Effects of multi-component ions on plasma flow-shear driven instabilities

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The drift wave instability driven by the parallel ion flow velocity shear is observed to be anomalously suppressed by superimposing light potassium (K) and heavy cesium (Cs) ions in the magnetized plasma. In addition, the shear strength which yields the peak of the fluctuation amplitude becomes larger with an increase in the superimposed K or Cs ion density. These phenomena are considered to be caused by enhancement of the ion Landau damping effect due to a mixture of the unequal-mass ion species.

I. Introduction

The effects of ion flow velocity shears parallel to magnetic field lines have been recognized to be an origin of various kinds of instabilities and investigated by many researchers [1,2]. For example, it is theoretically proposed that an ion acoustic instability predominantly observed in Earth's ionosphere is enhanced by the field-aligned sheared flow which degrades the ion Landau damping of the ion acoustic mode [3]. This hypothesis was benchmarked by several experiments [4,5]. The shear modified instability has recently been investigated in a more general case, namely, a drift wave instability caused by a density gradient in magnetized plasmas. In our recent works, it is clarified that the drift wave instability is excited and suppressed by the parallel ion flow velocity shears [6,7]. In order to extend this result to the real situation of fusion oriented and space plasmas, it is necessary to clarify the effects of several kinds of ions (multi-component ions) on the shear-driven instability because the actual fusion and space plasmas contain the multi-component ions. Therefore, as the fundamental experiment to simulate the actual multi-component ion plasmas, potassium (K) and cesium (Cs) ions are taken up as light (mass number = 39.1) and heavy (mass number = 132.9) ions, respectively, to investigate the effects of the flow shears in the multi-component ion plasma on the drift wave instability.

II. Experimental Apparatus and Method

Experiments are performed in the Q_T-Upgrade machine of Tohoku University which is shown in Fig. 1. A plasma is produced by a modified plasma-synthesis method [8,9], where tungsten (W) hot plates are situated in both the ends of the cylindrical machine, one of which is used as an electron emitter, and the other is used as an ion emitter. In the case of the ion emitter, K and Cs ovens are separately located in front of the W hot plate. Heated K and Cs are sprayed from the ovens to the W hot plate, and then, the K and Cs ions are generated by contact ionization. The K (n_K) and Cs (n_{Cs}) ion densities can be controlled by the oven temperature T_{ov}. Although the ion emitter also emits the thermionic electrons, the electrons are reflected by a negatively biased mesh grid (V_g = –30 V) that is placed in front of the W hot plate. In this synthesized plasma, the electron emitter is negatively biased at typically V_{ee} = –2.0 V, which determines the plasma potential. Since the potential difference between the plasma and the ion emitter determines the ion flow velocity parallel to magnetic field lines (B = 0.24 T) and the ion emitter is concentrically segmented into three sections which can be biased individually, the parallel ion flow velocity shears are generated by means of the difference between central (V_{ie1}) and peripheral (V_{ie2}) bias voltages of the ion emitter. Typical plasma parameters are as follows: plasma density $n_p \sim 10^9$ cm^{-3}, electron temperature $T_e \sim 0.2$ eV, space potential $\phi_s \sim -6$ V, and background gas pressure $p < 10^{-4}$ Pa.

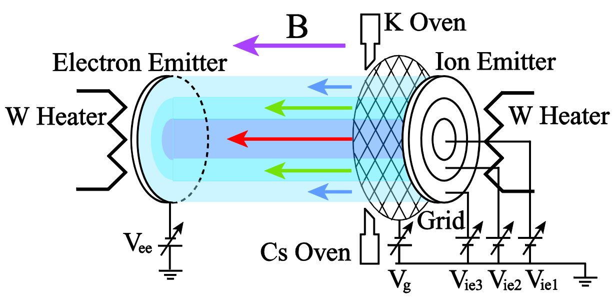

Fig. 1. Schematic of the experimental apparatus.

III. Experimental Results and Discussion

Figure 2 shows frequency spectra of the electron saturation current I_{es} of the probe with the parallel shear strength ΔV_{ie} (= $V_{ie2} - V_{ie1}$) as a parameter at r = –1.3 cm for (a) K and (b) Cs ion plasmas. Since the fluctuations are measured in the region where the density gradient has the maximum value, the fluctuations are identified as a drift wave [6]. It is found that the fluctuation is excited with increasing the shear strength, and is suppressed with more increasing the shear strength.

Figure 3 presents the normalized fluctuation amplitudes $\tilde{I}_{es}/\bar{I}_{es}$ as a function of the shear strength ΔV_{ie} at r = –1.3 cm with the density ratio ($n_K : n_{Cs}$) as a parameter ($\bar{I}_{es}$: time averaged value of I_{es}). It is found that the shear strength dependence of the fluctuation amplitude is different between the K ($n_K : n_{Cs}$ = 10:0) and Cs ($n_K : n_{Cs}$ = 0:10) ion plasmas. In the case of the Cs ion plasma, the larger shear strength is necessary

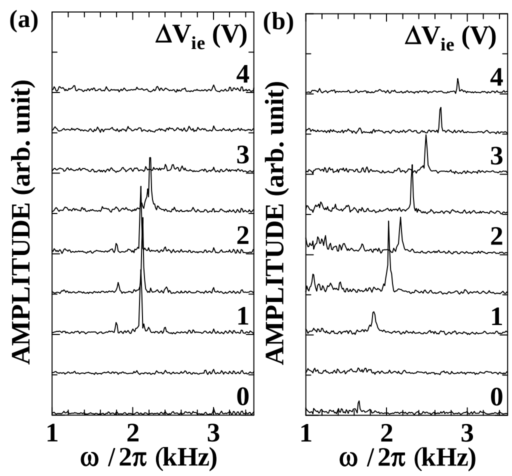

Fig. 2. Frequency spectra of electron saturation current of the probe with ΔV_{ie} as a parameter at r = –1.3 cm for (a) K and (b) Cs ion plasmas.

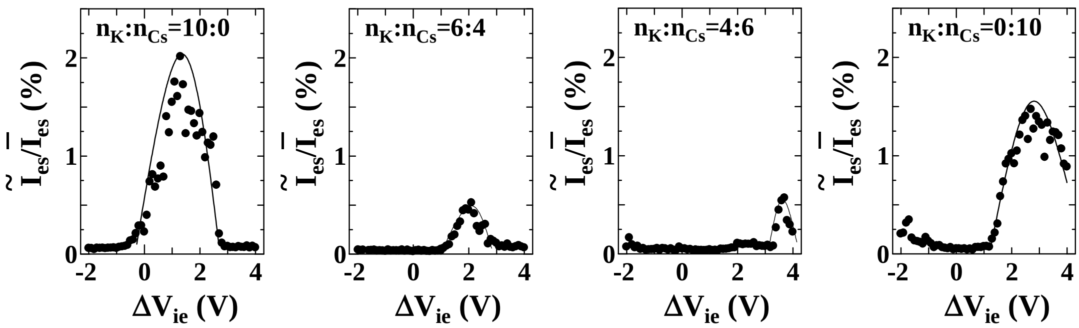

Fig. 3. Normalized fluctuation amplitudes $\tilde{I}_{es}/\bar{I}_{es}$ as a function of ΔV_{ie} at r = –1.3 cm with $n_K : n_{Cs}$ as a parameter.

to make the fluctuation amplitude maximum (ΔV_{ie} = 2.5 ~ 3.0 V) compared with that in the K ion plasma (ΔV_{ie} = 1.5 ~ 2.0 V). This phenomenon is attributed to the difference in mass number of the K and Cs ions.

Taking account of this difference between the K and Cs ion plasmas, we try to superimpose these ions to generate the multi-component ion plasma. When the Cs (K) ions are superimposed on the K (Cs) ion plasma and the density ratio becomes $n_K : n_{Cs} = 6:4$ ($n_K : n_{Cs} = 4:6$), the fluctuation amplitude drastically decreases compared with the pure K or Cs ion plasma. In addition, the shear strength which yields the maximum fluctuation amplitude in the multi-component ion plasma becomes larger than that in the pure K or Cs ion plasma.

In order to analyze the phenomena that the fluctuation amplitude of the shear-driven drift wave strongly depends on the superimposed ion density ratio, we numerically solve the linear dispersion relation. The theoretical growth rate γ as a function of the shear strength ΔV_{ie} is calculated using the plasma parameters experimentally obtained with density ratio $n_K : n_{Cs}$ as a parameter, which is presented in Fig. 4.

The theoretical growth rate of the drift wave is observed to increase with increasing the shear strength, but the growth rate is found to gradually decrease 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 [6,7].

In the case of the multi-component ion plasma [Figs. 4(b) and 4(c)], the shear strength which

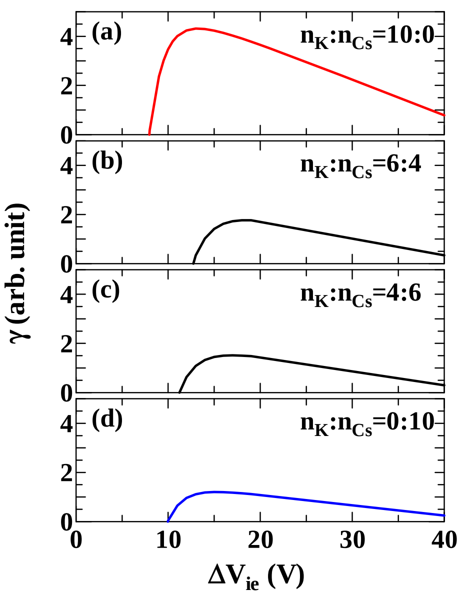

Fig. 4. Dependence of theoretical growth rate γ of the drift wave on shear strength ΔV_{ie} with density ratio $n_K : n_{Cs}$ as a parameter.

yields the peak of the growth rate becomes larger than those in the pure K and Cs ion plasmas, and the growth rate decreases compared with that in the pure K ion plasma. Since the flow velocity of the heavy Cs ions is smaller than that of the light K ions in the laboratory (electron) frame, the distribution function of the Cs ions is placed between the distribution functions of the K ions and the electrons in the K ion frame. In this situation, the Cs ions can interact with the drift wave whose phase velocity is out of range of the K ion distribution function. The number of the ions that interact with the drift wave increases, therefore, the effect of Landau damping is enhanced, resulting in the suppression of the drift wave.

Furthermore, since the Cs ion velocity distribution function locates in the larger phase velocity region in the K ion frame, the larger shear strength is necessary to increase the phase velocity of the drift wave to have no interaction with the Cs ion velocity distribution function, i.e., to reduce the effect of the Cs ion Landau damping. When the K ions are superimposed on the Cs ion plasma, on the other hand, since the phase velocity of the drift wave is confirmed to decrease with an increase in the K ion density, the larger shear strength is necessary to increase the phase velocity, where the effect of the ion Landau damping becomes small.

IV. Conclusion

The drift wave driven by the parallel ion flow velocity shear in the multi-component ion plasmas is investigated and it is found that the dependence of the fluctuation amplitude on the shear strength is different between the K and Cs ion plasmas. By superimposing Cs ions on the K ion plasma, the drift wave is drastically and anomalously suppressed. In addition, the shear strength which yields the peak of fluctuation amplitude becomes larger with an increase in the Cs ion density. These phenomena are also observed in the case that the K ions are superimposed on the Cs ion plasma. These experimental results are explained by taking into account the relation between the phase velocity of the drift wave and the distribution functions of the light K ions, heavy Cs ions, and electrons.

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