

Summary of Workshop on  
Polarized Protons at the SSC\*

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The Workshop on Polarized Protons at the SSC, which took place during June 10-15, 1985 in Ann Arbor, was organized by a committee consisting of:

O. Chamberlain	Berkeley
E.D. Courant	Brookhaven
A.D. Krisch	Michigan
K.M. Terwilliger	Michigan

There were many motivations for this workshop, but I think that the principal reasons were to study three subjects:

1. The technical feasibility of accelerating polarized protons to 20 TeV.
2. The importance of spin physics at the very highest energies.
3. The importance of the SSC to those high energy physicists who are enthusiastic about spin.

I will first show the overall layout of the SSC in Fig. 1, where we have highlighted those items especially related to having polarized protons in SSC. This figure is not to scale. One can see the polarized ion source which injects polarized protons into the preaccelerator and then the LINAC. Next, in the 70 GeV Booster, notice the pulsed quads and the correction dipoles for dealing with depolarizing resonances up to 20 or 30 GeV. There are also 2 Siberian Snakes for acceleration up to 70 GeV without depolarization. In the 1 TeV Booster there are a small number of Siberian Snakes (perhaps 6); while in each 20 TeV Main ring there are a large number of Siberian Snakes (perhaps 50) to allow acceleration to 20 TeV without serious depolarization. There are also a number of polarimeters to measure and monitor the beam polarization at various stages in the acceleration cycle such as 20 KeV, 760 KeV, 1 GeV, 70 GeV, 1 TeV, and 20 TeV.

# POLARIZED PROTONS AT THE SSC

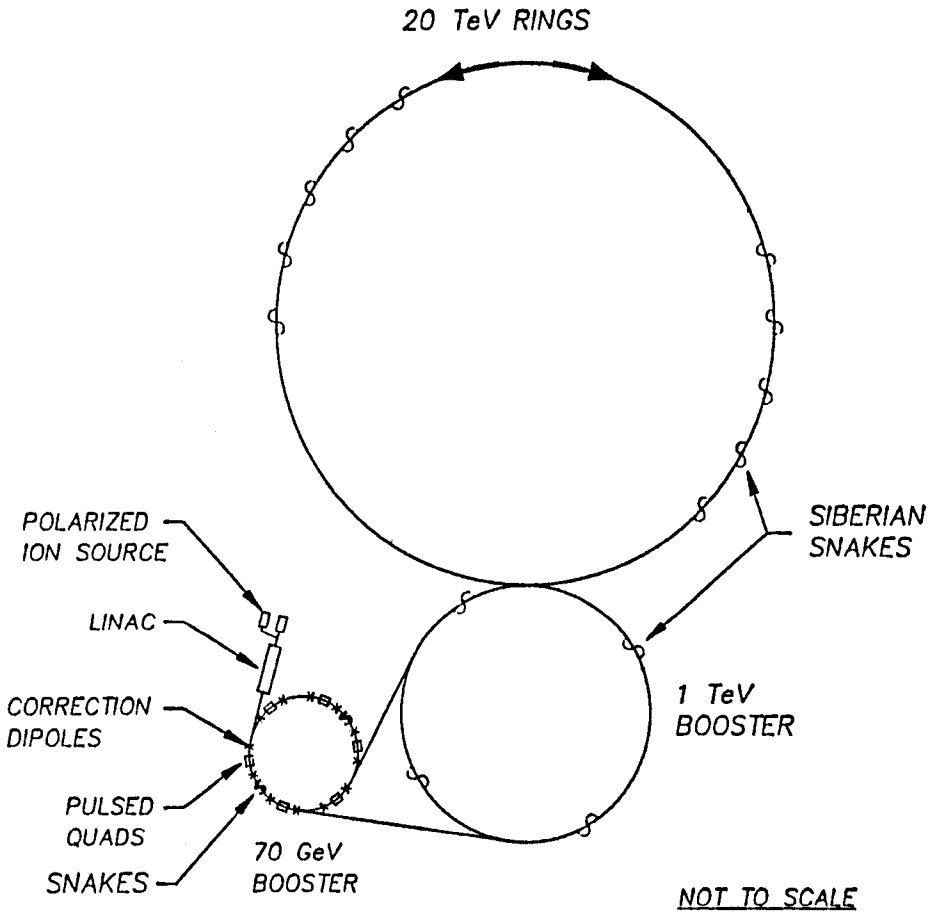


Fig. 1 Acceleration of Polarized Protons at the SSC.

The workshop was organized around six working groups and indeed the majority of the week was spent in meetings of these working groups which were:

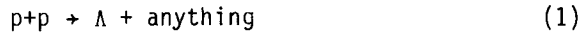
- SPIN-----Physics Motivation for Spin Physics at 20 TeV  
 Coordinator: O. Chamberlain, Berkeley  
 Deputy Coordinators:  
   E. Leader, Queen Mary College, London  
   M. Simonius, E.T.H. Zurich  
 Scientific Secretary: D. Hochberg, Rutherford-  
 Appleton Lab
- MAIN-----Accelerating and Storing Polarized Protons in the  
 20 TeV Main Rings  
 Coordinator: R.D. Ruth, SLAC  
 Scientific Secretary: S. Tepikian, Brookhaven
- BOOSTER-----Accelerating and Storing Polarized Protons in the  
 1 TeV Booster  
 Coordinator: L.C. Teng, Fermilab  
 Scientific Secretary: S. Tepikian, Brookhaven
- 70 GeV-----Accelerating and Storing Polarized Protons  
 in the 70 GeV Booster, the LINAC, and the  
 Preaccelerator  
 Coordinator: Y.I. Makdisi, Brookhaven  
 Scientific Secretary: F.Z. Khiari, Michigan
- DEMO-----Designing and Testing a Demonstration Siberian Snake  
 Coordinator: L.G. Ratner, Brookhaven  
 Scientific Secretary: R.R. Raylman, Michigan
- POLARIMETER---Designing and Testing Polarimeters for 70 GeV to  
 20 TeV  
 Coordinator: J.B. Roberts, Rice  
 Scientific Secretary: A.M.T. Lin, Michigan

I will try to briefly summarize the conclusions of each of these working groups. Of course the detailed report of each working group contains a much more detailed discussion.

## HIGH ENERGY SPIN PHYSICS

It seems quite clear that the role of spin in high energy interactions is not yet fully understood. The popular theoretical belief is that spin effects should become less and less important as the incident energy and the transverse momentum,  $P_{\perp}$ , are increased. However during the last decade a number of unexpected experimental results have seriously questioned this belief.

Inclusive hyperon polarization experiments involve scattering an unpolarized proton beam on an unpolarized target and observing an inclusive reaction such as



The self analyzing power of the  $\Lambda$  decay allows a measurement of the polarization of the final state  $\Lambda$ . The hyperon polarization is quite large except near  $P_{\perp}^2 = 0$  and seems to be quite independent of energy from about 12 GeV to 3000 GeV, as can be seen in Fig. 2. Since neither the beam nor target is polarized, this is quite a straightforward experiment and has been done at KEK, the CERN PS, the AGS, Fermilab and the CERN ISR.<sup>1,2</sup>

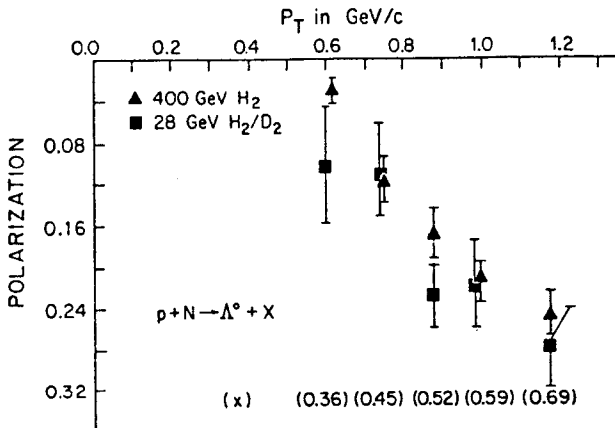


Fig. 2 Polarization in inclusive  $\Lambda$  production by 28 and 400 GeV protons<sup>2</sup> is plotted against  $P_{\perp}^2$ .

There have been two very surprising results involving proton-proton elastic scattering at high- $P_{\perp}^2$  using a polarized proton beam and/or a polarized proton target. The first result<sup>3</sup> came from two-spin measurements of  $p+p \rightarrow p+p$  using the Argonne ZGS polarized beam and a polarized target. The  $90^\circ_{cm}$  data is shown in Fig. 3 where  $d\sigma/dt$  is plotted against  $P_{\perp}^2$  as the incident energy is varied for the cases when the two spins are parallel and when they are antiparallel. The ratio of these pure initial spin state cross-sections clearly starts growing sharply at the start of the hard scattering region near  $P_{\perp}^2 = 3.5$  (GeV/c)<sup>2</sup>. The ratio continues to grow to about 4 at the maximum energy of 13 GeV at the ZGS. These measurements should soon be extended to higher  $P_{\perp}^2$  at the new AGS polarized beam which should operate in the 17 to 28 GeV range.

Recent single spin measurements of  $p+p \rightarrow p+p$  have been made using the 28 GeV unpolarized AGS proton beam scattering from the Michigan polarized proton target. The spin-orbit Analyzing Power,

$A$ , is shown in Fig. 4 plotted against  $P_{\perp}^2$  for the AGS experiments<sup>4</sup> and an earlier CERN experiment.<sup>5</sup> There is a sharp increase in  $A$ , which appears to grow with  $P_{\perp}^2$ . This is quite unexpected since perturbative QCD calculations indicate that the helicity flip amplitude and thus  $A$  should be zero. Moreover these calculations should become more reliable at large  $P_{\perp}^2$  which is instead where  $A$  seems largest.

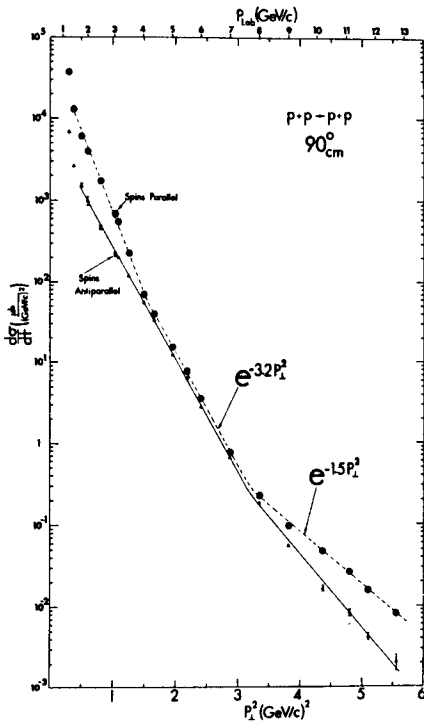


Fig. 3  $d\sigma/dt$  for p-p elastic scattering with the initial spins parallel and antiparallel.

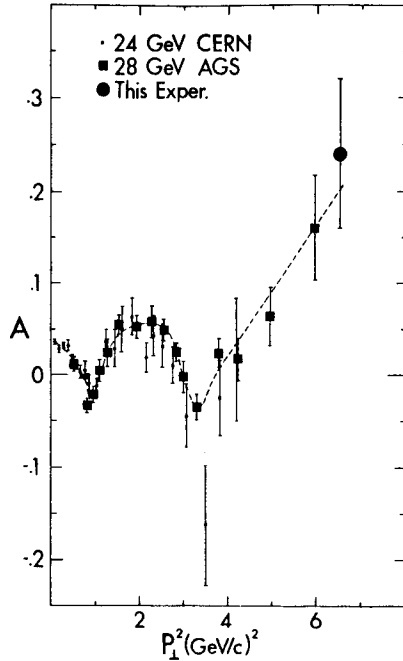


Fig. 4 The one-spin Analyzing Power,  $A$ , for p-p elastic scattering.

It is certainly not possible to predict with certainty the exact nature of spin effects in strong interactions at SSC energies. Indeed the prediction of any strong interaction behavior at 20 TeV is quite speculative. However, the expectation of finding unknown new physics is one of the SSC's most exciting and important aspects.

There have been some estimates of the expected behavior of spin effects based on extrapolations from our present energy region. In Fig. 5 we have shown, as an example, some predictions of Bourrely<sup>6</sup> on the behavior of the analyzing power,  $A$ , as a function of  $P_{\perp}^2$  at SSC energies. Note that they predict quite large effects in the

region  $P_{\perp}^2 = 2$  to  $7$   $(\text{GeV}/c)^2$ . There should be similar large effects in  $A_{nn}$ , the spin-spin correlation parameter, at high- $P_{\perp}^2$  at the SSC. If the differential elastic cross-section continues to drop as an exponential in  $P_{\perp}^2$ , then  $P_{\perp}^2$  of  $7$  or  $8$   $(\text{GeV}/c)^2$  may be the maximum value which can be observed at SSC.

The spin effects in inclusive hadronic interactions may be even more important than those in elastic scattering. We expect that high- $P_{\perp}^2$  inclusive cross-sections will be both larger and more easily observable at SSC energies. In view of the widely held belief that elastic diffraction scattering is caused by the inelastic channels, it seems very likely that the large elastic spin effects may be "reflections" of even larger spin effects in the inelastic channels. We must find some way to effectively study these inclusive spin effects at SSC energies and indeed at lower energies.

Longitudinally polarized beams would also let us distinguish between left and right handed currents in the "weak" interactions of protons at SSC energies. It will be especially interesting to look for right-handed  $W$  production ( $W_R$ ) since the lower bound on the  $W_R$  mass is presently about  $400$   $\text{GeV}$ .

Measurements of the  $A_{LL}$  asymmetry with longitudinally polarized beams could also help to establish the predicted onset of SUSY thresholds. The  $A_{LL}$  asymmetry is predicted to change sign as a threshold is passed. A more detailed discussion of these and other theoretical problems studied during this brief workshop can be found in the papers and reports of the SPIN working group. However there is clearly a strong need for more detailed and extensive theoretical studies of spin effects at SSC energies.

## BEAM DEPOLARIZATION

If a circular accelerator has only vertical magnetic fields, then a vertically polarized proton will only precess about the vertical axis and there will be no depolarization. However any horizontal magnetic fields can cause depolarization. The depolarization is especially serious whenever  $\omega_C$ , the cyclotron frequency with which the proton circles the accelerator, becomes

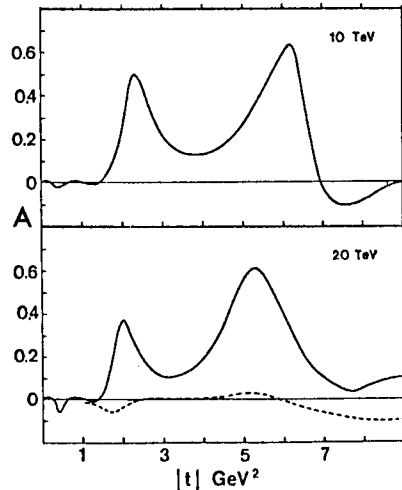


Fig. 5 Predicted behavior of the Analyzing Power,  $A$ , at SSC energies.

equal to an integer multiple of the frequency with which the proton sees horizontal magnetic fields; for then a depolarizing resonance exists.

There are two major types of depolarizing resonances. The intrinsic depolarizing resonances are caused by the horizontal field components of the focusing quadrupole magnets which are an "intrinsic" part of all strong focusing accelerators. These resonances occur whenever

$$G\gamma = kP \pm \nu \quad (2)$$

where  $G = (g-2)/2 = 1.79$  for a proton,  $\gamma = E/m$  is the Lorentz energy factor,  $k$  is any integer 0, 1, 2, ...,  $P$  is the periodicity of the accelerator (This is 12 for the AGS since it has 12 superperiods.), and  $\nu$  is the vertical tune, which is the number of vertical oscillations that a proton makes in one turn around the accelerator ( $\nu$  is about 8.75 for the AGS.). The horizontal focusing fields cannot be corrected since this would eliminate the vertical focusing and the beam would be lost. Thus the technique of "resonance jumping" has been developed, where fast pulsed quadrupole magnets are used to quickly shift the tune,  $\nu$ , and thus destroy the resonance equality in the equation  $G\gamma = kP \pm \nu$ . This technique has been successfully used at the ZGS<sup>7</sup> and the AGS<sup>8,9</sup> as can be seen from Fig. 6.

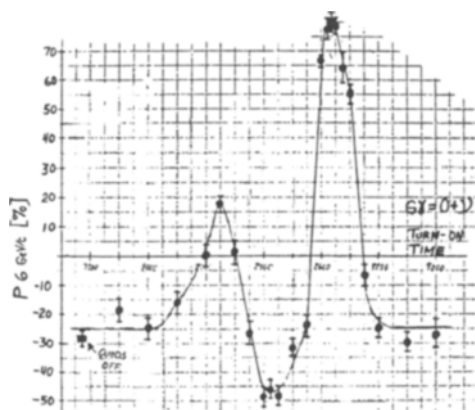


Fig. 6 Beam polarization vs. turn-on time for pulsed quads at  $G\gamma = 0+\nu$  resonance at AGS.

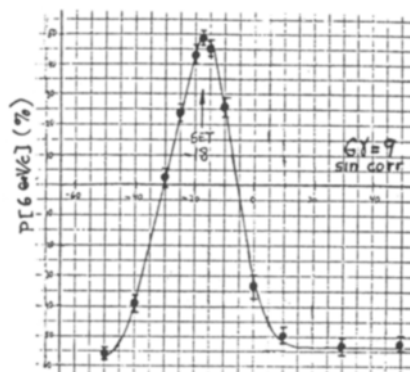


Fig. 7 Beam polarization vs. 9th harmonic correction dipole current at  $G\gamma = 9$  resonance at AGS.

Imperfection depolarizing resonances are caused by field imperfections in the ring magnets due to magnet misalignments and imperfect magnets. These imperfection depolarizing resonances occur in the acceleration cycle whenever  $\gamma$  passes through the value:

$$G\gamma = n \quad (3)$$

where  $n$  is any integer 2, 3, 4, .... These resonances are corrected at the AGS by using 95 small correction dipole magnets to create the  $n^{\text{th}}$  harmonic of horizontal magnetic field just as the proton's energy passes through the value  $\gamma = n/G$ . A correction curve for the strongest AGS imperfection resonance,  $G\gamma = 9$ , is shown in Fig. 7.

There seems to be a special type of imperfection depolarizing resonance, caused by the interference (or beats) between the imperfection frequency and the periodic frequency. These "beat" resonances occur whenever

$$G\gamma = kP \pm n \quad (4)$$

They appear to be especially strong when  $n$  is very close to  $\nu$ . Thus at the AGS the strongest beat resonance occurred when  $kP$  was  $3(12) = 36$  and  $n$  was  $-9$ . This resonance occurred at  $G\gamma = 27$  but could only be corrected by the  $9^{\text{th}}$  harmonic and was not affected by the  $27^{\text{th}}$  harmonic. There can also be higher order resonances such as

$$G\gamma = kP \pm \nu_{\text{HOR}} \pm \nu_{\text{VERT}} \quad (5)$$

which seem to be small at the AGS but could be serious at SSC.

The difficulty in dealing with depolarizing resonances using the resonance jumping and correcting techniques developed at the ZGS and AGS is well illustrated in Fig. 8. The AGS ring magnet field, the correction dipoles and the fast pulsed quadrupoles are shown simultaneously for the acceleration of polarized protons to 16.5 GeV/c. The fast quadrupoles had to be pulsed 3 times for the  $G\gamma = 0 + \nu$ ,  $G\gamma = 12 + \nu$  and  $G\gamma = 36 - \nu$  resonances and there are correction dipole pulses for each of the 26 imperfection resonances from  $G\gamma = 6$  to  $G\gamma = 31$ .

This resonance correcting and jumping procedure is quite difficult, but still possible, for 10 to 100 GeV accelerators where there are typically 20 to 200 resonances. Each of the quadrupole or dipole pulses must be experimentally calibrated by running a curve such as Fig. 6 or Fig. 7. This clearly seems an inappropriate procedure for dealing with depolarization in the SSC 20 TeV main rings, where there will be about 35,000 imperfection and depolarizing resonances to correct in each ring.



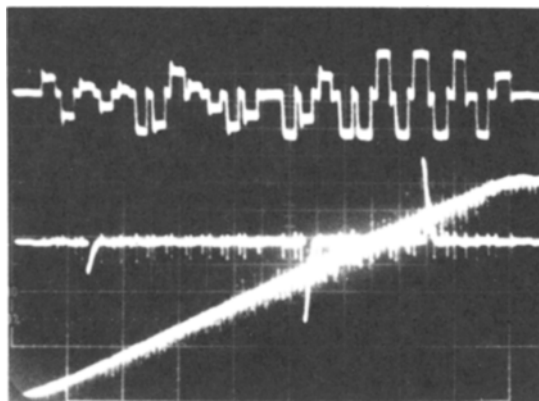


Fig. 8 AGS 16.5 GeV/c acceleration cycle showing correction dipoles (top), pulsed quadrupoles, and the AGS main ring magnet.

#### SIBERIAN SNAKES

A novel solution to the problem of depolarizing resonances was proposed around 1977 by Derbenev and Kondratenko.<sup>10</sup> They suggested using a string of magnets which gives a net rotation of the spin vector by  $180^\circ$ , while giving no net motion to the beam orbit itself. Within the string of 8 or so magnets, there is considerable beam motion, in fact the beam wiggles like a snake. Thus at the 1977 AGS Polarized Beam Workshop in Ann Arbor, these devices were named Siberian Snakes by E.D. Courant.<sup>11</sup>

The basic idea of the simplest Siberian Snake solution is to rotate the spin through  $180^\circ$  after one turn around the accelerator. Any depolarization (spin rotation) which occurred during this first turn is then exactly cancelled by the identical rotation which occurs during the second turn around the accelerator. The motion of the 3 different components of the spin vector can be seen in the 3 drawings in Fig. 9.<sup>12</sup>

The typical Siberian Snake is a string of perhaps 8 magnets, each with a transverse magnetic field which rotates the spin vector by  $90^\circ$  and simultaneously bends the beam by some small angle. The transverse magnetic field integral needed for this  $90^\circ$  spin rotation is

$$\int B \cdot dl = \pi/2 (B\rho/G\gamma) = 2.75 \text{ T-meter} \quad (6)$$

This  $\int B \cdot dl$  is totally independent of energy. This energy independence is perhaps the greatest advantage of the Siberian Snake technique; the snake magnets do not have to be ramped during the acceleration cycle. At the 20 TeV SSC this is certainly an advantage over the fast pulsed quadrupole/correction dipole technique where each of the 35,000 resonances must be tuned individually.

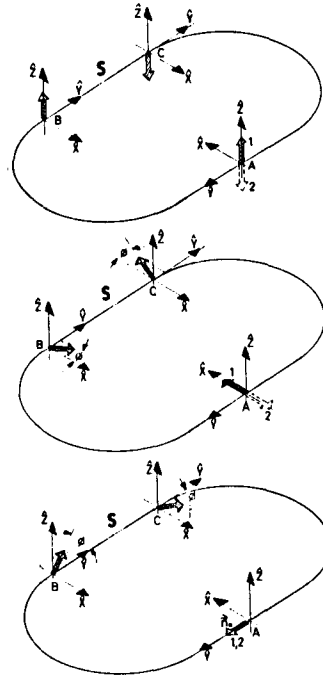


Fig. 9 The rotation of the spin vector during one revolution starting at A. The snake, S, is between B and C.<sup>12</sup>

#### DEMONSTRATION SIBERIAN SNAKE

In spite of considerable theoretical work, the Siberian Snake concept has never been tested experimentally. Since the Siberian Snake technique is by far the most feasible solution for having polarized beams at the SSC or any other TeV range facility, it seems quite important to test the technique. However the most attractive snakes consist of a string of about 8 transverse field magnets, of 2.75 Tesla-meters each. Such snakes would require a straight section of about 8 meters length which does not exist at any accelerator with an operational polarized proton beam. The maximum straight section length at the AGS is about 3 meters.

The workshop thus developed an alternate way to test the Siberian Snake concept using a single longitudinal solenoid magnet to rotate the spin vector by  $180^\circ$  while causing zero beam motion. The magnetic field integral needed for a spin rotation of  $180^\circ$  in a longitudinal solenoid is

$$\int B \cdot dl = 3.52 \beta \gamma \text{ Tesla-meters} \quad (7)$$

The direct dependence of  $\int B \cdot dl$  on energy would cause two major problems if one tried to use a single longitudinal solenoid at the SSC.

1. The solenoid would have to be ramped to exactly match the SSC energy at each point in the acceleration cycle.

2. At 20 TeV  $\beta\gamma$  is about  $2 \cdot 10^4$  so the solenoid would require an  $\int B \cdot dl$  of  $7 \cdot 10^4$  Tesla-meter. With a 7 Tesla field we would thus require a 10 km long solenoid.

However one could build a quite modest solenoid to test the Siberian Snake concept at the AGS. With an 18.5 Tesla-meter solenoid one can rotate the spin by  $180^\circ$  up to about 5 GeV/c. This would allow an experimental test of passing, without significant depolarization, through 2 strong imperfection resonances ( $G\gamma = 8$  and  $G\gamma = 9$ ) and through one strong intrinsic resonance ( $G\gamma = 0 + \nu$ ). The preliminary plan is to build a solenoid of about 2 meters length with about 9 Tesla field and place it in one of the 3 meter long AGS straight sections. Using an internal polarimeter the beam polarization could then be maximized by tuning the solenoid ramp to match the AGS energy ramp up to 5 GeV/c. This demonstration Siberian Snake is discussed in more detail in the report of the DEMO working group.

## POLARIZED BEAMS IN SSC

Recall that Fig. 1 showed an overview of SSC highlighting those areas where special attention was required to allow the acceleration of polarized beams. I will now discuss briefly the polarized beam requirements in each stage of the SSC. Each of these topics are discussed in much more detail in the reports of the working groups 70 GeV, BOOSTER, MAIN, and POLARIMETER, which are in these proceedings. The most significant parameters for obtaining polarized protons in the SSC are the strength of the depolarizing resonances. These resonance strengths,  $\epsilon$ , were calculated<sup>13</sup> using the DEPOL program and are plotted against  $\gamma$  in Fig. 10 for each stage of the SSC.

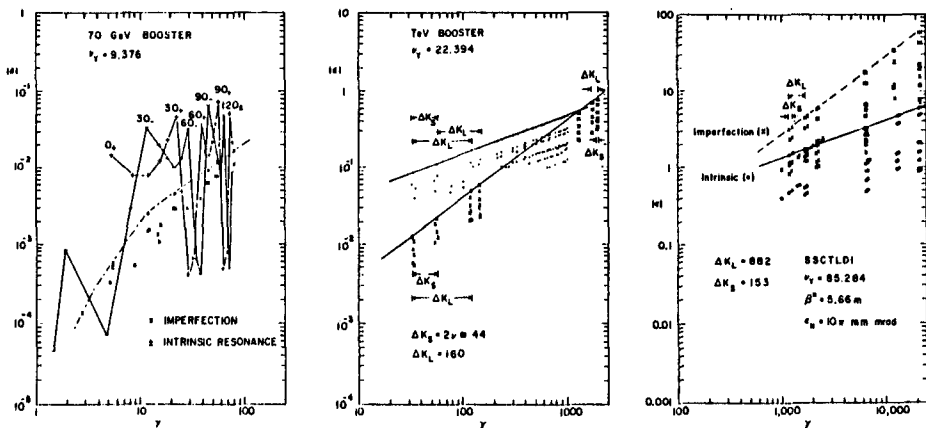


Fig. 10 Depolarizing resonance strengths,  $\epsilon$ , for the 70 GeV Booster, the 1 TeV Booster, and the 20 TeV SSC main rings.<sup>13</sup>

## LOW ENERGY STAGE

The modifications required to give polarized proton capability to the low energy stages of the SSC are quite straightforward. As shown in Fig. 1 the modifications are almost identical to what has already been done at the AGS. A high intensity polarized proton ion source would inject polarized protons into the SSC LINAC which would accelerate them to about 1 GeV. Their polarization could then be measured by p-Carbon scattering as in the AGS 200 MeV polarimeter. The polarized protons might then be stored in an "Accumulator Ring" which might be a scaled-down version of the AGS booster; this might enhance the polarized beam intensity by a factor of about 20. The 1 GeV polarized protons would then be injected into the first booster where they would be accelerated to 70 GeV.

The polarization could be maintained to 70 GeV by using either of two techniques or by using a combination of them. One technique is to jump intrinsic resonances with pulsed quadrupoles and to correct imperfection resonances with correction dipoles, as was done at the ZGS and more recently at the AGS. The second technique is to use one or two Siberian Snakes to remove the effects of the depolarizing resonances. With some effort either of the two techniques might be used alone to span the 1 to 70 GeV energy range of the 1<sup>st</sup> Booster. However it might be more sensible to combine the two techniques and to use the correction jumping technique from 1 to 20 GeV and then turn on the Siberian Snakes for acceleration of the polarized beam from 20 to 70 GeV. A polarimeter similar to the present AGS internal polarimeter could easily monitor the polarization up to 70 GeV.

## 1 TEV BOOSTER

The conclusions concerning acceleration of polarized protons from 70 GeV to 1 TeV were perhaps the most straightforward. While using the correction/jumping technique used at the ZGS and AGS would be a possible way to get through the almost 2000 depolarizing resonances, it would probably be both painful and unwise. However, the Siberian Snake technique seems both well defined and practical in this energy range. Thus we would plan to use Siberian Snakes to deal with these resonances. In its simplest form, a Siberian Snake rotates the spin by 180° about the beam axis. Assume that the spin is longitudinally polarized and each "period" of the ring has one Siberian Snake. Then whatever spin rotation occurs in one "period" is canceled by an identical rotation in the next "period" because of the 180° rotation occurring between the two "periods".

The BOOSTER working group led by L.C. Teng concluded:

With a slight modification of the ring lattice and with the addition of 6 Siberian Snakes, 3 of each type,  
 [Type 1 precesses spin 180° about the longitudinal axis,  
 Type 2 precesses spin 180° about the radial axis]

the vertical polarization of the beam can be preserved essentially 100% throughout the acceleration from 70 GeV to 1000 GeV in the 1-TeV Booster.

## POLARIMETERS

The POLARIMETER group headed by J.B. Roberts and D.G. Crabb concluded that it would also be straightforward to measure the polarization up to 1 TeV or indeed 20 TeV. The favored polarimeter would use Coulomb-Nuclear interference in proton-proton elastic scattering at small momentum transfer. Such a polarimeter should also be useful for the 20 TeV main rings. It was shown by Buttimore et al.<sup>14</sup> and Kopeliovich and Lapidus<sup>15</sup> that at  $t \sim 3 \cdot 10^{-3} (\text{GeV}/c)^2$  the value of the analyzing power,  $A$ , should be about 5% in the 1 to 20 TeV range. This energy independent spin effect is caused by the interference between the hadronic non-flip amplitude and the electromagnetic spin-flip amplitude. It should be possible to get about  $10^5$  elastic events per sec. in a polarimeter using a hydrogen gas jet inside the SSC. This should give a polarization measurement with about  $\pm 2\%$  error in 16 sec. Note that since this polarimeter is based on QED calculations the estimate of  $A$  should be rather reliable, even at 20 TeV.

## SSC MAIN RINGS

Dealing with depolarizing resonances in the two 20 TeV main rings was clearly the most difficult problem. There are about 36,000 depolarizing resonances in each ring, many of the resonances overlap, and many of them are very strong.

Nevertheless it does appear feasible to overcome the depolarizing resonances using Siberian Snakes. The number of snakes required is not totally certain because of some uncertainty in the strength of the resonances. For a maximum resonance strength of  $\epsilon = 5$  about 80 snakes would be needed in each ring. This large number of snakes is required to avoid a new type of depolarizing resonance caused by the snakes which eliminate the normal intrinsic and imperfection depolarizing resonances. These new depolarizing resonances, which are called integer snake resonances, occur when the total "spin tune" including the contribution of the snakes becomes equal to an integer.

If the Main Ring lattice could be slightly modified to reduce  $\epsilon$  to about 3 then the number of snakes could be reduced to about 26 in each ring. An alternate scheme of snake placement was studied which might significantly lower the number of snakes.

A typical Siberian Snake would be a unit of about 8 magnets, each with an  $\int B \cdot dl$  of about 2.75 T-m, for a total of about 22 T-m per snake. Thus in the "worst case" of  $\epsilon = 5$  where about 80 snakes are required, the total  $\int B \cdot dl$  for snakes is about 1760 T-meters.

This is about 0.4% of the total  $\int B \cdot dl = 420,000$  T-meters for the Main Ring. Because the snakes are more complex than the normal main ring dipoles the cost factor would be several times this 0.4% figure. However this makes it quite clear that adding polarization capability to the SSC would increase the cost of the main ring (and the 1 TeV Booster) by only a few percent. The cost of adding polarization capability below 70 GeV can be easily estimated from recent similar projects at the ZGS and the AGS.

The workshop considered the relation of "terrain following" to polarized beam acceleration. While it was generally agreed that we would prefer a flat SSC, J. Buon proposed<sup>16</sup> a technique to render vertical bends harmless. Each vertical bend of the SSC would require about 1/2 of a snake, and thus a few vertical bends could easily be handled.

## CONCLUSION

It appears scientifically important, technically possible and fairly inexpensive to add polarized proton capability to the SSC. A number of large and surprising spin effects have been discovered at existing accelerators especially at large  $P_{\perp}^2$ . The workshop concluded that similar large- $P_{\perp}^2$  spin effects will probably be found at the SSC. These and other unexpected spin effects may contribute significantly to the discovery of unknown new physics which I consider to be the SSC's main goal.

To add polarized beam capability to the SSC requires three systems:

1. Polarization in the early stages up to 70 GeV.
2. Polarimeters which will operate at 20 TeV.
3. Siberian Snakes to deal with the depolarizing resonances in the 1 TeV Booster and the 20 TeV Main Rings.

Polarized protons can be accelerated to 70 GeV using the correction/jumping technique developed at the ZGS and AGS. A polarimeter using Coulomb-Nuclear interference in  $p+p \rightarrow p+p$  at small  $t$  should give an  $A$  of about 5% up to 20 TeV based on QED calculations. The only outstanding question is whether Siberian Snakes really eliminate depolarizing resonances as the world's leading accelerator theorists believe. I hope that this question can soon be answered experimentally with a demonstration Siberian Snake.

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