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POLARIZED ION SOURCE DEVELOPMENT AT TRIUMF

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Abstract.- The TRIUMF Lamb-shift polarized ion source produces 1.5 μA of H^- within a normalized emittance of 0.3 π mm-mrad in both transverse planes and is routinely used to produce up to 200 nA of polarized protons between 200 and 500 MeV. This source is presently being upgraded to satisfy current experimental requirements. An rf spin filter and a rapid spin reversal system are being installed in a compact, magnetically-shielded design. The duoplasmatron will be replaced by an electron cyclotron resonance proton source. In order to meet future experimental needs, development has started on an intense polarized H^- ion source (IPHIS) which is expected to yield currents in excess of 50 μA. This source, which uses a charge exchange reaction between an intense 5 keV proton beam and an optically pumped sodium vapour, is presently being assembled in the laboratory. The status and results of both programs are described.

1. Introduction.- The polarized proton source has been in operation at TRIUMF since 1976. Since then about 25% of the available beam time each year has been scheduled for accelerating polarized protons. Modifications to the source and tests with the polarized beam have been performed during the remaining, unscheduled periods. As a result of this continuous upgrading, 1.5 μA of polarized H^- current were recently measured on a beam stop in the 300 keV injection beam line. In order to satisfy the requirements of approved experiments planned for the near future, a redesign incorporating many features of newer sources was begun last year. The major goals of this redesign were to introduce the capability of rapid spin reversal and to improve the shielding of the stray magnetic field from the cyclotron.

An ion source which is capable of producing 3 to 6 μA is needed in order to take full advantage of TRIUMF's unique capability of delivering polarized protons between 180 and 520 MeV with a high energy resolution. An increase in current is also necessary for the polarized neutron experiments. With the existing source, the current is limited to ~1.5 μA because of space charge effects. These space charge limitations can be almost completely overcome by replacing the duoplasmatron with an electron-cyclotron-resonance (ECR) type proton source. It is believed that this change, which will be tested in the near future, will satisfy the above intensity requirements.

During meson production, proton currents between 30 and 120 μA are normally delivered to the meson experimental hall. Simultaneously, through partial stripping, a low intensity, variable energy proton beam is extracted to a second experimental hall. At present, requests for meson production time and requirements for the applied program compete with the requests of beam time for accelerating polarized protons. A polarized H^- source capable of providing an extracted current of the order of 30 μA or more could, to a large extent, resolve this conflict. Work has begun on developing and testing an H^- source making use of an ECR source which is coupled to an optically pumped sodium vapour. This scheme has the possibility of providing the required currents. A series of experiments are planned to determine both the capabilities and ideal design parameters for such a source.

2. Lamb-shift source.

2.1. Operational source.- The TRIUMF polarized H^- ion source is a Lamb-shift type source. The source, shown schematically in figure 1, has been described in some detail previously [1]. Protons from a duoplasmatron are extracted at ~5 to 8 keV and then slowed down to 500 eV by means of an acceleration-deceleration lens system. This lens system focusses the proton beam into the cesium charge exchange canal from which 1/3 of the protons emerge as hydrogen atoms in the metastable 2S state. Charged particles, which also exit from the cesium cell with the atomic hydrogen beam, are removed from the beam path by means of a transverse electric field. Nuclear polarization of the metastable atoms

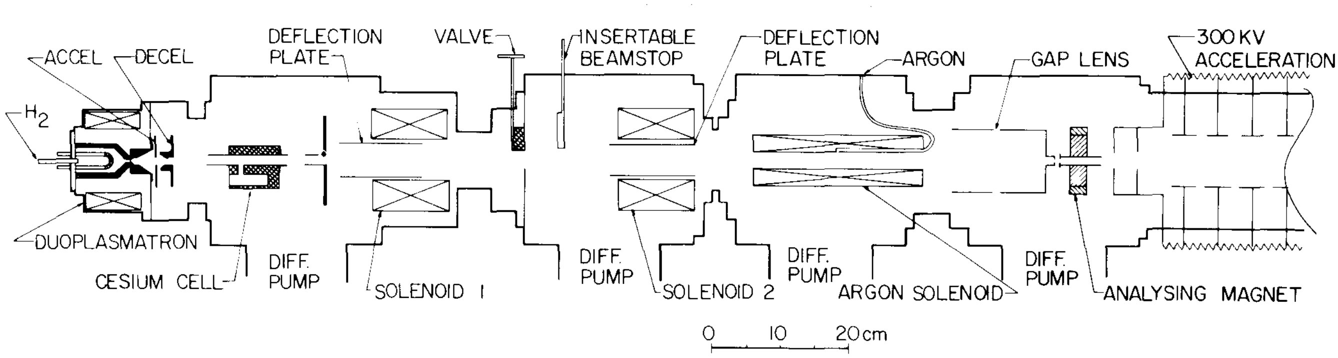

Fig. 1 : A schematic layout of the TRIUMF Lamb-shift polarized H^- source.

is achieved by passing the atomic beam through two solenoids, wired to produce axial magnetic fields in opposing directions; the first at ~575 G and the second at ~-200 G. The zero field crossing technique of Sona [2] is used to enhance the polarization. In the polarization process, metastable atoms having the undesired spin orientation in the first solenoid, decay to the ground (1S) state. A third solenoid containing argon follows the polarizer. This combination selectively ionizes the aligned metastable atoms with a much higher probability than the ground state atoms to produce polarized H^- ions. A more detailed explanation of this type of source can be found in a review article by Haeberli [3].

The beam emittance at the beginning of the injection line has been measured to be 0.3 π mm-mrad (normalized). The effective emittance is, however, larger due to the fact that the beam centroid shifts slightly when changing from one spin direction to the other. Approximately 80% of this beam can be transported through the 45 m long injection beam line to the cyclotron, and 25 to 30% is accelerated up to 520 MeV. The proton polarization, as measured on the beam extracted from the cyclotron, is between 70 and 80% [1]. Spin reversal is achieved by reversing the current in each of the three solenoids labelled in figure 1; a process which requires ~2 sec. A faster spin reversal scheme would be desirable for certain types of experiments.

2.2. Rapid spin reversal.- In consultation with J.L. McKibben of LANL, design was begun last year on a source which could alter the spin direction at up to 1 kHz rates. (The time to change from one direction to the other will be less than 20 μsec). This design also included modifications to improve the polarization. A sketch of the modified source is shown in figure 2. An rf spin filter is used to select one of the four states of the metastable atoms. Rapid spin reversal is achieved by precessing the spin with a transverse magnetic field [4]. In order for this technique to work satisfactorily, the area between the spin filter and the argon solenoid must be well shielded magnetically (stray fields $\lesssim$ 0.06 G). In the TRIUMF case, it is necessary to shield not only from the field of the two solenoids but also from the stray field (~5 G) of the cyclotron. This is achieved by means of a steel vacuum chamber (1.3 cm thick) and mu-metal

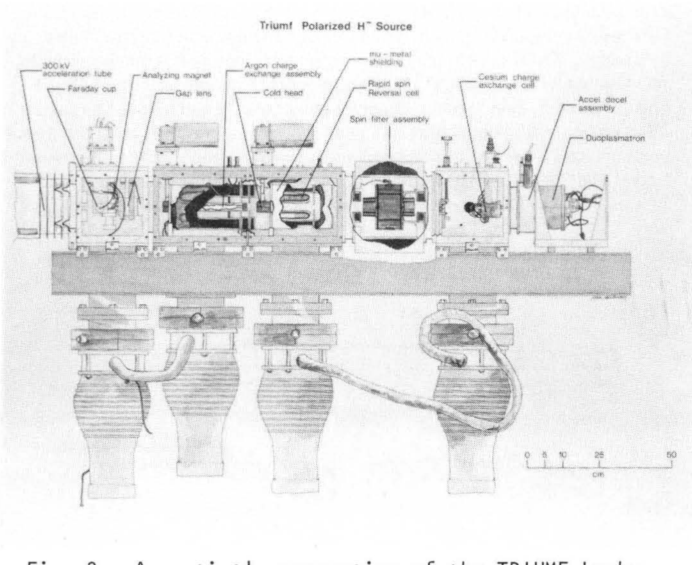

Fig. 2 : An artist's conception of the TRIUMF Lamb-shift polarized ion source modified for rapid spin reversal.

shielding inside the vacuum housing. The mu-metal shielding decreases the speed at which argon is pumped from the system. Hydrogen atoms could be ionized outside the field of the solenoid which would result in lower beam polarization. In order to avoid this, cryopumping of the argon gas was introduced by installing special cold surfaces (~20°K) at both ends of the argon solenoid. The cold heads condense the argon gas, preventing argon from ionizing the hydrogen atoms in the field free region, prior to the spin axis being defined by the rapid spin reversal coil.

There will be less polarized beam current when rapid spin reversal is in use. The rf spin filter selects only 1 of the 4 metastable hyperfine energy states, whereas the Sona technique selects 2 of the states. Consequently, the H^- current is approximately one half of that compared to the Sona technique. This reduction in current is slightly compensated by the fact that the magnetic field in the argon solenoid can be nearly zero with the result that the H^- beam has a smaller emittance. In the Sona technique a field of about 100 G is required. There are experiments in which the need for more current supercedes the need for rapid spin reversal. Therefore, the source has been designed to easily run with a Sona zero cross. This is quickly achieved by turning off the rf power to the spin filter, shutting off the transverse magnetic field in the rapid spin reversal coil and adjusting the currents in the solenoids to the appropriate values. The changeover can be accomplished within minutes.

The overall length from the exit of the cesium canal to the entrance of the argon canal is only 82 cm. It is felt that the shorter this distance is, the larger the percentage of metastable atoms reaching the argon cell. In fact, the design includes the capability, when using the Sona technique, of removing the vacuum box housing the rapid spin reversal coil and shortening the source by about 25 cm. Changing to run in this mode would require that the source be out of operation for several days.

2.3. Modifications for higher intensities.- The maximum current from a Lamb-shift type of source is thought to be limited by two important factors. First, a space charge limit of about 100 μA is imposed on the 500 eV protons by the dimensions of the cesium charge exchange canal (1 cm diameter, 10 cm long). Space charge neutralization, of course, substantially increases the proton current which actually passes through this canal. The useful proton current for a source producing 1.5 μA of H^- is believed to be about 500 μA [5]. Second, the metastable atoms can be quenched to the ground state by electric fields. Emerging out of the cesium canal are not only protons, but also electrons and H^- ions. These ions give rise to microscopic electric fields. External fields are required to remove these charged particles from the beam path. A field of $\gtrsim$10 volts/cm is sufficient to substantially quench the metastable beam.

A measurement was carried out at TRIUMF to estimate the magnitude of the quenching effect at the maximum currents that could be obtained from the duoplasmatron. In figure 3 the measured currents are shown as a function of the arc current in the duoplasmatron. Four smooth curves have been drawn through the measured data points. The currents were read from a beam stop in the 300 keV injection beam line. The ground state H^- current (quenched current) was obtained when electrostatic plates were used to quench all the metastable atoms to the ground state. This is the unpolarized component in the H^- beam. The polarized H^- current contains the ground state H^- beam plus the ionized

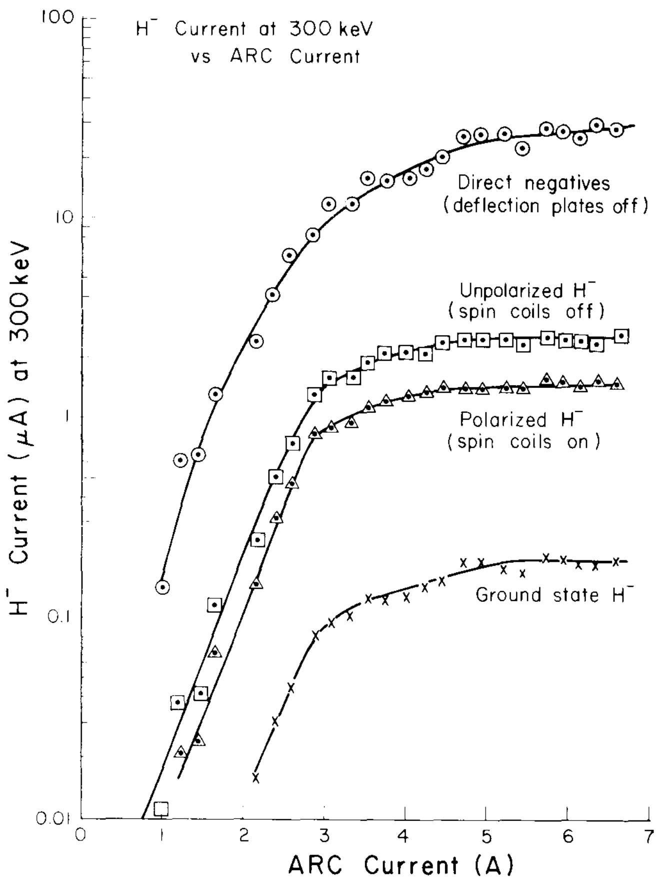

Fig. 3 : The H^- current from the Lamb-shift ion source as a function of the duoplasmatron arc current.

metastable atoms from the two states with the desired spin alignment. The unpolarized H^- current is obtained by turning off the spin selecting solenoids and contains all four metastable states. The direct negative (H^-) current is formed by double charge exchange in the cesium vapour. The H^- currents resulting from the unpolarized ground state atoms as well as the polarized metastable atoms have a similar dependence on arc current which, over this range is thought to be proportional to the proton current out of the duoplasmatron. This implies that beam quenching is not yet limiting the polarized current.

The ratio of the polarized to unpolarized currents (of figure 3) is shown in figure 4, where the quench ratio is given. The quench ratio is the H^- current resulting from ground state atoms (unpolarized) divided by the H^- current from the metastable atoms (polarized). It is, in fact, a measure of the beam polarization. The quench ratio does not increase, even at polarized currents as high as 1.5 μA. The only increase occurred above ~4.2 A of arc when the voltage

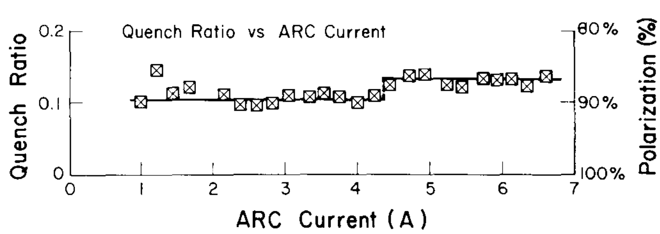

Fig. 4 : The quench ratio and estimated beam polarization as a function of duoplasmatron arc current.

on an electrostatic deflection plate was increased by ~25% in order to completely deflect out the H^- current that was coming from the cesium charge exchange region. Consequently it is concluded that if it were possible to increase the useful proton current through the cesium canal, the polarized current would increase without significantly lowering the polarization.

The deuteron electron-cyclotron resonance (ECR) source [6] has been designed to operate in an environment which can be very easily adapted to be the initial stage of a Lamb-shift source. Moreover, since the source operates within a 3 to 4 kG axial magnetic field, the space charge neutralization is almost 100%. The problem arising from the space charge limit because of the dimensions of the cesium canal has been solved. In fact, 64 mA/cm^2 of D^+ through the cesium canal have already been achieved [7]. The ECR source emittance is compatible with the acceptance of the Lamb-shift source, so, very little loss in beam is expected from geometrical considerations. A feature which could prove to be extremely useful is the low energy spread (~2 eV) in the proton beam. This is to be compared to ~20 eV for the duoplasmatron. Bunching of the 500 eV beam ought to be much more effective. Two restrictions, imposed by the Lamb-shift source, will probably limit the overall performance. First, a $2P_{3/2}$ state in the hydrogen atom crosses the upper $2S_{1/2}$ states at ~2.3 kG. The metastable atoms will not survive this crossing. Hence the magnetic field in the cesium vapour will have to be less than 2.3 kG. Second, a magnetic field gradient larger than 100 G/cm will severely depopulate the metastable levels. This implies a minimum length of about 17 cm between the exit of the cesium canal and the entrance of the rf spin filter. Ideally, one would like this distance to be shorter.

Plans exist both at Grenoble [8] and at TRIUMF to build an ECR-Lamb-shift test source as soon as possible. The TRIUMF design is shown in figure 5. The ECR source will be mounted in the 300 keV terminal so that the H^- beam can be accelerated and the polarization of a proton beam extracted from the cyclotron can be measured directly with existing polarimeters. The magnet coils are being assembled. A Varian 300 W-10 GHz travelling wave tube amplifier has been acquired. The duoplasmatron and cesium cell will be removed from the existing source and replaced by the ECR source and a redesigned cesium cell combination. Plans call for the first tests to be carried out in December. Tests in Grenoble are planned in October.

3. IPHIS.

3.1. Techniques for high intensities.- Various schemes for producing intense polarized H^- ion sources have been examined. The colliding beam technique of Haeberli [1] at Wisconsin which has produced 3 μA and the sodium charge exchange technique used by Grüebler [9] at ETH which also has given a 3 μA H^- beam were considered. It was concluded that developments at both laboratories will lead to substantial increases in the intensity within the next few years. However, both approaches use a ground state atomic source which is too large to fit into the existing TRIUMF 300 kV terminal. In addition, a great deal of research and development is required before these sources produce a 50 μA H^- beam. Consequently, these schemes have, at present, been ruled out as a solution to the long term needs at TRIUMF. The cold atomic source [10] described by Kleppner has the potential to provide intense polarized proton beams but would be difficult to operate in a 300 kV terminal. It is unlikely, given present technology, that a Lamb-shift source can be upgraded to provide the required H^-

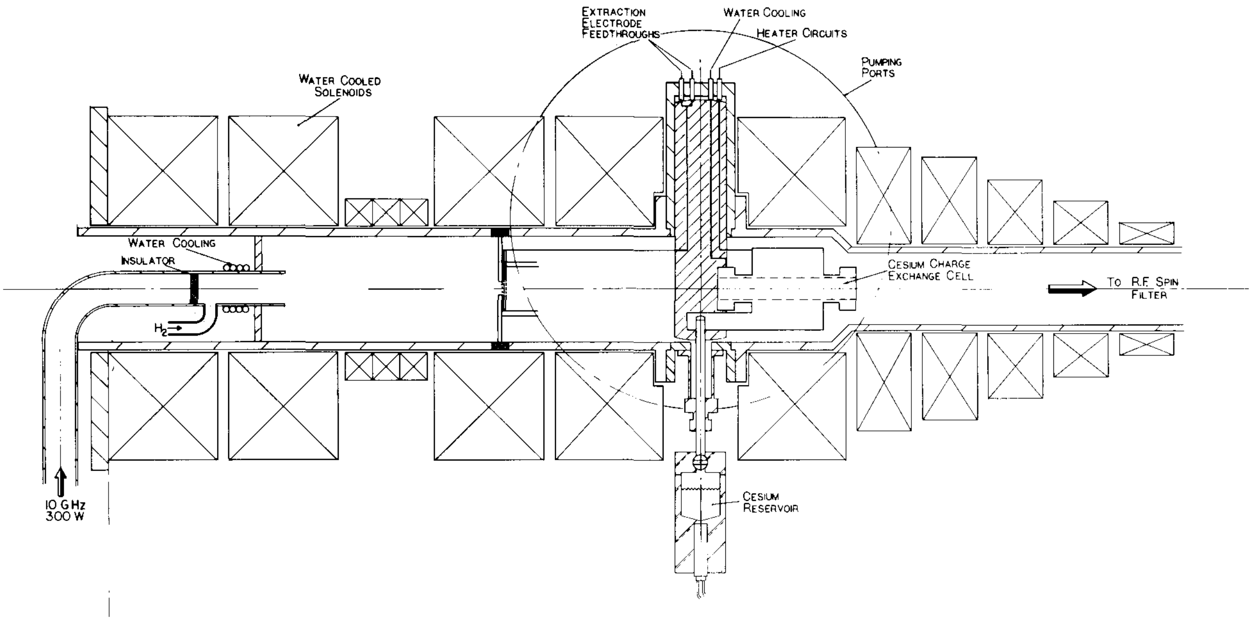

Fig. 5 : The initial design and field plot for the proposed TRIUMF ECR proton source.

intensities. A recent proposal by Anderson [11)] for an optically pumped polarized proton source was examined in detail. It was concluded that this source could satisfy TRIUMF's requirements but that various aspects of the technique needed to be examined experimentally. As a result work has begun on setting up a test facility to determine the ideal design criteria.

3.2. Optically pumped ion source.- The scheme proposed by Anderson involves polarizing a sodium vapour ($\sim 10^{13}$ atoms/cm^2) by optical pumping at the D1 line (5896 Å). Using a circularly polarized laser beam parallel to the magnetic field, it is possible to align the electron spin of the sodium atoms in a direction defined by an axial magnetic field. A polarization of $\gtrsim 70\%$ should be achieved with commercially available dye lasers having an output power of 1 W. Protons passing through the sodium vapour can pick up a polarized electron from the sodium atoms through the charge exchange reaction, $H^+ + Na^o \rightarrow H^o + Na^+$. The probability of this reaction peaks at a proton energy of about 5 keV and is about 6% for a target thickness of 10^{13} atoms/cm^2. The atomic hydrogen beam emerging from the sodium vapour will have the electron spins aligned. A diabatic zero crossing technique is used to transform this atomic beam into a proton-spin-aligned beam. A second charge exchange reaction, $H^o + Na^o \rightarrow H^- + Na^+$, yields polarized H^-. The probability for this process is $\sim$7%. The current is estimated to be 4 μA of H^- per mA of protons. In his original paper, Anderson calculated that with 6 W of laser power it should be possible to reach 12 μA of H^- per mA of protons and achieve $\sim$100% polarization.

A description of the difficulties associated with this scheme can be found elsewhere [12)] and will not be discussed in detail here. The magnitude of the magnetic field in the first charge exchange region is determined by the need to prevent radiative depolarization. The electron, captured by the proton in an excited atomic state, may not maintain its polarization as it cascades to the ground state if the magnetic field is too small. Increasing the magnetic field results in a larger Zeeman splitting. The laser bandwidth must be large enough to cover not only the frequency spread due to Doppler broadening of the D1 lines but also the separation due to Zeeman splitting. The actual polarization of the sodium atoms depends on the laser intensity over the required bandwidth. Consequently increasing the magnetic field also implies more laser power is required. The optimum magnetic field needs to be determined experimentally.

The amount of H^- current from this type of source will depend on the amount of useful proton current that can be put through the sodium vapour canal. Space charge will limit the maximum current, in the absence of space charge neutralization. The dimensions of the canal will be similar to that for the Lamb-shift source. The space charge limit is slightly larger than that for the Lamb-shift source but still too small ($\sim$1 mA).

The protons, entering the magnetic field of the solenoid surrounding the charge exchange region, experience a radial magnetic field and will pick up a transverse velocity component. This transverse velocity will be maintained after neutralization and will lead to an unacceptably large emittance, for reasonable magnetic fields ($\gtrsim$4 kG).

3.3. Design status.- A sketch of the proposed TRIUMF source is shown in figure 6. Unique to the TRIUMF design is the proton ECR source. This choice of source circumvents two of the major problems associated with the Anderson proposal. The proton beam does not experience a radial magnetic field. The magnetic field between the ECR source and the sodium charge exchange canal is continuous. The neutral atomic beam leaving the solenoid will not be influenced by the radial component at the second canal. Consequently, the emittance degradation of the neutral beam will not be a

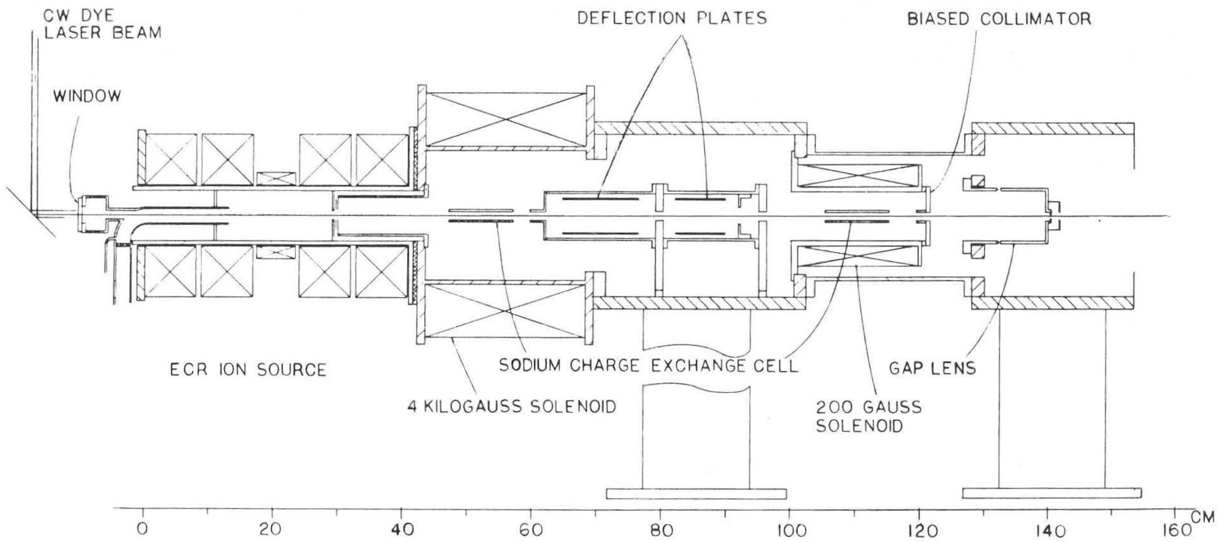

Fig. 6 : IPHIS—a schematic layout of the proposed intense polarized H^- ion source.

problem. The H^- beam leaving the magnetic field of the second charge exchange canal will experience a slight, but acceptable emittance increase, due to the small magnetic field (~200 G). The second advantage of the ECR source is the fact that essentially 100% space charge neutralization has been achieved with a 1 keV deuteron beam. The D^+ ECR source has demonstrated a 60 mA beam through a cesium canal having dimensions comparable to those of the sodium canal.

Two other laboratories have already carried out measurements towards developing an optically pumped source. At LAMPF the polarization of the sodium vapour has been measured as a function of the vapour density [13]. At KEK a 3 μA polarized beam has been obtained from an optically pumped source [14].

At TRIUMF, an argon laser, a 1 W dye laser, and associated optical components have been purchased and tested. A dual temperature sodium cell is ready to be installed into a solenoid that has been designed for 5 kG. This solenoid is currently being tested and the fields are being mapped. Once assembled, the initial tests will concentrate on measuring the sodium polarization as a function of sodium vapour density, of laser power and of magnetic field. Experiments to determine the average time between depolarizing collisions are also planned. The ECR source will shortly be tested with the Lamb-shift polarized ion source.

Acknowledgements.- The authors would like to thank J.L. McKibben of LANL for his many hours of useful consultation in the design of the rapid spin reversal and rf spin filter systems for the Lamb-shift source.

" DISCUSSION "

W. JOHO : Do you think that in the future you can obtain even 50-100 μA of polarized protons, so that you can have simultaneously polarized protons as well as protons for the meson users ?

P. SCHMOR : This is my hope. The optically pumped source has the potential to produce sufficient current for the meson physics program.

References.-

1. J.L. BEVERIDGE, G. DUTTO, P.W. SCHMOR, G. ROY in 3rd Int. Symp. on High Energy Physics with Polarized Beams and Polarized Targets, Argonne, 1978, AIP conference proceedings no. 51, p.341-346.
2. P.G. SONA, Energ. Nucl. 14 (1967) 295.
3. W. HAEBERLI in 3rd Int. Symp. on High Energy Physics with Polarized Beams and Polarized Targets, Argonne, 1978, AIP conference proceedings no. 51, p.269-289.
4. J.L. MCKIBBEN in 5th Int. Symp. on Polarization Phenomena in Nuclear Physics, Santa Fe, 1980, AIP conference proceedings no. 69, p.830-847.
5. T.B. CLEGG, Proc. of the Workshop on High Intensity Polarized Proton Ion Sources, Ann Arbor, 1981 (to be published).
6. R. GELLER, C. JACQUOT, P. SERMET in Proc. 2nd Symp. on Ion Sources and Formation of Ion Beams, Berkeley, 1974, III-5-1.
7. M. DELAUNAY, J.L. FOUCHER, R. GELLER, C. JACQUOT, P. MAZHARI, E. RICARD, J.C. ROCCO, P. SERMET, F. ZADWORNY in Proc. 2nd Int. Symp. on the Production and Neutralization of Negative Hydrogen Ions and Beams, Brookhaven, 1980, p.255-261.
8. R. GELLER, private communication.
9. W. GRUEBLER, P.A. SCHMELZBACH in 5th Int. Symp. on Polarization Phenomena in Nuclear Physics, Santa Fe, 1980, AIP conference proceedings no. 69, p.848-864.
10. D. KLEPPNER in Proc. of the Workshop on High Intensity Polarized Proton Ion Sources, Ann Arbor, 1981, (to be published).
11. L.W. ANDERSON, Nucl. Instr. and Methods, 167 (1979) 369.
12. P.F. SCHULTZ, ed. Informal Workshop on Intense Polarized Ion Sources—A Summary, Chicago, 1980 ANL-80-73.
13. R.L. YORK in Proc. of the Workshop on High Intensity Polarized Proton Ion Sources, Ann Arbor, 1981, (to be published).
14. Y. MORI, *ibid.*