Effects of E×B Velocity Shear on High and Low Frequency Fluctuations Excited by Electron Temperature Gradient

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Abstract

Electron temperature gradient (ETG) perpendicular to magnetic field lines is formed by superimposing high-temperature electrons of an electron cyclotron resonance (ECR) plasma upon low-temperature thermionic electrons emitted from a tungsten hot plate. The formed ETG is found to excite a high-frequency fluctuation, i.e., ETG mode, and also, to enhance a low-frequency fluctuation originally caused by an E×B velocity shear. Furthermore, the strong E×B velocity shear is demonstrated to suppress the ETG mode experimentally.

1. Introduction

In recent years, anomalous electron heat transports in magnetically confined plasmas are a big issue [1], which are difficult to be explained clearly even though many researchers try to understand the mechanism of the heat transports in fusion devices [2]. There are strong experimental evidences that the anomalous heat transports are attributed to an electron temperature gradient (ETG) driven instability (ETG mode). Actually, it is seen that the instability is driven by the ETG and nonlinear effects of the ETG mode generate the significant electron transport. In addition, it is theoretically reported that the ETG mode is difficult to be suppressed by an E×B velocity shear, which is reported to regulate an ion temperature gradient mode [3]. Although there are some earlier theoretical [4], numerical [5], and experimental [6] studies on the ETG mode, experimental observations of the ETG mode in large fusion devices are not sufficient to clearly explain the excitation mechanism, because the electron density gradient, which also affects the ETG mode, is unexpectedly generated in the magnetically confined fusion plasmas, when the ETG is formed by using a high-power microwave which heats the electrons.

In this sense, we have claimed that the basic laboratory experiments, which can realize the individual control of the ETG and the density gradient, is indispensable for the elucidation of the excitation and suppression mechanisms of the ETG mode. In the laboratory experiments, several advanced techniques have been applied to the control of the electron temperature. Thus the aim of this work is to control the ETG by using a novel plasma synthesis method superimposing high and low temperature electrons in a basic plasma device and to experimentally investigate the ETG mode with changing the plasma parameters [7].

2. Experimental Apparatus and Method

Experiments are carried out in a linear machine (Q_T-Upgrade) of Tohoku University, the schematic of which is shown in Fig. 1. In order to form the ETG, we divide the machine into two sections. One is called as a source region where an electron cyclotron resonance (ECR) plasma with high electron temperature is generated using microwave (power: P_μ) and the other is called as an experimental region where the high-temperature electrons of the ECR plasma are superimposed on low-temperature thermionic electrons. Here, the axial center of the machine is defined as z = 0 cm. In the source region, a magnetic field is well shaped and the bottom of the well is set to be the electron cyclotron resonance field B_{ECR} =

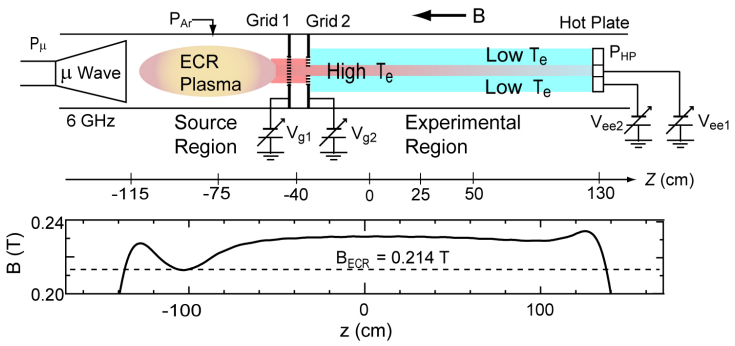

Fig. 1. Schematic diagram of the experimental apparatus and an axial profile of the magnetic field strength.

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0.214 T. Two types of stainless mesh grids [grid 1 (ϕ 6 cm, 10 mesh/inch) and grid 2 (doughnut shape, outside diameter: ϕ 6 cm, inside diameter: ϕ 3 cm, 30 mesh/inch)] are located at z = –40 cm and divide the source region from the experimental region. The ETG is easily formed by controlling the bias voltages applied to the grids. A tungsten (W) hot plate set at the end of the experimental region is heated by applying DC power P_{HP} = 3 kW and generates the low-temperature thermionic electrons (T_e = 0.2 eV), which works as an electron emitter. Since the electron emitter is concentrically segmented into two sections, a radial profile of the space potential is controllable by applying different bias voltages between central (V_{ee1}) and peripheral (V_{ee2}) sections of the electron emitter. The low-temperature thermionic electrons compensate the density gradient of the ECR plasma penetrating the grid 2. Therefore, the large ETG is formed in the experimental region keeping the radial density profile uniform. A Langmuir probe is used to measure radial profiles of plasma parameters at z = 0 cm in the experimental region [7].

3. Experimental Results and Discussion

Using this novel plasma synthesis method superimposing the high-temperature electrons on the low-temperature electrons with spatially control, the ETG can be formed in the experimental region. Figure 2 shows the electron temperature as functions of the bias voltages of (a) grid 1 (V_{g1}) and (b) grid 2 (V_{g2}) in the radially central (r = 0 cm) and peripheral (r = 2 cm) regions for $V_{ee1} = V_{ee2} = 0$ V, P_μ = 30 W. When V_{g2} is decreased, the electron temperature only in the peripheral region rapidly decreases, while the electron temperature in the central region is almost constant. Therefore, the electron temperature difference between the central and peripheral regions, i.e., the ETG, is easily formed by controlling V_{g2} with an appropriate adjustment to V_{g1}.

On the other hand, the decrease in V_{g1} causes the decrease in the electron temperature in both the central and peripheral regions. However, when V_{g1} is less than 0 V, the decrease in the electron temperature in the central region (r = 0 cm) is observed to mitigate in contrast to that in the peripheral region. It is considered that the ions of the ECR plasma are accelerated and collide with the negatively biased grid 1, and as a result, secondary electrons are generated from the grid 1. The secondary electrons are accelerated by the potential difference between grid 1 and plasma potential in the experimental region, and then, the accelerated high energy electrons are thermalized by collision with neutral gas or low temperature electrons, resulting in the mitigation of the decrease in the electron temperature in the central region. On the other hand, the secondary electrons are not accelerated in the peripheral region because the grid 2 prevents the electrons from penetrating into the experimental region. When V_{g1} is less than –20 V, the ions are difficult to collide with grid 1 because the ions

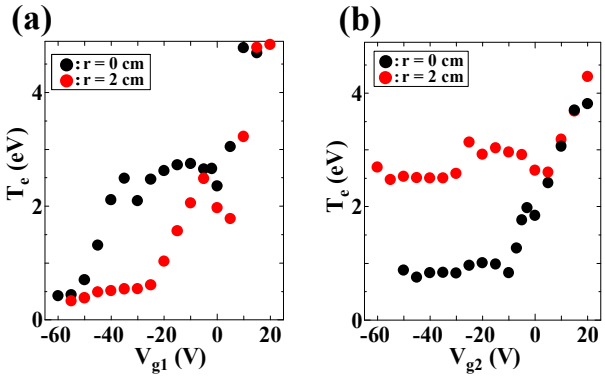

Fig. 2. Electron temperature (T_e) in the central and peripheral regions as functions of (a) V_{g1} for floated V_{g2}, and (b) V_{g2} for floated V_{g1} for $V_{ee1} = V_{ee2} = 0$ V, P_μ = 30 W.

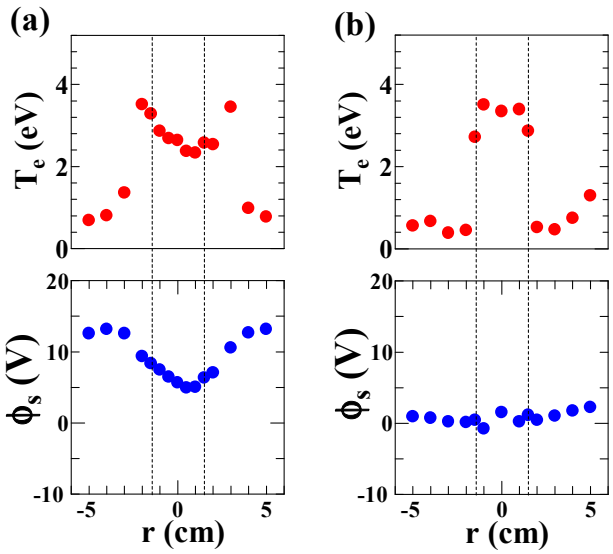

Fig. 3. Radial profiles of electron temperature T_e and space potential ϕ_s for (a) V_{g2} = 10 V and (b) V_{g2} = –30 V. V_{g1} = –10 V, $V_{ee1} = V_{ee2}$ = 0 V, and P_μ = 30 W. Dotted lines indicate the boundary between grid 1 nad grid 2.

with higher energy have smaller Coulomb collision frequency.

Figure 3 shows the radial profiles of the electron temperature (T_e) and the space potential (ϕ_s) for (a) V_{g2} = 10 V and (b) V_{g2} = –30 V, where V_{g1} = –10 V. In the case of V_{g2} = 10 V, the radial profile of the electron temperature is almost flat at the boundary region between grid 1 and grid 2. When V_{g2} decreases to –30 V, on the other hand, the high temperature electrons of the ECR plasma in the peripheral region are reflected back to the source region, and therefore, the electron temperature only in the peripheral region becomes small, resulting in the formation of the steep ETG around r = –1.5 cm.

The space potential is almost flat, even when the ETG is formed [Fig. 3(b)], which is caused by the same bias voltages (V_{ee1} and V_{ee2}) applied to the electron emitters. However, the large positive bias voltage such as V_{g2}=10 V affects the space potential as shown in Fig. 3(a). Here, the radial profiles of the electron density are relatively uniform even when the ETG is formed.

Figure 4 gives frequency spectra of the fluctuation of the electron saturation current (I_{es}) with (a) high and (b) low frequencies under the same conditions as in Fig. 3. In the case of the high frequency range [Fig. 4(a)], the fluctuation is more strongly excited when the ETG is formed for V_{g2} = –30 V. Furthermore, the low frequency fluctuation around 3~4 kHz is also enhanced when the ETG is formed. Since the ETG is not considered to directly affect the low frequency fluctuation, the ETG can enhance the low frequency fluctuation through the coupling with the high frequency ETG mode.

Figure 5 presents the normalized peak amplitudes $\tilde{I}_{es}/\bar{I}_{es}$ of fluctuations as a function of V_{g2} ($\bar{I}_{es}$: time averaged value of I_{es}) for (a) high-frequency (5 MHz) and (b) low-frequency (about 3 kHz) fluctuations. The peak amplitude of the high-frequency fluctuation gradually increaases with a decrease in V_{g2} in the same way as the strength of the ETG which is estimated from Fig. 2(b). Therefore, this fluctuation is believed to be the ETG mode. On the other hand, the peak amplitude of the low frequency fluctuation also increases with a decrease in V_{g2}. This phenomenon is explained by the coupling between the high and low frequency fluctuations, namely, the ETG mode can enhance the low frequency fluctuation.

In order to investigate the suppression mechanism of the ETG mode by the E×B velocity shear, we control the bias voltage of the central electron emitter V_{ee2} to generate the local radial electric field in the magnetized plasma. Figure 6 gives the normalized peak amplitudes $\tilde{I}_{es}/\bar{I}_{es}$ of the fluctuations as a function of V_{ee2} for (a) high-frequency (5 MHz) and (b) low-frequency (about 3 kHz) fluctuations. Here, since V_{ee1} is 1 V, the E×B velocity shear is not formed for V_{ee2} = 1 V, and its strength increases with increasing or decreasing V_{ee2} from 1 V.

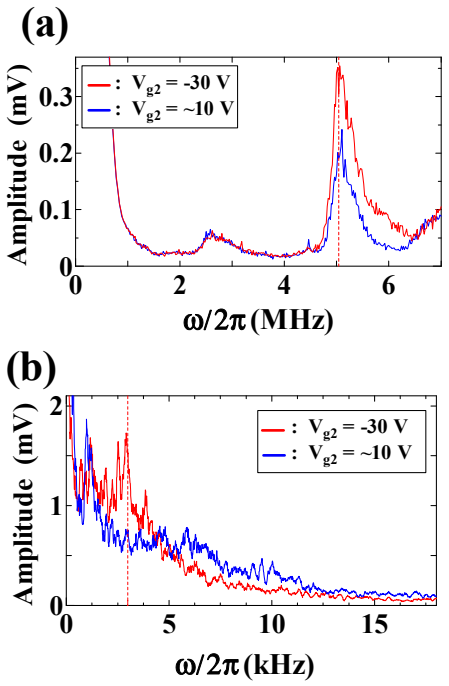

Fig. 4. Frequency spectra of the fluctuation of electron saturation current I_{es} with (a) high and (b) low frequencies for V_{g1} = –10 V, V_{ee1} = V_{ee2} = 0 V, and P_μ = 30 W at r = –1.5 cm.

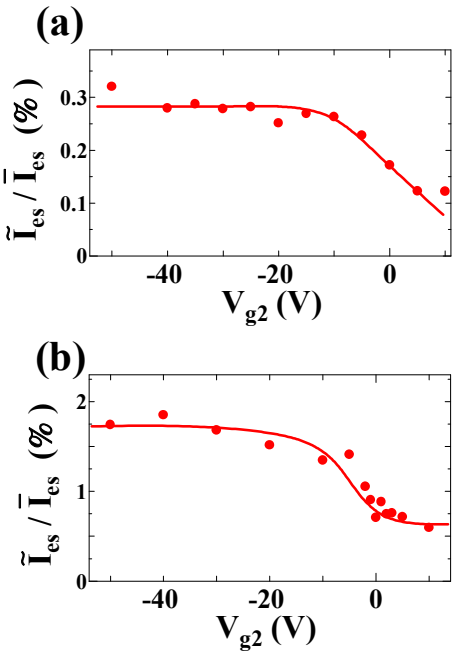

Fig. 5. Normalized peak amplitudes $\tilde{I}_{es}/\bar{I}_{es}$ of fluctuations with low and high frequencies as a function of V_{g2} ($\bar{I}_{es}$: time averaged value of I_{es}) for (a) high-frequency (5 MHz) and (b) low-frequency (about 3 kHz) fluctuation.

The peak amplitude of the high frequency ETG mode is found to gradually decrease with an increase in the E×B velocity shear strength, which means that the ETG mode could be suppressed by the E×B velocity shear. On the other hand, the peak amplitude of the low frequency fluctuation becomes large, when the strength of the E×B velocity shear increases. Therefore, the low frequency fluctuation is considered to be the Kelvin-Helmholtz (K-H) instability. Since the peak amplitude of this K-H instability in the presence of the ETG is larger than that in the absence of the ETG, it is expected that the K-H instability is enhanced by the coupling with the ETG mode.

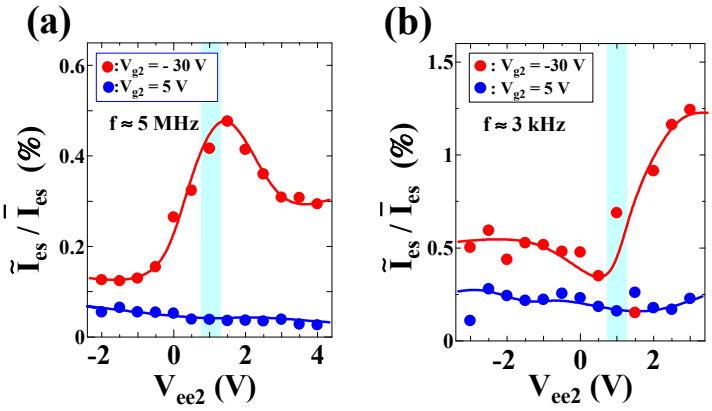

Fig. 6. Normalized amplitudes $\tilde{I}_{es} / \bar{I}_{es}$ of fluctuation with (a) high and (b) low frequencies as a function of V_{ee2} for $V_{ee1} = 1$ V, $V_{g1} = -10$ V, and $P_{\mu} = 30$ W at $r = -1.5$ cm.

4. Conclusion

A novel plasma synthesis method superimposing the high-temperature electrons on the low-temperature electrons has developed to form and control the ETG in a magnetized plasma. The formed ETG is found to excite the high-frequency fluctuation, i.e., ETG mode, and also, to enhance a low-frequency fluctuation originally caused by the E×B velocity shears. Furthermore, it is clarified that the strong E×B velocity shear suppresses the ETG mode experimentally.

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