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THE POSSIBILITY OF ACCELERATION OF POLARIZED PROTONS IN THE BROOKHAVEN AGS*

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Abstract

The unexpected importance of high energy spin effects and the success of the 12 GeV Argonne ZGS in jumping many intrinsic and imperfection depolarizing resonances suggests that polarized proton acceleration should be tried at higher energy. The 1977 Ann Arbor Workshop concluded that it might be possible to jump depolarizing resonances in strong focusing synchrotrons. During the past year we have evaluated the possibility of accelerating polarized protons in the Brookhaven AGS. We found that for about $2 million one could obtain a polarized ion source, fast resonance jumping magnets, and 3 polarimeters which should allow acceleration of 10^{11} to 10^{12} polarized protons to 23 GeV/c with about 70% polarization or to 26 GeV/c with about 50% polarization.

Introduction

A two-week study was held at Brookhaven during July 1978 to investigate polarized proton acceleration at the AGS and to produce a preliminary design and a cost estimate.[1] The Brookhaven study discovered no new problems which cannot be solved. We prefer a polarized proton ion source of the H^- type, which could yield pulses of 75% polarized H^- ions with an intensity of 10-100 μA and a length of 1 to 3 ms. Upon injection this would result in an AGS intensity of 3×10^{10} to 10^{12} polarized protons per pulse which, together with the 2 sec repetition rate and the high extraction efficiency of the AGS, would yield an extracted beam intensity 5 to 150 times larger than that of the ZGS. Twelve new pulsed tune-shift quadrupoles will be necessary to jump the intrinsic resonances while the existing 96 correction dipoles can be used to tune out the imperfection harmonics. Most of the polarization monitors necessary are simply extensions of existing polarimeters; however, a fast internal polarimeter with an associated thin internal target would be useful for rapid tuning during the acceleration cycle. With these modifications it should be possible to accelerate polarized protons through the 8 intrinsic and 47 imperfection resonances in the AGS up to 26 GeV/c by mid 1981. Although no decision has yet been reached with regard to the implementation of such a program, it is presently being considered together with other options for future AGS operation.

Polarized Ion Source. H^+ vs. H^-

Both positive (H^+) and negative (H^-) polarized ion sources (PIS) exist, with the highest intensities (pulsed operation) presently available being ~100μA (H^+) and ~5μA (H^-). These sources are ground state atomic beam devices commercially available from ANAC, Inc.[2] The H^+ source uses an electron beam to ionize the atomic hydrogen, while the H^- source[3] uses a 40 KeV Cesium (Cs^o) charge exchange cell for ionization ($H^o\uparrow + Cs^o \rightarrow H^-\uparrow + Cs^+$).

Source development activities presently underway at several laboratories should result in significant current increases, particularly for the H^- sources, within the next year or so. ANAC is presently redesigning their entire ion source which should lead to an H^+ PIS with a 100-200 μA output current. The H^- sources will also benefit from these improvements and the Cs^o charge exchange H^- source current could reach 10 μA. Significantly higher H^- source currents could result from an H^- source development program presently underway at ANL.[4] In this program a deuterium (D^-) charge exchange cell ($H^o\uparrow + D^- \rightarrow H^-\uparrow + D^o$) is being tried out as an ionizer. Since its cross section is a factor of 10 larger than the Cs^o cross section and high current Dimov-type D^- sources are now available, this technique is expected to yield $H^-\uparrow$ currents of several hundred microamperes within the next 12 to 18 months, and currents approaching 1 mA may be possible.

Table I. Cost Estimate of AGS Acceleration of Polarized Protons

	$ Thousands	
Injection System:		
Polarized Ion Source	405	
Pre-accelerator Modification	180	
750 KeV Beam Line	85	$ 670K
Pulsed Quadrupole System for Intrinsic Resonances:		
Magnets	300	
Power Supply and Switching System	220	
Other Components, Labor	100	$ 620K
Pulsed Dipole System for Imperfection Resonances:		
Power Supplies and Control System	150	
Other Components, Labor	80	$ 230K
Polarimeters:		
200 MeV Polarimeter	25	
Internal Polarimeter	25	
Internal Target (Gas Jet $75K or Rotating Wheel $15K)	45	$ 95K
Absolute HE Polarimeter		
Magnets and Power Supplies	660	
LH_2 Target System	55	
Counters, Electronics, etc.	45	$ 760K
TOTAL		$2375K
Contingency (20%)		$ 475K
		$2850K
Transfer of ZGS Equipment		$-750K
Total Cost to DOE		$2100K

Although the cost and complexity of both types of PIS's (H^+ or H^-) are about the same, their relative value per microampere of beam current is quite different. Present thinking at BNL is that 2 mA of H^- current from the linac will, with charge exchange injection, produce the same circulating intensity in the AGS as 65 mA of H^+ (~10^{13} p/p). Thus, the 5 μA of $H^-\uparrow$ presently available with a Cs^oH^- PIS will produce more beam than the 100 μA of $H^+\uparrow$ presently available. With H^+ injection the best one might hope for is circulating beam of $2\text{-}3 \times 10^{10}$ p↑/p, while with H^- the expected intensity range is 3×10^{10} to 10^{12} p↑/p or even more if the H^- source can produce milliampere currents.

If the AGS is given a polarized beam capability, it might be converted to H^- injection for both its unpolarized and polarized operation. Ion sources capable of producing 25 to 50 mA of linac current exist, so the 250 μs of available linac beam pulse width would still be adequate to operate the AGS at full intensity. To

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take advantage of polarized H^- injection, however, the linac rf system must be modified to allow beam pulse widths of 1 to 3 ms and a charge exchanging stripper and orbit bump system must be designed and installed.

To summarize, significant and straightforward modifications are required on the injector if the AGS is to be given a polarized beam capability. The utility and flexibility of this facility will be much greater if the AGS is converted to H^- injection. If H^- injection is used and the polarized beam development activity begins in mid 1980, the injector could be ready to provide 10 to 100 μA ($H^-\uparrow$) for injection into the AGS by mid 1981. The injected beam polarization would be 75% and rapid spin reversal would be possible.

Depolarization in the AGS

Particles undergoing vertical betatron oscillations experience horizontal depolarizing magnetic fields from the quadrupole fields in an alternating gradient synchrotron. The horizontal field frequencies seen by the particle are $kP \pm \nu$ where k is an integer, P is the machine periodicity and ν is the vertical betatron tune. Depolarization can occur during acceleration when the spin precession frequency, $\gamma(g/2 - 1) \equiv \gamma G$, becomes equal to one of these frequencies. Thus, the resonances are given by

$$\gamma G = kP \pm \nu \qquad \text{"Intrinsic Resonances"} \qquad (1)$$

Accelerators also have horizontal imperfection field components of frequency k; thus, resonance will also occur when

$$\gamma G = k \qquad \text{"Imperfection Resonances"} \qquad (2)$$

Either of these types of resonance may be characterized by an effective strength, ϵ, calcuable from the machine lattice for a given beam emittance.[5]

The effect of traversing a resonance at a uniform rate, α, was calculated by Froissart and Stora[6] to be

$$P/P_o = (2e^{-\pi\epsilon^2/2\alpha} - 1) \qquad (3)$$

where

$$\alpha \equiv \begin{cases} G d\gamma/d\theta & \text{for imperfection resonances} \\ G d\gamma/d\theta \pm d\nu/d\theta & \text{for intrinsic resonances} \end{cases} \qquad (4)$$

and

θ = the turning angle.

This relation clearly indicates the relative importance of ϵ and α; however, in practice we would like to approach a resonance slowly, jump it quickly, and leave it again slowly. In this case, if we let the crossing be instantaneous, the depolarization is[7]

$$\frac{P}{P_o} = \frac{\delta^2 - \epsilon^2}{\delta^2 + \epsilon^2} \qquad \text{for } \alpha \to \infty \text{ during a jump from } -\delta \text{ to } \delta \qquad (5)$$

where δ is the difference between the particles precession frequency and the resonant frequency when the jump is performed at an energy γ, i.e.

$$\delta = \gamma G - (kP \pm \nu) \qquad \text{for intrinsic resonances} \qquad (6)$$

Equation (5) provides us an upper limit to the polarization when a finite fast jump is performed. In order to estimate the effect of α being finite but large we simply construct the product of (3) and (5) to obtain

$$\frac{P}{P_o} = \frac{\delta^2 - \epsilon^2}{\delta^2 + \epsilon^2}(2e^{-\pi\epsilon^2/2\alpha} - 1) \qquad \text{finite fast jump "slow" approach and departure} \qquad (7)$$

Figure 1 shows values calculated for the AGS intrinsic and imperfection resonance strengths, ϵ,[5] and the resulting depolarization for a complete transversal of each resonance at the normal AGS acceleration rate ($d\gamma/dt$ = 60 sec) calculated with Eq. (3). Clearly fast resonance jumping is essential to minimize polarization losses from the AGS intrinsic resonances.

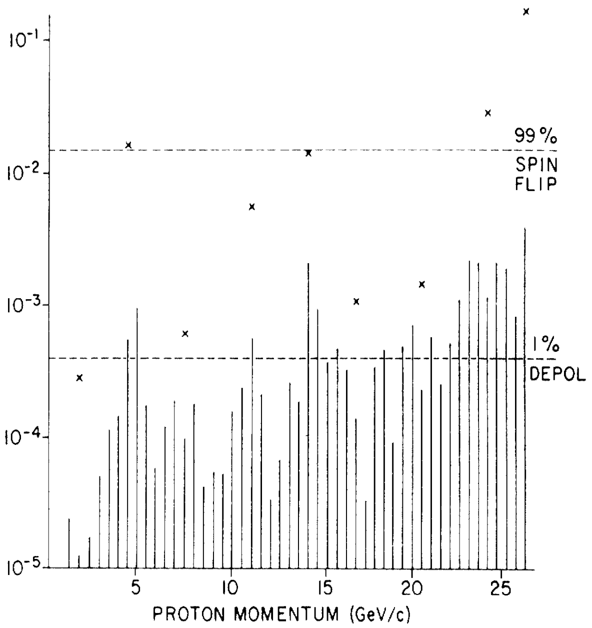


Fig. 1 AGS Resonance Strengths, ϵ. (AGS emittance = 10 π/γ mr-mm, magnet errors = ± 0.1 mm, x - intrinsic resonances; | - imperfection resonances)

The standard method[8] to accomplish a resonance jump is the pulsing of quadrupoles to change the tune abruptly (which by Eq. (4) increases α at the resonance). It is also necessary to decrease the depolarization due to Eq. (5) so we choose a maximum tolerable tune shift of .25 at 14 GeV/c. This change can be accomplished with twelve 1/2 meter long "unit" quadrupoles with equal gradients of 11.7 KG/m placed in a region where the vertical betatron function is a maximum ($\beta \simeq$ 22m). If we select a rise time of 2 μsec for these magnets, we obtain the estimates for depolarization given in Table II.

Table II.

Depolarization Due to AGS Intrinsic Resonances
Magnet full field risetime = 2 μsec (4π/3 radians)
The numbers in parentheses refer to the fixed "unit" Quadrupoles. (Tune shift of .25 at 14 GeV/c).

$G\gamma_{res}$= $kP \pm \nu$	γ_{res}	ϵ	$\Delta\nu=2\delta$ Total Tune Shift	Relative Quad Strength	$\alpha=d\nu/d\theta$ Resonance Crossing rate	Polarization P/Po [Eq. (7)]
$12-\nu$	1.81	.0054	.25	0.10	.0597	.994
$0+\nu$	4.88	.0154	.25	0.32	.0597	.958
$24-\nu$	8.51	.0006	25	0.56	.0597	1,000
$12+\nu$	11.57	.0054	.25	0.76	.0597	.994
$36-\nu$	15.20	.0137	.25	1.0	.0597	.966
$24+\nu$	18.26	.0010	.25(.208)	1.20 (1.0)	.0597(.0498)	1.000(1.000)
$48-\nu$	21.89	.0015	.25(.173)	1.44 (1.0)	.0597(.0413)	1.000(1.000)
$36+\nu$	24.96	.0266	.25(.152)	1.65 (1.0)	.0597(.0363)	.880(.734)
$60-\nu$	28.86	.1576	.25(.132)	1.90 (1.0)	.0597(.0315)	----*
$48+\nu$	31.65	.0023	.25(.120)	2.08 (1.0)	.0597(.0287)	.999(.996)
Resultant polarization after acceleration up to:						
$48-\nu$	21.89					.914(.914)
$36+\nu$	24.96					.804(.671)

*An effective fast passage through this resonace is impossible; however, slow spin flip may be possible.

The values for the polarization obtained in Table II assume that the effects of the imperfection resonances have been eliminated. Since from Eq. (2) these resonance frequencies are independent of the betratron oscillation frequency, ν, jumping them with a rapid betatron tune shift does not work here as it did for the intrinsic (ν dependent) resonances. The rate of traversal through an imperfection resonance is determined only by $d\gamma/dt$, while the strength of a particular imperfection resonance, k, depends on the strength of the synchrotron's imperfection field component of harmonic k.

The approach used at the ZGS to eliminate depolarization at these resonances is to apply a horizontal field correction pulse during the resonance crossing period. A similar technique can be used at the AGS. The horizontal field correction required to cancel the effect of the k^{th} resonance can be written in the form:

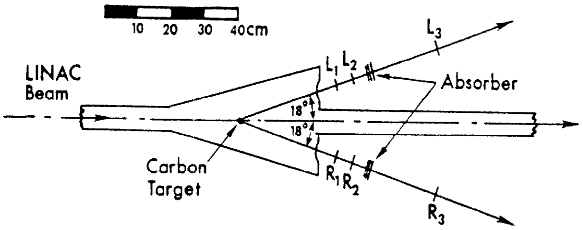
$$B_k(\theta) = \alpha_k \sin k\theta + \beta_k \cos k\theta \qquad (8)$$

The two independent parameters, α_k and β_k, can be experimentally determined by minimizing the polarization loss. Fortunately, there are 96 correction dipoles currently installed in the AGS (an adequate number to generate the required harmonics for all the 47 resonances up to 26 GeV); however, new power supplies, a control system, and considerable additional software will be necessary to generate the finesse required to tune out these imperfection harmonics.

Polarimeters

A 200 MeV polarimeter (Fig. 2) similar to the ZGS 50 MeV polarimeter[8] would be used to give an absolute measurement of the beam polarization prior to injection into the AGS by continuously intercepting and scattering a few percent of the 200 MeV beam.

Fig. 2 200 MeV Polarimeter



After extraction from the AGS the beam polarization could be measured by an absolute polarimeter (again similar to that at the ZGS[8]); however, in order to facilitate tuning through depolarizing resonances during the acceleration cycle, it is useful to have a polarimeter which is capable of a rapid relative measurement of the beam polarization before and after each depolarizing resonance. To insure that each resonance has been optimally jumped, an absolute knowledge of P_B at each energy is also necessary; therefore, such a polarimeter must be calibrated against the absolute polarimeter. At the ZGS the CERN polarimeter, consisting of two identical scintillator range telescopes, is used for such tuning; however, it is situated in the extraction line, so the beam must be extracted to measure the polarization. The measurement would be much more efficient if the polarimeter were situated in the ring so that it could sample the beam polarization at a number of points during the acceleration cycle. The polarimeter target could be a wheel of CH_2 or metal fibers or possibly a hydrogen gas jet. The internal polarimeter itself, as shown in Fig. 3, could be similar to the CERN polarimeter and consist of two identical left and right scintillation counter telescopes which each detect the recoil proton in proton-nucleon elastic scattering at small $P_\perp^2$. The target wheel might contain CH_2 fibers of 0.05 mm diameter (or metal fibers of 0.02 mm diameter) with a mean spacing of 5 mm. During the 250 ms that this target would be in the beam, it would absorb about 10% of the beam. Estimates of analyzing power, data time and precision in P_B at various momenta are:

P_{lab}	6 GeV/c	14 GeV/c	24 GeV/c
$A_{pp}[P_\perp^2=0.15]$	12.5%	5.5%	3%
Time	10 s	60 s	120 s
Events	$5x10^6$	$3x10^7$	$6x10^7$
Error in P_B	± .6%	± .6%	± .8%

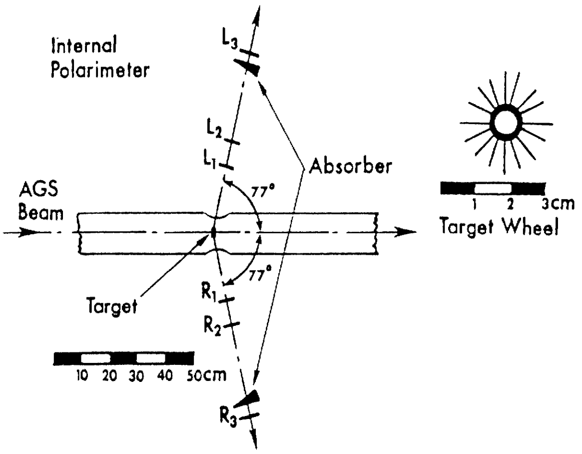


Fig. 3 Internal Polarimeter

Scattering from a metal or CH2 fiber target is dominated by heavy nuclei which reduces the effective analyzing power. This can be eliminated by using a hydrogen gas jet target; however, this gives a factor of about 100 lower luminosity and may require perhaps 25 times more running time to acquire similar precision in the polarization. Since the gas jet is also technically more complex and more expensive, it was not studied in detail during the workshop.

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