POLARIZED PROTONS FROM THE SOURCE TO 70 GeV*

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ABSTRACT

This energy range covers the current project at the AGS and extends well beyond it. I shall report on our learning experience at BNL, discuss the potential for improvement, and the limitations of extending the AGS resonance jumping technique beyond 25 GeV.

I. The AGS Experience

The polarized proton project at the Brookhaven Alternating Gradient Synchrotron completed an initial phase of commissioning and ran for high energy physics at a beam energy of 16.5 GeV and peak polarization of 40%. Efforts are continuing to reach the goal of a 50% polarized proton beam at 24 GeV.

The magnitude of the project can be seen in Fig. 1 which depicts the major pieces of new hardware that were added to the AGS. The hardware was functionally divided into two areas:

- (a) The equipment needed to produce and inject polarized H^- into the AGS. This consisted of a new polarized H^- ion source, a radio frequency quadrupole accelerator (RFQ), two new low energy beam transport lines 20 and 760 keV, and a 200 MeV polarimeter.
- (b) The machinery needed to preserve the polarization in the AGS while accelerating the beam. This consisted of new fast tune changing quadrupoles and reworking of 96 low level correction dipoles. Permeating all this was a new control system and various types of new, high sensitivity diagnostic instrumentation.

Fig. 1. The AGS layout highlighting the polarized proton project hardware.

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1. Intensity

The polarized H^- ion source utilized the colliding beam approach through the reaction

that produced a peak current of 25 μA and a pulse width of 300 μsec . Approximately 60% of this beam was injected into the AGS and about 1×10^{10} polarized protons were extracted to the experimental areas. A developmental effort is underway to improve the source current by cooling the atomic beam stage down to (8-10) $^{\circ}K$ and use a more efficient charge exchange reaction with deuterons which promises a considerably higher cross section. The payoff is expected to be currents approaching the mA range.

2. Polarimeters

At this time we have one polarimeter at each energy stage to measure the beam polarization.

- (a) At 20 keV, a carbon foil is used to produce excited polarized H^0 atoms. The polarization of the decay γ -rays is measured by a quarter wave plate. The counting rate in this polarimeter is too low to be used for tuning the source.
- (b) The 760 keV polarization is measured by the reaction ${}^6Li(p, {}^3He){}^4He$ with has a high analyzing power approaching 50%. 3He at 2.3 MeV is detected by silicon surface barrier detectors. A 5% measurement is expected in 2 min. This device is currently being tested.
- (c) The 200 MeV polarimeter utilizes scintillation counter telescopes to measure p-carbon elastic scattering at 12° and 16° respectively. Its high counting rate gives a 2% measurement per min. The device was calibrated using the 200 MeV polarized beam at the Indiana University Cyclotron.
- (d) The internal polarimeter uses the old ZGS 50 MeV polarimeter hardware adapted to spool and flip a fishline target into the AGS beam. It is a relative measurement until calibrated by the external polarimeter.
- (e) The high energy polarimeter resides in one of the extracted beam lines. A double arm spectrometer measures the asymmetry in pp elastic scattering at $t \sim 0.3 (GeV)^2$ with an analyzing power of 4.5% at 16.5 GeV/c.

The front end layout is shown in Fig. 2. The peak beam polarization measured at 200 MeV was $(75 \pm 2)\%$. This approaches the theoretical prediction from the source of 82%, showing little loss, if any, as the beam passes through the RFQ and the 200 MeV linac.

Fig. 2. The polarized protons low energy beam transport from the source through the 200 MeV linac.

II. Depolarizing Resonances in the AGS

In a circular accelerator, the proton spin vector can be rotated away from the vertical direction by a horizontal magnetic field component. At such a point the guide vertical magnetic field precesses the spin about the vertical axis. Depolarizing resonances develop when the spin precession frequency matches the frequency of the driving magnetic fields. Three types of resonances were anticipated in the AGS:

- (a) Intrinsic resonances are driven by the horizontal fields acting on the beam as it executes betatron oscillations. Resonances arise when

$$G\gamma = kp \pm \nu_y$$

where

$$G = (g-2)/2 = 1.79 \text{ for the proton}$$

$$\gamma = E/m \text{ the Lorentz factor,}$$

$$p=12 \text{ the periodicity of the AGS}$$

$$\nu = 8.75 \text{ is the vertical harmonic tune of the machine}$$

and

$$k \text{ is an integer.}$$

- (b) Imperfection resonances are due to the misalignment of magnets. The condition $G\gamma = n$ has to be satisfied, thus these resonances occur at $\sim .5 \text{ GeV}$ intervals.

- (c) A peculiar kind of "beat" resonances occur as an interference between the natural vertical betatron oscillations and imperfection driven betatron oscillations. The condition $G\gamma = kp \pm k'$ manifests itself near the strongest intrinsic resonances. In the AGS $G\gamma = 36 \pm k'$ where k' 8 or 9 an integer nearest the vertical tune of the AGS.

Figure 3 depicts the depolarizing resonances as predicted by a computer program simulating the AGS magnetic lattice and a random rms displacement of the magnets of 0.1 mm.

Fig. 3. The strength of the depolarizing resonances in the AGS. The dotted lines show the expected level of polarization loss.

III. Resonance Correction

The commissioning plan called for initially neglecting all resonances that are below the 1% level while correcting the strong ones on the first pass. Fine tuning will handle the weak resonances later. Reality would have it differently. While the intrinsic resonance strengths were as predicted, the imperfections did not follow the game plan; all appeared a lot stronger than anticipated as if, on Fig. 3, the 1% dotted line was lowered by an order of magnitude. We had to correct every imperfection resonance from $\gamma=5$ onwards.

Imperfection resonances were corrected by applying, at the appropriate time, a dipole magnetic field with the proper Fourier component to cancel out the perturbing field. Two sets of 48 dipoles were used to generate orthogonal ($A \sin n\theta$) and ($B \cos n\theta$) terms of the correcting field. These corrections were applied separately (see Figs. 4a,b), searching for the peak polarization in the cosine correction setting the magnets there and then proceeding to find the corresponding sine correction. The strengths of these resonances are inversely proportional to their widths.

A totally different technique was used to correct the intrinsic resonances. At the proper γ or time in the machine cycle, the vertical tune of the machine was changed by $\pm \Delta\nu$, typically .15-.2 units. This was achieved by 8 fast pulsing ferrite quadrupoles that were designed to reach peak current in 1.5 μsec , a time shorter than one proton revolution at peak energies. Correction curves are displayed in Figs. 5(a,b) for resonances $\gamma = 0 + \nu_y$ and $\gamma = 36 - \nu_y$. Notice the partial spin flip at the $(0 + \nu_y)$ resonance before a complete correction is achieved.

Fig. 4. The $G\gamma=9$ imperfection resonance correction. Plotted are the measured beam polarization versus the dipoles current.

Fig. 5. Beam polarization vs. Gauss clock counts (or beam energy) for (a) intrinsic resonance $G\gamma=0+\nu_y$ and (b) intrinsic resonance $G\gamma=36-\nu_y$.

An example of the beat resonance occurred at $G\gamma = 36 - 9$. An attempt to correct it by the imperfection dipoles as $G\gamma=27$ resonance had little effect (Fig. 6). However, correcting with the 9th harmonic was dramatic (Fig. 7). This was a clear indication that the driving force is a harmonic close to the intrinsic machine tune of 8.75.

Fig. 6. $G\gamma=27$ corrected using the 27th harmonic.

Fig. 7. $G\gamma=27$ resonance corrected using the 9th harmonic. Notice the sharp response.

We hope to continue the commissioning of the AGS polarized beam to higher energies. Two additional fast quads have been installed; this will give us the capability to go as high as 23.2 GeV. The 96 correction dipoles have been beefed up to run at 30% higher currents.

IV. The 70 GeV Injector

Based upon our experience at the AGS, I shall list a few points to consider in the design of this machine to make it amenable to the acceleration of polarized protons.

1. Since the intrinsic resonance condition is $G\gamma = kP \pm \nu_y$, the number of resonances to deal with is inversely proportional to the periodicity of the machine. Can P be increased so as to eliminate most of these resonances? What price do we pay in the lack of long enough straight sections?
2. Imperfection resonances strength depend on magnet alignment in the machine. The capability for quick survey and diagnostics to pick up misalignment problems is invaluable.
3. We have not been able to achieve total spin flip in the AGS. Is this a viable alternative to jumping resonances, a la Saturne? What conditions should be met to make it work?
4. The lattice structure can be altered to selectively enhance (as to completely spin flip) or suppress certain resonances.
5. If conventional corrections (quads and dipoles) are used up to 25 GeV and Siberian snakes for higher energies from 25-70 GeV,
 - How do we turn these snakes on?
 - Can we use fast kickers to bypass the snakes at the low energies?
6. At the AGS we experience a noticeable beam emittance growth when the fast quads are pulsed. This results in considerable beam loss. Further studies are needed to reduce the perturbation.
7. Is a shift in $\Delta\nu$ of .25 units adequate for resonance jumping at energies higher than 25 GeV? One should bear in mind that the current needed in the fast quads is proportional to the beam momentum and is about 2500A at 23 GeV.

I hope that we will address these issues and converge on an acceptable configuration for the 70 GeV injector.

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