A REVIEW OF POLARIZED $H^{\pm}$ AND $D^{\pm}$ ION SOURCE TECHNOLOGY

Thomas B. Clegg, Department of Physics and Astronomy, University of North Carolina at Chapel Hill, 27599-3255 and Triangle Universities Nuclear Laboratory*, Duke University, 27706-0308

Abstract

A review is presented of recent technological developments which make possible beams of nuclear-spin-polarized $H^{\pm}$ and $D^{\pm}$ ions with milliampere level or greater intensities. We begin by discussing key physics processes underlying the creation and use of polarized beams. Then, we discuss how these apply to optically-pumped and atomic-beam polarized ion sources, the two principal types used today. Next, the typical performances of these sources are compared. Finally, specific technical advances which have led to recent improvements and which still promise further enhancements are presented.

1 PHYSICS PROCESSES USED

1.1 Basic Mechanisms

Nuclear spin polarization in $H^{\pm}$ or $D^{\pm}$ ion beams is created by using the atomic hyperfine interaction, because the electronic magnetic moment for H or D atoms is much larger than the nuclear moment. Thus, when nuclear polarization is desired, it is far easier first to polarize atomic electrons, and then through their mutual magnetic coupling, to transfer the preferred angular momentum to the atomic nucleus.

This means that several basic processes *must* be present to create beams of polarized nuclei. First, one must make a beam of H or D atoms. Second, one must create a population imbalance in these atoms between states having *electron* spin orientation parallel to, and opposite to, a selected magnetic field direction. This 'polarizes' the atomic electrons. Third, one causes transitions to occur which 'swap' the populations of selected atomic states, so the imbalance in populations then appears between states having *nuclear* spin parallel to, and opposite to, the defining B-field direction. This 'polarizes' the atomic nuclei. Finally, one removes an electron from, or adds an electron to the nuclear-polarized atoms, to create the ion species desired.

1.2 Polarization Definitions

The nuclear polarization of a beam is defined in terms of relative spin-state populations[1]. Thus, for $H^{\pm}$ beams, in which the proton may have spin projections with respect to the external B-field of $m_I = \pm 1/2$, the beam's *vector* polarization is defined as $P_z = (N^+ - N^-)/(N^+ + N^-)$. Here, N^+ and N^- indicate the populations in the respective atomic states. For $D^{\pm}$ beams, where deuteron spin projections may be $m_I = +1, 0,$ or -1, one has $P_z = (N^+ - N^-)/(N^+ + N^o + N^-)$. Also, because of its larger number of allowed spin projections, one may create deuteron beams with *tensor* polarization, defined as $P_{zz} = (3N^o - 1)/(N^+ + N^o + N^-)$.

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1.3 Measurement Techniques

Experiments using polarized beams usually alternate data collection with beams having maximal vector or tensor polarization difference, to enhance the sensitivity to the quantity being measured. The figure-of-merit determining the usefulness of polarized beams is $(\Delta P)^2 I$, where ΔP is the polarization difference between the states being used, and I is the beam intensity. Switching between states of different polarization can easily be accomplished at rates up to 10 Hz. One seeks to switch polarization states within a beam with minimum change in all other beam characteristics.

2 POLARIZED ION SOURCE TYPES

Polarized $H^{\pm}$ and $D^{\pm}$ sources used today are almost exclusively of two types: optically-pumped polarized ion sources (OPPIS) and atomic beam polarized ion sources (ABPIS). The technologies for both are being developed continually, and have been reviewed frequently at recent workshops and conferences [2-5].

2.1 Optically pumped polarized ion sources

Optically-pumped sources are based on ideas proposed originally by Anderson et al.[6], and have been enhanced enormously by the work of Y. Mori, A. Zelenski, and their collaborators at KEK, TRIUMF, and RHIC.[7] Basic components of OPPIS-style sources are shown in Fig. 1.

These sources create the H or D atoms needed by first creating H^+ or D^+ ions in an ECR source. The ions are then extracted, accelerated to ~3 keV, and injected into a charge-exchange canal containing rubidium vapor. Since the Rb atoms are spin-polarized by optical pumping, they provide a source of polarized electrons which are picked up by the passing H^+ or D^+ to form a beam of ~3 keV electron-spin-polarized H or D atoms. In the TRIUMF source shown in Fig. 1, light from the optical-pumping laser enters from the right, while light from a probe laser used to measure the Rb polarization enters from the left. The optical pumping occurs in a ~1 Tesla B-field to attain full Rb polarization. The direction of the polarization can be reversed easily by reversing the handedness of the circularly polarized optical-pumping light.

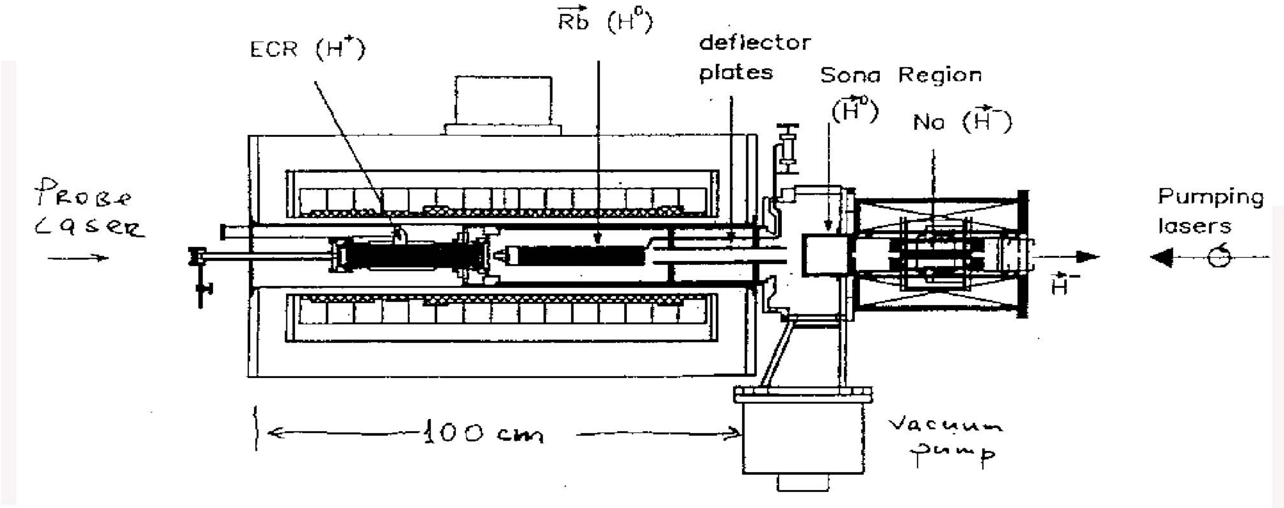

Figure 1: A schematic drawing of the OPPIS-type source installed at TRIUMF, showing the principal components required to produce a polarized H^- beam.

The polarized H or D atoms then move into a Sona region where the axial B-field reverses direction abruptly, such that there is an interchange of selected atomic state populations [8]. This converts the previous electron-spin-polarized atomic beam into one having nuclear spin-polarization. The polarized atoms proceed then into a second solenoidal field region where, inside a field of ~0.12 mT, charge-exchange occurs in sodium vapor to produce the desired polarized H^- ion beam. If instead polarized H^+ ions are needed, Na can be replaced with He.

The above process also provides polarized $D^{\pm}$ ions with a mixture of vector and tensor polarizations[9]. Enhanced vector polarization for D^- can be obtained by also optically pumping the Na vapor, which then provides a second polarized electron for pickup by the passing atom [10]. Enhanced tensor polarization for D^- may also be possible with the further addition of new RF transition systems[11], but these have not yet been tried.

2.2 Atomic beam polarized ion sources

Early atomic beam sources were demonstrated in the late 1950's, and continual development has led to their use today in 12-15 laboratories worldwide [11]. The atomic beam systems they employ have been separately developed further for producing polarized H or D gas targets for storage rings [12]. Basic components of ABPIS-style sources are shown in Fig. 2.

In these sources, one first makes H or D atoms by dissociation of H_2 or D_2 in an RF discharge. These exit

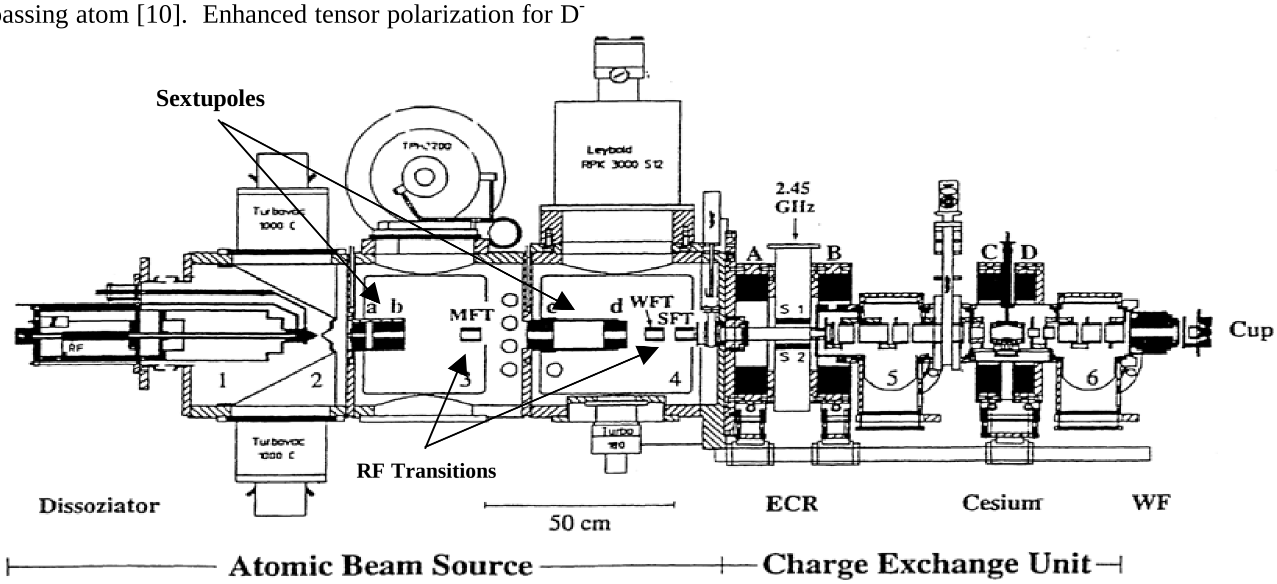

Figure2: A schematic drawing of the Munich atomic beam polarized ion source, showing the principal components needed to produce a polarized H^- or D^- beam.

the dissociator through a cooled nozzle to form a collimated atomic beam moving at a mean velocity of ~10^3 m/s. This beam passes down the axis of several sextupole magnets where their strong inhomogeneous B-field acts on the atoms' electronic magnet moments to focus those having spin aligned with the B-field and defocus those oppositely aligned. The remaining beam thus becomes electron-spin-polarized.

Then, to create nuclear polarization, the H or D atoms traverse several RF transitions designed to interchange atomic hyperfine state populations by adiabatic-fast-passage [13]. Transitions are switched on as needed to create nuclear vector-, and/or for D, tensor-polarization in the atomic beam.

Ionization in ABPIS-style sources occurs in several ways. Shown in Fig. 2 is the most common ECR ionizer, where a weak microwave-driven discharge is maintained. Inside this discharge, collisions of fast electrons with the passing polarized atoms implement the process $H + e \rightarrow H^+ + 2e$. The resulting H^+ (or D^+) ions are extracted from the discharge and may be fully accelerated immediately. Alternatively when needed, they may be accelerated only to ~500 eV (or 1000 eV for D^+) and focused into a cesium charge-exchange canal, where pickup of two electrons occurs to make H^- (or D^-).

Another ionization process used is charge-exchange with a fast neutral cesium beam [14] to make negative polarized ions by the process $H + Cs \rightarrow H^- + Cs^+$. Most successful have been other ionizers, discussed in detail below, in which polarized H atoms undergo resonant charge exchange inside a quasi-neutral, thermal plasma of D^- and D^+ ions and electrons [15].

3 PERFORMANCE COMPARISONS

Picoampere beams of polarized H or D ions were first created and accelerated for nuclear physics experiments over 40 years ago. Today, some new systems provide beam intensities nine orders of magnitude larger. Many also provide extremely reliable beams, with high-stability and, especially for D, wide flexibility in polarization choice. In many laboratories, these sources can operate for a month or more without significant maintenance.

Polarized ion source designs differ, so any direct comparisons of performance must account for these details. Design choices are dictated strongly by characteristics of the accelerator where a source is installed, and by the physics programs which use it. Thus, some sources provide only positive or only negative ions, some only polarized protons, some only operate DC, others only pulsed. Typically, sources with greater flexibility of output beams and polarizations provide lesser output intensity.

3.1 DC Systems

DC beams are used at tandem accelerators and cyclotrons. Most common there are ABPIS systems like that shown in Fig. 2. Merely by changing operating parameters, these sources provide either polarized $H^\pm$ or $D^\pm$. If positive beams alone are needed, typically 0.1 mA is available within a normalized emittance of ~0.1π mm-mrad [16]. When such a source must also provide negative beams, positive (or negative) currents of 50 (or 8) μA are more typical. When ECR ionizers are used, beam polarizations obtained are ~75% (for H) and ~80% (for D) of the theoretical maxima [17,18].

The DC OPPIS source at TRIUMF provides only polarized H^- beams. However, its high output current, polarization, and stability are truly impressive: up to 0.55mA of 85%-polarized H^- is available within a normalized emittance of 2π mm-mrad. More typically the aperture in this source has been limited to provide up to 150μA inside 0.8π mm-mrad for weeks during demanding experimental tests of nuclear parity violation in p-p elastic scattering[19, 20].

3.2 Pulsed Systems

Pulsed polarized sources for cyclic accelerators provide higher beam intensities. This is possible primarily by operation with much higher instantaneous gas loads, and/or powers, which cannot be sustained for DC operation.

The most recent pulsed ABPIS is now operating at IUCF providing both polarized and unpolarized H^- and D^- beams for their Cooler-injector-synchrotron [21]. This source employs a new pulsed plasma ionizer (discussed below) and provides 1.5 mA into 1.2π mm-mrad, in 150 μs pulses at 1 to 4 Hz, with beam polarization >80% of the maxima both for H^- and D^-.

A pulsed OPPIS has been installed at Brookhaven to inject polarized H^- beams into RHIC [22]. Based on designs developed during earlier tests at KEK and TRIUMF, it provides 0.6mA at 1 to 4 Hz inside 2π mm-mrad with beam polarization >85%. [7]

4 RECENT TECHNICAL ADVANCES

4.1 OPPIS-style Sources

Recent improved OPPIS performance [23] can largely be attributed to three developments: new high power laser technology, enlarged beam diameter enabled by a new biased Na vapor jet ionizer, and a redesigned ECR source with improved pumping.

Increased optical pumping capacity has come with a new flash-lamp pumped Cr^{3+}:LiSrAlF laser, developed initially at Lawrence Livermore Laboratory, but now available commercially. It provides 1kW in 500μs long pulses at 4 Hz. This provides higher Rb vapor polarization at higher Rb density than previously possible when the same charge-exchange region was pumped with the DC Ti:Sapphire laser traditionally used at TRIUMF. The new laser enables significantly higher H^- polarization and output beam intensity, as shown in Fig. 3.

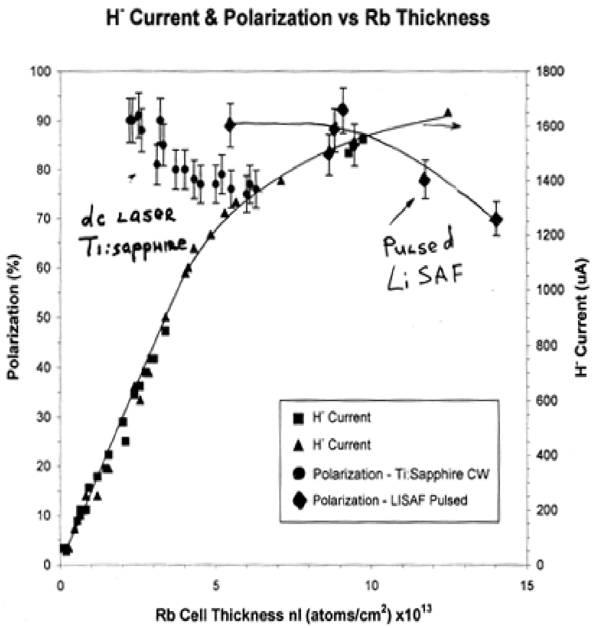

Figure 3: The H^- beam polarization and output current obtained with the RHIC OPPIS source when installed for early tests at TRIUMF. This shows that significantly increased polarization is obtained with the pulsed Cr^{3+}:LiSrAlF laser, especially at higher Rb vapor thickness in the charge-exchange region.

Further increase in output current was made possible by the development of a new, larger (2 cm) diameter, transverse Na jet ionizer. This employs recirculation of the Na to minimize its loss into other parts of the source; a 100 gm load in the oven lasts for 3 to 4 months of operation. This system is also biased at -32 kV. This feature enables both rapid acceleration of the resulting polarized H^- ion beam, to minimize emittance growth caused by the beam's internal space charge, and improved axial confinement of the Na^+ ions produced by charge exchange. A positive side effect to the improved Na confinement is greater overall reliability because Na^+ migration into nearby regions of the source is substantially reduced.

4.2 ABPIS-style Sources

All atomic-beam-type sources have been enhanced in the past decade by improvement in atomic H and D beam focusing made possible by the development of high-field permanent magnet sextupoles [24]. These provide pole-tip fields up to 1.5 Tesla with central apertures as small as 14 mm [25] and have been incorporated into all recent atomic beam systems, both for ion sources and for polarized H or D jet target applications.

ABPIS sources for $D^\pm$ now have RF transition systems which routinely and reproducibly provide atomic beams with purely vector- or purely tensor-polarized beams of high polarization and opposite sign. This feature greatly enhances experimental measurements [26].

Most important for pulsed ABPIS systems have been the plasma ionizers developed at INR-Moscow by A. Belov and his collaborators. First implemented over a decade ago [27], they utilize the very large, resonant, low-energy charge-exchange reactions first proposed by Haeberli [14] to implement the processes $H + D^\pm \rightarrow H^\pm + D$. Originally, Haeberli suggested ionizing polarized H with $D^\pm$ ions of ~1 keV, but implementation of this idea was frustrated by the large internal space charge present in these low energy beams. The use instead of a quasi-neutral plasma in the pulsed ionizers of Belov *et al.* has overcome this problem.

A schematic of this ionizer type is shown in Fig. 4. Here, the neutral polarized atomic beam enters the ionizer from the left, passing through the poles of a bending magnet and through the electrodes of an ion extraction system. It then enters a storage cell at the end of the ionizer's ~0.1 mT solenoid.

The storage cell is filled with a deuterium plasma jet injected from the opposite direction. The $H^\pm$ ions produced there by charge exchange are confined by the axial B-field and, when an extraction voltage pulse is applied, reverse direction and are extracted as a polarized ion beam. Since the beam is charged, it is easily separated by the analyzing magnet from $D^\pm$ plasma ions which are extracted simultaneously.

The D^+ or D^- plasma used is created in an intense pulsed discharge. This creates ~10 eV D^+ ions directly, and when D^- ions are needed, these are produced by a two-step process. First, the D^+ are directed by a cusp magnetic field onto a conical metal surface where they are almost completely neutralized. The neutral atoms then reflect onto a cesium-coated surface where they are converted efficiently to D^- ions. This type of negative-ion, surface plasma source is discussed in another contribution to this conference.[28]

When producing polarized H^- ions, one wants to minimize the number of plasma electrons because they

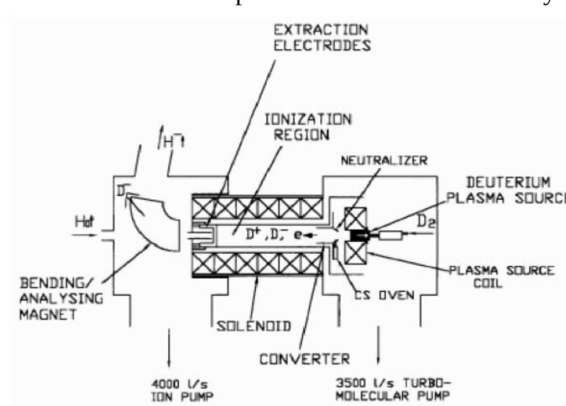

Figure 4: Schematic diagram of the resonant charge-exchange plasma ionizer developed at INR-Moscow.

cause the polarized H to be stripped to H^+, a process which competes with the D^- charge-exchange process needed to create H^-.

Belov reports [29] that with a plasma discharge current of 460 A, which produced a peak extracted D^- current of 42 mA from the storage cell, he could extract polarized H^- currents up to 2.5 mA in 150 ms pulses at repetition rates up to 10 Hz. The extracted polarized beam's normalized emittance was 2π mm-mrad.

5 OPPORTUNITIES AND CHALLENGES

5.1 OPPIS-style Sources

Further improvement of OPPIS-style sources of polarized H^- seems likely. Already, Zelenski has reported early tests of a modified pulsed OPPIS source [30] in which the ECR system usually used for producing H^+ was replaced by a two-stage system. This employed an intense H^+ injector developed at BINP-Novosibirsk to produce up to 10 A of H^+ at 3 to 5 keV. This intense, space-charge-neutralized positive ion beam was quickly injected into a He cell where charge-exchange occurred to produce a beam of fast neutral H atoms. These were then magnetically focused along the axis of the traditional ~1 T solenoidal magnetic field of the TRIUMF OPPIS source without emittance growth, and entered the neutralizer cell containing polarized Rb vapor.

In these early tests, up to 8 mA of pulsed polarized H^-, and up to 50 mA of polarized H^+ was produced with a beam polarization of 42 ± 5%. The polarization would have been enhanced, it is believed, by a larger and more uniform B-field over the polarized Rb neutralizer cell.

An attractive addition to OPPIS sources would be development of π-flip RF transitions [11] to provide maximum, rapidly switched deuterium tensor polarization.

5.2 ABPIS-style Sources

Improvements are being tested also for ABPIS sources. Recent tests [32] indicate that the D^- plasma current in the pulsed plasma ionizer can be raised. Belov reports that, after refinements of his charge-exchange ionizer, he extracted up to 90 mA of D^- beam from the charge-exchange storage cell. Prior experience has shown the output, polarized ion current to be proportional to this extracted D^- current. However, subsequent tests of ionization efficiency have yet been made with polarized H atoms injected into the storage cell.

At some point, saturation must be reached, dictated by the flux of polarized H atoms entering the storage cell. Belov's atomic beam system, which has provided polarized H atoms for all his recent tests, has not been upgraded to include permanent magnet sextupoles. Were this done, he would likely also reach higher polarized H^- beam current before saturation occured.

A clear challenge, however for the Belov plasma ionizer, is developing them to operate in DC mode. Significantly improved pumping would surely be required before that could be achieved.

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