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High Plasma Rotation Velocity and Density Transitions by Biased Electrodes in RF Produced, Magnetized Plasma

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Abstract

A large density profile modification was successfully obtained by voltage biasing to electrodes inserted in a RF (radio frequency) produced, magnetized plasma, and formation of strong shear of azimuthal plasma rotation velocity in a supersonic regime was found. For the case of biasing to an electrode near the central plasma region, two types of density transitions were observed in the outer plasma region: one was an oscillatory transition between two states, and the other was a transition from high to low density states with a large reduction of density fluctuations.

Keywords:
magnetized plasma, density profile, plasma potential, azimuthal rotation, $\boldsymbol{E} \times \boldsymbol{B}$ drift, density transition, density fluctuation

1. Introduction

Plasma profile is determined by the balance between the plasma generation and diffusion processes, and the control of the profile is very important in many fields of plasma. The structural formation of the electric field and a bifurcation in plasmas have been major concerns in the fields such as space plasma, nuclear fusion related to the enhanced magnetic confinement with the shear of so-called $\boldsymbol{E} \times \boldsymbol{B}$ rotation ($\boldsymbol{E}$: electric field, $\boldsymbol{B}$: magnetic field) [1] and application fields. Recently, a new kind of oscillatory transitions of density and potential in the Compact Helical System (CHS) was reported [2]. However, experimental data [3-9] are not enough as to control the density, potential and rotation profiles, which were connected with the transport and structure formation, from a basic viewpoint.

Here, in this paper, we have demonstrated the control of a large change of the density profile, in addition to the azimuthal rotation velocity in a supersonic regime (Mach number M, defined as the plasma flow velocity normalized by the ion sound velocity, was greater than unity) with a strong shear, by voltage biasing to inserted electrodes. Furthermore, we have shown two types of density transitions in the outer radial region of a biased electrode: one was an oscillation between two states, and the other was a transition from the higher density state with giant fluctuations to the lower state with small fluctuations.

2. Experimental Setup

The experimental system [7] is shown in Fig. 1. Argon plasma was produced by a four-turn spiral antenna at a pressure of P = 0.1 ~ 2 mTorr. The continuous output RF power and frequency of P_{RF} = 160 ~ 500 W and f_{RF} = 7 MHz, respectively, were applied to a linear device, 45 cm in diameter and 170 cm in axial length, with the uniform magnetic field of B = 500 G. In order to control the radial potential profile, we used ten concentric, segmented rings with a thickness of 0.03 cm

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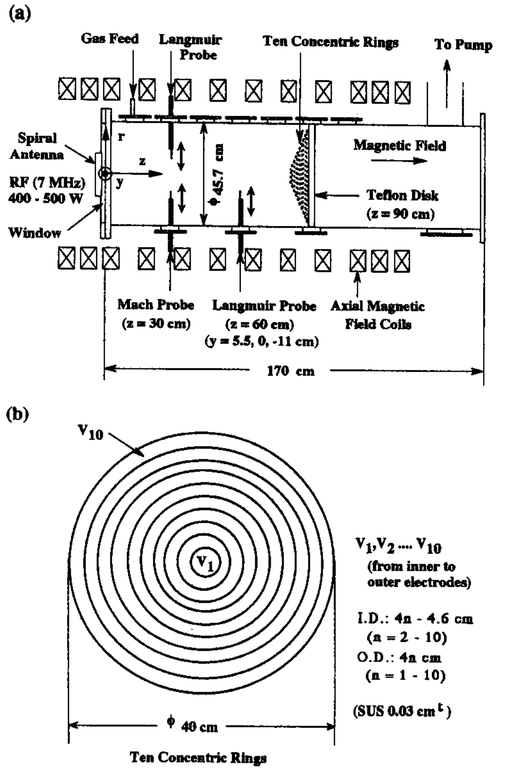

Fig. 1 Schematic view of (a) experimental setup and (b) biased electrodes with ten concentric rings.

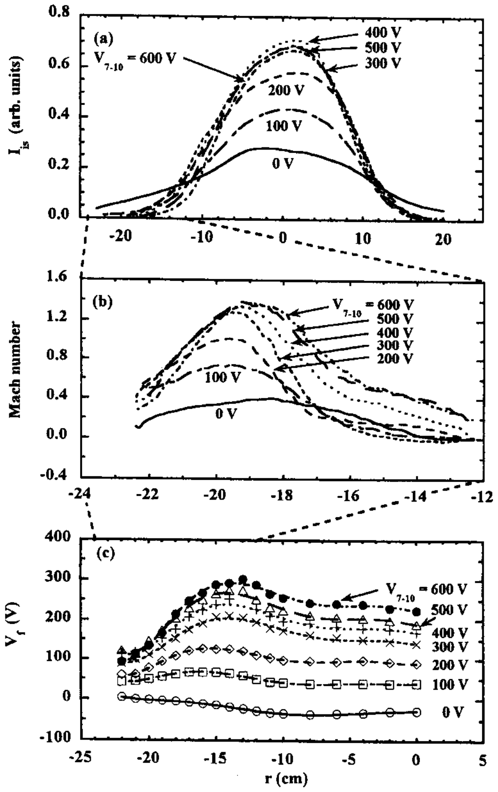

Fig. 2 Radial profile of (a) ion saturation current I_{is}, (b) Mach velocity M and (c) floating potential V_f, changing biased voltage $V_{7\text{-}10}$.

(in the axial direction) as biased electrodes (see Fig. 1 (b)). The inner and outer diameters of n-th ring (in order from the center) were $4n - 4.6$ cm ($2 \le n \le 10$) and $4n$ cm ($1 \le n \le 10$), respectively, and each ring was separated from the neighboring ones with an axial distance of 1.3 cm. The electrodes were put on the Teflon disk, 40 cm in diameter, to cover the plasma cross section at the axial direction of $z = 90$ cm from the window, which faces the spiral antenna.

The plasma parameters were measured by the Langmuir probes including the Mach probe, which is a directional probe, for the plasma flow measurements. The Mach probe (0.2 cm × 0.2 cm typically) was larger than the Debye length and smaller than the estimated ion Larmor radius ρ_i. The typical target (before biasing) plasma density n_e was in the range of $4 \times 10^9 \sim 2 \times 10^{11}$ cm^{-3} with the electron temperature $T_e = 3 \sim 6$ eV and estimated ion temperature < 1 eV ($\rho_i < 1$ cm).

3. Experimental Results

Figure 2 shows the radial profiles of the ion saturation current I_{is}, the Mach number (M) and the floating potential (V_f), changing the biased voltage ($V_b = 0 \sim 600$ V). Here, n_e is nearly proportional to I_{is}, since T_e did not change appreciably in the radial direction. As shown in Fig. 2(a) (Fig. 2(b)), with increasing V_b, change of this profile (affected region in the radial direction) was enhanced (broadened), but a gradual saturation of I_{is} with $V_b \sim 300$ V was obtained. Here, in this figure, $V_{7\text{-}10}$ means the applied voltage to the electrodes from Nos. 7 to 10, and $P = 0.16$ mTorr and $P_{RF} = 400$ W. In deriving the M value, for convenience, an unmagnetized model or a kinetic model with zero viscosity was employed: $K \sim 1.26$ for both cases, where $M = (1 / K) \ln R$ (R: ratio of the probe current facing upstream to that facing downstream) [10,11]. From Fig. 2 (b), the position of the maximum velocity was located on the outer edge region of biased electrodes, and the maximum velocity became large up to $M \sim 1.4$. Although there was an error in estimating the absolute velocity due the use of non-established theories, a gradual saturation of rotation velocity with $V_b \sim 300$ V was obtained, where observed maximum velocity was below the critical ionization velocity of $M \sim 2.5$, if exists, in our conditions [12]. This tendency of saturation of velocity corresponded

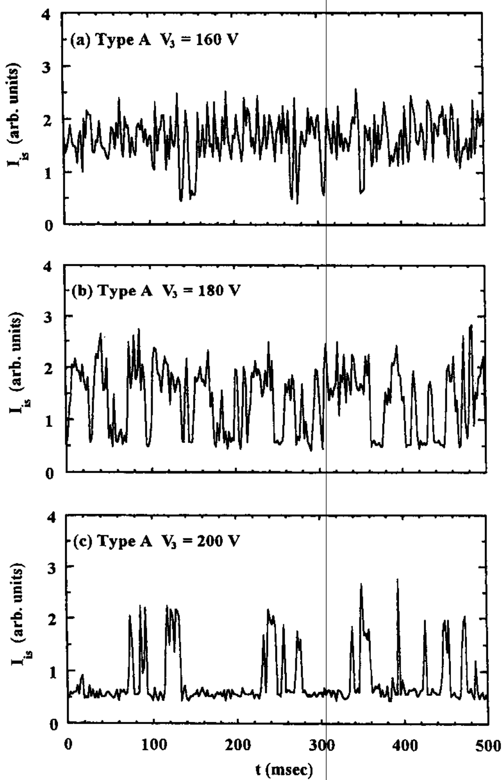

Fig. 3 Time evolution of ion saturation current I_{is} (r = −13 cm), for the biased voltage V_3 of (a) 160 V, (b) 180 V and (c) 200 V (they were different shots).

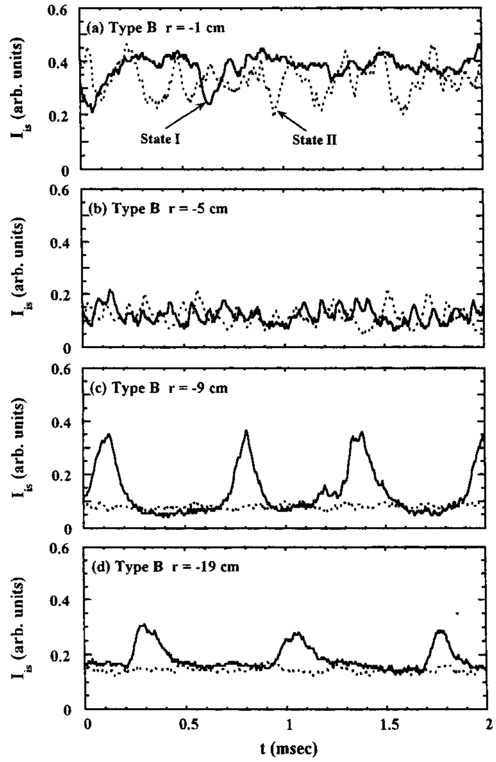

Fig. 4 Time evolution of ion saturation current I_{is}, (V_3 = 200 V) for the radial location r of (a) −1 cm, (b) −5 cm, (c) −9 cm and (d) −19 cm (Eight individual traces have different shots).

well with that of floating potential, as shown in Fig. 2(c).

Here, we will describe the new transition phenomena, i.e, self oscillatory and one way transitions (global structural changes) between two bistable states, observed by voltage biasing to the third ring electrode located near the central region. There were two types of transitions under the different conditions (type A: P = 1.6 mTorr and P_{RF} = 160 W, and type B: P = 0.16 mTorr and P_{RF} = 400 W). Figure 3 shows an example of the time evolution of I_{is} under the conditions of V_3 (this ring was distributed from r = 3.7 ~ 6 cm) = (a) 160 V, (b) 180 V and (c) 200 V (they were different shots) in the type A transition. For the lower biased voltage case of less than 140 V, only density fluctuations without a transition were observed (state I only, not shown). However, with increasing V_b, abrupt drops of I_{is} (and back transitions) appeared: the large density transition with a profile change from the states I to II was observed (see also Fig. 5(a)). Its transition rate and staying time in the state II gradually increased with increasing V_3, as is seen from Fig. 3, and finally only the state II existed by high voltage biasing. While the fluctuations of biased voltage were small of < 3 V and did not coincide with the I_{is} fluctuations, the biased current I_b (an order of 0.01 A) increased by a factor of about two, after the density tran-sitions to the state II, and the time of the I_b rise with an overshot positive spike was slightly earlier than that of the I_{is} drop.

An example of the type B transition is shown in Fig. 4 (time evolution of I_{is} with V_3 = 200 V for different radial positions). This density transition suddenly occurred: from a state with giant oscillations (state I, typical fluctuation frequency f = 1 ~ 2 kHz) to the other one with small fluctuations (state II, f = 2 ~ 5 kHz) in the outer region of a biased electrode. Once this transition took place, the state II stayed all the time with a low possibility to be back to the state I again, which is completely different from the type A. Lowering biased voltage less than 200 V caused no change of states (state I was found all the time).

The change of radial profiles of I_{is} with transitions is shown in Fig. 5. In both types of A and B, closed

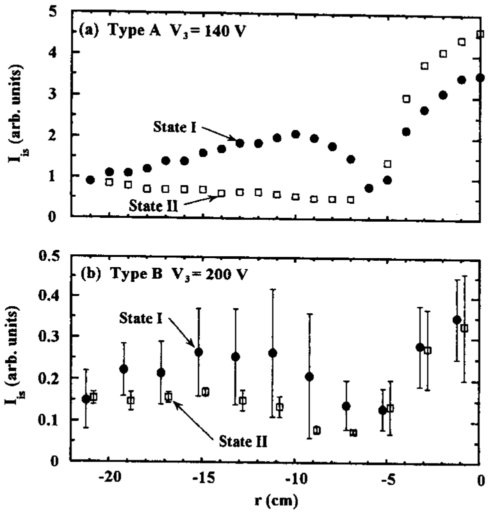

Fig. 5 Radial profile of ion saturation current I_{is}, in the (a) Type A and (b) Type B transitions. Here, vertical lines indicate typical fluctuation amplitude of I_{is}.

circles and open boxes indicate average value of I_{is} in the states I and II, respectively. For the type B case, vertical lines show typical amplitudes of oscillations. The average value of I_{is} decreased after the transitions from the states I to II, in the outer region of biased electrode. In the central region, the average value of I_{is} increased after the type A transition, but it did not change after the type B transition (no change of large fluctuation level). For the case of type B, a rigid plasma rotation was found near the biased electrode with $M < 0.5$, and rotation speed gradually decreased outside this electrode. However, a relationship between density transitions and, e.g., a shear velocity is still an open question to be solved. Although new transition phenomena were observed, a further investigation on the spatial and temporal behaviors of plasma parameters is necessary on clarifying the conditions and mechanisms of these transitions.

4. Conclusions

By the voltage biasing to the outer plasma region of electrodes inserted in a RF produced, magnetized plasma, density profiles became gradually peaked with increasing V_b (up to 600 V). At the same time, a local maximum azimuthal velocity increased near the edge of plasma column. However, a gradual saturation of changing profiles of I_{is}, V_f and M with $V_b \sim 300$ V was obtained: saturation values were $M \sim 1.4$ and $V_f \sim 300$ V.

With the use of the electrode (V_3) located in the inner plasma region, two different types of transition phenomena with reductions of the electron density in the outer region were observed. On the type A transition (an oscillation between the states I and II), its transition rate and staying time in the state II gradually increased with increasing V_3, and the state II became dominant for the high V_3 case. The type B transition (from the states I to II) suddenly occurred: from the first state with the giant oscillations to the second one with small fluctuations with a low possibility to be back to the initial state.

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References

[1] K.H. Burrell, Phys. Plasmas **4**, 1499 (1997).
[2] A. Fujisawa *et al.*, Phys. Rev. Lett. **81**, 2256 (1998).
[3] A. Tsushima and N. Sato, J. Phys. Soc. Jpn. **60**, 2665 (1991).
[4] A. Mase, A. Itakura, M. Inutake, K. Ishii, J.H. Jeong, K. Hattori and S. Miyoshi, Nucl. Fusion **31**, 1725 (1991).
[5] G.D. Severn, N. Hershkowitz, R.A. Breun and J.R. Ferron, Phys. Fluids B **3**, 114 (1991).
[6] S. Shinohara, H. Tsuji, T. Yoshinaka and Y. Kawai, Surf. Coat. Technol. **112**, 20 (1999).
[7] S. Shinohara, N. Matsuoka and T. Yoshinaka, Jpn. J. Appl. Phys. **38**, 4321 (1999).
[8] S. Shinohara, N. Matsuoka and S. Matsuyama, Trans. Fusion Technol. **39**, 358 (2001).
[9] S. Shinohara, N. Matsuoka and S. Matsuyama, Phys. Plasmas **8**, 1154 (2001).
[10] K-S. Chung and I.H. Hutchinson, Phys. Fluids B **1**, 2229 (1989).
[11] M. Hudis and L.M. Lidsky, J. Appl. Phys. **41**, 5011 (1970).
[12] H. Alfvén, Rev. Mod. Phys. **32**, 710 (1960).