INITIAL OPERATING EXPERIENCE AND RECENT DEVELOPMENT ON THE TRIUMF OPTICALLY PUMPED POLARIZED H$^-$ ION SOURCE

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Summary

A polarized H$^-$ ion source using optical pumping techniques has been developed at TRIUMF. This source was used to demonstrate (on an ion source test stand) the feasibility of producing 10 μA of ~60% polarized H$^-$ ion beam in a dc mode suitable for injection into the TRIUMF cyclotron. The source has been installed in a 300 kV high voltage terminal connected to the cyclotron via a recently constructed beam transport line. A polarization of 80% is anticipated near the end of 1988 after the installation of a superconducting solenoid to the source. In this paper we describe the initial operating experience, recent developments, and the future plans for the TRIUMF optically pumped polarized ion source.

Introduction

TRIUMF has been using a Lamb-shift polarized H$^-$ ion source capable of producing up to 1 μA of 75% polarized protons on target. This current is barely adequate for a number of approved experiments. An optically pumped polarized H$^-$ ion source (OPPIS) has been under development on an ion source test stand since 1983. This is expected to produce an intense dc H$^-$ beam of ~10 μA at a polarization of ~60% and with an emittance suitable for injection into the cyclotron. With the 50% anticipated cyclotron acceptance of the dc beam, this would result in ~5 μA of polarized protons on target. The TRIUMF OPPIS is so far the only existing dc optically pumped polarized H$^-$ ion source in the world. This OPPIS has been installed in a 300 kV high voltage terminal. A beam line extension has been built to connect this terminal to the existing cyclotron injection beam line.

In principle, the TRIUMF OPPIS is based on the proposal of Anderson[1] and is as follows. Circularly polarized dye laser light tuned to the sodium D$_1$ transition is used to electron polarize ground state sodium atoms in an optically thick sodium vapour. A beam of 5 keV protons, extracted from an electron-cyclotron-resonance (ECR) ion source, passes through a neutralizing cell containing the optically pumped sodium vapour. Polarized electrons are picked up by charge exchange, forming a beam of electron spin polarized H^0 atoms. A diabatic field reversal technique, similar to that used in Lamb-shift sources, transfers the electron polarization to the nucleus of the H^0 neutral beam. Charge exchange of the H^0 beam in a second unpolarized alkali vapour cell, i.e. the negative ionizer, yields a nuclearly polarized H$^-$ beam. Figure 1 shows the layout of the TRIUMF OPPIS and the beam optics to match the 5 keV H$^-$ beam to the 300 kV accelerating column.

ECR Proton Source

A hydrogen plasma is produced in a multi-mode ECR cavity by up to 400 W absorbed cw microwave power at 28 GHz from a Varian extended interaction oscillator (model VKQ-2H35F). With a quartz liner in the ECR cavity the proton ratio, $[H^+/(H^+ + H_2^+ + H_3^+)]$, is greater than 0.75. The extraction electrodes and the sodium neutralizing cell are located in a ~12 kG axial magnetic field. The field has a mirror configuration with a minimum at 8 kG, where the hydrogen gas and the microwave power are fed in radially through the same waveguide. The proton current, extracted at an energy of 5 keV from the water-cooled acceleration-deceleration type multi-aperture (9 apertures of 2 mm diameter each) molybdenum electrodes, can routinely reach 50 mA.

Sodium Polarization and The Laser System

The sodium atoms in the neutralizing cell are polarized by circularly polarized light tuned to the D$_1$ wavelength of sodium at 589.6 nm. The polarization of the atoms depends on the polarization rate due to optical pumping and the depolarization rates due to wall relaxation, effusion of polarized atoms out of the neutralizing cell, and at higher target thickness, radiation trapping.[2,3] The stainless steel cell is 66 mm in length with water-cooled baffles at both ends of the cell to confine the sodium. Wall relaxation of the longitudinal electron spin observable $\langle S_z \rangle$ of optically pumped sodium atoms on copper, dry-film and stainless steel surfaces has been measured as a function of the applied magnetic field.[4] It was found that a copper surface became less depolarizing as the applied magnetic field was increased (Fig. 2), whereas the atoms continued to relax after a single collision on a stainless steel wall even in high field. The dry-film coated surface became so effective that we were not able to measure the very low depolarization rate, since the observed polarization relaxation was dominated by the molecular flow of the polarized sodium atoms out of the cell. However, we found that the dry-film coatings were rapidly destroyed by the incident proton beam.

With the TRIUMF OPPIS mounted on the 300 kV terminal of the cyclotron, the laser system (Fig. 3) used to polarize the sodium vapour and monitor the target thickness and polarization of the sodium vapour is located in a separate room at ground potential.

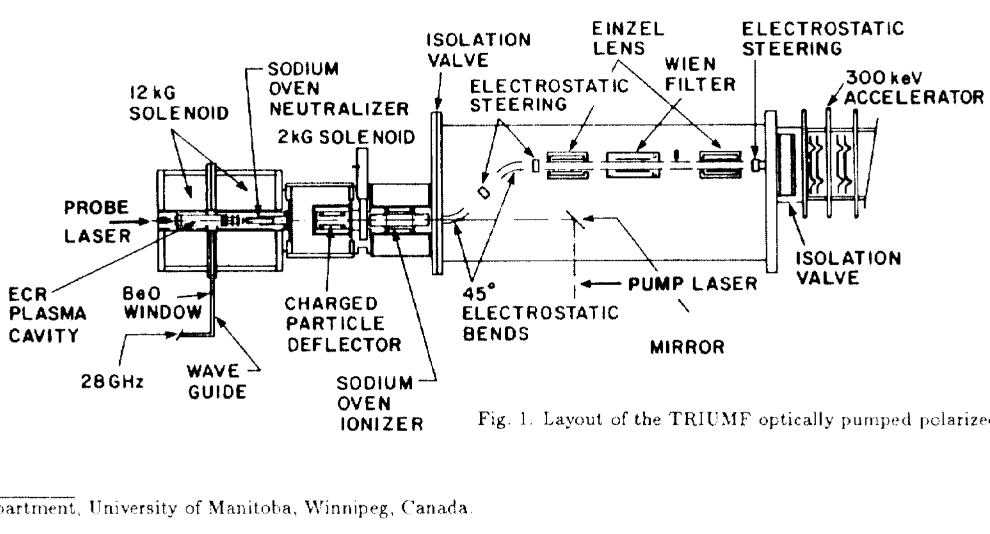

Fig. 1. Layout of the TRIUMF optically pumped polarized H$^-$ ion source.

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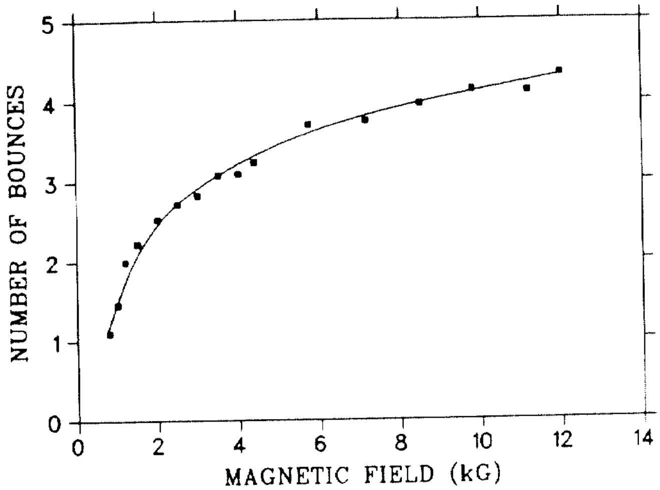

Fig. 2. Variation of mean number of non-depolarizing wall collisions N as a function of applied magnetic field for copper wall.

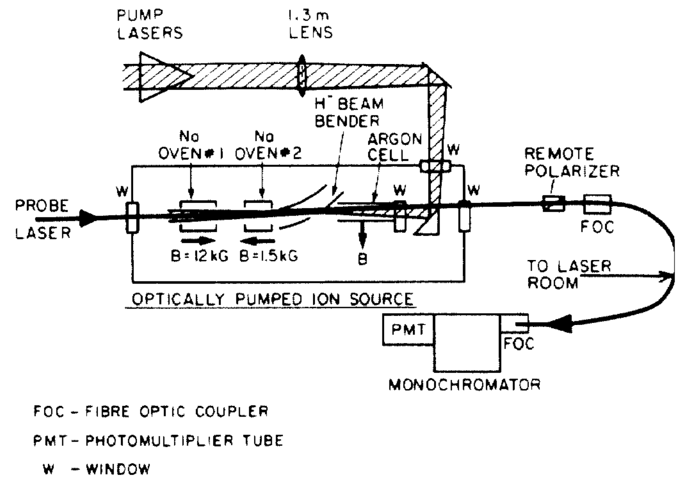

Fig. 4. Schematic drawing showing the directions of the pumping and probe laser beams entering the source.

In normal operation, three laser beams of total power of ~2 W from three Coherent CR-590 broadband dye lasers are used to optically pump the sodium vapour. Narrowing the bandwidth of each pumping beam from a nominal 30 GHz to ~6 GHz with an uncoated 0.5 mm thick intra-cavity etalon increases the spectral power density of the laser beam within the 3 GHz Doppler width of the sodium D_1 transition. The beams from the three pumping lasers combine with each other to form a single pumping beam before going through a Pockels cell, in which the helicity of the pumping beam may be flipped at 100 Hz by applying an external voltage. A beam of linearly polarized light at a wavelength of 589.3 nm (midway between the two sodium D lines) is obtained from a fourth dye laser of the same type and is used to probe the sodium vapour to determine the target thickness and the target polarization. The wavelengths of these four laser beams are individually monitored with a wavemeter and their spectral properties are measured with a spectrum analyser. A set of functional requirements to allow computer control of the laser system has been designed and both the hardware and the software have been partially implemented to the laser system.

The pumping beam polarizes the sodium vapour from the downstream direction of the source, while the probe beam enters the source from upstream (Fig. 4). The probe beam is transmitted back to the laser room by a fibre optic, where the thickness and polarization measurements on the sodium vapour are made. Also as seen in Fig. 4, a cell filled with argon gas at an average pressure of about 30 mTorr is used to prevent the H^0 neutrals, not ionized in the second alkali cell, from damaging the prism mirror. A transverse magnetic field is applied to this gas cell to eliminate any charged particles produced by charge exchange of H^0 neutrals with the argon gas in the cell.

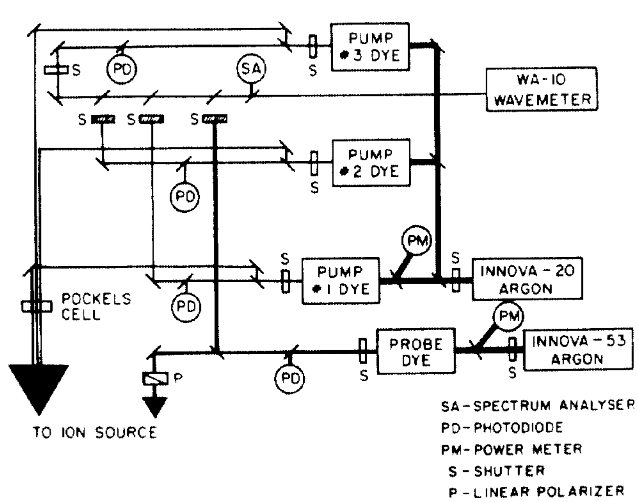

Fig. 3. The laser system employed in the TRIUMF optically pumped polarized H^- ion source.

Polarization Transfer Efficiency

A critical step in OPPIS is the transfer of polarization from the sodium atoms to the H^0 neutrals emerging from the neutralizer. We indirectly measured the parameter T defined as the ratio of electron polarization of the H^0 beam to sodium polarization, as it determines an upper limit to the nuclear polarization of the final H^- beam.

It is, in general, difficult to measure the vector polarization of protons having energy below several hundred keV. Instead, the tensor polarization P_{zz} of a deuterium beam was measured, assuming T is the same for both protons and deuterons (as the transfer is purely atomic). The asymmetric angular distribution of neutrons at 0° and 90° from the reaction ${}^3H(\vec{d},n){}^4He$ at a 50 keV deuteron energy was used to measure the tensor polarization of the D^- beam. It was found that $T = 0.62 \pm 0.09$ at a magnetic field of 12.6 kG for a deuteron beam at 5 keV energy.[5]

Theoretical calculations[6] suggest that the transfer efficiency increases with higher magnetic field strength in the sodium neutralizing cell region. We plan to replace the conventional solenoids in the neutralizer region with superconducting coils, thus increasing the magnetic field to 20–25 kG, where the polarization transfer efficiency T is at least 85%.

Beam Emittance

The emittance of the H^- beam is determined mainly by the emittance growth as the beam leaves the 1.5 kG field of the ionizer. The H^- beam emittance was measured as a function of the ionizer magnetic field using a Los Alamos type slit scanner,[7] and the results are shown in Fig. 5. The graph shows that the H^- beam has a zero field normalized emittance at the 60% contour level of 0.07π mm-mrad, which is equivalent to that of the H^0 beam accepted by the ionizer. At a 1.5 kG ionizing field, the H^- beam has an effective normalized emittance of 0.4π mm-mrad , which is about the same as the acceptance of the TRIUMF cyclotron.

The focusing elements used to transport the 5 keV H^- beam to the 300 kV accelerating column (Fig. 1) have been designed using the results of the H^- beam emittance measurements. A pair of parabolic 45° electrostatic deflectors separates out the H^- beam undergoing charge exchange in the sodium targets, and focuses the divergent H^- beam in both transverse directions, and also allows the pumping laser beam to enter the sodium neutralizer. The charge exchange

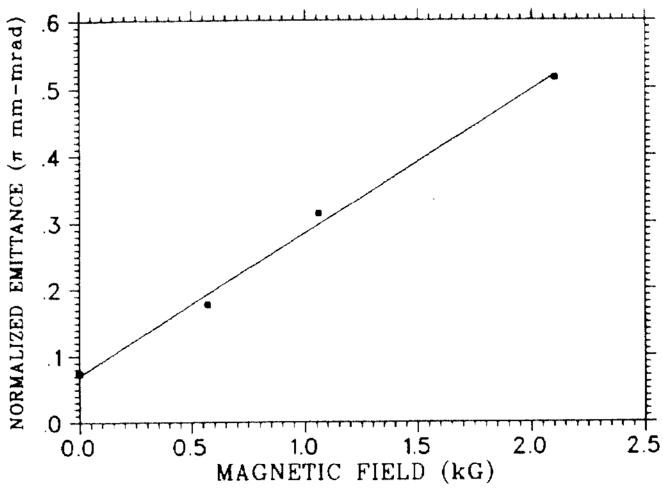

Fig. 5. Measured normalized emittance of H^- beam as a function of the ionizer magnetic field.

targets are biased at several hundred volts so that particles experiencing charge exchange in these targets can be distinguished by their energies. The electrostatic bends are set to select the specific energy which corresponds to charge exchange in the targets. Provision has been made for a Wien filter to rotate the nuclear spin of polarized H^- ions by 90° from the horizontal to the vertical plane, parallel to the magnetic field of the cyclotron. Two einzel lenses of focal lengths 7 cm and 18 cm are used to focus the H^- beam into the Wien filter and into the accelerating column. The geometries of these lenses were designed using particle tracing computer codes to give an aberration of $\leq 5\%$.

Commissioning Experience

Initial commissioning experience has shown stable operation of the source at currents up to 10 μA, and initial transmission through the injection beamline of 75%. Delivered current at 500 MeV is ~ 1 μA, limited by diagnostic probes. Running at these currents has produced a polarization at 290 MeV of 30%, after optimizing the zero field cross region in the source. Although the sodium polarization was ~80%, unpolarized background beam (believed to be due to neutralization in hydrogen) accounted for nearly one-half of the H^- beam. It is felt that this unpolarized component can be substantially reduced with improved pumping especially near the extraction lens. Optimizing the Wien filter, and biasing the charge exchange cells, would improve the polarization. Improvement in polarization is also expected from a redesigned neutralizing cell which reduces the effects of radiation trapping and uses copper walls.

Conclusion

The TRIUMF OPPIS is capable of producing ~10 μA H^- ion beam polarized at ~60% within a normalized emittance of 0.4π mm-mrad at the 60% contour level, suitable for injection into the cyclotron. Although the depolarizing effect from wall collisions using a dry-film coating is small, a problem with cw systems is the rapid destruction of the coating by the ion beam. The depolarizing effect of the copper wall, on the other hand, is reduced at high magnetic field, thus improving the performance of the neutralizer. The H^- beam current and polarization will be enhanced by using superconducting coils in the ECR and the neutralizer region. Present efforts are concentrated on optimizing the current and the polarization of the H^- beam and matching the beam to the TRIUMF cyclotron.

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