STATE OF THE ART IN POLARIZED PROTON SOURCES*

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Abstract

Present day polarized H^+ and H^- ion sources are reviewed by describing the performance of sources representative of each of the techniques being used. New ideas for producing higher intensities are then mentioned. Presently, pulsed $\vec{H}^+$ currents in the milliampere range, and $\vec{H}^-$ currents of hundreds of µA's, can be obtained

Introduction

The first polarized ion source was built approximately 30 years ago [1], and the steady increase in beam intensity over time has been very impressive (Fig. 1). The acceleration of polarized beams at high energy laboratories is of increasing interest. Workshops and Symposia on spin physics and polarized sources are held regularly, and there has even been a workshop on the acceleration of polarized protons in SSC [3]. There are presently on the order of 100 operating polarized sources, and novel ideas for polarized ion production continue to be suggested. The desire for higher intensity sources can be demonstrated by the situation at Brookhaven, where polarized protons have been accelerated to 22 GeV (P = 46%). The 25 µA polarized H^- source intensity is three orders of magnitude below the H^- intensity for unpolarized operation.

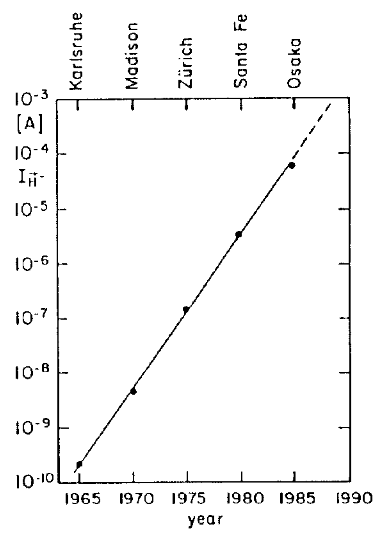

Fig. 1. Plot of polarized H^- intensity vs. year, as reported at the Polarization Symposia shown. From ref. 2.

Existing polarized proton sources can be grouped into three types. Ground state sources produce a thermal polarized atom beam by Stern-Gerlach type spin selection, and then the polarized atoms are ionized in one of several ways. Lamb shift sources rely on the production of a ~500 eV hydrogen atom beam, composed of unpolarized ground state atoms and polarized metastables. These polarized metastables are then selectively ionized by charge exchange. Finally, in optical pumping sources a ~5 keV polarized H^0 beam is produced by pickup by H^+ of an electron from polarized Na vapor. The Na is polarized via laser light, and the 5 keV polarized H^0 atoms are then ionized by charge exchange. Within these three categories of sources, there are many variations in the specific details. This paper will give examples of the various types of sources in operation, and also some of the improvements in progress. Fundamental principles of these sources can be found in review articles [2,4,5], and more details can be found in the series of workshops on Polarized Sources and Targets [6,7,8].

Lamb Shift Sources

As an example of a Lamb shift source, I will describe that from Kyushu University [9]. One starts with the production of an H^+ beam at an energy of 500 eV. A high brightness is essential for this proton source since the rest of the elements of the polarized source have a small acceptance (approximately ±0.5°). The proton source is a quartz capillary type, although a duoplasmatron or rf source, and more recently electron-cyclotron resonance (ECR) sources are used at other laboratories. The H^+ beam is then focused by a magnetic lens, and care is taken to assure space charge neutralization of the beam in this region (electrons are even added from a heated filament). The beam enters a Cs vapor neutralizer, where approximately 30% of the incident protons form H(2S) at a target thickness of 5×10^{13} atoms/cm^3. Ions are magnetically deflected. The neutrals then pass through a "spin filter", where 99% of the unwanted H(2S) hyperfine state are quenched while leaving 99% of the desired H(2S) state. The final step is to then selectively ionize only the H(2S) atoms while leaving the ground state atoms unchanged. This is accomplished by charge exchange in iodine to produce $\vec{H}^+$, or in argon to produce $\vec{H}^-$, both with about the same efficiency of 7%. At this 500 eV energy, the cross section for ionization of the ground state atoms is lower by about a factor of 50, so the final ion beam is highly polarized.

Losses in intensity can occur due quenching of metastables by electromagnetic fields (space charge from H^+ or Cs^+ ions) or quenching from collisions with background gas. However, obtaining good optics with the 500 eV proton beam is presently getting the most attention. While the Kyushu source can produce up to 100 mA in the initial proton beam, the usable current is only a few mA's. This source produces $\vec{H}^+$ or $\vec{H}^-$ currents of 3 µA (DC) with a polarization of 80%. Several other Lamb shift sources produce slightly lower intensities. Emittances are on the order of 0.02 π cm-mrad (normalized). These sources are reliable and relatively inexpensive, but intensities are no longer competitive with other methods (especially for $\vec{H}^+$, which is produced with the same intensity as $\vec{H}^-$), although work continues on improving the proton source.

Optical Pumping

This method of polarized ion production [10] is the newest to be employed. The basic idea is the production of polarized atoms by proton capture of a polarized electron through charge exchange with an electron spin polarized sodium atom. The Na is polarized by circularly polarized dye laser light tuned to the D_1 transition (5896 Å). When the proton picks up the polarized electron, it is predominantly in the n = 2 state, and as these atoms decay, polarization would be lost. Therefore, the application of a strong (>1 T) axial magnetic field is required to decouple L and S and reduce depolarization during the decay [11]. The source design must be such as to prevent emittance growth of an ion beam entering or leaving this field.

The first operational source of this type was developed at KEK [12]. H^+ ions are produced at 5 keV (the peak of the electron capture cross section) in an ECR source. This source was chosen because it operates in a strong magnetic field, and can therefore be located in the same field as the Na cell to prevent emittance growth of the proton beam. The Na cell is pumped by a flashlamp-pumped dye laser, producing 300-500 W in 60 µs pulses. After the capture of the polarized electron the H^0 leaves the solenoid and goes

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through a region of magnetic field reversal (to transfer polarization to the nucleus) before entering a second Na cell (unpolarized) for conversion to $\vec{H}^-$. This cell is in a field of approximately 2 kG to prevent loss of polarization during charge exchange. An $\vec{H}^-$ current of 50 μA has been produced with a polarization of 56% (70 μs pulses, 20 Hz) [13]. With a higher Na target thickness, 180 μA of H^- is produced with P = 43%.

At TRIUMF a similar source has been built, however for DC operation [14]. This source has produced >10 μA of $\vec{H}^-$ with P = 65% and a normalized emittance (60%) of 0.04 π cm mrad. The effort is now going towards installation, and operation is planned by the end of 1987. However, improvements have been made to the ECR source, and two extra lasers have been purchased (three broadband dye lasers, giving 3 watts total power, will be used). Therefore, higher currents should be forthcoming. LAMPF is also planning to install such an optically pumped source towards the end of 1988.

At INR, Moscow, a different approach has been taken to the problem of getting an H^+ beam into the strong field of the Na cell. This pulsed source [15] is shown in Fig. 2. A plasmatron source is used, and a 7 keV proton beam is extracted, focused, and then neutralized in H_2 before entering the solenoid. In the solenoid, the atoms are converted back to H^+ by stripping in a He cell. The conversion efficiencies of the two extra processes are approximately 90% and 70%, respectively, but one gains in the fact that the proton source does not have to operate in a strong magnetic field. A flashlamp dye laser is used for Na pumping, with a ~40 μs pulse width. An $\vec{H}^+$ beam is produced by final stripping in He, and the current is 4 mA, with P = 65% [16]. The normalized emittance is 0. .1 π cm-mrad. When the final cell is Na, 400 μA of $\vec{H}^-$ is produced.

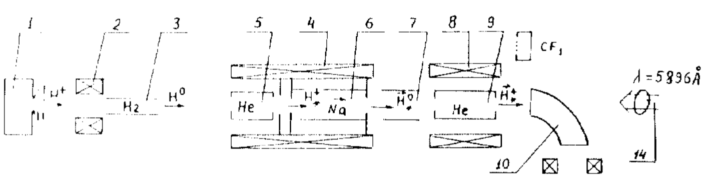

Fig. 2. Schematic of the optically pumped source at INR [15]. 1: plasmatron source, 3: H_2 cell, 4, 9: He cells, 6: polarized Na cell.

At higher Na target thicknesses, more laser power is required to maintain a good polarization. Also, the Na polarization is lower at higher densities due to loss of polarization from trapping of resonance radiation [17]. A variety of wall coatings for the Na cell are being studied [18] order to find surfaces which will allow a large number of collisions of the Na with the walls before losing polarization, which would lead to higher cell polarization. Surfaces with relaxation times of >1000 wall bounces have been found, but generally there are problems with survival of the various surfaces for long periods in the presence of a beam. The use of a polarizable buffer material to increase target polarization and polarized density has also been suggested [19].

Ground State Atomic Beam Sources

For discussion, this type of source can be subdivided into three areas. First is the production of a thermal atomic hydrogen beam. Second is the spin selection by magnetic separation of the two electron spin states. The transfer of polarization from the electron to the nucleus is done with rf transition units, which is straightforward and will not be discussed. The third step is ionization to either polarized H^+ or H^-, and this step is where the largest variety of techniques exist. Examples of sources using the various ionizers will be described.

The polarized source at ETH [20] and a similar source operating at SIN are good examples of those employing an electron bombardment ionizer. The key components of the ETH source are shown in Figure 3. Hydrogen is first dissociated with rf in a pyrex dissociator (recombination on pyrex is low at room temperature). In the simplest case, as the atoms exit the dissociator they would be cooled to approximately room temperature by collisions with the nozzle walls. An improvement in the atomic beam comes from further cooling of the atoms. This lowering of the velocity increases the solid angle acceptance of the spin selection magnet, and increases the probability of subsequently ionizing the atoms. (Countering this gain to some extent is the fact that the optimum intensity of atoms from the dissociator is frequently lower when cooled). In the ETH source, the beam cooling is to ~35 K via collisions with a cooled copper surface. They have found that a small amount of nitrogen mixed with the hydrogen improves the output due to a reduced recombination rate from nitrogen coating the cold copper. A skimmer and differential pumping stages are then used to remove the part of the atomic beam which does not fall within the acceptance of the magnetic spin selection system. The beam is electron polarized via passage through two sextupole magnets, and then nuclear polarized in an rf transition unit. Ionization of the atoms is by electron bombardment. The ionizer has an axial magnetic field of several kG, and an electron current density of a few A/cm^2. $\vec{H}^+$ is extracted at 5 keV, and then goes through a Na cell for $\vec{H}^-$ production by double charge exchange. Cooling of the atomic beam has resulted in a factor of 15 improvement in the $\vec{H}^0$ density at the ionizer entrance, compared to room temperature. Up to 400 μA of 5 keV $\vec{H}^+$, and 16 μA of $\vec{H}^-$ have been measured. This was a factor of 4 improvement over the room temperature current, less than the gain in atomic beam density due to the poorer match of the $\vec{H}^0$ beam to the ionizer acceptance.

The polarized source at BNL [21], shown in Figure 4, uses a different technique for the production of $\vec{H}^-$ ions. In this source, the polarized atoms are converted to $\vec{H}^-$ directly by charge exchange with a collinear 50 keV Cs^0 beam. The source is pulsed, and the atomic beam stage is similar to that described above, except that is is cooled to ~80 K. With a few mA's of neutral Cs passing through the ionization region, 25-30 μA of $\vec{H}^-$ are produced in 500 μs pulses with a polarization of 75% and a normalized emittance of 0.02 π cm-mrad (90%). Further improvements of the Cs beam should be possible [22]. A new DC source of this type has been constructed at the University of Washington [23], and with magnetic quadrupoles for focusing of the Cs beam >15 mA of Cs^0 can be transported

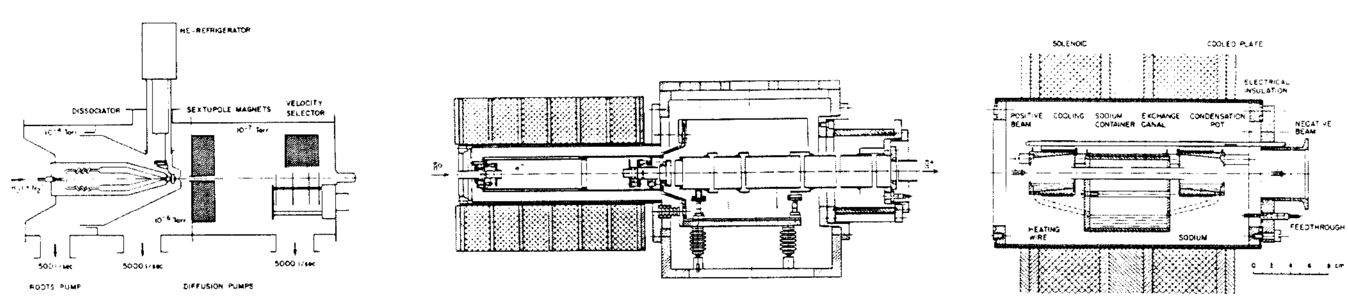

Fig. 3. The ETH cooled atomic beam, electron bombardment ionizer, and Na charge exchange cell.

through the ionization region. The $\vec{H}^-$ current from this source is still low (2 μA) due to poor initial operation of the atomic beam. The first source of this type was developed at the University of Wisconsin [24], and has produced 3 μA of $\vec{H}^-$, DC, with 91% polarization.

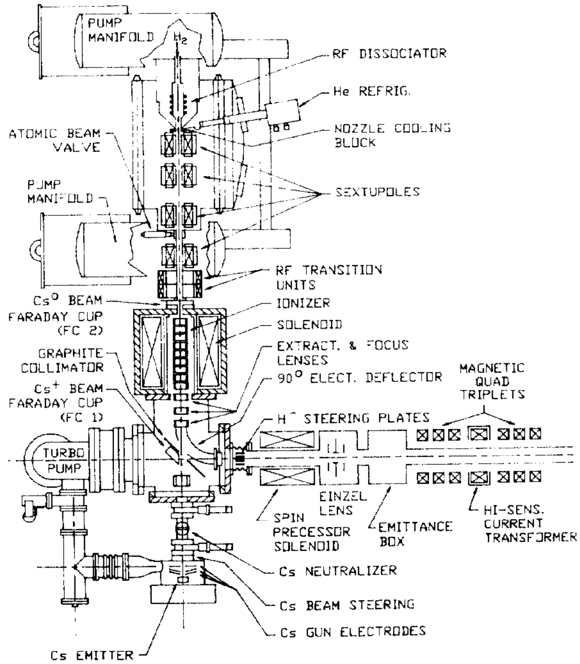

Fig. 4. Schematic of the BNL polarized H^- source.

In Figure 5, the pulsed $\vec{H}^+$ source from INR, Moscow, is shown [25]. This source is unique in that the polarized H^0 is ionized by charge exchange with D^+ in a deuterium plasma. The atomic beam is cooled to liquid nitrogen temperature, and spin selection is again by two sextupoles. The atomic beam stage performance is very good, with a density in the ionizer of 1.2×10^{12} cm^{-3}, and an atom flux into the ionization region of 2.2×10^{17} atoms/ cm^2/s. Deuterium plasma from a pulsed arc source is injected into the ionization region from the opposite end. The ionization efficiency is high due to the large charge exchange cross section (5×10^{-15} cm^2), but extraction and transport of the ions is complicated by the presence of the accompanying D^+ beam. A record pulsed $\vec{H}^+$ current of 10 mA has been extracted at 26 keV, with a polarization of 76% and a normalized emittance (90%) of 0.16 π cm-mrad in the horizontal and 0.22 π cm-mrad in the vertical direction. Unfortunately, a D^+ current on the order of several hundred mA (0.5 A/ cm^2) is extracted along with the polarized protons, dominating the extraction optics. Pulse widths are on the order of 50 μs half maximum at this current, at a 1 Hz repetition rate.

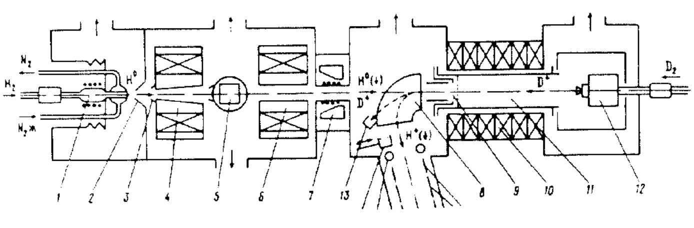

Fig. 5. The INR ground state atomic beam source, 1: cooled atomic beam, 4, 6: sextupoles, 7: rf transition unit, 11: D^+ plasma ionization region, 12: arc source. From ref. 25.

Future Sources

The use of an ECR ion source as an ionizer in a ground state atomic beam source has been considered, and offers the possibility of a high ionization efficiency (~20%) and large acceptance for the thermal polarized beam [26]. Problems with depolarization in an ECR ionizer are now considered to be unlikely, although this must still be verified experimentally. Such an ionizer will soon be tested at SIN, in a collaboration with Karlsruhe. If the ~20% ionization efficiency is realized, this should result in a factor of 4-5 improvement in intensity over that obtained with the present electron bombardment ionizer. An ionizer using the intense electron current and high density plasma from a hollow cathode discharge has also been proposed [27], but is untested.

At Brookhaven, components are being tested for a new source which combines three new developments [28]. This is shown in Figure 6. The atomic beam is cooled to ~6 K by collisions with a liquid helium cooled copper surface, which becomes coated with frozen H_2, producing a low recombination rate surface. This beam has been studied on a test stand, and the H^0 has a measured drift velocity of 6.4×10^4 cm/s and a Mach number of 5.4 [29]. Following the accomodator one has charcoal coated "skimmer" surfaces at 2.5 K to cryopump in that critical region, helping reduce beam losses from gas scattering. The spin selection and H^0 focusing will be provided by the gradient in the fringing field of a superconducting solenoid. In order to maximize this field gradient, the solenoid has three coils, with the current in the middle coil opposite to the outer two. The solenoid has been constructed, and its focusing will be tested soon. This test solenoid is not optimized for our atomic beam, and the final source will employ either a redesigned solenoid or sextupoles. The third element is an ionizer which uses the resonant charge exchange of polarized H^0 with D^- to produce polarized H^-. D^- is produced in a magnetron surface plasma source constructed in a ring geometry. A D^- current of ~0.5 A at the cathode energy of 200 V has been measured in the ring, giving an estimated D^- density of 10^{11} cm^{-3}. D^+ ions diffusing from the discharge are relied on to provide space charge neutralization of the D^- and $\vec{H}^-$. $\vec{H}^0$ atoms are ionized during passage axially through the ring, which has a large acceptance due to its short length. This ionizer has so far been tested with an unpolarized H^0 beam and 0.5 mA of H^- was extracted for an estimated atom density in the ionizer of 10^{12}. We expect to reach a pulsed $\vec{H}^-$ current of ~1 mA when all elements are combined.

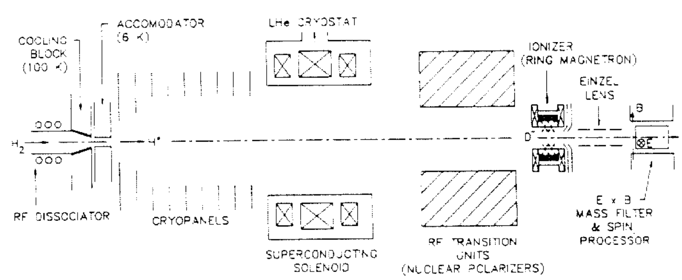

Fig. 6. Schematic of the planned BNL $\vec{H}^-$ source. Components are now being tested individually.

A potentially spectacular improvement in atomic beam intensity could come from an idea now being tested by a Michigan/MIT/ CERN collaboration, and shown in Figure 7 [30]. Atomic hydrogen is cooled to ~0.5 K by collisions with helium lined walls. They then approach the fringe field of an 8 T solenoid magnet, and atoms of one electron spin are pulled into the strong field and trapped ($\mu_B B$ > kT). Densities in the magnet of 10^{16} atoms/cm^3 seem possible from calculations. After the buildup of atoms, microwaves of the appropriate frequency will be sent into the trap in an attempt to cause a spin flip [31]. This would result in ejection of the atoms from the solenoid, which are accelerated and focused by the fringe field of the solenoid, forming an electron polarized H^0 beam. This beam could then pass through an rf transition unit and into an ionizer. A density in the pulsed (> 1 Hz) $\vec{H}^0$ beam of at least 10^{14}

Table I. Examples of Operating Sources of Various Types

Laboratory	Type	Approximate H° Temp. (K)	Pulse	$\vec{H}^+$ (μA)	$\vec{H}^-$ (μA)	Polarization
Kyushu Univ.	Lamb Shift	-	DC	3	3	80%
ETH-Zurich	G.S. + e^-	35	DC	400	16	-
SIN	G.S. + e^-	35	DC	~400		86%
Saclay	G.S. + e^-	100	2.5 ms, ~1 Hz	280		85%
BNL	G.S. + Cs^0	80	500 μs, ~1 Hz		30	75%
U. of Wisconsin	G.S. + Cs^0	300	DC		3	91%
INR, Moscow	G.S. + D^+	80	~50μs, 1 Hz	10,000		76%
KEK	Opt. Pumping	-	70 μs, 20 Hz		50 180	56% 43%
INR, Moscow	Opt. Pumping	-	40 μs, 1 Hz	4,000	400	65%
TRIUMF	Opt. Pumping	-	DC		≥10	60%

atoms/cm^3 is estimated (100 times higher than present densities). The dilution refrigerator has been operated, the external helium film established, and the 8 T solenoid is installed. Full testing, including density measurements in the cell, the effectiveness of the microwave ejection, and the density of the extracted beam, will begin this summer.

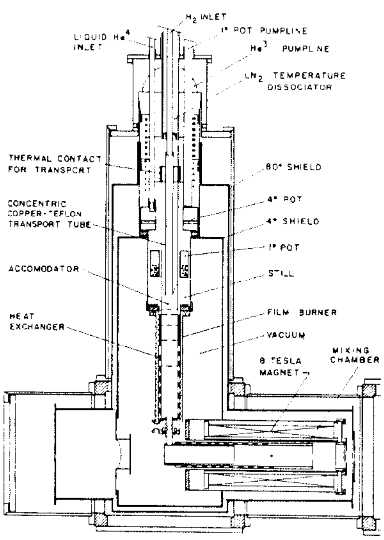

Fig. 7. The 0.5 K atomic beam device being prepared for testing by Michigan/MIT/CERN.

Another proposal, called "collisional pumping" in analogy with optical pumping, involves the passage of a beam through a thick polarized target in a weak magnetic field [32]. Here, multiple charge changing and spin exchange collisions, combined with the mixing between the electron and nuclear spins (in the weak magnetic field) between collisions, cause the ion beam to emerge almost purely neutral and with almost complete nuclear and electron polarization. Estimates for a 2.5 keV proton beam passing through an optically pumped Na target predicted a nuclear polarization of 95% for a Na target thickness of of 3×10^{15}/cm^2. This is about 30 times thicker than what is presently achieved in optical pumping sources [33], and radiation trapping could well limit the degree of polarization. If such a target could be obtained, mA's of $\vec{H}^-$ would be relatively easily produced. The required laser power was estimated to be 30 W/cm^2, although this depended on the spin relaxation time in the target. The result of a recent experiment done at INR, Moscow, suggests an obstacle to the use of Na, however [33]. At Na target densities above 10^{14} cm^{-3} the effective thickness of the target for H^- production falls off by nearly two orders of magnitude. This is attributed to the anomalously rapid formation of Na^+ and Na_2^+ ions, (for which the charge exchange cross sections are much smaller) when the cell was illuminated with resonant light. The use of a mixed Na/K cell [19], was suggested as a possible way to avoid this problem.

An idea which probably does not qualify as an "ion source", but does result in the production of polarized H^- ions, is selective neutralization [34]. Here, selective photodetachment of only one nuclear spin state of an H^- beam in a magnetic field, followed by separation of the negative and neutral beams, results in the production of a polarized H^- beam of half the intensity of the original unpolarized H^- beam. Lasers of the required power at the right frequencies are hard to find, so while several combinations of beam energy and lasers have been considered to test the concept, at this time all are either marginal or expensive.

Conclusions

Table I summarizes present performance of the various types of sources. Pulsed $\vec{H}^+$ currents have now reached 10 mA, and 400 μA has been obtained steady state. $\vec{H}^-$ currents of 400 μA pulsed and 16 μA steady state have been measured. (One must, of course, look more carefully at pulse width and duty factor when comparing performance among pulsed sources). One should note that polarized sources are quite complicated, and while we can be confident of higher intensities, the designs do not seem to be getting simpler

Speculating about what could be obtained in the near future (only $\vec{H}^-$ intensities will be considered in what follows), one could imagine a combination of the INR atomic beam stage with the University of Washington cesium ionizer producing in excess of 100 μA of $\vec{H}^-$. Or, one might decelerate the 10 mA $\vec{H}^+$ beam from the INR plasma ionizer source, send it through Na vapor, and produce ~500 μA, pulsed. The replacement of the electron bombardment ionizer at ETH by an ECR ionizer might produce >100 μA, DC. Future expectations for optical pumping sources generally are at the mA level. It has been calculated that the addition of D ions to the INR plasma ionizer could lead to 2 mA of $\vec{H}^-$, pulsed. At BNL, we are also expecting to reach the mA level in 500 μs, 7 Hz operation on our new source. Collisional pumping currents for an accelerator would also be in the mA range. A combination of the "ultracold" atomic beam and the ring magnetron ionizer could take one to many tens of mA's pulsed. While admittedly the above are speculative, the point to be made is that one can conceive of reaching, before too long, polarized intensities equal to present unpolarized currents used in accelerators. Development efforts to reach such intensities are underway, and recent progress, particularly in pulsed sources, has been quite impressive.

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