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THE POSSIBILITY OF POLARIZED BEAMS AT THE AGS*

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INTRODUCTION AND SUMMARY

The physics done with high energy polarized proton beams has generated considerable interest during the last few years. Recent data[1,2] suggest that spin effects are growing with increasing $p_\perp^2$ and energy, and to understand the significance of these effects, it is necessary to extend the available polarized proton beam energy.

The success of the Argonne ZGS in accelerating polarized protons[3] to 12 GeV through many intrinsic and imperfection depolarizing resonances has developed confidence that a similar approach will work at the Brookhaven AGS. The 1977 Ann Arbor Workshop[4] concluded that acceleration of polarized protons to about 25 GeV does look possible, so a two week study was held at Brookhaven this summer to investigate polarized proton acceleration at the AGS in more detail and to produce a preliminary design and cost estimate.[5] The principal participants in the study are listed under Reference 5; however, a number of other staff members from Brookhaven were involved contributing ideas, information, advice, and design work.

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 μamp and a length of 1 to 3 msec. 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

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DISCLAIMER

imperfection resonances in the AGS up to 23 GeV/c by late 1980. 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.

The purpose of this paper is to highlight some of the findings of the workshop while leaving the details of the cost estimates to the preliminary design study.[5] However, the results of the preliminary cost estimates are included in the following table:

Table I Cost Estimate AGS Acceleration of Polarized Protons

Injection System:	$ Thousands	
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

POLARIZED ION SOURCE, H^+ v.s. H^-

Both positive (H^+) and negative (H^-) polarized ion sources (PIS) exist, with the highest intensities (pulsed operations) presently available being ~100 μA (H^+) and ~5 μA (H^-). These sources are ground state atomic beam devices commercially available from ANAC, Inc.[6] The H^+ source uses an electron beam to ionize the atomic hydrogen, while the H^- source[7] uses a 40 keV Cesium (Cs^o) charge exchange cell to ionize the atomic hydrogen, i.e.:

$$H^o{\uparrow} + Cs^o \rightarrow H^-{\uparrow} + Cs^+ \qquad (1)$$

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. The atomic beam stage will contain a more powerful dissociator, and the single large sextupole will be replaced by three smaller independently adjustable sextupoles. This should increase the amount of atomic hydrogen available for ionization, either H^+ or H^-. The length of their electronic ionizer will be increased, and its optics improved to give it a higher ionization efficiency. These improvements should lead to an H^+ PIS with a 100-200 μA output current. The H^- sources will also benefit from the atomic beam stage 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.[8] In this program a deuterium (D^-) charge exchange cell ($H^o{\uparrow} + D^- \rightarrow H^-{\uparrow} + D^o$) is being tried 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^- currents of several hundred microamperes within the next 12 to 18 months, and currents approaching 1 mA may be possible.

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^- presently available with a Cs^oH^- PIS will produce more beam than the 100 μA of H^+ presently available. With H^+ injection the best one might hope for is circulating beam of 2-3x10^{10} p/p, while with H^- the expected intensity range is 3x10^{10} to 10^{12} polarized protons per pulse or even more if the H^- source can produce milliampere currents.

It is not unreasonable to have both H^+ and H^- injection on the AGS. The ZGS ran for several years this way. Today, however, with both polarized and unpolarized H^- ion sources available which can produce as much or more circulating beam intensity as H^+ ion sources, this is not required or desired. Thus, if the AGS is given a polarized beam capability, it might be converted to H^- injection for both its unpolarized and polarized operation. At ANL, when the ZGS ran for over two years with H^- injection, the operating efficiency, stability, and intensity were much better than that ever achieved with H^+ injection. Preliminary results from FNAL, where H^- injection is now standard on the 8 GeV booster, likewise indicate H^- injection is a better mode of injection.

If the AGS is converted to H^- injection, ion sources capable of producing 25 to 50 mA of linac current exist, so the 250 μsec of available linac beam pulse width will still be adequate to operate the AGS at full intensity. To take full advantage of polarized H^- injection, however, the linac rf system must be modified to allow beam pulse widths of 1 to 3 milliseconds. The additional energy required to support the copper losses associated with increasing the rf pulse length by a factor of ~10 is offset to some extent by the absence of any significant beam power requirements, but some additional energy storage may be required. Of course, to make use of the H^- beam, a charge exchanging stripper and orbit bump system must be designed and installed.

To summarize, significant but 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 early 1979, the injector could be ready to provide 10 to 100 μA ($H^-\uparrow$) for injection into the AGS by late 1980. The injected beam polarization will be about 75% and rapid spin reversal on each AGS cycle will be possible. Assuming a 50% beam transmission efficiency in the LINAC and no beam loss in the AGS during acceleration, the expected AGS beam intensities for various ion source and LINAC conditions are as follows:

$H^-\uparrow$ Source Intensity	LINAC Pulse Length	AGS Intensity
10 μamps	1 millisec	$3\ 10^{10}$
10 μamps	3 millisec	10^{11}
100 μamps	1 millisec	$3\ 10^{11}$
100 μamps	3 millisec	10^{12}

DEPOLARIZATION IN THE AGS

The Causes

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

$$\gamma G = kP \pm \nu \qquad \text{"Intrinsic Resonances"} \tag{2}$$

{frequency in terms of the turning angle, θ}

On the other hand all accelerators have horizontal imperfection field components of frequency k; thus, resonance will also occur when

$$\gamma G = k \qquad \text{"Imperfection Resonances"} \tag{3}$$

Either of these types of resonance may be characterized by an effective strength, ϵ, calculable from the machine lattice for a given beam emittance.[9]

Consider, for example, the case in which the perturbing fields and the particles precession frequency differ by a constant amount δ (a beam on a flat top near a resonance). Then the vertical component of the polarization is given by

$$\frac{P}{P_o} = \frac{\delta}{\sqrt{\delta^2 + \epsilon^2}} \tag{4}$$

If the beam has vertical polarization P_o very far from the resonance, and we accelerate "slowly" to within δ of the resonance, then we will measure the polarization given above. However, this is not yet a true depolarization since if we reverse the above process after a flat top, the spin reorients itself along the vertical direction.

On the other hand the effect of traversing a resonance at a uniform rate, α, from $\delta = -\infty$ to $\delta = +\infty$ was calculated by Froissart and Stora[10] to be

$$P/P_o = (2e^{-\pi\epsilon^2/2\alpha} - 1) \tag{5}$$

where

$$\alpha \equiv \begin{cases} G d\gamma/d\theta & \text{for imperfection resonances} \\ G d\gamma/d\theta \pm d\nu/d\theta & \text{for intrinsic resonances} \end{cases} \tag{6}$$

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 [11]

$$\frac{P}{P_o} = \frac{\delta^2 - \epsilon^2}{\delta^2 + \epsilon^2} \qquad \alpha \to \infty \text{ jump from } -\delta \text{ to } \delta \tag{7}$$

This relation 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 (5) and (7) and obtain

$$\frac{P}{P_o} = \frac{\delta^2 - \epsilon^2}{\delta^2 + \epsilon^2}\left(2e^{-\pi\epsilon^2/2\alpha} - 1\right) \qquad \text{finite fast jump "slow" approach and departure} \qquad (8)$$

The above result is useful for intrinisic resonances in which one can change the tune abruptly to increase α and thus decrease the depolarization. However, the effect of imperfection resonances is calculated with Eq. (5).

Figure 1 shows values calculated for the AGS intrinisic and imperfection resonance strengths, ϵ,[9] and the resulting depolarization for a complete traversal of each resonance at the normal AGS acceleration rate ($d\gamma/dt = 60$/sec) calculated with Eq. (5). Clearly fast resonance jumping is essential to minimize polarization losses from the AGS intrinsic resonances.

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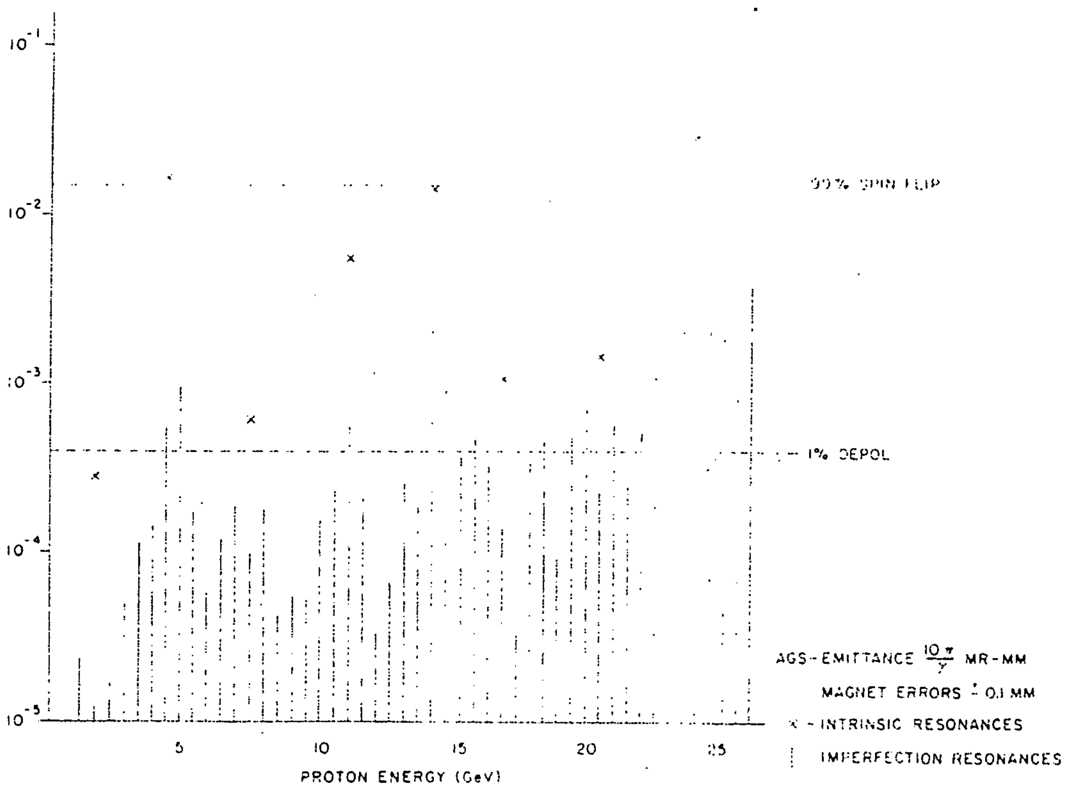

Fig. 1. AGS Resonance Strengths, ϵ.

The Cures

The standard method[3] to accomplish a resonance jump is the pulsing of quadrupoles to change the tune abruptly which by Eq. (6) increases α at the resonance. It is also necessary to decrease the depolarization due to Eq. (7) so we choose a total 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 ($\beta \simeq 22$m). If we select a rise time of 2 μsec for these magnets, we obtain the estimates for depolarization given in Table II.

Table II

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DEPOLARIZATION DUE TO AGS INTRINSIC RESONANCES
Magnet full field risetime = 2 μsec ($4\pi/3$ radians)
The numbers in parentheses refer to the fixed "unit" Quadrupoles. (tune shift of .25 at 14 GeV/c).

Resonance $G\nu_{res}$ = $kP \pm \nu$	ν_{res}	ϵ Resonance Strength Parameter	$\Delta\nu = 2\delta$ Total Tune Shift Assumed	Relative Pulsed Quad Strength	$\alpha = d\nu/d\theta$ Resonance Crossing rate	Depolarization [Eq. (8)]
12-ν	1.81	.0054	.25	0.10	.0597	.994
0+ν	4.88	.0154	.25	0.32	.0597	.958
24-ν	8.51	.0006	25	0.56	.0597	1.000
12+ν	11.57	.0054	.25	0.76	.0597	.994
36-ν	15.20	.0137	.25	1.0	.0597	.966
24+ν	18.26	.0010	.25(.208)	1.20 (1.0)	.0597(.0498)	1.000(1.000)
48-ν	21.89	.0015	.25(.173)	1.44 (1.0)	.0597(.0413)	1.000(1.000)
36+ν	24.96	.0266	.25(.152)	1.65 (1.0)	.0597(.0363)	.880(.734)
60-ν	28.86	.1576	.25(.132)	1.90 (1.0)	.0597(.0315)	----*
48+ν	31.65	.0023	.25(.120)	2.08 (1.0)	.0597(.0287)	.999(.996)
Resultant Depolarization after acceleration up to:						
48-ν	21.89					.914(.914)
36+ν	24.96					.804(.671)

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

In the above calculations we have optimistically assumed that the spread in δ is much less than the total tune shift. The range of δ from the γ spread is

$$\Delta\delta = G\Delta\gamma \simeq G\gamma \frac{\Delta P}{P} \tag{9}$$

Since the full beam has $\Delta P/P \sim .15\%$ at $\gamma = 25$, this yields

$$\Delta\delta_{full} = .07 \tag{10}$$

This is certainly smaller than .25 but not much smaller than .152 the tune shift for the chosen "unit" strength pulsed quadrupole at γ=25.

On the other hand, these calculations have also ignored the spread in ϵ, since they apply to a representative beam in which all the particles have the same vertical excursion (that of the outside of the beam envelope). The beam really contains a distribution of ϵ's proportional to the distribution of the beam in the vertical direction which means that the effective ϵ of the beam is somewhat less than that indicated. So we feel that the optimism in some parts of the calculation is balanced by a corresponding pessimism in other parts.

We have one other problem to address in that the values for the polarization obtained in Table 2 assume that the effects of the imperfection resonances have been eliminated. These imperfection resonances occur when

$$G\gamma_k = k \tag{11}$$

Since the value of γ_k is independent of the betatron oscillation frequency, ν, jumping the resonances 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 and on its proximity to ν.

The properties of the various AGS imperfection resonances assuming uncorrected, random magnet misalignments of ± 0.1 mm were shown in Fig. 1. Most imperfection resonances cause depolarization of less than 1% and can almost be ignored; however, several cause depolarization of 10% or more and must be corrected.

To eliminate depolarization at these resonances one could measure the vertical orbit distortions accurately enough to determine the field imperfections at the 0.1 mm magnet displacement level and correct these imperfections directly. However, this precision would be difficult with the present AGS beam position detection systems. The approach used at the ZGS is to apply a horizontal field correction pulse which covers the resonance crossing period with the correct field strength to minimize the polarization loss. A similar technique can be used at the AGS. The horizontal field correction required for the k^{th} resonance can be written in the form:

$$B_k(\theta) = \alpha_k \sin k\theta + \beta_k \cos k\theta \tag{12}$$

The two independent parameters, α_k and β_k, can then be experimentally determined to minimize 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.

AN INTERNAL POLARIMETER

As we have indicated, most of the polarization monitors necessary are extensions of those already in use at the ZGS.[3] 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 <u>absolute</u> knowledge of P_B at each energy is also necessary; therefore, such a polarimeter must be calibrated against an 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 be electronically sampled to obtain a value of 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 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 $P_\perp^2$ ($P_\perp^2 \approx .15$ $(GeV/c)^2$). At this value of $P_\perp^2$ the scattering angle ($\sim 77^o$) and momentum ($\sim$400 MeV/c) of the recoil particle are almost independent of the beam momentum so the polarimeter arms can be fixed. The low recoil momentum allows the elastic signal to be separated by time of flight, dE/dx pulse height discrimination, and ranging. In this region the cross section is large ($d\sigma/dt$ is about 20 mb/$(GeV/c)^2$) and independent of energy from 4 GeV/c to 26 GeV/c; thus, the event rate is quite high. However, over this momentum range the analyzing power falls with momentum P according to the empirical formula $A_{pp} = .75/p$ (see, for example, ref. 5). Therefore, the time necessary to obtain a given precision on the beam polarization varies by a factor of 20 over the range 4 to 26 GeV/c.

To estimate the time necessary to obtain a given precision on the beam polarization measurement at various representative momenta, we choose an internal polarimeter looking at a rotating CH_2 fiber wheel target with the following parameters:

Acceptance in Each Arm $\Delta t[\Delta\phi/2\pi]$	$10^{-3}(GeV/c)^2$
Internal Beam Intensity $[I_o]$	10^{11} protons/pulse
AGS Turn Time	2.7 μsec
Polarimeter Sample Time	5 millisec [1850 passes]
"Average" Thickness of CH_2 Target (ℓ)	$6\ 10^{-5}$ cm $[10^{-6}\ L_{coll}]$
Target Time in Beam	250 millisec $[10^5$ passes]
$d\sigma/dt$ (at $P_\perp^2 = .15$)	$2\ 10^{-26}\ cm^2/(GeV/c)^2$

Such a 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 millisec that this target is in the beam, it would absorb about 10% of the beam. The polarimeter event rate during the suggested 5 millisec electronic sampling time is:

$$\begin{aligned}\text{Events} &= 2\, I_o\, [5\ \text{millisec}/2.7\ \mu\text{sec}]\, (N_o \rho \ell)\, [d\sigma/dt]\, \Delta t \Delta\phi/2\pi \\ &= 2\ 10^{11}\ [1850]\ \ (3.4\ 10^{19})\ \ [2\ 10^{-26}]\ \ [10^{-3}] \qquad (24) \\ &\approx 10^{6}\ \text{events}/2\ \text{sec pulse}\end{aligned}$$

The corresponding analyzing power, data time and precision in P_B at various momenta are:

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

The beam polarization was calculated using:

$$P_B = A_M/A_{effective} \qquad (13)$$

while the error in P_B was obtained by assuming somewhat pessimistically that

$$\Delta P_B = \frac{1}{(.5A_{pp})\ \sqrt{Events})} \qquad (14)$$

Scattering from a metal or CH_2 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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