IEEE Transactions on Nuclear Science, Vol. NS-26, No. 3, June 1979

HIGH ENERGY POLARIZED DEUTERONS AT THE ARGONNE NATIONAL LABORATORY ZERO GRADIENT SYNCHROTRON*

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Introduction

High energy polarized deuterons became available for elementary particle research for the first time in the fall of 1978 when a polarized deuteron beam was developed at the Argonne National Laboratory (ANL) Zero Gradient Synchrotron (ZGS). The beam was used for research in November and December 1978 and, during that period circulating beam intensities of 1.5×10^9 deuterons per pulse were obtained with pulse-to-pulse polarization reversal of both the tensor and vector polarizations. The tensor polarization averaged 75% and the vector polarization 53%.

This report briefly describes the modifications made on the ZGS to allow the acceleration of polarized deuterons and our operational experiences with the first production run with this beam.

Ion Source

The ZGS polarized ion source can produce deuterons as well as protons, the conversion requiring only the replacement of the H^2 gas bottle with a D^2 gas bottle. The deuteron however, being a spin one object, gives deuterium six hyperfine states instead of four, like hydrogen. With six states, three RF transitions are required to produce maximum polarization and rapid polarization reversal. In order to make room to mount this third RF transition, the compression sextupole[1] had to be removed. The removal of this sextupole magnet reduced the current capability of the source by 10% to 20%.

Figure 1 is the Breit-Rabi diagram for deuterium atoms showing the splitting of the six hyperfine states as a function of magnet field strength. In the weak field region, the electron and nucleon spins are coupled and characterized by the quantum number F, the vector sum of the two spins, and m, the projection of this vector in the external field direction. In the strong field region, the spins are decoupled and the states are characterized by m_j ($= \pm 1/2$), the projection of the electron spin (1/2) in the field direction and m_i ($= \pm 1,0$), the projection of the deuteron spin. In the $m_i = \pm 1$ states, the deuteron spin is aligned (parallel or antiparallel) to the magnet field direction while in the $m_i = 0$ state, the spin lies in the plane normal to the field. Asymmetries in the state population relative to the field direction define the "vector" polarization of the beam; i.e.,

$$P_z = \frac{N_+ - N_-}{N_+ + N_0 + N_-}$$

where N_+, N_0, and N_- are the fractional populations in the +1, 0, and -1 states respectively. In an unpolarized beam $N_+ = N_0 = N_- = 1/3$. A non-normal population (1/3) in the plane perpendicular to the magnetic field defines the "tensor" polarization of the beam; i.e.,

$$P_{zz} = 1 - 3 N_0 \quad .$$

*Work supported by the U.S. Department of Energy.
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The sextupole magnet in the atomic beam stage removes the deuterons in states 4, 5, and 6 and the subsequent RF transitions selectively shift the atoms in states 1, 2, and 3 into states 4, 5, and 6 as shown in Table 1. From Table 1 and Fig. 1 it is seen that a variety of tensor and vector polarizations are possible. These possibilities are listed in Table 2. In our first production run the user required maximum tensor polarization with continuous cycling through the four possible tensor/vector sign combinations. The second run required maximum vector polarization for which $P_{zz} = 0$; therefore, there were only two states to cycle.

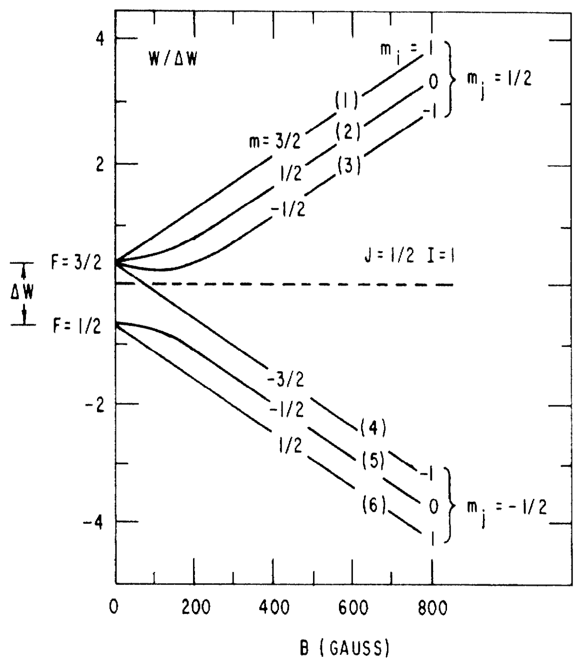

Fig. 1. Magnetic splitting of the hyperfine states of the deuterium atom ΔW/h = 327.3843 MHz.

Table 1. RF Transitions

Type	Transitions	Frequency	Magnetic Field
Weak Field	1↔4 2↔3 5↔6	7.2 MHz	Increasing 4 to 12 G
3-5	3↔5	329.2 MHz	Increasing 75 to 80 G
2-6	2↔6	454.0 MHz	Decreasing 80 to 75 G

Table 2. Polarizations vs RF Transitions

Weak Field	3-5	2-6	P_z	P_{zz}
Off	On	Off	1/3	-1
Off	Off	On	1/3	1
On	On	Off	-1/3	-1
On	Off	On	-1/3	1
Off	On	On	2/3	0
On	Off	Off	-2/3	0

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Accelerator

The deuterons were accelerated to 375 keV in the preinjector and to 25 MeV by the 50 MeV proton injector linac. The RF level and quadrupole magnet currents used for accelerating deuterons in the 2 $\beta\lambda$ mode were essentially the same as normally used for protons. No great effort was made to maximize the transmission through the linac. Normal tuneup procedures resulted in a deuteron transmission efficiency of about 25% compared to about 65% for protons in the μA current range.

The ZGS RF system was designed to handle particles from $\beta = 0.31$ (= 50 MeV protons) to $\beta = 1$ on the 8th harmonic of the cyclotron frequency. In order to handle deuterons with an injection $\beta = 0.15$, the RF was operated on the 16th harmonic up to $\beta = 0.5$, then switched to the 8th harmonic. The original RF frequency (F) vs accelerator magnet field (B) programer is not capable of producing an F vs B profile which includes a harmonic jump, so a new device built around a minicomputer was constructed for the deuteron program. A detailed description of this device is given in Ref. 2. Figure 2 shows an oscilloscope trace of the circulating beam intensity, as measured by an ac pickup in the accelerator, during the acceleration cycle along with a graph of the accelerating RF voltage. The beam is accelerated to $\beta = 0.5$ on the 16th harmonic. At this point the guide magnet field is held constant and the RF voltage reduced to zero in 200 μs. The RF frequency is then reduced by a factor of 2 and the voltage returned to normal with a rise time of 5 ms. As seen on the ac pickup graph in Fig. 2, the beam debunches when the RF is turned off and rebunches with about 90% efficiency when the RF is turned back on.

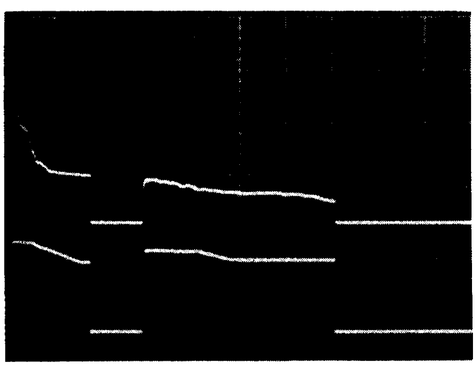

Fig. 2. Beam Intensity and RF Voltage Profile. The upper trace shows the beam intensity as measured by an ac detector during the acceleration cycle. The lower trace is the accelerating RF voltage during the acceleration cycle.

Depolarization Avoidance

Intrinsic and imperfection depolarization resonances in a synchrotron are located at energies corresponding to values of γ for which the two relations, $G\gamma = kP \pm \nu_y$ and $G\gamma = k$, are satisfied. P is the sector number of the machine, ν_y is the vertical betatron tune, k is an integer, and $G_p = 1.73$. $G_D = -0.143$. With $\nu_y = 0.8$ and $P = 4$, there are 10 intrinsic and 22 imperfection resonances in the ZGS for protons (k = 1, 2, 3, 4, 5) but only one (k = 0) intrinsic and no imperfection resonances for deuterons. We used the pulsed quadrupoles in the ZGS[3] to produce the fast tune shift, $d\nu/dt$, to pass through this resonance. The decay times, however, had to be lengthened from 2 ms to 50 ms to compensate for the 24 times slower speed with which the deuterons are accelerated away from the resonance; i.e., $\dot{\nu} = G\dot{\gamma}$ and $G_p/G_D \approx 12$ and $\dot{\gamma}_p/\dot{\gamma}_D \approx 2$.

The $G\gamma = \nu_y$ resonance also required a shift from the normal $V_x = 2/3$ resonance extraction mode to the $V_x = 1$ mode. In the $V_x = 2/3$ mode, V_x is shifted from ~ 0.8 down to 0.67 at flattop, which means V_y shifts from ~ 0.8 to ~ 0.9. During the tune shift, the $G\gamma = V_y$ condition is satisfied once more with a subsequent loss of polarization. This problem was avoided by shifting to $V_x = 1$ extraction.

Polarization Measurements

The tensor polarization, P_{zz}, was measured periodically in the preinjector terminal using the momentum analyzed deuteron beam accelerated to $\sim$ 55 keV. The magnitude of the deuteron tensor polarization is measured by detecting the neutrons from the $T(d,n)He^4$ reaction. Two scintillator detectors oriented at 0° and 90° with respect to the spin quantization axis measured the anisotropy of the neutron angular distribution. The measured anisotropy is then used to calculate the tensor polarization parameter P_{zz}. Assuming the reaction proceeds only through the $J = 3/2^+$ channel, the neutron angular distribution is

$$W(\theta) = W_0\ [1 - 1/4\ (0.95) P_{zz} (3\cos^2\theta - 1)]$$

where the factor 0.95 corrects for the analyzing power of the d-T reaction at these energies and θ is the average production angle for each of the detectors. For the arrangement used for these measurements, θ was 8° and 82° for the 0° and 90° detectors, respectively. The anisotropy, A, is then defined to be

$$A = \frac{R_p}{R_u} = \frac{1 - 1/4\ (0.95)\ P_{zz}(3\cos^2 8^\circ - 1)}{1 - 1/4\ (0.95)\ P_{zz}(3\cos^2 82^\circ - 1)}$$

where R_p and R_u are the measured ratios of neutron fluxes (0° rate divided by the 90° rate) into the two detectors for polarized and unpolarized beams, respectively. Solving for P_{zz}, we get

$$P_{zz} = \frac{1 - A}{0.461 + 0.224\ A} .$$

These measurements were made during the 25 minute daily ZGS maintenance period when access to the source was possible.

Continuous monitoring of the beam polarization after extraction from the ZGS was accomplished by looking at the asymmetry of the low energy recoil protons produced in Np scattering. A polarimeter consisting of a pair of three-fold coincidence counter telescopes looking at a polyethylene target measured the left-right asymmetry of the recoil proton. Absorbers placed just in front of the last of the three counters allowed energy selection by means of pulse height discrimination. This polarimeter monitored the vector polarization only, but since the measurement had a large background as well as being unconstrained, the polarimeter had to be calibrated from knowledge of the polarization as measured in the source or from measurements made by the experimenters with their own polarimeters. Counting rates were such as to provide a 5% or better measurement in fifteen minutes.

Operations Experience

The ion source modifications discussed above, coupled with the reduced transmission efficiencies of the ion source and linac for deuterons relative to protons, resulted in an average injector current of about 6 μA compared to about 30 μA for proton operations. Injection and capture efficiencies were about normal and beam loss at the harmonic jump was no more than 10%. After the harmonic jump, there was a continual beam loss which was attributed to noise in an A-D converter in the RF system minicomputer, for which there was no spare. In earlier tests of the system, this loss was not observed. With the low injector current and this beam loss, the accelerated beam intensity peak was only 1.5×10^9 deuterons per pulse.

Tuning through the depolarizing resonance was no problem using the Np scattering polarimeter described above. The depolarization caused by the tune shift during the $V_x = 2/3$ resonance extraction process took several hours to understand and correct since it had not been anticipated beforehand.

Absolute tensor polarization measurements were only possible at low energy (55 keV) and this required turning off the preinjector for approximately 30 minutes each day to set up and make this measurement. Vector measurements could be made using the high energy absolute polarimeter in beam 1.[3] The low beam intensity, coupled with the low efficiency of the device meant that 24 hours was required to obtain a 2.5% measurement.

Because of the limited operational life of the ZGS, it was mandatory that the first attempt at accelerating polarized deuterons also be scheduled as a physics run. All of the hardware and techniques required to produce this beam operated together for the first time at the same time the first physics run using the beam got underway. Obviously, the operating efficiency for this run was below normal but at 79% was not unreasonable.

With the ZGS scheduled for shutdown at the end of September 1979, the pressures of the polarized beam physics program are being carefully weighed to optimize the remaining running time. At this time, a second polarized deuteron run is being considered for the last month of ZGS operations.

References

1. The ZGS ion source has been modified to include a 10 cm long "compression" sextupole magnet between the primary sextupole and the RF transitions to improve the matching of the atomic beam into the ionizer.

2. F. Brandeberry et al., "A Mini-Computer Based Digital RF Control System for the ZGS," IEEE Transactions on Nuclear Science, Vol. NS-24, No. 3, pp. 1756-1758 (June 1977).

3. T. Khoe et al., "Acceleration of Polarized Protons to 8.5 GeV/c," Particle Accelerators, Vol. 6, pp. 213-236 (1975).