HIGH INTENSITY SOURCES OF POLARIZED PROTONS

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Summary

The capabilities and future possibilities of intense polarized proton sources are summarized. The best Lamb-shift sources have achieved ~4 μA of $\vec{H}^-$. Atomic sources have achieved 6 μA $\vec{H}^-$ dc (30 μA pulsed) and 125 μA $\vec{H}^+$ dc (200 μA pulsed). Planned developments are described which should increase the atomic source output current to the multi- milliampere range for both $\vec{H}^+$ and $\vec{H}^-$. Optical pumping techniques have succeeded in producing 25 μA of $\vec{H}^-$ and 200 μA of $\vec{H}^+$. Polarized ion sources using optical pumping which may eventually lead to amperes of $\vec{H}^-$ have been proposed.

Introduction

It has been four years since the last report on the status of intense polarized proton sources to a PAC meeting[1] and almost thirty years since the first operational polarized ion source. Developments during the past four years have led to substantial improvements in both beam intensity and quality. The motivation for developing higher intensity polarized ion sources is varied. Both high and medium energy physicists are requesting increasing amounts of polarized beam time, frequently at the expense of high intensity users. However, the users of intense unpolarized primary or secondary beams need not be excluded if the polarized current equalled the unpolarized current. The success at avoiding depolarization with resonance crossing techniques in strong-focusing machines[2] and the proposal to use 'Siberian snakes'[3] in large accelerators have removed the major technical obstacle in accelerating polarized ions. Negatively charged ions are preferred in many machines together with multi-turn injection and stripping to reach the full space-charge-limited capability of the accelerator. At least two types of existing polarized sources as well as several new proposals for polarized proton sources have the potential of providing adequate current. For fusion reactor applications[4] it is the new techniques that will have to be pursued in order to obtain the required multi-ampere currents of $\vec{D}^-$.

In existing sources the procedure for achieving a polarized beam can be summarized in four basic steps. Initially a high quality atomic beam is formed. Next the electron spin of the atoms is aligned in a preferred direction. Then, making use of the hyperfine interaction, the nuclear spin of the atoms is aligned by transferring the electron polarization to the nucleus. Finally the nuclear-polarized atoms are ionized. In principle, any nucleus with a nonzero spin can be polarized with similar techniques.

In this paper discussion is restricted to schemes suitable for producing intense beams of polarized hydrogen ions ($\vec{H}^+$ and $\vec{H}^-$), although note is made when the source is readily adapted to other particles such as deuterons or tritons. The sources to be reviewed here include: Lamb-shift, atomic, ultra-cold atomic and optically pumped.

Lamb-shift Sources

The physics and technological details of Lamb-shift type polarized sources have been thoroughly reviewed.[5] A block diagram outlining the important processes is given in Fig. 1. Protons from an ion source are transported at ~550 eV through a cesium vapour ($n\ell \approx 3\times10^{14}$ atoms/cm^2) to produce a metastable atomic hydrogen [H(2S)] beam. Nuclear polarization is achieved through the use of appropriate magnetic and electric fields which cause mixing between the metastable $2S_{1/2}$ states (having the unwanted spin orientation) and the short-lived $2P_{1/2}$ states. A selective ionizer is used to preferentially ionize the remaining metastables, now polarized. The H^- ($\approx H^+$) current from the best sources has increased to ~2 μA[6] per hyperfine state, albeit with slightly less polarization. The primary limitation appears now to be the brightness of the initial proton ion source. The Lamb- shift source technology is believed to be mature and substantial increases in current are not expected in the near future. The source will, however, continue to be used on accelerators for some time because of: 1) the good emittance (~0.015 π cm-mrad normalized); 2) the ability to polarize T, D or H; 3) the ease of choosing either pure vector or pure tensor states; and 4) the suitability (the ~1 m long 550 eV drift length) for producing pulsed beam bunches.

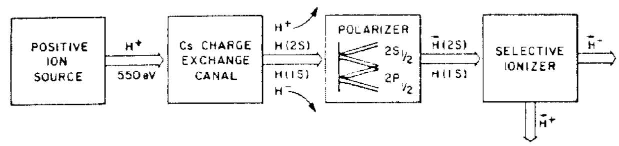

Fig. 1. Block diagram of a Lamb-shift polarized ion source.

Atomic Beam Sources

Atomic beam sources have also been thoroughly reviewed in the literature.[7,8] A block diagram outlining the important processes in a source is given in Fig. 2. A dissociator, nozzle and skimmer are used to form a slow collimated beam of atomic hydrogen (or deuterium). Spin selection is accomplished with Stern-Gerlach style separation magnets and rf-induced transitions from one hyperfine state to another state of opposite electron spin. An electron ionizer is used to produce $\vec{H}^+$, followed by an alkali vapour target if $\vec{H}^-$ is desired. Alternatively $\vec{H}^-$ is also produced directly with the charge exchange reaction $\vec{H}^0 + Cs^0 \rightarrow \vec{H}^- + Cs^+$. The $\vec{H}^-$ current from the best sources is ~6 μA dc and ~30 μA pulsed. The $\vec{H}^+$ currents are ~125 μA dc and 200 μA pulsed.

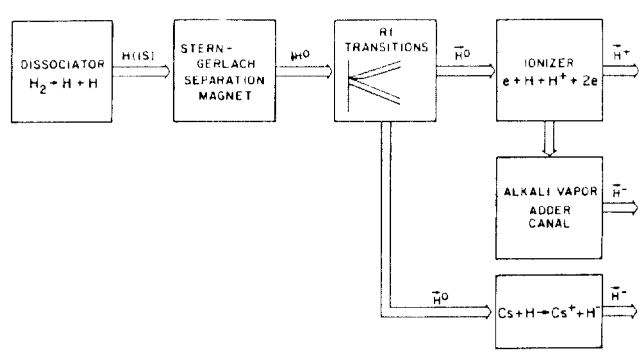

Fig. 2. Block diagram of an atomic beam polarized ion source indicating the various ionization techniques.

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The atomic beam source has the potential for substantially higher currents. In the atomic beam formation region it is important to efficiently cool (<20 K) the atoms since the beam density is proportional to $T^{-1/2}$. This anticipated gain in density when cooling the atomic beam from room temperature to 20 K may not be seen unless the surface of the cooled accommodator is coated with a material having a recombination coefficient comparable to that for existing sources at higher temperatures. Also, in order to realize the larger currents it is essential to redesign the separation magnets to match the slower velocity atomic beam. The magnets can be shortened and their vertical aperture enlarged, thereby increasing the acceptance. The atomic beam density after the separation magnets is expected to be proportional to $T^{-3/2}$. It is estimated for an ideally designed atomic beam formation region that the current could be increased by a factor of 20 to 30 over existing sources. Experiments at ETHZ[9] have demonstrated a 2.5 beam density increase after the accommodator with a liquid N_2 coated surface at 15 K (compared to room temperature densities). A further factor of 6 increase was observed after a redesigned set of separation magnets which were optimized for the cooled beam. Hence it is expected that the ETHZ ionic beam should increase by a factor of 15; i.e., the dc $\vec{H}^-$ current should increase from ~6 to ~90 μA and the dc $\vec{H}^+$ current from ~0.1 to ~1.5 mA. J. Alessi at BNL has built and is testing an accommodator designed to cool the atomic hydrogen beam to 7 K.[10] This system will use permanent magnets for focussing the atoms.

Further increases in output current can be expected by improving the ionizer. For $\vec{H}^+$ ions, a modern electron impact ionizer is capable of ionizing only 3-5% of the $\vec{H}^0$ beam. Much more efficient ionizers exist. An electron-cyclotron-resonance (ECR) source, for instance, would be expected to give an efficiency of ~35% for hydrogen atoms. In the ETHZ source, where double charge exchange is used to produce $\vec{H}^-$, it is estimated that a further increase of a factor of 5 can be obtained with alkaline earth vapours. Thus dc currents of 3 mA for $\vec{H}^-$ and 10 mA for $\vec{H}^+$ seem obtainable in the future. At Brookhaven a pulsed $\vec{H}^-$ beam is obtained directly through the charge exchange reaction

$$\vec{H}^0 + C_s^0 \rightarrow \vec{H}^- + C_s^+$$

with a design similar to that developed by Haeberli at Wisconsin. Optimization of the 40 keV neutral cesium beam by the BNL group has resulted in 400 μsec long $\vec{H}^-$ beam pulses of 30 μA with ~75% polarization. A substantial improvement in current is expected with the use of a D^- ring-type magnetron, shown in Fig. 3.[11] This ionizer takes advantage of the much larger cross sections in the reaction

$$\vec{H}^0 + D^- \rightarrow \vec{H}^- + D^0.$$

The ring magnetron design should avoid the space charge problems with the D^- beam that led to failure in earlier attempts.[1] The magnetron has been successfully tested as an atomic beam ionizer. Unpolarized H^- currents of ~100 μA have been observed. When installed on the 7 K atomic beam source, pulsed $\vec{H}^-$ intensities substantially higher than 1 mA are anticipated.

Although the beam emittance from an atomic source depends on the ionization technique and the mode of hyperfine state selection, for maximum current operation the normalized emittance is about 0.05 π cm-mrad. These sources work equally well with either hydrogen or deuterium and turn-key systems designed for 10 μA of $\vec{H}^-$ (or 100 μA of $\vec{H}^+$) can be purchased. A great deal of development effort is required to reach the multi-milliampere current range, but there appears to be no major technological reason for not succeeding.

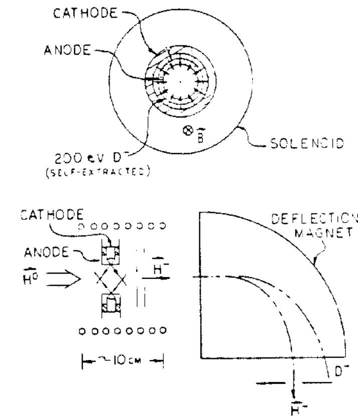

Fig. 3. Diagram of a ring magnetron ionizer as proposed by J. Alessi of BNL.

Ultra Cold Atomic Sources

A promising application from low temperature physics research is the proposal of Kleppner[12] for an ultra cold atomic source. The source has many design variations depending on the required beam properties. A scheme suited for pulsed currents, shown in Fig. 4, has been tested by Niinikoski and his group at CERN. Hydrogen atoms are cooled in stages down to ~0.3 K and then trapped in a confinement cell within an axial magnetic field. In fact, only atoms with their electron spin (two hyperfine states for hydrogen) in one of the two possible orientations are stored in the magnetic well; the other atoms are directed away from the solenoid by the magnetic field. The trapped atoms can be extracted by using μ-waves to induce transitions to either one of the other two hyperfine states. Ionization techniques would be similar to those used in conventional atomic beam sources.

The μ-wave extraction technique is particularly useful for applications requiring intense pulsed beams, since it is possible to accumulate atoms in the solenoid between pulses. Laboratory experiments have demonstrated storage densities ~3.10^{17} atoms/cm^3 with an

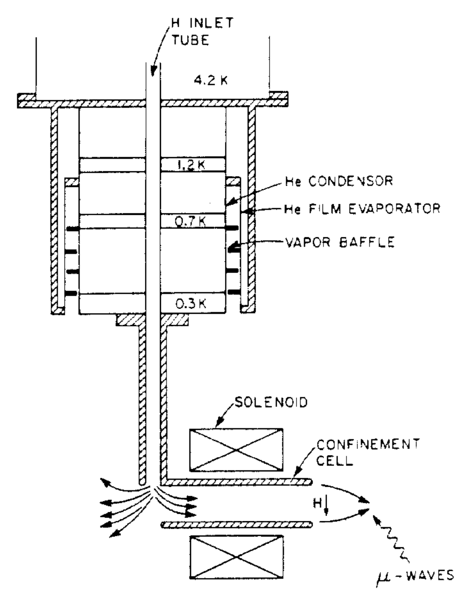

Fig. 4. An ultra cold atomic beam source using magnetic field storage and μ-wave extraction.

input flux ~10^{16} atoms/sec. For low-duty cycle accelerators, such as the AGS, it should be possible to reach peak intensities of ~2.10^{19} atoms/sec. An interesting feature of the scheme is that the extracted atoms would be both accelerated and focussed by the fringe field of the solenoid into a slow, nearly monoenergetic atomic beam. This should lead to a much higher ionization efficiency than that achieved in existing atomic sources. However, for accelerators requiring dc or high duty cycle beams, there is no advantage of the ultra cold atomic beam source over conventionally cooled atomic sources, given present technology.

Optically Pumped Polarized Proton Sources

Six years ago Anderson proposed a technique based on optical pumping of sodium atoms with dye lasers to obtain intense polarized proton currents.[13] Four years later Mori of KEK described the characteristics of a working source based on the Anderson proposal.[14] The source design is shown schematically in Fig. 5.

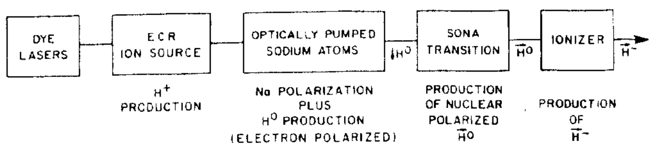

Fig. 5. Block diagram of an optically pumped polarized ion source based on the proposal by Anderson.

The technique, as proposed by Anderson, involves polarizing the electron spin of sodium atoms in an optically dense sodium vapour ($n\ell \gtrsim 10^{13}$ atoms/cm^2) by optical pumping with a dye laser tuned to the sodium D1 absorption wavelength. Protons, at an energy of approximately 5 keV, pick up with relatively large probability a polarized electron from the sodium to form an electron-spin polarized atomic hydrogen beam. The polarization transfer efficiency from the sodium atoms to the atomic beam increases with the strength of an applied axial magnetic field, the loss mechanism being radiative depolarization occurring when hydrogen atoms created in an excited state cascade to the ground state. The magnetic field along the source axis in the region following the sodium vapour is reversed in direction to form a Sona-type zero crossing.[15] This diabatic field reversal technique transforms the electron-spin aligned atomic beam into a proton-spin aligned atomic beam. Charge exchange in a second (unpolarized) alkali vapour within the reversed magnetic field yields a proton polarized H^- beam. The estimated current, neglecting aperture restrictions, is about 4 μA of H^- for each mA of protons (with a polarized sodium vapour target thickness of 10^{13} atoms/cm^2). The proton polarization is determined by how effectively the sodium can be polarized, the polarization transfer efficiency, and the quality of the Sona zero crossing. The total current depends on the initial proton ion source brightness, the beam diameter and the maximum sodium target thickness that can be reasonably polarized.

The KEK optically pumped polarized ion source uses a 16.5 GHz electron-cyclotron-resonance proton ion source (ECRIS) operating with 1 ms long pulses at a 20 Hz repetition rate. The peak magnetic field within the sodium vapour is 9 kG although tests are currently underway at ~18 kG. Initial measurements of the current and beam polarization at 355 keV are shown in Fig. 6. The beam current was increased by increasing the sodium target density without increasing the pumping laser output power by a corresponding amount, thus

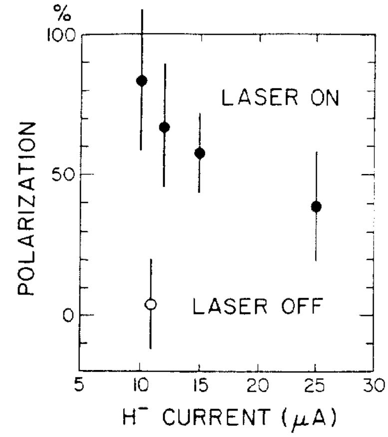

Fig. 6. Initial polarization measurements from the KEK optically pumped polarized ion source.

reducing the target polarization. A high background gas pressure is also suspected of leading to a substantial unpolarized background. Nevertheless, the results from this pioneering work are impressive and the system has a large potential for improvement both in current and polarization.

An optically pumped polarized ion source has been built at TRIUMF in order to test the feasibility of producing intense polarized dc H^- beams. This source incorporates several innovations which should improve both the efficiency of the optical pumping and the polarization transfer to the proton beam. Protons are produced in a dc mode with an ECRIS operating cw at 28 GHz and at powers up to 1 kW. The extraction electrodes and sodium vapour target are located in a 12 kG uniform axial magnetic field. Provision has been made for two counter-propagating beams to polarize the sodium as well as for a third low intensity probe beam to monitor the polarization. A second alkali target, located in a 2 kG field to define the spin direction, produces H^-. Potassium is being used here, initially, rather than sodium because it does not interact with the pumping beam and has the added advantage of requiring lower temperatures to achieve adequate vapour densities. Fig. 7 shows the source layout together with the neutron scattering chamber designed to permit measurements of the polarization transfer from the sodium to deuterons.

Parker in his review paper[1] correctly pointed out that the development areas for this source were: 1) production of an adequately thick polarized sodium target, 2) optimization of the beam polarization and 3) proper coupling of adequate proton current into the sodium target. Developments at TRIUMF have shown that areas 1) and 3) can be successfully achieved and development work is now underway on area 2).

The sodium polarization was measured using the experimental apparatus shown in Fig. 8. A broadband dye laser was used for the pump beam. A ring dye laser set midway between the sodium D lines measured both the polarization and thickness by an optical rotation method.[16] The results are summarized in Fig. 9, where the sodium polarization is shown as a function of target thickness under various conditions. The optical pumping efficiency is increased by reducing the bandwidth of the pumping laser from a nominal 30 GHz to about 6 GHz by means of an intra-cavity etalon since the Doppler broadened D1 line is only about 4.5 GHz wide. The primary polarization loss mechanism occurs

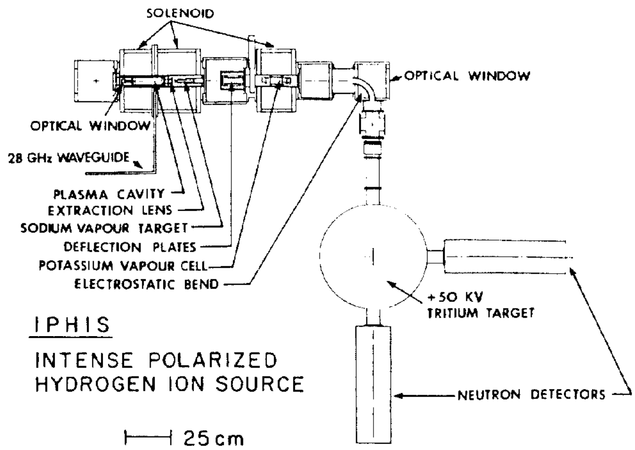

Fig. 7. Layout of TRIUMF optically pumped ion source with scattering chamber.

as the result of the collision of sodium atoms with the cell wall. A Viton wall liner decreases the loss by increasing the time between depolarizing wall collisions by a factor of 15. Further increases in pumping efficiency were observed with bi-directional pumping with the same laser. It is noteworthy that even at the higher densities, there appears to be no evidence of significant radiation trapping. With a second pump laser it should be possible to reach 90% sodium polarization at a thickness of 5.10^{13} atoms/cm^2. Thus optical pumping of sodium can produce a high sodium polarization, even with modest laser power.

The extraction electrodes have not yet been optimized for maximum neutral beam. Preliminary results show that 300 mA/cm^2 of positive current can be extracted through a 2 mm diameter extraction hole in a dc mode. With a quartz liner in the ECRIS multi-mode cavity it is possible to obtain proton fractions $[H^+/(H^+ + H_2^+ + H_3^+)]$ greater than 75%. If this current density can be maintained with a 5 mm diameter extraction hole and sodium cell diameter together with a sodium thickness of 5.10^{13} atoms/cm^2, then a neutral beam density of $\gtrsim 10$ equivalent particle milliamperes is expected. Initial measurements at TRIUMF have to date observed only ~10% of the expected neutrals, albeit in a much better than expected emittance (normalized at the 90% level) of 0.007 π cm-mrad with a 2 mm diameter

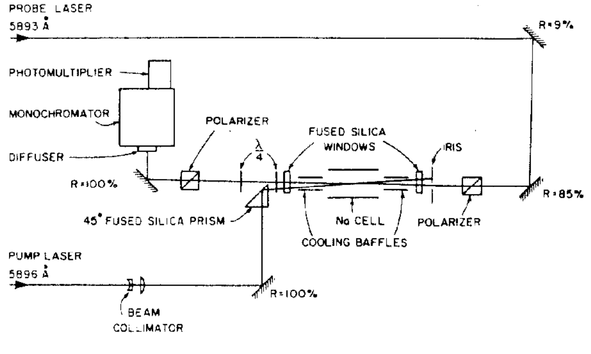

Fig. 8. Schematic of experimental apparatus used to produce and measure polarization of a sodium vapour target at TRIUMF

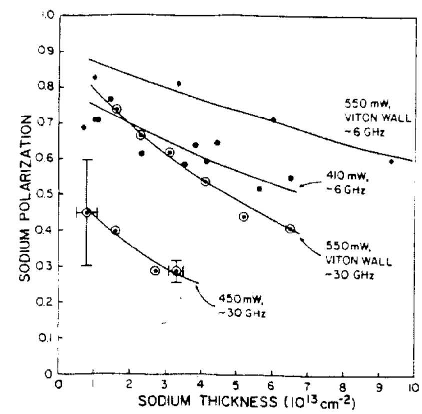

Fig. 9. Measured polarization of sodium target vs target thickness for optical pumping with ~30 GHz and ~6 GHz bandwidth at Sodium D1 line with and without a Viton wall liner

extraction hole and a 4 mm diameter sodium cell collimator. By comparison, Mori at KEK measured a normalized emittance of 0.011 π cm-mrad after accelerating 50% of the polarized H$^-$ beam to 750 keV.[17] This beam quality should be adequate for most accelerators. The source brightness exceeds that of other polarized sources for $\vec{H}^-$. As is the case in the Lamb-shift source, the relatively long neutral beam drift length, coupled with the low beam energy spread readily allow beam bunching at the source.

Experiments to measure and optimize the beam polarization are presently being set up. Initial measurements comparing the H$^-$ produced by double charge exchange in the sodium vapour with and without optical pumping confirmed that the beam is indeed polarized and that the electronic polarization transferred to the H^o is not less than 80% efficient at 12 kG, provided the proper beam energy and spin direction are chosen. If deuterium rather than hydrogen is used, a maximum 33% tensor nuclear polarization can be expected from an electron-spin polarized atomic beam. A scattering chamber has been set up to permit angular asymmetry measurements from the reaction $^3H(d,n)^4He$ at 50 keV in order to estimate the tensor polarization and hence the polarization transfer efficiency.

Anderson's scheme is not the only one being pursued. A variation of the scheme is under development for the Moscow Meson Factory where a pulsed proton current of 200 μA with a 65±5% polarization has been achieved. Happer of Princeton proposes to use spin exchange collisions to make polarized $\vec{H}$.[18] In this scheme rubidium and hydrogen atoms are combined in a cell. The rubidium is electron-spin polarized by optical pumping. The electronic polarization is transferred by spin exchange to the hydrogen atoms. Frequent spin exchange collisions lead to nuclear polarization. The power requirements, assuming 100% efficiency, are about 4 watts of optical power per ampere of protons. The group at Princeton has demonstrated the technique, in principle, by producing highly polarized ^{129}Xe through spin exchange reactions with optically pumped Rb. Kaplan et al of Berkeley in a separate contribution to this conference propose to use a process they refer to as "collisional pumping" to make polarized D^- beams in the ampere range. They calculate that successive spin-dependent charge-transfer collisions in an optically pumped thick target can be utilized to produce highly nuclear-polarized $\vec{H}^-$ currents.[19] The process requires a spin-polarized target thickness of order 10^{17} atoms/cm^2, almost two orders of magnitude thicker than the existing optically pumped spin-aligned targets.

Conclusion

The future for intense polarized proton ion sources is indeed promising. There are several new groups actively building sources and new ideas are being pursued. After three decades of effort to reach the ~10 μA range, polarized ion source builders are confident of being able to demonstrate ~100 μA dc $\vec{H}^-$ currents in the near future. Corresponding $\vec{H}^+$ currents will likely be around the 1 mA dc level. Pulsed currents should be at least a factor of two higher. For the more distant future, schemes have been proposed which would lead to $\vec{H}^-$ sources equalling today's unpolarized H^- ion sources. Accelerator designers and builders should not preclude the acceleration of polarized beams in future machines on the basis of inadequate polarized currents.

Acknowledgements

The collaboration on the TRIUMF optically pumped ion source has been international. Dr. R. Geller of CENG, France originally suggested, in private conversation, the use of an ECRIS to avoid the beam loss associated with coupling a proton source to the high magnetic field surrounding the sodium vapour target. Dr. V. Bechtold of KfK, West Germany and Dr. C. Jacquot of CENG, France have contributed substantially to the ECRIS development effort at TRIUMF. Dr. Y. Mori of KEK, Japan worked hard at TRIUMF to bring the source into operation. Dr. R. York, Dr. R. Stevens Jr., and Dr. W. Cornelius of LANL, U.S.A. have provided many useful suggestions which have been incorporated into the design. Dr. S.Z. Yao of the Northwest Telecommunication Engineering Institute, Republic of China began the initial sodium polarization measurements at TRIUMF. Finally I wish to acknowledge the effort of my colleagues in the development group, namely: Dr. C.D.P. Levy, Mr. M. McDonald, Dr. J. Uegaki and Mr. H. Wyngaarden.

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