VOLUME 63, NUMBER 11 PHYSICAL REVIEW LETTERS 11 SEPTEMBER 1989

First Test of the Siberian Snake Magnet Arrangement to Overcome Depolarizing Resonances in a Circular Accelerator

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(Received 25 July 1989)

We studied the $G\gamma=2$ imperfection depolarizing resonance at 108 MeV, both with and without a Siberian snake, by varying the resonance strength while storing beams of 104- and 120-MeV polarized protons at the Indiana University Cooler Ring. We used a cylindrically symmetric polarimeter to simultaneously study the effect of a depolarizing resonance on both the vertical and radial components of the polarization. At 104 MeV we found that the Siberian snake eliminated the effect of the nearby $G\gamma=2$ depolarizing resonance.

PACS numbers: 41.80.−y, 07.77.+p, 29.25.Fb, 29.75.+x

In all circular proton accelerators there are certain energies where the spin precession frequency exactly matches the frequency with which the protons see depolarizing magnetic fields. At these "depolarizing resonances" any horizontal fields can interact coherently with the spins and rapidly depolarize the beam. The successful acceleration of polarized proton beams to GeV energies at the ZGS,[1] Saturne,[2] the AGS,[3] and KEK[4] required considerable effort to overcome the depolarizing resonances individually. The number of resonances is approximately proportional to the energy; thus, at TeV energies there are thousands of depolarizing resonances, and maintaining polarization will be very difficult.

An arrangement of magnets, called a Siberian snake, was proposed[5] to simultaneously overcome all imperfection and intrinsic depolarizing resonances. On each turn around the ring, a snake rotates the spin of each proton by 180° about a horizontal axis. The effects of the depolarizing horizontal magnetic fields then exactly cancel themselves on successive turns; this cancellation should eliminate all depolarization. To test[6] this concept, we constructed and installed a Siberian snake in the new Indiana University Cyclotron Facility (IUCF) Cooler Ring[7] which is shown in Fig. 1.

We recently injected, stored, cooled, stacked, and spin analyzed 104- and 120-MeV polarized proton beams in the Cooler Ring. We then studied the effect of the $G\gamma=2$ depolarizing resonance at 108 MeV on these polarized proton beams. The stored beams of polarized protons each had an intensity of about 20 nA and a cycle period of about 4 sec. We used the CE-01 detector,[8] which is cylindrically symmetric, to simultaneously measure the vertical and radial components of the beam polarization. We estimated that this polarimeter, with a 4.5-mm-thick skimmer-type carbon target and a $\Delta\phi$ range of ±45°, had an effective analyzing power over its 5° and 17° laboratory scattering angle range of about 25%±2% at 120 MeV and 19%±2% at 104 MeV.[9] Each vertical and radial polarization measurement was obtained in a run of about 1 h with a statistical error of ±3% to 5%. The vertical beam polarization before injection into the Cooler Ring was measured using a polarimeter[10] in the beam line between the two IUCF cyclotrons and found to be 77%±2% at both 120 and 104 MeV.

At each point in the Cooler Ring there exists a unique

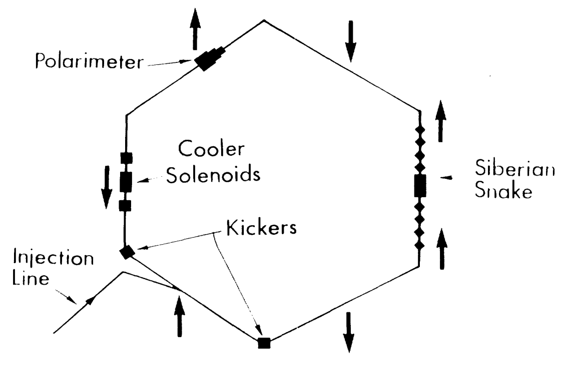

FIG. 1. Diagram of the IUCF Cooler Ring with the Siberian snake test installed. Note the kicker magnets for injection of polarized beam, the CE-01 detector used as a polarimeter, the Siberian snake, and the Cooler Ring solenoids. Each arrow indicates the stable horizontal polarization direction at 108 MeV with the snake on.

stable polarization direction; 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. The snake rotates the polarization about the longitudinal axis. The main effect of the three Cooler Ring solenoids is also a polarization rotation about the longitudinal axis; the ring-bending magnets each rotate the polarization about the vertical axis. All these rotations together produce an effective spin rotation matrix at each point in the ring; this matrix gives a fixed spin-precession axis, which is the only time-stable beam polarization direction at that point. The calculated stable horizontal polarization directions at $G\gamma=2$ with the snake turned on are shown in Fig. 1 at various points around the ring.

For a vertically polarized injected beam the magnitude of the time-average polarization along the stable spin direction is

$$P_s = P\cos\phi\,, \tag{1}$$

where P is the injected polarization and ϕ is the angle between the stable spin direction and the vertical. With no snake, the vertical, radial, and longitudinal components of the polarization at the polarimeters are as follows:

$$P_{\text{vert}} = P\cos^2\phi\,, \tag{2}$$

$$P_{\text{radial}} = -P\sin(G\gamma\theta)\sin\phi\cos\phi\,, \tag{3}$$

$$P_{\text{long}} = P\cos(G\gamma\theta)\sin\phi\cos\phi\,, \tag{4}$$

where $G(g-2)/2=1.7928$ 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. If we take $\theta=0$ for the snake, then $\theta=2\pi/3$ for the polarimeter and $\theta=\pi$ for the Cooler Ring solenoids as shown in Fig. 1. Notice that the stable polarization direction angle ϕ can be related to the longitudinal $\int \mathbf{B}\cdot dl$ in the Cooler Ring solenoids by the formula

$$\tan\phi = -\frac{\tan\{[e\int \mathbf{B}\cdot dl(1+G)]/2cp\}}{\sin(\pi G\gamma)}\,, \tag{5}$$

where p is the proton's momentum, e is its charge, and c is the speed of light.

We tested the polarimeter[8] before the Siberian snake was installed. The results turned out to be quite interesting; apparently, no one has ever before studied how a depolarizing resonance simultaneously affects two polarization directions. Both the vertical and radial polarizations at 120 MeV were measured while we varied the longitudinal magnetic field in the Cooler Ring; thus, we varied the resonance strength while holding the energy fixed. We produced a longitudinal imperfection field in the Cooler Ring by varying the $\int \mathbf{B}\cdot dl$ in the main cooling solenoid and in two nearby compensating solenoids. The main solenoid's $\int \mathbf{B}\cdot dl$ was typically 0.5 Tm. Figure 2 contains the data for both variations plotted on a single axis using an empirical relative calibration of the solenoids.[11] When the correction made this field approximately zero, two things happened simultaneously: The vertical polarization peaked to its maximum value and the radial polarization passed through zero. The stable polarization direction was then vertical. When the correction was poor, the vertical polarization decreased significantly while the radial polarization increased to a positive or negative value depending on the sign of $\int \mathbf{B}\cdot dl$. This means that the "stable polarization direction" rotated as the solenoids were adjusted.

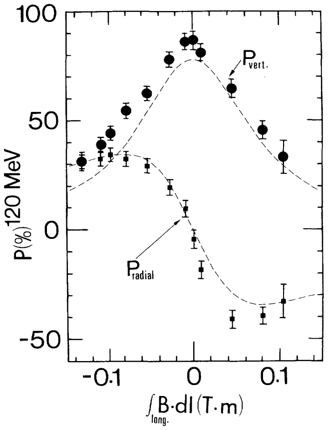

FIG. 2. The vertical and radial components of the beam polarization at 120 MeV are plotted against the longitudinal magnetic field integral in the Cooler Ring solenoids with the snake off and the injection of vertically polarized protons. There is a systematic normalization uncertainty of about ±4%. The dashed curves are the predicted behavior.

These 120-MeV data show for the first time that nonvertical stable polarization directions can exist in a stored polarization beam. At an $\int \mathbf{B}\cdot dl$ of about -0.135 Tm, there is clearly a stable polarization of about 46% at an angle of about 45° with the vertical. Notice that this nonvertical polarization value lasts throughout the 3-sec storage time, which corresponds to about 6×10^6 turns around the Cooler Ring. This observation of a stable nonvertical polarization direction is perhaps the first experimental hint that the Siberian snake concept may be correct. One can think of the three Cooler Ring solenoids as a partial Siberian snake.[12]

We then made the first study of a depolarizing resonance with a Siberian snake. The results with 104-MeV polarized protons show that the snake significantly changes the effect of the nearby $G\gamma=2$ depolarizing resonance. Exactly on resonance the polarization may be so sensitive to the horizontal magnetic fields that maintaining polarization may require a Siberian snake; the snake's 180° spin rotation should dominate the spin precession near the resonance. At high energy, Siberian snakes are best made using about eight transverse field magnets. Fortunately, a solenoid, which gives a 180°

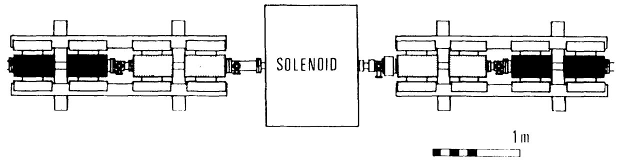

FIG. 3. The Michigan-IUCF Siberian snake as installed in the Cooler Ring.

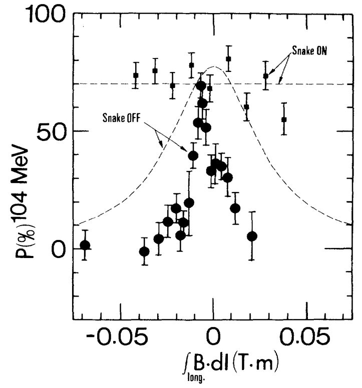

FIG. 4. The beam polarization in each stable polarization direction at 104 MeV is plotted against the longitudinal magnetic field integral in the Cooler Ring solenoids. The circles are the vertical polarization with the snake off and the injection of vertically polarized protons. The squares are the radial polarization with the snake on and the injection of horizontally polarized protons. We combined all data into bins of width 0.001 15 Tm. There is a systematic normalization uncertainty of about ±5%. The dashed curve is the predicted behavior. The straight dashed line is a fit.

longitudinal spin rotation, is a type-1 snake that is much easier to construct at low energy. The Michigan-IUCF Siberian snake, which is shown in Fig. 3, contains a superconducting solenoid that rotates each proton's spin by 180° about the longitudinal axis. The four outer quadrupoles, shown in black, focus the beam to compensate for the focusing of the solenoid; the four inner skew quadrupoles, shown in shading, rotate the beam to compensate for the orbit rotation caused by the solenoid.

We injected horizontally polarized protons at 104 MeV by using another superconducting solenoid[13] to rotate the vertical polarization by 90° prior to injection. At the injection point, the calculated horizontal polarization direction and the calculated stable spin direction were both about 30° from the radial direction; these directions have an uncertainty of about ±2°. We then used the polarimeter[8] to measure both the radial and vertical polarizations while again varying the longitudinal $\int \mathbf{B}\cdot dl$ using the Cooler Ring solenoids. We operated the snake without using the eight correction quadrupoles since it was then easier to store the beam at the previously untested energy of 104 MeV. This somewhat shifted the ν_x and ν_y of the Cooler Ring; however, such shifts should not strongly affect the strength or width of the $G\gamma=2$ imperfection resonance.

We made two sets of measurements at 104 MeV, each in the appropriate stable spin direction. The circles in Fig. 4 were measured with the snake solenoid turned off and with the injection of vertically polarized protons; the stable spin direction is vertical with no snake. The squares were measured with the injection of horizontally polarized protons and the snake set to rotate the polarization by 180° on each turn around the Cooler Ring. With the snake turned on the stable polarization direction is always horizontal as shown in Fig. 1. The Siberian snake clearly caused a dramatic change in the effect of the $G\gamma=2$ depolarizing resonance. With the snake off the vertical polarization decreased very sharply when the longitudinal field was not exactly corrected to zero; this peak was about 10 times sharper than the 120-MeV peak shown in Fig. 2. We also injected horizontally polarized protons at 104 MeV with the snake off; then both the measured, but unplotted, vertical and radial polarizations varied rapidly as we changed the longitudinal field.

The width of the P_{vert} curve and equivalently the sharpness of the P_{radial} zero crossing each give an indication of the proximity of the $G\gamma=2$ imperfection resonance. As shown in Fig. 2, the measured polarizations at 120 MeV agreed rather well with the calculations using Eqs. (2), (3), and (5). But there was only qualitative agreement at 104 MeV as shown in Fig. 4. The disagreement at 104 MeV may come from an energy miscalibration or from additional imperfection fields. Such factors are more important at 104 MeV, because 104 MeV is much closer to the $G\gamma=2$ resonance than 120 MeV.[14] Thus, with no snake the polarization was extremely sensitive to the imperfection magnetic fields in the Cooler Ring.

The behavior was totally different when the snake was turned on to rotate the polarization by 180°. The measured, but unplotted, vertical polarization was then always consistent with zero, as expected. However, the radial polarization maintained a constant value of about 70% at all settings of the imperfection longitudinal field as shown in Fig. 4. This 70% was close to the calculated radial polarization at the polarimeter of $(77\%)\cos 30° = 67\%$. Note that our variable imperfection field was always parallel to the longitudinal stable spin direction at the Cooler Ring solenoid; we hope to soon have a variable radial imperfection field available.[15] In summary, the snake apparently made the beam polarization at 104 MeV independent of the effect of the nearby depolarizing resonance at 108 MeV. We consider these data to be a strong indication that the Siberian snake concept is correct.

We also made some preliminary studies of partial Siberian snakes,[12] which might be especially important at medium-energy facilities where the depolarizing resonances are fairly weak. Our next goal is to accelerate a polarized proton beam through the $G\gamma = 2$ imperfection depolarizing resonance at 108 MeV and the $G\gamma = -3 + \nu_y$ intrinsic depolarizing resonance near 179 MeV. The rather slow Cooler Ring acceleration rate of about 0.1 $\sec^{-1}$ will sharply increase the effects of these resonances compared to the AGS,[3] where $d\gamma/dt$ is about 50 $\sec^{-1}$. In fact, the Cooler Ring resonances may cause total spin flip rather than depolarization; this might make the test more difficult, since a spin-flipped beam is still fully polarized. Therefore, we plan to improve our capacity to correct both longitudinal and radial imperfections.[15] This should help us to directly test the ability of a Siberian snake to eliminate depolarizing resonances during acceleration. Siberian snakes might then be used to accelerate polarized protons to very high energy at facilities such as SSC, UNK, Tevatron, and HERA; they might also be used at facilities near 100 GeV, such as RHIC, U-70, KAON, and the AGS.

We would like to thank T. Bertuccio, J. M. Cameron, G. East, T. Ellison, D. L. Friesel, J. Hicks, K. Komisarcik, R. Palmer, W. T. Sloan, P. Schwandt, and the entire IUCF staff for the successful operation of the IUCF Cyclotron and Cooler Ring and for the successful installation of the Siberian snake. We also thank A. Berdoz, H. Nann, S. Pate, and A. Roberts for their help with the CE-01 detector. We are grateful to O. Chamberlain, W. Fry, J. Geller, R. Raylman, H. Sato, L. C. Teng, and U. Wienands for advice and help. This research was supported by grants from the U.S. Department of Energy and the U.S. National Science Foundation.

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