
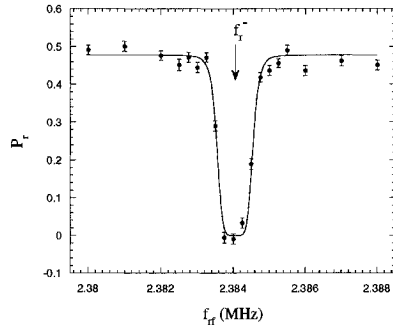

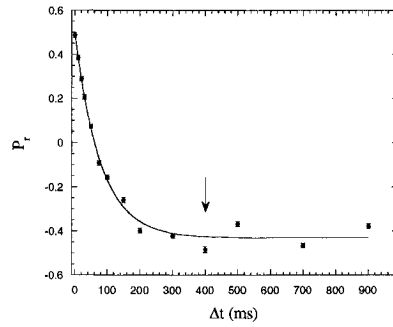**Fig. 1.** The measured radial proton polarization plotted against the rf-dipole's frequency; arrow shows f_r^-. [3]

Fig. 2 Radial polarization plotted against the ramp time for a fixed frequency range of $\Delta f = 10$ kHz. [3]

The parameter Δt was then optimized as shown in Fig. 2; it indicated that *spin flips with* **slow** *rf ramp times.*

In addition, remnant polarization of the beam was measured after various number of flips. From these graphs, a maximum spin-flip efficiency of 86.5 ±0.5 % was obtained.
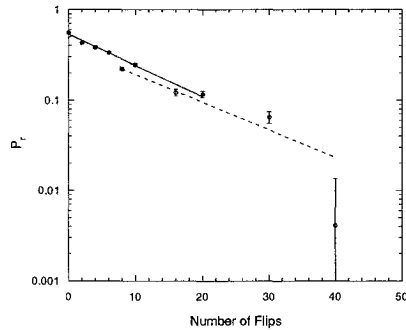
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Fig. 3 Radial proton polarization plotted against number of spin-flips. The two fitted lines gave a spin-flip efficiency η of about 92.5 ± 0.5%.
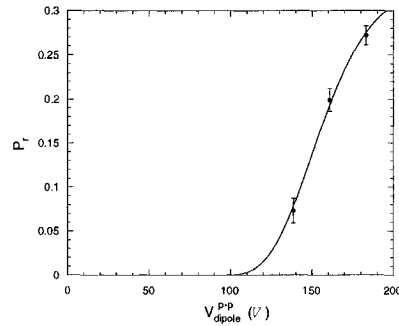
Fig. 4 Maximum radial polarization after ten spin-flips plotted against the peak-to-peak dipole voltage.

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In June 2000, CE-69 enhanced the rf dipole strength by sweeping through a lower resonant frequency of $f_r^- = f_c(1 - \nu_s)$. The data for multiple spin-flips is shown in Fig. 3; the two curves were fitted to $P_n = P_i \cdot \eta^n$, where η is the efficiency and n denotes the number of flips. The maximum spin-flip efficiency was found to be increased to $92.5 \pm 0.5\%$.

Fig. 4 shows how the maximum spin-flip efficiency grows with the rf dipole's strength; a higher spin-flip efficiency should be possible with a higher strength.

During the June run, a new method was developed to locate the rf depolarizing resonance as outlined below:

- first make a large frequency sweep range, containing the spin-flip;

- then divide the frequency sweep range into two equal sweeps;

- continue subdividing the range, always keeping the ones containing the spin-flip.

This method was much more efficient and has the advantage of observing the actual spin-flips, instead of a depolarizing dip.
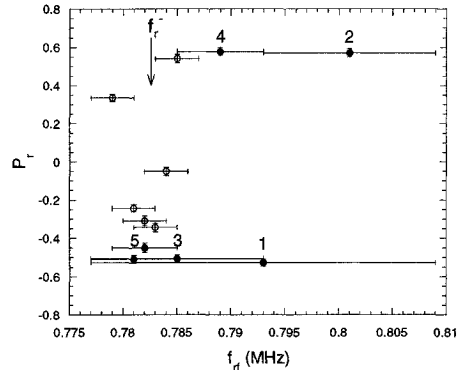
Fig. 5 Radial proton polarization plotted against the rf-dipole's central frequency, with widths indicating the frequency range; arrow shows f_r^-.

Such a process is shown graphically in Fig. 5 by points 1 to 5, which were done sequentially. Notice also that, once roughly located, the resonance was mapped out by (small) equal frequency ranges of ± 2 kHz around the resonance. The arrow indicates the resonance frequency f_r^- thus obtained; the same value was later obtained by mapping the polarization at many fixed frequency points around the resonance.

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3. Spin-flipping with an rf-dipole and a full Siberian snake, B.B. Blinov et al., Phys. Rev. ST–AB **3**, 104001 (2000).