OBSERVATIONS OF SOLITON MODES IN AN UNSTABLE ELECTRON-BEAM PLASMA

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Abstract. Experimental studies were performed on one-dimensional evolution and formation of the nonlinear structure of unstable waves in an electron-beam plasma. The plasma system is linearly unstable in a frequency range lower than the critical value ω_{cr} ($\approx \omega_{pe}$, plasma frequency), but is stabilized in its nonlinear stage by generating wave packets irregularly. The system is also unstable for an external rf-burst. The burst wave initially grows linearly along the electron-beam path and the amplitude gradually saturates in its nonlinear stage. Finally the plasma system becomes stable by the emission of a series of burst waves. The number of emitted bursts increases with the beam density.

1. Introduction

Since the 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 wave phenomena of unstable modes. Wong and Cheung [3] experimentally investigated nonlinear evolution and collapse of the electron beam instability. They explained their observed results with Zakharov's theory of three dimensional Langmuir collapse in which the beam effect is not included. The dispersion properties of unstable modes [4-7], however, are quite different from stable ones. Intrator *et al*. [4] observed unstable electron-beam wave packets. They tentatively explained their experimental results by a nonlinear geometrical optics theory, rather than Zakharov Langmuir-wave collapse. N. Yajima and M. Tanaka [5] predicted the existence of soliton modes of unstable electron-beam waves which are described by a nonlinear Schrodinger equation with the beam correction.

The present authors have experimentally studied on nonlinear wave phenomena in an electron-beam plasma [6, 7]. The plasma system is linearly unstable against electrostatic perturbations with frequencies lower than the critical frequency ω_{cr} ($\approx \omega_{pe}$), but is stabilized in its nonlinear stage by generating nonlinear wave packets. The system is also unstable against a small rf-burst signal which is externally introduced to the beam plasma system. Again it becomes stable by emission of a series of burst waves, which are called soliton-like excitation.

2. Plasma device and experimental setup

A target plasma is produced by a dc discharge in a so called magnetic-multipole plasma device shown in Fig.1. 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. The working pressure of Ar gas for the discharge is adjusted to 1×10^{-5} Torr to reduce collisional loss of beam electrons with neutral particles. We inject a pulse electron beam with duration of 7×10^{-6} s into a target plasma along the external magnetic field. The beam current I_b passing through the plasma is measured by using a collector located at the opposite end from the beam gun. Density fluctuations $\tilde{n}(t)$ are picked up with two plane probes (Mo disks of 3mm in diameter) located at different positions, z_1 and z_2, measured from the beam gun and then two sets of realtime data are captured by a fast digitizing oscilloscope (HP54510A, 1GSa/s, 2ch, 8kW/ch). The maximum amplitude of the density fluctuations normalized by the equilibrium plasma density, $\tilde{n}(t)/n_0$, seems to be over ten percent in the present experiment. However we find it difficult to determine the exact value of it because of the high frequency ($\omega \approx \omega_{pe}$). Hence, we will show the data of $\tilde{n}(t)$ in relative units. Typical experimental parameters are summarized in Table 1.

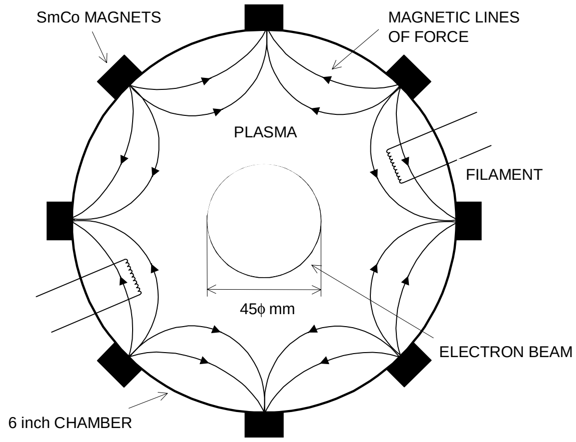

Figure 1: *Electron-beam plasma device.*

Table 1. *Experimental parameters*

Working pressure (Ar)	p	$= 1\times10^{-5}$ Torr
Plasma density	n_0	$= 3\times10^{14}$ m^{-3}
Electron temperature	T_e	$= 3 \sim 4$ eV
Plasma frequency	$\omega_{pe}/2\pi$	$= 150 \sim 160$ MHz
Debye length	λ_D	$= 0.9$ mm
Beam density	n_b/n_0	$= 0.02 \sim 0.5$ %
Beam velocity	v_b/v_T	$= 4 \sim 6$
Unstable wavenumber	$k\lambda_D$	$= 0.2$ (typical value)
Beam diameter	$2r_b$	$= 45$ mm ($kr_b = 7$)
Beam duration	t	$= 7\times10^{-6}$ s ($\omega_{pi}t = 20$)
System length for beam path	l	$= 50$ cm

3. Experimental results and discussion

3.1 Fundamental properties of unstable beam modes

When an electron beam is injected into the target plasma, unstable noise patterns are spontaneously excited along the beam path and the rms-density fluctuation $<\tilde{n}(t)/n_0>_{rms}$ grows to several percent in the downstream region. The system becomes stable in its nonlinear stage by generating nonlinear wave packets. Typical data of the beam current $I_b(t)$, density fluctuations $\tilde{n}(t)$ and its Fourier spectrum $A(f)$ are shown in Figs. 2(a), (b) and (c), where beam density $n_b/n_0 = 0.15\%$, beam velocity $v_b/v_T = 5$ and the probe position z_2 = 31cm. The critical frequency f_{cr} indicated by an arrow in Fig. 2(c) is nearly equal to plasma frequency $f_{cr}(\approx 160\text{MHz})$. The plasma system should be unstable in a frequency range lower than the critical frequency f_{cr}. Density fluctuations in Fig. 2(b) appear very spiky when viewed on the oscilloscope. Similar data sets are observed at z_1 = 28cm. In Fig.3, both data sets of the density fluctuations detected at 28cm and 31cm are magnified by 16 times in time scale on the horizontal axis. It is found that (1) irregular wave packets with a width less than

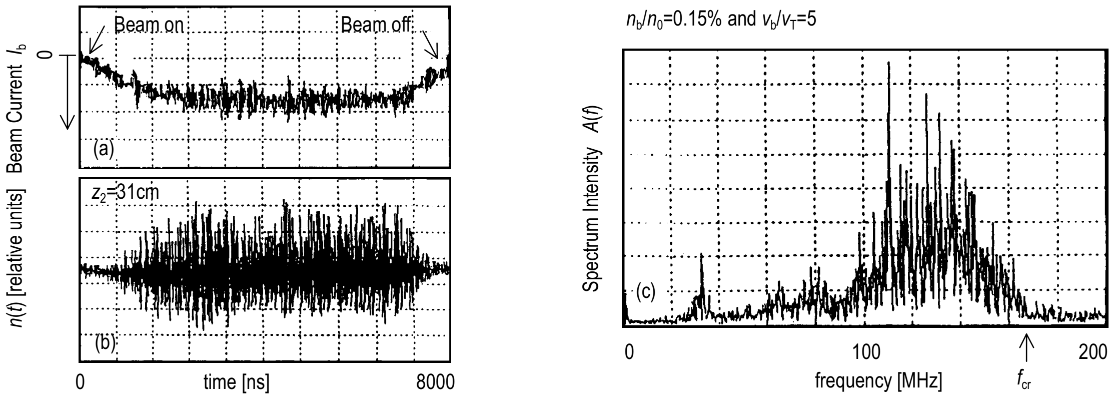

Figure 2: (a) *Beam current* $I_b(t)$, (b) *Density fluctuations* $\tilde{n}(t)$ and (c) *Fourier spectrum* $A(f)$ of $\tilde{n}(t)$.

20ns are generated, (2) wave packets at z_2 = 31cm are delayed by 12ns compared with ones at z_1 = 28cm, that is, they propagate downstream with the group velocity $v_g = 2.5\times10^6$ m/s and (3) the phase velocity $v_\phi = 3.7\times10^6$ m/s.

We found that the empirical relation between the average time-width Δt and the beam density n_b/n_0 is given by $\Delta t \propto (n_b/n_0)^{-1/3}$. It is well known that the linear growth rate γ of the beam modes is proportional to $(n_b/n_0)^{1/3}$ and the maximum growth rate γ_{max} is given by $3^{1/2}2^{-4/3}(n_b/n_0)^{1/3}\omega_{pe}$. Therefore observed values Δt (= 10 ~ 20ns) are proportional to γ^{-1}, and their magnitude are 2 times $(\gamma_{max})^{-1}$. Details are discussed in the reference [7].

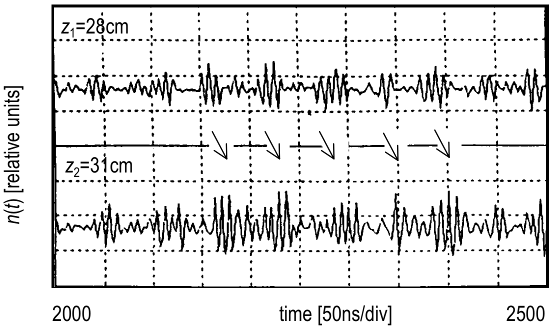

Figure 3: *Density fluctuations* $\tilde{n}(t)$ *at* z_1 = 28cm *and* z_2 =31cm, $\tilde{n}(t)/n_0$ =0.15%, *beam velocity* $v_b/v_T = 5$.

3.2 Evolution of a single rf-burst and stabilization by the emission of bursts

Results of the test wave experiment are interesting. When a small rf-burst signal with the time width of 50ns as an initial perturbation is applied to the control grid of the beam gun, a single burst wave is excited from the noise level. This burst wave initially grows linearly along the electron stream and the amplitude of the unstable burst gradually saturates in its nonlinear stage. Finally the system becomes stable by the emission of a series of burst waves. In Figs. 4(a), (b) and (c) we show how a single rf-burst grows, saturates and generates new burst waves. In the case of a weak-beam injection ($n_b/n_0 = 0.03\%$) a single burst wave only grows from noise level along the beam path. On the other hand, in the case of a medium beam injection ($n_b/n_0 \geq 0.05\%$), a single burst wave initially grows linearly along the electron stream and the amplitude of the unstable burst wave saturates in its nonlinear stage. Finally the system becomes stable by the emission of a series of burst waves along the beam path as shown in Figs.4(b) and (c). Ion motion has no effect on the phenomena because the ion response time ($1/\omega_{pi} \approx 300$ns) is longer than the observed time scale (10 ~ 200ns).

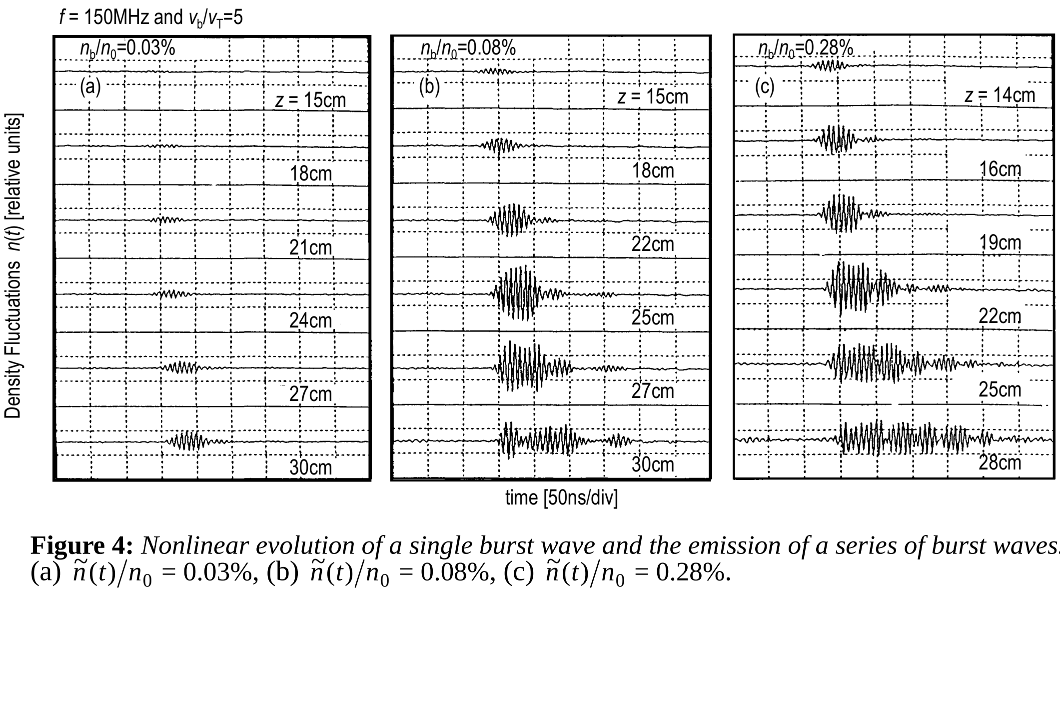

Figure 4: *Nonlinear evolution of a single burst wave and the emission of a series of burst waves.* (a) $\tilde{n}(t)/n_0$ = 0.03%, (b) $\tilde{n}(t)/n_0$ = 0.08%, (c) $\tilde{n}(t)/n_0$ = 0.28%.

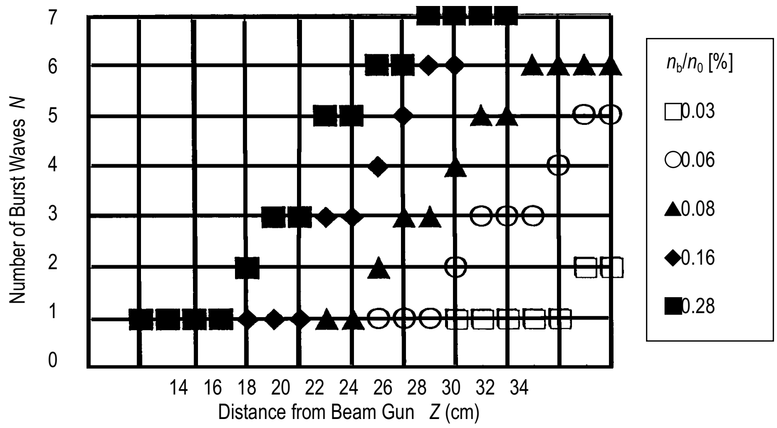

Figure 5: *Number of burst waves as a function of the distance from beam gun, for several values of* $n(t)/n_0$.

Figure 5 shows the number *N* of emitted burst waves as a function of probe position *z*, the distance from the beam gun, where the beam density n_b/n_0 is varied from 0.03 to 0.28%. It is noticeable that the number of emitted bursts increases with the beam density n_b/n_0 and the electron-beam plasma system becomes stable by emitting a series of burst waves.

N. Yajima and M. Tanaka [5] theoretically studied nonlinear evolution of unstable electron beam waves in an electron-beam plasma. When the beam velocity v_b is sufficiently large compared with the thermal velocity of electrons v_T, the system is governed by a nonlinear Schrodinger equation with an additional term of beam correction. They showed that the plane wave is unstable for long wavelength modulation and is stabilized by the emission of a series of envelope solitons.

The present experiment showed that the unstable beam modes with localized structures are soliton-like excitations. However they are developed differently from Zakhalov's Langmuir soliton, because the number of solitons and their identities are not conserved. The present observations shown in Figs. 3 and 4 are qualitatively in agreement with the above theoretical prediction [5].

4. Conclusions

The electron-beam plasma is unstable for a single rf-burst wave and becomes stable by emission of burst waves along the beam path. The number of emitted burst waves increases with the beam density n_b/n_0 . The characteristic time for formation of the structure is much shorter than the ion response time ($\approx 1/\omega_{pi}$).

References

[1] Zakharov V.E.: Sov. Phys. JETP **35**, 908 (1972).
[2] Goldman M.V.: Rev. Mod. Phys. **56**,709 (1984).
[3] Wong A.Y. and Cheung P.Y.: Phys. Rev. Lett. **52**, 1222 (1984).
Cheung P.Y. and Wong A.Y.: Phys. Fluids **28**, 1538 (1985).
[4] Intrator T., Chan C., Hershkowitz N. and Diebold D.: Phys. Rev. Lett. **53**, 1233 (1984).
[5] Yajima N. and Tanaka M.: Prog. Theor. Phys. Suppl. No.**94,** 138 (1988) .
[6] Yamagiwa K., Tanaka M., Itoh T. and Nakayama T.: *Proc. 1996-ICPP* (Nagoya) **1**, 774.
[7] Yamagiwa K., Itoh T. and Nakayama T.: *Invited paper of ICPIG* (Toulouse, 1997),
a special issue of Journal de Physique IV (France) **7** C4-413 (1997).