A polarized \( ^1 \)H current of 1 mA has been achieved within a normalized emittance of 0.3 mm-mrad from a Lamb-shift type source. 80% of the beam is routinely extracted 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. An 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) with good energy resolution makes TRIUMF an ideal facility for accelerating polarized protons. Depolarizing effects along the 45 m long external injection path and during the ~5000 turns in the machine were calculated and found not important, in spite of the strong non-uniform stray magnetic field in the injection path and resonances in the cyclotron. The 85% 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 mA 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. Beam line 4B, with 100 nA maximum allowable current, is equipped with a Q3 type 0.1% 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 \( ^1 \)H stripping, two simultaneous beams. The polarized beam was commissioned at the beginning of 1976 and presently accounts for 25% of the operational time.

The polarized source, shown schematically in Fig. 2, is an \( ^1 \)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 \( ^1 \)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.

The TRIUMF source is characterized by an overall length from the duoplasmatron to the argon solenoid of only 26 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 accelerating lens system, for instance, is mounted as a single unit which can only be adjusted transverse to the beam direction. The zero field crossing technique of Sonnenschein 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 Helmoltz coils reduce the cyclotron fringe field, about 20% in the zero-crossing region between solenoids 1 and 2. The spin direction can be altered by reversing the field in all three solenoids.
beam emittance. A ray trace program integrating the
wherever possible and small permanent barium-ferrite
was installed for the transport of the normal H- beam,
and its performance in terms of beam transmission has
be made empirically for maximum extracted beam polariza-
tion, 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_z component associated with changes in longitudinal
field remains essentially in one 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
a 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_z gradi-
ent 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 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
\[(g/2 - 1)y = n + \nu x \pm m\nu x\]
where \(\gamma, \alpha, \nu x, \nu y\) have the usual significance and \(n, \alpha\) and \(m\) are integers. The only intrinsic resonance
over the TRIUMF energy range occurs when \(k = m = 0, n = 2\) 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 differ-
ent 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

![Fig. 3. Longitudinal (B_x) and vertical (B_y) stray
magnetic field components along the horizontal and
vertical sections of the injection line after magnetic shielding and field
compensation with permanent magnets.](image)

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 6° 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 depolarization is negligible. The B_z
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, opti-
mized empirically for maximum extracted beam polariza-
tion, corresponded to a spin precession only a few
degrees different than calculated.

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 unpolared H- beam. From the 300 kV terminal the beam
is first transported horizontally above the
cyclotron vault through a 25 m long transport line,
and then deflected by 90° to line up with the cyclotron axis and finally, after a 20 m long vertical line,
jected into the cyclotron via a spiral inflector and a cylindrical deflector. All deflection and focusing
nents are electrostatic. The transport is com-
licated by the presence of a fairly high stray
magnetic field, varying between 5 and 100 G along the
horizontal line and between 100 and 1000 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 compen-
sate 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_y) 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. 

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harmonic of I G in the transverse component, with the worst possible phase relationship to the processing polarized ion, will cause the vertical spin component to alter from 1 to 0.95 over a resonance region of about 10 turns. Therefore, during the magnetic field shimming program the transverse second harmonic field component was measured to a precision of ±0.3% and shimmed out to be less than 2%. In this region, hence little depolarization is expected from this resonance.

Non-zero values of k 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 k ≠ 0 and m ≠ 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 a scattering from a CH2 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 pB scattering analyzing 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. 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 obtained 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.

### 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 x 1010 neutrons/s for the 200 nA proton beam. A superconducting solenoid, capable of processing the spin of 500 MeV protons through 270°, can be housed 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 np scattering in order to measure the Wolfenstein polarization transfer parameters.

Bean 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.

BLIB was recently installed to permit a second independent polarized proton experiment to run simultaneously with the BL4 experiments. A 65 cm Browne-Buechner magnetic spectrometer has been installed in the line for measuring the angular dependence of spin-dependent effects in (p,n) reactions.

### References