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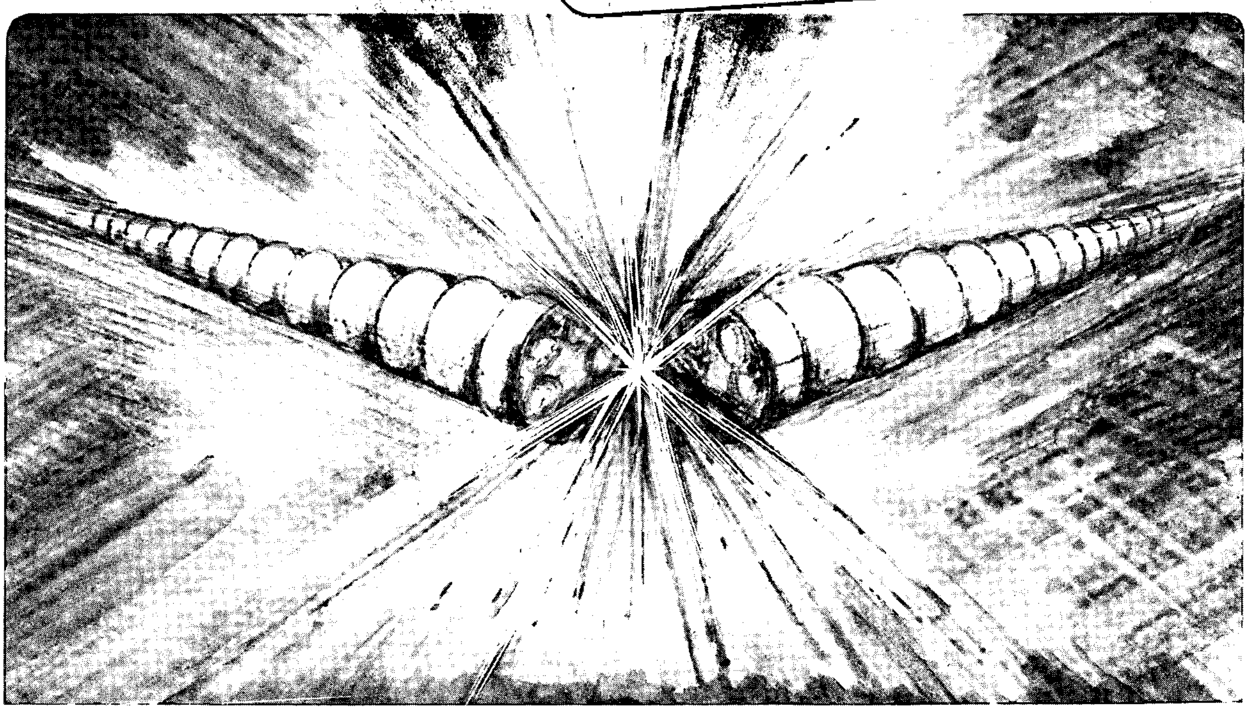

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Application of Anomalous Diffusion in Production of Negative Ions*

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ABSTRACT

The production of negative hydrogen ions is investigated in the reflex-type negative ion sources. When anomalous diffusion in the positive column was found by Lehnert and Hoh (1960), it was pointed out that the large particle loss produced by anomalous diffusion is compensated by the large particle production inside the plasma. Anomalous diffusion was artificially encouraged by changing the radial electric field inside the reflex discharge. The apparent encouragement of negative ion current by the increase of the density fluctuation amplitude is observed. Twice as much negative ion current was obtained with the artificial encouragement as without. On the other hand, the larger extracted negative ion current was observed with a lower electron temperature, which is calculated from the anomalous diffusion coefficient derived from a simple nonlinear theory. This result is consistant with the Wadehra's calculated results (1979).

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I. INTRODUCTION

In this work, we study production of negative ions in the reflex-type negative ion source. Presently, the injection of fast neutral hydrogen atoms appears to be a highly attractive method for heating toroidal plasmas for bringing a fusion reactor to ignition. For experiments in the near future, neutral beams of higher energy and of a single atomic component might be necessary to penetrate to the center of large fusion plasma. Negative ions seem to be the only effective intermediary for efficient production of such neutral beams. The "neutral beam" sources currently used in controlled fusion research convert the extracted positive hydrogen ions into neutral atoms by electron capture in hydrogen gas. However, for high energy beams the efficiency of neutralization falls off rapidly. For a negative ion beam, the neutralizer efficiency does not suffer from the same unfortunate energy dependence as for a positive ion beam. This makes the high efficiency production of neutral atom beams possible. Therefore, the higher energy one-component beams (> 200 keV) can be produced most efficiently by stripping an accelerated negative hydrogen ion beam. The reflex-type ion source produces negative ions through volume production, and it is well known that it gave the highest negative hydrogen ion current density (40 mA/cm^2) in the 1960's: Ehlers (1965)[1].

In the late 1950's anomalous diffusion in the positive column was found by Hoh and Lehnert[2] (1960). They believed that the increased particle loss by anomalous diffusion is reflected in the increased rate of ion-electron pair production. The large particle loss produced by anomalous diffusion must be compensated by the large particle production inside the plasma.

In our experiment when the magnetic field increases, the extracted positive and negative ion currents first increase, and then, after reaching the maximum value, begin to decrease. The investigations of ion diffusion in the reflex discharge have shown similar relations between the ion escape flux and the magnetic fields; this is observed by Bonnal et al.[3] (1961), Pavlichenko et al.[4] (1964), and Thomassen[5] (1966); this is observed only in the reflex discharge. The order of the critical magnetic fields B_M are the same in all experiments (about 500 gauss). Therefore, in the reflex-type ion source, which operates in a magnetic field of 1500 gauss or stronger, we assume that the extracted charged particle currents across the magnetic field are controlled by the anomalous diffusion mechanism.

We have attempted to increase volume production of negative ions by encouraging anomalous diffusion inside ion source. In section II, the basic concept of negative ion production through the electron volume process in the reflex-type ion source will be discussed. In section III, using quasilinear theory, we will show that the radial electric field destabilizes the plasma in this source. The experimental results and discussion will follow.

Under ideal magnetohydrodynamics a fluid of infinite conductivity is considered, and the E X B drift transforms the electric field away and so does the fluid velocity. When resistivity exists, the fluid is detached from the magnetic field in a small region around the rational surface (singular surface on which the phase of the perturbation is constant along the lines of force: Newcomb[6] (1960)). Charge separation arises in that localized region. The dissipative effect enables the system to attain states of lower potential energy and instability develops.

Instabilities in a weakly ionized plasma under a uniform axial magnetic field were investigated by Kadomtsev and Nedospasov[7] (1960) and Hoh[8] (1963). Kadomtsev and Nedospasov discussed the growth of a screw-shaped disturbance in the positive column (the screw instability), which is observed by Allen, Paulikas, and Pyle (1960)[9]. Hoh discussed the instability in the reflex discharge (the three-fluid instability). In weakly ionized plasmas the Coulomb collision cross section is much smaller than the collision cross section with neutral atoms. Any dissipative effects produce drag forces between particles; the drag forces with neutral atom being stronger than those between the charged particles. When the dissipative effect is strong and slow, instabilities set in and produce strong turbulent states and the localization is over a very narrow range. These instabilities arise even in the case when ion inertia is neglected. The ion inertia, which determines the localization, cannot be neglected for drift instability. Therefore, those instabilities in weakly ionized plasmas are not the resistive drift instability. We may call them as "the resistive drag instability" since it is produced by the drag force. Inertialess instability produces strong turbulence and leads to strong anomalous diffusion, which is observed in the positive column and reflex discharge; the cross field flux increases with magnetic field.

Anomalous diffusion can be divided into two classes which depend on the character of the nonlinear effect. Kaufman[10] (1972) considered it from the standpoint of the kinetic equation. The diffusion arises from the resonant interaction of particles with collective modes of electrostatic oscillation. In first order the fluctuating fields are sinusoidal and produce no time average net effect. If the resonant particle exists in the azimuthal direction under the axial magnetic field, they produce the second order fluctuating fields which lead net flow of plasma across the magnetic field.

Even though resonant particles are not considered, fluctuating quantities have nonlinear components. Yoshikawa and Rose[11] (1962) considered it from the standpoint of a fluid equation. When the plasma is destabilized, the electrostatic fluctuations are produced. The density and flux fluctuations are produced in response to the electrostatic fluctuations. These fluctuating electrostatic fields coupled with the density and flux fluctuations, in the presence of the magnetic field, determine the motion in the direction of the density gradient. The electrostatic fluctuation are correlated with the density and flux fluctuations through the first order continuity equation.

In section IV, based on the method of Yoshikawa, the anomalous diffusion coefficient in the reflex-type ion source is derived phenomenologically from a simple non-linear theory. It is assumed that instabilities are already saturated. Important physical quantities inside the ion source will be estimated from the diffusion coefficients. Summary and discussion is given in section V.

II. EXPERIMENTAL APPARATUS AND ASSUMPTIONS

This investigation employed negative ion production from a reflex-type negative ion source in D.C. operation. The reflex-type ion source is a reflex discharge with an exit slit so that the ions are extracted radially or normally to the magnetic field (Fig. 1). The reflex discharge is a cylindrical gas discharge with the electrode configuration of a Philips ionization gauge (one hot cathode and one cold cathode located on either side of the cylinder at the same potential) operated in a strong axial magnetic field. The Faraday cup, which is located near the extracting electrode, is large enough to collect all particles with 100% efficiency. The source structure is biased negatively in order to extract negative ions, or biased positively in order to extract postive ions. For operation with negative bias, we utilize a mass filter in order to measure the negative ion current separately from the electron current. The electron drain current coming out through the exit slit is measured as the ground current. The arc is generally operated with current of 3A, a voltage of 300 V, and an extracting potential of 6 kV. The magnetic field is variable with a maximum 5000 gauss. To control the radial electric field inside the plasma, the cylindrically-shaped anode is separated into two parts so that we can change the potential between the wall anode and top part of the anode (Fig. 2).

In addition the arc plasma column has been defined so as to be recessed from the ion exit slit (the diameter of the arc-defining hole is half of the diameter of the cylinder column). These arrangements allow the incoming molecular gas to surround the plasma column completely in the region where ions can be immediately extracted. It is expected that the strong magnetic field confines the high energy primary electrons accelerated at the cathode sheath to the central part of the cylinder. To analyze the negative ion production mechanism in the reflex-type ion source, we divide it into two regions; the central region and the surrounding region (Fig. 3).

Three methods for the formation of negative ions are reviewed by Hiskes[12] (1979): double charge-exchange processes, surface processes, and electron-volume processes. We assume that the reflex-type ion source produces observable hydrogen atoms only through the electron-volume process: Ehlers (1965)[1]. According to the production mechanism proposed by Wadehra[13] (1979) to explain the high negative ion density observed by Bacal and Hamilton[14] (1979), we need both high energy electrons to produce the vibrationally excited molecules and low energy electrons to produce the negative ions by dissociative attachment to the vibrationally excited molecules. The first process has the maximum cross section at an electron energy of about 40 eV: Hiskes[15] (1980), and the latter reaction has the maximum cross section at an electron energy of order of 1 eV: Wadehra and Bardsley[16] (1978).

In ordinary discharge plasmas, most electrons are produced by ionization and the electron energy is low. To get many negative ions, we also need high energy electrons to produce the vibrationally excited molecules; we need something to "heat" the plasma. In the reflex-type ion source, both high and low energy electrons exist. In the central region, the primary electrons both ionize neutral gas and excite neutral gas into vibrational states, thus heating the plasma. In the surrounding region, where there are not so many high energy primary electrons, nearly all of the electrons, produced in the central region, come there by diffusion with positive ions. The average electron energy in the region is expected to be much lower than that in the central region. In the surrounding region, the negative ion production through electron dissociative attachment to vibrationally excited molecules may be very large since high dissociative attachment rate is expected for low electron temperature.

In the reflex-type ion source, we have assumed that the two regions have different electron temperatures. The higher temperature electrons produce electrons that have a lower temperature, and also excite molecular vibrational states. Lower temperature electrons dissociately attach to the vibrationally excited molecules and produce negative ions. By this mechanism, the reflex-type ion source can produce negative ions of high density: Jimbo (1982)[17].

III. THEORETICAL PREDICTION AND EXPERIMENTAL RESULTS

In a weakly ionized plasma under a strong axial magnetic field, where the ion inertia is neglected, there is no pure resistive drift instability. However, if there is a constant zeroth order electric field which exists only in a weakly ionized plasma, the electric field with help of dissipative effects destabilizes the dispersion relation. Here we are particularly concerned with weakly ionized plasmas in the positive column and reflex discharge.

For weaky ionized plasmas, the fluid equations are shown below; n_s is the density of species "s", q_s is the charge of species "s", u_s is the fluid velocity of species "s", P_s is the pressure of species "s", ν_s is the collision frequency of species "s" with neutrals, and Z is the production term.

From the continuity equation,

$$\frac{\partial n_s}{\partial t} + \nabla n_s u_s = Z n_s \tag{3.1}$$

From the equation of motion neglecting the effect of gravity,

$$n_s m_s \frac{d\vec{u}_s}{dt} + \nabla P_s = n_s q_s\left(\vec{E} + \frac{\vec{u}_s \times \vec{B}}{c}\right) - n_s m_s \nu_s \vec{u}_s \tag{3.2}$$

From the equation of state,

$$\frac{\nabla P_s}{P_s} = \gamma \frac{\nabla n_s}{n_s} \tag{3.3}$$

where γ is the ratio of specific heats C_p/C_v.

These equations can be solved by the procedure of linearization.

The dependent variables are separated into two parts as follows:

$$\vec{u}_s = \vec{u}_{so} + \vec{u}_{s1} \qquad n_s = n_{so} + n_{s1}$$

$$\vec{E} = \vec{E}_o + \vec{E}_1 \qquad \vec{B} = \vec{B}_o + \vec{B}_1$$

where $\vec{u}_{s1}$, n_{s1}, $\vec{E}_1$, and $\vec{B}_1$, are the first order term of species "s" and are very small. By this we mean that the amplitude of oscillation is small, and terms containing higher powers of the amplitude factor can be neglected.

When only the low frequency instability (much less than ion cyclotron frequency) is considered, we need to keep the time derivative only in the continuity equation. The time derivative in the equation of motion will be negligible since the collision frequency with neutrals is large enough (inertialess instability). We assume that the first order magnetic field $\vec{B}_1$ is very small and that the first order electric field $\vec{E}_1$ is static and produced by a first order potential ϕ. We also assume that zeroth order fluid velocity u_o is zero and that the zeroth order density n_o is uniform in both y and z direction; n_o has a gradient only in the x direction. Since we consider only low frequency instabilities, the change caused by the instability is isothermal; that means $\gamma = 1$ in Eq. (3.3).

We shall omit subscripts "1" for the first order terms, and substitute subscripts "s" for the 0th order terms. Then, we get the following two linearized first order equations with

$P_s = T_s \nabla n_s$:

$$\frac{\partial n_s}{\partial t} + n_o(\nabla \cdot \vec{u}_s) + u_s \frac{\partial n_o}{\partial x} = Zn_s \tag{3.4}$$

$$T_s \nabla n_s = n_o q_s\left(-\nabla\phi + \frac{\vec{u}_s \times \vec{B}_o}{c}\right) + n_s q_s \vec{E}_o - n_o m_s \nu_s \vec{u}_s \tag{3.5}$$

Then, we assume that there is a constant magnetic field B_o only in the z direction. We also assume that there are constant electric fields $\vec{E}_o$ both in the x and z directions. We treat them under periodic boundary conditions in Cartesian coordinates. We shall omit the subscript "O" for the zeroth order quantities. From the linearized equation of motion for electrons, we get the following equations; n_e is the first order electron density, ν_e is the collision frequency of electrons with neutrals and u_e is the first order fluid velocity vector of the electrons.

$$u_{ex} = b_e \left[i \frac{A}{nB} (k_y - a_e k_x) + \frac{n_e}{nB} (E_y - a_e E_x)\right]$$

$$u_{ey} = -b_e\left[i \frac{A}{nB} (k_x + a_e k_y) + \frac{n_e}{nB} (E_x + a_e E_y)\right] \tag{3.6}$$

$$u_{ez} = -\mu_e \frac{n_e}{n}\left(iA \frac{k_z}{n_e} + E_z\right)$$

where $\Omega_e = \frac{eB}{mc}$ and $\mu_e = \frac{e}{m\nu_e}$

$$a_e = \frac{\nu_e}{\Omega_e}, \quad b_e = \frac{1}{1+a_e^2}, \quad \text{and} \quad A = \frac{n_e T_e}{e} - n\phi$$

From the linearized equation of continuity for electrons,

$$-i\omega n_e + in\,(k_x u_{ex} + k_y u_{ey} + k_z u_{ez}) + u_{ex}\frac{\partial n}{\partial x} = Zn_e \tag{3.7}$$

We define that the perturbed electrostatic waves are traveling along the z direction, which is the direction of the magnetic field, and the y direction, which is the Hall direction. For prevailing conditions, we can assume $k_x \simeq 0$ and $E_y \simeq 0$. Generally for electrons with $a_e^2 \ll 1$ and $b_e \simeq 1$, we get

$$\frac{n_e}{n} = \frac{-k_y \frac{c}{B}\frac{n'}{n} + i\,k_z^2\,\mu_e}{(\omega + k_y\,v_{D_e}) + k_y\,c\,\frac{E_x}{B} + k_z\mu_e E_z + i(k_z^2 D_e - Z)}\,\phi \tag{3.8}$$

where $D_e = \frac{T_e}{m\nu_e}$, $v_{D_e} = -\frac{T_e}{eB}\frac{n'}{n}$, and $n' = \frac{\partial n}{\partial x}$

In the same manner, we get an equation for ions assuming $k_z^2 \ll k_y^2$

$$\frac{n_i}{n} = \frac{X}{(\omega - k_y b\,v_{D_i}) + k_y b\,\frac{cE_x}{B} - k_z\mu_i E_z + iY}\,\phi \tag{3.9}$$

where $X = -k_y\,b\,\frac{c}{B}\frac{n'}{n} - i\,k_y^2\,a^2 b\mu_i$

$$Y = k_y^2\,a^2 bD_i + a^2 b\mu_i\,E_x\,\frac{n'}{n} - Z$$

$$a = \frac{\nu_i}{\Omega_i},\quad b = \frac{1}{1+a^2},\quad \text{and } \nu_{D_i} = -\frac{cT_i}{eB}\frac{n'}{n}$$

$$\Omega_i = \frac{eB}{Mc},\quad \mu_i = \frac{e}{M\nu_i},\quad \text{and } D_i = \frac{T_i}{M\nu_i}$$

If we assume charge neutrality, we get the following instability criterion from the dispersion relation.

$$[a^5b^2(k_y^2 - (\frac{n'}{n})^2)\mu_i^2 - ab \frac{k_z^4}{k_y^2} \mu_e^2] \frac{ck_y^2}{B} (- \frac{n'}{n}) (-E_x)$$

$$+[b(k_z^2 + a^2k_y^2)\mu_e\mu_i + a^2bk_y^2 \mu_i^2 + bk_z^2\mu_e^2] c\frac{k_zk_y}{B} (- \frac{n'}{n})(-E_z)$$

$$+ [(a^2b\, k_y \frac{c}{B}\frac{n'}{n})^2 + (k_z^2 \mu_e + k_y^2\, a^2b\mu_i)^2]\, Z$$

$$> [a^2b(k_yk_z^2\mu_e)^2 + (a^2b\, k_y^2k_z)^2\mu_i\mu_e + (a^2b\, k_y^2\, \frac{c}{B}\frac{n'}{n})^2]\, D_i$$

$$+ [(a^2b\, k_y^2k_z\mu_i)^2 + a^2b\, k_y^2k_z^4\mu_i\mu_e - (a\, b\, k_z\, k_y \frac{c}{B}\frac{n'}{n})^2]\, D_e$$

$$+ (b^2k_y^2k_z^2\, \mu_e + a^2b^2k_y^4\mu_i) \frac{e}{T_i} v_{D_i}^2$$

$$+ (a^2b\, k_y^4\mu_i + b\, k_y^2k_z^2\, \mu_e) \frac{e}{T_e} v_{D_e}^2$$

Notice $(n'/n) < 0$.

In prevailing conditions for the positive column, $\nu_i >> \Omega_i$ ($a_i >> 1$, $b_i \simeq 0$, $a_i^2b_i \simeq 1$) and $E_z < 0$, $E \simeq E_x > 0$. We can also assume that $k_y^2 >> k_z^2$, $\mu_e >> \mu_i$, $D_e >> D_i$ and that $(-n'/n)^2$ is small. Then, we get the following instability criterion for the positive column.

$$k_y^3 k_z \mu_e\mu_i \left(-\frac{n'}{n}\right)\left(-\frac{cE_z}{B}\right) + \left[\left(k_y^2 \frac{c}{B}\frac{n'}{n}\right)^2 + \left(k_z^2 \mu_e + k_y^2 \mu_i\right)^2\right] Z$$

$$> a\, k_y^4 \mu_i^2 \left(-\frac{n'}{n}\right)\left(\frac{cE_x}{B}\right) + \left[\left(k_y^2 k_z \mu_i\right)^2 + \left(k_y k_z^2\right)^2 \mu_i\mu_e\right] D_e$$

$$+ \left[\left(k_y k_z^2 \mu_e\right)^2 + \left(k_y^2 k_z\right)^2 \mu_i\mu_e + \left(k_y^2 \frac{cn'}{Bn}\right)^2\right] D_i$$

$$+ \left(k_y^4 \mu_i \frac{e}{T_e}\right) v_{D_e}^2 \qquad (3.10)$$

In the case of the positive column, E_z and Z terms contribute to destabilize the plasma; $E_x \simeq E_r$, v_{De}^2, D_i and D_e terms contribute to stabilize the plasma. A similar relation is derived by Kadomtsev and Nedospasov[7] (1960), however, the physical meaning of each term is less apparent.

When an instability sets in, many particles are lost by anomalous diffusion. Then the particle production has to be increased to compensate the particle loss in order to keep the plasma in the same state. More charged particles (ions and electrons) are produced by the primary electrons, which are supplied from the cathode by the steady axial electric field E_z. The increase of axial electric field $|E_z|$ was observed in Lehnert's experiment[18] (1958) when instabilities set in. Therefore, the production rate and axial electric field are increased by anomalous diffusion. The relation between the electric field E_z and the magnetic field in the anomalous region was theoretically explained in cylindrical geometry by Kadomtsev and Nedospasov[7] (1960).

Alternatively the anomalous diffusion is induced by the large particle production to reduce the particle density and the large production is provoked by the increase of the axial electric field. On the other hand, the azimuthal E X B drift, the particle diffusions, and electron diamagnetic drift try to eliminate the charge separation which causes the instability, and stabilize the plasma.

Since this method succeeded to explain the physical mechanism of anomalous diffusion in the positive column, we try to apply it to explain anomalous diffusion in the reflex discharge. In prevailing conditions for the reflex discharge, it is satisfied that $\nu_i \simeq \Omega_i$ ($a_i \simeq 1, b_i \simeq 1/2$); which will be explained precisely later. It is also satisfied that $E_x \simeq E_r < 0$ and $E_z \simeq 0$. We can assume that $k_y^2 \gg k_z^2$, $\mu_e \gg \mu_i$, $D_e \gg D_i$ and that $(-n'/n)^2$ is large in the reflex discharge: Chen[19] (1962). Then we got the following instability criterion for the reflex discharge.

$$
\begin{aligned}
&\frac{1}{4} k_y^2 \mu_i^2 \left(\frac{n'}{n}\right)^2 \left(-\frac{n'}{n}\right) \frac{cE_x}{B} + \left[\frac{1}{4}\left(k_y \frac{cn'}{Bn}\right)^2 + \left(k_z^2 \mu_e + \frac{1}{2} k_y^2 \mu_i\right)^2\right] Z \\
&> \left[\frac{1}{2}(k_y k_z^2 \mu_e)^2 + \frac{1}{4} k_y^4 k_y^2 \mu_i \mu_e + \frac{1}{4}\left(k_y^2 \frac{cn'}{Bn}\right)^2\right] D_i \\
&+ \left[\frac{1}{4}(k_y^2 k_z \mu_i)^2 + \frac{1}{2} k_y^2 k_z^4 \mu_i \mu_e - \frac{1}{4}\left(k_y k_z \frac{cn'}{Bn}\right)^2\right] D_e \\
&+ \left(\frac{1}{4} k_y^2 k_z^2 \mu_e + \frac{1}{4} k_y^4 \mu_i\right) \frac{e}{T_i} v_{D_i}^2 \\
&+ \left(\frac{1}{2} k_y^4 \mu_i + \frac{1}{2} k_y^2 k_z^2 \mu_e\right) \frac{e}{T_e} v_{D_e}^2 \qquad (3.11)
\end{aligned}
$$

In the case of the reflex discharge, $E_x \simeq E_r$ and Z terms contribute to destabilize plasma. D_i, v_{Di}^2 and v_{De}^2 terms contribute to stabilize the plasma. The contribution of the D_e term must be examined in more detail.

Since $E_x \simeq E_r$ is negative in the reflex discharge, the plasma will be unstable when $(-n'/n)E_x < 0$, which is shown by Simon[20] (1963). A similar relation is also derived by Hoh[8] (1963). However, neglecting the effect of a sharp density gradient, Hoh concluded that the plasma is destabilized when E_r turns to be more negative (dV/dr is increased). Our conclusion is opposite: the plasma is destabilized when E_r turns to be less negative (dV/dr is decreased).

When an instability sets in, many particles are lost by anomalous diffusion. Then, the number of electrons inside the column, which keeps the radial electric field $E_x \simeq E_r$ negative is reduced. The potential in the center of the cylinder turns to be less negative, and the voltage drop in the cathode sheath (not axial electric field E_z) is increased. That effect accompanies an increasing supply of the primary electrons and an increasing particle production rate Z and compensates particle loss by anomalous diffusion. On the other hand, the ion diffusion and the diamagnetic drifts try to eliminate the charge separation which causes the instability, and stabilize plasma. The electron diffusion might encourage the instability since a large electron current increase is observed in our experiment. In prevailing condition for the reflex discharge, $E_z \simeq 0$, so it contributes nothing.

According to Hoh[8] (1963), the experimentally obtained critical magnetic field of most of the reflex discharges is lower than 500 gauss. In the reflex-type ion source, the magnetic field is variable from 1500 gauss to 5000 gauss. Thus, the reflex type ion source is completely in the anomalous region. If the diffusion across the magnetic field is controlled by anomalous diffusion mechanism, we may obtain more cross field flux by encouraging instabilities. From Eq. (3.11), it is seen that the less negative radial electric field contributes to destabilize the plasma. Then, anomalous diffusion may be encouraged. In hot cathode reflex discharges, the variation of potential is affected more by variation along the axial direction than by variation along the radial direction. The top part of the anode which faces the central region of the plasma determines the potential of that region, and the wall which faces the surrounding region of plasma determines the potential there (Fig. 2).

In order to change the radial electric field between the two parts, the top part of the anode and the wall anode are electrically separated in the reflex-type ion source (Fig. 2). Using another power supply, the potential of the wall anode was biased either positive or negative in respect to the top part of the anode, which acts as a main anode.

In our experiment with an exit slit area 9.7×10^{-2} cm^2, the relations between the extracted negative ion current and the magnetic field with changing biased potential are shown on Fig. 4. The encouragement of anomalous diffusion with increasing negative bias potential as predicted before is clear. The maximum negative ion current of 9.7 mA (100 mA/cm^2) was obtained, which is as large as the maximum positive ion current under same operation condition. The relations between the biased potential and both the extracted negative ion current and its density fluctuation amplitude are shown on Fig. 5. The measured fluctuation was on the order of 100 kHz.

For a given magnetic field of 2500 gauss, we achieve twice as much negative ion current with a negative bias of 6 volts compared to unbiased operation. On the other hand, for a positive potential of 6 volts, we get one-fourth as much negative ion current as compared to unbiased operation.

From the relation of the electron drain current, the encouragement of anomalous diffusion with increase of negative bias is also clear. We have observed considerable increase of the electron drain current as the negative ion current increases or as the instabilities are encouraged.

In Fig. 5 we observe increases in both the density fluctuation amplitude and negative ion current when the wall anode is more negative; the instability encourages the anomalous diffusion. We believe this experimental result supports our assumption that the cross field diffusion is controlled by the anomalous diffusion mechanism.

We have observed similar relations between the negative ion current and the magnetic for deuterium gas D_2. Maximum deuterium negative ion current of 4.1 mA (42 mA/cm^2) was obtained: Jimbo (1982)[17].

IV. PHENOMENOLOGICAL ANALYSIS

We shall assume a macroscopically homogeneous plasma, which is subject to a homogeneous turbulence. We can make use of modified fluid equations to explain non-linear effects. We assume that instabilities are already excited and saturated. All physical quantities in the fluid equations are Fourier-expanded to include non-linear effects. The contribution by the ordinary diffusion based on the classical collision theory is neglected.

In a weakly ionzed plasma, the continuity equation and the equation of motion in steady state are given from Eq. (3.1) and (3.2). We introduce the density gradient effect by replacing n by n(1 + sx) and the particle flux $\vec{\Gamma}_s = n\vec{u}_s$. We introduce E_o and n_o, which are defined as the average value of E and n. E_o has components in both x and z directions. Then we get for each species,

$$\vec{\nabla}\cdot\vec{\Gamma} = Zn \qquad (4.1)$$

$$nT\vec{s} - qn\vec{E} - q\frac{\vec{\Gamma}\times\vec{B}}{c} = -m\nu\vec{\Gamma} \qquad (4.2)$$

The quantities, which change with the applied external field, are defined as follows:

$$\vec{E} = \vec{E}_o + \vec{E}'$$

$$\vec{B} = \vec{B}_0$$

$$\vec{\Gamma} = \vec{\Gamma}_0 + \vec{\Gamma}'$$

$$n = n_0 + n'$$

where $\vec{E}'$, $\vec{\Gamma}'$, and n' are the responses to the external effects assuming that the magnetic field B is given from outside. The effective electric field $\vec{\varepsilon}$ is defined

$$q\,\vec{\varepsilon} = q\vec{E}_0 + T\vec{s}$$

where s is an unit vector in the x direction.

If there is an electrostatic fluctuation in the azimuthal direction, flux fluctuation must be set up in steady state because of the continuity equation. From Eq. (4.1),

$$\cdot\vec{\Gamma}' = 0 \qquad (4.3)$$

We assume that the characteristic length of the fluctuations exceeds the Debye length, but small compared to the dimensional length. We proceed with the Fourier analysis, and impose periodic boundary conditions. Then, the first order quantities are Fourier-expanded as follows:

$$\vec{E}' = \Sigma' \vec{E}_k \exp(i\vec{k}\cdot\vec{r})$$

$$\vec{\Gamma}' = \Sigma' \vec{\Gamma}_k \exp(i\vec{k}\cdot\vec{r})$$

$$n' = \Sigma' n_k \exp(i\vec{k}\cdot\vec{r})$$

where Σ' indicates a summation over all k except k=0 since no electric field remains in the uniform state besides ε (for a system of charged particles, this assumption corresponds to the quasineutrality in background). By definition, E' averaged over a macroscopic plasma must be zero. Furthermore, $n_k = n^*_{-k}$, $\vec{\Gamma}_k = \vec{\Gamma}_{-k}$, and $\vec{E}_k = \vec{E}^*_{-k}$.

The zeroth order equation is obtained by putting the above quantities into Eq. (4.2). Multiplying Eq. (4.2) by $n_{-k'}\exp(-ik'r)$, integrating with r, and summing over k'. Then, we get

$$q \Sigma' n_k E_{-k} + q n_o \vec{\varepsilon} + q \frac{\vec{\Gamma}_o \times \vec{B}}{c} = m\nu_o \vec{\Gamma}_o \qquad (4.4)$$

Next we get the k-th order equation of Eq. (4.2). We neglect the cross terms. Then,

$$q n_o \vec{E}_k + q n_k \vec{\varepsilon} + q \frac{\vec{\Gamma}_k \times \vec{B}}{c} = m\nu_o \vec{\Gamma}_k \qquad (4.5)$$

We define the following quantities.

$$a = \frac{\nu_o}{\Omega}, \quad b = \frac{1}{1+a^2}, \quad \text{and} \quad \Omega = \frac{qB}{mc}$$

From Eq. (4.3) and (4.5), we get the following equation.

$$b \frac{cE_{-kx}}{B}(a k_x - k_y) + b \frac{cE_{-ky}}{B}(k_x + a k_y) + \frac{1}{a} \frac{cE_{-kz}}{B} k_z$$
$$+ b\left(\frac{n_k}{n_o}\right) \frac{c\varepsilon_x}{B}(a k_x - k_y) + \frac{1}{a}\left(\frac{n_k}{n_o}\right) \frac{c\varepsilon_z}{B} k_z = 0 \qquad (4.6)$$

From Eq. (4.4), and (4.5), we get the following equations:

$$\vec{\Gamma} = \begin{bmatrix} 2b \; \Sigma' \frac{c n_k E_{-ky}}{B} + 2\,ab\, \Sigma' \frac{c n_k E_{-kx}}{B} + ab\, n_o \frac{c \varepsilon_x}{B} \left(1 + \Sigma' \left(\frac{n_k}{n_o}\right)^2\right) \\ -2b \; \Sigma' \frac{c n_k E_{-kx}}{B} + 2\,ab\, \Sigma' \frac{c n_k E_{-ky}}{B} - b\, n_o \frac{c \varepsilon_x}{B} \left(1 + \Sigma' \left(\frac{n_k}{n_o}\right)^2\right) \\ \frac{2}{a} \; \Sigma' \frac{c n_k E_{-kz}}{B} + \frac{1}{a} n_o \frac{c \varepsilon_z}{B} \left(1 + \Sigma' \left(\frac{n_k}{n_o}\right)^2\right) \end{bmatrix} \quad (4.7)$$

We are interested in electrostatic fluctuations in the reflex discharge, which have wave amplitudes in both y (azimuthal) and z (axial) directions but not in x (radial) direction: $k_x = 0$ and $E_{-kx} = 0$. The electrostatic fluctuations produce incoherent density fluctuations. Then,

$$\Sigma' n_k = 0, \quad \Sigma' E_{-ky} = 0$$

However $\quad \Sigma' n_k \, E_{-ky} \neq 0$

E_{-ky} should be calculated from Maxwell's equations. However, this is a difficult task. Therefore we are going to use a phenomenological method to estimate the saturation level of electrostatic wave amplitude. The maximum fluctuating electric field produced should be balanced with the pressure in laboratory frame. If the effect of fluctuating electric fields is stronger than the pressure, the plasma will be heated until the fluctuating field is balanced with pressure. Then,

$$P_s = -q_s \int \Sigma' n_k E_{-ky} dr$$

$$\Sigma' n_s E_{-ky} = -\frac{T_s}{q_s}\frac{dn_o}{dr} \qquad (4.8)$$

The similar relation is obtained by Kadomtsev[21] (1965). Kadomtsev argued that the upper limit on the density gradient is that level at which it cancels the initial density gradient. Considering very strong anomalous diffusion in a weakly ionized plasma (the cross field flux increases with the magnetic field), this assumption appears quite reasonable.

We are interested in the anomalous flux in x direction. Then,

$$\Gamma = 2b \quad \Sigma' \frac{cn_k E_{-ky}}{B} \tag{4.9}$$

Since $(\frac{n_k}{n_o})^2 << 1$ (Fig. 5), we get the following relations from Eq. (4.6)

$$\frac{E_{-kz}}{E_{-ky}} \simeq -\frac{k_y}{k_z} \frac{1}{1 + (\frac{\Omega s}{\nu_s})^2} \tag{4.10}$$

For the reflex-type ions source with an exit slit area 7.26×10^{-2} cm^2, the radial flux increases with increasing magnetic field. However, at a strong magnetic field, the radial flux decreases again monotonically: Fig. 6 and 7. The cross field flux, which has the maximum value with the increasing magnetic field, was observed only in the reflex discharge. Therefore, the mechanism which we have discussed will be applied.

In the case of the reflex-type ion source, the discharge column is recessed from the wall. Even though a strong negative potential and electric field are expected in the central region, a relatively uniform potential is expected in the outside region surrounding the central region. No strong zeroth order electric field exists in the surrounding region. Although the instabilities are produced in the central region, the surrounding region is affected by the instabilities. In fact, the surrounding region is diffusion dominant. The ions coming out from the cylinder are represented with Eq. (4.8) and (4.9) as follows:

$$\Gamma_i = -2 \frac{(\Omega_i/\nu_i)}{1+(\Omega_i/\nu_i)^2} D_i \frac{\partial n}{\partial r} \tag{4.11}$$

where $D_i = \frac{T_i}{m\nu_i}$

For the first approximation in cylindrical geometry, we assume the following:

$$\frac{\partial}{\partial r} \simeq -\frac{\beta}{R}$$

where β is the first zero of zeroth order Bessel function, β=2.42, and R is the radius of the cylinder.

For the ion flux, Eq. (4.11) we can define a function f(x)

$$f(x) = \frac{x}{1 + x^2}$$

$$x = (\Omega_i/\nu_i)$$

f(x) has a maximum value $f(x)_{max} = 1/2$ at x = 1. Therefore, Γ_i has a maximum value for $\Omega_i = \nu_i$. With the maximum ion flux being achieved when $\Omega_i = \nu_i$, or

$$\Gamma_{imax} = \frac{\beta}{R} n_i D_i \tag{4.12}$$

Conversely at the maximum flux Γ_{imax},

$$\Omega_i = \nu_i \tag{4.13}$$

Eq. (4.11) represents cross field ion flux in the anomalous region. It has a maximum point at $\Omega_i = \nu_i$. Considering its relatively low pressure compared to the positive column, an assumption $\Omega_i \simeq \nu_i$ ($a_i \simeq 1$) for the reflex discharge seems very reasonable. This results should be applied to the reflex-type ion source.

In our experiment, electron flux is inversely proportional to the magnetic field (Bohm like diffusion) at relatively high pressures (Fig. 8). It is quite reasonable since $\Omega_e >> \nu_e$ is satisfied. At relatively low pressures, the cross field electron flux has a maximum point with increasing magnetic field. However, we cannot assume that $\Omega_e = \nu_e$, as in the case of ion flux, since the electron temperature should be on the order of keV for this to be valid. It is found that the Debye length relatively low pressures is close to the electron Larmor radius. In this case, an electron is expected to spend a relatively long time around one particular ion. Then, the electron will oscillate with the plasma frequency. When it oscillates in the plane perpendicular to the magnetic field, the high frequency oscillation has same effect as the collisions with neutrals if the average distance between ions is less than the Debye length. The increased effective collision frequency encourages diffusion perpendicular to the magnetic field. We replace ν_e with ω_p in Eq. (4.11). Then, we can apply the discussion of ion fluxes to electron fluxes: where ω_p represents plasma oscillation frequency. In this case Γ_{er} has a maximum value for $\Omega_e = \omega_p$. For the magnetic field which gives the maximum electron flux, we get the following relations:

$$\Gamma_{er} = \frac{\beta}{R} n_e D_e \qquad (4.14)$$

$$\Omega_e = \omega_p \qquad (4.15)$$

In the negative ion production experiment the size of the ion source is very small. The source is in a strong magnetic field and it is at a high electric potential for the extraction of the charged particles. No direct measurement of any quantities inside the ion source is possible. Diagnostics are limited to external measurements of voltage, currents and electrical-noise signals. All important quantities inside the ion source must, therefore, be estimated phenomenologically from the relation between the extracted charged particle currents and the magnetic fields.

The relations between the extracted ion current and the magnetic fields are expressed by Eq. (4.11). The maximum extracted currents of positive and negative ions, and the critical magnetic fields B_M of each species are given from Fig. 6 and Fig. 7. Because, at the critical magnetic field B_M, the cyclotron frequency is equal to the collision frequency the ion temperature is obtained from Eq. (4.13).

The elastic collision frequencies between the charged particles and the hydrogen gas are given by Brown[22] (1966). No precise data exists in the low ion-temperature region. Thus, we extrapolated the original elastic cross section data by Simons et al.[23] (1943) and Muschlitz et al.[24] (1956) into the low temperature region. Both the positive ion temperature T_i=1.5 eV, and the negative ion temperature T_i=1.5 eV are given for all pressures. Then ion densities are obtained from Eq. (4.12).

On the other hand, the maximum electron drain current and the critical magnetic field B_M are given from Fig. 8. Because at the critical magnetic field B_M, the cyclotron frequency is related to the plasma frequency the electron density may be obtained from Eq. (4.15). Then, the electron temperature T_e is obtained from Eq. (4.14).

The calculated temperature and densities for each specie according to gas flow rate are shown in Fig. 9 and Fig. 10. A comparison of important physical quantities with other reflex discharge experiments are shown in Table 1. Considering the small size and relatively large arc current in the reflex-type ion source, our calculated values look reasonable. Actually there is an ambiguity in the evaluation of the collision frequency with neutral hydrogen gas. However, the calculated results enable us to infer something about the conditions inside the ion source.

Wadehra[13] (1979) expected the largest negative ion production rate at an electron temperature of order of 1 eV. If his calculated production rates are correct, the negative ion production should increase as the plasma is cooled from high electron temperatures to low electron temperatures (order of 1 eV), which is much lower than previously believed; a sharp peak of the cross section with a maximum at electron energy 14.2 eV is observed by Schulz[28] (1959) and Rapp et al.[29] (1965). However, the production of vibrationally excited molecules should not decrease in order to keep a high dissociative attachment rate. In the reflex-type negative ion source, the primary electrons ionize neutral gas and produce vibrationally excited molecules in the central region. Their production is constant since the arc current and the voltage are kept constant. The calculated electron temperature, $T_e = 4 \sim 44$ eV, and ion temperature, $T_i = 1.5$ eV, are obtained. Qualitatively our result is in agreement with Wadehra's[13] result (Fig. 10); the higher negative ion density is observed when the plasma is cooled from high electron temperature to low electron temperature. The maximum negative ion density is estimated to be $n = 8 \times 10^{11}$ #/cm^3.

We assumed that the anomalous diffusion mechanism presented by the author is valid only in the diffusion dominant region, which is the surrounding region in the reflex-type ion source. Therefore all calculated physical quantities are valid only in the surrounding region.

V. SUMMARY AND DISCUSSION

A hot cathode reflex-type negative ion source was investigated. When the magnetic field is increased, the extracted positive and negative ion currents initially increase. Then, after reaching the maximum value, the currents begin to decrease. This observation led us to look for an anomalous diffusion mechanism. The extracted charged particle currents in the reflex-type ion source are assumed to be controlled by the anomalous diffusion mechanism.

Negative ions cannot survive very long inside of a dense plasma. Instabilities which increase the radial diffusion, as described earlier, can increase the external H^- current. However, the increased radial diffusion does not have to be followed by decreased density. The plasma trys to compensate what has been lost with increasing particle production.

To investigate the correlation between the instabilities and the negative ion current, the reflex-type ion source was modified in order to change the radial electric field. As shown in Eq. (3.11), the resistive drag instability should grow faster if the inwardly-directed radial electric field is reduced. In order to change the radial electric field, the wall anode was biased negatively with respect to the top part of the anode. Twice as much negative ion current was observed with a negative potential as with zero potential. Simultaneously, an increase of negative ion density fluctuation amplitude, which is in the order of 100 kHz, was observed. Consequently, we can say that our model is self-consistent.

The anomalous diffusion coefficients in the anomalous regime of the reflex-type ion source were also obtained. Using the experimentally obtained critical magnetic fields for maximum H^- currents, the phenomenological anomalous diffusion model was used to estimate plasma properties. The highest negative ion density is obtained when the plasma is cooled from high electron temperature to low electron temperature (Fig. 10). The phenomenologically obtained results are consistent with the production mechanism of negative ions through the electron volume production process proposed by Wadehra[13] (1979). However, it was not possible to make experimental measurements of densities and temperatures for comparison.

It is also pointed out in Eq. (4.10) that no anomalous effect happens if the fluctuation in the axial direction is neglected. The anomalous diffusion is initiated by the net azimuthal electric field, which arises as the second order effect from charge separation. However, anomalous diffusion is not a two-dimensional (radial-azimuthal) problem. Oscillating waves should exist in the axial direction as well as in the azimuthal direction. When charge separation arises, it should not be neutralized by electron flow in the axial direction. If travelling waves exist in the axial direction, many electrons are trapped by the wave through the resonant interaction. This process increases the effective resistivity and prevents perfect neutralization of the charge separation. The increase of impedance when an instability develops is observed in our experiments.

Experimentally, we succeeded in increasing volume production of negative ions by encouraging anomalous diffusion inside the ion source. A maximum D. C. negative ion current of 9.7 mA(100mA/cm^2) for H^- and of 4.1 mA (42mA/cm^2) for D^- were obtained. This is the largest negative hydrogen and deuterium current density ever obtained continuously from a volume-production source within the author's knowledge. In the history of plasma physics, anomalous diffusion has been something which has distressed scientists. The author believes this experiment is the first example in which successful advantage has been made of it.

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Table 1. Comparison of important physical quantities of the reflex discharges.

Author	Pressure P[torr]	Arc Current I[A]	Length R[cm]	Radius R[cm]	Electron Temperature T_e[eV]	Ion Temperature T_i[eV]	Plasma Density n[#/cm^3]
Chen *et al.*[a] (1962)	1.5×10^{-2}	0.4	55	0.65	3	0.4	3×10^{11}
Brifford *et al.*[b] (1963)	1.4×10^{-2}	0.2	14	0.75	3.0	0.4	4.5×10^{11}
	5.7×10^{-3}	0.1	85	1.50	2.5	0.4	1.0×10^{11}
Pabichenko *et al.*[c] (1964, 1966)	5×10^{-3}	0.3	70	2.20	20	--	5×10^{11}
	1×10^{-3}	1.0	100	1.75	50	0.5	1×10^{12}
Thomassen[d] (1966, 1968)	3×10^{-3}	0.3	66	2.05	---	---	10^{11}
	1×10^{-2}	0.3	130	1.50	5	---	10^{11}
Reflex-type negative ion source	1×10^{-2}	3	6	0.24	4	1.5	2×10^{12}

[a]Reference 19

[b]Reference 25

[c]Reference 4 and 26

[d]Reference 5 and 27

Figure Captions

Fig. 1 Experimental geometry of the reflex-type negative ion source.

Fig. 2 Experimental arrangement for the modified reflex-type negative ions source.

Fig. 3 Conceptual view of the central part and surrounding part of the reflex-type negative ion source.

Fig. 4 Relations between the extracted negative ion current and the magnetic field with changing the bias potential.

Fig. 5 Relation between the bias potential and the extracted negative ion current (left), and relation between the bias potential and the density fluctuation amplitude (right).

Fig. 6 Relations between the extracted positive ion current and the magnetic field for various of gas flow rate.

Fig. 7 Relations between the extracted negative ion current and the magnetic field for various values of gas flow rate.

Fig. 8 Relations between the electron drain current and the magnetic field for various values of gas flow rate.

Fig. 9 Relations between the calculated density of each species and the gas flow rate.

Fig. 10 Relation between the calculated electron temperature and the gas flow rate (left), and relation between the calculated negative ion density and the gas flow rate (right).

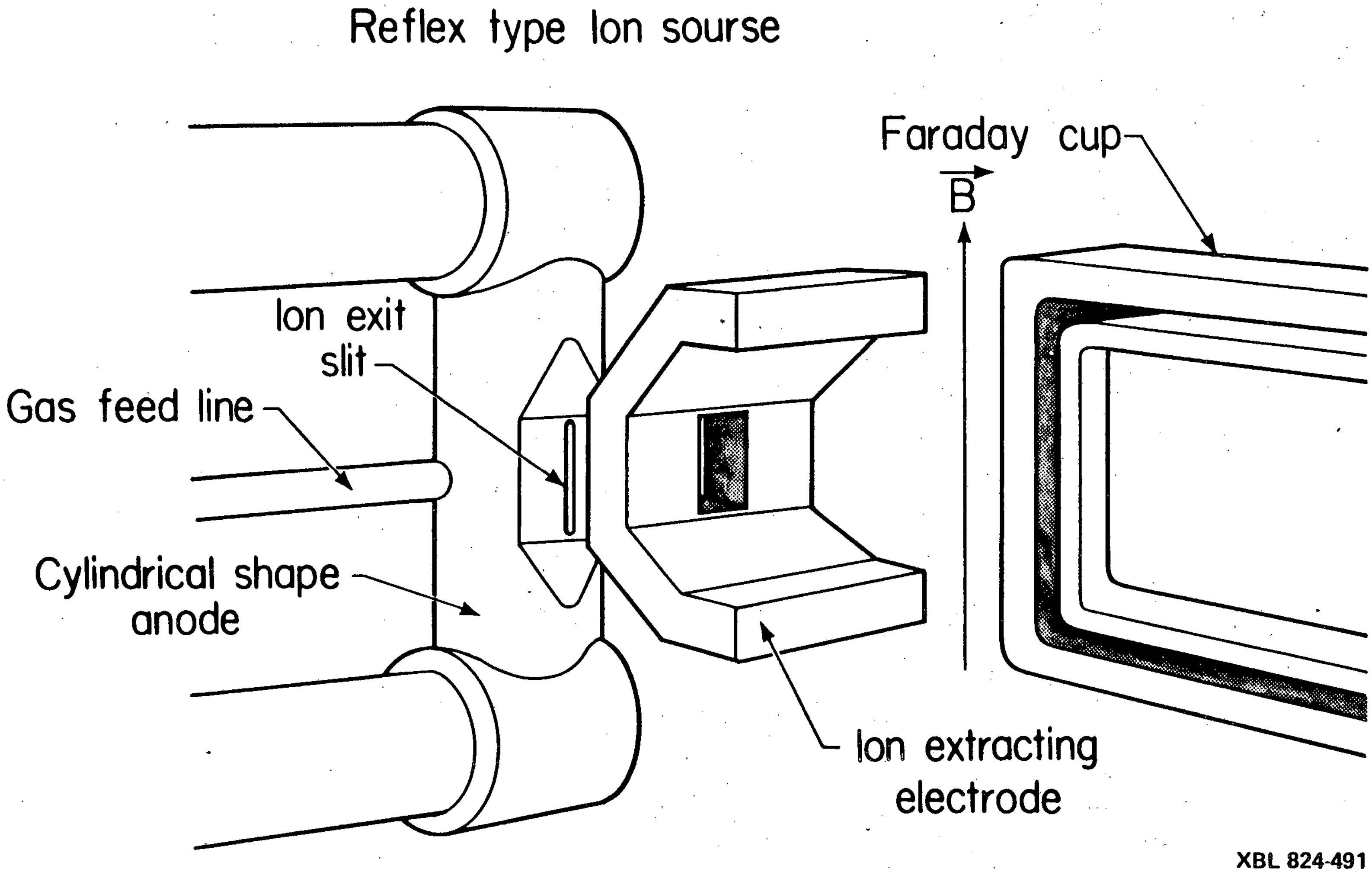

Reflex type Ion sourse
Faraday cup
B
Ion exit
slit
Gas feed line
Cylindrical shape
anode
Ion extracting
electrode
XBL 824-491

Fig. 1

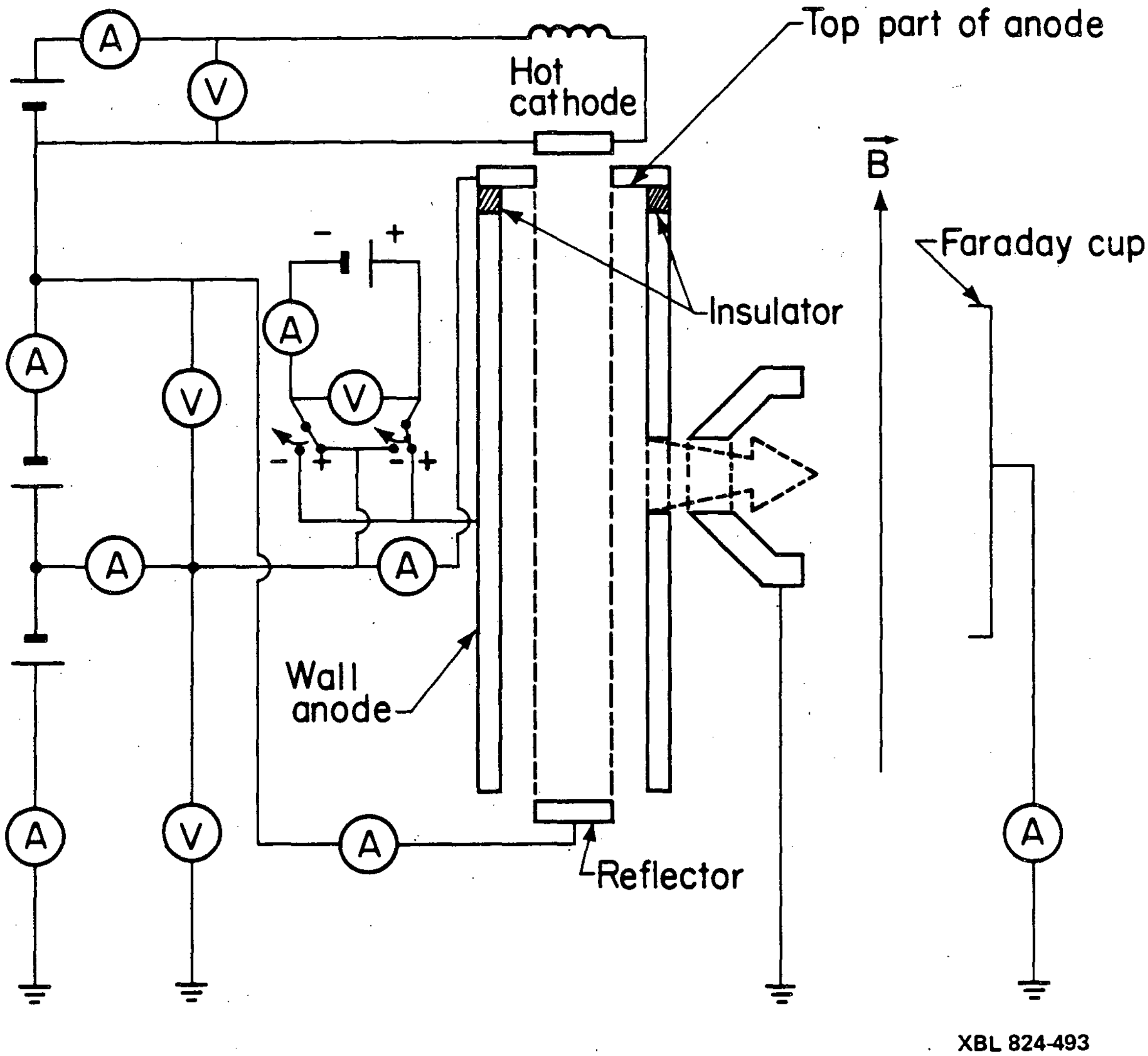

Top part of anode
Hot
cathode
B
Faraday cup
Insulator
Wall
anode
Reflector
XBL 824-493

Fig. 2

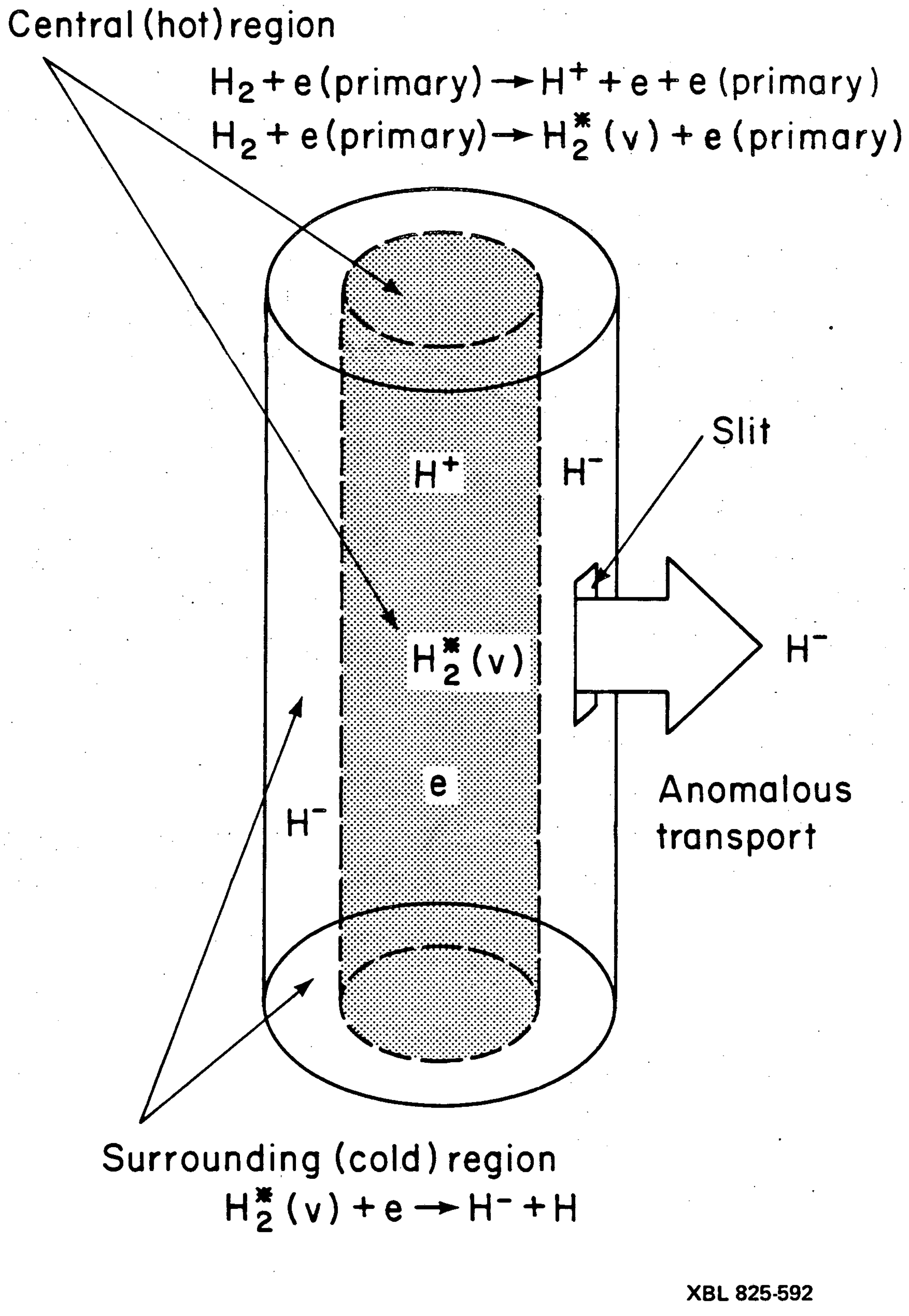

Central (hot) region
$H_2 + e(\text{primary}) \rightarrow H^+ + e + e(\text{primary})$
$H_2 + e(\text{primary}) \rightarrow H_2^*(v) + e(\text{primary})$
H^+
H^-
Slit
$H_2^*(v)$
H^-
e
H^-
Anomalous transport
Surrounding (cold) region
$H_2^*(v) + e \rightarrow H^- + H$
XBL 825-592

Fig. 3

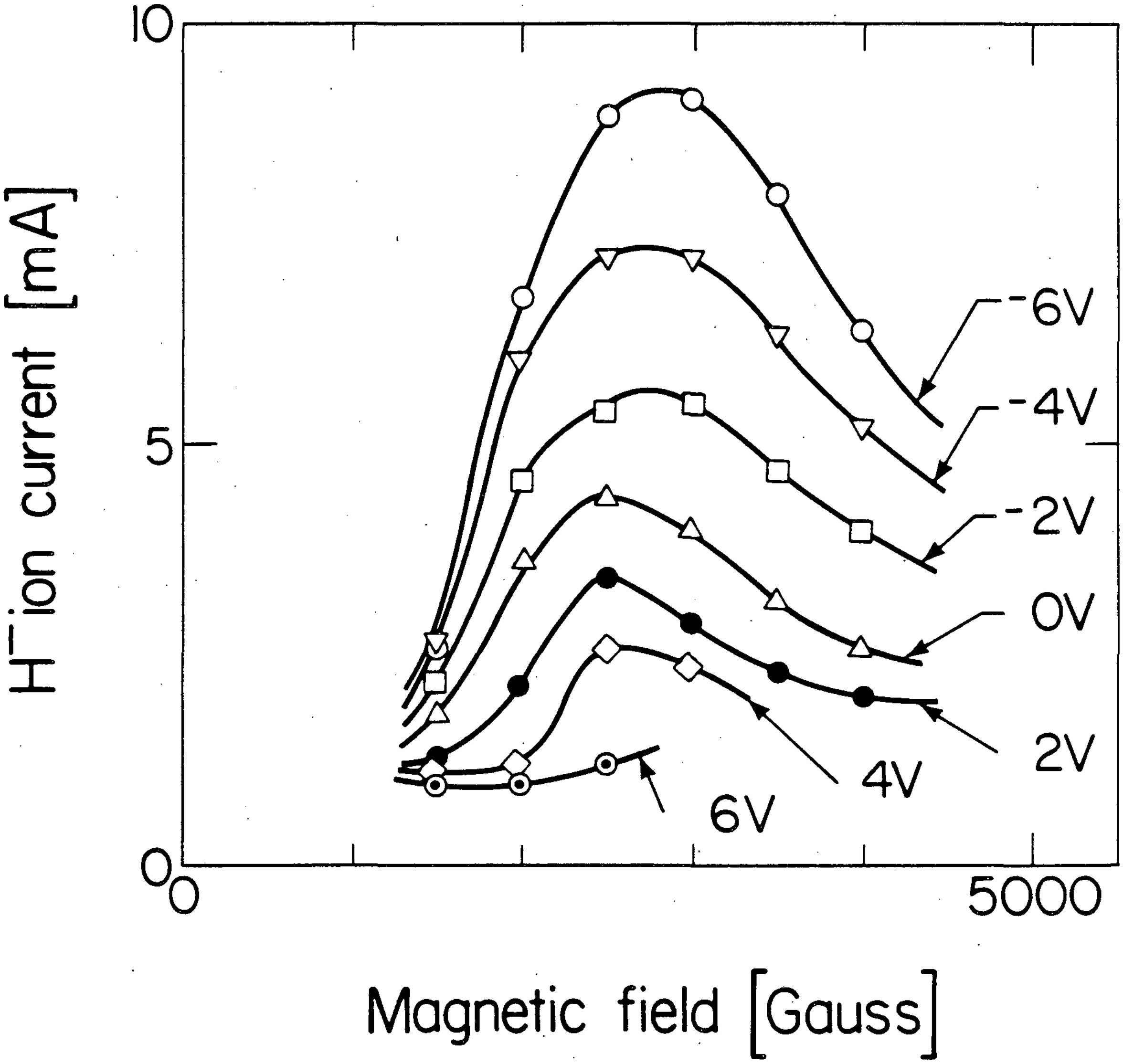

10
5
0
0
5000
H⁻ ion current [mA]
Magnetic field [Gauss]
-6V
-4V
-2V
0V
2V
4V
6V
XBL 824-512

Fig. 4

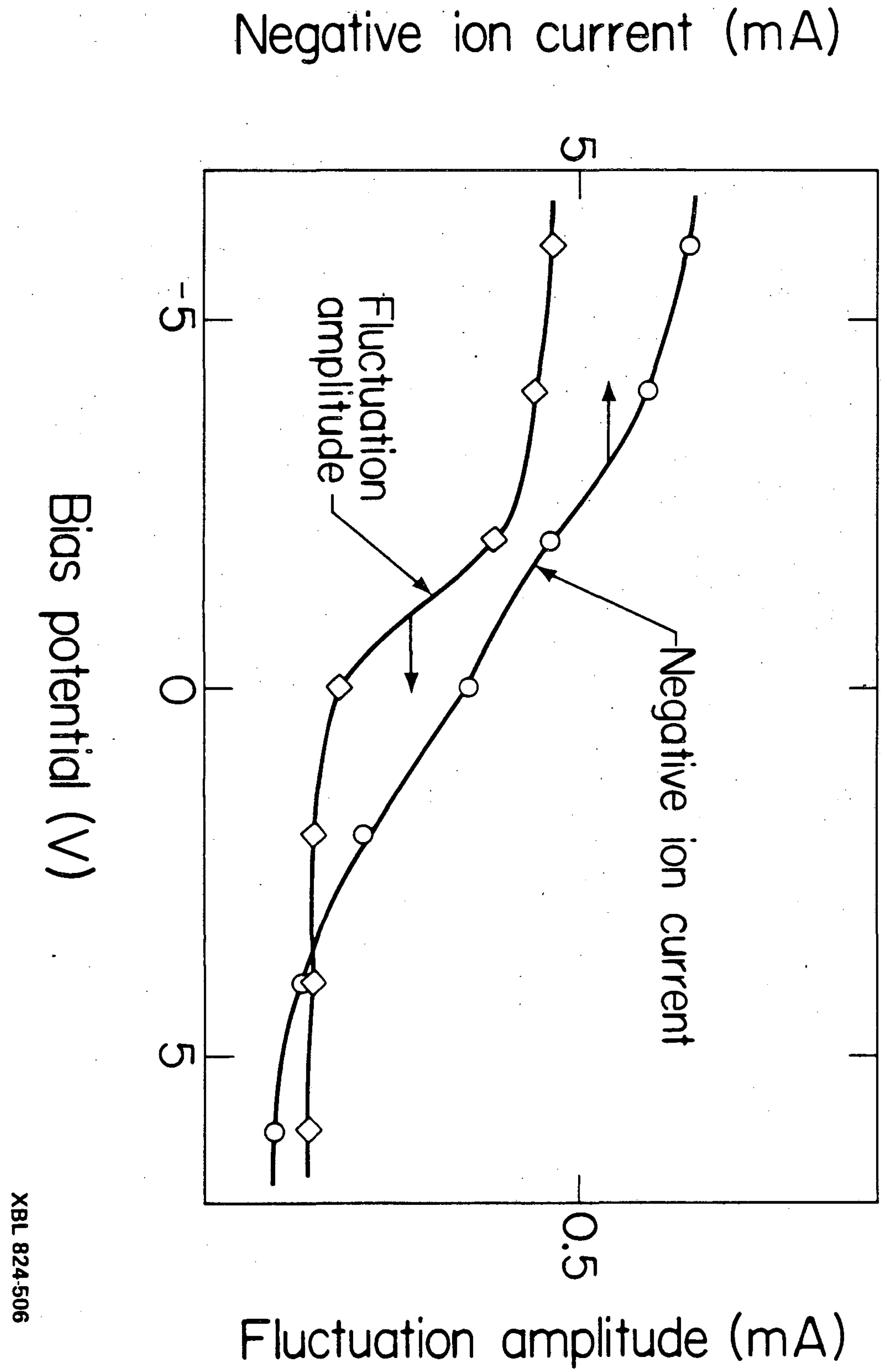
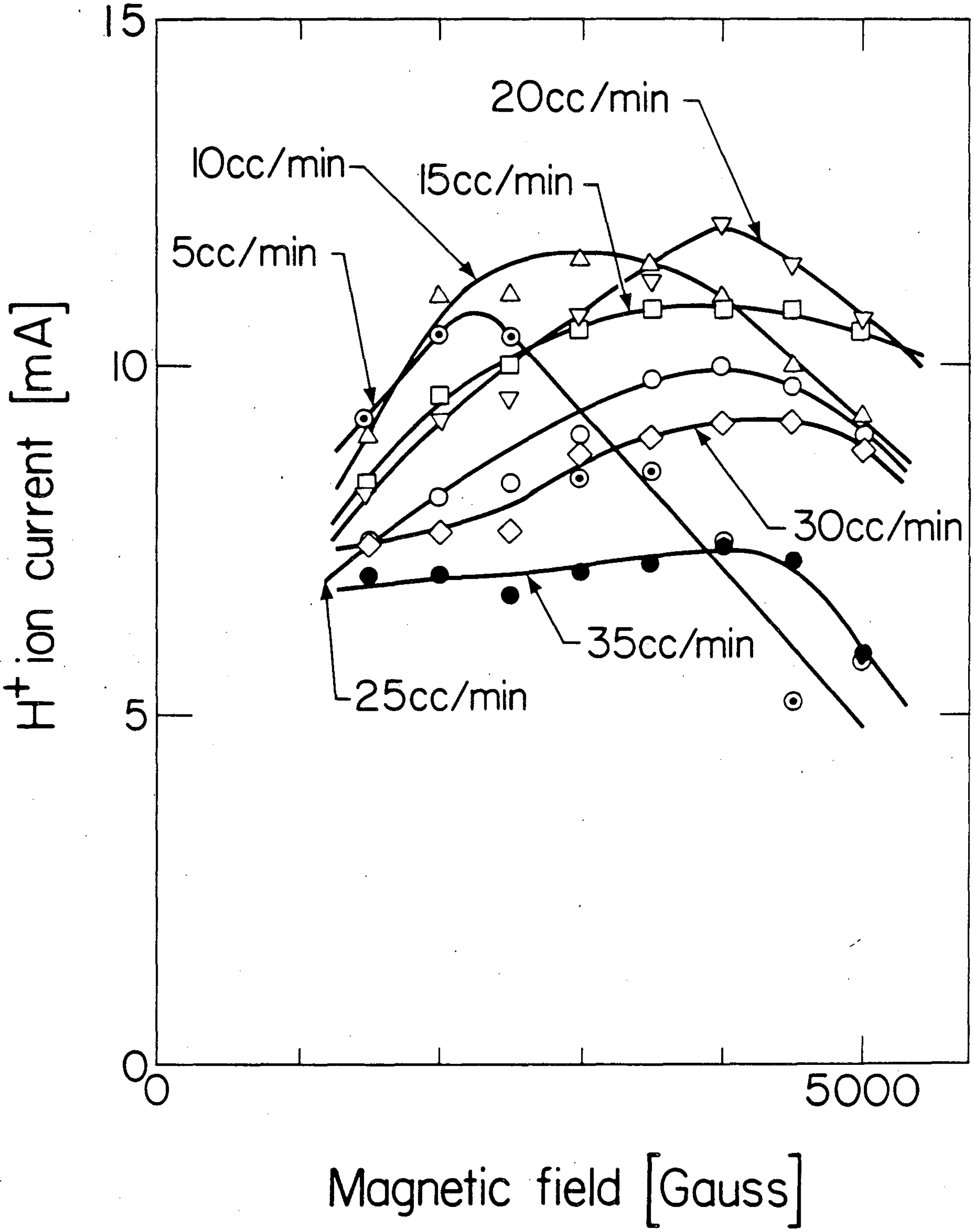

Negative ion current (mA)
5
-5
0
5
0.5
Fluctuation amplitude
Negative ion current
Bias potential (V)
Fluctuation amplitude (mA)
XBL 824-506

Fig. 5



15
10
5
0
0
5000
H⁺ ion current [mA]
Magnetic field [Gauss]
20cc/min
10cc/min
15cc/min
5cc/min
30cc/min
35cc/min
25cc/min
XBL 824-509

Fig. 6

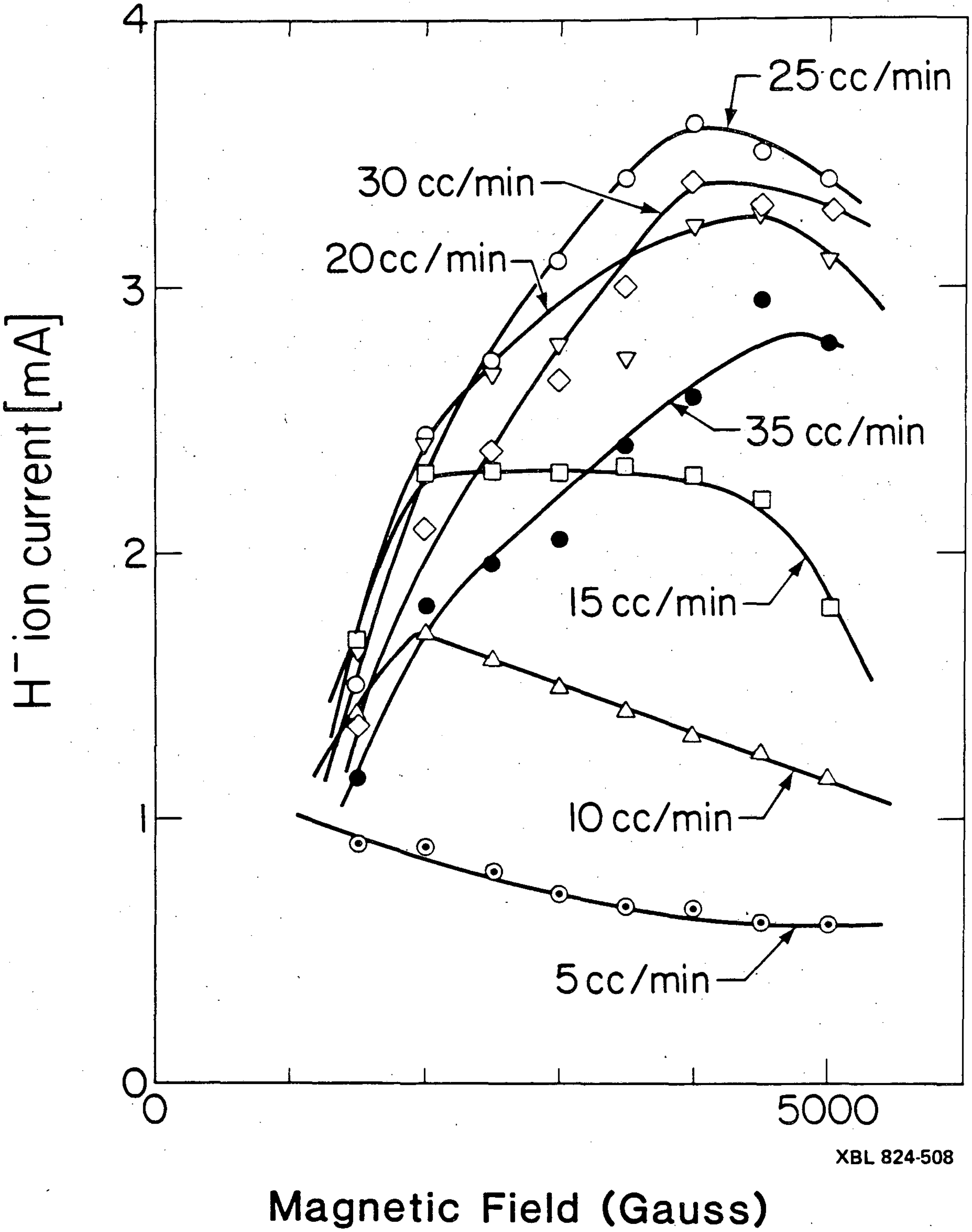

4
3
2
1
0
0
5000
H⁻ ion current [mA]
Magnetic Field (Gauss)
25 cc/min
30 cc/min
20 cc/min
35 cc/min
15 cc/min
10 cc/min
5 cc/min
XBL 824-508

Fig. 7

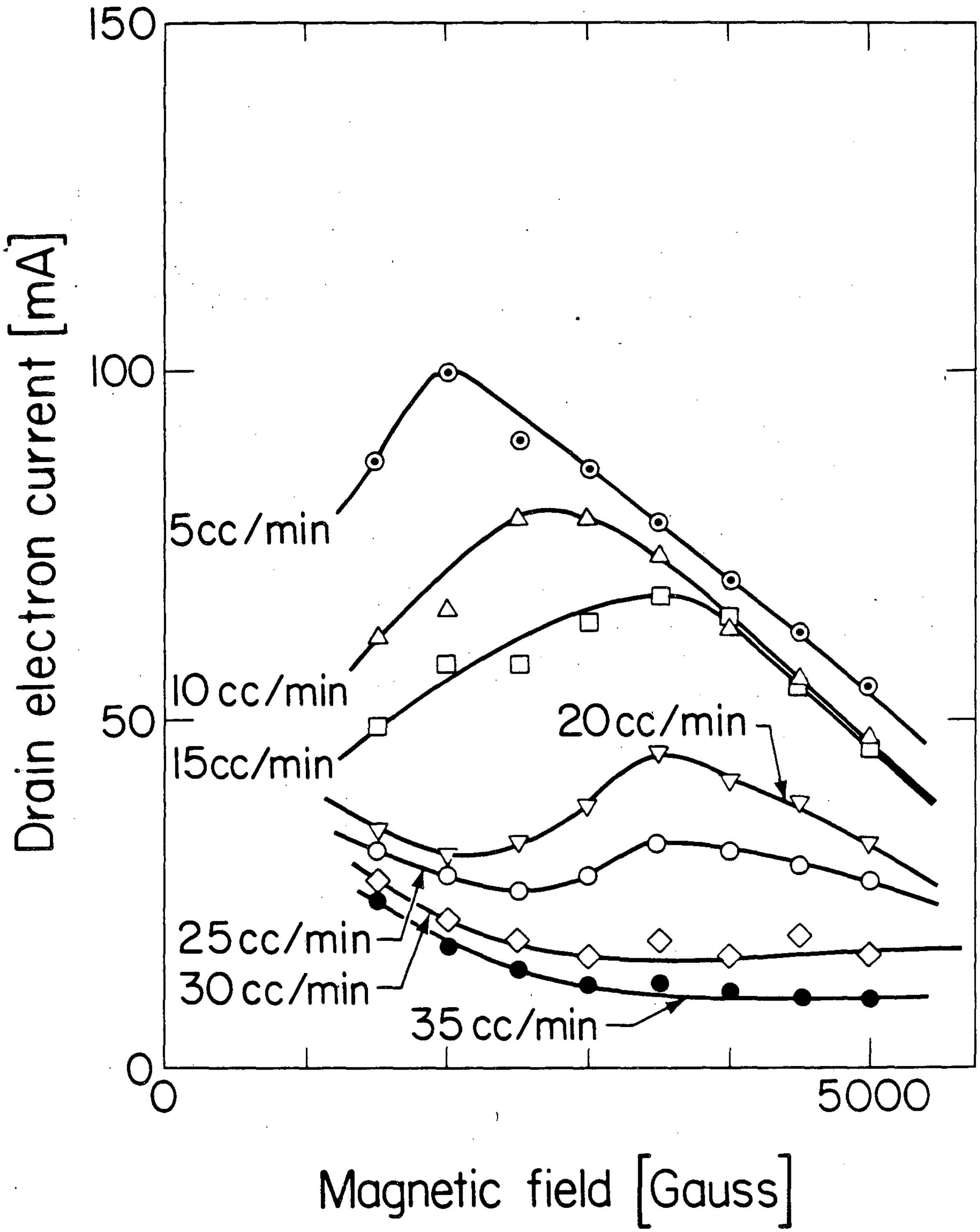

150
100
50
0
0
5000
Drain electron current [mA]
Magnetic field [Gauss]
5cc/min
10 cc/min
15cc/min
20cc/min
25cc/min
30cc/min
35cc/min
XBL 824-507

Fig. 8

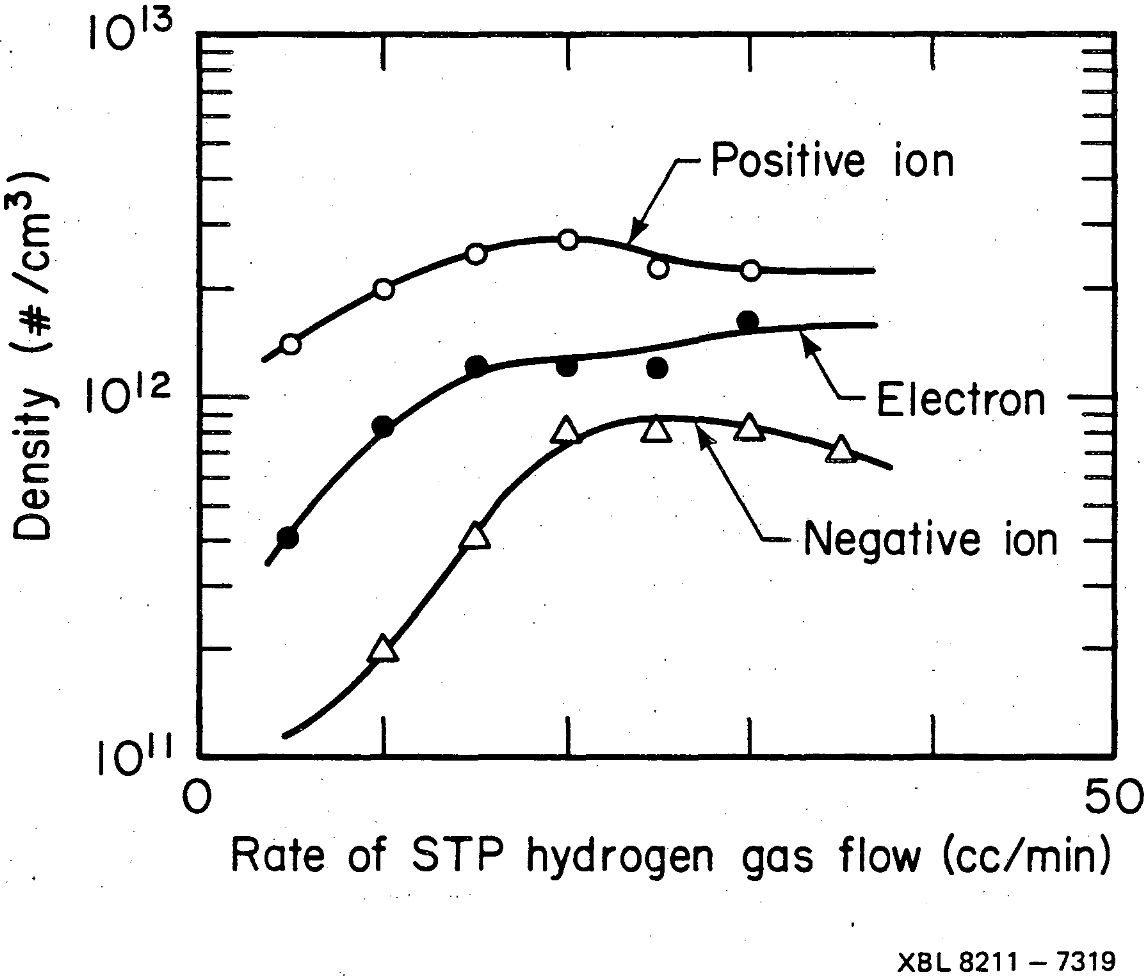
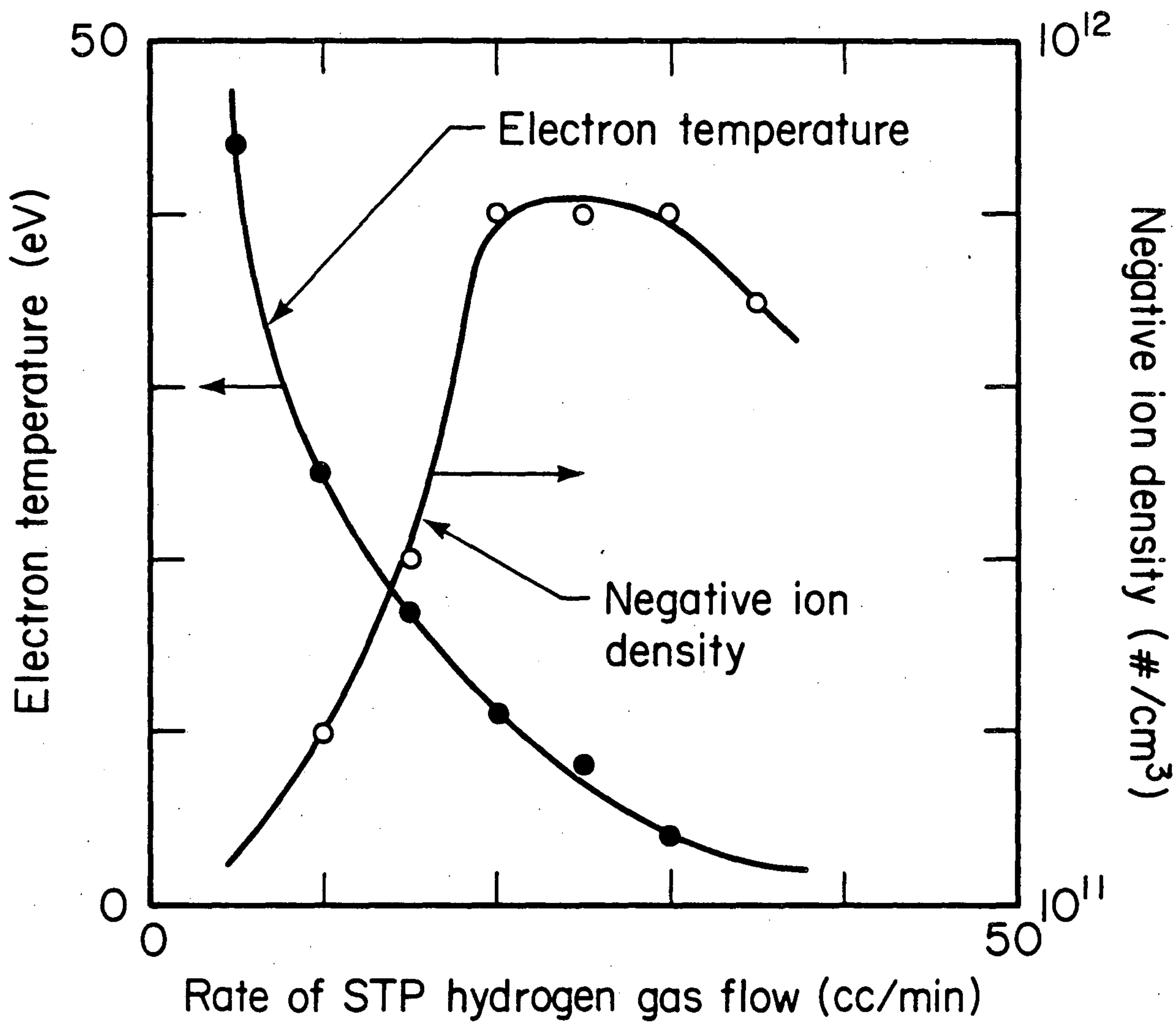

Positive ion
Electron
Negative ion
Density (# /cm3)
10^{13}
10^{12}
10^{11}
0
50
Rate of STP hydrogen gas flow (cc/min)
XBL 8211 – 7319

Fig. 9



XBL 8211 – 7318

Fig. 10

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