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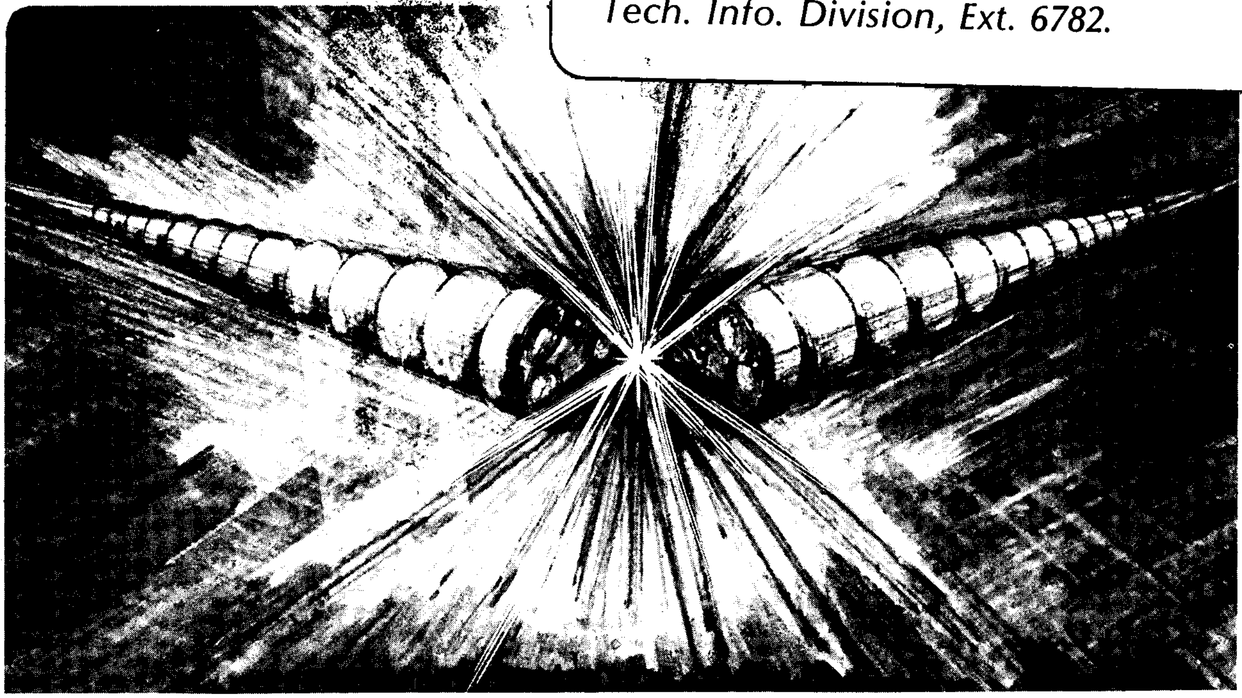

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REVIEW OF NEGATIVE ION SOURCE TECHNOLOGY*

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Abstract

H$^-$ or D$^-$ ions are required for generating high energy neutral beams in heating fusion plasmas. Two distinct types of H$^-$ ion sources can be identified: (1) surface sources - in which the H$^-$ ions are generated by particle collisions with low work function metal surfaces, and (2) volume sources - in which the H$^-$ ions are produced by electron-molecules and electron-ion collision processes in the volume of a hydrogen discharge. Recent experiments demonstrate that reasonable H$^-$ ion current density can be obtained from both types of sources. However, further technology must be developed on the control of cesium and the reduction of electron drain before these sources become practical units of a multi-ampere neutral beam injection system.

Introduction

The use of H$^-$ ions for accelerator applications was first proposed by Alvarez in 1951.[1] Since then, H$^-$ ion sources have found important applications both in fusion technology and in particle accelerators. In recent years, neutral beam injection has proven to be an effective way to heat plasmas in fusion devices to thermonuclear temperatures.[2,3] Higher energy neutral beams will be required for plasma heating and for current drive in some future fusion reactors.[4] The high neutralization efficiency ($>60\%$) of H$^-$ and D$^-$ ions makes their usage desirable to form atomic beams with energies in excess of 150 keV.[5] For this reason, appropriate programs to develop negative ion based neutral beam systems are now in progress at various fusion laboratories in the world.

There are two distinct types of negative ion sources. In the surface plasma type of sources, H$^-$ ions are generated by surface conversion processes and a self-extraction negative ion source based on this principle has already been operated successfully to produce a steady-state H$^-$ ion beam current greater than 1 A.[6] Experiments have been conducted to extract volume-produced H$^-$ ions directly from a hydrogen plasma.[7-9] This technique of generating H$^-$ ions has the advantage over the surface process in that it requires no cesium and it can use presently developed large area positive ion source geometries. However, one must find methods to handle the electron problem in order to make the volume negative ion source practical. This paper will briefly describe the development of these two kinds of negative ion sources.

Surface-production H$^-$ source

In 1972, the Novosibirsk group discovered that the yield of H$^-$ ions was increased from 5 to 20 mA by adding cesium to the hydrogen discharge in a planotron source (similar to the source shown in Fig. 6).[10] H$^-$ current density greater than 3 A/cm^2 has been achieved in milli-second pulses. Measurements of the negative ion energy spectrum showed that the H$^-$ ions were made both by the desportion and the reflection processes on the cathode surface.[11,12] The low work function of the cathode surface is provided by a partial monolayer of adsorbed cesium, and for reasons not yet understood, molybdenum seems to be the best substrate.

By 1974, short pulses of approximately 1 A (current density ≈ 3 A/cm^2) of H$^-$ had been obtained from larger sources at Novosibirsk and their operation were later confirmed at Brookhaven.[13]

In 1981, in Novosibirsk, Bel'chenko developed a "honeycomb" multi-aperture source with focusing of H$^-$ ions from spherical dimples on a cathode surface to the circular emission holes in the anode. A total H$^-$ ion current of 11 A was obtained at pulse lengths less than 800 μ sec.[14]

In 1979, a surface-production H$^-$ source was developed at LBL with the purpose of generating a continuous, self-extracted H$^-$ ion current of 1 A, and to accelerate this beam to ≈ 40 keV. Fig. 1 is a schematic of the negative ion source. The device is a 38-l multicusp source with 14 columns of permanent magnets installed on the external wall.[15] The source pressure is normally maintained at 1×10^{-3} Torr and a steady-state hydrogen plasma is generated by primary electrons emitted from eight tungsten filaments. To produce negative ions, a water-cooled concave, molybdenum converter (8 cm high and 25 cm long) is inserted into the plasma through two

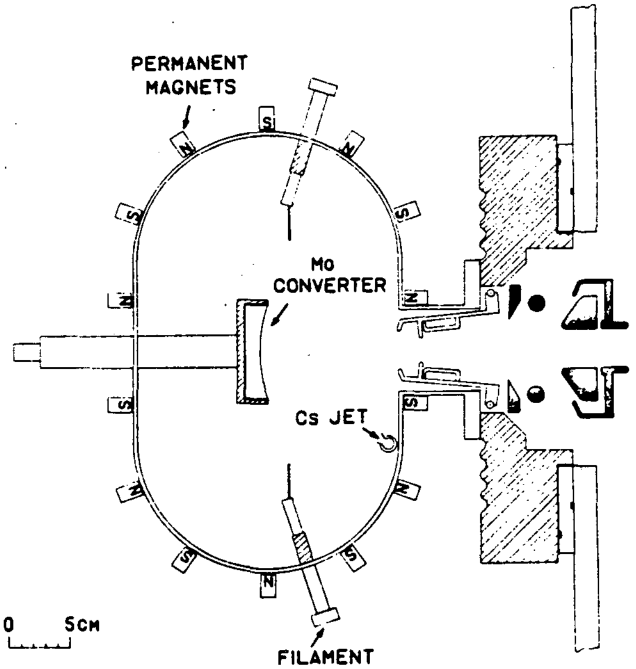

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Fig. 1. Schematic diagram of the LBL self-extraction negative ion source.

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feed-through insulators. By biasing the converter negatively (~200 V) with respect to the plasma, positive ions from the plasma are accelerated across the sheath and strike the converter surface. Negative ions that are formed at the converter surface are then accelerated back through the sheath by the same potential. The bias voltage on the converter thus becomes the ion extraction potential. The converter surface is curved to geometrically direct the negative ions through the plasma to a position at the exit aperture. The B- field in this region is made strong enough to reflect all energetic electrons, but it produces only a small lateral displacement on the trajectories of the energetic H^- ions. The electrode defining the exit aperture is electrically isolated so that a positive bias potential can be applied for electron suppression as well as for space-charge control. Cesium vapor is introduced into the system from an external oven through an ohmically heated coaxial tube located below the exit aperture.

After emerging from the source exit aperture, the H^- ion beam is accelerated to higher energies by a four-electrode accelerator. With the discharge operating at 80 V and 100 A, a continuous, self-extracted beam of H^- ions higher than 1 A has been obtained.[15] The converter was biased at -160 V and the converter current was 20 A. The spectrometer signals show that the high mass impurity in the beam is less than 1%. The self-extracted beam has been accelerated to 34 keV for a pulse length of 7 s. The pulse length was limited by the thermal capacity of the inertial beam stop. With maximum pumping capacity, the ratio of electrons to negative ions I_e/I^- in the accelerated beam was 0.38 and the gas efficiency of the source was about 13%.[15]

In short-pulsed sources, the converter can be covered with cesium atoms during the off-time between pulses. The optimum cesium and hydrogen coverage on the converter surface will enable the source to generate high H^- ion current density. In dc source operation however, it is difficult to maintain the proper coverage as the Cs^+ ions are very effective at sputtering away the cesium coverage. For this reason, the new surface-conversion source[16] constructed at LBL for the 400 keV TFP based beamline has an independently heated source chamber wall (Fig. 2). This arrangement will enable the cesium condensed on the wall to recycle back to the source volume and therefore increase the amount of neutral cesium arriving at the converter surface. The permanent magnets are encapsulated in rectangular stainless-steel tubes through which water can be passed. Thus, the magnets are kept under a maximum operating temperature of 250° C.

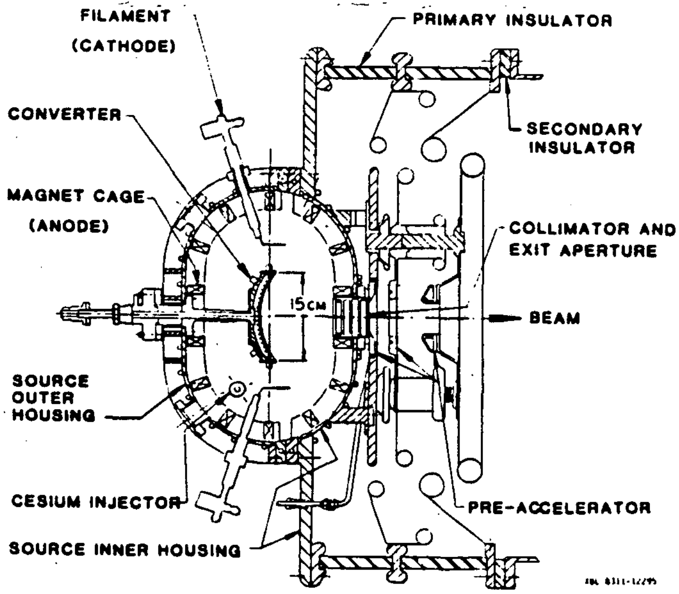

Fig. 2 Surface conversion source and 80 keV pre-accelerator.

In 1981, a large Mark V magnetron source had been developed at Brookhaven.[17] This source was operated in dc mode and could generate 100 mA of H^- beam current. A new method of providing plasma for a surface converter has also been pursued. This method employs hollow cathodes, mounted in a 200 G axial magnetic field to provide a dense, thin strip plasma at a source pressure much less than that required by the magnetron geometry. Figure 3 shows a schematic diagram of this HCD source.[17] H^- ions are formed at a biased converter and self-extracted across the magnetic field. H^- beams in excess of 0.1 A have been obtained.

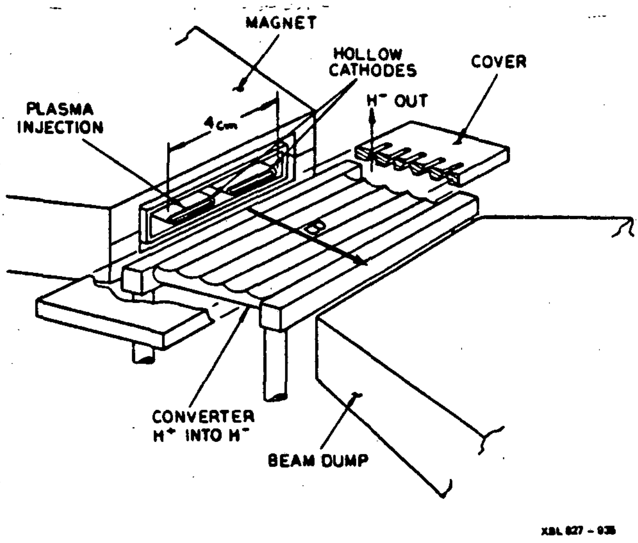

Fig. 3 Schematic of the Brookhaven HCD source.

At Oak Ridge National Lab., a calutron source (Fig. 4) has been used to generate H^- ions by surface process.[18] A biased molybdenum converter is aligned along the magnetic field, and operating with 5 sec pulses. With the converter biased at -150 V, the source has produced 23 mA of H^- at an extraction density of 56 mA/cm^2. The $\bar{E} \times \bar{B}$ extracted electrons are intercepted on a +1.5 kV electrode.

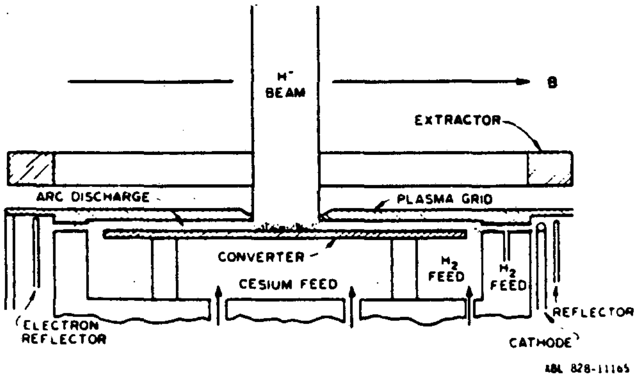

Fig. 4 The ORNL SITEX source.

Volume H$^-$ Ion Source

There are many reaction processes which can lead to the formation of H$^-$ ions in a hydrogen discharge.[19] However, the cross-sections are usually too small to account for the large concentration of H$^-$ ions observed in the plasma. Experiments in the Ecole Polytechnique, France have shown that under certain conditions, H$^-$ ion concentration can be higher than 20% in the central part of a hydrogen discharge.[20] It is now generally believed that dissociative attachment of vibrationally excited H_2 molecules could be the main process of H$^-$ ion production.[21,22]

In the last three decades, attempts have been made to extract H$^-$ ions directly out from the plasmas of various kinds of ion sources. From the duoplasmatron, H$^-$ ion current between 11 μA to 2mA (current density $J^- \approx 120$ mA/cm^2) have been obtained in short pulse mode operation.[23]

In 1963, Ehlers et al. in Berkeley developed a Penning-type ion source to generate H$^-$ ions for cyclotrons.[24] Figure 5 shows a diagramatic drawing of the source. The magnetic field of 4 kG needed for the operation of the ion source is normally generated by the magnet of the cyclotron. A D$^-$ ion beam of 2 mA has been extracted from the arc in a direction normal to the magnetic field with a discharge voltage of 300V and a discharge current of 5 A. The gas consumption was approximately 23 sccm. Subsequently, this source was modified so that a recess was made on the arc chamber where the extraction slit was located. With this new geometry, continuous H$^-$ ion currents in excess of 5 mA ($J^- \approx$ 40 mA/cm^2) have been obtained.[25]

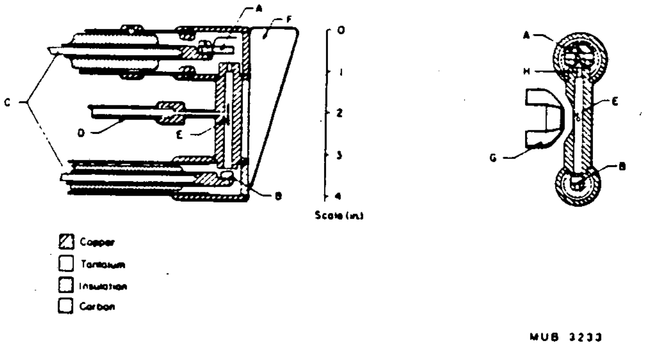

Fig. 5 Cross-sectional view of the Penning H$^-$ ion source.

In 1982, this reflex-type negative ion source was again modified in Berkeley so that the anode was divided into two sections; a top anode part and a wall anode part. By applying a proper biasing potential between these two anodes, the extracted currents of 9.7 mA ($J^- \approx 100$ mA/cm^2) for H$^-$ and of 4.1 mA ($J^- \approx 42$ mA/cm^2) for D$^-$ were obtained in a dc operating mode.[26]

In 1971, a magnetron plasma source, shown schematically in Fig. 6, was developed in Novosibirsk by Bel'chenko et al.[27] In this source, the discharge chamber has the shape of a race track and the plasma is kept circulating in the narrow space by the E x B drift motion. The H$^-$ ions were extracted from the plasma through the slit in the anode, elongated perpendicularly to the magnetic field. A short pulsed beam of H$^-$ ions with a current up to 22 mA and a high emission density of 220 mA/cm^2 was obtained with discharge currents as high as 100 A and at an arc voltage of 500 V. The source pressure was estimated to be about 1 Torr.

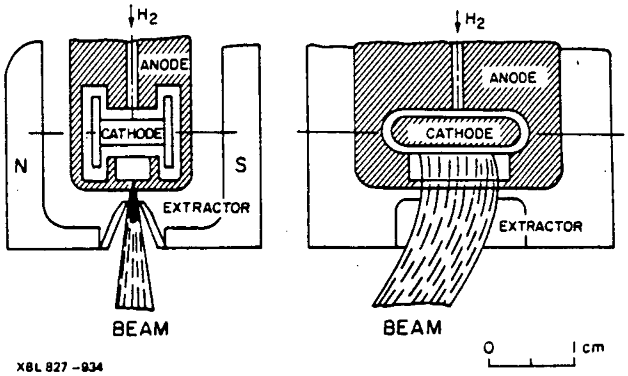

Fig. 6 The magnetron H$^-$ ion source.

Although the sources mentioned above can provide reasonably high H$^-$ ion current density, they are not easy to be scalable to form amperes of H$^-$ ion beam in long pulse or continuous operation. In these sources, the gas flow and the arc power required are too high to be useful for a neutral beam injection system. In addition, one must find some methods to remove the large currents of electron which accompany the H$^-$ ion beam.

Recently, a novel method of extracting volume-produced H$^-$ ions directly from a multicusp ion source has been reported.[28] This type of plasma generator has demonstrated its ability to produce large volumes of uniform and quiescent plasmas with good gas and electrical efficiency. It is shown that the addition of a "magnetic filter" to the source will not only enhance the H$^-$ ion yield but sizably reduce the extracted electron component.

Under normal operating conditions, the plasma potential in a multicusp source is several volts positive relative to the anode wall. The beam-forming electrode (plasma grid) floats negative with respect to the plasma. Thus positive ions are accelerated to this electrode by free-fall. Negative ions however, are trapped electrostatically within the plasma volume as their thermal energy is too low to surmount the potential barrier. In order to extract negative ions from the source, the beam forming electrode must at least be connected to anode potential. Then, a small H$^-$ current could be extracted, but it was accompanied by a large electron current (~9000 times the H$^-$ ion current). When the electrode was biased more positive than the anode, the plasma potential also increased by about the same amount. There was no significant change in the extracted H$^-$ ion or electron current.

Figure 7 is a schematic of the multicusp source with the magnetic filter in place. The filter was constructed by inserting square permanent magnet rods into copper tubes through which a square broach had

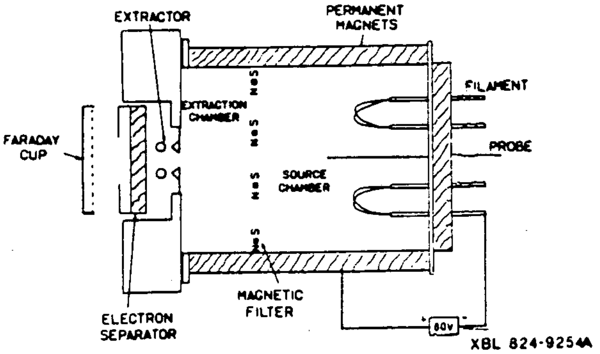

Fig. 7 Schematic diagram of the multicusp ion source with a magnetic filter.

been passed. The filter magnetic fields are made strong enough to prevent energetic primary electrons from leaving the source chamber. Positive ions however, can penetrate the filter fields and the interesting feature of this filter geometry is that the electrons which accompany these ions are very cold. These cold electrons are unable to generate additional positive ions but they can enhance the formation of H^- ions by reacting with the vibrationally excited H_2 or with the H_2^+ or H_3^+ ions.[29,30]

The magnetic filter reduces the positive ion and electron density in the extraction chamber and this effect can be enhanced by applying a positive voltage V_b to the beam-forming electrode. An additional effect of this positive bias is to raise the potential of the plasma in the extraction chamber relative to the potential in the source chamber, and the result is to enable the H^- ions formed in the source region to flow into the extraction chamber.

Figure 8 shows the use of a weak filter and a positive bias produces a factor of 10 increase in the H^- current plus a factor of 3 decrease in the number of electrons extracted. The use of a stronger filter results in a slight increase of H^- at the proper bias plus an additional factor of 2 decrease in electrons extracted. The net improvement of using the filter in this case is nearly two orders of magnitude with an I_e/I_{H^-} ratio of 100.

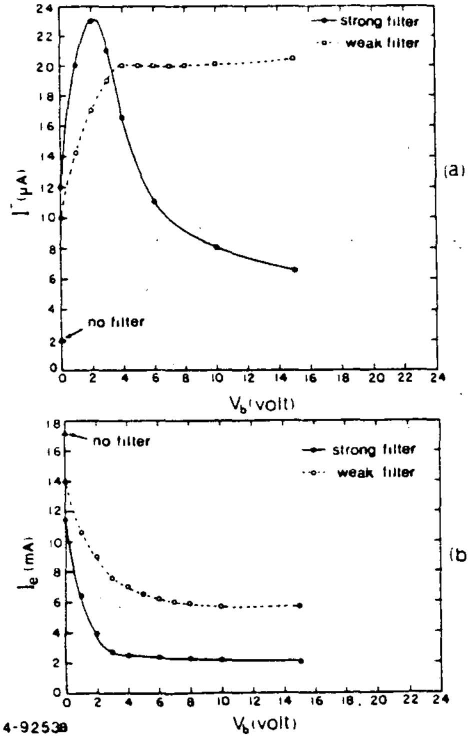

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Fig. 8 (a) The extracted H^- ion current and, (b) the extracted electron current as a function of the bias voltage on the beam-forming electrode.

It has been demonstrated in the same experiment that the extracted electron current can be further reduced by installing two tiny ceramic magnets at the extraction aperture. The extraction electric fields cause the electrons to E x B drift vertically in a cycloidal motion, and they are thus separated from the beam. The much heavier H^- ions pass through the extraction gap with little effect. A small wire (biased positive relative to the beam-forming electrode) placed at one end of the extraction slot was used to intercept the drifting electrons so that they would not leak out of the extractor. With this arrangement, the ratio of I_{H^-}/I_e has been improved to almost unity.

Recently, H^- ions were extracted from this same magnetically-filtered cusp source but it was operated at much higher current and in a pulse mode at Los Alamos National Lab.[31] The accelerated beam was mass-analyzed for accurate H^- current and emittance measurements. A plot of the H^- beam current as a function of the arc current I_d is shown in Fig. 9. The H^- ion beam current increases almost linearly with I_d. At an arc current of 350 A, an H^- current density of 38 mA/cm^2 was obtained. The source pressure was adjusted between 2.5 to 4.5 x 10^{-3} Torr. The total impurity content was found to be less than 2% and the I_{H^-}/I_e ratio varied from 1/3 at low extracted current to 1/12 at the highest current density of 38 mA/cm^2. These new results demonstrate that volume-produced H^- ions extracted from a magnetically-filtered, multicusp source can provide high quality H^- beams with sufficient current density to be useful for both neutral beam injection and accelerator applications.

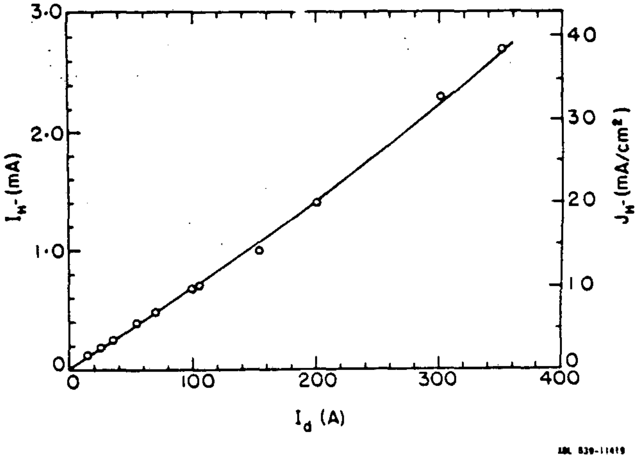

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Fig. 9 The extracted H^- beam current and current density from a 3-mm diam. aperture as a function of arc current.

In recognizing the high potential of volume H^- ion production, several other neutral beam development laboratories in the world have started to extract H^- ions from the multicusp or "bucket" sources. At Culham Laboratory, H^- ion current density of about 5 mA/cm^2 has been obtained from a 20 x 20 x 24 cm^3 bucket source operated with an arc current of 50 A. In Japan, the neutral beam group at JAERI has recently succeeded in extracting a beam of H^- ion with current density as high as 4 mA/cm^2 from a bigger bucket source. However, more research and development work is needed in order to scale the source operation to larger extraction area and perhaps with multiple beamlets. In addition, the magnet geometry at the extraction electrode must be optimized to achieve electron suppression without degeneration of ion optics. Should this succeed, one could operate a large area multicusp source to provide H^- ions in much the same manner as is now used to provide positive hydrogen ions for neutral beam systems.

Summary

In just 20 years, steady-state H^- ion beams have been improved from several milli-ampere to more than 1 ampere. However, it must be recognized that negative ion source development for fusion application is still in the early stage and many problems remain to be solved. Volume H^- or D^- ion sources appear to be the best candidate for the production of high energy neutral beams. These sources do not require cesium and this may be important for maintaining very high ion accelerating potentials. Nevertheless, one must find schemes to reduce the large current of electrons which could accompany the extracted negative ion beam.

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