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THE VARIABLE ENERGY POLARIZED PROTON BEAM AT TRIUMF

[illegible].L. Beveridge,* M.K. Craddock,** G. Dutto,* G.H. Mackenzie,*
C. Oram,** L.W. Root,* G. Roy,*** P.W. Schmor.*

Abstract

A polarized H⁻ current of 1 μA has been achieved within a normalized emittance of 0.3π mm-mrad from a Lamb-shift type source. 80% of the beam is routinely transported at 300 keV along the 45 m long electrostatic injection line to the cyclotron, where 200 nA can be accelerated to 500 MeV and extracted. A Wien filter, located near the entrance of the injection line, is used to compensate for the precession resulting from the cyclotron's fringe field and to align the spin vertically. Depolarization along the line has been calculated to be less than a few per cent. The polarization, enhanced with a diabatic zero crossing in the source, is approximately 80%; however, a slight loss in polarization has been measured in the cyclotron between 200 and 500 MeV.

Introduction

A variable energy beam (180 to 520 MeV)[1] with good energy resolution[2] makes TRIUMF an ideal facility for accelerating polarized protons. Depolarizing effects along the 45 m long external injection path and during the ~1500 turns in the machine were calculated and found not important, in spite of the strong non-uniform stray magnetic field along the injection path and resonances in the cyclotron. The 80% polarization measured at 200 MeV is close to the polarization expected from the source. A slight loss in polarization of 8% has been observed over the extraction region between 200 and 500 MeV, and the reasons for this loss are being investigated.

Typically, a 1 μA beam at the source is transported with 80% efficiency through the injection line. Approximately 25% of the current injected into the cyclotron is then accelerated to 520 MeV. The variable energy beam can be extracted along all external proton lines (Fig. 1). In the proton hall, beam line 4A is equipped with a 10 cm liquid deuterium target which is used to produce a 50-65% polarized neutron beam.[3] Beam line 4B, with 100 nA maximum allowable current, is equipped with a QD type 0.1% medium resolution spectrometer (MRS). Recently an additional low-intensity (<10 nA) beam line has been constructed in the meson hall to utilize the capability of extracting, by H⁻ stripping, two simultaneous beams. The polarized beam was commissioned at the beginning of 1976 and presently accounts for 24% of the operational time.

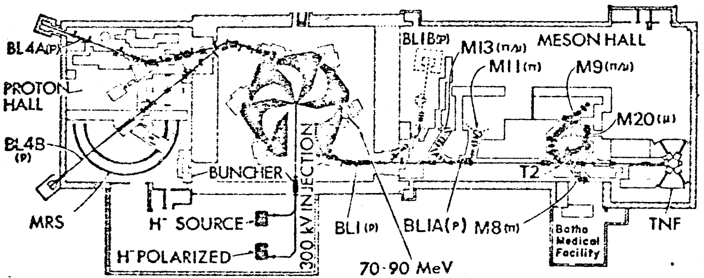

Fig. 1. Layout of the TRIUMF facility.

Source

The polarized source, shown schematically in Fig. 2, is an H⁻ Lamb-shift type source. Protons are extracted at ~7 keV from the duoplasmatron, and then slowed down to 500 eV before being neutralized by charge exchange in the cesium cell. The hydrogen atoms remaining in the metastable 2S state, after passing through the first two solenoids, have nuclear polarization. These atoms are then selectively ionized to H⁻ in a third solenoid containing argon. A more detailed description of this type of source can be found in a number of review articles.[4]

The TRIUMF source is characterized by an overall length from the duoplasmatron to the argon solenoid of only 86 cm. It was felt that the maximum polarized current should increase significantly, as the source was shortened, because of the reduced probability of the 2S states decaying to the ground state. In order to realize a design in which the various elements are quite close to one another, some of the versatility found in other sources was not included. The accel-decel lens system, for instance, is mounted as a single unit which can only be adjusted transverse to the beam direction. The zero field crossing techniques of Sona[5] is used to polarize the beam. The beam polarization is at least 80%, despite the fact that an RF spin filter is not being used. Two sets of Helmholtz coils reduce the cyclotron fringe field, about 3 G in the zero-cross region between solenoids 1 and 2. The spin direction can be altered by reversing the field in all three solenoids.

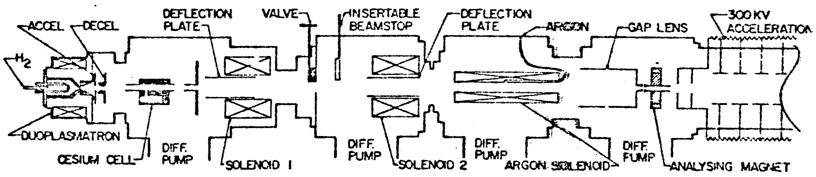

Fig. 2. Schematic layout of the TRIUMF Lamb-shift polarized source.

A system of two lenses is used to match the 500 eV H⁻ beam to the 300 keV acceleration tube and the beam line acceptance. First, a gap lens at approximately 5 kV focuses the beam through a 3 mm aperture. Next, a hole lens at approximately 0.1 kV is used to make small adjustments to the virtual position of the focus to match the stringent acceptance conditions of the acceleration tube. The proper transverse positioning of the ground cylinder of the gap lens is critical and is performed using the beam. A momentum-analysing magnet, located between the hole lens and the acceleration tube, is used during the initial source optimization procedure to select and bend only the 500 eV H⁻ beam onto a Faraday cup. The accel-decel system position, the duoplasmatron parameters, and the accel voltage are optimized by maximizing the Faraday cup current reading. The analysing magnet is also used to provide horizontal steering; voltages applied to insulated plates on the pole faces provide vertical steering.

The vertical beam emittance, as measured approximately 40 cm downstream of the acceleration tube, is 0.3π mm-mrad normalized. The beam centroid shifts slightly with spin orientation; however, the beam line and cyclotron can be set up to accept the overall

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*TRIUMF, Vancouver, B.C., Canada V6T 1W5
**University of British Columbia
***University of Alberta

emittance, which is approximately 50% larger than the emittance corresponding to one spin orientation.

Injection Line

The location of the polarized H^- source with respect to the cyclotron is shown in Fig. 1. The injection line is partially common with the one for the unpolarized H^- beam.[6] From the 300 kV terminal the beam is first transported horizontally above the cyclotron vault through a 25 m long transport line, then deflected by 90° to line up with the cyclotron axis and finally, after a 20 m long vertical line, injected into the cyclotron via a spiral inflector and a cylindrical deflector. All deflecting and focusing elements are electrostatic. The transport is complicated by the presence of a fairly high stray magnetic field, varying between 6 and 100 G along the horizontal line and between 100 and 3000 G along the vertical line. The field is quite substantial due to the high level of saturation of the cyclotron magnet yokes.

In order to reduce the beam deflection caused by the transverse magnetic component along the horizontal line, mild steel cylinders, 4 mm thick, were installed wherever possible and small permanent barium-ferrite magnets added to the edges of the cylinders to compensate for the transverse field in the unshielded regions. The residual longitudinal and vertical transverse field components are shown in Fig. 3. In the gap between the shielding cylinders there is an enhancement of the longitudinal component (B_z). The vertical component (B_x) is generally reduced, and the compensating action obtained with the permanent magnets is evident from the figure. The horizontal transverse component was generally small and did not require further action. Along the vertical line the transverse component was small in both directions, and neither shielding nor compensation were required. The system was installed for the transport of the normal H^- beam, and its performance in terms of beam transmission has been previously described.[6]

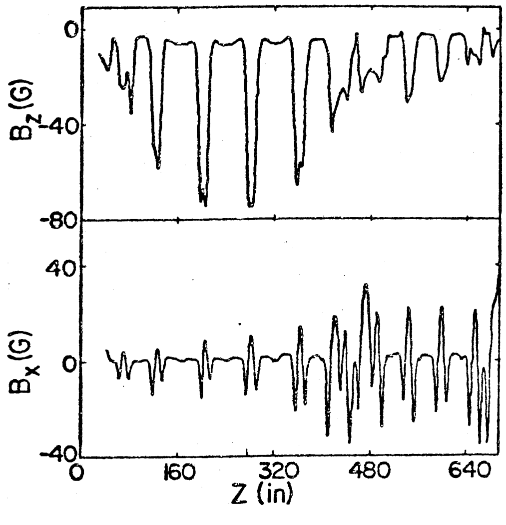

Fig. 3. Longitudinal (B_z) and vertical (B_x) stray magnetic field components along the horizontal injection line after magnetic shielding and field compensation with permanent magnets.

Detailed measurements and calculations were performed in order to calculate the spin precession introduced by the system and the depolarizing aberrations caused by the field gradients and by the finite beam emittance. A ray trace program integrating the equations of motion and the spin precession equations was written. The net spin precession was found to be about 63° mainly due to the residual longitudinal field in the horizontal section. Here the contributions of the various non-shielded regions add whereas along the vertical section the field and the spin are almost parallel and the precession is negligible. The B_r component of the cyclotron's magnetic field introduces only a 2° spin rotation as the beam passes through the spiral electrostatic inflector. The magnetic field and angle of the Wien filter at the injection line entrance were set to compensate for the calculated spin rotation, in order to have the spin oriented vertically at the cyclotron entrance. The Wien filter parameters, optimized empirically for maximum extracted beam polarization, corresponded to a spin precession only a few degrees different than calculated.

Calculations indicate that most serious aberrations are associated with the vertical line. Here the B_r component associated with changes in longitudinal field is essentially along the spin direction and particles at the outside of the beam envelope will end up with an overall rotation different from that for the central ray. However, for a beam with vertical spin at the top of the vertical beam line, the effect has been calculated to be within ±7° for an emittance ten times larger than the nominal one, corresponding to a depolarization of less than one to two per cent. Along the horizontal line, even though the gradients are quite large (up to 10 G/in., Fig. 3), there is cancellation due to the fact that the gradients change sign rapidly within the gap between shielding cylinders. The effect at the entrance of the gap is compensated by the effect at the exit, since the particle position with respect to the central trajectory does not change substantially within the gap. Including a 1° aberration resulting from the B_r gradient through the inflector, the overall aberrations along the injection line should not introduce more than a 2% depolarization. This was confirmed by the high value of polarization (up to 80%) obtained at the extraction from the cyclotron. Also, the polarization does not seem to depend significantly on the tuning conditions along the line and seems practically independent of the particular central trajectory path which is followed.

Cyclotron

Previous calculations[7,8] on resonant beam depolarization in cyclotrons indicate that depolarization should not be a serious problem provided that field imperfections are kept at reasonable values. The TRIUMF magnet structure makes it possible for substantial transverse imperfections to arise on the median plane and the beam is more susceptible to imperfections due to the low rotation frequency, 4.2 MHz.

Depolarization resonances are expected to occur when

$$(g/2 - 1)\gamma = n \pm \ell\nu_z \pm m\nu_r$$

where γ, g, ν_z, ν_r have the usual significance and n, ℓ and m are integers. The only intrinsic resonance over the TRIUMF energy range occurs when $\ell = m = 0$, $n = 2$ and $\gamma = 1.118$, at an energy of about 110 MeV. This is driven by a second harmonic of a transverse field component in the cyclotron. If the phase width were narrow the spin of all particles in a bunch would rotate independent of amplitude and phase. In practice, particles with different phases will perform a different number of turns in the resonance and the net effect will be a depolarization. The relativistic spin equations were incorporated into the general code Goblin and several cases were examined. A second harmonic of 5 G in the transverse component, with the worst possible phase relationship to the precessing polarized ion, will cause the vertical spin component to alter from 1 to 0.95 over a resonance region of about 80 turns. Therefore, during the magnetic field shimming program the transverse second harmonic field component was measured to a precision of ±0.3 G and shimmed out to be less than 2 G in this region; hence little depolarization is expected from this resonance.

Non-zero values of ℓ and m correspond to particles executing betatron oscillations experiencing different field components than the central ray. If these are sufficiently strong and in resonance they will cause a depolarization. There are a large number of $\ell \neq 0$ and $m \neq 0$ resonances; several were investigated theoretically assuming a betatron amplitude of 0.25 in., and no depolarization could be predicted. Beam profile measurements since have confirmed that 0.25 in. is a reasonable amplitude for the bulk of the beam, even though some particles may exceed this.

The polarization of the extracted beam has been measured over the TRIUMF energy range using a polarimeter on beam line 4A. The polarimeter is a four-arm detector, each arm viewing $\vec{p}p$ elastic scattering from a CH_2 foil at 24°. Two arms on each side measure the forward and recoil protons in coincidence. In order to eliminate errors arising from the uncertainties in the energy dependence of the $\vec{p}p$ scattering analysing power, a portion of the cyclotron beam was allowed to bypass a narrow extraction foil, to slip out of phase at full energy (525 MeV) and to be decelerated back to the stripping foil.[9] Two beams, out of phase by about 180°, could therefore be extracted at the same energy and the effects of the acceleration at large radii obtaine~~d~~ independently from the analysing power.

The results are shown in Fig. 4. If the difference in polarization is assumed to correspond to twice the polarization loss during acceleration to large radii, then the loss would be 5% between 250 and 300 MeV and 3% between 460 and 480 MeV. However, strong depolarizing resonances are not expected in these energy regions, and other explanations could be possible. For instance, since it was measured that the polarization of the external beam at a fixed energy varies vertically across the beam by 5% (perhaps due to a non-uniform polarization distribution within the injected beam) and since it was found that the decelerated beam can be wider than the accelerated one due to the effect of betatron oscillation resonances, an apparent loss in polarization may just be the consequence of extracting different portions of the accelerating and decelerating beams. Further investigations of these effects are being pursued.

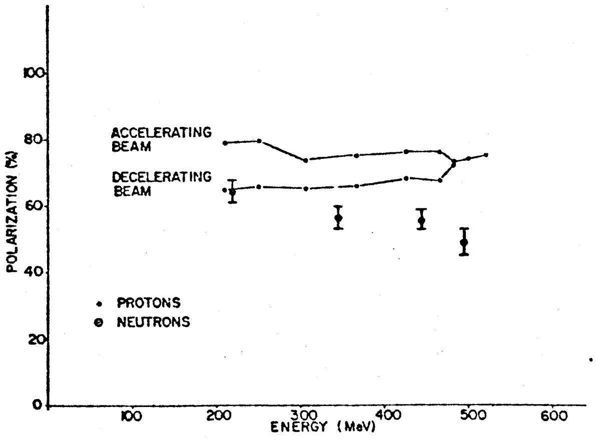

Fig. 4. The polarization of the extracted proton beam and of the neutron beam produced from an external deuterium target as a function of energy.

Beam Lines

Along beam line 4A (Fig. 1), a 10 cm long deuterium target can produce a monoenergetic polarized neutron beam, through a 5 cm aperture, with a flux of approximately 2×10^6 neutrons/s for the 200 nA proton beam. A superconducting solenoid, capable of precessing the spin of 500 MeV protons through 270°, can be located in front of this target. The measured neutron polarization, from 50 to 65%, is shown at four neutron energies as open circles in Fig. 4. This polarized neutron beam has been used to do $\vec{n}p$ scattering in order to measure the Wolfenstein polarization transfer parameters.

Beam line 4B has two experimental stations. The first is a general purpose station with four movable arms for detection apparatus. The second station has a medium resolution (0.5 MeV) magnetic spectrometer. Experiments using the polarized beam have examined elastic scattering on helium and deuterium, quasi-free scattering on calcium and oxygen, and inclusive scattering on helium.

BL1B was recently installed to permit a second independent polarized proton experiment to run simultaneously with the BL4 experiments. A 65 cm Browne-Buechner magnetic spectrograph has been installed in the line for measuring the angular dependence of spin-dependent effects in $\vec{p}\pi$ reactions.

References

1. J.R. Richardson, E.W. Blackmore, G. Dutto, C.J. Kost, G.H. Mackenzie, M.K. Craddock, IEEE Trans. NS-22(3), 1402 (1975).
2. E.W. Blackmore, M.K. Craddock, G. Dutto, D.A. Hutcheon, C.J. Kost, R. Liljestrand, G.H. Mackenzie, G.A. Miller, J.G. Rogers, P.W. Schmor, these proceedings.
3. C. Amsler, R.C. Brown, D.V. Bugg, J.A. Edgington, C. Oram, D. Axen, R. Dubois, L. Felawka, S. Jaccard, R. Keeler, J. Va'vra, A. Clough, D. Gibson, G.A. Ludgate, N.M. Stewart, L.P. Robertson, and J.R. Richardson, Nucl. Instr. & Meth. 157, 203 (1978).
4. B.L. Donnally, Proc. 3rd International Phenomena in Nuclear Reactions, eds. H.H. Barschall and W. Haeberli, (University of Wisconsin Press, Madison, 1971) p. 295.
5. P.G. Sona, Energ. Nucl. 14, 295 (1967).
6. J.L. Beveridge, E.W. Blackmore, P.F. Bosman, G. Dutto, W. Joho, R.I.D. Riches, V. Rodel, L.W. Root, B.L. White, IEEE Trans. NS-22(3), 1707 (1975).
7. G. Besnier, Proc. of 5th Int. Cyclotron Conference, ed. R.W. McIlroy (Butterworths, London, 1971) p. 769.
8. H.G. Kim, W.E. Burcham, Nucl. Instr. & Meth. 27, 211 (1964).
9. G.H. Mackenzie, Proc. of 8th Int. Conf. on Cyclotrons and their Applications, Bloomington, 1978 (to be published).