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PROGRESS IN THE DEVELOPMENT OF STEADY STATE NEGATIVE ION SOURCES FOR FUSION APPLICATIONS*

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INTRODUCTION

Neutral hydrogen or deuterium beams have been used very efficiently for plasma heating in tokamaks, mirror machines and even in some stellarators.(1)(2)(3) Common features of neutral beam systems, either existing or under construction, are a relatively low beam energy (< 120 keV) and a pulsed operation. Neutralization efficiency of positive hydrogen or deuterium ions, in this energy range, is sufficiently high(4) and all the existing neutral beam systems are based on acceleration and neutralization of positive ions.

For fusion machines presently considered as the next step toward future reactors and even more so for reactors themselves, the demands on neutral beam systems will be much more challenging. During the past few years needs for future machines have been considered in detail and tentative parameters of neutral beams defined. For tokamaks there are two applications, plasma heating and toroidal current drive. The former would require a beam system operating in the range of energies 200-400 keV and delivering a power of about 10 MW in pulses of about 1 minute duration. The possibility of driving a toroidal current in tokamaks has recently been investigated experimentally and theoretically; it is clear that if such a current could be maintained indefinitely, a tokamak would become a steady state machine, eliminating in this way one of the major drawbacks in this approach to a fusion reactor. One of the methods to drive a steady state toroidal current is by injecting tangentially high energy neutral beams. However, before a decision is made whether to incorporate this feature into any future device, experiments will have to be performed on TFTR or another similar machine to prove the viability of the concept. This experimental verification could be tried with the same neutral beam system as envisioned for plasma heating, i.e., about 10 MW of power at an energy of 400 keV and a pulse length of about 1 minute.

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Should such an experiment demonstrate an efficient current drive, the next generation of tokamaks may include this feature, although the requirements would then call for a steady state operation and probably an energy around 1 MeV. Concerning tandem mirror machines, needs for beam energies of 200 keV or higher may arise around the year 1990, to be used on devices beyond MFTF-B. For this application, a steady state operation will be required, with a power of about 10 MW per unit.

A much higher beam energy, longer pulse length (up to a steady state mode) and a higher injected power are not the only considerations in the design of a future neutral beam system. To be a viable component of a fusion power plant, such a neutral beam system should operate with an acceptable power efficiency. In the energy range 200-400 keV, the neutralization efficiency of D^+ ions decreases from 20% to about 3% (Figure 1), a fact that excludes their application in any neutral beam line operating at these or higher energies. It is only the negative ions that can offer a neutralization efficiency between 60% and 100%, depending on the stripping method, practically independent of the beam energy up to and above 1 MeV (Figure 1). The objective of the source development program is, therefore, a negative ion source, that can operate steady state or with pulses up to 1 minute long, deliver a beam of about 10A per unit, have acceptable power and gas efficiencies, and requiring regular maintenance in intervals not less than several thousands of hours.

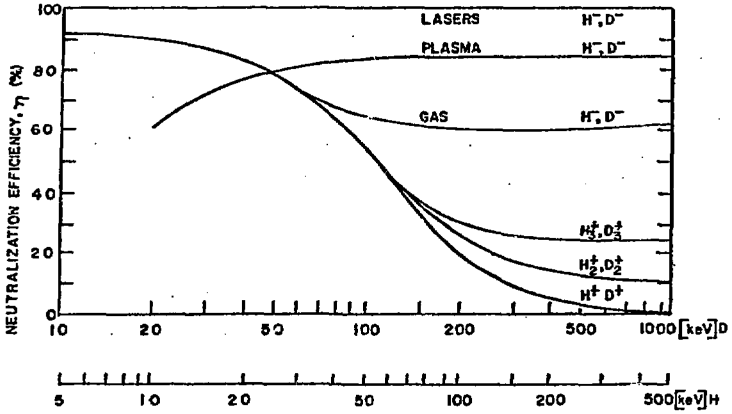

Figure 1 - Neutralization efficiency of H and D ions.

Recently another way of plasma heating with neutral beams has been suggested:(5) instead of using D° beams, much heavier neutral particles

($A \geq 6$ amu) would be injected into the plasma, with energies of 1-2 MeV/amu. Similar to D° beams, heavy negative ions would be produced in a source, accelerated to the required energy and then stripped of one electron. After injection into the plasma, particles would go through successive stages of ionization, heat the plasma as they slow down and drive the toroidal current. Eventually particles would become fully ionized and confined in the plasma the same way as alpha particles produced by D-T fusion. The main advantage of heavy particle injection lies in a higher beam energy and a higher beam power density. It is desirable to inject at the highest energy still allowing adequate confinement of the fully stripped ions and for which the plasma is opaque. The mass range at its upper end will be limited by the radiated power by thermalized heavy ions; it seems that the mass range would be limited to roughly $6 \leq A \leq 30$. A negative heavy ion source should deliver a steady state beam current of the order of 1A; after acceleration to 1-2 MeV/amu and taking into account losses in the striping process, one would still have a 10 MW neutral beam system.

PRODUCTION OF NEGATIVE IONS

Volume processes. Although volume processes, resulting in the production of negative hydrogen ions, have been used in early sources,(6) the source geometry (duoplasmatron, Penning) was such that the equilibrium between the production and destruction was very unfavorable and the H^- yield was low. It was not until about 1977 that much higher production rates and densities of H^- ions have been measured in a large volume multipole discharge.(7) Subsequently, experiments have been performed on other, similar devices(8),(9),(10) and under proper operating conditions a maximum H^- density of $10^{10}cm^{-3}$ was measured,(8) with a ratio of H^- density to plasma density of 0.2. It has been proposed that such a high relative density of H^- ions is due to a very high reaction rate for the dissociative attachment of vibrationally excited H_2 molecules by thermal electrons. The dependence of H^- density on the plasma density n_p was found to be rather steep ($\propto n_p^2$) in the range of n_p up to $10^{10}cm^{-3}$; above that, H^- density was proportional to n_e.

Surface processes. It has been known for some time that interactions between particles, both charged and neutral, and a low work function surface can result in the formation of a negative ion. First applications of this method in the production of high density H^- beams date from

1972-1974, in experiments done at Novosibirsk.(11) Although there is a number of ways to produce a negative ion on a surface,(12) requirements of future neutral beam lines limit the choice to only a few. The promising approach is still the system plasma-surface, where a dense plasma in the vicinity of a low work function surface serves as the source of fast particles to bombard the surface. There are two processes leading to the formation of negative hydrogen ions on a surface. First, if there is some hydrogen adsorbed on the surface, a fast primary particle (hydrogen or heavier ions) can by impact desorb a negative hydrogen ion. Second, fast primary particles (H°, H^{+}, H_2^{+}, H_3^{+}) can be reflected from the surface (after dissociation of molecular ions) as negative ions. It has been found by experiment, that the highest yield of negative ions is obtained if a partial monolayer of cesium exists on a metal surface; molybdenum is most widely used as a substrate because of a relatively low sputtering rate, a low work function of the system Cs-Mo, and a low impurity content in the extracted beam. Measurements of energy spectra of surface produced negative ions have shown that both mechanisms, desorption and reflection, contribute to the production. Figure 2, from Ref. 13, shows the energy spectrum of negative ions, produced on a biased electrode (V = -200V), which was immersed in a plasma and covered with a partial monolayer of cesium. The sharp peak at the energy of 200 eV corresponds to negative ions produced by desorption; their initial velocity is small and their final energy

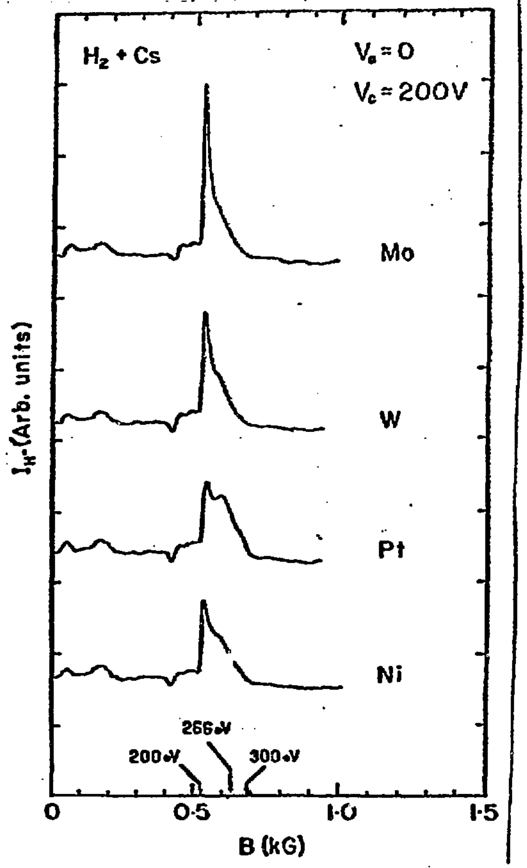

Figure 2 – Energy spectra of H^- ions produced at constant converter voltage.

is very close to the accelerating potential of the surface itself. The second group of ions, in a broad range of energies above 200 eV, consists of ions produced by reflection of atomic particles, which in the case of molecular ions follows their dissociation. A part of the impinging energy is conserved and added to the accelerating potential of the surface.

The possibility of using beams of charged particles either to sputter negative ions from the surface or to be converted into negative ions during the scattering process, has also been investigated, but there is still no high current density source in operation based on this method.

STATUS OF STEADY STATE H^- OR D^- SOURCES

Magnetic multipole source (volume processes). Figure 3 shows a cross-section of the multipole (bucket) source of volume produced negative ions, developed at Culham Laboratory.(10) The discharge is maintained by electron emission from hot Ta wire cathodes. Electrons are accelerated to the plasma potential and then contained in the field-free volume within the high magnetic multipole field covering the anode region. The fast primary electrons lose energy by inelastic collisions, including ionization and direct or indirect production of vibrationally excited molecules, which lead to the formation of negative ions. The magnetic field in the extraction region has been shaped in such a way as to prevent the escape of electrons; ions suffer only a displacement of trajectories. Dimensions of the source are 24 cm x 20 cm x 10 cm, the maximum power input necessary to maintain the discharge at a pressure of about 0.3

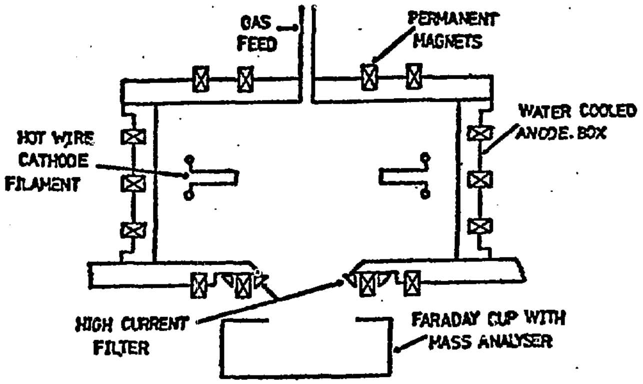

Figure 3 - Cross-section of the multipole negative ion source (volume production).

mTorr was 4.3 kW, while the extraction aperture was 2 cm x 15 cm. The maximum H$^-$ current extracted with a potential of 2 kV was about 100 mA, corresponding to a current density above 3 mA/cm^2. Figure 4 shows the H$^-$ current density as a function of the plasma density. Although this method of production of negative ion beams seems very attractive (low operating pressure, simple design, no need for cesium), future neutral beam systems will require extracted beam current densities at least an order of magnitude higher than presently achieved. It has been found that in this source the negative ion yield scales proportionally to the plasma density, which scales as the input power: a beam of 1A of negative ions would, therefore, require about 40 kW of discharge power, which is almost an order of magnitude too high. The gas efficiency, which is estimated to be between 5% and 10%, would also have to be improved substantially.

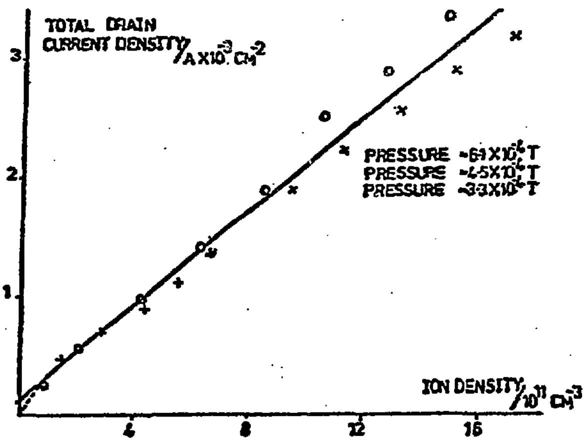

Figure 4 - Negative ion current density vs. ion density in the multipole negative ion source.

Surface-plasma sources. There are two possible approaches in the design of a surface-plasma source. In the first approach, the converter serves not only as an electrode for production of negative ions, but takes an active role in the establishing and maintaining the discharge as well. Magnetron and simple Penning geometries belong to this group. A simpler design is the main advantage of this apporach, while a low ionization degree (resulting in a poor gas efficiency) and a more or less not controllable energy of particles impinging on the converter (the energy is determined by the discharge voltage) are its disadvantages. In the second approach, a plasma is produced in an electrode system independently of the converter and then let to diffuse into the vicinity of the converter. There are several ion sources based on this approach, beginning with the first generation of Penning sources modified by the addition of a third, independently biased converter electrode,(11),(14),(15) followed by more sophisticated designs, among them a source based on the injection of a plasma from a hollow cathode discharge,(16) a modified calutron source(17) (SITEX), and a modified bucket source.(18),(19) In this paper only those sources will be described that have been designed for long pulse or steady state operation, to be used in an advanced neutral beam system. In addition to the pulse length requirement, an average extracted beam current density of 10-50 mA/cm^2 is desirable, with acceptable (from the fusion device point of view) gas and power efficiencies.

a. BNL steady state Mk V magnetron. A cross-section of this source is shown in Figure 5. Its geometry is standard racetrack, with several new features and improvements incorporated. All electrodes are water cooled, so that the source can operate either in a pulsed mode or steady state. Table I lists some of the design parameters. The new features are, first, the application of the geometrical focusing of negative ions by means of cylindrical grooves into the extraction slits, and, second,

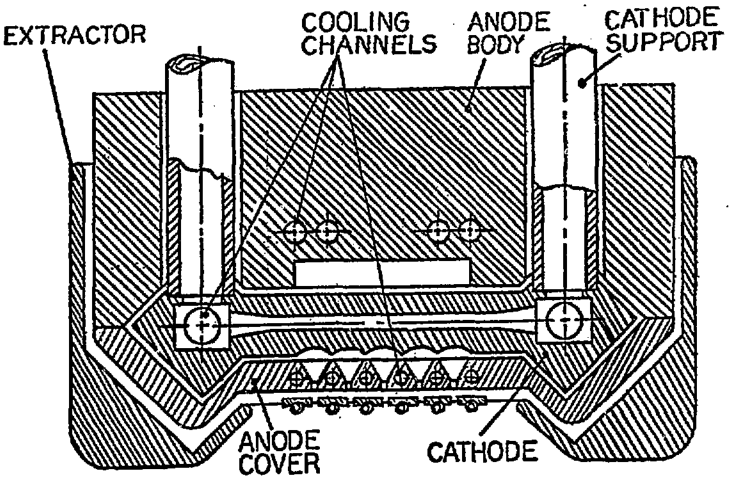

Figure 5 - Cross-section of the BNL Mk V magnetron source.

widening of the discharge gap in the back of the racetrack. In smaller, pulsed magnetron sources,(20) these changes in the geometry have resulted in a substantial improvement in gas and power efficiencies. Initial tests with the Mk V magnetron source have been done in a steady state mode (several days duration); the maximum extracted current was only 0.12 A and it was obtained at a reduced power level. The main reason for this unsatisfactory performance lies in the fact that it was not possible to achieve a uniform cesium coverage on the cathode surface; a water cooled electrode structure operates at temperatures below 100°C and cesium tends to condense on the coldest spot. The cooling system is being upgraded to operate at 150°C, which should be high enough to maintain a proper density of cesium vapors. If the design parameters are achieved, the Mk V current density and power efficiency would be satisfactory, while the relatively low gas efficiency would require a high speed pumping system downstream from the source.

Table I

H^- or D^- Current	1 A
H^- or D^- Current Density	0.5 A/cm^2
Average H^- or D^- Current Density	50 mA/cm^2
Cathode Current, Max.	100 A
Cathode Power Density, Max.	200 W/cm^2
Power Efficiency	0.1 A/kW
Gas Efficiency	5%

b. <u>BNL hollow cathode discharge source.</u> As it has been mentioned before, both drawbacks of the first approach in the source design can be eliminated if a separate plasma generator is used. A very attractive source of highly ionized plasmas is the hollow cathode discharge. Plasma densities of 10^{13} to 10^{14}cm^{-3} can be easily achieved, in a background gas with a pressure of 10^{-3} Torr or lower, which compares very favorably with 10^{-1} Torr or higher pressures in a standard magnetron source. In principle, such a source would consist of one or more hollow cathodes, injecting a steady state plasma along magnetic field lines into a perpendicular electrostatic field created by a voltage between the converter and the source wall.(21) A negatively biased converter would draw an ion current, and if the work function of the surface is low, negative ions will be produced by sputtering or reflection, and accelerated by the same difference of potential toward extraction slits in the wall to form the H^- or D^- beam outside the source. A few preliminary tests have been performed first,(22) to show the feasibility of the approach. For these tests, a 3 mm diameter tantalum tube was used, in a long solenoidal magnetic field of about 500 G. Two flat electrodes, one biased and serving as a converter and the other grounded and serving as a collector, were mounted on opposite sides of the plasma column. At a bias of -82V, the positive ion current density on the converter reached 1 A/cm^2, when the cathode current was 27 A. The corresponding plasma density was about 10^{14}cm^{-3}, with a background pressure of less than 10^{-3} Torr. With no cesium added to the system, the collector current was at a constant value of 0.8 A, regardless of the bias, position or material of the converter. When cesium was deposited on the surface of the converter, the collector current depended on the bias and on the position of the converter and collector; the highest value was 2.9 A and was obtained only when the converter was drawing the highest current and when the collector was intercepting trajectories of fast H^- ions originating at the converter surface after being bent in the magnetic field of the device. It has been estimated, that the emission H^- current density was 0.3 A/cm^2. Based on preliminary tests, a larger device was fabricated and its sketch and photo are shown in Figures 6 and 7; two flat tantalum hollow cathodes (15 mm x 0.5 mm inside dimensions) are mounted inside one magnetic pole,

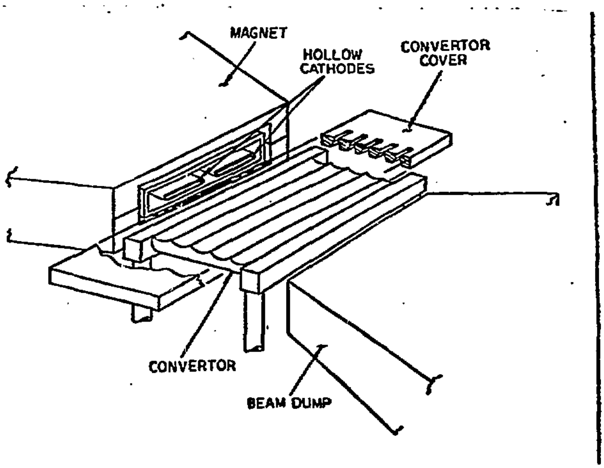

Figure 6 - Sketch of the BNL hollow cathode discharge source.

the converter (with an active surface area of 5×5 cm^2) has five cylindrical grooves for geometrical focusing of fast negative ions into corresponding slits in the source cover. A filament used to ignite the cathodes is mounted inside the opposite magnetic pole.(23) The flat shape of the hollow cathodes was chosen in order to achieve a ribbon shaped plasma column, wide enough to illuminate a large area converter and not too thick to cause appreciable losses of negative ions during their transit to the extraction apertures. Cathodes have been operating for long stretches of time (up to 60 hours), at 40 A each. The maximum converter current density was 0.3 A/cm^2 and with cesium deposited on the converter surface, a maximum H^- current of 0.5 A was extracted at 7.5 kV. The source still has not been operated at full power (120 A) and, as it was the case with the Mk V magnetron source, the converter surface was only partially covered with cesium. Several methods are being studied to

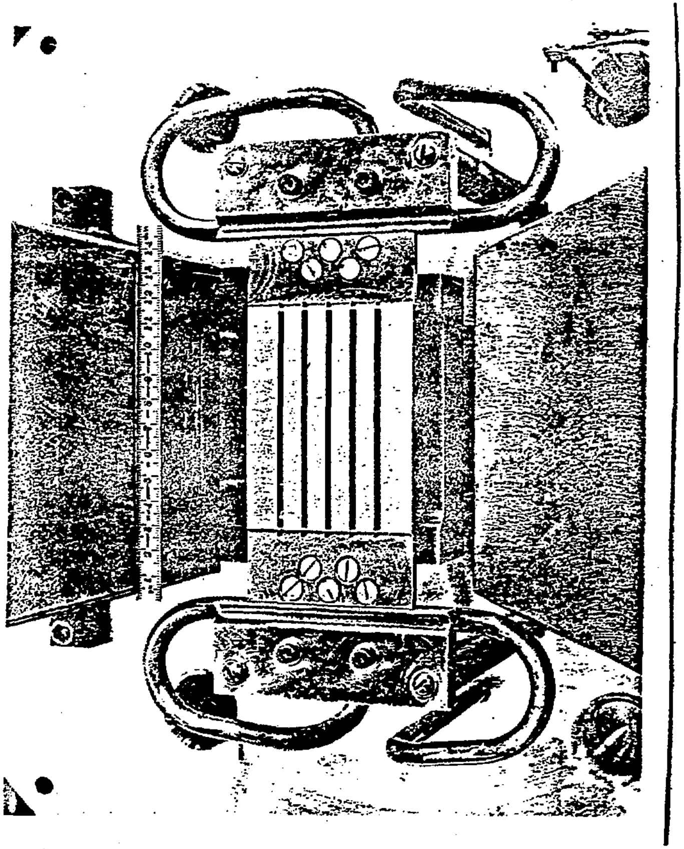

Figure 7 - Photo of the BNL hollow cathode discharge source.

achieve a uniform cesium layer on the surface; when this is achieved, it is expected that the source will deliver 1 A of negative ions, in a steady state and with an average beam density of 40 mA/cm^2. However, a gas efficiency, that may reach 20-50%, will be the main advantage of this approach. A new source, capable of delivering 2 A of H^- ions and with the possibility to be scaled up to 10 A, is in the design stage.

c. <u>LBL bucket source</u>. The approach selected at Lawrence Berkeley Laboratory(13),(18),(19) was to modify the existing and very reliably working source of positive ions of the multipole or bucket type; main modifications consisted of the addition of a biased converter electrode for negative ion formation and in the changes in the extraction area to prevent the diffusion of plasma electrons out of the source. Figure 8 shows a cross section of the source;(19) permanent magnets placed on the outside of the source will serve to create a multipole field necessary

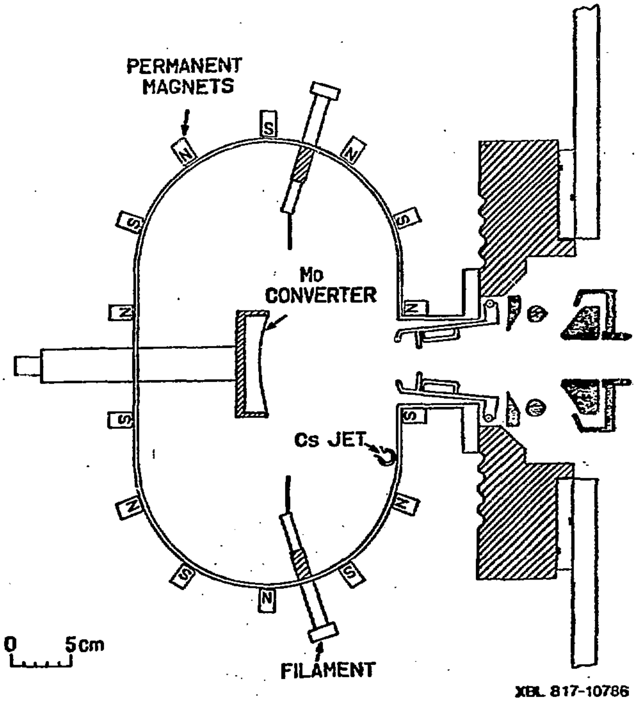

Figure 8 - Cross-section of the LBL multipole negative ion source (surface production).

for plasma confinement, and hot filaments serve to maintain a steady state discharge. Multipole or bucket sources are known to produce very uniform and stable plasmas, although at a relatively low density of about $10^{12} cm^{-3}$. With the molybdenum converter installed as shown in Figure 8 and biased at -200 V with respect to the anode, the collected current was 20 A (0.1 A/cm^2) for a discharge power input of about 12 kW. In the pure hydrogen mode of operation, the H^- current measured on a Faraday cup was a few mA only; after cesium was injected into the discharge, the H^- yield gradually increased to 1 A, which was then accelerated to 34 keV. The converter has a cylindrical curvature to focus fast negative ions into the extraction slit. If the average beam current density is defined in a similar way as previously (by dividing the current by the active converter area), it would be 5 mA/cm^2. The gas efficiency was determined by measuring the total hydrogen gas flow and it was 13%. A steady state operation (up to 10 minutes) with an improved gas efficiency and a very low contamination of the H^- beam with electrons and heavier ions seem to be the main advantages of this approach; however, the beam density (which eventually, after scaling up, will determine the size of the neutral beam system) is still on the low side, while the power efficiency (about 0.05 A/kW) is not as good as it has been achieved with other sources.

d. SITEX-ORNL Surface Ionization source with Transverse Extraction. Initial experiments with this type of a source were performed on a modified ORNL calutron source,(15) and from a 0.4 cm^2 aperture an H^- beam of 18 mA in pulses of 30 s duration was extracted. This has led to the design of the next model, the SITEX source; Figure 9 shows schematically one of the versions as given in Ref. 17. Plasma is maintained by electrons emitted from a hot filament and oscillating along the 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 and then it diffuses onto the surface exposed to the plasma. Recently, an improved version of the SITEX source has been fabricated.(24) The new features are a double anode slit for the extraction and cylindrical grooves for focusing of fast negative ions. The extraction slits are oriented along the magnetic field lines, which facilitates the removal of extracted plasma electrons in the E x B direction, away from the H^- beam. Electrons are intercepted by a separate electrode, with a potential equal to 10% of the extraction potential in order to recover most of their energy. The active surface area of the converter is 20 cm^2, while the extraction slit area is 5 cm^2. The source operates in pulses of 5 s duration. With a total power input of about 3.5 kW and with an extraction voltage of 18 kV, 0.2 A of H^- were recorded on a distant Faraday cup; however, it is estimated that due to stripping losses during the transit between the source and the Faraday cup actually extracted current may have been 0.65 A. In either case, the average beam current density is higher than 10 mA/cm^2. The power efficiency of the source has been calculated to be about 0.06 A/kW for the target H^- current or about 0.2 A/kW if normalized to the estimated extracted current. Gas efficiency is only 3%, which is lower than for any other long pulse or steady state source.

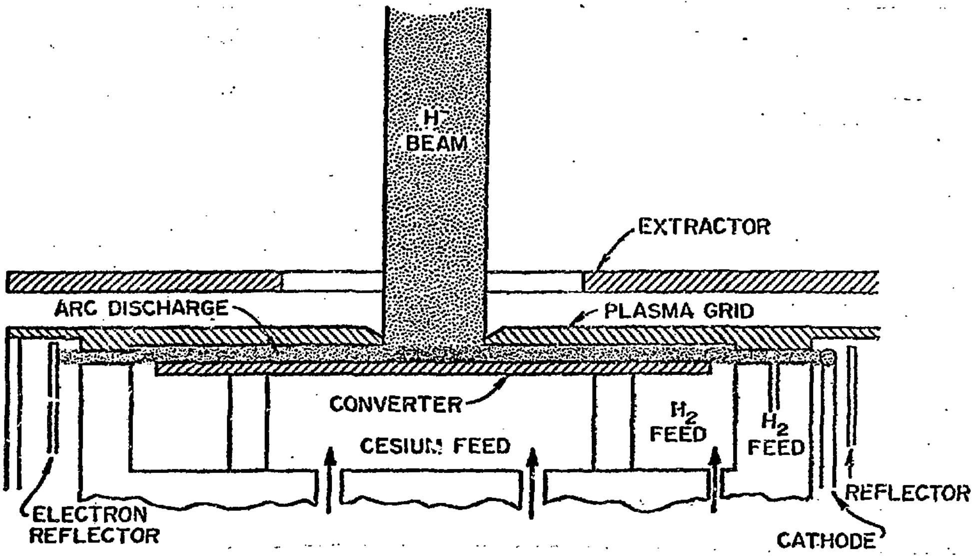

Figure 9 - Cross-section of the ORNL SITEX source.

SURFACE-PLASMA SOURCES OF HEAVY NEGATIVE IONS

The idea of using beams of neutral particle heavier than hydrogen has been suggested very recently and only preliminary studies have been done on possible approaches to the negative ion source design.(5) Negative ions of many elements have electron binding energies similar or even higher than hydrogen (Li^-: 0.62 eV; C^-: 1.27 eV; O^-: 1.46 eV; Si^-: 1.39 eV) and could be easily produced. In addition to the generally more complex method of double electron capture of fast positive ions in a metal vapor curtain, it should be possible to produce heavy negative ions in any of the just described three sources with an independent plasma production (hollow cathode discharge source, multipole source, SITEX source). However, due to its inherent property of producing almost fully ionized plasmas, a source based on hollow cathode discharges may be the most attractive.

CONCLUSION

During the past few years or so, the development of steady state sources of negative hydrogen or deuterium ions has made a substantial progress. There are several approaches under investigation, some operating with long pulses and some in a true steady state, and delivering H^- or D^- beam currents of several hundred mA up to 1 A. The improvement in the gas efficiency from a few percent for pulsed sources to the range of 5% to 15% and possibly even higher for the new sources, is another advance that was not anticipated only 4-5 years ago. A higher gas efficiency has come as the result of using independent plasma generation and geometrical focusing of surface produced negative ions. The power efficiency has not been changed so much, but, in a high energy system, savings of a few kW/A are less important than the reduction of the gas load. It can be expected that within five or so years a small (< 1 MW) long pulse or steady state neutral beam system based on negative ions could be put into operation.

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