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Profile Control and Plasma Rotation by Biased Electrodes in Large Diameter RF Produced Plasma

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Control of the plasma profile has been carried out using three types of biased electrodes in a large-diameter (45 cm), radio-frequency (RF)-produced plasma with a magnetic field in the low-pressure region. The radial profile of the electron density changed from a hollow to a peaked one, while the electron temperature distribution did not appreciably change. The azimuthal rotation velocity was changed with this biasing. It decreased with a lower magnetic field and/or in a high-pressure regime, and a localized velocity profile near the edge region was obtained with a few kHz oscillation of the ion saturation current.

KEYWORDS: RF plasma, profile control, biasing, electrode, plasma rotation, $E \times B$ drift

1. Introduction

The control of the various properties of the plasma profile such as the electron density profile, is very important in many fields of plasmas, and the obtained profile is governed by the balance between the plasma generation and the diffusion processes. Therefore, in principle, varying the generation profile, i.e., the power deposition profile, or the spatial profile of the diffusion can change the plasma distribution. The former method was executed, *e.g.*, by changing of the resonance zone in the electron cyclotron resonance heating scheme. The latter method in the plasma application field involved, *e.g.*, the use of arrays of permanent magnets to reduce the particle diffusion near the wall, or the use of the cusp magnetic configuration[1,2] from the straight magnetic field to change the plasma diffusion and also modify the wave propagation characteristics.

Historically, studies on the instabilities brought about by changing the electric field profile have been done using Q-machines.[3,4] Recently, probe biasing (voltage) was attempted in order to modify the potential profile to change the plasma profiles in tokamak[5] and mirror[6–9] machines, in terms of the enhanced plasma confinement, partly due to the change of the plasma rotation by $E \times B$ drift (E: electric field, B: magnetic field).

However, there have been few experiments on voltage biasing, which is also related to plasma rotation, for demonstrating a large change in the electron density and/or investigating the dependencies of the shape (biased electrodes) and of filling pressure on the plasma.[9] Here, we try to change the plasma profile and the azimuthal plasma rotation using two types of concentric electrodes as well as the filament loop type of electrode, in the large-diameter (45 cm), RF-produced plasma with a uniform magnetic field. The obtained results can be used as a database for the basic understanding of the profile change and the plasma rotation. The results will also be useful for considering the effects of the substrate shape with the voltage biasing on the plasma properties in the plasma processing field.

In this article, following the description of the experimental system in §2, results on the changes of the plasma profile (mainly the ion saturation current) and plasma rotation measured using the Mach probe, at various bias voltages, are reported in §3. Conclusions are presented in §4.

2. Experimental Setup

The experimental setup is shown in Fig. 1.[10,11] Argon plasma was produced by a four-turn spiral antenna at a pressure of $P = 0.1$–0.2 mTorr, unless otherwise specified. The continuous output RF power and frequency were 400–500 W and 7 MHz, respectively, with a uniform magnetic field ($B < 1200$ G) being applied to a linear device, 45 cm in diameter and 170 cm in length. The plasma parameters were measured by the Langmuir probes including the Mach probe, which is a directional probe, mainly at z (axial length from the inner left surface of the vacuum chamber)=30 cm, for the plasma flow measurements. The typical target (before biasing) plasma density n_e was in the range of 4×10^9–2×10^{10} cm^{-3} with the electron temperature $T_e = 3$–8 eV.

We used two types of the biased electrodes located at $z = 90$ cm, as shown in Fig. 2. Three (on the same z plane) and ten concentric rings, made of stainless steel with a thickness of 0.03 cm, were put on the Teflon disk, 40 cm in diameter and 1 cm thick, to cover the plasma cross section. For ten rings, the inner and outer diameters of the n-th ring (in order from the center) were $4n$–4.6 cm ($2 \leq n \leq 10$) and $4n$ cm ($1 \leq n \leq 10$), respectively, and each ring was separated from the neighboring ones with an axial distance of 1.3 cm. In addition, another type of a filament loop (30 cm in diameter) made of tungsten wire (0.1 cm in diameter), located in the vacuum chamber at $z = 60$ cm, was tested (not shown).

3. Experimental Results

First, the results for three concentric rings are presented. Figure 3 shows a large change in the electron density (n_e) profiles with various bias voltages for $P = 0.16$ mTorr and $B = 800$ G. Here, (V_1, V_2, V_3) stands for the voltages applied to the inner (V_1), middle (V_2) and outer (V_3) electrodes. For positive (negative) bias with $V_1 = 0$ V and $V_3 = 2V_2$, n_e near the center increased (decreased). The effect of biasing on the profile change became weaker as the magnetic field was lowered. However, the nearly flat profile of the electron temperature T_e (several eV) did not change appreciably with this biasing.

In this case, the absolute bias currents of I_1 and I_2, which corresponded to those at voltages V_1 and V_2, respectively, were less than 10 mA, and decreased slowly from positive to small negative values as positive bias was increased (positive current means that flowing out from the electrode). The current I_3, corresponding to voltage V_3, was negative (positive)

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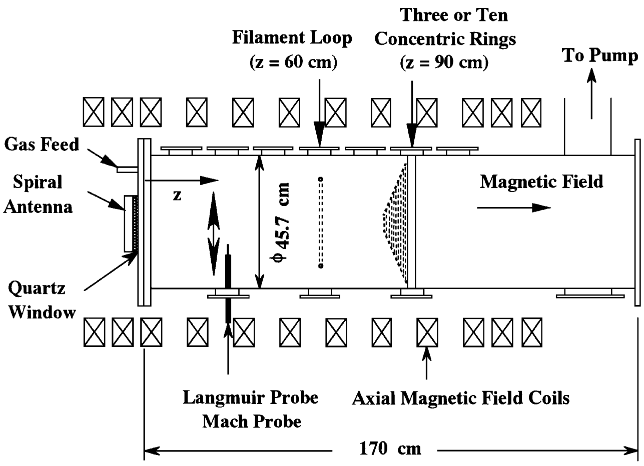

Fig. 1. Schematic view of experimental setup.

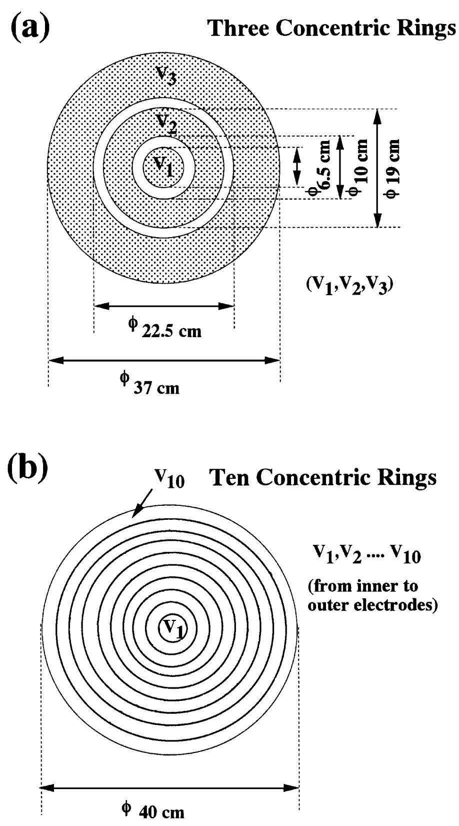

Fig. 2. Biased electrodes with (a) three and (b) ten concentric rings.

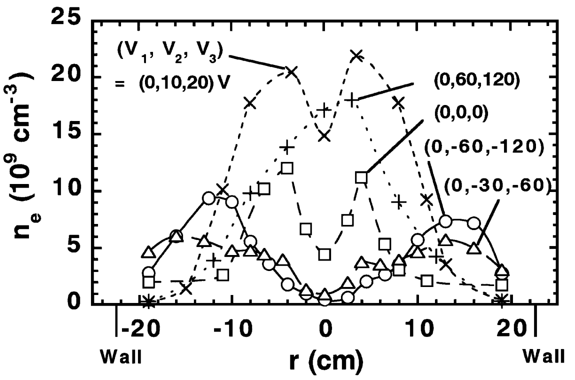

Fig. 3. Radial profiles of electron density n_e with various bias voltages (V_1, V_2, V_3) for three rings with $P = 0.16$ mTorr and $B = 800$ G.

with values up to -18 (25) mA for negative (positive) bias. Results in Fig. 3 and other cases (not shown), that positive (negative) bias of V_2 and V_3 caused the peaked (hollow) density profile, are consistent with the previous one explained below, which were obtained using a midsize ring in the low-pressure regime.

In the previous study,[9] several types of biased electrodes were tested for a wide range of filling pressure, $P = 0.08$–20 mTorr. In the high-pressure region, an increase in I_{is} near the central region was observed with positive bias voltage irrespective of the shape of the electrodes. To the contrary, in the low-pressure region, positive (negative) bias resulted in a peaked (broad) n_e profile when using the midsize ring with the inner and outer diameters of 9 cm and 18 cm, respectively. In addition, when a disk with a small diameter of 5 cm was used, a large dip of n_e in the central region, which was more exaggerated with positive bias, disappeared and became peaked with negative bias.

The present and the previous results of the effect of bias on the plasma profile can be discussed as follows. Generally, in the low-pressure and low-density regimes where the electron collision is not important (the mean free paths determined by electron-ion Coulomb collisions[12] and electron-neutral collisions,[13] *e.g.*, in both cases$>$1 m in our experiments, are larger than the device size), the positively-biased electrodes have parallel electron current along the magnetic field, which causes a decrease in the electron density in the neighborhood of the radial electrode position. On the other hand, for negative bias, the plasma loss is considered to be negligibly enhanced due to the small ion current. Here, the mean free paths by the ion-neutral[13] and ion-ion Coulomb[12] collisions are estimated to be in the range of several cm. The above discussion leads to the conclusion that the plasma density profile becomes peaked (hollow) for the case of positive (negative) bias on the outer electrodes, since the relatively positive potential in the outer (inner) plasma region causes the decrease in the outer (inner) region of the plasma density. In fact, when the outer electrodes were positively (negatively) biased, i.e., they were at V_2 and V_3, the plasma potential was hollow (peaked) except at the edge of the plasma region, and a major component of bias current I_3 was positive (negative) as mentioned above, which supports our consideration.

The change of the plasma rotation with this bias was measured by the tungsten Mach probe through a hole, 0.1 cm in diameter, of the ceramics. Figure 4 shows an example of the radial profiles of the Mach number M for (V_1, V_2, V_3) $=$ (0, -30, -60) V and $P = 0.16$ mTorr for various values of B. With increasing B, the rotation velocity became high and had a tendency to saturate around $B = 800$ G, and the peak position of the velocity was in the intermediate region of the plasma. Here, M was defined as the plasma flow velocity (mainly azimuthal direction, which was determined by the polar plots obtained using the Mach probe) normalized by the ion sound velocity. Although there are a number of theories, such as those in refs. 14, 15 and 16, on estimating the Mach number parallel to the magnetic field but not across the field, it is difficult to determine the correct value of M in the direction perpendicular to the magnetic field (see the trials on estimating the poloidal flow velocity in refs. 17 and 18). Here, for

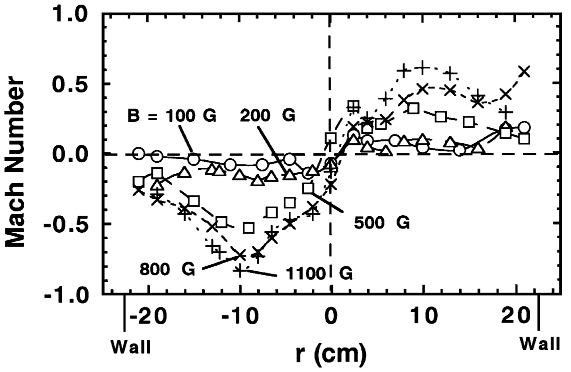

Fig. 4. Radial profiles of Mach number M with variations in the magnetic field B for three rings with (V_1, V_2, V_3) = (0, −30, −60) V and $P = 0.16$ mTorr.

convenience, an unmagnetized model[14)] or a kinetic model with zero viscosity[16)] was employed. Both models assume nearly the same value of $K \sim 1.26$ under some assumptions, where $M = (1/K) \ln R$ (R: ratio of the probe current facing upstream to that facing downstream).

The Debye length λ_D, depending on the radial position, was roughly ∼0.02 cm (typically, $n_e = 5 \times 10^9\,\mathrm{cm}^{-3}$ and $T_e = 5$ eV in our experiment), and the Larmor radius r_{Li} of an argon ion was <0.25 cm for $B = 800$ G, at an ion temperature of $T_i < 0.1$ eV, which was comparable to the probe size of 0.1 cm in diameter. Thus, there might be some errors in the rotation measurements, but the results obtained might qualitatively reflect the rotation profile. In fact, by increasing the probe size from the circular shape of 0.1 cm diameter to rectangular shapes of 0.1 cm×0.5 cm and 1 cm×1 cm, we found that values of M decreased by a factor of up to 3–4 keeping the rotation profile constant. This profile was also confirmed qualitatively by the plasma potential profile using the Langmuir and emissive probes and by preliminary Doppler shift measurements (Ar II line) with a visible monochromator. Note that $\omega_c\tau$ is much larger than unity for electrons and small (typically less than three) for ions, which means that the ion $E \times B$ drift velocity might be slower than the electron one by roughly ∼20% (factor $f \equiv 1/\{1+[1/(\omega_c\tau)^2]\} \sim 0.8$) under our typical experimental conditions with $B = 500$ G (ω_c: cyclotron angular frequency, τ: collision time).

By changing the bias voltages, we obtained the different profiles of the plasma rotation M and plasma density n_e. With decreasing B, as shown in Fig. 4, and increasing P to more than 1 mTorr (not shown), the rotation speed M became slower. Considering the $\omega_c\tau$ term, the ion $E \times B$ drift velocity is considered to become low in the low B field and/or in the high-pressure (high collision frequency) region if the electric field does not change. Here, the value of I_3 became more negative, dropping from −3 mA ($B = 100$ G) to −12 mA ($B = 800$ G) with the higher B value while the values of I_1 and I_2 (5–10 mA) did not change appreciably, with an increase in B. Note that λ_D was typically ∼0.02 cm, which was smaller than the probe diameter of 0.1 cm, and r_{Li} was <2 cm to <0.19 cm when B was increased from 100 G to 1100 G with $T_i < 0.1$ eV, which was larger than the probe diameter in most cases. Therefore, we again used $K = 1.26$ for convenience. As for the dependence of the plasma rotation on the axial position, radial profiles of n_e and M changed only slightly along the z axis, and the results were similar when the position of the concentric rings was changed from $z = 90$ cm to 120 cm or 160 cm. For the reverse direction of the magnetic field B, the radial profiles of n_e and T_e did not change appreciably, but the Mach number changed its sign while keeping the same profile. These results show that the plasma rotated mainly as a result of being driven by the $E \times B$ drift (note that the radial plasma flow velocity measured near the plasma edge cannot be neglected). This was also qualitatively confirmed through plasma potential measurements, and under our experimental conditions, the ion pressure gradient, as well as the centrifugal force could be considered to be neglected.

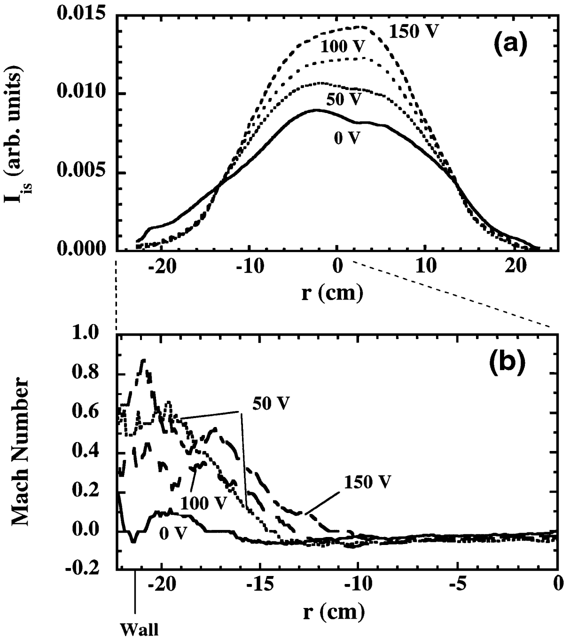

Fig. 5. Radial profiles of (a) ion saturation current I_{is} and (b) Mach number M with variations in the bias voltage V applied to the 8th and 9th electrodes numbered from the axis to the outer radius (see Fig. 2), i.e., $V = V_8 = V_9$ ($V_1, V_2 \cdots V_7$ and V_{10} were floating voltages), for ten rings with $P = 0.11$ mTorr and $B = 500$ G.

Next, in order to achieve a finer control of the profile in the radial direction, ten concentric rings were tested. Figure 5 shows radial profiles of ion saturation current I_{is} and Mach number M, changing the bias voltage V from 0 V to 150 V with $P = 0.11$ mTorr and $B = 500$ G. Here, the biased electrodes were the 8th and 9th ones numbered from the center to the outwards, where $V = V_8 = V_9$ (V_1, $V_2 \cdots V_7$ and V_{10} were floating voltages), and the Mach probe had a size of 0.2 cm×0.2 cm in Figs. 5 and 6. In this figure, we can see that with increasing bias voltage V (bias current was from 6 mA to 14 mA), the profile of I_{is}, which was nearly proportional to plasma density n_e, became peaked, which was again consistent with the previous results. It was also found that the penetration length of the azimuthal flow from the plasma edge and the poloidal velocity (close to the high velocity at $M = 1$, which was $\sim 3.5 \times 10^3$ m/s) of the plasma column were enhanced when the bias voltage was increased. Needless to say, we could change the density profile; *e.g.*, a hollow profile was obtained with positive bias of the inner electrode (a dip in the density was observed at the same radial position as the biased electrode).

When we changed the biased electrodes, keeping the bias

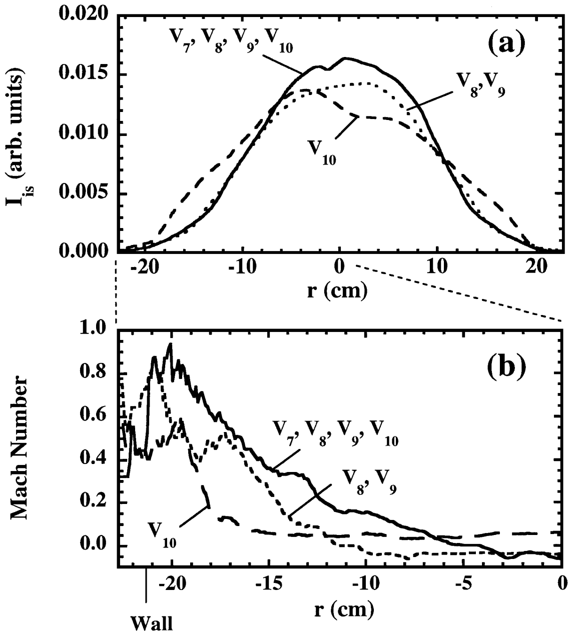

Fig. 6. Radial profiles of (a) ion saturation current I_{is} and (b) Mach number M with variations in the biased electrodes for ten rings with $V = 150\,\mathrm{V}$, $P = 0.11\,\mathrm{mTorr}$ and $B = 500\,\mathrm{G}$. Here, the suffix n of V_{n} specifies the n-th electrode (see Fig. 2); the other electrodes were floating.

voltage constant at $V = 150\,\mathrm{V}$, we were also able to modify the profiles of I_{is} and M, as shown in Fig. 6, for the case of the ten rings with $P = 0.11\,\mathrm{mTorr}$ and $B = 500\,\mathrm{G}$. Here, the bias current was 7 mA–14 mA, and the suffix n of V_{n} refers to the n-th electrode (see Fig. 2), where the other electrodes were floating. With the use of more electrodes from near the edge of the plasma region, i.e., from the use of V_{10} to $V_7 = V_8 = V_9 = V_{10}$ through $V_8 = V_9$ (all voltages were 150 V), the I_{is} profile became peaked and the penetration from the plasma edge and the poloidal flow velocity (also close to $M = 1$) were enhanced.

For the case of biasing with a high plasma rotation velocity, especially near the edge region, large fluctuations (sometimes non-sine shapes) of the ion saturation current were found. With the bias voltage of $V_7 = V_8 = V_9 = V_{10} = 150\,\mathrm{V}$, as shown in Fig. 6, the peak fluctuation frequency of 2.7–3 kHz in the power spectrum was observed in the outer plasma region. To the contrary, the fluctuation was negligible for the broad spectrum near the central region or for the case of low bias voltage. This fluctuation had the azimuthal mode number m of 1 with nearly the same structure along the axis z, i.e., a low parallel wave number, and the rotation direction of the fluctuation was reversed on changing the direction of the magnetic field. The fluctuation frequency remained nearly constant along the radial direction, i.e., the rotation (fluctuation) of the shell remained almost rigid, although, as a function of the radius, there were variations of the rotation velocity (corresponding to the maximum frequency of less than 2.5 kHz), the plasma potential and plasma density. The reason for this instability is believed to be a drift wave or flute, rotational and Kelvin-Helmholtz instabilities, but further study is needed for verification. Note that a wave propagating azimuthally in the rest frame of the plasma would appear Doppler-shifted by the azimuthal plasma rotation in the laboratory frame.

Finally, a test for controlling the density profile was done, using the tungsten filament loop. When a heated filament is used, more electrons can be expected to escape from a filament with the negative voltage bias. Figure 7 shows radial profiles of the ion saturation current I_{is}, with changes in bias voltage V and filament current I_{f} with $B = 500\,\mathrm{G}$ and $P = 0.11\,\mathrm{mTorr}$. Positive biasing led to the peaked profile, which is the same as the results mentioned above (two types of concentric rings) and previous ones.[9] Here, the plasma rotation was induced with $M < 0.5$ near the plasma edge (outside the filament loop region). For the case of negative bias using the filament current ($I_{\mathrm{f}} = 40\,\mathrm{A}$), a flatter profile was obtained compared to that obtained without heating the filament ($I_{\mathrm{f}} = 0\,\mathrm{A}$); within a diameter of 20 cm, I_{is} was uniform at less than ±6.5%. On the other hand, the change of the I_{is} profile with the filament current, compared to that with no current, was negligible for positive bias of $V = 150\,\mathrm{V}$.

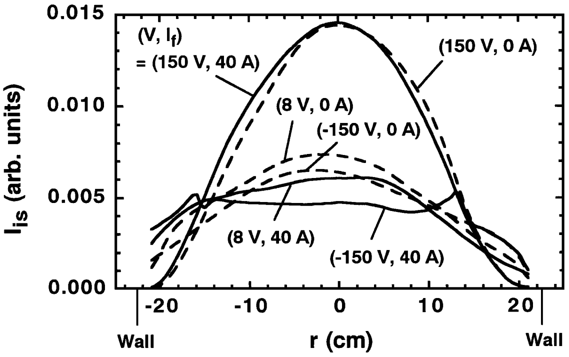

Fig. 7. Radial profiles of ion saturation current I_{is} for the filament loop with $P = 0.11\,\mathrm{mTorr}$ and $B = 500\,\mathrm{G}$, with various bias voltage V and filament current I_{f}. Here, full (dotted) lines are for $I_{\mathrm{f}} = 40(0)\,\mathrm{A}$.

We have also tried to produce the plasma using this filament without supplying RF power. For negative voltage bias up to $-160\,\mathrm{V}$ with $I_{\mathrm{f}} = 40\,\mathrm{A}$, $P = 0.18\,\mathrm{mTorr}$ and $B = 50$–$500\,\mathrm{G}$, the plasma was produced with the hollow profile of I_{is} (peak position was near the same radius of the filament). Good uniformity in the radial direction was found with $B = 300\,\mathrm{G}$; within a diameter of 19 cm, I_{is} was uniform at less than ±6.5%. When P was raised from 0.18 mTorr to several mTorr, the hollow profile was enhanced with the increased value of I_{is}. Here, the obtained density n_{e} was in the range of 10^9–$10^{10}\,\mathrm{cm}^{-3}$.

4. Conclusions

Controlling the plasma profile with voltage biasing of two types of inserted electrodes with concentric rings and one filament loop type was attempted in the large-diameter (45 cm), RF-produced plasma with a magnetic field in the low-pressure regime (typically 0.1–0.2 mTorr). We could change the electron density profile drastically from the hollow (or broad) to the peaked one without a major change of the electron temperature profile. The radial profile of the azimuthal rotation velocity ($M < 1$) also changed with biasing. This velocity decreased with a lower magnetic field and/or in the higher-pressure regime. Furthermore, a localized velocity distribution, i.e., velocity shear, near the edge region with a few kHz oscillation of the ion saturation current, could be obtained.

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