# STRENGTHENING AN INTRINSIC DEPOLARIZING RESONANCE TO SPIN-FLIP A POLARIZED BEAM

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We recently performed an experiment in the IUCF Cooler Ring to study a new method of overcoming an intrinsic depolarizing resonance for a polarized proton beam: increasing the vertical betatron oscillations with a kicker magnet might make the intrinsic depolarizing resonance strong enough to flip the spin rather than depolarize the beam.

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 $\nu_s$, 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 $\gamma$ 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 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 $\nu_y$ by the equation

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

where $n$ and $k$ are integers. The beam polarization $P$ after passing through an isolated depolarizing resonance of strength $\epsilon$ is given by the Froissart-Stora formula [1] :

$$P = P_i \left( 2 \exp\left( -\frac{\pi\epsilon^2}{2\alpha} \right) - 1 \right) , \tag{3}$$

where $P_i$ is the injected beam polarization; the resonance crossing speed $\alpha$, which is proportional to the acceleration rate, is assumed to be constant. The Froissart-Stora equation predicts full spin-flip for either a large resonance strength or a slow passage through the resonance [1].

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; and the beam's polarization should 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 risetime and typically a 20-G field; it is normally used to measure the vertical betatron tune, which is typically 4.8. 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;[2] 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.

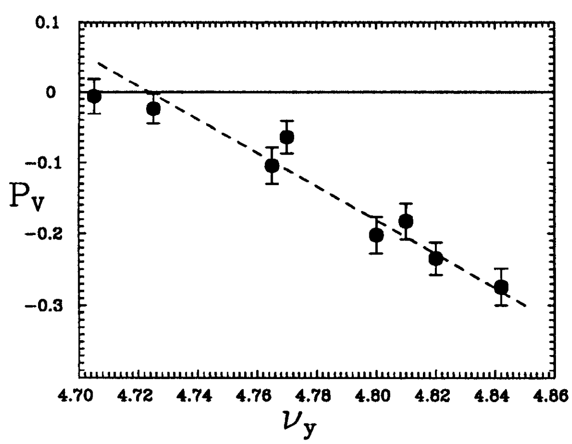


*Figure 1.* The measured vertical polarization at 380 MeV is plotted against the vertical betatron tune $\nu_y$. The horizontal betatron tune $\nu_x$ was about 3.785. The dashed line is a linear fit suggesting emittance growth during acceleration.

We 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 $\nu_y$ at a fixed horizontal betatron tune $\nu_x$ of about 3.785. The measured vertical polarization $P_v$ is plotted against $\nu_y$ in Fig. 1. The energy of the $G\gamma = 7 - \nu_y$ intrinsic depolarizing resonance depended on the value of $\nu_y$; at a larger $\nu_y$ the resonance was crossed at a lower energy, while at a lower $\nu_y$ 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 flipped the spin earlier in the accelerator cycle.[2]

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 the phase space distribution, which was initially maximum at the center, to a "hollow" distribution with most protons having a large vertical betatron amplitude.

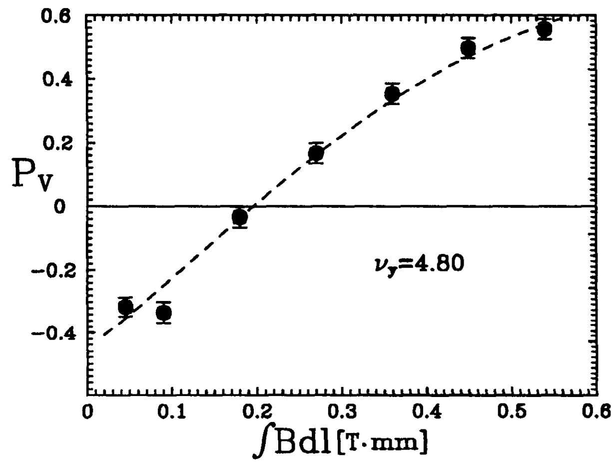


*Figure 2.* The measured vertical polarization at 380 MeV is plotted against the strength of the vertical kicker magnet in T·mm. The beam was kicked at 0.84 s, while the betatron tunes were $\nu_y = 4.80$ and $\nu_x = 3.77$; the dashed curve is a fit to Eq. 3 using $\epsilon = 6.2\ 10^{-5} + 2.4\ 10^{-4}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

We then fixed the kicker's strength at 0.45 T·mm and varied its pulse 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, then 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.

In summary, we accelerated a polarized proton beam from 95 MeV 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

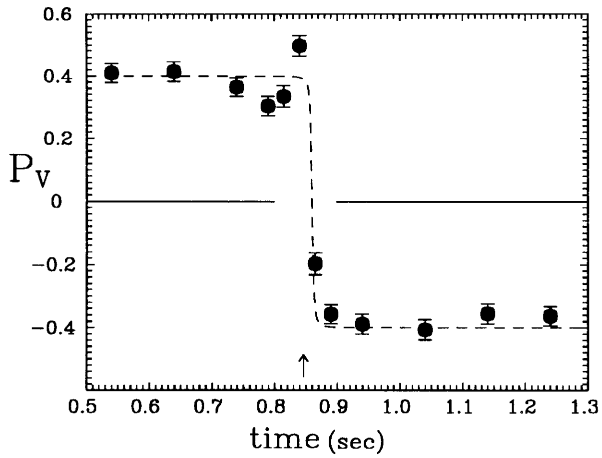


*Figure 3.* The measured vertical polarization at 380 MeV is plotted against the time of the vertical beam kick. The kicker magnet strength was 0.45 T·mm. The betatron tunes were fixed at $\nu_y = 4.80$ and $\nu_x = 3.77$. The arrow shows the predicted position of the $G\gamma = 7-\nu_y$ resonance. The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

kicker, then 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 proposed 20-GeV LISS,[3] or in the booster rings at RHIC,[4] Fermilab,[5] HERA[6] or LHC.

We would like to thank J.M. Cameron and the entire Indiana University Cyclotron Facility staff for the successful operation of the Cooler Ring. We are grateful to A.W. Chao, E.D. Courant, T.J.P. Ellison, S. Hiramatsu, F.Z. Khiari, H.-O. Meyer, M.G. Minty, C. Ohmori, R.E. Pollock, T. Roser, H. Sato, T. Toyama, and U. Wienands 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.

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