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ACCELERATING POLARIZED PROTONS WITH SIBERIAN SNAKES*

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There is a brief review of the history of polarized proton beams and the unexpected and still unexplained large transverse spin effects found in high energy proton spin experiments at the ZGS, AGS and Fermilab. Next there is a detailed discussion of Siberian snakes and some of their tests at the IUCF Cooler Ring. Finally there is a report on the use of Siberian snakes in some possible high energy polarized proton beams at RHIC, HERA and Fermilab.

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The world's first high energy polarized proton beam was accelerated at the ZGS in 1973. The ZGS polarized beam's design work started in 1969; for the first time one had to overcome depolarizing resonances. Fortunately, at the weak focusing ZGS, the resonances were not too strong and we did overcome them [1]. At that time, we did not yet know very much about polarized proton beams, but we were lucky.

From 1973 until 1979 the ZGS polarized proton beam operated and produced some exciting physics. Fig. 1 shows the p-p elastic cross-sections in different initial spin states plotted against $P_\perp^2$ [2]. At small $P_\perp^2$ the spin-parallel and the spin-anti-parallel cross-sections are almost equal. But at large $P_\perp^2$, where the protons' constituents directly interact, we found that the hard scattering component only occurs when the spins are parallel. When the spins are anti-parallel, the protons' constituents apparently pass through each other. This was a very surprising result in 1977; despite hundreds of theory papers, it still has not been adequately explained.

Bethe and Weisskopf then suggested that since, at 12 GeV, this spin effect was only large near $90^\circ_{\rm cm}$, perhaps it was due to particle identity effects

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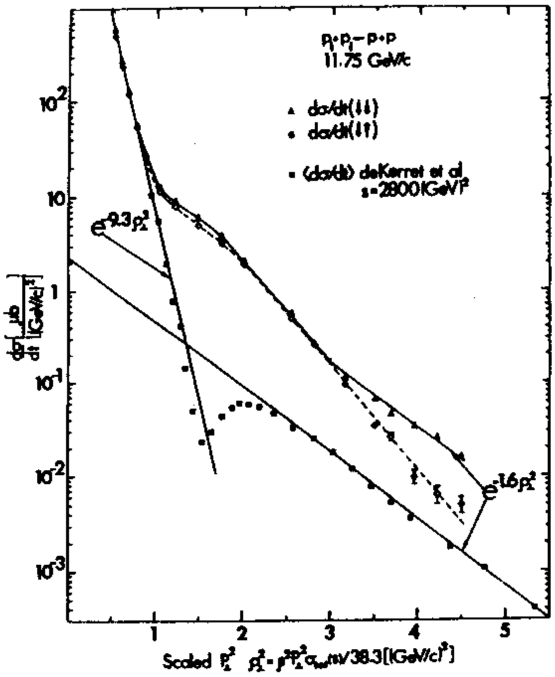

Fig. 1. Proton-Proton Elastic scattering cross-sections in parallel and anti-parallel initial spin states plotted against the scaled $P_\perp^2$ variable [15].

rather than large-$P_\perp^2$, hard scattering. To answer this question, we redid the experiment while holding fixed the center-of-mass scattering angle at exactly 90°_{cm} [3] and varying $P_\perp^2$ by varying the incident energy. We found that this large spin effect still occurred at the large-$P_\perp^2$ higher energy points, while from about 3 to 8 GeV/c, where $P_\perp^2$ was smaller, the spin asymmetry was small, although one was still at 90°_{cm}. I later made Fig. 2 [4] with some help from Prof. Haeberli, who is an expert on lower energy spin effects. This plot of the spin-spin asymmetry A_{nn} at 90°_{cm} shows dramatic structure below 2 GeV/c; then near 3 GeV/c the A_{nn} asymmetry drops to almost zero; perhaps this drop convinced many people that spin effects would disappear at high energy. But then A_{nn} rises dramatically near 8 GeV/c. This curve certainly did not confirm the belief that spin effects would disappear at high energy.

At Fermilab in the late 1970's, some people were studying Λ hyperons produced with both the beam and the target unpolarized [5]. By studying their decay distribution, they found a large Λ polarization near $P_\perp = 1$ GeV/c. Moreover, the Λ polarization seems to be independent of energy. Fig. 3 shows, as dashed lines, the many small-error 400 GeV points from

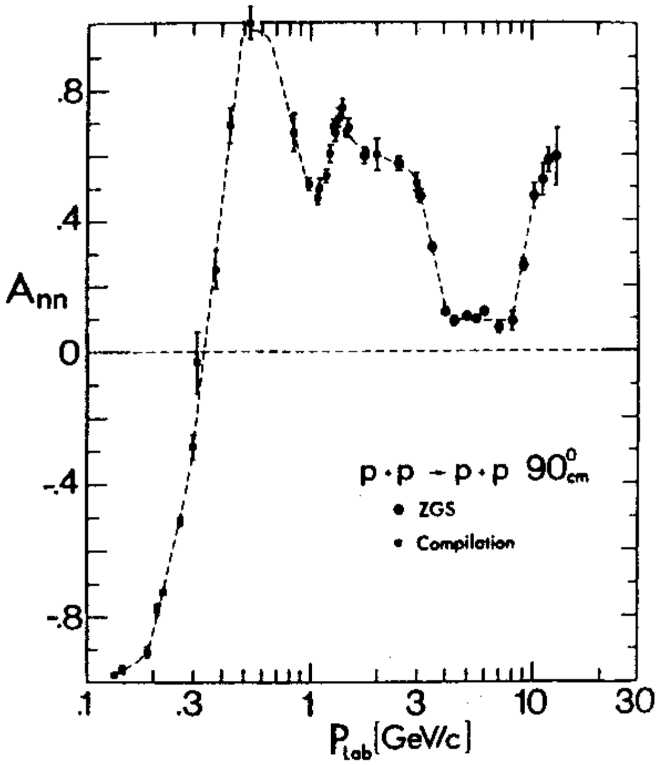

Fig. 2. Compilation of the proton-proton elastic spin-spin parameter at 90 $^\circ_{\rm cm}$ [3, 4].

Fermilab; the 12 GeV KEK data and the 2000 GeV ISR data are also shown. These hyperon polarization data indicated that hadronic interactions have large spin effects which do not decrease with energy.

Perturbative QCD predicted that spin effects should disappear at high energy and at large $P_\perp^2$. Our 1985 to 1990 Brookhaven AGS experiments on p-p elastic A_n at 24 and 28 GeV indicated that this prediction may not be true; the data are shown in Fig. 4. We first confirmed, with better precision, some CERN-Oxford small-$P_\perp^2$ data. We then built a much better polarized target, which allowed rather precise measurements at larger $P_\perp^2$ [6]. The large-$P_\perp^2$ data clearly do not agree with the $A_n = 0$ prediction of perturbative QCD; apparently this is not a region of validity for PQCD.

Yokosawa's group used this hyperon-decay polarization to develop a 200 GeV polarized proton beam at Fermilab. The intensity was too low for experiments at large $P_\perp$, however, at moderate $P_\perp$ they did find a large A_n in inclusive $\pi^\pm$ production in 200 GeV p-p collisions. The asymmetries are large and are very different for π^+ and π^-, as shown in Fig. 5. [7]; this is more evidence that spin effects are large at high energy.

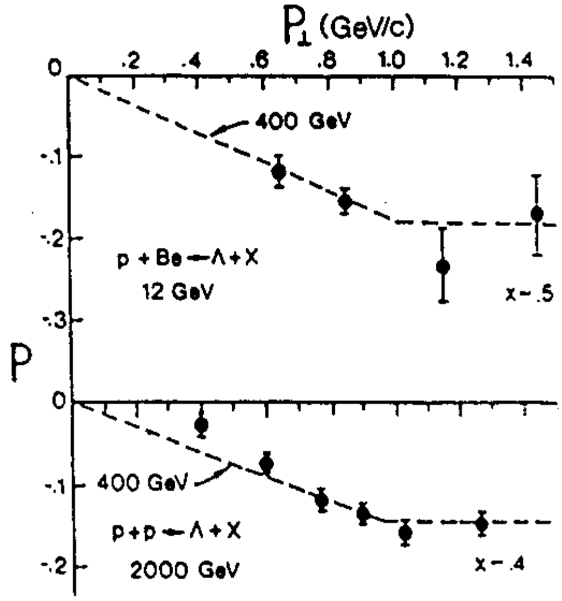

Fig. 3. Inclusive hyperon polarization data from Fermilab (400 GeV); KEK (GeV) and the CERN ISR (2000 GeV) [5].

Next, I will discuss higher energy polarized proton beams. The Brookhaven AGS polarized beam design started at a 1977 workshop in Ann Arbor [8]. In 1984 the AGS polarized beam started operating and some spin experiments started. Developing the AGS polarized beam was a difficult job, because the AGS is a strong focusing accelerator and its depolarizing resonances are quite strong. These depolarizing resonances occur when the spin precession frequency gets in phase with the frequency of passing through some horizontal magnetic fields. The proton's spin then has the same orientation each time it passes through these depolarizing fields; the resulting coherence can rapidly depolarize the proton beam.

Developing the AGS polarized beam cost about 10 Million 1980 Dollars and took about 5 years. To reach 22 GeV, we individually overcame 45 depolarizing resonances by tuning each to maximize the polarization; Fig. 6 is a typical tuning curve where we overcame the $G\gamma = 9$ imperfection resonance near 4 GeV [9]. Overcoming these 45 resonances required exclusive use of the AGS for 7 weeks; Dr. Samios, Brookhaven's Director, visited me about once a week in the AGS control room to politely remind me that these studies were costing \$1 Million a week. I am very pleased that we did accelerate the AGS polarized beam up to 22 GeV, but the 7 weeks of tune-up time cost about \$7 Million. Clearly this individual resonance correction technique was impractical for a much higher energy. The SSC would have had 36,000 de-

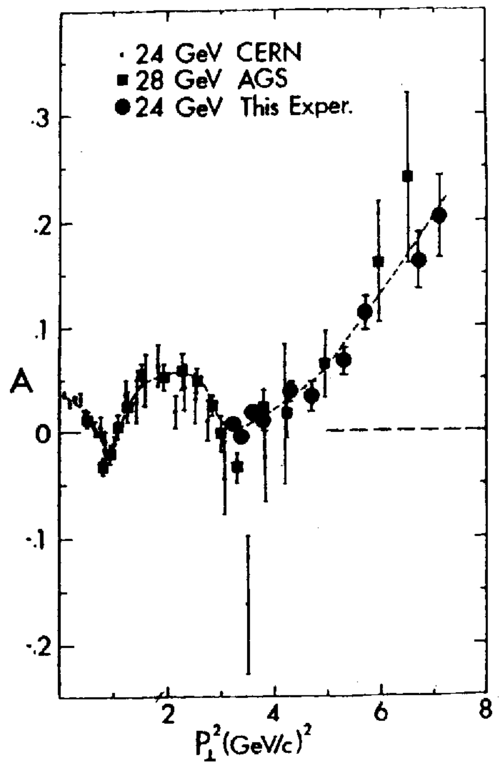

Fig. 4. The analyzing power A_n plotted against momentum transfer squared $P_\perp^2$ for proton–proton elastic scattering [6].

polarizing resonances; at the same tuning rate of one day per resonance, an SCC polarization tune-up would have required almost 100 years.

Polarized electron people do not have to overcome depolarization resonances and do not have to build polarized sources. Around 1963 two bright Russian theorists, Sokolov and Ternov [10], calculated that some self-polarization should occur because the synchrotron radiation rates are slightly different when the electron spin is either parallel or antiparallel to the ring magnets' field. At first, this self-polarization was considered a clever theoretical curiosity, but of little practical interest. However, this technique is now used at both the world's large electron rings, HERA and LEP. Moreover, the LEP depolarizing resonances allowed calibrating the Intermediate Boson mass with the unusual precision of about 1 part in 10^4; without self-polarization such precision would have been impossible. The late Sokolov and Ternov certainly deserve great credit for this clever idea.

One would need a 70 TeV proton accelerator before the Sokolov-Ternov self-polarization would become useful because of the proton's much smaller

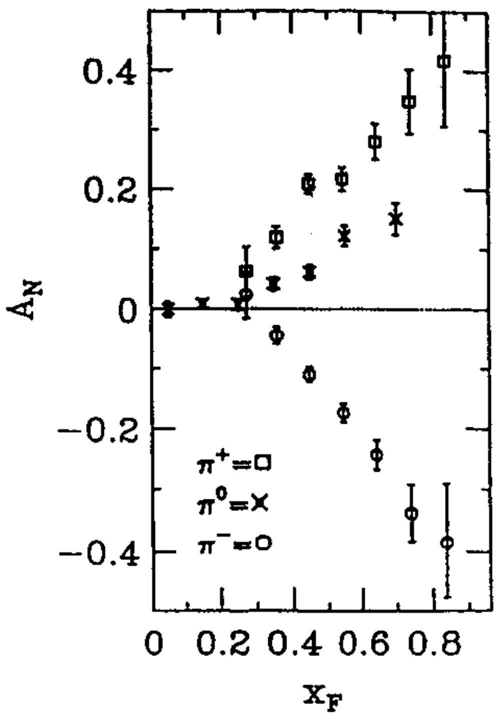

Fig. 5. Left–right asymmetry in inclusive pion production in 200 GeV p–p collisions at Fermilab [7].

magnetic moment and much larger mass. Fortunately, around 1976, two other bright Russian theorists, Derbenev and Kondratenko [11], invented Siberian snakes. A snake rotates the spin direction by exactly 180° on each turn around a ring; this makes all the depolarizing fields cancel themselves. To understand snakes, let us assume that, before going around the ring, a proton starts with its spin vertically up at 0°. Next assume that all the depolarizing fields in one turn around the ring rotate the spin from 0° to 5°; then after this one turn, the snake rotates the spin by 180° to 185°. When the proton goes around the ring a second time, the same depolarizing fields now rotate the proton's spin by 5° in the opposite direction from 185° back to 180°; finally the snake again rotates the spin by 180°, which returns it to 0°. The Siberian snake is a very clever idea; it makes the difficult-to-correct depolarizing fields cancel themselves.

At a 1985 workshop in Ann Arbor, [12] it became clear that accelerating polarized protons to very high energies would need Siberian snakes. Probably Ernest Courant already understood this during the 1977 Ann Arbor Workshop; I recall him trying to convince Owen Chamberlain and me that

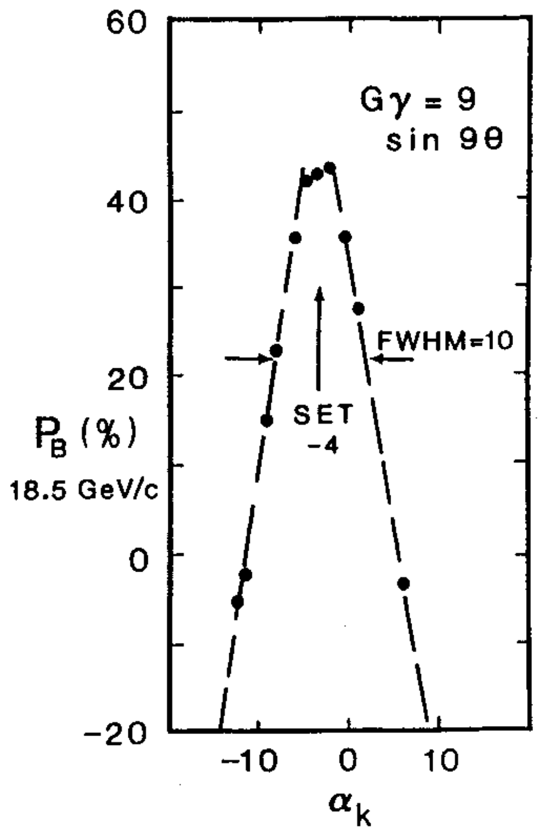

Fig. 6. Overcoming the $G\gamma = 9$ imperfection depolarizing resonance at the AGS [9].

Siberian snakes were a great idea, but apparently with little success. In any case, at the 1985 Workshop, Courant finally convinced us, and off we went to try this Siberian snake idea at a new accelerator. The Indiana Cooler Ring was just coming on line; its energy was only about 500 MeV; however, it had 6-meter-long straight sections and we put a Siberian snake in one of them. The snake was a large superconducting solenoid of about 2 Tesla-meters, which was enough to rotate the spin by 180° up to a few hundred MeV.

The first experimental results using the Siberian snake are shown in Fig. 7 [13]. We studied the $G\gamma = 9$ imperfection depolarizing resonance which always occurs near 108 MeV. With no snake, there was full polarization only when we exactly corrected the field; any small imperfection field clearly destroyed the polarization. Fig. 7 looks quite similar to Fig. 6, where we had individually corrected the $G\gamma = 9$ resonance at the AGS. On the other hand, with the Siberian snake turned-on, there was full polarization over the entire

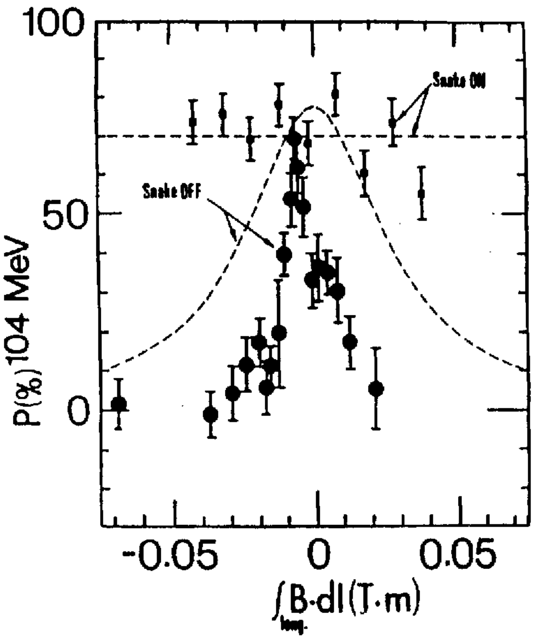

Fig. 7. Siberian snake overcoming the $G\gamma = 2$ imperfection depolarizing resonance at IUCF [13].

range. This result got a lot of attention. For some reason CNN decided that Siberian snakes were newsworthy; they broadcast a story about them five times. More importantly, a number of accelerators around the world are now using or designing Siberian snakes.

Since then there have been many other Siberian snake experiments. As shown in Fig. 8, we found that the Siberian snake could also overcome intrinsic depolarizing resonances [14]. We also studied: RF depolarizing resonances, which can calibrate the beam energy or flip the spin direction; synchrotron side band resonances; snake depolarizing resonances; partial Siberian snakes; and many other things unknown when the ZGS polarized proton beam was somehow accelerated in 1973.

After the Siberian snake concept was tested, we formed the US-Russian-Japanese-Canadian SPIN Collaboration to try to get all the world's proton beams polarized. This Collaboration has had several permutations. It started in 1990 with the first SSC proposal EOI-001; this proposed to make 26 extra spaces in each SSC ring for the installation of Siberian snakes [15]. The SSC Management somewhat accepted the proposal as shown in Fig. 9; they actually changed the lattice to make 52 extra spaces of about 20 meters each for the later *possible* installation of Siberian snakes. But of course the SSC is now gone, so this is just history.

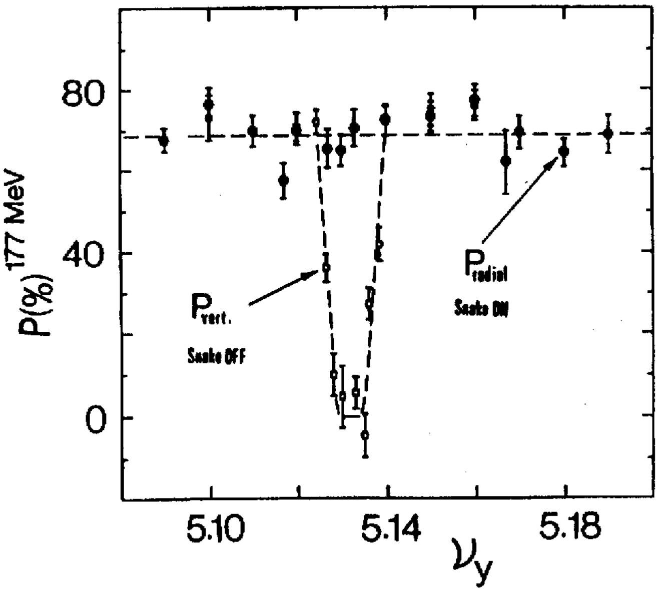

Fig. 8. Siberian snake overcoming the $G\gamma = 3 + \nu_y$ intrinsic depolarizing resonance at IUCF [14].

In late 1990, John Peoples, Fermilab's Director, apparently became interested in accelerating polarized protons at Fermilab; during the next few years, Fermilab paid our SPIN Collaboration $366,000 for a 225-page Design Study Report [16]. As shown in Fig. 10, we found that one could accelerate polarized protons with: 6 Siberian snakes in the Tevatron, 2 snakes in the 120 GeV Main Injector, and some AGS-ZGS-type hardware in the 8 GeV Booster. This polarized beam project would cost about $20 Million including some accelerator modifications. We submitted the Report in July 1995; however, Fermilab's Management apparently soon decided that they did not then want to accelerate polarized protons.

In 1995, Bjorn Wiik, DESY's Director, was watching these studies because they involved testing a HERA dipole at DESY. When it was learned that Fermilab was apparently not planning to proceed, DESY paid our SPIN Collaboration DM 100,000 to do a similar study for HERA. In November 1996 we submitted the 92-page Design Study Report [17]. SPIN and DESY both got a good bargain because HERA is not very different from the Tevatron. We estimated that accelerating polarized protons in HERA would cost about DM 25 Million. The proposed HERA proton polarization hardware is shown in Fig. 11. We found that HERA's 820 GeV proton ring may be a bit more difficult to polarize than the Tevatron because it has 4-fold

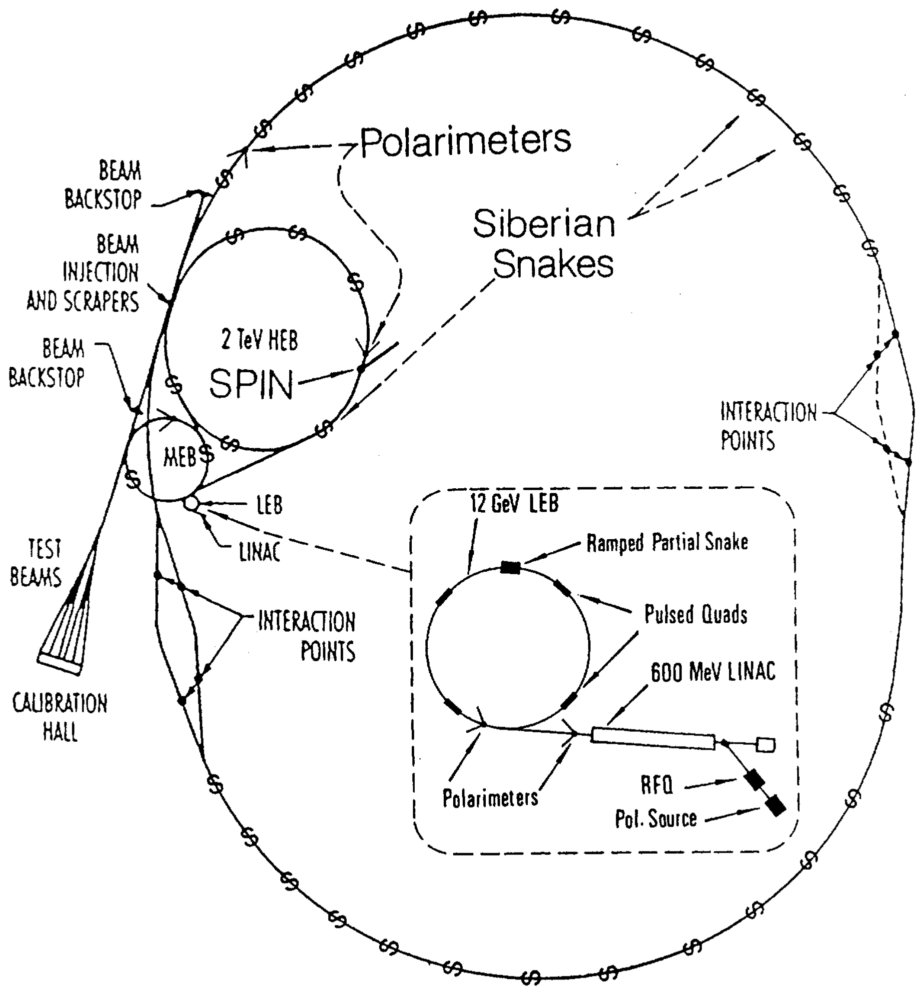

Fig. 9. The planned 20 TeV polarized proton beam at SSC [15].

rather than 6-fold symmetry. For reasons which Courant and Derbenev understand, an odd number of pairs of snakes is best; thus, 6 snakes are much better than 4. The DESY Directors seem quite interested; however, because of recent financial problems, they cannot even consider funding this project before 2000. Thus, they decided to give our SPIN Collaboration DM 200,000 for polarized beam R & D during 1997 and 1998.

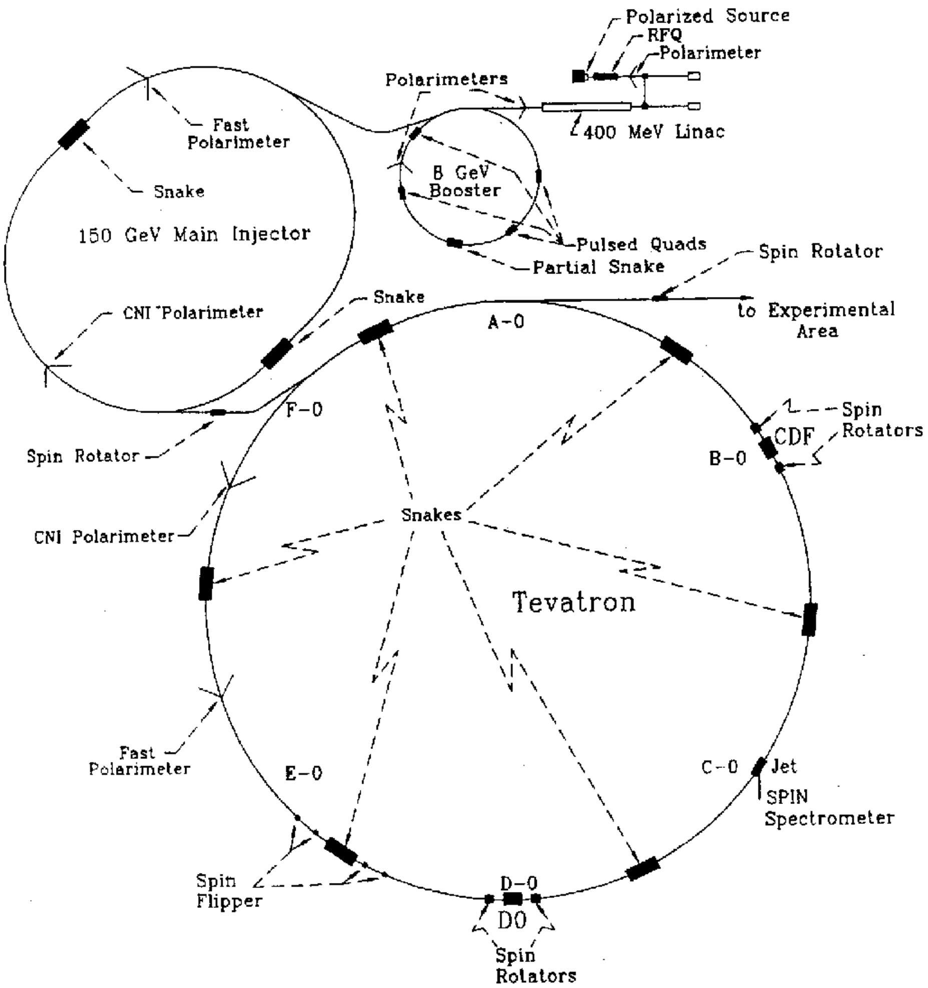

Fig. 10. The proposed polarized proton beams at Fermilab [16].

The RHIC polarized proton beam at Brookhaven is now proceeding fairly quickly. The AGS now has a partial Siberian snake which allowed the Brookhaven team, during two runs in 1994, to successfully overcome [18] about 40 imperfection depolarizing resonances, without the earlier [9] painful correction studies; they are now working on the intrinsic depolarizing resonances. Brookhaven has decided to accelerate polarized protons at RHIC;

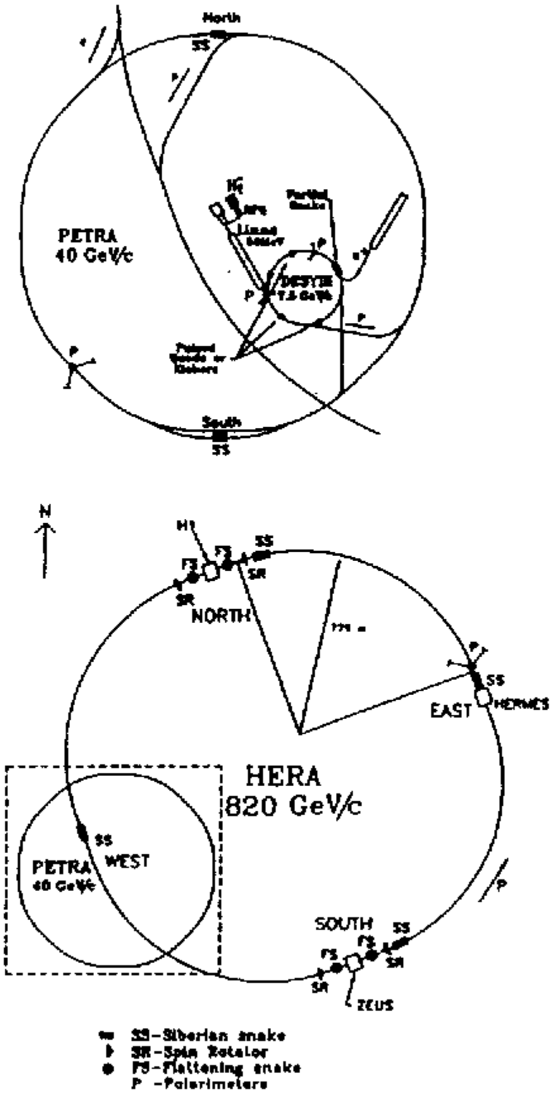

Fig. 11. The proposed 820 GeV HERA polarized proton beam at DESY [17].

the Japanese RIKEN contributed $20 Million to this project. The RHIC Siberian snakes, shown in Fig. 12, may be installed by 1999 [19]. Hopefully some RHIC polarized proton experiments could then start fairly soon. One should be able to make detailed studies of spin effects in p-p elastic scattering and in various inelastic channels. I certainly would like to see the data in Figs. 1, 2, 4 and 5 extended to higher $P_{\perp}^2$ and to higher energy; this may be possible at RHIC.

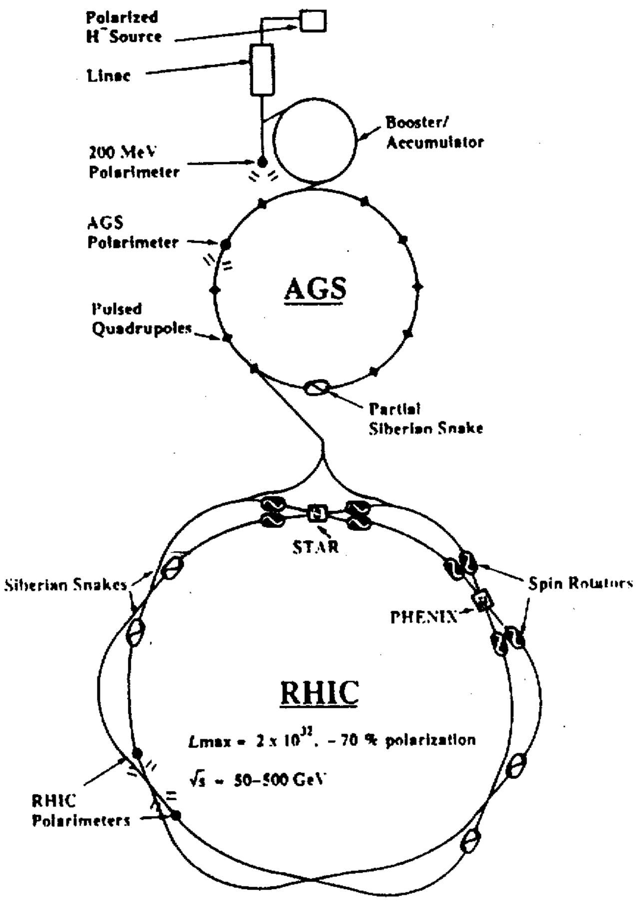

Fig. 12. Polarized protons at RHIC [19].

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