NEGATIVE HYDROGEN SOURCES FOR BEAM CURRENTS BETWEEN ONE MILLIAMPERE AND ONE AMPERE

Th. Sluyters
Brookhaven National Laboratory
Upton, New York 11973

Abstract

Reviewed are the methods employed in the production of negative hydrogen ions in the current range of 1 mA to 1A.

1. Introduction

Before 1972 the output of practically all negative hydrogen ion sources was limited to beam currents less than one milliampere. In recent years considerably higher beam currents have been achieved from newly developed sources for possible applications in fusion reactors as well as in high energy accelerators or storage rings. For controlled fusion experiments, dense negative ion beams may improve the trapping efficiency by multturn charge exchange injection.

For the production of negative ion beams one can distinguish two methods: the direct production of negative ions in a plasma environment and the indirect production of these ions either by charge exchange of energetic protons in a charge exchanger or by the interaction of energetic beams with surfaces (secondary ion emission).

The direct production of negative ions in a discharge is of a complex nature. Its development is therefore slow: negative hydrogen production in the milliampere range was limited for more than eight years to Ehlers' 5 mA PIG source. This period ended in 1972 with the development of new types of plasma sources: the hydrogen-cesium magnetrons at the Institute of Nuclear Physics (Novosibirsk), the hollow discharge duoplasmatron at the Efremov Scientific Research Institute (Leningrad), and the hydrogen-cesium duoplasmatron at Brookhaven National Laboratory (Upton).

In the hydrogen discharge of these sources the negative ion output was improved by an order of magnitude. The yield of negative ions was further enhanced by adding cesium to the discharge.

The indirect production of negative hydrogen ions by charge exchange is well developed by its extensive use in tandem accelerators. In these sources protons are accelerated and focused into an electron donor cell or jet. Recent progress in the development of uniform dense proton beams in conjunction with hydrogen or alkali vapor charge exchange cells or jets enhanced the currents to tens of milliamperes.

Another potential candidate of the indirect method of negative ion production in the multi-milliampere range is secondary ion emission from a solid material by energetic ion beams. So far the yield of these sources is still lower than 1 mA and therefore outside the scope of this article.

In a recent review of formation of negative hydrogen ions in direct extraction plasma sources, the data on the most fundamental processes leading to the creation and destruction of a negative hydrogen ion in a discharge are discussed, as well as the theories and experimental results in Penning discharges, duoplasmatrons and a "low density" magnetron.

This paper is an attempt to supplement this information with a summary of the fundamental processes in plasma as well as in charge exchange sources and to survey the direct and indirect H⁻ sources for beam currents more than 1 mA.

2. Collision Processes in Hydrogen Plasmas

The essential cross sections and reaction rates for H⁻ creation and destruction in a hydrogen discharge have been described in detail in Ref. 15.

Negative hydrogen ions are mainly produced by their formation in a molecular gas or a molecular ion gas with dissociation of the molecule with or without capture of the electron. These processes for the creation of negative ions are...
The experimental production data for these collisions as a function of the electron energy are summarized in Fig. 1, while Table I shows the maximum cross sections and corresponding reaction rates. Not all fundamental processes are here considered. It may well be that at certain source conditions the excited states of the ions and neutrals play a role. However, the lifetime of the excited, radiative states is very short ($1.6 \times 10^{-9}$ sec), so that the time between successive collisions is in general longer than the excited state lifetime. Although the lifetime for metastable states is much longer ($0.14$ sec), most of them will de-excite very fast in plasma sources, like the duoplasmatron and magnetron, where high electric and magnetic fields exist.

**TABLE I.** Maximum values of cross sections and corresponding energies for elementary processes leading to the production or destruction of a negative hydrogen ion. For the reaction rate values the corresponding energy or temperature is indicated in parentheses.

<table>
<thead>
<tr>
<th>Process</th>
<th>Reaction</th>
<th>$\sigma_{\text{max}}$ (cm$^2$)</th>
<th>Energy for $\sigma_{\text{max}}$ (eV)</th>
<th>Reaction Rate (at kT) (&lt;\sigma_0&gt;) ((\text{cm}^3/\text{sec})$$)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Productions</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dissociative Attachment</td>
<td>e + H$_2$ → H$^-$ + H$^+$</td>
<td>$1.6 \times 10^{-21}$</td>
<td>3.7</td>
<td>$5 \times 10^{-13}$ (4 eV)</td>
</tr>
<tr>
<td></td>
<td>e + H$_2$ → H$^-$ + H$^*$</td>
<td>$2.1 \times 10^{-20}$</td>
<td>14</td>
<td>$3 \times 10^{-12}$ (15 eV)</td>
</tr>
<tr>
<td></td>
<td>e + H$_2$ → H$^-$ + H$^+$ + e</td>
<td>$1.7 \times 10^{-20}$</td>
<td>38</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>rising</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dissociative Recombination</td>
<td>e + H$_2$ → H$^-$ + H$^+$</td>
<td>$10^{-17}$</td>
<td>3</td>
<td>$3 \times 10^{-10}$ (3 eV)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Collisional Detachment</td>
<td>e + H$^-$ → H + 2e</td>
<td>$4 \times 10^{-15}$</td>
<td>15</td>
<td>$7 \times 10^{-7}$ (15 eV)</td>
</tr>
<tr>
<td></td>
<td>H$^+$ + H$^- + 2H + e$</td>
<td>$1.6 \times 10^{-15}$</td>
<td>500</td>
<td>$10^{-9}$ ($\sim 1$ eV)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Associative Detachment</td>
<td>H$^-$ + H$^-$ → e</td>
<td>$10^{-15}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Collisional Detachment</td>
<td>H$^+$ + H$_2$ → H + H$_2$</td>
<td>$2.5 \times 10^{-13}$</td>
<td>0.15 (c.m.)</td>
<td>$5 \times 10^{-7}$ ($&lt; 1$ keV)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Destruction</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dissociative Attachment</td>
<td>H$^-$ + H$_2$ → OH$^-$ + H$_2$</td>
<td>2</td>
<td>$3 \times 10^{-8}$ (2 eV)</td>
<td></td>
</tr>
</tbody>
</table>
Distinction between dissociative attachment and dissociative recombination is that the dissociative attachment reaction has a significant isotope effect up to an electron energy around 15 eV.

A comparison of these processes suggest that dissociative attachment and dissociative recombination are probably the main processes for the creation of negative ions in a plasma. In particular dissociative recombination between low energy electrons and molecular ions (with a theoretical cross section of $10^{-17}$ cm$^2$) is three orders of magnitude above the values for dissociative attachment. Supplemental calculations are required; experimental verification of dissociative recombination is contemplated by B. Peart et al.\textsuperscript{17}

The collision processes for the destruction of negative ions are the reactions between the negative ion and electron as well as between the negative ion and the neutral or charged hydrogen particle.

Charge Transfer
\begin{align*}
\text{H}^- + \text{H}^+ & \rightarrow 2\text{H} \\ 
\text{H}^- + \text{H}_2 & \rightarrow \text{H} + \text{H}_2
\end{align*}
\tag{6}
\tag{7}

Collisional Detachment
\begin{align*}
\text{H}^- + \text{e}^- & \rightarrow \text{H} + 2\text{e} \\ 
\text{H}^- + \text{H}^- & \rightarrow \text{H} + \text{H} + \text{e} \\ 
\text{H}^- + \text{H}_2 & \rightarrow \text{H} + \text{H}_2 + \text{e}
\end{align*}
\tag{8}
\tag{9}
\tag{10}

Associative Detachment
\begin{align*}
\text{H}^- + \text{H}_2 & \rightarrow \text{H} + \text{H}_2 + \text{e}
\end{align*}
\tag{11}

Dissociative Attachment
\begin{align*}
\text{H}^- + \text{H}_2\text{O} & \rightarrow \text{OH}^- + \text{H}_2
\end{align*}
\tag{12}

The experimental destruction data as a function of energy are shown in Fig. 2, while in Table I the maximum destruction cross sections and corresponding reaction rates are summarized.

Comparison of the production and destruction collisions show that the cross sections for destruction are much larger (three orders of magnitude) than the cross sections for creation of such an ion.

An important "destruction" mechanism is charge exchange between a fast negative ion and a slow atom, leading to a slow negative ion and a fast atom.

\begin{align*}
\text{H}^- + \text{H} & \rightarrow \text{H} + \text{H}^-
\end{align*}
\tag{13}

It was suggested by Bel'chenko et al.\textsuperscript{7,18} that this reaction plays an important role in the population of H\textsuperscript{−} particles in the magnetron.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{fig2}
\caption{Negative hydrogen destruction cross sections as a function of energy.}
\end{figure}

3. Charge Exchange Collisions in Hydrogen and Alkali Vapors

Knowledge of the elementary processes, which govern the indirect production of negative ions, is not only required for the understanding of charge exchange sources, but they may well be of interest for plasma sources as well. Therefore, the energy range of interest considered here, starts from several eV to the resonant energies. It should be mentioned that the experimental data for the low (< 1 keV) energy range are very limited by practical limitation of the measuring equipment.

During passage of energetic protons through gases or vapors the dominant process in the formation of negative hydrogen ions is the double charge exchange collisions. The first charge exchange process is the formation of neutral atoms by electron capture.

\begin{align*}
\text{H}^+ + \text{X}^0 & \rightarrow \text{H}(\text{ls,2s,2p...}) + \text{X}^+ + \Delta\text{E}
\end{align*}
\tag{14}

in which X\textsuperscript{0} is the target particle and the energy defect $\Delta\text{E}$ is the difference between the internal energies of particles before and after the collision process. The probability of this charge exchange process to the ground state is presented by $c_{1,0}$. While the H(2p) radiative state decays immediately ($1.6 \times 10^{-5}$ sec) to the ground state, emitting a Lyman $\alpha$ photon, the H(2s) metastable state has a long lifetime (0.14 sec) in the...
absence of strong electric and magnetic fields. The cross section of the formation of \( H(2s) \) of this process is \( \sigma_{1,m} \).

In the second stage of this multiple step process the negative ion is formed by electron attachment, as for instance

\[
H(1s) + X - H^-(1s,1s) + X^+ + \Delta E . \tag{15}
\]

The probability of this second charge exchange collision is then \( \sigma_{0,-1} \).

The most widely spread target applied in today's accelerators is hydrogen gas. Donally et al.,\(^{16}\) introduced the more effective alkali vapor targets by comparing the trends in data on cross sections for charge exchange reactions. If the ionization potential of the target and the energy defect \( \Delta E \) in the collision process are small, then the charge exchange cross section is large.\(^{20}\) Therefore, with the low ionization potentials of the alkali metal atoms and the low energy defects in the alkali metal targets in the formation of the metastable hydrogen atom. According to the theory of Massey\(^{21}\), the energy at which the maximum of these cross sections occurs is proportional to the energy defect. Although this theory does not hold strictly for these reactions, the energy for maximum cross section shifts towards higher values with increased energy defects. As Table II demonstrates, the maximum energies for maximum cross sections in alkali vapor targets are much lower than for the hydrogen target.

<table>
<thead>
<tr>
<th>Donor</th>
<th>Ionization Potential (eV)</th>
<th>Energy Defect (eV)</th>
<th>( \sigma_{0,-1} )</th>
<th>( \sigma_{1,m} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>H(_2)</td>
<td>15.6</td>
<td>12</td>
<td>0.02</td>
<td>15</td>
</tr>
<tr>
<td>Li(_2)</td>
<td>3.4</td>
<td>1.99</td>
<td>0.06</td>
<td>4.0</td>
</tr>
<tr>
<td>Na(_2)</td>
<td>5.1</td>
<td>1.69</td>
<td>0.12</td>
<td>2.5</td>
</tr>
<tr>
<td>K(_2)</td>
<td>4.3</td>
<td>0.80</td>
<td>0.14</td>
<td>1.0</td>
</tr>
<tr>
<td>Cs(_2)</td>
<td>3.9</td>
<td>0.49</td>
<td>0.26</td>
<td>0.4</td>
</tr>
</tbody>
</table>

3.1 Negative Hydrogen Production in Hydrogen

Charge exchange collisions of hydrogen ions in hydrogen has been reviewed by Allison in the energy range above 0.2 keV.\(^{22}\)

The maximum negative hydrogen component of the total equilibrated beam \( (F^2) \) traversing a hydrogen target is quite low; namely, 0.02 and it occurs at an energy of 15 keV. At this energy the cross section \( \sigma_{1,0} \) and \( \sigma_{0,-1} \) are respectively \( 4.6 \times 10^{-16} \) \( \text{cm}^2 \) and \( 5.0 \times 10^{-17} \) \( \text{cm}^2 \).

The cross section \( \sigma_{1,-1} \) for double electron capture by a proton in hydrogen gas at 15 keV is more than two orders of magnitude smaller \( (6.2 \times 10^{-19} \text{ cm}^2) \) than the single electron charge exchange reactions.

3.2 Negative Hydrogen Production in Cesium

Cesium is the most explored alkali vapor target because it is the most powerful electron donor. For the one electron charge exchange process between a proton and a cesium atom the smallest energy defect corresponds to the first excited state of the hydrogen atom

\[
H^+ + Cs \rightarrow H^+(2s, 2p) + Cs^- - 0.49 \tag{16}
\]

With an energy defect for the \( H(2s) \) state only -0.49 eV and the energy defect for the ground state \( H(1s) \) 9.6 eV, one can expect that at low proton energies practically all neutral atoms are formed in the \( n=2 \) states.

The formation of metastable and ground state hydrogen atoms in low energy proton-cesium collisions has been studied accurately in recent years.\(^{23-28}\) Figure 3 shows the electron capture cross sections in the metastable state \( (\sigma_{1,m}) \) in the energy range between 0.25 and 3.0 keV. The formation of the metastable hydrogen has an apparent maximum cross section of \( 6 \times 10^{-18} \) at about 500 eV. The cross section for the production of all neutral states of hydrogen is about \( 10^{-13} \) \( \text{cm}^2 \). These cross sections are larger than the theoretical predictions from Rapp et al.\(^{29}\)

The reaction proceeds either by decay of the excited hydrogen atom to the ground state and (or) continues with the charge exchange process

\[
H(1s, 2s) + Cs \rightarrow H^- + Cs^+ + \Delta E . \tag{17}
\]

Electron attachment cross sections in the presence of cesium was measured by Schlachter et al.,\(^{25}\) in the energy range between 1.0 and 20 keV. The \( H^- \) yield increases slowly with decreasing energy. These results suggest a \( H^- \) production cross section larger than \( 3 \times 10^{-16} \text{ cm}^2 \) at 500 eV.

The maximum \( H^- \) yield for optimum cesium target thickness \( F^- \) can be expected at energies, where the maximum cross sections occur. Equi-
librium yields have been measured in the energy range 0.5 - 20 keV by Schlachter and Gruebler. The reported yield of $0.21 \pm 0.04$ occurred at a proton energy around 0.75 keV, and falls off steeply towards higher energies. In a later experiment by Khirnyi larger yields were observed at 400 eV.

The production of $H^-$ in the single two electron process can be neglected at low energies. Its cross section at 2 keV is about $4 \times 10^{-17}$ cm$^2$. Destruction of negative ions in a cesium target by the charge exchange process has been measured by Leslie et al. in the energy range between 2 and 30 keV. The cross section ($\sim 2 \times 10^{-16}$ cm$^2$) falls slowly below 5 keV. The loss of two electrons in a single process ($\tau_{-1,1}$) is smaller than $5 \times 10^{-18}$ cm$^2$.

### 3.3 Negative Hydrogen Production in Li, Na and K

A systematical study of the one and two electron charge exchange cross sections with protons in Li, Na and K vapors was made by Gruebler et al. in the energy range between 1 and 20 keV.

The total cross sections at the optimum incident proton energy for the charge exchange process ($\sigma_{1,0}$) is large ($\sim 10^{-14}$ cm$^2$) for all alkali vapors, while the cross sections for the two electron charge exchange in this low energy range is 2-3 orders of magnitude smaller. The energy at which a maximum cross section occurs shifts towards lower energies from lithium to potassium, and is proportional with the energy defect. The simple Massey criterion does not seem to hold, which may be explained by the dependence of the adiabatic parameter on the nature of the colliding particles.

A total charge exchange cross section for the reaction $H^+ + K^+ \rightarrow H^- + K^+$ has recently been measured by Inoue in the proton energy range of 150 eV to 8 keV and compared with some theoretical values, assuming that the hydrogen atoms are primarily in the $2s$ state. An apparent maximum cross section of $2 \times 10^{-14}$ cm$^2$ has been observed at 150 eV, which does not agree with the above mentioned criteria nor with the experimental results of Gruebler.

The maximum values of fractional negative hydrogen yields of protons traversing Li, Na, K and Cs targets and their corresponding energies ($E_m$) are summarized in Table II. The averaged optimum target thickness is about $2 \times 10^{16}$ atoms/cm$^2$. Figure 4 shows the equilibrium yield in alkali-metals as a function of proton energy. Although cesium appears to be the most efficient electron donor, its corresponding low energy and narrow half-width is not very attractive for intense proton beam...

---

**FIG. 3.** Metastable and negative hydrogen production cross sections in cesium as a function of energy.

**FIG. 4.** Negative hydrogen component of the total equilibrated beam in alkali metals as a function of proton energy.
production. Instead, the broad maximum observed at higher energies with a sodium target suggest that sodium may be a more practical target, despite its lower $H^-$ conversion capacity.

4. Charge Exchange Sources

Up to now intense (more than 1 mA) negative hydrogen ion beams are only applied in high energy accelerators, using the charge exchange method. Although alkali vapors show a much larger production of negative ions per incident proton, the most widely spread exchange target is hydrogen. The reluctance in applying alkali-vapor donor cells has its origin mainly in the safe construction of a "clean" cell, that does not affect the high voltage capability of the accelerator structure. In addition the production of the negative ion current is energy dependent and the primary beam current is proportional to $U^{1/2}$. Therefore, the choice of the donor cell is limited by practical current limitations of the ion source and its extraction system in the presence of the charge exchanger.

4.1 Exchange Sources With Hydrogen as Electron Donor

The most convenient charge exchange arrangement is with the hydrogen donor cell. With carefully designed structures, tens of milliamperes negative beam currents have been obtained such as in the recently published source of Dimov et al., which produces a 54 mA $H^-$ beam in a 100 usec pulse within a normalized emittance smaller than 0.2 cm-mrad. The mono-energetic yield of 1.8% which is very close to the optimum value, has been achieved a) by the formation of a uniform 3A proton beam across a large multislit extraction system and b) by avoiding the formation of molecular ions in the beam before entering the charge exchange cell by maintaining a low pressure ($< 10^{-3}$ mm) in the expansion chamber and extraction region. Up to 92% of the protons pass the extraction slit structure, after which the space charge is compensated by electrons. The powerful hollow cathode plasma source is designed in such a way as to shape and transport the plasma uniformly into the extraction region, without external magnetic field. Figure 5 shows the layout of this source with hydrogen cell.  

There are only a few high energy negative ion injectors operating in the milliampere range. In the Nuclear Physics Institute at Novosibirsk a pulsed (200 usec), 20 mA (proton current 1.5 A) negative ion beam operates in a 1 MeV electrostatic accelerator. At Argonne National Laboratory, Fasolo et al., reaches maximum beam currents of 10 mA (proton current 1 A) in an operational 750 keV tube, while at the Los Alamos Meson Factory, Allison et al., accelerates 1 mA (proton current 100 mA) in a similar 750 keV injector. The normalized emittances (phase space area $\times$ $E^2$) for all these beams are smaller than 0.3 cm-mrad.

4.2 Exchange Sources With an Alkali Vapor as Electron Donor

When a further increase of the intensity of $H^-$ beams is required, the alkali vapors are the obvious media. So far they are not applied in operational injectors. The production of low energy high intensity beams in the presence of alkali metals is difficult to realize. But significant progress in recent years in the production of intense low energy hydrogen beams and the development of "clean" cells or jets are encouraging factors in the practical use of alkalis.

The choice of a sodium charge exchange target has the above mentioned advantage, that the optimum incident proton beam occurs at a relatively high energy without a significant loss in the charge exchange yield. Therefore the primary beam current can be increased significantly. This approach has been applied by Dimov et al., reaching beam currents of 76 mA with a hydrogen donor cell and a sodium donor jet. The hydrogen charge exchanger was used to vary the primary beam composition ($H^+, H^0$) for optimum negative ion yield. A higher yield was obtained with mixed beams. The proton beam is matched into the pulsed sodium vapor jet by two quadrupoles. The optimum negative hydrogen current of 76 mA was reached at around 7 kV. More than 100 mA negative deuteron flux was obtained around 15 kV.

The production of intense negative ion beams with a cesium donor cell has been re-
ported by Osher et al.\textsuperscript{3} A total negative deuteron beam of 32 mA (1.5 keV) and 18 mA (0.75 keV) was measured. The total intensity (average density 0.05 A/cm\textsuperscript{2}) corresponds to previously measured equilibrium fractions of around 0.25. With the cell close to the source breakdown problems appear to be a severe limitation.

5. Plasma Negative Ion Sources

Contrary to charge exchange production of negative ions, formation and extraction of negative ions from a discharge cannot be analyzed so easily, because of the complexity of the mechanisms involved. The development of plasma negative ion sources with the desirable feature of compactness and nearly monoenergetic beams, was practically for almost a decennia stalled. The then intense negative ion sources were limited to the duoplasmatron with off-axis extraction with a maximum output of 0.4 mA\textsuperscript{37} and 2.2 mA\textsuperscript{38} and to the PIG source with a maximum output of about 5 mA.\textsuperscript{4} New frontiers were opened with the construction of a magnetron negative ion source,\textsuperscript{6} a hollow discharge duoplasmatron,\textsuperscript{6} and by the introduction of cesium injection into the magnetron\textsuperscript{6} as well as in the duoplasmatron.\textsuperscript{6,39} Table III summarizes the experimental results in the hollow discharge duoplasmatrons and magnetrons without and with cesium.

5.1 Penning Sources

The first source, that produced negative ion beams in the milliampere range is the well known Penning source with radial extraction developed by Ehlers.\textsuperscript{4} The advantage of this source was not only the large negative ion current, but also the low electron beam content by extraction perpendicular to the magnetic field. Despite extensive research of this type of discharge in several laboratories\textsuperscript{15} the beam intensity of 5 mA could not be greatly improved except for an 8 mA reported current, obtained with a calutron.\textsuperscript{10} A possible explanation is that the hydrogen flow into the extraction region limits the output. Collisonal detachment processes destroy additional negative ions with increased source pressure.\textsuperscript{6} In addition, in all experiments the source dimensions and the arc parameters were essentially the same. Improved performance of this source can be expected with smaller dimensions, new geometries combined with an effective distribution of the hydrogen gas, addition of alkal vapors, etc. A magnetron without the flat center cathode appears to be such an improved version of the classic Penning source.\textsuperscript{16}

5.2 Hollow Discharge Duoplasmatron (HDD\textsuperscript{39})

A significant improvement in the production of negative ion beams from a duoplasmatron has been reported by Golubev et al.\textsuperscript{6} A pulsed high current (100 A) hollow discharge was created by inserting a rod through the center of the arc chamber. Figure 6 illustrates the principle of this source. The obstruction in the center shapes the arc into an annular dense plasma near the anode region. Negative hydrogen ions are mainly extracted from the inner periphery of the discharge, avoiding the high density, high temperature core of the arc.

The same principle has been explored at Brookhaven, which will be discussed in detail

<table>
<thead>
<tr>
<th>TABLE III. Parameters of negative hydrogen plasma sources</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Source</th>
<th>Maximum output (mA)</th>
<th>Gas flow</th>
<th>Arc current</th>
<th>Electron current</th>
<th>Negative ion current</th>
<th>Extraction voltage</th>
<th>Normalized emission</th>
<th>Gas flow (L/Sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Penning</td>
<td>5 mA</td>
<td>100</td>
<td>10</td>
<td>0.22</td>
<td>30</td>
<td>0.5</td>
<td>0.3</td>
<td>0.5</td>
</tr>
<tr>
<td>Magnetron</td>
<td>5 mA</td>
<td>100</td>
<td>5</td>
<td>0.7</td>
<td>30</td>
<td>0.5</td>
<td>0.5</td>
<td>1.0</td>
</tr>
</tbody>
</table>

The same principle has been explored at Brookhaven, which will be discussed in detail.
CESIUM VAPOR

FILAMENT
(CATHODE)

INTERMEDIATE
ELECTRODE

LOW DENSITY
PLASMA

CENTER TUBE

ANNULAR DENSE
PLASMA

ANODE

EXTRACTION
ELECTRODE

H.

FIG. 6. Illustration of hollow discharge negative hydrogen duoplasmatron.

In a separate paper during this Conference,\(^{38}\) in the Brookhaven source the rod used by Golubev was replaced for an insulated tube a) to study the effect of bias voltage and b) to inject a gas or vapor into the source independent of the main hydrogen leak. The optimum \(\mathrm{H}^-\) yield occurred with the tube near plasma potential (floating). With hydrogen as the operating gas, up to 9 mA of \(\mathrm{H}^-\) current was obtained, corresponding to an ion current density of 0.25 A/cm\(^2\) near the emission aperture with an extraction voltage of 40 kV. The normalized emittance is 0.3 cm-mrad.

A significant improvement was achieved by injecting cesium through the hollow center tube. The beam intensity increased to 18 mA, which corresponds to a current density of 0.57 A/cm\(^2\).

It is not possible to obtain a clear picture of the dominant processes responsible for the extraction of the intense negative ion beams from the plasma of an HDD source. However, the experience obtained at Brookhaven justifies some speculations on the origin of negative ions.

In a hydrogen discharge it is likely that the two reactions: polar dissociation and dissociative recombination will contribute to the \(\mathrm{H}^-\) production. In a BNL experiment with deuterium instead of hydrogen gas no significant isotope effect was observed.\(^{40}\) This result suggests that the temperature of the electrons involved in collisions with hydrogen and hydrogen ions is limited to either a few eV or at least 10 eV. Low energy (secondary) electrons are readily available around the tip of the center tube and high energy electrons are plenty in the plasma sheath around the tube as well.

The fact, that an optimum \(\mathrm{H}^-\) output occurs with the tube near plasma potential, suggests a strong interaction between plasma and tube. The tube bombarded by intense energetic beams of ions, acts as a "cold" cathode at a potential of around -50 V. It is therefore possible that in the HDD source secondary ion emission from the center tube plays an important role in the production of negative hydrogen production. When cesium was added to the source, the \(\mathrm{H}^-\) output more than doubled; the source operated then for several hours without cesium supply and without high voltage breakdown across the extraction gap. Although the charge exchange rate for tens of \(\mathrm{e}^+\) protons and cesium atoms can be as large as \(10^{-9}\) cm\(^3\)/sec, the apparent low cesium pressure suggests that charge exchange collisions described above, apparently are not responsible for the increased output, but rather surface ionization effects.

An accurate analysis of the energy spectrum of the negative ions and knowledge of the source temperature, may provide more information concerning the location and creation of the negative ions in the duoplasmatron without and with cesium injection.

5.3 Magnetron Sources

A new type of negative ion source is the pulsed, high discharge current, "cold" cathode magnetron source designed by Bel'chenko, Dimov and Dubnikov.\(^7,8,10\) When operated with hydrogen gas only, the source yields higher currents than obtained from the HDD source. From an extraction slit 1 mm x 10 mm pulsed \(\mathrm{H}^-\) currents ranged up to 22 mA, which corresponds to a current density up to 0.22 A/cm\(^2\). Higher densities were obtained when cesium was injected into the source. The maximum reported current density was 3.7 A/cm\(^2\) and a maximum \(\mathrm{H}^-\) current of 0.88 A has been reached with an emission slit of 30 mm x 1 mm in preliminary measurements. Figure 7 shows the cross sections of the magnetron as it appeared in the first publication.

The principle of the operation of the negative hydrogen magnetron is illustrated in Fig. 8. The small discharge chamber has the shape of a racetrack with the center part the flat cathode and the outer part the anode. The discharge is limited by the end shields of the cathode. The anode has an expansion chamber with the extraction slit in one of its walls. The gas feed is through the opposite
FIG. 7. A magnetron source.

FIG. 8. Illustration of negative ion magnetron.

Most extracted electrons will not reach the extraction electrode: they will drift away along equipotential lines in tight spiralling trajectories, improving the electric strength across the extraction gap. With the extractor connected to the magnetic pole tips the ratio of extracted ion current to electron current is more than 0.2 which is at least an order of magnitude larger than in the HDD source. A disadvantage of the magnetron is that the negative ions have a velocity component from the source magnetic field in the direction of the slit, so that some means have to be provided to compensate for that.

Two similar models of the magnetron source were recently built at Brookhaven National Laboratory. These results will be detailed in a separate paper during this Conference. While the early model showed a behavior similar to the original source, there were several weak points in the construction and a new improved model was designed. By using a narrow extraction slit (0.5 mm x 10 mm) and with hydrogen as the operating gas, extracted \( H^- \) currents reached 17 mA with normalized emittances in two directions of 0.44 and 0.60 cm-mrad at an extraction voltage of 8 kV. A dramatic change was observed after cesium was injected into the source. The extracted current of negative ions increased to 100 mA which corresponds to a current density of 2.0 A/cm\(^2\). For a 45 mA beam the normalized emittance measured in the direction of the extraction slit was 1.2 cm-mrad. In an effort to test the idea of using multiple slits a double 0.5 mm x 10 mm slit was installed. In a mixed hydrogen-cesium mode, the current was 150 mA and the corresponding density 1.5 A/cm\(^2\).

The dense negative ion currents from the magnetron (as obtained in discharges with cesium) cannot be explained from the fundamental collision processes in hydrogen plasmas nor from the charge exchange collisions of protons and cesium atoms in mixed hydrogen-cesium arcs. Estimates of the \( H^- \) current density, taking into account the most favorable experimental conditions does not exceed 0.1-0.2 A/cm\(^2\).

In an analysis of the energy spectra for the extracted \( H^- \) ions in a hydrogen and hydrogen-cesium discharge, Bel'chenko et al. discovered the existence of two very distinct energy peaks. The ion energy of one peak corresponds to the cathode voltage, while the second peak corresponds to the extraction voltage. For the cesium mode and with minimum hydrogen pressures in the discharge only the broad "cathode peak" exist. Towards higher hydrogen pressures the narrower "anode peak" appears, while the "cathode peak" dimin-

An important advantage of magnetron sources (unlike duoplasmatrons) is related to the extraction across the magnetic field.
lishes in amplitude.

A likely explanation of these results is that the negative ions from the "cathode peak" are created in or near the cathode by collisions with fast (~ 150 eV) ions from the discharge. Negative ions emitted from the cathode either gain energy across the cathode sheath or they create slower ions by the resonant charge exchange process (H^- + H -> H + H^0), which explains the broader cathode peak. Only the fast H^- ions can pass the plasma layer and arrive in the anode expansion chamber, where they may interact with the hydrogen, again by the resonant charge exchange process. For large hydrogen pressure this charge exchange process in the anode space becomes dominant in a pure hydrogen discharge, which explains the disappearance of the cathode peak under those circumstances.

If the total arc current density at the cathode surface is 100 A/cm^2 and the observed flux of negative ions in the hydrogen-cesium discharge is 2-3 A/cm^2, then the minimum negative ion secondary emission coefficient is 2-3%, without taking into account the destruction processes during passage of the plasma layer.

Secondary emission of negative hydrogen ions from a metal surface (molybdenum) by impact of energetic particles (protons) have been studied only at higher energies (> 10 keV). At 100 eV and with clean surfaces the negative ion yield appears to be much smaller than 1%. The observed increase in negative ion production with cesium in the magnetron suggest that the work function of molybdenum for secondary hydrogen emission is reduced significantly by cesianated molybdenum, such as is found for the emission of negative halogen ions from thoriated tungsten. The presence of alkali atoms in or on the outer surface of the cathode appears therefore of great importance for the production of negative ions. Another possible cause of increased negative ion production is field emission due to electric field concentration in the plasma sheath.

**Discussion**

The fast developments in recent years in direct as well as in charge exchange sources have significantly modified the outlook in the production of intense negative ion beams. Beam currents have reached levels far beyond the required intensities for practically all applications in nuclear physics laboratories. Phase space areas as measured for beam currents smaller than 100 mA are well within the acceptance of existing accelerators. The newly developed sources do not appear to have basic problems in the adaptation to many existing machines, although the application of alkali-vapors is not well under control. The 18 mA hollow discharge duoplasmatron is ready for tests in the BNL linear accelerator. However there is no long term experience about its reliability or cesium reloading procedure. The experience with the low density (~ 0.2 A/cm^2) magnetron without cesium suggest, that it can be developed into a reliable operating source. By means of a relatively small quadrupole triplet, the asymmetric beam may readily be focussed.

Much higher beam currents are required for injection of neutrals into fusion reactors. Indirect methods for the construction of very intense negative ion sources have been proposed in particular at Lawrence Livermore Laboratory, extrapolating the experience obtained with the 50 mA negative beam in a cesium vapor charge exchange cell. Practical realization of such a system appears to be more complicated than proposals, utilizing plasma sources.

Intense H^- beam currents have been obtained with the magnetron sources with structures considerably simpler than the indirect sources and the duoplasmatron. Although these features are very appealing for the intense ion source designer, there are also disadvantages for such a system.

A serious problem is containment of the high density beam emerging from the source; the beam diverges rapidly in free space by large space charge forces. Due to the H^- destruction processes the negative ions cannot be expanded to larger emitting areas as in plasma expansion chambers of proton sources. Density dilution may be possible by the construction of larger secondary emission surfaces (cathodes) and lower arc current densities. However, the larger configurations reduce the efficiency of the source. Fast acceleration of the H' beam to the required high energy (100-1000 kV) without prefocussing is an additional possibility of containing a high density beam within the acceptance of focussing lenses. A second disadvantage of the high current magnetron is the inefficient use of hydrogen gas, which requires high pumping capacity.

Presently obtained results on H' yields from magnetron sources show that it is possible to reach 1 A of H' ions from a single slit. It has been proposed and demonstrated that multiple slits in a magnetron source better utilize the discharge and so achieve still higher H' currents with the same arc current. In Ref. 8 it has been suggested that the source be made in the shape of a ring of
2 m diameter, yielding a radially converging ribbon of 200 A of $^1$H ions. Neutral particles would be directed into a plasma column having a diameter of several centimeters (Fig. 9a).

For the contemplated injection of neutral particles into a Tokamak, a different type of a ring source than described above would be preferable. As shown in Fig. 9b the beam of $^1$H ions would be hollow and of conical shape so as to achieve an initial convergence and to limit space charge effects. An accelerating system (possibly of the two dimensional Pierce type) placed closely to the source, would decrease the effect of azimuthal velocity components.

A cluster of magnetron sources is a more straightforward method to increase the intensity. Several single units (single or multiple slit types) with or without angle compensation capability, may be put together with thin mild steel plates in between them to assure the uniformity of the magnetic field (Fig. 9c). It is possible to envisage a cluster ring source as well.

![FIG. 9. Possible multi-ampere negative ion source structures.](image)

It is clear from the foregoing that we have arrived at a new era of negative ion production.

References

17. Private communication with B. Peart (University of Newcastle upon Tyne, U.K.).