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Experimental Study on Instabilities of Explosive Type in Beam-Plasma Systems

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Abstract

In this experiment, a slow ion-beam mode externally excited in an ion-beam-plasma system, which is a negative energy wave, is observed to be self-modulated above a threshold probably because of wave-wave interaction among three different waves (ω_0, k_0), (ω_1, k_1) and (ω_2, k_2). Spectral analysis of such evolving waves and identification of each of the three waves make it possible to clarify the feature of the wave interaction, characterized by $\omega_0 = \omega_2 - \omega_1$, although $k_0 = k_2 - k_1$ can not be precisely confirmed because of difficult measurement of the exact value of $|k_1|$. In spite of this, the results are enough to verify the realization of instabilities of explosive type in the system.

Keywords:

ion-beam mode, self-modulation, three-wave interaction, negative energy waves, instability of explosive type, beam-plasma system

1. Introduction

According to the theoretical works [1], explosive instabilities are known to be possibly caused by resonant three-wave interaction in a system including negative and positive energy waves. However, only a few experimental works have been tried to realize explosive instabilities in plasmas. Among them Nakamura [2] succeeded in observation of explosive instability in an ion-beam-plasma system. Thereafter, Kawai *et al.* [3] also tried to make a similar experiment, but they could observe only an instability of decay type because of the deficiency of pump power.

In this paper, we wish to report observation of instabilities of explosive type during the nonlinear modulation of a large amplitude wave excited in an ion-beam-plasma system. Here, the "slow" ion-beam mode, being a negative energy wave, is found to be self-modulated above a threshold. Further, we identify each of the three waves causing the self-modulation of the pump wave and then verify the realization of instabilities of explosive type in the system.

2. Experimental Methods

Experiments were carried out with a conventional double plasma (DP) device [4-5]. In the device two argon plasmas were produced by dc discharges at a pressure $P \simeq (2\text{–}3) \times 10^{-4}$Torr. Plasma parameters were such as densities $n_e \simeq (4\text{–}6) \times 10^8\text{cm}^{-3}$, electron temperature $T_e \simeq 2\text{–}3$ eV and ion temperature $T_i \simeq T_e/20$. An ion-beam with an average energy of 5–10 eV was stationarily injected into the target plasma. Here, the beam energy was externally controllable by changing the potential difference V_B between the two plasmas. Thus, an ion-beam-plasma system was formed in the target plasma region. To excite a wave in the system, an rf voltage with a maximum amplitude $V_{ex} \simeq 0.5\text{–}6$V was superposed to V_B. In most cases the rf frequency f_{RF} was

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in the range of 160–300kHz. Furthermore, the rf voltage was externally amplitude-modulated at a low frequency of 1–10kHz.

3. Experimental Results

In this experiment we used an ion-beam-plasma system, containing an ion-beam with a velocity $v_b \gtrsim 3C_s$ and a density $n_b \simeq (0.1–0.2)n_0$, where C_s is the ion-acoustic velocity and n_0 is the background plasma density. Dispersion relations of waves excitable in the system are shown in Fig. 1. Further, we also studied the dependences of the wave velocities on the beam velocity v_b. These results show that the velocity u_w of the main (pump) wave is always slightly lower than v_b and is roughly proportional to v_b. This leads us to conclude that the pump wave belongs to the "slow" ion-beam mode, being a negative energy wave. Fig. 1 also indicates that the ion-acoustic wave is also possibly excited in the system, though its damping is strong.

When the applied rf voltage V_{ex} was raised above a level, the pump wave was observed to be self-modulated and to cause a series of spikes on its wave envelope. The spikes spatially grow in amplitude and they also change their forms during propagation. Typical oscilloscope traces of evolving waves are shown in Fig. 2. The traces demonstrate that the self-modulation of the pump wave first starts at $x \simeq 2.5$cm around the central part of an externally given broad packet and proceeds more and more with increasing x. At the same time the spikes gradually grow in amplitude and number per group with increasing x. In addition to this, the pump wave was found to be self-modulated at any fixed position x, if V_{ex} became above a threshold. Typical examples of wave forms, observed at various values of V_{ex} but at x = 5.0cm, are shown in Fig. 3. Here, the threshold of V_{ex} for the self-modulation to occur is about 2.2V. Further, the amplitude and number per group of the resultant spikes on the envelope increase with increasing V_{ex}.

From evolving waveforms as shown in Fig. 2, we can get an information on the propagation of the spikes or wave packets. Distance-time relations of individual

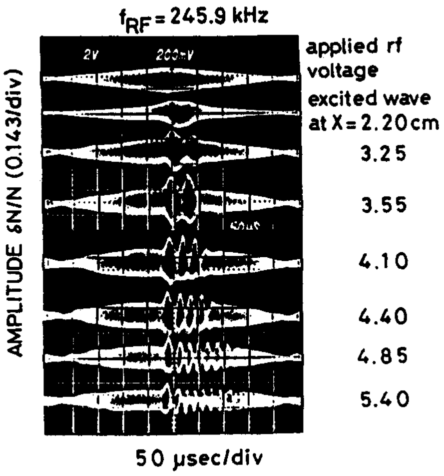

Fig. 2 Typical oscilloscope traces of evolving waves, showing the self-modulation.

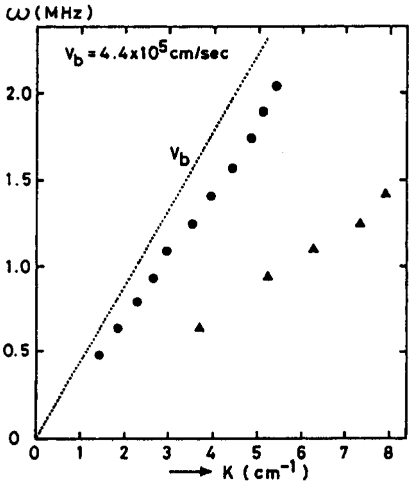

Fig. 1 Dispersion relations of waves excited in an ion-beam-plasma system.

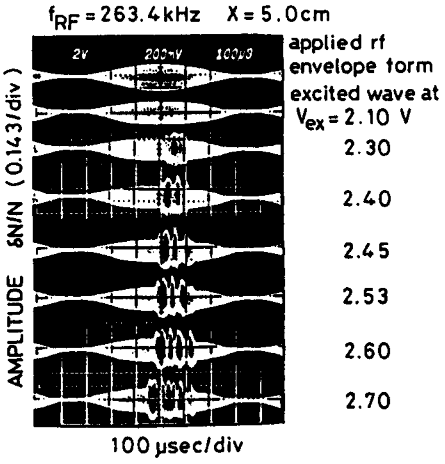

Fig. 3 Oscilloscope traces of waveforms as a function of the rf voltage V_{ex}.

spikes in traces of Fig. 2 (not shown here) indicate that most of spikes propagate in the negative x-direction with velocities as low as (4–8) × 10^4cm/sec. This fact suggests that a low frequency wave with an average frequency $\Delta f \simeq$ 30–60kHz, consisting of a series of spikes described above, probably belongs to an ion-sound or acoustic wave propagating in the negative x-direction. This means that the wave number k becomes negative ($k < 0$). Another different way for measuring the wave patterns, as will be described below, enables us to identify this low frequency wave with an ion-acoustic wave from its velocity.

Spatial changes of the frequency spectra of evolving waves were studied by use of a spectral analyzer. Typical examples of such spectra at various x are shown in Fig. 4. It is found from these that the self-modulation of the pump wave (with $f_{\rm RF}$) is caused by the nonlinear excitation of an upper sideband wave (with $f_{\rm US}$) and a low frequency one (with Δf). From this we can find that the three-wave interaction satisfies a resonant condition such as

$$f_{\rm RF} = f_{\rm US} - \Delta f \qquad (1)$$

among these wave frequencies. In addition to these, we could observe the wave pattern of each of the three waves, using a technique for selecting only one of them with a band-pass filter. Wavelengths of the waves estimated from these patterns, obtained at frequencies known from the spectra, enable us to identify each of the waves. As a result, it is known that the low frequency wave (with Δf) belongs to the ion- acoustic mode and the upper sideband wave (with $f_{\rm US}$) to the "fast" ion-beam mode. Both the waves are known to be positive energy waves.

Furthermore, we observed the frequency spectra of the waves at various values of $V_{\rm ex}$(at $x \simeq 4.5$cm) to study the correlation among the changing three wave powers. Relations of the wave powers with $V_{\rm ex}$ thus obtained are shown in Fig. 5. The data indicate that the pump wave power increases roughly in proportion to $V_{\rm ex}$ at small values of $V_{\rm ex}$, but it clearly deviates from the linear increase above a threshold ($V_{\rm ex} \simeq 1.8$V). We also find that the upper sideband (with $f_{\rm US}$) and the low frequency (with Δf) waves newly appear above the threshold and their powers rapidly increase up to some levels with increasing $V_{\rm ex}$. The fact, indicating that all the three wave powers simultaneously increase with increasing $V_{\rm ex}$ above the threshold, lets us conclude that the realization of instabilities of explosive type is confirmed at $V_{\rm ex} \gtrsim 1.8$V in the ion-beam-plasma system.

4. Discussions and Conclusion

In this experiment we observed the self-modulation of the "slow" ion-beam mode (pump wave) externally excited in an ion-beam-plasma system. As a result of the self-modulation, the pump wave was observed to split into a series of wave packets. On the other hand, spectral analyses of the evolving waves indicate that the

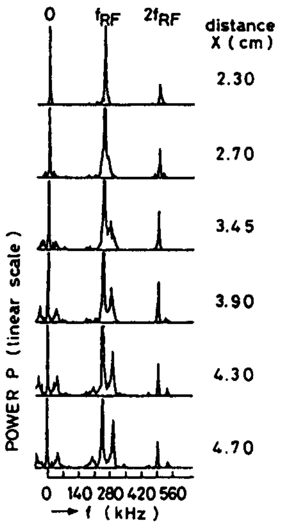

Fig. 4 Frequency spectra of evolving waves, observed at various positions x.

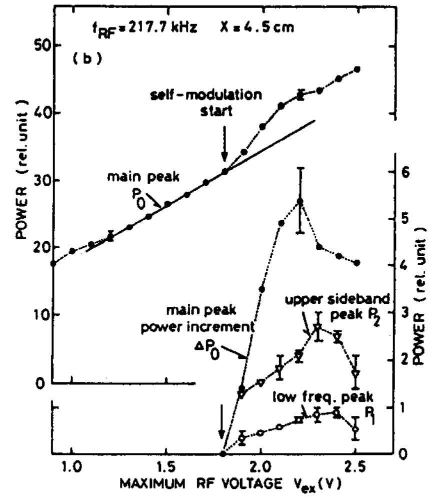

Fig. 5 Relations of the three wave powers with the applied rf voltage $V_{\rm ex}$.

self-modulation is caused by the nonlinear excitation of upper sideband (with f_{US}) and low frequency (with Δf) waves. It is also found from these that a resonant condition such as $f_{RF} = f_{US} - \Delta f$ is always satisfied among the three wave frequencies. The resonant condition as $f_{RF} = f_{US} - \Delta f$ makes us expect the occurrence of resonant interaction among the three coherent waves, including a negative and two positive energy waves. On the other hand, observations of the wave patterns of the three waves enable us to know that the low frequency (with Δf) and the upper side band (with f_{US}) waves belong to the ion-acoustic mode and the fast ion-beam mode, respectively. However, such observations for the low frequency wave were not precise enough to certify the resonant condition in wavenumber such as $k_{RF} = k_{US} - \Delta k$, where k_{RF}, k_{US} and Δk correspond to the waves with f_{RF}, f_{US} and Δf, respectively. This is because the wavelength $\lambda(= \Delta k/2\pi)$, being comparable to the size of the wave-existing region, could be roughly but not precisely measured. In spite of these, considering the fact that all the powers of the interacting three waves (negative and positive waves) simultaneously increase with increasing V_{ex} in a range of V_{ex} ($1.8\text{V} \leq V_{ex} \leq 2.2\text{V}$), we conclude that such wave-wave interaction possibly causes instabilities of explosive type in an ion-beam-plasma system.

In the above discussions we interpret the experimental results on the basis of the three wave interaction. Another treatment of the phenomenon, based on the wave-particle interaction [6], may be also possible. Discussions on the latter subject will be made in future reports.

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