

Nonlinear Behavior of Ion-Beam Modes in Beam-Plasma Systems

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Experimental study is reported on the nonlinear behavior of the ion-beam modes in beam-plasma systems. Packets of the modes are observed to be self-modulated and then partly enhanced in amplitude. Further, they are also found to form plasma cavities with two-storied structures corresponding with their amplitude structures.

INTRODUCTION

Since the 1970's when a double plasma (DP) device [1] became available, experimental studies on nonlinear ion waves in plasmas have been intensively made by many workers in the world. In our laboratory we have also made experiments on nonlinear phenomena of large amplitude ion waves in plasmas, as reported in Refs [2, 3]. In this paper we report new experimental results on the nonlinear modulation of the ion-beam modes and the plasma cavity formation by them. Here, we treat the 'slow' ion-beam modes, being well known to become 'negative' energy waves at large amplitudes. In addition, it is theoretically well known that the three-wave coupling among waves, including a 'negative' energy wave, possibly yields explosive instability. In this experiment we could observe three-wave coupling yielding such an instability above a threshold [4], when the 'slow' ion-beam mode (corresponding to the pump wave) was self-modulated. At the same time, the wave pressures of the beam modes were observed to form plasma cavities with two-storied structures.

EXPERIMENTAL DEVICE AND METHODS

Experiments were performed using a conventional DP device [1]. In the device two argon plasmas were produced by dc discharges at a pressure $P = (2-3) \times 10^{-4}$ Torr. Then, an ion-beam with a controllable energy in a range of 5-10 eV was stationarily injected into the target plasma. Thus, an ion-beam-plasma system was formed in the 'target' plasma region. To excite a wave in the system, an rf voltage with amplitude $V_{ex} = 0.5-6$ V and frequency $f_{RF} = 160-550$ kHz was applied to the 'driver' plasma chamber. Measurements of plasma parameters and excited wave signals were made with a small probe movable along the device's axis (x-axis). A small energy analyzer was also available to observe ion energy distributions.

EXPERIMENTAL RESULTS

A. Self-modulation of ion-beam modes

Dispersion relations of small amplitude waves excitable in the beam-plasma system were first studied. From the observed relations two kinds of waves were found to be possibly excited in the system. One of them belongs to the ion-beam mode with a little slower velocity than the beam velocity v_b and the other belongs to the ion-acoustic mode. But the latter was observed to rapidly damp. Hence, only the beam mode, being called the 'pump' wave hereafter, was observable at large distances ($x \gtrsim 2$ cm).

When the applied rf voltage amplitude V_{ex} was raised above a level, the pump wave was observed to be self-modulated and to give rise to a series of spikes on the wave envelope, as shown in Fig.1. Traces in Fig.1, which were observed at a fixed position ($x = 5.4$ cm), demonstrate that the pump wave can be self-modulated above a threshold ($V_{ex} \simeq 0.7$ V). Further, these traces also indicate that both the number of spikes on the wave envelope and their amplitudes increase with increasing V_{ex} .

In addition, frequency spectra of such evolving waves were studied with a spectral analyzer. Typical examples of such spectra, observed at $x = 4.5$ cm, are shown in Fig.2. These are similar to those of the evolving waveforms as given in Fig.1. It is found from these spectra that the self-modulation of a pump wave (at frequency f_{RF}) is caused by the nonlinear excitation of upper sideband (at f_{US}) and low frequency (at Δf) waves. The three-wave interaction of interest occurs above a threshold, for example, $V_{ex} \simeq 1.7$ V in Figs.3 and 4. We also find from these that the three-wave interaction always satisfies a resonant condition such as

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

among these wave frequencies. However, it is noted that both the newly excited wave frequencies f_{US} and Δf change their values with changing V_{ex} , as shown in Fig.3, while the above resonant condition Eq.(1) is always satisfied. Next, we take account of the changes of their wave powers with changing V_{ex} . From spectra like those in Fig.2, we can know the changes of the three wave powers [the powers of the pump wave (at f_{RF}), the upper sideband wave (at f_{US}) and the low frequency wave (at Δf)] with changing V_{ex} . Each of the three wave powers is shown as a function of V_{ex} in Fig.4. These data indicate that the power of the pump wave increases roughly in proportion to V_{ex} at small values of V_{ex} , but it clearly deviates from the linear increase and rapidly increases above a threshold ($V_{ex} \simeq 1.7$ V), at which the self-modulation of the pump wave or the generation of the new daughter waves (at f_{US} and Δf) starts. This fact that all the three wave powers simultaneously increase with increasing V_{ex} lets us conclude that 'explosive' instability possibly occurs at $V_{ex} \gtrsim 1.7$ V in the beam-plasma system, supposing that the pump wave (at f_{RF}) is a 'negative' energy wave and the new two daughter waves (at f_{US} and Δf) are 'positive' energy waves [4].

B. Formation of plasma cavities by the beam modes

In our recent paper [3] details of the plasma cavity formation by ion-acoustic

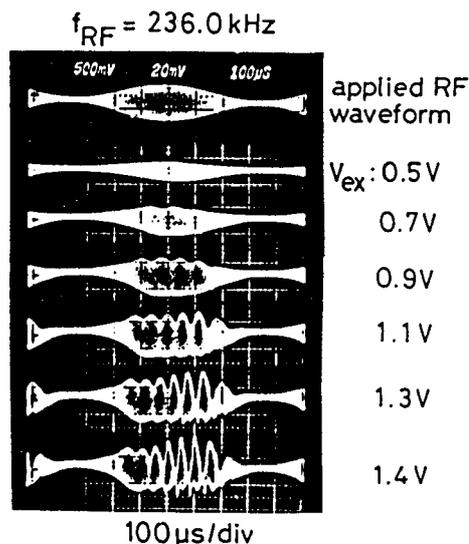
wave packets were described. In this paper we show the possibility of the plasma cavity formation caused by packet-form *ion-beam modes*. Typical examples of oscilloscope traces, observed at a fixed position ($x = 4.1$ cm), are shown in Fig.5. The data were obtained using the applied rf voltage with frequency as high as $f_{RF} = 533$ kHz. In the figure the top trace represents a wave envelope form of the applied rf voltage and the lower three traces are wave envelope forms of observed signals; the upper trace among the three ones corresponds to a raw probe signal, the middle to a high frequency part ($f \gtrsim 200$ kHz) and the bottom to a low frequency part ($f \lesssim 60$ kHz). The high frequency part is partly enhanced in wave amplitude only in the latter half of the packet. On the other hand, the low frequency part, showing the density depression in the plasma cavity region, indicates that the density depression is also enhanced in depth in the latter half of the cavity corresponding with the amplitude pattern of the high frequency part.

DISCUSSIONS AND CONCLUSION

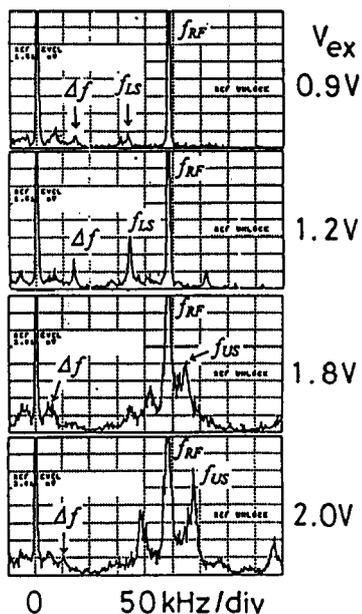
In this experiment it was confirmed that the pump wave (at f_{RF}) was a 'slow' ion-beam mode (being a 'negative' energy wave) and one (at f_{US}) of the two daughter waves was a 'fast' ion-beam mode ('positive' energy wave), although another daughter wave (at Δf) could not be well identified. So, supposing that another wave (at Δf) belongs to the ion-acoustic mode ('positive' energy wave), it is concluded that the three-wave coupling possibly yields the explosive instabilities above a threshold of the pump power. From this reason we interpret the nonlinear modulation or partial enhancement in amplitude of the pump wave packet to be caused by such an instability. Furthermore, we found experimentally that the packet-form ion-beam modes could also form plasma cavities just as ion-acoustic wave packets did so [3]. In this case it is noted that the plasma cavities thus formed possibly have two-storied structures.

References

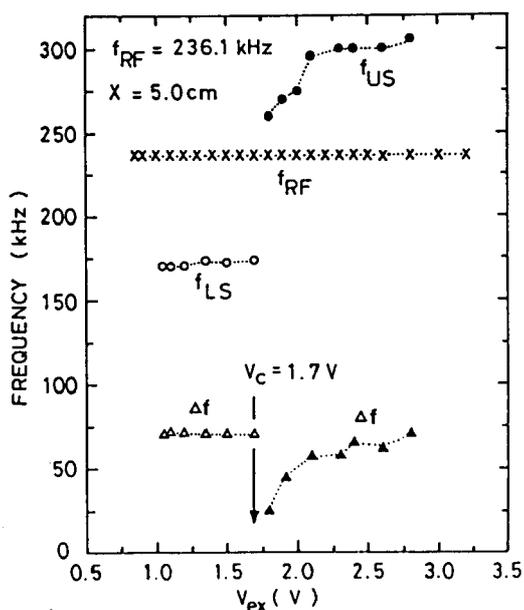
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 [2] T.Honzawa, M.Hattori, and Y.Saitou, Phys. Plasmas **4**, 3943 (1997).
 [3] T.Honzawa, S.Watanabe, and Y.Saitou, J. Plasma Phys. **61**, 489 (1999).
 [4] T.Honzawa, T.Hoshina, and Y.Saitou, J. Plasma Fusion Res. SERIES, **2**, 356 (1999).



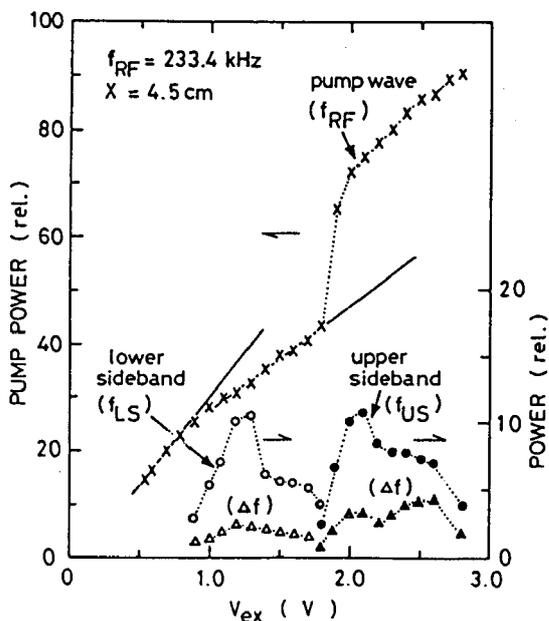
[Fig.1] Oscilloscope traces of evolving wave packets of ion-beam mode, observed at various V_{ex} .



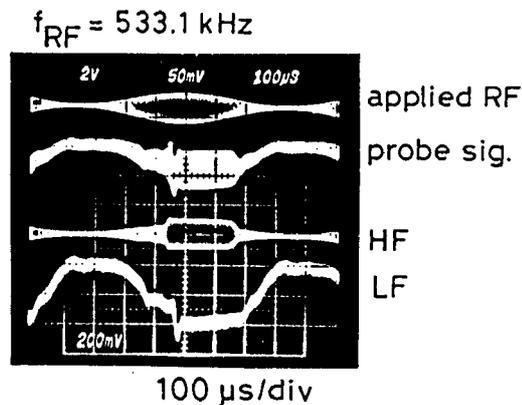
[Fig.2] Spectra of evolving waves observed at $x = 4.5$ cm.



[Fig.3] Relations of observed wave frequencies with V_{ex} . The upper sideband wave (at f_{US}) appears at $V_{ex} \gtrsim 17$ V. Eq.(1) is always approximately satisfied in the range of V_{ex} , though f_{US} and Δf change with V_{ex} .



[Fig.4] Relations of observed wave powers with V_{ex} . Above $V_{ex} \gtrsim 1.7$ V the pump wave power rapidly increases with increasing V_{ex} and new two daughter waves appear, too.



[Fig.5] Oscilloscope traces of the applied rf signal, raw probe signal, high-pass filtered (HF) and low-pass filtered (LF) signals.