Effects of Superimposed Parallel and Perpendicular Flow Velocity Shears on Drift-Wave Instabilities in Magnetized Plasmas

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Plasma flow velocity shears parallel and perpendicular to magnetic field lines are independently controlled and superimposed using a modified plasma-synthesis method with concentrically three-segmented electron and ion emitters. The fluctuation amplitude of the drift wave which has an azimuthal mode number $m = 3$ is observed to increase with increasing the parallel shear strength in the absence of the perpendicular shear. When the perpendicular shear is superimposed on the parallel shear, the drift wave of $m = 3$ is found to change into that of $m = 2$. Furthermore, the parallel shear strength required for the excitation of the drift wave becomes large with a decrease in the azimuthal mode number. Based on these results, the superposition of the parallel and perpendicular shears can affect the characteristics of the drift wave through the variation of the azimuthal mode number.

Keywords: plasma flow velocity shear, drift wave, azimuthal mode number, plasma-synthesis method

1 Introduction

Plasma flows and their velocity shears in magnetized plasmas have attracted much attention not only in fusion oriented plasmas but also in space plasmas, because the ion flow velocity shear parallel to the magnetic field lines has been reported to enhance the ion-acoustic [1, 2], ion-cyclotron [3, 4], and drift-wave [5, 6] instabilities, while the perpendicular flow velocity shear has been confirmed to regulate not only the drift-wave but also ion-cyclotron instabilities independent of the sign of the shear [7]. In order to clarify the mechanisms of excitation and suppression of these instabilities in the real situation of the fusion and space plasmas, it is necessary to realize the controlled superposition of the parallel and perpendicular flow shears in magnetized plasmas.

Thus, the aim of the present work is to independently control and superimpose the parallel and perpendicular flow shears in the basic plasma device with concentrically three-segmented electron and ion emitters [8], and to carry out laboratory experiments on the drift-wave instability excited and suppressed by the superimposed flow shears in collisionless magnetized plasmas.

2 Experimental Setup

Experiments are performed in the Q_T-Upgrade machine of Tohoku University. We attempt to modify a plasma-synthesis method with an electron (e^-) emitter using a 10-cm-diameter tungsten (W) plate and a potassium ion (K^+) emitter using another W plate, which are oppositely located at the machine ends as shown in Fig. 1. The collisionless plasma is produced when the surface-ionized potassium ions and the thermionic electrons are generated by the spatially separated ion and electron emitters, respectively, and are synthesized in the region between these emitters. A negatively biased stainless (SUS) grid, the voltage of which is typically $V_g = -60$ V, is installed at a distance of 10 cm from the ion emitter surface. Since the grid reflects the electrons flowing from the electron emitter side, the electron velocity distribution function parallel to the magnetic fields are considered to become Maxwellian.

Both the emitters are concentrically segmented into three sections with the outer diameters of 2 cm (first electrode), 5.2 cm (second electrode), and 10 cm (third electrode), each of which is electrically isolated. When each section of the electron emitter is individually biased, the radially-different plasma potential, or radial electric field is expected to be generated even in the fully-ionized collisionless plasma. This electric field causes the E×B flows and flow shears perpendicular to the magnetic-field lines. Voltages applied to the electrodes set in order from the center to the outside are defined as $V_{ee1}, V_{ee2}, V_{ee3}$, respectively. On the other hand, the parallel K^+ flow with radially different energy, i.e., the parallel K^+ flow shear, is generated when each section of the segmented ion emitter is individually biased ($V_{ie1}, V_{ie2}, V_{ie3}$) at a positive value above the plasma potential that is determined by the bias voltage of the electron emitter. Therefore, these

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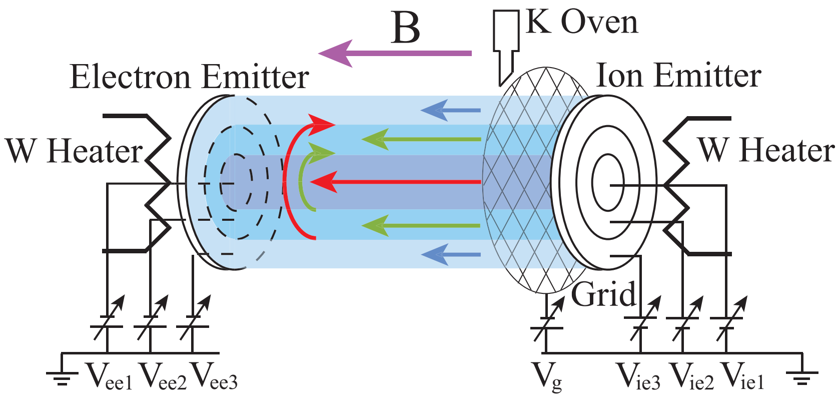

Fig. 1 Schematic of experimental setup.

parallel and perpendicular K^+ flow velocity shears can be superimposed by controlling the bias voltage of the ion and electron emitters independently. Here, V_{ee3} and V_{ie3} are always kept at 0 V. A small radially movable Langmuir probe and an electrostatic energy analyzer are used to measure radial profiles of plasma parameters and ion energy distribution functions parallel to the magnetic fields, respectively. Under our conditions, the plasma density is 10^9 cm^{-3}, the electron temperature is 0.2 eV, and the ion temperature is almost the same as the electron temperature. A background gas pressure is less than 10^{-6} Torr.

3 Experimental Results

At first, we demonstrate the independent control of the parallel and perpendicular K^+ flow velocity shears and the superposition of these shears. Figure 2 shows the plasma potential ϕ (closed circles) and the K^+ flow energy E_{K^+} (open circles) at the radial center r = 0 cm of the plasma column as functions of V_{ie1} and/or V_{ee1}, where V_{ie2} and V_{ee2} are fixed at 5.0 V and −2.0 V, respectively. When V_{ie1} is changed at constant $V_{ee1} = -2.2$ V [Fig. 2(a)], the K^+ flow energy is found to increase in proportion to V_{ie1}, while the plasma potential is almost constant at $\phi = -5.5$ V. Since the K^+ flow energy and the plasma potential in the second electrode region are confirmed to have constant values of 7 eV and −5.5 V, respectively, only the parallel flow velocity shear can be generated in the boundary region between the first and second electrodes by changing V_{ie1}.

When V_{ie1} and V_{ee1} are simultaneously changed keeping the bias-voltage difference $V_{ie1} - V_{ee1}$ constant [Fig. 2(b)], on the other hand, the K^+ flow energy does not change, while the plasma potential is found to increase in proportion to V_{ee1}. This result denotes that the parallel shear does not change as far as $V_{ie1} - V_{ee1}$ is constant, and the radial plasma potential difference, i.e., the perpendicular flow velocity shear can be con-

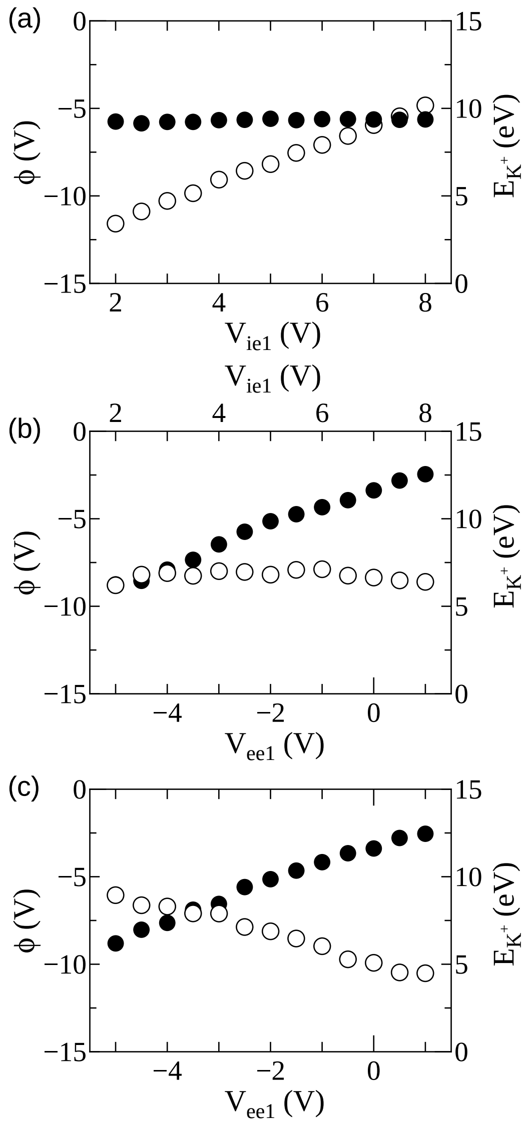

Fig. 2 Plasma potential ϕ (closed circles) and K^+ flow energy E_{K^+} (open circles) as functions of (a) V_{ie1}, (b) V_{ie1} and V_{ee1}, and (c) V_{ee1}. $r = 0$ cm, $V_{ie2} = 5.0$ V, $V_{ee2} = -2.0$ V.

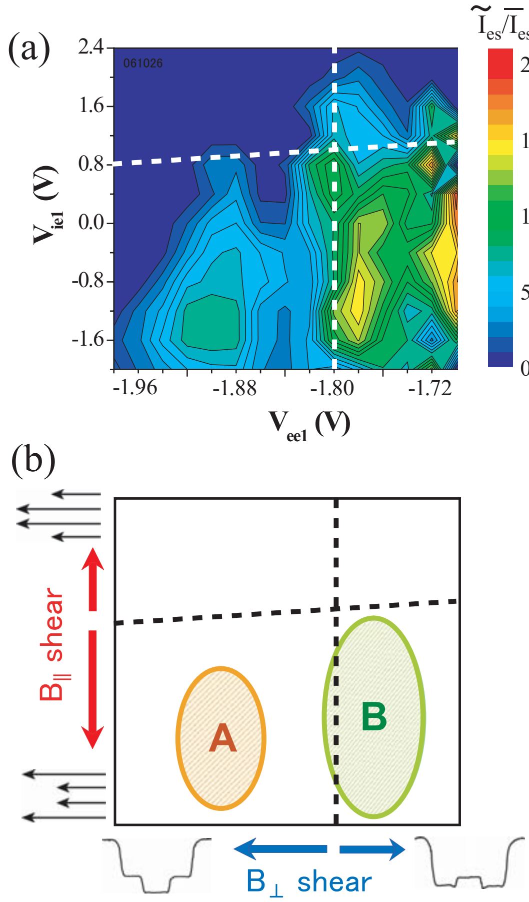

Fig. 3 Contour views of normalized fluctuation amplitudes as functions of V_{ie1} and V_{ee1}. $r = 1.5$ cm, $V_{ie2} = 1.0$ V, $V_{ee2} = -2.0$ V.

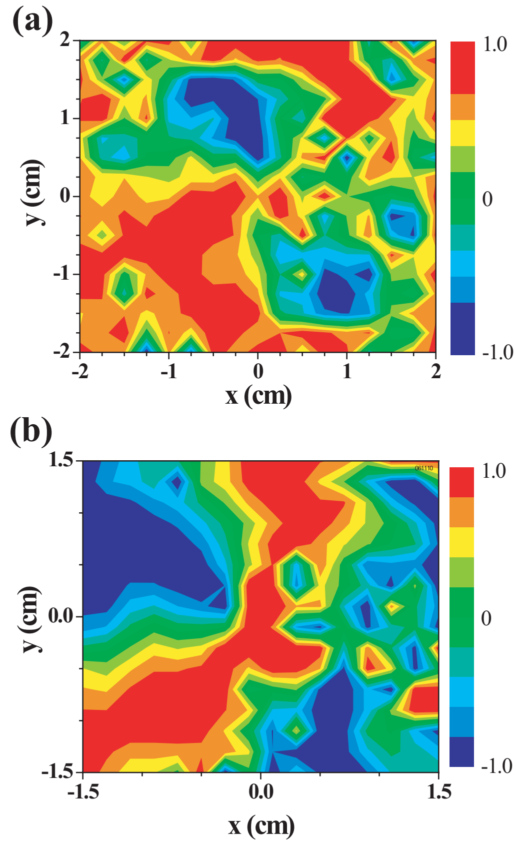

Fig. 4 2-dimensional profile of fluctuation phase θ which is plotted as $\sin\theta$ for (a) fluctuation A ($V_{ee1} \simeq -1.90$ V) and (b) fluctuation B ($V_{ee1} \simeq -1.78$ V). $V_{ie1} = -1.0$ V, $V_{ie2} = 1.0$ V, $V_{ee2} = -2.0$ V.

trolled by the bias voltages of the electron emitter. Since the parallel and perpendicular shears are now able to be controlled independently, we attempt to superimpose these shears.

Figure 2(c) presents the plasma potential and the K^+ flow energy as a function of V_{ee1} at constant $V_{ie1} = 5$ V. In this case, the plasma potential is directly changed by V_{ee1}, and the K^+ flow energy is also changed by V_{ee1}, because the bias-voltage difference $V_{ie1} - V_{ee1}$ decreases with an increase in V_{ee1} for the fixed V_{ie1}. Based on these results, the superposition of the parallel and perpendicular flow velocity shears is realized by controlling the V_{ie1} and V_{ee1} simultaneously. These parallel and perpendicular shears are found to give rise to several types of low-frequency instabilities. Here, we concentrate on the drift-wave instability which is excited in the density gradient region around $r = 1.0 \sim 1.5$ cm.

Figure 3(a) shows a contour view of normalized fluctuation amplitudes $\tilde{I}_{es}/\bar{I}_{es}$ obtained from frequency spectra of an electron saturation current I_{es} of the probe as functions of V_{ie1} and V_{ee1} for $V_{ie2} = 1.0$ V and $V_{ee2} = -2.0$ V. Schematic model of the parallel and perpendicular shears introduction is shown in Fig. 3(b), where black arrows described at ordinate axis mean the parallel ion flow velocity and solid curves described at abscissa axis mean the radial potential profiles, which are controlled by V_{ie1} and V_{ee1}, respectively, corresponding to the variation of the parallel and perpendicular flow velocity shears. Here, horizontal and vertical dotted lines in Fig. 3 denote the situations in the absence of the parallel and perpendicular shears, respectively, which are confirmed by the actual measurements of the ion flow energy and the space potential.

In the case that the perpendicular shear is not generated at $V_{ee1} = -1.8$ V, the fluctuation amplitude of the drift-wave instability is observed to increase with increasing the parallel shear strength by changing V_{ie1} to the negative value from 1.0 V, but the instability is found to be gradually stabilized when the shear strength exceeds the critical value. The destabilizing and stabilizing mechanisms are well explained by a plasma kinetic theory including the effect of radial density gradient [5]. When the perpendicular shear is superimposed on the parallel shear, the drift wave excited by the parallel shear is found to be suppressed by the perpendicular shear independently of the sign of the perpendicular shear. Furthermore, we can observe two characteristic fluctuation peaks depending on the perpendicular shear strength as presented in the contour views [Fig. 3(a)], which are defined as fluctuations A and B as described in the schematic model [Fig. 3(b)].

To readily identify the azimuthal component of each fluctuation's wavevector, we measure 2-dimensional (x, y) profiles of fluctuation phase in the plasma-column cross section. The phase is measured with reference to a spatially fixed Langmuir probe located at an axial distance of 26 cm from the 2-dimensionally translatable probe. Figure 4 presents the 2-dimensional phase profiles for (a) fluctuation A and (b) fluctuation B. Since the phase difference θ between the 2-dimensional probe and the reference probe is plotted as $\sin\theta$, red (1.0) and blue (-1.0) indicate the phase of $+\pi/2$ and $-\pi/2$, respectively, relative to the reference probe. Green corresponds to zero and π relative phase. In the case of the small perpendicular shear strength, i.e., fluctuation B [Fig. 4(b)], the azimuthal mode is found to be $m = 3$. On the other hand, in the presence of the relatively large perpendicular shear, i.e., fluctuation A [Fig. 4(a)], the azimuthal mode changes into $m = 2$. The perpendicular shear can modify the azimuthal mode number depending on its strength.

For these two kinds of drift waves, we measure the dependence of fluctuation amplitudes on the parallel shear strength, which are obtained from Fig. 3(a). As a result, with an increase in the parallel shear strength, it is found that $m = 3$ mode ($V_{ee1} \simeq -1.78$ V) first excited and $m = 2$ mode ($V_{ee1} \simeq -1.90$ V) needs strong parallel shear strength to excite the mode. These phenomena can be explained by the theoretical calculation that the growth rate of the parallel-shear excited drift wave sensitively depends on the azimuthal wave number, i.e., mode number [6]. Therefore, the superposition of the parallel and perpendicular shears can affect the characteristics of the drift wave through the variation of the azimuthal mode number.

4 Conclusions

The independent control of parallel and perpendicular flow velocity shears in magnetized plasmas is realized using a modified plasma-synthesis method with segmented plasma sources. The ion flow velocity shear parallel to the magnetic-field lines is observed to destabilize the drift-wave instability depending on the strength of the parallel shear. On the other hand, when the perpendicular shear is superimposed on the parallel shear, the drift wave of $m = 3$ is found to change into that of $m = 2$, and the instability is suppressed for strong perpendicular shears. The superposition of these shears can affect the characteristics of the drift wave through the variation of the azimuthal mode number.

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