Effects of Controlled Flow-Shear on Low-Frequency Instabilities in Magnetized Plasmas

HATAKEYAMA Rikizo, KANEKO Toshiro and TSUNOYAMA Hokuto
Department of Electronic Engineering, Tohoku University, Sendai 980-8579, Japan
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Abstract:
The external and independent control of parallel and perpendicular flow shears in collisionless magnetized plasmas are realized using two newly-developed plasma sources. The ion flow velocity shears parallel to the magnetic-field lines are then observed to destabilize not only the D’Angelo mode but also the drift-wave instability depending on the sign of the parallel shear in the absence of field-aligned electron drift flow in laboratory experiments. On the other hand, perpendicular ion flow velocity shears are demonstrated to suppress the drift-wave and the ion-cyclotron instabilities, and furthermore, these suppressions are found to take place independently of the sign of the perpendicular shear.

Keywords:
ion flow velocity shear, drift-wave instability, ion-cyclotron instability, D’Angelo mode, magnetized plasma

1. Introduction

Investigations of magnetic-field-aligned (parallel) and transverse (perpendicular) sheared plasma flows have been widely performed in connection with the excitation or the suppression of plasma fluctuations and turbulences, which are considered to generate energetic particles and induce cross-field transport in fusion-oriented [1-4] and space [5] plasmas. However, both the parallel and perpendicular flow shears often coexist in most of the large confinement devices and in the space environment, and cannot be controlled independently. As a result, it is difficult to understand the effects of each flow shear on the turbulences in real situations.

In basic laboratory experiments, on the other hand, a number of works on each of the flow shears have been reported. In the parallel shear case, some experimental investigations related to parallel-flow-shear driven instabilities, such as the D’Angelo mode [6-8], ion-acoustic [9,10], and ion-cyclotron [11-13] instabilities, have been performed in various situations. In these experiments, it is to be noted that the instabilities are excited by a slight amount of parallel shear in the presence of the parallel electron current which often exists in conventional configurations such as Q machine experiments [14], and therefore it is very difficult to experimentally evaluate the precise value of the parallel shear, which leads to difficulty in understanding the effects of the parallel shear on these instabilities.

In the perpendicular shear case, many experimental investigations on the relation between the perpendicular flow shears and the instabilities have been performed [15-21], and it has been recently reported that the net ion flow shear which is determined based on both $E \times B$ drift and diamagnetic drift is important for stabilizing the drift-wave instability [22]. In such experiments, however, there exists neutral gas and collisional effects on the fluctuations may have to be considered. Thus, it is necessary to carry out experiments in a fully-ionized plasma from the viewpoint of making a comparison with the results obtained in collisionless fusion-oriented plasmas. Although some basic experiments using a fully-ionized collisionless plasma have been done [23-25], it is difficult to actively change the sign of the radial electric field, or the sign of the perpendicular flow shear in these experimental configurations.

Therefore, it is required to develop novel plasma sources that enable us to actively control the parallel and perpendicular flow velocities and their shears in the electron-currentless plasma. The goal of the present works is to develop new plasma sources which can separately generate and actively control the parallel and perpendicular flow velocity shears, respectively, and to clarify the relation between each of these flow shears and the low-frequency instabilities in the Q-machine or modified Q-machine device as a fully-ionized plasma source.
2. Theory of the Flow Shear Driven Instabilities

2.1 Fluid Treatment

Over three decades ago, D’Angelo first proposed the fluid theory of a magnetic-field-aligned (parallel) shear driven instability [26], which assumes a uniform magnetic field $B$ in the $z$ direction, a nonuniform parallel relative drift velocity between ions and electrons $v_d(x)$, and a density gradient $dn/dx$. The local dispersion relation for a slab plasma is described as

$$\omega^2 - \left[ \frac{\omega_i^2 + k^2 C_i^2}{2} + \frac{\kappa^2}{\sigma^2} \right] (1 + \tau) \omega + \sigma^2 \omega_i^2 k_i^2 C_i^2 (1 + \tau) = 0 ,$$

(1)

and

$$\sigma^2 = 1 - \frac{k_z}{\omega_i} \frac{\partial v_d}{\partial x} .$$

(2)

where $\tau = T_i/T_e, C_i = (T_i/m_i)^{1/2}$, $\omega_i = eB/m_i, \omega^*_i = k_z T_e/eB$. $\kappa = -d \ln n/dx, k_i^2 + k_z^2 + k_x^2$ and $k_i$ and $k_z$ are perpendicular and parallel wave numbers, respectively. For the low frequency range ($\omega \ll \omega_i$), the fourth order term is negligible, and by using $\tau \ll 1$, we obtain [27]

$$\omega = \frac{\omega_i^*}{2} \pm \sqrt{\left( \frac{\omega_i^*}{2} \right)^2 + \sigma^2 k_i^2 C_i^2} .$$

(3)

When $\omega^2$ becomes negative in the presence of the parallel flow velocity shear $\partial v_d/\partial x$, and then $(\omega_i^* - 4\sigma^2 k_i^2 C_i^2) < 0$, this mode becomes unstable with $\text{Re}(\omega) = \omega_i/2$. Although the instability was originally defined as the Kelvin-Helmholtz instability [26], it is now referred to as the D’Angelo mode.

For the higher frequency range ($\omega = \omega_i$), on the other hand, we must consider the full fourth-order dispersion relation of Eq. (1), obtaining the ion-cyclotron mode as [28,29]

$$\omega^2 = \left[ \frac{\omega_i^* + k^2 C_i^2}{2} \right] + \sqrt{\left( \frac{\omega_i^* + k^2 C_i^2}{2} \right)^2 - \sigma^2 k_i^2 C_i^2 \omega_i^2} ,$$

(4)

where the density gradient, i.e., $\omega_i^*$ is neglected for the sake of simplicity. When $(\omega_i^* + k^2 C_i^2)^2 - \sigma^2 k_i^2 C_i^2 \omega_i^2 < 0$, this mode becomes unstable with $\text{Re}(\omega) = (\omega_i^* + k^2 C_i^2)/2$. In the conventional magnetized plasma, however, $\omega_i$ is much larger than $k_i C_i$, and as a result, it is difficult to destabilize this mode in the fluid treatment even for large $\sigma^2$. For $\omega_i \gg k_i C_i$, we can simplify Eq. (4) as

$$\omega^2 = \frac{\omega_i^* + k^2 C_i^2}{2} - \frac{1}{4} \sigma^2 k_i^2 C_i^2 .$$

(5)

2.2 Kinetic Treatment

In recent theoretical works using a kinetic treatment, the parallel shear is found to cause not only the D’Angelo mode [26] but also electrostatic ion-acoustic instabilities for $\omega \ll \omega_i$ depending on the sign of the parallel shear [30-32]. In these theories, however, the effect of the radial density gradient, which universally exists in real plasmas, has not been considered, and consequently the drift-wave instability has not been discussed at all. Since the drift-wave instability is closely related to cross-field particle and energy transports in magnetized plasmas, it is indispensable to clarify the effects of the parallel shear on the drift-wave instability from the viewpoint of the improvement of fusion-oriented plasma confinement and the understanding of space plasma process and structure. Thus we try to express the effect of the density gradient in terms of the electron $\omega_e$ and ion $\omega_i$ diamagnetic drift frequencies. The local kinetic dispersion relation is described as [30]

$$1 + \sum_i \Gamma_i (b) F_{m_i} + \tau \left( 1 + F_{m_i} \right) k^2 \lambda_{e_i}^* = 0 ,$$

(6)

$$F_{m_i} = \left( \frac{\omega + \omega_i^* - k \nu_e}{\sqrt{2 \lambda_{e_i}}} \right) Z \left( \frac{\omega - \rho_{e_i} - k \nu_e}{\sqrt{2 \lambda_{e_i}}} \right)$$

$$- \frac{k}{\nu_e} \frac{\partial v_d}{\partial x}$$

$$\left[ 1 + \left( \frac{\omega - \rho_{e_i} - k \nu_e}{\sqrt{2 \lambda_{e_i}}} \right) Z \left( \frac{\omega - \rho_{e_i} - k \nu_e}{\sqrt{2 \lambda_{e_i}}} \right) \right].$$

(7)

$$F_{m_i} = \left( \frac{\omega - \omega_i^*}{\sqrt{2 \lambda_{e_i}}} \right) Z \left( \frac{\omega}{\sqrt{2 \lambda_{e_i}}} \right)$$

$$- \frac{m_i}{m_e} \frac{k}{\nu_e} \frac{1}{\alpha} \frac{\partial v_d}{\partial x}$$

$$\left[ 1 + \left( \frac{\omega}{\sqrt{2 \lambda_{e_i}}} \right) Z \left( \frac{\omega}{\sqrt{2 \lambda_{e_i}}} \right) \right].$$

(8)

where $\Gamma_i (b) = L_i (b) \exp (-b), L_i$ are the modified Bessel functions, $Z$ is the plasma dispersion function, $b = (k_i \rho_i)^2$, $\nu_e = (T_e/m_e)^{1/2}$, $\alpha$ indicates the species (electron or ion), $\lambda_{e_i}$ and $\rho_i$ are ion Debye length and gyroradius, respectively. It is noted that the parallel relative drift velocity $v_d$ is included in Eq. (7) as an ion drift velocity.

From this dispersion relation, the real frequency $\omega$ and the growth rate $\gamma$ of the drift-wave instability for the low frequency range ($\omega \ll \omega_i$) can be given by

$$\omega_i (\omega_{m_i} - k \nu_e) = \frac{\omega_i^*}{2} + \sqrt{\left( \frac{\omega_i^*}{2} \right)^2 + \sigma^2 k_i^2 C_i^2} .$$

(9)
\[ \frac{\gamma}{\omega} = \sqrt{\frac{3}{2}} \frac{\omega_{i}}{\tau} \left( \frac{\omega_{i}}{\omega_{e}} - 1 \right) \left( \frac{\omega_{i}}{k_{v_{i}}} - 1 \right) - \sigma^{2} \exp \left( - \frac{\omega_{i}^{2}}{2 \left( k_{v_{i}} \right)^{2}} \right) \]  

where \( \mu = m_{e}/m_{i} \), \( \omega_{e0} \), and \( \omega_{i} \) are the real frequency of the drift-wave instability in the laboratory frame and in the ion frame, respectively. The expression of this \( \omega_{i} \) is the same as the formula of the D’Angelo mode in the fluid analysis in Eq. (3). The first and second terms in the large brackets of Eq. (10) represent the effects of the inverse electron Landau damping and the ion Landau damping, respectively.

Here, let us discuss the meaning of \( \sigma^{2} \), which is directly connected with the parallel shear strength. As shown in Eq. (9), the positive and negative values of \( \sigma^{2} \) bring about an increase and a decrease in \( \omega_{i} \), respectively, which leads to the modification on the parallel phase velocity. \( \sigma^{2} \) in Eq. (2) can be transformed into

\[ \sigma^{2} = 1 - \frac{k_{x}}{k_{z}} \frac{m_{e}}{m_{i}} \frac{\partial v_{i}}{\partial x} \]

The first term \( e^{-iE_{x}} \) indicates the force exerted by the \( z \) component of the oscillating electric field, which causes the ion acoustic wave to propagate parallel to the magnetic field. On the other hand, \( E_{x}/B \) and \( \partial v_{i}/\partial x \) in the second term indicate the \( x \) component of the oscillating \( E \times B \) drift velocity \( v_{i} \) and the parallel flow velocity gradient in the \( x \) direction, respectively. The product of \( v_{i} \), and \( \partial v_{i}/\partial x \) is the \( z \) component of the time-varying acceleration, namely the second term of Eq. (11) means the force exerted by the oscillating \( E \times B \) drift in the presence of the parallel flow velocity shear. Since the sign of the second term changes depending on the sign of the shear, the second term is added positively or negatively to the first term. Thus, the parallel flow velocity shear described in \( \sigma^{2} \) is found to work as the enhancement or degradation of the phase velocity of the ion acoustic wave.

For the higher frequency range (\( \omega = \omega_{e0} \)), on the other hand, the effect of the density gradient is neglected because \( \omega \) is much larger than \( \omega_{e} \) and \( \omega_{i} \). Thus the solution of the dispersion relation Eq. (6), or the real frequency \( \omega \), and growth rate \( \gamma \) of the ion-cyclotron instability can be expressed as [33,34]

\[ \omega = n \omega_{e0} + \sqrt{\frac{1}{\tau^{2}}} k_{z}^{2} C_{s}^{2} \gamma^{2} \]  \( \gamma \)

(12)

and

\[ \frac{\gamma}{\omega_{e0}} = \sqrt{\frac{3}{2}} \frac{\omega_{e0}}{\tau} \left( \frac{\omega_{e0}}{\omega_{i}} - 1 \right) \left( \frac{\omega_{e0}}{k_{v_{i}}} - 1 \right) - \sigma^{2} \exp \left( - \frac{\omega_{e0}^{2}}{2 \left( k_{v_{i}} \right)^{2}} \right) \]  \( \gamma \)

(13)

where

\[ \sigma^{2} = 1 - \left( 1 - \frac{n \omega_{e0}}{\omega_{i}} \right) \frac{k_{x}}{k_{z}} \frac{m_{e}}{m_{i}} \frac{\partial v_{i}}{\partial x} \cdot \frac{e B}{E} \]  \( \sigma \)

(14)

In the case of no shear \( (\sigma^{2} = 1) \), Eq. (13) reverts to the homogeneous current-driven ion-cyclotron instability [35,36]. In the presence of the shear \( (\sigma^{2} < 1) \), the critical drift velocity \( v_{i} \) which triggers off an excitation of the instability decreases with a decrease in \( \sigma^{2} \). Furthermore, for \( \sigma^{2} < 0 \), it is noted that the growth rate of the ion-cyclotron instability possesses a positive value even for extremely small \( v_{i} \). This new possibility for wave growth is called inverse cyclotron damping.

3. Experiments on Parallel Flow Shear

3.1 Experimental Apparatus

The experiments are performed in the Q-Upgrade machine of Tohoku University. In the case of parallel flow shear experiments, a plasma is produced by a modified plasma-synthesis method as shown in Fig. 1, where potassium ion and electron emitters are oppositely set at cylindrical machine of Tohoku University. In the case of parallel flow shear experiments, a plasma is produced by a modified plasma-synthesis method as shown in Fig. 1, where potassium ion and electron emitters are oppositely set at cylindrical machine of Tohoku University. In the case of parallel flow shear experiments, a plasma is produced by a modified plasma-synthesis method as shown in Fig. 1, where potassium ion and electron emitters are oppositely set at cylindrical machine of Tohoku University. In the case of parallel flow shear experiments, a plasma is produced by a modified plasma-synthesis method as shown in Fig. 1, where potassium ion and electron emitters are oppositely set at cylindrical machine of Tohoku University.

![Fig. 1 Schematic of experimental setup of parallel flow shear, and model of the potential profile.](image-url)
The ion emitter is made of a 10.0-cm-diameter tungsten (W) plate and the ions are generated by surface ionization of potassium (K) atoms on the tungsten plate. Here, the tungsten plate is uniformly heated by a PG-PBN (Pyrolytic Graphite - Pyrolytic Boron Nitride) heater to a temperature of 1,100 K, in order to prevent the potassium atoms from contaminating the plate surface under the condition that the thermionic electrons are not emitted. Furthermore, the ion emitter is concentrically segmented into three sections with outer diameters of 2 cm, 5.2 cm, and 10 cm, each of which is electrically isolated and individually biased with respect to the grounded vacuum chamber. Hereafter, the electrodes set in order from the center to the outside are called as the first (No.1), second (No.2), and third (No.3) electrodes and the voltages applied to them are defined as $V_{ie1}$, $V_{ie2}$, and $V_{ie3}$, respectively. The electron emitter, i.e., the cathode using a 10.8-cm-diameter nickel plate coated with barium oxide (BaO) is mounted at a distance of 170 cm from the ion emitter surface. Since the grid reflects the electrons flowing from the electron emitter, an electron velocity distribution function parallel to the magnetic field is considered to become Maxwellian, i.e., there is no electron drift flow.

In this synthesized plasma, the electron emitter is negatively biased at typically $V_{ve} = -4.0$ V, which determines the plasma potential $\phi$, and thus, 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. Since the ion emitter is concentrically segmented into three sections, each of which is electrically isolated and is individually biased as mentioned above, the field-aligned ion flows with radially-different energies, or ion flow velocity shears, are generated in the radially-uniform plasma potential.

A small radially movable Langmuir probe is used to measure radial profiles of the plasma parameters. Ion energy distribution functions parallel to the magnetic field are measured by a directional electrostatic energy analyzer, the collector diameter of which is 0.3 cm. Here, the axial position $z$ is defined as the distance from the Sus grid ($z = 0$ cm) toward the electron emitter.

### 3.2 Experimental Results and Discussion

Figure 2 shows the radial profiles of plasma density $n_p$ (solid line) and plasma potential $\phi$ (dotted line) of the synthesized plasma, 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 shaded areas in Fig. 2 indicate the projected location of the segmented ion-emitter electrodes. $\phi (= -4$ V) is uniform radially within the third electrode, the flat region of which corresponds to the diameter of the electron emitter. Since this radially uniform $\phi$ profile means that there is no radial electric field $E_r$ and no sheared flow perpendicular to the magnetic field, we need not consider the effects of the $E_r \times B$ drift and its shear on the instabilities measured within the plasma column. On the other hand, $n_p$ is about $10^9$ cm$^{-3}$ at the radial center and the plasma is produced almost within the second electrode, gradually decreasing toward the outside. In this plasma, electron $T_e$ and ion $T_i$ temperatures are around 0.2 eV and their profiles are almost uniform in the radial direction.

Figure 3 shows the ion energy distribution functions parallel to the magnetic field $F_{\parallel} (= -dI/\partial V_C)$ with the radial
position $r$ as a parameter for $V_{ie1} = 8$ V and $V_{ie2} = 16$ V, where $I_e$ is the current flowing to a collector of the energy analyzer and $V_c$ is the collector voltage applied with respect to the ground. The long arrows numbered in this figure denote the location ranges of the first (No. 1) and the second (No. 2) ion-emitter electrodes. In the third electrode region, however, the plasma density is too small to obtain $F_{||}$. Large peaks of $F_{||}$ at $V_c = 5$ V and $13$ V are observed in the regions of the first and the second electrodes, respectively. Since $\psi$, which is indicated as the small peak of $F_{||}$ at $V_c = -4$ V, is radially constant as described above, the values of the ion flow energy are $\varepsilon = 9$ eV and $17$ eV, which are almost equivalent to $V_{ie1}$ and $V_{ie2}$, respectively. Thus, the ion drift difference between adjacent layers, or the field-aligned ion flow velocity shear in the boundary region of these electrodes is found to be easily formed and controlled by means of biasing the ion-emitter electrodes independently. Here, the direction of the radial gradient in the flow velocity, i.e., the sign of the flow shear, can also be easily reversed by setting $V_{ie1}$ larger or smaller than $V_{ie2}$. These parallel shears are observed to give rise to several types of low-frequency instabilities [38,39].

Figure 4 presents the normalized fluctuation amplitudes $\tilde{I}_{es}/I_{es}$ of electron saturation current $I_{es}$ of the probe as a function of $V_{ie1}$ for $V_{ie1} < V_{ie2}$ ($=-0.8$ V) at $r = -1.0$ cm ($\tilde{I}_{es}$; time averaged value of $I_{es}$). Here the position of $r = -1.0$ cm corresponds to the central shear region between the first and second electrodes. Typical examples of the frequency spectra of $I_{es}$ are shown in the inset. When $V_{ie1}$ is nearly equal to $V_{ie2}$, the fluctuation is not excited. However, with a decrease in $V_{ie1}$, namely as the parallel shear strength in the central shear region increases, the fluctuation amplitude gradually becomes large. This fluctuation is localized in the shear region, the frequency of which is around $1$ kHz and increases slightly with an increase in $V_{ie1}$.

The normalized fluctuation amplitudes $\tilde{I}_{es}/I_{es}$ as a function of $V_{ie1}$ are presented for $V_{ie1} > V_{ie2}$ ($=-0.8$ V) in Fig. 5, together with the frequency spectra of $\tilde{I}_{es}$ in the inset. When $\Delta V_{ie}$ is large, the fluctuation is almost zero, the fluctuation is not excited like the case for $V_{ie1} < V_{ie2}$. Once $|\Delta V_{ie}|$ exceeds a certain threshold, the fluctuation with a frequency of about $6.5$ kHz is observed to grow as $|\Delta V_{ie}|$ becomes large. Furthermore, the fluctuation is confirmed to be localized in the density gradient region which is a different radial position from the shear region. When $|\Delta V_{ie}|$ further increases, $\tilde{I}_{es}/I_{es}$ attains a maximum value and gradually decreases after that. This suppression phenomenon of the fluctuations is discussed later.

As previously recognized in Figs. 4 and 5, $\tilde{I}_{es}/I_{es}$ becomes large with an increase in $|\Delta V_{ie}|$, demonstrating that the parallel shear excites these fluctuations. However, the fluctuations observed in the cases of negative and positive values of $\Delta V_{ie}$ have differences in the maximum fluctuation amplitude and the threshold of $|\Delta V_{ie}|$ to excite the fluctuations. In order to clarify these differences, it is required to acquire a knowledge of the propagation characteristics of the fluctuations in both the directions parallel and perpendicular to the magnetic field. Since the slab plasma model is adopted in the theory described in Sec. 2, we assume that the radial, azimuthal, and axial directions for the experimental cylindrical plasma correspond to the $x$, $y$, and $z$ directions in the theory, respectively. Parallel (axial) $k_x$ and perpendicular (azimuthal) $k_y$ wave numbers of the fluctuations are measured by two pairs of probes at $r = -1.0$ cm separated axially by $26$ cm and azimuthally by $90$ degrees, respectively. The results are presented in Table 1. The signs of $k_x$ and $k_y$ are always positive.
even when the sign of $\Delta V_{ie}$ is changed. In addition, the ratio of parallel to perpendicular wavenumbers $k_x/k_z$ is found to be larger than unity in any case.

In the case of $\Delta V_{ie} < 0$, i.e., shear strength $\partial v_x/\partial x > 0$, the observed fluctuation is considered to be the D’Angelo mode excited by the parallel shear, because the shear parameter $\sigma^2$ becomes negative, and then $\omega$ acquires the imaginary part as discussed in Eq. (3). The theoretical growth rate $\gamma$ obtained from Eq. (3) is plotted in Fig. 4 (solid line) for comparison with the experimental results. Although the theoretical threshold of $|\Delta V_{ie}|$ to excite the D’Angelo mode is slightly different from the experimental results, the dependence of $\bar{I}_{es}/I_{es}$ on $V_{ie1}$ shows almost the same tendency. For $V_{ie1} < -3$ V, however, the experimental $\bar{I}_{es}/I_{es}$ decreases contrary to the theoretical growth rate. Since the plasma density becomes small when $V_{ie1}$ is decreased and approaches the plasma potential, $\bar{I}_{es}/I_{es}$ is considered to become small corresponding to the decrease in the plasma density.

In the case of $\Delta V_{ie} > 0$, on the other hand, $\sigma^2$ becomes positive and the fluctuation is observed to be localized in the large density gradient region. Thus, this fluctuation appears to be the drift-wave instability enhanced by the parallel shear, which has never been observed so far in other experiments. In order to identify the parallel-shear enhanced drift-wave instability, the theoretical growth rate $\gamma$ as a function of $V_{ie1}$ is calculated from Eq. (10) using the plasma parameters experimentally obtained, and is plotted in Fig. 5 (solid line). The experimental results are in good agreement with the theoretical curves and it turns out that the growth rate changes into positive when $V_{ie1}$ exceeds the threshold and gradually increases with an increase in $V_{ie1}$. This means that the ion-frame phase velocity of the fluctuation becomes large due to the presence of the parallel shear [see Eq. (9)], and thus, the effect of the ion Landau damping on the waves is reduced. For larger $V_{ie1}$, however, the growth rate saturates and gradually decreases with a further increase in $V_{ie1}$. When the phase velocity exceeds the ion flow velocity, or the relative electron-ion drift velocity in the ion frame, due to the increase in $V_{ie1}$, the effect of the inverse electron Landau damping in the ion frame is reduced, which leads to the stabilization of the waves.

Figure 6 shows the normalized fluctuation amplitude $\bar{I}_{es}/I_{es}$ as functions of $V_{ie1}$ and $V_{ie2}$ at $r = -1.0$ cm. When $V_{ie1}$ is nearly equal to $V_{ie2}$, which is given as a dotted line in Fig. 6, the fluctuation is not excited. With an increase or a decrease in $V_{ie1}$ at a fixed value of $V_{ie2}$, however, the fluctuation amplitude gradually becomes large. What is important and to be emphasized in Fig. 6 is that these instabilities are excited not by the absolute value of $V_{ie1}$ or $V_{ie2}$ but by the relative difference between $V_{ie1}$ and $V_{ie2}$, namely the parallel flow velocity shear in the boundary between the first and the second electrodes.

The parallel flow velocity difference equivalent to $\Delta V_{ie}$ $\approx 1$ V, which leads the instability to be excited in our experimental condition, corresponds to the shear parameter $\sigma^2 \approx 20$, and this value is much larger than $\sigma^2 = 1 \sim 2$ in the case of the shear-modified ion-acoustic instability reported previously [10]. In our synthesized plasma, no parallel electron drift flow (electron current) is actually generated, so that the large parallel shear is needed to give rise to the instability in the presence of only the ion drift flow, the velocity of which is much less than that of electrons. These situations enable us to understand the essential effects of the parallel shear on the instability in detail, giving clear evidence of the drift-wave destabilization by the parallel shear in the absence of parallel electron current.

### 4. Experiments on Perpendicular Flow Shear

#### 4.1 Experimental Apparatus

In the case of perpendicular flow shear experiments, a plasma is produced by the surface ionization of potassium atoms on a 10.0-cm-diameter tungsten (W) hot plate under a magnetic field of 1.6 kG in a single-ended Q machine as

<table>
<thead>
<tr>
<th>$\Delta V_{ie}$ (V)</th>
<th>$k_x$ (cm$^{-1}$)</th>
<th>$k_z$ (cm$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$-3.0 \sim -2.0$</td>
<td>$\pm 0.65$</td>
<td>$\pm 0.04$</td>
</tr>
<tr>
<td>$2.0 \sim 3.0$</td>
<td>$\pm 0.67$</td>
<td>$\pm 0.067$</td>
</tr>
</tbody>
</table>

Table 1 The parallel $k_x$ and perpendicular $k_z$ wavenumbers of the fluctuations detected by two pairs of probes at $r = -1.0$ cm separated axially by 26 cm and azimuthally by 90 degrees, respectively.
shown in Fig. 7 [38,40]. The hot plate is concentrically segmented into three section, each of which is electrically isolated and is individually biased. Thus, the radially-different plasma potential, i.e., radial electric field is generated even in the fully-ionized collisionless plasma. Voltages applied to the electrodes set in order from the center to the outside are defined as $V_{H1}$, $V_{H2}$, and $V_{H3}$, respectively. Here, $V_{H3}$ is always kept at 0 V. Experimental conditions of $n_p$, $T_e$, and $T_i$ are almost the same as in the case of the parallel flow shear experiments. A glass end plate is located at $z = 170$ cm from the hot plate ($z = 0$ cm), which terminates the plasma column.

In the case of an experiment on ion-cyclotron instabilities, a small disk electrode, the diameter of which is 2 mm, is inserted and a positive bias voltage $V_D$ is applied to the electrode in order to excite the ion-cyclotron instability.

4.2 Experimental Results and Discussion

Radial profiles of plasma potential $\phi$ are presented in Fig. 8 with $V_{H1}$ as a parameter for $V_{H2} = 0$ V at $z = 60$ cm. As usual in the Q-machine plasma under an electron-rich condition, the plasma potential is negative around the radial center of the plasma column and increases towards the edge region. When $V_{H1}$ is changed from $–2.0$ V to $1.0$ V, the plasma potential profile in the central region is changed from the well shape to the hill shape, while that in the edge region is almost constant. The potential difference in the central region can be controlled in a range of $–10 \sim 5$ V with the accuracy of 0.05 V. This radially-different plasma potential, or the radial electric field $E_r$, gives rise to the $E_r \times B$ drift flow and its shear perpendicular to the magnetic-field lines.

Figure 9 shows the radial profiles of the perpendicular ion flow velocity, which are measured by a directional Langmuir probe (DLP) [41], with $V_{H1}$ as a parameter for $V_{H2} = 0$ V. Since it is difficult to determine the absolute value of the flow velocity [42], we present the ratio of the ion saturation current of DLP $\left( I_{up} - I_{down} \right) / \left( I_{up} + I_{down} \right)$ which is proportional to the actual ion flow velocity [41], where $I_{up}$ and $I_{down}$ denote that the collector surface of DLP faces up and down at the plasma cross section, respectively, which corresponds to the direction parallel or anti-parallel to the $E_r \times B$ ion flow. The perpendicular flow velocity and its shear are found to actually increase when the radial electric field becomes large. This result ensures that the perpendicular flow velocity shear can be controlled by changing the radial electric field, i.e., the voltage applied to the hot plate.

Figure 10 gives normalized fluctuation amplitudes $\tilde{I}_{es} / I_{es}$ of the electron saturation current $I_{es}$ of the probe as a function of $V_{H1}$, which are observed at $r = 2.5$ cm for $V_{H2} = 0$ V. As $V_{H1}$ is increased from $–1.6$ V to $–0.3$ V, the fluctuation
amplitude is found to increase, gradually decreasing for \( V_{H1} > -0.7 \) V. The frequency of the fluctuation is about 20 kHz, which corresponds to the frequency of the drift-wave instability Doppler-shifted due to the \( E_r \times B \) drift. When the fluctuation amplitude has a maximum value for \( V_{H1} \approx -0.7 \) V, the radial profile of plasma potential is almost flat in the central region as shown in Fig. 8. The result demonstrates that the drift-wave instability excited in the edge region is suppressed by only the slight radial electric field, or the perpendicular shear in the central region, generated by biasing the segmented hot plate.

In order to investigate effects of the perpendicular shear on the instabilities in the ion-cyclotron frequency range, we insert the small disk electrode at the center of the plasma cross section (see Fig. 7), which has been known to excite the ion-cyclotron instabilities by changing the bias voltage \( V_D \) applied to the electrode [43-46]. Figure 11 shows the frequency spectra of electron current \( I_D \) flowing to the small disk electrode, together with a \( V_D - I_D \) characteristic of the disk electrode. Figure 10 presents the frequency spectra of electron saturation current and normalized fluctuation amplitudes \( \tilde{I}_{es}/I_{es} \) as a function of \( V_{H1} \) for \( V_{H2} = 0 \) V at \( r = -2.5 \) cm.

Fig. 10 Frequency spectra of electron saturation current and normalized fluctuation amplitudes \( \tilde{I}_{es}/I_{es} \) as a function of \( V_{H1} \) for \( V_{H2} = 0 \) V at \( r = -2.5 \) cm.

suppressed with an increase or a decrease in \( V_{H1} \). The perpendicular shear is found to be effective in suppressing the ion-cyclotron instability in the same way as the drift-wave instability.

In the case of ion-cyclotron instability, the potential difference \( |V_{H1} - V_{H2}| \approx 0.5 \) V is sufficient to suppress the instability. Since this potential difference is generated in the width of about 0.2 cm as shown in Fig. 8, \( E_r \times B \) drift velocity \( v_{E_r \times B} \) is calculated to be about 830 m/s for \( B = 3 \) kG. Furthermore, this \( v_{E_r \times B} \) varies radially in the width of about

Fig. 11 Frequency spectra of electron current \( I_D \) of the small disk electrode with \( V_D \) as a parameter at \( r = 0 \) cm for \( B = 3 \) kG in the case of no shear, together with \( V_D - I_D \) characteristic of the disk electrode.

Fig. 12 Frequency spectra of electron saturation current and normalized fluctuation amplitudes \( \tilde{I}_{D}/I_{D} \) as a function of \( V_{H1} \) for \( V_{H2} = 0.7 \) V and \( V_D = 90 \) V at \( r = 0 \) cm.
0.5 cm as shown in Fig. 9, which yields the strength of perpendicular flow velocity shear $\partial V_y/\partial r = 160$ kHz. Considering that the ion-cyclotron frequency is about 120 kHz in our experimental configuration, the instability appears to be suppressed when the perpendicular shear strength exceeds the ion-cyclotron frequency. Theoretical analyses of the suppression of instabilities by the perpendicular shear have been reported in cases of low frequency range such as the drift mode [47,48] and the flute mode [49], while the effect of the perpendicular shear on the suppression of the ion-cyclotron instability has not yet been thoroughly discussed and is currently under consideration.

5. Conclusions

Basic laboratory experiments are performed regarding low-frequency instabilities modified by the parallel flow shears and the perpendicular flow shears. In the case of parallel flow shear experiments, not only the D’Angelo mode but also the drift-wave instability is found to be excited by the ion flow velocity shear in the absence of the electron drift flow depending on the sign of the shear. The fluctuation amplitude is observed to increase with increasing the shear strength, but the instability is found to be gradually stabilized when the shear strength exceeds the critical value. For the drift-wave instability, the experimental results are in good agreement with the dependence of the theoretical growth rate on the shear strength, which is calculated in the kinetic treatment including the effect of the radial density gradient. The experimental results of the D’Angelo mode also yield the same tendency as the theoretical growth rate which is derived in fluid treatment.

In the case of perpendicular flow shear experiments, on the other hand, not only the drift-wave instability which exists in the density-gradient region but also ion-cyclotron instability excited by the small disk electrode inserted at the center of a magnetized plasma column is observed to be suppressed by only the slight shear of the perpendicular flow velocity. Furthermore, the suppressions are found to take place independently of the sign of the shear.

Based on the results mentioned above, it is concluded that the plasma flow shears in the magnetized plasma are important for controlling the low-frequency instabilities, where the parallel and perpendicular shears play different roles in these instabilities, respectively. A goal of our future laboratory experiments is to investigate the intermingled and interrelated effects of these controlled parallel and perpendicular flow shears on the instabilities in order to clarify the characteristics of the flow-shear modified instabilities in real situations of the fusion-oriented and space plasmas.

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