Siberian Snake Experiments[‡]

A. D. Krisch

Randall Laboratory of Physics, The University of Michigan
Ann Arbor, Michigan 48109-1120 USA

We began studying Siberian Snakes at the 1985 Ann Arbor Workshop on Polarized Protons at the SSC[1]. Fig. 1 is a diagram of how a polarized SSC might appear with Siberian Snakes installed in the various rings. By the end of the Workshop it appeared that it would be practical to have polarized protons at the SSC, but only if the Siberian Snake Concept worked as everyone hoped. The Workshop's first conclusion was that polarized beam acceleration would probably be possible at the SSC. The second conclusion was that one must test the Siberian Snake Concept, which had been invented around 1974 by Derbenev and Kondratenko[2]. While most of the world's distinguished accelerator theorists were quite convinced that the concept would work, we felt that it would be difficult to convince the SSC Director and the funding people to spend tens of millions of dollars on Siberian Snakes, if it was an untested theoretical concept.
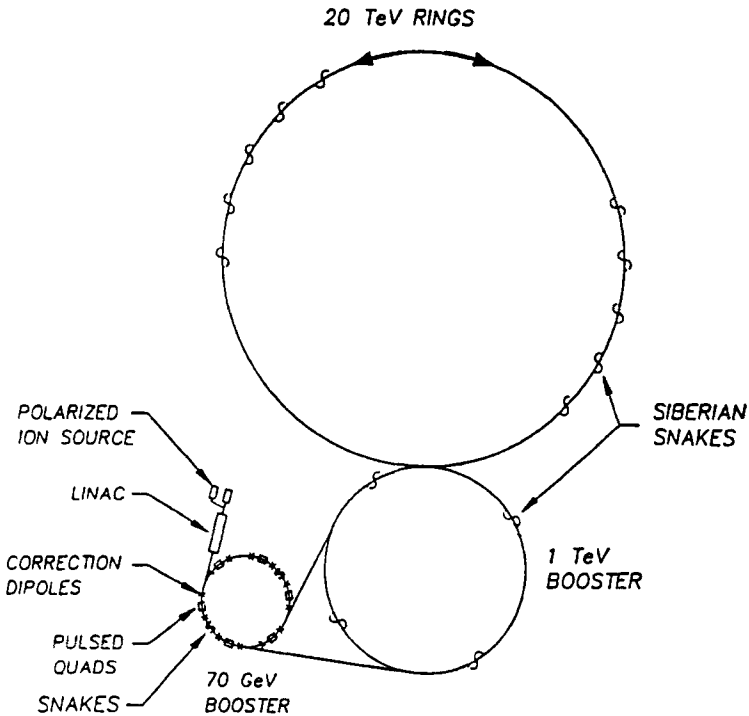

Fig. 1 Polarized proton acceleration at the SSC as seen in 1985.

To understand the importance of Siberian Snakes, recall the difficulty of accelerating polarized protons to 22 GeV at the AGS, which was the world's highest energy polarized proton beam. It was necessary to individually overcome each of the many intrinsic and imperfection depolarizing resonances. Fig. 2 shows the oscilloscope trace from the AGS main control room; the bottom curve is the AGS magnet cycle during the acceleration of polarized protons to 16.5 GeV. The correction currents in the 96 correction dipoles for some 25 imperfection resonances are shown in the upper curve; the middle curve shows the pulsed quadrupoles firing three times to overcome three intrinsic resonances. To reach 22 GeV we had to overcome about 45 resonances; this required seven weeks of total dedication of the AGS to these polarized beam studies which cost a million dollars each week. At the SSC each 20 TeV ring will have 36,000 depolarizing resonances; it seems completely impractical to try to overcome them individually. It was clear that one needed a new technique to accelerate polarized protons to TeV energies.

Dipole
Correction
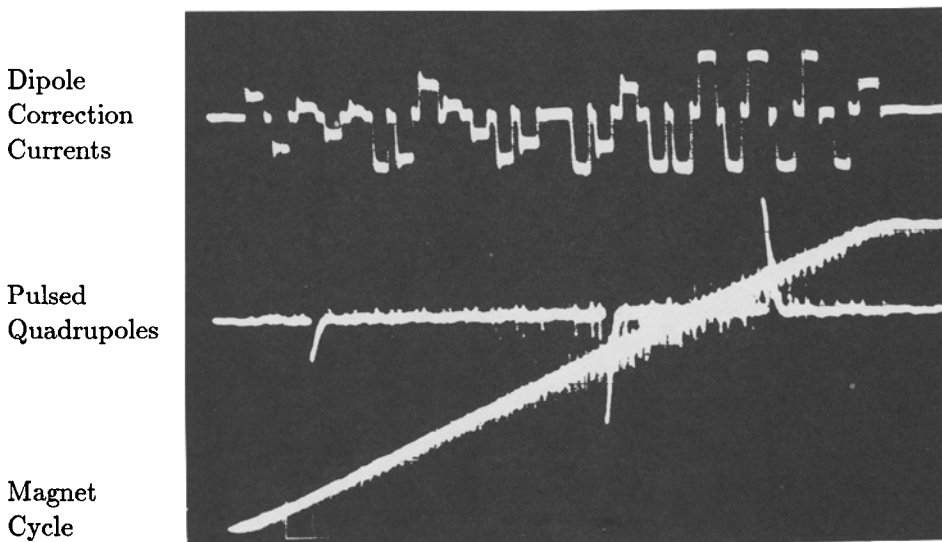Currents

Pulsed
Quadrupoles

Magnet
Cycle

Fig. 2 AGS main control room oscilloscope trace showing the acceleration of polarized protons to 16.5 GeV.

Shortly after the Ann Arbor Workshop, some of the participants began looking around the world for some accelerator where we could test the Siberian Snake concept. As I recall, we looked seriously at the AGS, at Saturne, at KEK, and at Indiana. We settled on the Indiana Cooler Ring mostly because its straight sections were long enough for a Siberian Snake. We then formed a collaboration and began to study Siberian Snakes. The first results were published during the past year in two Physical Review Letters[3,4]. The collaboration includes people from Michigan, Indiana, and Brookhaven who are listed in reference 3.

The Indiana University Cyclotron Facility Cooler Ring is shown in Fig. 3. IUCF had the potential for injecting polarized beam into the Cooler Ring from the two stage cyclotron injector; the maximum energy of the second Cyclotron is 200 MeV. The Cooler Ring itself is a synchrotron storage ring, which can accelerate protons up to 500 MeV. The study of Siberian Snakes at the Cooler Ring required several new hardware items. We used the electron cooling solenoids to create imperfection fields to study the depolarizing resonances. To inject polarized protons into the Cooler Ring, we installed some kicker magnets. The Cooler Ring normally used stripping injection of H$^-$ ions; however the polarized source emitted normal polarized protons, which made stripping injection impossible. Two kicker magnets were built quickly and inexpensively at Michigan using some spare ferrite that remained after building the pulsed quadrupoles for the AGS. These kickers had a risetime of about 100 ns and effectively injected the polarized beam into the Cooler Ring.
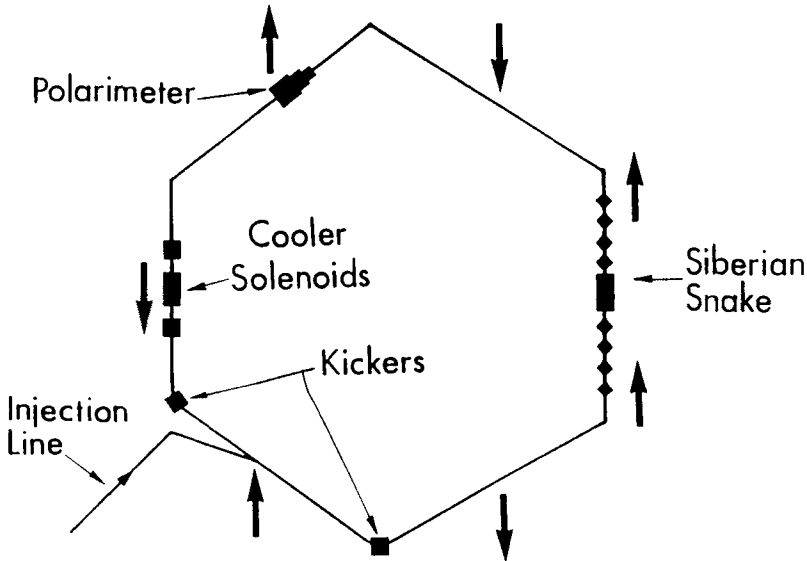
Fig. 3 The IUCF Cooler Ring with the Michigan-Indiana Siberian Snake.

The polarimeter for our experiment was built by Indiana as a spectrometer for various nuclear physics experiments. It had azimuthal symmetry and contained a carbon target, wire chambers, and scintillation counters. We used it as a polarimeter by accepting the $\Delta\theta$ region of about 5° to 17° and splitting it into four $\Delta\phi$ bins of 90° each. The left and right quadrants measured the up-down polarization, while the up-down quadrants measured the sideways polarization. Near the $G\gamma = 2$ depolarizing resonance, which occurs at 108 MeV, the average analyzing power was about 25%. Near the $G\gamma = -3 + \nu_y$ depolarizing resonance at 177 MeV, the cross-section was smaller but the analyzing power was larger.

It normally took about 10 minutes to make a 3% measurement of the beam polarization with about 20 nA of stored beam.

The Siberian Snake is shown in Fig. 4; this was of course our most important piece of hardware. This was not a conventional high energy Snake where 8 transverse dipole magnets produced the 180° spin rotation. Such snakes were not very practical at these low energies; instead we used the superconducting solenoid magnet, shown at the center, which easily rotated the spin by 180°. It was a rather strong solenoid magnet, with an $\int B \cdot d\ell$ of about 2 Tesla-meters. Unfortunately, this solenoid caused considerable optical distortion to the low energy beam. This orbit distortion focused the beam and rotated its phase space by about 30° which produced considerable xy-coupling. To compensate for this orbit distortion we used a series of eight quadrupole magnets; the four magnets on the outside were standard quadrupoles, the four on the inside were identical quadrupoles which could be rotated to become skew quadrupoles at various angles. By properly adjusting the currents and the rotation angles of these eight quadrupoles we could eliminate all of the orbit distortions introduced by the solenoid magnet and thus make this straight section optically transparent. The quadrupoles had to be carefully adjusted because they were rather strong; but when all eight were properly adjusted the Snake was optically transparent and there was no beam loss.
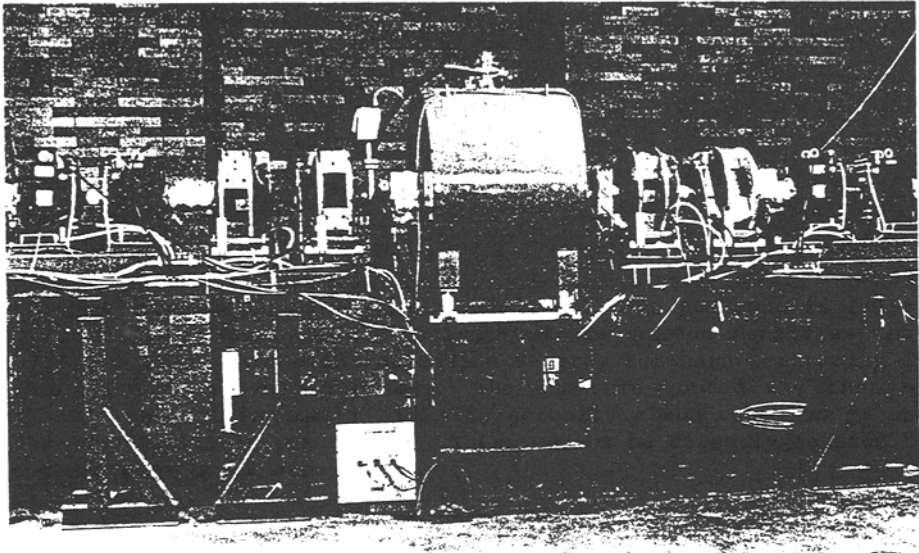

Fig. 4 The Michigan-IUCF Siberian Snake.

In our first experiment we studied the beam polarization at 120 MeV, while varying the strength of the $G\gamma = 2$ imperfection resonance at 108 MeV. This energy was some distance from the resonance, but its effect was still strong. With the injection of vertically polarized protons, the measured vertical polarization had a clear peak which looked similar to the imperfection depolarizing resonance correction curves at the ZGS[5] and AGS[6]. The radial polarization was fairly large; it also had a zero crossing and changed sign. We later came to understand that we were rotating the stable spin direction as we varied the longitudinal imperfection field. The imperfection field came from the cooling solenoid which was itself a weak partial Snake that could rotate the stable spin direction.

We repeated this study with the Snake off at 104 MeV as shown in Fig. 5; the curve was now about 10 times sharper than at 120 MeV. We could only maintain full polarization with the Snake off if we exactly corrected the imperfection fields. Any slight imperfection would quickly change the polarization. We next turned the Snake on and injected protons polarized in the radial direction, which was the stable spin direction when the Snake was on. We then found that the polarization remained large and constant as we varied the imperfection field over a wide range. With the Snake on, the polarization appeared totally insensitive to the imperfection fields; the beam remained horizontally polarized even with a strong imperfection field. We considered Fig. 5 to be the first clear indication that the Siberian Snake concept worked.
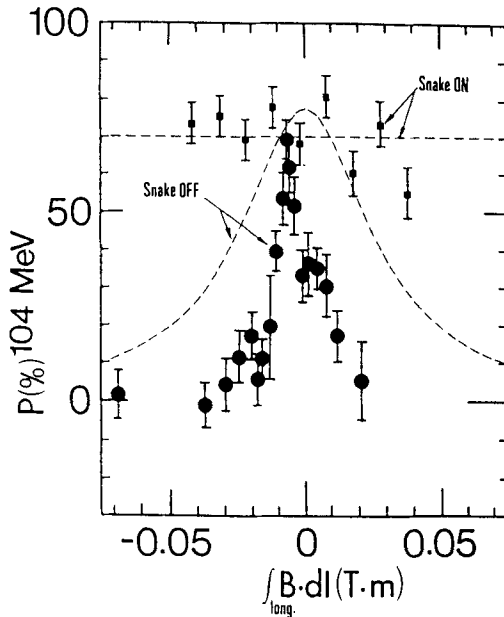

Fig. 5 The 104 MeV polarization in the stable spin directions with the Snake on and the Snake off.

The dashed curve in Fig. 5 shows our calculation of the polarization at 104 MeV. This calculation, which assumed that the resonance was at 108 MeV, did not agree very well with the Snake-off data. At first we were not sure if the calculation was correct, so we did not take this disagreement too seriously. We were quite pleased that the Snake-on calculation agreed with the Snake-on data which showed that the Snake worked.

During 1989 and 1990 we had eight different running periods each lasting about a week. We did many different experiments; I will discuss some of these experiments in an order which is more logical than temporal.

By mid-1990 our measurement ability had improved considerably. We, therefore, remeasured the polarization at 104 MeV in much finer detail as shown in Fig. 6. This curve should have been similar to Fig. 5, but on a much expanded scale. However, with this fine detail, we found a surprise; at first we saw one low data point which we thought was an incorrect measurement. But when we remeasured the curve several more times, there were clear dips on both sides of the central peak. The existence of these dips was further confirmed by identical dips in the radial polarization. Note that the beam was not spin-rotated in these dips; it was fully depolarized because both the vertical and the radial polarizations were zero. We thought that these dips must be due to some type of depolarizing resonance. Eventually we decided that each dip might be a synchrotron depolarizing resonance, which would occur whenever $G\gamma = 2 \pm \nu_s$, where ν_s was the synchrotron tune.
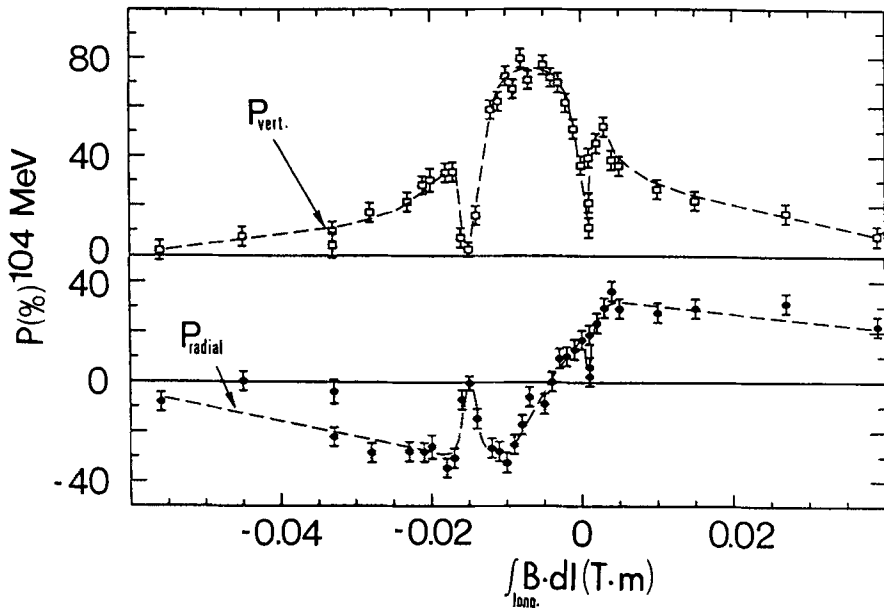

Fig. 6 Observation of synchrotron depolarizing resonances.

To prove that each dip was a synchrotron depolarizing resonance, we measured the polarization while changing the synchrotron tune, ν_s. We thought that the easiest way to vary ν_s might be to vary the RF voltage. Therefore, we set $\int B \cdot d\ell$ in the center of the dip on the left and then measured the polarization while varying the RF voltage. As shown in Fig. 7 this experiment worked very well; there was clearly a strong relationship between the polarization and V_{rf}, the RF voltage. A synchrotron depolarizing resonance seemed to be the only explanation for this relationship. It seems highly probable that each dip in Fig. 6 was due to a synchrotron depolarizing resonance.
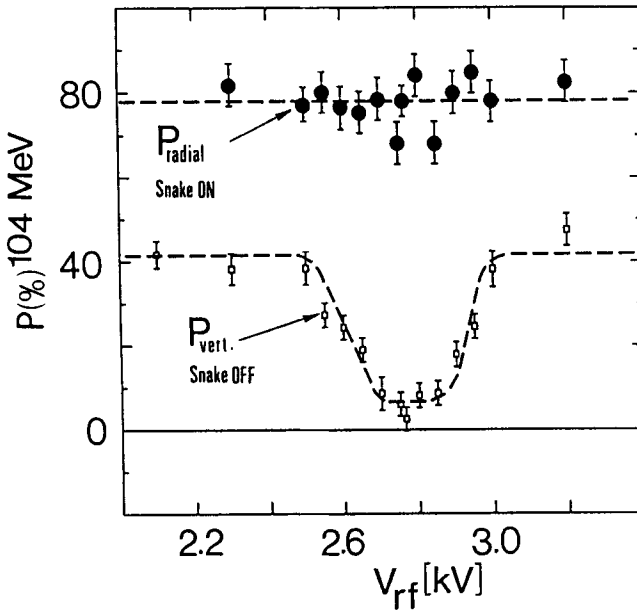

Fig. 7   The Snake overcoming a synchrotron depolarizing resonance

Then with $\int B \cdot d\ell$ still set in the center of the dip, we turned the Snake on and again varied V_{rf} and thus ν_s. As shown in Fig. 7 the Snake now maintained full polarization over the entire range of V_{rf}. We had not originally considered synchrotron depolarizing resonances, but Fig. 7 showed that a Snake can certainly overcome these resonances.

Our next experiment was a study of the effect of the $G\gamma = 2$ resonance on the polarization at some nearby energies. Recall that the calculation did not quite agree with the data in Fig. 5; we thought that perhaps the energy of the Cooler Ring was not properly calibrated. We recalled that at two previous accelerators, the ZGS[5] and AGS[6], the polarized beam studies had discovered an energy miscalibration of about 1%. Our IUCF colleagues were rather concerned about this possibility. Bob Pollock and Hans-Otto Meyer believed that the

calibration was correct. Fig. 8 shows a study at 108 MeV which should be near the resonance if the energy calibration was correct; but the width of the resonance curve was quite similar to the width at 104 MeV shown in Fig. 6. This increased the concern about the energy calibration. [This curve was less detailed than Fig. 6, but one could again see the synchrotron resonance dips.]
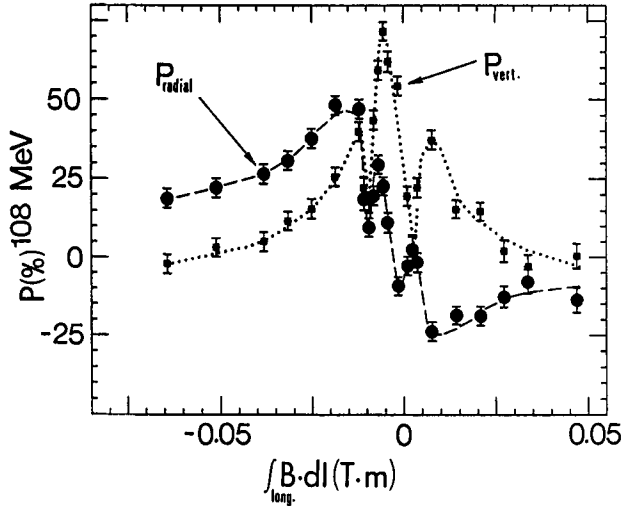
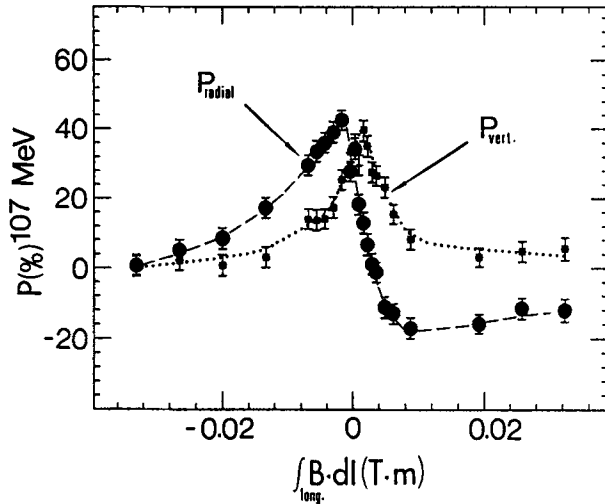Fig. 8 The $G\gamma = 2$ resonance as seen at 108 MeV.

Fig. 9 The $G\gamma = 2$ resonance as seen at 107 MeV.

The 104 and 108 MeV curves suggest that the resonance might be near 106.5 MeV. Therefore, we studied the polarization at 107 MeV which is shown in Fig. 9. This curve was very narrow; it was about a factor of 2 sharper than the 108 MeV curve. Also note that one never reached full polarization in the vertical direction, apparently because 107 MeV was so close to the resonance. Moreover, the synchrotron depolarizing resonances now apparently either disappeared or became very narrow. Thomas Roser and S.Y. Lee believed that

as one approached the resonant energy, the two synchrotron resonances should move together, eventually merge, and then cease to exist. [The 107 MeV data was certainly consistent with no synchrotron resonances; but the existence of very narrow dips can never be completely ruled out. However, we had about reached the stability limit of the Cooler Ring; probably we cannot reliably get points much closer together than in Fig. 9.]

We were eager to determine if a Siberian Snake could overcome an intrinsic depolarizing resonance; Fig. 10 shows the polarization at 177 MeV plotted against the vertical betatron tune, ν_y. The correction quads were not always used; however for this study of the $G\gamma = -3 + \nu_y$ intrinsic resonance we used the correction quads to insure that the vertical betatron tune, ν_y, was exactly right. It was difficult to ramp the Snake because the superconducting solenoid and the quads must then exactly match the Ring ramp. Therefore, S.Y. Lee proposed ramping the tune instead. Normally, during acceleration one holds the tune fixed and ramps the energy; here we held the energy fixed and changed ν_y in discrete steps. We did a measurement at one tune and then we changed the tune for the next measurement. Notice in Fig. 10 that with no Snake, the polarization was zero near the resonance. However, with the Snake on, full polarization was maintained over the entire ν_y range. This clearly demonstrated that the Snake was capable of overcoming a quite strong intrinsic depolarizing resonance.
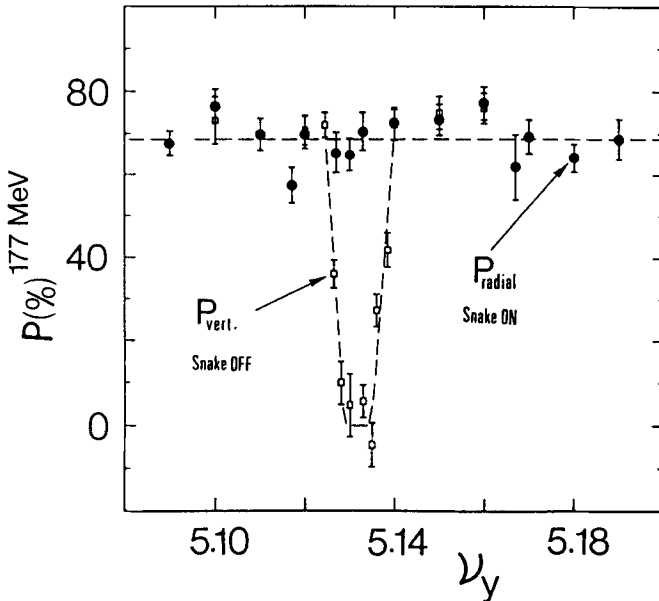

Fig. 10 The Siberian Snake overcoming the $G\gamma = -3 + \nu_y$ intrinsic resonance.

Now I will discuss partial Siberian Snakes. Many people have considered these partial Snakes; probably Derbenev and Kondratenko were first. Courant has been quite involved with them and Roser and Ratner have recently been actively studying partial Snakes. We made a study of partial Snakes by measuring the polarization at 104 MeV, while lowering the spin rotation angle in the Snake. As shown in Fig. 11, the Snake was able to maintain full polarization from a 100% Snake, down to about a 5% Snake. When the Snake was less than a few percent, then it was no longer strong enough and the polarization dropped rapidly. The broad flat region of full polarization seems to be clear evidence that an appropriate partial Snake can overcome imperfection resonances.
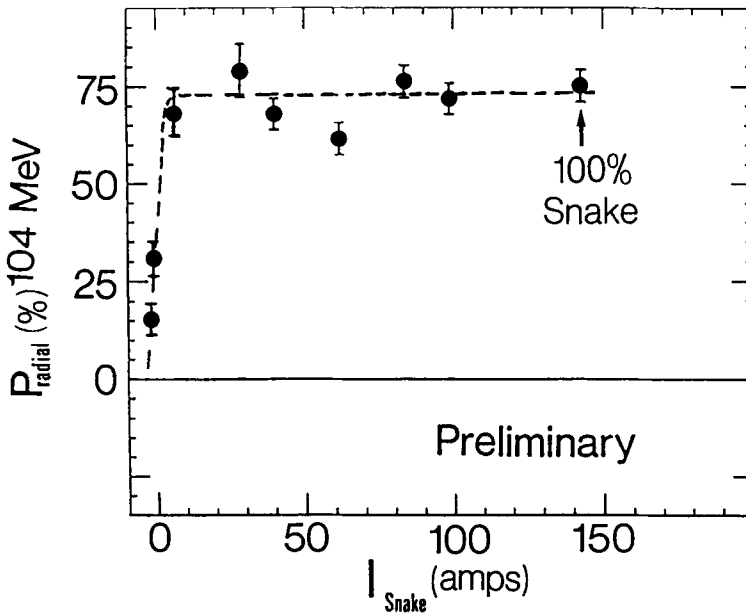

Fig. 11 A partial Snake overcoming the $G\gamma = 2$ intrinsic depolarizing resonance.

We now have rather extensive studies of the interactions of Siberian Snakes with various depolarizing resonances. We have about 50 data curves of one sort or another, but many of them are not yet organized. Our thesis student, Michiko Minty, is organizing all of this data. She has compiled a book about one inch thick with many cross references. It is important to keep track of all this data; several times we were almost ready to start some new measurement when we discovered that we had already done it some months earlier.

By Spring 1990 we had shown that a Siberian Snake was capable of overcoming an imperfection depolarizing resonance, an intrinsic depolarizing resonance, and a synchrotron depolarizing resonance. We had also shown that a partial Snake could overcome an intrinsic depolarizing resonance.

It was predicted that partial Snakes could only overcome imperfection depolarizing resonances; a full Snake is needed for an intrinsic resonance. I will not give a detailed theoretical discussion; however a partial Snake could apparently shift the spin tune and thus drive an intrinsic resonance to a different energy. We searched for this shift by using a 25% Snake while ramping the Cooler Ring energy from 104 to 120 MeV; we measured the radial polarization while injecting horizontally polarized protons. We changed the total percentage of Snake in the Ring by varying the correction solenoids; they were weak partial Snakes which could vary the percentage of total Snake by a few percent. As shown in Fig. 12 there was a strong depolarization in the predicted region. This seemed to be a clear indication that the spin tune shift in the partial Snake shifted the energy of the $G\gamma = -3 + \nu_y$ intrinsic resonance from 177 MeV into the 104 to 120 MeV ramp. There was another intrinsic resonance, $G\gamma = 7 - \nu_y$, which normally occurred well below injection. However the partial Snake apparently made both these intrinsic resonances occur at the same energy. In any case, we were apparently moving some intrinsic depolarizing resonance into the ramp region of 104–120 MeV; there was certainly a strong depolarization.
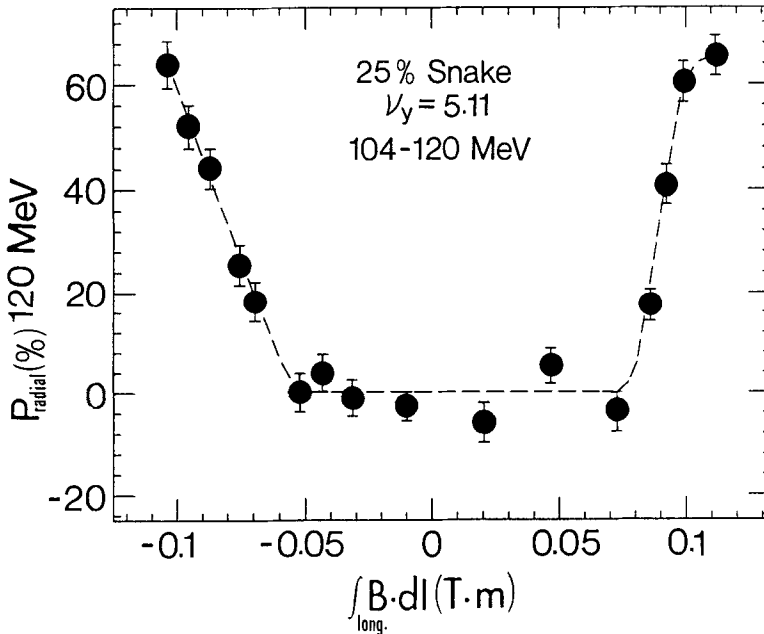

Fig. 12 The 25% partial Snake moving the intrinsic depolarizing resonances into the 104 to 120 MeV range.

During our August 1990 run, we found for the first time a depolarizing resonance that the Snake did not overcome. This surprising result is shown in Fig. 13 where we varied the current in the correction solenoids while sitting at 106 MeV near the $G\gamma = 2$ intrinsic resonance. There was a very clear dip in this

curve.* We had a 100% Snake turned on, but this was the first time that we ran
with the Snake quadrupoles turned on near the $G\gamma = 2$ imperfection resonance.†
We had been looking for Snake resonances for some time, but never before saw
any depolarization when the Snake was on. Derbenev and I now believe that
the depolarization in Fig. 13 was probably due to a Snake resonance which was
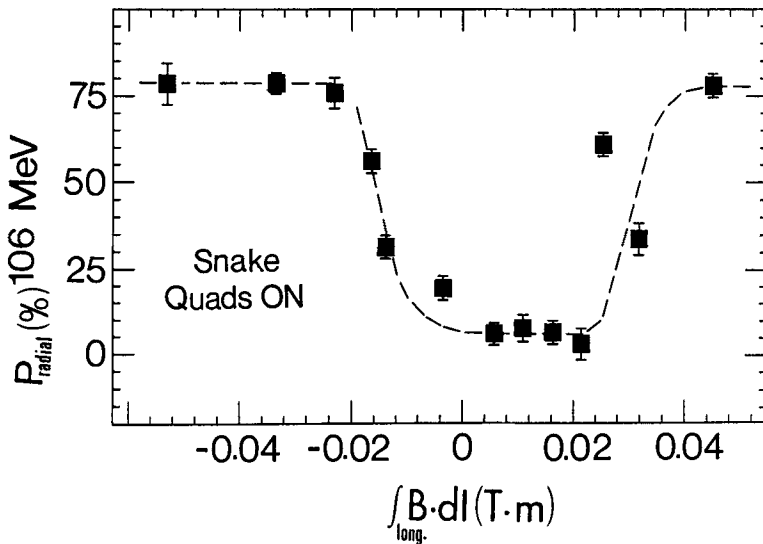driven by the Snake quadrupoles.

Fig. 13 A possible Snake resonance.

    To understand something about a Snake resonance, let us first recall how a
Snake works. Consider a vertically polarized proton circling a ring containing
a Snake. Normally the spin gets slightly rotated during each turn around the
ring by the horizontal imperfection fields. On one turn the vertical spin may get
rotated from 0° to perhaps 3°; then it passes through the Snake which rotates it
by 180° to 183°. On the next turn around the Ring, the imperfections act in the
same direction as on the first turn; therefore, they now rotate the spin by 3° back
to 180°. Finally the Snake again rotates the spin by 180° bringing it back to 0°
after two full turns around the ring. Thus, the Snake makes each imperfection
field cancel itself. The only exceptions to this cancellation are apparently the
magnetic fields inside the Snake itself.

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 * Do not yet take too seriously the two points on the right which may not agree; one may
    just be due to an error in recording the data.
 † Recall that at 104 MeV the Snake easily overcame the $G\gamma = 2$ resonance, as was shown
    in Fig. 5. We later made a similar Snake-on study at 108 MeV; there was again no
    depolarization. However these studies were done with the Snake quadrupoles turned off.
    Often we did not use the quadrupoles because they were so strong that they had to be
    finely adjusted or they would kill the beam. The quadrupoles shifted the horizontal tune,
    ν_x, by a full unit of one.

Recall that our Snake was not a normal high energy Snake constructed of 8 dipoles; it instead contained a solenoid and eight quadrupoles. To see how the Snake quadrupoles might drive a Snake resonance, first note that there was a sharp focus at the center of the solenoid. Therefore if a proton in the upstream quadrupole was above the beam axis, then in the downstream quadrupole it would be below the axis. Moreover, the proton's spin was rotated through 180° by the Snake. Finally, the quadrupoles were mirror symmetric. These three factors combined to force the two quadrupoles to have a constructive depolarizing effect on the spin. If in the upstream quadrupole the field pointed to the left and the spin was up, then in the downstream quadrupole the field pointed to the right and the spin was down. The two quadrupoles would therefore interact coherently with the proton's spin and cause a coherent depolarization inside the Snake. We think that the depolarization in Fig. 13 was probably a Snake resonance which was being driven by the Snake quadrupoles; these were much stronger than the normal Cooler Ring quadrupoles. The Snake apparently could not overcome the depolarizing quadrupole fields because they existed inside the Snake itself. The Snake could cure other problems, but it could not cure its own problems. This type of Snake resonance should not occur with a high energy Snake made of eight dipoles.

We studied this Snake resonance by slightly varying the strength of the Snake solenoid. As shown in Fig. 14, there was clearly a dip in the polarization as the solenoid current was varied near 144.2 amps which gives a 100% Snake at 106 MeV. Notice that the width of the dip was about 2%; this width may provide information about the nature of the Snake resonance.
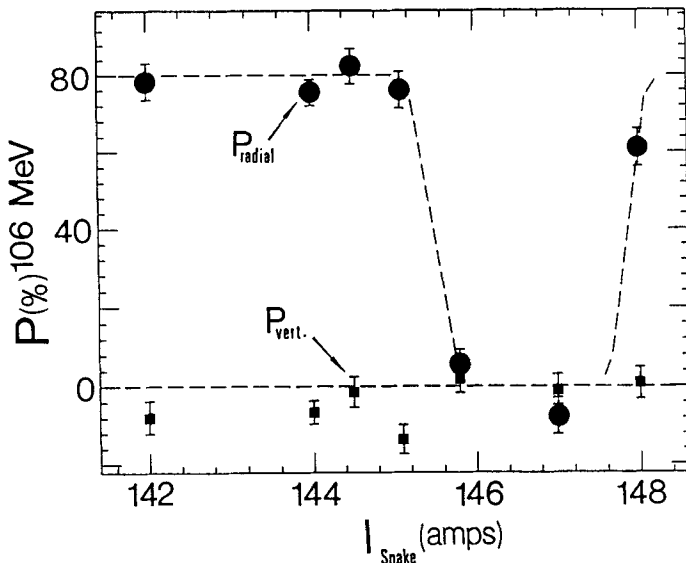

Fig. 14 Studying a Snake resonance by varying the Snake Solenoid.

We then studied the Snake resonance by varying the horizontal and vertical betatron tunes. As shown in Fig. 15, we again saw clear dips in the polarization. During the first data run, where we were changing the vertical tune, we were not careful enough about keeping fixed the horizontal tune. We did obtain good data where we held fixed the vertical betatron tune and varied the horizontal tune. Fig. 15 clearly shows that the resonance depended strongly upon the horizontal betatron tune, ν_x, and probably upon the vertical betatron tune, ν_y. Notice that the dip occurred near $\nu_x + \nu_y \approx 1.50$ for both curves. Since the spin tune, ν_s, was close to one-half, this data showed a strong depolarization near $\nu_x + \nu_y + \nu_s \approx 2$ which is an integer. The shift from an exact integer was probably due to the Type-3 Snake which we will soon discuss. This $\nu_x + \nu_y + \nu_s = $ integer behavior supports the Snake resonance hypothesis. Notice that the width of the dip in the horizontal curve, $\Delta\nu_x$, was considerably larger than the vertical width, $\Delta\nu_y$. These widths may provide important information about the nature of the Snake resonance. In other similar curves with the Snake solenoid on, there was no evidence of depolarization. Thus the unusually strong driving term due to the Snake quadrupoles may be essential for this Snake resonance.
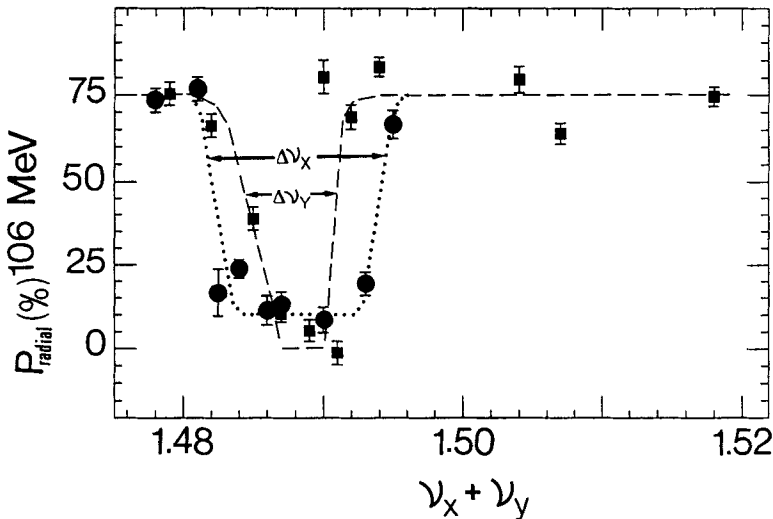

Fig. 15 Studying a Snake resonance by varying ν_x and ν_y.

Recall the concern about the possible miscalibration of the Cooler Ring energy. Our data indicated that the $G\gamma = 2$ resonance was occurring near 106.5 MeV, while much data was based upon a well established 108.4 MeV energy calibration for both the Cooler Ring and the Cyclotron. Pollock believed that this 108.4 MeV calibration was correct. Pollock, with some advice by Roser, then proposed that there might be a third type of Snake in the Cooler Ring. Type-1 Snakes rotate the spin about the longitudinal direction, while Type-2 Snakes rotate the spin about the radial direction. At the June meeting in Brookhaven

on partial Snakes, Roser apparently suggested that there could also be Type-3 Snakes which could rotate the spin about the vertical direction. Just before our August run, Pollock submitted a paper[7] proposing that a Type-3 Snake would explain our apparent shift in the energy calibration. He suggested that the Electron Cooler magnet system was a Type-3 Snake, because it contained several solenoids and toroids. Spin operators do not commute, so these magnets could produce a weak Type-3 Snake which could shift the spin tune and thus the resonant energy. I afterwards found a paper by Shatunov and Skrinsky[8], which never refers to Type-3 Snakes, but stresses that a depolarizing resonance energy calibration is only reliable provided there are no longitudinal fields.

We tested the Type-3 Snake proposal by first measuring the vertical polarization at 106 MeV as a function of $\int B \cdot dl$ with the cooling magnets on; this data is shown in Fig. 16. As expected, we saw a sharp peak. This peak at 106 MeV had a width almost identical to the peak at 107 MeV shown in Fig. 9; this equality gave a calibration of the resonance energy at about 106.5 MeV. Then we turned the cooling system completely off. This made the measurements somewhat more difficult because the beam intensity and life-time both deteriorated; however, we were able to make some measurements. Notice that with the cooling magnets turned off and thus any Type-3 Snake turned off, the peak was much broader; in fact it was quite consistent with the resonance having shifted back up to near 108 MeV. This shift seems to be rather direct evidence for the existence of a weak Type-3 Snake which was accidentally built into the Ring's cooler section. This was a clever bit of detective work by Pollock and Roser.
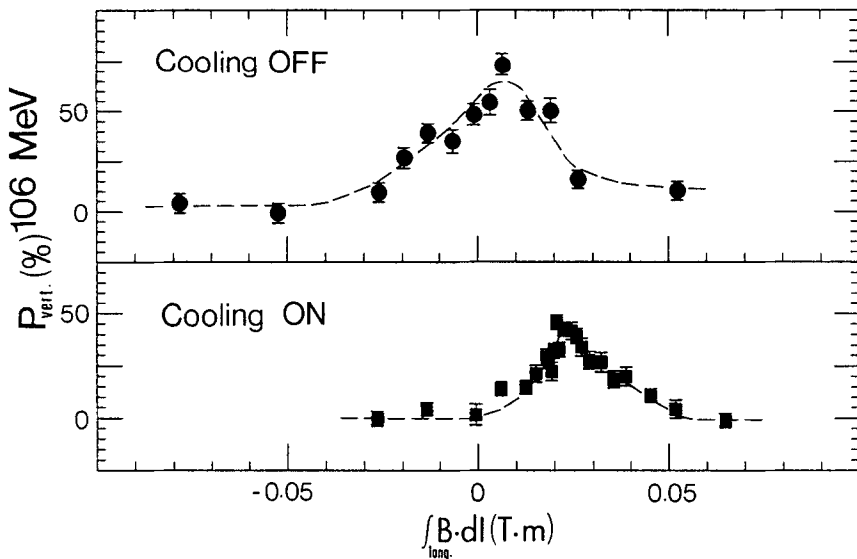

Fig. 16   Measuring the resonance width at 106 MeV with a Type-3 Snake on and off.

At multi-TeV facilities there will be a new problem called overlapping depolarizing resonances; these will occur as the various resonances get stronger and thus wider, while the 523 MeV spacing between the imperfection resonances remains fixed. This overlapping was no problem up to the maximum AGS energy of 22 GeV. However, at multi-TeV energies, overlapping depolarizing resonances should be common. Experts, such as Courant and Derbenev, believe that Siberian Snakes should be able to overcome the overlapping resonances at the SSC. We plan to experimentally study these overlapping resonances by creating an induced depolarizing resonance at the Cooler Ring as was done at Novosibirsk[8]. We will then move this induced resonance near either the $G\gamma = 2$ or the $G\gamma = -3 + \nu_y$ resonance. We are now building a high power RF solenoid to create a strong induced depolarizing resonance that can interfere with each of these two resonances.

During our August run we made a simple first study of an induced depolarizing resonance. We disconnected the RF knock-out system which was normally used for measuring the Cooler Ring betatron tunes; we then connected its power supply to one of our two kicker magnets. This produced a rather weak RF vertical field. With 106 MeV radially polarized protons injected, we then turned on the Snake and thus forced the spin tune to be about 1/2. The spin tune was not exactly 1/2 because the cooling was on, which presumably shifted ν_s slightly. Then we varied the RF frequency in an attempt to produce a weak induced depolarizing resonance. As shown in Fig. 17, this study was quite successful. We saw a clear depolarizing resonance when we varied the frequency around the calculated resonant frequency. We estimate that the center of the dip was about 771.0 ± 0.2 kHz; thus the relative error was about $3 \cdot 10^{-4}$. This seems a very precise way to directly measure the spin tune with a precision of about $3 \cdot 10^{-4}$.
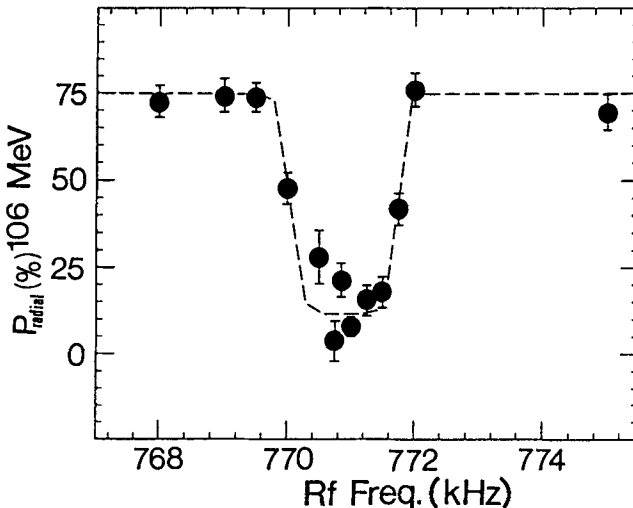

Fig. 17 A depolarizing resonance induced by an rf dipole field.

A major goal of our Siberian Snake studies was the acceleration of polarized protons to TeV energies at some facilities such as the SSC. Our SPIN collaboration recently submitted a preliminary proposal to install Siberian Snakes in the SSC and then accelerate polarized protons to 2 TeV and then to 20 TeV. At the June PAC meeting at SSC our collaboration contained 38 people from Michigan, Protvino and Dubna; recently 28 additional accelerator physicists and experimenters from Indiana, Moscow, KEK, and Kyoto joined our SPIN collaboration. We have had considerable interaction with the SSC people and they now seem rather interested in polarized proton beams but certainly not yet committed. This SSC project could be the first significant application of Siberian Snakes to a very high energy facility. Other possibilities include using Siberian Snakes to accelerate polarized protons at the Fermilab Main Ring, at RHIC, or at the 400 GeV and 3 TeV UNK rings.

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