

STATUS OF THE TRIUMF OPTICALLY PUMPED POLARIZED H⁻ ION SOURCE

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ABSTRACT

The TRIUMF optically pumped polarized H⁻ ion source has been installed in a 300 keV high voltage platform connected by a 45 m beam transport line to the cyclotron. Several different extraction electrode systems have been tested in the electron cyclotron resonance (ECR) ion source generating the initial proton beam. Beam transport calculations for the initial section of the source demonstrate that the beam transport depends strongly on the degree of space charge compensation. H⁻ currents of up to 8 μA at a neutralizer Na thickness of 5×10^{13} atoms cm^{-2} have been transported into the 300 keV beam line. A polarized H⁻ beam has been accelerated in the cyclotron and a proton polarization of up to 50% has been achieved. The installation of a superconducting solenoid for further improving the source performance is planned for this summer.

1. INTRODUCTION

Since the proposal by Anderson¹⁾ to use electron transfer from optically pumped sodium to obtain polarized proton beams, substantial progress has been reported²⁻⁴⁾ in the development of optically pumped polarized ion sources (OPPIS). In particular, H⁻ peak currents of 30 μA with proton polarizations of over 50% have been reported for a low duty cycle source.⁴⁾

However, in each of the sources reported the achieved H⁻ currents compared to the initial proton currents are far lower than previously expected from the well-known charge exchange cross-sections (1-5% of predictions based on these cross-sections). In addition, the proton beam polarizations stay below the theoretically calculated values. Some reasons for both problems are dealt with in this paper.

The principle of operation of an OPPIS has been reported elsewhere.²⁾ In short, as displayed in Fig. 1 for the TRIUMF source, a high current proton beam (5 keV) is

produced by an ECR source in the same magnetic field in which the first neutralizing Na-cell is placed. The Na is optically pumped by dye lasers tuned to appropriate frequencies. By electron exchange the protons are neutralized and drift out of the magnetic field through a zero/Sona crossing into an opposing magnetic field about 1/10th as strong. Here the neutral H⁰ beam encounters another Na cell where by electron capture it becomes the final H⁻ beam, which is further transported, accelerated (300 keV) and injected into the 500 MeV TRIUMF cyclotron. In the 300 keV injection line the spin of the proton is rotated by a Wien filter into a transverse direction.

Since the TRIUMF cyclotron is driven in a cw mode, the TRIUMF OPPIS operates continuously, which leads to specific problems reported below.

2. BEAM PROPERTIES

2.2 Transport and current

The beam transport properties of the OPPIS ion beam through two magnetic fields and two corresponding charge exchanges are not completely understood. To help relieve this situation a beam transport program has been developed which at present traces particles through the first magnetic field and the neutralizer to the point of entry into the second Na cell. Plasma sheath calculations in this program have been performed by tracing ions of a given (but unknown, assumed 20 eV) temperature in the extraction region and choosing an equipotential surface matching the penetration of the electrons into the extraction field. From there the ions are transported, as shown in Fig. 2 for a 2 mm extraction hole, and totally neutralized later on. For this particular case, taking charge exchange cross sections into account, Fig. 2 represents about 0.5 μA of H⁻ beam obtained for each mA of drawn proton current into the acceptance of the second Na cell (diam 15 mm).

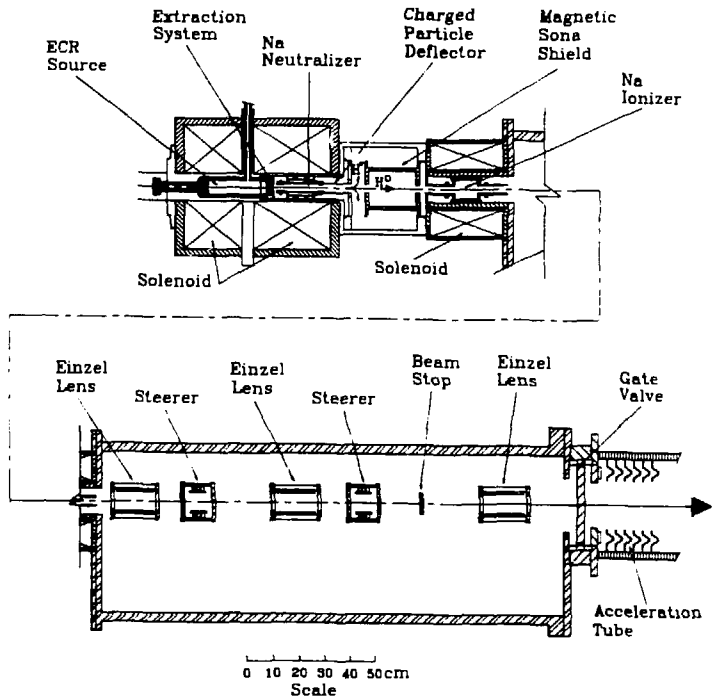


Fig. 1. The present TRIUMF optically pumped polarized ion source (OPPIS).

However, a back integration of the trace charge distribution reveals that the beam transport is highly dominated by space charge forces. In fact, using currents observed demonstrates that the space charge fields are stronger than the given static, boundary ones obtained by the code RELAX available at TRIUMF.⁵⁾ Thus it can be concluded that the currents observed are only feasible due to the fact that the space charge in the extraction region is highly compensated.

The source is on the same axis as the acceleration tube. Three einzel lenses (diam 5 cm) transport the beam over about 1 m and match it into the accelerating section. Two pairs of (x/y) steerers provide additional control. The number and the position of the einzel lenses were calculated using the first order beam transport program SPEAM.⁶⁾ Further optimization was experimentally achieved by slightly changing the lens positions. The emittance of the H^- beam was varied by a factor of six by changing the ionizer magnetic field to test the transmission through this part of the beam line. No intensity changes after the 300 kV acceleration were noticed after proper tuning, indicating little loss in this section of the beam line even at the highest emittance ionizer magnetic field.

2.2 Experimental Results

The beam transport calculations indicate that the amount of obtainable H^- beam is dominated by the way in which space charge is compensated throughout the extraction system, as well as in the first Na cell. Experimental indications for this are: 1) The current drawn from the 5 kV supply generally increases when the Na neutralizer cell contains a measurable Na density. It is assumed the current drawn is mainly proton current. 2) The proton current drawn does not follow a Child-Langmuir relation, but rather rises steeply at low voltages (up to about 100 V) to a nearly constant value at higher voltages. Since the Child-Langmuir relation is derived from the equivalence of the space charge field with the electrical field at the plasma sheath, such a sudden rise in current indicates a small space charge field. 3) Biasing the first Na cell with a low voltage and drawing large negative currents increases the final H^- current available. Electrons seem to be pumped this way into the ion beam. 4) Biasing the second electrode in the extraction system to about -200 V increases the final H^- current 6x preventing electrons outside the extraction region from being driven into the ECR source.

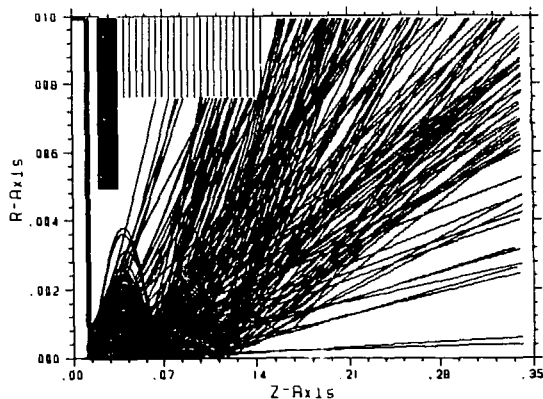


Fig. 2. Ion beam transport out of a 2 mm diameter extraction hole with no space charge calculation involved. The figure shows the rotation symmetry axis z (beam propagation) and the radius r in meters. The beam is extracted at the 1 cm position with a potential of 5000 V, passes an electrode of -300 V (1.2 cm) and enters a sodium cell at ground potential at 2 cm. Between 2 cm and 14.1 cm the beam is completely neutralized. The vertical lines in the drawing represent physical boundaries. The magnetic field is 1.2 T. 175 trajectories are displayed.

Several electrode systems have been tested, including multiple round holes, slits and single holes. Large area single hole electrodes seem to be inferior both experimentally as well as theoretically due to their sensitivity to beam blow up caused by radial space charge forces; multiple hole electrodes as well as slit systems gave better results due to higher radially focussing electrical forces present during initial acceleration. The H^- current achieved scaled with the extraction area. Typically for a 9 hole extraction system with 2 mm diameter holes at 50 mA drawn proton current and a neutralizer Na thickness of $5 \times 10^{13} \text{ cm}^{-2}$, an H^- beam of 6.5 μA current before the 300 kV acceleration stage can be achieved; for a slit system with slightly larger area 8 μA under similar conditions can be obtained. Increasing the extracted proton current to 120 mA should yield an H^- current of 14 μA under similar conditions. About one third of this current is fully accelerated in the cyclotron.

The efficiency of the RF cavity (28 GHz) in ionizing hydrogen is in the range of 30-80% for the operational gas flows (1-2 s-ccm).

Large fractions of the beam power are dumped into the first Na cell, causing the Na density in the cell to be coupled to the proton beam current. At present a heating/air cooling system applied to a copper pipe inserted into the Na reservoir allows for some control. However, further improvements are under way.

2.3 Polarization

A layout of the laser system is shown in Fig. 3. The Na density in the two cells is measured with the help of a probe laser tuned between the Na D lines, using Faraday rotation in the magnetic fields. The electronic polarization of the Na in the neutralizer cell is also determined by this method.³⁾

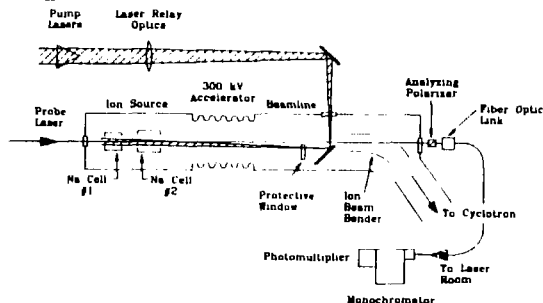


Fig. 3. Laser paths through the TRIUMF OPPS. The pump laser beams are guided over the 300 kV terminal and injected into the source at an angle of about 2 mrad to the ion beam axis.

Three broadband dye pump lasers are used to optically pump sodium with inserted power levels of about 2 W. Na polarization of up to 87% at a Na thickness of $2.9 \times 10^{13} \text{ cm}^{-2}$ has been achieved.⁹⁾ For higher Na thicknesses radiation trapping keeps the electronic polarization below what is required.¹⁰⁾

The nuclear polarization of the proton beam has been determined by accelerating the H^- beam through the TRIUMF cyclotron to 230 MeV and using the TRIUMF in-beam polarimeter (beam 4a (Ref. 11)). Proton polarizations of up to 53% for a single 3.5 mm hole extraction system and up to 43% for larger area multiple hole systems have been obtained.

The dependence of the proton polarization on several parameters has been determined and optimized (e.g. Wien filter fields and rotational angles, H^+ deflection). An observed doubling of the proton polarization as the magnetic field of the ionizer is raised from zero to 1.5 kG shows that the Sona spin transfer works properly.

By comparing the nuclear spin of the proton to the electronic polarization of the sodium, the spin transfer coefficients can be deduced, as shown in Fig. 4. The drop off of this coefficient at low Na densities can be attributed to a beam component which is neutralized either outside the polarized Na region or by unpolarized H_2 molecules. The data show a large scattering probably due to a beam position dependency of the proton in-beam polarimeter and errors in the determination of the electronic polarization. Statistical fluctuations due to the polarimeter counting rates are insignificant. The cross-section for one possible source of the background beam, charge exchange of the protons with molecular hydrogen, is only a factor 6-8

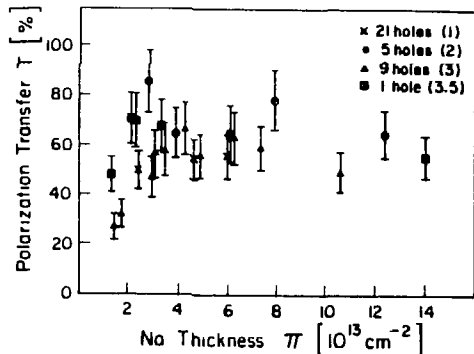


Fig. 4. Measured polarization transfer T (ratio of proton polarization/Na polarization) for different neutralizer thicknesses π and different extraction systems.

lower than the charge exchange with sodium. From this data the observed transfer coefficient is estimated to be about 60% (less than the predicted 75% (Ref. 12)).

The reasons for the lower measured transfer may include charge exchange in Na not polarized by the lasers, either due to incomplete illumination effects or to Na in off-laser-resonance magnetic fields, as well as depolarizing effects through the rest of the beam transport system including the cyclotron.

Another method of determining the proton polarization is under development. The H^- current produced by double charge exchange in the neutralizing cell depends on the electronic polarization of both the sodium and the hydrogen according to¹³⁾

$$(I_{\text{off}} - I_{\text{on}}) I_{\text{off}} = P_{\text{Na}} P_{\text{H}} \quad (1)$$

where I_{off} is the H^- current without optical pumping, I_{on} is the H^- current with optical pumping, P_{Na} is the electronic polarization of the Na and P_{H} is the electronic polarization of the hydrogen, allowing the hydrogen polarization to be determined. It is assumed that the total electronic spin of the hydrogen is transferred to the nucleus. First measurements with this method yield results similar to those obtained with the in-beam polarimeter.

3. CONCLUSION AND OUTLOOK

As the TRIUMF optically pumped polarized ion source is about to reach its operational stage, several major steps in performance and understanding have been achieved. However, further improvements in current as well as proton polarization are desirable.

The brightness of the source has to be increased by better extraction systems. At present this seems to mean an increase in the actual extraction area without increasing the initial beam size. Beyond this, further improvements may be difficult to achieve, since the beam is already operating under extreme space charge limited conditions.

To improve the polarization transfer it is planned this summer to install a 2.5 T superconducting magnet. The large borehole (15 cm) of the superconducting magnet will also allow for better vacuum pumping, thus reducing the unpolarized background beam. In addition, a longer neutralizer Na cell will reduce radiation trapping, allowing thicker Na targets and as a consequence higher H^- currents. Further attention will be given to depolarizing effects and the electron transfer process.

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