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Spin Experiments at UNK, Fermilab, and SSC*

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This talk has a brief introduction and then three parts. The first part is about NEPTUN-A at UNK, where we plan to study spin effects in 400 GeV proton-proton interactions. Next I will discuss the SPIN program at Fermilab which includes plans to accelerate polarized protons to 150 GeV in the new Main Injector and then to 1 TeV in the Tevatron. Finally, I will cover the SPIN collaboration's proposal at SSC; this includes accelerating polarized protons first to 2 TeV and then to 20 TeV.

Let me begin the introduction by noting that spin effects are apparently large at all energies, even with unpolarized beams and unpolarized targets. As Ken Heller showed earlier, a large hyperon polarization was found at 12 GeV at KEK, at 400 GeV at Fermilab, and at 2 TeV at the ISR. Certainly, the hyperon polarization is large wherever it has been measured.

When one incident proton is polarized, as in our 24 GeV AGS experiments[1], there are large spin effects in p-p elastic scattering. Perturbative QCD suggests that all spin effects should go to zero at high $P_\perp^2$. Instead, as shown in Fig. 1, we found that the analyzing power A is quite large at high $P_\perp^2$ where the perturbative QCD prediction of zero analyzing power should become better. We hope to some day study even larger $P_\perp^2$, although it is rather difficult because of the small cross-section.

The PQCD predictions should also become better at higher energies; fortunately, there are accelerators with higher energy than the AGS. In 1989, we formed the NEPTUN-A collaboration to study the analyzing power in large $P_\perp^2$ elastic p-p scattering at UNK in Protvino, Russia, first at 400 GeV around 1995 and then later at 3 TeV. As shown below, NEPTUN-A contains about 40 physicists from Russia and America. Dr. Solovianov is the responsible Russian physicist for NEPTUN-A and the spokesperson for the related NEPTUN.

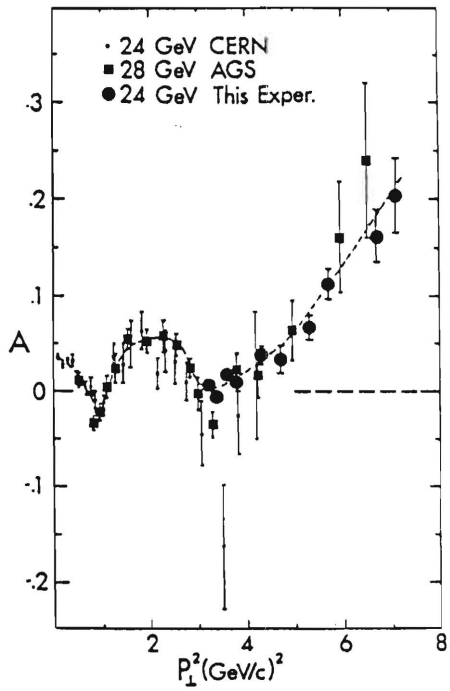

Fig. 1 Analyzing power for p-p elastic scattering.

V.A. Anferov, J.A. Bywater, C.M.Chu, D.G. Crabb*, D.A. Crandell, Ya.S. Derbenev, J.W. Duryea, W.A. Kaufman, A.V. Koulsha, A.D. Krisch , A.M.T. Lin, T.S. Nurushev, D.C. Peaslee, R.A. Phelps, R.S. Raymond, D.S. Shoumkin, J.A. Stewart, V.K. Wong; MICHIGAN (Ann Arbor).

O.V. Buyanov, V.V. Churakov, O.A. Grachov, V.N. Grishin, V.A. Kachanov, Yu.V. Kharlov, V.Yu. Khodyrev, Yu.M. Melnik, A.P. Meschanin, N.G. Minaev, V.V. Mochalov, S.B. Nurushev, D.I. Patalakha, A.F. Prudkoglyad, V.V. Rykalin, P.A. Semenov, V.L. Solovianov, M.N. Ukhanov, A.N. Vasiliev, A.E. Yakutin; IHEP (Protvino).

V.V. Fimushkin, V.G. Luppov, Yu.K. Pilipenko, V.V. Shutov; JINR (Dubna).

G.R. Court†, D. Kleppner; MIT (Cambridge). L.G. Ratner; BNL (Upton).

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Fig. 2 UNK, U-70, Protvino, and Serpukhov.

The UNK ring has a circumference of 21 km as shown in Fig. 2. The tunnel digging is about 99.8% finished. An underground river caused a collapse at SS-4, which is now being repaired. Both NEPTUN-A and NEPTUN will run in the large SS-3 cave, which is about 60 m underground and about 11 km from the 70 GeV U-70 injector and the town of Protvino. When the 3 TeV ring operates around 1998, there will be an extracted beam to the neutrino and hadron areas with several approved experiments including GLUON, MPS, and POLEX. During my October 1992 visit, I found continued good progress on UNK. The underground SS-3 area for NEPTUN and NEPTUN-A is shown in Fig. 3. Most of the tunneling is finished; some parts have smooth floors. Note the underground electronics hall and the two elevator shafts. The final arch in the 60 m long by 15 m wide main hall was finished in late October.

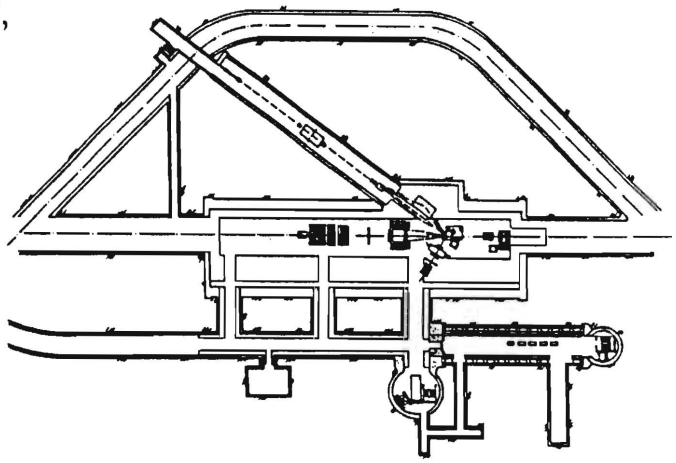

Fig. 3 The SS-3 Underground Cave.

The TONOT tunneling team recently finished the 25 m long horizontal tunnel for our NEPTUN-A recoil spectrometer arm; they are now digging the 30 m long tunnel extension with a 12° slope. The bypass tunnel around NEPTUN-A is competely finished. All NEPTUN and NEPTUN-A experiments will use a polarized gas jet placed in the 400 GeV UNK proton beam. Notice our 55 m long spectrometer, the forward spectrometer of Solovianov et al. of IHEP, and the spectrometer of Kazarinov et al. of Dubna and Sarycheva et al. of Moscow. Nikitin et al. of Dubna and Glonty et al. of Tbilisi might place their spectrometers near the upstream nuclear jet.

Our 55 m long recoil spectrometer contains three bending magnets; four quadrupoles to increase the acceptance solid angle; some wire chambers for momentum analysis; two Cherenkov Counters; and recoil hodoscopes. We also plan to have two small forward hodoscopes. Measuring the momentum of each elastic recoil proton with a high precision of about 0.1% should cleanly tag elastic scattering at 400 GeV. Fortunately, in a fixed target experiment, the angle and momentum of the elastic recoil proton are essentially independent of the incident energy. Therefore, at 400 GeV or at 3 TeV this recoil momentum is only a few GeV for $P_\perp^2$ near 5 $(\mathrm{GeV}/c)^2$.

The jet is essential to NEPTUN-A and to the other NEPTUN spectrometers. Around 1987 we built the prototype ultra-cold spin-polarized atomic-hydrogen jet shown in Fig. 4. The hydrogen molecules are first dissociated into hydrogen atoms which then pass down the central tube. The hydrogen atoms' temperature drops first to 80° K near the liquid nitrogen shield, and next to 4° K near the helium-4 shield. Then the atoms pass the 1° K still of the dilution refrigerator; eventually the atoms enter the mixing chamber which cools them to about 0.3° K as they enter a very strong magnetic field of 7.6 Tesla. The combination of the low temperature and the high field causes all the atoms in one spin state (high field seekers) to be trapped in the center of the magnet, because the magnetic energy $\mu \cdot B$ is much larger than the thermal energy kT. However, the atoms in the other spin state (low field seekers) are driven away. Therefore hydrogen atoms in one electron spin state are rather effectively trapped. We then inject microwaves at 213 GHz which cause spin-flip transitions. The high field seekers then become low field seekers which the strong magnetic field accelerates out as a jet, that we focus with a sextupole and then detect with several detectors.

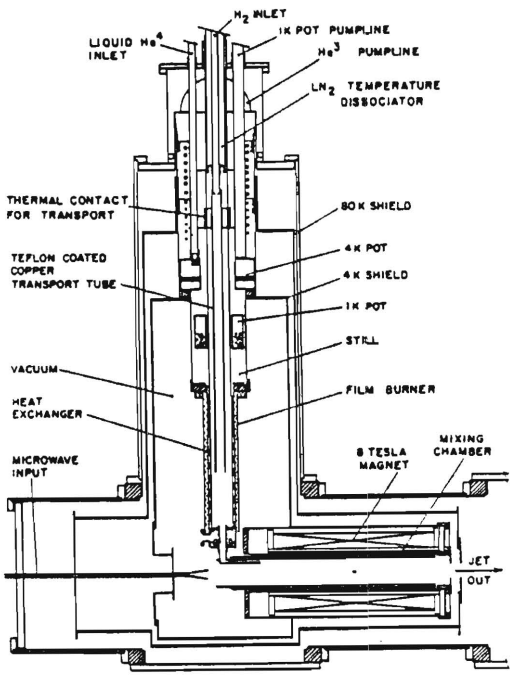

Fig. 4 Michigan prototype ultra-cold jet.

Our colleague, Vladimir Luppov, proposed using a superfluid helium-coated focusing parabolic mirror. Physicists at Amsterdam showed that a low-temperature surface coated with superfluid helium-4 efficiently reflects hydrogen atoms. We recently built such a mirror; as shown in Fig. 5, the hydrogen atoms enter from the left into the mixing chamber. The hydrogen beam emerges because of the magnetic acceleration by the 8 T solenoid fringe field. The focusing mirror contains four cones that form a quasi-parabolic surface which is coated with superfluid helium. This focusing mirror reflects the accelerated atoms into a parallel beam; it increased the intensity in our detector by a factor of about 7.5. This focusing mirror may be the first practical application of "atomic optics".

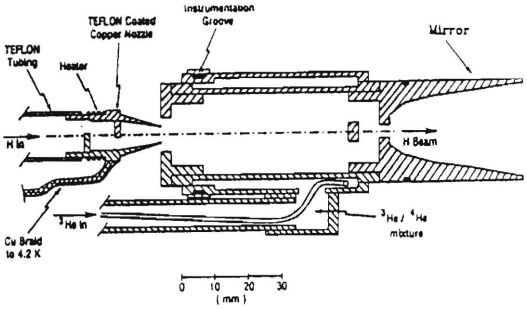

Fig. 5 Superfluid ^{4}He-coated focusing mirror.

We are now building in Ann Arbor the much bigger and stronger Mark II Jet, which must live 60 m underground in the SS-3 cave. This Mark II Jet is shown in Fig. 6; it is about 6 meters high. We already tested the liquid helium tanks, the liquid nitrogen tanks, and the 12 T solenoid built by Cryomagnetics; it works well at 12 T. At this higher field, there is more magnetic acceleration, and a cleaner beam. However, microwave extraction is impossible at 12 T because the matching frequency is about 380 GHz, which is far outside the high-power microwave source range. Fortunately, our group also developed a "no-microwave" extraction method where the atoms in one spin state are continuously extracted. A superconducting sextupole magnet then focuses the extracted spin-polarized atoms into a jet which passes through the UNK beam; there are windows for the various spectrometers. We are now assembling the Mark II Jet; we expect to begin testing it in early 1994.

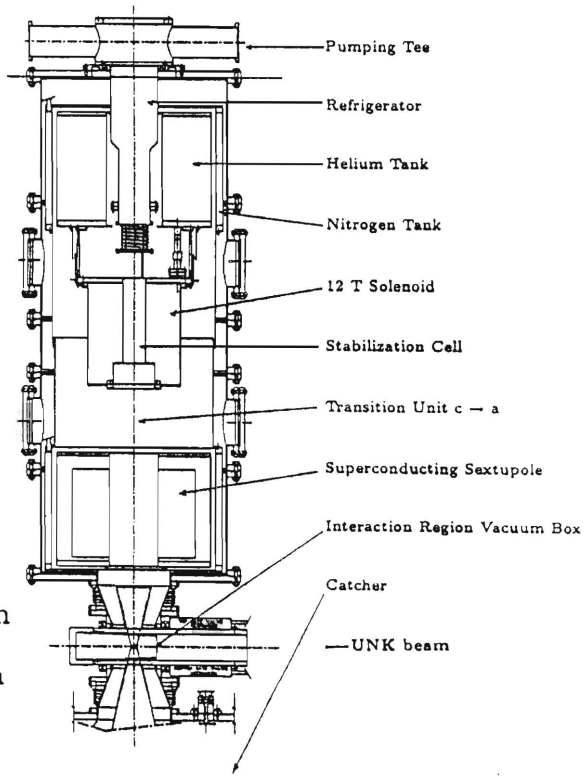

Fig. 6 The Mark II Ultra-Cold Jet.

Thus, there is good progress on our experimental area and the jet; we are also making good progress on our detectors. But, of course, we also need UNK which has had some funding problems because of the many changes in Russia. However I am very pleased that the UNK progress still continues steadily. During my October 1992 visit, I walked through the transfer tunnel

from the existing 70 GeV accelerator to the UNK tunnel. This transfer tunnel, which is shown in Fig. 7, is about 2 km long; it now contains all 50 of the normal 6 m long UNK dipole magnets, some quadrupoles, some corrector magnets, and some vacuum pipe. The plan is to extract beam from U-70 and then pass it through this new 1.7 km transfer line up to a beam stop. The UNK people are eager to soon reach this important milestone.

Fig. 7 The U-70 to UNK transfer tunnel.

I will next talk about accelerating polarized proton beam at Fermilab. One reason why this is interesting is shown in Fig. 8, where the spin-spin parameter, A_{nn}, at exactly 90°_{cm} is plotted against P_{lab} for p-p elastic scattering. This data extends from very low energy to the highest energy ZGS data. Notice the enormous structure in A_{nn}; this graph certainly does not suggest that spin effects are disappearing at high energy. There is much enthusiasm to see what happens at even higher energy; therefore we are eager to accelerate a higher energy polarized proton beam.

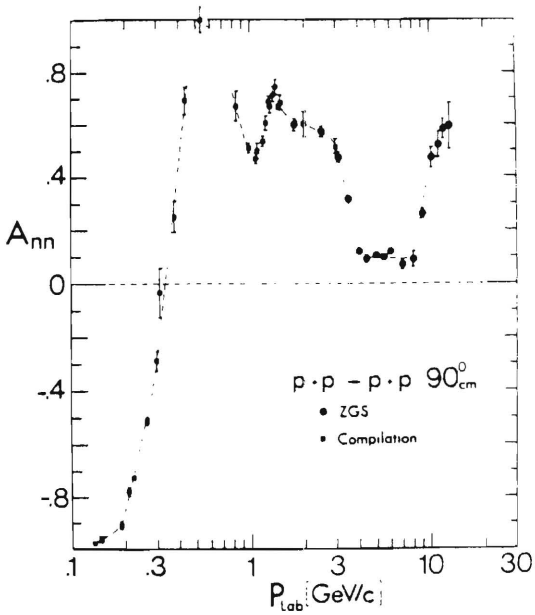

Fig. 8 A_{nn} at 90°_{cm} for p-p elastic scattering.

Unfortunately, it is difficult to accelerate polarized protons to very high energy. The ZGS[2] technique of correcting imperfection resonances and jumping intrinsic resonances worked rather well at the ZGS, KEK[3], and Saturne[4]. The same technique did work at the AGS[5], but it was quite painful, time consuming, and expensive. Fortunately, around 1975 Derbenev and Kondratenko[6] proposed a new idea, called the Siberian snake, which should simultaneously overcome all depolarizing resonances by rotating the spin by 180° on each turn around a ring. To understand a Siberian snake,

consider a proton starting around a ring with its spin direction vertically up at 0^0. Next assume that in one turn around the ring, the imperfection fields rotate the spin from 0° to 5°; then the snake rotates the spin by 180° taking it to 185°. During the second turn around the ring, the imperfections again work in the same direction, but now rotate the angle from 185° back to 180°. Finally the snake again rotates the spin direction by 180° back to exactly 0°. It is a very clever idea; it makes the imperfections cancel themselves.

In 1985 Courant, Chamberlain, Terwilliger, and I organized in Ann Arbor the Workshop on Polarized Beams at the SSC[7], which concluded that the Siberian snake concept should soon be tested somewhere. We chose to test a Siberian snake at the IUCF Cooler Ring; this was a nice new polarized proton storage ring. We constructed and installed a Siberian snake containing a 2 T · m superconducting solenoid magnet, which rotates the spin by 180°, and eight quadrupole magnets which do nothing to the spin, but compensate the orbit distortions caused by the strong solenoid.

We first demonstrated[8] 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. 9. With no snake the circles show a full polarization of about 70% only when you exactly correct all imperfection fields. Just the tiniest imperfection field rapidly kills the polarization. However with the Siberian snake on, the squares show full polarization over the entire range. It certainly appears that the Siberian snake can overcome this imperfection resonance.

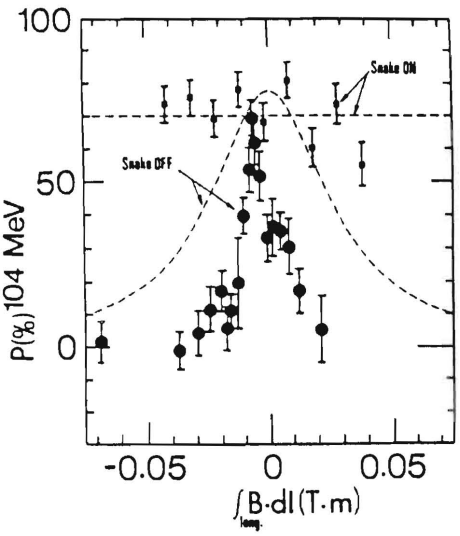

Fig. 9 Siberian snake overcoming the $G\gamma = 2$ imperfection resonance.

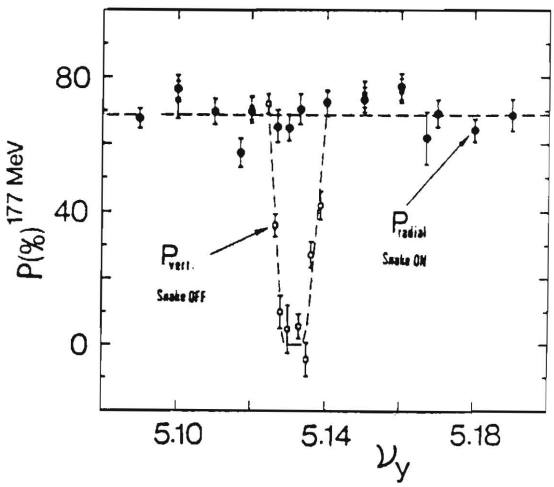

Fig. 10 Siberian snake overcoming the $G\gamma = \nu_y - 3$ intrinsic resonance.

We also studied[9] an intrinsic depolarizing resonance which is caused by the vertical betatron oscillation that exist in all accelerators. This resonance occurs when $G\gamma = \nu_y - 3$, where ν_y is the number of vertical betatron oscillations in one turn around the Cooler Ring. The polarization at 177 MeV is plotted against the vertical betatron tune in Fig. 10. With the snake off, the beam is totally unpolarized at the resonant ν_y of 5.13. However, with the snake on there is full polarization over the entire range.

The Siberian snake appears capable of overcoming all types of known depolarizing resonances. However it seems dangerous to naively extrapolate from 100 MeV to 20 TeV; we are concerned about yet unknown polarization problems at the SSC. Therefore, we are now actively studying many properties of Siberian snakes and polarized beams; I will only mention a few[10,11]. We recently built an rf solenoid magnet to create an rf induced depolarizing resonance by sweeping through the resonant frequency. We also studied synchrotron depolarizing resonances which are caused by the synchrotron oscillations in the ring; they are very narrow and sharp. We found that the Siberian snake can easily overcome both the rf and synchrotron depolarizing resonances and all other types of resonances that we have yet studied.

To properly utilize Siberian snakes, we formed two slightly different variations of the SPIN Collaboration: SPIN at Fermilab and SPIN at SSC; both contain about 80 American, Russian, and Japanese experimenters and accelerator physicists and one Russian theorist. People from Michigan, Indiana, Fermilab, North Carolina, IHEP-Protvino, JINR-Dubna, Moscow, INR-Moscow, KEK, and Kyoto are in one or both collaborations. In late 1991, Fermilab commissioned SPIN to produce a detailed Design Report on accelerating polarized protons to 150 GeV in the Main Injector. This 146 page Design Report was finished in March 1992; it was a very hectic 5 months.

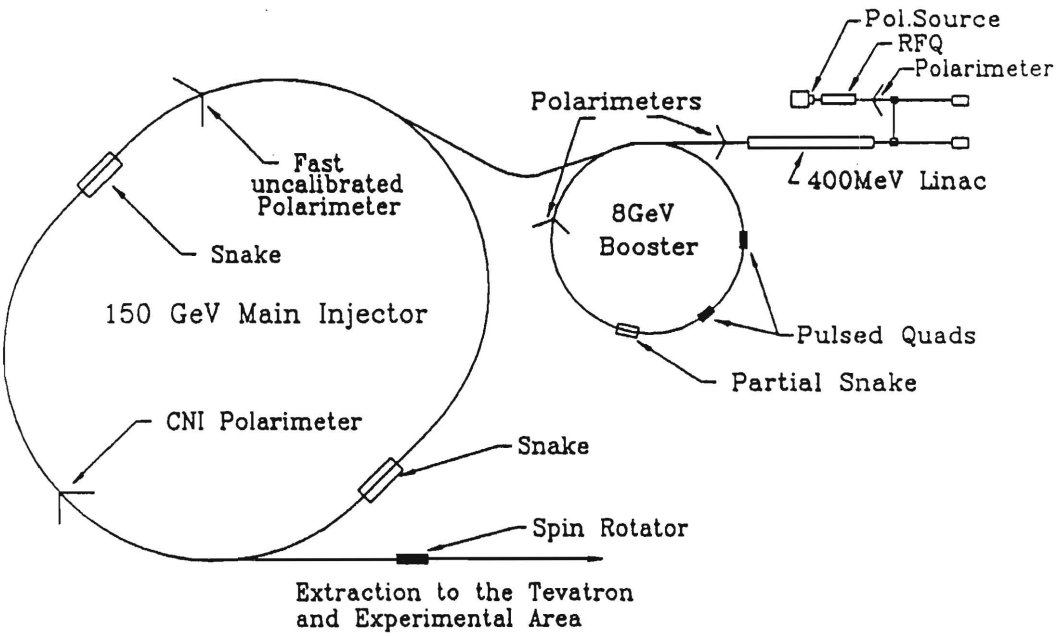

Fig. 11 Fermilab Main Injector Polarized Proton Beam.

Fig. 11 shows Fermilab with the proposed polarized beam capability installed. There is a polarized ion source, an RFQ, a low energy polarimeter, and a new switching magnet in the injector. Polarimeters are also installed at the end of the LINAC and in the 8 GeV Booster, where we propose two pulsed quadrupoles and a partial snake because a full snake is not economical here. The Main Injector would have two full Siberian snakes, a fast uncalibrated

polarimeter, and a slower but calibrated Coulomb-Nuclear Interference (CNI) polarimeter. Because spin matrices do not commute, there is some spin rotation when transporting polarized protons in and out of the Main Injector whose level is a few feet different than the other levels at Fermilab. Thus, we proposed a spin rotator to adjust the spin direction.

The modified injector at Fermilab is shown in Fig. 12. A hole in the existing wall allows a new polarized beam transfer line to pass into the new building. This building would contain the polarized ion source, the RFQ, the control consoles, and the beam-line power supplies. Fig. 13 shows a typical RFQ. Professor Teplyakov, who invented the RFQ, and several of his colleagues from IHEP-Protvino joined the SPIN collaboration to design and build the RFQ.

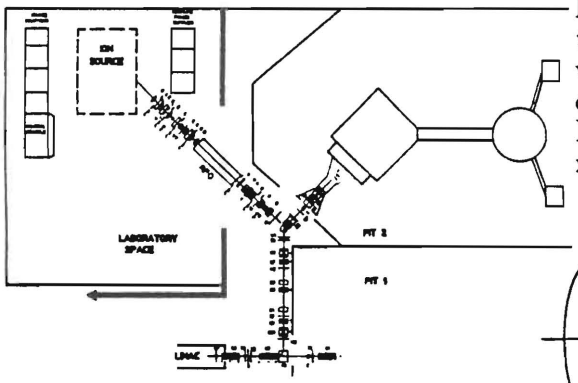

Fig. 12 Fermilab injector with polarized beam hardware.

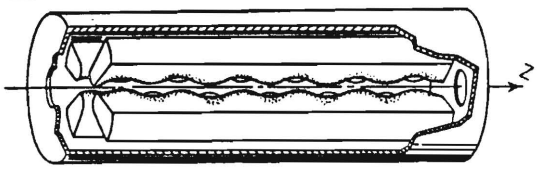

Fig. 13 A typical RFQ.

We had a marvelous, but somewhat exhausting, time designing many different kinds of Siberian snakes for the Main Injector. Our snake team, containing Ado, Anferov, Baiod, Courant, Derbenev, Krisch, and Shoumkin, finally proposed a helical snake; this snake consists of four dipole magnets and one "helical" magnet whose dipole field direction rotates as a helix. Helical snakes are very useful in a 150 GeV ring because they reduce the transverse beam size at 8 GeV injection. We found that one must also carefully consider the direction about which the snake rotates the spin by 180°. A type-1 snake rotates the spin about the longitudinal direction, a type-2 snake rotates it about the radial direction, while a hybrid snake rotates the spin about an arbitrary direction. Ideally the rotation axes of the two snakes in any ring should be orthogonal to each other. This was somewhat difficult at the Main Injector; therefore, the two rotation axes are ±35°. Courant, Derbenev, and others concluded that the resulting 70° angle was orthogonal enough. The helical snake would have a total length of about 12.8 m; it would easily fit into the 14 m Main Injector straight section spaces.

Our budget estimate for polarized beam acceleration to 150 GeV at Fermilab, including contingency and inflation, was $7.9 Million. This seems a significant, but not outrageous, amount of money. The Fermilab directors and staff studied our Polarized Main Injector report; John Peoples then indicated that Fermilab is especially interested in having polarized protons in the Tevatron Collider. Therefore, Fermilab has just commissioned our SPIN Collaboration to produce another Report on Accelerating and Storing Polarized Protons in the Tevatron Collider. We agreed to produce this Report by 15 April 1994; Fermilab agreed to provide funding for two years.

The SPIN Collaboration had earlier submitted to the SSC an Expression of Interest which is designated EOI-001. Our first goal was to accelerate polarized protons to 2 TeV; we also proposed studying spin-spin effects in p-p elastic scattering at 2 TeV using a spin-polarized jet target, similar to our Mark II Jet. Other spectrometers could simultaneously look at various inclusive spin effects using the same jet target with no extra beam time, as with NEPTUN and NEPTUN-A. We proposed that these experiments could run prior to 20 TeV operation; the SSC seemed somewhat interested.

The main spin physics goals at 20 TeV are high-$P_\perp^2$ spin effect studies, spin tests of electroweak physics, spin used in the search for new physics, polarization of inclusive hyperons, and spin effects beyond the standard model. Elastic scattering experiments at 20 TeV on 20 TeV would be difficult; it seems impossible to discriminate against an inelastic event with only one π^0 at E_{cm} of 20 TeV. There have been many recent discussions of the physics interest in TeV polarized proton beams; I recommend the proceedings of the workshops at Ann Arbor (1985), and Penn State (1990), and the symposia at Protvino (1986), Minnesota (1988), Bonn (1990), and here in Nagoya.

The budget to accelerate polarized proton beams to 20 TeV at the SSC was estimated at $39.2 Million FY 91 dollars; this estimate was done in rather close collaboration with the SSC staff. One would need 26 snakes in each of the two 20 TeV rings; this would require a total of 416 Siberian snake dipoles. These dipoles are relatively inexpensive, at $22,000 each as estimated by the SSC staff, since one can construct many identical shorter magnets with the same aperture as the normal SSC dipoles. The total cost of $39 Million, is a rather small fraction of the total SSC cost.

Our SPIN collaboration made two formal presentations to the SSC PAC. At the June-July 1991 meeting, the PAC and the SSC Director, Roy Schwitters, approved a change of the 20 TeV ring lattice to leave about 1 km of empty spaces for the possible later installation of 52 Siberian snakes in the two 20 TeV rings. They certainly did not yet agree that they would install the snakes, but they did approve changing the lattice and indeed the lattice has been changed. The SSC did not approve the proposed early spin experiments in the 2 TeV High Energy Booster. In fact, they declined early approval of any 2 TeV physics experiments. The PAC requested in their report that our SPIN collaboration keep abreast of all details of each SSC ring to help insure that polarized beam acceleration is later possible. Roy Schwitters requested that our collaboration should seriously consider this request. We plan to keep in touch with the SSC as requested; we hope to do SSC spin physics experiments at 2 TeV and then at 20 TeV.

Fig. 14 shows the SSC with the hardware needed for polarized beam acceleration. The low energy stages are shown as a blow-up. Notice a polarized ion source, an RFQ, a switching magnet, and a LINAC polarimeter. There is a polarimeter, four pulsed quadrupoles and one ramped partial snake in the 12 GeV Booster. In the 200 GeV Medium Energy Booster there is a polarimeter and two full Siberian snakes; they might be helical snakes. In the 2 TeV High Energy Booster, we propose using six Siberian snakes and a polarimeter; a jet and spectrometer similar to our NEPTUN-A experiment at UNK would allow 2 TeV spin physics experiments. Finally, in each 20 TeV ring there are 26 snakes and two polarimeters. Note that many of the SSC polarization problems are similar to those discussed in the detailed Fermilab Report.

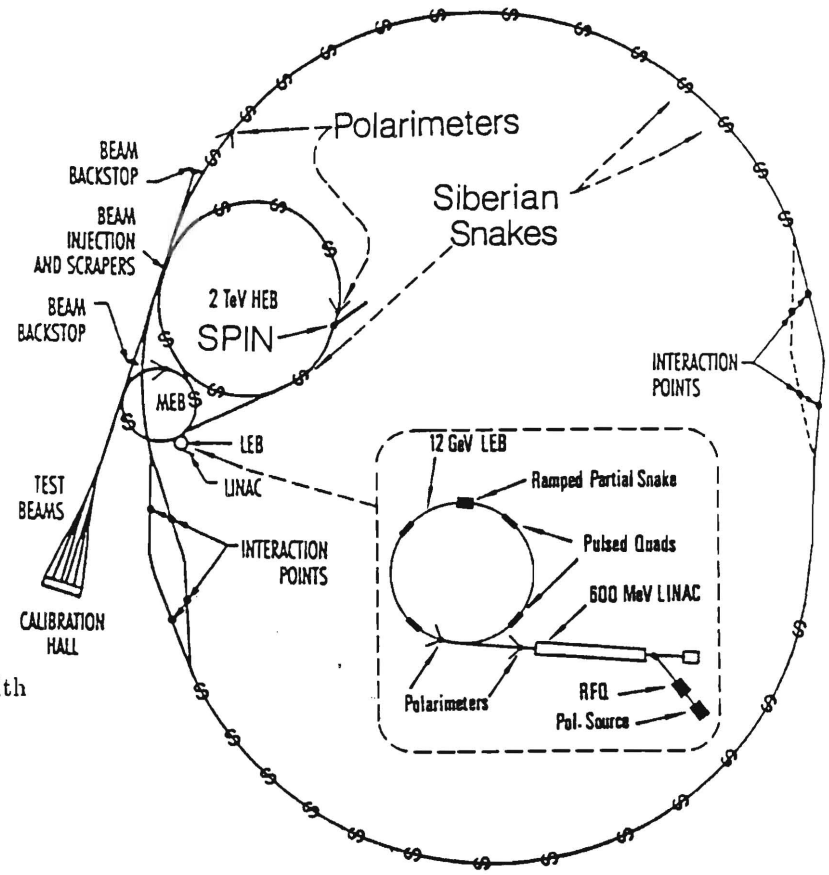

Fig. 14 The SSC with polarized beam hardware.

It is especially interesting that the Siberian snake concept gets better and better at higher energies. This is true because the main problem with a snake is the transverse orbit excursions caused by the snake magnets at injection; fortunately, these decrease exactly proportionally to the energy. Therefore, Siberian snakes provide a simple and hopefully reliable technique to accelerate high intensity polarized proton beams to TeV energies.

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