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Low-Frequency Instabilities Arising from Radial-Profile Jump of Field-Aligned Plasma Flow Velocity

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Abstract

Magnetic field-aligned ion flows with radially-different energies are generated in a radially-uniform plasma potential by means of a modified plasma-synthesis method. This ion drift difference between adjacent layers, or a radial jump of the field-aligned ion flow velocity is found to give rise to several types of low-frequency instabilities which have not been argued in the conventional plasma. However, these instabilities are observed to be stabilized when the ion flow velocities and/or flow-velocity gradients exceed critical values.

Keywords:
flow-velocity jump, field-aligned plasma flow, modified plasma-synthesis method, low-frequency instabilities

1. Introduction

It is well known that sheared plasma flows perpendicular to magnetic-field lines are recognized as an important element in the transition from L to H mode confinement in fusion-oriented plasmas [1], which are also related to the suppression of low-frequency fluctuations. On the other hand, magnetic field-aligned sheared plasma flows have been regarded as playing an important role in the generation of plasma fluctuations and turbulences, which induce cross-field transport and can, in turn, affect the plasma steady state. In recent theoretical works, the field-aligned ion velocity shear is found to cause not only the Kelvin-Helmholtz instability, which was first studied experimentally over three decades ago [2], but also electrostatic ion-cyclotron, ion-acoustic, drift, and their coupled wave instabilities [3-6].

In this sense we claim that the external control of radial profile of field-aligned ion flows is a key of experimentally clarifying general features of the topic associated with the origin of induced plasma-turbulence and transport. In the early laboratory work, several different experimental arrangements were applied to produce the relative ion drift between adjacent layers using a double-ended Q-machine plasma [7,8]. However, these configurations have crucial disadvantages that electrodes inserted into the plasma bring undesirable disturbances or the ion flow velocity can not be easily changed in a controlled way. Thus, it is required to develop a novel plasma source which can actively control the ion flow velocity without inserting the electrodes into the plasma and generate the ion-velocity difference perpendicular to the magnetic-field lines.

The aim of the present work is to realize the generation of field-aligned ion flows with a wide range of velocities and precisely control their radial profiles in the absence of cross-field plasma flow, demonstrating the existence of new kinds of the radial-profile dependent instabilities.

2. Experimental Apparatus and Detail of Plasma Source

Experiments are performed in the Q_T-Upgrade machine of Tohoku University as shown in the top of

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Fig. 1. A plasma is produced by a modified plasma-synthesis method [9,10], where ion and electron emitters are oppositely set at cylindrical machine ends under a strong magnetic field of B = 2 kG.The ion emitter is made of a 9.8-cm-diam tungsten (W) plate and the ions are generated by surface ionization of potassium atoms on the tungsten plate. Here, the tungsten plate is heated to a temperature of 1000 K for the potassium atoms not to contaminate the plate surface under the condition that the thermionic electron is not emitted. The electron emitter using a 10.8-cm-diam barium oxide (BaO) cathode is mounted at a distance of 170 cm from the ion emitter. Since this cathode is heated to a temperature of 1100 K enough to generate thermionic electrons, the collisionless plasma is synthesized by these ions and electrons. A negatively biased titanium (Ti) grid (V_g = –60 V) is installed at a distance of 0.5 cm from the ion emitter. An electron velocity distribution function parallel to the magnetic field is considered to become Maxwellian because the grid reflects the electrons flowing from the electron emitter.

Since a voltage applied to the electron emitter (V_{ee} ≃ –3 V) determines the plasma potential in this synthesized plasma, a voltage applied to the ion emitter can control the potential difference between the plasma and the ion emitter. This potential difference can accelerate the ions and generate the field-aligned ion flow [see the bottom of Fig. 1]. Furthermore, the ion emitter is concentrically segmented into three sections, each of which is electrically isolated and is individually biased. Thus, the field-aligned ion flows with radially-different energies are generated in the radially-uniform plasma potential. Hereinafter, the electrodes set in order from the center to the outside are called as the first, second, third electrodes and the voltages applied to them are defined as V_{ie1}, V_{ie2}, V_{ie3}, respectively. A small movable Langmuir probe is used to measure plasma parameters and their radial profiles. An ion energy distribution function parallel to the magnetic field is measured by a directional electrostatic energy analyzer, the collector diameter of which is 0.3 cm. The axial position z is defined as the distance from the Ti grid (z = 0 cm).

3. Experimental Results and Discussion

Figure 2 shows radial profiles of electron density n_e, electron temperature T_e, and plasma potential ϕ of the synthesized plasma described above, which are measured at z = 60 cm for V_{ie1} = V_{ie2} = 0 V. In the present experiment, V_{ie3} is always kept at 0 V. Here, the dotted lines in the figure indicate the boundaries of the segmented ion-emitter electrodes. T_e is almost constant (≃ 0.2 eV) in the radial direction. n_e is about 10^8 cm^{-3} at the radial center and almost uniform within the second electrode, gradually decreasing toward the outside.On the other hand, ϕ is uniform radially within the third electrode, the radius of which corresponds to that of the electron emitter.

This means that we need not consider effects of the $E \times B$ drift due to the radial potential gradient and the sheared flow perpendicular to the magnetic field when the instabilities are measured within the plasma column.These radial profiles of the plasma parameters do not change even if the ion-emitter voltages applied are varied.

In Fig. 3, an ion energy distribution function $F_{i\parallel}$ at the radial center (r = 0 cm) and z = 100 cm is presented with V_{ie1} as a parameter for V_{ie2} = 0 V, where I_c is the current flowing to a collector of the energy analyzer and

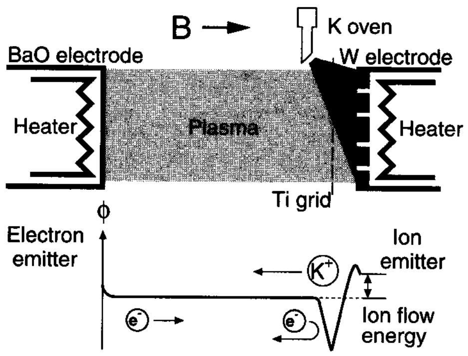

Fig. 1 Schematic of experimental setup and model of the potential profile.

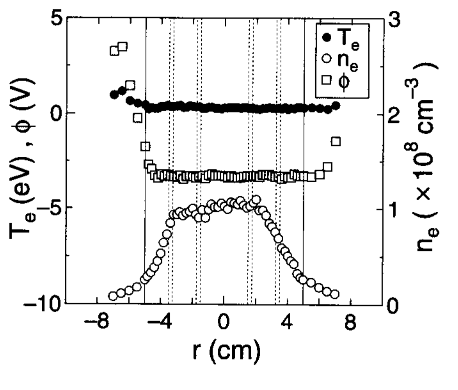

Fig. 2 Radial profiles of electron density n_e, temperature T_e, and plasma potential ϕ at z = 60 cm for V_{ie1} = V_{ie2} = 0 V.

V_c is the collector voltage applied with respect to the ground. V_c yielding a large peak of $F_{i\parallel}$ shifts toward the positive value of V_c when V_{ie1} is increased. On the other hand, a small peak of $F_{i\parallel}$ at $V_c \simeq -4$ V is independent of V_{ie1}. Thus, the small peak is considered to be a signal of the electrons which are not reflected by the electron-repeller grid of the energy analyzer and V_c yielding this peak indicates ϕ ($\simeq -4$ V) which almost coincides with the result of $\phi \simeq -3$ V in Fig. 2. Since the work function of the energy analyzer changes due to a potassium coating on a part of the collector, the peak of $F_{i\parallel}$ measured by the energy analizer is considered to shift by about -1 V. The difference between the small and the large peaks means the ion flow energy ε, which is found to correspond to the potential difference between the plasma and the ion emitter. However, ε is slightly less than the value equivalent to the sum of V_{ie1} and $|\phi|$. This discrepancy is considered to be caused by some dissipation of the ion energy. The ion flow energy can be controlled in a range of 0–100 eV with the accuracy of 0.1 eV.

In Fig. 4, radial profiles of the peak intensities of $F_{i\parallel}$ at the values of V_c which correspond to $\varepsilon \simeq 9.5$ eV (closed circle) and 17 eV (open circle) are presented for V_{ie1} = 8 V and V_{ie2} = 16 V. The peak intensities of ε = 9.5 eV and 17 eV are large around the center of the first and the second electrodes, respectively. These peak intensities gradually decrease toward the boundary region and almost vanish in another electrode region. Thus, the ion drift difference between adjacent layers, or a radial jump of the field-aligned ion flow velocity in the boundary region of these electrodes is found to be easily formed by means of biasing the ion-emitter voltage. However, the ion with the flow energy of ε = 9.5 eV emitted from the first electrode seems to penetrate into the second electrode region and ions with the different flow energies appear to be superimposed in the boundary region. The distance of this superimposed region is about 0.5 cm. Since the diameter of the collector of the energy analyzer is 0.3 cm and the ion Larmor radius is about 0.2 cm in this experiment, the guiding centers of these ions are not actually superimposed but the Larmor motions of the ions are only detected at the same region by the energy analyzer with the low spatial resolution.

The radial jump of the ion flow velocity, which is generated in the boundary region, is found to give rise to several types of low-frequency instabilities. One is observed around the radial center where the density profile is almost uniform. This instability is localized around the region of the flow-velocity jump, and the fluctuation amplitude becomes large when the flow-velocity difference between the first and the second electrodes increases. Thus, this instability is considered to be related to the Kelvin-Helmholtz instability to some extent.

Another is observed in the region where the density gradient is relatively large. Figure 5 shows frequency spectra of the electron saturation current of the probe as a function of V_{ie2}, which are observed at $r = -4$ cm and z = 60 cm. Here, V_{ie1} is fixed at 0 V. As V_{ie2} is increased, the fluctuation amplitude is found to increase, gradually decreasing for V_{ie2} > 0.5 V. The fluctuation is observed

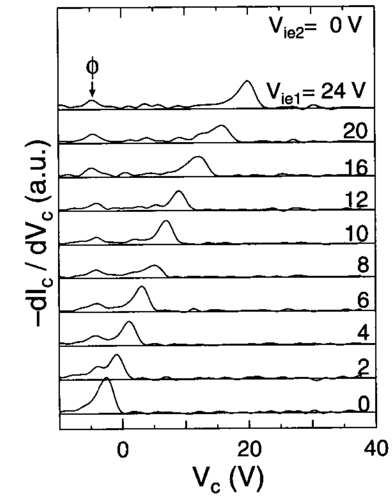

Fig. 3 Energy distributions of ions parallel to the magnetic field $F_{i\parallel}$ at z = 100 cm with V_{ie1} as a parameter for V_{ie2} = 0 V.

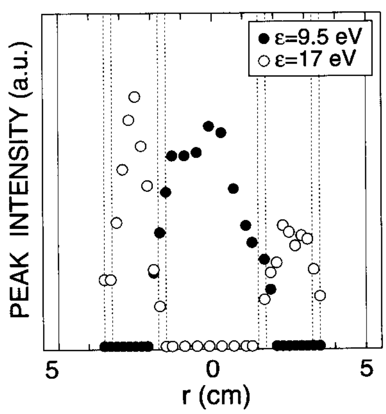

Fig. 4 Radial profiles of peak intensities of $F_{i\parallel}$ at V_c corresponding to ε = 9.5 eV (closed circle) and 17 eV (open circle) for V_{ie1} = 8 V, V_{ie2} = 16 V.

even at V_{ie2} = 0 V. This is because the flow-velocity jump is generated even when the applied voltage of each electrode is the same under the ion-rich condition, where the potential just in front of the second electrode is considered to be slightly higher than that of the third electrode due to the difference of the emitted ion density.

On the other hand, the frequency of the spectrum peak increases with an increase in V_{ie2}. The relation between the observed frequency $\omega/2\pi$ and V_{ie2} is presented in Fig. 6. Here, the dotted line indicates the calculated real frequency of electron-drift and ion-acoustic coupled wave $\omega = |\omega^*/2| + k_z v_{i\|0}$ ($v_{i\|0}$: ion flow velocity) [5], where the wave length parallel to the magnetic-field lines is assumed to be twice the length of the plasma column ($2\pi/k_z \simeq 170$ cm) and the measured drift frequency is used ($\omega^*/2\pi \simeq 800$ Hz). The experimentally obtained value roughly coincides with the calculated value. From these results, this instability appears to be related to the electron-drift and ion-acoustic coupled wave, which has not been argued in the conventional plasma.

However, these instabilities described above are found to be stabilized when the ion flow velocities and/or flow-velocity jumps exceed critical values. Since the observed phenomena can not be predicted by the current theories, experimental details are under investigation.

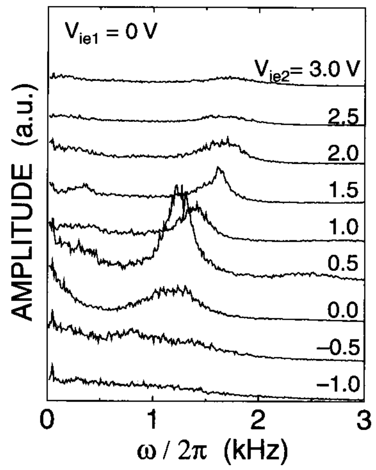

Fig. 5 Frequency spectra of the electron saturation current as a function of V_{ie2} for V_{ie1} = 0 V at r = –4 cm, z = 60 cm.

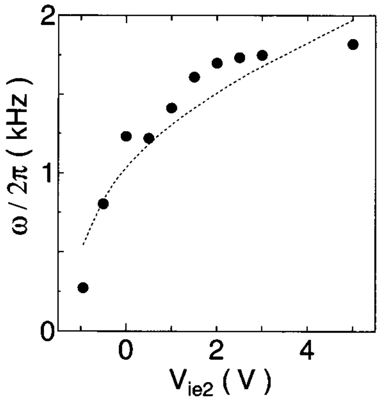

Fig. 6 Observed fluctuation frequency $\omega/2\pi$ as a function of V_{ie2} for V_{ie1} = 0 V at r = –4 cm, z = 60 cm. Dotted line indicates the calculated frequency of electron-drift and ion-acoustic coupled wave.

4. Conclusion

The ion drift difference between adjacent layers, or a radial jump of the field-aligned ion flow velocity is generated by means of a modified plasma-synthesis method. It is found that the several types of low-frequency instabilities are excited by the flow-velocity jump around the radial center or in the density-gradient region. In particular, the latter appears to be related to the electron-drift and ion-acoustic coupled wave, which have not been argued in the conventional plasma, while their detailed characteristics are not clarified and are under investigation.

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