ELSEVIER

Surface and Coatings Technology 112 (1999) 20–24

SURFACE & COATINGS TECHNOLOGY

Control of plasma profile by voltage biasing in large diameter RF produced plasma

Shunjiro Shinohara *, Hiroshi Tsuji, Toshiro Yoshinaka, Yoshinobu Kawai

Interdisciplinary Graduate School of Engineering Sciences, Kyushu University, Kasuga, Fukuoka 816-8580, Japan

Abstract

Control of plasma profile by voltage biasing to the various inserted electrodes was tried in the large diameter RF produced plasma in a wide range of filling pressure P. With an addition of positive DC biasing voltage V of 30 V on the metal disk ($P=$ 20 mTorr), an increase in the ion saturation current by 20% was obtained near the central plasma region, while for the negative biasing case this saturation current changed little. For the case of biasing the inner one of two concentric cylinders to $V=20$ V, a drastic increase in the ion saturation current near the central plasma region by 60% was observed. Optical measurements on Ar I and Ar II line intensities exhibited consistent results with the probe data. In the lower filling pressure region ($P=0.09$ mTorr) with the use of the ring- and disk-type electrodes, the voltage biasing showed pronounced effects on changing ion saturation current profiles.

Keywords: Large diameter; Profile control; RF plasma; Voltage biasing

1. Introduction

Plasma profile is very important in many fields of plasmas, and it is determined by the balance between the plasma generation and diffusion processes. Control of plasma profile by injections of various waves and neutral beams has been tried in the nuclear fusion field in order to enhance the plasma confinement, partly due to changes of the rotation of the plasma column by $\boldsymbol{E}\times\boldsymbol{B}$ drift ($\boldsymbol{E}$: electric field, $\boldsymbol{B}$: magnetic field), which was accompanied by the change of plasma profiles such as plasma density and temperature. Recently, probe biasing (voltage) was attempted to modify the potential profile for the purpose of changing the plasma profiles in tokamak [1] and mirror [2–4] machines, leading to, e.g. the enhanced confinement.

However, there have been few trials of the voltage biasing to demonstrate a large change of the electron density and/or to investigate the dependences on the shape of the biasing electrode and on a filling pressure. In addition, biasing experiments have been scarcely reported in the straight uniform magnetic field or in the plasma application field, which aims at having a large diameter plasma with high plasma density. Here, we try to change the plasma profile by inserting various types of the biasing electrodes into a large diameter plasma of 45 cm, in a wide range of the filling pressure, which is connected with the plasma density, under uniform magnetic field configuration. The results obtained will also be very useful for simulation experiments on the effects of the substrate shape with or without voltage biasing on the plasma properties, including the plasma rotation.

In this paper, after describing an experimental system in Section 2, experimental results on changes of plasma profiles (especially ion saturation current distributions) with various types of electrodes, changing the bias voltages, are reported in Section 3. Finally, the conclusion is presented in Section 4.

2. Experimental

The experimental system is shown in Fig. 1 [5,6]. Argon plasma was produced by the four-turn spiral antenna in a pressure range of $P\approx0.08$–20 mTorr. The continuous output RF power and frequency were <1 kW and 7 MHz, respectively, with the uniform magnetic field of $\boldsymbol{B}=100$ G. Plasma parameters were measured by the movable Langmuir (electric) probes

* Corresponding author. Tel: +81 92 5837649;
Fax: +81 92 5718894; e-mail: sinohara@aees.kyushu-u.ac.jp

0257-8972/99/$ – see front matter
PII S0257-8972(98)00758-0

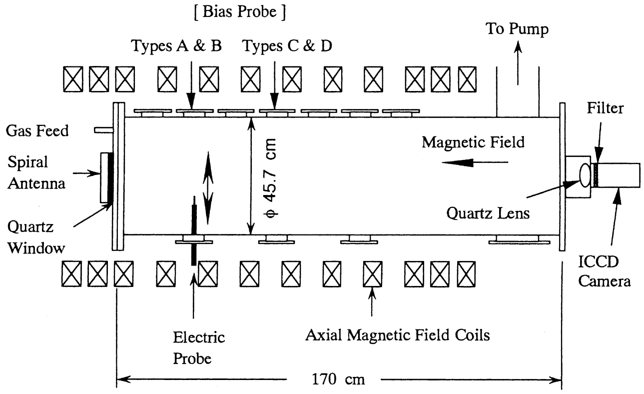

Fig. 1. Schematic view of experimental setup.

located on z (from the inner surface of the quartz window facing the antenna) = 30 cm, including a Mach probe [7] for the plasma flow measurements in the azimuthal direction. Plasma light was monitored by a CCD camera with an image intensifier and line filters. The target (before biasing) plasma density n_e and temperature T_e were in the wide ranges of 4×10^9–10^{13} cm^{-3} and 3–8 eV, respectively.

The four biasing probes, made of stainless steel, used in our experiments are shown in Fig. 2: (1) a metal disk ($z = 30$ cm), 3 cm in diameter with 1 cm thickness (type A); (2) two concentric cylinders ($z = 30$ cm), 10 cm and 30 cm in diameter with 5 cm width and 0.1 cm thickness (type B); (3) a ring ($z = 60$ cm), 9 cm and 18 cm in inner and outer diameters, respectively, with 0.02 cm thickness (type C); and (4) a metal disk ($z = 60$ cm), 5 cm in diameter with 0.02 cm thickness (type D). In order to feed currents from the power supply, two metal disks (type A) were also installed near the plasma outer region for the cases of types B, C and D. Note that the normal line of the electrode surface was parallel to the radial (axial) direction for the cases of types A and B (C and D). For the cases of types A and B (C and D), the filling pressures P were mainly 20 (0.09) mTorr and the diameters of insulating windows at the both ends of the machine, i.e. at $z = 0$ and 170 cm, were 21.5 (44.5) cm.

3. Experimental results

Here, we mention the results by the use of four types of electrodes. First, biasing the disk-type electrode (type A) was tried. Here, $P = 20$ mTorr and the input and net RF power [8], $P_{inp} \approx 500$ W and $P_{net} \approx 400$ W, respectively. The central T_e (slowly decreasing radial profile) and n_e (nearly parabolic radial profile) before biasing were ~ 3 eV and $\sim 10^{13}$ cm^{-3}, respectively. Since the most clear effect of biasing was observed when the disk was placed near the center of the plasma, the results below are the case for the disk placed in the central position.

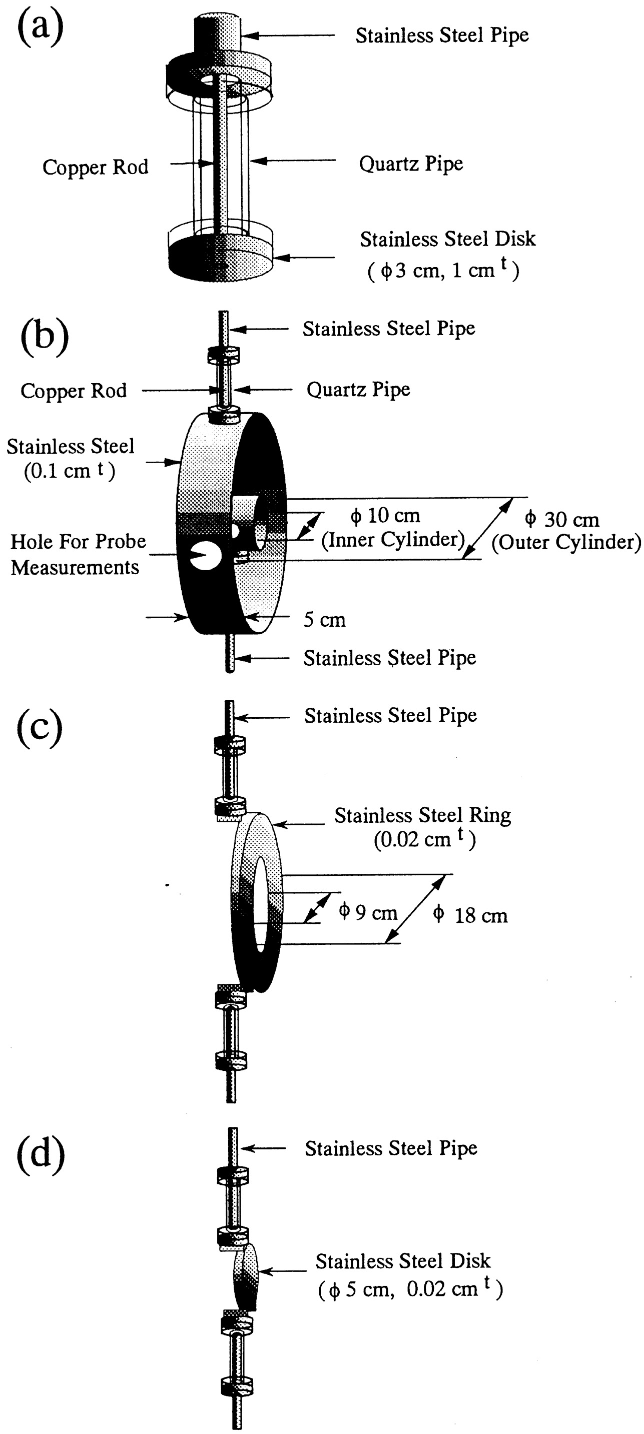

Fig. 2. Bias probes of (a) disk (type A), (b) cylinder (type B), (c) ring (type C) and (d) disk (type D) shapes.

The current (I)–voltage (V) characteristic of this disk was similar to that taken by a single Langmuir probe but the absolute value of I was much smaller than the expected value from the Langmuir probe theory by up to three orders of magnitude: $I = 2.6$ A at $V = 30$ V, whose product was about 20% of P_{net}, and I was unstable (oscillation) above $V = 30$ V. With an increase

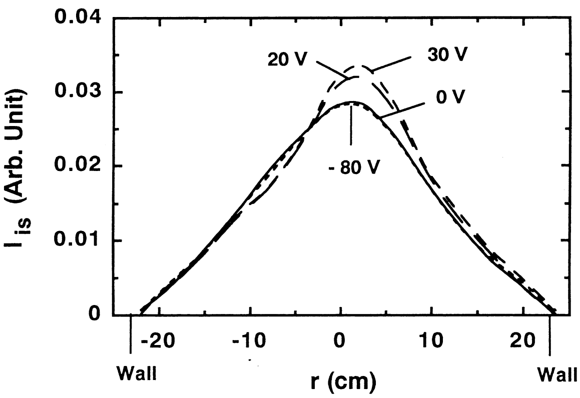

Fig. 3. Radial profiles of ion saturation current I_{is} with various bias voltages (disk shape, type A).

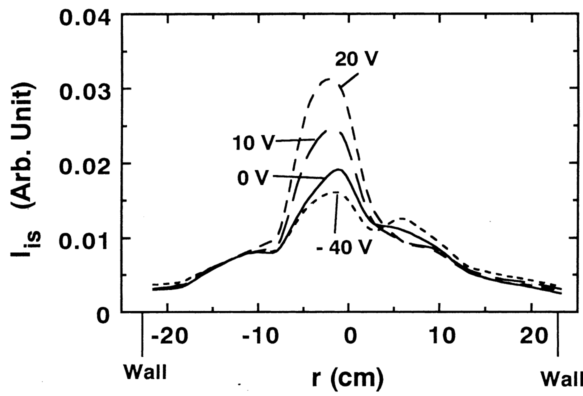

Fig. 4. Radial profiles of ion saturation current I_{is} with various bias voltages (cylinder shape, type B).

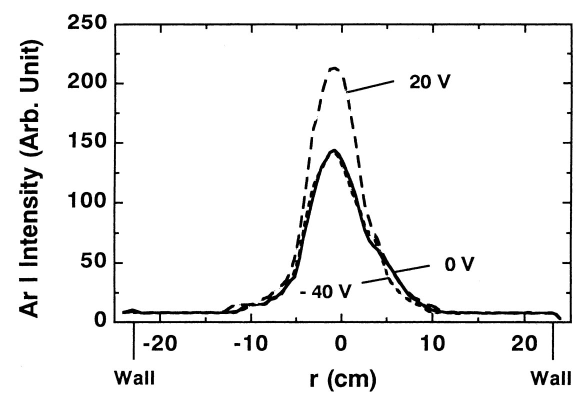

Fig. 5. Radial profiles of Ar I line intensity with various bias voltages (cylinder shape, type B).

in V from 0 V (positive voltage biasing), the ion saturation current I_{is} increased near the central region, as shown in Fig. 3. At $V=30$ V, an increase in I_{is} by 20% was observed, while for the negative biasing case this I_{is} changed little. A small decrease (increase) in T_e by less than 20% was observed for the positive (negative) biasing case. Therefore, the main change of I_{is} came from the n_e change. The plasma potential V_p was increased with an application of the positive biasing voltage, but the weak static radial electric field E_r has not been changed appreciably. For the negative biasing, the change of V_p was small.

Second, results on biasing the cylinder-type electrode (type B) are described with the same conditions of the RF power and filling pressure as the disk-type case. Since the inserted cylinders were large, distorted plasma profiles were observed: central T_e and n_e before biasing were ~ 5 eV and $\sim 5\times10^{12}$ cm^{-3}, respectively. For simplicity, the inner ring was voltage biased and the outer one was grounded, and the voltage power supply was connected between the two cylinders. The I–V characteristic was different from the disk-type case, and $I=6.5$ A and -5.2 A at $V=20$ V and -40 V, respectively. When V was biased to 20 V, a large increase in the I_{is} near the central plasma region (within the inner cylinder) by 60% was observed, as shown in Fig. 4. For the negative biasing case, there was not an appreciable change of I_{is} event though the bias current could not be neglected compared with the positive biasing case; the product of I and V at $V=20$ (-40) V corresponded to 33 (52)% of P_{net}.

There was a tendency for a small decrease (increase) in T_e for the positive (negative) biasing case. Optical measurements on Ar I (420 nm), as in Fig. 5, and Ar II (488 nm) line intensities by the CCD camera showed consistent results with the probe data, since these lines are expressed as a function of the plasma density and electron temperature (and neutral density in addition, for the Ar I line) [8]: For the positive biasing Ar I intensity increased due to the increase in n_e and Ar II increased only slightly mainly due to the temperature decrease. The plasma potential behavior was the same as the disk case (type A) and no clear change of E_r was found. This was supported by the Mach probe measurements on the result of a small azimuthal flow velocity (Mach number M, which is defined as the ratio of the flow velocity to the ion sound velocity, was well less than 0.1). Here, the ion (electron) Larmor radius was estimated to be roughly <2 cm (<0.1 cm), which was much smaller than the plasma radius. Note that E_r and the flow velocity are governed by the momentum balance equation. Here, the pressure gradient term in this equation was small, and in this higher pressure range of 20 mTorr compared with the cases described later, the mean free paths for the electron–ion collision and electron–neutral elastic collision were only orders of cm.

Third, results on the ring-type electrode (type C) are described. The similar effects on plasma parameters with the first and second cases (types A and B) described above were obtained when the RF power and filling pressure were the same. In order to see the pressure effect (and also plasma density effect), P was lowered to 0.09 mTorr, resulting in a smaller coupling power of $P_{net}=60$–70 W with $P_{inp}\approx400$ W. Here, the low central

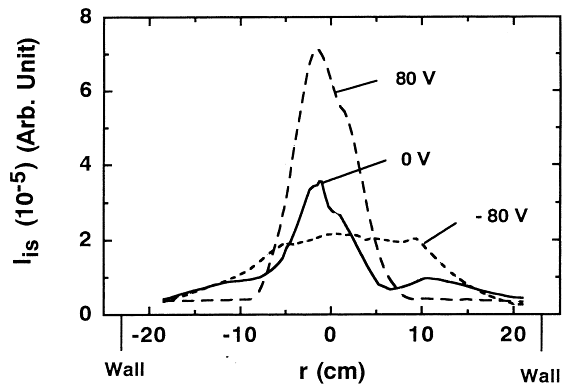

Fig. 6. Radial profiles of ion saturation current I_{is} with various bias voltages (ring shape, type C).

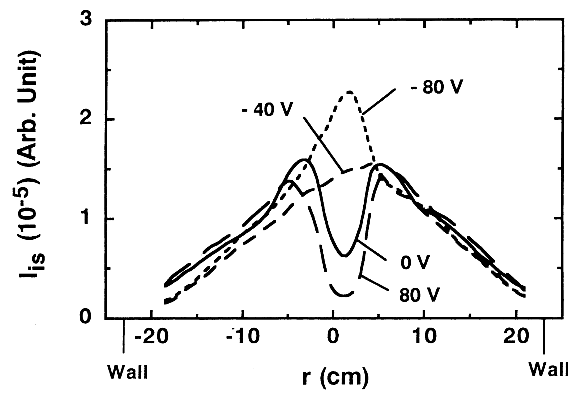

Fig. 7. Radial profiles of ion saturation current I_{is} with various bias voltages (disk shape, type D).

n_e of $\sim 10^{10}$ cm^{-3} with the relatively high T_e of ~ 7 eV was obtained before biasing. The bias current I of this electrode was small at 0.06 A and -0.025 A at $V=80$ V and -80 V, respectively. Note that the maximum product of V and I normalized by P_{net} was less than 10%. There was a tendency that the plasma potential V_p (T_e) increased (decreased) with an increase (decrease) in V in the positive (negative) biasing region.

Fig. 6 shows radial profiles of I_{is} under the different bias voltages. When V was between 0 V and ~ 30 V, I increased with V but radial profiles of I_{is} did not change appreciably. The amplitude of low frequency (10–15 kHz) oscillation of I_{is} was larger at $V \approx 30$ V, where the peak value of $I=0.065$ A was obtained, than those at the different bias voltages. Above this voltage of 30 V the saturation of I was observed, and the central peaking profile of I_{is} with an increase in the bias voltage V was obtained, e.g. near the center I_{is} increased by 100% at $V=80$ V, as in Fig. 6. On the contrary, with a decrease in V for the negative biasing case, I_{is} near the central (middle) region decreased (increased), resulting in the broad profiles. From the Mach probe measurements, the plasma column at the larger radius, i.e. outside the ring electrode region, rotated in the azimuthal direction when V was between ~ 30 V and ~ -20 V with $M<0.2$. Here, the mean free paths for electron–ion collision and electron–neutral elastic collision were >30 m and >2 m, respectively, which were larger than the device size.

Finally, results from the disk electrode (type D), are briefly described. Fig. 7 shows radial I_{is} profiles, changing the bias voltages under the same conditions of $P_{inp} \approx 400$ W and $P=0.09$ mTorr (low filling pressure and density with long mean free path) as in the case of the ring-type electrode (type C). Before biasing a large dip of I_{is} profiles in the central plasma region was observed due to the insertion of this electrode: I_{is} in the plasma center was only 40% of that at $r \approx 5$ cm (peak position, $n_e \approx 4 \times 10^9$ cm^{-3}). For the positive biasing case up to $V=80$ V with $I=0.035$ A, this dip of I_{is} profiles became larger. On the contrary, for the negative biasing case, I_{is} increased only near the central region ($r<5$ cm) with a decrease in V. This dip disappeared at $V \approx -30$ V and further decrease in V caused the peaked I_{is} profile. For the case of $V=-80$ V with $I=-0.015$ A (this current was smaller by a few times than that expected from the Langmuir probe theory), I_{is} in the plasma center was larger than that at $r=5$ cm for $V=0$ V by 50%. Here, the maximum product of I and V normalized by P_{net} was only $<5\%$. Measurements by the Mach probe showed that the plasma column rotated with $M<0.2$ in the outer plasma region for the case when V was between -20 V and 100 V.

4. Conclusion

Control of plasma profile by inserting various electrodes with voltage biasing was tried in the large diameter (45 cm) RF produced argon plasma in a wide range of the filling pressure. The results obtained are also useful for simulating the effects of inserting obstacles (such as substrates and electrodes) on the plasma characteristics. With an addition of positive DC biasing voltage $V=30$ V on the metal disk (type A) with $P=$ 20 mTorr, an increase in I_{is} by 20% was obtained near the central plasma region, while for the negative biasing case I_{is} changed little. For the case of biasing the inner one of two concentric cylinders (type B) to $V=20$ V, a large increase in I_{is} near the central plasma region by 60% was observed. Optical measurements on Ar I and Ar II line intensities exhibited consistent results with the probe data.

In the lower pressure region of $P=0.09$ mTorr with the use of the ring-type electrode (type C), the higher positive (negative) voltage biasing of $V=80$ (-80) V showed pronounced effects to obtain the peaked (broad) I_{is} profile, and the azimuthal plasma rotation was observed in the outer region of the plasma column. On the contrary, insertion of the disk electrode (type D) without the biasing, which was placed in the plasma center, in this low pressure region showed a large distortion of the I_{is} profile, i.e. a large dip in the central region, and the peaked profile was obtained for the negative biasing case.

References

[1] R.J. Taylor, M.L. Brown, B.D. Frial, H. Grote, J.R. Liberati, G.J. Morales, P. Pribyl, D. Darrow, M. Ono, Phys. Rev. Lett. 63 (1989) 2365.
[2] A. Tsushima, T. Mieno, M. Oertl, R. Hatakeyama, N. Sato, Phys. Rev. Lett. 56 (1986) 1815.
[3] A. Mase, A. Itakura, M. Inutake, K. Ishii, J.H. Jeong, K. Hattori, S. Miyoshi, Nucl. Fusion 31 (1991) 1725.
[4] O. Sakai, Y. Yasaka, R. Itatani, Phys. Rev. Lett. 70 (1993) 4071.
[5] S. Shinohara, S. Takechi, Y. Kawai, Jpn. J. Appl. Phys. 35 (1996) 4503.
[6] S. Shinohara, S. Takechi, N. Kaneda, Y. Kawai, Plasma Phys. Control. Fusion 39 (1997) 1479.
[7] P.C. Stangeby, Phys. Fluids 27 (1984) 2699.
[8] S. Shinohara, Y. Miyauchi, Y. Kawai, Plasma Phys. Control. Fusion 37 (1995) 1015.