HIGH CURRENT POLARIZED PROTON SOURCES*

James G. Alessi
AGS Department,
Brookhaven National Laboratory,
Upton, New York 11973

Abstract

Polarized proton sources are now being used more frequently on linacs. In pulsed operation up to 10 mA of $\vec{H}^+$ and 0.4 mA of $\vec{H}^-$ have been produced. The present status of these sources, and developments to reach even higher intensities, are reviewed.

Introduction

Although ion source developments are frequently covered in this series of linac conferences, polarized ion sources are not normally included. When polarized sources first appeared, more than 30 years ago, they were primarily used on Van de Graaff accelerators and small cyclotrons. Later, they were installed at higher energy meson facilities (TRIUMF, PSI/SIN, and LAMPF), where they now play a major role in the experimental programs. Recently, however, polarized physics has been a part of the program at several high energy synchrotron facilities (ZGS, Saturne, KEK, and the AGS), and polarized beams are frequently considered in new machines as they are proposed (European Hadron Facility, SSC). Therefore, polarized proton ($\vec{H}^+$, $\vec{H}^-$) sources are now often built to inject into linacs, and their review at this conference is no longer out of place. This evolution to the use of these sources on linacs has had an impact on the source development, in that one has gone from dc operation on Van de Graaffs, to the need for only a pulsed (typically low duty factor) device for high energy machines. This has contributed to the fact that polarized intensities are now in the milliampere range. As will be discussed below, some of the techniques presently used on high current sources would be difficult to implement for steady state operation.

Present polarized proton sources can be grouped into three basic types – Lamb Shift sources, ground state atomic beam sources, and optical pumping sources. Particularly with atomic beam sources, however, there are many differences in the techniques used in sources operating at various labs, and here comparisons of individual aspects are difficult since one is trying to compare dc, pulsed (with various pulse widths and rep-rates), $\vec{H}^+$, and $\vec{H}^-$ sources, with currents or emittances measured at varying places, etc. In the following, I will try and survey the areas where major differences exist among sources, and give examples of sources employing the various techniques. The fundamental principles of polarized ion production can be found in a review such as Haeberli's,[1] and further details can be obtained from the proceedings of several polarized ion source workshops.[2,3,4]

Lamb Shift Sources

In Lamb Shift sources, one first produces a ~500 eV H^+ beam, which then passes through a Cs vapor neutralizer, where approximately 30% of the incident protons exit as H^0 atoms in the 2S state. The atoms then pass through a "spin filter", which quenches one H(2S) hyperfine state, leaving a polarized H(2S) beam. A selective ionization then follows, where in the passage of the atom beam through an iodine vapor essentially only the H(2S) atoms are stripped, resulting in a polarized H^+ beam. Alternatively, in passage through argon vapor only the H(2S) atoms pick up an electron, forming polarized H^-. Unlike other techniques, this method produces H^+ or H^- with almost equal intensity.

The Lamb Shift source at Kyushu University[5] produced $\vec{H}^+$ or $\vec{H}^-$ currents of 3 μA (dc), with a polarization of 80% and a normalized emittance of 0.02 π cm-mrad. This is about the highest intensity so far attained with this type source, and significant future gains seem unlikely since one has the difficult problem of producing a high brightness, 500 eV proton beam, and then as the intensity is increased, quenching of the metastables due to space charge fields becomes a problem. Therefore, although quite a few of these sources are still in reliable operation, intensities are no longer competitive with other techniques (especially for $\vec{H}^+$), and these sources are slowly being replaced.

Ground State Atomic Beam Sources

In "ground state" atomic beam sources, one first produces an electron polarized atomic hydrogen beam. This is done via a Stern-Gerlach type spin separation of a thermal H^0 beam in an inhomogeneous magnetic field (the force on an H^0 atom is $\mu_e \cdot$grad B). This electron polarized atomic beam passes through rf transition units, where the atoms are nuclear polarized by inducing a spin flip of one of the hyperfine levels. The nuclear polarized atomic beam is then ionized, usually in a magnetic field of $\gtrsim$ 1 kG to preserve maximum polarization. For convenience, the atomic beam production and the ionization will be discussed separately, although they are not decoupled systems in an optimally designed source.

Atomic Beam Production

Atomic hydrogen is first produced by dissociation of H_2 via an rf field. This dissociator is made from pyrex, on which hydrogen has a low recombination rate. The atoms flow out of the dissociator, and a small fraction pass through a skimmer aperture into a sextupole magnet, while the rest, which would be outside the acceptance of the sextupole, are pumped to reduce the pressure (and therefore gas scattering) in the rest of the system. In this sextupole magnet, the m_j=+1/2 component is focussed, while the m_j=-1/2 component is defocussed. It can be shown that the solid angle acceptance of the sextupole is approximately $2.1\mu_e B/kT$, where B is the pole tip field of the magnet and T is the temperature of the atoms. That is, more atoms can be captured and focussed into the ionization region if the velocity of the atoms is reduced. There is an additional gain in that the ionization efficiency will be higher at lower velocities (increased dwell time). Therefore, this cooling of the atomic beam is one of the main areas where these sources are being improved. The beam is cooled at the exit of the dissociator by passage through a cooled channel, and one attempts to do this cooling without losing flux through recombination. To fully utilize the colder beam, the sextupole must then be designed with an acceptance matched to the beam velocity, so ideally, the velocity distribution of the cooled atomic beam is first measured, and then an optimized sextupole can be designed via ray tracing calculations. An additional benefit of cooling is the reduction in the energy spread of the beam, which allows one to better focus the H^0 atoms. On the other hand, the larger atomic beam acceptance into the sextupole also results in a larger H^0 emittance out of the sextupole, so to fully utilize this beam, one needs a large acceptance ionizer. The use of acceptance diagrams in the design of an atomic beam source is described in Reference 6.

At this time, high intensity atomic beam sources generally incorporate cooling to at least 100 K, for example by cooling the exit nozzle of the pyrex dissociator. Measured velocities are $1.5\text{-}2 \times 10^5$ cm/s (versus ~3×10^5 at room temperature), and one typically gains a factor of 2-3 in intensity over room temperature operation. By cooling a copper exit channel ("accomodator") to 35 K, the velocity can be reduced to ~1×10^5 cm/s. At 35 K, the intensity of the ETH source[7] was improved by a factor of 4 over room temperature, and was limited by the acceptance of the ionizer, since the H^0

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density at the ionizer entrance was increased by a factor of 15 through cooling. They found that the output was improved by adding a small amount of nitrogen to the system, presumably forming a favorable surface on the copper accomodator for reduced recombination. No one has yet gone to lower temperatures on an operating polarized source, but in tests at BNL a pulsed atomic beam has been successfully cooled to 6 K.[8] The beam passes through a liquid helium cooled copper accomodator, and in this case H_2 freezing on the surface inhibits recombination. The velocity of the beam was found to be 7×10^4 cm/s, with a spread of only 2×10^4 cm/s FWHM. This atomic beam also has a carbon coated skimmer held at 2.5 K, giving excellent cryopumping in a very critical region. Steady state operation at 6 K has not been tried.

Spin selection is done by passage of the H^0 beam through one or more sextupoles. For a given velocity atomic beam, the solid angle acceptance of the sextupole is proportional to the pole tip field. In a conventional sextupole, the aperture is $\lesssim 3$ cm diameter, and the pole tip field is 0.7-1.0 T. Somewhat higher fields (1.2 T) have been obtained in a permanent magnet sextupole,[9] and calculations for a hybrid coil/permanent magnet[10] suggest that this can even do slightly better. A superconducting sextupole magnet, part of a polarized atomic deuteron source used as gas target, reaches fields of 1.7 T in a 2.5 cm diameter aperture.[11] Calculations for another superconducting sextupole, considered as part of a proposed polarized atomic beam target, suggest that 4 T pole tip field could be obtained in a 6-8 cm diameter aperture.[12] At BNL, a test was made of a novel suggestion by T. Niinikoski[13] to use a type of superconducting solenoid for spin selection. This was a large acceptance magnet, desirable for a proper match to a 6 K atomic beam. The solenoid consisted of three short coils, each approximately 10 cm diameter, operated with the current in the middle coil opposite to that in the outer coils. The result was a high gradient field (almost zero on axis and 5 T at the coil inner diameter), although unlike a sextupole, the gradient was very nonlinear. Ray tracing calculations of an atomic beam through this gradient field exhibited focussing, but with considerable aberrations. The calculations also showed that the solenoid dimensions were not optimally matched to the 6 K atomic beam with which it was tested. At low H^0 densities, focussing was observed,[14] although less than one would expect from a sextupole. There was an additional problem in that at high H^0 densities the focussing decreased due to H-H gas scattering. At this time it is not clear whether this is primarily due to the fact that one is operating at 6 K, or if one is hindered by the fact that defocussed H^0 atoms do not recombine on the inner bore of the solenoid (4 K), and therefore scatter back into the primary beam.

The performance of present atomic beam stages can be summarized as follows. H^0 velocities vary between $0.7\text{-}3.0 \times 10^5$ cm/s, with colder beams also having narrower velocity distributions. So far, gains in final output intensity from a polarized source as the H^0 beam is cooled have not not been as great as predicted from simple scaling laws (which is not suprising), but the gains are still very substantial. It has been observed that pulsed operation of the atomic beam allows one to gain a factor of $\gtrsim 2$, because one has less of a gas load on the system (one can go to higher dissociator pressures before scattering is a problem). The best performance on a dc source seems to be that at ETH[7] (and a similar source at PSI), which operates at 35 K. The H^0 flux at the entrance to the ionization region was 10^{17} H^0/s, and the density at that point was 2×10^{12}/cm^3. The pulsed atomic beam at INR,[15] operating at 77 K, produces a flux in the ionizer of 2.2×10^{17} H^0/s, and a density in the ionization region of 1.2×10^{12}/cm^3.

In a Michigan/MIT/CERN collaboration, a polarized atomic beam is being developed for use as a target, which, if successful could also be used in a source.[16] Atoms from a dissociator operating dc are cooled to 0.5 K by collisions with helium lined walls of a dilution refrigerator. They flow out of this cooling section directly into the fringing field of an 5 T superconducting solenoid. Atoms with m_J=+1/2 are pushed out of the field, while atoms with m_J=-1/2 are pulled into the field and trapped, since $\mu_e B = 10kT$. It is estimated that the H^0 density in the solenoid can be built up to 10^{16} H^0/cm^3. Microwaves of the appropriate frequency would then be sent into the trap, causing a spin flip and ejection of the atoms, which would be accelerated out of the solenoid (at the end opposite from injection) by the fringe field, forming an electron polarized H^0 beam. This beam could then pass through a conventional rf transition unit and into an ionizer. A pulsed density in the ionizer of 10^{14}/cm^3 might be possible. It could also be used to produce a steady state polarized beam of lower density. The system is now operating, and atoms have been injected, trapped, and then ejected via microwaves. The density or flux have not yet been measured.

Ionization of the Polarized Atomic Beam

Following the production of the thermal, polarized H^0 beam, it must be ionized to produce either $\vec{H}^+$ or $\vec{H}^-$. At this time, $\vec{H}^+$ is produced in sources either by bombardment via an electron beam, ionization in an ECR source, or by charge exchange with D^+ in a plasma. $\vec{H}^-$ can be produced indirectly, by first producing $\vec{H}^+$ by one of the methods mentioned above, followed by acceleration of the beam and passage through a Cs or Na vapor to produce $\vec{H}^-$ via double charge exchange. Alternatively, $\vec{H}^-$ can be produced directly by charge exchange with a Cs^0 beam, or by charge exchange with D^-. In addition to the efficiency of ionization, there are several other aspects of the ionizers to be considered. On would like a large acceptance ionizer to take full advantage of the cooled atomic beam. The emittance of the extracted beam is determined by the ionization technique. Finally, the electron and ECR ionizers efficiently ionize H_2 also, while the Cs^0, D^+, and D^- ionizers do not. When H_2 is ionized, the polarization of the extracted beam is reduced, so care must be taken in the e^- and ECR ionizers to reduce the background pressure of H_2, coming either from H atoms recombining on surfaces, or from hydrocarbons in the vacuum system.

The electron bombardment ionizer is the most common. Electron currents of a few A/cm^2 are produced in a ~35 cm long region with a solenoidal field of several kG to confine the electrons radially and also to preserve polarization during ionization. There are electrodes biased to confine the electrons axially. The active ionization diameter is about 1 cm. The efficiency (ions extracted/atoms injected) of this type of ionizer is $\lesssim 5\%$ for a room temperature beam, and higher as the beam velocity is decreased. A problem with this type ionizer is that the space charge of the electron beam produces a energy spread of several hundred volts or more on the extracted beam. One does not seem to be able to increase the electron beam density due to problems of stability. Higher magnetic fields would increase the already fairly large emittance. Therefore, major improvements in this type ionizer seem unlikely. In spite of this, the highest intensity dc $\vec{H}^+$ sources, those at ETH[17] and PSI, use this type ionizer to produce 400 μA of $\vec{H}^+$ with a polarization of 90%. Both have atomic beams cooled to 35 K. At Saturne, a pulsed source with an e^- ionizer and a 80 K H^0 beam produces a similar current.[18] The emittances of these sources, however, are larger than any of the other techniques.

The use of an ECR source as an ionizer was promising due to its high ionization efficiency, simplicity, and smaller energy spread of the output beam (since the ions are extracted from a plasma). Such an ionizer was recently tested in a PSI/KfK collaboration.[19] The ECR operated at 2.45 GHz, with typically 50 W of power. Operating with deuterium for test purposes, it had an efficiency about twice that of an electron ionizer, with a somewhat smaller emittance, and a polarization of the ionized beam which was 85% of its theoretical maximum. A D^+ current of 600 μA was extracted, and 150 μA was transported past a 90° bend, where the measured emittance (normalized) was 0.1 π cm-mrad. Based on these encouraging results, an ECR ionizer was selected for the new dc source being built to inject into the Van de Graaff at TUNL.[20] The atomic beam stage of this source operates at 35 K, and tests of the ionizer are just beginning. This could soon become the highest intensity dc $\vec{H}^+$ source. The ECR ionizer acceptance is not much better than the e^- ionizer, since it is still ~30 cm long, with ionization only over a diameter of ~1 cm.

At INR, Moscow, a D^+ plasma ionizer has been developed for pulsed operation, and this ionizer, with a 77 K atomic beam, produces the highest intensity $\vec{H}^+$ beam to date, 10 mA, with P=76%.[15] The reaction $\vec{H}^0 + D^+ \rightarrow \vec{H}^+ + D^0$ has a large cross section (5×10^{-15} cm^2), and an arc plasma source has produced a T_i=10 eV, n(D^+)=6×10^{11}/cm^3 plasma in a 40 cm long ionization region. The ionizer efficiency is approximately 30%, although the actual ionization could be considerably higher since extraction efficiency is not 100%. As mentioned above, this source produces peak currents of 10 mA, but the pulse is very narrow, having a FWHM of 50 μs. In addition, extraction and transport is complicated by the large D^+ beam extracted (several hundred milliamperes), which dominates the optics. The measured normalized, 90% emittances were 0.16 and 0.22 π cm-mrad in x and y.

For $\vec{H}^-$ production, any of the above ionizers could be combined with an alkali vapor cell for double charge exchange. Passage at 5 keV through a sodium vapor is typically used, giving a conversion efficiency of ~7%. This is done on the ETH source, producing 16 μA of $\vec{H}^-$ steady state (less than 7% of the $\vec{H}^+$ beam, due to losses in matching to the Na cell). At TUNL, a cesium vapor will be used, where a conversion efficiency of 30% is possible at 500 V, although the beam optics is more difficult. Therefore, the TUNL source, combining the ECR ionizer with a Cs double charge exchange cell, could conceivably have an overall $\vec{H}^0 \rightarrow \vec{H}^-$ efficiency of >5%, in contrast to the present e^- ionizer plus Na cell which gives $\vec{H}^0 \rightarrow \vec{H}^-$ of ~0.5%.

The only technique presently in use for direct conversion of $\vec{H}^0$ to $\vec{H}^-$ is the reaction $\vec{H}^0 + Cs^0 \rightarrow \vec{H}^- + Cs^+$ (σ=8×10^{-16} cm^2 at 40 keV). Here, a 40-50 keV Cs^0 beam is produced and travels collinear with the oppositely directed $\vec{H}^0$ beam through a 30 cm long ionization region. This ionizer is operated dc at the Univ. of Wisconsin,[21] where 3 μA of $\vec{H}^-$ is produced with P=91%, with a room temperature atomic beam stage. This is with a 2-3 particle-mA Cs^0 beam through the ionizer. They have also demonstrated that their Cs^0 beam intensity can be improved by a factor of 3-5,[22] but have not implemented it on their source. At the Univ. of Washington, a 15 mA dc Cs^0 beam has been produced for their polarized source,[23] but the reliability is poor with this intense beam, due to sputtering or melting of materials, and voltage breakdowns, so operation is normally at lower currents. The source produces only a few μA's due to poor atomic beam operation. At BNL, where operation is pulsed, this type ionizer is much more reliable, and 30-40 μA are obtained with P=75-80%.[24] The atomic beam is cooled to 80 K, and the $\vec{H}^0 \rightarrow \vec{H}^-$ efficiency is approximately 0.4%. The normalized, 90% emittance is 0.02 π cm-mrad, which is smaller than all but Lamb Shift sources.

Another pulsed ionizer being tested at BNL involves the use of the reaction $\vec{H}^0 + D^- \rightarrow \vec{H}^- + D^0$, as suggested by Haeberli.[25] A 200 V D^- beam of > 0.5 A has been produced using a magnetron surface-plasma source of annular geometry ("ring magnetron"),[26] in which plasma ions are allowed to diffuse out of the magnetron to space charge neutralize the "self-extracted" D^-. At this energy, the charge exchange cross section is 6×10^{-15} cm^2. The $\vec{H}^0$ beam crosses the D^- beam by passing through the center of this annular ionization region. In tests with an unpolarized H^0 beam, the ionization efficiency is so far only slightly better than that of the Cs^0 ionizer at BNL, but improvements are expected if gas scattering in the ionizer can be reduced. This ionizer has the largest acceptance of any to date, with a 2 cm diameter and length of the ionization region of only 2 cm.

Optical Pumping

This is the newest technique to be used for polarized ion production,[27] and there are presently three operating sources and a fourth nearing completion. Atomic hydrogen cannot be directly polarized with a laser, since lasers of the appropriate wavelength (1216 Å) are not available with sufficient power. Sodium, however, is easily polarized via circularly polarized laser light at 5896 Å. A 5 keV H^+ beam passing through such a Na cell will pick up a polarized electron to form an electron polarized H^0 beam. By passing through a region of rapid magnetic field reversal, this beam is easily transformed into a nuclear polarized H^0 beam (Sona transition). Ionization of this fast beam to form $\vec{H}^+$ or $\vec{H}^-$ is then simply a matter of sending it through a second, unpolarized vapor cell. Helium is used to produce $\vec{H}^+$, with an efficiency of ~70%, and sodium is used to produce $\vec{H}^-$ with a 7% efficiency. These various steps to the production of a polarized beam, which contain some unmentioned complications, will be explained in more detail below.

The cross section for electron pickup in Na by a 5 keV proton is 6×10^{-15} cm^2, so for efficient $\vec{H}^0$ beam production one would like a Na cell thickness of a few 10^{14}/cm^2. At densities of a few 10^{12}/cm^3, sodium can be easily polarized to near 100% with only a few watts of circularly polarized laser power. At densities above ~5×10^{12}/cm^3, however, the sodium polarization begins to drop,[28] even with essentially infinite laser power, due to radiation trapping.[29] In this case, photons emitted during the decay of excited Na are reabsorbed by other Na atoms, limiting the polarization that can be reached. To reach optimum thickness while staying below this density limit, one would need a cell ≳ 1 m long, which is difficult since the 5 keV proton beam should pass through efficiently. Typically, then, this cell is shorter (10-20 cm), and one is forced to operate at a Na thickness below the optimum (~5×10^{13}/cm^2). The $H^+ \rightarrow \vec{H}^0$ efficiency is therefore approximately 25%. The Na cell can, of course, be operated at higher densities, giving higher beam currents at reduced polarization, but there are also ways to raise or circumvent the Na density radiation trapping limit. One is to coat the walls of the cell with a material which decreases the probability of depolarization of Na when it collides with the walls. Various materials have been studied, and surfaces with relaxation times of > 1000 wall collisions have been found,[30] and while so far the surfaces do not seem to survive well in the presence of a beam, this still holds promise. Another technique is the use of a polarizable buffer gas.[31] In this case, Na is optically pumped at a density below that at which radiation trapping is important. The buffer gas (potassium was suggested), is then polarized via spin exchange collisions with the sodium. The density of this buffer gas is not limited, since it is not excited by photons from decaying Na atoms. A test of the use of a potassium buffer, with encouraging results, was recently reported.[32]

A second difficulty in optical pumping sources arises from the fact that when the proton picks up a polarized electron in the Na cell, the H^0 atom is formed predominantly in the n=2 state. The decay to the ground state then causes a loss of polarization unless the orbital and spin angular momenta are decoupled via a strong magnetic field. Assuming a Na polarization of 100%, calculations predict H^0 polarizations less than 50% for fields below a few kG, and polarizations near 90% are not expected until this field approaches 20 kG.[33] If one were to send a proton beam into such a strong magnetic field where it would then undergo charge exchange, the emittance growth would be prohibitively large. There are two techniques used to get around this emittance growth, and these will be described below.

The first optically pumped polarized source was built at KEK,[34] and operates pulsed (100 μs, 20 Hz). The problem of emittance growth was avoided by locating the H^+ source in the same magnetic field as the Na cell. An ECR source is used, operating at 16 GHz, and approximately 50 mA of protons are extracted. The Na cell is pumped by a pulsed dye laser, having a bandwidth of 30 GHz and a power of 500 W. The magnetic field of the Na cell is only 12 kG, and the final beam polarization is only 65%. When the $\vec{H}^0$ beam is passed through a helium ionizer, $\vec{H}^+$ currents up to 600 μA are produced, and 60 μA of $\vec{H}^-$ are produced if the second cell is Na vapor.

At TRIUMF, an ECR is also used for H^+ production in their dc polarized source.[35] Their Na cell is pumped by three 1 W cw dye lasers having a 6 GHz bandwidth. The cell is in a field of 12 kG, but installation of a 25 kG superconducting solenoid is expected soon. The source is now installed on the accelerator, and so far the $\vec{H}^-$ current is in the range of 5-10 μA, and the polarization is 40-50%.

At LAMPF, a similar polarized source is being built for pulsed operation (12% duty factor). They are using a 20 kG superconducting solenoid for their Na cell. While the laser has not yet been installed on the source, 5 μA of H^- has so far been produced during testing of the remainder of the source.

At INR, Moscow, a pulsed source has been built which does not use an ECR for the proton source, but circumvents the problem of emittance growth in the magnetic field in another way.[36] In this source, a plasmatron produces the H^+ beam outside the high field region. The beam is focussed, and then neutralized in an H_2 cell before entering the strong field of the solenoid. Once in the solenoid, it passes through a helium cell where it is converted back to H^+. The efficiencies of these two extra processes are 90% and 70%, respectively, and the losses are more than offset by the fact that the source is outside the magnetic field. The Na cell, in a field of 15 kG, is polarized by a 50 μs pulsed dye laser with a 5 GHz bandwidth and a power up to 1 kW. The output is 4 mA of $\vec{H}^+$ or 400 μA of $\vec{H}^-$, with P=65%. The normalized emittance is 0.1 π cm-mrad. There are plans to increase the magnetic field to 20-30 kG for higher polarization, and a new laser is being developed for operation of the source at 100 μs pulse width and 100 Hz repetition rate.

There are several other ideas being pursued for the production of polarized beams using a laser-polarized Na cell. Polarization of an H^0 beam through spin exchange collisions with a polarized target gas (H^0 entering, $\vec{H}^0$ exiting) can occur in a weaker magnetic field, since the polarized H^0 atoms are not produced in the 2s state. Large quantities of thermal H^0 are easily produced (a simple dissociator). Therefore, one could imagine polarizing this thermal beam by spin exchange, followed by one of the ionization techniques used in a ground state atomic beam source. A recent measurement of this spin exchange cross section gave $\sigma=3.4 \times 10^{-15}$ cm^2,[37] implying that a polarized Na target thickness of $\sim 5 \times 10^{14}$ cm^2 would be needed for good polarization of the H^0. Alternatively, one could polarize a 5 keV H^0 beam by spin exchange, in which case the H^0 beam is harder to produce, but subsequent ionization is much easier. At this energy, the spin exchange cross section is calculated to be 1.2×10^{-15} cm^2,[38] implying a Na target thickness in the 10^{15} cm^2 range. Another possibility, requiring an even thicker Na target, (estimated at 3×10^{15}/cm^2), is called collisional pumping.[39] In this case, an H^+ beam of a few keV, in passing through the Na cell, undergoes multiple charge changing and spin exchange collisions, causing the beam to emerge with almost complete nuclear and electron polarization. The magnetic field can be very weak, so emittance growth is not a problem. Such a polarized H^- source would consist of an intense H^+ source, followed by an optically pumped Na cell, and then finally an unpolarized Na cell. Milliamperes of $\vec{H}^-$ would be easily produced.

The above polarized cell thicknesses are about an order of magnitude higher than what is presently achieved. Unlike present optical pumping sources, where one can operate at less than the optimum polarized Na cell thickness at the expense of reduced beam current, with these spin exchange or collisional pumping schemes one would pay a bigger penalty for operation at less than optimum thickness, in that the beam polarization is reduced. Therefore, the successful application of one of these schemes in a source seems to depend on the development of an appropriate wall coating, or the use of a buffer gas.

Conclusions

In Table 1, some parameters of sources mentioned above are given. I have tried to show the best example of a pulsed and steady state source for each of the major methods of polarized ion production. By arranging them from highest to lowest intensity, one sees the clear correlation between narrower pulse widths and higher intensities, seemingly independent of the method used. While this is to some extent coincidental, it is indicative of the fact that techniques used for pulsed operation are not so easily extrapolated to dc operation due to decreased reliability, increased gas loads, heat loads, limits to the technology, etc. There is a fairly good correlation between the beam emittance and the method used. Optical pumping source polarizations are all low, but they are all hoping to improve to around 80% as they go to higher magnetic fields in the polarized Na cell region.

While pulsed $\vec{H}^+$ currents are now in the milliampere range, and $\vec{H}^-$ currents are approaching that, many ideas were mentioned which suggest that higher intensities can be expected in the future. The ECR ionizer should soon improve the intensities of dc sources. The combination of the 6 K atomic beam and D^- charge exchange ionizer under development at BNL is expected to produce mA level pulsed $\vec{H}^-$ currents. The ultracold atomic beam storage, and the advanced laser pumping techniques, are examples of longer range developments with even greater potential.

References

[1] W. Haeberli, Ann. Rev. Nucl. Sci. **17** (1967) 373.
[2] Polarized Proton Ion Sources, (Ann Arbor, 1981), AIP Conf. Proc. No. 80 (1982).
[3] Polarized Proton Ion Sources, (Vancouver, 1983), AIP Conf. Proc. No. 117 (1984).
[4] Inter. Workshop on Polarized Sources and Targets, (SIN/Montana, 1986), Helv. Phys. Acta **59** (1986) 513.
[5] A. Isoya and H. Nakamura, in ref. 4, p. 628.
[6] W.Z. Zhang, et. al., Nucl. Instrum. Meth. **A240** (1985) 229.
[7] P.A. Schmelzbach, et. al., Nucl. Instrum. Meth. **A251** (1986) 407.
[8] A. Hershcovitch, et. al., Rev. Sci. Instrum. **58** (1987) 547.

Table I. Examples of Operating Sources of Various Types

Laboratory	$\vec{H}^+$(μA)	$\vec{H}^-$(μA)	Pulse	Polarization	Normalized Emittance (π cm-mrad)	Method
INR, Moscow	10,000	–	~50 μs, 1 Hz	76%	0.16×0.22 (90%)	G.S. & D^+
INR, Moscow	4,000	400	40 μs, 1 Hz	65%	0.1	Opt. Pumping
KEK	600	60	100 μs, 20 Hz	65%	–	Opt. Pumping
BNL	–	40	500 μs, ~1 Hz	75-80%	0.02 (90%)	G.S. & Cs^0
Saclay	400	–	1 ms, ~1 Hz	90%	0.37 (90%)	G.S. & e^-
ETH/PSI	400	16	dc	90%	0.12 (~20%)	G.S. & e^-
TRIUMF*	–	5-10	dc	40-50%	0.04 (60%)	Opt. Pumping
Kyushu Univ.	3	3	dc	80%	0.02	Lamb Shift
U. of Wisconsin	–	3	dc	91%	0.04 (90%)	G.S. & Cs^0

*Source still in commissioning phase.

[9] Y. Wakuta, et. al., Nucl. Instrum. Meth. **A260** (1987) 543.
[10] P. Schiemenz, priv. comm.
[11] A.V. Evstigneev, et. al., Nucl. Instrum. Meth. **A238** (1985) 12.
[12] L. Dick and W. Kubischta, 8th Inter. Symp. on High Energy Spin Physics, (Minneapolis, 1988), to be published in AIP Conf. Proc.
[13] M. Ellila, et. al., Nucl. Instrum. Meth. **B14** (1986) 521.
[14] J. Alessi, et. al., 8th Inter. Symp. on High Energy Spin Physics, (Minneapolis, 1988), to be published in AIP Conf. Proc.
[15] A.S. Belov, et. al., Nucl. Instrum. Meth. **A255** (1987) 442.
[16] R.S. Raymond, et. al., 8th Inter. Symp. on High Energy Spin Physics, (Minneapolis, 1988), to be published in AIP Conf. Proc.
[17] W. Gruebler, et. al., in ref. 4, p. 568
[18] J. Faure, et. al., European Particle Accelerator Conf. (Rome, 1988), proc. to be published in Nuovo Cimento.
[19] L. Friedrich, et. al., to be published in Nucl. Instrum. Meth.
[20] T. Clegg, 8th Inter. Symp. on High Energy Spin Physics, (Minneapolis, 1988), to be published in AIP Conf. Proc.
[21] W. Haeberli, et. al., Nucl. Instrum. Meth. **196** (1982) 319.
[22] T. Wise and W. Haeberli, Nucl. Instrum. Meth. **B6** (1985) 566.
[23] T.A. Trainor, et. al., Proc. Sixth Int. Symp. Polar. Phenom. in Nucl. Phys. (Osaka, 1985), Suppl. J. Phys. Soc. Jpn. **55** (1986) 435.
[24] J.G. Alessi, et. al., in ref. 4, p. 563.
[25] W. Haeberli, Nucl. Instrum. Meth. **62** (1968) 62.
[26] J.G. Alessi, in ref. 4, p. 547.
[27] L.W. Anderson, Nucl. Instrum. Meth. **167** (1979) 363.
[28] Y. Mori, et. al., Nucl. Instrum. Meth. **A268** (1988) 270.
[29] D. Tupa, et. al., Phys. Rev. **A33** (1986) 1045.
[30] D.R. Swenson and L.W. Anderson, in ref. 4, p. 652.
[31] W.D. Cornelius and Y. Mori, Phys. Rev. **A31** (1985) 3718.
[32] A.N. Zelenskii, et. al., 8th Inter. Symp. on High Energy Spin Physics, (Minneapolis, 1988), to be published in AIP Conf. Proc.
[33] E.A. Hinds, et. al., Nucl. Instrum. Meth. **189** (1981) 599.
[34] Y. Mori, 8th Inter. Symp. on High Energy Spin Physics, (Minneapolis, 1988), to be published in AIP Conf. Proc.
[35] C. Levy, et. al., 8th Inter. Symp. on High Energy Spin Physics, (Minneapolis, 1988), to be published in AIP Conf. Proc.
[36] A.N. Zelenskii, et. al., Nucl. Instrum. Meth. **A245** (1986) 223.
[37] A. Ueno, et. al., Nucl. Instrum. Meth. **A271** (1988) 343.
[38] D.R. Swenson, et. al., in ref. 4, p. 662.
[39] S.N. Kaplan, et. al, in ref. 4, p. 670.