Spin manipulation of 1.94 GeV/c polarized protons stored in the COSY cooler synchrotron

V. S. Morozov, A. D. Krisch, M. A. Leonova, R. S. Raymond, V. K. Wong, and K. Yonehara
Spin Physics Center, University of Michigan, Ann Arbor, Michigan 48109-1120, USA

U. Bechstedt, R. Gebel, A. Lehrach, B. Lorentz, R. Maier, D. Prasuhn, A. Schnase, and H. Stockhorst
Forschungszentrum Jülich, Institut für Kernphysik, Postfach 1913, D-52425 Jülich, Germany

D. Eversheim, F. Hinterberger, H. Rohdjeß, and K. Ulbrich
Helmholtz-Institut für Strahlen- und Kernphysik, Universität Bonn, D-53115 Bonn, Germany
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We recently studied spin flipping of a 1.94 GeV/c vertically polarized proton beam at COSY in Jülich, Germany. We swept an rf-dipole's frequency through an rf-induced spin resonance to flip the beam's polarization direction. After determining the resonance's frequency, we varied the dipole's strength, frequency range, and frequency ramp time. At the rf-dipole's maximum strength, and optimum frequency range and ramp time, we measured a spin-flip efficiency of 99.3% $\pm$ 0.1%. This result indicates that an rf dipole may allow efficient spin flipping in high energy proton rings.

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I. INTRODUCTION

During the past decade, polarized beam experiments have become an important part of the programs in storage rings such as the IUCF Cooler Ring [1], AmPS at NIKHEF [2], the MIT-Bates Storage Ring [3], COSY [4], LEP at CERN [5], RHIC at BNL [6], and HERA at DESY [7,8]. Many polarized scattering experiments require frequent spin-direction reversals (spin flips), while the polarized beam is stored, to reduce their systematic errors. Spin resonances [9,10] induced by either an rf solenoid or an rf dipole can produce such spin flips in a well-controlled way [11–20]. At high energy, the spin-flipping efficiency with an rf dipole should be essentially independent of energy due to the Lorentz invariance of a dipole magnet's $\int Bdl$; this is quite important for very high energy polarized proton rings. Therefore, we recently used an rf dipole to study the spin flipping of 1.941 GeV/c polarized protons stored in the COSY ring.

In any flat storage ring or circular accelerator, each proton's spin precesses around the stable spin direction (SSD), which is defined by the ring's magnetic structure. In a ring with no horizontal magnetic fields, the SSD points along 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.

The vertical polarization can be perturbed by a horizontal rf magnetic field from either an rf solenoid or an rf dipole. This perturbation can induce an rf depolarizing resonance, which can flip the spin of the stored polarized protons [11–20]; the resonance's frequency is

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

where f_c is the protons's circulation frequency and k is an integer. Adiabatically ramping the rf magnet's frequency through f_r can flip each proton's spin. The Froissart-Stora equation [9] relates the beam's initial polarization P_i to its final polarization P_f after crossing the resonance,

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

the ratio $\Delta f/\Delta t$ is the resonance crossing rate, where Δf is the ramp's full frequency range during the ramp time Δt. The resonance strength ϵ is given by [21]

$$\epsilon = \frac{1}{\pi\sqrt{2}}\frac{e(1 + G\gamma)}{p}\int B_{\mathrm{rms}}dl, \tag{4}$$

where e is the proton's charge, p is its momentum, and $\int B_{\mathrm{rms}}dl$ is the rf-dipole's rms magnetic field integral.

II. EXPERIMENTAL APPARATUS

The apparatus used for this experiment, including the COSY storage ring [22–25], the EDDA detector [26], the low energy polarimeter, the injector cyclotron, and the polarized ion source [27–29] is indicated in Fig. 1, along with the rf dipole. The dipole, which consisted of two 4-turn air-core copper coils in series, was part of an LC resonant circuit; it normally ran at about 6.6 kV rms producing an $\int B_{\mathrm{rms}}dl$ of about 0.11 ± 0.005 T mm. An earlier version was used to spin flip polarized deuterons [30]. The beam emerging from the polarized H^- ion source was accelerated by the cyclotron to COSY's 45 MeV injection energy. Then the low energy polarimeter (LEP) monitored the beam's polarization before injection

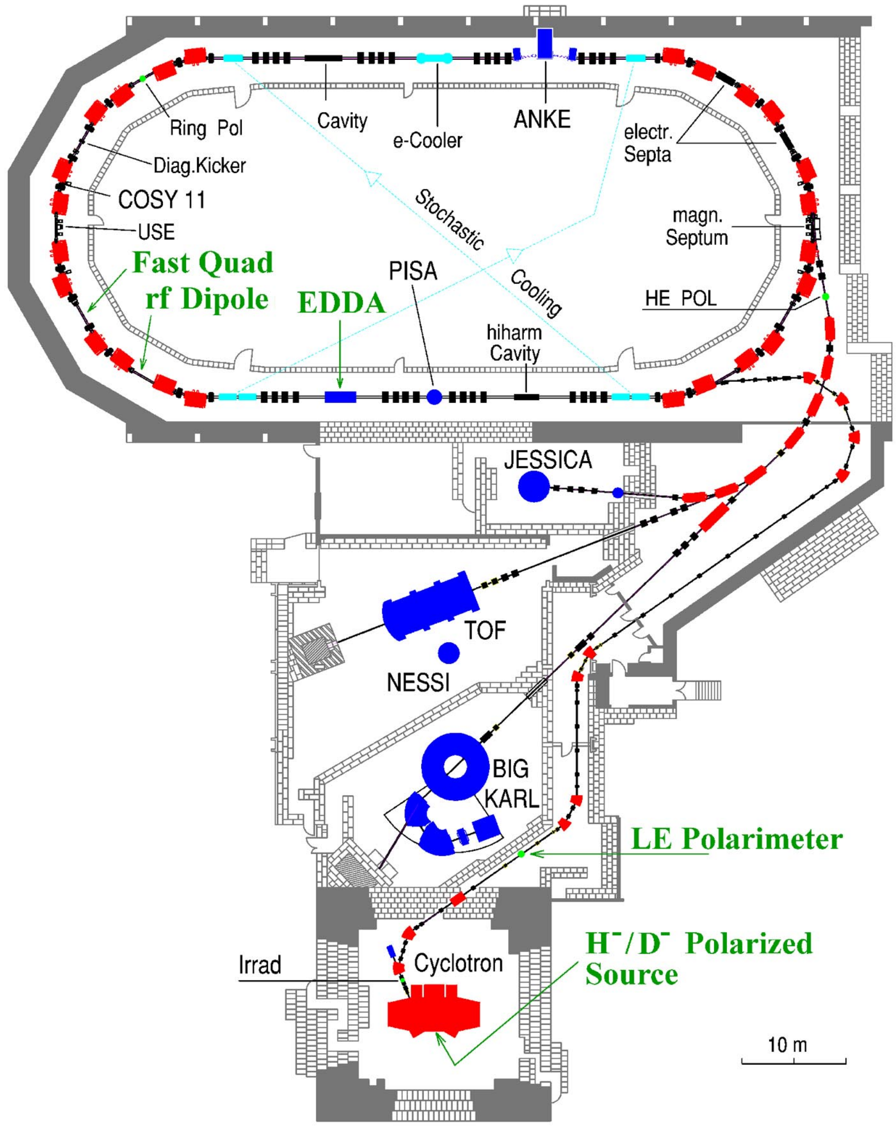

FIG. 1. (Color) Layout of the COSY Storage Ring, with its injector cyclotron and polarized ion source. Also shown are the rf dipole, the EDDA detector, and the low energy polarimeter.

into COSY to check the stable operation of the ion source and cyclotron.

We measured the polarization in COSY using the EDDA detector [4,26] as a polarimeter; we reduced its systematic errors by cycling the polarized source between the up and down vertical polarization states. The rf acceleration cavity was turned off and shorted during COSY's flattop; thus, there were no synchrotron sideband effects [13,31,32]. The measured flattop polarization, before spin manipulation, was typically about 80% with an error below 1%.

III. EXPERIMENTAL RESULTS

The stored protons' measured circulation frequency in COSY was $f_c = 1.471\,17$ MHz giving a nominal Lorentz energy factor of $\gamma = 2.2977$ and a momentum of 1.9410 GeV/c. With these parameters, Eq. (1) gave a spin tune $\nu_s = G\gamma$ of 4.1195; then Eq. (2) implied that the $k = 5$ depolarizing resonance should be centered at

$$f_r = (5 - G\gamma)f_c = 1295.4 \text{ kHz}. \tag{5}$$

We first determined the resonance frequency by linearly ramping the rf-dipole's frequency by $\Delta f/2 = \pm 2$ kHz around the calculated f_r; we then continued by making ± 2 kHz ramps next to each side of the previous frequency range until the beam was either spin flipped or depolarized, as shown in Fig. 2. The ± 2 kHz data's behavior suggested that the resonance width was comparable to the ± 2 kHz frequency ramps.

Thus, we next studied $\Delta f/2 = \pm 1$ kHz frequency ramps with different central frequencies, which are shown in Fig. 2 as open circles; fitting these ± 1 kHz data

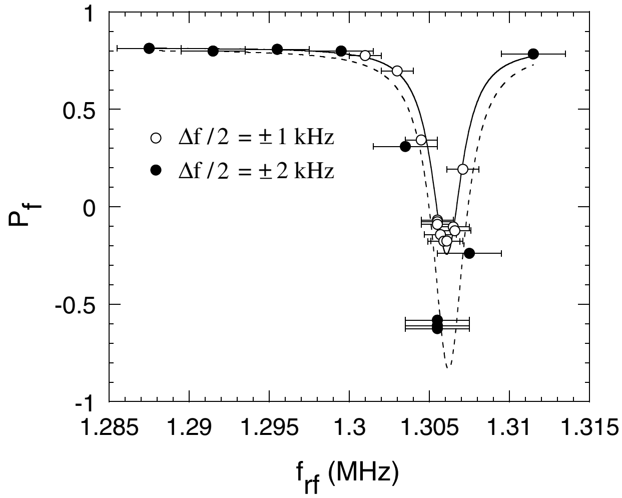

FIG. 2. The measured proton polarization at 1.941 GeV$/c$ is plotted against the central frequency of each ramp; each ramp's Δf range is shown by a horizontal bar. The rf dipole's $\int B_{\rm rms} dl$ was 0.11 T mm; its Δt was 10 s. The curve is a fit using a first-order Lorentzian.

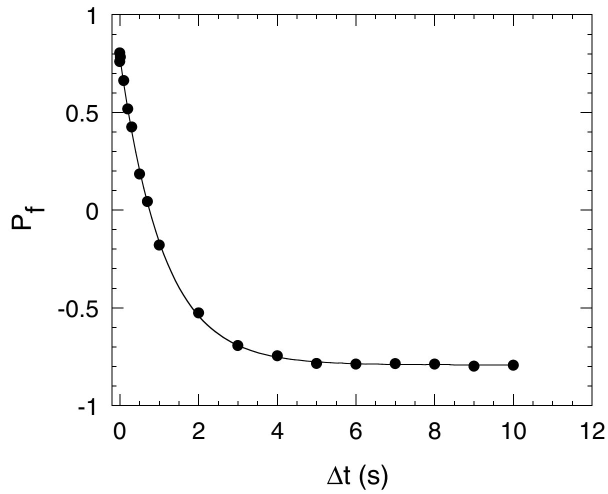

FIG. 3. The measured proton polarization at 1.941 GeV$/c$ is plotted against the rf-dipole ramp time Δt. The rf-dipole's frequency half range $\Delta f/2$ was 5 kHz, and its $\int B_{\rm rms} dl$ was 0.11 T mm. The curve is a fit using Eq. (6).

gave $f_r = 1306.0 \pm 0.5$ kHz and an upper limit on the full width at half maximum of $w = 2.3 \pm 0.9$ kHz. The FWHM width due to the resonance's ϵ, given by $w = 2\epsilon f_r$ [11], is only 59 ± 3 Hz. The beam had a measured momentum spread $\delta p/p$ of about 6×10^{-4} FWHM. This gives an additional resonance width of about 3 kHz in Eq. (5), which is consistent with the upper limit $w = 2.3 \pm 0.9$ kHz.

The $\Delta f/2 = \pm 2$ kHz data in Fig. 2 gave $f_r = 1306 \pm 1$ kHz; its w had too large an error to be useful. The 10.6 kHz difference between the measured and calculated f_r is dominated by the measured closed orbit distortions in COSY's ring due to a slight mismatch between the rf accelerating frequency and the dipole field. This changed the beam's circumference and thus its γ; thus, the f_r in Eq. (5) changed. Any contribution due to a higher-order type-3 Siberian snake [33,34] in COSY's vertical-plane electron cooling system should be negligible.

Based on previous studies we chose the frequency range $\Delta f/2$ of ± 5 kHz, which seemed to safely cover the whole resonance. We then spin flipped the proton beam by ramping the rf-dipole's frequency through this Δf, with various ramp times Δt, while measuring the polarizations after each ramp. The measured data are plotted against the ramp time in Fig. 3; this suggests setting Δt near 7 s. Since the spin-flip efficiency is never exactly 100%, the modified Froissart-Stora formula [16,18] was earlier introduced empirically to describe nonideal single-flip data:

$$\frac{P_f}{P_i} \equiv -\hat{\eta} = (1 + \eta) \exp\left[\frac{-(\pi \epsilon f_c)^2}{\Delta f / \Delta t}\right] - \eta. \qquad (6)$$

The parameter η is defined as the upper limit of the achievable spin-flip efficiency $\hat{\eta}$ when the exponential approaches zero. This limit could be due to many depolarizing mechanisms such as Δf being too small to completely cover the resonance width; or any weak nearby resonance. This η seems a useful parametrization for these many possibilities.

Fitting the Fig. 3 data to Eq. (6) gave a spin-flip efficiency η of $100.8\% \pm 1.2\%$ and a resonance strength ϵ of $(20.7 \pm 0.2) \times 10^{-6}$; this is consistent with the ϵ of $(20 \pm 1) \times 10^{-6}$ obtained from Eq. (4) using the measured $\int B_{\rm rms} dl = 0.11 \pm 0.005$ T mm.

To more precisely determine the spin-flip efficiency, we then measured the polarization after 11 spin flips, while varying the rf-dipole's rms voltage $V_{\rm rms}$, its ramp time Δt, and its full frequency range Δf. This technique enhanced small changes in the spin-flip efficiency's dependence on the rf-dipole's parameters, because the 11th power of even a small single spin-flip depolarization is large. The measured polarization after 11 spin flips P_{11} is plotted in Fig. 4 against the rf dipole's $\Delta f/2$, with its Δt now set at 7.5 s and its $\int B_{\rm rms} dl$ set at 0.11 T mm. Figure 4 shows a clear maximum of P_{11} centered near $\Delta f/2 = 4$ kHz.

After setting Δt, Δf, and $\int B_{\rm rms} dl$ to maximize the spin-flip efficiency, we then determined it more precisely by varying the number of spin flips. We measured the vertical polarization after 0, 1, 11, and 30 spin flips, while keeping Δt, Δf, and $\int B dl$ all fixed; these data are plotted against the number of spin flips in Fig. 5. We fit these data using the *measured* $\hat{\eta}$ defined by

$$P_n = P_i \cdot (-\hat{\eta})^n, \qquad (7)$$

where P_n is the measured polarization after n spin flips. The fit gave a measured spin-flip efficiency of $\hat{\eta} = 99.3\% \pm 0.1\%$. Note again that, in the limit that the

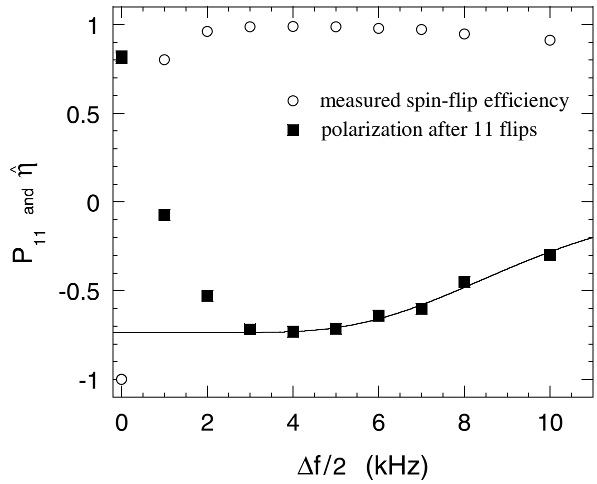

FIG. 4. The measured proton polarization at 1.941 GeV/c after 11 spin flips is plotted against the rf-dipole's frequency half range $\Delta f/2$. The rf-dipole's ramp time Δt was 7.5 s, and its $\int B_{\mathrm{rms}} dl$ was 0.11 T mm. The curve is a fit to Eq. (8). Also shown is the measured spin-flip efficiency $\hat{\eta}$ for each Δf obtained using Eq. (7) to take the 11th root of the measured ratio $-P_{11}/P_i$.

exponential in Eq. (6) goes to zero, comparing Eq. (7) for a single flip with Eq. (6) yields $\eta = \hat{\eta}$.

We also tried to fit the data in Fig. 4 by taking the 11th power of Eq. (6)

$$\frac{P_{11}}{P_i} = \left\{(1+\eta)\exp\left[\frac{-(\pi\epsilon f_c)^2}{\Delta f/\Delta t}\right] - \eta\right\}^{11}. \qquad (8)$$

The curve in Fig. 4 is a fit to Eq. (8), where we set η equal to the $\hat{\eta} = 99.3\% \pm 0.1\%$, obtained from Fig. 5. The fit gave a resonance strength of $\epsilon = (19.9 \pm 0.2) \times 10^{-6}$, while the initial polarization P_i was $80\% \pm 2\%$. However, we fit only the data at or above $\Delta f/2 = 4$ kHz. At small Δf, when the frequency range is smaller than the resonance width, P_{11} must decrease sharply. This is certainly not described by Eq. (8), since Eq. (8), the Froissart-Stora formula [9], is certainly not valid when Δf is smaller than the resonance's width. A more general formula is still needed for cases when Δf is not infinite or when the resonance is not totally isolated.

In summary, by adiabatically ramping an rf-dipole's frequency through an rf-induced spin resonance, we were able to spin flip the polarization of a stored proton beam. After optimizing the spin-flipping parameters, we obtained a 99.3% ± 0.1% measured spin-flip efficiency for 1.94 GeV/c polarized protons stored in COSY. We now plan to enhance the rf-dipole's strength by enclosing it in a ferrite box and using water-cooled coils to allow running at a higher current and thus a higher $\int B dl$. This should allow a further increase in the spin-flip efficiency, even with a faster ramp time.

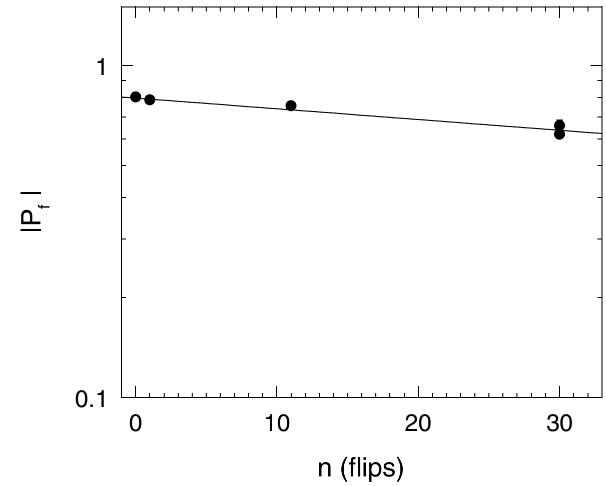

FIG. 5. The measured proton polarization at 1.941 GeV/c is plotted against the number of spin flips. The rf-dipole's frequency ramp time Δt was 10 s; its frequency half range $\Delta f/2$ was 4 kHz, and its $\int B_{\mathrm{rms}} dl$ was 0.11 T mm. The line is a fit using Eq. (7).

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