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The yield of volume-produced H^- ions is investigated in several configurations of magnetic multipole plasma sources as a function of plasma density, gas pressure, electron temperature and other operating parameters. At optimum conditions, 6 mA H^- ion beam is extracted at a beam energy of 10 keV with a current density of 12 mA/cm^2. The gas pressure in the plasma source is as low as 0.5 Pa. The H^- current was confirmed by the calorimetrical measurements.

Keywords: Negative Ion Sorce, Negative Hydrogen, Volume Production
Multipole Plusma Source, Neutral Beam Injector

体積生成型負イオン源の開発

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（1984年5月8日受理）

磁気多極プラズマ源に於いて，体積生成される水素負イオン源の生成効率が，磁場配位，プラズマ密度，ガス圧，電子温度等の関数として調べられた。最適条件のもとで，6mAの水素負イオンが，エネルギー10keV，電流密度12mA/cm^{2}で引き出された。プラズマ源のガス圧は，0.5Paと低い。引き出された負イオン電流値は，熱的な測定によっても確認された。

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1. Introduction

The neutral beam injection in future fusion reactors will require negative deuterium ion beams in order to achieve an acceptable electrical efficiency at beam energies in excess of 200 keV. There are three main methods now used to produce negative deuterium (or hydrogen) ion beams; double electron capture in vapor cell, surface production and volume production. Out of these methods, the volume production has big advantages over the other two methods. They are

(1) No use of cesium,

(2) Simple structure of the source,

(3) Low divergence of extracted beams,

(4) Low impurity content in the beams,

(5) Stable and reliable operation.

These advantages makes the volume production method the most attractive one for use in future neutral beam injectors.

In this method, however, there are two big problems that must be solved. One is the problem of electron separation. Since the negative ions produced have no more than thermal energies (< 1 eV), it is difficult to separate the negative ions from plasma electrons. Leung et al have installed a pair of magnets on a extraction aperture of the accelerator and observed a significant reduction of electron current /1/. But the ratio of electrons is still high and the problem will become more serious in multi-aperture accelerators.

Another problem is the current density. For practical use, a current density of more than 20-30 mA/cm^2 will be required. Although such high current density beams were extracted in a modified Penning type ion source /2/ or a magnetron type ion source /3/ from a very small aperture, scaling up these sources is not practical because of extremely low gas efficiencies. Bacal et al found that there can be a copious amount of H^- ions in a large area hydrogen plasma source /4/. Since then, the efforts have been made by the workers in LBL /1/, Culham /5/, Ecole Politechnique /6/ and Nagoya Univ /7/ to extract high current density beams from a large area plasma source under a low gas pressure.

At JAERI, our efforts have been concentrated on the latter problem. As a first step, the dependence of extracted H^- current on various plasma parameters such as plasma density, gas pressure and arc voltage was investigated in simple multicusp plasma sources in order to determine what the most crucial parameter is. Then an attempt was made to increase the H^- yield by using a tandem multicusp plasma source, where the discharge chamber is divided into two zones by magnetic fields. The tandem structure has been studied theoretically by Hiskes et al /8/ and experimentally by Leung et al /1/, Holmes et al /9/ and Bacal et al /10/. Our tandem source is characterized by the fact that the depth of the discharge chamber is changeable so as to optimize the size.

It is the purpose of the present paper to describe the developmental work being conducted at JAERI and to present the experimental results obtained with volume H^- ion sources.

2. Experimental set-up

A schematic of the experimental apparatus is shown in Fig. 1. Three types of plasma sources were used; a small size magnetic multicusp plasma source (S-Bucket), a high-magnetic field large size magnetic multicusp plasma source (L-Bucket) and a medium size tandem multicusp plasma source (T-Bucket). The S-Bucket source produces high electron temperature plasma, and the ratio of molecular ions (H_2^+ , H_3^+) in the plasma is relatively high /11/. On the contrary, the plasma produced by the L-Bucket source has low electron temperature and has extremely high proton (H_1^+) yield because of a good plasma confinement /12/. Since the structures of S-Bucket and L-bucket sources are shown in Ref.13 (in Fig. 15,16) and Ref.12, respectively, only the cross sectional view of the T-Bucket source is supplied in Fig.2. TABLE I summarizes the size and the characteristics of these three sources.

Beam was extracted from each source using the same accelerator. The accelerator has three grids denoted plasma grid, extraction grid and acceleration grid. Each has 1020 extraction apertures of 4 mm diam within the requtangular area of 12 x 27 cm^2. In the present experiment, all but the central 4 apertures of the plasma grid are masked by a molybdenum plate. Thus the extraction area is 0.50 cm^2.

The H^- ions are extracted from the apertures by applying a negative potential of 2-20 kV to the plasma grid. The other two grids are connected to the ground. Since we do not employ any method to suppress the electrons, a large amount of electrons are extracted together with the H^- ions. In order to separate the electrons and to have a clear measure of the H^- flux, a magnetic field is applied in the downstream to increase the H^- yield by using a tandem multicusp plasma source, where the discharge chamber is divided into two zones by magnetic fields. The tandem structure has been studied theoretically by Hiskes et al /8/ and experimentally by Leung et al /1/, Holmes et al /9/ and Bacal et al /10/. Our tandem source is characterized by the fact that the depth of the discharge chamber is changeable so as to optimize the size.

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The H^- current and its profile are measured by the Faraday cup, which is mounted on the two-dimensional scanning mechanism. The cup has two grids biased positively or negatively so as to suppress the beam plasma particles and secondary emitted electrons. The diameter of the entrance aperture is 1.0 mm. Behind the Faraday cup is a movable calorimeter, which is made of a copper disk of 8 cm diam with a thermocouple buried in the back side of the disk. In order to identify the H^- ions and to measure the impurity concentration in the beam, a compact magnetic mass analyzer was used. The distances from the accelerator grid to the Faraday cup, the calorimeter and the mass analyzer are 85 cm, 92 cm and 135 cm, respectively.

The vacuum in the beam drift tank is maintained by six turbo molecular pumps. The total pumping speed is about 12000 l/sec. If necessary, an additional pumping speed of 15000 l/sec can be produced by a cryopump. But, too much pumping makes the beam divergence worse due to the space charge effect. Thus the pressure in the tank is maintained at typically 2×10^{-2} Pa. The hydrogen gas is introduced continuously into the ion source.

The experiment was made in a pulse mode. The beam duration was 0.1-1 sec with the duty cycle of 1/30.

3. Measurement of H^- current

In experiments on H^- ion sources special attention should be paid to the measurement of the H^- current. Since the H^- ions often accompany a large amount of electrons, the observed H^- current tends to be larger than the true value. To avoid this error, we employed both electrical and calorimetical measurements, and spent a lot of time to confirm the measurements.

In the electrical measurement, the two-dimensional profile of the H^- beam was measured by the Faraday cup. The unneutralized H^- current at the position of the Faraday cup $I^-(FC)$ can be evaluated by integrating the H^- profile over the whole area. The extracted H^- current was then beam drift region by using Helmholtz coils, whose center is placed at 80 cm downstream of the accelerator grid. The coils have a diameter of 65 cm and typically produce a 50 Gauss magnetic field at the beam axis. The H^- ions are scarcely bent by this magnetic field, while the fast electrons are deflected completely toward the electron beam dump.

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In order to confirm the accuracy of this method, the measured currents were compared with the known approximate values for cases of H^+ extraction and H^- plus electron extraction. For H^+ extraction the true output current is approximately 90 % of the power supply I_{acc} while for electron extraction the output and power supply I_{acc} currents are nearly identical. Figure 4 shows an example of the H^+ ion beam profile. The H^+ ions were extracted by reversing the polarity of the acceleration voltage and applying a deceleration voltage to the extraction grid. Integrating the profile, the H^+ current is estimated to be 7 mA, which is consistent with the output current of the power supply (9 mA). The extracted electron current I_e was also measured by this method by turning off the Helmholtz coil current. The measured value showed a good agreement with the output current. Thus in the following sections, we regard the output current I_{acc}as the extracted electron current I_e.

The neutralization efficiency of H^- ions was measured experimentally. Figure 5 shows the unneutralized current at the position of the Faraday cup I^-(FC) as a function of the pressure in the beam drift tank, where the accel voltage, the accel current (or the extracted electron current) and the pressure in plasma source P_A are kept constant. The unneutralized current decreases exponentially with the pressure. The extracted H^- current can be estimated by extrapolating the curve toward the zero line density. It should be noted that the slope of the curve is consistant with the data of cross sections for neutralization and re-ionization of H^-.

The current thus measured electrically was confirmed by the calorimetrical measurement. The equivalent beam current (which means the current including the equivalent current of neutralized beam) was estimated from the temperature rise of the calorimeter. Figure 6 presents the measured current as a function of the pressure in drift tank. All operating parameters are same as those in Fig.5. Although the extracted H^- current is kept constant, the measured current decreases at a lower pressure. This is due to the space charge effect; at lower pressure, the beam divergence becomes worse as shown in Fig.6 by dotted line, and the fraction of the beams intercepted by the calorimeter decreases rapidly. (Remember that the diameter of the calorimeter is relatively small.) In order to know the extracted H^- current, the measured value should be calibrated by this geometrical efficiency. If calibrated, the current becomes constant as shown in Fig.6. The current is 4.05 mA, which almost agrees with the electrical measurement in Fig.5 (4.7 mA).

Figure 7 shows an example of momentum spectra of the negative ion beam measured by the compact mass analyzer. Considering the neutralization efficiencies for H^- and impurities, we can estimate impurity content at the ion source. When the plasma source is conditioned, the impurity content decreases to a few percent of extracted H^- ions.

4. Experimental results on conventional multicusp plasma source

The dependence of the extracted H^- current on various operating parameters was investigated in S-Bucket and L-Bucket sources.

Plasma grid bias voltage

Figure 8 shows the dependence of H^- current on the bias voltage of the plasma grid for the S-Bucket source, where the extracted electron current is kept constant. The bias voltage was applied with respect to the anode and changed by using the outer electrical circuit as shown in Fig.1. The H^- current is small when the plasma grid is left floating electrically and it increases rapidly with the bias voltage. This tendency is more evident when the pressure in the plasma source becomes lower. The H^- current did not increase when the plasma grid was biased more positive than the anode.

Pressure in plasma source

Figure 9 shows the pressure dependence for the S-Bucket source. The arc voltage is 80 V and the arc current is changed in the range of 5 A to 10 A to keep the extracted electron current constant. There is a tank. All operating parameters are same as those in Fig.5. Although the extracted H^- current is kept constant, the measured current decreases at a lower pressure. This is due to the space charge effect; at lower pressure, the beam divergence becomes worse as shown in Fig.6 by dotted line, and the fraction of the beams intercepted by the calorimeter decreases rapidly. (Remember that the diameter of the calorimeter is relatively small.) In order to know the extracted H^- current, the measured value should be calibrated by this geometrical efficiency. If calibrated, the current becomes constant as shown in Fig.6. The current is 4.05 mA, which almost agrees with the electrical measurement in Fig.5 (4.7 mA).

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Arc voltage

Figure 10 shows the dependence on the arc voltage. The arc voltage was changed by controlling the filament emission current so as to keep the extracted electron current constant. The H^- current has its maximum value at the arc voltage of 70 V and it decreases rapidly at lower arc voltage.

Filament diameter

It was found that the filament diameter has a significant effect on the H^- current. Our bucket source usually employ large diameter filaments ($D= 1.5^{\phi}-1.8^{\phi}$) to obtain a long life time. But it was found that the H^- current increases by factor 2 or 3 when the large diameter filaments were replaced by small diameter filaments ($D= 0.8^{\phi}$). Same effect was observed when the arc discharge was turned on right after the filament current was turned off. This effect is considered to be caused by the magnetic field induced by the filament current.

Plasma density

The plasma density was then increased with keeping the parameters mentioned above at the optimum condition. Figure 11 shows the H^- current as a function of the extracted electron current for both S-Bucket and L-Bucket sources, where the arc current is increased up to 230 A in case of S-Bucket and 500 A in case of L-Bucket. The acceleration voltage V_{acc} was also increased up to 18 kV with the electron current I_e so as to keep the beam divergence (or perveance) almost constant. The H^-current increases linearly with the electron current at low density region but is gradually saturated at higher density region. In case of L-Bucket source, the H^- current has a plateau value of 2 mA (4 mA/cm^2) at I_e = 2 A (4 A/cm^2), which corresponds to the bulk plasma density of about 1.2×10^{12} cm^{-3}, and then decreases rapidly.

At the condition of I_e = 2 A, the positive ion current I^+ of about 50 mA was extracted when the polarity of the acceleration voltage was reversed. Thus, from Fig. 11, the ratio of I^-/I^+ is 0.04 for L-Bucket and 0.018 for S-Bucket. The maximum value of I^-/I^+ is 0.12 and 0.04, respectively.

Discussion

The difference in the ratio of I^-/I^+ between the S-Bucket and the L-Bucket sources is suggestive. It has been proposed by Bacal et al /14/ and Hiskes et al /15/ that the H^- ions are mainly formed by the collision between cold electrons ($\lesssim 1$ eV) and vibrationally or rotationally excited hydrogen molecules. The excited molecules are formed by wall collisions of the molecular ions (H_2^+ , H_3^+) or by fast electron (~60 eV) collisions with molecular hydrogens. In the case of the S-Bucket source, there will exist a large amount of excited molecules because the wall collisions are enhanced by the small chamber size and the population of excited molecular ions and fast electrons is large. However, in practice, the ratio of I^-/I^+ is small. This is thought to be due to the lack of the cold electrons. On the contrary, the L-bucket source has a large amount of cold electrons. In this case, the ratio I^-/I^+ is relatively large in spite of the low population of the excited molecules. The electron temperature seems to be the most crucial parameter.

5. Experimental results on tandem multicusp plasma source

For formation of H^-, not only the fast electrons to produce the excited molecules but also the low temperature electrons for electron attachment are needed. These two requirements, which oppose each other in conventional multicusp plasma source, can be satisfied in the tandem multicusp plasma source, where the discharge chamber is divided into two zones by a magnetic field. In order to increase the H^- current, we employed the tandem multicusp plasma source (T-Bucket) and made a preliminary experiment on it.

Optimization of chamber depth and filter configuration

The discharge chamber of the T-Bucket source is composed of four units called cathode unit (C-unit), short anode unit (S-unit), long anode unit (L-unit) and filter unit (F-unit). In the present experiment, the F-unit, which produces the magnetic filter like the LBL source /1/, is not used. The transverse filter field is formed by the and 0.018 for S-Bucket. The maximum value of I^-/I^+ is 0.12 and 0.04, respectively.

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Figures 12-15 show the extractable H^- current for various magnet configurations. The symbols N and S refer to north or south pole of the magnets facing the discharge, and the set of the symbols indicates the row of magnets on the left side of the source in Fig.2. The right side is of the opposite polarity. The symbols N' and S' refer to stronger cusp lines which is formed by adding a strong magnet (10 mm wide, 20 mm thick) to the original magnet (5 mm wide, 15 mm thick). The chamber depths are 30 cm, 22 cm, 15 cm and 8 cm in Figs. 12, 13, 14 and 15, respectively. The pressure in the arc chamber is kept to be the optimum value of 0.5 Pa.

In all cases, the H^- current increases linearly with the electron current at low plasma density, gradually becomes saturated at higher density and then decreases. The maximum value of H^- current was 6 mA (12 mA/cm^2), which was obtained with the NS'NS configuration. In this case the positive ion current of 30 mA was obtained when the polarity of the acceleration voltage was reversed. Thus the ratio I^-/I^+ is 0.2. The maximum value of I^-/I^+ was obtained with the NS'NS and NS' configurations at $I_e = 0.15$ A (0.3 A/cm^2) and it was about 0.35.

The dependence of H^- current on the chamber depth is interesting. Concentrating on the data from weak filter configurations (NSNSNSNS, NSNSNS, NSNS, NS), which are shown by solid lines in Figs. 12-15, it can be seen that the extractable H^- current tends to increase with the chamber depth. This is thought to be due to the reduction of the electron temperature. In the strong filter configurations, there exists an optimum chamber depth.

Electron temperature

The electron temperature T_e was measured for three typical magnetic configurations; NS'NS, NSNS and NS corresponding to high, middle and low H^- yield. The maximum values of I^- are 6 mA, 2.1 mA and 1.2 mA, respectively. A Langmuir probe, which was inserted into the center axis of the source, was used to measure T_e . The distance from the plasma grid to the probe is 1.5 cm. Figure 16 shows typical probe traces for the three cases, where almost the same values of electron saturation current are obtained by adjusting the arc power. The primary electron component was not observed in the traces. At a glance, we can see that the plasma produced in NS'NS configuration, where the H^- yield is highest, has the lowest electron temperature and the highest space potential of the three configurations. In Fig. 17, T_e is shown as a function of the electron current for the three configurations. The numbers suffixed to the data points indicate the arc power in kW. Although a large arc power is input in the NS'NS configuration, T_e is lower than other two configurations. There seems to be a strong correlation between T_e and the H^- yield; as T_e increases, the H^-yield decreases.

Calorimetrical measurement

The H^- current was confirmed by the calorimetrical measurement. Figure 18 shows the calorimetrically measured H^- current for NS'NS configuration, where all operating parameters are same as those in Fig. 14. The currents are almost same but somewhat smaller than those measured electrically.

6. Concluding remarks

The experimental results on the three types of multicusp plasma source (S-Bucket, L-Bucket and T-Bucket) are summarized as follows;

1) The maximum value of H^- current of 6 mA (12 mA/cm^2) was obtained in T-Bucket source by optimizing the magnetic filter configuration , chamber depth and other operating parameters. The pressure in arc chamber was as low as 0.5 Pa.
2) The H^- current increases linearly with the electron current at low plasma density but is gradually saturated at higher density. The maximum value of I^-/I^+, of 0.35, is obtained in the T-Bucket source at lower density.
3) The electron temperature seems to be the most crucial parameter affecting the H^- yield.
4) Extractable H^- current increases when the plasma grid is biased positive with respect to the anode.
5) Optimum arc voltage is 50-70 V.
6) Optimum pressure in the arc chamber is 0.5-0.9 Pa.

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We are now going to make additional experiments with the T-Bucket source to enhance the H^- yield. Our present objective is to obtain the H^- current density of 20-30 mA/cm^2 at low pressures. In parallel to the study of H^- production, the study of the separation and the acceleration of H^- ions will start in near future.

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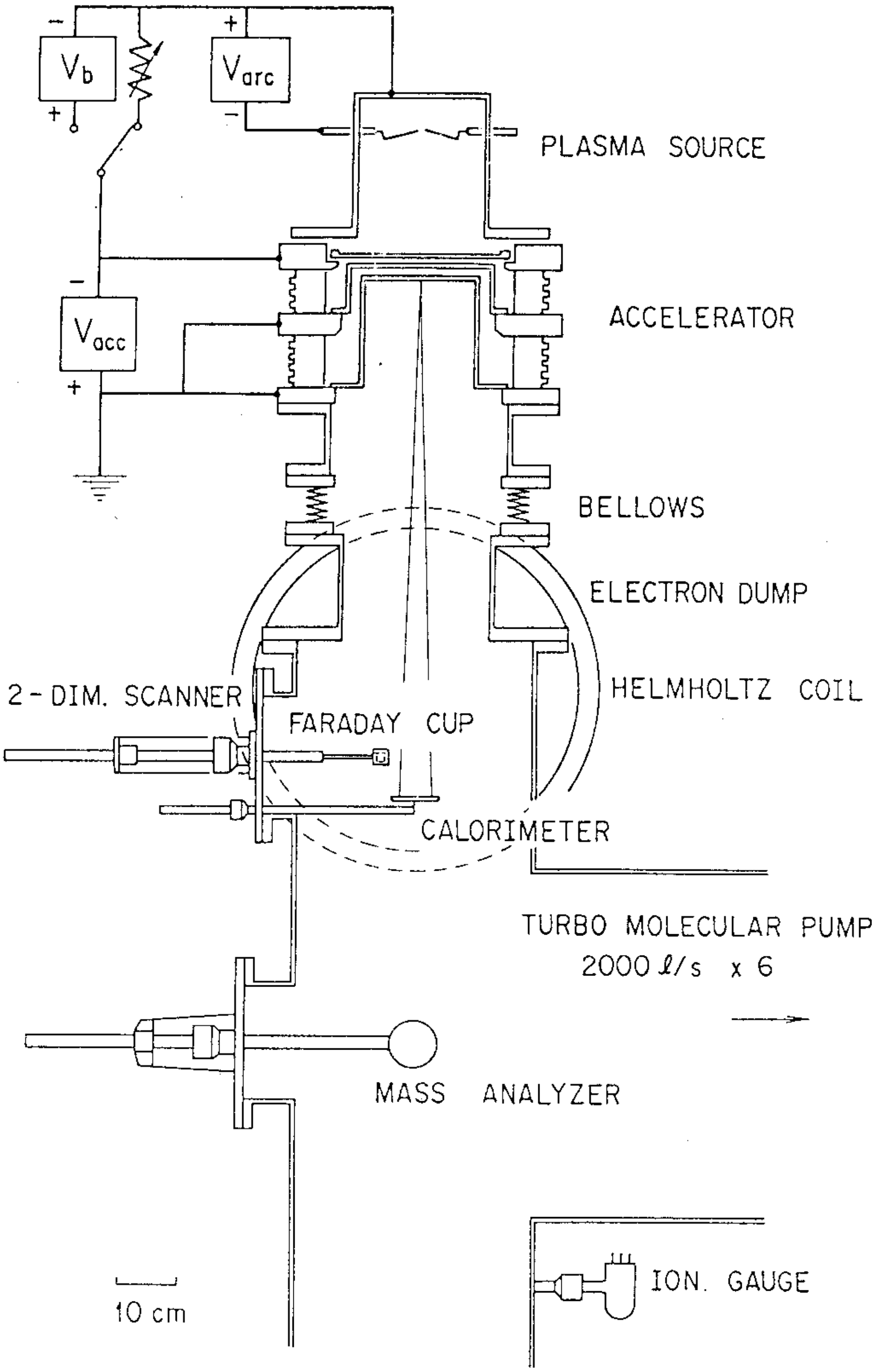

Fig. 1 Schematic of experimental apparatus.

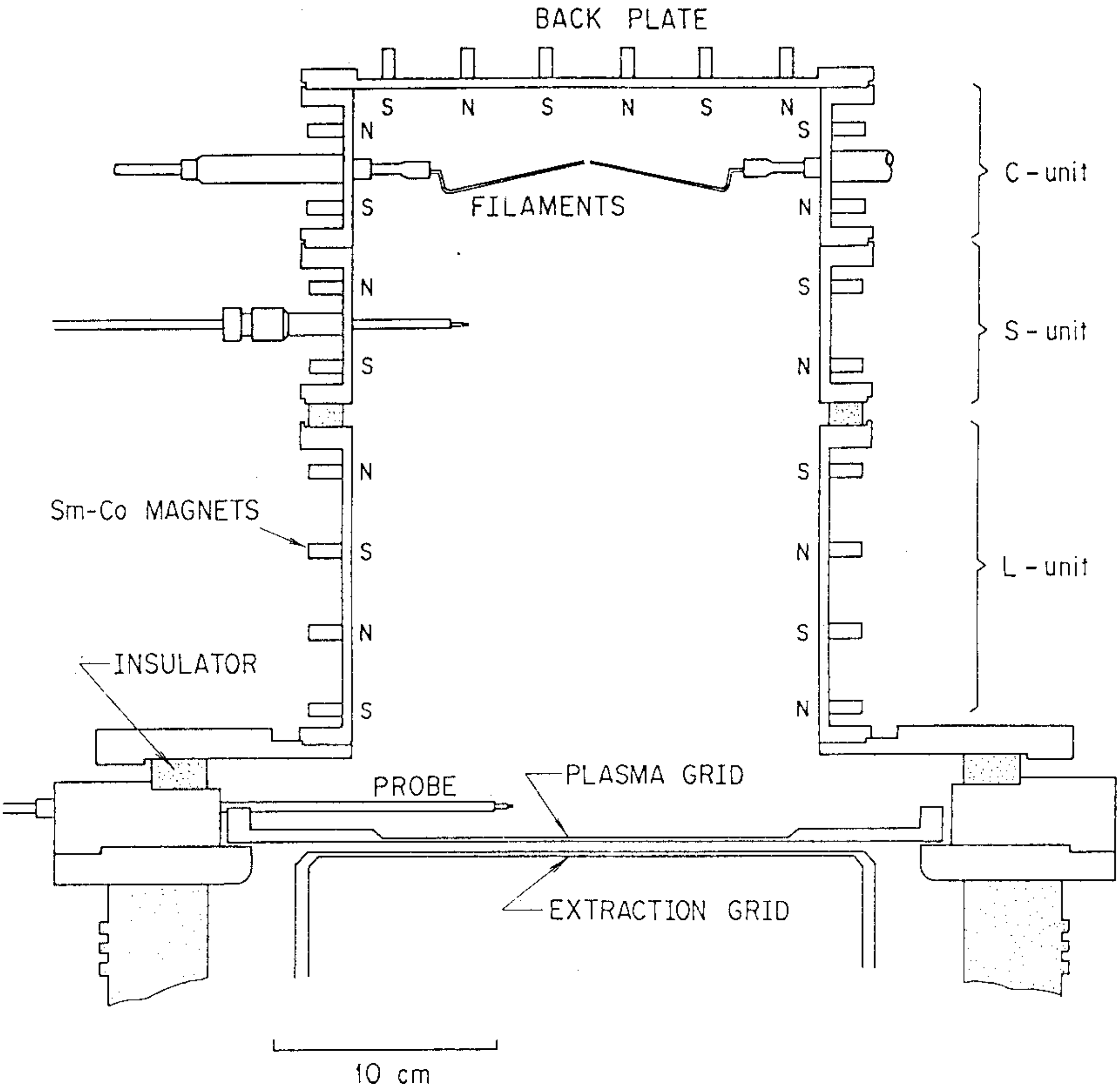

Fig. 2 Cross sectional view of T-Bucket source.

TABLE I Parameters of JAERI volume H^- source

	S-Bucket	L-Bucket	T-Bucket
Chamber length	19.2 cm	40 cm	36 cm
width	12 cm	25 cm	21 cm
depth	15.5 cm	34 cm	variable
Cusp length	258 cm	950 cm	variable
Cusp arrangement to beam axis	parallel	perpendicular	l-direc; per. w-direc; par.
Magnetic field strength at wall	1.25 kG	2.7 kG	1.25 kG
Filaments	1.0^{ϕ}x 4	1.0^{ϕ}x 8	1.0^{ϕ}x 8
Chamber material	Copper	Copper	sus
Cooling	active	active	inactive

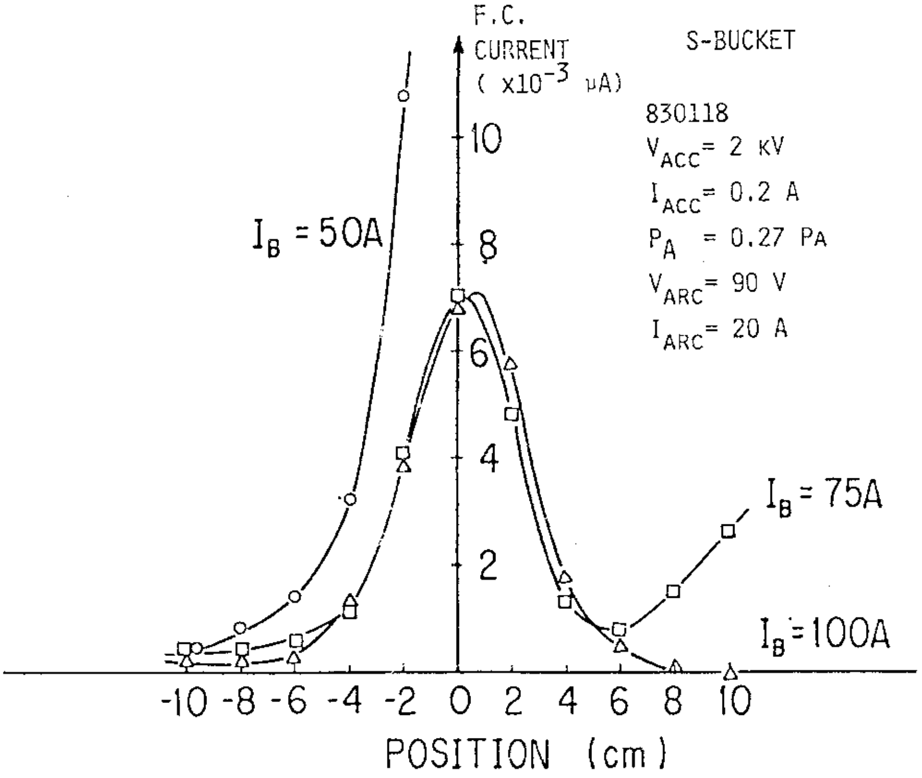

Fig. 3 An example of the beam profile measured by Faraday cup for various Helmholtz coil current.

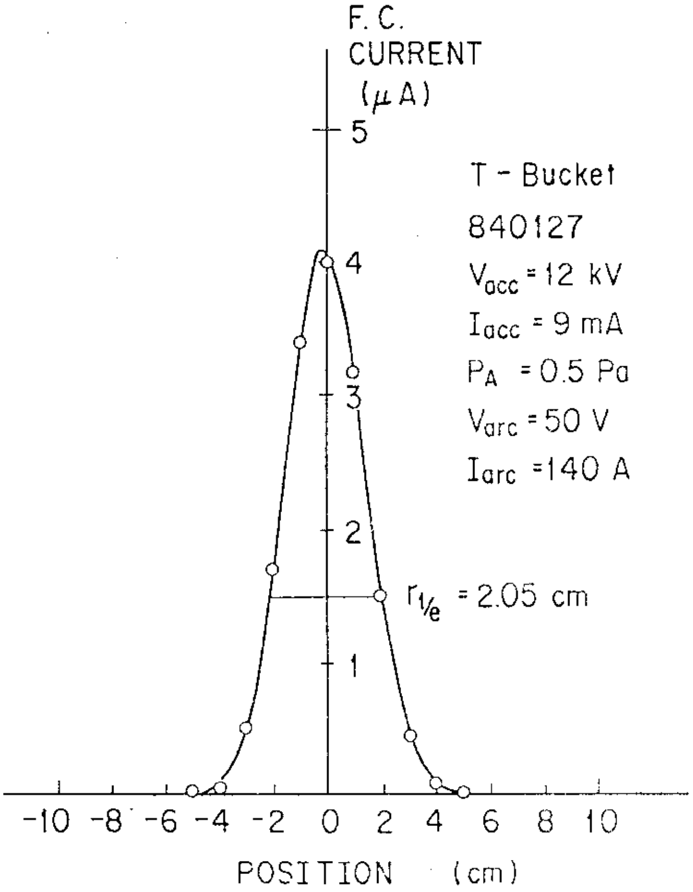

Fig. 4 An example of H^+ ion beam profile.

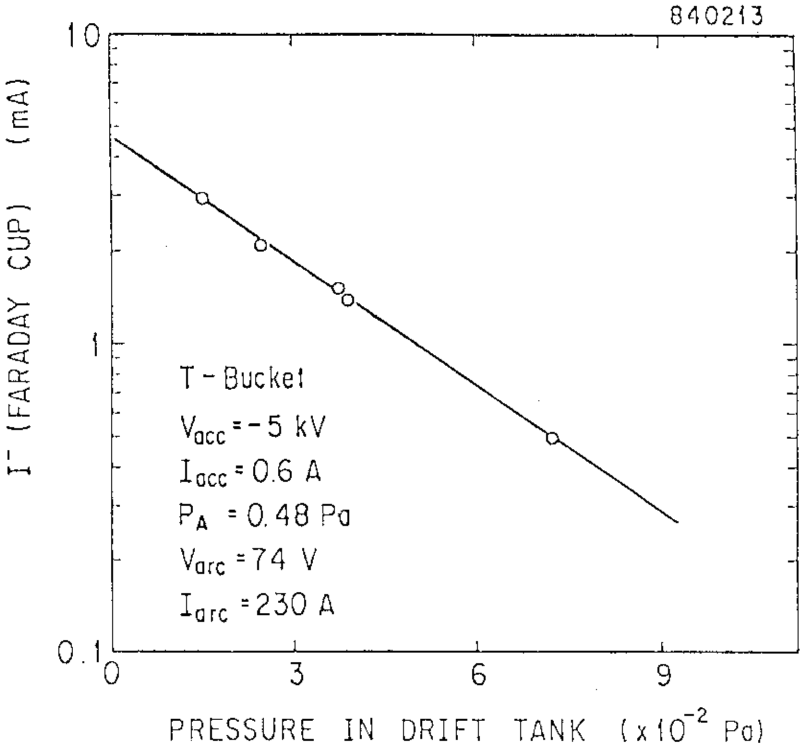

Fig. 5 Unneutralized negative ion current measured by Faraday cup versus pressure in drift tank.

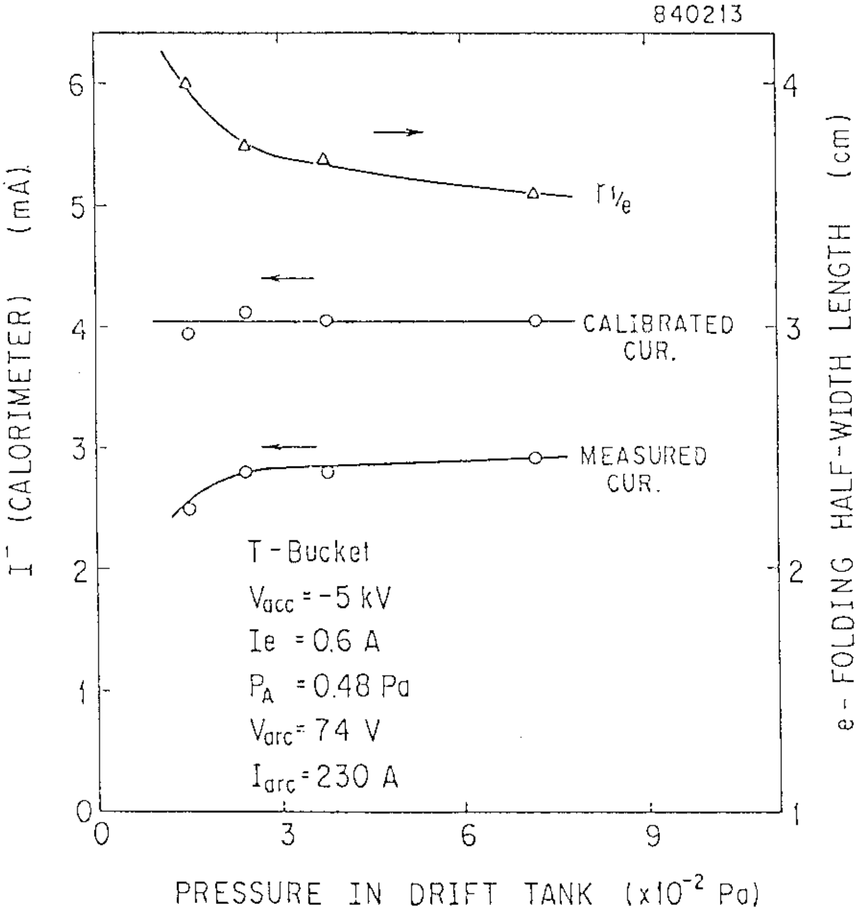

Fig. 6 Equivalent negative ion current measured by calorimeter versus pressure in drift tank. The variation of beam divergence is also shown.

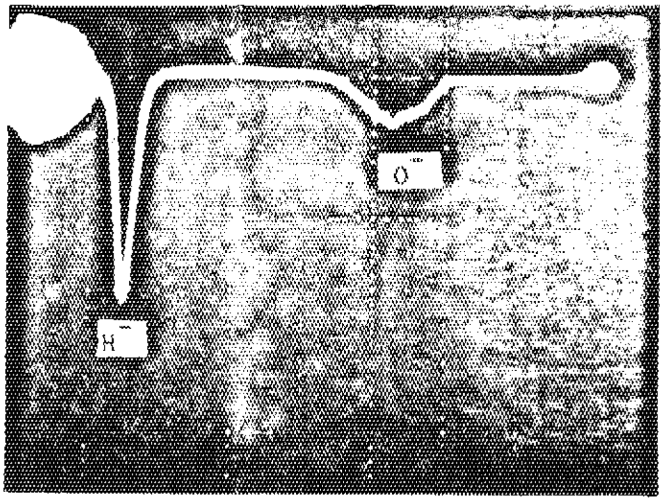

Fig. 7 An example of momentum spectra of negative ion beam.

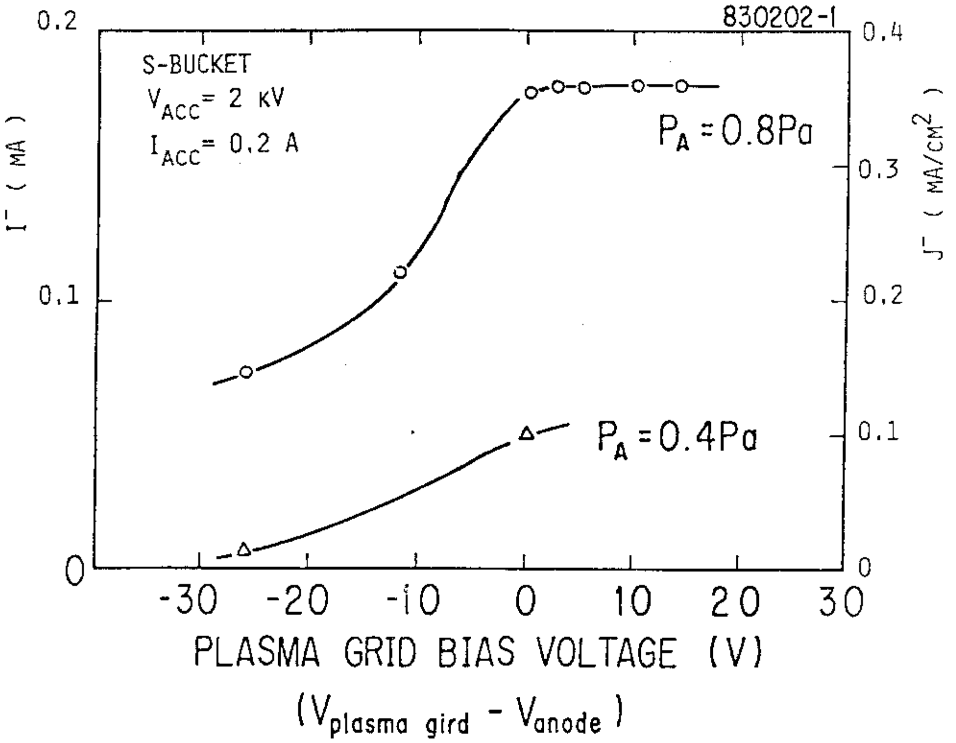

Fig. 8 Effect of the bias voltage on H^- current.

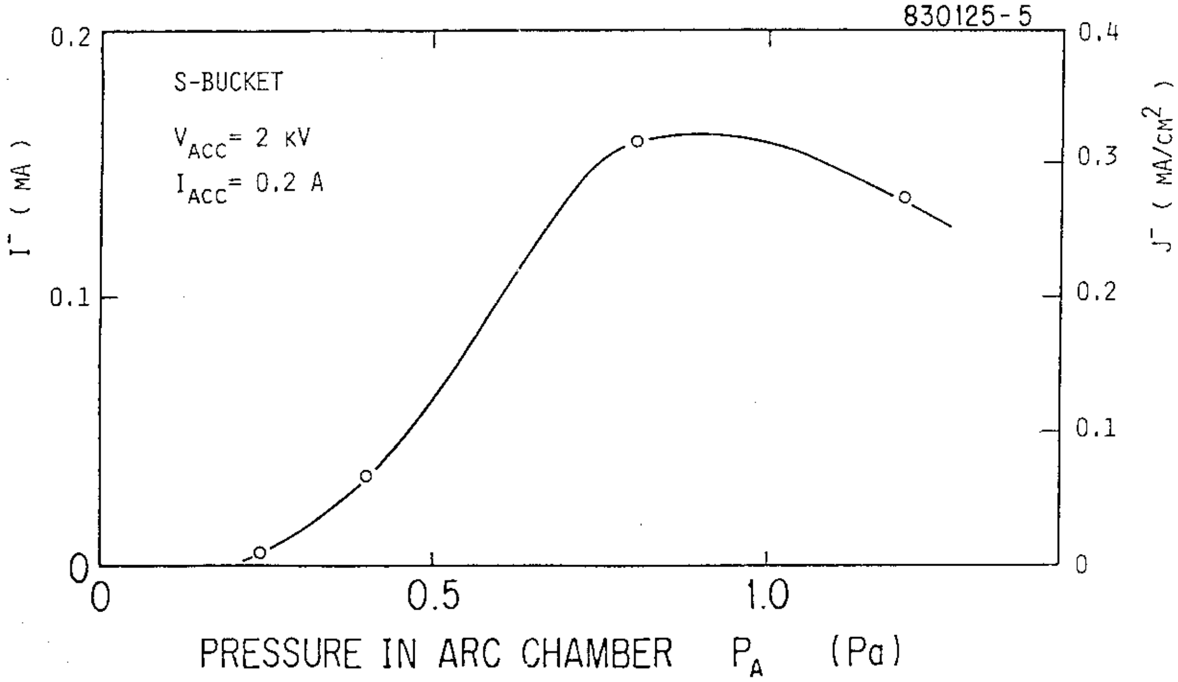

Fig. 9 Dependence of H^- current on the pressure in arc chamber.

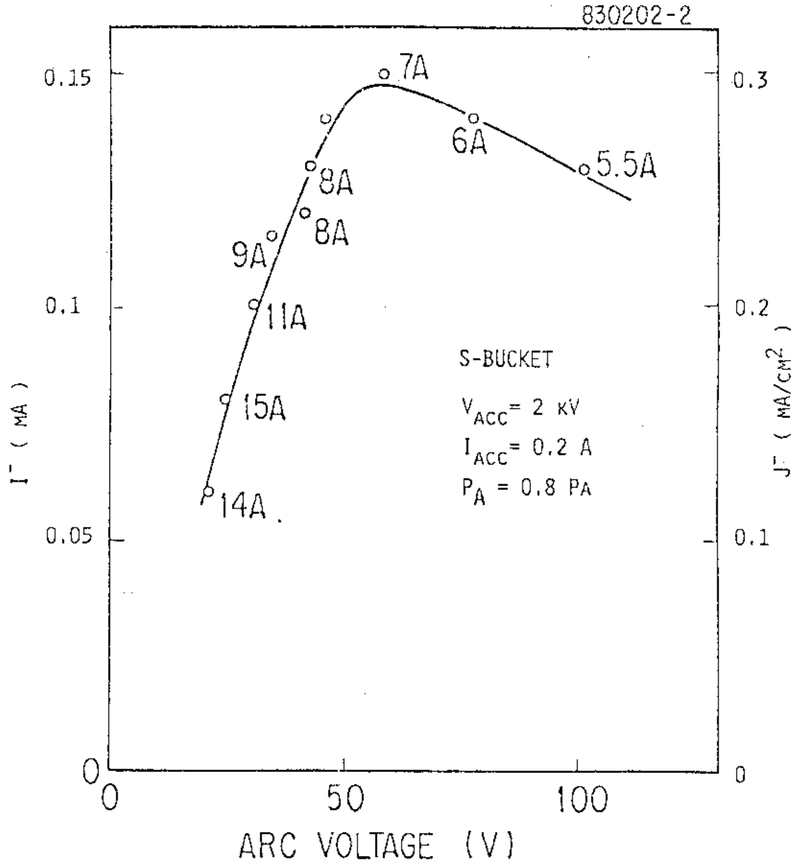

Fig.10 Dependence of H^- current on the arc voltage. The extracted electron current is kept constant by controlling the arc current, which is suffixed to the data points.

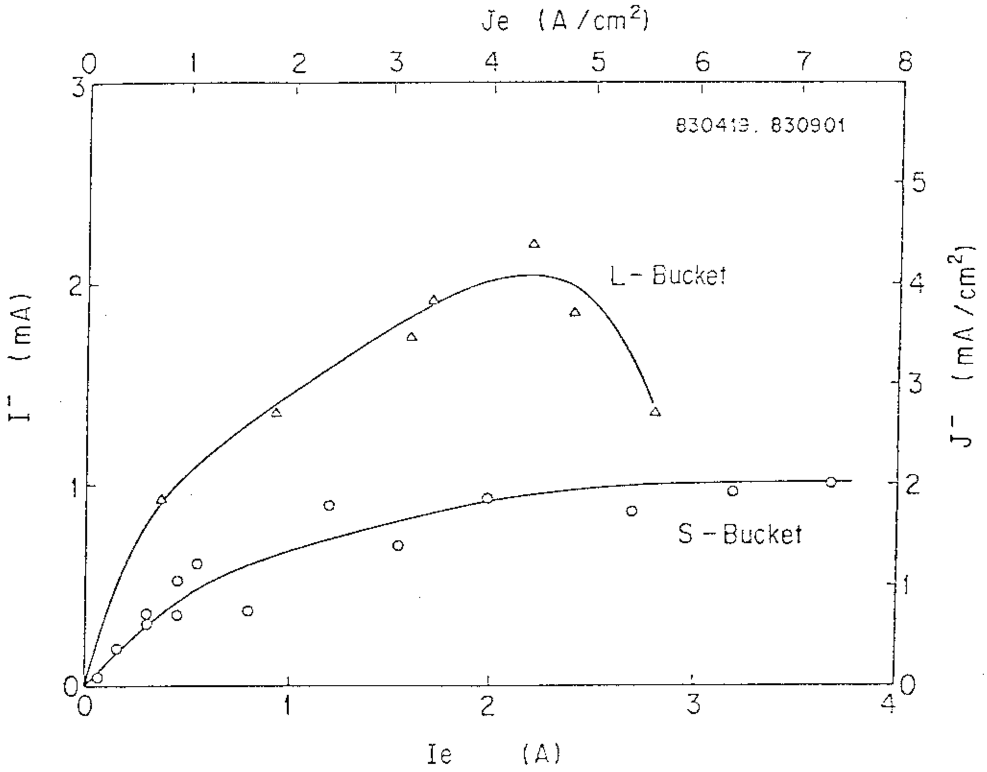

Fig.11 Dependence of H^- current (or current density) on extracted electron current for two types of conventional multicusp plasma sources; S-Bucket and L-Bucket sources.

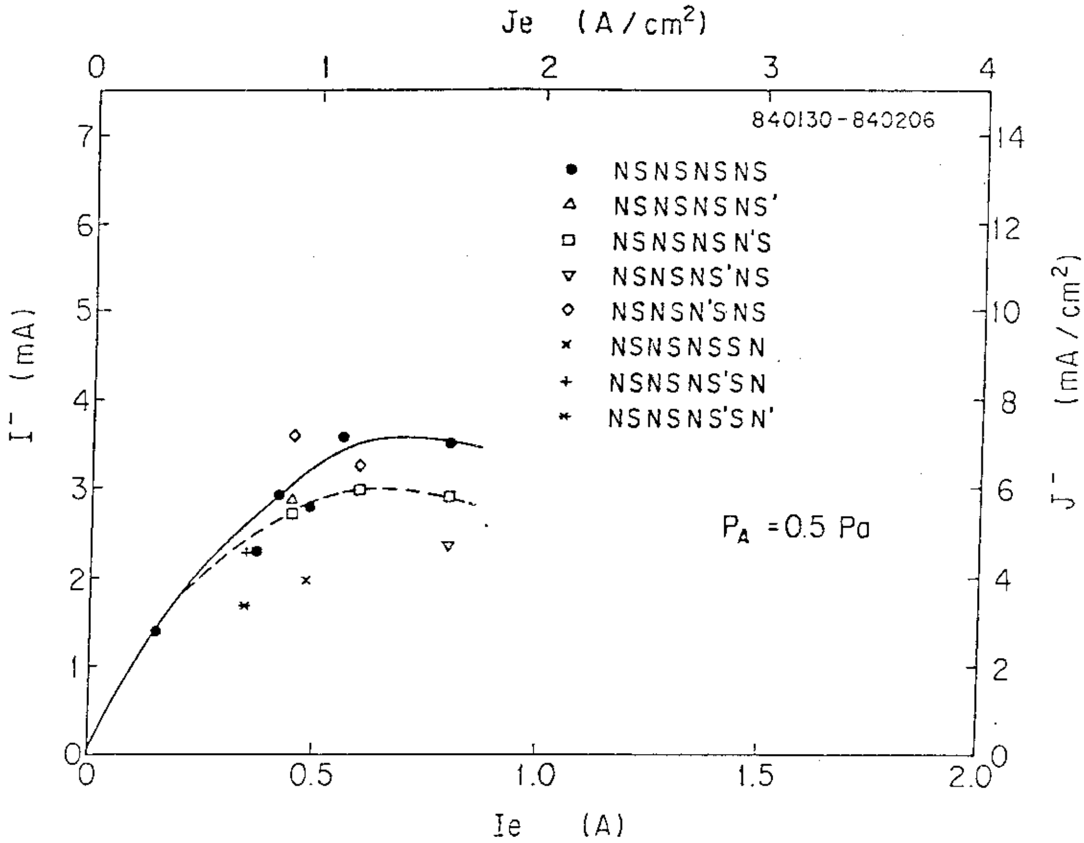

Fig.12 H$^-$ current for various magnetic filter configurations. The units of C, S and L are used.

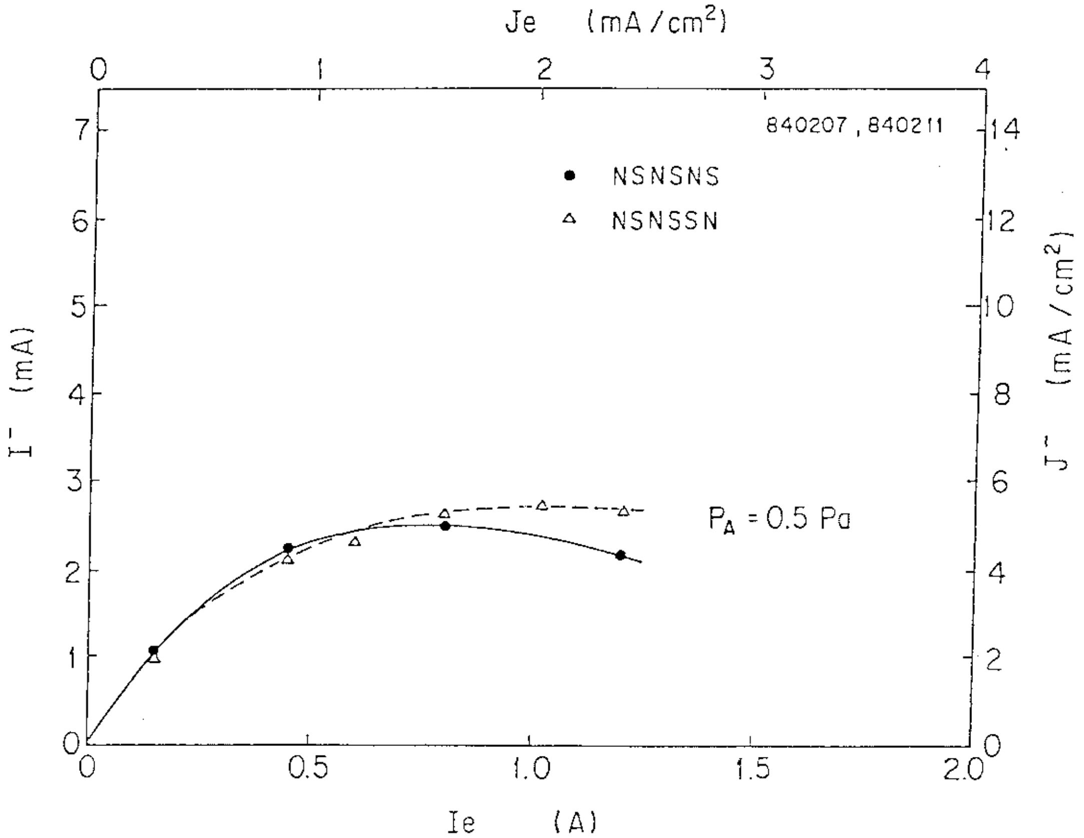

Fig.13 H$^-$ current for various magnetic filter configurations. The units of C and L are used.

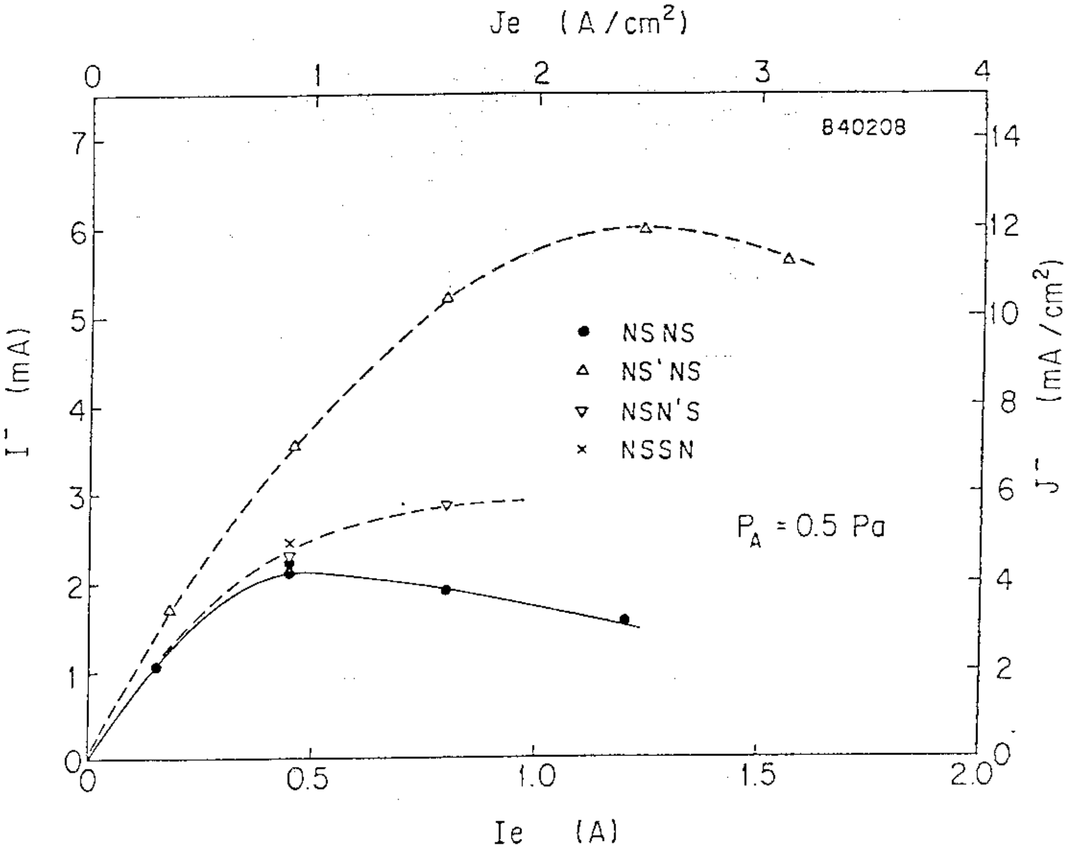

Fig.14 H^- current for various magnetic filter configurations. The units of C and S are used.

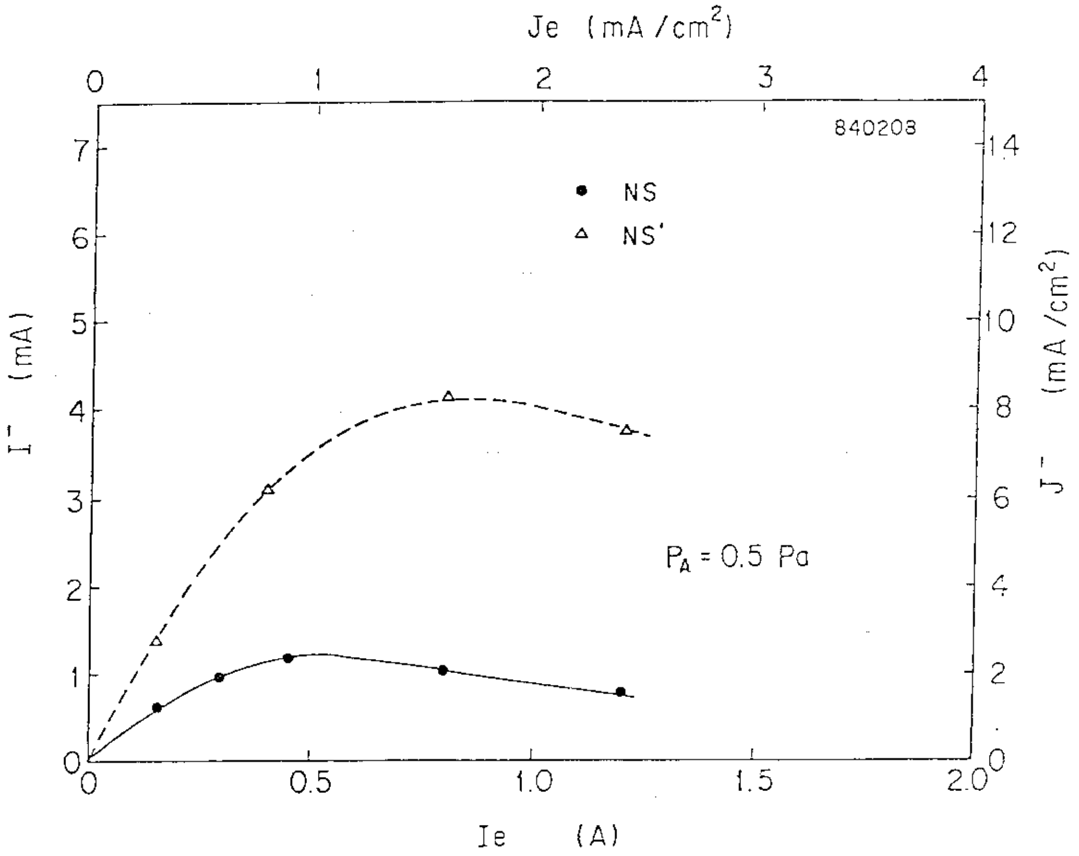

Fig.15 H^- current for various magnetic filter configurations. The unit of C is used.

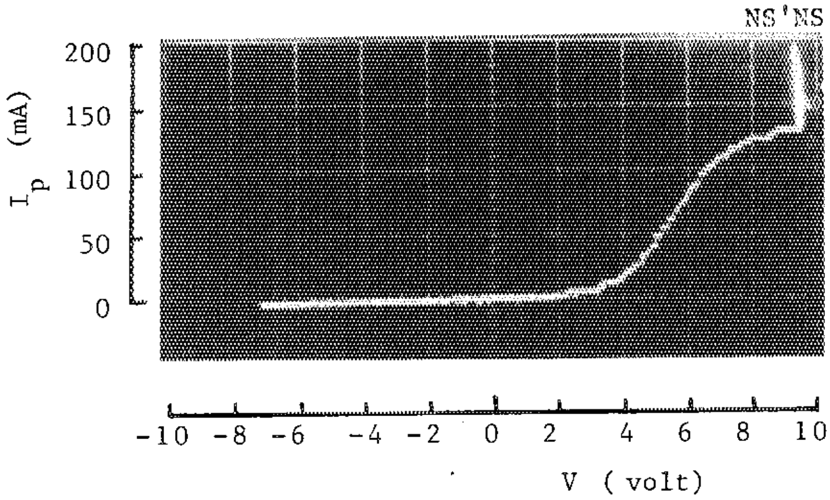

Fig.16-(a)

75V/410A

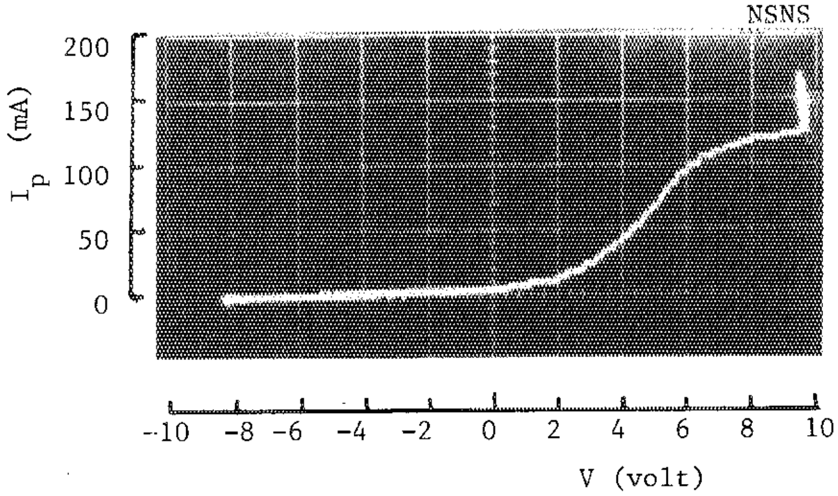

Fig.16-(b)

82V/140A

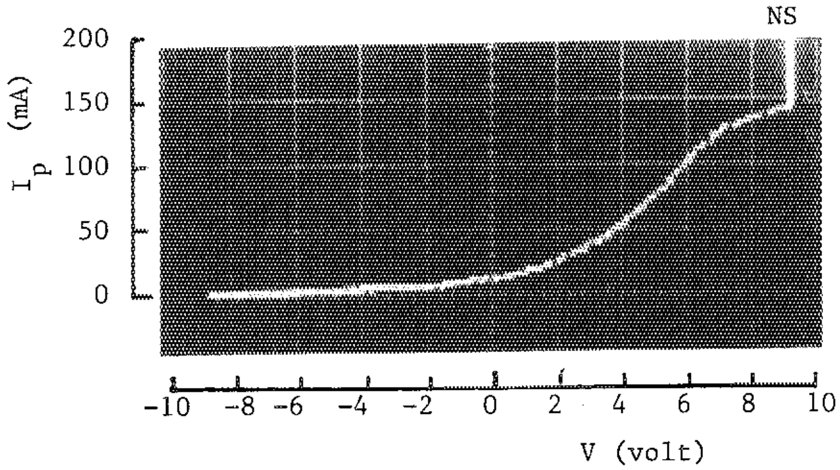

Fig.16-(c)

87V/100A

Fig.16 Langumuir probe traces obtained in various filter configurations ; (a) NS'NS (b) NSNS and (c) NS. Electron saturation currents are almost the same in each case, while the arc powers are (a) 30.8 kW, (b) 14.5 kW and (c) 8.7 kW.

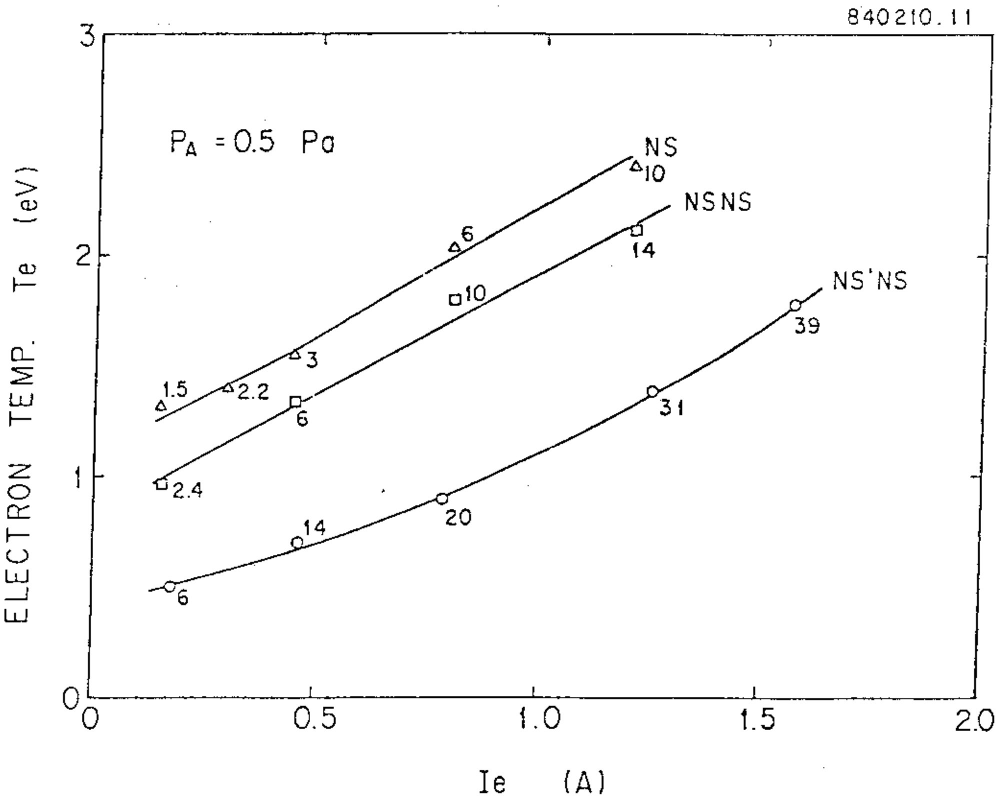

Fig.17 Electron temperature for three types of filter configurations.

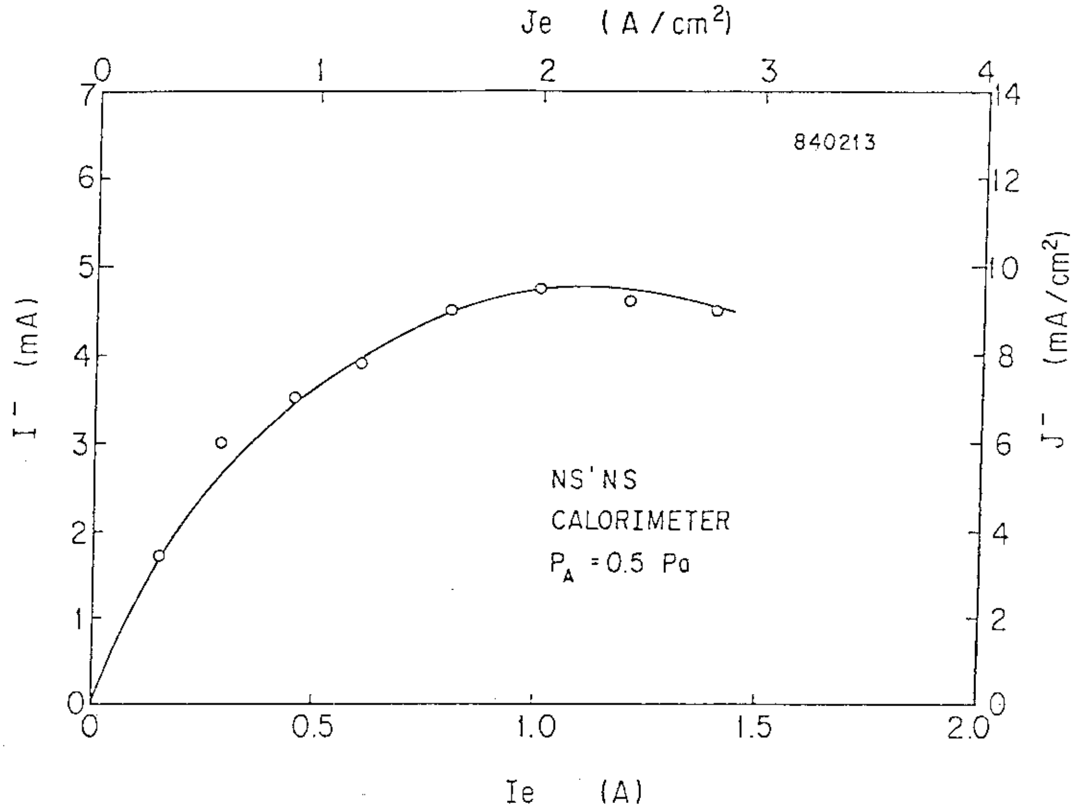

Fig.18 H^- current measured by the calorimeter for NS'NS configuration.