Effects of Perpendicular Plasma Flow Velocity Shear on Parallel Shear Driven Drift Wave

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Abstract

Plasma flow velocity shears parallel and perpendicular to magnetic field lines are independently controlled and superimposed using a modified plasma-synthesis method. The drift wave which has an azimuthal mode number m=3 is observed to grow 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, and furthermore, the parallel shear strength required for the excitation of the drift wave becomes large. These experimental results are confirmed by theoretical calculations of the growth rate of the drift wave using an eigenmode analysis.

1. Introduction

Plasma flows and their velocity shears in magnetized plasmas have attracted much attention not only in space plasmas but also in fusion oriented 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 space and fusion plasmas, it is necessary to realize the controlled superposition of the parallel and perpendicular flow shears in magnetized plasmas.

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.

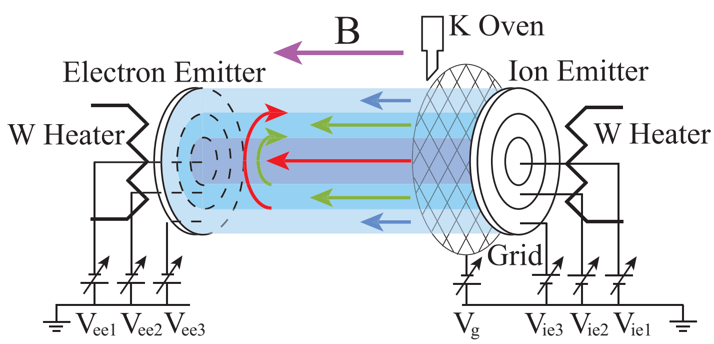

Fig. 1. Schematic of experimental setup.

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 ExB 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 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 and Discussion

We have demonstrated the independent control of the parallel and perpendicular K^+ flow velocity shears and the superposition of these shears by controlling V_{ie1} and V_{ee1} simultaneously, where V_{ie2} and V_{ee2} are fixed [9]. 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 2(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. 2(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. 2 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. 2(a)], which are defined as fluctuations A and B as described in the schematic model [Fig. 2(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 3 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

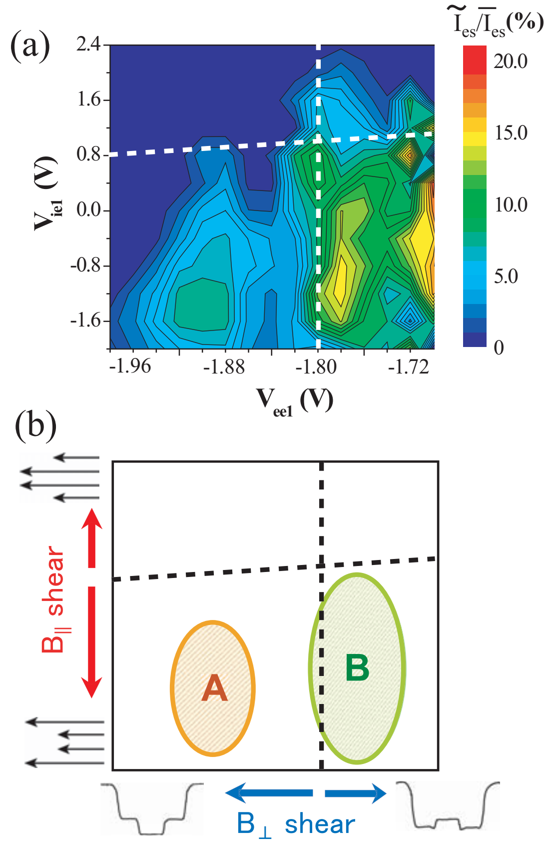

Fig. 2. Contour views of normalized fluctuation amplitudes as functions of V_{ie1} and V_{ee1}. r = 1.5 cm, $V_{ie2} = 1.0$ V, $V_{ee2} = -2.0$ V.

plotted as sinθ, 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. 3(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. 3(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. 2(a). As a result, with an increase in the parallel shear strength, it is found that m=3 mode ($V_{ee1} \sim -1.78$ V) first excited and m=2 mode ($V_{ee1} \sim -1.90$ V) needs strong parallel shear strength to excite the mode. These phenomena can be explained by the theoretical calculation of the growth rate of the drift wave modified by the velocity shears using an eigenmode analysis. We model the region near the plasma-column edge using slab geometry, in which case $dv_d/dr = dv_d/dx$ and $k_\theta = m/r = k_y$ in the limit that the radial position of the drift waves is much larger than both the ion gyroradius and the annular width of the radial profile of fluctuation amplitude. The eigenmode equation can be found in Ref. [10,11] and are not repeated here. Figure 4 presents a threshold that the growth rate of the drift wave changes into positive (unstable) as functions of the parallel and perpendicular flow velocity shears, where the superior and inferior regions from the lines mean the stable and unstable conditions, respectively. The parameters for the calculation of the growth rate almost corresponds to the experimentally obtained values in this experimental condition except for the larger parallel electron drift velocity $V_{e\|}$ and the smaller density gradient.

In the case that the perpendicular shear is small, i.e., $V_{\perp 0}/v_{ti} \sim 0$, the drift wave changes to unstable with an increase in the parallel-shear strength, first at $|V_{\|0}/v_{ti}| \sim 0.1$ for $k_y\rho_i = 0.5$, then at $|V_{\|0}/v_{ti}| \sim 0.3$ for $k_y\rho_i = 0.3$. Here, $k_y\rho_i = 0.3$ and 0.5 correspond to the experimentally obtained azimuthal mode numbers m=2 and 3, respectively. When the perpendicular shear becomes relatively large, i.e., $V_{\perp 0}/v_{ti} \sim -0.005$, the unstable drift wave appears around $|V_{\|0}/v_{ti}| \sim 0.5$ which is larger than that in the case of $V_{\perp 0}/v_{ti} \sim 0$. Furthermore, the drift wave becomes unstable first for $k_y\rho_i = 0.3$ and next for $k_y\rho_i = 0.5$ with an increase in the parallel shear, which is opposite tendency to the case of $V_{\perp 0}/v_{ti} \sim 0$.

Based on these theoretical results, it is found that the drift wave with the larger azimuthal mode number can be excited by the smaller parallel shear strength in the absence of the perpendicular shear, while the wave with the smaller azimuthal mode number is easily excited in the presence of the relatively large perpendicular shear, explaining the experimentally obtained results that the modes with m=3 is excited in the absence of perpendicular shear and the mode changes into m=2 for the relatively large perpendicular shear as shown in Fig. 2. The theoretical results can also verify the experimental result that the larger parallel shear is needed to excite the drift wave in the larger perpendicular shear. Since the growth rate of the parallel-shear excited drift wave sensitively depends on the azimuthal mode number changed by the

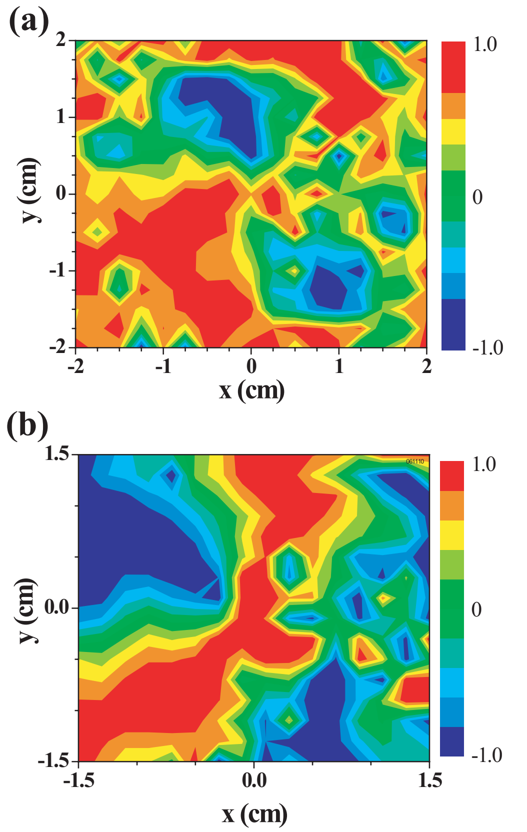

Fig. 3. 2-dimensional profile of fluctuation phase θ which is plotted as sinθ for (a) fluctuation A ($V_{ee1} \sim -1.90$ V) and (b) fluctuation B ($V_{ee1} \sim -1.78$ V). $V_{ie1} = -1.0$ V, $V_{ie2} = 1.0$ V, $V_{ee2} = -2.0$ V.

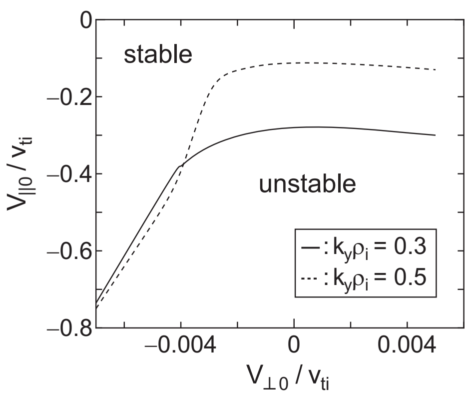

Fig. 4. Threshold of stability for the drift wave as functions of parallel and perpendicular flow velocity shears using eigenmode analysis. The superior and inferior regions from the lines mean the stable and unstable conditions, respectively.

perpendicular shear, 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. Conclusion

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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