Establishment of strong velocity shear and plasma density profile modification with associated low frequency fluctuations

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Strong shear of azimuthal plasma rotation velocity and a large density profile modification from a hollow to peaked profiles were successfully obtained in a cylindrical magnetized plasma, using voltage biased electrodes. The shear region and density profiles could be finely controlled by changing the voltage biased position as well as by the magnetic field configurations. A low frequency (<4 kHz) density oscillation was identified as a drift wave type: propagation in the electron diamagnetic direction with a rigid rotation (Mach number $M \sim -1$ at the edge), opposite to the direction of the edge plasma rotation with $M \sim 1$. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1350663]

I. INTRODUCTION

Fluid flow (hydrodynamic)[1] has been investigated to supply many physically interesting understandings so far, and plasma flow (magnetohydrodynamic), including a rotational flow with associated instabilities (nonlinear self-organizing phenomena), has been attracting many researchers in various fields, such as space plasma,[2] nuclear fusion related to the enhanced magnetic confinement (bifurcation) with the shear of so-called **E**×**B** rotation (**E**: electric field, **B**: magnetic field),[3] and application fields (isotope separation,[4] propulsion in space,[5] plasma processing,[6] environment,[7] etc.). These plasmas often exhibit inherent, similar, and universal characteristics in spite of the different parameter regimes.

As for rotating plasmas in the basic field with an axial magnetic field, historically, studies on instabilities brought about by changing the **E** profile leading to the velocity shear were done using *Q*-machines.[8,9] Also the instabilities were investigated in a non-neutral plasma.[10] It is important to understand the formation mechanism of the transverse component of **E**, so that the desired **E**×**B** azimuthal rotation[3] can be induced. The pulsing of the electrostatic potential was first observed to change the transport.[11] The parallel component of **E** is also interesting,[12] e.g., as a double layer[13] related to particle acceleration in the aurora phenomena and a thermal barrier in a tandem mirror.[12,14] Recently, probe biasing (voltage) has been attempted in order to modify the potential profile in a tokamak[15] in terms of the enhanced plasma confinement, partly due to the change of **E**×**B** velocity shear. In mirror-based devices, there is an increasing interest in the stabilization of low-frequency instabilities, such as flute and drift modes, and an interest in the wave excitation with a strong shear.[16–21] However, in contrast to this active research, there have been few experiments[22,23] to show a large change of the density profile with high azimuthal rotation velocity, which is connected with transport, in a controlled manner from a basic viewpoint. This topic is expected to become a critical issue in the various fields mentioned previously.

In this paper, we demonstrate for the first time the control of large profile change of the azimuthal rotation velocity in a supersonic regime (Mach number *M*, defined as the plasma flow velocity normalized by the ion sound velocity C_s, was greater than unity) with a strong shear, i.e., high vorticity, in addition to the density control from a hollow to peaked profiles. Using ten-separated voltage biased electrodes, under various magnetic field configurations, the plasma rotation and density profiles were finely varied with the associated low frequency fluctuations (fundamental frequency <4 kHz) propagated in the opposite direction of the edge plasma rotation. To our knowledge, novel control of this high *M* with a strong shear, not temporally, and of large density profile change have not been attempted previously. These results will contribute to many plasma application fields (e.g., plasma source and an isotope separation), as well as to the profound understanding of the characteristics of plasma fluids and stabilities.

II. EXPERIMENTAL SETUP

The experimental system used is shown in Fig. 1.[23,24] Argon plasma was produced by a four-turn spiral antenna at a pressure of $P = 0.1-0.2$ mTorr. Continuous output 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) field curvatures.

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

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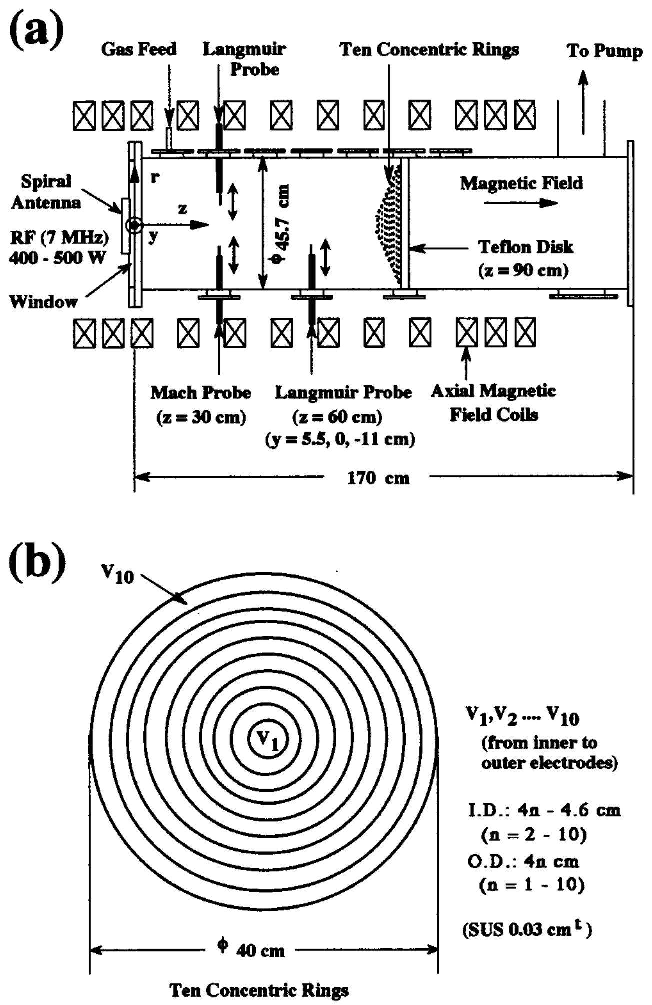

FIG. 1. Schematic view of (a) experimental setup and (b) biased electrodes with ten concentric rings.

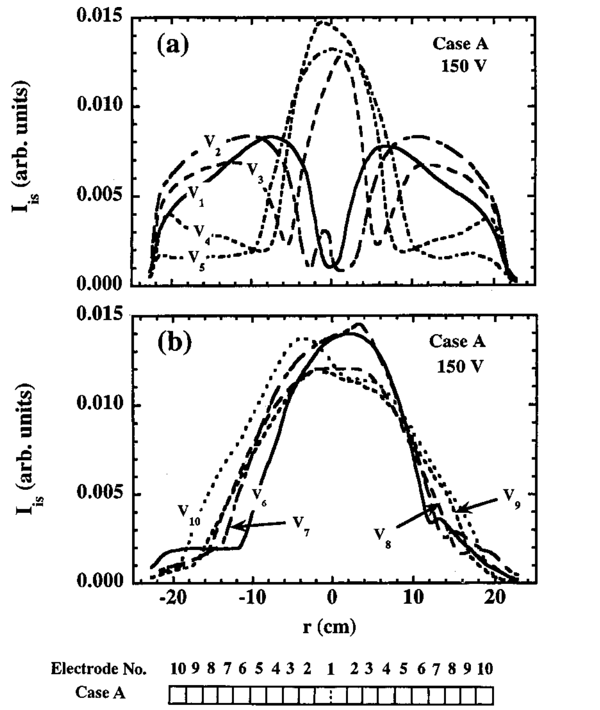

FIG. 2. Radial profiles of ion saturation current, I_{is}, changing a position of biased electrode (case A: biased voltage $V_b = 150$ V). Radial positions of the electrodes are also shown for reference.

<1 cm). In order to control the radial potential profile, we used ten concentric, segmented rings[23] with thickness of 0.03 cm (in the axial direction) as biased electrodes [see Fig. 1(b)]. The inner and outer diameters of the nth ring (in order from the center) were $4n - 4.6$ cm ($2 \leqslant n \leqslant 10$) and $4n$ cm ($1 \leqslant n \leqslant 10$), respectively, and each ring was separated from the neighboring ones by an axial distance of 1.3 cm. The electrodes were placed on a Teflon™ disk, 40 cm in diameter, to cover the plasma cross section at the axial position of $z = 90$ cm from the window, which faces the spiral antenna.

III. EXPERIMENTAL RESULTS

Figure 2 shows the radial profiles of the ion saturation current I_{is} for different biasing position (case A: bias voltage $V_b = 150$ V). Here, V_b up to 280 V (see Fig. 3) could be successfully applied, contrary to the result of an experiment[25] that indicated that the plasma was not sustained at $V_b > 60$–70 V in a tandem mirror. A dip in n_e, which is nearly proportional to I_{is} since T_e did not change appreciably in the radial direction, was obtained at the same radial position as the biased electrode: A hollow (peaked) profile was obtained with positive biasing to the inner (outer) electrode, which was consistent with previous results in low pressure conditions less than 1 mTorr.[22,23] In addition, with the increase in V_b (number of biased electrodes), the change of this profile (affected region in the radial direction) was enhanced (broadened). By a proper choice of applied voltages to electrodes, a very uniform profile also could be obtained. This profile had an effective diameter defined as the region where I_{is} was within $\pm 8\%$ of 33 cm for $V_1 = V_2 = -70$ V, $V_3 = V_4 = -50$ V, and $V_9 = V_{10} = -150$ V (other electrodes were floating). These results might be an important basis for developing plasma sources for applications such as plasma processing,[6] beam sources, accelerators, and lasers.

Figure 3 shows radial profiles of the azimuthal rotation velocity, u_θ normalized by C_s, i.e., M, for different plasma conditions (strong velocity shear formation). Here, a positive value of Mach number M in the azimuthal direction shows a rotation in the ion diamagnetic direction. Although there are a number of theories, e.g., Refs. 26–28, on estimating the plasma flow parallel to the magnetic field and trials on estimating the azimuthal (perpendicular) flow, e.g., Refs. 29 and 30, it is difficult to estimate the correct value of M in the perpendicular direction. Here, for convenience, an unmagnetized model[26] or a kinetic model[28] 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 downstream). Note that in our experiments, the size of the Mach probe ($0.2\,\text{cm} \times 0.2\,\text{cm}$ typically) is larger than the Debye length and is smaller than the estimated ion Larmor radius ρ_i. From Fig. 3(a), which has the same conditions as Fig. 2(b), a local maximum velocity of $M \sim 0.5$ was obtained just near the

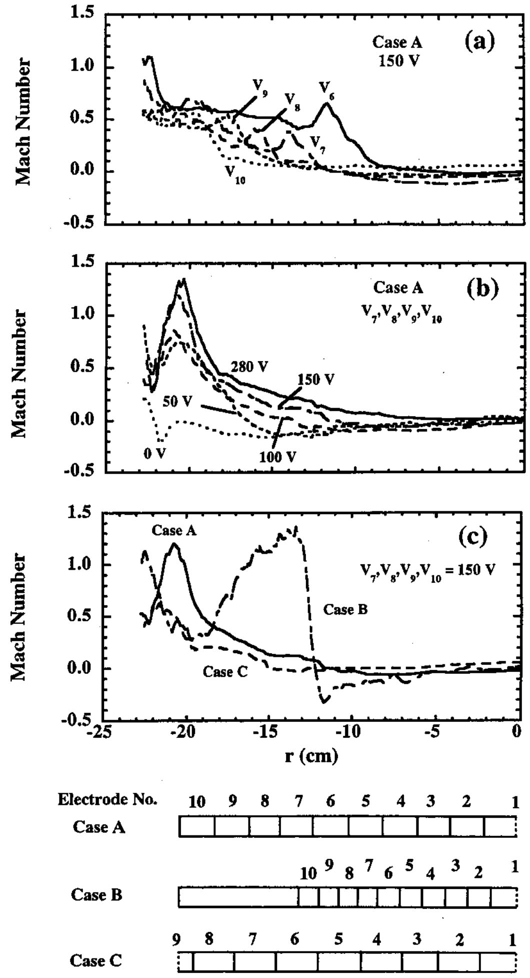

FIG. 3. Radial profiles of Mach number M in the azimuthal direction, changing (a) position of biased electrode (case A: biased voltage $V_b=150\,\mathrm{V}$), (b) V_b with the use of Nos. 7–10 electrodes (case A), and (c) magnetic field configuration with the use of Nos. 7–10 electrodes ($V_b=150\,\mathrm{V}$). The expected radial biasing position for each electrode is also shown for three cases of A, B, and C. This position in the central region at $z=30$ cm was traced along the magnetic field lines coming from each electrode positioned at $z=90$ cm.

edge of the outer side of a given biased electrode: strong velocity shear in the intermediate radial region was first realized, and a change of polarity of the vorticity Ω_z (axial component of $\nabla\times\mathbf{u}$ ($\mathbf{u}$: velocity)) across the maximum velocity region was achieved: absolute value of Ω_z was $\sim 9\times 10^4$ l/s from the slope near the maximum velocity region. Here, the derivative in the azimuthal direction in deriving the vorticity could be neglected from the results in the measurement. The typical width of the velocity peak was nearly the same as the radial width (2.3 cm) of each electrode and was slightly smaller than the magnetic sheath expressed as several times ρ_i or as C_s/ω_{ci} from Ref. 31 ($\leqslant 3$ cm in our experiments), where ω_{ci} is the ion cyclotron angular frequency. Note that a nearly rigid rotation profile was also obtained with proper voltage biasing, e.g., for case A with the present use of ten concentric rings as well as with the use of three rings.[23]

Figure 3(b) shows that the edge velocity shear was enhanced with the increase in the biased voltage V_b: M was up to 1.4 and Ω_z was as high as $\sim 3\times 10^5$ l/s. Here, the condition of $M>1$ obtained in the azimuthal direction is larger than the value generally obtained in fusion torus machines. We believe that this is generated without a shock, due to the motion across the magnetic field (not along the field). The Alfvén wave velocity was larger than the ion sound velocity by more than two orders of magnitude in our experiment, which excluded the possibility to have a perpendicular shock. Although there may be an error in estimating the absolute velocity due to the use of the nonestablished theories mentioned previously, a gradual saturation of rotation velocity with biased voltage up to $V_b=280\,\mathrm{V}$ was obtained. The velocity observed so far was below the critical ionization velocity of $M\sim 2.5$, if this exists, in our conditions.[32] Mostly, we had results with $B=500\,\mathrm{G}$, but there was a tendency that M became saturated at ~ 1.6 with the field more than several hundred G, keeping V_b constant of 150 V, which is consistent with the previous results for the three ring case.[23]

Even under the various magnetic configurations, the plasma could still feel the biased voltage along the curved field lines from the electrodes due to the electron mean free path (mainly dominated by electron–neutral collisions) being longer than the device size, as shown in Fig. 3(c). Since case B (C) had the smaller (larger) waist near the central region in the axial direction (e.g., $z=30$–60 cm) than that in the end section at $z=90$ cm from the field configurations, the I_{is} profile was peaked (broadened) and had smaller (larger) effective radius than those for case A, and azimuthal velocity profiles had the corresponding patterns reflecting this field configuration. Here, M was again up to 1.4 and a large velocity change (distinct velocity barrier) was found, in which Ω_z at radial position r of 12–13 cm was as high as $\sim 7\times 10^5$ l/s for case B.

From the force balance equation in the radial direction, the azimuthal velocity u_θ in the outer plasma region (in the radial direction) may be roughly expressed as a summation of three terms of $\mathbf{E}\times\mathbf{B}$ drift (positive radial electric field near the plasma edge was induced for the case of the positive biasing to the outer region of electrodes), $(\nu_i/\omega_{ci})u_r$, and $(u_r/\omega_{ci})(\partial u_r/\partial r)$. Here, ν_r and u_r are the ion neutral collision frequency and radial flow velocity, respectively, and centrifugal force u_θ^2/r ($u_\theta/r\omega_{ci}<0.15$ in this outer region), ion pressure gradient, and radial current terms could be neglected for our conditions. Approaching the plasma edge, for the case of biasing the electrodes in the outer region, the third term became larger due to the larger radial ion flow. This flow (also the axial electron flow due to a requirement of the total ambipolar condition) was confirmed by a preliminary measurement using a Mach probe, although the primary driven mechanism was $\mathbf{E}\times\mathbf{B}$ drift.

Fluctuations of the electrostatic component were studied, changing the biased conditions. Figure 4 shows an example of the time evolution of (a) fluctuating ion saturation current I_{is} and (b) power spectrum of I_{is} for case B with positive biasing to the outer region of the electrodes. Here, y means the vertical axis in the plane of the plasma cross section, which has r and y axes (see Fig. 1). From Fig. 4(a), it can be seen that propagation was in the electron diamagnetic direc-

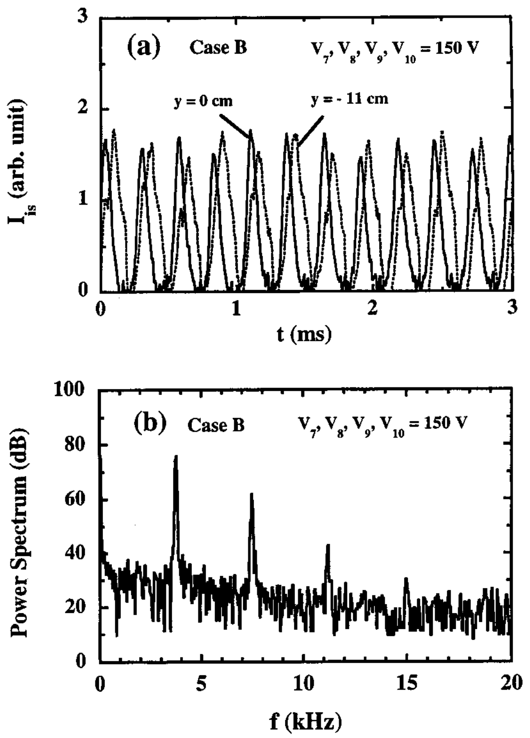

FIG. 4. (a) Time evolution of fluctuating ion saturation current $\tilde{I}_{is}$ at radial position of $r = -11$ cm and vertical position of $y = 0$ and -11 cm (see Fig. 1 for axes), and (b) the corresponding power spectrum at $r = -11$ cm and $y = 0$ cm (case B: biased voltage $V_b = 150$ V applied to Nos. 7–10 electrodes).

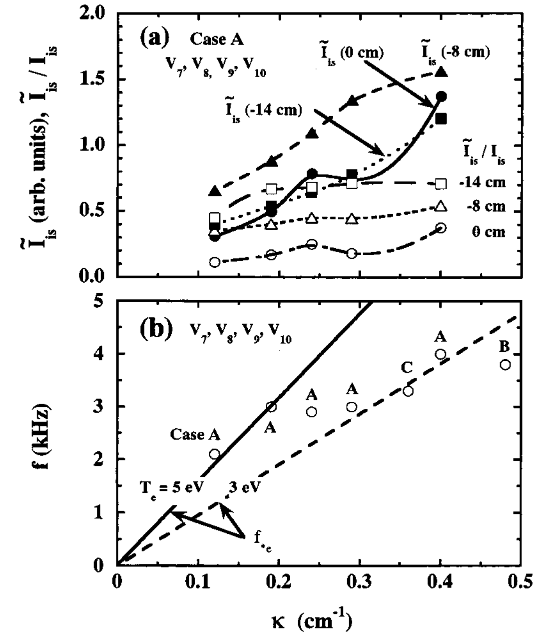

FIG. 5. Dependences of (a) fluctuating component of ion saturation current $\tilde{I}_{is}$ and its relative amplitude $\tilde{I}_{is}/I_{is}$ on three radial positions $r = 0$, -8, and -14 cm (case A), and (b) observed fluctuation frequency (cases A, B, and C) on κ, an inverse length of the maximum density gradient, with the use of Nos. 7–10 electrodes. For reference, a line of an estimated electron diamagnetic frequency f_{*e} is also shown.

tion (global structure with a rigid rotation of fluctuations with a large amplitude), which is opposite to the edge plasma rotation in the ion diamagnetic direction with the same order of magnitude: the observed fundamental frequency was close to 4 kHz with up to fourth harmonics appearing [Fig. 4(b)]. This frequency was 0.2 times the argon ion cyclotron frequency and it corresponded to the rotation velocity with $M = -0.8$ at $r = 11$ cm. Note that in observing fluctuations in the entire plasma region, a picture using a Doppler shifted frequency by a rigid plasma rotation cannot be employed in our experiment due to the presence of a strong velocity shear. For cases A and C, the observed fluctuations had broader spectra and slightly lower fundamental frequencies (3–3.5 kHz) than those for case B with the same biased voltage $V_b = 150$ V, due mainly to the lower maximum density gradient from the field curvature mentioned previously [see also the three open circles in the region of κ (an inverse scale length of the maximum density gradient) $= 0.29$, 0.36, and 0.48 cm^{-1} in Fig. 5].

The fluctuation amplitudes of ion saturation current, both absolute $\tilde{I}_{is}$ and relative $\tilde{I}_{is}/I_{is}$, were larger near the edge and/or with the increased voltage V_b, as shown in Fig. 5(a) for the case of the positive biasing to the outer region of the electrodes. Here, κ increased monotonically with the increase in V_b from 0 to 280 V, and for the excitation case of drift waves, it is expected that the growth rate increases with κ, which is proportional to the electron diamagnetic frequency f_{*e}.[33] Figure 5(b) shows the relation between the observed frequency f of fluctuations and κ, for three cases of A, B, and C. In estimating the line for f_{*e} in this figure, we took the following typical parameters: $T_e = 3$ and 5 eV, $B = 500$ G, azimuthal mode number m is one, and the radius of the fluctuations excited is 10 cm. With the increase in κ, a rise of f was observed, which was consistent with the estimated f_{*e} value. Note again that there would be a large difference of frequencies between these two, if we consider the Doppler shifted frequency by the edge plasma rotation with a typical frequency of several kilohertz.

From Figs. 4 and 5 and the following results, the observed fluctuations in the presence of strong velocity shear were identified as a drift wave type (rotational, Kelvin–Helmholtz, and other shear driven instabilities could be excluded[9,20]): (i) mode number m was one, (ii) phases of this fluctuation in the radial and axial directions were nearly the same (parallel wave number was less than 0.01 cm^{-1}), (iii) fluctuation was global in the entire plasma region (rigid rotation), (iv) fluctuation amplitude of $\tilde{I}_{is}$ was larger near the region which has the maximum density gradient, (v) observed fundamental frequency [see Fig. 5(b)] was nearly the same as the estimated frequency of f_{*e} in this maximum gradient region where almost no plasma rotation was found, (vi) density fluctuation led potential one by 30–50 deg, and (vii) amplitude of potential fluctuation normalized by T_e was less than the relative amplitude of $\tilde{I}_{is}/I_{is}$, especially near the plasma edge.

Although a fully computational calculation has not been done, from a simple numerical analysis[34] using some assumptions, the observed characteristics of the observed fluctuations could be qualitatively understood as this drift wave.

For the case of the biasing to electrodes in the outer region, we could expect the stabilization of the drift wave neither by a small connection length (roughly axial device size shorter than $20\kappa^{-1}$ is needed[33]) nor by good curvature for case B (roughly radius of field curvature less than $2\kappa^{-1}$ is needed[33]), since κ^{-1} became shorter with the increase in V_b from our results. Drift wave suppression by a strong radial electric field under some conditions in a tandem mirror has been achieved,[18] but in our case this stabilization was not observed probably due to the reason that the drift waves with global structures were affected only slightly by the strong velocity shear, which was very localized at the edge of the plasma with a low density. Although it was a temporary behavior, a similar experiment of rotating a plasma (rigid rotation near the central region) at a supersonic speed was performed using a coaxial plasma gun, and it did not show a drift wave but showed a flute structure with a velocity shear under different plasma parameters from ours.[35]

IV. CONCLUSION

A discharge characterized by very strong velocity shear (a large change of vorticity Ω_z) in the edge region as well as in the intermediate radial position was successfully generated in a cylindrical magnetized plasma, using ten concentric rings with biased voltage V_b up to 280 V: Mach velocity M up to $\sim$1.4 and a large velocity barrier with a vorticity Ω_z as high as $\sim 7\times 10^5$ l/s were obtained. Furthermore, novel control of the density profile from a hollow to a peaked one was demonstrated. The shear region and density profiles could be finely controlled by changing the voltage biasing position as well as by the magnetic field configurations with a condition that an electron mean free path was larger than a device size.

A low frequency ($<$4 kHz) density oscillation was identified as a drift wave type from a detailed analysis of the spatial structures of the density and potential fluctuations, the phase between these fluctuations, and power spectrum. This oscillation propagated as a rigid body, in a reverse direction to the edge shear plasma rotation with a supersonic velocity.

These universal results and established techniques obtained should be very useful for advanced studies in basic plasma physics and fusion fields, such as eddies, turbulence, bifurcation, chaos, and self-organization as well as in the various application fields.

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