Achieving 99.9% Proton Spin-Flip Efficiency At Higher Energy With A Small rf Dipole

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We recently used a new ferrite rf dipole to study spin flipping of a 2.1 GeV/c vertically polarized proton beam stored in the COSY Cooler Synchrotron in Jülich, Germany. We swept the 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 frequency range, frequency ramp time, and number of flips. At the rf dipole's maximum strength and optimum frequency range and ramp time, we measured a spin-flip efficiency of $99.92 \pm 0.04\%$. This result, along with a similar 0.49 GeV/c IUCF result, indicates that, due to the Lorentz invariance of an rf dipole's transverse $\int Bdl$ and the weak energy dependence of its spin-resonance strength, an only 35% stronger rf dipole should allow efficient spin flipping in the 100 GeV BNL RHIC Collider or even the 7 TeV CERN Large Hadron Collider.

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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], the e^+e^- collider LEP at CERN [5], the Relativistic Heavy Ion Collider at BNL [6], and the ep collider 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 rf dipole can produce these spin flips in a well controlled way [11–21].

An rf dipole was earlier used [19] to spin flip 120 MeV (490 MeV/c) polarized protons stored in the IUCF Cooler Ring with a $99.93 \pm 0.02\%$ spin-flip efficiency. At very high energy, the spin-flip efficiency with an rf dipole should become almost independent of energy, mostly due to the Lorentz invariance of a magnet's transverse $\int Bdl$ [22]; this invariance is quite important for very high energy polarized proton rings [23]. To confirm this we recently used an rf dipole to study the spin flipping of 2.1 GeV/c polarized protons stored in the COSY ring.

In any flat storage ring or circular accelerator 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.

The vertical polarization can be perturbed by an rf dipole's horizontal rf magnetic field. This perturbation can induce an rf depolarizing resonance, which can flip the spin direction of the stored polarized protons [11–21]; 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 [24]

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

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

The apparatus used for this experiment, including the COSY storage ring [25–28], the EDDA detector [29], the Low Energy Polarimeter (LEP), the injector cyclotron, and the polarized ion source [30–32], are indicated in Fig. 1, along with the rf dipole. The beam emerging from

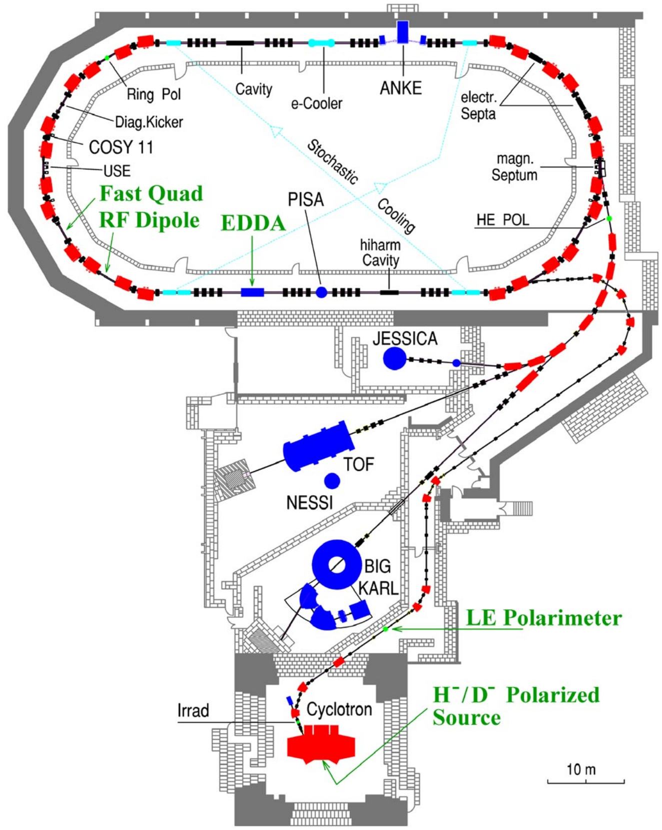

FIG. 1 (color online). Layout of the COSY storage ring, with its injector cyclotron and polarized ion source. Also shown are the rf dipole and the EDDA and Low Energy Polarimeters.

the polarized H^- ion source was accelerated by the cyclotron to COSY's 45 MeV injection energy. Then the LEP measured the beam's polarization before injection into COSY to monitor the stable operation and polarization of the ion source.

The new ferrite-core rf dipole contained an 8-turn copper coil with the spacing between its turns optimized to produce a uniform radial magnetic field; it was part of an LC resonant circuit operating near 2.4 kV rms near $f_r = 902.6$ kHz, for an $\int B_{\rm rms} dl$ of 0.46 ± 0.03 T mm; Eq. (4) gave a resonance strength $\epsilon = (80 \pm 5) \times 10^{-6}$. A weaker air-core rf dipole was previously used at COSY to spin flip polarized protons [21] and polarized deuterons [33] with lower spin-flip efficiency.

We measured the polarization in COSY using the EDDA detector [4,29] 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 [13,34,35]. The measured flattop polarization, before spin manipulation, was typically 75 to 80%.

The stored 2.1 GeV/c protons' measured circulation frequency in COSY was $f_c = 1.491\,892$ MHz giving a nominal Lorentz energy factor of $\gamma = 2.4514$; with this γ, Eq. (1) gave a spin tune $\nu_s = G\gamma$ of 4.395. Thus, Eq. (2) implied that the $k = 5$ depolarizing resonance should be centered at

$$f_r = (5 - G\gamma) f_c = 902.6 \text{ kHz}. \tag{5}$$

We roughly measured this resonance frequency by first linearly ramping the rf dipole frequency by $\Delta f/2$ of 2 kHz around the calculated f_r with Δt set at 10 s. We then continued by making these ± 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. This 2 kHz data's behavior and previous experience [21] suggested that the resonance half-width was comparable to the ± 2 kHz frequency ramps. Thus, we next repeated this study with frequency ramps of $\Delta f/2 = 1$ kHz and then finally with $\Delta f/2 = 0.2$ kHz; these data are also shown in Fig. 2. Fitting the 0.2 kHz data to the indicated first-order Lorentzian curve gave $f_r = 902.4 \pm 0.1$ kHz and a resonance width of $w = 2.4 \pm 0.3$ kHz FWHM.

We spin flipped the proton beam by ramping the rf dipole's frequency through f_r with a frequency range Δf, and various ramp times Δt, while measuring the polarizations after each ramp. To maximize the spin-

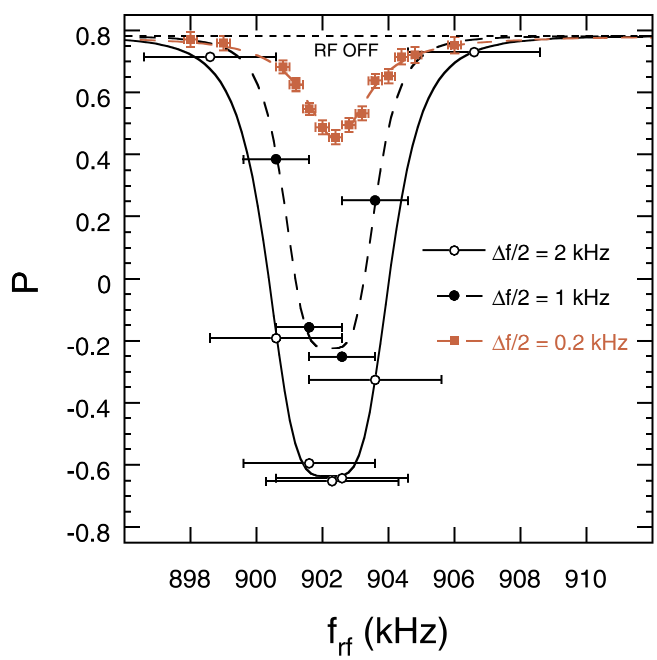

FIG. 2 (color online). The measured proton polarization at 2.1 GeV/c is plotted against the central frequency of each ramp; each ramp's full-frequency range Δf is shown by a bar. The rf dipole's $\int B_{\rm rms} dl$ was 0.46 ± 0.03 T mm; its Δt was 10 s. The 0.2 kHz data were renormalized to the measured LEP asymmetry and its typically $\pm 3\%$ relative error was added in quadrature. The curves are fits using first-order (0.2 kHz) and second-order (1 and 2 kHz) Lorentzians.

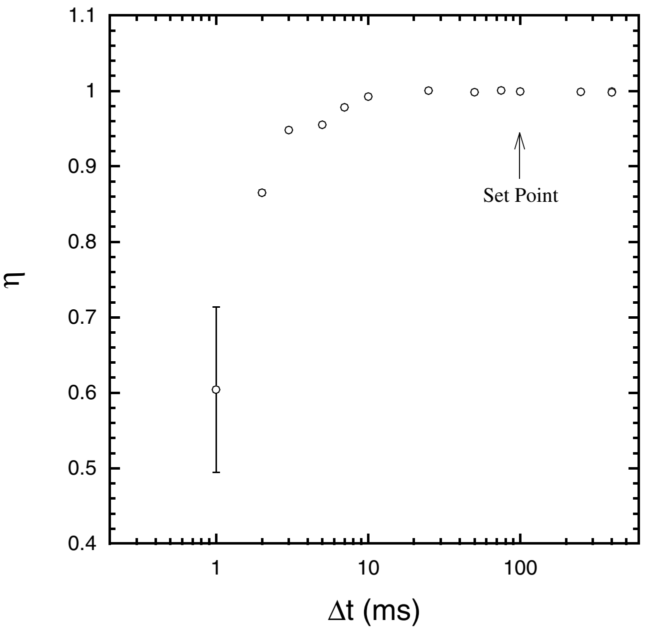

FIG. 3. The proton spin-flip efficiency η at 2.1 GeV/c, measured after 11 spin flips, is plotted against the rf dipole's ramp time Δt. The rf dipole's frequency half-range $\Delta f/2$ was 6 kHz, and its $\int B_{rms}dl$ was 0.46 ± 0.03 T mm. The arrow indicates the Δt used in Fig. 4.

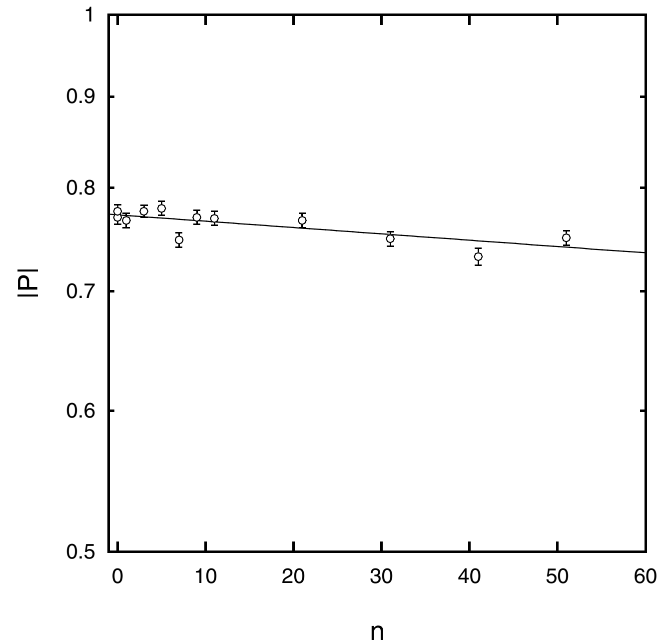

FIG. 4. The magnitude of the measured proton polarization at 2.1 GeV/c is plotted against the number of spin flips. The rf dipole's frequency ramp time Δt was 0.1 s; its frequency half-range $\Delta f/2$ was 6 kHz, and its $\int B_{rms}dl$ was 0.46 ± 0.03 T mm. The line is a fit using Eq. (7).

flip efficiency, we measured the polarization after 11 spin flips, while first varying the rf dipole's frequency range Δf, and later its ramp time Δt, at the maximum $\int B_{rms}dl$. 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 can be significant. The measured polarization after 11 spin flips P_{11} showed no dependence on the rf dipole's frequency half-range $\Delta f/2$ in the region of about 2 to 10 kHz; thus we set $\Delta f/2 = 6$ kHz.

Then we measured the polarization after 11 spin flips P_{11} while varying the rf dipole's frequency ramp time Δt. We obtained the single spin-flip efficiency from

$$\eta = \sqrt[11]{-P_{11}/P_i}, \tag{6}$$

where P_i is the initial polarization. We then plotted this measured η against Δt in Fig. 3. Using Fig. 3, we set Δt at 0.1 s, where the spin-flip efficiency was high, while Δt was small enough to allow 51 spin flips fairly quickly.

After setting Δt and Δf to maximize the spin-flip efficiency, we then determined it much more precisely by measuring the vertical polarization while varying the number of spin flips, up to 51, with Δt, Δf, and $\int Bdl$ all fixed at their optimum values. These data are plotted against the number of spin flips in Fig. 4. We fit these data to obtain the measured spin-flip efficiency η, which is given by

$$P_n = P_i \times (-\eta)^n, \tag{7}$$

where P_n is the measured polarization after n spin flips. The fit gave an efficiency of $\eta = 99.92 \pm 0.04\%$.

In summary, by adiabatically ramping a new ferrite-core water-cooled rf dipole's frequency through an rf-induced spin resonance, we spin flipped the polarization of a stored proton beam. After optimizing the spin-flipping parameters, we obtained a $99.92 \pm 0.04\%$ measured spin-flip efficiency for 2.1 GeV/c polarized protons stored in COSY. This is consistent with the $99.93 \pm 0.02\%$ obtained at 0.49 GeV/c at IUCF [19]. An rf dipole's $\int Bdl$ is Lorentz invariant and its resonance strength becomes almost energy independent at high energy. Thus, if no unknown problems emerge, our small rf dipole's $\int Bdl$ may need to be increased by only about 35% to about 0.6 T mm to allow more than 99.9% proton spin-flip efficiency at the 100 GeV Relativistic Heavy Ion Collider [36] or even the 7 TeV Large Hadron Collider.

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