Operational Experience with the TRIUMF Optically Pumped Polarized H^- Ion Source

P.W. Schmor, L. Buchmann, K. Jayamanna, C.D.P. Levy, M. McDonald, and R. Ruegg
TRIUMF, 4004 Wesbrook Mall, Vancouver, B.C., Canada V6T 2A3

Abstract

The initial goal of a polarized proton beam extracted from the TRIUMF cyclotron, having a current of 5 μA with 60% polarization, has been achieved with the development of the optically pumped polarized H^- ion source. This beam is now being used to produce an intense secondary beam of polarized neutrons for the TRIUMF experimental program. Much of the recent development effort has addressed the reliability requirements for routine operation. This paper describes the results with emphasis on the laser stabilization subsystem, the modifications to the electron cyclotron resonance proton ion source (ECRIS), the sodium charge exchange cells and the development of a low energy polarimeter. Also discussed are the developments which should lead to a higher polarization.

I. Introduction

TRIUMF has developed a 100% duty cycle, high intensity, optically-pumped, polarized ion source which now produces 5 μA of 60% polarized beam after acceleration to 200 MeV in the cyclotron [1]. The polarization is slightly less at 500 MeV due to two depolarizing resonances which are crossed during acceleration.

The polarized H^- beam is transported at 300 keV, approximately 50 m from the source to the cyclotron, through a beam line which uses only electrostatic focusing elements. The H^- beam is injected into the median plane of the cyclotron with an electrostatic spiral inflector. Protons are extracted from the cyclotron, by stripping the two electrons from the accelerated H^- ions, at energies which can be varied from 180 to 500 MeV, independently, into two beam lines. A Wien filter in the 300 keV beam transport line is used to rotate the spin direction from the horizontal into the vertical; i.e., aligned with the cyclotron magnetic field in order to preserve the polarization during acceleration.

The optically pumped polarized ion source (OPPIS) is based on a proposal by Anderson [2]. A hydrogen plasma is created within an electron-cyclotron-resonance (ECR) cavity by 28 GHz microwave ionization in an axial magnetic field. The typical absorbed power is 850 W. Protons are extracted from the ECR cavity plasma and are directed, at 5 keV, through a polarized sodium vapour where a fraction of the protons are neutralized by picking up a polarized electron. The polarization is induced by optical pumping of the sodium vapour with laser light tuned to the sodium D_1 transition at 590 nm. Most of the neutralized hydrogen is created in an excited atomic state and it is necessary to use the high magnetic field of a superconducting solenoid to preserve the polarization as the hydrogen atom decays to the ground state. An electrostatic deflector immediately downstream of the neutralizer removes all charged species from the beam which have passed through the sodium. The axial magnetic field reverses sign, between the neutralizer and a subsequent negative ionizer, in order to enhance the nuclear polarization through a Sona type transition. The sodium vapour of the ionizer produces an equilibrium fraction converting about 7% of the atomic hydrogen beam into an H^- ion beam. This negative ion beam is accelerated to 300 keV and transported to the cyclotron.

II. Developments

A. Extraction Electrodes

Several extraction electrode systems for the ECRIS were investigated. The best results were obtained from a system of three electrodes, consisting of 1 mm thick molybdenum disks spaced 1 mm apart, with an hexagonal array of 1 mm diameter holes. The electrodes are powered in an accel-accel mode with the first electrode at the cavity potential, the second electrode about 1 kV below the cavity potential and the final electrode at ground (or slightly negative) potential.

B. Neutralizer

The sodium neutralizer cell consists of three thermally isolated components; i.e., an entrance snout, a vapour canal and a sodium reservoir. The canal and reservoir are independently heated. The sodium thickness (usually about 3 to $5 \cdot 10^{13}$ atoms/cm^2) can be maintained reliably stable over periods of a week, with or without beam. While the optically pumped region of the canal is roughly only 1 cm in diameter, the actual canal diameter is, in fact, 3 cm in order to improve vacuum pumping of hydrogen from the canal and thereby reduce the probability of proton neutralization from the unpolarized hydrogen (and consequently increase proton polarization).

C. Ionizer

The ionizer cell, which also uses sodium vapour, is about 8 cm long and has 1.6 cm diameter condensation canals, both at the entrance and exit to the cell. With the higher sodium thickness (typically 40 to $80 \cdot 10^{13}$ atom/cm^2) in the ionizer, it is necessary to recirculate the sodium in order to achieve a reasonable operating period for each sodium charge and to avoid frequent maintenance of the electrostatic elements.

0-7803-0135-8/91$01.00 ©IEEE

C. Laser System

Two Coherent CR-599 dye lasers, which have been modified with 0.5 mm thick solid etalons to reduce the bandwidth to 3 GHz (FWHM), now each provide approximately 3 W in stable operation. Dye laser power up to 5 W each has been attained with argon pump powers of 25 W, although the stability was poor. The modifications of the dye lasers to increase the output power included: the installation of higher output transmission mirrors, the addition of 20% water to the ethylene glycol solvent and continuous charcoal filtering, improved cooling of the dye solution, the addition of water-cooled beam blocks inside the laser cavities, and higher dye flow rates.

The divergent beams from the dye lasers are brought by a relay lens assembly to a 1 mm diameter waist near a mirror in the beam line. A small diameter beam at that location is important as it allows the laser beams to be brought as close as possible to the source axis without obstructing the ion beam and enter the source at an angle only 3 mrad from parallel to the source axis. Each beam expands to approximately fill the central 1 cm of the neutralizer canal. To prevent damage to the mirror by the 5 keV neutrals and sodium escaping from the ionizer, it is protected by a movable microscope slide.

The laser frequency is in resonance with the Zeeman shifted D_1 absorption line in the neutralizer. The proton polarization is reversed by changing the helicity of the light and simultaneously changing the laser frequency, by tilting the etalon, to account for the Zeeman shift. The laser frequency is stabilized with an analog feedback signal derived from a scanning spectrum analyzer that samples a small fraction of the laser output. The correction signal is applied to the etalon galvanometer. The spectrum analyzers have a reference drift of about 0.3 GHz over a 24 hour period, when hermetically sealed. The laser power must also be stabilized in order to maintain the laser frequency over long periods. As the power drops, due to drifts in the alignment of the birefringent filter (BRF), the laser will begin to oscillate on an adjacent etalon peak which is separated in frequency by 200 GHz. The laser power is stabilized by a computer system which samples the laser power and makes adjustments to the BRF. The system is described in a separate paper in these proceedings [3].

D. Polarimeter

A nuclear polarimeter based on the low energy analyzing power of the $^6Li(p,^3He)\alpha$ reaction has been developed. Although the polarimeter is used at 300 keV with current up to 2 μA, it has, in fact, been shown to work at energies as low as 200 keV [4]. The analyzing power for detecting ^3He at 130° is approximately 0.21 at 300 keV. With a current of 2 μA of H^-, 1% statistics are achieved in about 3 minutes. A second polarimeter based on selective quenching of the metastable 2S state of hydrogen [5] has been used for source polarization studies but this device can not easily be adapted to co-exist within the operational demands of polarized beam production.

III. Operational Experience

A. Source Characteristics

The H^- current from the source depends on a number of parameters such as the thicknesses of vapour in both the ionizer and the neutralizer as well as the proton current drawn from the ECR plasma. The current can easily be changed, albeit at the expense of the polarization, by changing the thickness of the neutralizer vapour. There is a substantial unpolarized component in the beam which originates from proton neutralization by hydrogen upstream of the charge deflection plates. This unpolarized background is nearly independent of the sodium thickness and its relative contribution to the total H^- becomes less as the sodium neutralizer vapour thickness is increased. However, the polarization of the sodium vapour drops as the thickness is increased, due to radiation trapping and to the limited number photons from the dye lasers. As a result, there is an optimal sodium thickness of 3 to $5{\cdot}10^{13}$ atoms/cm^2 which gives the maximum proton polarization.

With a 31 hole extraction electrode system, a proton current of 22 mA is extracted from the plasma. With the neutralizer at $5.1{\cdot}10^{13}$ atom/cm^2 and the ionizer at $55{\cdot}10^{13}$ atoms/cm^2, there is about 35 μA on the first beam stop in the 300 keV beam line and 9 μA extracted from the cyclotron. By reducing the hydrogen fed to the ECRIS, to reduce the extracted current from the cyclotron to 5 μA and consequently improving the polarization slightly because of the reduced unpolarized background, the polarization (at 200 MeV) as measured on a polarimeter in an external beam line is 60.9%.

B. Source Emittance

The effective emittance of the H^- beam leaving the source is primarily determined by the ionizer [6]. The total change in emittance, in the transverse plane, as the beam passes through the ionizer is given by, $\delta\epsilon = \pi r^2/2r_c$, where r_c is the radius of the ion orbit in the peak magnetic field of the ionizer and r is the radius of the beam envelope which in this case is equal to the radius of the ionizer canal condenser. Beam transmission between the source and the cyclotron inflector is about 35% for a 61 hole extraction electrode to 45% for a 31 hole array which is consistent with a normalized source emittance of 0.7 π·mm·mrad for the 61 hole system.

C. Stability

A typical polarized proton user requests a few percent stability in the current and polarization over periods of weeks. At the source, this implies stability criteria to: a) the proton current from the ECRIS, b) the sodium neutralizer thickness, c) the sodium ionizer thickness, d) the laser power into the neutralizer, and e) the laser frequency.

The proton current, from the ECRIS, remains remarkably stable for periods of 24 hours and then only requires small changes to the hydrogen flow and to the voltage on the second electrode; processes which require only a few minutes to complete and are transparent to the user. After the first few hours, to reach thermal equilibrium, the sodium thicknesses in the neutralizer and the ionizer remain stable without further adjustment for periods of one week. The laser power into the neutralizer gradually decreases due to deposits on the microscope slide which is upstream of the beam-line mirror. The slide must regularly be moved to insert clean segments and ensure high laser transmission. The rate of slide movement (typically about once per day) depends on the quality of the vacuum around the slide. This procedure requires a negligible 5 minute beam interruption. In addition, approximately once per week the slide must be replaced; a procedure which shuts the beam off for a 2 to 3 hour period.

Since most experiments require that the proton spin regularly be flipped, it is necessary to quickly restabilize the lasers after each spin flip (84 GHz frequency shift). To achieve this rapid restabilization, the BRF is kept in a position where its transmission peak is midway between the optimum positions of the two frequencies. The resulting 10% loss in laser power is acceptable. The laser power stabilization system is programmed to keep the laser power roughly equal in both states. This technique works for spin flip rates up to once per minute. Gating the power measurements should allow the rates to be increased. Spin flip rates are limited to 1 Hz if only the laser frequency is stabilized and to about 10 Hz with no stabilization. The dye lasers are designed to permit a more rapid frequency switching, eventually up to 100 Hz. The etalon has a measured mechanical response time of 1 ms. The laser system is still not fully automated and requires periodic manual intervention. Nevertheless, the ion source has, recently, operated flawlessly for a continuous 290 hour experimental run.

IV. Future Planned Developments

A. Optical Pumping

The optical pumping needs to be improved to yield a proton polarization beyond the present 60% maximum. To achieve this goal, the dye lasers are now being replaced with inherently more stable titanium sapphire lasers. In addition the sodium neutralizer is being replaced with a rubidium neutralizer. This change should simplify and improve the polarization stability task. In addition, a higher nuclear polarization is expected for several reasons. The maximum output power of each titanium sapphire laser exceeds that from the modified dye lasers. Moreover since rubidium is pumped at 795 nm (compared to 590 nm for sodium), the optical pumping rates are higher as a result of the 33% more photons per watt. The major loss of polarization in the neutralizer is due to the wall depolarization rate and this rate will be less with the slower velocity (lower temperature, higher mass) rubidium atoms. Finally, rubidium has a wider absorption bandwidth than sodium and as a result there is less radiation trapping (therefore higher ultimate polarization) at a given neutralizer thickness. These factors should allow thicker targets to be more highly polarized, leading to relatively less unpolarized background and higher nuclear polarization. The charge exchange cross sections are similar for both rubidium and sodium. These changes to OPPIS are expected to be completed prior to an experimental run in September 1991.

B. Polarimeter

A more compact version of the 300 keV polarimeter is being installed. It incorporates somewhat larger solid angles and includes two (angular) channels of observation (at about 100° and 140°). The target ladder and the associated beam collimator are retractable so that the proton beam can be transmitted, without additional losses, into the TRIUMF cyclotron. A cryopump is mounted close to the polarimeter target, to ensure a good clean vacuum in the region and thus reduce the amount of (lifetime-limiting) deposits on the target.

C. Spin Exchange

The source conversion from sodium to rubidium is the first step of a planned study to investigate the feasibility of using spin exchange rather than charge exchange to establish the polarized atomic hydrogen beam [7]. The higher current from this type of ion source could substantially increase the beam availability to TRIUMF polarized users.

V. References

[1] L. Buchmann, K. Jayamanna, C.D.P. Levy, M. McDonald, R. Ruegg, P.W. Schmor, A. Belov, V.G. Polushkin, A.N. Zelenskii, "A DC Optically Pumped, Polarized Ion Source", Nucl. Inst. Meth., in press, 1991.

[2] L.W. Anderson, "Optically Pumped Electron Spin Polarized Targets for use in the Production of Polarized Ion Beams", Nucl. Inst. Meth., 167, pp. 363-370, 1979.

[3] S. Sarkar, C.D.P. Levy, "Laser Power Stabilization in the TRIUMF Optically Pumped Polarized H^- Ion Source", these proceedings.

[4] L. Buchmann, "A Proton Polarimeter for Beam Energies Below 300 keV", Nucl. Inst. Meth., in press, 1991.

[5] A.N. Zelenskii, S.A. Kokhanovskii, V.M. Lobashev, V.G. Polushkin, "A Laser Source of Polarized Protons and H^- Ions", Nucl. Inst. Meth., A245, pp. 223-229, 1986.

[6] W.M. Law, C.D.P. Levy, P.W. Schmor, J. Uegaki, "Emittance Growth due to Hydrogen Ionisation by Charge Exchange in a Solenoid", Nucl. Inst. Meth., A263, pp. 537-539, 1988.

[7] A.N. Zelenskii, S.A. Kokhanovskii, V.G. Polushkin, K.N. Vishnevskii, "Investigation of Spin-Exchange Polarized Ion Source", in *Proceedings of the International Workshop on Polarized Ion Sources and Polarized Gas Jets*, KEK, Tsukuba, Japan, February 1990, pp.310-316.