FIRST PARTIAL SIBERIAN SNAKE TEST DURING ACCELERATION, ADIABATIC PARTIAL SIBERIAN SNAKE TURN-ON AND SPIN FLIPPING[†]

V.A. Anferov,[a] B.B. Blinov,[a] C.M. Chu, E.D. Courant,[b] D.A. Crandell, W.A. Kaufman, A.V. Koulsha,[a] A.D. Krisch, T.S. Nurushev, R.A. Phelps, D.B. Raczkowski, L.G. Ratner,[b] S.E. Sund, and V.K. Wong[c]
Randall Laboratory of Physics, University of Michigan, Ann Arbor, Michigan 48109-1120

D.D. Caussyn,[d] Ya.S. Derbenev,[e] T.J.P. Ellison, S.Y. Lee, T. Rinckel, P. Schwandt, F. Sperisen, E.J. Stephenson, and B. von Przewoski
Indiana University Cyclotron Facility, Bloomington, Indiana 47408-0768

R. Baiod
Fermilab, Batavia, Illinois 60510

F.Z. Khiari
Energy Research Laboratory, King Fahd University, Dhahran 31261, Saudi Arabia

M.G. Minty
Stanford Linear Accelerator Center, Stanford, California 94309-4349

C. Ohmori,[f] and H. Sato
KEK, 1-1 Oho, Tsukuba-shi, Ibaraki-ken 305, Japan

U. Wienands[g]
SSC Lab, Dallas, Texas 75237-3946

Many spin-depolarizing resonances occur during the acceleration of a polarized proton beam in a high energy circular ring. The individual resonance correction technique used at the ZGS,[1] Saturne,[2] KEK[3] and the AGS[4] becomes impractical above beam energies of about 20 GeV. Recent experiments[5–10] at the IUCF Cooler Ring demonstrated that a full Siberian snake[11] could overcome an imperfection depolarizing resonance,[5] an intrinsic resonance[6] and overlapping resonances[9] by rotating the spin of each proton by 180° on each turn around the ring.

However, the orbit distortions caused by a full transverse Siberian snake are especially large at injection in medium-energy accelerators such as the Fermilab Main Injector and the Brookhaven RHIC. This large orbit excursion problem could be overcome if the adiabatic turn-on of a Siberian snake does not cause depolarization. The strong higher energy depolarizing resonances could then be overcome by adiabatically turning on a full snake

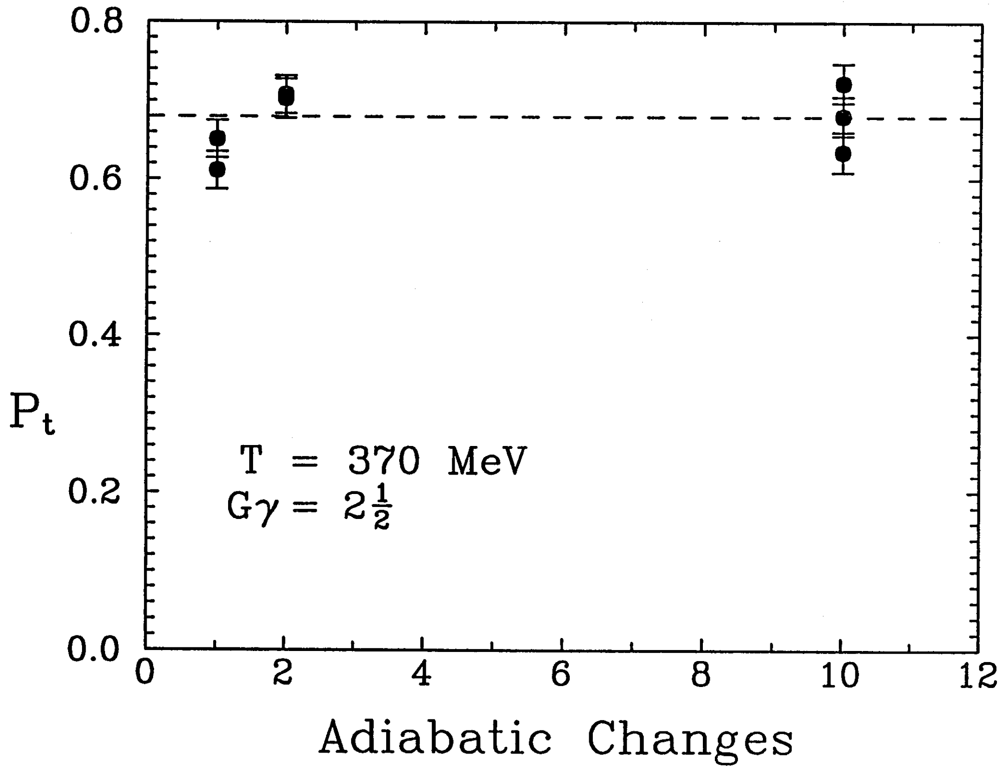

Figure 1. The transverse polarization, $P_t = \sqrt{P_v^2 + P_r^2}$, at 370 MeV is plotted against the number of times the 25% partial Siberian snake was turned on or off. The dashed line is the best fit to the data; the data show no depolarization within our 2% precision.

near 20 GeV; while the weaker low energy resonances could be overcome using either earlier techniques[1–4] or a partial Siberian snake.[8]

We recently constructed two rampable warm solenoid magnets which bracketed our existing superconducting solenoid to form a variable strength Siberian snake; we could vary the snake's strength between about 0 and 25% at 370 MeV, where the spin tune, ν_s, is exactly $2\frac{1}{2}$ either with or without a snake. As shown in Fig. 1, we measured the beam polarization after adiabatically varying the snake either once, twice or ten times; we found no polarization loss within our 2% precision.[10] This result supports the conjecture that a Siberian snake can be ramped adiabatically at an energy where the spin tune is a half-integer. This adiabatic Siberian snake turn-on capability could allow more efficient acceleration of polarized proton beams at medium-energy accelerators by avoiding the low energy orbit distortion problems.

We also studied the capabilities of a partial Siberian snake during polarized beam acceleration.[12] We accelerated a polarized proton beam from 95 to 140 MeV, while ramping a 10% partial Siberian snake along with the acceleration cycle. As shown in Fig. 2, the 10% partial snake successfully overcame all observable depolarization due to acceleration through the $G\gamma = 2$ imperfection depolarizing resonance near 108 MeV. Note that $G = 1.792847$ is the proton's anomalous magnetic moment while γ is the proton's total energy divided by its rest mass.

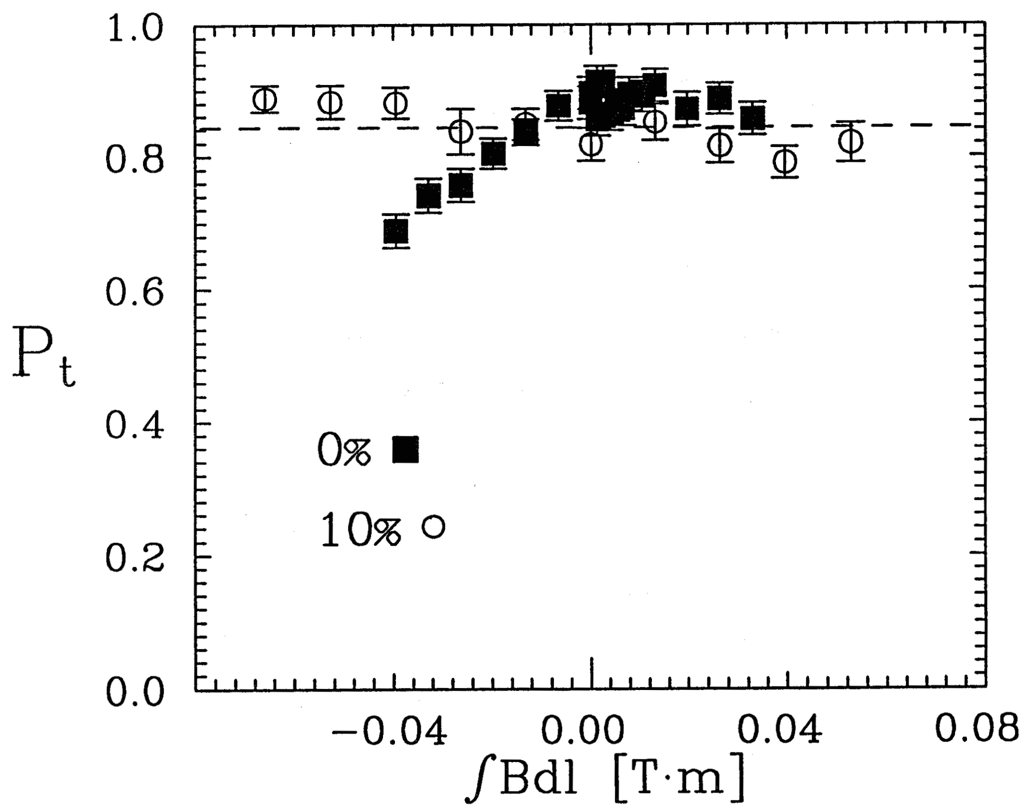

Figure 2. The transverse polarization, $P_t = \sqrt{P_v^2 + P_r^2}$, measured[12] at 140 MeV is plotted against the imperfection $\int B \cdot d\ell$ with no snake and with a 10% partial Siberian snake. The dashed line is the best constant polarization fit to the snake-on data. The beam was accelerated from 95 to 140 MeV.

However, we also found[12] that a 20% or 30% partial Siberian snake apparently moved the $G\gamma = 7 - \nu_y$ intrinsic depolarizing resonance from its normal energy near 177 MeV into our 95 to 140 MeV acceleration range. This caused some interesting but not yet fully understood behavior of the beam polarization during acceleration; this behavior is shown in Fig. 3, where we study the beam polarization during acceleration with a partial Siberian snake of strength 0%, 10%, 20% or 30%.

In most polarized beam and polarized target experiments, reversing the polarization direction reduces the systematic errors due to possible efficiency and acceptance mismatches of the detectors. We studied the spin-flip of a stored vertically polarized proton beam by using our RF solenoid[9] which could induce an artificial depolarizing resonance. We measured the vertical and radial polarization at 139 MeV, while ramping the solenoid frequency through the spin precession frequency; this caused a depolarizing resonance which induced spin-flip. In Fig. 4, the vertical polarization after ramping through the resonance once is plotted against the RF ramp time. A complete spin-flip occurs for ramp times of 20 msec or longer, with an RF solenoid strength of 0.0014 T·m and with the RF frequency ramping from 1.75 kHz below the resonance to 1.75 kHz above the resonance. The curve shown in Fig. 4 is calculated using the Froissart-Stora equation.[13]

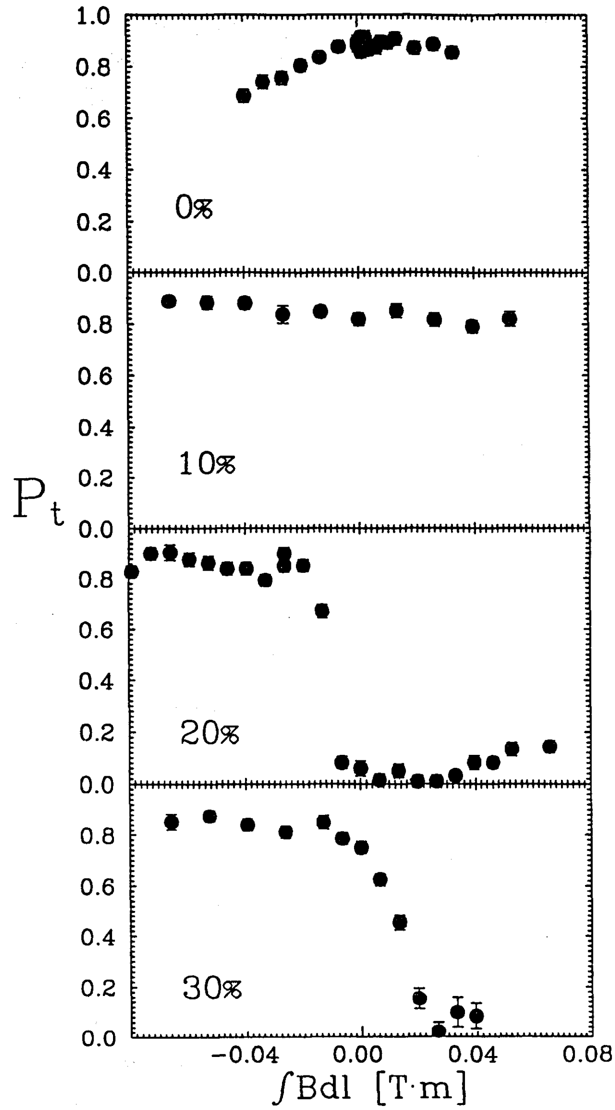

Figure 3. The transverse polarization, $P_t = \sqrt{P_v^2 + P_r^2}$, measured[12] at 140 MeV is plotted against the imperfection $\int B \cdot d\ell$ for a partial Siberian snake of strength 0%, 10%, 20% and 30%. The beam was accelerated from 95 to 140 MeV.

Figure 5 shows the vertical polarization plotted against the number of RF ramps for a 160 ms RF ramp time with the same RF field strength and frequency range as in Fig. 4; the best polarization loss per flip was then about 0.4%.

Finally, we measured the polarization loss as a function of the RF ramp time, while fixing the number of spin-flips to be 50. As shown in Fig. 6, the data suggested that the optimum ramp time for efficient spin flip was about 60 ms; notice that the polarization loss for a single spin-flip was less than 0.05%.

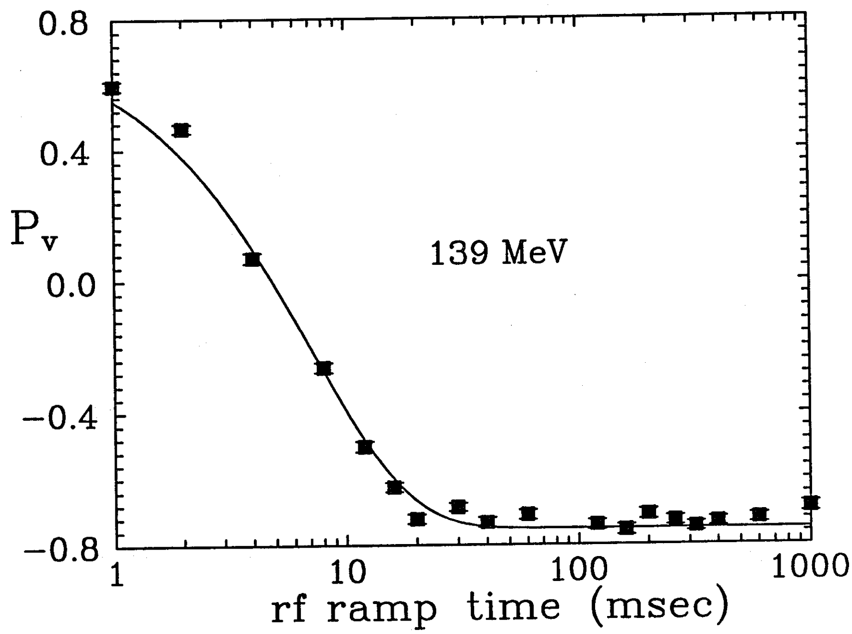

Figure 4. The vertical polarization at 139 MeV after one RF ramp is plotted against the time to ramp the frequency through a 3.5 kHz range around the RF resonance; the RF magnetic field strength was fixed.

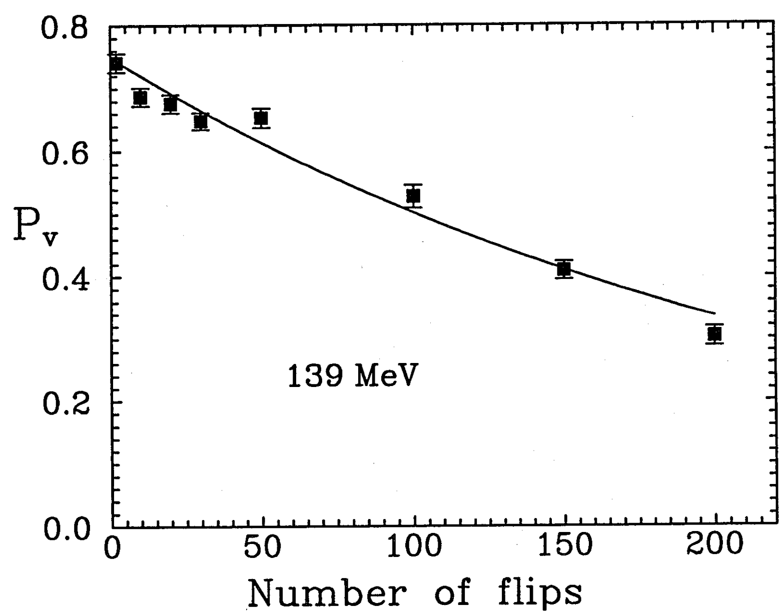

Figure 5. The vertical polarization at 139 MeV is plotted against the number of RF ramps through a 3.5 kHz range around the RF resonance frequency. The ramp time and the RF magnetic field strength were fixed. The curve is the best fit to $P_v = P_o \times p^n$ where n is the number of RF ramps.

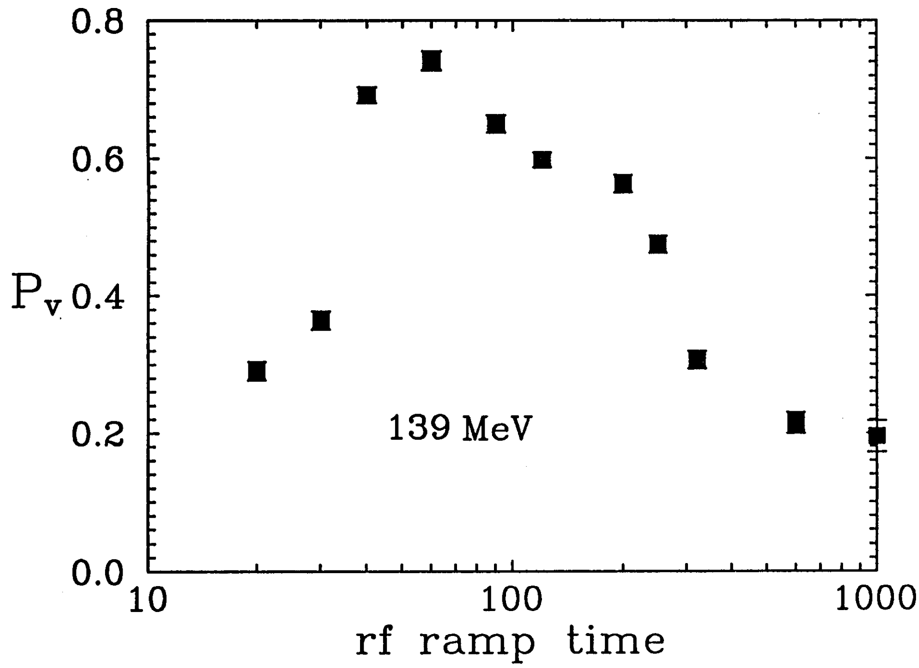

Figure 6. The vertical polarization at 139 MeV after 50 ramps is plotted against the RF ramp time. The RF magnetic field strength was the same for each ramp through a 3.5 kHz range around the RF resonance.

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a. Also at: Moscow State University, Moscow, Russia.
b. Also at: Brookhaven National Laboratory, Upton, New York, 11973.
c. Also at: Office of the Provost, University of Michigan at Flint.
d. Present address: Department of Physics, University of Michigan.
e. Also at: Department of Nuclear Engineering, University of Michigan.
f. Also at: Institute for Nuclear Study, University of Tokyo, Tokyo, Japan.
g. Present address: SLAC, Stanford CA 94309-4349

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COOLED BEAM INTENSITY LIMITS IN THE IUCF COOLER

Daniel Anderson, Mark S. Ball, Vladimir Derenchuk, Gary East, Michael J. Ellison, Tim Ellison, Brett J. Hamilton, Sergei S. Nagaitsev, and Peter Schwandt
Indiana University Cyclotron Facility, Bloomington Indiana 47408

The maximum cooled proton beam peak current stored in the IUCF Cooler at 45 MeV is about 6 mA (i.e., 6 mA coasting beam or about 1 mA for RF–bunched beams with bunching factors $[BF = I_{peak}/I_{ave}]$ of about 6). These currents have been obtained using a combination of stripping injection with electron cooling accumulation and transverse beam damping. This performance limitation is similar to that reported at other laboratories operating with similar beams:

- The LEAR ring has stored 5 mA of coasting beam using electron cooling and dampers.[1,2]
- CELSIUS has accumulated 2 mA using electron cooling accumulation and dampers.[3]

The *un-cooled* beam limit in the Cooler, however, may be 1 to 2 orders of magnitude higher. CELSIUS, for example, has accumulated and accelerated 40 mA (corresponding to a peak current of about 200 mA) using stripping injection *without* cooling[4] – about 40 times the maximum current stored at IUCF; the principal reason for this difference is the higher CELSIUS injector current, ≈ 75 μA of H_2^+ as compared to ≈ 0.75 μA of H_2^+ at IUCF.

Peak Current Limitation

As might be expected, the intensity limit in the IUCF Cooler is a peak current (I_{peak}) limit, rather than an average current (I_{ave}) limit. Since to first order we expect the bunch length to vary as $I_{ave}^{1/3}$ in the space-charge dominated regime[5,6] for a constant RF voltage, V_{rf}, it can be shown that for a constant peak current, I_{ave} should vary as $(h/V_{rf})^{1/2}$, where h is the harmonic number. Such is indeed the case in the Cooler, as illustrated in Fig. 1, where the measured maximum-achievable average stored-current is plotted as a function of the $h = 1$ RF voltage.

This suggests an operating mode that would increase I_{ave} without actually addressing the I_{peak} limit: for highly cooled beams, the balance between the space charge and RF