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Electron Heating by Nonlinear Landau Damping of Electrostatic Waves in an Electron Beam-Plasma System

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Abstract

The large axial inhomogeneity of electron temperature due to nonlinear Landau damping of electrostatic waves (space chargewave and Trivelpiece-Gould mode) in an electron beam-plasma system is occurred. At the same time, inhomogeneity of the space potential is also observed. We evaluate and compare the forces to the plasma electrons from the pressure gradient and the inhomogeneity of the space potential. This suggests that the two forces are balanced and the space potential plays an important role on maintaining the inhomogeneity.

Keywords:

nonlinear Landau damping, space chargewave, Trivelpiece-Gould mode

1. Introduction

Nonlinear Landau damping is one of the most interesting phenomena in weak plasma turbulence. This process has been investigated theoretically [1-5] and experimentally [6-12]. In ref. [11], Sugaya *et al.* reported detailed investigations for explosive instabilities by nonlinear Landau damping of electrostatic waves in electron beam-plasma system: The externally launched space charge waves of the electron beam excitethe Trivelpiece-Gould (T-G) mode via nonlinear Landau damping with beam electrons. Because the slow mode of the space charge waves is a negative-energy wave, it excites an explosive instability and grows rapidly together with the T-G mode. The scattered T-G mode causes an electron heating and an energy transport via its quasi-linear electron Landau damping. Namely, energy and momentum of the electron beam are transferred into plasma electrons, and then plasma electrons obtain a small drift velocity. Hence, large axial inhomogeneity of the electron temperature and density are occurred and maintained. However, the evaluated value of the drift velocity from the profiles of the electron temperature and the electron density was not reasonable [11].

In recent years, the relationship between 'potential and structure' has been investigated as one of the most important subjects in fusion science. From the analogy, we suspect that the potential has also something to do with the inhomogeneity in our small linear device. Therefore, we start to measure the space potential as well as electron temperature and density. In this paper, we evaluate the drift velocity by considering the force balance between the space potential and pressure gradient. Thus, we discuss the role of the space potential for maintenance of the axial inhomogeneity by nonlinear Landau damping.

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2. Kinetic Wave Equations and Transport Equations

The kinetic wave equations are expressed by [4,5]

$$\frac{\partial U_0}{\partial t} = -S_0\, \alpha_0\, U_0 \left| E_{\omega 1} \right|^2, \quad \frac{\partial U_1}{\partial t} = \alpha_1\, U_1 \left| E_{\omega 0} \right|^2. \quad (1)$$

Here, α_0, α_1 are the nonlinear wave-particle coupling coefficients, E_ω is the wave electric field, U is the absolute value of the wave energy density, S_0 is the sign of wave energy. The subscript 0 and 1 denote the space charge wave and the Trivelpiece-Gould (T-G) mode, respectively.

The transport equations for energy and momentum densities of beam and plasma electrons are given as follows [4,5]:

$$\frac{\partial U_b}{\partial t} = \frac{\omega 1}{\omega 0}\, \alpha_0\, U_0 \left| E_{\omega 1} \right|^2, \quad (2)$$

$$\frac{\partial P_{\parallel b}}{\partial t} = \frac{k_{\parallel 1}}{k_{\parallel 0}}\, \alpha_0\, P_{\parallel 0} \left| E_{\omega 1} \right|^2, \quad (3)$$

$$\frac{\partial U_e}{\partial t} = -2\gamma_1\, U_1, \quad \frac{\partial P_{\parallel e}}{\partial t} = -2\gamma_1\, P_{\parallel 1}, \quad (4)$$

where $P_\parallel = (k_\parallel/\omega)U$ is a momentum density of the wave, γ_1 is the linear damping rate and U_s, $P_\parallel$ are the energy and momentum densities for beam ($s = b$) and plasma electrons ($s = e$).

In the present work, energy and momentum transfer by nonlinear Landau damping are represented as follows [11]: The externally launched fast and slow space charge waves of the electron beam (ω_0, $\mathbf{k}_0$) excite the Trivelpiece-Gouldmode (ω_1, $\mathbf{k}_1$) via nonlinear Landau damping when the resonance condition, $\omega_0 - \omega_1 - (k_{\parallel 0} - k_{\parallel 1})v_b = m\omega_{ce}$, is satisfied, where $k_{\parallel 0}$ and $k_{\parallel 1}$ are the components of wave vectors parallel to the magnetic field, v_b is the velocity of the electron beam, ω_{ce} is the electron cyclotron frequency, and m is an integer. The slow space charge wave excites an explosive instability and grows rapidly together with the T-G mode because it is a negative-energy wave ($S_0 < 0$) as shown in eq. (1). The scattered T-G mode causes an electron heating and an energy transport along a magnetic field via its quasi-linear Landau damping (eq. (4)). Namely, energy and momentum of the electron beam are transferred into plasma electrons by nonlinear Landau damping, and then plasma electrons have a small drift along the magnetic field. This leads to the axial inhomogeneity of electron temperature.

3. Experimental Apparatus and Results

In this experiment, a monoenergetic electron beam with energy $U_b \simeq 300$ eV, current $I_b \simeq 2$ mA, and diameter $D_b \simeq 2$ mm is continuously injected along a uniform magnetic field into a beam-generated plasma at argon gas pressure of 0.4 mTorr (Fig. 1). The diameter of plasma is $D_p \simeq 15$ mm. The electron cyclotron frequency is adjusted to $\omega_{ce}/2\pi = 190$ MHz. The fast and slow beam modes are excited by applying an external RF signal with the frequency $\omega_0 = 275$ MHz

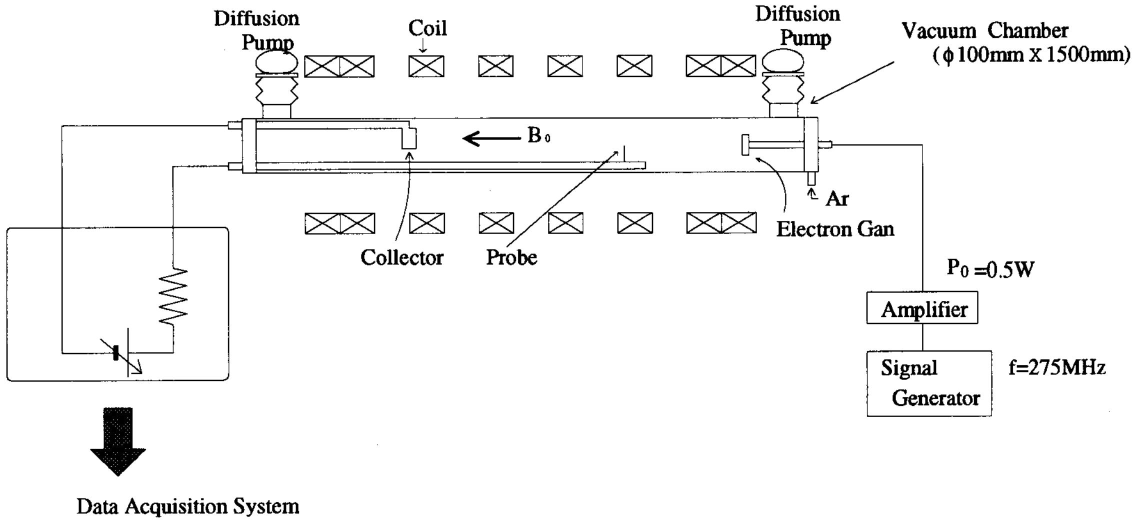

Fig. 1 Schematic view of the experimental apparatus. The uniformity of the magnetic field is 2.7 percent over an axial length of 60 cm.

and the power $P_0 = 0.5$ W. This parameters correspond to one of the best conditions for occurrence of the local heating [11]. All data are obtained by the Langmuir probe.

Figure 2 shows that (a) electron density n_e, (b) electron temperature T_e, (c) energy density n_eT_e and (d) space potential V_s versus axial distance z from the electron gun. The electron density is almost constant in the range of $\simeq 2\text{–}3 \times 10^9$ cm^{-3} and is not changed so much by applying the external RF signal. On the other hand, the electron temperature rises at $z \simeq 10$ and $\simeq 13$ cm by applying RF signal. Figure 2 (c) shows that energy density also becomes large at $z \simeq 10$ and $\simeq 13$ cm. This shows that local heating occurs. At the same time, the space potential increases at $z \simeq 10$ and $\simeq 13$ cm as shown in Fig. 2(d). This suggests that the space potential has something to do with maintaining the inhomogeneity of the electron temperature.

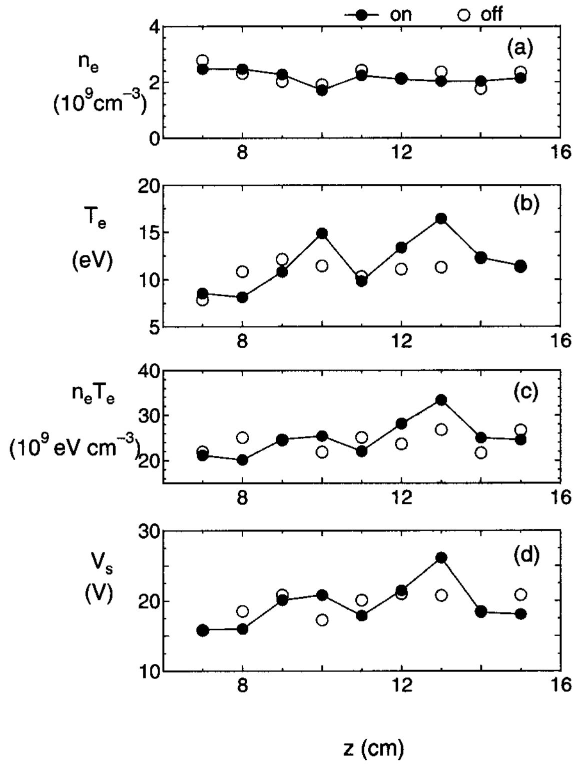

Fig. 2 (a) Electron density, (b) electron temperature, (c) energy density and space potential versus axial distance *z* (cm). Closed circles with lines denote applying the external RF power. Open circles denote no RF power.

4. Discussion

It is predicted from eq. (4) that plasma electrons are drifted by momentum input from T-G modes, and this drift maintains the inhomogeneity. Figure 2 (d) suggests that contribution from the space potential to maintaining the inhomogeneity is not negligible. In order to discuss the role of the space potential, the drift velocity of plasma electrons is evaluated. We deduce the drift velocity from the fluid equation of motion, $d\mathbf{v}/dt = -|e|n_e\mathbf{E} - \nabla(n_eT_e) - m_en_e\nu_e\mathbf{v}$ by neglecting the contribution from r-components and vanishing the term of $d\mathbf{v}/dt$:

$$v_d \simeq v_1 + v_2 \tag{5}$$

$$v_1 = \frac{T_e}{m_e\nu_e}\left[\frac{1}{n_eT_e}\frac{\partial n_eT_e}{\partial z}\right] \tag{6}$$

$$v_2 = \frac{T_e}{m_e\nu_e}\left[\frac{1}{T_e}\frac{\partial |e| V_s}{\partial z}\right], \tag{7}$$

where ν_e is the electron-neutral collision frequency. This equation shows that the drift velocity consists of two parts. One is v_1, which corresponds to the pressure gradient. The other is v_2, which represents the contribution from the space potential. Since eq. (6) and (7) include the derivatives, we fit the experimental data by polynomial (Fig. 3). By using this fitting and $\nu_e = 10$ MHz, we evaluate the velocity, v_1, v_2 and v_d (Fig. 3(c)). Since n_eT_e and V_s show the similar behavior (Fig. 3(a), (b)), v_1 and v_2 are almost symmetrical to the horizontal axis ($v = 0$), and $|v_d|$ becomes small. Here, we simply discuss by comparing v_d with the velocity of the beam electron v_b. The energy of the beam electron (300 eV) corresponds to the velocity of 10×10^8 cm/s. If the contribution from V_s is not considered, $|v_d| = |v_1| > v_b$, which is unreasonable. On the other hand, in considering the contribution from V_s, the obtained value of $|v_d| \simeq 0\text{–}4 \times 10^8$, which is somewhat larger than $|v_d| \ll v_b$, may be reasonable because we have large roughness of the fittings. Hence, we can point out that the force from the space potential is balanced with the force from the pressure gradient and plays an important role on maintaining the inhomogeneity of the electron temperature in our experiments.

5. Summary

In an electron-beam plasma system, inhomogeneities of the electron temperature and space potential come from nonlinear Landau damping of electrostatic waves. We evaluate the drift velocity of plasma electrons by considering the forces to the plasma

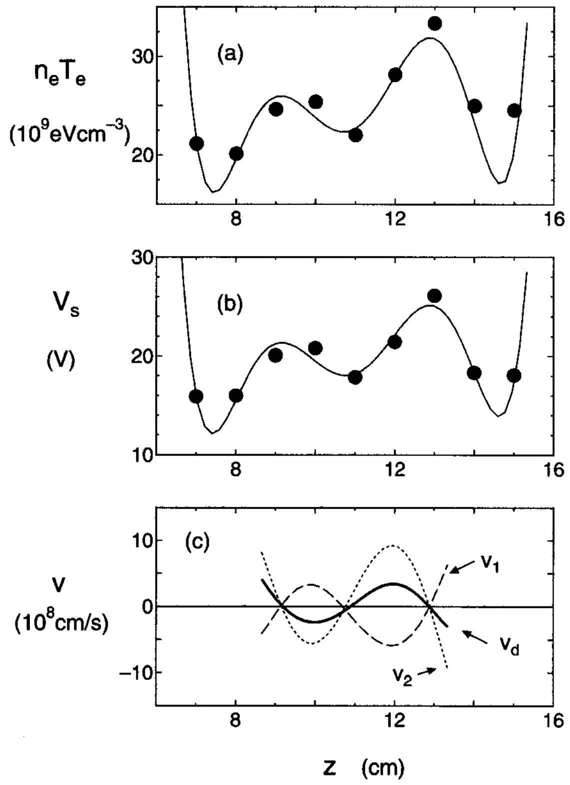

Fig. 3 (a) energy density and (b) space potential versus axial distance z (cm). Closed circles denote experimental data for applying RF power. Curves denote the lines fitted by using the polynominal. (c) The drift velocity (solid curve) versus z (cm). Dashed and dotted lines show v_1 and v_2, respectively (see eq. (5)).

electrons from the pressure gradient and the space potential. This suggests that the two forces are balanced and the space potential plays an important role on maintaining the inhomogeneity.

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