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Change of magnetized plasma performance by inserted voltage biased plate

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Abstract

Two-dimensional profiles of ion saturation current, transverse plasma flow and floating potential were measured in a magnetized r.f. produced plasma, varying an applied voltage on the rectangular metal plate and a filling pressure with a semi-circular earthed plate. It was found that near the plate surface, plasma density was lower and the spatial inhomogeneity of shifted profile was enhanced. This was consistent with the Mach probe measurement and $E\times B$ drift behavior (E: electrostatic field, B: magnetic field).

Keywords: Magnetized r.f. plasma; Voltage biasing; Plasma profile; $E\times B$ drift

1. Introduction

Control of the plasma profile with good stability is crucial in developing plasma sources in various plasma processing fields [1] as well as in high temperature plasmas. In the industrial applications of the plasma, knowledge of plasma physics combined with plasma chemistry and plasma engineering are very important. The balance between the plasma generation and diffusion processes, which are affected non-linearly by many parameters, governs the obtained profile such as the plasma density profile. In the plasma processing, voltage biasing to a substrate in a magnetized plasma is important for plasma distributions as well as the ion energy and flux control. In mirror machines, control of the electric field in the end sections by the voltage biasing is also important for the profile control and the plasma stability [2–9], and enhanced confinement was found by this biasing [10], similar to the tokamak experiment inducing the H mode by the $E\times B$ velocity shear [11] (E: electrostatic field, B: magnetic field). Recent high power neutral beam injection (NBI) system utilizes negative hydrogen/deuterium ions for their good neutralization efficiency [12]. However, the production of negative ions is less efficient than that of positive ions, which makes the ion source very large.

Therefore, one of the problems of the large area plasma source in the various fields is spatial inhomogeneity of the plasma production. In a magnetized plasma, the electric field E is supposed to affect the plasma distribution, plasma flow and stability. However, the effect of and role of E on the plasma performance has not been investigated in detail from a basic viewpoint except for our experiments [5–9]. In the previous experiments [8], we have shown in a simple configuration, in which a voltage-biased plate was immersed in a magnetized plasma, that the distorted plasma profiles were understood by the $E\times B$ drift. Nevertheless, detailed spatial distribution measurements were not carried out, due to a problem with the probe driving system. In addition, the effect of the boundary condition near the biased plate on the plasma distribution was not studied.

Here, we investigated in more detail how the plasma density, bulk plasma flow and floating potential in two-dimensional space changed in the presence of the magnetic field by applying a voltage on the inserted metal plate along with the effect of the neighboring earthed metal plate. In this article, following the description of the experimental system in Section 2, results on the various plasma profiles are reported in Section 3. Conclusions are presented in Section 4.

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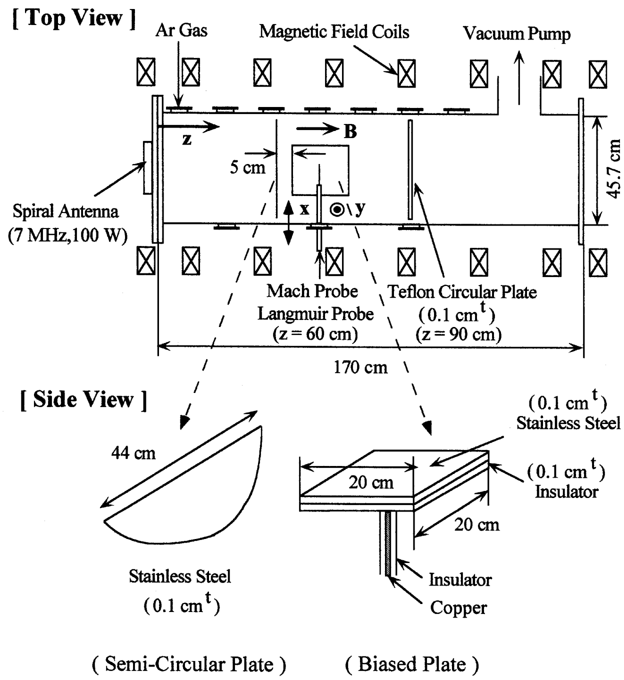

Fig. 1. Schematic view of experimental setup.

2. Experimental setup

The experimental system [8,13] is shown in Fig. 1. Argon plasma was produced by a spiral antenna at a pressure of $P=0.3\sim3$ mtorr with uniform magnetic field $B=500$ G. The r.f. power and frequency of 100 W and 7 MHz, respectively, were applied to a linear device, 45 cm in diameter and 170 cm in axial length. A voltage biased metal plate (biased voltage $V_b=-50\sim50$ V) was made of stainless steel (20 cm$\times$20 cm with 0.1 cm thickness) with an insulator plate (the same size as the metal plate) on the back side. The biased voltages V_b in this experiment were chosen as -50 V, -25 V, 0 V, V_f (floating voltage), 25 V and 50 V, while in the previous experiment [8] they were only -50 V, 0 V and 50 V. This metal plate was located at $z=60$ cm, and the Teflon circular plate with 0.1 cm thickness was at $z=90$ cm in order to have an insulation on the other side of the antenna window, i.e. avoiding a short circuit effect (electric current) at the right hand side window. Here, z is taken from the inner surface of the quartz window, facing the spiral antenna. The surface of the metal plate was 5 cm lower in the center of the vacuum chamber, and an earthed semi-circular plate, made of stainless steel with 0.1 cm thickness, was located at $z=$ 45 cm (see Fig. 1) to see the boundary effects. A gap between two plates was 5 cm, and the vertical position of the straight section of this semi-circular plate (top position) was the same as the metal biased plate.

The electric probe, made of two tungsten plates with a size of 0.1 cm$\times$0.3 cm each, was used to measure the plasma parameters such as the plasma density n_e, the electron temperature T_e and the floating potential V_f. This probe was also used as the Mach probe to measure the radial plasma flow v derived from the ratio of the ion saturation current I_{is} collected from the two opposite directions. Here, the probe was located at $z=$ 60 cm, and could be scanned in the radial (x) as well as the vertical (y) directions, without changing the position of the biased plate. Typical measuring vertical positions were $y=1$, 1.5, 2, 2.5, 3, 4, 5, 6, 7, 8, 9, 10 cm (12 points). Note that in the previous experiments [8], the probe was scanned radially and the metal plate vertically (five points) to have two dimensional plasma profiles, which had a problem that a slight change of plasma parameters was expected when the plate was moved. In the present experiment, typical density n_e without biasing was in the range of $(1\sim5)\times10^9$ cm^{-3} with $T_e=3\sim8$ eV, and estimated ion temperature T_i was ≤1 eV (ion Larmor radius ρ_i was less than 1 cm for the magnetic field $B=500$ G).

3. Experimental results

Dependences of the plasma density n_e, floating potential V_f and plasma flow v (x direction: parallel to a plate surface and perpendicular to the magnetic field) on the biased voltage V_b and the filling pressure P were measured. First, we present the comparison of the plasma density distributions between the negative and the positive voltage biasing to a metal plate. Fig. 2 shows an example of the radial profiles of the ion saturation current I_{is} at $P=1$ mtorr with $V_b=-50$ V and 50 V, changing the distance y between the metal plate and the probe. Here, as was mentioned, x and y show radial (parallel to the plate surface and perpendicular to B) and vertical (perpendicular to the plate surface and to B) directions, respectively, by moving the probe (see Fig. 1), and $y=5$ cm is the case that the probe is in the center of the chamber in the vertical direction. The plasma density n_e, which is proportional to I_{is}, was lower near the plate than that far from the plate. This can be seen more clearly for $V_b=-50$ V case (Fig. 2a). Here, n_e corresponded $\sim2\times10^9$ cm^{-3} for $I_{is}=0.1$ taking $T_e=5$ eV. For the positively (negatively) voltage biased case, the plasma density shifted to the positive (negative) x direction. This inhomogeneity of the plasma density faded when y was more than several cm for the negative biasing case.

The shifted profile observed especially near the plate was mainly due to the $E\times B$ drift. This could be ascertained by changing polarities of V_b and B. Furthermore, this profile was consistent with the measurements of the plasma flow due to this drift, described later. The characteristics of this shifted distribution along the x direction and the observed hump (peak height observed was smaller than that in the previous one [8]) near the

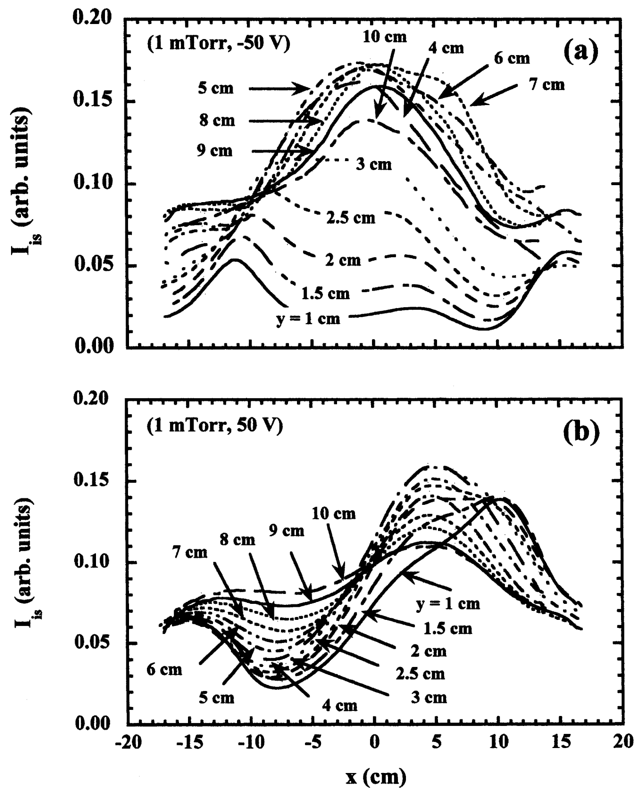

Fig. 2. Radial profiles of ion saturation current I_{is}, changing the distance y between the plate and the plasma: (a) $P=1$ mtorr and $V_b=-50$ V and (b) $P=1$ mtorr and $V_b=50$ V.

edge of the plate, especially at the smaller y position, was also found in the previous experiment [8]. However, even far from the plate, this asymmetry was still observed for the positively biasing case in contrast to the previous result. This may be due to the fact that the plasma parameters at a fixed spatial position was unchanged in this experiment regardless of the measuring position in the y direction in contrast to the previous results. It was also found that the biased current I_b of the metal plate decreased drastically with increasing y from -11 mA at $y=1$ cm to -0.7 mA at $y=10.5$ cm through -7 mA at $y=5.5$ cm in the previous result, while I_b was constant of -14 mA in the present experiment with the same conditions of $P=1$ mtorr and $V_b=50$ V. This means that in the previous result that with increasing y, biasing effect became weaker. Here, the positive (negative) current means that the current flowed into (out from) the metal plate. For the negatively voltage biasing case, I_b was 4 mA (Fig. 2a), and assuming $T_e=5$ eV this current corresponded to $n_e \sim 3\times10^8$ cm^{-3}, which is the same order as the plasma density in the present experiment, if the probe theory holds good even for the case of this large collecting area and I_b can be taken as I_{is}.

Fig. 3 shows radial profiles of I_{is} at $P=1$ mtorr with $y=1$ cm and 2.5 cm, changing V_b. As can be seen, with increasing V_b, the peak of I_{is} moved to the positive x direction, which is considered again as the effect of the $E\times B$ drift, and this tendency became weaker with increasing y. Asymmetries of I_{is} profiles between positively and negatively biased voltage cases with the same absolute values might mainly come from effects of the different biased currents as was mentioned above and of the different sheaths (electron and ion). For the zero voltage biasing, this profile was nearly symmetric and has the same tendency as the floating biased case. In this pressure of 1 mtorr, the electron mean free path (m.f.p) derived from an electron-neutral collision was estimated to be ~ 30 cm assuming $T_e=5$ eV, which is larger than a gap between the biased and semi-circular plates. However, this effect did not seem to work effectively in the present experiment. Note that the Coulomb collision can be neglected because the m.f.p in this case was in the order of 10 m, which was much larger than the device size.

The effect of the filling pressure P on the radial profiles of the ion saturation current I_{is} was studied. Figs. 4 and 5 show the distributions of I_{is} at $P=0.3$ mtorr ($V_b=0$ V and 50 V) and 3 mtorr ($V_b=-50$ V and 50 V), respectively. As was observed for the case of $P=1$ mtorr (Fig. 2), the shifted profile depending on

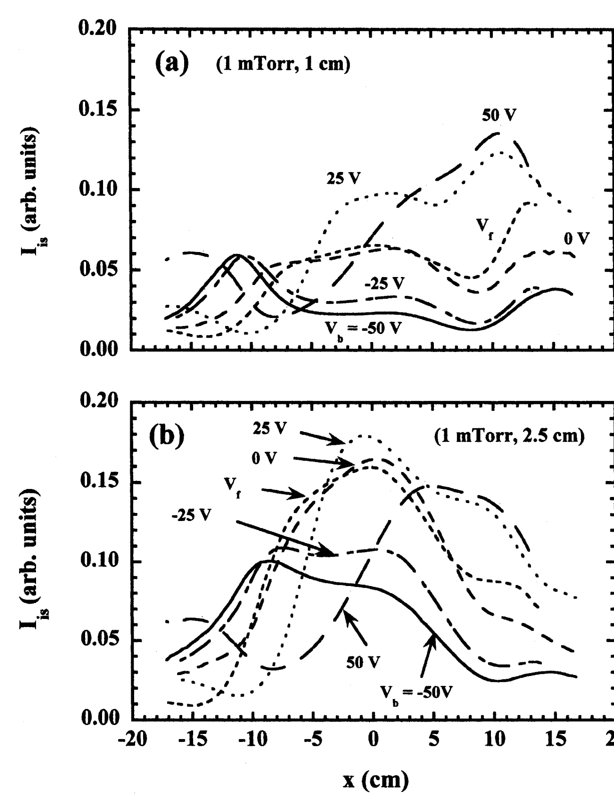

Fig. 3. Radial profiles of ion saturation current I_{is}, changing the biased voltage V_b: (a) $P=1$ mtorr and $y=1$ cm and (b) $P=1$ mtorr, $y=2.5$ cm.

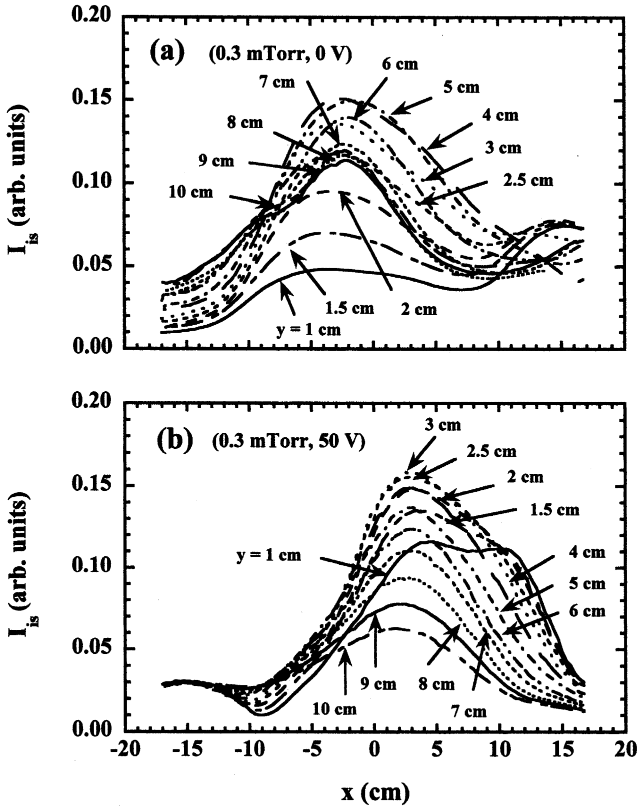

Fig. 4. Radial profiles of ion saturation current I_{is}, changing the distance y between the plate and the plasma: (a) $P=0.3$ mtorr and $V_b=0$ V and (b) $P=0.3$ mtorr and $V_b=50$ V.

the polarity of V_b was found. For the positive biasing, I_{is} decreased monotonically with y ($y>3$ cm) at $P=0.3$ mtorr, while it did not change appreciably at $P=3$ mtorr. For the case of $P=3$ mtorr and $V_b=-50$ V, the I_{is} profile at y being greater than 6 cm was omitted due to a large fluctuation of the signal.

Next, we present the potential and plasma flow distributions under the different pressures and biased voltages. Fig. 6 shows radial profiles of the floating potential V_f, changing the distance y at $P=0.3$ mtorr with $V_b=0$ V and 50 V [I_{is} and V_f profiles with no biased case are nearly the same as those with 0 V biasing (see also Fig. 3)]. Here, the experimental condition was the same as that in Fig. 4. From Fig. 6 and other data, V_f increased with V_b in the whole plasma region due to the flux balance between ions and electrons, and a change of V_f decreased at the larger y position. Depending on V_b, a peak or local minimum positions of V_f were changed, e.g. as shown in Fig. 6b and Fig. 7a, both of which had the positive biasing, V_f peaked at the positive x position. Comparing Fig. 7a (V_f) with Fig. 2b (I_{is}), similar profiles were found, which may satisfy the Boltzmann relation. Note that the plasma parameters such as I_{is} and V_f were determined self-consistently imposed by conservation, balance etc. This tendency was also found for the case of $P=0.3$ mtorr and 3 mtorr with the positive biasing. Since V_f is different from the plasma potential, it is difficult to estimate the electric field to derive the value of $E\times B$ drift. Fig. 7b shows a ratio of I_{is} collected from the opposite x directions. If R is larger (smaller) than 1 assuming the same collected metal area, the plasma flows towards the positive (negative) x direction. Generally, flows with positive (negative) x directions were found with the positive (negative) voltage biasing, and the flow velocity was larger near the biased plate. This was consistent with the plasma density distributions. Here, Mach velocity M, which is the ratio of flow velocity v to the ion sound velocity C_s, can be represented as $M=(1/K)$ ln R, and $M=0.32$ if we use $K\sim1.26$ for unmagnetized model [14] or kinetic model with viscosity [15]. When R had a larger value, we also found the larger difference of V_f between two collected metal plates due to the effect of the strong flow.

In summary, the obtained results so far were mostly consistent with the previous ones [8]. Finally we will have a short discussion on the affected plasma region, conditions of the $E\times B$ drift and the plasma stability. In our experimental conditions, the typical Debye length

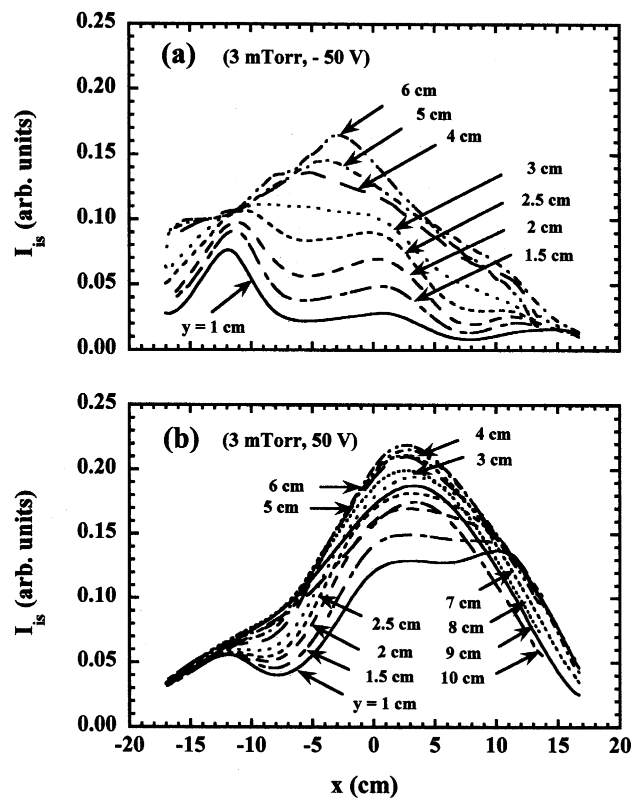

Fig. 5. Radial profiles of ion saturation current I_{is}, changing the distance y between the plate and the plasma: (a) $P=3$ mtorr and $V_b=-50$ V and (b) $P=3$ mtorr and $V_b=50$ V.

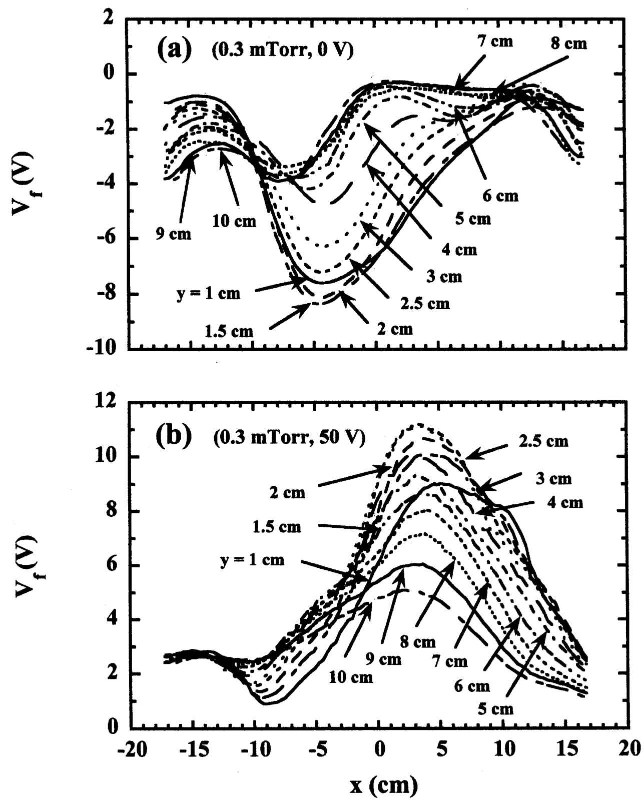

Fig. 6. Radial profiles of floating potential V_f, changing the distance y between the plate and the plasma: (a) $P=0.3$ mtorr and $V_b=0$ V and (b) $P=0.3$ mtorr and $V_b=50$ V.

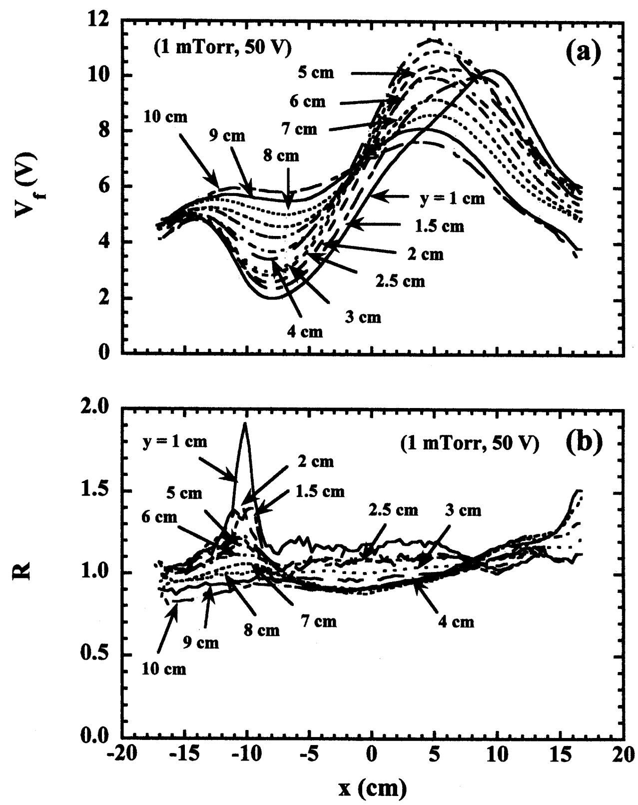

Fig. 7. Radial profiles of floating potential V_f and ratio R of ion saturation currents I_{is} collected from the opposite x directions, changing the distance y between the plate and the plasma at $P=1$ mtorr and $V_b=50$ V.

was ~ 0.03 cm, which was smaller, by two orders of magnitude, than the vertical scale length (y direction) of the affected plasma region. This vertical length is comparable to a magnetic sheath length of C_s/ω_{ci} (ω_{ci}: ion gyration angular frequency) [16] (~ 2 cm typically in our conditions) or several times of ion Larmor radius ρ_i (<1 cm). As for $E\times B$ drift, we need to have the typical plasma size L to be much larger than ρ_i, and the multiplying factor of $f=1/[1+1/(\omega_{ci}\ \tau_{in})^2]$ must be considered. Here, $f\sim 0.8$ at $P=3$ mtorr ($v=f\,E/B$, τ_{in}: ion-neutral collision time), so a correction of the drift velocity from f is small. Note that M becomes 0.57 without a correction of f if we take E as 1 V/cm. In measuring plasma parameters, we found an unstable operating region that had larger oscillations of signals (a few tens of % modulation) and sometimes had density transitions between two states (also a few tens of % change of the global spatial structure). These unstable characters were found generally with the higher pressure and lower biased voltage, i.e. negatively biased case, and the transitions are considered to be universal in the plasma discharge system [17,18]. However, these unstable regimes should be avoided in the operation to develop steady-state reliable plasma source, in addition to investigating the physical mechanism to control the plasma with good stability.

4. Conclusions

In order to see effects of the electric field on the plasma performance in the presence of the magnetic field, detailed two-dimensional spatial profiles of ion saturation current I_{is}, plasma flow v and floating potential V_f were measured in r.f. produced plasma with a voltage biased plate. Changing the biased voltage V_b (-50 V$\sim$50 V, six cases of biasing voltage) and argon filling pressure P (0.3, 1 and 3 mtorr), the clear spatial inhomogeneity in the x direction was observed, especially near the plate. Changing a polarity of B or V_b reversed the radial distribution of I_{is}. The effect of the semi-circular earthed plate was not found clearly. These results obtained could be understood by the $E\times B$ drift, based on the estimation of ρ_i/L and $\omega_{ci}\ \tau_{in}$.

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