IEEE Transactions on Nuclear Science, Vol. NS-28, No. 3, June 1981

RECENT DEVELOPMENTS IN POLARIZED ION SOURCES

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Abstract

After many years and a great deal of success in developing the Lamb-shift and ground-state-type polarized ion sources the polarized ion source users are now shifting their attention to several fundamentally different approaches. These new approaches appear to have the potential of producing $H^-\uparrow$ currents that are many orders of magnitude larger than allowed by conventional sources.

Introduction

Twenty-five years have passed since the pioneering work of Clausnitzer, Fleishmann, and Schopper[1] on the first operational polarized ion source. In the intervening years substantial improvements have been made in both current and polarization and today there is a large number of operational polarized beams around the world. Most of these beams are produced using either a ground-state source or a Lamb-shift source. Ground-state sources for positive beam applications have reached the 100 μA[2,3] range and Lamb-shift sources and ground-state sources for negative ion applications have reached the μA range.[4,5,6] These sources have allowed very productive polarized beam experimental programs at many nuclear physics laboratories, at the high intensity medium energy facilities and, until it was shut down in late 1979, at the 12 GeV ZGS at Argonne National Laboratory (ANL).

While strong polarized beam programs exist, experimental and operational limits imposed by fundamental accelerator intensity limits have not yet been reached. At low energy facilities the experimental limits tend to be the key consideration whereas at the medium- and high-energy facilities operational limits are a problem. At the Los Alamos Meson Physics Facility (LAMPF), the Lamb-shift source produces ~1 μA while the unpolarized H^- program requires 200-300 μA.[7] At the ZGS, before its shutdown, the polarized beam intensity was $\sim 5 \times 10^{10}$ p/p whereas the unpolarized beam program required 5×10^{12} p/p. With the polarized beam intensities orders of magnitudes below that required to run the unpolarized program, operational scheduling problems develop because of the necessity to time share between the polarized and unpolarized programs. If adequate polarized beam current were available both programs could be operated simultaneously and polarized beam users would be rate-limited only by the accelerator itself. While sources are not available that are capable of operating pulsed machines at their space charge limits, or experimental areas at their intensity limits, significant advances have been made and several new approaches are being developed which may eventually lead to this.

Ground-State Sources

The many users of ground-state sources around the world have, over the past 25 years, made various modifications to their sources. Some of these modifications actually led to improvements on their performances and, if one were to incorporate all of these improvements into a new design, the results would be impressive. Pulsed sources incorporating all of these features could be expected to produce $H^+\uparrow$ currents of 200 to 500 μA.

The key improvements made on operational sources in recent years have involved cooling of the dissociator, segmenting the sextupole magnet and increasing the ionizer efficiency. The expected value of cooling the dissociator stems from the T^{-1} sextupole acceptance temperature dependence and the $T^{-\frac{1}{2}}$ ionization probability dependence. As a result of the positive results obtained by Wakuta, et al.[8] when they cooled a dissociator tube nozzle to LN_2 temperatures, Schultz, et al.[2] cooled the dissociator nozzle on the ANL source to 30°K. They observed a $T^{-\frac{1}{2}}$ current response and a total current improvement of a factor of 2.5.

The thermal atomic hydrogen beam produced by the dissociator has a very large percentage momentum spread which cannot be efficiently matched into the ionizer. Following a proposal by Glavish,[9] a number of groups have added a second sextupole in a series with the main separation magnet. This additional drift space and focusing element should improve the matching efficiency into the ionizer by a factor of 1.3 or better.

The big improvement in ground-state source technology of recent years is in ionizer efficiency. These so-called superionizers are basically scaled-up models of standard configuration. The length increase coupled with better solenoid field shapes and electron gun power supplies have produced very impressive (up to x10) current increases.[3,10]

Change Transfer Source

In 1968 Haeberli[11] proposed the direct conversion of polarized atomic hydrogen into negative ion beams by a process of the type

$$H^o\uparrow + X^n \rightarrow H^-\uparrow + X^{n+1}$$

This suggestion did not generate much interest at that time because of the successful development of the Lamb-shift source. Now this idea is being developed by at least two groups, the University of Wisconsin for use on the Wisconsin tandem Van de Graaff[12] and ANL for use on the Brookhaven National Laboratory (BNL) AGS.[13]

Figure 1 shows a schematic of this type of source for a neutral and negative X^n since the two top candidates for X^n are Cs^o and H^-. The $H^o\uparrow$ beam is produced by a conventional atomic beam stage, i.e., atomic hydrogen produced in an Rf dissociator is passed through a Stern-Gerlach separation magnet and then an Rf transition stage to produce an aligned nucleous atomic hydrogen beam. This beam is then crossed with the X^n beam which has a velocity corresponding to the peak of the charge exchange cross section. The charge exchange region is simply a channel maintained at a high voltage (10-20 kV) to allow extraction of the $H^-\uparrow$ ions. The channel is provided with a solenoidal field to maximize the degree of polarization and, in the case of a charged X^n beam, to control space charge effects.

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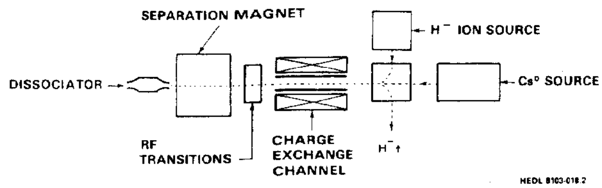

Figure 1. Charge Exchange Source

The output current from this type of source is

$$I_{H^-\uparrow} = \frac{I_{H^O}\, V\sigma}{v_{H^O}}\, I_X n$$

where I_{H^O} is the intensity of the atomic hydrogen beam, v_{H^O} is the average velocity of the H^O beam, V is the volume of the overlap of the two beams, $I_X n$ is the intensity of the ionizing beam and σ is the charge exchange cross section. I_{H^O}/v_{H^O} is determined by the design of the atomic beam stage. Combining the best features developed to date in a single unit should, in pulsed operations, produce a H^O density in the range of $2\text{-}5 \times 10^{11}$ atoms/cc. The optical properties of the atomic beam stage and the very large percentage momentum spread in a thermal beam combine to give a practical upper limit on V of about 30 cc ($\sim$1 cm^2 x 30 cm long cylinder). Being neutral, a Cs^O beam will not restrict V and the output current depends only on $I_X n$. For H^- and D^- beams, space charge effects will give V a dependence on $I_X n$.

The development areas for this source are the production of the ioning beam, X^n, and coupling this beam to the H^O beam in the charge exchange volume V. With the advent of the magnetron-type ion source,[14] high current density H^- and D^- beams are readily available, particularly for pulsed beam applications. The H^- or D^- exchange is a zero energy resonance process so its cross section is large only at very low energies, and low-energy-charged beams present difficult space charge problems. Calculations for a mA/cm^2 H^- beam decelerated from 10 keV to 0.5 keV indicated a V_{max} of 1 cc. Thus, although 50-100 mA H^- beams are available they are not useful unless space charge effects can be controlled. Simple scoping calculations indicate that a 2-Telsa solenoid might contain a few mA/cm^2 beam and the resulting $H^-\uparrow$ ions. The $H^-\uparrow$ beam produced under such circumstances will have a large transverse emittance and energy spread.

Cs^O does not present this coupling problem and this is the reason the two groups, University of Wisconsin and ANL, developing this source have selected Cs^O as the ionizing beam. There is a production problem with Cs however and there are no well-developed Cs sources available for this application. The Wisconsin group uses a 3/4-inch diameter porous tungsten plug as the Cs^+ gun emitter in a Pierce gun operated at about 40 kV.[15] The Cs^+ gun is followed immediately by a Cs charge exchange cell for neutralization. Ten to twelve mA can be extracted and neutralized with this gun, however, only 2 or 3 mA can be matched into a 30-cm long charge exchange channel. The Wisconsin group feels considerably higher useful Cs^O currents can be produced using tungsten buttons given some development.[16]

The ANL source development program is directed toward producing a pulsed $H^-\uparrow$ beam for the BNL AGS. This pulsed-beam-only application not only allows the use of a pulsed atomic beam stage with its higher atomic beam intensity, but it also allows the use of a low duty factor pulsed Cs beam. Operating the Cs beam at a low duty factor will remove the need to engineer protection against the surface erosion problems associated with intense low-energy heavy-ion beams.[15] There is concern that the porous tungsten button-type gun will be difficult to operate in a pulsed mode. For this reason they are considering alternate techniques.[13,17] The technique that appears particularly interesting is a Cs-impregnated alumina-silicate button. A gun using this type of button will look essentially like one using a tungsten button but without a Cs boiler. This type of emitter does not produce a Cs vapor background like the porous button so insulator shorting should not be a problem. It should be capable of 10-20 mA/cm^2 when operated at 100 kV. At this voltage, V, $\sigma V^{3/2}$ is a maximum.

It appears that with some development work Cs^O beams of at least 20-30 mA should be practicable. Such beams coupled to a good atomic beam stage could be expected to yield a pulsed current of the order of 50 to 100 µA of $H^-\uparrow$. For synchrotrons H^- ion injection is 20 to 30 times more efficient than H^+, so 100 µA of H^- is equivalent to 2-3 mA of H^+.

As stated above this source is being developed at the University of Wisconsin and ANL. The Wisconsin source has been operational for over 2 years. It has produced currents up to 3.3 mA and polarizations of 91%.[16] At ANL an atomic beam stage is operational and Cs gun design is underway. They expect to produce their first Cs beams using an alumina-silicate button in the Spring of 1981. Experiments coupling this Cs beam to the atomic hydrogen beam should begin in the Summer of 1981.[17]

Laser-Pumped Na

The conventional ground-state source, the Lamb-shift source and the charge exchange source discussed above all start out with atomic hydrogen which is then polarized by passing the beam through some filtering stage which transmits only those atoms in some particular state. In 1957, Zarviskii[18] proposed starting out with bare protons and allowing them to pick up a polarized electron. This idea did not appear to be very practical for the production of high-intensity beams until Anderson[19] proposed the use of laser-pumped Na as the source of the polarized electron. Figure 2 is a schematic of a source based on these ideas proposed by Anderson.

Circularly polarized 6Å light produced by a dye laser and quarter-wave plate is incident on the Na cell parallel to the solenoidal field. The nuclear spin of

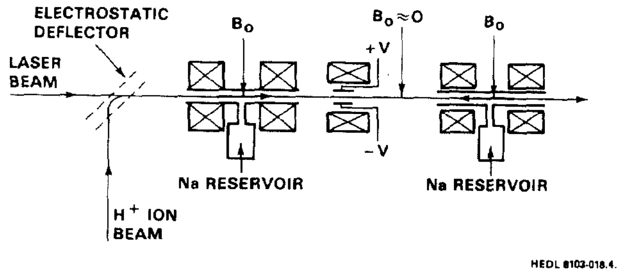

Figure 2. Laser-Pumped Na Source.

^{23}Na is 3/2 and its ground state is a $3^2S_{1/2}$ level. In a strong magnetic field the ground state level splits into eight sublevels, i.e., $M_J = +\frac{1}{2}$, $M_I = \pm\frac{1}{2}$; $M_J = +\frac{1}{2}$, $M_I = \pm 3/2$; $M_J = -\frac{1}{2}$, $M_I = \pm\frac{1}{2}$; and $M_J = -\frac{1}{2}$, $M_I = \pm 3/2$. Each set of four states associated with each M_J is contained within an energy band of about 1.5×10^9 Hz. The first excited state, $3^2P_{1/2}$, is about 6Å above the ground state. The incident light, if left circularly polarized, will pump $3^2S_{1/2}$, $M_J = -\frac{1}{2}$ atoms to the $3^2P_{1/2}$, $M_J = +\frac{1}{2}$ state according to the $\Delta M_J = +1$ selection rule. The $3^2P_{1/2}$, $M_J = +\frac{1}{2}$ excited state radiatively decays back to the ground state. Those atoms returning to the $3^2S_{1/2}$, $M_J = -\frac{1}{2}$ state will once again be pumped to the $3^2P_{1/2}$, $M_J = +\frac{1}{2}$ state until the $3^2S_{1/2}$, $M_J = -\frac{1}{2}$ state is depleted. If the pumping is complete all of the Na atoms will then be in a $M_J = \frac{1}{2}$ state, i.e., completely polarized. Right circular polarization for which $\Delta M_J = -1$ will produce polarization with $M_J = -\frac{1}{2}$. In order for complete pumping to take place the frequency spread of the light must be adequate to encompass all four M_I sublevels associated with the M_J state being pumped.

Protons at 5 keV are injected via an inflector into the Na cell. The 5 keV energy corresponds to the peak in the $H^+ + Na \rightarrow H^0 + Na^+$ cross section. The inflection is required to allow the laser light to enter along the magnetic field lines, a requirement for the optical transitions (σ) needed here. Emerging from the Na cell we have a fast H^0 beam with electronic polarization. The beam then traverses a second Na charge exchange cell mounted in a solenoid where the H^0 atoms pick up an electron to form an H^- beam. Nuclear polarization is produced by making the two solenoidal fields oppose each other. Properly adjusted, a field reversal with the proper gradient can be produced to allow a Sona-type transition.[20]

The development areas for this source are (1) production of an adequately thick polarized Na target, (2) maximizing the beam polarization and (3) coupling adequate proton current to the Na cell. The first problem simply involves the question of how many Na atoms can be maintained in the proper state with practical lasers. Anderson[19] calculates that a 1-Watt laser can produce a target thickness of 5×10^{13} atoms/cm^2 with an electron polarization near 100% if the cell walls are such that wall collisions do not depolarize the Na. If collisional depolarization cannot be avoided, up to 6 Watts might be required to produce a 5×10^{13} atoms/cm^2 density. The 5×10^{13} atoms/cm^2 is an upper limit on the Na cell thickness for pumping from only one end. This results from imprisonment of the resonance radiation. At a density of about 10^{12} atoms/cc, the probability is high that the photons emitted when the $3^2P_{1/2}$, $M_J = +\frac{1}{2}$ state decays to the ground state will be absorbed by Na instead of the walls. This will excite the atoms to the P state which, upon decay, can lead to atoms in the $3^2S_{1/2}$, $M_J = -\frac{1}{2}$ state. Thus, as the Na density increases, more resonance radiation is "trapped" in the cell and this decreases the pumping efficiency.

The only experimental results reported to date that this author is aware of on the question of pumping effiency comes from Mori, et al.[21] Using an 0.8-Watt laser they report a Na polarization of about 70% for a target thickness of 3×10^{12} atoms/cm^2. This is in good agreement with Anderson's[19] calculations assuming wall depolarization. Preliminary results from a Los Alamos Scientific Laboratory (LASL) experiment indicate that the power requirements calculated by Anderson may be overly conservative.[22]

The difficulty of obtaining high H^0 polarizations results from the fact that the H^0 atoms will most probably be formed in the n = 2 excited state. Those atoms in the 2p excited state will radiatively decay to either the $3^2_{1/2}$, $M_J = +\frac{1}{2}$ or $3^2_{1/2}$, $M_J = -\frac{1}{2}$ state. This reappearance of the $M_J = -\frac{1}{2}$ state means a lower H^0 polarization than Na polarization. Anderson[19] calculates a H^0 polarization of 40% assuming all of the atoms are produced in the 2p state. This is in general agreement with the polarization obtained by both Witteveen[23] and Mori[24] on sources where the polarized Na is produced by a Na oven and Stern-Gerlach separation magnet. Witteveen and Mori both conclude however that these low polarizations are due to background effects.

If the H^0 is formed in a magnetic field strong enough to decouple L and S, the transition from the 2p state to the 1s state will not lose polarization. Figure 3 shows the calculated polarization as a function

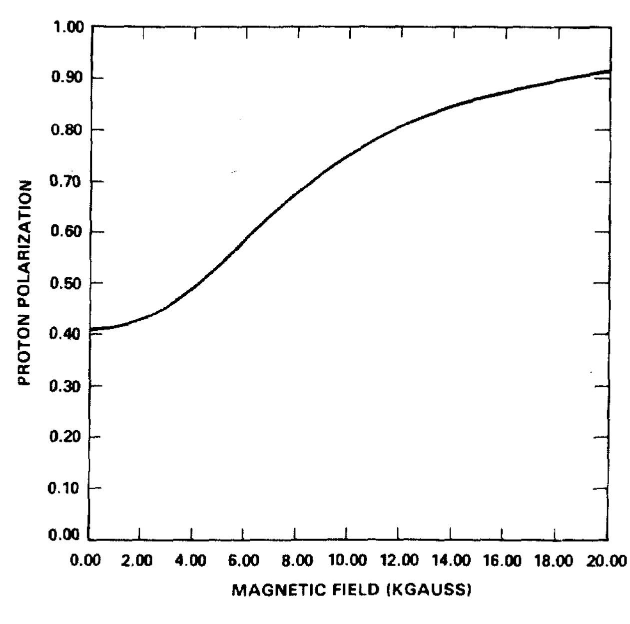

Figure 3. Polarization vs Magnetic Field Assuming All Atoms in the 2p Level.

of magnetic field assuming all H^0 atoms are formed in the 2p state.[22] This shows that very high fields are required to produce high polarizations. Such fields present not only engineering problems but also emittance problems.

The third problem, i.e., how to couple adequate proton current to the Na cell, results from the ever-present space charge and emittance considerations associated with charged beams and solenoids. Clearly the way to handle both aspects of this problem simultaneously is to mount the proton source inside the solenoid and arrange to get the pumping light in some other way.[22] If the Na in the second charge exchange cell were replaced by something transparent to the pumping light the first cell could be pumped from the opposite end. With this type of arrangement proton currents in the 10s of mA could certainly be produced and currents of ≈ 100 mA may be possible. Figure 4 is a schematic of such a source.

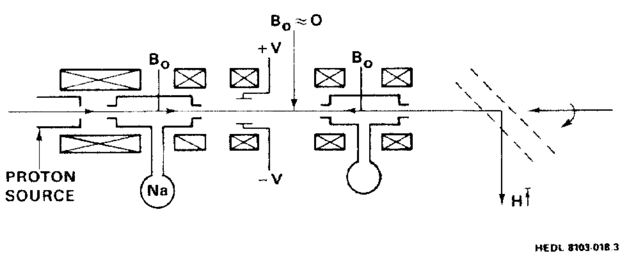

Figure 4. Laser-Pumped Na Source with Proton Source Mounted in Solenoidal Field.

If we assume that the above problems are solved to produce the "plausible" results included, i.e., a target thickness of $5x10^{13}$ atoms/cm^2, ∿100% polarization, a proton current of 100 mA, an ideal second Na charge exchange cell (7.3% conversion eff) and an adequately powered laser, we could expect a $H^-\uparrow$ current of 2 mA. Currents of this level would come close to allowing normal beam intensities at most accelerators.

At this time there are at least two groups involved in developing this type of source. The only full-scale development program this author is aware of is at the National Laboratory for High Energy Physics in Japan. The status of this program will be reported at this conference.[25] LASL has a program presently directed at studying the optical pumping problem and polarization problem.[22] As mentioned above, their preliminary results indicate that the laser power requirements are considerably smaller than that indicated as worst case in Anderson's calculations.[19] In the near future they expect to couple a proton source to their pumped Na cell in order to measure the polarization vs solenoidal field strength. This should indicate the magnitude of the excited state problem and what minimum field will be required to produce an adequate polarization.

Summary

In summary it appears that work going on at ANL, LASL, Wisconsin and Japan will shortly lead to a new generation of $H^-\uparrow$ ion sources. Early versions of these sources can be expected to produce currents in the 10 to 100 μA range with high polarization. Once several such sources become operational the inevitable improvement efforts will lead to higher and higher currents and perhaps eventually to the mA range.

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