Influence of High Frequency Electric Field on the Dispersion of Ion-Acoustic Waves in Plasma

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The modification of the ion-acoustic wave dispersion under the action of a high frequency electric field was studied experimentally, the wave propagating along and against the plasma stream. The frequency of the field amounted to approximately half the electron plasma frequency. It was found that the phase velocity of the ion wave and the plasma drift velocity decrease as the effective high frequency field power increases.

1. Introduction

The propagation characteristics of ion-acoustic waves in the presence of high frequency electric fields have been studied both experimentally [1, 2, 3] and theoretically [4, 5, 6]. It was demonstrated that the field may cause pronounced changes in the propagation of the waves. Takamura et al. [1] observed a decrease of the wave phase velocity by the field. However, both their theory and experiment were restricted to small field amplitudes. In a recent publication, Watanabe et al. [2] found that the modulation of a high frequency field increases linearly with the amplitude of the ion wave and the high frequency field. The phase of the modulated wave depends on the frequency of the applied field. Under the action of the ponderomotive force, originated from the modulation of the high frequency field by the low frequency ion wave, the phase velocity of the ion wave decreases as the effective high frequency field power increases in the case where the frequency of the field is lower than the electron plasma frequency.

Lee et al. [3] studied experimentally the propagation of ion-acoustic waves in the presence of a high frequency electric field with amplitudes much higher than those used in [1, 2]. Their results show good agreement with the theory of Albright [6].

In the present work, the modification of the ion-acoustic wave dispersion due to the externally excited high frequency electric field was studied. The experiments were performed in an argon plasma generated, in a magnetic field, at the electron cyclotron resonance. These studies were done in the case of ion wave propagation along and against the plasma stream.

The paper is organized as follows: in Sect. 2 we present the theoretical analysis as used to illustrate our experimental results, while Sect. 3 contains the description of the experimental set up, the results and discussion.

2. Theoretical Analysis

Consider a plasma located in a magnetic field and a uniform external high frequency electric field (HFEF) given by

$$E_0(t) = E_0 \cos \omega_0 t \,. \tag{1}$$

Both the magnetic and electric field are oriented parallel to the z-axis.

If an ion-acoustic wave of a frequency $\omega \ll \omega_0$ is excited in the plasma, the HFEF is modulated in space and can be represented by

$$E_0(t) + E_1(t, z) \,, \tag{2}$$

where E_1 is the modulated part of HFEF.

The modulation of HFEF by the low frequency ion wave produces a ponderomotive force which is given by [7, 8]:

$$F_{\mathrm{NL}} = -\frac{\omega_{\mathrm{Pe}}^2}{\omega_0^2}\, \varepsilon_0 \frac{\partial}{\partial z} \langle E_0(t)\, E_1(t, z)\rangle \,, \tag{3}$$

where ω_{Pe} is the electron plasma frequency and the angle brackets denote averages over the period of the high frequency oscillations. To express the modulated part of HFEF, the equation of motion and continuity for electrons and Poisson's equation are used [1, 2, 4].

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When this force is out of the phase of the force given by the electron pressure, the phase velocity of the ion wave is decreased [1].

The dispersion relation of the ion wave in the presence of HFEF is similar to that used in references [1, 2, 4]:

$$\omega/K = \frac{(k\,T_e/m_i)^{1/2}}{(1+K^2/K_{de}^2)^{1/2}} \cdot \left[1 + (3\,T_i/T_e)\,(1+K^2/K_{de}^2) + \frac{a_e^2}{2}\,\varphi(\omega_0)\,(K_{de}^2/K^2)\right]^{1/2}, \qquad (4)$$

where $a_e = K_e E_0/m_e \omega_0^2$ and

$$\varphi(\omega_0) = \frac{\omega_0^2 - K^2 k\,T_e/m_e}{\omega_0^2 - \omega_{Pe}^2 - K^2 k\,T_e/m_e}\,.$$

In the above equations, K and ω are the wavenumber and frequency of the ion wave, m, T, k and K_{de} are the mass, temperature, Boltzmann's constant and Debye wavenumber, respectively, while the subscripts i and e denote the ion and electron components.

The relative variation of the wavelength of the ion wave due to the presence of HFEF is given by [1]:

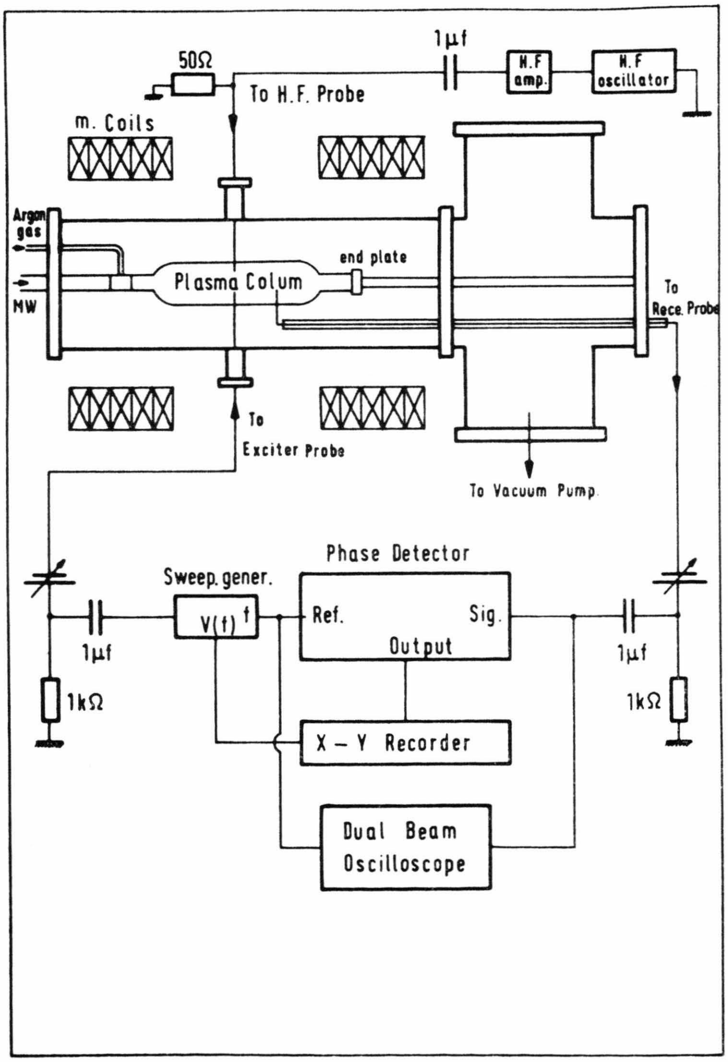

Fig. 1. Schematic diagram of the apparatus including a block diagramm of the measuring equipment for ion wave dispersion.

$$\Delta\lambda/\lambda = \frac{\varphi(\omega_0)}{4}\left(\frac{K_{\mathrm{de}}\, e\, E_0}{m_{\mathrm{e}}\,\omega_0}\right)^2 \cdot \frac{1+K^2/K_{\mathrm{de}}^2}{1+(3\,T_{\mathrm{i}}/T_{\mathrm{e}})(1+K^2/K_{\mathrm{de}}^2)}\,. \tag{5}$$

This equation shows that $\Delta\lambda/\lambda$ is proportional to the square of the amplitude E_0 (or power $W \propto E_0{}^2$) of HFEF.

3 A) Experimental Set Up

The experiments were performed in a cylindrical metallic vessel (diameter 14 cm, length 140 cm) as shown in Figure 1. The plasma source is an open-ended circular waveguide. Microwave power (10 W, 9.3 GHz) is fed into the waveguide. The magnetic field in the discharge chamber is so chosen that there exists an electron cyclotron resonance region within it. The plasma created forms a column of a diameter depending upon the precise value of the magnetic field and is typically about 5 cm in diameter and 50 cm long. Argon gas is continuously bled through the system. The pressure (about 5×10^{-3} Torr) is controlled by a needle valve. The plasma density was about 2×10^9 cm^{-3} and the electron temperature 2—4.2 eV. Both were measured by a Langmuir probe. From the measurements of the ion wave it was found that $T_{\mathrm{i}}/T_{\mathrm{e}} < 0.1$.

The ion-acoustic wave was excited in the plasma by applying an a.c. voltage signal of 3 $V_{\mathrm{p-p}}$ to a 0.25 mm diameter and 5 mm long negatively biased tungsten probe. A 200 MHz high frequency electric field was excited by another probe. Both probes were situated perpendicularly to the magnetic field (Figure 1). The signal was received by a thin fixed probe, also situated perpendicularly to the chamber axis.

The phase velocity of the ion-acoustic wave was measured by a standard interferometer method. The distance between the exciter and receiver probes was kept constant. The frequency of the exciting signal was swept from 200 kHz up to 1.25 MHz. Typical examples of measured phases as a functions of the wave frequency with and without HFEF, drawn on an X-Y recorder, are shown in Figure 2. The phase velocity of the ion wave was determined by analyzing the phase measurements. The exciting and received signals were also displayed on the dual beam oscilloscope.

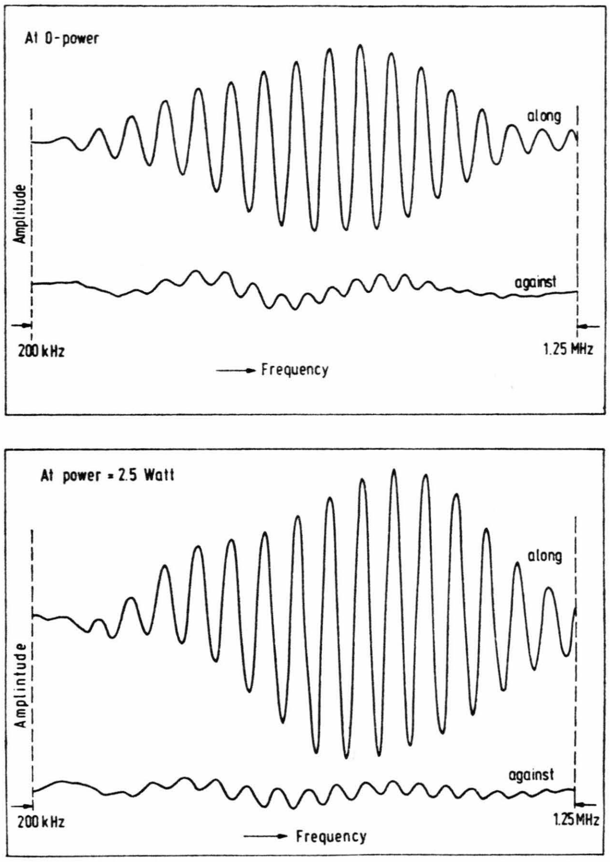

Fig. 2. Typical phase measurements as functions of ion wave frequency with and without HFEF.

3 B) Experimental Results and Discussion

The plasma produced was drifting from the source towards the end plate. So the phase velocity of the ion wave propagating in the plasma was Doppler shifted:

$$V_{\mathrm{p}}{}^{+} = V_{\mathrm{s}} + V_{\mathrm{d}} \quad \text{along the plasma stream,}$$
$$V_{\mathrm{p}}{}^{-} = V_{\mathrm{s}} - V_{\mathrm{d}} \quad \text{against the plasma stream,}$$

where V_{s}, V_{d} are respectively the sound velocity and plasma drift velocity. The half value of the difference between these $V_{\mathrm{p}}{}^{+}$ and $V_{\mathrm{p}}{}^{-}$ corresponds to V_{d}. On the other hand, the half value of the sum corresponds to the sound velocity, and it agrees with the one calculated from the temperature measurements in the absence of the high frequency electric field. $V_{\mathrm{p}}{}^{+}$, $V_{\mathrm{p}}{}^{-}$ and V_{d} as functions of the H.F. power are shown in Figs. 3 A, B, C, respectively. In Fig. 3 A, $V_{\mathrm{p}}{}^{+}$ decreases at lower powers

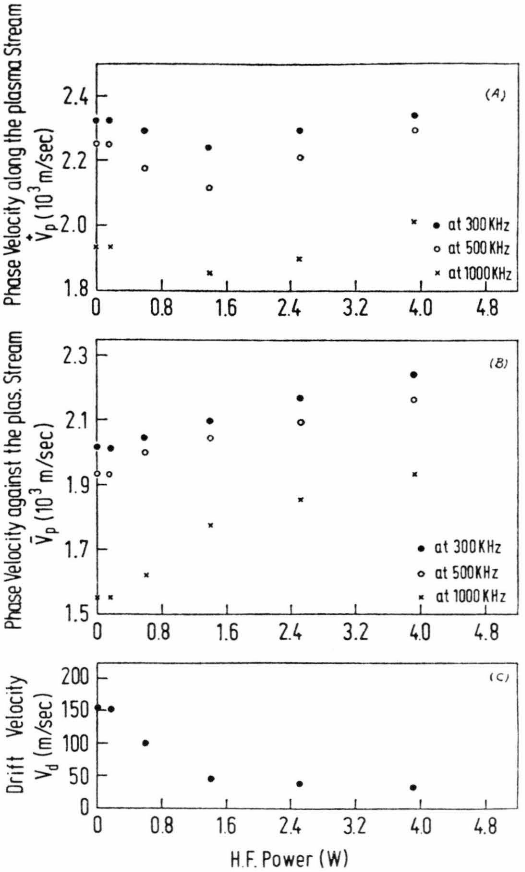

Fig. 3. Phase velocity of an ion wave (along and against the plasma stream) and plasma drift velocity as a function of the H.F. power in the case where $\omega_0 \simeq 0.5\ \omega_{Pe}$.
A) Phase velocity along the plasma stream V_p^+.
B) Phase velocity against the plasma stream V_p^-.
C) Plasma drift velocity.

of HFEF and increases at higher ones. Figure 3B shows that V_p^- increases as the H.F. power increases. These variations of V_p^+ and V_p^- with the H.F. power come from the decrease of the plasma drift velocity (Fig. 3C) and the increase of the electron temperature (Fig. 4) with increasing H.F. power. The decrease of the plasma drift velocity might be explained by a randomisation of the plasma drift motion at higher power levels of HFEF.

Figure 4 shows that the electron temperature and the plasma density increase with the H.F. power. The measured phase velocity and the calculated one, which is given by $V_{calc} = (kT_e/m_i)^{1/2}/(1 + K^2/K_{de}^2)^{1/2}$, are shown in Fig. 5 as a function of the H.F. power. These two velocities as functions of the normalized frequency, with and without the H.F. field, are shown in Figure 6. In the two figures it appears that the measured phase velocity of the ion wave is smaller than the calculated one. This is due to the ponderomotive force produced by the modulation of HFEF by the low frequency ion wave [1, 2].

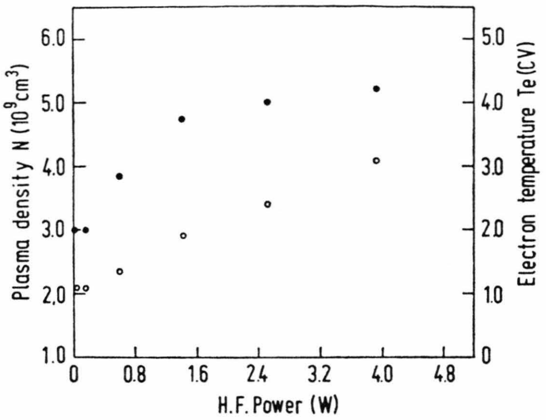

Fig. 4. Electron temperature and plasma density as functions of the H.F. power in the case where $\omega_0 \simeq 0.5\ \omega_{Pe}$.
● Electron temperature T_e (eV).
○ Plasma density N (10^9 cm^{-3}).

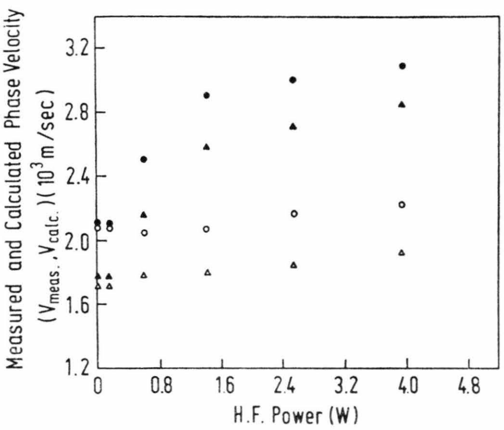

Fig. 5. Phase velocity of the ion wave as a function of the H.F. power in the case where $\omega_0 \simeq 0.5\ \omega_{Pe}$. Open circles show the measured phase velocity V_{meas} and closed circles the calculated phase velocity V_{calc}.
○ V_{meas} at 500 kHz, △ V_{meas} at 1000 kHz,
● V_{calc} at 500 kHz, ▲ V_{calc} at 1000 kHz.

The relative variation of the wavelength of the ion wave is defined as

$$\Delta\lambda/\lambda = (\lambda_{meas} - \lambda_{calc})/\lambda_{calc}\,, \tag{6}$$

and it is proportional to the square of the amplitude

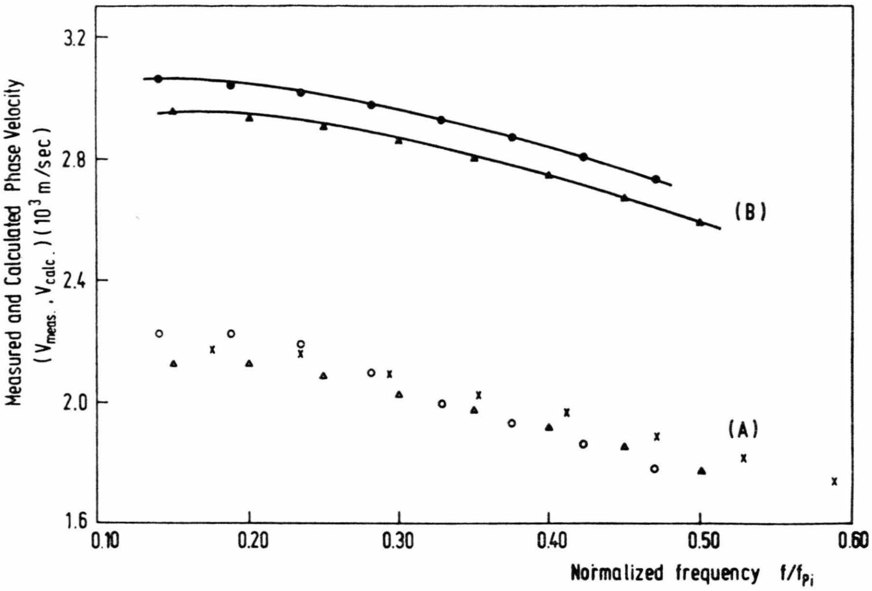

Fig. 6. Phase velocity of the ion wave V_p as a function of the normalized frequency f/f_{p_i}:

A) measured phase velocity:
× HF power = 0 , $\omega_{p_i} = 1.7$ MHz,
△ HF power = 1.4 W, $\omega_{p_i} = 2$ MHz,
○ HF power = 2.5 W, $\omega_{p_i} = 2.13$ MHz.

B) Calculated phase velocity
—▲— H.F. power = 1.4 W, $\omega_{p_i} = 2$ MHz,
—●— H.F. power = 2.5 W, $\omega_{p_i} = 2.13$ MHz.

E_0 (or power $W \propto E_0^2$) of the high frequency field as shown in Figure 7. The solid lines are based on (5), where the frequency of the HFEF is approximately half the electron plasma frequency and $T_i/T_e < 0.1$. It should be noted that the phase velocity of the ion wave increases when the electron temperature increases. So the decrease in the wavelength may not be based on the change of the plasma parameter. Further $\Delta\lambda/\lambda$ is independent of the ion wave amplitude.

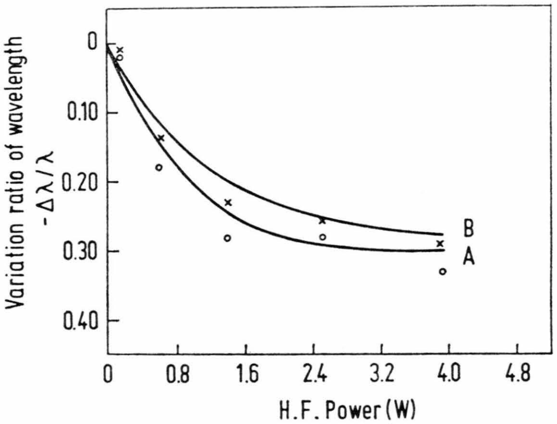

Fig. 7. Relative wavelength variation of the ion wave as a function of the H.F. power at different ion wave frequencies. The solid lines are the theoretical curves according to Eq. (5) where $T_i/T_e < 0.1$, A, 0 at 300 kHz; B, x at 500 kHz.

To summarize, we have examined the effect of HFEF on the propagation of ion acoustic waves in the plasma. There is a ponderomotive force produced by the modulation of the HFEF by a low frequency ion wave. Under the action of this ponderomative force the phase velocity of the ion wave has been found to decrease in the case where the frequency of the field is lower than the electron plasma frequency.

It was found also that the plasma drift velocity decreases as the power of the HFEF increases. This might be explained by the randomisation of the plasma drift motion at the higher power levels of high frequency field.

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