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A Small Multicusp H⁻ Source*


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A small multicusp H⁻ source*


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Abstract

High quality H⁻ beams have been generated from a multicusp source equipped with a permanent magnet filter. It is shown that a large improvement in H⁻ yield can be achieved by employing a small multicusp source, fabricated with the proper wall material and extraction chamber length. From this small source, H⁻ current densities higher than 250 mA/cm² have been extracted from a 1-mm-diam aperture for a discharge voltage of 150 V and a discharge current of 450 A. When the source is operated with deuterium, the extractable negative ion current density is reduced approximately by 30 percent.
Introduction

H\(^{-}\) and D\(^{-}\) ions have useful applications in high energy accelerators and in neutral beam heating of fusion plasmas. Among the different techniques for producing H\(^{-}\) ions, direct extraction from a hydrogen discharge is the most attractive. This scheme requires no cesium and the H\(^{-}\) ions generated by volume processes have lower average energy than those formed by surface conversion or by charge exchange processes.\(^1\)-\(^3\) For this reason, intensive research and development of volume H\(^{-}\) sources are now being conducted in various accelerator and fusion laboratories.

In 1983, a novel method of extracting H\(^{-}\) ions directly from a multicusp source was reported by Leung et al.\(^4\) From the prototype source, high quality H\(^{-}\) beams with current densities as high as 38 mA/cm\(^2\) have been produced in an experiment performed at Los Alamos National Laboratory.\(^5\) Since then, different schemes to improve the extractable H\(^{-}\) current density have been investigated. By optimizing the extraction chamber length, a large improvement in the H\(^{-}\) output has been achieved.\(^6\) Experimental results have demonstrated that the H\(^{-}\) yield can be enhanced by choosing aluminum or copper as the chamber wall material.\(^7\) A substantial increase in H\(^{-}\) yield also occurs when very low-energy electrons (E \(\approx\) 1 eV) are added into the filter or extraction regions.\(^8\)

Most recently, a small multicusp source has been fabricated and operated successfully to generate volume-produced H\(^{-}\) ions. From this new source, H\(^{-}\) current densities higher than 250 mA/cm\(^2\) have been extracted. The large increase in H\(^{-}\) output is mainly due to an enhancement of the source plasma density. When deuterium is used, the extractable D\(^{-}\) current...
density is reduced by about 30%. In this paper, the design and the operational characteristics of this negative ion source are presented.

(I) Experimental Setup

A schematic diagram of the small multicusp source used for producing volume H\(^+\) or D\(^+\) ions is shown in Fig. 1. The source chamber is a thin-walled (2 mm thick) copper cylinder\(^7\) (7.5 cm diam by 8 cm long) surrounded by 14 columns of samarium-cobalt magnets which form a longitudinal line-cusp configuration for primary electron and plasma confinement.\(^9\) Four rows of the same size magnets are mounted on the end flange to complete the line cusps. Figure 2 shows a cross-sectional plot of the calculated magnetic field distribution. It can be seen that the discharge volume with magnetic field less than 30 G is small (approximately 3.5 cm diam by 4 cm long). In order to achieve a quiescent discharge, the cathode must be placed inside this central "field-free" region.\(^{10}\)

The permanent magnet columns are enclosed by a second anodized aluminum cylinder. When the discharge is on, the magnets are cooled by water circulating in between the two cylinders. With adequate water flow, the source is capable of steady-state operation even at relatively high discharge power.

A pair of water-cooled permanent magnet filter rods are installed on the exit flange of the source (Fig. 1). The filter divides the source chamber into a discharge and an extraction region. Detailed description of this
filtered multicusp source arrangement has been reported previously. In brief, the filter provides a narrow region of transverse magnetic field which is strong enough to prevent the energetic primary electrons from entering the extraction zone. However, a plasma consisting of positive and negative ions, and cold electrons (\(T_e \lesssim 1\) eV) is found in the filter and extraction regions.

The open end of the source chamber is enclosed by a two electrode acceleration system. \(H^-\) or \(D^-\) ions were extracted from the source through a small aperture. To enhance the \(H^-\) yield, the first (or plasma) electrode is placed very close to the filter to reduce the length of the extraction chamber. A hydrogen plasma is produced by primary electrons emitted from two 1-mm-diam tungsten filaments (mounted on the end flange). The entire source chamber, together with the filter rods, serve as the anode for the discharge. During source operation, the \(H^-\) output can be optimized by biasing the plasma electrode at a potential equal to or more positive than that of the chamber wall.

Plasma parameters at low discharge power are obtained by a small planar Langmuir probe located near the center of the source. A compact magnetic deflection mass spectrometer, located just outside the extractor, is used for relative measurement of the extracted \(H^-\) ions. In addition, a permanent magnet mass separator is used with a Faraday cup (Fig. 1) to measure the accelerated \(H^-\) and electron currents.

(II) **Experimental Results**

(a) *Optimization of filter geometry*

The small multicusp source has been tested for \(H^-\) generation with
different filter strengths. Unlike the large multicusp source reported in Ref. (4), the small source is equipped with only two filter rods. The strength and the integrated magnetic flux of the filter field can be varied by employing either samarium-cobalt or neodymium-iron magnets at two different filter-rod separations (4 or 6 cm).

Figure 3 shows the magnitude of the spectrometer output signal for H\(^-\) ions as a function of plasma electrode bias for a constant source pressure and discharge power of 80 V, 3 A. In all cases, an optimum H\(^-\) output can be obtained with the plasma electrode biased positively between +1 and +1.5 V relative to the anode. (For comparison, the H\(^-\) output for the large multicusp source is also shown in Fig. 3). It can be seen that the highest H\(^-\) yield (with source pressure optimized) occurs when the small source is operated with the samarium-cobalt magnet filter and with the rods separated by 4 cm. This H\(^-\) yield is approximately a factor of four higher than that obtained with the large source. On the other hand, the plasma density measured near the center of the small source is 3 \(\times\) 10\(^{11}\) cm\(^{-3}\) for a discharge power of 80 V, 1 A. Comparing with the probe measurement obtained in the large source,\(^{12}\) this plasma density is about four times higher for the same discharge power. This suggests that the increase in H\(^-\) output by using the small source is primarily due to an enhancement in the source plasma density.

(b) Optimization of discharge voltage

The dependence of the H\(^-\) output on the discharge voltage \(V_d\) has been investigated for two samarium-cobalt magnet filter separations. With the
plasma electrode biased at the optimum potential, and for a constant
discharge current of 3 A, Fig. 4 shows that the H\(^-\) signal increases
monotonically as \(V_d\) is varied from 60 to 140 V. Above 140 V, the H\(^-\)
output levels off and decreases slightly as \(V_d\) reaches 160 V. Figure 4
also shows that the same discharge voltage dependence occurred in the
large source except that the H\(^-\) output is smaller.

In a previous experiment,\(^6\) it was found that the extracted positive
ion current had the same dependence on the discharge voltage as the H\(^-\)
output. The increase in H\(^-\) yield by using higher discharge voltage can arise
from the increase in plasma production in the source chamber. The
reaction rates for ionizing or vibrationally exciting the H\(_2\) molecules
remain essentially constant for electron energy above 50 eV.\(^{13}\) However,
higher energy electrons (E > 50 eV) can improve the plasma density and
vibrationally excite more H\(_2\) by performing multiple ionization or
excitation processes before being lost to the anode wall or degraded to
form background plasma electrons. But the primary electron confinement
time in a multicusp system varies inversely as the energy.\(^{14}\) In that
respect, higher energy primaries do not stay very long in the source
chamber. Hence, there exists an optimized primary electron energy which
can provide the highest source plasma density and H\(^-\) yield.

(c) H\(^-\) or D\(^-\) current density measurement

Figure 1 shows the experimental setup for measuring the extractable
negative ion current density. The H\(^-\) ions are extracted from the source
through a 1-mm-diam aperture with a two-electrode acceleration system. After leaving the accelerator, electrons in the beam are separated from the H\(^-\) ions by the magnetic field generated by a pair of permanent magnets. These electrons are trapped and collected by the grooved graphite plates and the current is then measured. The accelerated H\(^-\) ions suffer a slight deflection and are then detected by a Faraday cup which is biased slightly positive relative to ground potential in order to suppress secondary electron emission.

In order to study the H\(^-\) yield at high discharge power, the source is operated in a pulse mode by employing an electronic switch which has been described in a previous article.\(^{15}\) Figure 5 shows some typical oscilloscope traces for a 1 millisecond pulse discharge operation. It can be seen that the discharge voltage, discharge current and the collected electron current are nearly constant for the duration of the pulse. However, the H\(^-\) current behaves quite differently. It first reaches a maximum and then decreases to a lower value at the end of the pulse.

The time dependent behavior of the H\(^-\) current is not yet understood. But it is found that the pulse shape of the H\(^-\) current can be changed by adjusting the source pressure. This observation suggests that the variation of the H\(^-\) current during the pulse is closely related to the change in density of H\(_2\) molecules in the source chamber.

Figure 6 is a plot of the peak H\(^-\) current (and the corresponding current density) as a function of the discharge current at a discharge voltage of 160 V. Each data point on the curve is obtained with the source pressure properly optimized. The optimized source pressure varies from
about 17 mTorr at discharge currents of 150 A to about 45 mTorr at 450 A. The highest $H^-$ current density achieved (limited by power supply) is approximately 250 mA/cm² at a discharge power of 150 V, 450 A. However, the data in Fig. 6 shows that higher $H^-$ current density is attainable if the source is operated with higher discharge current and perhaps with higher source pressure.

The ratio of the extracted electron to $H^-$ current ($I_e/I^-$) is much higher in this small source than the large multicusp source. In the range of discharge current considered, this ratio typically varies between 100 to 200. Attempts have been made to reduce the $I_e/I^-$ ratio by biasing the first accelerator or plasma electrode positive with respect to the source anode. This scheme is effective only at low discharge currents ($< 50$ A) where a positive bias of 2 V can enhance the $H^-$ yield while the electron current is substantially reduced. At high discharge currents, however, a positive bias voltage applied on the plasma electrode always results in a reduction in both the extracted electron and $H^-$ current.

In future fusion reactors, energetic neutral deuterium beams can be used for plasma heating and current drive. The small multicusp source with the same filter arrangement has also been tested for $D^-$ ion production. Figure 6 shows a plot of the extracted $D^-$ current density versus discharge current with the discharge voltage maintained at about 160 V. In this measurement, each data point is also obtained with the source pressure optimized. The highest $D^-$ current density achieved is about 180 mA/cm² at a discharge current of 500 A. Comparing with the
extractable H⁺ current density at similar discharge powers, the D⁻ current density is about 30% lower. On the other hand, the extracted electron current is increased by a factor of 1.4. No attempt has yet been made to optimize the filter strength to compensate for the change in gas mass. However, it is hoped that the D⁻ current density and the Iₑ/I⁻ ratio can be improved after the filter is optimized.

Thus far, we have demonstrated that high current densities of volume-produced H⁻ ions can be generated in short pulses from a small filtered multicusp source. However, the large Iₑ/I⁻ ratio as well as the high operating source pressure indicate that further development is needed in order to make this negative ion source practical for producing high H⁻ or D⁻ current for long pulse or steady-state operations.

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References

Figure Captions

Fig. 1  Schematic diagram of the small multicusp ion source equipped with a magnetic filter for negative ion extraction.

Fig. 2  A computer plot of the magnetic field produced by the multicusp magnets surrounding the source chamber. The upper half plot shows the field lines (10, 50, 100, 300 gauss-cm), and the lower half plot shows the field intensity contours (10, 30, 100, 300, 1K gauss).

Fig. 3  H\(^{+}\) yield as a function of plasma electrode bias voltage for different filter and source geometries.

Fig. 4  H\(^{+}\) yield as a function of discharge voltage for the small and the large multicusp source.

Fig. 5  Oscilloscope traces showing the extracted electron and H\(^{+}\) currents, the discharge current and voltage for one millisecond pulse operation.

Fig. 6  Extracted H\(^{+}\) and D\(^{+}\) current densities as a function of discharge current for a constant discharge voltage of 160 V.
Fig. 1

- Faraday cup
- Mass separator
- Magnetic filter
- Water jacket
- Filament
- Permanent magnets
$B_{rem} = 6.0 \quad A=1.00(0.39) \quad B=1.27(0.50)$

Magnet Periods = 7 \quad Magnets per Period = 2

FIELD LINES .01,.05,.1,.3 KG-CM. FIELD INTENSITY 10,30,100,300, AND 1000 GAUSS.

XBL 869-3409

Fig. 2
Fig. 5