

Possible Design of a Volume H- Ion Source

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Volume sources of H^- ions have been under development in many places for several years, with the hope that one day they might replace plasma-surface sources. Their main advantage is no need for cesium in the source, because negative ions are produced in collisions between electrons and hydrogen molecules and not on a cesium covered surface. So far H^- currents of the order of at most 10 mA have been obtained; however, one of drawbacks of volume sources seems to be an inverse proportionality between the current and current density. A volume source of H^- ions is being considered as an option to serve in the 35 keV ion gun, planned for the future RFQ preinjector at AGS. In addition to the absence of cesium, such a source would have a rotational symmetry (which is preferable for an RFQ) and possibly a lower emittance. Its development will not be straightforward because the requirements for a current of 30-50 mA and a current density of about 30mA/cm² would have to be met simultaneously.

Extensive theoretical work has been done by groups at Lawrence Livermore Laboratory (J.R. Hiskes, et al.) and the Ecole Polytechnique (M. Bacal, et al.). The present thinking is that H^- ions are produced in collisions between low energy electrons ($T_e \leq 1$ ev) and hydrogen molecules in high excited states. Excited molecules are formed in collisions between fast electrons and molecules or in wall neutralization of molecular ions. Presence of atomic hydrogen is detrimental in many ways: in a highly dissociated gas less molecules are available for excitation and ionization; collisions between atoms and excited molecules may lead to molecule de-excitation or dissociation; collisions between atoms and H^- ions may lead to the detachment. Due to different optima in electron temperature for the processes of molecule excitation and dissociative attachment (production of H^- ions), a volume source is preferably divided by a magnetic field into two regions (tandem geometry), one where highly excited molecules are produced in collisions with fast electrons and the other where H^- ions are produced by dissociative attachment with low energy electrons. In the latter, the density of fast electrons is low, and therefore, few new excited molecules can be produced there. Best experimental results have, indeed, been obtained with tandem sources and considerations in this note will be limited to such systems.

In a series of papers and reports Hiskes, et al.¹ have presented results of their calculations of vibrational population distributions vs. vibrational level, for several combinations of values of plasma density and molecular density, once for atomic density equal to the molecular density and once for the former equal to 10% of the latter. Either one or both possible processes for the production of excited molecules have been taken into account. Most favorable distributions are obtained at lower molecular densities, higher fast electron densities and lower atomic densities; surface neutralization of H_2^+ ions followed by excitation makes a substantial contribution. Assuming a certain velocity distribution of excited molecules crossing the boundary between the two chambers the density of H^- ions in the second chamber was then calculated as function of the distance from the

boundary, for several combinations of parameters in the two chambers. Highest H^- ion densities resulted from higher molecular densities (assumed to be equal in either chamber), lower atomic densities and higher plasma densities (within the investigated range of parameters). For good operating conditions there is always a maximum in H^- density, situated rather close to the boundary (at a normalized distance z/R from the boundary smaller than 0.3). As the H^- ion energies are pretty well known, one can estimate the maximum current density obtainable from such a source, under ideal conditions. From studies like these it is possible to establish some general guidelines for the design of an experimental volume source:

a) differential equations describing conditions in the two chambers contain always products of the density of any species and the system scale length (chamber radius R); the extractable H^- current density will, however, depend on the system scale length (inversely proportional to R); it follows that a smaller source operating at higher densities should yield higher H^- current densities;

b) presence of molecules in the first chamber is desirable, presence of atoms detrimental; it follows that high atomic recombination surfaces are desirable, not only to reduce the atomic component but to enhance the production of excited molecules via surface neutralization of H_2^+ as well;

c) the length of the second chamber should be short compared to the radius ($z/R < 0.3$) if the source is operated at higher densities, with the magnetic filter as transparent as possible to the flux of excited molecules;

d) a high pole multiplicity seems to be desirable to produce a magnetic field-free volume in the first chamber with steep magnetic walls for a good plasma confinement.

Most of the experimental work in this country has been done by the Lawrence Berkeley Laboratory group (K.N. Leung, K.W. Ehlers). Early studies² have shown that a permanent magnet filter, dividing the source chamber into two regions with different electron temperatures, and a

small positive bias on the first electrode (also called plasma grid) of the extractor structure can produce a sizable increase in the H^- yield and a very significant reduction in the electron component. The best H^- yield was about $20 \mu A$ at 1 A of discharge current ($100 \mu A/A \cdot cm^2$). High power studies³ have shown that the H^- current density would scale up proportionally to the discharge current up to 350 A, although the total extracted current remained small, 2.7 mA. Several⁴⁻⁵ improvements have been tried, with following results:

a) optimization of the discharge voltage; with no bias on the plasma electrode (which by itself may improve the yield by up to an order of magnitude) the yield increased by more than a factor of 3 when the discharge voltage was varied between 40 V and 120 V;

b) magneto-electrostatic containment; plasma confinement in first chamber can be improved by shielding parts of the wall surface (between the cusps) with positively biased strip electrodes; when the strip electrodes were biased at +10 V, the H^- yield was about 50% higher than with electrodes at the anode potential (plasma electrode potential was always optimized);

c) optimization of source pressure; a pronounced optimum in the H^- yield was observed at 5×10^{-4} torr;

d) optimizing the filter position; an almost a factor of 3 improvement in both, H^- yield and electron drain reduction was observed when the length of the extraction chamber was reduced from 8 cm to 2 cm, bringing the extractor into the filter magnetic field;

e) optimizing the extraction chamber length; with a constant length of the first chamber the length of the extraction chamber was varied and a steady improvement in the performance observed (similar to case d) with shortening of the chamber length; the closer the extractor was to the filter, the better was the performance;

f) optimizing the first chamber length; length of the first chamber has little effect on the H^- yield, but a shorter chamber requires a higher optimum pressure;

g) addition of Ar and Xe to the discharge; better results were achieved with xenon (an increase in the H^- yield of 75%).

Although each of the improvement methods, when optimized separately starting from certain reference conditions, resulted in impressive increases in H^- yield, it is not known whether the ultimate source performance with all the changes optimized simultaneously would improve by a factor equal to the product of all individual contributions.

A large source was subsequently built at LBL and it yielded a total current of 30-40mA from five extraction holes, 1.5 cm^2 each. This would correspond to a current density of $4\text{-}5\text{mA}/\text{cm}^2$.

Abroad, there are several groups working on the development of volume H^- sources. Most ambitious is the Culham group (T. Green, A. Holmes). They are studying several sources, among them a large, rectangular cross section source with dimensions of about $20 \text{ cm} \times 40 \text{ cm}$. The source configuration is tandem, with the dipole field across the chambers achieved through special arrangement of permanent magnets on the outside of the chamber wall. Preliminary results show that H^- current densities (probably at the source boundary) up to $50\text{mA}/\text{cm}^2$ are achievable and that about $25\text{mA}/\text{cm}^2$ can be obtained over most of the source exit area. However, it is not known whether the source was tested already with a very large extraction area, although a total H^- current of 30mA was reported recently from a single extraction hole of 1 cm^2 . Acceleration of H^- beam to 100 keV is also under development, assuming a 100 mA beam with a density of $30 \text{ mA}/\text{cm}^2$.

At JAERI, Japan, several H^- volume sources have been studied as well. Best results have been obtained with a geometry similar to Culham's, by using a tandem configuration (arrangement of permanent magnets). Highest current was about 7.5 mA, from 0.5 cm^2 aperture ($15 \text{ mA}/\text{cm}^2$); the extraction voltage was 10 kV and arc current about 400 A, which indicates a poor power efficiency. A lower H^- yield (3 mA, $3 \text{ mA}/\text{cm}^2$) was obtained at KfK from a tandem multicusp H^- source, but the power efficiency was among the best ($0.15 \text{ mA}/\text{A}\cdot\text{cm}^2$). Finally, a small, rotationally symmetric source was developed at CERN, Geneva, with an outside mild steel shell to hold the magnets and increase the pole tip magnetic field. There are no data on the performance of the source itself, but the extracted beam was injected into a RFQ device, captured and accelerated to 520 keV; at that position 5 mA of H^- ions were measured, which implies a source yield of 7-8 mA (about $15 \text{ mA}/\text{cm}^2$).

Possible guidelines for the design of a volume H^- source to be used on the AGS can be summarized as follows:

a) magnetic confinement: multicusp field produced by Sm-Co magnets; magnets will be arranged on the inside of a thin mild steel shell, to facilitate the mounting of magnets and changing the configuration; two types of cusp fields should be investigated, line cusps and point cusps; use of mild steel shield will make possible an easy change of cusp multiplicity;

b) dipole filter field: by far the best results have been obtained with a filter field, situated close to the extraction aperture; in order to investigate the effect of the field strength, it is desirable to use conductors instead of permanent magnets, with a pulsed current; the H^- yield may be substantially increased by shaping the filter around the extraction aperture (filter in the form of cage or half sphere; Fig. 1), to increase the area of the boundary and to reduce the distance between the main discharge and the extraction aperture (small effective z/R);

c) electrostatic confinement: plasma electrode (with the extraction aperture in it) should be biased positively (a few volts); addition of longitudinal strip electrodes (LBL) may be considered if this would not complicate the design, with the option of connecting them to the plasma electrode (somewhat smaller improvement in the H^- yield); the dipole filter structure should be biased as well;

d) wall effects : if theoretical studies are correct, then the presence of metal walls in the first chamber, coupled with a good plasma confinement, should be beneficial (recombination of atomic hydrogen); one may consider adding thin stainless steel wings in the radial direction, (Fig. 2) mounted on the filter conductors, to facilitate even further the recombination of atoms and to enhance the production of excited molecules via recombination of molecular ions in the vicinity of the magnetic filter;

e) xenon gas admixture (LBL studies) : means should be provided to add xenon gas into the discharge.

f) use of hollow cathode discharges : it is possible that the neutral gas component leaving a hollow cathode that operates with a poor gas efficiency contains a substantial flux of excited molecules; the filament flange can be designed in such a way that the gas flow from the hollow cathode is directed toward the top filter plane, enabling excited molecules (if any) to cross into the extraction chamber; this system would operate steady state, with the possibility of pulsing the regular discharge by applying a negative voltage on the filament;

g) cooling : the source side wall could consist of a thin copper cylinder with cooling tubes brazed on the outside to fit in the spacings between the magnets; tubes would be connected by two manifolds, one at each end;

h) extraction : first tests could be performed with an aperture of 0.5 cm^2 and an extraction voltage of a few kV; it may be necessary to incorporate a small magnetic filter into the plasma electrode to reduce the electron drain from the source.

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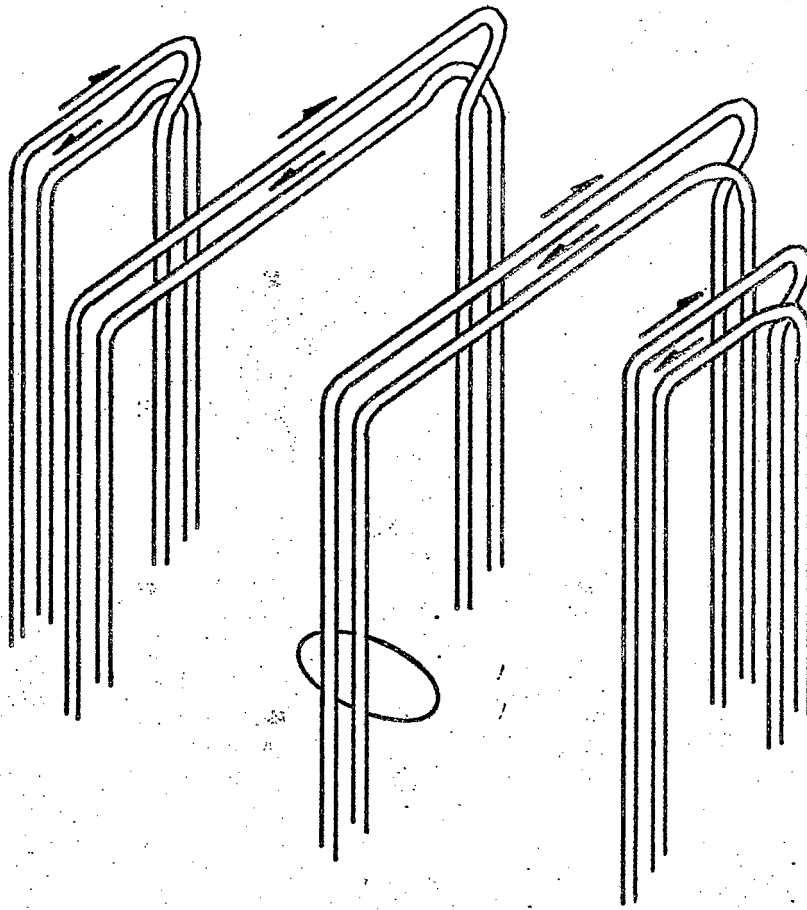


Figure 1

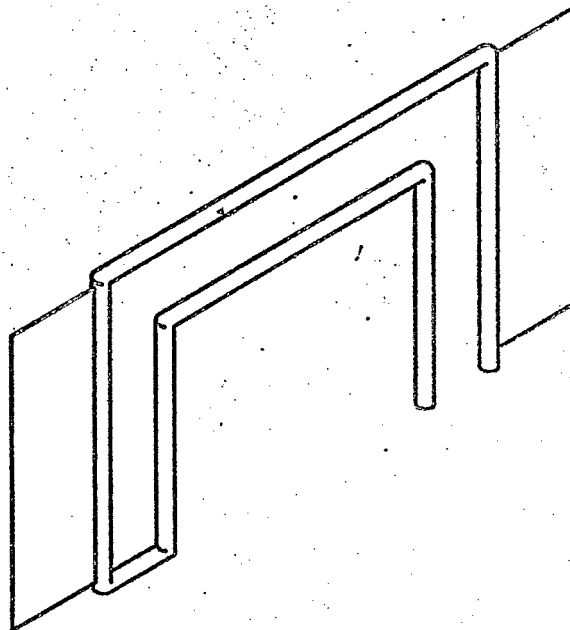


Figure 2