99.6% Spin-Flip Efficiency in the Presence of a Strong Siberian Snake

B. B. Blinov, Z. B. Etienne,* A. D. Krisch, M. A. Leonova,† W. Lorenzon, V. S. Morozov,
C. C. Peters, V. K. Wong, and K. Yonehara
Spin Physics Center, University of Michigan, Ann Arbor, Michigan 48109-1120

V. A. Anferov, P. Schwandt, E. J. Stephenson, and B. von Przewoski
Indiana University Cyclotron Facility, Bloomington, Indiana 47408-0768

H. Sato
KEK, High Energy Accelerator Research Organization,
Tsukuba, Ibaraki 305-0801, Japan
(Received 3 August 2001; published 17 December 2001)

We recently studied the spin-flipping efficiency of an rf-dipole magnet using a 120-MeV horizontally polarized proton beam stored in the Indiana University Cyclotron Facility Cooler Ring, which contained a nearly full Siberian snake. We flipped the spin by ramping the rf dipole's frequency through an rf-induced depolarizing resonance. By adiabatically turning on the rf dipole, we minimized the beam loss. After optimizing the frequency ramp parameters, we used 100 multiple spin flips to measure a spin-flip efficiency of 99.63 ± 0.05%. This result indicates that spin flipping should be possible in very-high-energy polarized storage rings, where Siberian snakes are certainly needed and only dipole rf-flipper magnets are practical.

DOI: 10.1103/PhysRevLett.88.014801 PACS numbers: 29.27.Bd, 29.27.Hj, 41.75.Ak

Polarized beam experiments are now an important part of the programs 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 the DESY ep collider HERA [4,5]. Frequent reversals of the beam polarization direction can significantly reduce the systematic errors in spin asymmetry measurements. An rf solenoid was used earlier to spin flip a horizontally polarized proton beam stored in the Cooler Ring containing a Siberian snake [6] with 97 ± 1% spin-flip efficiency [7,8]. However, the spin rotation due to a solenoid's magnetic field integral decreases linearly with energy because of the Lorentz contraction of its $\int B\,dl$; thus, a solenoid is impractical for spin flipping in high-energy rings. Fortunately, the spin rotation due to a dipole's magnetic field integral is energy independent. Therefore, we recently studied an rf dipole's ability to spin flip a 120-MeV horizontally polarized proton beam stored in the IUCF Cooler Ring operating with a nearly full Siberian snake.

In any flat circular accelerator or storage ring with no horizontal magnetic fields, each proton's spin polarization is vertical as it 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 polarization 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 [7–14]. The frequency f_r, at which an rf-induced depolarizing resonance occurs, is given by

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

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 beam's spin direction. The Froissart-Stora equation [15] relates the beam's polarization after crossing the resonance P_f to its initial polarization P_i,

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

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 apparatuses used for this experiment, including the rf dipole, the IUCF Cooler Ring, and the polarimeter were discussed earlier [7–13,16–27] and are shown in Fig. 1. An rf dipole was also used to manipulate the spin at the Brookhaven Alternating Gradient Synchrotron [28]. The 120-MeV horizontally polarized proton beam in the Cooler Ring was obtained using IUCF's Cooler Injector Polarized IOn Source (CIPIOS) [29] and Cooler Injection Synchrotron (CIS) [30]. The beam polarization was typically 77% after the 7-MeV Linac and was practically the same at injection into the Cooler Ring.

At 120 MeV, the circulation frequency in the Cooler Ring was $f_c = 1.597\,84$ MHz. With a nearly full Siberian snake in the Ring, the spin tune ν_s is very near but not

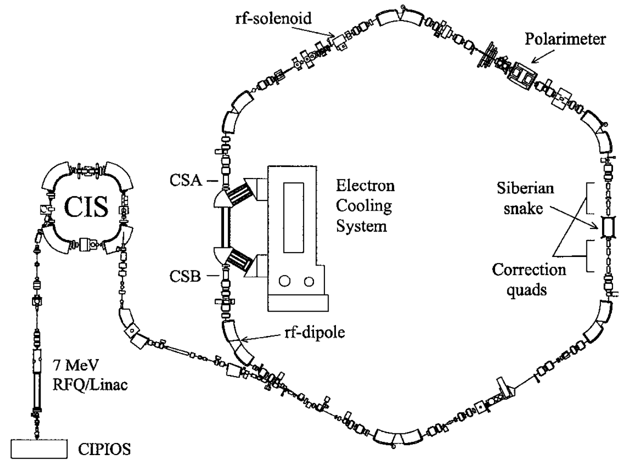

FIG. 1. Layout of the IUCF Cooler Ring with its new Cooler Injector Synchrotron (CIS) and its new CIPIOS polarized ion source. Also shown in the Cooler Ring are the rf dipole, the rf solenoid, the polarimeter, and the Siberian snake.

exactly equal to $\frac{1}{2}$. Therefore, at 120 MeV, Eq. (2) implies that there should be two closely spaced rf depolarizing resonances centered around

$$0.5 f_c = 0.798\,92 \text{ MHz}, \tag{4}$$

with their frequencies at

$$\begin{aligned} f_r^- &= f_c(1 - \nu_s), \\ f_r^+ &= f_c(0 + \nu_s). \end{aligned} \tag{5}$$

Our snake's strength was about 1.02, which means that it rotated the spin by 102% of 180^0; therefore the spin tune ν_s was about 0.510; thus, the f_r^- resonance should have a frequency slightly below $0.5 f_c$.

We first determined that the f_r^- resonance's frequency was near 0.777 MHz by using our new resonance search technique [13]:

(i) We first measured the beam polarization after sweeping the rf dipole through some frequency range Δf, which might flip the spin.

(ii) Then we cut the previous Δf range into two equal halves and measured the polarization after sweeping the frequency through each half.

(iii) Then we chose the Δf range which caused spin flip and repeated the process.

Figure 2 shows the measured radial polarization plotted against each sweep's central frequency; the horizontal bars show the frequency range Δf for each sweep.

We then more precisely determined f_r^- by measuring the radial polarization at different fixed rf-dipole frequencies; this measured radial polarization is plotted against the rf dipole's frequency in Fig. 3a. The curve is a second-order Lorentzian fit to the data with a central frequency of $f_r^- = 777\,580 \pm 14$ Hz and a width w of 775 ± 21 Hz. Figure 3b shows the similar but much more precise data for the f_r^+ resonance. The f_r^+ resonance's central frequency is $802\,840 \pm 6$ Hz while its width is 867 ± 13 Hz. Also

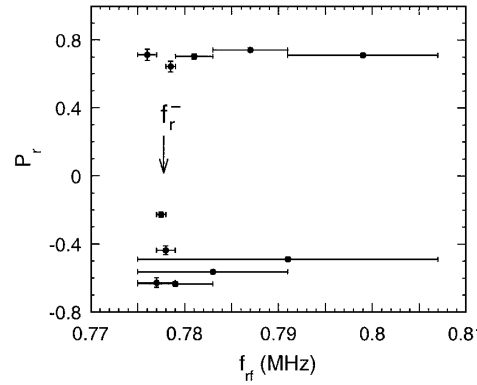

FIG. 2. The measured radial proton polarization at 120 MeV is plotted against the range of each frequency ramp; each frequency ramp's Δf range is shown by a horizontal bar. The rf dipole's $\int B\,dl$ was 0.10 T mm rms; its Δt was 1 s. The arrow shows f_r^-.

notice the very interesting behavior of its vertical polarization data; the reason for its very clear and sharply asymmetric behavior, as it crosses zero, needs some theoretical explanation.

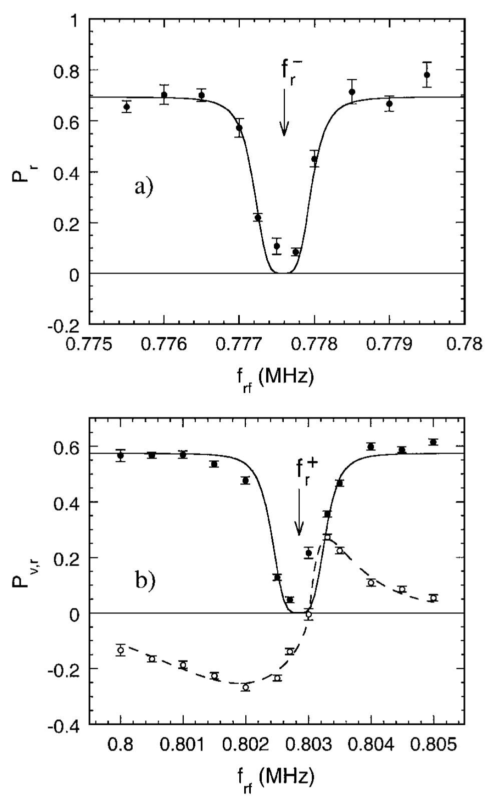

FIG. 3. The measured radial (and vertical) proton polarizations at 120 MeV are plotted against the rf-dipole's fixed frequency for the f_r^- (a) and f_r^+ (b) resonances. The rf dipole's $\int B\,dl$ was 0.10 T mm rms. The solid curves are fits using a second-order Lorentzian. The dashed curve in (b) is a hand-drawn curve to demonstrate the interesting behavior of the vertical polarization when the rf voltage is turned on adiabatically. The arrows show f_r^- and f_r^+.

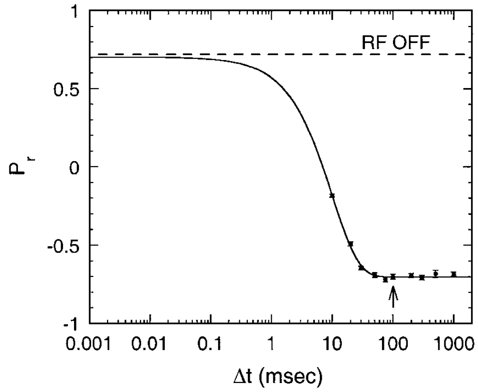

FIG. 4. The measured radial proton polarization at 120 MeV is plotted against the rf-dipole ramp time Δt. The rf dipole's frequency range Δf was ± 5 kHz, and its $\int B\, dl$ was 0.16 T mm rms. The curve is a fit to the data using Eq. (3). The dashed line shows the polarization with the rf dipole off; the arrow shows the 100 ms setting used for later studies.

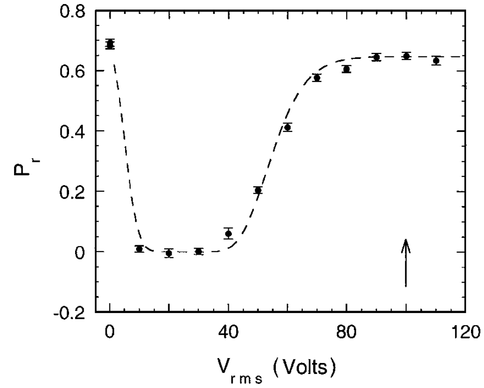

FIG. 5. The measured radial proton polarization at 120 MeV after ten spin flips is plotted against the rms rf-dipole voltage $V_{\rm rms}$. The rf dipole's frequency range Δf was ± 5 kHz, and its ramp time Δt was 100 ms. The dashed curve is a fit to the data using Eq. (6); the arrow shows the 100 V setting used for later studies, corresponding to $\int B\, dl = 0.16$ T mm rms.

We next studied whether the fast turn-on of the rf dipole was reducing the stored beam's current and possibly increasing its emittance; we set the rf dipole's frequency to 0.7775 MHz and linearly ramped its voltage from 0 to 280 V, and then back to 0 V, while varying its voltage turn-on time τ and holding its voltage-on time fixed at 1 s. Above about 10 ms, the beam current is somewhat independent of voltage turn-on time; thus, we set the voltage turn-on time at 10 ms for the later spin-flipping studies.

We then spin flipped the beam by crossing this rf-induced resonance at f_r^- by linearly ramping the rf dipole's frequency from $f_r^- - 5$ to $f_r^- + 5$ kHz, with various ramp times Δt, while measuring the beam polarization after each frequency ramp. The measured radial polarization is plotted against the ramp time in Fig. 4. This measured polarization is a good fit to the Froissart-Stora formula [Eq. (3)], which is shown by the curve. The best fit to the resonance strength is $\epsilon = (198 \pm 2) \times 10^{-6}$ [31].

To study more precisely the spin-flip efficiency η, we next performed ten spin flips while varying the rf dipole's frequency range Δf, its ramp time Δt, and its voltage V. The beam polarization after ten spin flips is plotted in Fig. 5 against the rf-dipole's voltage, with its Δf and Δt set to their optimum values. The dashed curve is a fit to the formula obtained by taking the 10th power of $\eta \equiv P_f/P_i$ in Eq. (3), where P_i and P_f are the initial and final polarizations after one spin flip:

$$P_{10} = P_i \eta^{10} = P_i \left\{ 2 \exp\left[\frac{-(\pi \epsilon f_c)^2}{\Delta f / \Delta t} \right] - 1 \right\}^{10}. \quad (6)$$

After setting Δt, Δf, and V to maximize the spin-flip efficiency, we more precisely determined this efficiency η by varying the number of spin flips. We measured the radial polarization after many spin flips while keeping the ramp time, the frequency range, and the rf voltage all fixed for each spin flip. This measured radial polarization is plotted against the number of spin flips in Fig. 6. We fit this data using

$$P_n = P_i \eta^n, \quad (7)$$

where P_n is the measured radial beam polarization after n spin flips, P_i is the initial polarization, and η is the spin-flip efficiency. The best fit gave a spin-flip efficiency of $99.63 \pm 0.02\%$; while this technique seems free of any known systematic errors, we decided to be conservative and to increase the quoted error to $\pm 0.05\%$. This very high spin-flip efficiency was probably due to our new ability to operate the rf dipole at a high voltage by turning it on rather slowly; this slow turn-on apparently helped to preserve both the beam current and beam polarization.

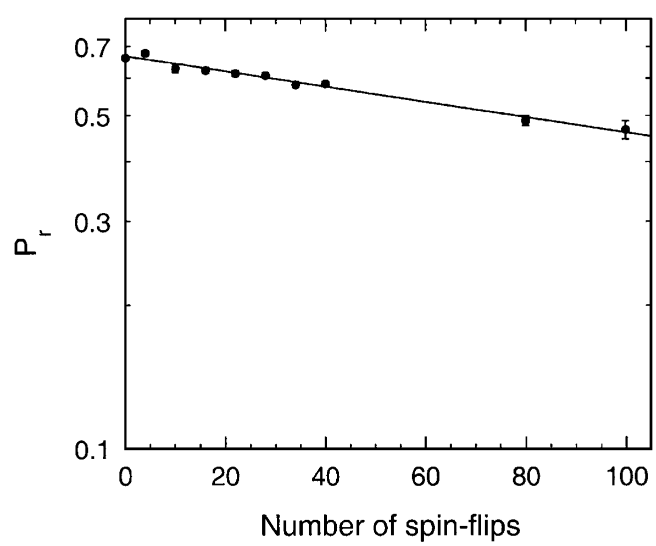

FIG. 6. The measured radial proton polarization at 120 MeV is plotted against the number of spin flips. The rf dipole's frequency ramp time Δt was 100 msec; its frequency range Δf was ± 5 kHz, and its voltage was 100 V rms corresponding to an $\int B\, dl$ of 0.16 T mm rms. The curve is a fit to the data using Eq. (7).

In summary, by adiabatically turning on an rf dipole, we were able to very efficiently spin flip a stored 120-MeV horizontally polarized proton beam with a nearly full Siberian snake in the IUCF Cooler Ring. The measured spin-flip efficiency was 99.63 ± 0.05%. This very high spin-flip efficiency might be further increased by increasing even further the rf dipole's voltage. In any case, the present data clearly demonstrate that an rf-dipole spin flipper would allow up to 100 spin flips in scattering experiments with polarized beams in rings, which need Siberian snakes, such as the IUCF Cooler Ring, the MIT-Bates Storage Ring, Brookhaven's RHIC, or DESY's HERA.

We thank J. M. Cameron, A. S. Belov, V. P. Derenchuk, G. W. East, D. L. Friesel, T. Rinckel, W. T. Sloan, and the entire Indiana University Cyclotron Facility staff for the successful operation of the Cooler Ring with its new Cooler Injector Synchrotron CIS and CIPIOS polarized ion source. We are grateful to A. W. Chao, C. M. Chu, E. D. Courant, F. Z. Khiari, S. Y. Lee, A. M. T. Lin, H. O. Meyer, M. G. Minty, C. Ohmori, R. A. Phelps, R. E. Pollock, L. G. Ratner (deceased), T. Roser, D. W. Sivers, T. Toyama, and others for their help with earlier parts of this experiment. This research was supported by grants from the U.S. Department of Energy and the U.S. National Science Foundation.

*Also at Indiana University, Bloomington, IN 47408.
†Also at Moscow State University, Moscow, Russia.

[1] H. O. Meyer *et al.,* Phys. Rev. Lett. **81**, 3096 (1998); B. von Przewoski *et al.,* Phys. Rev. C **58**, 1897 (1998).
[2] BLAST Collaboration, R. Alarcon *et al.,* in MIT-Bates Report No. 2-39, 1999.
[3] Y. Makdisi, in *High Energy Spin Physics,* edited by Kenneth J. Heller and Sandra L. Smith, AIP Conf. Proc. No. 343 (AIP, Woodbury, NY, 1995), p. 75.
[4] SPIN Collaboration, A. D. Krisch *et al.,* "Acceleration of Polarized Protons to 820 (and 920) GeV in HERA," University of Michigan Report No. UM-HE 96-20, 1996; University of Michigan Report No. UM-HE 99-05, 1999.
[5] HERMES Collaboration, A. Airapetian *et al.,* "The HERMES Physics Program & Plans for 2001-2006," DESY-PRC Report No. 99-08, 1999.
[6] Ya. S. Derbenev and A. M. Kondratenko, Part. Accel. **8**, 115 (1978).
[7] B. B. Blinov *et al.,* Phys. Rev. Lett. **81**, 2906 (1998).
[8] V. A. Anferov *et al.,* in *Proceedings of the 13th International Symposium on High Energy Spin Physics,* edited by N. E. Tyurin *et al.* (World Scientific, Singapore, 1999), p. 503.
[9] D. D. Caussyn *et al.,* Phys. Rev. Lett. **73**, 2857 (1994).
[10] D. A. Crandell *et al.,* Phys. Rev. Lett. **77**, 1763 (1996).
[11] V. A. Anferov *et al.,* Phys. Rev. ST Accel. Beams **3**, 041001 (2000).
[12] B. B. Blinov *et al.,* Phys. Rev. ST Accel. Beams **3**, 104001 (2000).
[13] A. M. T. Lin *et al.,* in *Spin 2000,* edited by K. Hatanaka, AIP Conf. Proc. No. 570 (AIP, Melville, NY, 2001), p. 736.
[14] B. W. Montague, Phys. Rep. **113**, 35 (1984).
[15] M. Froissart and R. Stora, Nucl. Instrum. Methods **7**, 297 (1960).
[16] A. D. Krisch *et al.,* Phys. Rev. Lett. **63**, 1137 (1989).
[17] J. E. Goodwin *et al.,* Phys. Rev. Lett. **64**, 2779 (1990).
[18] M. G. Minty *et al.,* Phys. Rev. D **44**, R1361 (1991).
[19] V. A. Anferov *et al.,* Phys. Rev. A **46**, R7383 (1992).
[20] R. Baiod *et al.,* Phys. Rev. Lett. **70**, 2557 (1993).
[21] R. A. Phelps *et al.,* Phys. Rev. Lett. **72**, 1479 (1994).
[22] B. B. Blinov *et al.,* Phys. Rev. Lett. **73**, 1621 (1994).
[23] C. Ohmori *et al.,* Phys. Rev. Lett. **75**, 1931 (1995).
[24] L. V. Alexeeva *et al.,* Phys. Rev. Lett. **76**, 2714 (1996).
[25] R. A. Phelps *et al.,* Phys. Rev. Lett. **78**, 2772 (1997).
[26] C. M. Chu *et al.,* Phys. Rev. E **58**, 4973 (1998).
[27] B. B. Blinov *et al.,* Phys. Rev. ST Accel. Beams **2**, 064001 (1999).
[28] M. Bai *et al.,* Phys. Rev. E **56**, 6002 (1997).
[29] V. P. Derenchuk and A. S. Belov, in *Polarized Gas Targets and Polarized Beams,* edited by R. J. Holt and M. A. Miller, AIP Conf. Proc. No. 421 (AIP, Melville, NY, 1998), p. 422.
[30] D. L. Friesel and S. Y. Lee, in *Proceedings of the 1997 Particle Accelerator Conference, Vancouver, 1997,* edited by Martin Comyn (IEEE, Piscataway, NJ, 1998), p. 935.
[31] The resonance strength obtained from Eq. (6), using the $\eta = 99.63 \pm 0.05\%$ from Fig. 6, is $\epsilon = (158 \pm 2) \times 10^{-6}$. Similarly from the Δt curve in Fig. 4, when the spin-flip efficiency was not yet fully maximized, we obtained $\epsilon = (198 \pm 2) \times 10^{-6}$. Moreover, from the widths in Figs. 3a and 3b (775 ± 21 Hz and 867 ± 13 Hz), using $\epsilon = w/f_c$, we obtained ϵ of $(485 \pm 13) \times 10^{-6}$ and $(543 \pm 8) \times 10^{-6}$, respectively. This increased width may be partly due to factors, such as the stored beam's energy spread, which cause a spin tune spread. However, the resonance strength obtained from the rf dipole's calculated $\int B\,dl$ of about 0.16 ± 0.04 T mm rms was only about $\epsilon = (22 \pm 6) \times 10^{-6}$. Perhaps this ϵ is somehow enhanced by the rf dipole increasing the horizontal betatron amplitudes and thus enhancing the resonance strength through the spins' interactions with the stronger vertical fields in the outer parts of the Cooler Ring's quadrupoles.