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Nonlinear Wave Phenomena in an Electron-Beam Plasma: Observations of Electric Field Fluctuations

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Abstract

A double electric probe was applied to detect local electric fields of unstable waves excited in an electron-beam plasma. In the investigation (beam density $n_b < 0.3\%$ of the plasma density n_0), the wave field energy was less than 10% of the plasma thermal energy and nonlinear phenomena, the generation of a series of rf-bursts, were observed.

Keywords:
unstable electron-beam waves, electric fields, double probe

1. Introduction

Since Zakharov's pioneering work [1] on nonlinear phenomena of Langmuir waves, considerable progress has been made in this area [2]. There has also been a growing interest [3-7] in nonlinear phenomena of unstable beam modes. Yajima and Tanaka [5] predicted the existence of soliton modes of unstable waves in an electron-beam plasma. The present authors have experimentally studied on evolution and formation of nonlinear structure of the unstable electron-beam waves [6,7].

In this work we will report observations of electric fields of the unstable beam waves and compare the wave field energy with the plasma thermal energy. Finally we will briefly discuss the stabilization mechanism of the beam modes in the nonlinear stage.

2. Plasma Device and Experimental Setup

A target plasma is produced in argon gas of 1×10^{-5} Torr by a dc discharge in a so called magnetic-multipole device [6,7]. An additional magnetic field (= 90G) is externally applied parallel to the axis of the plasma chamber to observe the one-dimensional behavior of the beam modes, where the electron cyclotron frequency ($\omega_{ce}/2\pi \approx$ 250MHz) is larger than the plasma frequency ($\omega_{pe}/2\pi \approx$ 150MHz). As is well-known, in a plasma of finite transverse dimensions an electron beam interacts with two possible plasma waves, Trivelpiece-Gould modes. For $\omega_{ce} > \omega_{pe}$, one is the plasma wave in a lower frequency band ($\leq \omega_{pe}$). The other is the upper hybrid wave ($\approx (\omega_{pe}^2 + \omega_{ce}^2)^{1/2}$). In the present study we focus on observations of the beam-plasma interaction in the lower frequency band. We inject a pulse electron beam (beam diameter 45 mm) with duration of 7×10^{-6} s into the target plasma along the external magnetic field. The beam current I_b passing through the plasma is measured by a collector located at the opposite end from the beam gun. Local electric fields $E(t)$ are detected by a double electric probe [8] which is connected with a wide-band differential circuit (HP1141A: DC ~ 200MHz). Langmuir probes are also used for observing local density fluctuations $\tilde{n}(t)$. The realtime data picked up are captured by a fast digitizing oscilloscope (HP54510A: 1GSa/s, 2ch, 8kW/ch). Plasma parameters are as follows: plasma density $n_0 = 3 \times 10^{14}$ m^{-3}, electron temperature $T_e = 2 \sim 4$eV, beam density $n_b = (0.2 \sim 3) \times 10^{-3} n_0$, and beam velocity $v_b = (5 \sim 8) \times v_T$

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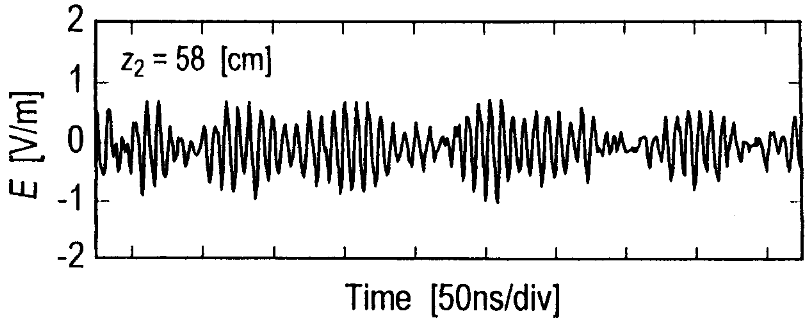

Fig. 1 Realtime data of electric fields $E(t)$ at $z = 58$cm. Here beam density $n_b/n_0 = 0.045\%$, beam velocity $v_b/v_T = 8.4$.

(v_T; electron thermal velocity).

3. Experimental Results and Discussion

3.1 Unstable beam waves and their wave energy

When an electron beam is injected into the target plasma, unstable waves are spontaneously excited and grow linearly along the beam stream. After the initial development of the waves, nonlinear wave packets [6, 7] are generated and the wave energy becomes maximum. Finally the instability is stabilized as the beam electrons lose their energy mostly in the beam-plasma interaction.

An example of local electric fields $E(t)$ observed at z = 58 cm is shown in Fig. 1, where the beam density normalized by the plasma density $n_b/n_0 = 0.045\%$ and the beam velocity normalized by the thermal velocity $v_b/v_T = 8.4$ (; $v_b = 4.9 \times 10^6$m/s). The position z is the distance from the beam gun. In this case, the phase velocity $v_\phi = 4.6 \times 10^6$m/s, and the group velocity of wave packets $v_g = 3.3 \times 10^6$m/s. These velocities are dependent on the beam velocity v_b, but not much on the beam density n_b. Figure 2 shows the Fourier spectrum $A(f)$ of the realtime data in Fig. 1. The beam plasma system is unstable in a frequency range lower than the plasma frequency ($\omega_{pe}/2\pi \approx 150$MHz). Details on the nonlinear properties of the wave packets were already reported in the reference [7].

Figure 3 shows the wave energy $\varepsilon_0 < E^2 > / 2n_0k_BT_e$ as a function of the beam density n_b/n_0. In the present experiment ($n_b < 3 \times 10^{-3}n_0$), wave energy $\varepsilon_0 < E^2 > / 2$ is no more than 10% of the plasma energy $n_0k_BT_e$.

3.2 Evolution of a single rf-burst and generation of bursts: test wave experiment

The test wave experiment is reproducible. When a small rf-burst signal with a time-width of 50ns is

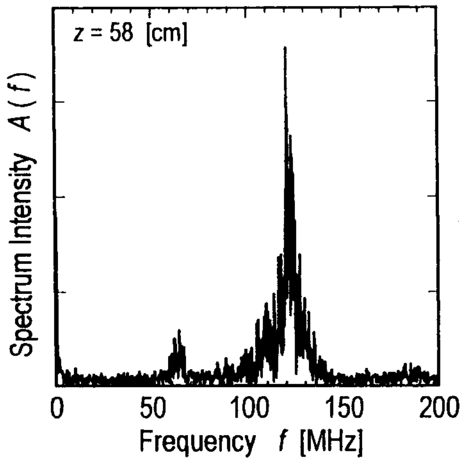

Fig. 2 Fourier spectrum of realtime data shown in Fig. 1.

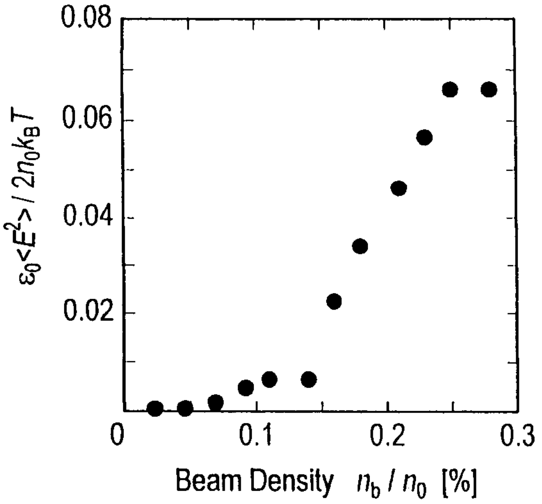

Fig. 3 Wave energy normalized by the plasma thermal energy $\varepsilon_0 < E^2 > /2n_0k_BT_e$ as a function of the beam density n_b/n_0.

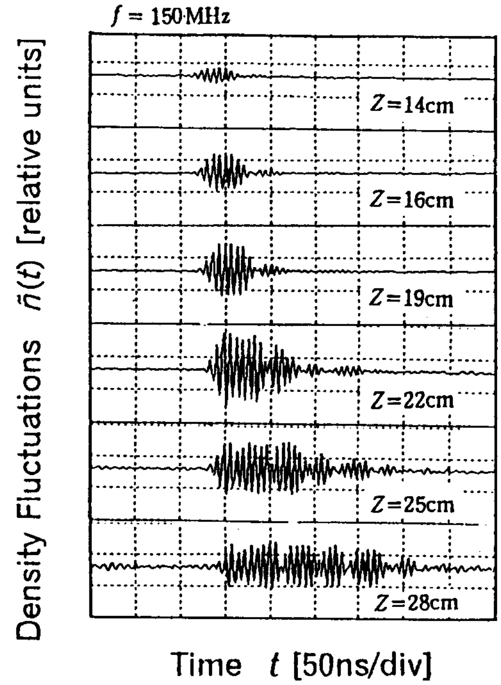

Fig. 4 Nonlinear evolution of a single burst wave and generation of a series of burst waves. Here beam velocity $v_b/v_T = 5$ and beam density $n_b/n_0 = 0.28\%$.

applied to the control grid of the beam gun, a single burst wave is excited and propagates downstream. Figure 4 shows how a single burst wave initially grows, saturates and generates new burst waves. The number of burst waves is proportional to the beam density. Finally the system becomes stable in the same manner as abovementioned.

In Fig. 5 the initial growth rate k_i/k_D of those burst waves is plotted on a logarithmic graph as a function of the beam density n_b/n_0. The solid line in the figure is an empirical one with a gradient of 1/3, which shows the initial growth rate k_i/k_D is proportional to $(n_b/n_0)^{1/3}$. Their magnitudes also agree with the calculated values from the linear dispersion relation of the beam modes.

The rf-burst waves seem to be soliton-like excitation discussed by Yajima and Tanaka [5]. They are developed differently from Zakhalov's Langmuir solitons, because the number of burst waves and the identities are not conserved.

4. Conclusions

A double electric probe was successfully applied to detect electric fields of the unstable beam waves. In the present study, the wave energy was less than 10% of the plasma energy. The electron-beam plasma is linearly unstable for a single rf-burst, and generates a series of burst waves along the beam stream. Finally it becomes stable as the beam electrons lose their energy in the beam-plasma interaction.

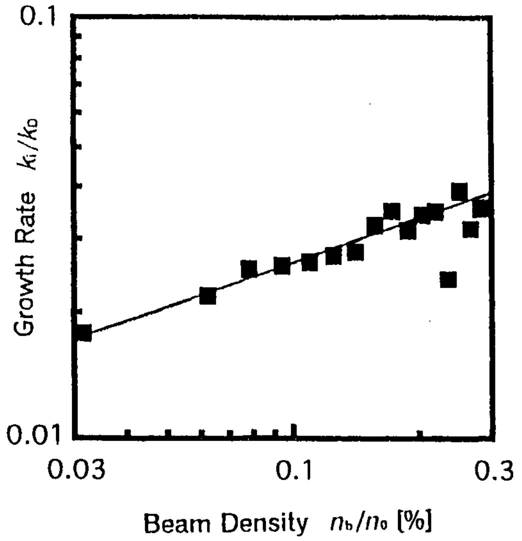

Fig. 5 Logarithmic plotting of the initial growth rate k_i/k_D as a function of the beam density n_b/n_0. The empirical line with a gradient of 1/3 is also shown in this figure.

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