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NEGATIVE-HYDROGEN-ION SOURCES*

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1. Introduction

There are two main areas of negative hydrogen ion applications: injection into high energy accelerators and production of beams of energetic hydrogen atoms for fusion devices. In both cases, the ease with which the charge state of negative ions can be changed by either single or double electron stripping is the reason that made their application attractive. In tandem accelerators, the final energy of H^+ ions is twice as high as it would correspond to the terminal voltage, in circular accelerators (synchrotrons, storage rings) injection of H^+ ions by full stripping of H^- ions in a foil inside the ring is not limited by the Liouville's theorem and results in a higher phase space density than achieved by direct H^+ injection. Finally, beams of hydrogen atoms at energies above 100 keV, which will be required for plasma heating and current drive in future fusion devices, can efficiently be produced only by acceleration of negative ions and their subsequent neutralization.

Until about ten years ago, most negative hydrogen ion sources were actually adapted positive ion sources (duoplasmatrons, Penning sources) delivering up to 5 mA of H^- ions, in pulsed or steady state mode of operation [1]. From their operating conditions (energy and density distributions of different components of the source plasma) it was concluded that the important mechanisms for H^- production in such sources were dissociative attachment and dissociative recombination. The progress in the development of H^- sources has begun to accelerate with the discovery that in a small, pulsed magnetron source negative hydrogen ions can be very efficiently produced on low work function, cesiated surfaces [2]. This method has been successfully tried in similar, but large magnetron sources [3], Penning sources [4], [5], [6], and recently, in newly developed high current steady state sources of the multi-cusp type [7] and hollow cathode discharge sources [8]. The result of this effort has been to achieve H^- beam currents above 1A, both in smaller pulsed sources and in large, steady state devices, with some characteristics (current density, gas efficiency, emittance) approaching those of positive ion sources. A few years ago, after preliminary experiments at Ecole Polytechnique [9], [10] on the production of H^- ions through the process of electron attachment to vibrationally excited hydrogen molecules, H^- ion beams were extracted from a source of the multi-cusp type, but without the use of cesium [11], [12].

The importance of and interest in the production and applications of negative hydrogen ions has led to the organization of several meetings dedicated to this field, among them symposia at Brookhaven National Laboratory in 1977 [13] and 1980 [14].

2. Processes Relevant to Formation and Loss of H^- Ions

Although in the strict sense of the word an H^- source would be a device delivering at its exit aperture a beam of negative ions, it is customary to

include here systems for conversion of positive ions into negative ones as well. Processes in the latter devices, i.e., capture of two electrons, will therefore also be considered.

A. Processes in Volume

Dissociative attachment (DA) of an electron to a hydrogen molecule in the ground state may result in the formation of a negative ion

$$e + H_2 \rightarrow H^- + \ldots$$

There are several possible channels for this reaction [1], but the cross section is at best of the order of 10^{-20} cm^2. Still, in some low current, high pressure ion sources this reaction probably plays an important role.

Measurements of H$^-$ densities in large volume, low pressure discharges [9], [10] have shown values two orders of magnitude higher than expected from DA to molecules in the ground state. This fact has stimulated experimental and theoretical studies of DA to vibrationally excited molecules

$$e + H_2 (v \geq 6) \rightarrow H_2^- \rightarrow H^- + H$$

The result of these studies has been very surprising: compared to the same process involving molecules in the ground state, cross sections were enhanced by several orders of magnitude (Figure 1), reaching values of 10^{-16} cm^2 for $v > 6$. Other possible processes, as e.g., DA to rotationally excited molecules or dissociative recombination with an H_3^+ ion, contribute much less to the H$^-$ density [15], [16].

Losses of H$^-$ ions in the volume of a plasma are caused by diffusion to the walls at low plasma densities and by collisional destruction of several types [1]. Especially detrimental is mutual neutralization with positive ions, with cross sections of the order of 10^{-14} cm^2 in a wide range of energies. Collisional detachment by electrons in the energy range around 10 eV also has a high cross section, about 5×10^{-15} cm^2, while collisional detachment by neutral molecules becomes important at higher energies ($\approx$ 10 keV), which means outside the source.

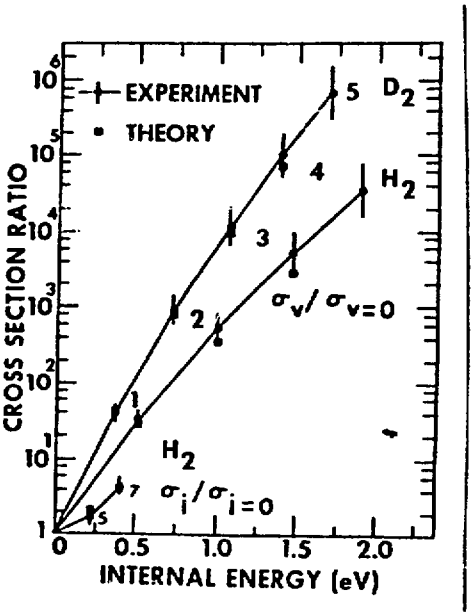

Figure 1 - Cross section enhancement in H_2 and D_2 for DA via vibrationally excited molecules [15].

B. Charge Exchange Processes in Metal Vapors

Charge exchange processes in alkali and alkaline-earth vapor targets result in a fraction of the positive ion beam to be converted into negative ions. In the equilibrium, the fraction of negative ions F_-^∞ will mainly be determined by cross sections for single electron processes leading to or from the H$^-$ state. The highest value of the equilibrium fraction of H$^-$ ions has been measured in Sr, about 50% at 0.5 keV energy (Figure 2), followed by about 35% in Cs at somewhat lower energies [17]. However, this low energy represents a problem

due to very pronounced space charge effects; very often higher values of F_-^∞ obtainable with Cs and Sr are sacrificed and, e.g., sodium is used instead, yielding about 7% of H^- at 5 keV.

C. Processes on Surfaces

It has been known for some time that interactions between particles having sufficient energy and a low work function surface can result in the formation of a negative ion, but the real progress has begun with experiments at Novosibirsk [2] with alkali coated surfaces exposed to the bombardment by plasma particles. Since that time, a variety of experiments have been performed to study the yield of negative ions and their properties, as a function of primary particle and surface parameters. Theoretical studies have become more and more sophisticated [16] but a complete understanding of all the phenomena is still in the future.

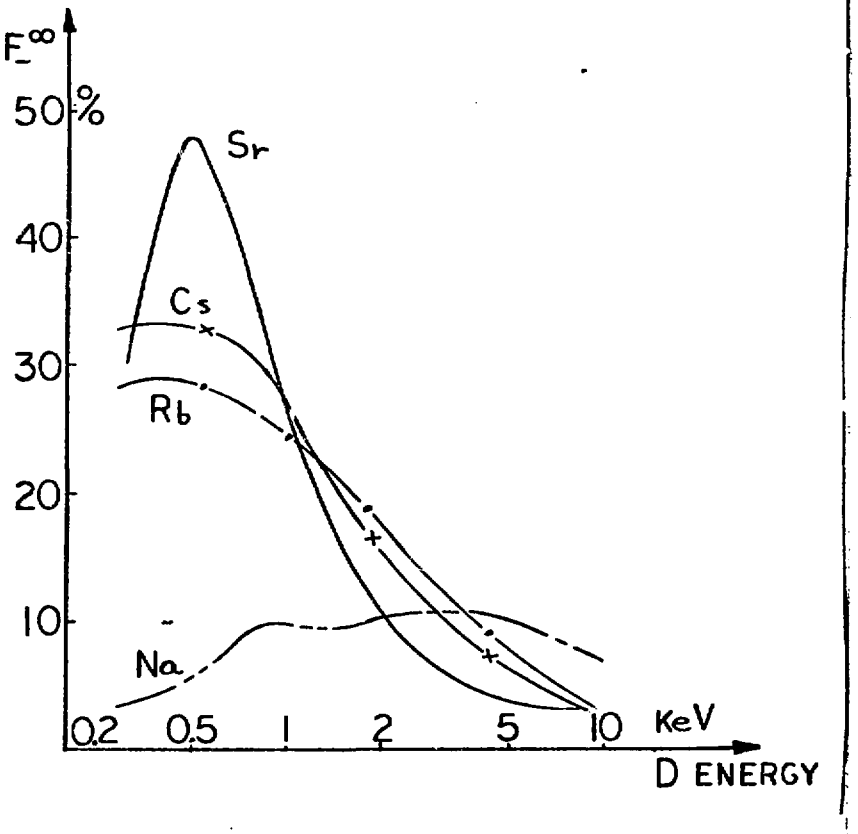

Figure 2 - Equilibrium fraction F_-^∞ for deuterium as function of energy (for hydrogen, the energy values should be divided by 2).

There seem to be two processes leading to the formation of negative ions on a surface, desorption of H^- ions from the surface by energetic primary particles (hydrogen, cesium or other) and backscattering of primary hydrogen particles (H°, H^+, H_2^+, H_3^+) from the surface in the form of negative ions (following dissociation of molecular ions). In the first process, the yield of negative ions will be determined by the yield of desorbed particles and by the negative ion production probability [16]; the second process will include the yield of backscattered particles and, again, the negative ion production probability. It is especially the negative ion production probability that depends on the surface work function: best yields of negative ions have been obtained with lowest values of the work function. While it is possible to study separately the desorption and backscattering as processes for negative ion formation, in an ion source both will be usually present and their contributions to the total yield will be difficult to estimate.

Seidl, et al. [18] have investigated the production of negative hydrogen ions by bombarding hydrogen adsorbed onto a cesiated molybdenum surface with positive cesium ions in the range of energies 500-1250 eV. The highest negative ion yield of 0.4 was achieved at 750 eV, when the Cs coverage was close to that for the minimum work function. It has been estimated in the same paper, that the optimum production probability was also close to 0.4. Measurements of energy spectra have shown that the most probable energy of H^- ions is 1.3% of the incident Cs^+ ions, with an energy spread of about 0.5%. The same authors [19] have measured the emission of negative hydrogen ions from metal hydrides (LiH, CsH, VH) bombarded with Cs^+ ions in the energy range up to 10 keV; the best yield of 0.4 was obtained with CsH target at about 8 keV.

Investigations of the production of negative ions by backscattering have been concentrated on two distinct cases: normal incidence and grazing incidence. For the normal incidence, most experimental data on the backscattering yield are limited to energies above 1 keV. Theoretical results [20] seem to be reliable down to energies of 10 eV; they show an increase in the yield with decreasing energies, with values for the yield of about 0.8 for Cu and Mo and between 0.5 and 0.6 for some alkalis. Total yield of negative ions has been measured for many different targets and in a wide range of energies; best results, about 13%, have been obtained with a partial monolayer of Cs on a metal substrate [21]. From the data on the backscattering yield and the measured total yield of negative ions, it is possible to estimate [16] the probability for production of negative ions. There seems to be an optimum range of energies for the production of negative ions (around 100 eV), where values approaching 0.4 have been obtained [21]. Extrapolation of experimental data, by using theoretical results for backscattering yields, predicts values of the total negative ion yield up to 0.6 at 10 eV [16].

Extensive studies of negative hydrogen ion production on mono and polycrystalline tungsten surfaces by backscattering under grazing incidence have been done at FOM [22], [23]. The H^- ion fraction of the total number of scattered particles as well as the total yield of H^- ions have been measured for different incident energies (100-2000 eV), different incident angles (75° to 85° from the normal), and different values of the surface work function (Cs on W, 1.45 eV to 2.15 eV). Energy and angular distributions have also been determined. The fraction of H^- ions and the total H^- yield depend strongly, as expected, on the surface work function, they show a broad peak for incident angles between 80° and 85° from the normal and a broad peak around 200 eV incident energy. There is an improvement in the yeild by at least a factor of 2 when a monocrystal is used instead of a polycrystalline surface [22]. Best results for the total conversion efficiency were around 35%, for a W monocrystal with optimum Cs coverage (work function: 1.45 eV), an H^+ incident energy of 200 eV and an incident angle of about 83° [23]. Angular distributions of H^- ions depend strongly on the angle of incidence, with the narrowest distribution (FWHM equal to 9°) obtained for 85° incidence on a single crystal; distributions are substantially wider for polycrystalline surfaces [22]. Energy distributions depend both on the angle of incidence and scattering angle [23]; for single crystals, a double-peaked distribution is typical.

3. Sources Based on H^- Formation in the Volume

Production of negative hydrogen ions in a Penning discharge was first reported by Ehlers, et al. [24] and for many years since then this type of a source was the most popular and widely used one [1]. The yield was about 5 mA, with the beam extracted radially through a slit; corresponding values

of the current density in the slit were rather high, 30-50 mA/cm^2 and the emittance satisfactory. The source could operate either in a pulsed mode or steady state (with water cooling). Recently a new study was done on a modified version of this type of the source [25] and 9.7 mA of H$^-$ ions (100 mA/cm^2) were extracted in the steady state. A strong isotope effect was observed: currents of D$^-$ ions were lower by more than a factor of two. By using a longer aperture, Gabovich, et al. [26] have obtained a steady state H$^-$ current of 20 mA, with a density of 80 mA/cm^2. Their source showed an operating regime (0.1 Torr, 2 kG) with extremely low noise level of less than 0.05%. Processes involved in the formation of negative ions in this type of source are dissociative attachment and dissociative recombination, with rather low cross sections. This is the reason that both the power efficiency ($\approx$ 5 mA/kW) and the gas efficiency ($\approx$ 0.3%) do not allow scaling up to currents several orders of magnitude higher, as required for fusion applications.

As mentioned before, a different and much more efficient mechanism is responsible for the formation of negative ions in a large volume, low pressure multi-cusp (bucket) source. The discharge is maintained by electron emission from hot cathodes. Electrons are accelerated to the plasma potential and contained there in the field-free volume, where they lose energy by inelastic collisions; the latter lead eventually to the formation of negative ions in the volume. The H$^-$ ion density in the plasma and the extracted H$^-$ beam current depend among others on the configuration of the magnetic field around the extraction aperture; by careful design of the shape of the magnetic and electrostatic fields in the plasma boundary and extractor region, the electron component can be reduced to a level equal to the H$^-$ component. However, at this stage the performance of the multi-cusp source (power and gas efficiencies, beam current) would have to be substantially improved before the source can be considered for application in fusion devices. Results of studies will be presented to this conference by other participants.

4. Sources Based on H$^-$ Formation in Metal Vapors

Before relatively recent advances in the design of sources using surface production of negative ions, the formation of negative ions by double electron capture in metal vapors was the favorite approach, especially for applications in fusion devices [13], [14]. Since then the emphasis has shifted away from this method and some projects have been stopped. Experiments have been done mostly with cesium and sodium vapors, although extensive data exist on other alkali and alkaline-earth targets as well. D$^-$ currents of as much as 2.2A were produced at 12 keV [27] in a sodium target, with a current density of about 10 mA/cm^2. Similarly, in another experiment, more than 1A of H$^-$ ions were obtained, again in a sodium target [28]. A cesium vapor target is used in a double electron capture system at Grenoble [29]. From an ECR ion source about 0.3A of D$^+$ ions were extracted at 700 eV and with a current density of 15-20 mA/cm^2. The total detected D$^-$ current was 80 mA, but only 30 mA were accelerated to 30 keV, in pulses of 4s duration. The whole system, from the source up to and including the neutralizer, is immersed in a strong longitudinal magnetic field, to produce and maintain a beam with a controlled cross section. A larger source is under construction, to deliver 1A of D$^-$ ions with subsequent acceleration to 200 keV.

The application of metal vapor targets is not limited to intense negative ion beams for fusion: some systems for production of polarized negative ions use, e.g., sodium to convert polarized protons into negative ions, for injection into high energy accelerators [30].

5. Sources Based on Surface Formation of H⁻ Ions

Almost all existing negative hydrogen ion sources based on surface formation have a discharge plasma where primary particles are produced to bombard a low work function, negatively biased electrode. In such an arrangement, the incidence of particles onto the surface is very close to being perpendicular. Sources can be divided into two groups; in the first group, the H⁻ ion producing electrode serves also to initiate and maintain the discharge itself (Penning sources without converter, magnetrons), while in the second group, the discharge is maintained without the help of this electrode (Penning sources with converter, multi-cusp sources, hollow cathode discharge sources). The advantages of the second group, with separate plasma generation, are a better gas efficiency and a better control of the conditions on the H⁻ producing electrode (voltage, current, Cs coverage). In either case, addition of cesium into the source may change its operating parameters by changing the electron emission properties of cathodes (substantially lower discharge voltage with cesium).

Compared to sources using only volume processes for formation of negative ions, surface-plasma sources need a low work function electrode to produce negative ions either by sputtering or backscattering. There are many combinations of metals having a low work function surface; the most widely used is, however, a molybdenum substrate with about 0.6 of a monolayer of Cs resulting in a work function of 1.5 eV. Molybdenum has a relatively low sputtering rate, good thermal and electrical properties and produces few impurities in the negative ion beam. Need for cesium is a complicating factor in surface plasma sources, because the partial monolayer has to be maintained close to the optimum conditions under pulsed or steady state bombardment by plasma particles. There are several methods to introduce cesium into the source, either into the plasma or through the converter electrode itself, but none of them has been fully satisfactory yet except in relatively small sources operating with short pulses ($\approx$ 1 ms). The second complication is the unavoidable loss of cesium through the extraction aperture; it has to be minimized in order to prevent deposits of cesium on insulators and high voltage electrodes.

A. Magnetron and Other Sources With $\vec{E} \times \vec{B}$ Electron Drift

Chronologically magnetron was the first source of H⁻ ions where the production was enhanced by adding cesium vapors to a hydrogen discharge [2]. This first magnetron was a small device, that initially served for production of low H⁻ ion currents by volume processes [31]; its yield was up to 20 mA (without cesium), which is higher than obtained from comparable Penning sources. When cesium was added, the H⁻ current increased to 0.3A, with a current density of 3A/cm^2 and in pulses of 1 ms length. Over the past ten years, sources of this type have been studied in many places and different versions for specific applications were developed. The basic geometry is common to all of them: in a magnetic field of 1-2 kG, a discharge is established between a cold cathode and anode mounted in such a way that there exist closed $\vec{E} \times \vec{B}$ loops around the cathode. Electrons emitted from the cathode by secondary and photoelectric emission are accelerated by the cathode voltage fall and bent by the magnetic field, describing cycloidal trajectories around the cathode. Cesium is fed into the discharge and is deposited, among others, on the cathode creating the required conditions for surface production of H⁻ ions. There are two groups of H⁻ ions extracted from the source: fast, primary ions which have survived the passage through the plasma, and slow, secondary ions produced by resonant charge transfer between primary ions and slow background atoms. Most of the existing magnetron sources incorporate two substantial improvements: the cathode surface opposite the extraction slit has the shape of a cylindrical groove so that surface produced negative ions are focused into the slit [32], [33], and second, the gap between the cathode and the anode is not uniform [33].

A pulsed magnetron, developed along these lines at BNL [33], has delivered H^- currents up to 0.6A, at a current density of $2.2A/cm^2$ (Figure 3). The required cathode curent density was only $4A/cm^2$, which enabled the operation with pulses of 25 ms duration even without cooling. It is interesting to note that there was no isotope effect observed. The two improvements mentioned above resulted in the reduction of the required arc power from 33 kW/A to 8 kW/A, in an improvement of the gas efficiency from 1-2% to 6%, and in a reduction of the beam emittance by a factor of three compared to conventional magnetron sources.

Two large proton synchrotrons, AGS at BNL and the Fermilab booster, use charge exchange injection from their linacs. H^- sources for the two machines have been developed in cooperation between the laboratories [34], [35] and have similar characteristics, although the BNL source has geometrical focusing and asymmetric gap [33], [35]. The latter yields more than 50 mA of H^- current in pulses of 0.3 ms duration, at a duty factor of 0.1%. The operation is very stable and reliable over many months.

A large steady state magnetron source was designed and fabricated for possible applications in fusion devices [36]. It includes geometrical focusing and it has an asymmetric cathode-anode gap; all the electrodes are water cooled, which is necessary for long pulse or steady state operation (Figure 4). Only initial tests have been performed with this source and about 120 mA of H^- ions have been extracted at a reduced power level. The design value for H^- current of this source is 1A, but in order to reach this level, more studies will be required about the way cesium is injected into the source and how to achieve and maintain a uniform layer on the surface of the cathode (one of the methods under consideration is the operation of the cooling system at temperatures around 150°C).

A closed $\vec{E} \times \vec{B}$ loop is not necessary for the establishment of a discharge in the magnetron type sources; this has been shown by the development of the so-called semiplanotron source [32]. A semiplanotron basically consists of a cathode with one or more cylindrical grooves and the anode with the corresponding number of extraction

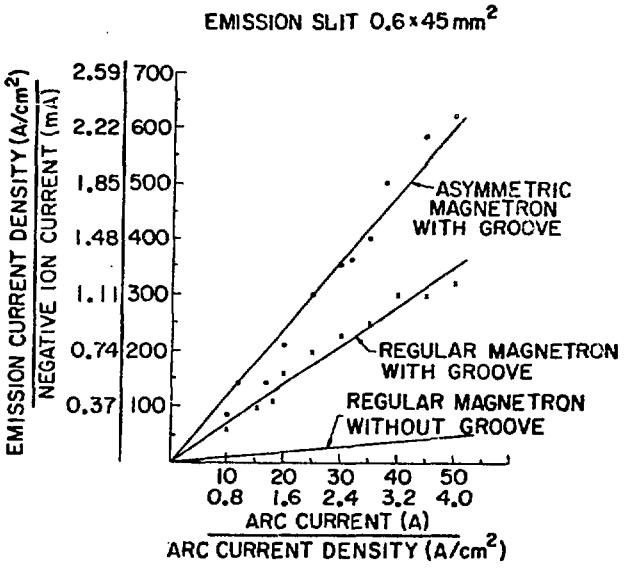

Figure 3 - Comparison of the H^- yield for different magnetron source geometries [33].

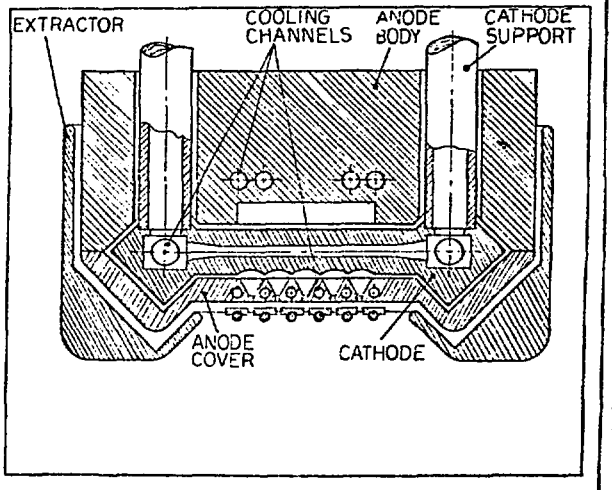

Figure 4 - Cross section of a steady state magnetron source [36].

slits (Figure 5). The discharge is initiated in the hydrogen gas and cesium vapor supply channel and is transferred by $\vec{E} \times \vec{B}$ drift into the cathode grooves. Negative ions formed on the surface of the grooves are focused into the extraction slits. The discharge is prevented from developing in other parts of the cathode-anode gap by proper electrode shaping (perpendicular E and B fields exist only in the active part of the gap, supply channel and opposite the extraction slits). Very high H^- yields have been obtained from this source [37]: up to 4A in pulses of 0.3 to 1.3 ms, with a power efficiency of 0.1 A/kW, a gas efficiency of 10% and a ratio of the H^- to the cathode current of 1%.

Finally, $\vec{E} \times \vec{B}$ drift has been used in a source to produce a hollow, cylindrical beam of H^- ions [38]. The magnetic field in this source is radial, which with an axial electrostatic field produces an azymuthal drift. The discharge is radially limited to a gap of a few mm width with a diameter of 80 mm and a single, circular extraction slit. To our knowledge, only the H^- current density in a number of small circular extraction apertures has been determined; at a discharge current of 500A, the H^- current density was 1.2A/ cm^2 in pulses of 0.2 ms.

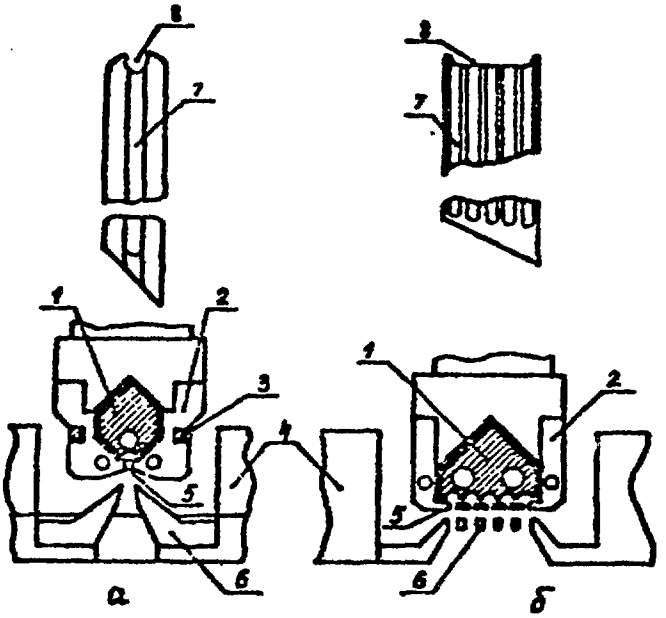

Figure 5 - Cross section of the semi-planotron source [37], with a single groove (a) and with 5 grooves (b) (1-cathode; 2-anode; 3-magnetic inserts; 4-magnet poles; 5-emission slits; 6-extractor; 7-cathode grooves; 8-gas supply groove).

B. Penning Sources Without Converter

Discovery of the enhanced H^- production on cesium covered surfaces has led to the modification of original Penning sources [4], [39]. The gap between the two cathodes was decreased to less than 1 cm to reduce the loss of negative ions while moving through the plasma. Negative ions are produced on molybdenum cathodes by sputtering and backscattering and accelerated back into the plasma by the cathode voltage fall. However, in a simple Penning geometry it is the secondary negative ions produced in the plasma by resonant charge transfer between slow atoms and fast H^- ions that are extracted from the source. Dimov, et al. [39] have obtained from their source up to 150 mA of H^- ions with a density in the slit of 3A/cm^2, in pulses of 0.2 ms duration and 2% duty factor.

A somewhat larger Penning source has subsequently been developed at BNL [5], with seven parallel extraction slits. Maximum H^- yield was 0.44A, in pulses of 3 ms duration. A very pronounced isotope effect was observed: the yield of D^- ions was only 0.2A. The group at LASL [40] has studied a Penning source similar to that described in Ref. 4. They have also obtained yields around 150 mA; beam emittance and cesium loss have been measured as well. In order to increase the duty factor up to 100%, a rotating Penning source has been designed to deliver 100 mA of H^- ions in steady state operation [41].

Common features of pulsed Penning sources without converter are: H^- currents around 0.1A, duty factor a few %, very good emittance (high brightness) in the low noise mode of operation, but poor gas and power efficiencies. Still, they seem to satisfy requirements of some accelerators.

C. Penning Sources With a Converter

The desire to extract from a Penning source not only secondary H^- ions produced by charge transfer in the plasma but fast primary ions as well has led to the introduction of a separate electrode converter, with the purpose to serve as an H^- ion producing electrode directly opposite extraction slits [5], [42]. This modification was a major improvement in the design of H^- sources, after the introduction of surface H^- ion production, and it has been used since in other types of sources as well. The discharge in such sources is maintained independently of the converter and may even be separated by limiting apertures from the region between the converter and extraction apertures to reduce the neutral gas flow and improve the gas efficiency [42]. Diffusion of cesium into the source serves to reduce the discharge voltage and to make the surface production of H^- ions on the converter possible.

Addition of a negatively biased converter has substantially enhanced the yield from the Penning source of the Dudnikov type [42]. For the same size of the extraction aperture, the H^- yield as well as the current density in the aperture were almost two times higher with a -100V bias on the converter. It is not known what the ion optical properties (emittance, brightness) of this source are.

For fusion applications much longer pulses (> 1s) or even steady state operation will be required, while some of the ion-optical properties can be sacrificed. A try to scale-up a cold-cathode Penning source with converter for steady state operation [43], was not successful: large area cathodes were never uniformly covered with cesium, which led to an unstable operation. More successful was the modification of the ORNL calutron source for H^- production [6], [44], [45]. Plasma in this source is maintained by electrons emitted from a hot filament and oscilating along magnetic field lines between the cathode and the reflector. Hydrogen gas is fed both into the cathode and anode regions, while cesium is injected behind the converter, from where it diffuses onto the surface exposed to the plasma.

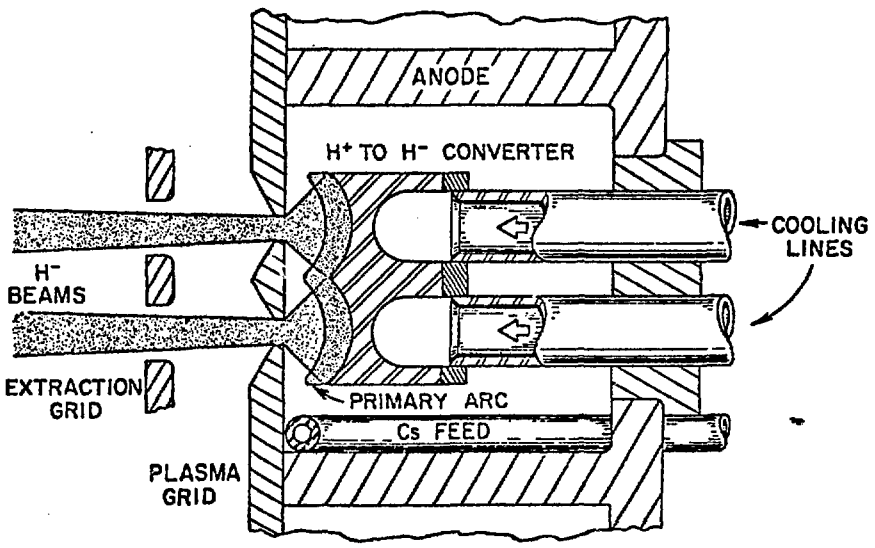

Figure 6 – Cross section of the SITEX source [45].

The latest model, SITEX [45], features two extraction slits along the magnetic field lines (which is opposite to the usual orientation) and cylindrical grooves for geometrical focusing of surface produced H^- ions into the slits (Figure 6). This orientation of slits facilitates the removal of extracted plasma electrons in the $\vec{E} \times \vec{B}$ direction, away from the H^- beam and recovery of their energy by intercepting them with a separate electrode. While the recovery of electron component energy was of relatively little importance in small, pulsed sources, in the case of large, steady state units it contributes substantially to the overall power efficiency and reduces cooling requirements. From a total converter surface area of 25 cm^2 up to 0.5A of H^- ions was obtained through the two slits (total area: 5 cm^2), in pulses of 10s duration. The extraction voltage was 18 kV. Although the gas efficiency has been improved compared to other Penning sources (to 3%), this is still not considered satisfactory.

D. Multi-Cusp Sources With a Converter

Multi-cusp sources of H^- ions, developed at LBL by Ehlers and Leung [7], are the most advanced sources for fusion applications. A short summary of their operation and performance will be given in this paper, while the details will be presented to this conference in another paper [46]. As shown on Figure 7, permanent magnets placed around the source create a multipole field which is necessary for plasma confinement; the discharge is maintained by electrons emitted from several hot filaments. The plasma produced in a multi-cusp field is very uniform and stable, with densities around $10^{12} cm^{-3}$. A molybdenum converter is mounted close to the center of the source, with a curvature such that negative ions produced on its surface are focused into the extraction slit. For its operation, the source requires a hydrogen pressure of 10^{-3} Torr, with cesium vapors added into the discharge. The source has been studied extensively, with different converter materials and different operating parameters. So far, more than 1A of negative ions has been extracted and accelerated to 34 keV. The main advantages of this approach are a reliable operation, a uniform beam, a good gas efficiency, and the possibility to scale-up the source. A larger

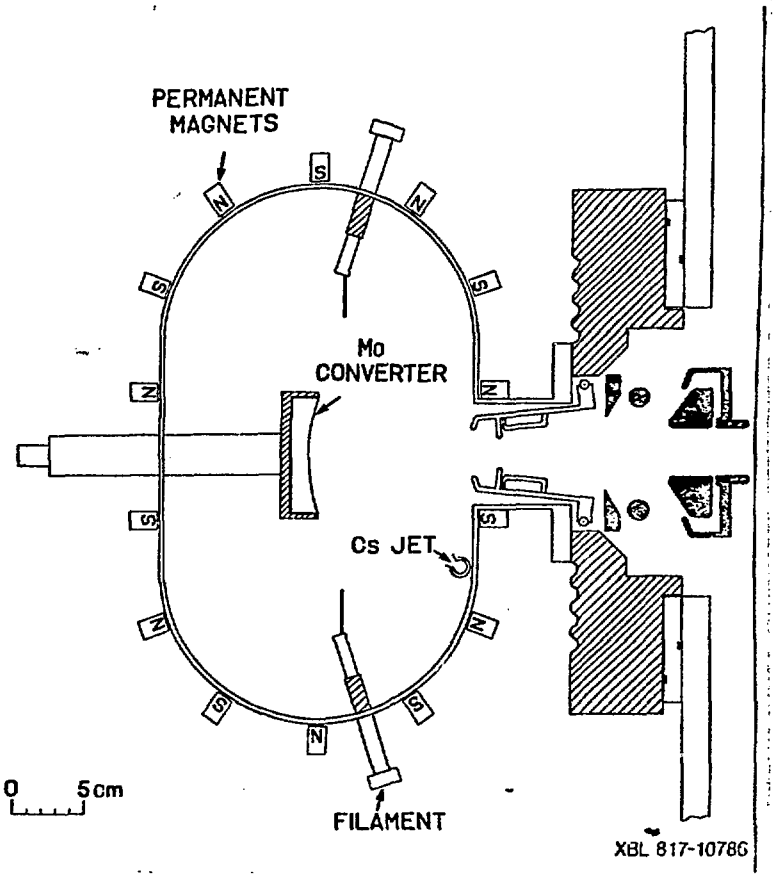

Figure 7 - Cross section of the multi-cusp source [7].

model is under construction, eventually to be used on an accelerator and neutralizer system.

A smaller model of this source is being tested at LASL [47] to produce an H^- beam of 20 mA for subsequent acceleration in the linear accelerator and storage in the proton storage ring. The duty factor of the source is 10% and the normalized emittance 0.13 cm mrad.

E. Hollow Cathode Discharge Source With a Converter

The hollow cathode discharge source of H^- ions is one of the very few sources that has been designed not as a modification of an existing H^+ source but specifically for the purpose of producing high current density H^- beams in a steady state operation and with an excellent gas efficiency. For this to be achieved, a source of highly ionized plasma is required, with a density above $10^{13}cm^{-3}$, that would fill the volume adjacent to the converter. A hollow cathode discharge is a very attractive plasma source: it can operate at ionization degrees above 50% and produce plasmas with densities 10^{13}–$10^{14}cm^{-3}$ in a background gas with pressures 10^{-4} to 10^{-3} Torr. Preliminary results [48] have indicated that from a hydrogen plasma produced by a 3 mm diameter tantalum hollow cathode up to 1 A/cm^2 of positive ions could be drawn on a negatively biased converter electrode. When cesium was deposited on the converter, a large increase was observed in the current collected by a separate electrode, that was mounted to intercept H^- ions produced on the converter and bent 90° in the magnetic field. A large model was subsequently fabricated and is still being studied (Figure 8). It has two flat hollow cathodes producing a 5 cm wide plasma sheet to fill 1 cm wide gap between the converter and the anode. The converter has five cylindrical grooves to focus negative ions into slots in the anode. A magnetic field of about 150 G serves to confine the plasma. The system operates steady state (a 60 hour run has been achieved). Injection of cesium into the discharge has as a result an increase in the current recorded in the converter circuit due to secondary electron and H^- emission. With a d.c. converter bias of about -120 V and a pulsed extractor voltage of 7.5 kV, H^- currents of up to 0.5A have been obtained [36], corresponding to current densities up to 0.1 A/cm^2 in the extraction slits. Maintenance of the optimum cesium layer on the surface of the converter, which should be uniform in space and time, is still a problem, but operation at a reduced level of 0.2A of H^- ions has been achieved over several hours. A new source, designed to yield 1A in steady state, will be tested soon; it may incorporate a porous molybdenum converter [49] as the method to supply cesium onto its surface instead of relying on bombardment by Cs^+ ions from the plasma.

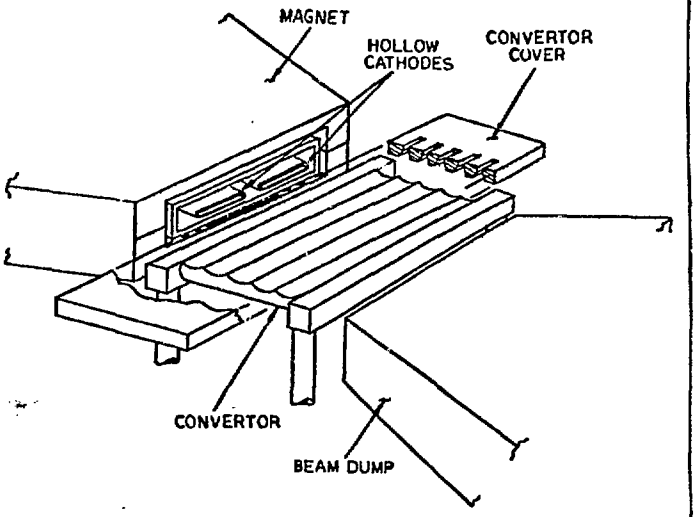

Figure 8 – Cross section of the HCD Source [36].

Main advantages of this approach in the design of H^- sources are: a steady state operation, a high H^- beam current density (0.05 to 0.1 A/cm^2 in the extraction slits), excellent gas efficiency (background pressure about 10^{-3} Torr), very flexible design and the possibility for scaling up in two directions.

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