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# ACCELERATOR PHYSICS R & D

Final Technical Report

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Alan D. Krisch
Department of Physics
College of Literature, Science, and the Arts

The University of Michigan
Ann Arbor, Michigan 48109

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## DISCLAIMER

# FINAL TECHNICAL REPORT

TO

# U.S. DEPARTMENT OF ENERGY

## High Energy Spin Physics Group — University of Michigan

During the 1990's, we focused our Accelerator Physics program on research and development of TeV polarized proton beams using Siberian snakes:

a. Siberian snake experiments at the IUCF Cooler Ring
b. Design of polarized beam capability for the SSC
c. Design of polarized beam capability for the Main Injector and Tevatron (funded by Fermilab)
d. Design of polarized beam capability for HERA (funded by DESY)

During FY 1994 to 1997, our Siberian snake experiments at IUCF continued to be unexpectedly successful. Their data have helped us to design polarized proton beam capability for Fermilab's Tevatron and Main Injector and now for DESY's HERA.

## 1 Siberian Snakes at IUCF

The Siberian snake experiments at the IUCF Cooler Ring [CE-05, CE-15, CE-20, CE-40, CE-57 and CE-69] have been unexpectedly successful *. A Siberian snake is a device which forces an accelerator ring's depolarizing fields to cancel themselves by rotating each proton's spin by 180° on each turn around the ring.

In 1985, we organized the Ann Arbor Workshop on Polarized Beams at the SSC †. This workshop concluded that the Siberian snake concept should soon be tested somewhere; we then chose to test the first Siberian snake in the IUCF Cooler Ring. As shown in Fig. 1, we constructed and installed a Siberian snake containing a 2 $T{\cdot}m$ superconducting solenoid magnet, which rotates the spin by 180°; the snake also contains eight quadrupole magnets which do nothing to the spin, but compensate the large orbit distortions caused by the strong solenoid.

In 1989, we first demonstrated[1] that the Siberian snake concept really works by studying the $G\gamma = 2$ imperfection resonance at 108 MeV; the measured beam polarization at 104 MeV is plotted against the imperfection magnetic field in Fig. 2. With no snake, there was a full polarization of about 70% only when we exactly corrected all imperfection fields; any imperfection field rapidly killed the polarization. However, with the Siberian snake on, there was full polarization over the entire range. The Siberian snake clearly overcame this imperfection resonance.

In 1990, we studied[2] an intrinsic depolarizing resonance which is caused by the vertical betatron oscillations that exist in all accelerators. This resonance occurs in the Cooler Ring when $G\gamma = \nu_y - 3$, where $\nu_y$ is number of vertical betatron oscillations in one turn around the Ring. The polarization at 177 MeV is plotted against $\nu_y$ in Fig. 3. With the snake off, the beam is totally depolarized at the resonant $\nu_y$ of 5.13. However, with the snake on,

*The FY 1993 NSF Budget submission to Congress listed our Siberian snake program as the highlight of the NSF High Energy and Nuclear Physics Program. (NSF funds IUCF)

†Workshop on Polarized Beams at the SSC, Ann Arbor 1985, edited by A.D. Krisch, A.M.T. Lin and O. Chamberlain, A.I.P. Conf. Proc. **145** (1986).

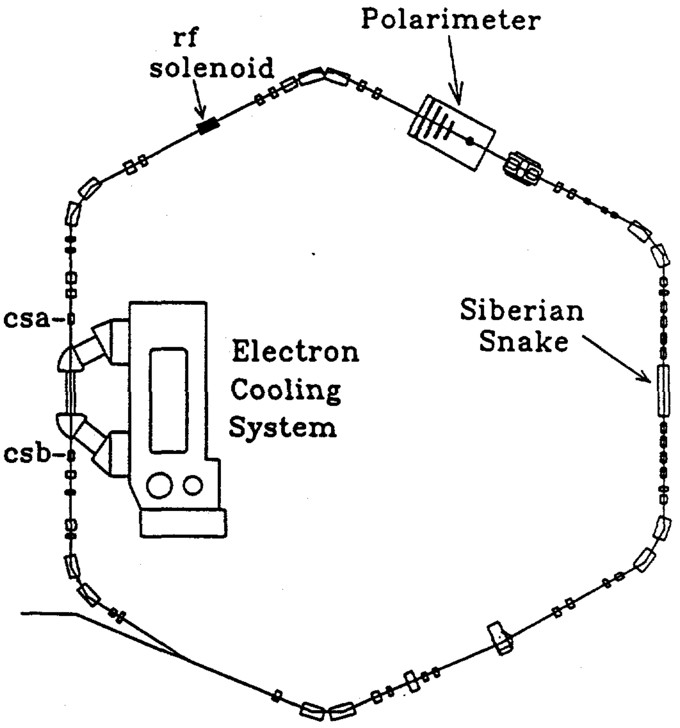


Fig. 1 Diagram of the IUCF Cooler Ring. Note the injection kicker magnets, the polarimeter, the Siberian snake, and the Cooler solenoids. [1]

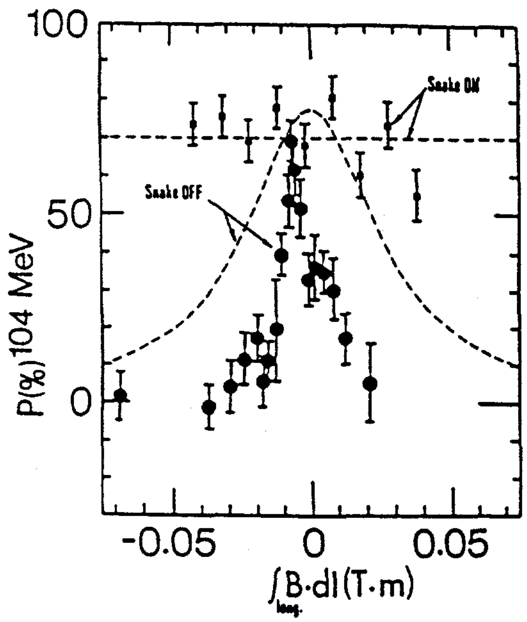


Fig. 2 Siberian snake overcoming the $G\gamma = 2$ imperfection resonance.[1]

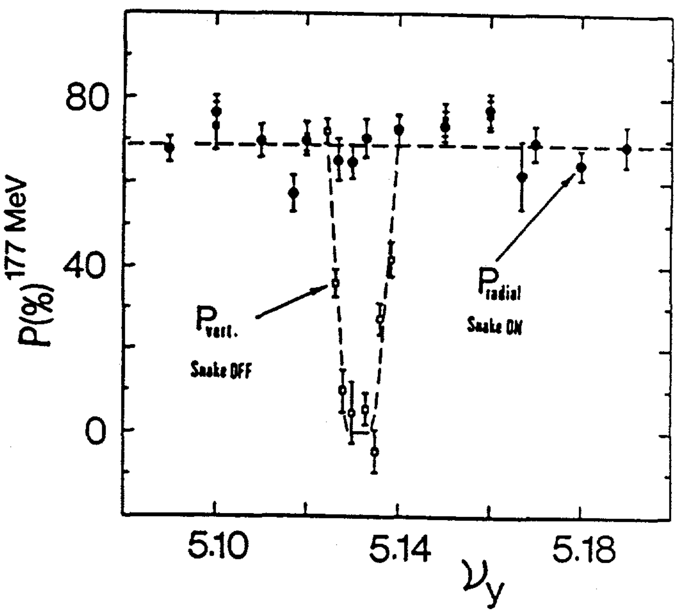


Fig. 3 Siberian snake overcoming the $G\gamma = \nu_y - 3$ intrinsic resonance.[2]

there is full polarization over the entire range. Thus the Siberian snake easily overcame this intrinsic depolarizing resonance.

In CE-15, we also found that a Siberian snake could easily overcome a synchrotron depolarizing resonance.[2] These resonances, which are caused by synchrotron oscillations in the protons' energy, appear as narrow sidebands on each side of some depolarizing resonance. Some Synchrotron sideband resonances are shown in Fig. 4.

We also discovered a "Type-3" Siberian snake which was inadvertently built into the cooling section of the Cooler Ring.[3] Type-1 and Type-2 snakes rotate the spin around the longitudinal and radial directions, respectively, while a Type-3 snake rotates the spin around the vertical direction. A Type-3 snake can only exist because spin matrices do not commute.

In CE-20, we fabricated a 25 kV rf solenoid magnet using a spare ceramic vacuum pipe from the AGS pulsed quadrupoles. We used this to create and study the properties of an "rf induced" depolarizing resonance. We first studied the effect of a partial Siberian snake on an rf depolarizing resonance[4] by measuring the resonant frequency at different snake strengths, s. As shown in Fig. 4, the measured frequency of each dip's center increases with s; these measured resonant frequencies fit quite well the predicted behavior, which is almost quadratic.

We also found that when the rf was turned on for a fixed time, the spin precessed around some stable spin direction by a fixed angle.[10] This resulted in the now-understood sinusoidal spin precession curve shown in Fig. 5.

We successfully flipped the spin of a stored polarized proton beam[15] by ramping the rf solenoid frequency through the resonant frequency as shown in Fig. 6. This spin-flip capability should allow future experiments using stored polarized proton beams to strongly discriminate against most systematic errors by flipping the spin direction every few seconds.

The behavior of "overlapping" depolarizing resonances was then studied[5] using a stored 106.4 MeV polarized proton beam and our new stronger rf solenoid magnet with a lower voltage but with a smaller diameter ceramic vacuum pipe. We created an "rf induced" depolarizing resonance, which we then forced to overlap with the $G\gamma = 2$ depolarizing resonance. We found significant interactions between the two resonances by varying their frequencies and strengths; the frequency of the rf resonance strongly affected the response of the imperfection resonance to correction magnetic fields. As shown in Fig. 7, there were strong interference dips as we varied the strength of the imperfection fields. When the Siberian snake was turned on, it overcame all observable depolarization due to the overlapping resonances and maintained full polarization over the entire range.

In CE-40, we found no measurable depolarization of a 370 MeV stored polarized proton beam when we adiabatically turned a partial Siberian snake on and off a total of 10 times[13], as shown in Fig. 8. This 370 MeV energy corresponds to a spin tune of $G\gamma = 2.5$. This data confirmed the prediction that Siberian snakes can be safely turned on adiabatically at half-integer spin tune energies. This result has some significance for polarized beam acceleration at the Brookhaven AGS, the Fermilab Booster, and DESY's PETRA.

Then we made the first test of a partial Siberian snake during polarized beam acceleration. By ramping our new warm solenoid magnets, we maintained a 10% partial snake while accelerating polarized protons from 95 to 140 MeV through the $G\gamma = 2$ imperfection depolarization resonance at 108 MeV. As shown in Fig. 9, the 10% snake suppressed all observable depolarizing effects.[14] The AGS later installed a partial Siberian snake and found similar results. We are preparing a detailed Physical Review paper[24] on accelerating a polarized proton beam through depolarizing resonances using a partial Siberian snake.

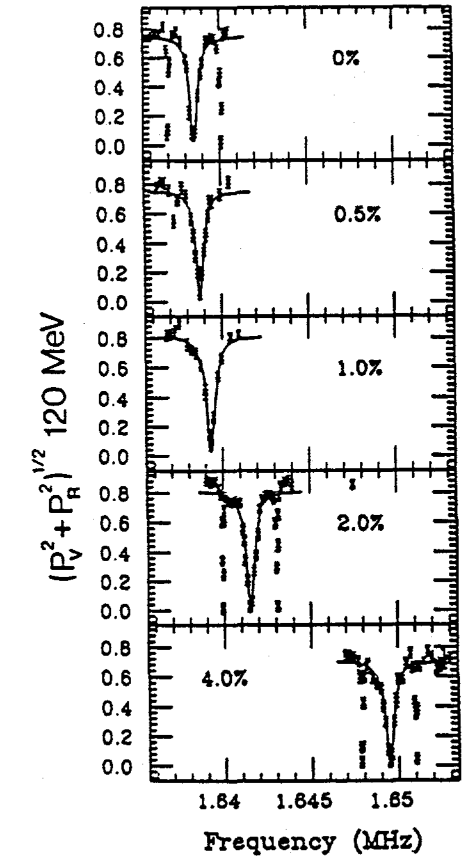


Fig. 4 The measured transverse beam polarization is plotted against the frequency of the rf solenoid magnet for five different partial snake strengths.[4]

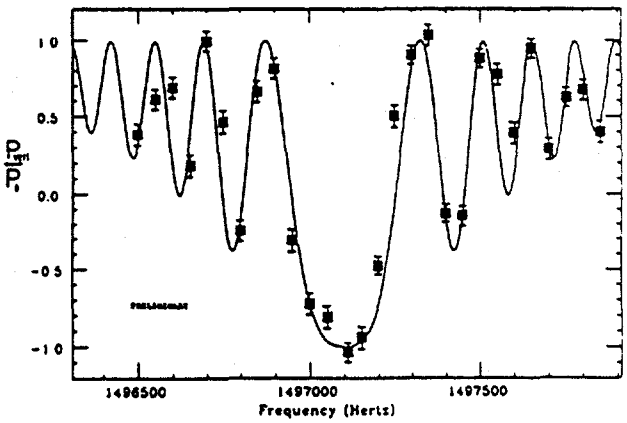


Fig. 5 The relative vertical beam polarization at 104 MeV is plotted against the rf solenoid on-time. The data fits a sinusoidal spin precession curve.[10]

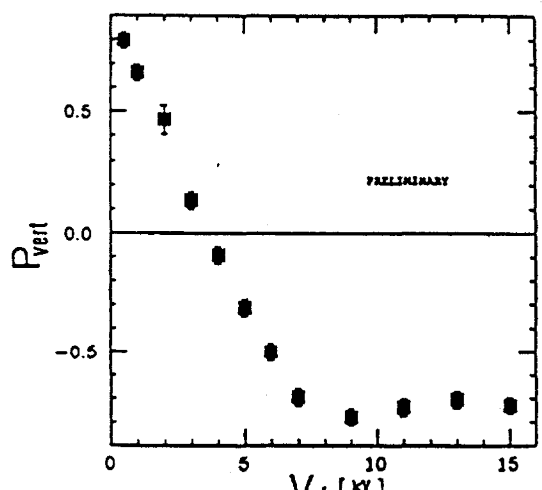


Fig. 6 The measured vertical beam polarization is plotted against the rf solenoid voltage, while ramping the frequency from 1.509 to 1.507 MHz. Full spin-flip occurs above 7 kV.[15]

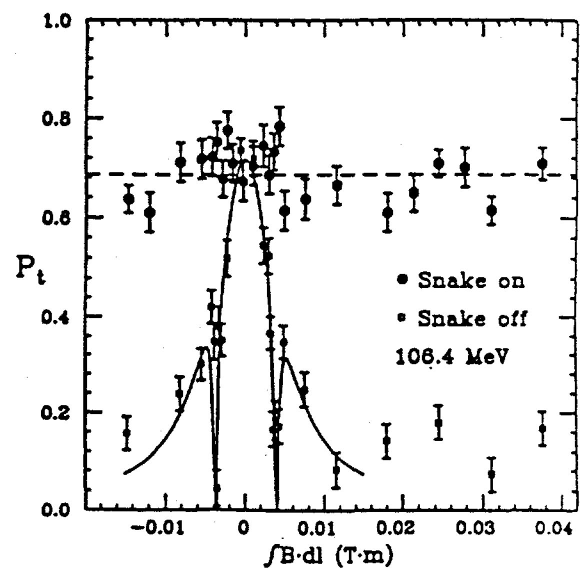


Fig. 7 Siberian snakes overcoming overlapping depolarizing resonances. With the snake off, the overlapping resonances cause sharp depolarizing dips. With the snake on, there is no depolarization.[5]

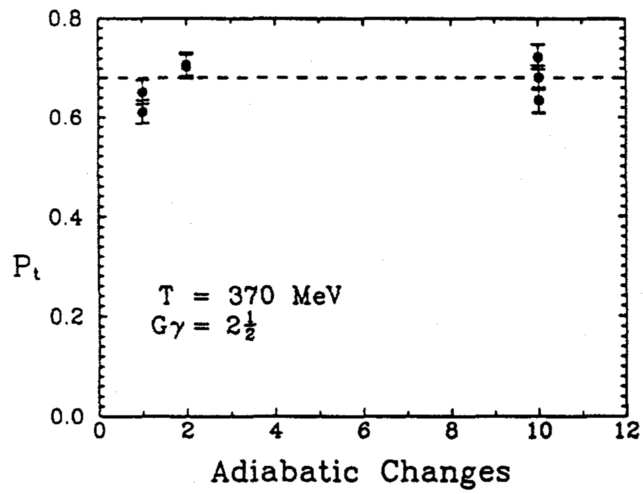


Fig. 8 The transverse polarization, $P_t = \sqrt{P_v^2 + P_r^2}$, at 370 MeV is plotted against the number of times the 25% partial Siberian snake was turned on or off. The dashed line is the best fit to the data, which show no depolarization within our 2% precision.[13]

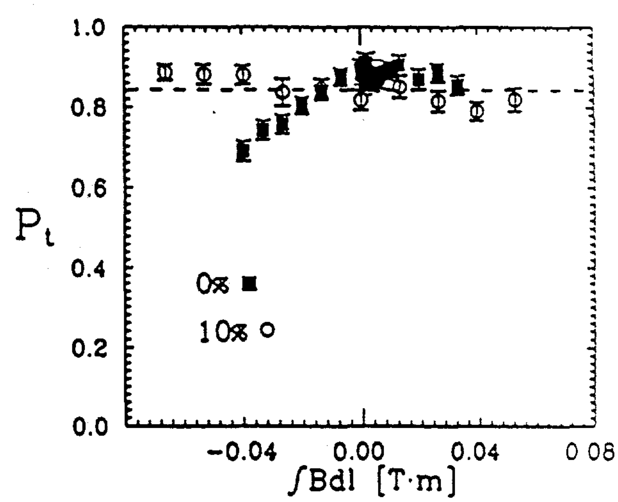


Fig. 9 The measured transverse polarization $P_t$ at 140 MeV is plotted against the imperfection $\int B{\cdot}dl$ with no snake and with a 10% partial Siberian snake. The dashed line is the best constant-polarization fit to the snake-on data. The beam was accelerated from 95 to 140 MeV.[14]

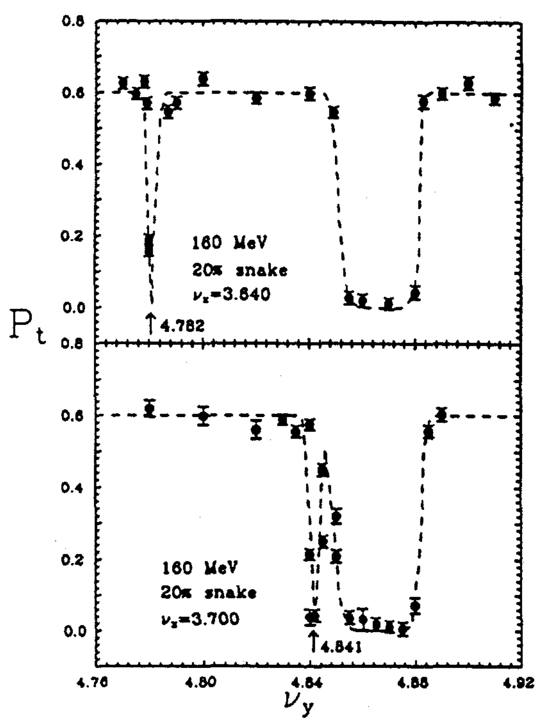


Fig. 10 The narrow dip's $\nu_y$-shift of 0.059±0.001 is equal to the 0.060 change in $\nu_x$, as predicted for the $\nu_s = \nu_y - \nu_x + 1$ second-order resonance.[18]

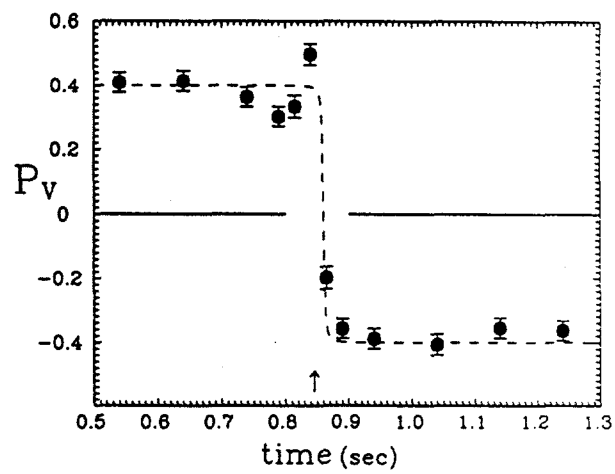


Fig. 11 The polarization spin-flips when the kicker is pulsed before crossing the resonance.[20]

We were able to flip the spin direction of a 139 MeV stored polarized proton beam 50 times with no observable polarization loss within our 2% errors. By adjusting the ramp time, *the polarization loss was reduced to 0.0000 ± 0.0005 per spin-flip.*[15] This new spin-flip capability should allow experiments using stored polarized proton beams to discriminate strongly against most systematic errors.

The CE-57 experiment was approved in 1995 with high priority. Using a 160 MeV stored polarized proton beam and a 20% partial snake, we found clear evidence for the second-order $\nu_s = \nu_y - \nu_x + 1$ intrinsic depolarization resonance.[18] By changing the horizontal betatron tune by $\Delta\nu_x = 0.06$, we found that the vertical betatron tune $\nu_y$ of the narrow second-order depolarizing resonance shifted by almost exactly the same amount, as shown in Fig. 10. These weak second-order resonances should be considered when using a partial Siberian snake with a medium-energy polarized proton beam.

We then succeeded in forcing a 140 MeV polarized beam to cross several intrinsic depolarization resonances by varying a partial Siberian snake's strength for different values of the vertical and horizontal betatron tunes.[19] This new capability could be used in medium energy proton beams.

Next, we accelerated a polarized beam from 95 to 380 MeV through both the $G\gamma$=2 imperfection resonance and the $G\gamma = 7$ - $\nu_y$ intrinsic depolarizing resonance.[20] As expected, the beam spin-flipped during the imperfection resonance crossing and partially depolarized while initially crossing the intrinsic resonance. We then pulsed a vetical kicker magnet for 500 ns to increase the beam's vertical betatron amplitude, which stengthened the intrinsic resonance. By varying the start time of the pulse, we observed a sharp spin-flip due to crossing the strengthened intrinsic resonance (see Fig. 11), which preserved the beam's polarization. This new alternative method of overcoming intrinsic depolarizing resonances should be useful for polarized beams in medium energy rings such as LISS and the injector rings at Brookhaven, UNK, Fermilab, DESY, and LHC.

Using a 104 MeV stored polarized proton beam and a full Siberian snake in the IUCF Cooler Ring, we made the first observation of a so-called higher-order "snake" depolarizing resonance.[21] A full Siberian snake forces the spin tune $\nu_s$ to be half-integer. If the vertical betatron tune $\nu_y$ is set near a quarter-integer, then the $\nu_s = n \pm 2\nu_y$ second-order snake resonance can depolarize the beam. With a full Siberian snake and $\nu_y = 4.756$, we found the deep depolarization dip shown in Fig. 12; when $\nu_y$ was changed to 4.781, the deep dip disappeared. This confirmed that the deep dip was a "snake" depolarizing resonance.

Using an rf solenoid magnet, we studied the depolarization of a stored 104.1 MeV vertically polarized proton beam. As shown in Fig. 13, the two primary rf depolarizing resonances were properly centered around the protons' circulation frequency $f_c$, at $f_c(3-\nu_s)$ and $f_c(\nu_s - 1)$, where $\nu_s$ is the spin tune. Moreover, each resonance was roughly consistent with the expected width of about 720 Hz. Each primary rf resonance had two synchrotron sideband resonances at the expected frequencies. The two $\nu_s - 1$ sidebands were deep dips while the two $3 - \nu_s$ sidebands were very shallow; this was not expected. Moreover, all four sideband frequencies were unexpectedly wider than the two primary resonances.[22]

In our recently approved CE-69, we used a snake resonance induced by an rf solenoid magnet to spin-flip a 104.1 MeV polarized proton beam stored in a ring containing a nearly 100% Siberian snake.[23] By varying the rf solenoid's ramp time, frequency range and voltage, as shown in Fig. 14, we reached a spin-flip efficiency of about 90%. This efficiency was probably reduced because the horizontal stable spin direction was not perpendicular to the longitudinal field of the rf solenoid, and was possibly reduced by nearby synchrotron sideband resonances. The use of a vertical rf dipole should probably improve the spin-flip efficiency.

Experiment CE-69[40] was approved with high priority in June 1997 for 96 shifts. Since we typically have three runs of 12 to 15 shifts each year, CE-69 should continue running through early 2000. We plan: to build an rf dipole; to further study overlapping depolarizing resonances; to further study both rf and intrinsic snake depolarizing resonances; and to increase the spin-flipping efficiency with a full snake. These studies should be important to possible high-energy polarized proton beams at RHIC, UNK, HERA, Fermilab, and LHC.

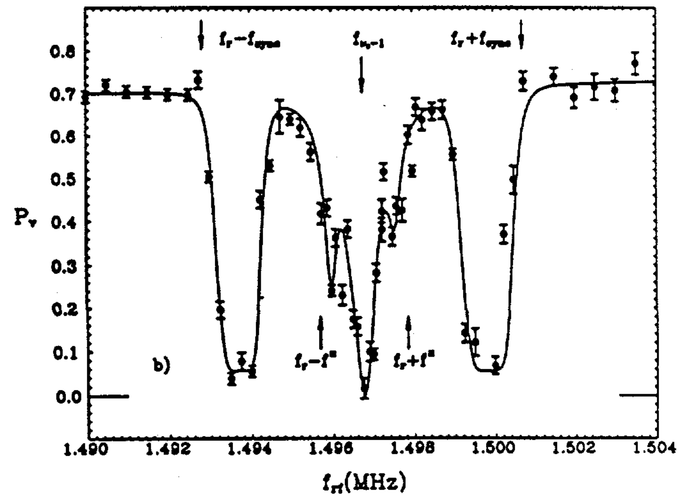


Fig. 13 The unexpectedly wide synchrotron sideband resonances near an rf depolarizing resonance.[22]

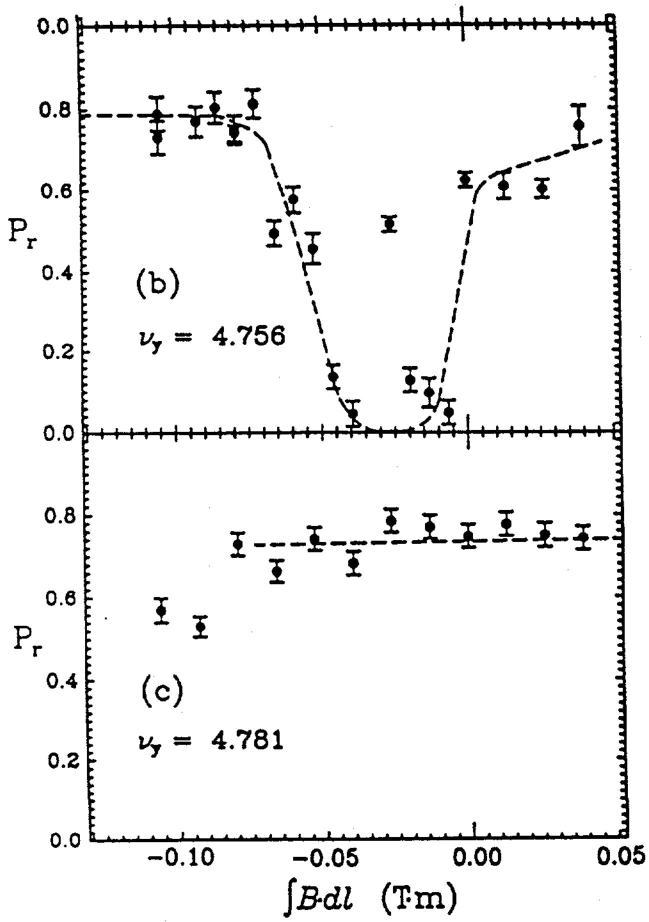


Fig. 12 Depolarization due to the second-order snake resonance occur when the vertical betatron tune is near a quarter-integer.[21]

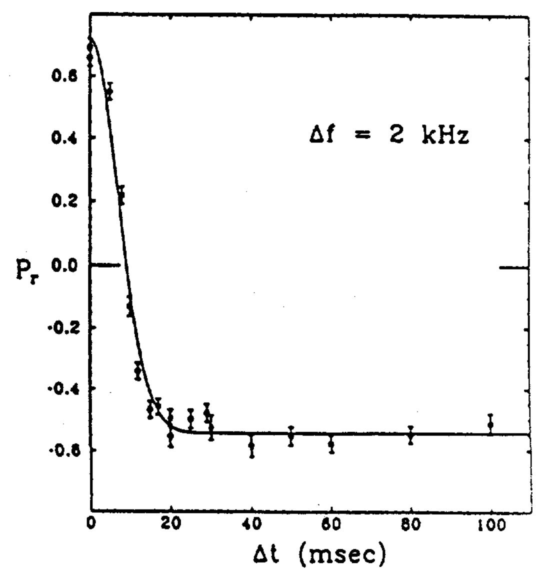


Fig. 14 The horizontal polarization is spin-flipped with about 90% efficiency in the presence of a full Siberian snake by ramping the RF solenoid frequency through 2 kHz in a time $\Delta t$.[23]

## 2 Polarized Proton Acceleration at Fermilab's Main Injector and Tevatron

Starting in September 1991, Fermilab provided Michigan with a total grant of $366,000 for the SPIN Collaboration to carefully study the possibility of accelerating polarized protons in Fermilab's LINAC, Booster, Main Injector and Tevatron. The resulting plan is shown in Fig. 15 and described in the Collaboration's detailed Reports on the *Acceleration of Polarized Protons in the Fermilab Main Injector and Tevatron*[9,37,38] which were submitted in 1992, 1994 and 1995. These Reports also discussed some possible high energy spin experiments. This polarization capability would allow studies of the one-spin dependence of $\overline{p}-p$ collisions at 2 TeV as well as fixed-target one-spin and two-spin experiments at 120 GeV.[6,7,8,11,12,16,17,25,26,27,28,29,30,31,32,33,34,35,36] In late 1995 Fermilab decided not to then proceed with this $25 Million program.

## 3 Polarized Proton Acceleration at DESY's HERA

The SPIN Collaboration, which is listed in Fig. C1, then began to study how to accelerate an 820 GeV polarized proton beam at HERA. In 1996, the DESY Directorate provided DM 100,000 to the SPIN Collaboration to study producing, accelerating, and storing polarized protons at the HERA accelerator complex. The 90-page Polarized HERA Report[39], which was based on the much longer 1995 Fermilab Report[38], was submitted on 8 November 1996. The HERA polarized proton beam design is shown in Fig. 16.

The cost of the new hardware needed to accelerate polarized protons through each stage of the HERA complex was estimated to be about DM 25 Million. The only significant scientific difficulty found was that the 4 Siberian snakes, which can fit easily into HERA's 4 long straight sections, might not be enough to overcome the strong depolarization resonances near 820 GeV. Moreover, the best existing polarized ion source intensity of about 3 mA is still below that of unpolarized ion sources; this low intensity would require a somewhat more complex stacking senario to equal the unpolarized HERA luminosity.

Due to the difficult financial situation in Germany, the DESY Directors decided to delay a decision on this DM 25 Million project for several years. To help maintain the involvement of the SPIN Collaboration,[31,32,33,34,35,36] DESY has provided DM 100,000 per year for polarized beam R&D during 1997 and 1998. This R&D has focused on increasing the output of the proposed Optically Pumped Polarized Ion Source to about 10 mA and studying whether: 6 or 8 Siberian snakes would be needed; or if HERA's planned luminosity improvements would provide adequate spin stability, as at the 6-fold symmetric Tevatron.

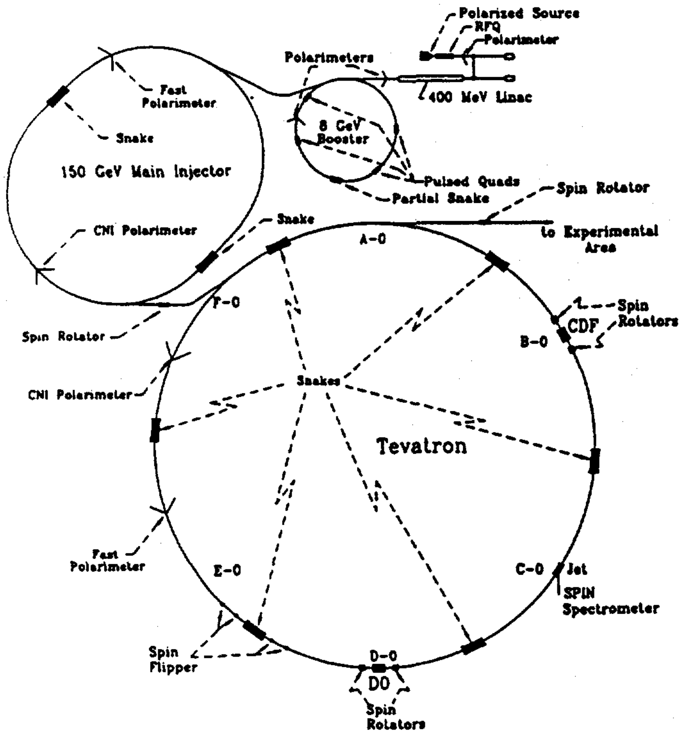


Fig. 15 Modifications to Fermilab's Main Injector and Tevatron for polarized proton acceleration.[38]

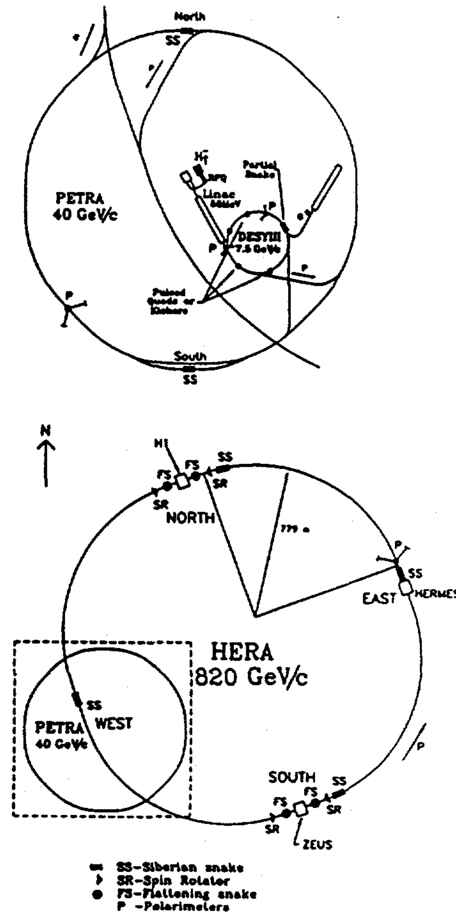


Fig. 16 Preliminary design of polarized proton hardware for HERA. SS denotes a full Siberian Snake; SR denotes a Spin Rotator; and SFS denotes a Spin Flattening Snake.[39]

# 4 PUBLICATIONS AND REPORTS (FY 1990-1993)

## 4.1 Published Manuscripts

1. First Test of the Siberian Snake Magnet Arrangement to Overcome Depolarizing Resonances in a Circular Accelerator, A.D. Krisch *et al.*, Phys. Rev. Lett. **63**, 1137 (1989).

2. Overcoming Intrinsic and Synchrotron Depolarizing Resonances with a Siberian Snake, J.E. Goodwin *et al.*, Phys. Rev. Lett. **64**, 2779 (1990).

3. Energy shift of a depolarizing resonance due to a type-3 Siberian snake, M.G. Minty *et al.*, Phys. Rev. **D44,** R1361 (1991).

4. Effect of a partial Siberian snake on an "rf induced" depolarizing resonance, V.A. Anferov *et al.*, Phys. Rev. **A46**, R7383 (1992).

5. A Siberian snake with overlapping depolarizing resonances, R. Baiod *et al.*, Phys. Rev. Lett. **70**, 2557 (1993).

## 4.2 Invited Lectures

6. Acceleration of Polarized Protons to 150 GeV at Fermilab, A.D. Krisch, Plenary lecture at SPIN-91 Workshop, Protvino, Russia (September 1991), UM HE 92-18.

7. Spin Experiments at UNK, Fermilab, and SSC, A.D. Krisch, Proc. $10^{th}$ International Symposium for High Energy Spin Physics, Nagoya, Japan (Universal Acc. Press, Tokyo, 1993), pp 301-310.

8. Polarized Beam at Fermilab, A.D. Krisch, Working Meeting on Spin Physics, Fermilab, Batavia, Illinois (May 1993).

## 4.3 Published Reports

9. Report on Acceleration of Polarized Protons to 120 and 150 GeV in the Fermilab Main Injector, commissioned by Fermilab, published by University of Michigan, March 1992.

## 4.4 Contributed Lectures and Papers

10. Partial Siberian snake Studies at the IUCF Cooler, R.A. Phelps, Proc. $10^{th}$ International Symposium for High Energy Spin Physics, Nagoya, Japan (November 9-14, 1992) (Universal Acc. Press, Tokyo, 1993), pp 423-427.

11. Siberian Snakes for the Fermilab Main Injector, V.A. Anferov *et al.*, 1993 American Physical Society Spring Meeting Washington, Bull. Am. Phys. Soc. **38**, 986 (1993).

12. Polarized proton beam acceleration at Fermilab, A.M.T. Lin *et al., ibid.*, Bull. Am. Phys. Soc. **38**, 987 (1993).

# 5 PUBLICATIONS AND REPORTS (FY 1994-1998)

## 5.1 Published Manuscripts

13. Adiabatic partial Siberian snake turn on with no beam depolarization, R.A. Phelps *et al.*, Phys. Rev. Lett. **72**, 1479 (1994).

14. First test of a partial Siberian snake during polarized beam acceleration, B.B. Blinov *et al.*, Phys. Rev. Lett. **73**, 1621 (1994).

15. Spin-flipping a stored polarized proton beam, D.D. Caussyn *et al.*, Phys. Rev. Lett. **73**, 2857 (1994).

16. Siberian Snakes with Small Numbers of Magnets for High Energy Accelerators, V.A. Anferov and Ya.S. Derbenev, Part. Accel. **44**, 201 (1994).

17. Helical Siberian snakes and their discrete analogs, V.A. Anferov, Part. Accel. **44**, 20 (1994).

18. Observation of a Second Order Depolarizing Resonance, C. Ohmori *et al.*, Phys. Rev. Lett. **75**, 1931 (1995).

19. Crossing Intrinsic Depolarizing Resonance by Varying a Partial Siberian Snake, L.V. Alexeeva *et al.*, Phys. Rev. Lett. **76**, 2714 (1996).

20. Spin-Flipping through an Intrinsic Depolarizing Resonance by Strengthening it, D.A. Crandell *et al.*, Phys. Rev. Lett. **77**, 1763 (1996).

21. First Observation of a Snake Depolarizing Resonance, R.A. Phelps *et al.*, Phys. Rev. Lett. **78**, 2772 (1997).

22. Unexpectedly Wide RF-Induced Synchrotron Sideband Depolarizing Resonances, C.M. Chu *et al.*, submitted to Phys. Rev. **E**, (1998).

23. Spin Flipping in the Presence of a Full Siberian Snake, B.B. Blinov *et al.*, to be submitted to Phys. Rev. Letters, (1998).

24. Accelerating a Polarized Proton Beam using a Partial Siberian Snake, D.A. Crandell *et al.*, to be submitted to Phys. Rev. **E**, (1998).

## 5.2 Invited Lectures

25. Siberian Snakes and Polarized Beam at Fermilab, A.D. Krisch, TRIUMF Users' Group Annual Meeting, Vancouver, Canada (7-8 December 1993).

26. Siberian Snakes and Polarized Beams, L.G. Ratner, Conf. on Unified Symmetry: in the Small and in the Large, Coral Gables (January 1994), (Plenum), pp 167-174.

27. Polarizing the Tevatron Beam, R.A. Phelps, Conference on Electroweak Physics Beyond 2000 at the Fermilab Tevatron, University of Michigan (21-22 October 1994).

28. Polarized Proton Beams at Fermilab, R.A. Phelps, Int'l Conf. on Unified Symmetry in the Small and in the Large, Coral Gables, Florida (February 1995), pp 293-299.

29. Acceleration of Polarized Protons at Fermilab, A.D. Krisch, Workshop on Spin Physics at HERA, Zeuthen-Berlin, GERMANY (August 1995), DESY 95-200, eds. J. Blumlein and W-D Nowak, pp 100-105 (1996).

30. Polarized Proton Beams, A.D. Krisch, SPIN 95 Workshop, IHEP-Protvino, RUSSIA (18-23 September 1995), Vol. 2, pp 254-257.

31. SPIN Collaboration and Polarized Proton Beams, A.D. Krisch, Adriatico Conf. on Trends in Collider Spin Physics, ICTP-Trieste, ITALY (5-8 December 1995), (World Scientific),

32. Accelerating Polarized Protons with Siberian Snakes, A.D. Krisch, Max Planck Inst. Polarization Workshop, Ringberg Castle, Munich, GERMANY (February 1997).

33. Siberian Snakes and Polarized Proton Beams, A.D. Krisch, $7^{th}$ Blois Meeting, Seoul, KOREA (June 1997), (to be published).

34. Accelerating Polarized Protons with Siberian Snakes, A.D. Krisch, Cracow Epiphany Conference on Spin Effects in Particle Physics, Cracow, POLAND (January 1998), (to be published)

35. Polarized Protons and Siberian Snakes, A.D. Krisch, April APS Meeting, Columbus, Bull. APS **43**, No. 2, 1095 (1998).

36. Polarized Protons and Siberian Snakes, A.D. Krisch, Workshop on QCD, American University, Paris, FRANCE (June, 1998)

## 5.3 Reports

37. Progress Report on Acceleration of Polarized Protons to 1 TeV in the Fermilab Tevatron, commissioned by Fermilab, University ofMichigan Report, UM HE 94-15, (1 August 1994).

38. Acceleration of Polarized Protons to 120 GeV and 1 TeV at Fermilab, SPIN Collaboration, commissioned by Fermilab, University of Michigan Report, UM HE 95-09 (24 July 1995).

39. Acceleration of Polarized Protons to 820 GeV at HERA, SPIN Collaboration and DESY Polarization Team, Michigan Report, UM HE 96-20 (8 November 1996).

## 5.4 Recent Proposals

40. Snake Resonances and Full-Snake Spin Flipping, SPIN@IUCF Collaboration (May1997) [Approved as CE-69 at IUCF].