ACCELERATOR PHYSICS

STUDY OF A DEPOLARIZING RESONANCE AT THE IUCF COOLER RING

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We studied the $G\gamma=2$ imperfection depolarizing resonance at 108 MeV using an electron-cooled beam of 120 MeV polarized protons, while varying the resonance strength. Using the CE-01 detector as a polarimeter allowed the first simultaneous study of the effect of a depolarizing resonance on both the vertical and radial polarization. The data indicates that the "stable polarization direction" rotates away from the vertical as the ring's net integrated longitudinal magnetic field is varied.

The $G\gamma=2$ imperfection resonance exists at 108 MeV in all circular proton accelerators. At this energy the spin of each proton precesses twice around the vertical axis on each turn around the ring. Any horizontal imperfection fields in the ring can then interact coherently with the spins and depolarize the beam. A novel arrangement of magnets, called a Siberian Snake, was proposed[1] to eliminate these depolarizing resonances. On each turn around a ring, a Snake rotates the spin of each proton by 180° about the longitudinal direction; the depolarizing horizontal magnetic fields on successive turns then exactly cancel each other, which eliminates the depolarizing resonances. In order to test[2] the Siberian Snake concept, the CE-05 collaboration[3] between the University of Michigan, the Indiana University Cyclotron Facility (IUCF) and Brookhaven National Laboratory has constructed a Siberian Snake for installation in the new IUCF Cooler Ring[4] which is shown in Fig. 1. We recently injected, stored, cooled, stacked, and spin-analyzed a polarized proton beam in the Cooler Ring; we then studied the effect of the $G\gamma=2$ depolarizing resonance on these 120 MeV polarized protons with the Snake absent.

Experiment

We used a stored beam of 120 MeV polarized protons at the IUCF Cooler Ring with an intensity of about 20 nA and a cycle period of about 4 s. We measured the vertical and radial polarizations of this beam using the CE-01 detector.[5] The detector is azimuthally symmetric and thus could simultaneously measure the vertical and radial component of the beam polarization. With a 4.5 mm thick carbon target, this polarimeter had an effective analyzing power of about 26.5% at 120 MeV over its 5° to 17° scattering angle range. Each vertical and radial polarization measurement was obtained in about 1 hour of running time

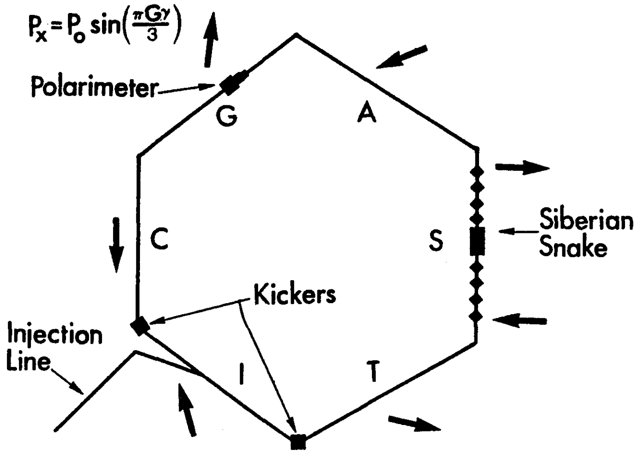

Figure 1. Diagram of CE-05 installed in the IUCF Cooler Ring. Note the kicker injection magnets, the CE-01 detector used as a polarimeter and the Siberian Snake. The arrows indicate the stable direction of the horizontal polarization at $G\gamma=2.5$.

with a statistical error of about ±0.03. The vertical beam polarization at injection into the Cooler Ring was measured to be 0.772 ± 0.002 using a polarimeter[6] in the beam line between the two IUCF cyclotrons.

We adjusted the net longitudinal $\int B\cdot d\ell$ in the Cooler Ring by varying the field in the main cooling solenoid in the C region and in two nearby compensating solenoids. The main solenoid $\int B\cdot d\ell$ was typically 0.5 T · m. In attempting to compensate for the main solenoid's field, we eventually reached the 375 A limit of the compensating solenoids' power supply. We then continued the measurements by reducing the main solenoid current. Figure 3 contains the data for both variations plotted on a single axis using the following relative calibration of the solenoids:

$$\int B\cdot d\ell = (1.19\ \mathrm{T\cdot m/kA})\mathrm{I_{comp}} - (0.440\ \mathrm{T\cdot m/kA})\mathrm{I_{main}} - 0.050\ \mathrm{T\cdot m} \qquad (1)$$

This calibration uses effective lengths of 0.519 m for each compensating solenoid and 2.74 m for the main solenoid. The arbitrary constant was chosen to zero the crossing in Fig. 3.

In March 1989 we installed the Michigan-IUCF Siberian Snake, which is shown in Fig. 2. The superconducting solenoid in the center rotates the spin by 180° about the

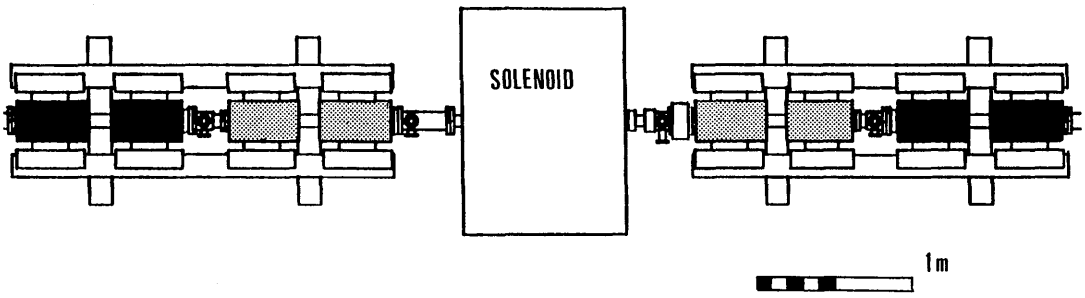

Figure 2. Michigan - IUCF Siberian Snake installed in the Cooler Ring.

longitudinal axis on each turn around the Cooler Ring. The 4 outer quadrupoles (in black) focus the beam to compensate for the focusing of the solenoid; the 4 inner quadrupoles (in shading) rotate the beam to compensate for an orbit rotation caused by the solenoid. In April 1989 we successfully tested the Snake with an unpolarized beam. We also studied a number of interesting beam dynamics properties including beam loss, $\nu_x - \nu_y$ coupling, and vertical dispersion. We hope to soon study these orbit properties in more detail.

Our main data taking runs with the Snake should begin this Spring using a polarized beam. We have already demonstrated four important points relevant to these studies:

1. The Cooler Ring can now store a 77% polarized beam using kicker injection.
2. The CE-01 detector is a versatile and fast polarimeter.
3. The $G\gamma=2$ resonance is certainly strong enough to adequately test the Snake Concept.
4. The Snake can be fully energized without destroying the beam.

We hope to have some information about the validity of the Siberian Snake concept by the end of 1989.

Spin Precession in the Cooler Ring

At each point in the Cooler Ring there exists a unique stable polarization direction; the polarization should always return unchanged to this direction after each turn around the ring. This stable polarization direction may have both a radial and vertical component, as well as an unobservable longitudinal component. The various ring and cooling system bending magnets each rotate the polarization about some axis. The main effect of the electron cooling system is to rotate the protons' polarization direction about the longitudinal axis. At each point in the ring all these rotations together produce an effective spin rotation matrix which gives the fixed precession axis for the protons' spins. The only time-stable beam polarization direction is along this fixed axis. As an example, the calculated stable horizontal polarization directions at $G\gamma=2.5$ (370 MeV) are shown in Fig. 1 at various points around the ring with the Snake turned on.

For a vertically polarized injected beam the magnitude of the polarization along the stable spin direction is:

$$P_s = P \cos\phi \tag{2}$$

where P is the injected polarization and ϕ is the angle between the stable spin direction at injection and the vertical. The equations that govern the vertical (P_{vert}), radial (P_{radial}), and longitudinal (P_{long}) polarizations near the polarimeter are:

$$P_{vert} = P \cos^2\phi \tag{3}$$

$$P_{radial} = P \sin[(\pi - \theta)G\gamma] \sin\phi \cos\phi \tag{4}$$

$$P_{long} = P \cos[(\pi - \theta)G\gamma] \sin\phi \cos\phi \tag{5}$$

where θ is the angle around the Cooler Ring ($\theta = 0$ for the Cooler solenoid in region C and $\theta = -\pi/3$ for the polarimeter), $G = \frac{g-2}{2} = 1.7928$ is the anomalous part of the proton's magnetic moment, and $\gamma = E/m$ is the energy parameter. Notice that the angle ϕ between the precession direction and the vertical can be related to the net longitudinal $\int B \cdot d\ell$ in the Cooler section by the formula

$$\tan\phi = \frac{\tan\left(\frac{e\int B\cdot d\ell\,(1+G)}{2\,cp}\right)}{\sin(\pi\,G\gamma)} \tag{6}$$

where p is the momentum and c is the speed of light.

When the compensating solenoids are adjusted to exactly cancel the remaining longitudinal $\int B \cdot d\ell$ of the Cooler Ring, the stable spin precession axis at the polarimeter should be vertical. At this point the radial and longitudinal polarization should both be zero and the vertical polarization should be maximized.

Results

Any horizontal magnetic fields can depolarize the beam near the $G\gamma=2$ imperfection depolarizing resonance at 108 MeV. We measured both the vertical and radial polarization at 120 MeV while changing the net longitudinal magnetic field in the Cooler Ring; thus, we varied the resonance strength while holding the energy fixed. The sensitivity to this magnetic field increases near the resonance energy. Thus, the width of the resonant behavior seen in Fig. 3 is strongly related to the proximity in energy to the 108 MeV

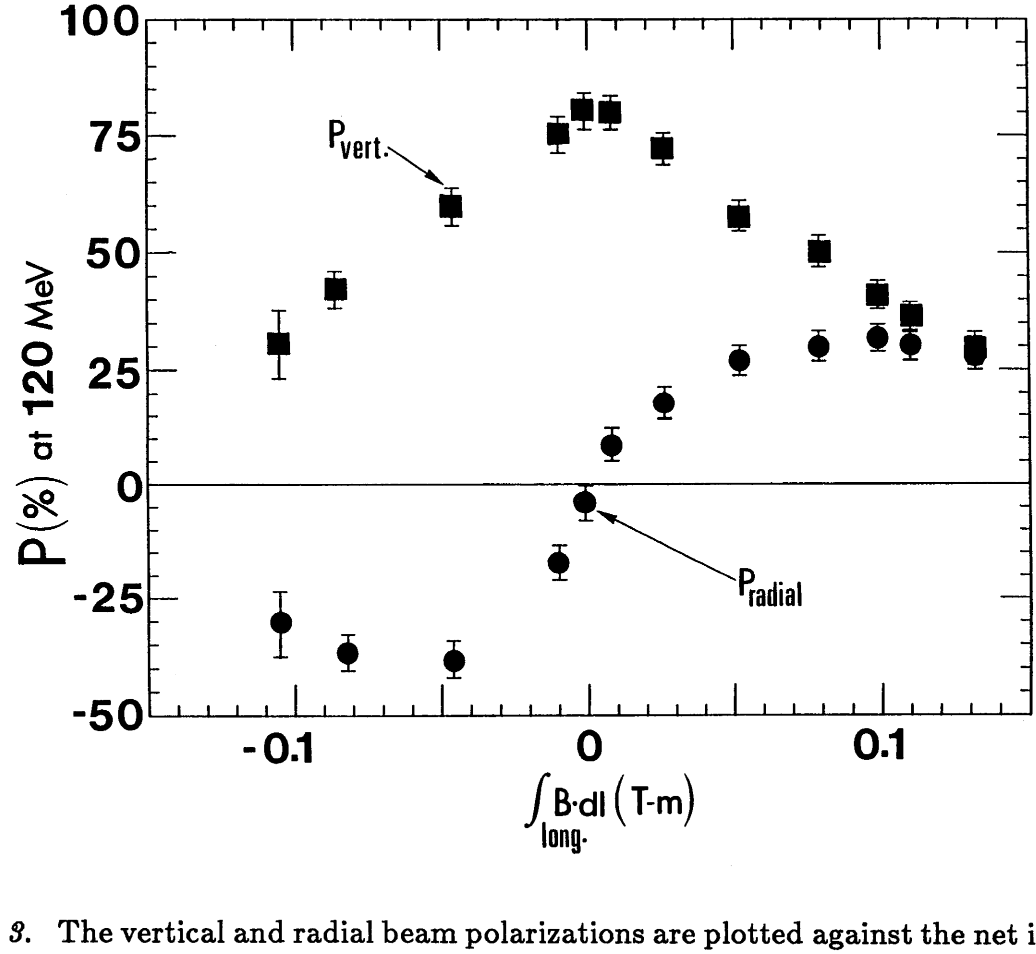

Figure 3. The vertical and radial beam polarizations are plotted against the net integrated longitudinal magnetic field in the IUCF Cooler Ring.

resonance. In fact, exactly on resonance the polarization is so sensitive to the longitudinal and radial magnetic fields that exact compensation becomes difficult. The easiest method of maintaining polarization may then be to use a Siberian Snake. The 180° spin rotation introduced by the Snake should overcome any imperfection fields and dominate the spin precession near the resonance. However, far from a resonance the polarization is less sensitive to the precession angle in the solenoids. Thus, the width of the P_{vert} curve and equivalently the sharpness of the P_{radial} zero-crossing give an indication of the proximity to the $G\gamma=2$ imperfection resonance.

Since the Siberian Snake was not yet installed, this run was intended as a polarimeter test, however the results also turned out to be most interesting with respect to spin dynamics in a storage ring. Apparently, no one has ever before studied how a depolarizing resonance simultaneously affects two polarization directions. Both the vertical and radial polarizations were measured while three small solenoids were used to vary the net longitudinal magnetic field in the Cooler Ring. As shown in Fig. 3, when the correction was perfect so that the net field was zero, two things happened simultaneously: the vertical polarization peaked to its maximum value of about 77% and the radial polarization passed through zero. When the correction was poor, the vertical polarization decreased to about 30% while the radial polarization increased to about +35% or −35% depending on the sign of the mismatch. This means that the "stable polarization direction" rotated as the solenoids were adjusted.

When the solenoidal field was zero, the "stable polarization direction" was vertical and the beam was vertically polarized. The new data shows for the first time that non-vertical stable polarization directions can exist in a stored polarized beam. At an $\int B \cdot d\ell$ of about 0.135 $T \cdot m$, there is clearly a stable polarization with a magnitude of about 0.42 which makes an azimuthal angle of about 45° with the vertical. Notice that this non-vertical polarization value lasts throughout the 3 seconds storage time, which corresponds to about $6 \cdot 10^6$ turns around the Cooler Ring. This observation of a stable, non-vertical polarization may be the first experimental hint that the Siberian Snake concept is correct. One can think of the 3 Cooler solenoids as a "partial Siberian Snake" which might overcome weak depolarizing resonances.[7]

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Note Added in Proof: In May 1989 we successfully made the first study of a depolarizing resonance with a Siberian Snake. The results using 104 MeV polarized protons are now being analyzed; they show that the Snake sharply changes the behavior of the $G\gamma=2$ depolarizing resonance at 108 MeV.

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