IEEE Transactions on Nuclear Science, Vol.NS-22, No.3, 1975

PRODUCTION OF HIGH ENERGY POLARIZED PROTONS*

E. F. Parker
Argonne National Laboratory
Argonne, Illinois

Introduction

Starting in 1925 with Uhlenbeck and Goudsmit's postulate that the electrons had a certain intrinsic "spin" to explain the fine structure observed in the spectra of some elements, spin has been found to play an important role in the interactions of elementary particles at all energy levels from atomic physics to nuclear physics to high energy physics. Experimental investigations in the more energetic regions of nuclear and particle physics usually involve the use of high velocity particle beams and targets. If spin effects are to be investigated, either the beam or target or both must be prepared in some known spin state; i.e., one needs a polarized target, or polarized beam, or both. The preparation of a primary polarized ion beam generally requires a source of polarized ions, a means of accelerating them to the required energy without depolarization, and a means of monitoring the degree of polarization. This article will describe the basic accelerator physics and equipment problems associated with the production of a high energy polarized beam. Specifically, the article will discuss: (1) the basic operating principles of polarized proton ion sources, their present state of development, and what the near future might hold; (2) the problems of depolarizing resonances in synchrotrons, and the present ideas on how to reduce their effect; (3) techniques for monitoring the polarization of the beam at various points along the acceleration process; (4) some of the operational problems associated with polarized beam running; and (5) the status of the high energy polarized proton beam programs at laboratories around the world.

Polarized Proton Ion Sources

Two basic types of polarized proton sources have been developed to the point of being useful in accelerator work: the atomic beam source, the development of which was initiated by Clausnitzer, Fleishmann, and Schopper[1] in 1956; and the Lamb-shift source, first proposed by Zavoiskii[2] in 1957. Both of these sources have been developed by nuclear physicists primarily for Van de Graaff applications, although several have been used or are in use on low energy cyclotrons and linacs.[3] In the last few years, efforts have been underway to adapt these sources to higher energy cyclotrons, linacs, and synchrotrons.

The Lamb-shift source uses the hyperfine structure of the first excited state of hydrogen and the Lamb-shift to produce polarized protons. Presently, operational Lamb-shift sources have output currents in the 0.1 to 0.5 μA range, which is not high enough to be of interest for synchrotron applications, even with the gains associated with negative ion injection. The operating principles of this source will therefore not be discussed here.

The atomic beam source takes advantage of the hyperfine structure in atomic hydrogen in the ground state to produce a polarized proton beam. Figure 1 shows the energy separation of these four states as a function of magnetic field. Figure 2 is a schematic of the Argonne National Laboratory (ANL) atomic beam source, which is characteristic of most atomic beam sources. Atomic hydrogen is produced by the dissoiation of molecular hydrogen using an electrodeless discharge operating in the range of 20 MHz. The dissociator tube is most commonly made of Pyrex, with a single 2-4 mm diameter nozzle. The important consideration is to have a tube which allows minimum recombination of the atomic hydrogen on the tube walls and a nozzle which produces a bright beam for matching into the separation magnet. The atomic beam is formed by the dissociated gas in the tube expanding through the nozzle into the vacuum system. Since this is a very low energy beam ($\approx 300°$K) the vacuum must be as high as possible to keep beam losses due to gas scattering at a minimum. To accomplish this in the face of a large gas flow from the dissociator tube (≈ 30 atmospheric cm^3/min for the ANL source operating in the dc mode) the atomic beam stage vacuum vessel is differentially pumped by high speed oil diffusion pumps. As shown in Figure 2, the ANL source is divided into four sections with two pumps on the first section and one each on the others. The first section normally operates at about 6×10^{-5} Torr, while the last section is at about 10^{-6} Torr.

The atomic beam produced by the dissociator is matched into a high gradient magnetic field, usually a sextupole field. The field of the sextupole lies in a plane perpendicular to its axis and has a value

$$B = B_o (r/r_o)^2 \qquad (1)$$

where B_o is the field strength at the pole tip at a radius of r_o. Upon entering this sextupole field, the hydrogen atoms align themselves with the field lines and experience a radial force because of their magnetic moments, i.e.,

$$F_r = -\mu \cdot \frac{\partial \beta}{\partial r} = -2 \mu B_o \frac{r}{r_o^2} . \qquad (2)$$

From Fig. 3, it is seen that states 1 and 2 have magnetic moments of equal magnitude, but opposite signs to states 3 and 4 in the strong field of the sextupole. States 1 and 2, therefore, experience a convergent radial force, while states 3 and 4 are deflected out of the beam. The beam leaving the sextupole is essentially 100% polarized in electron spin, but unpolarized in proton spin. The primary design considerations

*Work supported by the U. S. Energy Research and Development Administration.

for the sextupole are to give it the maximum acceptance and to locate it close enough to the dissociator tube to allow maximum filling of its acceptance. The sextupole acceptance is proportional to B_0/T where T is the temperature of the gas.

Just downstream of the sextupole, the beam enters the RF transition section where state 2 is transformed into state 4, or state 1 into state 3, using the so-called adiabatic passage method of Abragam and Winter.[4,5] Both transitions consist of a static magnetic field perpendicular to the beam direction and having a linear taper of about 10 G over their 3-4 cm extent. The 2 →4 transition has a rotating field of ≈1 G perpendicular to the beam direction, while the 1 →3 transition RF magnetic field is parallel to the beam direction. With a mean static field of 150 G, the 2-4 transition operates at a frequency of 1500 MHz. The 1→3 transition static field has a mean value of 10 G and a frequency of 15 MHz.

Emerging from the transition region, the beam is now unpolarized in electron spin and essentially 100% polarized in proton spin, with the sign being determined by which RF transition was used. The beam now passes into a strong field ionizer where the electron is removed to form an ion beam. The ionizer consists of a solenoid magnet with an electron gun mounted in the upstream end and extraction optics at the other. Electrons emitted by the gun travel helical paths along the solenoid and are mirrored by the retarding potentials at each end of the magnet. This allows a space charge limited electron current in the solenoid channel with a low emission gun. As the atoms drift along the solenoid, there is a small (< 1%) probability that it will be ionized and extracted. The entire ionizer is elevated to 10 to 20 kV to extract the positive ions produced. The solenoidal field is about 2 kG, which is strong enough to cause the 1 and 4 states to align themselves with the field to produce one spin state, or cause 2 and 3 to align themselves to produce the other spin state.

It is very important to maintain the vacuum in the ionizer as high as possible, since any ions produced in the ionizer will be extracted. Hydrogen-bearing compounds are a particular problem since they may dissociate upon ionization and produce unpolarized protons which will dilute the polarization of the beam.

The beam exiting the ionizer is longitudinally polarized. Other spin states are produced by passing the beam through appropriate spin precessing devices. At ANL, rotation of the spin into the vertical plane is accomplished by bending the beam 90° in the vertical plane with an electrostatic mirror.

Atomic beam sources developed to date for dc accelerator applications produce beams up to about 10 μA of H^- beam, or 200-300 nA of H^- ions if a charge exchange stage is added. Polarizations of 75% are typical for these sources, with about half of the polarization loss due to unpolarized background from the ionizer and half due to the sextupole allowing some leakage of the unwanted states. The ANL source was designed and built by the Auckland Nuclear Accessory Company, Ltd. (ANAC) of Auckland, New Zealand. It is essentially a copy of their standard dc source which is used on the Texas A & M University cyclotron[3] and the Rutgers University tandem.[6] In the two years the source has been at ANL, some development work has been carried out to improve the performance of this source for synchrotron applications.[7] The results of this limited effort have been rewarding to date. Pulsed beams of 30-40 μA with polarizations of 80% have been achieved. It appears that if one started from the beginning to develop an atomic beam source for synchrotron applications, pulsed output currents in the 100-200 μA range might be obtained.[8] CERN plans to undertake such a development program.[9]

For more detailed discussions of the operating principles of both types of polarized sources, the reader is referred to the articles by Haeberli[10] and Glavish[3] and to the references listed in these articles.

Acceleration

The problem of accelerating polarized protons to high energies has been studied by a number of people.[11, 12] These studies show that there are a series of depolarizing resonances, some of which are very strong, that must be overcome if high energy polarized beams are to be obtained. These resonances occur when the horizontal magnetic field, which appears as an alternating field in the rest frame of the proton, has a frequency component equal to the precessional frequency of the proton. There are two sources of such fields; one of which is intrinsic to the machine, the other due to imperfections. Particles traveling on the median plane experience only a vertical field, which has no effect on the polarization; assuming of course that the beam is vertically polarized. If there are imperfections such as magnet misalignments, horizontal fields will be experienced. Particles having finite vertical betatron oscillation amplitudes experience horizontal fields in any machine, since such fields are necessary for beam stability. The location of these resonances is given by the expressions

$$\gamma = (nk \pm \nu_y)/(\frac{g}{2} - 1) \rightarrow \text{intrinsic} \qquad (3)$$

$$\gamma = n/(\frac{g}{2} - 1) \rightarrow \text{vertical closed orbit imperfections} \qquad (4)$$

$$\gamma = (n \pm \nu_y)/(\frac{g}{2} - 1) \rightarrow \text{field gradient imperfections} \qquad (5)$$

where g = 5.585, k is the sector number or basic periodicity of the machine, ν_y is the vertical tune number and n = 0, 1, 2 .... The strength of intrinsic resonances is given by the equation[12]

$$t = 1 - \exp - \left[\pi \frac{(\omega_p r)^2}{2\lambda}\right] \qquad (6)$$

where t is the transition probability and

$$\omega_p = eg\gamma B_y/2m \qquad (7)$$

$$r = b_n/\gamma B_y \qquad (8)$$

$$\lambda = \frac{d}{dt}\left|(\omega_p - \omega_n)\right| \qquad (9)$$

$$\omega_n = (nk \pm \nu_y + \gamma)\, e\, B_y/m \qquad (10)$$

where B_y is the guide field strength and b_n is the rest frame amplitude of the nth Fourier component of the horizontal field rotating in the precessional direction, and m is the rest mass of the proton, b_n is dependent on the amplitude of the vertical betatron oscillation and the quantities $\frac{\partial B_y}{\partial x}$ and $\frac{\partial B_y}{\partial z}$. The transition probability for the imperfection resonances follow a similar expression, except that b_n is dependent only upon the magnitude of the error and ω_n is independent of ν_y for the vertical closed orbit imperfection resonances.

From Eq. (6) it can be seen that two possibilities exist for safe passage through these resonances; i.e., make the exponent small so that $t \approx 0$, or make it very large so that $t \approx 1$. The first results in negligible depolarization, and the second results in complete spin flip. Making the exponent small requires making b_n small and/or making λ, the speed at which the resonance is crossed, large. b_n is the only controllable parameter for the vertical closed orbit imperfection resonances. Making it negligibly small means removing the imperfection, which clearly has limited possibilities. The other approach, i.e., making it large, may prove to be a workable technique. b_n is essentially uncontrollable for the intrinsic resonances since it is a function of the magnet structure and the vertical betatron amplitudes. The amplitude can be controlled to some extent, but only at the expense of acceptance for the machine. λ is the only term which can be varied to any extent. To better see the functional dependence of λ, we carry out the differentiation in Eq. (9) to obtain

$$\lambda = \frac{1}{2\pi}\left(\frac{2\omega_p}{\gamma g}\right)^2 \left|\left[\frac{(g-2)}{2}\,\Delta\gamma \pm \Delta\,\nu_y\right]\right| \qquad (11)$$

where $\Delta\,\nu_y$ is the vertical betatron tune change per turn and $\Delta\gamma$ is the change in γ per turn. Normally, $\Delta\,\nu_y = 0$. If a large enough $\Delta\,\nu_y$ of the proper sign is introduced, λ can be made large enough to make the exponent in Eq. (6) small enough to make $t \approx 0$. This is usually referred to as tune jumping. It is also possible to use a smaller $\Delta\,\nu_y$ of the opposite sign or reduce $\Delta\gamma$ to produce a very small λ and, therefore, produce a $t \approx 1$ (spin flip) situation. It must be remembered here, however, that b_n is dependent upon the betatron amplitude; therefore, for some particles $r = 0$ and it will not be possible to have $t = 1$ for all amplitudes. At the Zero Gradient Synchrotron (ZGS) we use the tune jumping approach, employing two pulsed quadrupoles capable of producing a tune shift of 0.02 in 10 μs. Figure 4 shows a plot of beam polarization versus momentum with and without the pulse quadrupoles. Due to budget limitations, we have not yet tried to carry the beam above 8.5 GeV/c. Figure 5 shows that spin flipping can be induced. This is a plot of the beam polarization versus the time at which the quadrupole is pulsed at one of the stronger resonances in the ZGS. When the pulse is too early, the resonance occurs on the decay of the quadrupole pulse, which is approximately linear in time. On the decay, $\Delta\,\nu_y$ is much smaller than on the rise and has the wrong sign for this resonance. For this particular resonance, this is sufficient to produce the spin flip condition for a significant fraction of the betatron amplitudes.

Polarimeter

Beam polarization is a very important, yet difficult, quantity to measure. Unlike intensity or beam position or structure, beam polarization can change with no effects on any normal synchrotron diagnostic and monitoring equipment. Since the beam polarization can be lost either in the source or in the synchrotron, it is desirable to be able to separate these two by monitoring the polarization between the source and machine and, of course, after acceleration.

The polarization can be monitored by looking at the left-right asymmetry in the particles emitted in a reaction which exhibits a reasonable polarization analyzing power; i.e., reactions which have a reasonably large asymmetry parameter, A, which is defined as

$$A = \frac{\left(N_L - N_R\right)}{\left(N_L + N_R\right)} \qquad (12)$$

where N_R and N_L are the number of particles emitted to the right and left, respectively, when the incident beam is polarized. At typical preaccelerator energies; i.e., 0.5 to 1 MeV, the reaction $Li^6 + p \rightarrow He^3 + He^4$ has a usable A value and reasonable cross section. At 750 keV and 110°, A = 0.5.[13] This reaction has the added feature that the He^3 ions are emitted with a well-defined energy of several megaelectronvolts. This makes it easy to detect the He^3 ions in the large background of elastically scattered protons. In the injector linac energy range, proton-carbon elastic scattering is a very convenient reaction. At 50 MeV and 60°, A = 0.85 for this reaction.[14, 15] Protons from the first excited state of carbon and the other background radiation found at the high energy end of a linac are easily rejected using time-of-flight and coincidence counting techniques.

At the ZGS, polarimeters have been built using both of these reactions. The 50 MeV carbon polarimeter works extremely well and trouble free. It is used to continuously monitor the polarization of the 50 MeV beam. The carbon target is a 0.5 mm wide, 0.08 g/cm^2 thick filament mounted in the beam line. Being so small, it intercepts only a few percent of the beam.

The 750 keV polarimeter has never been made operational, due to a lack of effort plus the fact it is not really needed with the 50 MeV polarimeter working so well.

Polarization measurements at high energy are more difficult. The only apparent way is to use pp elastic scattering as the analyzing reaction. Unfortunately, this reaction has the limitations of a small cross section and small asymmetry parameter, plus the complications and expense of a typical high energy physics setup. Figure 6 shows the measured proton asymmetry parameter between 3 and 17 GeV/c.[16] The uncertainty in these data also presents a problem since they limit the accuracy of the polarization measurement. In order to isolate elastic events at the desired angle, two double-arm spectrometers are required, one looking left and the other right. The ANL polarimeter is shown in Figure 7. With the full intensity of the ZGS polarized beam on target, it takes about 30 min to make a measurement to the 5% statistical level at 6 GeV/c.

A good estimate of the polarization and the rapid detection of a significant change in polarization can be obtained with a much simpler setup which looks only at the low energy recoil protons in pp scattering with a much larger acceptance than is practical in a magnetic spectrometer. Since this is an unconstrained measurement, there is a very large background, but an asymmetry can still be detected. This background will be constant, so this polarimeter can be calibrated against the regular polarimeter and used as a monitor. A device like this consisting of a pair of three counter-coincidence telescopes viewing a small polyethylene target mounted in the beam just as it is extracted from the ZGS, is used at ANL to monitor the beam for polarization stability. It is periodically calibrated against the other high energy polarimeter.

Special Operating Problems and Features

The timing of the resonance jumping quadrupole pulses must be set empirically each time the magnet program is changed. The relative locations of the resonances can be calculated reasonably accurately; however, the location of one must be found experimentally and the location of the others checked for each new program. Locating the resonances requires making plots of the beam polarization versus quadrupole time.

At ANL we have found that pulse-to-pulse flipping of the beam polarization is almost mandatory. This feature was not originally included in the ANL system; however, once added, the users will accept nothing else. The rapid spin flipping feature requires the distribution of signals to the experimenters to indicate the spin direction of the next pulse. This means the source must be signalled to change polarization each pulse and then be interrogated each pulse to determine which RF transition is on.

Another problem is the distribution of adequate polarization information to the users. At ANL, fifteen minute averages of the three polarimeter readings are logged by the Main Control Room computer and distributed to the users on a regular basis. This allows the users to determine the average magnitude of the polarization in each state at any time of any day during the run.

Scheduling of the machine during polarized beam running is considerably more involved than for normal operations. During normal running, the users can usually adjust the momentum of their secondary beams without affecting anyone else. That is not possible with polarized protons, however, since everyone uses the primary beam. In one 30-day run in 1974, the ZGS beam energy was changed seven times to meet the full needs of the program.

With polarized proton sources operating in the 10-50 μA range, the accelerated beam intensities are down 3 to 4 orders of magnitude from normal. This means the gains of beam intensity dependent systems must be increased.

Program Plans

ANL-ZGS

At the present time, ANL has the only polarized proton facility operating above several hundred MeV. The ANL facility has been operational since June 1973 and has been used a total of five months for physics. The beam intensity is presently 1-2 x 10^9 protons/pulse with a polarization of 6 GeV/c of about 70%. A peak momentum of 8.5 GeV/c has been reached, but all of the production running has been between 1 and 6 GeV/c. Full energy (12 GeV/c) running is presently scheduled for late 1975 or 1976. Improvement efforts presently underway should allow accelerated beam intensities of 5 to 10 x 10^9 protons/pulse later in 1975.

Saclay-Saturne

Saclay is scheduled to have a polarized proton and deuteron facility operational in the spring of 1975.[17] The Saturne source is an atomic beam source with the atomic beam stage located at ground potential and the ionizer at the preaccelerator potenial of 375 kV. (They will operate the linac in the $2\beta\lambda$ mode.) As of October 1974, their source was producing about 1 μA of beam above source background, but efforts were underway to improve this situation. There is only one depolarizing resonance in Saturne, so polarized proton acceleration should not be difficult. Their main interest at this time is in high energy polarized deuterons.

CERN-PS

On January 29, 1975, a two-year polarized proton beam design study was approved at CERN for the PS.[9] They plan a collaborative effort with the Auckland Nuclear Accessory Company to develop a 100 to 200 μA atomic beam source. A 100 μA source is expected to produce a circulating beam of 10^{10} protons in the PS. They have at least six strong intrinsic resonances which could be jumped using pulsed quadrupoles similar to those used to jump through transition. Careful magnet alignment should reduce most of the closed orbit imperfection resonances to an acceptable level. The others could perhaps be reduced by using correction magnets. The idea of spin flipping is also under study. If a polarized beam is developed at the PS, the source will be mounted on their old 50 MeV linac (the new one will be completed in 1978). This will allow the PS to provide high intensity pulses to the SPS and polarized beam to the PS users on alternate pulses. At 10^{10} protons/pulse from the PS, ISR luminosities could be obtained which would allow some polarized beam physics.

TRIUMF

TRIUMF is scheduled to have an operational polarized proton beam in late 1975.[18] They have already developed a 300 nA 80% polarization Lamb-shift source and are presently constructing a 300 kV preaccelerator for it. The 300 nA source should produce a dc current of some 10's of nA at energies up to 500 MeV.

Indiana University Cyclotron Facility (IUCF)

A polarized proton capability is planned for the IUCF, but has at this time not been scheduled.[19] The present best guess is that it may be available by 1977. Since this is a positive ion machine, an atomic beam source similar to the ANAC dc source will probably be used. A source such as this can be expected to produce at least 10 μA.

LASL-LAMPF

The 800 MeV linac at LASL is scheduled to have a polarized proton beam capability by mid-1976.[20] They are presently involved in the design of a Lamb-shift source using the design of the LASL tandem source as a starting point. The current design goal is 1 μA, which is a factor of two above the tandem source capability. The source will be mounted in a 750 kV preaccelerator, the construction of which will be completed in the fall of 1975. With a 1 μA beam from the source, the high energy average current should be 15 to 30 nA. The system will include a spin precessor so that all spin orientations can be supplied. The source will also have a rapid (1-2 kHz) spin reversal capability, which should prove to be quite valuable to certain types of experiments.

Schweizerisches Institute für Nuklearforschung (SIN)

A polarized proton beam is being developed for the 600 MeV SIN cyclotron.[21] At this time, they have an operational atomic beam-type source producing ~1 μA. They have successfully accelerated the beam to 30 MeV in the injector and plan to have full energy beam later this year. The design goal is 30-50 nA at full energy.

National Laboratory for High Energy Physics (KEK)

A polarized beam is planned for the KEK synchrotron.[22] A source type selection has not been made yet, but serious consideration is being given to the Lamb-shift source to take advantage of the intensity gains of negative ion injection.

Other Laboratories

Brookhaven National Laboratory and Lawrence Berkeley Laboratory have carried out some theoretical studies of the problems of polarized proton acceleration in the AGS and Bevatron, respectively. However, neither laboratory has any plans for developing such beams at this time. Likewise, there appears to be no plans for high energy polarized beams in the Soviet Union.[23]

Summary

The acceleration of polarized protons to high energy requires the solution of a unique set of machine and equipment problems. None the less, adequate solutions do exist--at least for some machines. As measured by the world-wide effort to develop polarized beam facilities, it appears that the physics interest in polarization is substantial. In the next two years, a number of beams in the 0.1 to 3 GeV range will be available for research. Energies in the 3 to 12 GeV range will continue to be available only at the ZGS. If CERN elects to develop a polarized beam as a result of their two-year study, a second high energy beam could perhaps be available in 1978.

References

1. G. Clausnitzer, R. Fleishmann and H. Schopper, Z. Physik, (1956), 144, p. 336.
2. E. K. Zavoiskii, J. Exptl. Theor. Phys. (USSR) (1957), 32, p. 731; Transl. Soviet Phys. (1957), JETP 5, p. 603.
3. H. F. Glavish, Stanford Univ., A Survey of Ground State Atomic Beam Sources, Symposium on Ion Sources and Formation of Ion Beams, Brookhaven Nat'l Lab., Upton, N. Y., Oct. 19-21, 1971, BNL 50310, pp. 207-222.
4. A. Abragam and J. M. Winter, Phys. Rev. Letters, (1958), 1, p. 374.
5. A. Abragam and J. M. Winter, Compt. Rend. (1962), 255, p. 1099.
6. B. A. MacKinnon, J. P. Ruffell, I. J. Walker, Auckland Nuclear Accessory Co., A. B. Robbins and R. N. Boyd, Rutgers Univ., H. F. Glavish, Stanford Univ., Rutgers Univ. Ground State Atomic Beam Polarized Ion Source, Symposium on Ion Sources and Formation of Ion Beams, Bookhaven Nat'l Lab., Upton, N. Y., Oct. 19-21, 1971, BNL 50310, pp. 245-248.
7. E. F. Parker, N. Q. Sesol, and R. E. Timm, Argonne National Laboratory, Operating Results and Improvements on the Zero Gradient Synchrotron Polarized Proton Ion Source, to be published in the Proceedings of the 1975 Particle Accelerator Conf., Washington, D.C., Mar. 12-14, 1975.
8. H. F. Glavish, private communication.
9. D. Möhl, private communication.
10. W. Haeberli, Ann. Rev. Nucl. Sci., (1967), 17, p. 373.
11. M. Froisart and R. Stora, Nucl. Instrum. Methods, (1960), 7, p. 297.
D. Cohen, Rev. Sci. Instr. (1962), 33, p. 161.
Also see E. Courant, Accelerator Dept. Internal

Report EDC-45, Brookhaven National Laboratory, Jan. 22, 1962 (Unpublished) and F. Lobkowicz and E. H. Thorndike, Rev. Sci. Instr. (1962), 33, p. 454.

12. T. K. Khoe, "Acceleration of Polarized Protons in the KEK Synchrotron," Report No. KEK-73-8, (November 1973) National Laboratory for High Energy Physics, Oho-Machi, Tsukuba-Gun, Ibaraki, Japan.

13. L. Brown, E. Petitjean, Nuclear Physics (1968), A 117, pp. 343-352.

14. R. M. Craig, et al., in Proc. of the Second International Symposium on Polarization Phenomena of Nucleons, Karlsruhe (1965), pp. 322-323.

15. L. N. Blumberg, E. E. Gross, A. Van der Woude, A. Zucker, and R. H. Bassel, Phys. Rev. (1966) 147, p. 812.
M. P. Fricke, E. E. Gross, B. J. Morton, and A. Zucker, Phys. Rev. (1967), 156, p. 1207.

16. L. G. Ratner and T. K. Khoe, IEEE Trans. on Nuclear Science, (1973), Vol. NS-20, No. 3, p. 217.

17. P. A. Chamouard, J. P. Auclair, private communication.

18. M. Craddock, private communication.

19. R. Pollock, private communication.

20. R. R. Stevens, private communication.

21. W. Joho, private communication.

22. T. K. Khoe, private communication.

23. R. L. Martin, private communication.

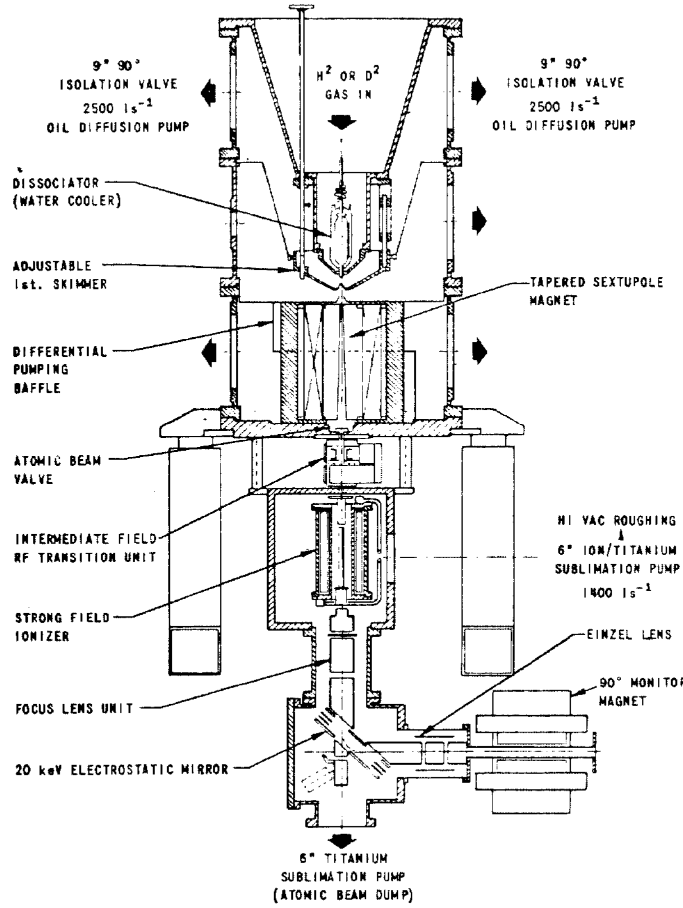

Fig. 2. ANL polarized proton ion source

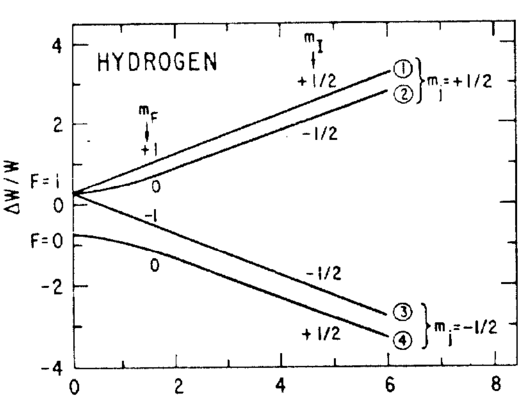

Fig. 1. Energy level diagram of the hydrogen atom in a magnetic field (in units of 507 G)

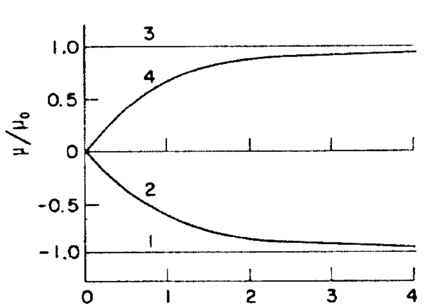

Fig. 3. Magnetic moments of the hyperfine states of the hydrogen atom in a magnet field (in units of 507 G). μ_0 is the Bohr magnetron = -9.27×10^{-21} erg/G

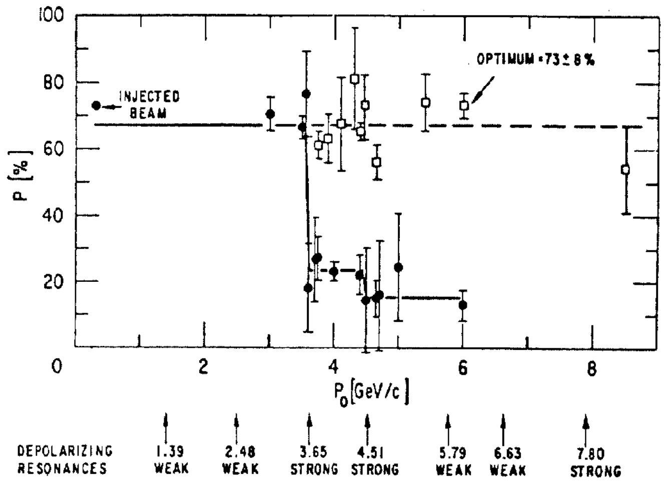

Fig. 4. Beam polarization versus momentum, with and without the pulsed quadrupoles operating.

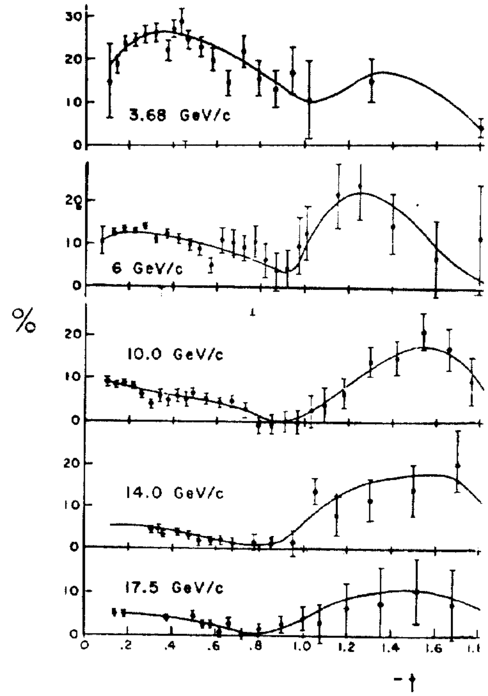

Fig. 6. PP asymmetry parameter versus the square of the four-momentum transfer, $(\text{GeV/c})^2$, for five different incident momenta.

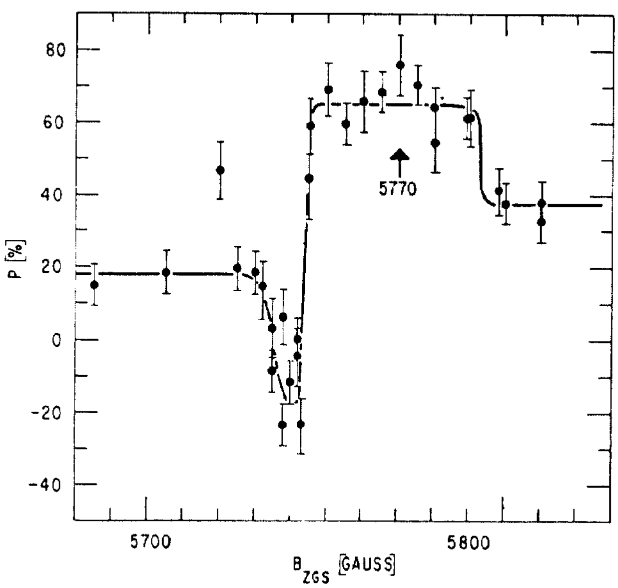

Fig. 5. Beam polarization verus quadrupole timing.

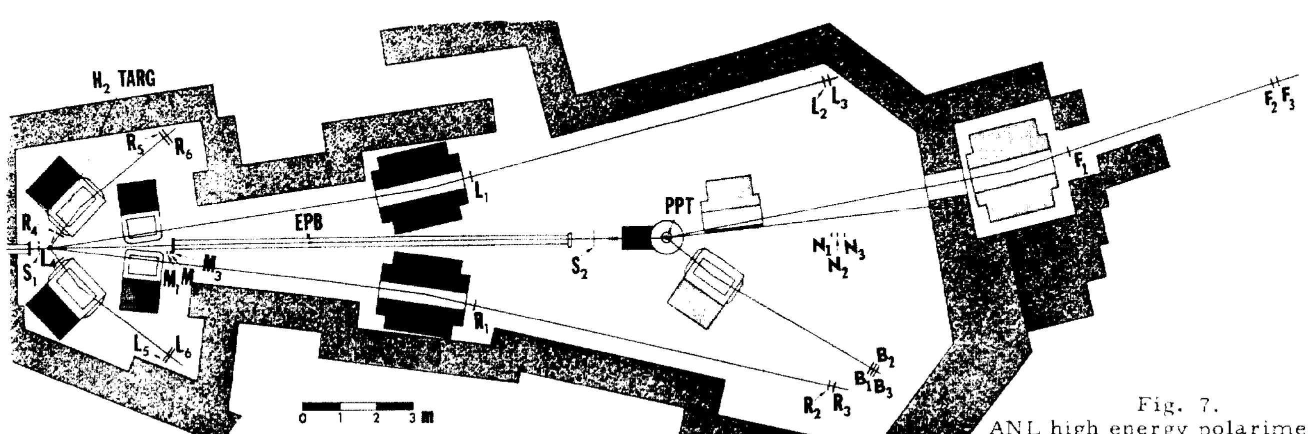

Fig. 7.
ANL high energy polarimeter