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CURRENT DRIVEN WEAK ION ACOUSTIC TURBULENCE IN A MAGNETIZED PLASMA

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ABSTRACT

The current driven ion acoustic instability has been studied in a quiescent magnetized argon plasma for electron densities n_e in the range from 10^{10} cm^{-3} to 10^{11} cm^{-3}, an electron temperature T_e of 2.2 eV, an electron-ion temperature ratio T_e/T_i of 15, a homogeneous magnetic field of 400 gauss, and neutral gas pressures in the range from 1×10^{-3} mmHg to 4×10^{-3} mmHg. Coulomb collisions are important for these experimental conditions. The instability occurs for a certain range of currents (100 mA $< I < 600$ mA). The saturation appears to be explained by electron trapping. The characteristic parameters of the instability (electron drift velocity, collisional damping, T_e, T_e/T_i) are determined from a measurement of the propagation properties of low frequency ion acoustic test waves using an unperturbative method of microwave interferometry.

INTRODUCTION

The current driven ion acoustic instability has been studied both theoretically and experimentally for a number of years[1-9]. The nonlinear mechanism of saturation, which determines the evolution of the instability into the turbulent state, is still an essential subject of research. Moreover, there is a considerable interest in new unperturbative methods of diagnostics, which allow the precise measurement of the characteristic parameters of the instability.

Aside from a few exceptions the experiments have been done in the unmagnetized plasma of the positive column of a gas discharge. The neutral gas pressure was typically in the range from .1 mmHg to 10 mmHg, since the mean free path for electron neutral collisions must be small compared to the diameter of the plasma column. Thus, ion acoustic waves are severely damped by ion neutral collisions if the wavelength exceeds a few millimeters. The diagnostics have been usually performed by means of Langmuir probes. Unperturbative methods like microwave scattering and CO_2-laser scattering have been applied in a few cases[1,7-9].

We have performed an experiment in a quiescent magnetized argon plasma, which was produced by means of a RF wave structure. A current was drawn between a disk anode and a hot electron emitting cathode, to avoid depletion of the plasma. This experimental arrangement allowed us to keep the plasma density constant for a certain range of currents and to study the onset of the instability from a very small level of background fluctuations. The neutral gas pressure has been considerably reduced, since owing to the confining magnetic field the mean free path of the electrons must be small only compared to the distance between the electrodes and because the effective collision rate is increased by a factor of two due to the gyrational electron motion. The collisional damping of the ion acoustic waves is also reduced. This allows us to study the propagation of low frequency ion acoustic test waves by use of an unperturbative method of microwave interferometry and to determine the characteristic parameters of the instability (electron drift, ion sound velocity, electron-ion temperature ratio, collision rates) in a very precise way. To our knowledge, this is the first time that this diagnostic method has been applied to study the current driven ion acoustic instability.

The paper is organized as follows: Section I gives an outline of the linear theory for the exponential growth of the instability in the presence of collisions. Secion II gives a description of the experimental arrangement and of the characteristics of the microwave interferometer, and presents the experimental results concerning the observation of the ion acoustic instability and the propagation of low frequency test waves. In Section III we discuss the power frequency spectrum of the instability in connection with the data obtained from the measurement of test waves.

I. THEORY

The ion acoustic modes are driven unstable by a current if the growth induced by the electron drift exceeds the Landau and the collisional damping. Solving an initial value problem for the linearized one-dimensional Boltzmann equation with a collisional term and assuming Maxwellian ion and electron velocity distribution one obtains the following expression for the relative growth rate[1,3,5]:

$$\frac{\omega_i}{\omega_r} = -\sqrt{\frac{\pi}{8}}\,\frac{1}{(1+k^2\lambda_D^2)^{3/2}}\left\{\left(\frac{T_e}{T_i}\right)^{3/2}\exp\left[-\frac{3}{2}-\frac{T_e}{2T_i(1+k^2\lambda_D^2)}\right]+\sqrt{\frac{m_e}{m_i}}\left[1-\frac{v_d}{C_s}\sqrt{1+k^2\lambda_D^2}\right]\right\}-\frac{\nu_{ic}}{2\omega_r} \quad (1)$$

where

T_e/T_i is the electron to ion temperature ratio,

m_e/m_i is the electron to ion mass ratio,

V_D/C_s is the ratio of the electron drift and the ion sound velocity ($C_s = \sqrt{\frac{kT_e}{m_i}}$),

ν_{ic} is an effective ion collision frequency, accounting for ion-neutral and ion-ion collisions

λ_D and ω_{pi} are the Debye-length and the ion plasma frequency, respectively.

Equation (1) is valid only for $T_e/T_i \gg 1$.

Frequency (ω_r) and wave number (k) are connected by the dispersion relation

$$\frac{\omega_r}{\omega_{pi}} = -\frac{k\lambda_D}{(1+k^2\lambda_D^2)^{1/2}} \left\{ 1 + \frac{3}{2} \left(\frac{T_e}{T_i}\right)^{-1} \left(1 + k^2\lambda_D^2\right) \right\} \tag{2}$$

The spatial growth (k_i) of ion acoustic waves is a parameter of interest for many experimental situations. It is related to the growth rate by a simple expression, if $T_e/T_i \gg 1$[10*]:

$$k_i = \omega_i \left(\frac{d\omega_r}{dk}\right)^{-1} \tag{3}$$

The linear state of the instability is fully described by Eqs.(1)-(3). For the interpretation of experimental results it is convenient to represent the following parameters:

a) the critical electron drift velocity for the onset of the instability ($\frac{\omega_i}{\omega_r} = 0$);

b) the spatial growth (k_i);

c) the frequency (ω^m) of the mode with maximum spatial growth ($\frac{dk_i}{dk_r} = 0$)

as functions of $k\lambda_D$ (or $\frac{\omega_r}{\omega_{pi}}$) (see Fig. 1, 7).

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*Equation (3) has been derived for the case of a local excitation of a wave at a given real frequency. Fenneman et al. found that it gives also an appropriate description of the initial growth of the current driven ion acoustic instability[3].

II. EXPERIMENT

1. Experimental Arrangement

The experimental arrangement is shown in Fig. 2. The plasma is created by resonant absorption of microwave power at the electron cyclotron frequency (ν_{ce} = 1.2 GHz) by means of a RF wave structure, which allows the production of quiescent plasmas of densities in the range from 1×10^{9} to 5×10^{11} cm^{-3} [11]. The density is controlled by the microwave power and the neutral gas pressure. A current is drawn along the plasma column of 85 cm length by applying a d.c. voltage to a heated Ba 0_2 cathode and a disk anode of 5 cm diameter. The electron emitting cathode is used to prevent depletion of the plasma by the current.

The electrons emitted from the cathode are accelerated by the potential drop of the sheath in front of the cathode. The potential drop is found to increase with the anode voltage. This leads to the excitation of electron plasma waves by beam plasma interaction at low densities of 10^{9} cm^{-3}, and neutral gas pressures of 5×10^{-4} mmHg if the current exceeds a certain value. A thermalization of the beam and thus a Maxwellian electron velocity distribution, for which the theory of Section I applies, is obtained for plasma densities above 10^{10} cm^{-3} and neutral gas pressures in the range of 1×10^{-3} mmHg tp 4×10^{-3} mmHg. Therefore the experiment has been done for these conditions. Owing to the elevated neutral gas pressure, the low frequency density fluctuation level ($\delta n/n$) is about .5% and the electron temperature about 2 eV.

We distinguish three experimental regions according to the variation of the plasma density and the electron drift velocity with current (see Fig. 3). For currents below 200 mA (Region I), the density remains constant and the electron drift increases in proportion to the current. For currents in the range 200 mA $< I <$ 400 mA (Region II) both the density and

This value exceeds the half width of the spectra of $\Delta\nu \approx$ 1 MHz by two orders of magnitude. The effective untrapping Coulomb collision frequency ($\nu_{90^o}\left(\frac{kT_e}{e\phi_w}\right) = 2.8 \times 10^2\ \nu_{90^o}$) reaches the value of the electron bounce frequency for the collision frequencies listed in Section II,1.

The variation of the spectra with current can be explained in the following way. The Coulomb collision rates increase with current in proportion to the plasma density. Thus, the saturation level of the instability is expected to rise, since the bounce frequency must exceed the untrapping electron Coulomb collision frequency. This is in agreement with the intensity variation of the spectra observed for currents somewhat above the critical current. On the other hand the growth rate can be reduced to zero by ion-ion collisions. This explains the disappearance of the instability for currents above 600 mA. A comparison of the experimental data and the theory of Section I is given in Fig. 7. We infer from this figure that the onset frequencies agree with the theoretical values obtained for the experimental ion-ion collision frequencies. The frequency of the intensity maximum of the spectra ($\nu^{(m)}$) corresponds to the frequency for maximum linear growth rate.

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the electron drift velocity increase with the current. For currents above 400 mA (Region III) the electron drift velocity remains practically constant and the plasma density increases in proportion to the current. This behaviour is easily understood by considering the variation of the anode voltage with current (Fig. 3). The anode voltage and the potential drop of the sheath in front of the cathode tend towards a saturation value for which the electrons gain sufficient energy to ionize.

An estimate of the relevant collision frequencies is given below, taking into account that due to the gyrational motion the effective collision rate is increased by a factor of two[12]:

ion-ion collisions:

$1 \times 10^5 < \nu_{ii} < 1 \times 10^6$ Hz for $10^{10} < n < 10^{11}$ cm^{-3} and $T_i = .1$ eV

ion charge exchange:

$2 \times 10^4 < \nu_{in} < 8 \times 10^4$ Hz for $1 \times 10^{-3} < p < 4 \times 10^{-3}$ mmHg and $T_i = .1$ eV

electron-ion collisions:

$3 \times 10^5 < \nu_{ei} < 3 \times 10^6$ Hz for $10^{10} < n < 10^{11}$ cm^{-3} and $T_e = 2$ eV

electron neutral (momentum transfer) collisions:

$7 \times 10^5 < \nu_{en} < 3 \times 10^6$ Hz for $1 \times 10^{-3} < p < 4 \times 10^{-3}$ mmHg and $T_e = 2$ eV.

2. Frequency Power Spectra of the Density Fluctuations

Figure 4 shows the frequency spectra of the density fluctuations observed for different currents. The measurements have been performed by frequency analyzing the fluctuations of the floating potential of a small grid probe*. The reference level, which is set to the top graticule line of the pictures in Fig. 4, is -30 dBm. The sensitivity, resolution and FREQ SPAN/DIV are set to 10 dB/DIV, 3 kHz and 500 kHz, respectively.

The spectra show the following features:

a) the onset of the instability is observed for a threshold current of 100 mA;

b) the intensity maximum is shifted towards higher frequencies with increasing current;

c) the instability exists only for a certain range of currents ($100\ \mathrm{mA} < I < 600\ \mathrm{mA}$);

d) the power level of the intensity maximum is about -70 dBm. Taking into account the reduction in amplitude due to the voltage divider formed by the dynamic resistance (5 kΩ) of the probe at floating potential** and the 50 Ω input impedance of the spectrum analyzer, we obtain a value of 7 mV for the amplitude of the fluctuations of the floating potential. Assuming that the fluctuations of floating and space potential ($\emptyset_s$) are identical we obtain for the density fluctuation level $\frac{\delta n}{n} = \frac{e\emptyset_s}{kT_e} \approx 3.5 \times 10^{-3}$;

e) the intensity of the spectra did not vary with the position of the probe. This indicates that the instability is in a state of saturation.

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*Similar spectra, which differed only with respect to the absolute value of the intensity, have been obtained by analyzing the fluctuations of the electron saturation current drawn by the anode. This confirms that the perturbation of the plasma by the floating probe is negligible.

**The dynamic resistance is determined from the slope of the dc Langmuir characteristic at floating potential, since the probe was carefully matched to a 50 Ω transmission line and losses through a stray capacitance of 5 pF are negligible for the range of frequencies considered.

3. Measurement of Ion Acoustic Test Waves

Precise information on the parameters determining the behaviour of the ion acoustic instability is obtained from a measurement of the propagation characteristics of ion acoustic test waves. The usual method of wave measurement, which involves the use of biased Langmuir probes as receivers to collect ion or electron saturation current, is not applicable in this case, since the plasma parameters may be more affected by the probe current than by the main current*. This effect is even more important in the presence of a magnetic field, as the electrons are guided by the field lines. In fact, in the presence of an anode current, we observed a filamentation of the plasma column by a small grid probe, if it was biased to collect ion saturation current.

A. Characteristics of the microwave interferometer

The problems mentioned above have been avoided by the use of a 30 GHz microwave interferometer (see Fig. 2), which offers the advantage of a direct non-disturbing measurement of the density fluctuations induced by an ion acoustic test wave. As a transmitter we used a movable coarse thin wire grid, which was kept on floating potential in order to minimize the perturbation of the plasma.

The polarisation of the horn antennas was chosen to detect the fluctuations of the index of refraction of the ordinary electromagnetic mode. Sum and difference of the electric fields of the transmitted beam and a reference beam were obtained by means of a MAGIC TEE and measured by square law crystal detectors. The difference of the detector signals is proportional to the cosine of the phase shift induced by the plasma. The interferometer

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*Fenneman et al. found that the intensity of the instability observed was sensitive to the bias of the receiving probe[3]. Watanabe studied the excitation of the ion acoustic instability by biased probes[2].

was adjusted for maximum sensitivity to small density fluctuations by a 90^{o} phase shift between the two beams. Density fluctuations of the order of .1% (corresponding to a phase shift of about 2×10^{-5} rad. for a density of 10^{10} cm^{-3}) could be measured by means of a Lock-in technique.

The use of the interferometer is restricted to a certain range of wavelengths $1 \text{ cm} < \lambda < \frac{1}{k_i} = \frac{2C_s}{\nu_{ic}}$. The lower limit is given by the resolution of the interferometer, which is determined by the microwave-wavelength and by the dimensions of the horn antennas. The upper limit corresponds to the e-folding length of collisional damping, which is the dominant damping mechanism for low frequency waves for the case of an elevated electron to ion temperature ratio.

B. Experimental results

The following results have been obtained by measuring the propagation of test waves in both directions of the plasma column for different anode currents:

a) the ion sound velocity ($C_s = \sqrt{\frac{kT_e}{m_i}}$) was 2.3×10^5 cm/s. This corresponds to an electron temperature $T_e = 2.2$ eV;

b) the ion drift velocity was found to increase continuously from 0 to $.1 \times 10^5$ cm/s with the anode current up to 400 mA. The drift velocity remained practically constant for higher current values;

c) the electron to ion temperature ratio, the ratio of the electron drift velocity to the ion sound velocity, and the effective ion collision frequency are obtained from a plot of the experimental values of the damping constant against the wave number (see Fig. 5). Landau damping or growth is given by the slope of the lines in Fig. 5. The collisional damping ($k_i = \frac{\nu_{ic}}{2C_s}$) is given by the ordinate of the intersection point for wave number zero. The slope and the collisional damping constant are found to increase with current. The electron to ion temperature ratio, obtained from the curve for zero current, is $T_e/T_i = 15$. This allows us to apply the theory of Section I to describe the linear development of the instability. The electron drift velocity is found to be in the range $0 < V_D < .4 \times 10^7$ cm/s . The effective ion collision frequency is in the range $8 \times 10^4\ s^{-1} < \nu_{ic} < 2 \times 10^5\ s^{-1}$ $(.004 < \frac{\nu_{ic}}{\omega_{pi}} < .01)$. From the data in Section II,1 we infer that the measured value of the ion collision frequency is close to the estimate of the collision frequency for ion-ion collisions.

From the measured value of the ion drift velocity and the value of the ion neutral collision frequency* one obtains an estimate for the electric field, which is in the range from 0 to 12 mV/cm.

III. DISCUSSION

As stated in Section II,2 we observe a shift of the intensity maximum of the instability towards higher frequencies with increasing current. From Fig. 6 we infer that $\nu^{(m)2}$ ($\nu^{(m)}$ corresponds to the frequency of the intensity maximum) increases in proportion to the current for values above 200 mA. This is similar to the variation of the plasma density with current. This is a confirmation that the spectra observed result from the ion acoustic instability, since according to the theory $\nu^{(m)}/\nu_{pi}$ remains practically constant, if the electron drift velocity exceeds the value of .03 v_e (see Fig. 7), which is the case for currents above 200 mA.

From the frequency spectrum obtained for zero anode current (Fig. 4) we infer that the thermal noise level in the frequency range of the instability is about -90 dBm. Using the theoretical curves of Fig. 1 and the experimental values obtained from the measurement of low frequency test waves (Fig. 5), we can extrapolate to the value of the maximum growth $k_i^{(m)}$ (at $\nu^{(m)}$) and calculate the distance $(x_s/\lambda^{(m)} = \frac{\ln(\emptyset_{s,inst.}/\emptyset_{s,thermal})}{k_i^{(m)}\ \lambda^{(m)}})$, for which the amplitude of the insta-

*The ion-neutral collision frequency can be experimentally determined from the propagation of ion acoustic test waves at plasma densities of about 10^9 cm^{-3}.

bility grows from thermal noise to the maximum value observed. Taking into account that $\lambda^{(m)}$ is of the order of 1 mm to 3 mm, we find 1 cm $< x_s <$ 3 cm. This indicates that the instability saturates within a short distance from the cathode. This is in agreement with the experimental result that the spectrum is independent of the position of the probe.

Different theoretical models have been proposed to describe the stationary turbulent state of the instability[13-17]. The theories of Kadomtsev and Tsytovich assume that the state of saturation is determined by a balance of the growth rate with nonlinear Landau damping. The theory predicts an enhancement of energy flow into waves at the lower beat frequency of two large amplitude ion acoustic waves, and an intensity maximum of the stationary turbulent spectrum near the ion collision frequency, since collisions produce a turbulent sink[13].

Nishikawa[15] and others[16,17] considered the possibility that the saturation of the instability is caused by electron trapping. Electron trapping can occur only if the bounce frequency ($\omega_b = \sqrt{\frac{e\,\phi_w}{m_e}}\,.k$) exceeds both the electron collision frequency and the half width $\Delta\nu$ of the spectrum, which is inversely proportional to the life time of a single wave. Considering the effect of Coulomb collisions one finds that velocity changes of the order of $\sqrt{\frac{e\,\phi_w}{m_e}}$ resulting from an accumulation of small angle deflections are sufficient to untrap the electrons. Thus, the first of the conditions mentioned above is written as: $\omega_b \geq \nu_{90^o} \left(\frac{kT_e}{e\phi_m}\right) + \nu_{en}$. The level of saturation is derived assuming equality of bounce and collision frequency.

From the spectra of Fig. 3 we exclude the possibility that the saturation of the instability is determined by nonlinear Landau damping, since we do not observe an intensity maximum near the ion collision frequency.

On the other hand we find that the saturation mechanism of electron trapping can explain the observed phenomena. An estimate of the electron bounce frequency for the maximum fluctuation level yields $\omega_b = 2.2 \times 10^8\ s^{-1}$.

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FIGURE CAPTIONS

Figure 1: Spatial growth $k_i \lambda_D$ against real wave number $k_r \lambda_D$ for $T_e/T_i = 15$ and different ratios of the electron drift v_d and ion velocity $c_s = \sqrt{\frac{kT_e}{m_i}}$. The collisional damping can be accounted for adding an appropriate damping constant $k_i = -\frac{\nu_{ic}}{2\,c_s}$.

Figure 2: Experimental arrangement: 1 - anode; 2 - horn antennas; 3 - longitudinally movable probe; 4 - RF wave structure; 5 - heated barium oxide cathode.
Microwave interferometer: K - Klystron (30-35 GHz, 100 mWatts); F - Frequency meter; C - Directional Coupler; A_1, A_2 - Variable Attenuators (0-30 dB); $\emptyset_s$ - Variable phase shifter (0-130^o); T - MAGIC TEE; D - Crystal Detector; D-A - Differential Amplifier; L-I - Lock-In Amplifier.

Figure 3: Variation of the electron plasma density (1) - as measured by means of the microwave interferometer - and anode voltage (2) with current.

Figure 4: (a) - (f) Power spectra of the density fluctuations obatined for a current of 0, 150 mA, 210 mA, 300 mA and 400 mA, respectively. The reference level (set to the top graticule line) is -30 dBm. The sensitivity, resolution and FREQ SPAN/DIV are 10 dB/DIV, 3 kHz and 500 kHz, respectively.

Figure 5: Experimental values of the damping constant (k_i) and wave number (k_r) of test waves in the frequency range from 50 kHz to 200 kHz, obtained for currents of 0, 300 mA and 400 mA, respectively. The value of the damping constant has been determined from a least squares fit of the observed amplitude variation to an exponential. The value of the linear regression factor was typically about .99.

Figure 6: Square of the frequency ($\nu^{(m)}$) of the intensity maxima of the power spectra in Fig. 4 as a function of the anode current.

Figure 7: Critical value of the electron drift velocity v_d (in units of $v_e = \sqrt{\frac{kT_e}{m_e}}$) for the onset of the instability ($\omega_i = 0$) as a function of ω_r/ω_{pi} (see Section I). The values of the parameter ν_{ic}/ω_{pi} correspond to the experimental values of the plasma density and the ion collision frequency, for currents in the range from 0 to 400 mA. The points give the experimental values of the onset frequencies ν_1, ν_2 (+) of the instability and the frequency $\nu^{(m)}$ (O) for the intensity maximum, obtained from the power spectra in Fig. 4. The values of the electron drift velocity (and the ion collision frequency) are derived from the damping constant of test waves. Curve (a) represents the theoretical value of $\nu^{(m)}$ as a function of the electron drift velocity.

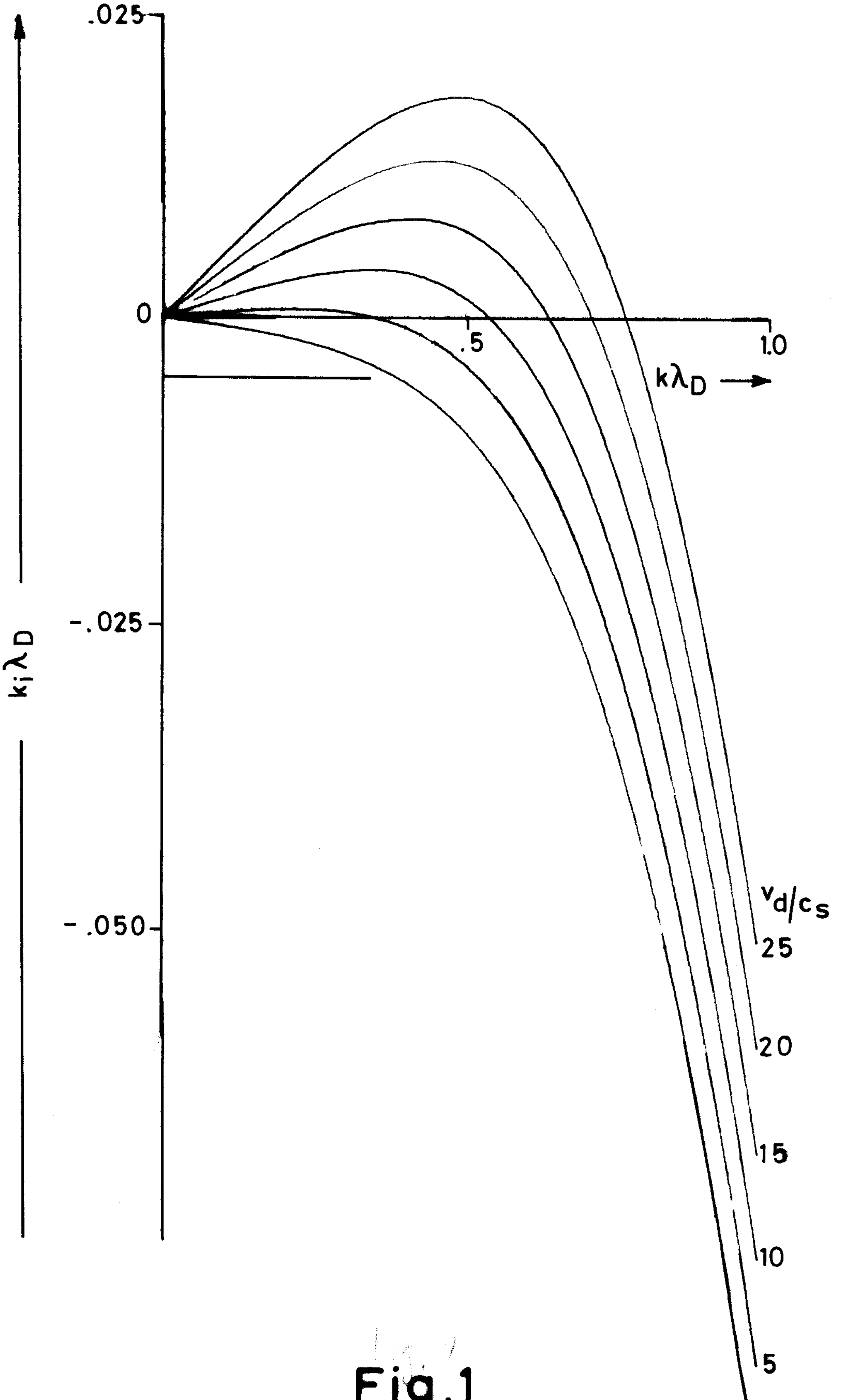


Fig.1

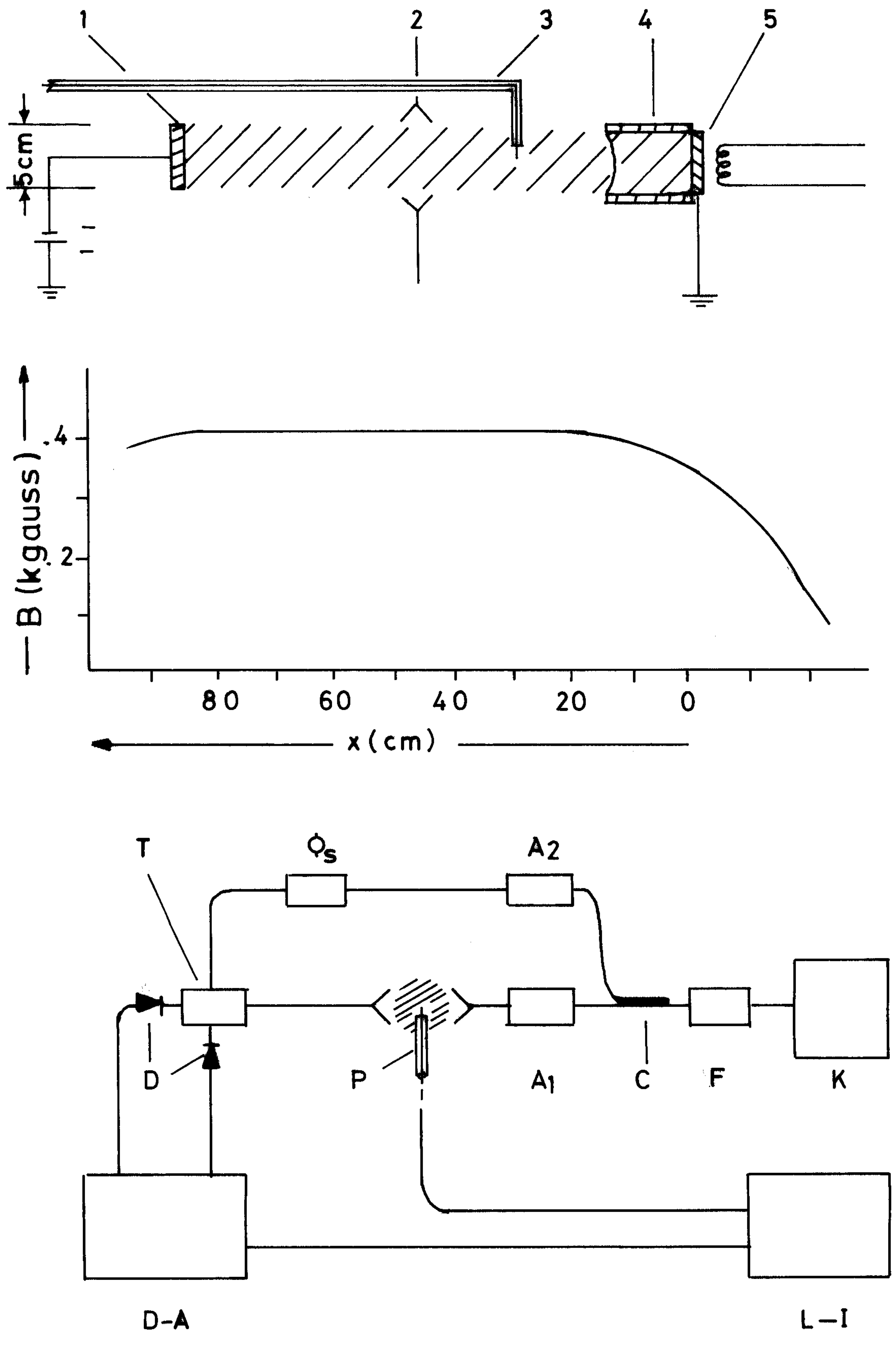


Fig.2

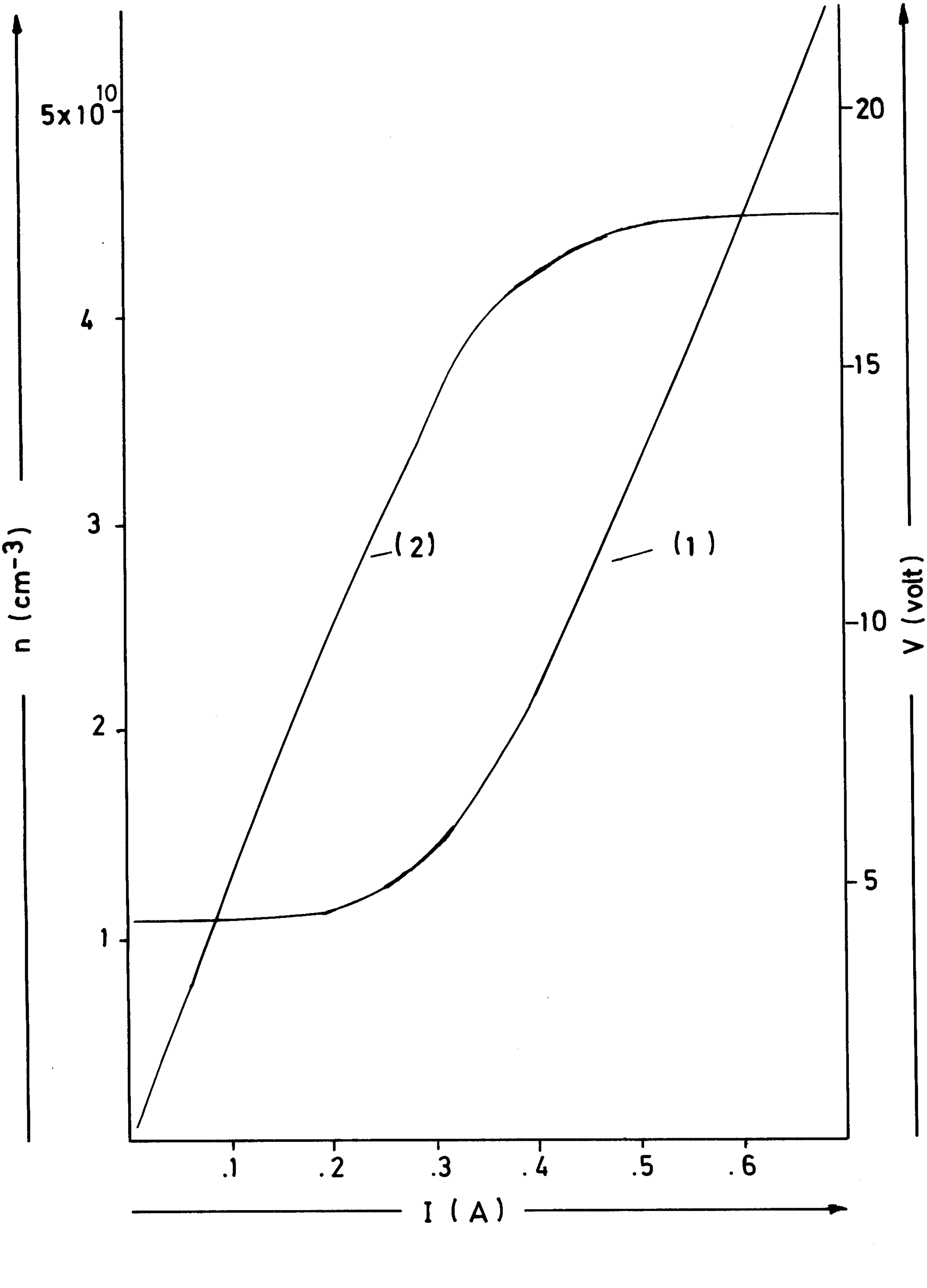


Fig.3

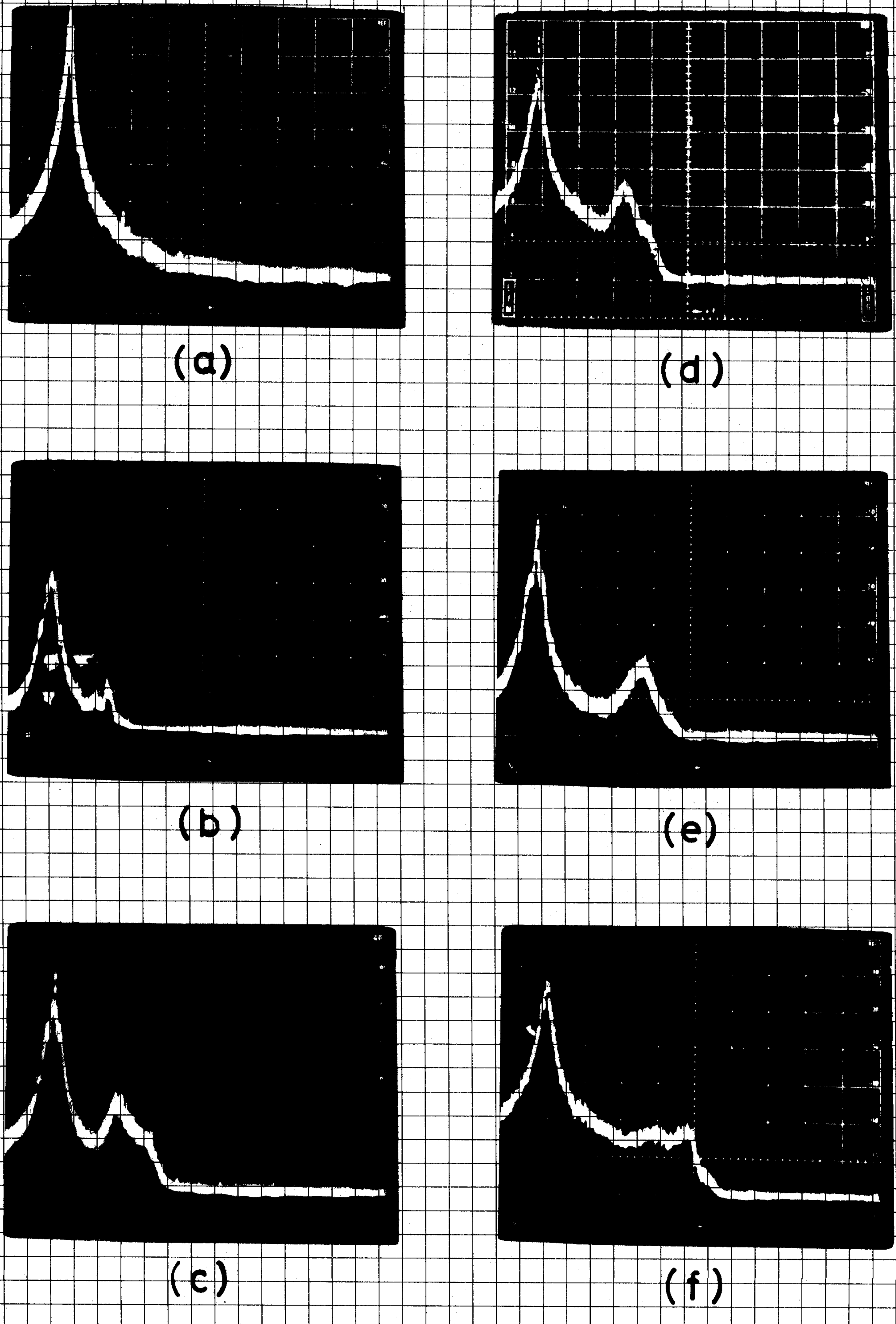


Fig. 4

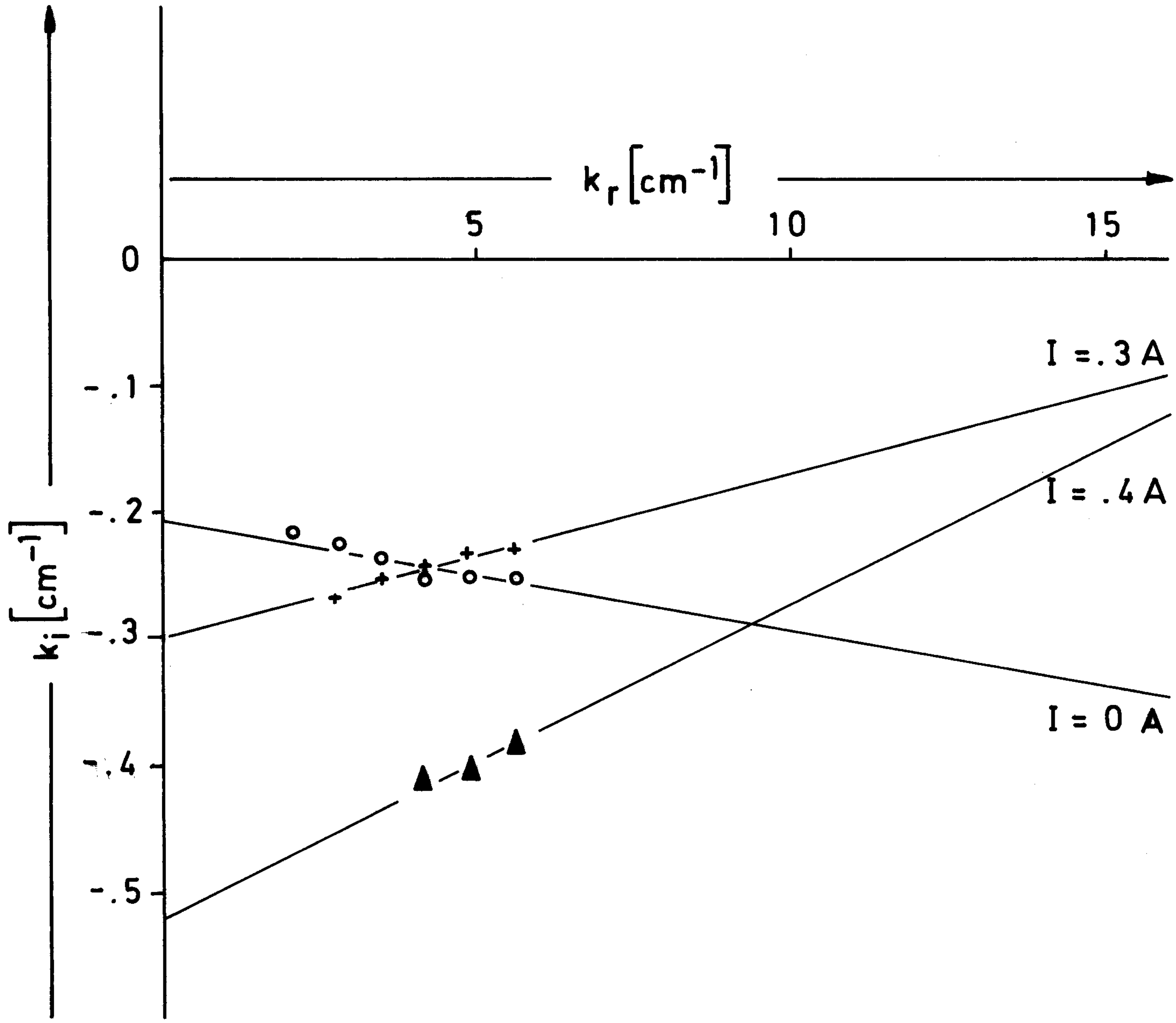


Fig.5

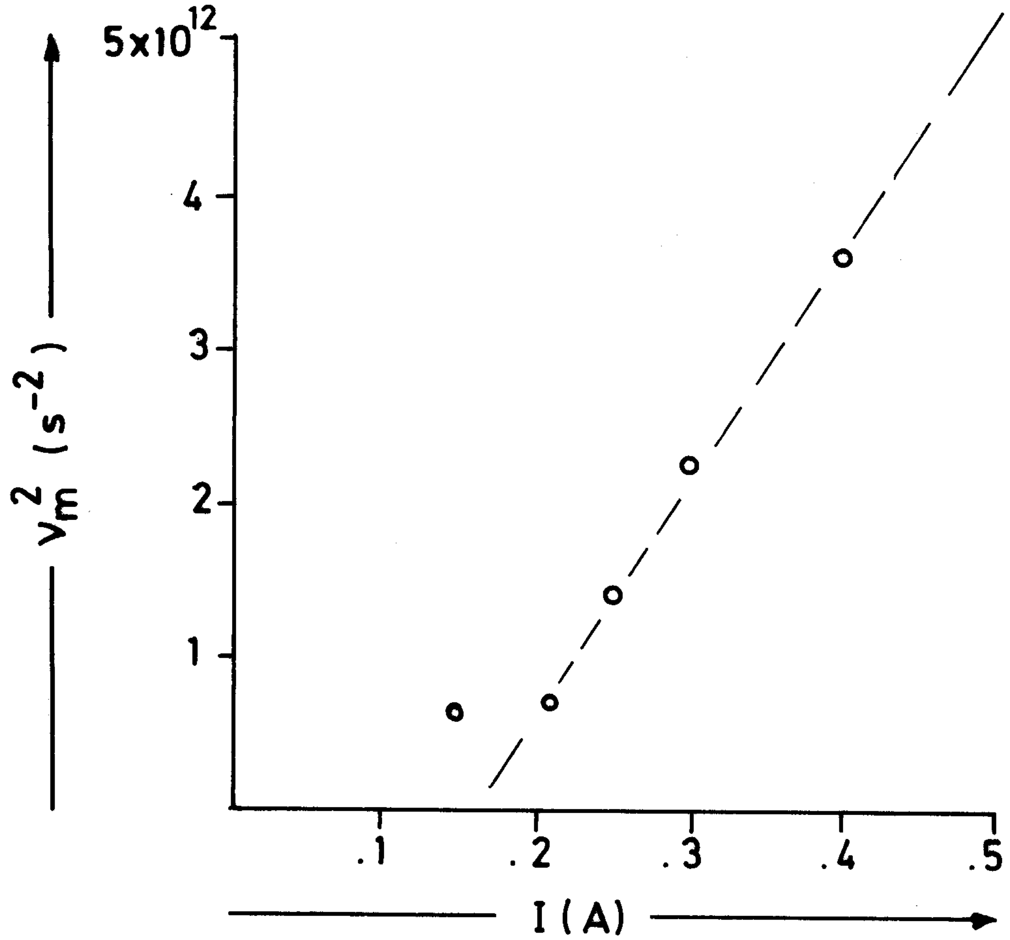
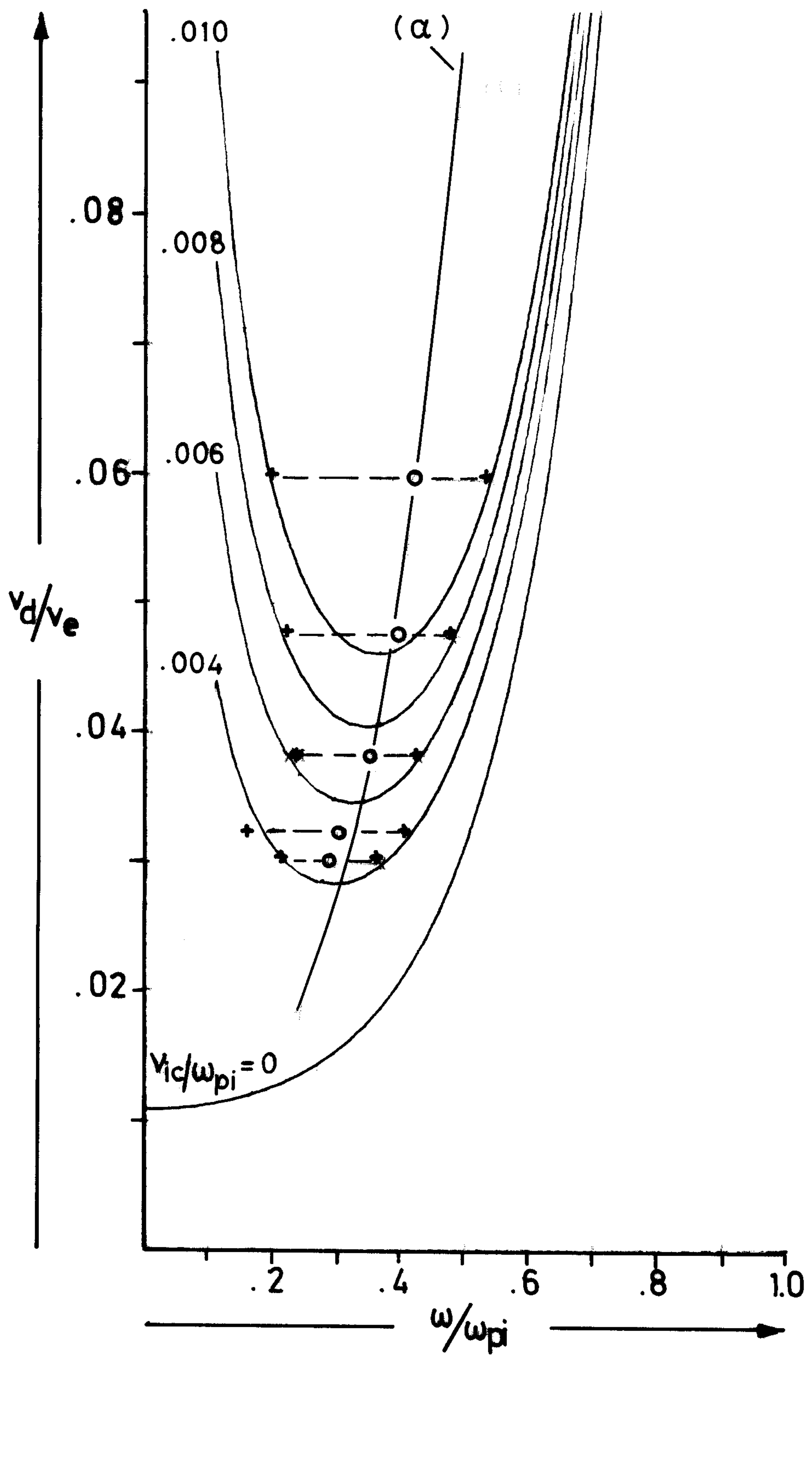


Fig 6



.010
(α)
.08
.008
.06
.006
v_d/v_e
.004
.04
.02
$\nu_{ic}/\omega_{pi} = 0$
.2
.4
.6
.8
1.0
ω/ω_{pi}

Fig.7