Spin Flipping through an Intrinsic Depolarizing Resonance by Strengthening It

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We recently accelerated a polarized proton beam from 95 to 380 MeV through both the $G\gamma = 2$ imperfection depolarizing resonance and the $G\gamma = 7 - \nu_y$ intrinsic depolarizing resonance. The imperfection resonance flipped the spin, while the intrinsic resonance initially caused partial depolarization. We then pulsed a vertical kicker magnet for about 500 ns to increase the beam's vertical betatron amplitude; this made the intrinsic resonance much stronger. By varying the strength and start time of the kicker, we observed a sharp spin flip due to the now very strong intrinsic depolarizing resonance. [S0031-9007(96)01002-2]

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To accelerate a polarized proton beam to high energy, one must overcome many spin depolarizing resonances. The imperfection resonance correction technique and the betatron tune jump method were used successfully to maintain the polarization at the ZGS [1], Saturne [2], KEK [3], and the AGS [4]. Recent experiments [5–16] suggest that the Siberian snake technique [17] should overcome all depolarization effects even at very high energy. However, below about 10 GeV a Siberian snake could strongly perturb the beam orbit; thus the individual resonance correction technique might still be needed in a low energy accelerator. Individually overcoming the intrinsic resonances has been especially difficult because this required many expensive devices and much beam time. Saturne spin flipped through their two intrinsic resonances, apparently by slowing the crossing rate at each resonance [2]; the ZGS [1], KEK [3], and AGS [4] jumped through their intrinsic resonance by quickly changing the vertical betatron tune using pulsed quadrupoles [1,3,4]. Each of the twelve 1.6 μs pulsed quadrupoles at the AGS required a costly 22 MW pulsed power supply; moreover, accelerating polarized protons to 22 GeV required seven weeks of beam tuning [4].

We recently performed an experiment in the IUCF Cooler Ring studying an alternate method of overcoming an intrinsic depolarizing resonance: Increasing the vertical betatron oscillations with a kicker magnet might make the intrinsic depolarizing resonance strong enough to flip the spin.

In a circular accelerator or a storage ring, each proton's spin precesses around the vertical magnetic fields of the ring's dipole magnets. The spin tune ν_s, which is the number of spin precessions during one proton revolution, is proportional to the proton's energy

$$\nu_s = G\gamma\,, \tag{1}$$

where γ is the Lorentz energy factor and $G = 1.792847$ is the proton's anomalous magnetic moment. This vertical spin precession can be perturbed by any horizontal magnetic fields in the accelerator. The ring's imperfection fields can interact coherently with the proton's spin and cause beam depolarization when the spin tune is equal to an integer; this is called an imperfection depolarizing resonance.

The intrinsic depolarizing resonances are caused by the vertical betatron oscillations in a ring. The horizontal fields in the ring's quadrupoles can depolarize the beam when the spin tune is related to the vertical betatron tune ν_y by

$$\nu_s = G\gamma = n + k\nu_y\,, \tag{2}$$

where n and k are integers. The beam polarization P, after passing through an isolated depolarizing resonance of strength ϵ, is given by the Froissart-Stora formula [18]

$$P = P_i(2e^{-\pi\epsilon^2/2\alpha} - 1)\,, \tag{3}$$

where P_i is the injected beam polarization; the resonance crossing speed α is assumed to be constant

$$\alpha = \frac{d\gamma}{dt}\,\frac{G}{2\pi f_c}\,, \tag{4}$$

where f_c is the circulation frequency. The Froissart-Stora equation predicts full spin flip for either a large resonance strength or a slow passage through the resonance [18].

The strength of an intrinsic depolarizing resonance depends on the vertical betatron oscillation amplitude;

thus protons with a large vertical amplitude will spin flip when crossing the resonance, while protons with a small vertical amplitude may see little spin rotation. This makes full spin flip very difficult when crossing an intrinsic depolarizing resonance. The situation could change when large coherent betatron oscillations are excited; each proton in the beam should then have a large vertical betatron oscillation; the beam's polarization should then flip when crossing an intrinsic resonance.

Our goal was to increase the strength of the $G\gamma = 7 - \nu_y$ intrinsic depolarizing resonance by pulsing a fast vertical kicker magnet just before crossing the resonance. The ferrite kicker was 20 cm long with about a 100 ns rise time and typically a 20 G field; it is normally used to measure the vertical betatron tune, which is typically 4.8. The other experimental apparatus and the Cooler Ring's operation with polarized protons were discussed earlier [5–15]. In this experiment, a 95 MeV vertically polarized proton beam was injected and accumulated for 30 s. After the beam was cooled, it was accelerated to 380 MeV during a 1.7 s energy ramp; then the beam polarization was measured. The acceleration from 95 to 380 MeV changed the spin tune from about 1.914 to 2.518; therefore, both the $G\gamma = 2$ imperfection depolarizing resonance and the $G\gamma = 7 - \nu_y$ intrinsic depolarizing resonance were crossed. The slow acceleration rate in the Cooler Ring caused a full spin flip during acceleration through the strong imperfection depolarizing resonance [12]; however, the weaker intrinsic depolarizing resonance caused partial depolarization during the acceleration.

With the present electron cooling hardware, the velocity of the cooling electrons is not well matched with the proton beam's velocity during the acceleration. This caused some complex cooling and beam emittance dynamics during acceleration. Therefore we turned off the electron gun during acceleration, while keeping the electron cooling optics unchanged. Then there was no electron cooling to damp the coherent betatron oscillations caused by the kicker magnet.

We then observed a polarization change due to the energy growth of the vertical betatron oscillations by measuring the 380 MeV beam polarization while varying the vertical betatron tune ν_y at a fixed horizontal betatron tune ν_x of about 3.785. The measured vertical polarization P_v is plotted against ν_y in Fig. 1. The energy of the $G\gamma = 7 - \nu_y$ intrinsic depolarizing resonance depended on the value of ν_y; at a larger ν_y the resonance was crossed at a lower energy, while at a lower ν_y the resonance was crossed at a higher energy. The data show that the intrinsic resonance caused only partial depolarization at $\nu_y = 4.84$, while at $\nu_y = 4.70$ the beam was completely depolarized. Note that the $G\gamma = 2$ imperfection depolarizing resonance either fully or partially flipped the spin earlier in the accelerator cycle [12].

We then set the vertical tune at $\nu_y = 4.80$ and pulsed the vertical beam kicker at 0.84 s after the acceleration start. The kicker pulse length was about 500 ns, which is a typical proton revolution period in the Cooler Ring. The horizontal betatron tune was set at about $\nu_x = 3.77$, which is about 0.03 from the fractional vertical betatron tune. The vertical beam polarization was then measured at 380 MeV; it is plotted against the kicker strength in Fig. 2. The polarization was negative for a small kicker strength and became positive for a large kicker strength. This suggests that increasing the vertical betatron amplitude made the $G\gamma = 7 - \nu_y$ intrinsic depolarizing resonance much stronger; thus double spin flip occurred while passing sequentially through the imperfection and intrinsic depolarizing resonances. Probably the kicker changed

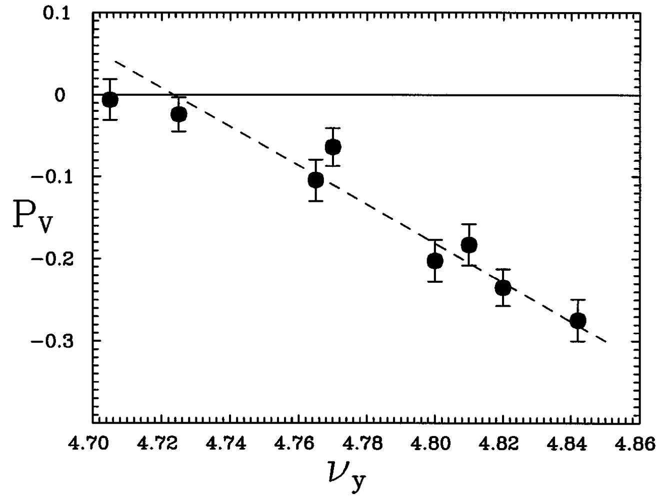

FIG. 1. The measured vertical polarization at 380 MeV is plotted against the vertical betatron tune ν_y. The horizontal betatron tune ν_x was about 3.785. The dashed line is a linear fit suggesting emittance growth during acceleration.

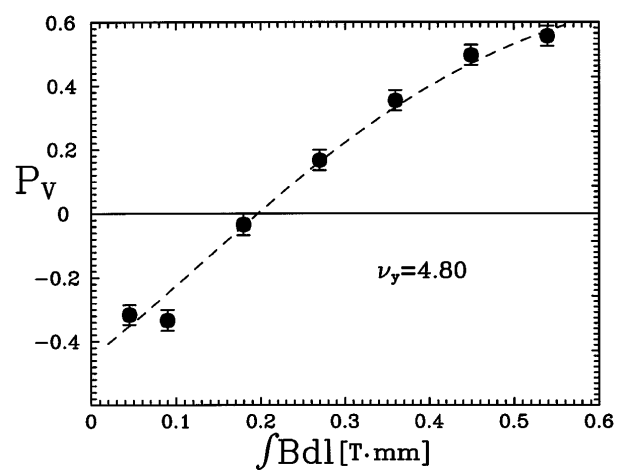

FIG. 2. The measured vertical polarization at 380 MeV is plotted against the strength of the vertical kicker magnet in T mm. The beam was kicked at 0.84 s, while the betatron tunes were $\nu_y = 4.80$ and $\nu_x = 3.77$; the dashed curve is a fit by Eq. (3) using $\epsilon = 6.2 \times 10^{-5} + 2.4 \times 10^{-4} \int B\,dl[T\,\text{mm}]$ and $\alpha = 2.7 \times 10^{-8}$.

the phase space distribution, which was initially maximum at the center, to an annular distribution with most protons having a large vertical betatron amplitude. We did not directly measure the beam emittance; however, a 0.45 T mm transverse kick should give an annular ring with an average normalized emittance magnitude of about 0.65π mm mr, while the estimated normalized emittance was about 0.25π mm mr before the kick.

We then fixed the kicker's strength at 0.45 T mm and varied its start time during the acceleration cycle. The measured polarization is plotted against the kicker time in Fig. 3. When the vertical betatron amplitude was kicked before the calculated resonance time of 0.845 s, then the measured polarization was about 40%. When the amplitude was kicked after this resonance time, the polarization was about -40%. The data clearly indicate that the resonance was crossed between 0.84 and 0.86 s; this certainly agrees with the 0.845 s prediction of Eq. (2), which is indicated by the arrow. (Note that the high polarization point of 0.50 in Fig. 3 was taken from the Fig. 2 curve at $\int B\,dl = 0.45$ T mm. The possible wiggling behavior could be an indication of some unknown accelerator physics effect; however, its position above the nearby points in Fig. 3 probably suggests that some unknown parameter was varying and changing the polarization. Note also that the polarization at $\nu_y = 4.80$ in Fig. 1 is about -0.20, while it is about -0.40 at the same $\int B\,dl = 0$ in Fig. 2. This is probably because the Cooler Ring was retuned between the two curves to improve its stability during the Fig. 2 run.)

In summary, we accelerated a polarized proton beam from 95 to 380 MeV through both the $G\gamma = 2$ imperfection depolarizing resonance, which always flipped the spin, and the $G\gamma = 7 - \nu_y$ intrinsic depolarizing resonance. When we made the intrinsic depolarizing resonance stronger by increasing the vertical betatron amplitude with a vertical kicker, we also observed a second spin flip during acceleration through this intrinsic resonance. This method might be used to overcome the intrinsic depolarizing resonances when accelerating polarized protons in a medium energy ring such as the Brookhaven AGS [19], the Fermilab Booster [20], the DESY III synchrotron [21], or the proposed 20 GeV LISS [22].

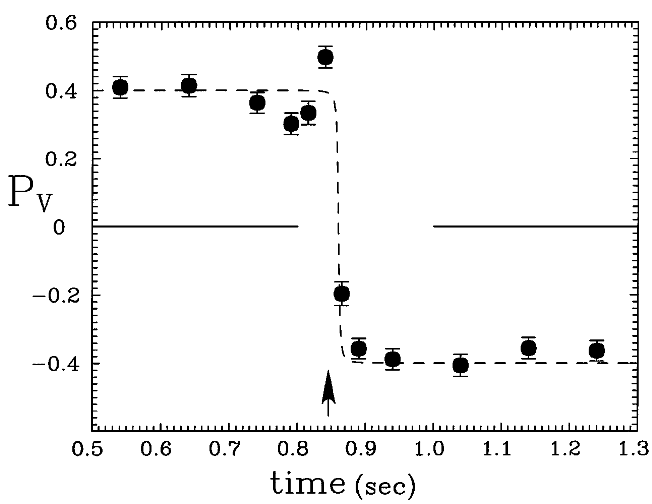

FIG. 3. The measured vertical polarization at 380 MeV is plotted against the time of the vertical beam kick. The kicker magnet strength was 0.45 T mm. The betatron tunes were fixed at $\nu_y = 4.80$ and $\nu_x = 3.77$. The arrow shows the predicted position of the $G\gamma = 7 - \nu_y$ resonance. The dashed line is a hand-drawn curve to guide the eye.

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