INSTITUTE OF PLASMA PHYSICS

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RESEARCH REPORT

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OBSERVATION OF FREE-STREAMING OF ELECTRON IN PLASMAS

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Abstract

The excitation and propagation of electron waves in a plasma has been studied experimentally in a low-density and large-volume plasma. For frequencies larger than the electron Langmuir frequency, an electron plasma wave was observed which is predicted by the linear theory for a Maxwellian plasma. For smaller frequencies, free-streaming electron or ballistic signal are observed. For frequencies close to the electron Langmuir frequency, both the electron plasma wave and the free-streaming electron are excited and show interference patterns. These observations are compared with the theoretical prediction. The effect of the free-streaming electron on a sheath formed around a transmitter it also discussed.

§1. Introduction

A number of experimental studies (1) of electrostatic waves in a collisionless plasma have been carried out since the experimental verification of Landau damping (2). In the case of ion wave experiments, it has recently been reported that a grid immersed in the plasma excites pseudo waves in addition to the ion-acoustic waves. These pseudo waves have been classified into two types: (i) an ion burst (3), which comprises free-streaming bunches of ions that have been accelerated through the grid sheath to a velocity which depends on the amplitude of the applied signal, and (ii) free-streaming ions (4), caused by ions that stream through the electric field created externally by the grid, so its velocity does not depend on the amplitude of external fields. Computational analysis (5) also shows the existence of both the ion burst and the free-streaming ions.

Similarly electron pseudo waves can be expected to occur in electron wave experiments. There is one experiment (6) on the electron "burst", and some preliminary reports on the free-streaming electrons (7). Electric fields for the free-streaming electrons in a Maxwellian plasma for frequencies smaller than the electron Langmuir frequency have been given by Landau (2)(8).

$$E(x,t) \equiv \frac{2}{\sqrt{3}} E_0 \frac{\omega_p^2}{\omega v_e} \left(\frac{\omega}{\omega_p}\right)^4 \left(\frac{\omega x}{2v_e}\right)^{1/3}$$

$$\exp\left[-\frac{3}{2}(1 - i\sqrt{3})\left(\frac{\omega x}{2v_e}\right)^{2/3} - i\omega t\right] \tag{1}$$

where ω_p and v_e are the plasma frequency and the thermal velocity of electrons, respectively, and E_0 is the amplitude at $x = 0$. From Eq.(1) the apparent phase velocity $\frac{\omega}{k_r}$ and the imaginary part of the wavenumber k_i are written as

$$\frac{\omega}{k_r} = \frac{2}{3\sqrt{2}} (2v_e)^{2/3} (\omega x)^{1/3} \tag{2}$$

and

$$\frac{k_i}{k_r} = \frac{1}{\sqrt{3}} \tag{3}$$

Theoretically, it has been predicted[9][10] for a plasma with a Maxwellian distribution that if the observed ratio of imaginary-to-real wavenumber were more than about 0.4, then the contribution of the free-streaming particles to the spatial response is dominant over the collective phenomena. Derfler and Simonen[11] made a detailed computational analysis of the spatial behavior of the electric field and predicted a lower efficiency for the excitation of the free-streaming electron compared with that of the Landau mode for $\omega \sim \omega_p$.

In this paper, we report an observation of the free-streaming electron. In §. 2 and §. 3 the experimental arrangement and the experimental results are given. We discuss the experimental results and summarize them in §. 4.

§2. Experimental Arrangement

The experiment was performed using the space chamber [12] at the Institute of Space and Aeronautical Science, University of Tokyo, as shown in Fig. 1. The chamber, which is grounded, is 2 m in diameter and 3 m in length. Two plasma sources were set face to face, one at each end on the axis of the chamber. They consisted of a mesh anode and hot cathode (15 cm in length). The density and the temperature of the plasma electrons were measured using the Langmuir probe and were found to be homogeneous over the chamber. The plasma density n_e was in a range of 10^6 - 10^7 /cc, and the electron temperature T_e was in a range of 3 - 5 eV. There was no electron beam in the propagation region which could be detected by the Langmuir probe. The Langmuir probe curve in Fig. 2 demonstrates that the electron velocity distribution function can be considered to be a Maxwellian. The experiments were carried out under conditions of continuous pumping and introducting of argon gas through a needle valve. The base pressure in the chamber was below 5×10^{-7}

Torr and the working pressure was about 10^{-4} Torr. The plasma potential was varied in a range from -30 to 30 V with respect to the ground potential by changing the bias potential of the mesh anodes, as shown in Fig. 1.

An electrostatic electron wave was excited by a transmitter which consisted of three grids (17 cm in diameter). The direction of propagation was chosen to be perpendicular to the axis to avoid effects due to any small electron beam current produced by the discharges in the plasma sources. A Faraday cup was used as a receiver; this was 10 cm in diameter and consisted of two mesh grids and a collector. The outer grids of the transmitter and the receiver were grounded.

The signal, picked up by the Faraday cup and amplified with a wide band amplifier, was fed into a balanced mixer with a reference signal from the transmitter to form an interferometer system. The position of the exciter was indicated on the x axis of an x - y recorder and the mixer output was applied to the y axis. The distance x between the transmitter and the receiver was varied from 7 to 87 cm by moving the position of the transmitter.

The excitation voltage applied on the transmitter grid ranged from 0.3 V to 10 V peak to peak. The frequency of the applied sinusoidal signal could be changed from 1 to 50 MHz to cover the range of ω/ω_p from 0.1 to 2.0 (ω: the frequency of the excited wave, ω_p: the electron Langmuir frequency).

§3. Experimental Results

An electron wave was excited and the frequency range of the excited wave was varied from 5 to 35 MHz, where the electron Langmuir frequency was 20 MHz. Some of raw wave patterns on the x - y recorder are shown in Fig. 3. The excitation voltage was kept at 0.3 V. The potential of the transmitter inner grid was at floating potential, and the plasma potential was about at 3 V. When the rf frequency is slightly below ω_p, the amplitude becomes very small. It should be noted that two modes do exist at the frequency of 20 MHz.

The dispersion relation is obtained from data like Fig. 3 by normalizing the real and the imaginary parts of the wavenumber by the Debye wavenumber k_D for different ω/ω_p, and is plotted as open circles (real part) and closed circles (imaginary part) in Fig. 4, where k_D and ω_p are calculated from the measured electron density and electron temperature. Experimentally there are two types of propagation modes as seen in Fig. 4. The experimental dispersion curve of the higher frequency mode agrees with the theoretical ones, (a) and (b), which correspond to the real part and imaginary part of the wavenumber obtained from the dispersion relation of the electron plasma wave. The phase velocity of this mode was independent of both the excitation voltage and the transmitter bias potential. It is concluded that the higher frequency mode observed is the Landau mode, which has been investigated in detail both theoretically[13] and experimentally[1].[12].

For the lower frequency mode, the wavelength was estimated from the data taken in the region of x/λ_D from 10 to 100. Curves (c) and (d) show the real and the imaginary part of the wavenumber, respectively, calculated from Eq. (2) and (3), where the independent variable x/λ_D is chosen to be 80 so as to fit the experimental results. We studied $\omega^{1/3}$ dependence of the phase velocity in detail which was predicted theoretically. Fig. 5 is a typical example of this variation, which shows that the dependence of the observed phase velocity on ω is in fairy good agreement with the theoretical prediction.

From Eq. (2), it is theoretically expected that the phase velocity of the free-streaming electron is also proportional to the cube root of the distance x. The dependence of the wavelength on the distance was observed when the excitation frequency was close to the electron plasma frequency, but this could not be clearly observed for $\omega < \omega_p$. The inhomogeneity of the plasma density (the half width of the spatial density distribution was about 1.6 m in the present case) may be considered to be a reason which makes it difficult to observe the variation of the phase velocity with the distance. This distance variation was not observed in ion acoustic wave work either[4].

The observed damping rate is found to be smaller than the expected value. However, Derfler and Simonen[11] have shown that the damping rate obtained from the numerical analysis is smaller than that obtained from the saddle point method. For $\omega/\omega_p = 1/2$ and $x/\lambda_D = 80$, the damping rate is smaller by about 30% than that obtained from Eq. (3). For instance, we find that for $\omega/\omega_p = 0.47$, k_i/k_D is calculated to be about 0.07 when the observed damping rate correspond to 0.035. Thus, the lower frequency mode observed in the present experiment can be regarded as the free-streaming electron predicted on §1.

To distinguish the free-streaming electron from the electron burst, whose phase velocity is proportional to the square root of the excitation voltage, the excitation voltage was increased. It was found that the phase velocity, that is, the wavelength for a given frequency, did not depend on the excitation voltage in the range from 0.1 to 10 volts.

In order to see the effect of changing the dc bias potential on the inner grid of the transmitter on the free-streaming electron, the plasma potential was varied in a range from negative to positive potential with respect to the ground potential. The outer grids of the transmitter were at ground potential and the inner grid was connected to an oscillator biased at -0.5 V. Fig. 6 shows that when the plasma potential is at 17 V, in which an ion sheath is formed around the outer grids of the transmitter, the free-streaming electron is excited very strongly. Both the wavelength and the damping rate do not depend on the dc bias potential as is predicted by the theory. These results suggest that the ground loop current[14] induced in a receiving grid by space charge bunches emanating from the transmitter grid is very weak when the ion sheath is formed around the transmitter grid. On the other hand, for the plasma potential smaller than about 2 V, the amplitude of the electron plasma wave was nearly constant, and for larger values, the amplitude was decreased. This will be due to the decrease of the number of the electrons around the transmitter.

Furthermore, we find that when the plasma potential becomes larger and larger such that the thickness of the ion sheath becomes large, the first peak position of the wave patterns shifts to right in the figure. This suggests that the excitation mechanism of the free-streaming electron is related to the thickness of the sheath formed around the transmitter.

Keeping the plasma potential close to the ground potential or smaller and increasing the excitation voltage, the electron burst, in addition to the free-streaming electron was observed. However, when the plasma potential was positive, the electron burst was not observed. In this case, there are no electrons except a small number of high-energy electrons in the sheath around the transmitter grid, and therefore it is difficult to observe the electron burst(6).

§4. Discussions and conclusions

As predicted theoretically by Derfler and Simonen[11], it has been found experimentally that as the frequency approaches the electron Langmuir frequency, the amplitude of the free-streaming electron decreases. For $\omega/\omega_p > 1$ it becomes much smaller than that of the electron plasma wave, and was not be observed for $\omega > \omega_p$. Thus, the absence of the free-streaming contribution in the experimental results is determined not only by comparing damping rates, but also from a knowledge of the frequency dependence of the expected signal level, at which the measurements were made.

When the independent variable, x/λ_D, was equal to 80, the experimental dispersion relation of the free-streaming electron was in good agreement with the theoretical prediction Eq. (2). However, since the equation (2) is an approximate dispersion relation, the experimental result should be compared with that obtained from solving an exact equation numerically, which, to our knowlegde, has not yet been made.

As is well-known, the dispersion equation has an infinite number of roots[15]. Since the wave length of the second-order Landau mode is larger than that of the free-streaming electron in the present case, the observed wave is not the second-order Landau mode, whose real part of the wavenumber is shown as a dashed line in Fig. 4. Theoretically, it was shown by Derfler and Simonen[11] that for

$\omega < \omega_p$ and $x >> \lambda_D$, the free-streaming electron was dominant, rather than the higher-order Landau mode. However, we can not absolutely neglect the influence[11] of the higher-order Landau mode on the free-streaming electron. The discrepancy between the experimental result and the theoretical one in the variation of the phase velocity with the distance may be attributed in part to this influence, besides the inhomogeneity of the plasma density.

In summary, electron waves were excited by a three mesh grid in a large-volume plasma. It was found that (i) for $\omega > \omega_p$, the Landau mode was observed, (ii) for $\omega \sim \omega_p$, both the Landau mode and the free-streaming electron in which the amplitude of the latter was much smaller compared with that of the former were observed, and (iii) for $\omega < \omega_p$, the free-streaming electron was observed. The observed variation of the phase velocity and the damping rate of the free-streaming electron with frequency were in good agreement with the theoretical prediction. When an ion sheath was formed around the transmitter grid, rather than an electron sheath, the free-streaming electron was excited much more strongly.

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Figure Captions

Fig. 1 Schematic diagram of the experimental apparatus.

Fig. 2 Langmuir probe curve. Probe current vs voltage, where $T_e = 4.5$ eV.

Fig. 3 The raw wave patterns.

Fig. 4 Dispersion relation. Solid lines (a) and (b) are real and imaginary part of the wavenumber of the Landau mode, respectively. Solid lines (c) and (d) are real and imaginary part of the wavenumber of the free-streaming electron respectively, calculated from Eq(2) and (3). Dashed line is the real part of the wavenumber of the second-order Landau mode.

Fig. 5 Phase velocity variations of the free-streaming electron as a function of frequencies.

Fig. 6 Wave patterns of the free-streaming electron as a parameter of the plasma potential, where $\omega/\omega_p = 0.68$.

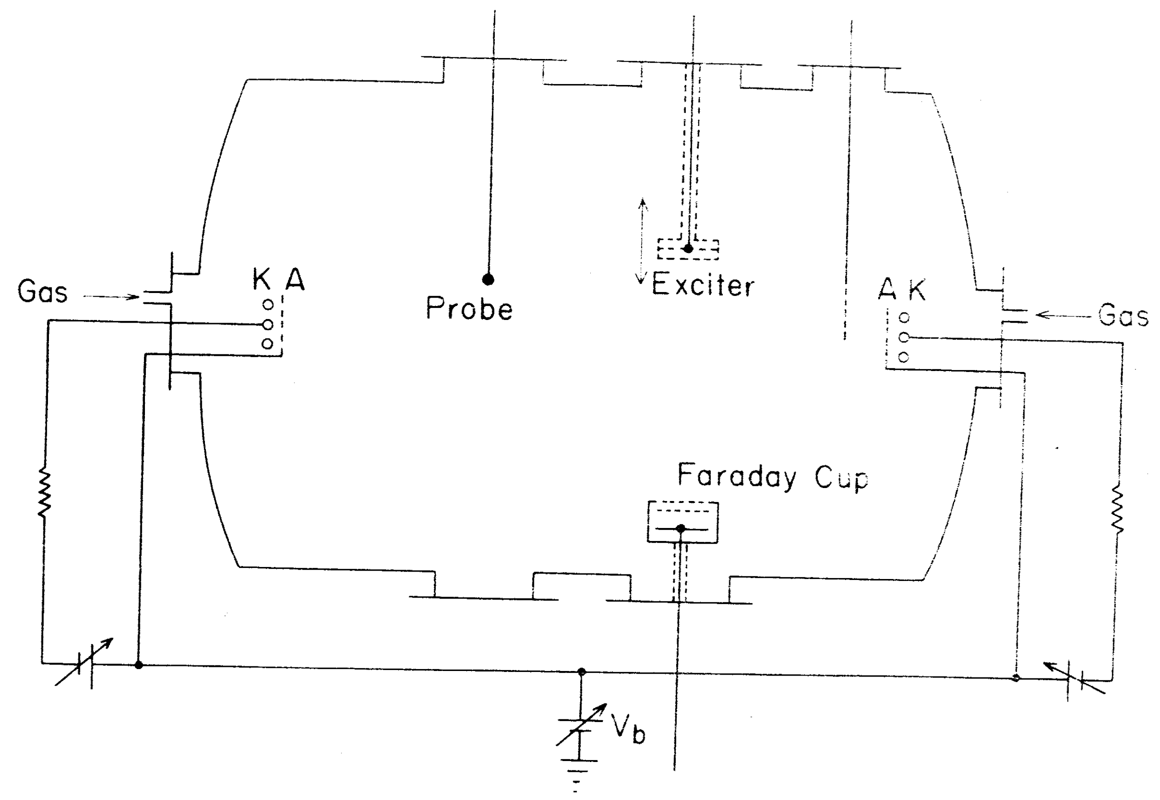


Fig. 1

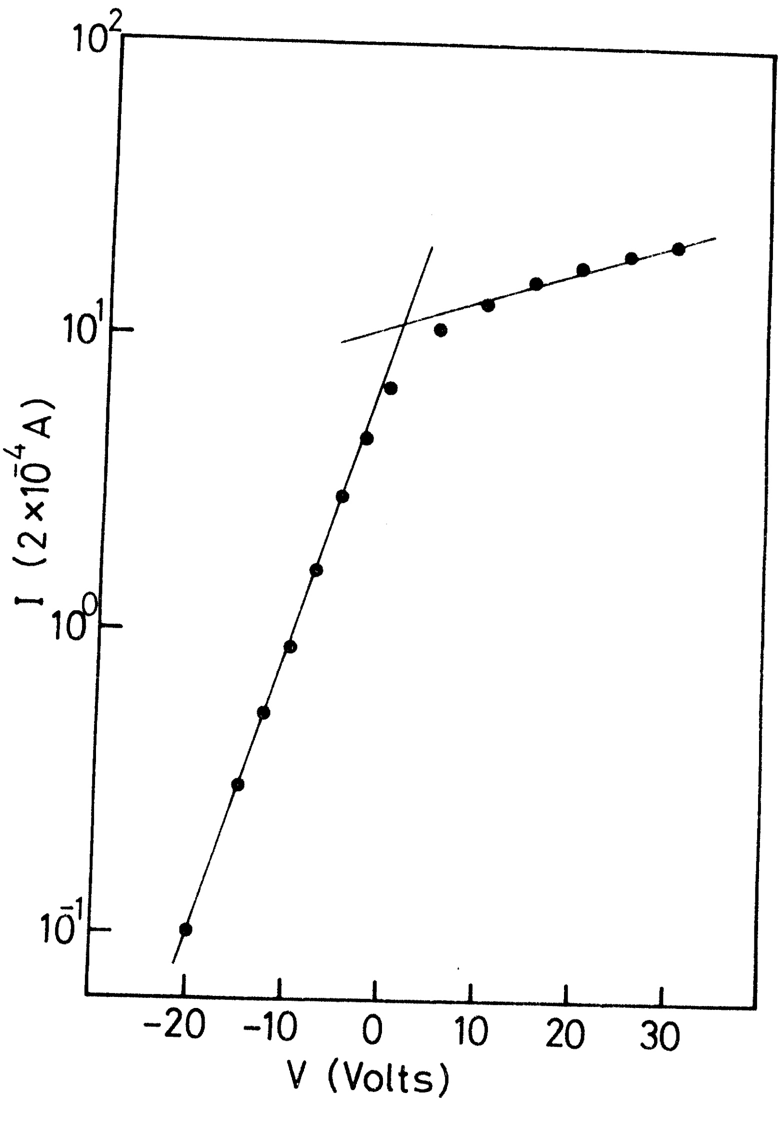


Fig. 2

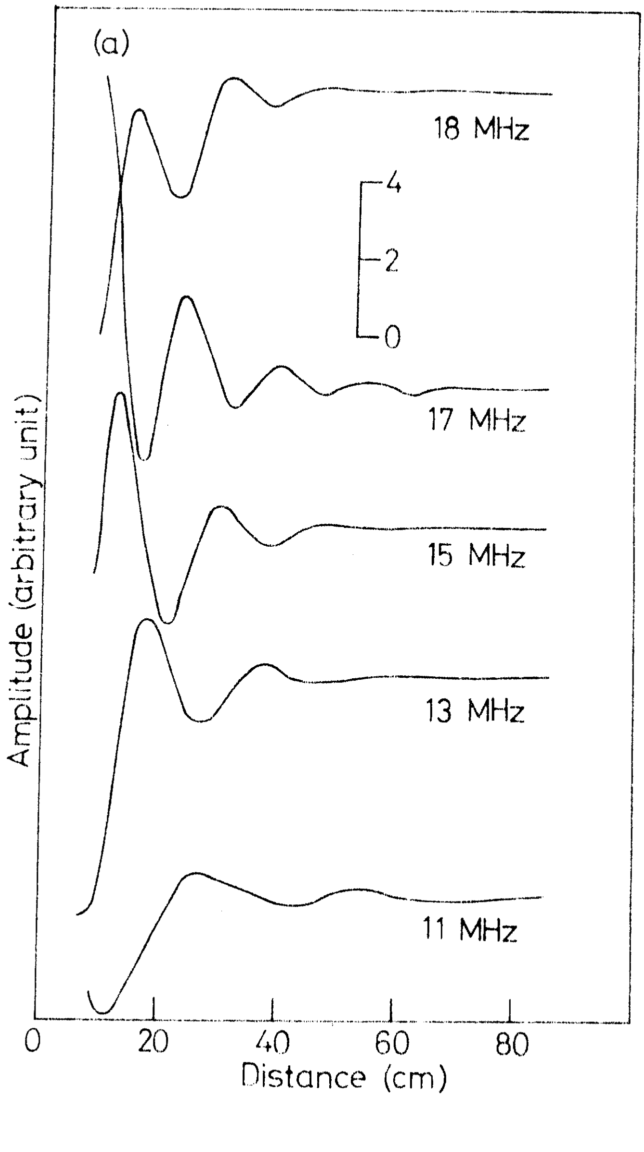
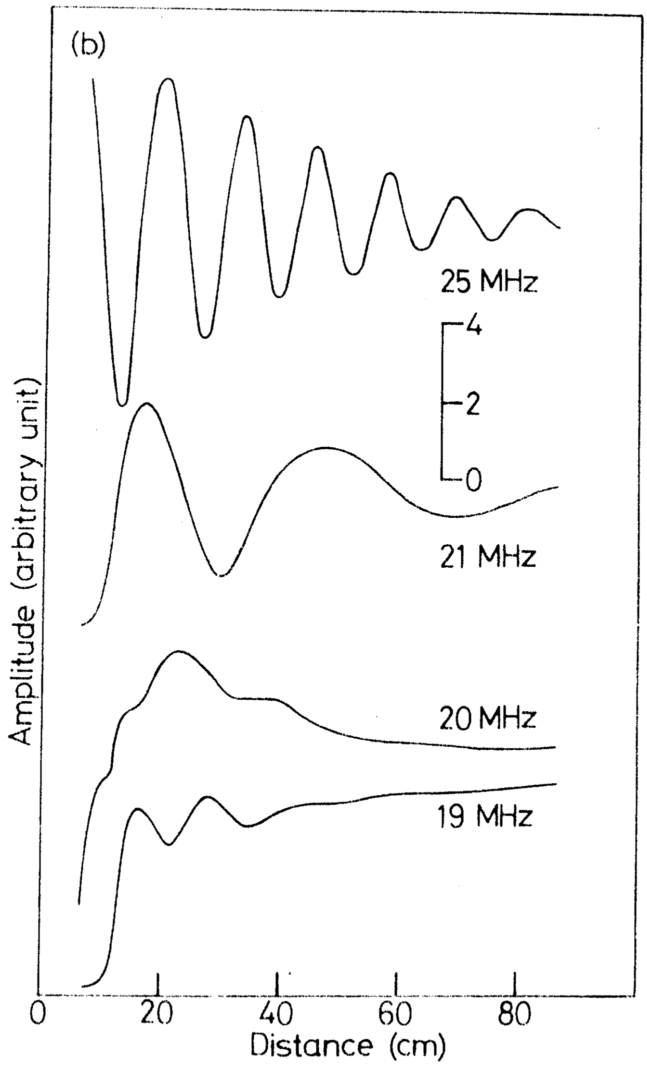

(a)
18 MHz
4
2
0
17 MHz
15 MHz
13 MHz
11 MHz
Amplitude (arbitrary unit)
0
20
40
60
80
Distance (cm)

Fig. 3(a)



(b)
25 MHz
21 MHz
20 MHz
19 MHz
4
2
0
Amplitude (arbitrary unit)
0
20
40
60
80
Distance (cm)

Fig. 3(b)

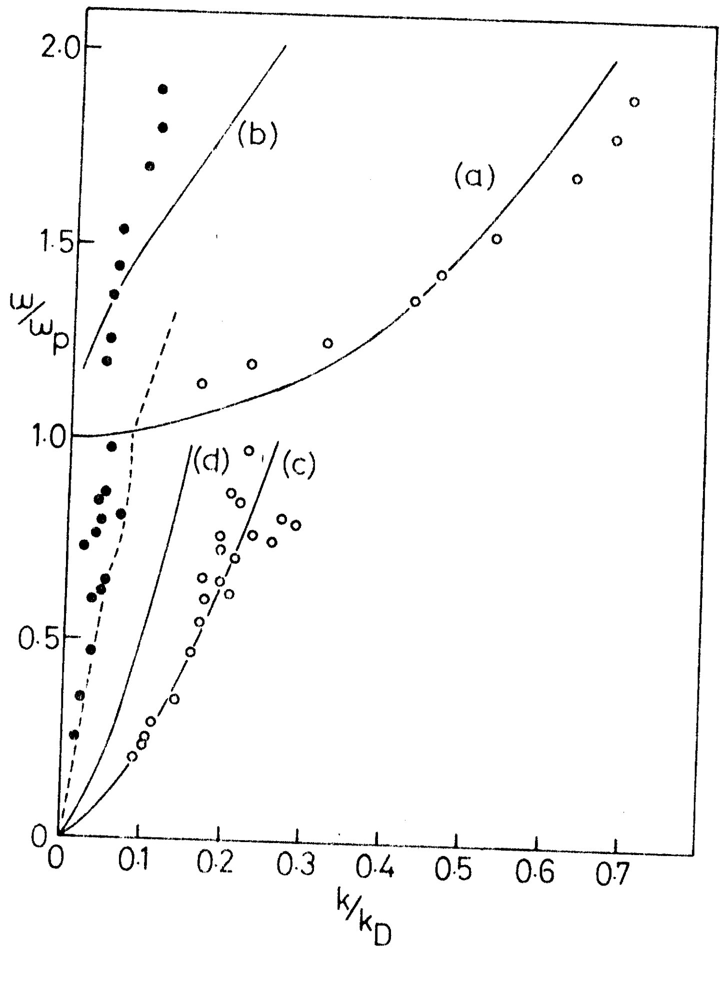
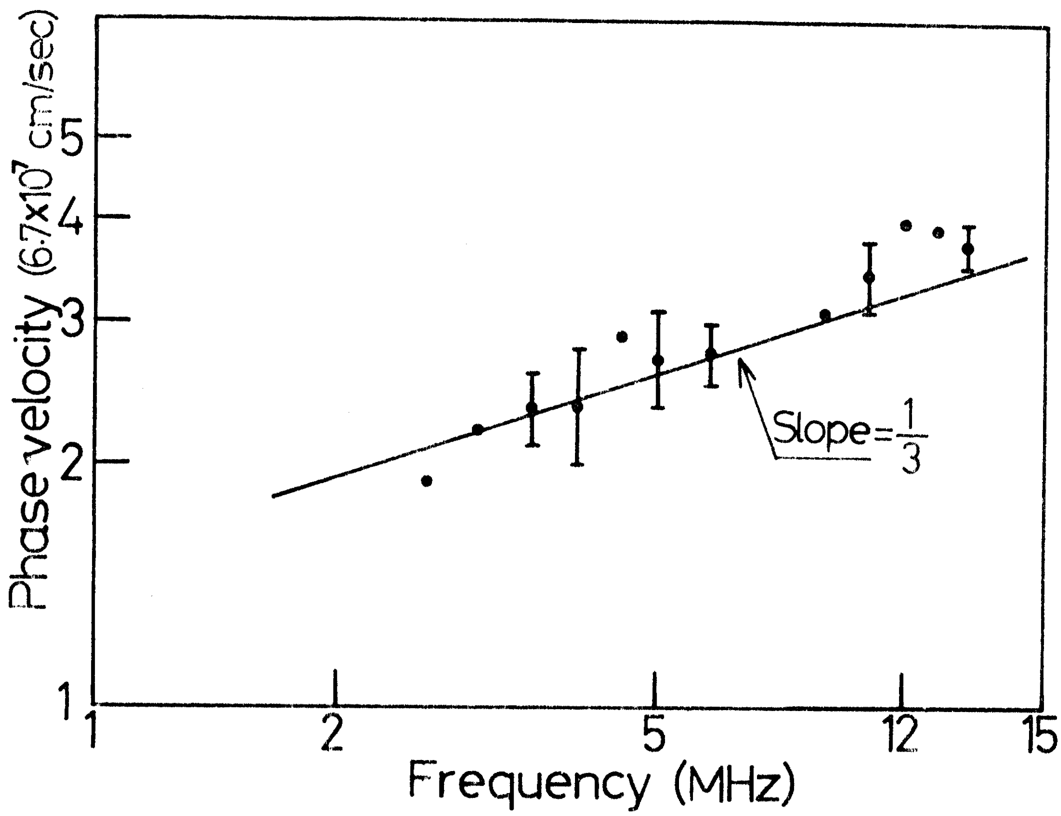


Fig. 4



Phase velocity (6.7x10^7 cm/sec)
5
4
3
2
1
Slope=$\frac{1}{3}$
1
2
5
12
15
Frequency (MHz)

Fig. 5

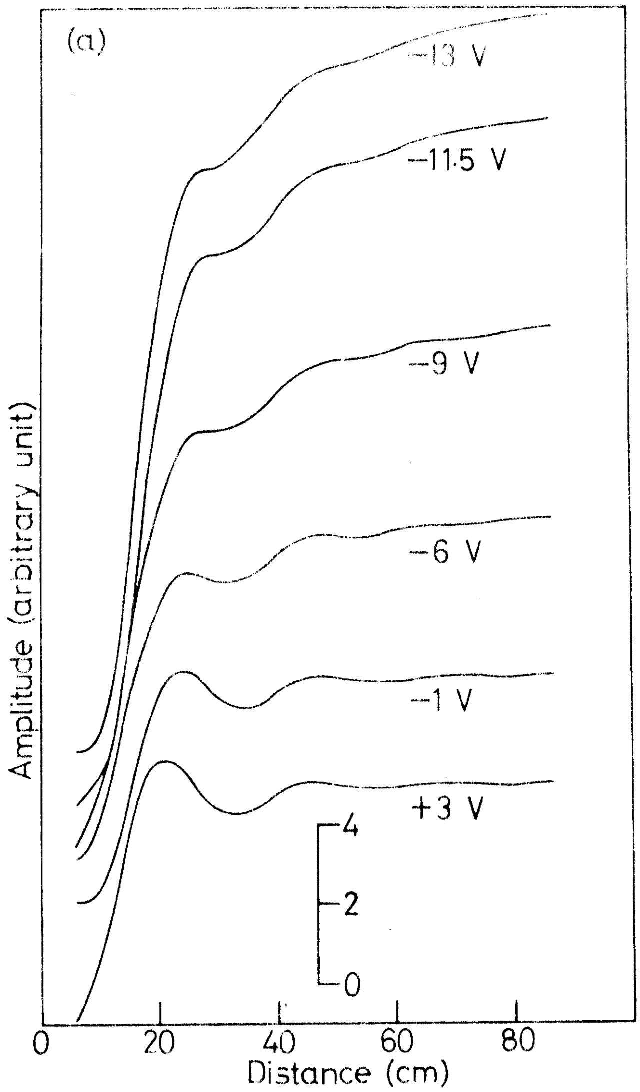

(a)
−13 V
−11.5 V
−9 V
−6 V
−1 V
+3 V
4
2
0
Amplitude (arbitrary unit)
0
20
40
60
80
Distance (cm)

Fig. 6(a)

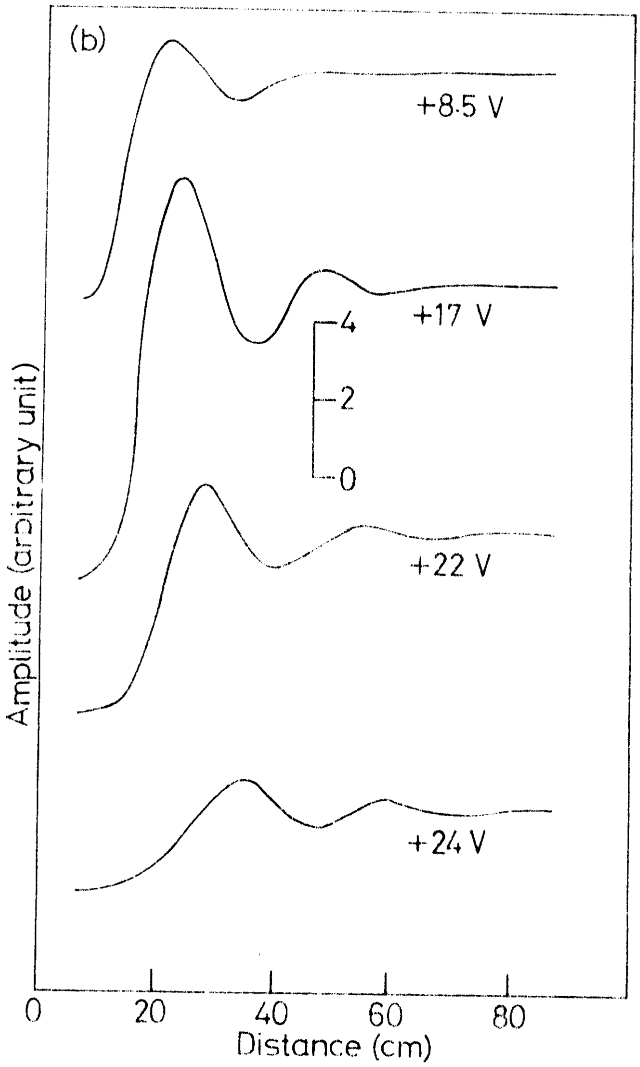

(b)
+8.5 V
+17 V
+22 V
+24 V
4
2
0
Amplitude (arbitrary unit)
0
20
40
60
80
Distance (cm)

Fig. 5(b)