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# Drift-Wave Instability Excited by Field-Aligned Ion Flow Velocity Shear in the Absence of Electron Current

T. Kaneko,* H. Tsunoyama, and R. Hatakeyama

*Department of Electronic Engineering, Tohoku University, Sendai 980-8579, Japan*

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The drift wave is observed to be destabilized by a magnetic-field-aligned ion flow velocity shear in the absence of field-aligned electron drift flow in laboratory experiments using a concentrically three-segmented plasma source. The fluctuation amplitude increases with increasing a shear strength, but the instability is found to be gradually stabilized when the shear strength exceeds a critical value. The destabilizing and stabilizing mechanisms are well explained by a plasma kinetic theory including the effect of radial density gradient.

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A parallel ion flow velocity shear, which is defined as transverse shear in the magnetic-field-aligned ion flow velocity, has recently been recognized to be an origin of low-frequency instabilities in magnetized plasmas such as fusion-oriented and space plasmas. Over three decades ago, D'Angelo first proposed the fluid theory of a parallel-shear driven instability in the low-frequency range ($\omega \ll \omega_{ci}$, where $\omega_{ci} = eB/m_i$ is the ion-cyclotron frequency) [1], which was immediately observed experimentally in a fully ionized collisionless plasma ($Q$ machine plasma) [2]. Although this instability was originally defined as the Kelvin-Helmholtz instability, it is now referred to as the D'Angelo mode. Some experimental [3,4] and theoretical [5] investigations related to the D'Angelo mode have been performed in various situations. In this connection the fluid treatment analysis also elucidates that the parallel shear can lead to the excitation of ion-cyclotron modes [6,7] in the higher frequency range ($\omega \simeq \omega_{ci}$). In recent theoretical works using a kinetic treatment, furthermore, the parallel shear is found to cause not only the D'Angelo mode but also electrostatic ion-acoustic and ion-cyclotron instabilities, depending on the sign of the parallel shear [8–10]. These shear-modified ion-acoustic [11,12] and ion-cyclotron [13–15] instabilities are experimentally observed in the $Q$ machine plasma.

In these experiments, however, the effect of 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 clarification of 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. In addition, it is to be noted that the shear-modified ion-acoustic and ion-cyclotron instabilities mentioned above are excited by just a little parallel shear in the presence of the parallel electron current which often exists in conventional configurations such as a $Q$ machine experiment [16], and therefore it is very hard to experimentally evaluate the precise value of the parallel shear, which leads to the difficulty in understanding the effects of the parallel shear on these instabilities. In this Letter, we for the first time clarify the feature of the drift-wave instability excited by the parallel ion flow velocity shear in the electron-currentless plasma which is realized by our newly developed plasma source [17], and analyze the experimental results by the kinetic treatment [8] which includes the effect of radial density gradient.

Experiments are performed in the $Q_T$–Upgrade machine of Tohoku University. A plasma is produced by a modified plasma-synthesis method, where potassium ion and electron emitters are oppositely set at cylindrical machine ends under a strong magnetic field of $B =$ 1.6 kG. A negatively biased stainless (Sus) grid, the voltage of which is typically $V_g = -60$ V, is installed at a distance of 0.5 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, namely, there is no electron drift flow. In this synthesized plasma, the electron emitter is negatively biased at typically $V_{ee} \simeq -4.0$ V, which determines the plasma potential, 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, the field-aligned ion flows with radially different energies, or ion flow velocity shears, are generated in the radially uniform plasma potential [17]. Hereinafter, the electrodes set in order from the center to the outside are called as the first, second, and third electrodes and the voltages applied to them are defined as $V_{ie1}$, $V_{ie2}$, and $V_{ie3}$, respectively. A small radially movable Langmuir probe is used to measure radial profiles of

  

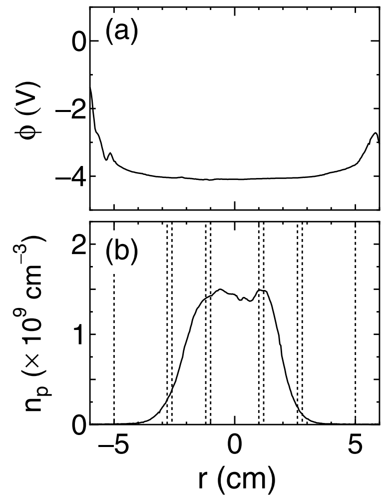


FIG. 1. Radial profiles of (a) plasma potential $\phi$ and (b) plasma density $n_p$ at $z = 60$ cm for $V_{ie1} = V_{ie2} = 0$ V, $V_{ee} \simeq -4.0$ V, and $V_g = -60$ V.

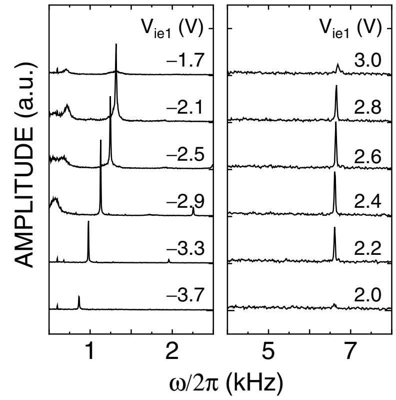


FIG. 2. Frequency spectra of electron saturation current of the probe with $V_{ie1}$ as a parameter for $V_{ie2} = -0.8$ V at $r = -1.0$ cm.

plasma parameters. Here, the axial position $z$ is defined as the distance from the Sus grid ($z = 0$ cm) toward the electron emitter.

Figure 1 shows radial profiles of (a) plasma potential $\phi$ and (b) plasma density $n_p$ 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 dotted lines in Fig. 1 indicate the boundaries of the segmented ion-emitter electrodes. $\phi$ ( $\simeq -4.0$ V) are 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 $E$ and no sheared flow perpendicular to the magnetic field, we need not consider effects of the $\mathbf{E} \times \mathbf{B}$ 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. When $V_{ie1}$ and $V_{ie2}$ are individually biased, the radial profiles of $\phi$ and $n_p$ do not change and the parallel ion flow velocity shears are generated at the boundary of each electrode as shown in Ref. [17]. These parallel shears are observed to give rise to several types of low-frequency instabilities [18].

In Fig. 2, frequency spectra of an electron saturation current $I_{es}$ of the probe are presented with $V_{ie1}$ as a parameter for $V_{ie2} = -0.8$ V at $r = -1.0$ cm which corresponds to the central shear region between the first and second electrodes. When $V_{ie1}$ is nearly equal to $V_{ie2}$, the fluctuation is not excited. However, with an increase or a decrease in $V_{ie1}$, namely, as the parallel-shear strength in the central shear region increases, the fluctuation amplitude gradually becomes large. In the case of $V_{ie1} < 0$, the fluctuation frequency is around 1 kHz and slightly increases with an increase in $V_{ie1}$. For $V_{ie1} > 0$, on the other hand, the fluctuation with the frequency of about 6.5 kHz is observed.

Figure 3 shows the normalized fluctuation amplitudes $\tilde{I}_{es}/\bar{I}_{es}$ as a function of $V_{ie1}$ for $V_{ie2} = -0.8$ V at (a) $r = -1.0$ cm and (b) $r = -2.4$ cm ($\bar{I}_{es}$: time averaged value of $I_{es}$). Here the position of $r = -2.4$ cm corresponds to the peripheral shear region between the second and third electrodes, where the radial density gradient is relatively large. At both the radial positions, the fluctuation is not excited when $\Delta V_{ie}(\equiv V_{ie1} - V_{ie2})$ is almost zero. Once $|\Delta V_{ie}|$ exceeds the certain thresholds, both the fluctuations are observed to grow as $|\Delta V_{ie}|$ becomes large. Thus, the fluctuations are found to be excited by the parallel shear. When $|\Delta V_{ie}|$ is more increased, however, $\tilde{I}_{es}/\bar{I}_{es}$

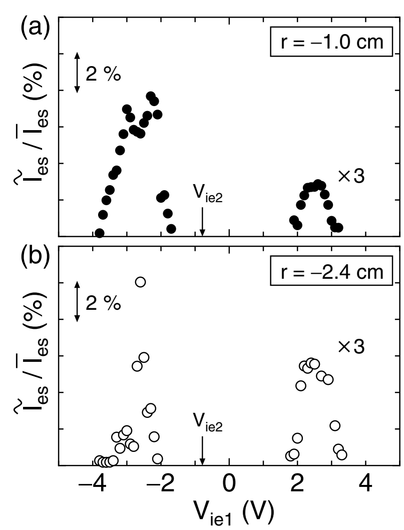


FIG. 3. Normalized fluctuation amplitudes $\tilde{I}_{es}/\bar{I}_{es}$ as a function of $V_{ie1}$ for $V_{ie2} = -0.8$ V at (a) $r = -1.0$ cm and (b) $r = -2.4$ cm.

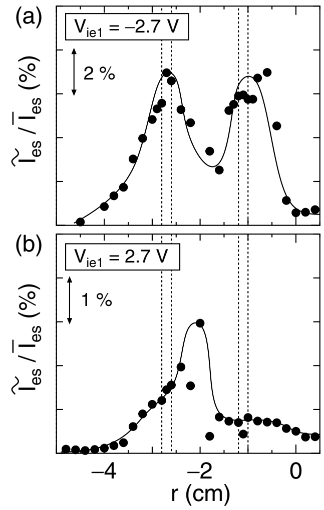


FIG. 4. Radial profiles of fluctuation amplitude $\tilde{I}_{es}/\bar{I}_{es}$ for (a) $V_{ie1} = -2.7$ V and (b) $V_{ie1} = 2.7$ V. Here, $V_{ie2}$ is $-0.8$ V in both the cases.

has the maximum value and gradually decreases. This suppression phenomenon of the fluctuations is discussed later. The maximum value of $\tilde{I}_{es}/\bar{I}_{es}$ for $\Delta V_{ie} < 0$ is larger than that for $\Delta V_{ie} > 0$ in both the shear regions. Furthermore, $\tilde{I}_{es}/\bar{I}_{es}$ in the peripheral region is larger than that in the central region for $\Delta V_{ie} > 0$, while $\tilde{I}_{es}/\bar{I}_{es}$ in both the regions are almost the same for $\Delta V_{ie} < 0$. These results imply that the fluctuations excited in the cases of negative and positive values of $\Delta V_{ie}$ belong to the different types of instabilities, respectively.

In Fig. 4, radial profiles of $\tilde{I}_{es}/\bar{I}_{es}$ for (a) $V_{ie1} = -2.7$ V and (b) $V_{ie1} = 2.7$ V are presented, where the dotted lines indicate the boundaries of the segmented ion-emitter electrodes. In the case of $V_{ie1} = -2.7$V, $\tilde{I}_{es}/\bar{I}_{es}$ is localized in both the boundaries between the first-second and second-third electrodes, namely, the parallel-shear regions. In the case of $V_{ie1} = 2.7$ V, on the other hand, $\tilde{I}_{es}/\bar{I}_{es}$ has the maximum value at $r \simeq -2$ cm which corresponds to the maximum radial density gradient region as shown in Fig. 1. The identification of the cause of these fluctuations requires a knowledge of their propagation characteristics in both the directions parallel and perpendicular to the magnetic field. The parallel $k_z$ and perpendicular $k_y$ wave numbers of the fluctuations are measured by two pairs of probes separated axially by 26 cm and azimuthally by 90°, respectively. The results are presented in Table I. The signs of $k_y$ and $k_z$ are always positive even when the sign of $\Delta V_{ie}$ is changed. In addition, the ratio of parallel to perpendicular wave numbers $k_y/k_z$ is found to be larger than unity in any case. In the case of $\Delta V_{ie} < 0$, namely, shear strength $V_d'(\equiv \partial v_d/\partial x) > 0$, the observed fluctuation is considered to be the D'Angelo mode excited by the parallel shear, because the shear parameter $\sigma^2 \equiv 1 - (k_y/k_z)(V_d'/\omega_{ci})$ becomes negative, as discussed in Ref. [9]. Here $v_d$ is the field-aligned ion flow velocity in the laboratory frame, or the relative electron-ion drift velocity in the ion frame. In the case of $\Delta V_{ie} > 0$, on the other hand, $\sigma^2$ becomes positive and the fluctuation is localized in the large density gradient region. Thus, this fluctuation appears to be the drift-wave instability excited by the parallel shear, which has never been observed so far in other experiments.

TABLE I. The parallel $k_z$ and perpendicular $k_y$ wave numbers of the fluctuations detected by two pairs of probes separated axially by 26 cm and azimuthally by 90°, respectively.

| | $\Delta V_{ie} < 0$ | | $\Delta V_{ie} > 0$ | |
|---|---|---|---|---|
| $r$ (cm) | $k_y$(cm$^{-1}$) | $k_z$(cm$^{-1}$) | $k_y$(cm$^{-1}$) | $k_z$(cm$^{-1}$) |
| −1.0 | ≃ +0.65 | ≃ +0.04 | ≃ +0.67 | ≃ +0.067 |
| −2.4 | ≃ +0.10 | ≃ +0.014 | ≃ +0.42 | ≃ +0.15 |

In order to identify the parallel-shear excited drift-wave instability in the case of $\Delta V_{ie} > 0$, we numerically solve the linear dispersion relation using the experimental parameters. Although Gavrishchaka *et al.* obtained the growth rate of the ion-acoustic instability [9], the radial density gradient was not taken into account in that analysis. Thus we try to express the effect of the density gradient in terms of the electron diamagnetic drift frequency $\omega_e^*$ ($= k_y T_e \kappa/eB$), where $\kappa = -d\ln n/dx$. From the general kinetic dispersion relation given by Ganguli *et al.* [8], the growth rate $\gamma$ of the drift-wave instability can be shown for the low-frequency range ($\omega \ll \omega_{ci}$),

$$\frac{\gamma}{\omega_r} = \sqrt{\frac{\pi}{2}}\frac{\omega_r}{\tau(2\omega_r - \omega_e^*)}\frac{\omega_r}{k_z v_{ti}}\left[\sqrt{\frac{\tau^3}{\mu}}\left(\frac{k_z v_d + \omega_e^*}{\omega_r} - 1\right) - \sigma^2 \exp\left(-\frac{\omega_r^2}{2(k_z v_{ti})^2}\right)\right], \quad (1)$$

and

$$\omega_r(\equiv \omega_{\rm obs} - k_z v_d) = \frac{\omega_e^*}{2} + \sqrt{\left(\frac{\omega_e^*}{2}\right)^2 + \sigma^2 (k_z C_s)^2}, \quad (2)$$

where $\tau \equiv T_i/T_e$, $\mu \equiv m_i/m_e$, $v_{ti} \equiv (T_i/m_i)^{1/2}$, $C_s \equiv (T_e/m_i)^{1/2}$, $\omega_{obs}$ and $\omega_r$ are the real frequency of the drift-wave instability in the laboratory frame and in the ion frame, respectively. The expression of this $\omega_r$ is the same as the formula of the D'Angelo mode in the fluid analysis [1,5].

The theoretical growth rates $\gamma$ as a function of the shear parameter $\sigma^2$ are calculated from Eq. (1) using the plasma parameters experimentally obtained at $r = -1.0$ cm and $-2.4$ cm, which are denoted by solid and dotted lines, respectively, in Fig. 5. It turns out that the growth rate changes into positive when $\sigma^2$ exceeds the threshold and gradually increases with an increase in $\sigma^2$. This means that the ion-frame phase velocity becomes

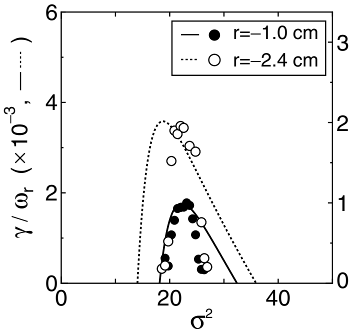


FIG. 5. Dependence of theoretical growth rate $\gamma$ of drift-wave instability on shear parameter $\sigma^2$. Experimental fluctuation amplitudes $\tilde{I}_{es}/\bar{I}_{es}$ of Fig. 3 are also replotted.

large due to the presence of the parallel shear, and thus, the effect of the ion Landau damping on the waves is reduced. For larger $\sigma^2$, however, the growth rate saturates and gradually decreases with a further increase in $\sigma^2$. 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 $\sigma^2$, the effect of the inverse electron Landau damping in the ion frame is reduced, which leads to the stabilization of the waves. The growth rate in the peripheral region ($r = -2.4$ cm), where the density gradient is relatively steep, is found to be larger than that in the central region ($r = -1.0$ cm). Thus, the density gradient is also responsible for enhancing this instability. In Fig. 5, we replot the experimentally obtained fluctuation amplitude $\tilde{I}_{es}/\bar{I}_{es}$ of Fig. 3 in the case of only $\Delta V_{ie} > 0$ as a function of $\sigma^2$ instead of $\Delta V_{ie}$. Here, the shear strength $V_d'$ in the central region is adopted even for the fluctuation observed in the peripheral region. The experimental results are in good agreement with the theoretical curves.

The shear parameter $\sigma^2 \simeq 20$ which leads to the excitation of the instability in our experimental condition is much larger than $\sigma^2 = 1 \sim 2$ in the case of the shear-modified ion-acoustic instability reported previously [12]. 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.

In conclusion, our experiments for the first time demonstrate an excitation of the drift-wave instability by the ion flow velocity shear in the absence of the electron drift flow. 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. The experimental results are in good agreement with the dependence of the theoretical growth rate on the shear parameter, which is calculated in the kinetic treatment including the effect of the radial density gradient. The observations of the excitation and the suppression of the drift-wave instability with increasing the shear strength are theoretically explained in terms of the decreases in the ion Landau damping and the inverse electron Landau damping in the ion frame, respectively.

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*Electronic address: kaneko@ecei.tohoku.ac.jp

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