PROGRESS IN THE DEVELOPMENT OF H^- ION SOURCES*

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Abstract

Charge state of an H^- ion can be changed easily by either single (neutralization) or double (ionization) electron stripping, in a very wide energy range. Development of H^- ion sources has been stimulated by several areas of application: production of high power beams of hydrogen atoms with energies of several hundred keV for plasma heating and current drive in fusion devices, production of high brightness beams of hydrogen atoms in the energy range around 100 MeV, and for use in some accelerators where H^- ions facilitate and improve the injection or ejection processes. This paper will put most emphasis on the accelerator application. Two types of sources will be considered, those where H^- ions are produced in processes on a low work function surface and those where they are produced in collisions occurring in the plasma. After a short outline of theoretical work and experimental studies of relevant processes and phenomena, a review of existing source designs will be given, describing their performance.

Introduction

Until about 10 or 15 years ago most H^- ion sources were actually adapted positive ion sources delivering up to 5 mA of H^- ions in pulsed or steady state mode of operation.[1,2] At that time, dissociative attachment of electrons to molecules and dissociative recombination of molecular ions were considered to be dominant processes for H^- ion formation. In the early 1970's it was discovered that H^- ions can be produced very efficiently on low work function cesiated surfaces,[3] and several types of sources have been developed since then using this method. They all have a discharge chamber where a plasma is produced; plasma particles (fast atoms, ions) bombard a cesiated surface placed in the plasma and produce H^- ions either via back-scattering or by desorption. Achieved H^- ion currents have reached 1 A in the steady state mode of operation and 10 A in the pulsed mode.[4,5,6] A more recent development has been in the area of volume sources. First experiments were done at Ecole Polytechnique,[7] showing an unexpectedly high density of H^- ions in some low density plasmas. Further studies at Ecole Polytechnique and elsewhere have led to present designs of volume sources, where H^- ions are produced most probably by dissociative attachment of electrons to molecules in high excited states. Although their total H^- current and their current density cannot yet match the performance of plasma-surface sources, there are accelerator applications where the advantages of volume sources (simple operation, no cesium) may outweigh their disadvantages.

Processes Relevant for the Operation of Plasma-Surface Sources

Performance of a plasma-surface H^- ion source is determined by plasma parameters and by the processes on the surface which serves to produce H^- ions. A high ionization degree coupled to a good plasma confinement will be reflected in high power and gas efficiencies, which may be an important consideration in high current and/or steady state devices. An H^- ion can be produced by back- scattering of hydrogen particles (H°, H^+, H_2^+, H_3^+), or by desorption of adsorbed hydrogen atoms. The energy range of primary particles in either case is between several tens of eV to several hundred eV. Parameters of the emitted H^- ions (yield, energy spectra) depend on the process of formation; therefore, characteristics of a source (yield, emittance, brightness) will also depend on the dominant mechanism.

Formation of the plasma. Gas discharges that serve as a source of particles for surface processes producing H^- ions, can be classified into two groups, one where the cesiated surface (converter) acts also as one of the electrodes for the formation and maintenance of the discharge, and the other where the discharge is formed independently of the converter. Magnetron sources and simple Penning sources (without converter) belong to the first group, while modified Penning sources (with converter), multicusp sources with converter and hollow cathode discharge with converter belong to the second group. Although the addition of a separate converter electrode for this specific purpose somewhat complicates the design, it has definite advantages because it offers the possibility to optimize its potential and, therefore, the yield of H^- ions. It is also true that sources with an independent converter in general have a better gas efficiency and a higher power efficiency.

Cesium Coverage on the Converter Surface. The best conditions for H^- ion production on the converter correspond to the minimum in the work function; only about 60% of a monoloyer of cesium is required for that. To maintain the optimum coverage of cesium on the converter is one of the most difficult problems facing the designer of long pulse or steady state sources; fortunately, for short pulse operation it is much easier to maintain the optimum. Cesium is usually injected into the discharge in the vapor form and reaches the converter surface either as neutral atoms or ionized. During the operation, the adsorbed cesium is sputtered away mostly by Cs^+ ion bombardment. If the source operates with short pulses, cesium is mainly deposited on the converter during off periods and a close to optimum coverage may last during the whole pulse. Even at moderate plasma densities ($\approx 10^{12}$ cm^{-3}) most of the cesium would be ionized[8] and the equilibrium coverage would be below the optimum (a high sputtering rate and a low sticking probability for Cs^+ ions). A theoretical model developed later[9] agreed with this conclusion (at Cs^+ ion energies of about 200 eV any increase in the Cs ionization degree above 40% would reduce the coverage below optimum). A fully ionized Cs flux would produce only 26% of a monolayer, corresponding to a work function of about 2 eV instead of about 1.5 eV at the optimum. On the other hand, measurements of the work function of molybdenum when bombarded with Cs^+ ions[10] have shown that if Cs^+ ion energies are around 100 eV or lower it is possible to reach optimum conditions. Sputtering problems can be greatly reduced by using

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deposition of cesium by diffusion through a porous converter.[11]

Back-scattering of hydrogen particles from surfaces. In many experiments, where a low work function surface was bombarded by fast protons, it was found that H^- ions could be produced with a high conversion probability[12,13] (up to 60-70%). However, large values of the angle of incidence of primary particles have been often studied in great detail, while for plasma-surface sources the normal incidence is most important. In general, there is an optimum proton energy and an optimum angle of incidence. Energy spectra and angular distributions of H^- ions are rather wide; it has been also found that hydrogen coadsorbed with cesium on the surface substantially reduces the H^- yield.[14] Measurements of angular distributions and energy spectra of H^- ions from ion sources do not point to backscattering as an important contribution to the total H^- ion yield since many of the ions scattered under wide angles cannot reach the extraction aperture.[15]

Desorption by cesium ions. H^- ions can be efficiently produced by desorption of hydrogen from a low work function surface (cesium on molybdenum), using fast Cs^+ ions as primary particles. The investigated energy range was 150 - 1000 eV, and the yield, angular distributions and transverse energy spectra determined.[16] At the minimum work function the yield of H^- ions was 0.41 at a Cs^+ ion energy of 750 eV. The H^- ion temperature depended on Cs^+ ion energy, ranging between 0.35% and 0.65% of the incident Cs^+ ion energy (lower values for high energies); practically all H^- ions were emitted with an initial energy less than 2% of the incident Cs^+ ion energy. This mechanism has been suggested to explain rather low measured values of beam emittance in some ion sources; however, for converter voltages optimized for a good H^- yield and stable source operation, the H^- yield should not be larger than a few percent[16] of the incident Cs^+ flux.

Desorption by hydrogen ions. It seems that by the process of elimination, the most important contribution to the H^- yield should be from desorption by hydrogen ions. Unfortunately, very little is known about this process experimentally, while theoretical studies predict a wider energy distribution (higher H^- temperature) than for Cs^+ impact.

Charge exchange. In many plasma-surface sources the density of hydrogen atoms is sufficiently high that the charge exchange process between fast H^- ions and low energy atoms may take place, resulting in a fast atom and a slow H^- ion. The energy spectra of extracted ions will show a very low energy group indistinguishable from ions produced by other processes in volume (in some sources, like the simple Penning source, where there is no direct path between the surface and the extraction aperture, this is the only group). Their temperature could, however, be higher than the temperature of atoms as the result of elastic collisions with positive ions in the plasma. Still, beams formed from such ions will usually have a lower emittance than those including ions produced on surfaces.

Processes Relevant for the Operation of Volume Sources

First H^- ion sources delivering milliamperes of current were of the Penning type.[17] Polar dissociation $e + H_2 \rightarrow H^- + H^+ + e$ was considered to be the dominant mechanism for production of negative ions. Although there are still arguments advanced about the importance of this process,[18] there is a general consensus that most H^- ions in volume sources of recent design are produced by dissociative attachment (DA) of low energy electrons to hydrogen molecules in high vibrational states

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

This is, however, only the final step in a complex process that involves production and destruction mechanisms of excited molecules, together with destruction of H^- ions on their way to the extraction aperture. Studies at Ecole Polytechnique by M. Bacal and her co-workers[19] stimulated further theoretical and experimental work. Distributions of vibrational populations have been calculated[20,21] for different sets of parameters in typical magnetic multicusp source geometries. Fast electrons (50-100 eV) are required for the electronic excitation of H_2 molecules, which is followed by a radiative decay leaving the molecule in the ground electronic, and a high vibrational state. The other production mechanism is the neutralization of molecular ions on walls, with molecules bouncing off in a high vibrational state. Atoms are detrimental because excited molecules may collide with them and fall into a lower state. Energy of electrons required for the production of H^- ions from excited molecules by DA is of the order of only 1 eV, while higher energy electrons would only contribute to the loss of H^- ions via collisional detachment. Most recent volume sources separate the region where excited molecules are formed (collisions with fast electrons) from the region where negative ions are formed (collisions of such molecules with low energy electrons); density of fast electrons should be as small as possible in the latter. Separation of the two regions may be done by a dipole magnetic field (tandem geometry), or by the cusp field itself. Calculations of H^- ion densities and of the achievable current yields have been performed by several groups.[20-26] In general, they predict that some parameters of the source (e.g. gas density, plasma density, some dimensions) can be optimized and that under optimum conditions extracted H^- current densities up to 50 mA/cm^2 should be achievable.

Multicusp sources have been studied experimentally as well, measuring population distributions of molecular excited states using CARS,[27] and electron density and temperature and H^- ion density distributions by means of probes and photodetachment.[28] H^- ion density shows a proportionality with the square of the arc current at a low plasma density and a linear dependence at higher values;[22] more recent measurements at high arc currents[29] have confirmed the linear dependence followed by saturation. Plasma potential distribution is another important factor for the operation of volume sources: plasma tends to be more positive than the anode,[22] trapping H^- ions. There are two essential (and possibly interrelated) features of an efficient volume source: the extraction (or plasma) electrode has to be biased positively with respect to the anode (a few V) and a magnetic filter field parallel to this electrode has to be present in the vicinity of the extraction aperture. These two features modify the densities of different plasma species in the space around the aperture. A sharp reduction in the fast electron density has been found[29] when crossing the filter field toward the extractor; source neutral gas pressure and plasma electrode potential can be optimized for the highest H^- ion density and lowest electron density.[30]

Plasma-Surface Sources of H^- Ions

Plasma-surface sources represent a group of devices, of various designs, with cesiated molybdenum converter surface as a common feature. Designs differ according to the intended application and its requirements (current, current density, efficiencies, phase space characteristics, duty factor); some of them have reached the stage of reliable operation, while some of them are still experimental. Efforts to develop a steady state device have shown that increasing the pulse length requires reducing the electrode power density, with the result that extracted current density is in general also reduced and that one cannot expect to achieve the same source brightness as is possible with short pulses.

Magnetron and other sources with $\vec{E} \times \vec{B}$ drift. Chronologically, the magnetron was the first source of H^- ions where the production was enhanced by adding cesium vapors to a hydrogen discharge.[31] The discharge is maintained by $\vec{E} \times \vec{B}$ electron drift in the narrow chamber between the cathode and anode. H^- ions are produced on the cathode surface, while the extraction aperture is in the anode wall. Depending on plasma parameters (plasma density, neutral gas density, length of the path between the cathode and extraction aperture) a smaller or larger part of surface-produced H^- ions will survive the travel through the plasma and be directly extracted as fast ions, while some of the rest will undergo charge exchange with atoms and be extracted as low energy ions. Several models have subsequently been developed[2] and many improvements incorporated.[32] Magnetron sources serve presently to provide H^- ions for the charge exchange method of proton injection into synchrotrons at Brookhaven National Laboratory and Fermilab; the source has been developed in cooperation between the two laboratories[33,34] and its operating parameters are shown in Table I. Its operation is very stable, after some initial conditioning, and runs lasting six months are routine with the same cesium load. Extraction from a slit aperture yields a beam with very different emittances in the two directions, but after acceleration in a Cockcroft-Walton machine they differ less.[34] There are plans to change the extraction aperture to a circular one.[35]

A large magnetron,[2] designed for steady state operation with electrode cooling, delivered lower current densities compared to short pulse sources (60 mA/cm^2 or 120 mA total current); it was difficult to maintain an optimum cesium layer over the whole surface of the cooled cathode. A large cathode surface area semiplanotron source, for short pulse operation, has been developed at Novosibirsk;[36] it is similar to a magnetron source, but it has one side of the cathode only. The source has delivered 11A, in pulses of 0.2 - 0.8 ms duration, but it is doubtful that it could be scaled up with similar parameters to a long pulse or steady state operation. In a smaller size version, developed for accelerator use, a rather bright beam of 100 mA was obtained through a slit aperture with dimensions 0.5 mm x 10 mm, in 0.25 ms pulses.[37]

Penning-type sources. Discovery of the enhanced H^- production on cesium covered surfaces has led to the modification of original Penning sources,[38] by changing the dimensions and adding cesium vapors. In Penning sources without a converter, H^- ions are produced on cesiated cathodes, but only those resulting from charge exchange collisions with atoms can be extracted. Therefore, energy spectra of H^- ions show only the low energy group and the brightness of such sources can be much higher than of those where surface produced H^- ions are extracted directly.[39-41] Extensive studies have been done at LANL and the characteristics of two models, one with a slit extraction aperture[40] and the other with a circular aperture (4X source)[41] are included in Table I. While similar extracted currents and current densities can be obtained with both magnetron and Penning sources, the latter tend to require more power and higher gas flow for the same output, especially in the low noise mode of operation, which is also the high brightness mode. This is the reason that it will be even more difficult to extend the pulse length of Penning sources beyond a few tens of milliseconds without a substantial sacrifice of their performance.

The desire to extract from a Penning source not only H^- ions produced in the volume by charge exchange, but the fast, surface produced ions as well has led to the introduction of a separate converter electrode with the purpose of serving as an H^- producing electrode placed directly opposite extraction slits.[42,43] This modification was a major improvement in the design of H^- ion sources, separating in principle the plasma generation from surface processes producing H^- ions. The yield of H^- ions in a small source was almost doubled,[43] with about -100V bias on the converter. A much larger version of a Penning source with converter was developed at ORNL[44] for fusion applications (SITEX); while small sources of the Penning type have cold cathodes, the SITEX source has a hot filament as an electron source and well separated plasma and H^- producing regions. H^- ion currents in excess of 0.5A have been reported through a thin slit extraction aperture of 5 cm^2.

Multicusp sources with converter. Discharge in a

TABLE I
Parameters of Plasma-Surface Sources

SOURCE TYPE	ARC PARAMETERS	CONVERTER VOLTAGE	EXTRACTOR VOLTAGE	EXTRACTION APERTURE	H^- YIELD	H^- CURRENT DENSITY	PULSE LENGTH, RATE	GAS FLOW RATE	Cs LOSS RATE	EMITTANCE(S) π cm mrad
MAGNETRON [34]	40–50 A 125–150 V	——	20 kV	1 mm x 10 mm	35–50 mA	0.5 A/cm^2	0.5 ms 5 Hz		0.6 mg/hour	0.035 x 0.14
SEMI-PLANOTRON [37]	100 A 100 V	——	20–25 kV	0.5 mm x 10 mm	100 mA	2 A/cm^2	0.25 ms 50 Hz	4.5–6 scc/min (pulsed)		0.02 x 0.006 (at 80 mA)
PENNING [40]	150 A 100–120 V	——	25 kV	0.8 mm x 7 mm	160 mA	2.8 A/cm^2	1 ms 5 Hz	3–4 scc/min (pulsed)	1 mg/hour	0.028 x 0.078
PENNING (4X) [41]	50–180 A 130–540 V (diff. modes)	——		5.4 mm ϕ	67–110 mA (diff. modes)	up to 0.5 A/cm^2	1 ms 50 Hz	260 scc/min (steady state)		0.011 x 0.012 (quiet mode) (rms)
MULTICUSP [48]	60 A 100 V	−250 V	(94 kV)	10 mm ϕ	20 mA	15 mA/cm^2	0.8 ms 120 Hz	2 scc/min	30 mg/hour	0.08
MULTICUSP [50]	30 A 130–150 V	−300 to −500 V		18 mm ϕ	21 mA	8 mA/cm^2	0.2 ms 20 Hz	7.5 scc/min	1.25 mg/hour	0.13 (at 750 keV)
MULTICUSP [51]	30 A 70 V	−200 V (at 3A)		13 mm ϕ	70 mA	50 mA/cm^2	steady state	2 scc/min	50–100 mg/hour	0.12 (estimate)

magnetic multicusp ion source is maintained by electron emission from a hot cathode (tungsten, oxide, LaB_6), while magnetic cusp fields produced by arrays of permanent magnets at the source boundary serve to improve the plasma confinement. Compared to magnetron and Penning sources, multicusp sources operate at much lower pressures, but their plasma density and the extracted current density are lower. On the other hand, a steady state source of electrons (hot cathode) makes them suitable for continuous mode of operation as well. Addition of a negatively biased, cesiated converter electrode in the magnetic field-free central region of the discharge[45] has extended the use of this source to the production of negative ions. On their way from the converter through the plasma toward the extraction aperture, H^- ions acquire only an energy corresponding to the potential difference between the converter and the plasma, hence the name self-extracted for these type of sources. First models were meant for fusion applications and have grown into a long pulse device delivering in excess of 1A of H^- ions.[46,47] As a spin-off, several smaller devices have been built and put into operation. The first of these, developed at LASL, has been reported and described previously;[48] its characteristics are summarized in Table I. In a high pulse rate mode of operation (120 Hz), with a pulse length of 0.8 ms, it delivers abut 20 mA of H^- current at a current density of 15 mA/cm^2. The emittance is aperture determined. A relatively short tungsten filament life-time (200 hours) may be considered as a drawback for some applications. At KEK, LaB_6 cathodes[49] used in a similar source have lasted more than 2,000 hours[50] and the source has delivered up to 20 mA of H^- ions. Comparing the two sources, one can notice a much lower consumption of cesium in the KEK source, probably due to a much lower average power in the source. A multicusp source with the converter has been tested in the steady state mode of operation;[51] it delivered more than 70 mA through an extraction hole of 1.3 cm diameter, with an excellent gas efficiency of 20% (Figure 1).

Volume Sources of H^- Ions

It is in the field of volume sources that most recent activities have been concentrated and where the greatest progress has been made during the last few years. However, in spite of that, there are only a few sources that are operational; most of them are experimental devices serving either for studies of basic properties or as a stage for scaling up to larger models. Most of them have magnetic multicusp fields for plasma confinement and separate the extraction region from the main discharge chamber.

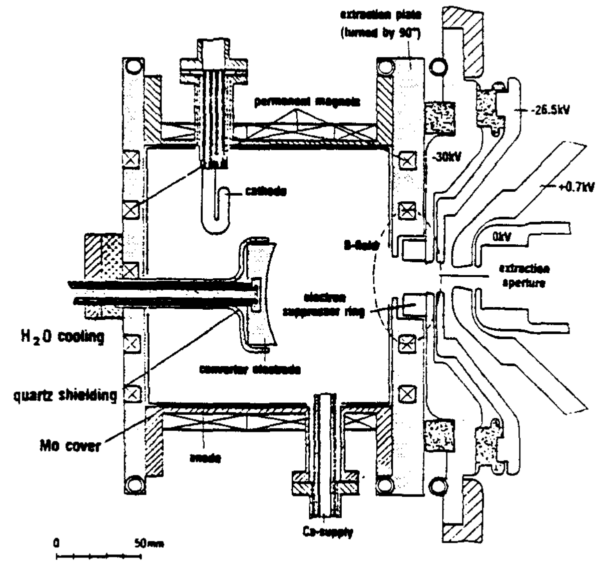

Figure 1 – Multicusp source with converter.[51]

Sources for accelerator applications. Correlation of extracted H^- currents (and current densities) with plasma parameters and understanding of the source functioning are the main objectives of studies at Ecole Polytechnique.[52] Effects of plasma electrode bias and size, plasma density, H^- ion density and gas pressure on the extracted H^- ion current have been determined for different source geometries; an isotope effect (H^- vs D^-) was also observed, but it was less pronounced at higher densities.

Extensive studies of tandem multicusp sources (Figure 2) have been done at LBL with the intent of optimizing the H^- yield and improving other source characteristics.[53–55] A list of subjects includes the effects of the discharge voltage and source pressure, introduction of magneto-electrostatic plasma confinement, optimization of the filter position, main discharge chamber length and extraction chamber length (the closer the filter field was to the extraction aperture, the better was the performance), effects of adding argon and xenon into the discharge, and effects of cold electron injection into the

TABLE II
Parameters of Volume Sources

SOURCE TYPE	ARC CURRENT	ARC VOLTAGE	SOURCE PRESSURE	EXTRACTION VOLTAGE	EXTRACTION APERTURE	H^- YIELD	H^- CURRENT DENSITY	PULSE LENGTH, RATE	GAS FLOW RATE	EMITTANCE π cm mrad
LBL–LANL MULTICUSP 56	350 A	> 100 V	4.5 m torr	8–27 kV	3 mm ⌀	2.7 mA	38 mA/cm^2	0.4 ms 7.5 Hz		0.025 (at 82 kV)
TRIUMF MULTICUSP 58	100 A	145 V		(3) 25 kV	6.5 mm ⌀	4 mA	12 mA/cm^2	d.c.	15 scc/min	0.02
CERN MULTICUSP 59	230 A	120 V			8 mm ⌀	12(5) mA	24 (10) mA/cm^2	0.15 ms		
CULHAM MULTICUSP, #1 63	100 A	90 V	18 m torr	27 kV	8 mm ⌀	10 mA	20 mA/cm^2	30 s	11 scc/min	——
CULHAM MULTICUSP, #2 64	1100 A	100 V	12 m torr	6.5 kV	1.5 mm ⌀	1 mA	57 mA/cm^2	1 s		——
JAERI #1 MULTICUSP 65	500 A	70 V	4 m torr	10 kV	4x4 mm ⌀	6 mA	12 mA/cm^2	0.1–1 s 1/30 Hz		——
JAERI #2 MULTICUSP 66	800 A	70 V	5.2 m torr	25 (5) kV	12x10 mm ⌀	100 mA	10 mA/cm^2	0.2 s 1/150 Hz		——
NAGOYA PLASMA SHEET 68	175 A	120 V	2.5 m torr	4.5 kV	25x6 mm ⌀	200 mA	28 mA/cm^2	d.c.	115 scc/min	——

extraction chamber (both resulted in a substantial improvement). High power tests of such a source were subsequently performed at LANL,[56] but with a small extraction aperture (Table II). At the highest arc current of 350 A, the extracted H^- current density was 38 mA/ cm^2, with a total current of 3 mA, but recent efforts have resulted in a substantial improvement in the arc efficiency.[57]

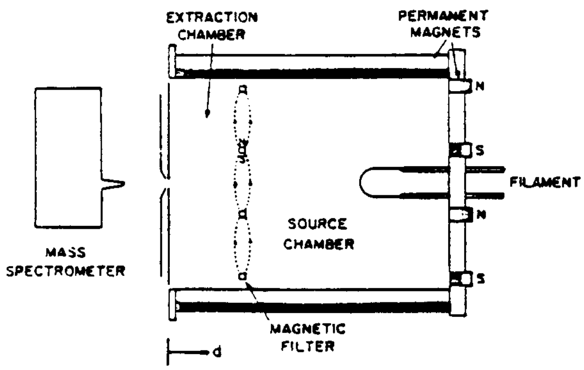

Figure 2 - Multicusp volume source.[53-55]

A steady state operating source was developed at TRIUMF[58] and an extracted current of 4 mA was obtained through an aperture of 0.33 cm^2 (12 mA/cm^2). A magnetic filter was used to maximize the H^- yield and reduce the electron drain; its best position was 0.5 cm from the plasma electrode. At the final energy of 25 keV, the normalized emittance was 0.02 cm mrad (Table II). The source is ready for final tests before installation on the cyclotron.

While all sources described so far have a rather large volume (5-10 ℓ), a much smaller version (~ 1.5 ℓ) was designed and put into operation on CERN Linac I. It has an outside mild steel shell to hold the magnets and increase the pole tip magnetic field. The extracted current was 12 mA (possibly with some electrons) through a 0.5 cm^2 aperture; the beam was injected into an RFQ linac and an H^- current of 5 mA measured at the output (520 keV).[59]

The existence of H^- ions in a modified electron cyclotron resonance (ECR) source has also been detected;[60] it was necessary to separate the extraction region from the main ECR discharge by a magnetic mirror (this is similar to the dipole field effect in a multicusp geometry). Preliminary results have led to estimates of up to 20 mA/cm^2 of extractable H^- current.

Large extraction area sources. Large sources of the volume type are studied at Culham Laboratory as part of their neutral beam program for fusion applications. In distinction from the designs at Ecole Polytechnique and LBL, the magnets on Culham sources are arranged either to form closed loop cusps (parallel to the extraction aperture plane) or in so-called checker-board configuration (alternating in both directions); a dipole field perpendicular to the axis separates the discharge from the extraction region. There are two sources presently in operation at Culham,[61-64] a smaller one with closed loop cusps and a larger one, with checker-board geometry (Figure 3). Both have been designed for long pulse or steady state operation. In spite of different sizes, the dependence of the extracted H^- current density on the arc current and source pressure is similar. From the smaller source a current of 10 mA has been extracted through a 0.5 cm^2 aperture in a 30 s pulse (Table II). A test was done with a 1.5 cm^2 aperture and with up to 60 A in the arc, the same current density obtained as with the smaller aperture (26 mA total, 17 mA/cm^2). A larger source has been studied with an aperture of only 1.5 mm diameter, but at full power (110 kW) the current density was almost 60 mA/cm^2, which is very promising for future scaling up. A strong isotope effect was observed: the maximum D^- current density was only 27 mA/cm^2.

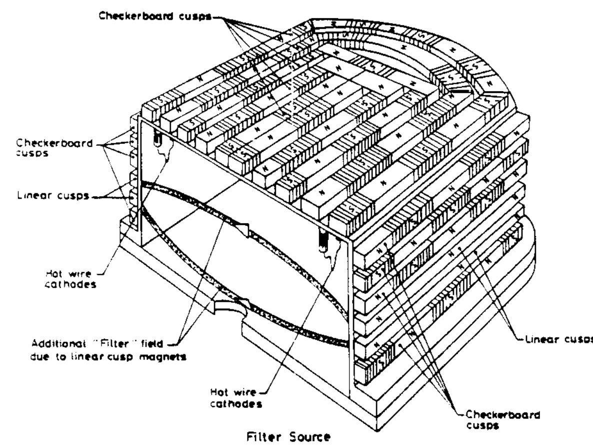

Figure 3 - Large multicusp volume source.[64]

The objective of the program at JAERI is to develop a large, high current source for neutral beam applications. Initial studies have included investigations of several configurations of source geometries, especially the effects of the length of the chamber on source performance.[65] At optimum conditions, a 6 mA H^- beam was extracted at 10 keV through a 0.5 cm^2 aperture (Table II). After selecting the best source configuration, an array of 12 apertures was made, each with 10.3 mm diameter, and 100 mA of H^- current extracted[66] with a density of 10 mA/cm^2. A multiaperture grid has been fabricated with a total extraction area of 133 cm^2 and tests have begun to achieve a current of 1A.

A novel approach has been introduced at Nagoya University.[67] Although the dissociative attachment of low energy electrons is again thought to be the mechanism responsible for the production of H^- ions, plasma production, confinement and H^- ion extraction differ from multicusp sources. A cylindrical plasma is produced between the cathode and the anode through two intermediate electrodes; magnetic field between the second intermediate electrode and the anode has such a shape that the plasma column is flattened into a wide and thin plasma sheet. Fast electrons (≈ 50 eV) are confined by a longitudinal magnetic field to the center of the sheet where excited molecules are produced. H^- ions are produced in the boundary layer, where the electron temperature is about 1 eV and the plasma density much lower. From an array of 5 x 5 round apertures with a total extraction area of 7 cm^2, steady state H^- current of 200 mA was obtained,[68] corresponding to an aperture current density of 28 mA/cm^2 (or a wall area current density of 15 mA/cm^2); the test with deuterium was done with 9 apertures only and a small isotope effect was observed (about 15% lower D^- current density for similar operating parameters). Compared with other source designs, this approach has a better gas and power utilization (Table II).

The SITEX source[44] has been operated without cesium, in the volume production mode[69] (VITEX). In this mode of operation, conditions are similar to those in Ref. 67: there is a dense plasma sheet confined by a magnetic field where excited molecules are produced and a lower density plasma region where H^- ions are produced. The extracted H^- ion current (at 17 kV) was not measured directly, but from the extractor power supply load it has been concluded that a long pulse operation at 55 mA (22 mA/cm^2) is possible.

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