ACCELERATION OF POLARIZED PROTONS AT THE AGS*

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INTRODUCTION

Spin physics in the past has provided an acid test of many models and theories and over the last decade has revealed new and unexpected phenomena to confront present day theories. This work received great impetus from the experiments at the ZGS, where for the first time multi-GeV polarized beams became available. This, in conjunction with polarized targets, allowed the complete specification of the initial quantum states in high energy proton-proton interactions and led to many startling new results. Although spin effects were important at the previously measured lower energies, practically all theorists felt that spin effects would become negligible at higher energies. Instead, the ZGS results showed in many cases even larger effects than those observed at lower energies.

By the time the ZGS was shut down in 1979, high energy polarized proton projects were planned for KEK in Japan, SATURNE in France, and the AGS at Brookhaven. At present, serious thought is being given to high energy polarized proton beams at Fermilab, CERN, and indeed in planning for the Superconducting Super Collider.

Today, I would like to describe the facility at Brookhaven and give you the present status of the project. We have been in the commissioning phase for the last three months on a part-time basis. To date we have injected 7 μ A of polarized protons with 70% polarization. We have accelerated a peak of 6.4×10^9 polarized protons to 10.3 GeV/c and have made a first pass at correcting about a dozen imperfection resonances and two intrinsic resonances.

We believe that this first tune gave us about an 80% polarization survival from injection to 10.3 GeV/c. The goal was to achieve 26 GeV/c polarized protons with about an 80% polarization survival and an intensity greater than 10^{10} per pulse.

FACILITY

The whole facility can be functionally divided into two sections: a front end consisting of the polarized ion source, the 20 keV beam transport, the RFQ linear accelerator, the 750 keV beam transport, the 200 MeV linac and 200 MeV polarimeter and the 200 MeV transfer line to the AGS; and the hardware necessary in the AGS to accelerate and maintain the polarization of the injected protons. Fig. 1 is a schematic of the whole facility and, in addition to the front end components, shows the correction dipoles, the pulsed quadrupoles and their power supplies, the internal polarimeter and high

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energy polarimeter which make up the AGS modifications necessary to produce a high energy accelerated proton beam.

Fig. 2 shows a schematic of the Cs section of the polarized H^- ion source. Since the AGS normally injects H^- for unpolarized operation, the polarized source was also designed to produce polarized H^- via the reaction

where a polarized atomic hydrogen beam collides with neutral cesium.

Fig. 1. AGS facility.

Fig. 2. Cesium section and collision region of polarized source.

Fig. 3. Polarized source in position.

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Fig. 3 is a photograph of the source in its operating position. To date this source has produced about a 300 μ sec FWHM pulse of 12 μ A. The energy of the beam leaving the source is 20 keV. This beam is transported through a 20 keV polarimeter and beam transport line into the Radio Frequency Quadrupole (RFQ). This is an accelerator that both focuses and accelerates by having its quadrupole focusing structure longitudinally modulated to bunch and accelerate the beam. Fig. 4 shows an end view of the four vanes and Fig. 5 shows the assembly without end caps. The RFQ has performed reliably from the day of its first installation and has accelerated beam with greater than 80% efficiency to 760 keV.

Fig. 4. End view of vanes.

Fig. 5. View of vanes and tank assembly.

Fig. 6 shows the RFQ with a part of the 760 keV transport line and part of the 20 keV line. In the foreground is BM1. The transfer line schematic is shown in Fig. 7 with the relevant hardware from the source to the linac. The beam is bunched leaving the RFQ so that the transfer line must match in both transverse and longitudinal phase space. The bunchers are used for the longitudinal match and the magnetic elements are selected to transport the beam achromatically through the two 60° bends. The beam then is accelerated through the linac to 200 MeV. The overall efficiency achieved to date is about 65% from source to exit of linac. This is not too far away from about the 80% expected limit. Although a 20 keV polarimeter is being studied on line, it has not yet been made operational. The 200 MeV polarimeter at the end of the linac is thus the first place where we can measure the beam polarization. Fig. 8 shows a schematic layout of this polarimeter which uses PC¹² scattering to measure the absolute value of the polarization to 1%. Fig. 9 shows a photograph of the polarimeter in the 200 MeV transfer line from the linac to the AGS. In addition to the two horizontal plane spectrometers, one sees the counters in the vertical plane, which can measure a transverse component of the nominally vertical spin. Beam polarization can be measured with 1% statistics in a few minutes. Beam polarization measured over many hours of running has been very stable and the polarimeter has performed reliably.

Fig. 6. RFQ and portions of 20 keV and 760 keV transfer lines

Fig. 7. Front end components.

Fig. 8 200 MeV polarimeter
schematic.

Fig. 9. 200 MeV polarimeter in transfer line.

We have brought a polarized beam to the AGS and now must inject, accelerate, and preserve its polarization. High gain amplifiers and some new low level pick-up devices were installed in the AGS and after a couple of tries, we found that injection and acceleration presented no special problems. During our last run, parameters were set to previous values and the beam accelerated on the first pulse. This may not seem to be so astonishing but I would like to remind you that accelerator people forgot how to accelerate low intensity beams many years ago and it did represent some new learning and some new devices.

To understand what the problems are in preserving the polarization of an accelerated beam, let me remind you of what depolarizes the beam.

There are basically two types of depolarizing resonances, one a so-called "intrinsic resonance" which is due to the natural periodicity of the accelerator and two, an "imperfection resonance" which is due to misalignments which lead to closed vertical orbit distortions. These are characterized by

$GY = kP \pm \nu_y$ intrinsic
 and $GY = k$ imperfection
 where $G = g/2 - 1$ anomalous magnetic moment
 $k = \text{integer}$
 $P = \text{periodicity of the accelerator } (= 12 \text{ in AGS})$
 $\nu_y = \text{vertical machine tune (number of betatron oscillations per revolution)}$
 $\gamma = \text{relativistic energy factor}$

Discussion and derivation have appeared many times before so we won't say anymore here other than that the intrinsic resonance can be corrected for by a fast vertical tune shift (ν_y) and the imperfection resonance by a radial magnetic field at the proper harmonic.

The fast vertical tune shift for crossing the intrinsic resonances are generated by ferrite quadrupoles with a 2μ sec rise time and a 3 msec decay time. These quadrupoles are placed around ceramic vacuum chambers with an $8000\text{\AA}$ aluminized coating on the inside surface. This allows efficient transmission of the 2μ sec pulse and prevents the ferrite from interacting with the beam by significantly attenuating frequencies above 4 MHz. Fig. 10 shows the ceramic vacuum chamber and Fig. 11 shows a quadrupole assembly with chamber installed.

Fig. 10. Ceramic vacuum chamber.

Fig. 11. Quadrupole with chamber.

For the imperfection resonances we generate a harmonic correction at the appropriate energy using 96 dipole magnets. The strengths of these resonances were calculated assuming an RMS magnet misalignment of 0.1 mm. The dipole fields have been designed to correct up to 3.3 times this error at 25 GeV. This factor increases at lower energies.

All these correction devices will do us no good unless we measure the polarization of the accelerated beam. To do this we have constructed and installed an internal polarimeter. This polarimeter is used to measure beam polarization during the acceleration cycle. A 0.003" nylon fiber target is swung into the circulating beam at a rate of about 1 M/sec before and after resonances to allow us to correct the depolarization at each resonance. This analyzes PP elastic scattering from the 10% H₂ in the nylon. The fiber on a spool containing about a KM of nylon also moves at a velocity of about 1 M/sec so that heating and radiation damage are at reasonable levels. The sampling time ranges from a few msec to 500 msec where the 500 msec occurs on a flip-top. Fig. 12 shows schematically the target mechanism and Fig. 13 shows the assembly in place in the G-10 straight section.

Fig. 12. Internal polarimeter target mechanism.

Fig. 13. Polarimeter in G10 straight section.

This device is good for making relative measurements of polarization but has to be calibrated. The absolute calibration is accomplished by extracting the polarized beam and measuring the polarization from the proton-proton elastic scattering on a liquid hydrogen target using a four arm spectrometer in an external beam line.

POLARIZATION PRESERVATION

The magnitude of this job can be seen in Fig. 14 which shows the AGS resonances. The x's are the intrinsic resonances and the lines represent the imperfection resonances. Despite the best estimates that went into these calculations we found that some resonances were stronger than predicted, primarily the imperfection

$\gamma_0 = 1$ IMPERFECTION
 $\gamma_0 \approx \pm \gamma$ INTRINSIC

99% SPIN FLIP
 99% DEPOL
 36%
 30%
 7%
 2%
 2 1/2%
 1%
 0.3% DEPOL
 0.1% DEPOL
 0.01% DEPOL
 UNCORRECTABLE

PRIMARY CORRECTIONS
 8 RESONANCES
 SECOND ROUND CORRECTIONS
 24 RESONANCES

PROTON MOMENTUM (Gauss/cm)

Graph showing ν_y (Y-axis, 8.5 to 9.0) versus γ (X-axis, 24.85 to 25.15). The graph displays a resonance curve (diagonal line) and a correction pulse (vertical line). The distance of closest approach is indicated as $P/P_0 = .711$. The curves are labeled with times: 1.2 m sec, 2.4 m sec, and 2.9 m sec. The text "NOM. TUNE 3.75" is also present.

Fig. 15 shows some typical corrections in tune-energy space. The resonance line is crossed in less than 1 turn (approximately 2 μ sec) and the tune remains a fixed distance from the resonance as the correction pulse decays at a rate comparable to the change of energy during the normal acceleration cycle (approximately 3 msec).

In tuning through $GY = 0 + \nu_y$, an intrinsic resonance, one sets a reasonable amplitude and then varies the time at which the quadrupole is energized. In this particular case we set the quads to produce a tune shift of 0.2 units. We then started to search in time near the calculated position of the resonance. The abscissa in Fig. 16 is the number of "Gauss clock counts" (a magnetic field generated number) which is proportional to the momentum of the accelerated beam. We see in this resultant curve a spin flip region at 8400 Gcc and the region where we have successfully jumped the resonance at 8635 Gcc. The bump at 8250 Gcc is still not understood but the flip and correction pattern is exactly what one expects from a resonance. The ordinate is a measure of the relative polarization as measured with the internal polarimeter. The location of the resonance was in excellent agreement with the predicted number of Gauss clock counts.

The correction technique for the imperfection resonance curve shown in Fig. 17 is a little more complex. Since the vertical orbit distortion of harmonic number k is driven by horizontal imperfection fields of harmonic k , we correct these $GY = k$ resonances by canceling the k th component of the horizontal imperfection field. We

Fig. 16. Intrinsic resonance correction.

Fig. 17. Imperfection resonance correction.

Fig. 18. Polarization at 10.3 GeV/c after $G\gamma = 19$.

correct by pulsing the 96 dipoles with the appropriate amplitude and phase to minimize depolarization. In Fig. 17 we have set the cos term to zero and are varying the sin term of the 9th harmonic. At zero correction the polarization is -33% but we then find that at -20 units of sin correction, this rises to +50%. We then set the sin correction at -20 and sweep the cos in a similar manner. At $G\gamma = 9$ this brought the polarization up to 60% at 6 GeV/c. Fig. 18 shows the measurements that were made at 10.3 GeV/c for the $G\gamma = 19$ resonance which lies just below. In this case no correction is necessary. We believe that this 60% number when calibrated will represent about 80% transmission efficiency from injection.

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