# Status of the optically pumped polarized H^- ion source at TRIUMF

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# STATUS OF THE OPTICALLY PUMPED POLARIZED $H^-$ ION SOURCE AT TRIUMF

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## ABSTRACT

An optically pumped polarized $H^-$ ion source, producing $\gtrsim$5 μA of $H^-$ current with $\gtrsim$50% polarization, has been developed at TRIUMF. The polarization transfer efficiency between sodium atoms and 5 keV deuterons was measured to be 0.62±0.09 at a magnetic field strength of 12.6 kG.

## 1. Introduction

The technique of optical pumping of a sodium vapour target on the $D_1$ transition as a means of producing nuclear polarized $H^-$ ions has been outlined by Anderson [1] and has already been described at this workshop [2]. At TRIUMF, a d.c. source using an electron-cyclotron-resonance (ECR) proton source has been under development since the last workshop. Compared to the pulsed source described by Mori at that time [3], the TRIUMF source operates at higher average power and relies on broadband optical pumping. Figure 1 shows it schematically.

## 2. ECR Proton Source

A Varian Extended Interaction Oscillator (Model VKQ-2H35F), capable of producing 1 kW cw power at 28 GHz, provides microwave power for plasma production in the multimode ECR cavity. The extraction electrodes and sodium vapour target are located in a ~12 kG, fairly uniform axial magnetic field. The field profile is a mirror configuration with a minimum near 8 kG. The microwave power is fed radially into the water-cooled plasma chamber where the magnetic field is less than the 10 kG required for resonance. Hydrogen gas is fed in through the same waveguide. With a quartz liner in the ECR cavity it is possible to obtain a proton fraction, $[H^+/(H^+ + H_2^+ H_3^+)]$ greater than 0.75.

The water-cooled extraction electrodes have not yet been optimized, although preliminary results show that a positive current density of 300 $mA/cm^2$ can be extracted through a 2 mm diameter extraction hole. At present an accel-decel lens system having 3 mm diameter apertures is in use, and plans are to install a molybdenum multi-aperture system. Proton and atomic hydrogen currents are sensitive to the magntic field strength, which is optimized using two independent power supplies. On the other hand, no significant change was observed when the sodium cell and extraction electrodes were shifted downstream 4 cms from the original configuration. Further work is planned on electrode optimization and on the magnetic field configuration.

## 3. Sodium Polarization

The sodium polarization under our conditions depends on the polarization rate due to optical pumping and the depolarization rate due to wall

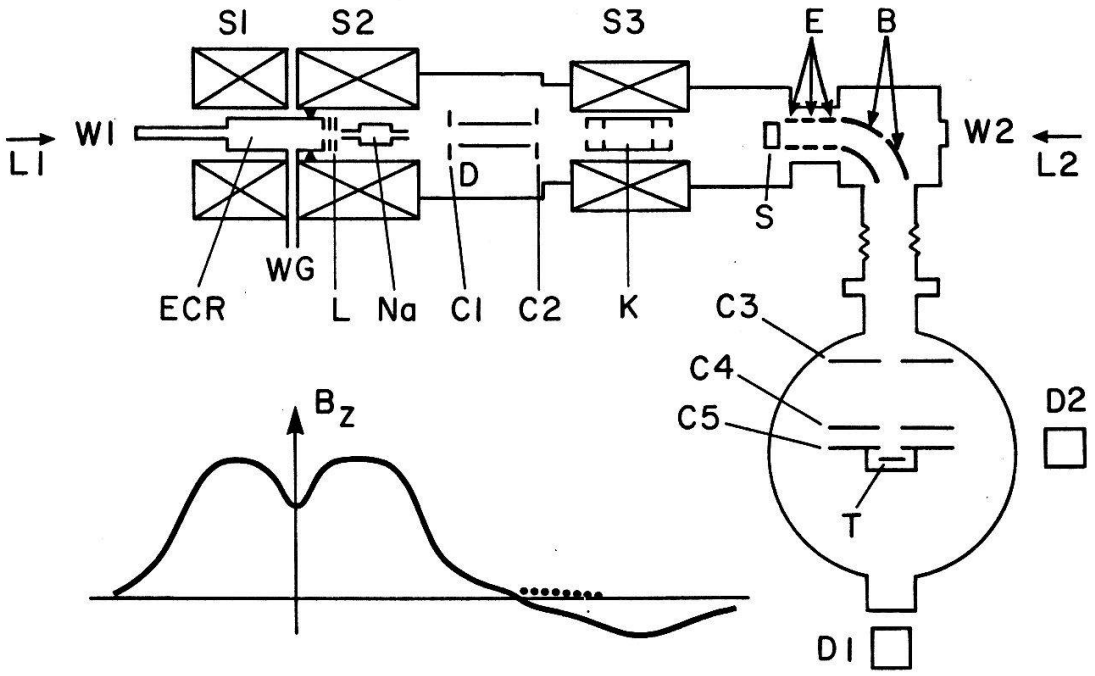


Fig. 1. Schematic of the optically pumped polarized $H^-$ ion source, including deuteron polarization measurement apparatus. The magnetic field profile along the beam axis is shown in the lower part of the diagram, where the solid line is for the $H^-$ case and the dotted line is for $D^-$. S1, S2, S3: solenoid coils; ECR: ECR cavity; WG: microwave waveguide and $H_2/D_2$ gas inlet; L: extraction electrodes; Na: sodium cell; D: charged particle deflector; C1, C2, C3, C4: grounded collimators; C5: 50 kV biased collimator and target box; K: potassium cell; S: vertical beam steering; E: Einzel lens; B: 90° inflector; W1, W2: fused silica windows; L1: pump laser; L2: probe laser; T: titanium tritide target; D1, D2: liquid scintillation counters.

collisions. The former can be increased by greater laser power, or by an improved match between the Doppler profile of the absorption transition (3.0 GHz bandwidth), and the laser bandwidth. The depolarization rate can be decreased by the use of a suitable wall material.

Polarization is measured by a Faraday rotation technique similar to that of Cornelius [4], with the difference that we use a minimum transmission method with crossed polarizers rather than measuring changes in transmitted probe intensity. A Coherent CR-590 dye laser is used for optical pumping at up to 1 W. An unstabilized Coherent CR-699 ring laser is used as a probe. The pump bandwidth is a nominal 30 GHz and that of the probe about 2 GHz. The pump beam diameter in the cell is 2 mm and that of the probe is 1 mm.

Early polarization measurements were made using a stainless steel sodium cell 12 cms long and 1.3 cms in diameter, located in a peak magnetic field of 9.6 kG, corresponding to 8.8 kG at the ends of the cell. Figure 2 shows the polarization of a target of thickness $1.7\times10^{13}$ $cm^{-2}$ for different pump powers and peak field values. Polarization increases not only with power, but also with magnetic field. The latter effect was due to the inhomogeneity of the field. Atoms in different field strengths experience different transition frequencies because of Zeeman splitting. In effect, the absorption bandwidth of the target is broadened by ~ 2 GHz for each kG

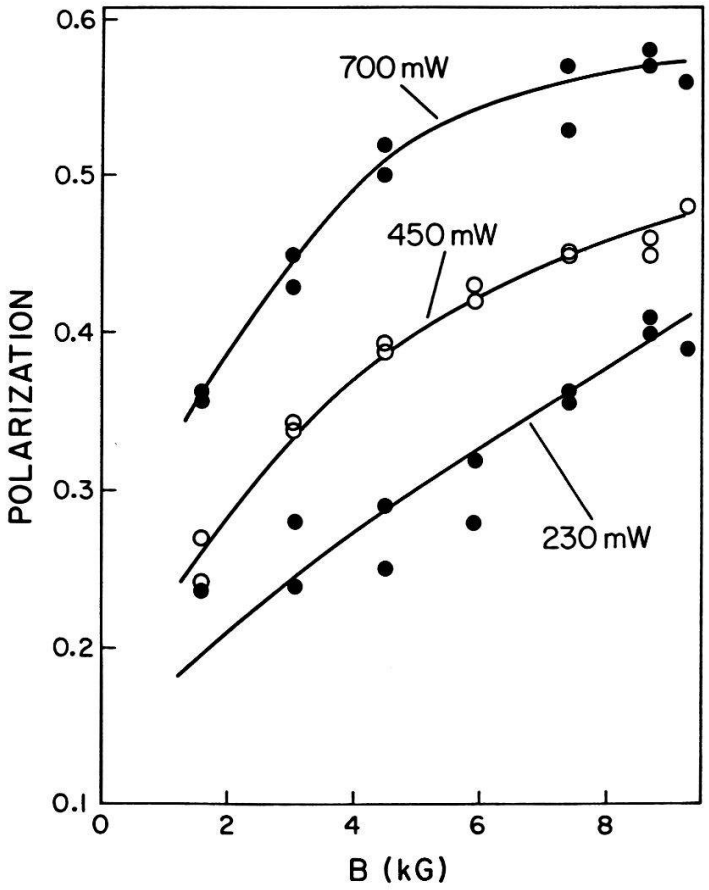


Fig. 2. Sodium polarization vs. peak magnetic field for different pump powers. Pumping was broadband (~30 GHz) on the $D_1$ line. Target thickness was $1.7\times10^{13}$ $cm^{-2}$.

variation in the field, to ~ 4.6 GHz in this case. When the cell length was shortened to 6.5 cm, reducing the variation in the field along the cell to ±1.5%, or when a single frequency pump laser was used, the dependence on field disappeared. A deliberately inhomogeneous field can be used as a means of matching the absorption profile of the sodium target to the broadband laser.

Figure 3 compares the polarization obtained using a single pumping beam and that obtained with two counter-propagating beams from the same laser. The improvement with the double beam is due to an effective doubling of the laser mode density (modes/GHz). In spite of the half power per mode, there is a net increase in polarization because of saturation effects. The broadband laser operates on many very narrow modes at any instant. Suppose one particular mode interacts with a population of atoms having velocity +v along the beam direction. By pumping from both directions, that mode will also interact with atoms having velocity -v, thus improving the laser coverage of the sodium Doppler profile. Each mode burns a hole in the absorption profile with a width approximately proportional to the square root of the power. Therefore, by increasing the effective number of modes in the above way, a net increase in laser optical pumping of the sodium atoms results.

Figure 4 illustrates the effects of a Viton wall coating (suggested by Anderson [5]), and a reduction in the pump laser bandwidth. In this case the sodium cell was copper, 7 cms long, 1.3 cms in diameter (1.0 cm with

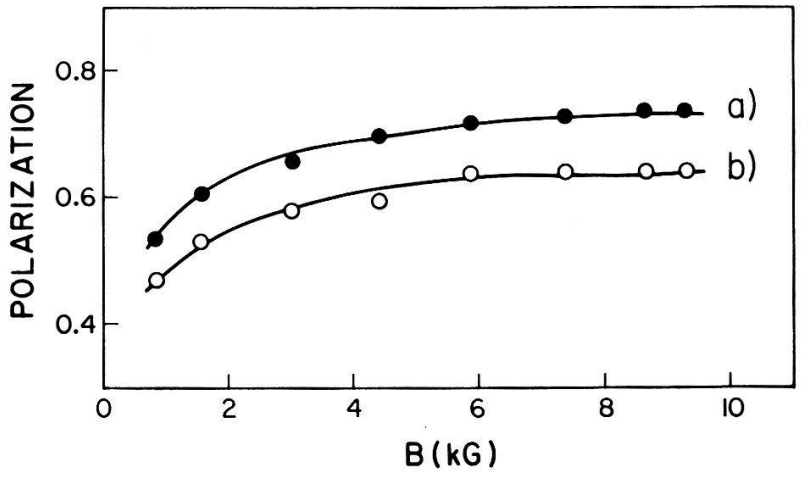


Fig. 3. Sodium polarization vs. magnetic field, sodium thickness $1.2\times10^{13}$ $cm^{-2}$, ~30 GHz pump bandwidth at 800 mW. a) counter-propagating beams, b) single beam.

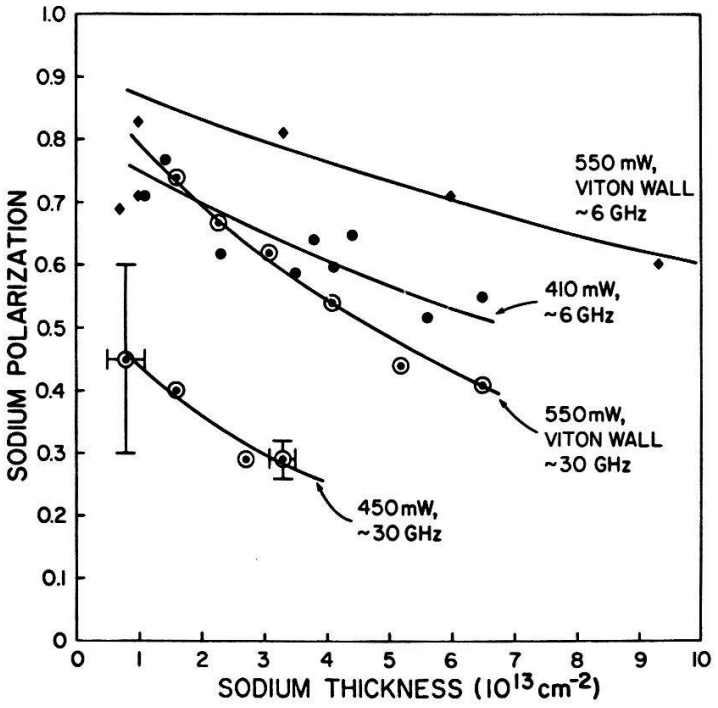


Fig. 4. Sodium polarization vs. target thickness, for different pump laser bandwidths and sodium cell wall materials.

Viton), and water-cooled copper condensation baffles were used. The bandwidth was reduced to about 6 GHz using an uncoated 0.5 mm thick intra-cavity etalon, with less than 10% reduction in laser power. Both measures greatly enhance the sodium polarization. Computer fits to the data, and a beam chopping experiment, indicate that with Viton a sodium atom undergoes 10-15 wall collisions on average before depolarizing. Also noteworthy is the absence of radiation trapping at the higher densities. The effectiveness of

Viton sheet appears to depend on its volatiles content and it was unsatisfactory for operational use. Any organic wall coating must be well protected from the ion beam, which quickly carbonized and destroyed Viton in our cell.

## 4. Polarization Transfer Efficiency

A critical step in the optically pumped source is the transfer of polarization from the sodium to the neutral hydrogen emerging from the cell. Besides preventing emittance blow-up of the proton beam when it leaves the ECR field, a high magnetic field lessens radiative depolarization of excited hydrogen atoms as they decay to the ground state [6].

We have measured T, defined as the ratio of ground state hydrogen beam polarization to sodium polarization. In practice, it is very difficult to measure the vector polarization of protons having energies below several hundred keV. We measured instead the tensor polarization $P_{zz}$ of a deuterium beam, produced in our $H^-$ source, and assumed that T is similar for both protons and deuterons, as the transfer is purely atomic. The magnetic field was modified by reducing it on axis to maximize the measured tensor polarization. A maximum 33% tensor polarization can be expected for $D^-$ ions created in a low magnetic field given an electron polarization of 100% in the deuterium atom created at high field. The anisotropy of neutrons produced in the $^3H(\vec{d},n)^4He$ reaction at 55 keV was measured in the scattering chamber shown in Fig. 1.

Our result of $T=0.62\pm0.09$ at a magnetic field of 12.6 kG and deuteron beam energy of 5.0 keV is similar to other measurements [7,8] and about 0.20 below theoretical estimates [6]. We consider it an under-estimate for two reasons. First, the measured sodium polarization is probably overestimated, because the pump laser beam diameter is less than that of the ion beam, and the sodium polarization is a maximum in the pumped region and decreases towards the cell walls. The probe laser intersects the pump laser in the cell and therefore measures the region having maximum polarization. That leads to an under-estimate of T. Second, there is a neutral beam background originating between the extraction electrodes and the sodium cell, from the reaction

$$D^+ + D_2 \rightarrow D^o + \ldots .$$

Although the neutral background was measured with no sodium vapour present, and this background was corrected for when T was calculated, it appears that the background increases by an unknown amount after introducing sodium vapour. Evidence for this was found both at KEK and TRIUMF; the $D^+$ beam intensity leaving the sodium cell increases by a factor of two when the sodium thickness rises from zero to $8\times10^{13}$ $cm^{-2}$, possibly due to different space charge neutralization conditions. Any increase of $D^+$ entering the cell would increase the background and lead to a further under-estimation of T.

## 5. Potassium Cell

Neutral hydrogen produced in the sodium cell picks up another (unpolarized) electron in a second alkali cell to become nuclear polarized $H^-$. Ideally one uses sodium here too because of its high $H^-$ equilibrium yield (~7%) [9]. We presently use potassium with its ~3% yield because of the lower oven temperature required (~220°C), and intend to switch to sodium. Figure 5 is a drawing of the cell, which produces potassium vapour of high

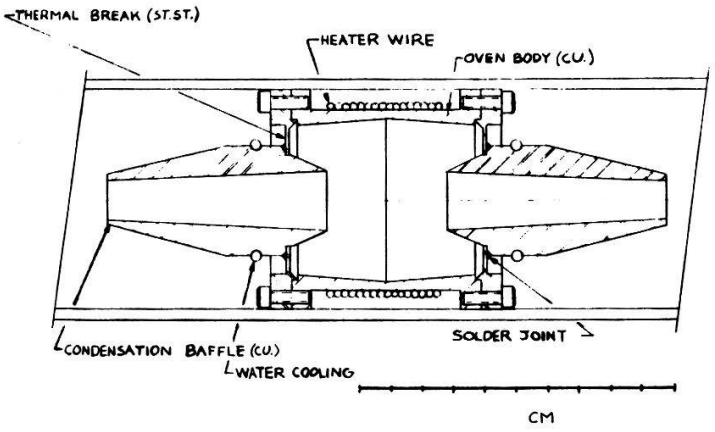


Fig. 5. Potassium charge exchange cell.

thickness ($\sim 10^{15}$ $cm^{-2}$) and recirculates it by means of water-cooled condensation baffles kept at 95°C. The oven body and baffles are copper, and a thermal break between them is provided by a stainless steel annulus 0.8 mm thick. The inlet and outlet apertures are 1.2 cm in diameter, and the effective cell length is ~6 cm.

## 6. Beam Current

Beam has been extracted using various electrode configurations, both single and multi-aperture. The highest current has been obtained using a 6 mm diameter multi-aperture design. Typically in the latter case $\gtrsim$6 mA of positive current was transmitted by the 8 mm aperture of the sodium cell downstream cooling baffle, given an ECR cavity loading current of ~50 mA. Upon introducing sodium vapour (thickness $\sim 5\times 10^{13}$ $cm^{-2}$) a neutral hydrogen atom current of ~220 μA equivalent was measured downstream of the potassium cell, both by secondary emission and calorimetry. The divergence of the neutral beam was limited by the potassium cell aperture to 19 mrad. The neutral beam divergence measured immediately downstream of the sodium cell was 65 mrad (with 3 mm extraction electrode apertures). Given a charge exchange cross-section of $6\times 10^{-15}$ $cm^2$ in the sodium cell, a neutral hydrogen atom current of $\gtrsim$1.5 mA equivalent should emerge from the sodium cell, and $\gtrsim 1.5 \times (19/65)^2 = 0.13$ mA from the second cell, consistent within a factor of two with the measurement quoted above.

An $H^-$ current of ~7 μA is expected if the equilibrium yield of $H^-$ is 3% in potassium. Neutral beam interference has hampered reliable direct measurements of $H^-$ current, although 310 nA of $D^-$ current was measured in the tritium target chamber, after the $D^-$ passed through a 2.5 cm diameter Einzel lens and electrostatic inflector plates which removed the neutral component. However, the Einzel lens should be ~3x larger in diameter and needs to be moved adjacent to the exit of the potassium cell exit to provide good beam optics.

The emittance of the $H^-$ beam is determined mainly by the emittance growth as the beam leaves the 2 kG field of the potassium cell. We are measuring the emittance of the $H^-$ beam and intend to investigate how it varies with the applied magnetic field.

## 7. Conclusion and Further Developments

The TRIUMF source produces $H^-$ currents of $\gtrsim$5 μA with a nuclear polarization of $\gtrsim$50%, demonstrating the feasibility of a d.c. optically pumped source. We expect an immediate factor of two improvement in intensity by using sodium in the second charge exchange cell. Polarization can be improved by increasing the laser power, by using the technique of Zeeman broadening of the target absorption profile, and possibly by bi-directional pumping. A new sodium cell has been built that is designed to protect wall coatings, and work is planned on investigating the effects of space charge neutralization and emittance degradation between the electrodes and the sodium cell. Finally, the distance between the two charge exchange cells will be shortened, thus increasing the neutral beam transmission.

Plans are to install the operational source by early 1987.

## 8. Acknowledgements

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