Overcoming Intrinsic and Synchrotron Depolarizing Resonances with a Siberian Snake

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We overcame the strong $G\gamma = -3 + \nu_y$ intrinsic depolarizing resonance using a Siberian snake acting on a stored beam of 177-MeV polarized protons at the Indiana University Cooler Ring. We also saw the first evidence for a synchrotron depolarizing resonance in a proton ring. Two synchrotron resonances were studied by varying the rf accelerating voltage and the imperfection field at 104 MeV. The Siberian snake also overcame these synchrotron depolarizing resonances.

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Depolarizing resonances exist in all circular proton accelerators at certain energies where the spin precession frequency exactly matches the frequency with which the protons encounter depolarizing magnetic fields. These horizontal fields can then interact coherently with the spins and rapidly depolarize the beam. It was quite difficult to overcome the depolarizing resonances individually when accelerating polarized proton beams to GeV energies at the ZGS,[1] Saturne,[2] the AGS,[3] and KEK.[4] At TeV energies there are thousands of depolarizing resonances, and maintaining polarization using the same techniques would be extremely difficult. An arrangement of magnets, called a Siberian snake, was proposed[5] to simultaneously overcome all depolarizing resonances. A snake rotates the spin of each proton by 180° forcing the effects of all depolarizing horizontal magnetic fields to exactly cancel themselves on successive turns; this cancellation should eliminate all depolarization. We installed a snake in the Indiana University Cooler Ring[6] and recently reported the first test[7] of a Siberian snake's ability to overcome an imperfection depolarizing resonance. We have now discovered a new type of "synchrotron" depolarizing resonance at 104 MeV and have overcome it using the snake. The snake also overcame the $G\gamma = -3 + \nu_y$ intrinsic depolarizing resonance at 177 MeV.

Polarized proton beams at 104 and 177 MeV were injected and stored in the Cooler Ring with an intensity of 20 to 50 nA and a cycle period of about 4 sec. We simultaneously measured the vertical and radial components of the beam polarization using the cylindrically symmetric CE-01 detector.[8] This polarimeter uses a 4.5-mm-thick skimmer-type carbon target and spans a $\Delta\phi$ range of $\pm 45°$ and a laboratory scattering angle range of 5° to 17°. We estimate that its effective analyzing power is about $19\% \pm 2\%$ at 104 MeV and $43\% \pm 2\%$ at 177 MeV.[9] Each polarization measurement required a run of about 30 min to obtain a statistical error of $\pm 3\%$ to 5%. The beam polarization before injection into the Cooler Ring was measured using a polarimeter[10] in the Cooler Ring injection line and found to be $77\% \pm 2\%$ at both 104 and 177 MeV. The main element of our Siberian snake was a superconducting solenoid magnet. A more detailed discussion of our apparatus can be found in our earlier paper.[7]

A unique stable polarization direction should exist at each point in an accelerator ring; the polarization should always return unchanged to this direction after each turn around the ring. This stable polarization direction may have radial, vertical, and longitudinal components. A type-1 snake, such as ours, rotates the polarization by 180° about the longitudinal axis on each turn and forces the stable spin direction to be horizontal. The horizontal spin motion is described by the following equations:

$$P_{\text{radial}} = -P_{\text{hor}} \sin(G\gamma\theta) , \quad (1)$$

$$P_{\text{long}} = P_{\text{hor}} \cos(G\gamma\theta) , \quad (2)$$

where P_{hor} is the horizontal component of the polarization, $G = (g-2)/2 = 1.7928$ is related to the proton's magnetic moment, $\gamma = E/mc^2$ is the energy parameter, and θ is the orbital angle around the Cooler Ring. In an earlier run[7] we studied the $G\gamma = 2$ imperfection depolarizing resonance with a Siberian snake. The results with 104-MeV polarized protons showed that the snake eliminated the effect of the strongly depolarizing resonance and maintained the full horizontal polarization.

To demonstrate with better precision that the $G\gamma = 2$ resonance has a strong effect at 104 MeV, we turned the snake off and injected protons polarized in the vertical direction. We then studied the depolarizing resonance with a high sensitivity. As shown in Fig. 1 we again saw

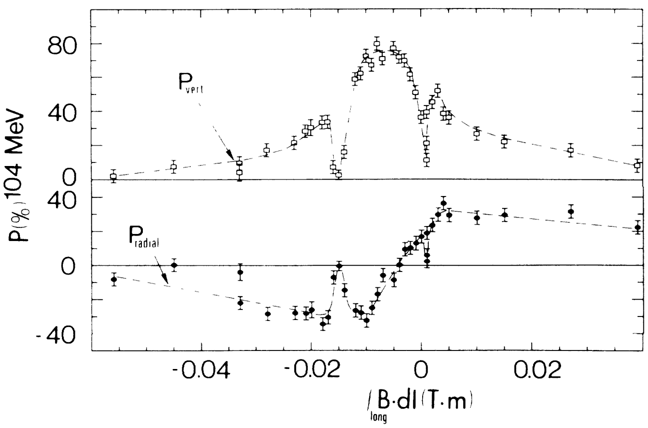

FIG. 1. The vertical (squares above) and radial (circles below) components of the beam polarization at 104 MeV are plotted against the longitudinal magnetic-field integral in the Cooler Ring solenoids with the snake off and the injection of vertically polarized protons. There is a systematic normalization uncertainty of about $\pm 4\%$. The dashed curves are hand-drawn lines to guide the eye.

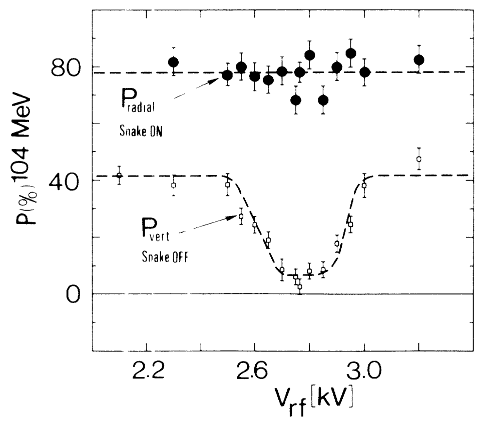

FIG. 2. The beam polarization in each stable polarization direction at 104 MeV is plotted against the voltage of the radio-frequency accelerating cavity in the Cooler Ring. The circles are the radial polarization with the snake on and the injection of horizontally polarized protons. The squares are the vertical polarization with the snake off and the injection of vertically polarized protons. The maximum vertical polarization is reduced significantly by a mismatch of the stable spin directions at injection. There is a systematic normalization uncertainty of about $\pm 4\%$. The dashed curves are hand-drawn lines to guide the eye.

the fairly sharp peak reported earlier;[7] however, the imperfection field in the Cooler Ring solenoids was now varied in much finer steps than before. This fine detail gave a most surprising result; there is an extremely sharp dip on each side of the peak. The polarization appears to go to zero in each dip. These narrow dips were unexpected; they seemed to be some new type of depolarizing resonance. These dips were at first difficult to believe because they were so narrow, but they were reproducible. Indeed, we first saw the unanticipated dip to the left of the peak in an earlier run.[11] Moreover, as shown in Fig. 1, these narrow dips occur simultaneously in the radial polarization at exactly the same $\int \mathbf{B} \cdot d\mathbf{l}$ values.

Of the several ideas about these narrow dips, the most likely explanation seemed to be synchrotron depolarizing resonances; these had been seen in an electron ring near an intrinsic resonance,[12] but had never been seen near an imperfection resonance. The synchrotron tune ν_{syn} is the number of times that a proton's energy oscillates about the average energy in each turn around the ring. Since a proton's orbit depends on its energy, each proton sees depolarizing magnetic fields which vary with this oscillation frequency. The spin tune ν_{spin} is the number of times that a proton's spin precesses in each turn around the ring. Thus, a synchrotron depolarizing resonance will occur whenever

$$\nu_{spin} = n \pm \nu_{syn} \quad (n = \text{integer}). \tag{3}$$

The spin tune is normally equal to $G\gamma$. However, the precession in the Cooler Ring solenoids can add to the spin rotation[7] and thus shift the spin tune by $\Delta\nu_{spin}$. Thus, whenever the equation

$$G\gamma + \Delta\nu_{spin} = n \pm \nu_{syn} \quad (n = \text{integer}) \tag{4}$$

is satisfied, then a synchrotron depolarizing resonance should occur. The distance of each narrow dip from the peak in Fig. 1 agrees approximately with recent estimates[13] of $\Delta\nu_{spin}$, but this does not prove that the dips are synchrotron resonances. Moreover, note that the two dips in Fig. 1 occur at equal distances from the peak, but their widths are not identical.

For the Cooler Ring at 104 MeV the synchrotron tune is related to the rf accelerating voltage, V_{rf} in volts, by the equation[14]

$$\nu_{syn} = 7.5 \times 10^{-5} (V_{rf})^{1/2}. \tag{5}$$

We tested the synchrotron depolarizing resonance hypothesis by varying the rf accelerating voltage in the Cooler Ring to study the effect of V_{rf} on the polarization. According to Eqs. (4) and (5) this variation should significantly shift the dips. Fortunately, we could vary V_{rf} over a wide range with little adverse effect on the beam optics in the Cooler Ring. It would have been very time consuming to repeat Fig. 1, where $V_{rf} = 2765$ V, for many different values of V_{rf}. We instead set the longitudinal solenoid imperfection field in the center of the left dip and then measured the vertical polarization while varying V_{rf}. These data, which are shown in Fig. 2, clearly demonstrate that the depolarization is related to V_{rf}. This appears to be direct evidence that the dips are indeed synchrotron depolarizing resonances.

We then tested the ability of a Siberian snake to overcome these synchrotron depolarizing resonances. With the imperfection solenoid field still set at the center of the left dip, we turned on the snake. Since the stable spin direction was then horizontal, we injected horizontally polarized protons at 104 MeV by rotating the vertical polarization prior to injection. The injected horizontal polarization direction and the calculated stable spin direction at the injection point were identical to within about $\pm 2°$. We then measured the radial polarization in the ring while varying the rf voltage. We again operated the snake without using the eight correction quadrupoles and tolerated the small shifts in the betatron tune of the Cooler Ring.[7] As shown in Fig. 2 the snake eliminated all observable effects of the synchrotron depolarizing resonance. We consider these data to be further indication of a Siberian snake's ability to overcome all types of depolarizing resonances.

We also made the first test of a Siberian snake's ability to overcome an intrinsic depolarizing resonance. An intrinsic resonance is caused by the vertical betatron oscillations which in turn are due to the focusing horizontal quadrupole fields in a proton ring. As the protons oscillate above and below the beam axis ν_y times on each turn around the ring, they can be depolarized by the same horizontal quadrupole fields; the quantity ν_y is called the vertical betatron tune. An intrinsic depolarizing resonance occurs whenever the spin precession frequency becomes equal to the frequency of encountering these horizontal fields. This equality occurs whenever in the acceleration cycle γ satisfies the relation

$$\nu_{\text{spin}} = G\gamma = \pm kP \pm \nu_y , \qquad (6)$$

where G and γ were defined earlier while k is any integer and P is the ring periodicity which is 3 for the Cooler Ring.

We studied the strong $G\gamma = -3 + \nu_y$ intrinsic depolarizing resonance by injecting and storing polarized protons at 177 MeV; we then measured the polarization while using the Cooler Ring quadrupoles to vary ν_y to different values near the resonance. We used rf knockout[15] and a frequency meter to measure ν_y to a precision of about ± 0.0005. The data shown in Fig. 3 include measurements in both stable spin directions. We first injected vertically polarized protons with the snake off and measured the vertical polarization. We then injected horizontally polarized protons with the snake on and measured the radial polarization. Clearly with the snake off the beam was totally depolarized for ν_y values between about 5.125 and 5.140. With the snake turned on we maintained full polarization for all measured tune values. These data are a direct demonstration of the ability of a Siberian snake to overcome a strong intrinsic depolarizing resonance. These data also gave an absolute calibration of the energy $m\gamma$ of the Cooler Ring to a precision of about $\pm 0.03\%$.

We also used the ring quadrupoles to ramp ν_y through the $G\gamma = -3 + \nu_y$ resonance. We then found significant

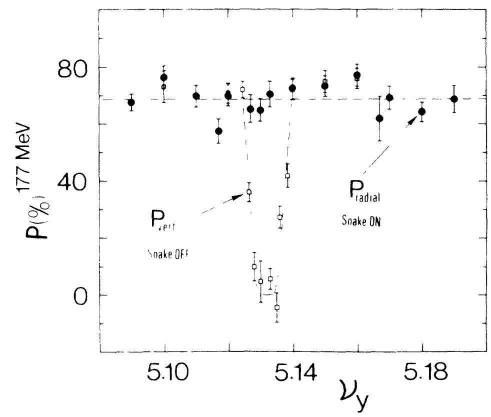

FIG. 3. The beam polarization in each stable spin direction at 177 MeV is plotted against the vertical betatron tune ν_y. The circles are the radial polarization with the snake on and the injection of horizontally polarized protons. The squares are the vertical polarization with the snake off and the injection of vertically polarized protons. There is a systematic normalization uncertainty of $\pm 4\%$. The dashed curves are hand-drawn lines to guide the eye.

depolarization without the snake $[P_{\text{vert}}/P_{\text{injected}} = (25.8 \pm 8.1)\%]$ and no observable depolarization with the snake turned on $[P_{\text{rad}}/P_{\text{injected}} = (94.8 \pm 8.0)\%]$. This tune ramping was equivalent to accelerating through the resonance; it thus directly tested a snake's ability to overcome a strong intrinsic depolarizing resonance during acceleration.

We made many other studies of the properties of Siberian snakes including the following: studies of partial snakes, studies of acceleration through the $G\gamma = 2$ imperfection resonance, studies of radial imperfection fields, and studies of the $G\gamma = 7 - \nu_y$ intrinsic resonance by shifting its energy using a partial snake. The studies were made with the injected polarization both horizontal and vertical and with both the radial and vertical polarization measured. Some of these results can be found in Refs. 11 and 16. We plan to later publish a detailed paper describing all these studies which consistently indicate that Siberian snakes overcome depolarizing resonances. We are now becoming more optimistic that snakes can be used to overcome all types of depolarizing resonances. Thus it may now be technically feasible to accelerate polarized beams to very high energies at facilities like KAON, U-70, RHIC, the Fermilab main ring, the Tevatron, HERA, UNK, and the SSC.

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