BNL--30370

DE82 004807

Submitted to International Symposium on Polarization Phenomena at High Energies,
Dubna, U.S.S.R., Nov. 17-20, 1981

MASTER

POLARIZED-PROTON ACCELERATION PROGRAM AT THE AGS*

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The unexpected importance of high energy spin effects and the success of the ZGS/1/ in correcting many intrinsic and imperfection depolarizing resonances led us to attempt to accelerate polarized protons in the AGS. A multi-university/laboratory collaborative effort involving Argonne, Brookhaven, Michigan, Rice and Yale is underway to improve and modify to accelerate polarized protons. From the experience at the ZGS and careful studies/2/ made us confident of the feasibility of achieving a polarization of over 60 percent up to 26 GeV/c with an intensity of 10^{11}~10^{12} per pulse. The first polarized proton acceleration at the AGS is expected in 1983.

General

The problems of the motion of spin in the magnetic field was studied by many others. V. Bargman, L. Michel and V. Telegdi in 1959/3/ worked the general equation of motion using classical relativistic electrodynamics. In 1960, M. Froissart and R. Stora/4/ investigated the depolarization in the Saclay accelerator. In 1962, E. Courant/5/ at Brookhaven studied the general problems of accelerating polarized particles in circular accelerators. Two major types of the depolarizing resonances were identified for the vertically polarized particles:

$\gamma G = Kp \pm N\nu_y$ Intrinsic
$\gamma G = K$ Imperfection

where γ is usual Lorentz factor, G is anomalous magnetic moment coefficient, P is the basic periodicity of the paticular accelerator, ν_y is the vertical tune of the accelerator, and K and N are integers. The first type is called intrinsic resonance because it is inherent in the particular accelerator, and the second type is called imperfection resonance because it arises from magnetic construction and alignment errors.

To avoid the intrinsic resonances, one could change the vertical tune of the machine rapidly by either pulsed quarupoles or by displacing the orbit rapidly. Courant concluded that the techniques of pulsed quadrupoles for the intrinsic resonances probably work at the ZGS and even at the AGS where the resonances are ten times stronger. However, for the imperfection resonances at strong focusing accelerators like the AGS, his calculation showed little hope of keeping the polarization. It thus appeared that the intrinsic resonances could be jumped for both types of accelerators. The imperfection resonance for the weak focusing machines were not expected to be strong, but they would be very serious in strong focusing accelerators.

In 1973, the first acceleration of polarized protons to multi-GeV energy was successful at the ZGS in Argonne. They were successful in accelerating polarized

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*Work performed under the auspices of the U.S. Department of Energy.

protons to 6 GeV only using tune jumping quadrupoles to avoid only intrinsic resonances. The tune jumping quadrupoles worked as expected and were able to maintain 70 percent polarization when the injected beam was 75 percent polarized. An attempt to reverse the spin of the protons via adiabatic passage was only successful to the extent about 50 percent of the spin reversed. In 1977, the ZGS accelerated polarized protons to 11.75 GeV/c and successfully corrected 22 imperfection resonances using pole face winding in one of the main magnets. It now appeared that going to AGS energies with 45 imperfection resonance was not such a formidable task.

In the meantime, there were unexpected and very exciting physics results from the ZGS being reported. One example of the result is shown in Figure 1. The figure shows differential elastic scattering cross sections in pure initial spin states along with the result from the ISR at $S = 2800$ GeV^2. It had been generally conjectured that the effect of the spin state of the particles are negligible in high energy, especially in the high momentum transfer range. The experiment shows that there is a sharp difference between spin parallel and spin anti-parallel scattering after $P_\perp^2 \approx 3.5$ (GeV/c)^2. These results may even force us to change our ideas about the constituents of the proton. Unfortunately, as the result of the physics became interesting, the ZGS ran out of energy but the desire to go on to yet higher energy made the physicists look elsewhere.

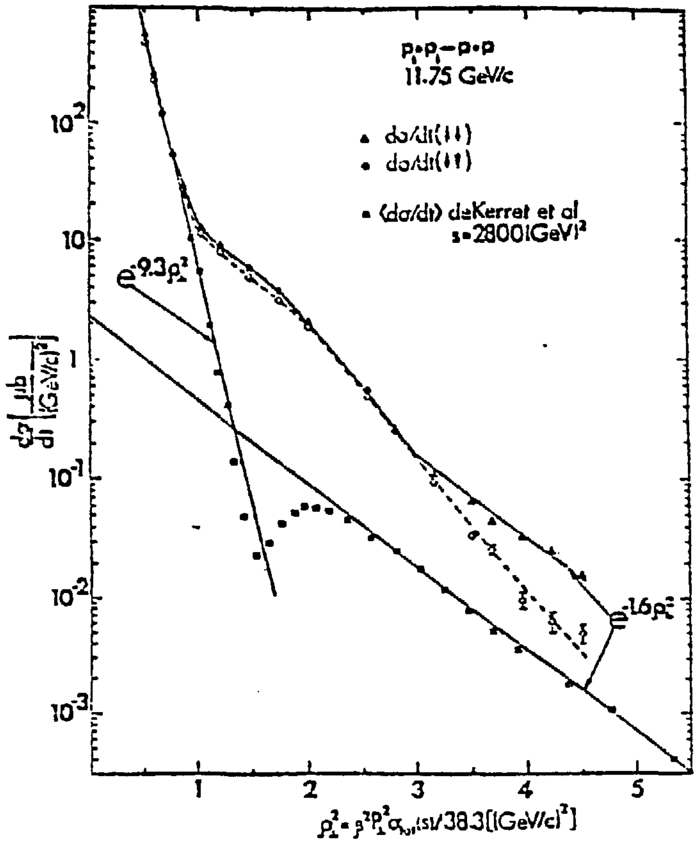

Figure 1 - The proton-proton differential elastic cross-section in pure initial spin states is plotted against the scaled $P_\perp^2$ variable. Unpolarized ISR data is shown for comparison.

In 1977, a two-week workshop was held in Ann Arbor, Michigan. E. Courant made some computer calculations of the effect of resonances for both the ZGS and the AGS./6/ The calculations for the ZGS agreed very well with the experimental results and gave confidence in the calculations for the AGS. According to Courant's calculations, which was refined by Courant and Ruth,/7/ it is possible that one could maintain polarization in the AGS up to 26 GeV/c. The resonances in the AGS are stronger, but still appeared to be amendable to the same sort of correction used in the ZGS.

Figure 2 shows the major modifications and improvements at the AGS required to accelerate the polarized protons. We decided to inject negative ions mainly because of intensity and the existing injection system for unpolarized protons. Following the ZGS success, fast pulsing quadrupoles to jump the intrinsic resonances are planned because the adiabatic reversal of the spin was not successful at the ZGS and SATURN II accelerator at Saclay. For imperfection resonances, we would correct the imperfections using 96 small dipoles already existing in the AGS ring.

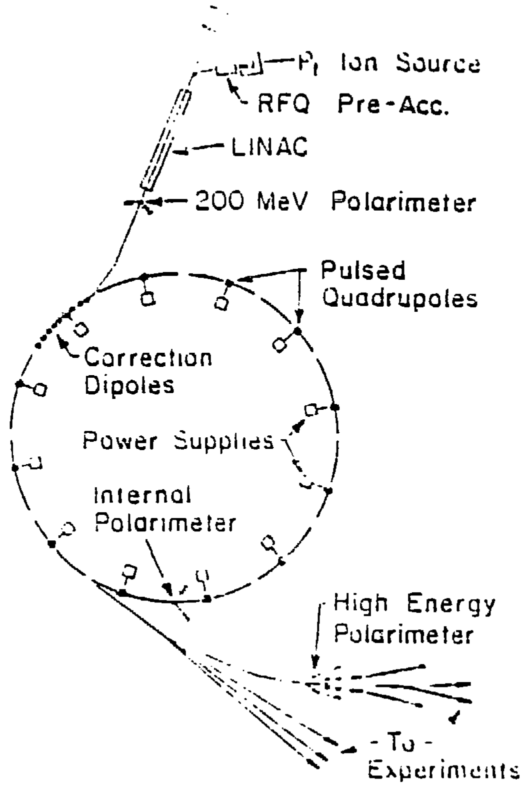

Figure 2 - AGS modifications for polarized proton acceleration.

Ion Source and Preaccelerator

The ion source is being developed in Argonne in collaboration with Yale and Brookhaven. The source is based on one developed and built at the University of Wisconsin.[8] The Wisconsin source produces approximately 3μ-Amp (d.c.) current of approximately 90 percent polarization. Using improvements, the new source should produce much higher pulsed intensity with the same polarization. Figure 3 shows the essentials of the source.

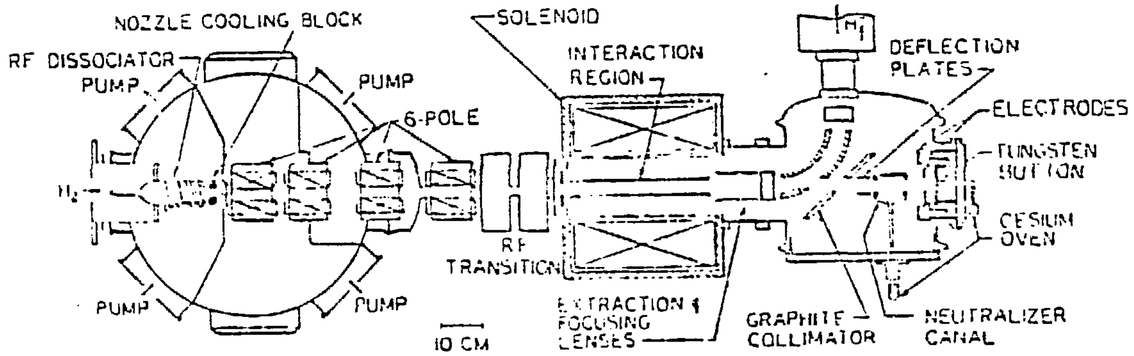

Figure 3 - The ion source.

An atomic beam is produced by the dissociator using an rf-induced discharge. The sextupoles select one state of electron spin, $m_j = 1/2$, by focusing it while defocusing the $m_j = -1/2$ state. By focusing the +1/2 state, they also increase the atomic beam intensity. The rf transitions are used to transfer the electron spin to the proton and align the proton spins. Either proton spin state can be selected. The atomic beam next enters the charge exchange channel where it collides with a 40 keV (or possibly higher energy) neutral cesium beam. A small fraction of the $H^0_\uparrow$ charge exchanges to form $H^-_\uparrow$ which are extracted out of the channel at 20 kV and then bent out of the source by a double-focusing electrostatic mirror.

According to the experience at the ZGS positive ion source, a factor of two gain in atomic stage intensity was realized when pulsing the dissociator rf and gas. An additional factor of 2-1/2 was obtained by cooling the dissociator bottle and nozzle, thus reducing the velocity and emittance of the atomic beam. Empirically, the intensity gain varies roughly at $T^{-1/2}$. The atomic density expected is 4×10^{16} atoms/cm^2-sec with the velocity of 10^5 cm/sec. This implies the atomic density in the charge exchange canal of 4×10^{11} atoms/cm^3.

The 40 keV Cs^+ gun of Pierce geometry is situated on the other isde of the source. The expected density is about 2 mA/cm^2 at the anode surface. Using an emitting surfce of 3 cm^2 (approximately the size of the Wisconsin source), leads to 6 mA of Cs^+. The Cs^+ current passes through the charge exchange chamber of Cs^0 vapor density of approximately 10^{14}/cm^3, and produces 40 keV Cs^0. Through the hole in the deflecting electrostatic mirror Cs^0 current goes into the charge exchange canal. Using the reaction

$$H^0_\uparrow + Cs^0 \rightarrow H^-_\uparrow + Cs^+$$

which has the cross section at this energy $\sigma = 3 \times 10^{-16}$cm^2 gives the expected polarized negative source current of 22 μ-amp.

There were many ideas presented at the Ann Arbor polarized ion source workshop (May 1981). The source current will improve considerably in the next few years, and it can be expected that an order of magnitude higher source density does not seem completely unreasonable. The source is expected to be delivered to Brookhaven in January 1982.

Considering the size and the complexity of the ion source, it is impractical and cumbersome to place the source inside a Cockcroft-Walton preaccelerator. We decided to build a radio-frequency quadrupole linear accelerator which was first proposed by I.M. Kapchinskii and V.A. Teplyakov and further developed at Los Alamos. The low-β accelerator is being built by Argonne and expected to be delivered to Brookhaven in early 1983.

Intrinsic Resonance

As mentioned earlier, there are many depolarizing resonances in a circular accelerator. The intrinsic resonances occur when the spin precession frequency resonates with the vertical focusing field of the accelerator.

Figure 4 shows the result of computer calculation of the strnegths of the resonances at the AGS done by Courant and Ruth. The vertical bars are for the imperfection resonances and x's are for the intrinsic resonances. The calculations are for the normal AGS acceleration rate of $d\gamma/dt = 60$ sec^{-1} and magnet misalignment of ± 0.1 mm with the normalized beam emittance of $10\ \pi \times 10^{-6}$ meter-radians.

We plan to jump the intrinsic resonances using the standard method used at the ZGS of pulsing the quadrupoles to rapidly changing the vertical tune of the AGS. Twelve 1/2-meter long quadrupoles placed in the region of maximum beta function (β = 22 m) will be used to jump the resonances. Because of the fast pulsed nature of the

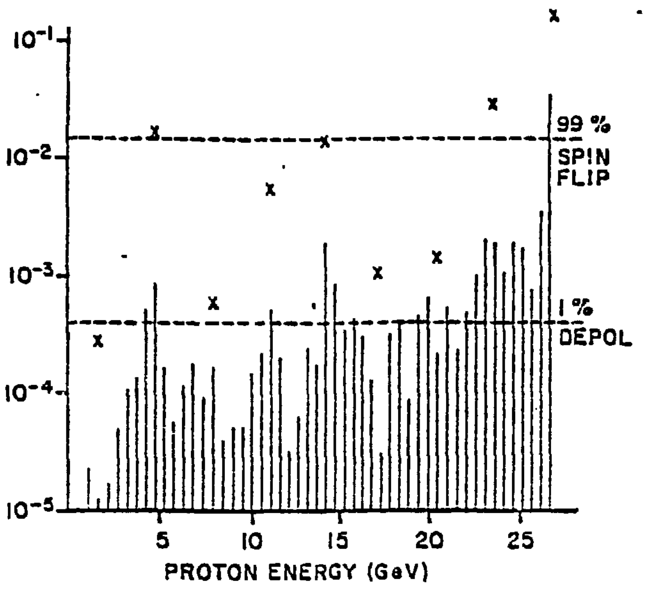

Figure 4 - AGS resonance strengths, ϵ. AGS emittance = 10 π/γ mr-mm, magnet errors = ± 0.1 mm, x - intrinsic resonances; | - imperfection resonances.

device, a special quadrupole of ferrite core is designed and being fabricated at the University of Michigan. Figure 5 shows the cross section of the quadrupole. As can be seen, both pole face and conductor placement are hyperbolic in order to reduce the inductance of the magnet. Using the ferrites from the now defunct ZGS rf cavity, the production of 12 quadrupoles is essentially finished. The test results of the prototype in both magnetic field and rise time, were as expected.

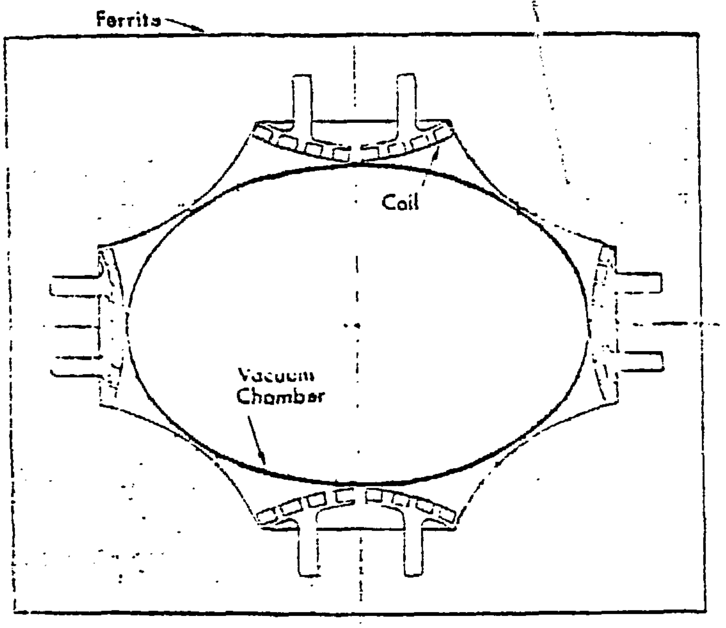

Figure 5 - A diagram of the ferrite pulsed quarupole magnets.

Table I shows Courant and Ruth's calculation of estimated depolarization due to each intrinsic resonance when the quadrupoles are pulsed with a rise time of 2 μ-seconds and tune jump of $\Delta\nu = 0.25$ which is about the stability limit.

Table I

Depolarization Due to Intrinisic Resonance
(2 μs Crossing Time)

$Kp \pm \nu$	γ_{res}	ε	$\Delta\nu_y$	Polarization (P/P_0)
12−ν	1.81	0.0003	0.25	0.994
0+ν	4.88	0.0154	0.25	0.958
24−ν	8.51	0.0006	0.25	1.000
12+ν	11.57	0.0054	0.25	0.004
36−ν	15.20	0.0.37	0.25	0.966
24+ν	18.26	0.0010	0.25(0.21)	1.000(1.000)
48−ν	21.89	0.0015	0.25(0.17)	1.000(1.000)
36+ν	24.96	0.0266	0.25(0.13)	0.911(0.780)
60−ν	28.86	0.1576	0.25(0.12)	~ 0.000

The numbers in parentheses are for a fixed quadrupole field of 11.7 KG/m. As can be seen in the table, one can jump the resonances up to γ ~ 28 without much difficulty; however, the resonance at 60−ν (γ ~ 28.9) is so strong that there are no effective means of jumping the resonances. It may be possible to cross this resonance with slow spin flip. The results from Argonne[10] and Saturn II[11] are discouraging so far. They could flip the sign of the spins less than 70 percent only.

The power supplies for the quadrupoles present special problems because the sign of the quadrupole field changes for successive resonances. The special circuits are developed at Brookhaven using very high powered hydrogen thyratrons specially designed for the purpose (see Figure 6). The system is expected to be ready in early 1983.

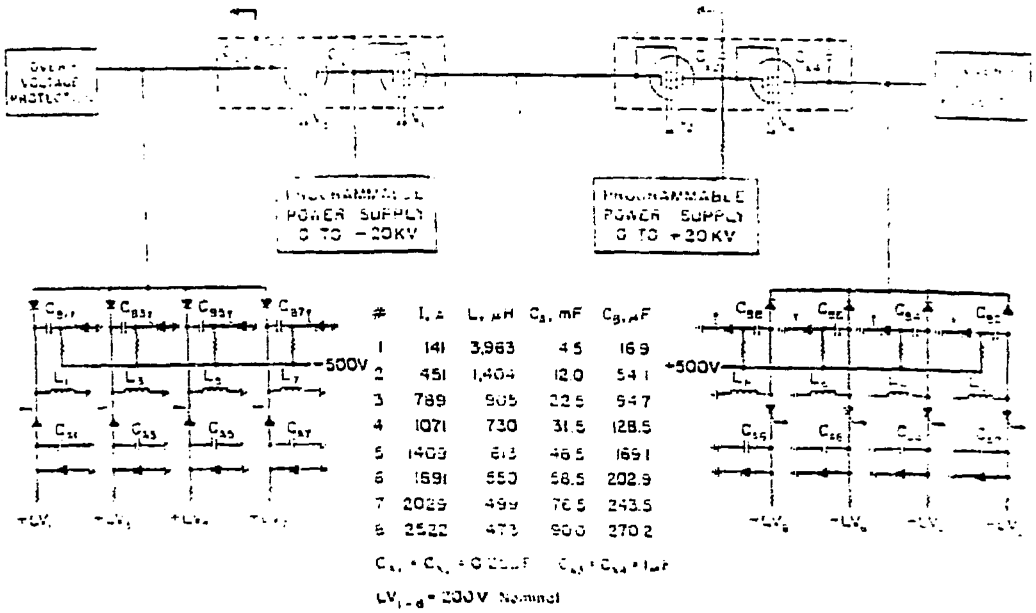

Figure 6 - Schematic of pulsed quadrupole power supply.

Imperfection Resonances

Imperfection resonances arise when the precesion frequency of the protons coincide with the harmonics of the horizontal field imperfection. Thus, the strength of Kth imperfection resonance depends on the Kth Fourier components of the imperfection field. Therefore, the driving force of a resonance can be represented:

$$B_K(\theta) = a_K \sin K\theta + b_K \cos K\theta$$

where θ is the turning angle of the particles in the accelerator and K is an integer.

The approach we are going to use is to introduce the same harmonics in opposite sign to cancel the particular imperfection harmonics. There are 96 air core low field correction dipoles already existing in the AGS. Estimated effects arising from imperfection field harmonics created by random misalignment of 0.1 mm rms is shown in Figure 4. Those 96 dipoles with improved power supply systems could be able to compensate for about 2-1/2 times of the misalignment assumed. The imperfection resonances occur about every half a GeV; at the AGS resonances occur approximately at 10 m-seconds. Fortunately, the microprocessor system development of recent years makes the task quite achievable where the task seemed unsurmountable before the microprocessor age. The conceptual system is shown in Figure 7. The system development is underway at Brookhaven and is expected to be complete late in 1982.

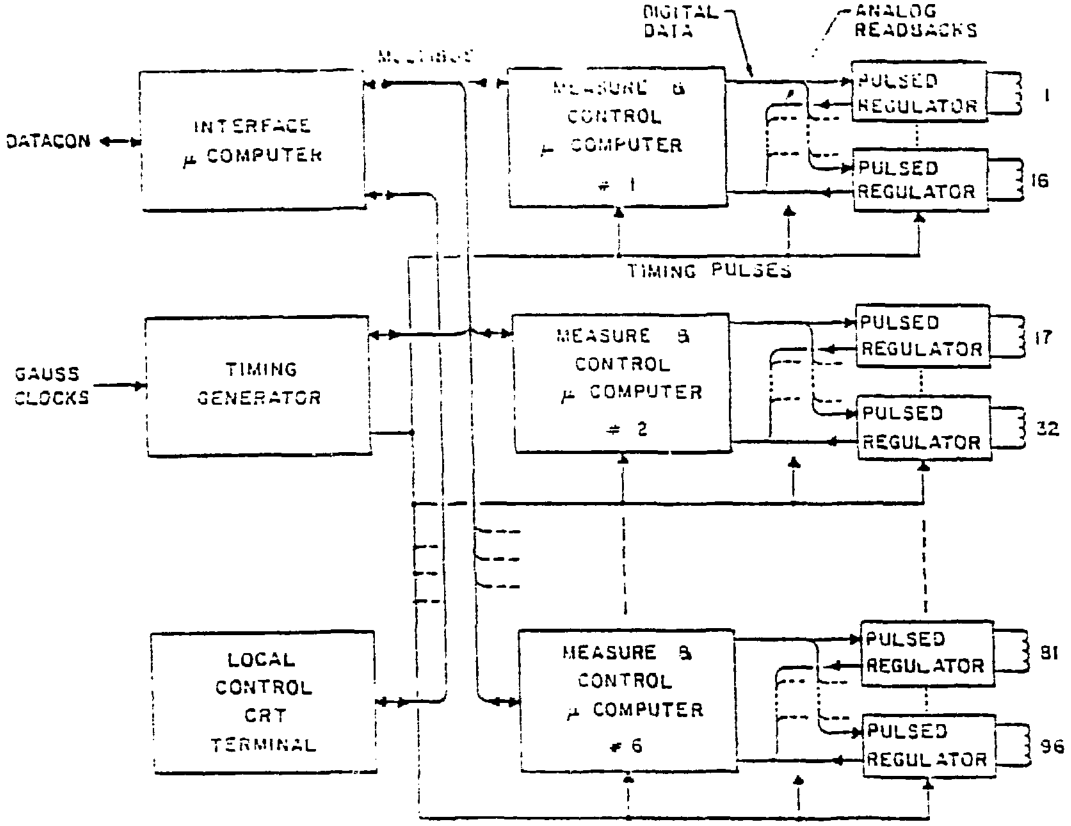

Figure 7 - Conceptual diagram of correction dipole controls.

Polarization Measurement

Polarization measurement in this project is very important. The measurement must be taken at several points during the acceleration cycle to insure that the protons do not become depolarized. As indicated in Figure 2, we plan to employ three polarimeters. All three systems measure left and right asymmetry, and the polarization is given by:

$$P = \frac{1}{A} \frac{(L - R)}{(L + R)}$$

where P is polarization, A is the analyzing power, and L and R are left and right counting rates.

The 200 MeV polarimeter is situated between the linac and the main ring. In this energy range, proton carbon scattering gives excellent analyzing power. The polarimeter measures the asymmetries of at least two different angles to assure the alignment. The polarimeter is being built at Rice University in collaboration with Los Alamos.

The internal polarimeter is very important because there are so many depolarizing resonances to cope with. The absolute polarization may not be very important for the polarimeter, but the relative polarization right before and after a resonance is very important. The scattering target used for this polarimeter is CH_2 at present. The polarimeter should give fast information of relative polarization for the accelerating crew to monitor the performances of the resonance jumping or correcting devices. The polarimeter is being developed in the University of Michigan collaboration with Brookhaven.

The external polarimeter or absolute polarimeter utilizes clean reaction of pp elastic scattering. The measurement is slow; however, it gives absolute polarization of the final protons. The polarimeter will give calibration to the internal polarimeter. The analyzing power of the reaction will be measured this year by measuring the asymmetry parameter of unpolarized proton scattering with a polarized target.

Schedule

The project started in 1980 with U.S. Department of Energy funding for the long-lead items. Expected turn-on will be sometime in the middle to late 1983 and we expect to start the first experiment shortly thereafter.

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