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Electron Temperature Effects for An Ion Beam Source

Jōshin Uramoto

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Further communication about this report is to be sent to the Research Information Center, Institute of Plasma Physics, Nagoya University, Nagoya, Japan.

Abstract

A hydrogen high temperature plasma up to 200 eV is produced by acceleration of electrons in a hot hollow cathode discharge and is used as an ion beam source. Then, two characteristics are observed: A rate of the atomic ion (H^+) number increases above 70%. A perveance of the ion beam increases above 30 times compared with that of a cold plasma, while a floating potential of an ion acceleration electrode approaches an ion acceleration potential (- 500 V) according as an increment of the electron temperature. Moreover, a neutralized ion beam can be produced by only the negative floating electrode without an external power supply.

Introduction

It has been reported,[1.2.] for ion beams extracted from hydrogen plasma sources under weakly ionized discharges or small current discharges, that rates of molecular ions (H_2^+, H_3^+) are dominant. In the plasma sources, electron temperatures are very low (< 10 eV). Therefore, we need high electron temperature plasmas in order to increase a percentage of the atomic ion (H^+) number.

Besides, it has been reported[3.4.5.] that a perveance of an extracted ion beam increases with electron temperature in a plasma source from which the ion beam is extracted. Generally, high electron temperature plasmas for the ion beam have been produced by beam-plasma discharges[3.] or microwave discharges[5.] which need a strong magnetic field for a wave resonance heating and confinement of plasma, and depend on a shape of the magnetic field and a neutral gas pressure with a boundary condition. However, systematic experimental data of the above electron temperature effects have not been reported.

In our experiments, a high electron temperature plasma with a sufficient density is produced beam-likely ($T_{\parallel} \gg T_{\perp}$) by acceleration of electrons in a dc discharge through a new method.[6.7.] The magnetic field is not essential for the production of high temperature plasma and is reduced usually below 50 gauss in front of the extraction electrode for the ion beam. Similarly, a critical neutral gas pressure is not found. Thus, systematic experimental data on increments of the atomic ion number rate and the perveance of ion beam, will be obtained.

Experimental Apparatus and Method

A schematic of the apparatus is shown in Fig.1. A primary plasma is produced by a dc hot hollow cathode discharge between an electrode S_1 and a Ta pipe electrode K through which a hydrogen gas is introudced. Next, the secondary discharge is fired between S_1 and an electrode S_2 by a voltage on a load resistance R_L for S_1. A stable plasma is produced between S_2 and an electrode S_3 around a hydrogen pressure 2.5×10^{-3} Torr (Argon equivalent). The plasma electrons injected from $\overline{S_2S_3}$ space to $\overline{S_3A_1}$ space are accelerated[6.7.] by a potential V_A as the hydrogen pressure in $\overline{S_3A_1}$ is kept around 5×10^{-4} Torr lower than that in $\overline{S_2S_3}$ or in $\overline{A_1A_2}$ space where a hydrogen gas is introduced and kept around 1.8×10^{-3} Torr.

Thus, a high electron temperature plasma is produced electron beam-likely by injecting the accelerated electrons from $\overline{S_3A_1}$. The electron temperature is controlled by the potential V_A between A_1 and S_3. This principle of electron acceleration in the discharge plasma has been reported already.[6.7.] (The neutral gas pressure in $\overline{S_3A_1}$ is most important and must be kept under a condition that electrons are collisionless with neutral particles while ions are collisional).

The electron temperatures in the cavity of the anode A_2 from which the ions are extracted, are measured by a retarding potential method between the anode A_2 and the ion extraction electrode E.

A magnetic field from A_1 to A_2 is reduced usually from 800 gauss to 50 gauss (in front of A_2). Only when a high electron current density is required, the magnetic field in front of A_2 is increased to 400 gauss.

A dependence of the electron temperature on the acceleration anode (A_1 and A_2) voltage V_A is shown in Fig.2 and the electron temperature is controllable from 15 to 200 eV.

An ion beam is extracted through an ion acceleration electrode E. The extracting aperture diameter (0.5 cm) is taken equally to the acceleration distance from the scaling law[8]. for reduction of ion beam divergence. A magnetic-deflection (60°) mass analyzer is set at the end. The hydrogen ion beam composition is studied at an ion acceleration voltage of 2 kV in order to avoid an electron neutralization due to high temperature components of the plasma electrons. On the other hand, when the electron temperature effect for the ion beam perveance is studied, the ion acceleration voltage is taken to - 500 V which is very effective for the perveance.

A plasma density in front of the anode A_2 is controlled by a current I_A to the anode A_2 as shown in Fig.1, which is usually adjustable through the discharge current I_d in the primary plasma source and a series resistance R_L to the electrode S_1. However, in our experiments, the current I_A is varied most effectively by adjusting the pressure P in $\overline{A_1A_2}$ region. A relation between I_A and P is shown in Fig.3 and varied from 0.3 A to 3.0 A independently of the anode voltage

V_A for acceleration of electrons. Then, a variation of the electron temperature is kept within 15% for the pressure P = 3 ~ 12 (× 2.5 × 10^{-4}) Torr. A central primary (visible) plasma diameter in front of the anode A_2 is about 2.6 cmφ at a magnetic field of 50 gauss in front of A_2. A current ΔI_A concentrated on the ion beam extraction aperture 0.5 cmφ is measured by a circuit as shown in Fig.1, and related to the total anode current I_A by

$$\Delta I_A \approx I_A/22.$$

When the magnetic field in front of A_2 is intensified to 400 gauss, the primary (visible) plasma diameter is reduced to about 1.3 cmφ. Then, a current $\Delta I_A'$ concentrated on the ion beam extraction aperture 0.5 cmφ increases about 4 times. That is,

$$\Delta I_A' \approx 4\ I_A \approx I_A/5.5.$$

(In position 2 and 2' operation of the circuit in Fig.1, the electron current passing through the central aperture of the extraction electrode E is about 70% of ΔI_A and enters into the collector C).

Experimental Result I (Ion Species)

A dependence of a number ratio between the atomic ion (H^+) and molecular ion (H_2^+) on the electron temperature is determined in Fig.4 under a neutral gas pressure of 1.8 × 10^{-3} Torr. We find the atomic ion rate exceeds 50% above the electron temperature 35 eV. Next, a dependence of the ratio on the neutral gas pressure between electrodes A_1 and A_2 is determined in Fig.5, while the electron temperature are determined under $V_A = 0$ (the electrons are not accelerated in $\overline{A_1S_3}$). Obviously, the electron temperature decreases with the pressure and the atomic ion number rate decreases also. If the electrons are accelerated in $\overline{A_1S_3}$ ($V_A = 100$ V), the atomic ion number rate is larger than the molecular ion number rate even if the pressure increases as shown in Fig.6.

Experimental Results II (Perveance)

A dependence of extracted ion beam current (space charge limited) on the electron temperature is shown in Fig.7 under an extracting voltage V_E (- 500 V). For the higher electron temperatures, negative bias voltages on the ion beam collector C are required for electron neutralizations. In a case of electron temperature $V_e = 100$ eV, the bias characteristic is shown in Fig.8.

The ion beam current increases abruptly from $V_e/V_E > 1/20$ (a ratio between an electron temperature and the extracting voltage) and above 10 times for the initial value.

Under various electron temperatures, dependences of the ion beam current on the anode current I_A to A_2 (I_A on the extraction aperture) are shown in Fig.9. Obviously under the lower electron temperatures, space charge limits appear for the extracted ion beam currents. On the other hand, when the electron temperature increases and the floating potential of electrode E exceeds the extracting voltage V_E, the space charge limit does not appear in this anode current region.

When a floating potential of the extracting electrode exceeds the extraction voltage V_E according as an increment of electron temperature, an ion acceleration is tried by only the floating electrode without the external power supply for the extracting electrode. While the floating potential around the electron temperature V_e = 170 eV is kept within (- 540 V ~ - 600 V) and the current $\Delta I_A'$ concentrated on the ion beam extraction aperture 0.5 cmϕ is intensified 4 times by increasing a magnetic field near A_2, we observe above 6.5 mA (30 mA/cm^2) of the ion beam current as shown in Fig.10.

Furthermore, when the ion beam current I_{if} increases with the anode current I_A ($\Delta I_A'$), the absolute value of the floating potential on the ion beam extraction electrode E begins to decrease from $I_{if} \gtrsim 10$ mA as shown Fig.11.

Discussion I

After ionizations of the hydrogen gas (H_2), the percentages of ion species are determined by the following three processes

$$H_2^+ + e \rightarrow 2H^+ + 2e, \qquad (R1)$$

$$H_2^+ + H_2 \rightarrow H_3^+ + H, \qquad (R2)$$

$$H_3^+ + e \rightarrow H^+ + 2H + e. \qquad (R3)$$

As the cross-section of the reaction (R2) is about 10 times larger than the reaction (R1), the molecular ion H_3^+ is dominant[2]. at low electron temperatures. The reaction (R3) has a sharp threshold[9]. near 17 eV of electron energy.

Therefore, for our experimental condition $V_e > 15$ eV, the number rate of molecular ion H_3^+ seems to be negligible. The reaction (R1) has a threshold at 46 eV of electron energy.[10.] For our experimental condition $V_e \gtrsim 40$ eV, the number rate of molecular ion H_2^+ decreases below 50%.

Discussion II

It is clear that the space charge limited ion beam current increases with the electron temperature. A theoretical space charge limited current I_{is} is estimated, for a cold ($V_E \gg V_e$) plasma and one dimensional model, by

$$I_{is} = \frac{1}{9\pi}\sqrt{\frac{2e}{M}}\, V_E^{3/2}\, \frac{S}{d^2}\,, \tag{1}$$

where M, V, S and d are an ion mass, extraction voltage, extraction cross-section and ion acceleration distance. For our experimental conditions $V_E \simeq -500$ V, d = 0.5 cm and $S = \pi(d/2)^2$, we obtain

$$\left.\begin{aligned} I_{is} &\approx 0.47 \text{ mA} \qquad \text{for } H^+ \\ &\approx 0.34 \text{ mA} \qquad \text{for } H_2^+ \end{aligned}\right\} \tag{2}$$

On the other hand, the experimental space charge limited current for a cold plasma is determined approximately from a case of $V_e \approx 15$ eV as seen in Fig.6. However, we must consider a variation from H_2^+ to H^+ with an increment of the electron temperature. The H_2^+ ion number is dominant (above 80%) at $V_e \approx 15$ eV where the experimental ion space charge limited current is about 0.13 mA. If we estimate this ion space charge limited current as that of H^+ ion, we obtain $0.13 \text{ mA} \times \sqrt{2} \approx 0.18 \text{ mA}$. Thus, the experimental ion current for a cold plasma is compared with cases of high electron temperatures.

Obviously, we find from Fig.6 that the ion beam currents for $V_e \gtrsim 150$ eV increase above 10 times compared with that of the experimental cold plasma (0.13 ~ 0.18 mA).

For $V_e \gtrsim 150$ eV, the floating potential V_f of the ion extraction electrode E exceeds the externally applied extraction voltage $V_E = -500$ V because of $V_f \approx 4\ V_e$ (experimental). Moreover, the extracted ion beam is almost neutralized by electrons. Then, we can point out that a neutralized ion beam with an extremely high current is extracted by the floating electrode acceleration due to the high electron temperature in the plasma source. A maximum ion beam current I_{if} at the floating electrode acceleration is estimated, under an assumption of electron neutralization, by

$$I_{if} = en \sqrt{\frac{2eV_f}{M}}\, \pi a_c^2 \qquad (3)$$

where n is the ion density near the floating electrode and a_c is a critical maximum radius of ion extraction electrode aperture which is determined from a reduction of the ion beam divergence.[4.] Accroding to the theory,[4.] the critical aperture radius a_c is given by

$$a_c = R_c \lambda_D = R_c \sqrt{\frac{V_e}{4\pi e n_o}} \qquad (4)$$

where λ_D and n_o are a Debye length and a source density, and R_c is a factor which depends on a ratio between the ion acceleration voltage and the electron temperature. If a relation between the floating potential V_f and electron temperature is expressed by

$$V_f \approx \xi V_e, \tag{5}$$

we can estimate, from a continuity law for the ion velocity accelerated by the floating potential and density, and the initial ion velocity due to the sheath criterion and density

$$\frac{n}{n_o} \approx \sqrt{\frac{V_e}{V_f}} = \frac{1}{\sqrt{\xi}} \tag{6}$$

from Eqs. (3), (4), (5) and (6), we obtain

$$I_{if} = \frac{1}{4}\sqrt{\frac{2e}{M}}\, V_f^{3/2}\, \frac{R_c^2}{\xi^{3/2}} \, . \tag{7}$$

When this ion beam current I_{if} accelerated by the floating electrode is compared with the usual theoretical ion space charge limited current for a cold plasma, we find, as $S = \pi a_c^2$ and $d = 2a_c$ in Eq.(1),

$$\frac{I_{if}}{I_{is}} = \frac{9R_c^2}{\xi^{3/2}} \tag{8}$$

For our experimental conditions $\xi \approx 4$ and $R_c \approx 7$ (from the theory[4].), we obtain

$$I_{if} \approx 5.5 \times 10\ I_{is} \, . \tag{9}$$

At $V_f \approx -500$ V, we find $I_{if} \approx 26$ mA.

As one of our experimental data in Fig.10, we find an extracted ion beam current $I_{if} \approx 6.5$ mA under $V_f \approx -550$ V, while the Debye length λ_D is estimated to be about 0.05 cm (for the plasma source density $n_o \approx 2 \times 10^{10}$/cc), we can estimate $R_c \approx a_c/\lambda_D \approx 5.0$ from the ion beam extraction aperture radius 0.25 cm.

As seen from Fig.11, the absolute value of floating potential $|V_f|$ of the electrode E decreases from the ion current $I_{if} \approx 10$ mA. Then, the aperture radius for the ion beam extraction is estimated to be about 6 times of Debye length (at $V_e \approx 170$ eV).

An electron current ΔI_A over a cross section πa_c^2 (a part of the current I_A to the anode A_2) which is required to produce the ion beam, is shown in Fig.9. This electron current ΔI_A may be understood from a relation between electron and ion saturation current to Langmuir probe in plasma,

$$\frac{I_{\ell.sat}}{I_{i.sat}} \approx \sqrt{\frac{\varepsilon M}{2\pi m}} \approx 28 \qquad \text{(for } H^+\text{)} \tag{10}$$

where m and M are electron mass and ion mass, and ε is 2.718 ..... . We observe, experimentally, for $I_{if} < 10$ mA,

$$\frac{\Delta I_A'}{I_{if}} \approx 80 \sim 100 \tag{11}$$

and, for $I_{if} > 10$ mA,

$$\frac{\Delta I_A'}{I_{if}} \approx 37 \sim 80 \ . \qquad (12)$$

This ratio decreases with the ion current while the Debye length decreases. The fact means that a large part of the electrons are reflected when the Debye length is larger. On the other hand, when the Debye length is much smaller than the aperture radius of E, the electrons pass through the aperture and the ratio between the electron (saturation) current and the ion saturation current approaches a value of Eq.(10).

Conclusion

For a plasma source of electron temperature V_e > 35 eV, number rate of the atomic ion H^+ in the extracted ion beam exceeds 50%.

When the electron temperature V_e increases and the floating potential of the ion acceleration electrode exceeds the externally applied acceleration voltage, the ion beam current increases 30 times compared with a space charge limited current for the cold plasma while a neutralized ion beam can be produced by only the floated extraction electrode without the externally applied power supply.

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Appendix

At the floating electrode ion acceleration as predicated in this paper, a limitation of an ion beam extraction aperture radius due to a Debye length may be avoided, if electrons which neutralize the ion beam are reflected on the end collector (biased negatively) along a strong magnetic field and the floating electrode potential drops through a charge up due to the reflected electrons. Then, the ion beam current will be determined, as estimated from a Langmuir probe theory, by

$$I_i \approx I_e \sqrt{\frac{2\pi m}{\varepsilon M}} , \tag{1}$$

where I_i and I_e are the ion beam current and the injected electron (beam like) current, and M and m are an ion mass and electron mass, and ε is 2.718 .... .

In order to confirm the above considerations, an experiment is tried by injecting a high current electron beam with a long pulse duration. A schematic and explanation of the apparaus using H_e gas is shown in Fig.A.

An electron beam current to the anodes (A_1, A_2, A_3) is about 400 A with a long decay time of 17 msec (in a fast rise time 200 μsec), under the electron accelerating voltage V_A = 600 V, the plasma source secondary discharge voltage V_s = 250 V and the pressure $P_A = 5.6 \times 10^{-3}$ Torr between A_1 and A_2. Then, the floating electrode F potential shows about 100 V. To determine a floating potential at center of each stage, two probes are inserted as shown in Fig.A. At the above conditions, the one floating probe potential V_{PA} between A_2 and A_3

is about 550 V and the other V_{PF} is about 50 V, while the collected ion current I_c (in about 1.4 cm) is about 10 A (7.8 A/cm^2 in the current density) with the same decay time 17 msec. The rough space potential distributions V_{SP} are shown in Fig.B. An ion beam with an energy of about 500 eV is produced over a long space between the floating electrode and the collector.

This large ion beam current of about 10^4 times above the space charge limit current ($\lesssim$ 0.5 mA) must be estimated from Eq.(1) while the limitation due to the Debye length does not appear.

Figure Captions

Fig.1 Schematic of Experimental Apparatus. K: Ta pipe cathode. S_1, S_2 and S_3: Primary plasma source Electrodes. A_1 and A_2: Acceleration anodes. E: Ion beam extraction electrode. C: Ion beam collector (10 cm apart from E). B: Magnetic field ($\overline{A_1S_1}$) = 800 - 1300 - 800 gauss. I_{ns}: Insulator. I_s: Primary discharge current (30 A). V_d: Primary discharge power supply (Discharge voltage between K and $S_3 \approx 85$ V). R_L: Road Resistance ($\sim 20\ \Omega$). V_A: Plasma electron acceleration power supply (0 ~ 500 V). V_E: ion beam extraction power supply (- 500 V usually). V_B: Collector negative bias. I_A: Current to acceleration anode A_2. I_i: Ion beam current. SW: Positions 1 and 1' for measuring I_i, Positions 2 and 2' for ΔI_A, and Positions 3 and 1' for I_i under floating acceleration electrode E. B: Magnetic field = 50 or 400 gauss (A_2) - 800 gauss (A_1) - 1300 gauss (S_3, S_2) - 600 gauss (S_1). M.A.: Mass Analyzer.

Fig.2 Dependence of electron temperature V_e (in A_2) on plasma electron acceleration voltage. V_A under a pressure in $\overline{A_1A_2}$ of 1.8×10^{-3} Torr. P_1: 5×10^{-4} Torr in $\overline{S_3A_1}$. P_2: 1.8×10^{-3} Torr in $\overline{S_3A_1}$ (without pumping).

Fig.3 Dependence of current I_A (to A_2) on pressure P in $\overline{A_1A_2}$.

Fig.4 Dependence of number rate γ of ion species on electron temperature V_e.

Fig.5 Dependence of number rate γ of ion species on pressure P in $\overline{A_1A_2}$. V_e: electron temperature at $V_A = 0$.

Fig.6 Dependence of number rate γ on pressure P in $\overline{A_1A_2}$ at $V_A = 100$ V.

Fig.7 Dependence of ion beam current I_i on electron temperature V_e. V_E: Ion beam acceleration voltage. (Ion beam extraction aperture 0.5 cmϕ and Ion beam acceleration distance 0.5 cm).

Fig.8 Dependence of collected ion beam current I_i on collector bias voltage V_B. V_e: electron temperature.

Fig.9 Dependence of ion beam current I_i on anode current I_A. $\Delta I_A \approx I_A/22$ (concentrated on the ion beam extraction aperture 0.5 cmϕ at B $\approx$ 50 gauss near A_2). V_e: electron temperature. V_E: Ion beam acceleration voltage.

Fig.10 Dependence of ion beam current I_{if} on anode current I_A. $\Delta I_A' \approx I_A/5.5$ (concentrated on the ion beam extraction aperture 0.5 cmϕ at B $\approx$ 400 gauss near A_2). V_f: Floating potential of ion extraction electrode E without external power supply V_E. V_e: electron temperature at $V_A \approx 400$ V.

Fig.11 Dependence of floating potential V_f of electrode E on extracted ion beam I_{if} at $V_e \approx 170$ eV. (R_c: a_c/λ_D ratio between ion beam extraction aperture radius and Debye length).

Fig.A Schematic of experimental apparatus (Appendix).

K: Ta pipe cathode. S_1: Plasma source first anode. S_2: Plasma source second anode. S_3: Plasma source third anode. A_1: Acceleration first anode. A_2: Acceleration second anode. A_3: Acceleration third anode. Ins: Insulator. F: Floating electrode. C: Ion beam collector. B: Magnetic field. p: Probe. I_e: electron beam current. I_c: ion beam current. V_d: power supply. I_d: discharge current. Explanation of experimental apparatus: A pulse plasma source with a fast rise time (below 100 μsec) is produced from a cold cathode. A primary plasma source is produced by a dc hollow cathode discharge between an electrode S_1 (with a central aperture of 0.6 cmϕ in diameter and 2.5 cm in length) and a Ta pipe electrode K (0.6 cmϕ in outer diameter and 0.4 cmϕ in inner diameter). The gap between S_1 and K is about 1.0 cm. Usually, the dc hollow cathode discharge is kept with a discharge voltage 75 V and current 26 A (R_d = 2 Ω and $V_d \approx 127$ V) in a helium gas pressure of about 2 Torr. To stop the primary dc plasma flow into $\overline{S_2S_3}$ space, an electrode S_2 (0.7 cmϕ in central aperture diameter and 4.0 cm in length) is put at a distance 10 cm apart from S_1. The pressure between S_1 and S_2 is about 10^{-1} Torr. A negative potential V_c through a resistance ($R_c \approx 20$ Ω) is applied between S_1 and S_2. A pulsed plasma for electron injection is produced between S_2 and the third electrode S_3 (with 0.8 cmϕ in central aperture and 1.0 cm in length) which is 12 cm apart from S_2. A pressure between S_2 and S_3 is kept at about 10^{-2} Torr, which is determined experimentally. Then, if the negative potential V_c between S_1 and S_2 is set at - 80 V, the dc primary plasma electron flow into $\overline{S_2S_3}$ space is reduced below 20 mA by the neutral particle collisions and the retarding electric field of V_c.

Here, if a pulse potential above V_c is applied between S_1 and S_3 electrode by a charged condenser $C_s = 1.44 \times 10^{-2}$ F through SCR, a pulsed secondary plasma is produced with a fast rise time (below 100 μsec) between S_2 and S_3, while the pulsed plasma electrons are injected between S_3 and an acceleration anode A_1. Then, to lead the secondary plasma from $\overline{S_1S_2}$ to $\overline{S_2S_3}$ space, a loading resistance $R_L \approx 0.5\ \Omega$ is connected to S_2. The pulsed plasma electron current between S_2 and S_3, and its pulse duration are adjusted by a charging voltage V_s for C_s and a capacitance of C_s.

The pulsed plasma electrons injected from $\overline{S_2S_3}$ space to $\overline{S_3A_1}$ space are accelerated by a potential of condenser $C_A = 3.6 \times 10^{-3}$ F which is charged by a dc power supply voltage V_A. Each space between K and S_1, S_1 and S_2, S_2 and S_3, or S_3 and A_1 is connected by a pyrex glass tube with a diameter of 10 cm. A length between S_3 and A_1 is 40 cm, where the helium gas pressure is kept within $(2.8 \sim 4.2) \times 10^{-4}$ Torr.

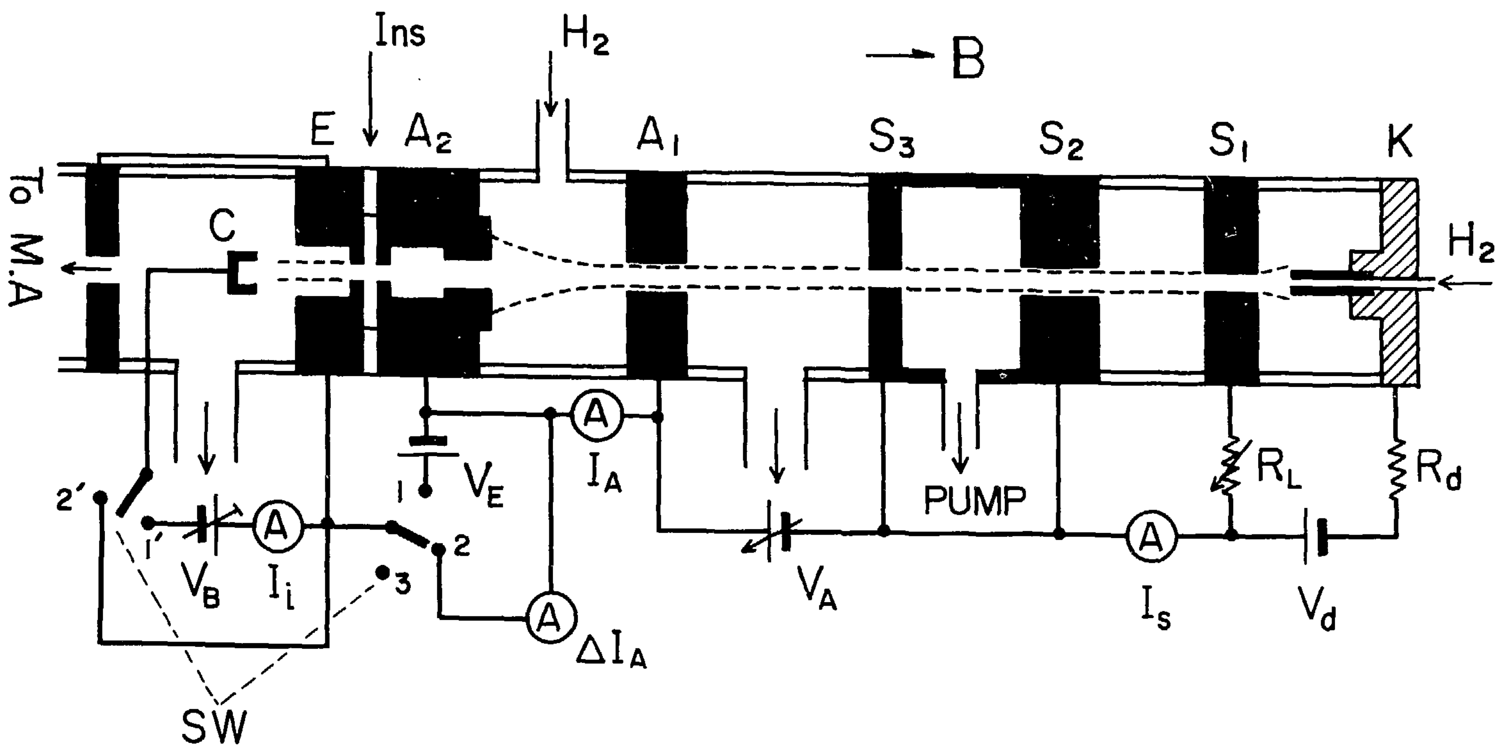
A magnetic field B is applied uniformly at B =

1.3 K gauss from A_3 to S_2. However, the magnetic field is diverged from S_2 to K and is set at B = 300 gauss on S_1 to stabilize the primary dc discharge.

A helium gas is introudced between two acceleration anodes A_1 and A_2 where the pressure is varied from 2×10^{-4} to 7×10^{-3} Torr. The distance between A_1 and A_2 is 16 cm. The A_1 or A_2 is 6 cm or 5 cm in length and has a central aperture of 1.6 cmϕ or 1.4 cmϕ. The third anode A_3 (a central aperture of 1.4 cmϕ and 1 mm in thickness) is put 20 cm apart from A_2. The pressure in $\overline{A_2A_3}$ region is kept below 2×10^{-5} Torr.

A floating electrode F (a central aperture of 1.4 cmϕ and 3 cm in length) is put behind A_3, which is insulated from A_3. An earthed ion beam collector C is put 20 cm apart from F. The pressure between F and C is kept below 10^{-5} Torr.

Fig.B Space Potential Distribution V_{sp}. $\overline{A_2A_3}$: Anode region. F: Floating electrode. C: Ion collector.



Ins
H2
B
E
A2
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K
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Fig. 1

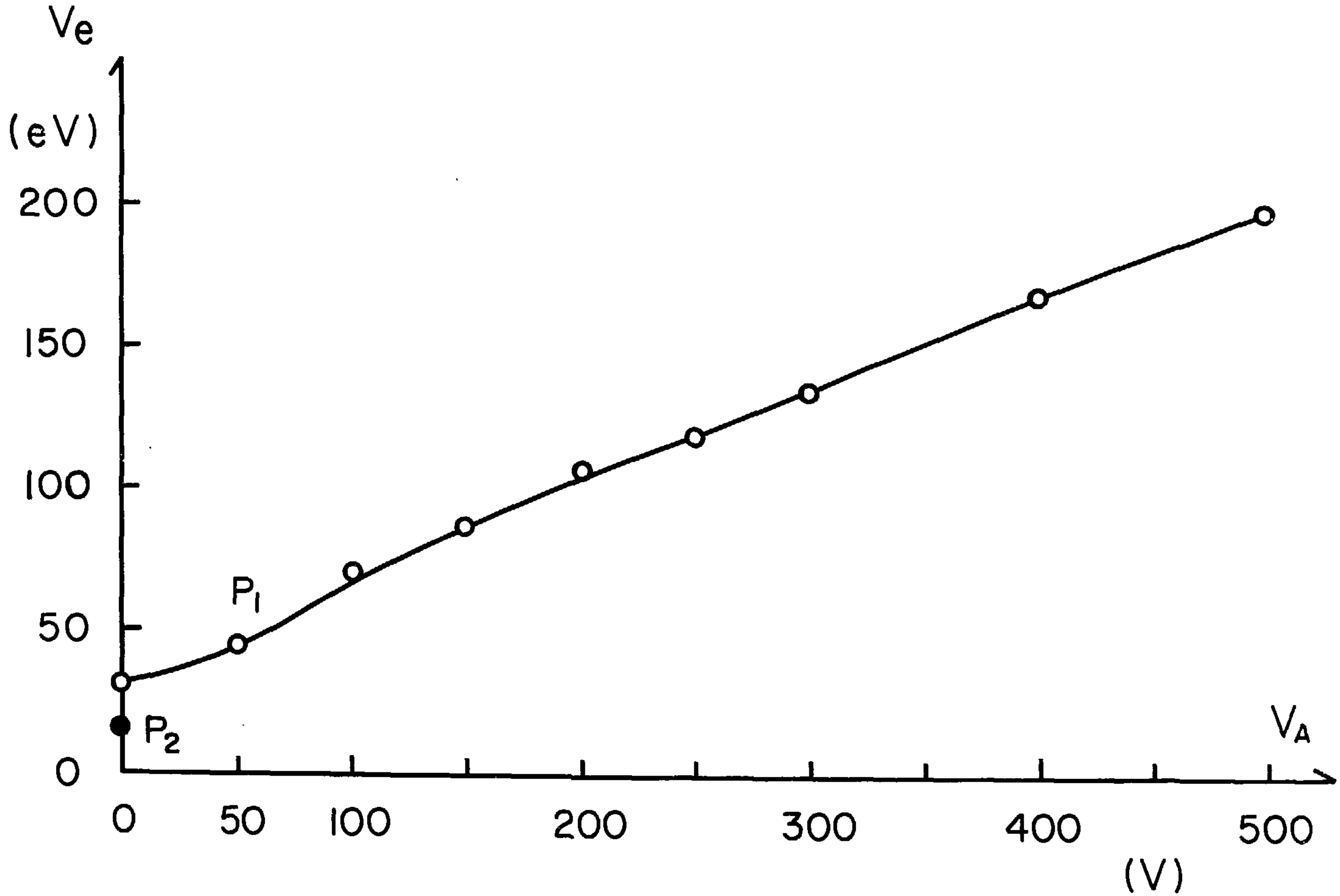


Fig. 2

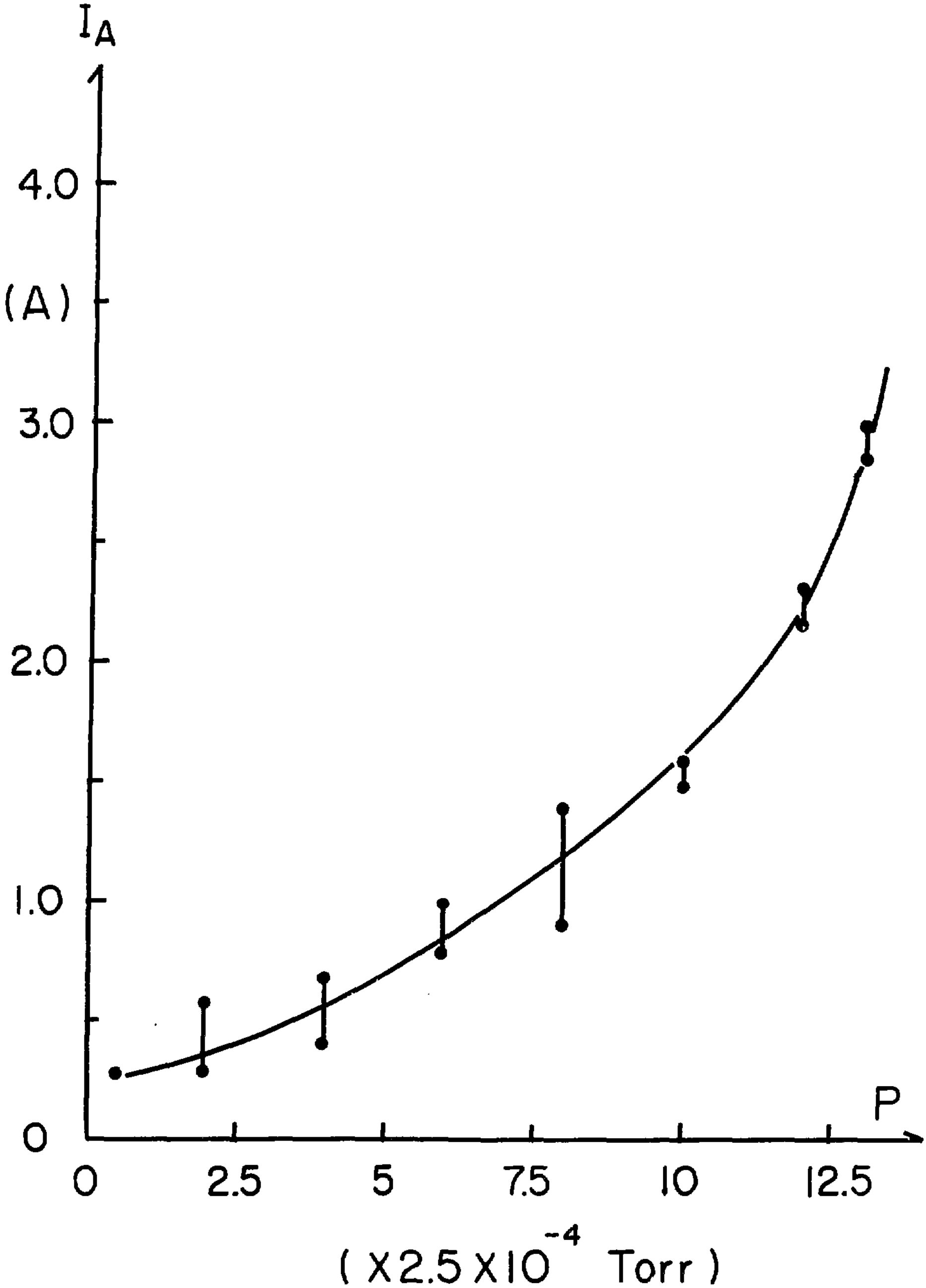


Fig. 3

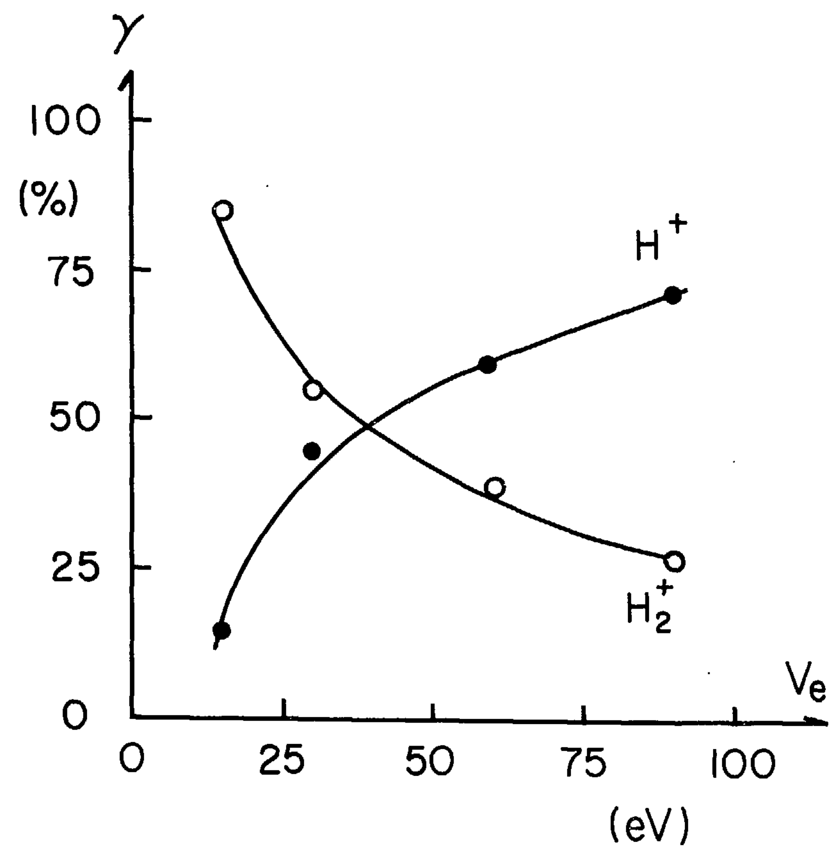


Fig. 4

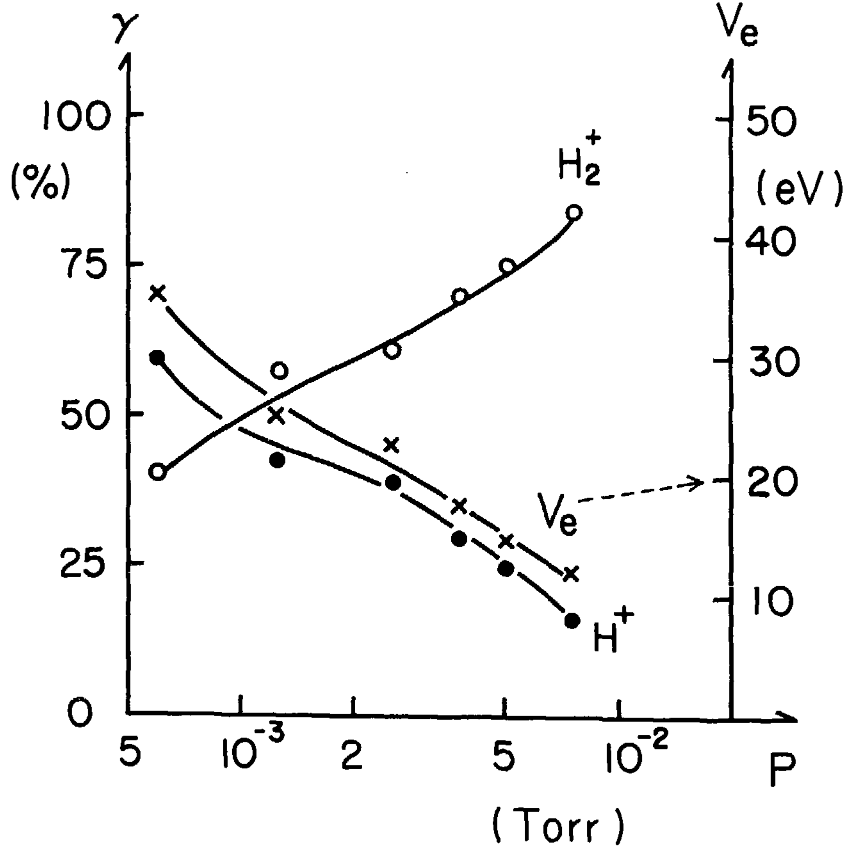

γ
(%)
100
75
50
25
0
Ve
50
(eV)
40
30
20
10
H₂⁺
H⁺
Ve
5
10⁻³
2
5
10⁻²
P
(Torr)

Fig. 5

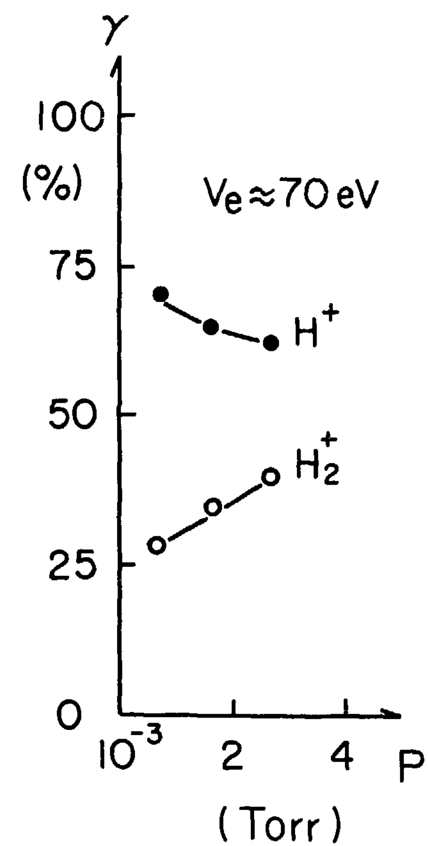

γ
(%)
100
75
50
25
0
Ve≈70 eV
H⁺
H₂⁺
10⁻³
2
4
P
(Torr)

Fig. 6

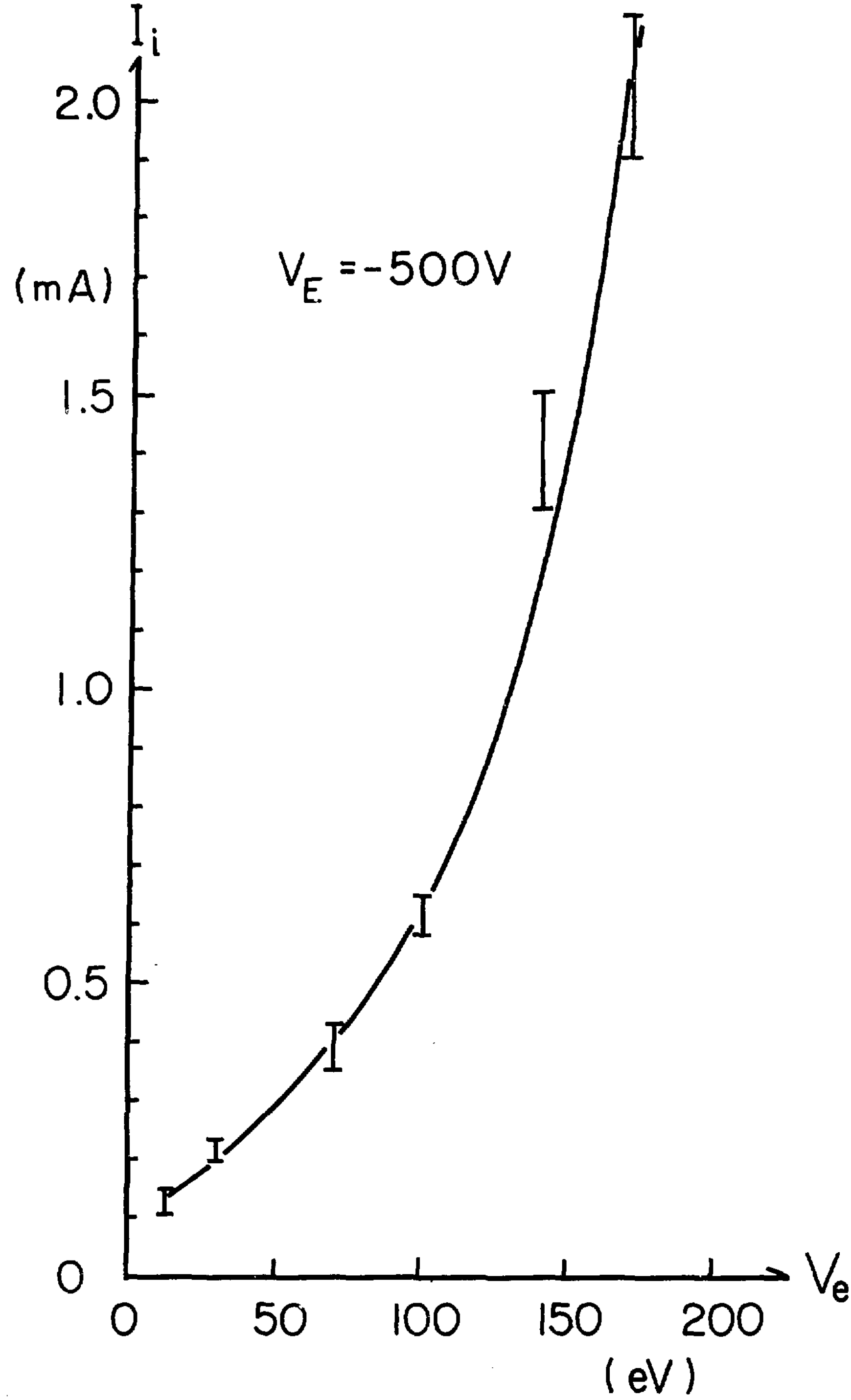


Fig. 7

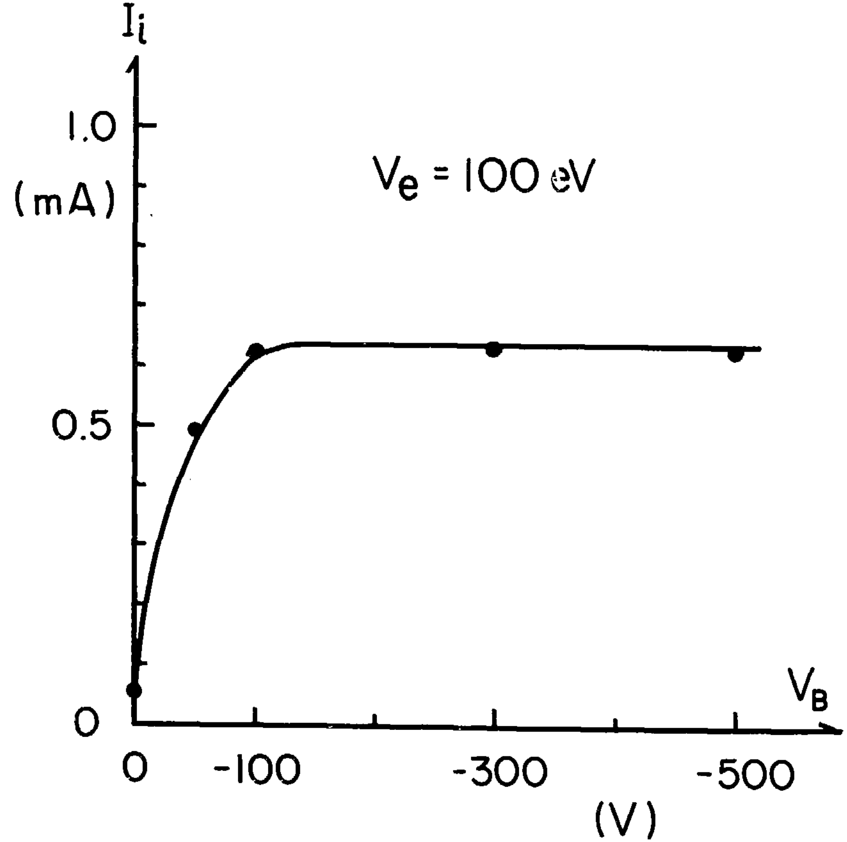
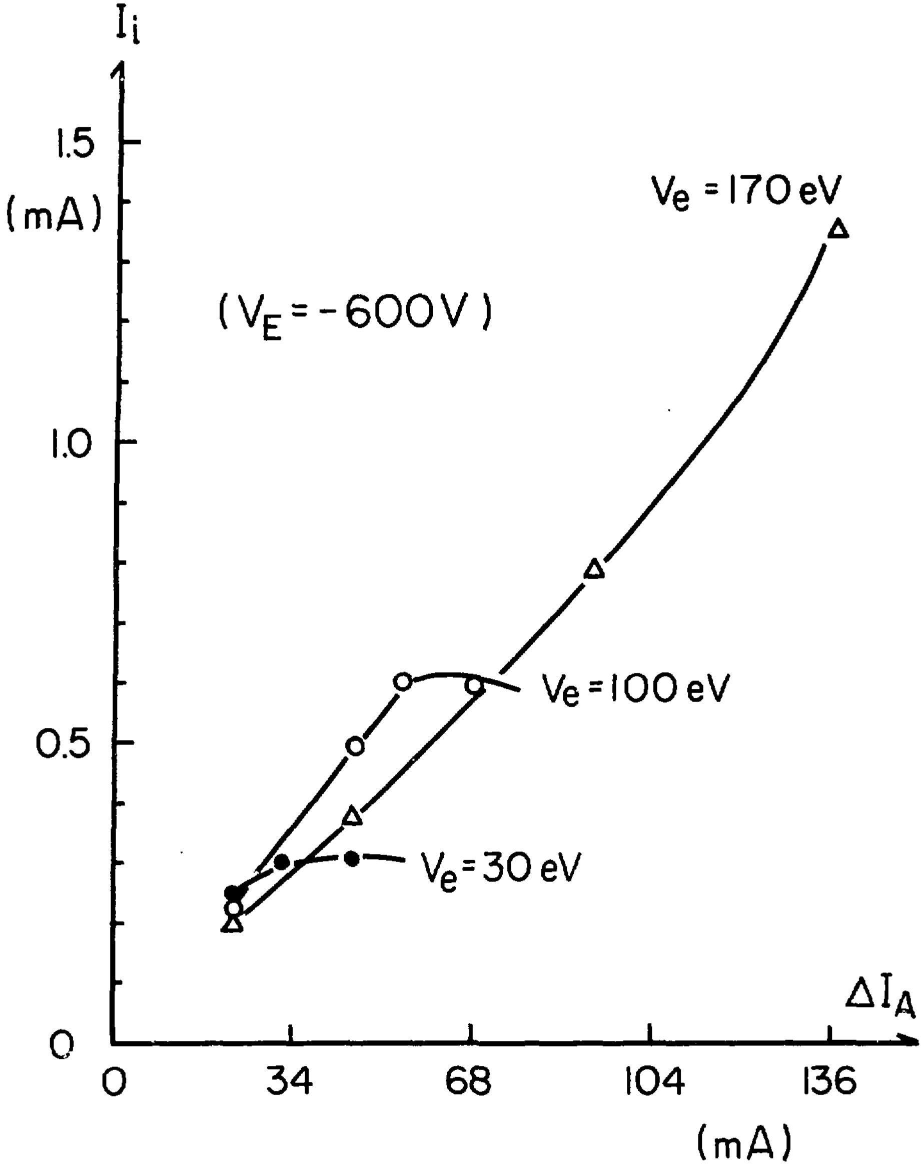


Fig. 8



I_i
1.5
(mA)
1.0
0.5
0
$(V_E = -600V)$
$V_e = 170$ eV
$V_e = 100$ eV
$V_e = 30$ eV
ΔI_A
0
34
68
104
136
(mA)

Fig. 9

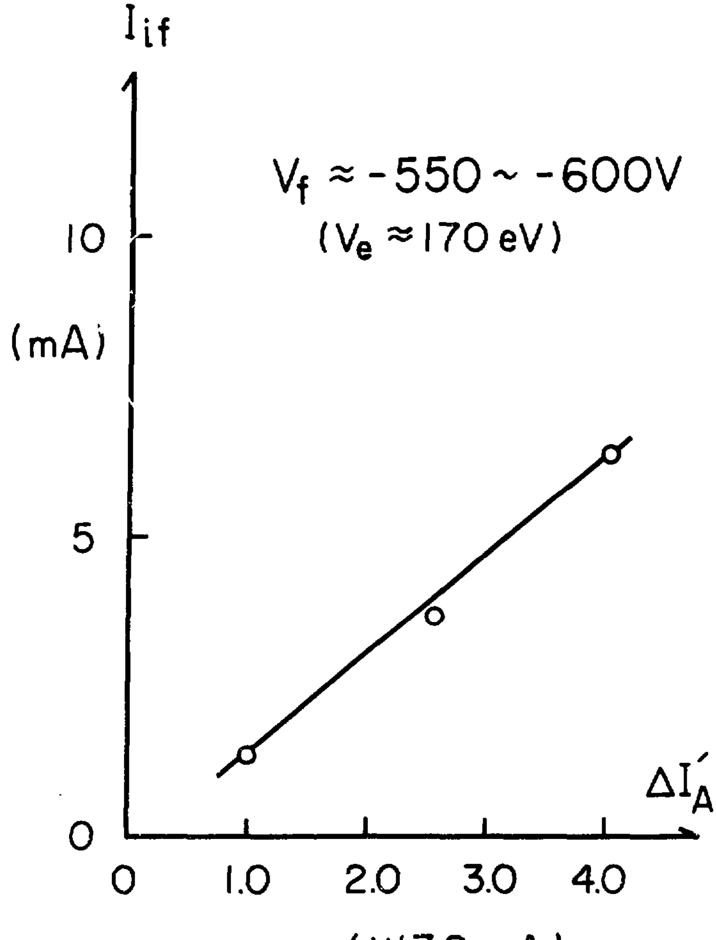
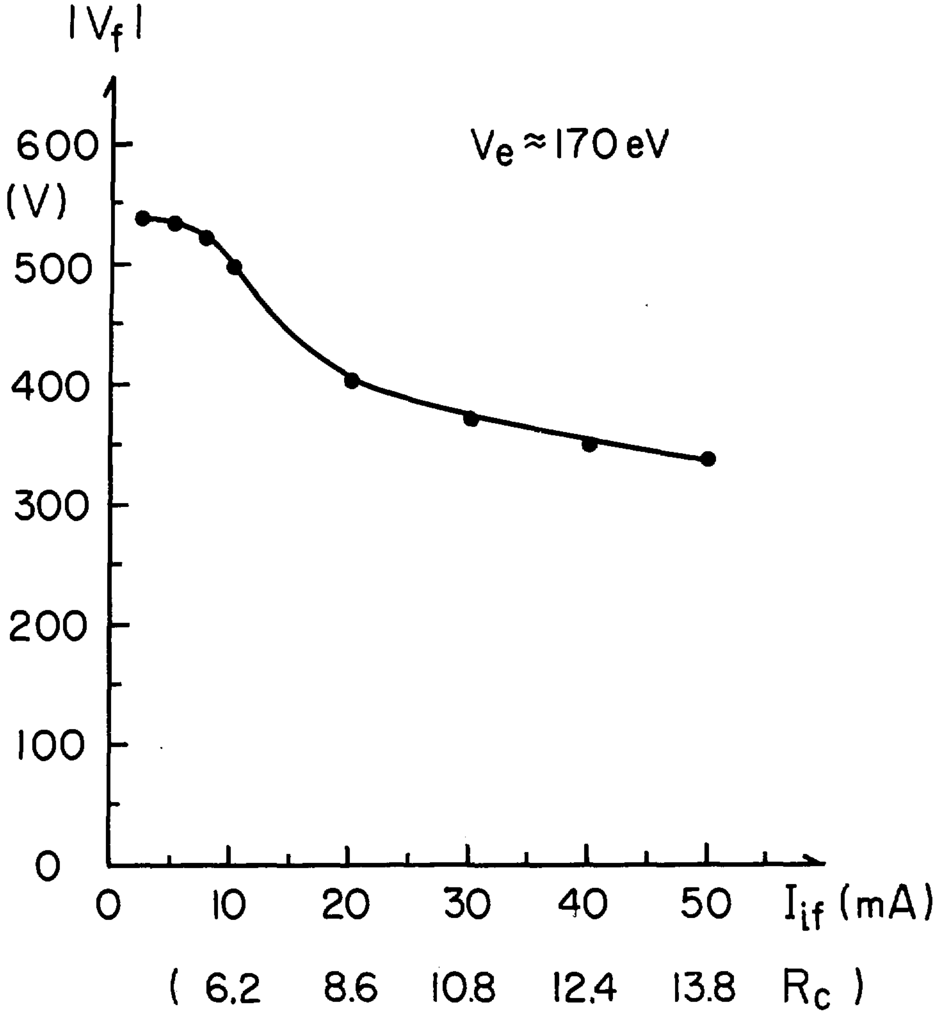


Fig. 10



|Vf|
600
(V)
500
400
300
200
100
0
Ve ≈ 170 eV
0
10
20
30
40
50
Iif (mA)
(6.2
8.6
10.8
12.4
13.8
Rc)

Fig. 11

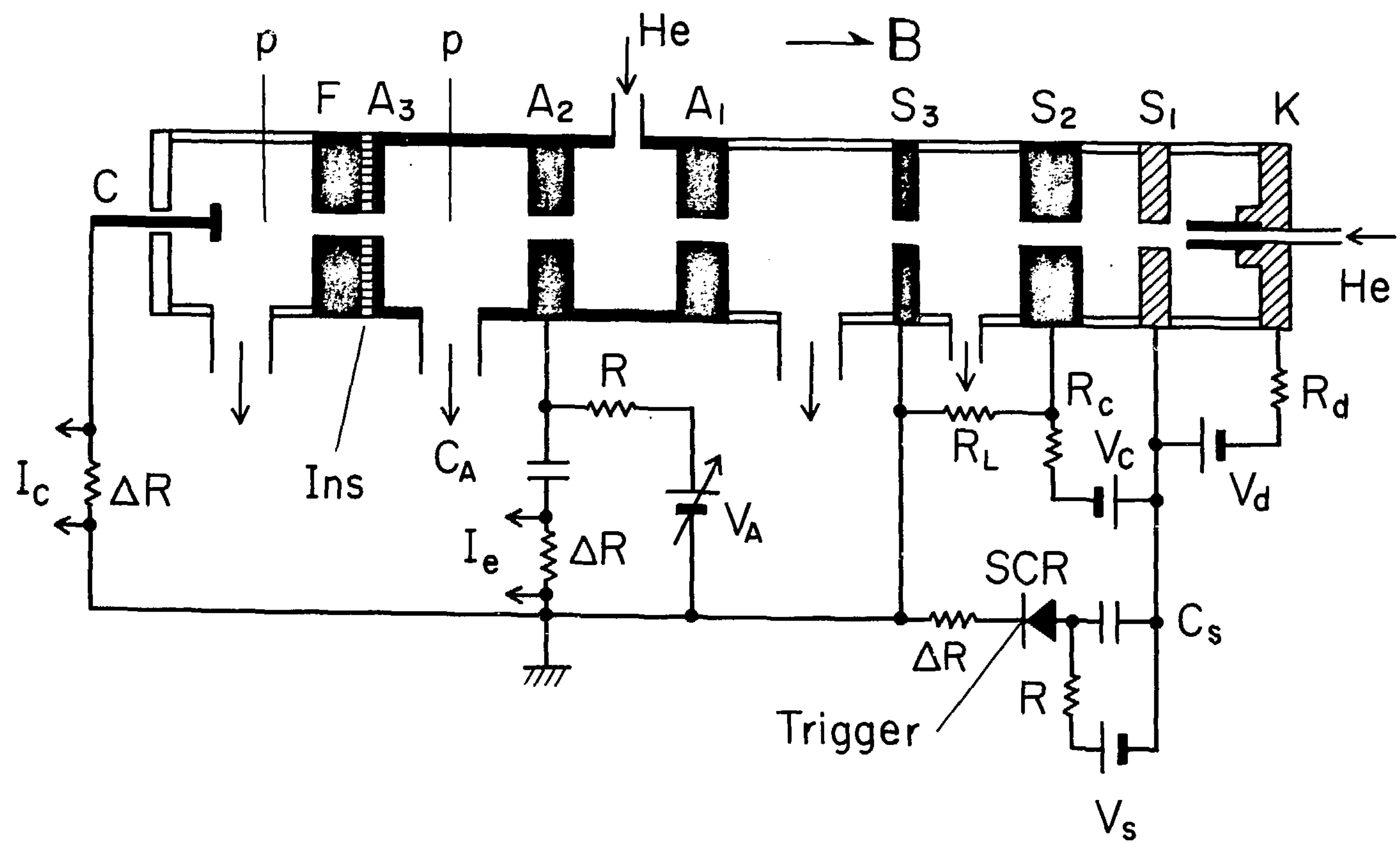

p
p
F
A3
A2
He
A1
B
S3
S2
S1
K
C
He
R
Rc
RL
Rd
Ic
ΔR
Ins
CA
Vc
Vd
Ie
ΔR
VA
SCR
Cs
ΔR
R
Trigger
Vs

Fig. A

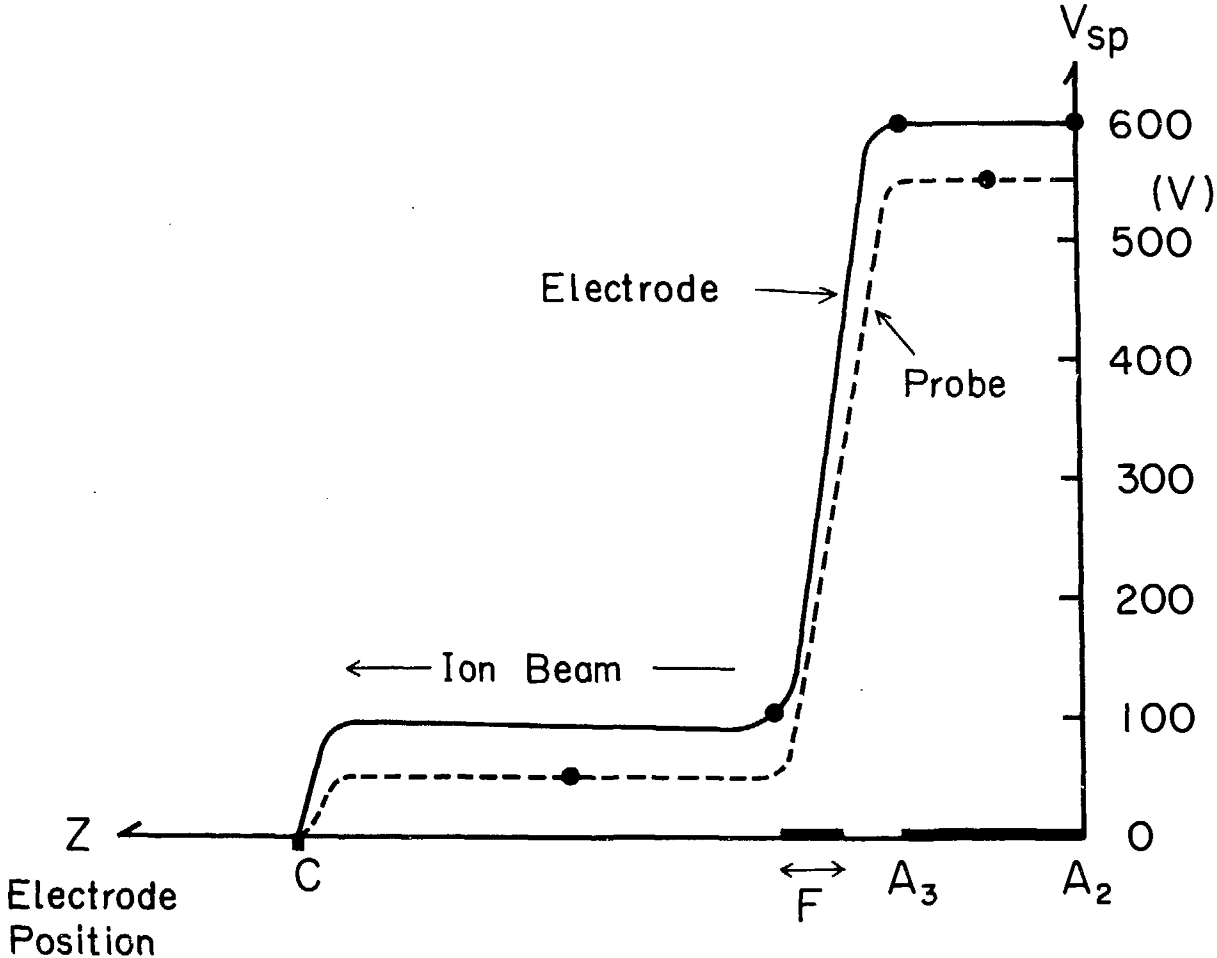

V_sp
600
(V)
500
400
300
200
100
0
Electrode
Probe
Ion Beam
Z
Electrode
Position
C
F
A3
A2

Fig. B