CONTROL OF ELECTRON DENSITY AND ROTATION PROFILES BY VOLTAGE BIASED ELECTRODES IN RF PRODUCED PLASMA

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ABSTRACT

Using voltage biasing to ten concentric rings, profiles of plasma density and high azimuthal rotation velocity in a supersonic regime were controlled under three magnetic field configurations in a cylindrical magnetized RF produced plasma. Low frequency (< 4 kHz) density oscillation was identified as a drift wave type: propagation in the electron diamagnetic direction, which is opposite to the edge plasma rotation.

I. INTRODUCTION

A plasma flow with instabilities has been investigated in various fields such as nuclear fusion, space plasma and application fields. As for rotating plasmas with an axial magnetic field, historically, studies of instabilities with an electrostatic field $\boldsymbol{E}$ leading to a velocity shear, were done using Q-machines.[1] Recently, probe biasing (voltage) was attempted to modify the potential profile in tokamaks[2] in terms of the enhanced confinement, partly due to the change of $\boldsymbol{E}\times\boldsymbol{B}$ velocity shear ($\boldsymbol{B}$: magnetic field). In mirror-based devices, there is an increasing interest in the stabilization of low-frequency instabilities such as flute and drift modes by biased end plates.[3-6] However, there have been few experiments[7,8] to show a large change of the density profile with high rotation velocity, whose findings become the critical issues in the various fields.

Here, we have demonstrated the control of a large profile change of the rotation velocity in a supersonic regime (Mach number M, defined as the plasma flow velocity normalized by the ion sound velocity C_s, is greater than 1) with a strong velocity shear (high vorticity), in addition to the density control from hollow to peaked profiles. Using biased electrodes, under the different magnetic field configurations, these profiles were varied with low frequency fluctuations (drift wave type with a fundamental frequency of < 4 kHz) propagated in the opposite direction of the edge plasma rotation.

II. EXPERIMENTAL SETUP

The experimental system was described elsewhere.[8,9] Argon plasma was produced by a spiral antenna at a pressure of P = 0.1 - 0.2 mTorr. The RF power and frequency of 400-500 W and 7 MHz, respectively, were applied to a linear device, 45 cm in diameter and 170 cm in axial length. Three magnetic field configurations were tested: uniform field (case A, magnetic field strength B = 500 G), good (case B, B = 360 - 700 G) and bad (case C: mirror field, B = 220 - 550 G) curvatures. Plasma parameters were measured by the Langmuir probes, including the Mach probe for the plasma flow measurements. Typical target 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 and estimated ion temperature < 1 eV (ion Larmor radius < 1 cm). In order to control the radial potential profile, we used ten concentric rings[9] as biased electrodes, which are put on the Teflon disk, 40 cm in diameter, to cover the plasma cross section in the axial position of z = 90 cm from the window. Here, the inner and outer diameters of the n-th ring in order from the center were $4n$ - 4.6 cm (n = 2 - 10) and $4n$ cm (n = 1 - 10), respectively.

III. EXPERIMENTAL RESULTS

Figure 1 shows radial profiles of ion saturation current I_{is}, changing the biased voltage V_b and magnetic field configurations. The electrode was numbered from the center to the outwards, and V_b up to 280 V could be applied, contrary to the experiment[10] that the plasma was not sustained at V_b > 60 - 70 V in a tandem mirror. From this figure, with the increase in V_b or the decrease in the waist size of the plasma near the central axial region (from case C to B through A), this profile was more peaked for the case of the biasing to the outer electrodes. Note that the plasma could feel the biased voltage along the magnetic field lines from the electrodes due to the longer electron mean free path (mainly dominated by the electron-neutral collision) than the device size. Figures 2 and 3 show I_{is} profiles changing the biased position. A hollow (peaked) profile was obtained with the positive biasing to the inner (outer) electrodes, consistent with the previous results,[7,8] and with the increase in the number of biased electrodes, an affected region was enhanced. A uniform profile could be also realized, e.g., the diameter where I_{is} was within ± 8 % was 33 cm, whose results are important for developing plasma sources.

Figure 4 (5) shows radial profiles of an azimuthal rotation velocity, changing V_b and magnetic field configurations (biased position). A positive value of M shows an ion diamagnetic direction. Since it is difficult to estimate the correct M value, for convenience, unmagnetized[11] or kinetic[12] models with zero viscosity were employed: $K\sim$ 1.26 and $M = (1/K)\ln R$ (R: ratio

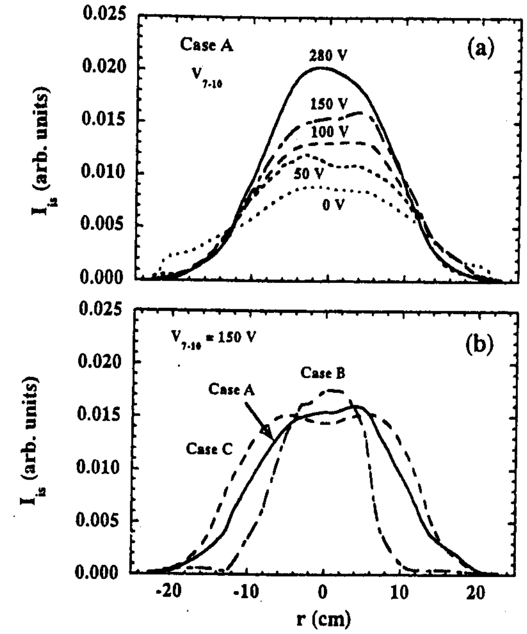

Fig. 1 Radial profiles of I_{is}, changing (a) V_b and (b) magnetic field configurations (outer electrodes).

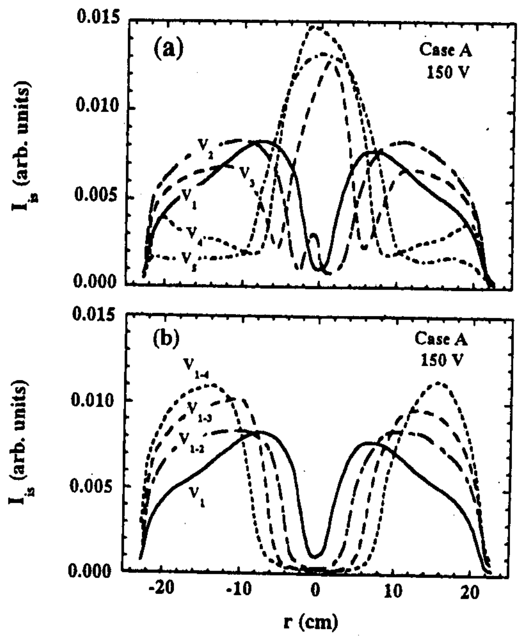

Fig. 2 Radial profiles of I_{is}, changing biased position (inner electrodes).

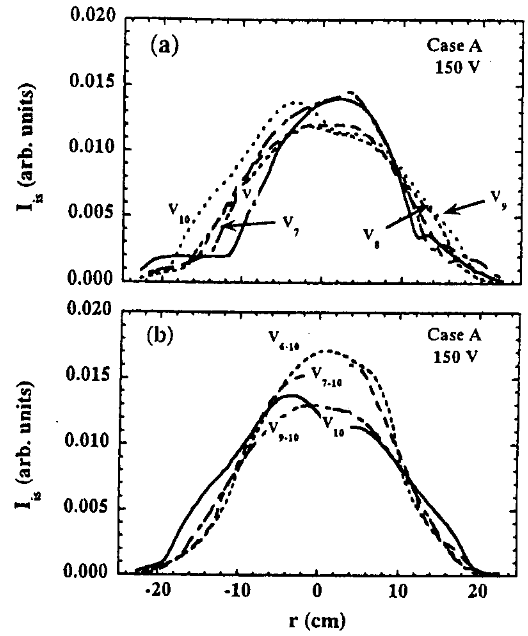

Fig. 3 Radial profiles of I_{is}, changing biased position (outer electrodes).

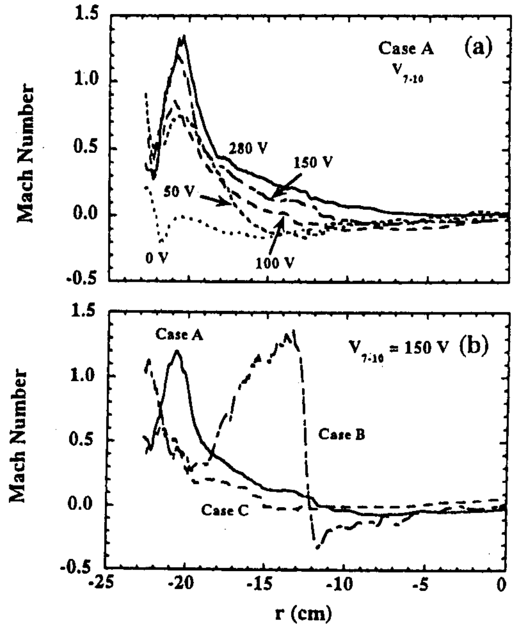

Fig. 4 Radial profiles of rotation velocity, changing (a) V_b and (b) magnetic field configurations (outer electrodes).

of the probe current facing upstream to downstream). Figure 4 (a) shows that edge velocity and its shear were enhanced with V_b (see also Fig. 1 (a)): M was up to 1.4 and z component of vorticity Ω_z near the velocity peak was as high as $\sim 3\times10^5$ 1/s ($\sim 7\times10^5$ 1/s for the case B in Fig. 4 (b)), and a polarity change of Ω_z was also found. Figure 4 (b) show a shift of the peak in the radial direction due to the change of the magnetic field lines. From Figs. 4 and 5, control of a strong velocity shear region at any plasma radial position was realized. Here, $M > 1$ is larger than a value in the azimuthal direction in fusion torus machines, and is considered to be obtained without a shock due to the motion across

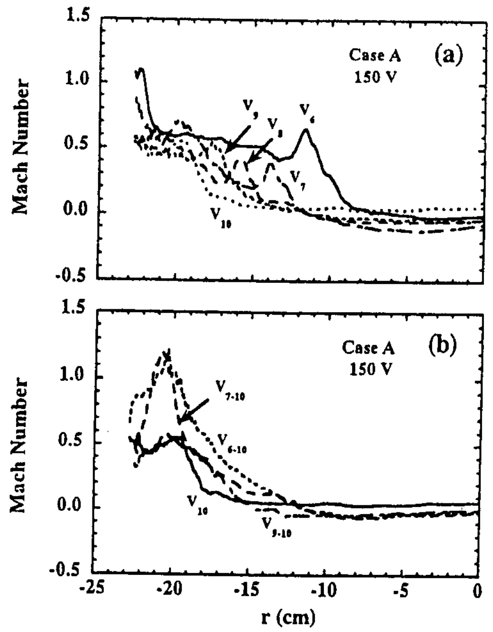

Fig. 5 Radial profiles of rotation velocity, changing biased position (outer electrodes).

the magnetic field. The Alfvén wave velocity was well greater than C_s by more than two orders of magnitude, excluding a perpendicular shock condition. Although there was an error in estimating the absolute velocity due to use of non-established theories, no clear indication of a fully saturation velocity with up to V_b = 280 V was found, where the obtained velocity was below the critical ionization one, proposed by Alfvén, of M ~2.5 in our conditions.

Typical width of the velocity peak was nearly the same as radial width of each electrode and was slightly smaller than a magnetic sheath[13] expressed as C_s/ω_{ci} (~ 3 cm in our experiments), where ω_{ci} is ion cyclotron angular frequency. Nearly rigid rotation profile was also realized with a proper voltage biasing, e.g., for the case A as well as for the use of three concentric rings.[8] From the force balance equation in the radial direction, azimuthal velocity v_θ in the outer plasma region may be roughly expressed as a summation of $\boldsymbol{E}\times\boldsymbol{B}$ drift (positive $\boldsymbol{E}$ near the plasma edge was induced for the case of the positive biasing to the outer electrodes), $(\nu_i/\omega_{ci})\, v_r$ and $(v_r/\omega_{ci})\,(\partial v_r/\partial r)$. The centrifugal force v_θ^2/r ($v_\theta/r\,\omega_{ci}$ < 0.15 in this region), ion pressure gradient and radial current terms can be neglected. Here, ν_i and v_r are ion neutral collision frequency and radial flow velocity, respectively. Approaching the plasma edge, with the use of the outer biased electrodes, the third term became larger due to the larger radial ion flow (and also axial electron flow due to the total ambipolar condition) confirmed by a preliminary Mach probe measurement,

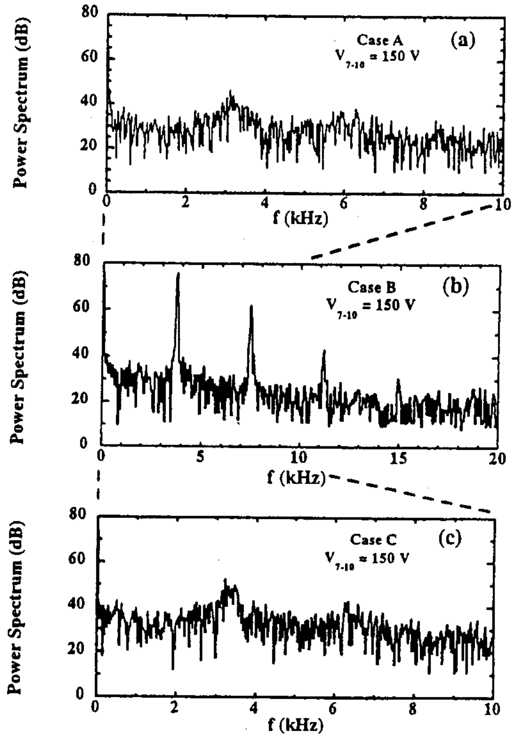

Fig. 6 Power spectra of I_{is} under three magnetic field configurations (outer electrodes).

although primary driven mechanism was $\boldsymbol{E}\times\boldsymbol{B}$ drift.

Changing the biased condition, electrostatic fluctuations were studied. Figure 6 shows power spectra of I_{is} under three magnetic field configurations with positive biasing to the outer electrodes. For the cases A and C, observed fluctuations had more broad spectra and slightly lower fundamental frequencies than those in case B due to the lower maximum density gradient. The amplitude of this fluctuation normalized by I_{is} was larger near the edge and/or with V_b. The propagating direction was in the electron diamagnetic one, opposite to the edge plasma rotation with the same order of magnitude: the fundamental frequency was < 4 kHz with up to fourth harmonics appeared for the case B. This frequency was 0.2 time of the argon ion cyclotron frequency, and it corresponded to the rotation velocity with M = -0.8 at r = 11 cm. Here, in observing fluctuations in the plasma, a picture using a Doppler shifted frequency by a rigid plasma rotation could not be employed in our experiment due to the strong velocity shear.

From the following results, the observed fluctuation were identified as a drift wave type, and rotational, Kelvin-Helmholtz and other shear driven instabilities could be excluded: i) azimuthal mode number was one, ii) phases of this fluctuation in the radial and axial directions were nearly the same (parallel wavenumber was less than 1 m^{-1}), iii) fluctuations were global (rigid rotation), iv) amplitude of this fluctuation was larger near

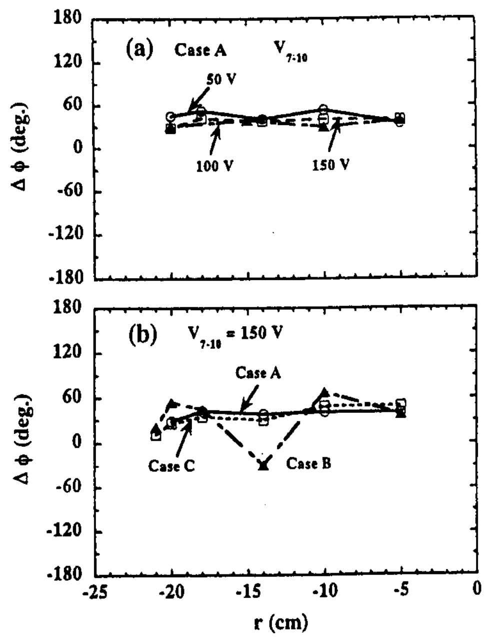

Fig. 7 Radial profiles of phase between fluctuation components of I_{is} and ϕ, changing (a) V_b and (b) magnetic field configurations (outer electrodes).

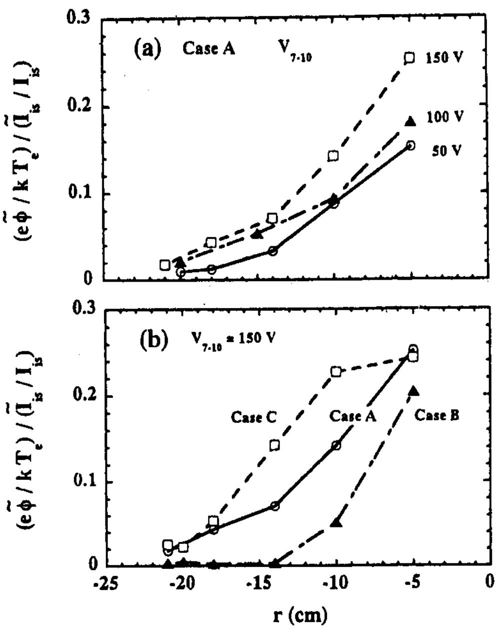

Fig. 8 Radial profiles of ratio of relative fluctuation amplitude of I_{is} to that of ϕ, changing (a) V_b and (b) magnetic field configurations (outer electrodes).

the region with large density gradient, v) observed fundamental frequency was nearly the same as the estimated frequency of the electron diamagnetic frequency in this region where almost no plasma rotation was found, vi) density fluctuation led potential one by 30 - 50 degrees (see Fig. 7), and vii) fluctuation amplitude of potential ϕ normalized by T_e was less than the amplitude of this I_{is} fluctuation by mean I_{is} (especially near the plasma edge, see Fig. 8).

Although fully computational calculation has not been done, from the simple numerical analysis[14] using some assumptions, the characteristics of this fluctuation could be qualitatively understood as this drift wave. For the case of the biasing to outer electrodes, we could not expect the stabilization of the drift wave by small connection length (roughly axial device size shorter than 20 λ_n is needed[15] (λ_n: scale length of the density gradient)), and by good curvature for the case B (roughly radius of field curvature less than 2 λ_n is needed [15]), since λ_n became shorter with the increase in V_b.

IV. CONCLUSION

Control of density and rotation profiles, leading to a very strong velocity shear in a supersonic regime, was successfully demonstrated in a cylindrical magnetized plasma, using concentric biased rings under different magnetic configurations. Low frequency density oscillation, identified as a drift wave type, propagated in a reverse direction to the edge plasma rotation.

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