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EXPERIMENTAL STUDY OF LOW FREQUENCY SURFACE WAVES IN A RESISTIVE PLASMA COLUMN

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ABSTRACT

Low frequency ($\omega \ll \omega_{ci}$), non-axisymmetric ($m = \pm 1$) surface waves have been observed in a low temperature hydrogen plasma. Good agreement is found between the values of $\mathrm{Re}(k_\parallel)$ measured in the experiment and those calculated using a theory describing wave propagation in a uniform, resistive plasma column. However, the waves are observed to be much more strongly damped than is predicted from this theory. A possible explanation is that the presence of density and temperature gradients leads to enhanced damping due either to the larger resistivity in the vicinity of the plasma boundary, or to the effect of the spatial Alfvén resonance. A simple non-uniform plasma theory shows that, even for the low temperature plasma considered, the wave damping due to the spatial Alfvén resonance should be much greater than that calculated from the uniform plasma theory. A much closer agreement is obtained by comparing the experimental values of wave damping with those calculated from the non-uniform theory.

1. INTRODUCTION

Low frequency, non-axisymmetric waves in a uniform plasma column have been studied theoretically by several authors. Recently, it has been shown (Appert et al., 1984; Collins et al., 1984) that the first radial eigenmode of the non-axisymmetric fast wave in a cylindrical plasma surrounded by an insulating boundary region can be identified as a surface wave at low frequencies. For m positive (where m is the azimuthal wavenumber), there is a smooth transition at higher frequencies to body wave behaviour. For m negative, the wave merges into the slow wave spectrum at higher frequencies and therefore exists only for frequencies less than the ion cyclotron frequency.

These waves have also been experimentally observed in a low temperature argon plasma by Lehane and Paoloni (1972). Agreement has been found (Paoloni, 1973) between the experimental dispersion curves and magnetic field profiles for the $m = \pm 1$ surface waves and those calculated for the uniform, highly collisional plasma studied. However, as pointed out by Collins et al. (1984), the high resistivity of the argon plasma studied means that the resistive mode contributes strongly to the field profiles. The surface wave character predicted by collisionless MHD theory is therefore heavily masked. It has been proposed by Collins et al. to reduce the influence of the resistive mode on the surface wave fields by increasing the frequency. For observation of the $m = -1$ mode, this necessitates an increase in the ion cyclotron frequency.

Low frequency surface waves have also been observed in a theta pinch (Wootton et al., 1972; Grossmann et al., 1973) in which the plasma temperature was much higher ($T > 20$ eV). In these experiments the measured wave damping was much greater than could be explained by collisional effects such as resistivity and viscosity. Grossman and Tataronis (1973) suggested that the strong wave damping could be explained by the collisionless mechanism of phase mixing which occurs due to the presence of a continuous wave spectrum in a non-uniform plasma. Recently there has been a large effort, both theoretically and experimentally, towards using the wave damping at the spatial Alfvén resonance in a non-uniform plasma for plasma heating. (Recent reviews of this work have been given by Ross et al. (1982) and de Chambrier et al. (1982)).

In this report, an experiment is described which investigated the behaviour of low frequency surface waves in a low temperature plasma column which was uniform across most of the plasma cross-section. An increase in the ion cyclotron frequency, compared to the experiment of Lehane and Paoloni, was achieved by increasing the axial magnetic field strength and changing to a hydrogen plasma. A much higher wave frequency than that used by Lehane and Paoloni was therefore possible, and consequently the influence of the resistive mode on the surface wave fields was reduced.

The measured values of the phase velocity and attenuation are compared with the theory for surface wave propagation in a uniform resistive plasma column. Even for the low temperature plasma considered, discrepancies are found between the experimental and theoretical values of wave damping. Much better agreement is obtained by considering a simple non-uniform theory (Donnelly and Cramer, 1984) which takes into account the presence of the Alfvén resonance surface.

2. UNIFORM PLASMA THEORY

The theory for low frequency waves in a uniform, resistive plasma column has been developed by a number of authors. In the present study, we shall follow the theory of Collins et al. (1984) which is a specialization of the general theory of Woods (1962). We consider small amplitude waves propagating in a cylindrical, fully ionized plasma of radius r_p, with uniform density n_0 and uniform magnetic field $B_0\hat{\underline{z}}$. The plasma is surrounded by a vacuum layer and a conducting wall at radius r_w. For perturbation wave fields of the form

$$\underline{b}(\underline{r},t) = \underline{b}(r)\exp\left[i\left(k_{\parallel}z + m\theta - \omega t\right)\right] \tag{1}$$

in a zero pressure, inviscid plasma, two modes exist having the following magnetic field components:

$$\begin{aligned} b_r(r) &= iCm\frac{J_m(k_\perp r)}{k_\perp r} + iAk_\parallel J_m'(k_\perp r) \\ b_\theta(r) &= -Amk_\parallel\frac{J_m(k_\perp r)}{k_\perp r} - CJ_m'(k_\perp r) \\ b_z(r) &= Ak_\perp J_m(k_\perp r) \end{aligned} \tag{2}$$

where J_m is the Bessel function of the first kind and $J'_m(\xi) = dJ_m(\xi)/d\xi$.

The perpendicular wavenumber, $k_\perp$, is related to the parallel wavenumber, $k_\parallel$, via a dispersion relation that is quadratic in both $k_\perp^2$ and $k_\parallel^2$ (associated with the fast wave and slow wave). The constants A and C are functions of ω, $k_\parallel$, $k_\perp$, the Alfvén speed $(V_A = B_0/(\mu_0 n_0 m_i)^{1/2})$ and ion cyclotron frequency $(\omega_{ci} = eB_0/m_i)$.

Under the condition that the frequency is not in the vicinity of the Alfvén resonance frequency, ω_r, given by

$$\frac{\omega_r^2}{V_A^2} - k_\parallel^2 \left[1 - \left(\frac{\omega_r}{\omega_{ci}} \right)^2 \right] = 0 , \tag{3}$$

and that the resistivity ($\eta_\parallel = m_e \nu_{ei}/n_o e^2$, where ν_{ei} is the electron-ion collision frequency) is sufficiently small, that is,

$$\delta \equiv \frac{\omega \nu_{ei}}{\omega_{ci}\,\omega_{ce}} \ll 1 , \tag{4}$$

the perpendicular wavenumber can be approximated by

$$\left(k_\perp^{MHD}\right)^2 = \frac{(k_A^2 - k_\parallel^2)^2 - f^2 k_A^2}{(k_A^2 - k_\parallel^2)} ,$$

$$\left(k_\perp^{res}\right)^2 = \frac{i \mu_o \omega}{\eta_\parallel} \; \frac{(k_A^2 - k_\parallel^2)}{k_A^2} , \tag{5}$$

where

$$f = \frac{\omega}{\omega_{ci}} , \qquad k_A^2 = \frac{\omega^2}{V_A^2 (1 - f^2)} .$$

The effect of the resistive mode on the wave fields is to spread the surface current, predicted by collisionless MHD theory, over a skin depth proportional to $|k_\perp^{res}|^{-1}$. The resistive mode thus contributes substantially to the wave fields throughout the plasma cross-section unless

$$|k_\perp^{res} r_p| \gg 1 . \tag{6}$$

The magnetic wave field in the vacuum region surrounding the plasma column can be expressed in terms of modified Bessel functions. The reader is referred to Collins et al. (1984) for further details.

Applying the boundary conditions at the plasma vacuum boundary and the conducting wall leads to an eigenvalue problem for complex $k_\parallel$ (if ω is specified). The magnetic field profiles can then be obtained using eq. (2).

For the present study of surface waves, the eigenvalue problem has been solved numerically for non-axisymmetric waves with $m = \pm 1$. The method of solution is described in some detail by Collins (1982). Calculations have been made for the parameters relevant to the experiment described in section 3:

Hydrogen plasma
B_0 = 6 and 8 kG
$n_0 = 6.44 \times 10^{20}\ m^{-3}$ (10 mtorr H_2)
T = 20,000 K (1.72 eV)

with

r_p = 7.3 cm , r_w = 15.8 cm.

In Fig. 1 are shown the dispersion curves for the case B_0 = 6 kG, calculated for the frequency range $0 \leq \omega/2\pi \leq 4$ MHz (i.e., $0 \leq f \leq 0.44$). Since $k_\parallel$ is complex, the dispersion curve for each wave is a line in three-dimensional $(\omega, Re(k_\parallel), Im(k_\parallel))$ space. Figure 1(a) shows the projection onto the $(\omega, Re(k_\parallel))$ plane, while Fig. 1(b) shows the projection onto the $(\omega, Im(k_\parallel))$ plane. Four different waves have been considered; the $m = \pm 1$ surface waves and the first two radial eigenmodes of the $m = -1$ slow wave. (For simplicity of nomenclature, each wave is identified by the name appropriate at low frequency, $\omega < \omega_r$.) In Fig. 2, the corresponding curves for the case B_0 = 8 kG are plotted.

The dispersion curves shown in Fig. 1(a) and 2(a) exhibit at low frequencies the general behaviour calculated by previous authors

(Appert et al., 1984; Collins et al., 1984) for a collisionless plasma. A detailed study of how, in a resistive plasma, the $m = -1$ surface wave merges into the slow wave spectrum in the vicinity of $\omega = \omega_r$ will be the subject of a future report.

3. EXPERIMENT

3.1 AIM

The goal of the experimental study conducted on SUPPER IV was to observe the $m = \pm 1$ surface waves in a plasma in which the resistive mode does not mask the surface wave character. As seen from eq. (6), the effect of the resistive mode on the surface wave field profiles is minimized by making $|k_\perp^{res}|$ sufficiently large. From the low frequency surface wave dispersion relation, $\omega = \sqrt{2}\, V_A k_\parallel$, eq. (5) gives

$$|k_\perp^{res}|^2 \simeq \frac{\omega\, \omega_{ci}\, \omega_{ce}}{2\, \nu_{ei}\, V_A^2} = \frac{\mu_0\, \omega\, T_e^{3/2}}{130\, \ln\Lambda} .$$

For SUPPER IV the range of T_e (and $\ln\Lambda$) is very narrow. Therefore $|k_\perp^{res}|$ can only be substantially increased by increasing ω. Since the surface wave behaviour is evident only at frequencies below the ion cyclotron frequency (indeed, the $m = -1$ surface wave exists only for $\omega < \omega_{ci}$), increasing ω implies an increase in ω_{ci}. For the present study we have increased ω_{ci} (compared to the experiment of Lehane and Paoloni, 1972) by increasing B_0 and changing from an argon to a hydrogen plasma. Table I gives a comparison of the relevant parameters for the experiment of Lehane and Paoloni and the present study. Note that for the present work, the value of $|k_\perp^{res} r_p|$ is 2.4 and 2.9 times greater than that used in the experiment of Lehane and Paoloni, and that the inequality (6) is consequently better satisfied. In addition, the ratio ω/ω_{ci} is smaller for the present experiment implying a reduced effect of the Hall term on the wave fields.

In Fig. 3 is shown the radial profiles of the magnetic wave fields calculated using the theory described in section 2 for the parameters used in the experimental investigation. (In addition to the fields shown in Fig. 3, there exist small components which are $\pi/2$ out of phase arising from the resistive nature of the plasma.) Note that for the low frequency considered ($\omega \ll \omega_{ci}$), there is only a slight difference between the fields calculated for the two different values of B_0 and the two values of m.

3.2 TECHNIQUE

3.2.1 Plasma preparation

The plasma in the SUPPER IV machine was prepared in the same manner as described by previous workers (see e.g. Collins, 1982). Two values of the "steady" axial magnetic field were used: B_0 = 6 and 8 kG. Hydrogen gas at a filling pressure of 10 mtorr was used for the present study. The axial ionizing current pulse was initiated at the time when the magnetic field was at its maximum value (about 11 ms after the firing of the magnetic field capacitor bank). The plasma current was crowbarred to provide an afterglow plasma suitable for the wave experiments. The plasma current pulse is displayed in Fig. 4(a), showing the time at which the waves were launched.

Based on previous investigations of hydrogen plasmas in SUPPER IV (Cross and Blackwell, 1978), it is reasonable to expect that at the time at which the waves were launched the plasma was essentially fully ionized ($n_0 = 6.44 \times 10^{20} m^{-3}$) with a temperature of about 20,000 K. In addition, the electron density profile measured by laser interferometry (Collins, 1982) was shown to be uniform across most of the plasma cross-section, although unavoidable gradients occur in the vicinity of the wall of the pyrex vacuum vessel. (It should be noted that the laser interferometry measurements were made for an argon plasma. However, significant differences in the density profile for a hydrogen plasma are not expected.)

3.2.2 Wave excitation

To excite the m = ±1 waves, a launching circuit and antenna as described by Collins (1982) was used. The antenna consisted of two orthogonal loops through which flowed oscillating currents dephased by $\pi/2$. The wave frequency chosen for the present study was $\omega/2\pi$ = 1.34 MHz. This was the highest frequency attainable with the available capacitors (C = 10 nF, 10 kV) and wave antenna inductance. Relative delay was introduced between the triggering of the spark gaps of the two antenna circuits, thus providing the required two oscillating currents which were $\pi/2$ out of phase. It was found that the spark gaps could be fired reproducibly to within 50 ns, which was sufficient for the frequency used.

Figure 4(b) shows the resulting current in the two antenna loops. The antenna current amplitude and timing was not found to be significantly modified by the presence of the plasma.

3.2.3 Wave detection

The magnetic field associated with the waves was detected using a multi-turn coil probe. This probe was placed inside an 11 mm o.d. glass tube which could be inserted radially into the plasma. The voltage induced on the probe is

$$V = NA \frac{db}{dt} ,$$

where NA = 1.6×10^{-3} m^2. No integrator or filter was used at the output of the probe. The probe could be oriented to measure either the azimuthal or axial magnetic field.

Radial probe ports exist at four different axial locations. By recording the signal at each axial position, the phase velocity and wave attenuation could be measured. With the configuration used in the present study, the magnetic field could be measured at the following azimuthal and axial locations (the centre of the wave antenna is at $r = 0$, $z = 0$):

$z = 24.5$ cm , $\Theta = 0$

$z = 70$ cm , $\Theta = -\pi/2$

$z = 116.5$ cm , $\Theta = -\pi/2$

$z = 162$ cm , $\Theta = 0$

Unfortunately, the different azimuthal position of two of the available probe ports added an unnecessary complication.

4. RESULTS

The magnetic wave field at the four axial locations was recorded for B_0 = 6 and 8 kG. In Fig. 5 is shown, for B_0 = 8 kG, the detected probe signals on axis. It can be seen that even without integration or filtering the signals exhibit little high frequency noise.

Close to the wave antenna the magnetic field has a strong temporal resemblance to the current in the antenna. However, further away the fields exhibit significant distortion. This may be caused by the presence of two or more waves with different phase velocity.

4.1 PHASE VELOCITY

The delay of a number of different peaks of the magnetic wave field at the four axial locations (with due adjustment for the different azimuthal location of two of the probe ports) was measured for each value of B_0. Figure 6(a) and (b) show, for $B_0 = 8$ kG, the resulting plots for the m = +1 and m = -1 waves, respectively. Table II lists the measured values of $Re(k_\parallel)$ obtained from the experimental determination of the phase velocity $\left(V_{phase} = \omega/Re(k_\parallel)\right)$.

Also shown in Table II are the values of $Re(k_\parallel)$ for the surface wave and first radial eigenmode of the slow wave calculated using the theory outlined in section 2. (These calculated values were obtained assuming that the plasma was fully ionized. If the plasma contains a significant proportion of neutral atoms or molecules but with

$$n_T \equiv n_{ion} + n_{atom} + 1/2\, n_{molecule} = n_{filling}$$

then n_{ion} is less than assumed for the fully ionized case. V_A is consequently higher and therefore $Re(k_\parallel)$ lower - since at low frequency $\omega/Re(k_\parallel) \propto V_A$ for both the surface and slow waves).

4.2 WAVE ATTENUATION

Measurement of the wave attenuation was made by obtaining a weighted average throughout the waveform of the wave amplitude. These values were then normalized to the value measured at the probe port closest to the wave antenna. For $B_0 = 8$ kG, a plot of the natural logarithmn of the normalized amplitude as a function of axial position for m = +1 and m = -1 is shown in Fig. 7(a) and (b), respectively. Although the data points have a substantial associated experimental error, they do approximate the expected linear dependence.

In Table III is shown the values of $Im(k_\parallel)$ for the four different waves considered, obtained from the slope of the lines of best fit. Also shown in Table III are the corresponding values of $Im(k_\parallel)$ calculated using the uniform plasma theory outlined in section 2. The measured damping rate is much larger than that predicted by the uniform plasma theory: for each wave considered, the experimental value of $Im(k_\parallel)$ is a factor of ten larger than the theoretical value.

4.3 RADIAL PROFILES

The radial profile of the azimuthal and axial magnetic wave fields were recorded for the case B_0 = 6 kG. Measurements were made at an axial position 70 cm from the wave antenna and at radial positions 0 to 10 cm at intervals of 1 cm. The recorded signals at selected radial positions are shown in Fig. 8.

From Fig. 8(a), (b) it can be seen that the temporal waveforms for the m = +1 excitation closely resembles that of the antenna current. However, for the m = -1 excitation, shown in Fig 8 (c), (d), there are strong temporal distortions, particularly in the plasma region r < 7.3 cm, indicating the presence of more than one wave. From Fig. 8 one also notices that there is a substantial b_z wavefield for both m = +1 and -1 excitation. At the low frequency considered, this indicates the excitation of a surface wave since the slow waves have only a very small axial magnetic field component (c.f. Fig. 3).

In Fig. 9 is plotted for m = +1 excitation, both the in phase component and amplitude of the b_θ and b_z wavefields as a function of radial position. Due to the distortion present in the m = -1 signals, no corresponding plots were attempted for this case. It should be noted that each point on Fig. 9 represents only one measurement and is not an average of several different shots or a weighted average over the waveform. Thus the large fluctuations observed may, at least in part, be due to the paucity of data.

5. DISCUSSION

It is reasonable to expect that for the present experiment the surface wave is more likely to be launched than the slow waves since the theoretical calculations show that its field profiles (Fig. 3) resemble more closely those of the antenna and that it is less damped (Fig. 1,2) for the plasma conditions considered.

The presence of substantial wave fields in the vacuum region (Fig. 8,9) is a strong indication that surface waves have indeed been launched. However, the wave fields observed especially for the case B_0 = 6 kG, m = -1 (Fig 8 (c),(d)) exhibit the behaviour of superposition of more than one wave type.

While the experimentally determined values of $Re(k_\parallel)$ exhibit the correct dependence on B_0 and m (Table II), they are consistently higher than the values of $Re(k_\parallel)$ calculated for the surface waves. The presence of damping, however, increases the value of $Re(k_\parallel)$ for low frequency waves. Therefore if the wave damping is greater than that calculated for the assumed temperature (20,000 K), the experimental values of $Re(k_\parallel)$ are to be expected to be greater than those calculated from theory. In addition, it should be noted that the presence of neutral atoms or molecules (as mentioned in section 4.1), or an uncertainty in the measurement of the gas filling pressure, may result in a calculated value of $Re(k_\parallel)$ which is too high. It is therefore reasonable to conclude that there exists good agreement between the experimental values of $Re(k_\parallel)$ and those calculated for the surface wave.

The same conclusion can not be made for $Im(k_\parallel)$: the waves observed clearly damp much more rapidly than is calculated from the theory outlined in section 2. The measured damping rate can not be explained as due to classical resistivity in a uniform plasma. It should however be noted that the plasma in SUPPER IV, while approximating well a uniform plasma, nevertheless has gradients in both plasma density and temperature in the vicinity of the pyrex wall (Collins, 1982). This region of low temperature plasma should be expected to enhance wave damping, particularly for the surface waves being investigated. In the absence of strong damping in the bulk of the plasma (as existed for the argon plasma used in the study of Lehane and Paoloni, 1972), the contribution from the boundary region may be dominant.

Another possible explanation is that in the absence of strong damping due to classical resistivity, the waves are damped by the presence of turbulence and fluctuations in the plasma. It should be noted that low density discharges in hydrogen exhibit a high level of internal fluctuations (Cross and Blackwell, 1978). Strongly enhanced damping of m = 0, $k_\parallel$ = 0 magnetoacoustic waves has, for example, been attributed to drift wave turbulence in a non-uniform, magnetized plasma column (Ritz et al., 1982).

A tantalizing alternative explanation of the anomalously high damping rate observed is that the presence of a gradient in the plasma density results in damping of the waves at the spatial Alfvén resonance. An analysis of the spatial Alfvén resonance in a collisional plasma has been recently undertaken (Donnelly and Clancy, 1983; Donnelly and Cramer, 1984). It has been pointed out that in a collisional plasma, the wave energy that accumulates at the Alfvén resonance surface is absorbed in a resistive layer around the surface. Provided that the resistive layer is sufficiently narrow and enough energy is dissipated there, the wave fields near the resonance surface will be measurably enhanced.

An estimate of the damping rate which results from the spatial Alfvén resonance may be obtained using the expressions derived by Donnelly and Cramer (1984). From the fluid equations, a perturbation approach was used to obtain an approximate dispersion relation for a plasma having a density profile,

$$n(r) = \begin{cases} n_o & 0 \leqslant r \leqslant a \\ n_o(r_p - r)/(r_p - a) & a < r \leqslant r_p \\ 0 & r > r_p \end{cases} \qquad (7)$$

For small $k_\parallel$, narrow surface width ($|m| (r_p-a)/r_p \ll 1$) and a large surrounding vacuum layer, the damping of the surface wave is given by

$$\frac{Im(k_\parallel)}{Re(k_\parallel)} \simeq \frac{|m| \pi (r_p - a)}{8a} . \qquad (8)$$

The measured density profile (Collins, 1982) approximates well the above form with $a = 5$ cm, $r_p = 7.3$ cm. Substituting these values into eq. (8) yields

$$\frac{Im(k_\parallel)}{Re(k_\parallel)} \simeq 0.18$$

In Table III is shown for the experimental parameters, the values of $Im(k_\parallel)$ calculated using this simple non-uniform plasma theory. The damping rate which results from the spatial Alfvén resonance is seen to be much greater than that calculated for a uniform plasma. In fact, Table III shows that there is reasonable agreement, within the accuracy of the analysis, between the experimentally determined damping rate and that calculated using the non-uniform theory of Donnelly and Cramer (1984). We note that, for the experiment of Lehane and Paoloni (1972), the value of $Im(k_\parallel)$ obtained from uniform plasma theory is greater than that calculated from eq. (8). Therefore, under their experimental conditions, the effect of the spatial Alfvén resonance on the wave damping rate is expected to be small.

The location of the Alfvén resonance surface, $r = r_o$, may be obtained by substituting the appropriate values into eq. (3). If we consider the case B_0 = 6 kG, m = +1, we obtain

$$n(r_o) = 3.5 \times 10^{20} \; m^{-3} .$$

Therefore, assuming a density profile of the form given by eq. (7) with a = 5 cm, r_p = 7.3 cm, and an average plasma density determined by the initial filling pressure (i.e., fully ionized with no loss of particles), we obtain

$$r_o = 6.4 \text{ cm}.$$

Donnelly and Clancy (1983) have given an approximate expression for the minimum temperature, T_{min}, required to obtain enhancement of the wave fields, and an estimate of the half-width, Δ, of the enhanced wave fields. Substituting the values appropriate for the present case yields

$$T_{min} = 1 \text{ eV} , \Delta = 2.8 \text{ cm}.$$

We may therefore expect to observe an increased damping due to the spatial Alfvén resonance, although the resulting enhancement of the wave fields would be rather broad. (Note that for the parameters of the experiment of Lehane and Paoloni (1972), T_{min} = 2.8 eV : the spatial Alfvén resonance is therefore expected to have little influence on the wave fields).

The plot of $|b_\theta|$ verses radius for the case B_0 = 6 kG, m = +1 (shown in Fig. 9(a)) does in fact exhibit a peak at $r \simeq 4$ cm. While the experimental data for the radial profile is not sufficiently accurate to make any detailed conclusions, it may be that for the parameter region of the present study the spatial Alfvén resonance does play an important role.

6. CONCLUSION

The above analysis shows that the $m = \pm 1$ surface waves have been successfully launched in a low pressure, hydrogen plasma in SUPPER IV. While good agreement has been found between the values of $\mathrm{Re}(k_{\parallel})$ measured in the experiment and those calculated from theory, the waves are much more strongly damped than predicted by resistive effects in a uniform plasma. A possible explanation is that the presence of density and temperature gradients leads to enhanced damping due either to the larger resistivity in the vicinity of the plasma boundary, or to the effect of the spatial Alfvén resonance. The measured damping rates are in reasonable agreement with the values calculated using a simple non-uniform plasma theory. More detailed experimental profiles of the wave fields are, however, needed to correlate any local wave enhancement with that associated with absorption at the Alfvén resonant surface. In view of the inevitable presence of density and temperature gradients at the edge of a laboratory plasma, it may not be possible to obtain experimentally the weakly damped surface waves calculated using a uniform plasma theory.

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REFERENCES

Appert K., Vaclavik J. and Villard L. (1984) Phys. Fluids, 27, 432.

Collins G.A. (1982) PhD Thesis, University of Sydney.

Collins G.A., Cramer N.F. and Donnelly I.J. (1984) Plasma Phys. and Controlled Fusion, 26, 273.

Cross R.C. and Blackwell B.D. (1978) Aust. J. Phys. 31, 61.

de Chambrier A., Cheetham A.D., Heym A., Hofmann F., Joye B., Keller R., Lietti A., Lister J.B. and Pochelon A. (1982) Plasma Phys. 24, 893.

Donnelly I.J. and Clancy B.E. (1983) Aust. J. Phys. 36, 305.

Donnelly I.J. and Cramer N.F. (1984) Plasma Phys. and Controlled Fusion, 26, 769.

Grossmann W., Kaufmann M. and Neuhauser J. (1973) Nucl. Fusion, 13, 462.

Grossmann W. and Tataronis J. (1973) Z. Physik, 261, 217.

Lehane J.A. and Paoloni F.J. (1972) Plasma Phys., 14, 701.

Paoloni F.J. (1973) Plasma Phys. 15, 475.

Ritz Ch.P., Hoegger B.A., Sayasov Y.S., Schneider H. and Vaucher B.G. (1982) Helv. Phys. Acta, 55, 354.

Ross D.W., Chen G.L. and Mahajan S.M. (1982) Phys. Fluids, 25, 652.

Woods L.C. (1962) J. Fluid Mech. 13, 570.

Wootton A., Nalesso G.F. and Newton A.A. (1972) Proc. Second Topical Conf. Pulsed High-Beta Plasmas, Paper C4.

FIGURE CAPTIONS

1. Dispersion curves for a hydrogen plasma with $B_0 = 6$ kG, $n_0 = 6.44 \times 10^{20} m^{-3}$ and T = 20,000 K.
   (a) projection onto $(\omega, Re(k_\parallel))$ plane
   (b) projection onto $(\omega, Im(k_\parallel))$ plane

2. Same as Fig. 1 except $B_0 = 8$ kG.

3. Radial profiles of the magnetic wave fields $Re(ib_r, b_\theta, b_z)$ for the parameters used in the experimental investigation : $n_0 = 6.44 \times 10^{20} m^{-3}$, T = 20,000 K, $\omega/2\pi = 1.34$ MHz and
   (a) $B_0 = 6$ kG
   (b) $B_0 = 8$ kG.

   The four waves considered for each value of B_0 are, from top to bottom respectively,
   i) m = +1 surface wave
   ii) m = −1 surface wave
   iii) m = −1, ℓ = 1 slow wave
   iv) m = −1, ℓ = 2 slow wave

   Fields are normalized so that b_θ is positive on axis. b_z is zero on axis. The vertical line represents the plasma-vacuum boundary at $r = r_p = 7.3$ cm. $r_w = 15.8$ cm.

4. (a) The axial ionizing current pulse (4.4 kA/div; 50 μs/div)
   (b) The wave antenna current supplied to the two antenna loops, dephased by $\pi/2$. (400 A/div; 0.5 μs/div).

5. Probe signals db_θ/dt measured, for $B_0 = 8$ kG, on the plasma axis at different axial positions :
   i) z = 24.5 cm , $\theta = 0$
   ii) z = 70 cm , $\theta = -\pi/2$
   iii) z = 116.5 cm , $\theta = -\pi/2$
   iv) z = 162 cm , $\theta = 0$

   for (a) m = +1
   (b) m = −1 (0.5 μs/div)

Figure Captions (cont'd)

6. Measure time delay of different peaks of the magnetic wave field for B_0 = 8 kG.

(a) m = +1
(b) m = -1

7. Natural logarithmn of the normalized amplitude as a function of axial position for B_0 = 8 kG.

(a) m = +1
(b) m = -1

8. Magnetic wave fields recorded at z = 70 cm and different radial positions :

i) r = 0
ii) r = 3 cm
iii) r = 6 cm
iv) r = 9 cm

for B_0 = 6 kG.

(a) b_Θ , m = +1 (2 V/div, 0.5 μs/div)
(b) b_z , m = +1 (1 V/div)
(c) b_Θ , m = -1 (0.5 V/div)
(d) b_z , m = -1 (0.5 V/div)

9. In phase component (x) and amplitude (o) of the magnetic wave fields at z = 70 cm as a function of radial position for the case B_0 = 6 kG, m = +1.

(a) b_Θ component
(b) b_z component

	Previous experiment (Lehane & Paoloni, 1972)	Present Experiment
B_0 (kG)	4	6 ; 8
n_0 (m^{-3})	10^{21}	6.44×10^{20}
T (K)	18,000	20,000
m_i (kg)	6.68×10^{-26}	1.67×10^{-27}
r_p (cm)	7.3	7.3
r_w (cm)	8.8	15.8
ω (rad s^{-1})	4.65×10^5	8.42×10^6
k (m^{-1})	10.6 + i 4.94	14.47 + i 0.40 ; 9.98 + i 0.31
V_A (m s^{-1})	4.37×10^4	5.16×10^5 ; 6.88×10^5
ω_{ci} (rad s^{-1})	9.58×10^5	5.75×10^7 ; 7.66×10^7
ω_{ce} (rad s^{-1})	7.03×10^{10}	1.054×10^{11} ; 1.405×10^{11}
ν_{ei} (s^{-1})	5.20×10^9	3.02×10^9
$f = \omega/\omega_{ci}$	0.485	0.146 ; 0.110
$\delta = \omega\,\nu_{ei}/\omega_{ci}\omega_{ce}$	0.0359	0.00418 ; 0.00236
$(k^{res})^2$	$(2.23 + i1.28) \times 10^3$	$(0.27 + i1.47) \times 10^4$; $(0.26 + i2.18) \times 10^4$
$\lvert k^{res}\, r_p \rvert$	3.7	8.9 ; 10.8

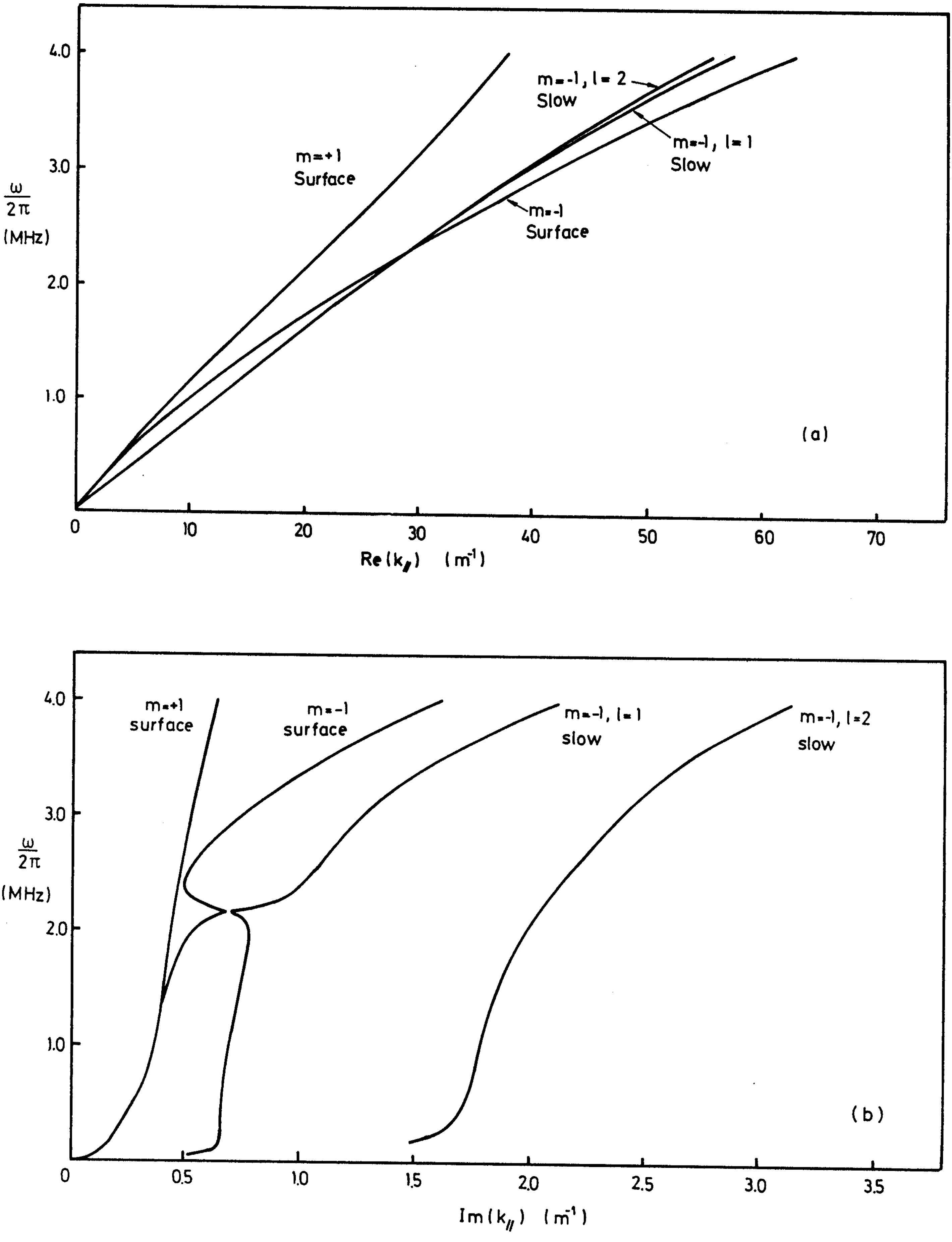
Table I : Comparison of parameters for previous and present experiments. (Wave parameters are those of the m = -1 surface wave calculated using the uniform plasma theory.)

B_0 (kG)	m	$Re(k_\parallel)$ (m^{-1}) Experiment	Theory surface	Theory ℓ = 1 slow
6	+1	13.0 ± 1	12.2	16.5
	−1	15.3 ± 1	14.5	16.5
8	+1	9.9 ± 1	8.8	12.3
	−1	11.5 ± 1	10.0	12.3

Table II : Values of $Re(k_\parallel)$ obtained from experiment and theory.

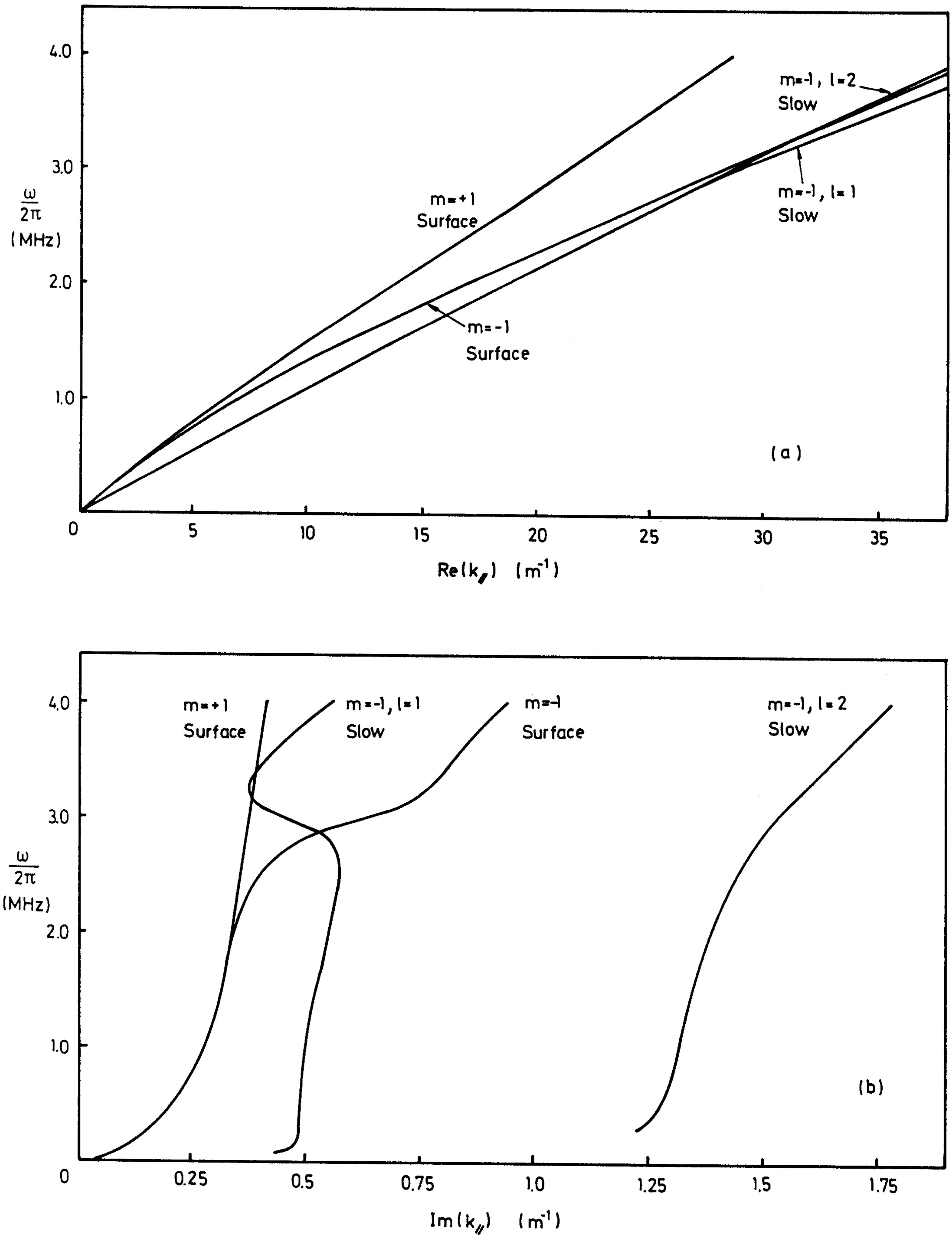
B_0 (kG)	m	Experiment $Im(k_\parallel)$ (m^{-1})	Theory uniform	Theory non-uniform
6	+1	3.6 ± 0.3	0.39	2.2
	−1	4.5 ± 0.6	0.40	2.6
8	+1	2.8 ± 0.5	0.31	1.6
	−1	4.0 ± 0.6	0.31	1.8

Table III: Values of $Im(k_\parallel)$ obtained from experiment and theory.



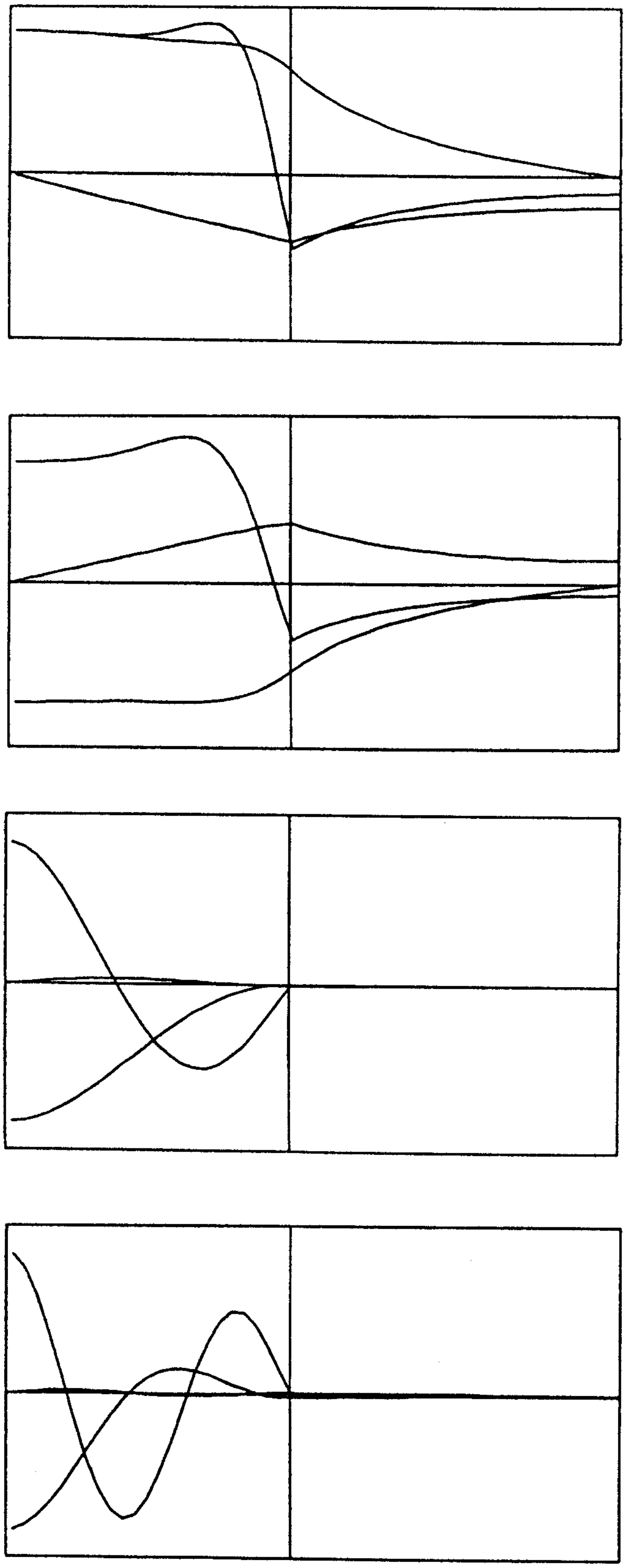
4.0
3.0
2.0
1.0
ω/2π (MHz)
m=+1
Surface
m=-1, l=2
Slow
m=-1, l=1
Slow
m=-1
Surface
(a)
0
10
20
30
40
50
60
70
Re(k∥) (m⁻¹)
m=+1
surface
m=-1
surface
m=-1, l=1
slow
m=-1, l=2
slow
(b)
0.5
1.0
1.5
2.0
2.5
3.0
3.5
Im(k∥) (m⁻¹)

Figure 1.



4.0
3.0
2.0
1.0
0
ω/2π (MHz)
m=+1 Surface
m=-1 Surface
m=-1, l=2 Slow
m=-1, l=1 Slow
(a)
5
10
15
20
25
30
35
Re(k∥) (m⁻¹)
4.0
3.0
2.0
1.0
0
ω/2π (MHz)
m=+1 Surface
m=-1, l=1 Slow
m=-1 Surface
m=-1, l=2 Slow
(b)
0.25
0.5
0.75
1.0
1.25
1.5
1.75
Im(k∥) (m⁻¹)

Figure 2.


(a)

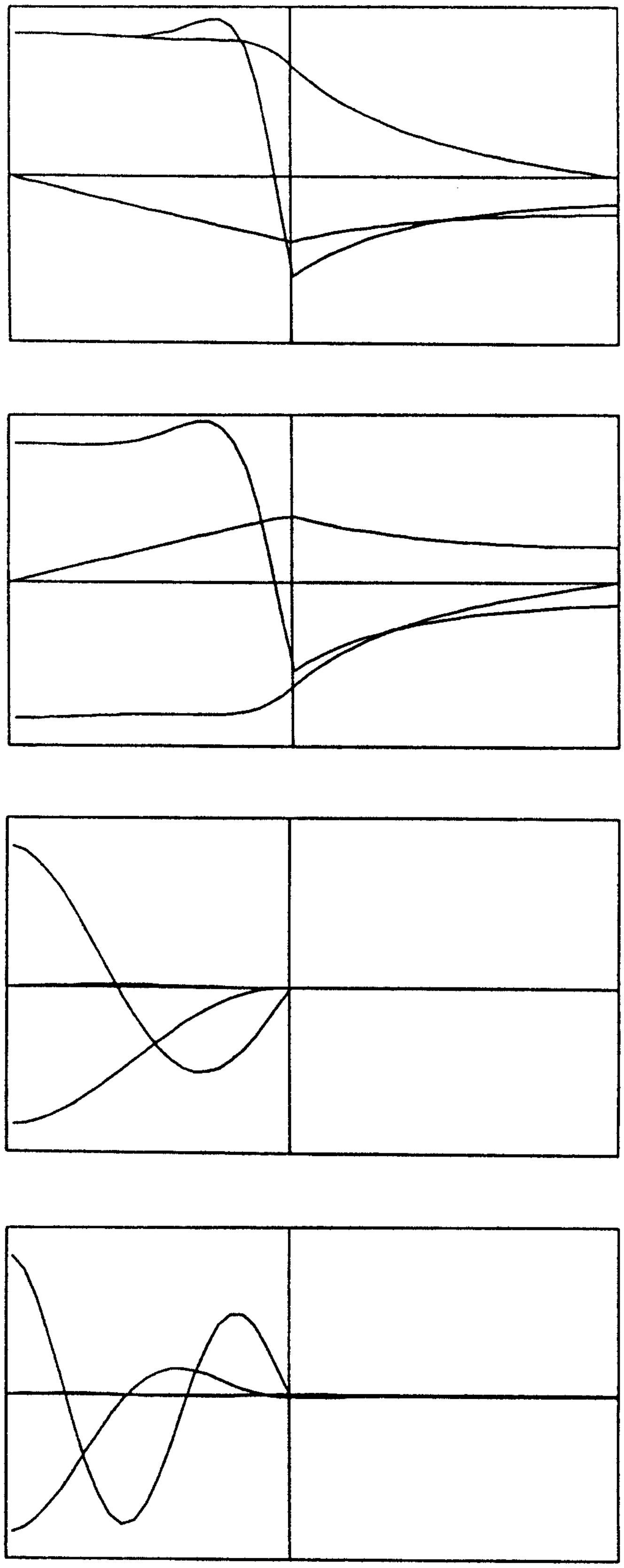

(b)

Figure 3.

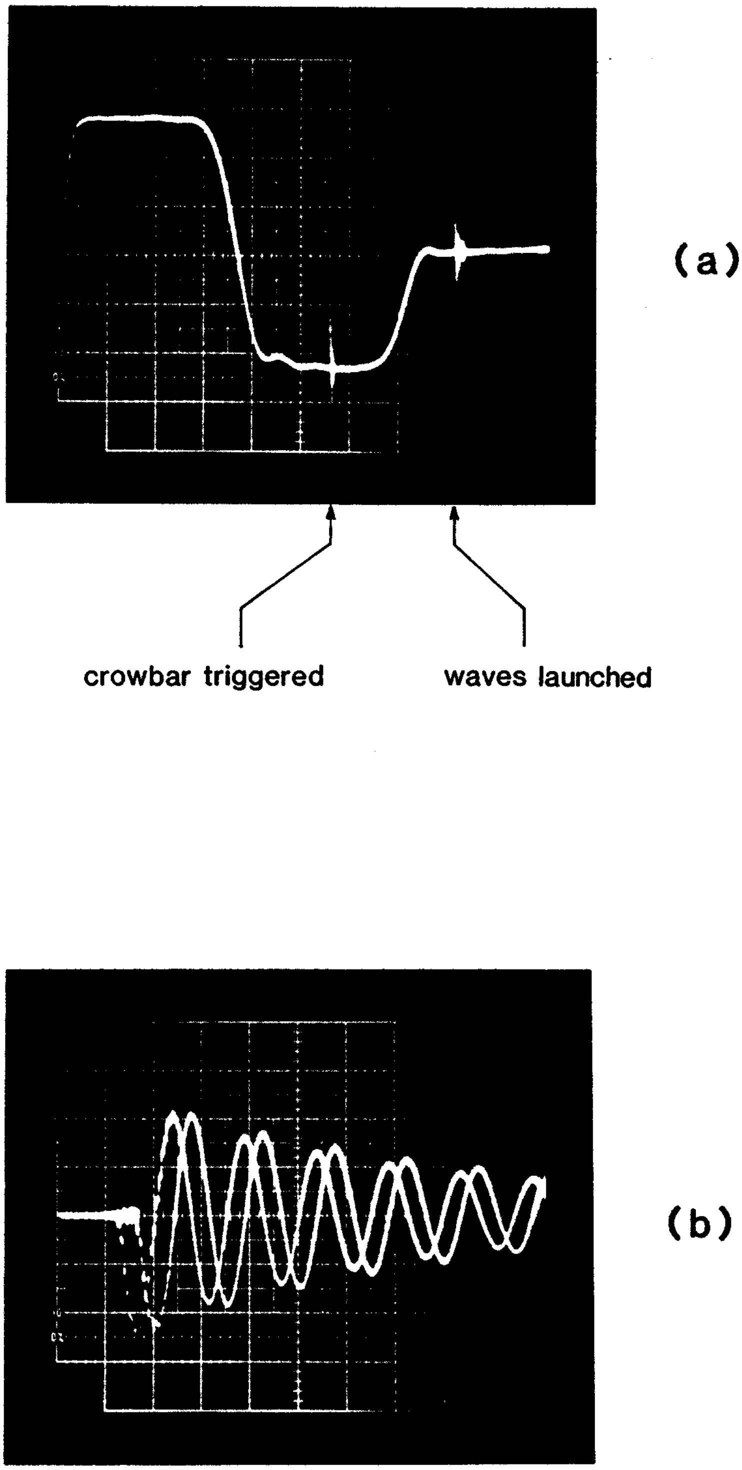
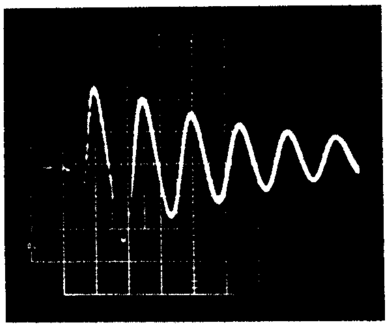
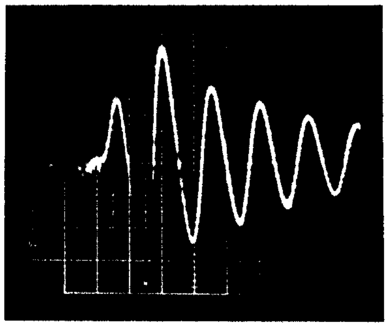


Figure 4.

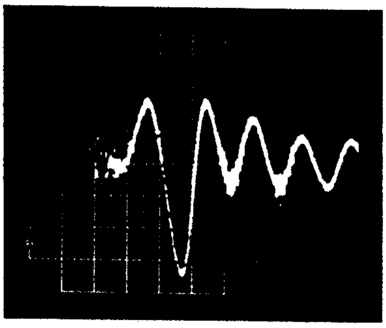
(a)



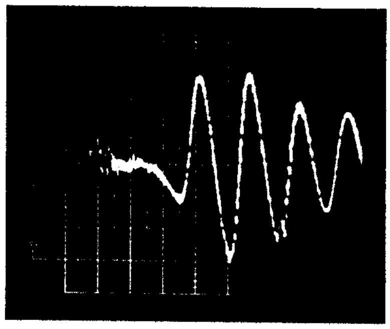
(i) (10 V/div)



(ii) (2 V/div)

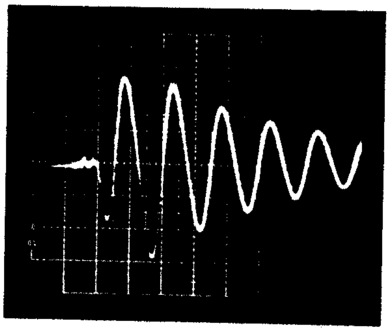


(iii) (0.5 V/div)

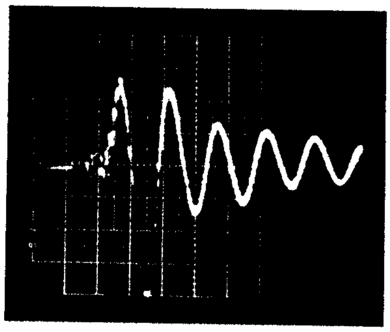


(iv) (0.5 V/div)

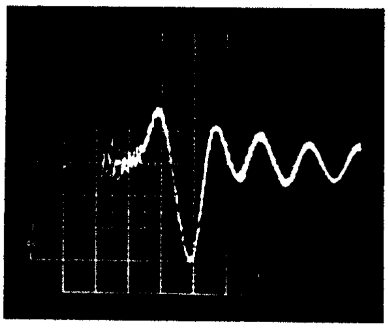
(b)



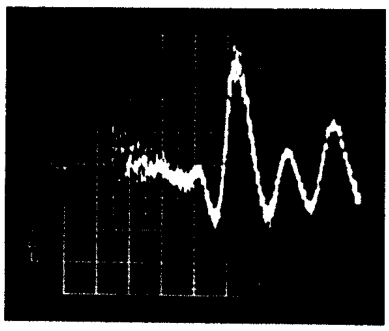
(i) (10 V/div)



(ii) (1 V/div)



(iii) (0.5 V/div)



(iv) (0.2 V/div)

Figure 5.

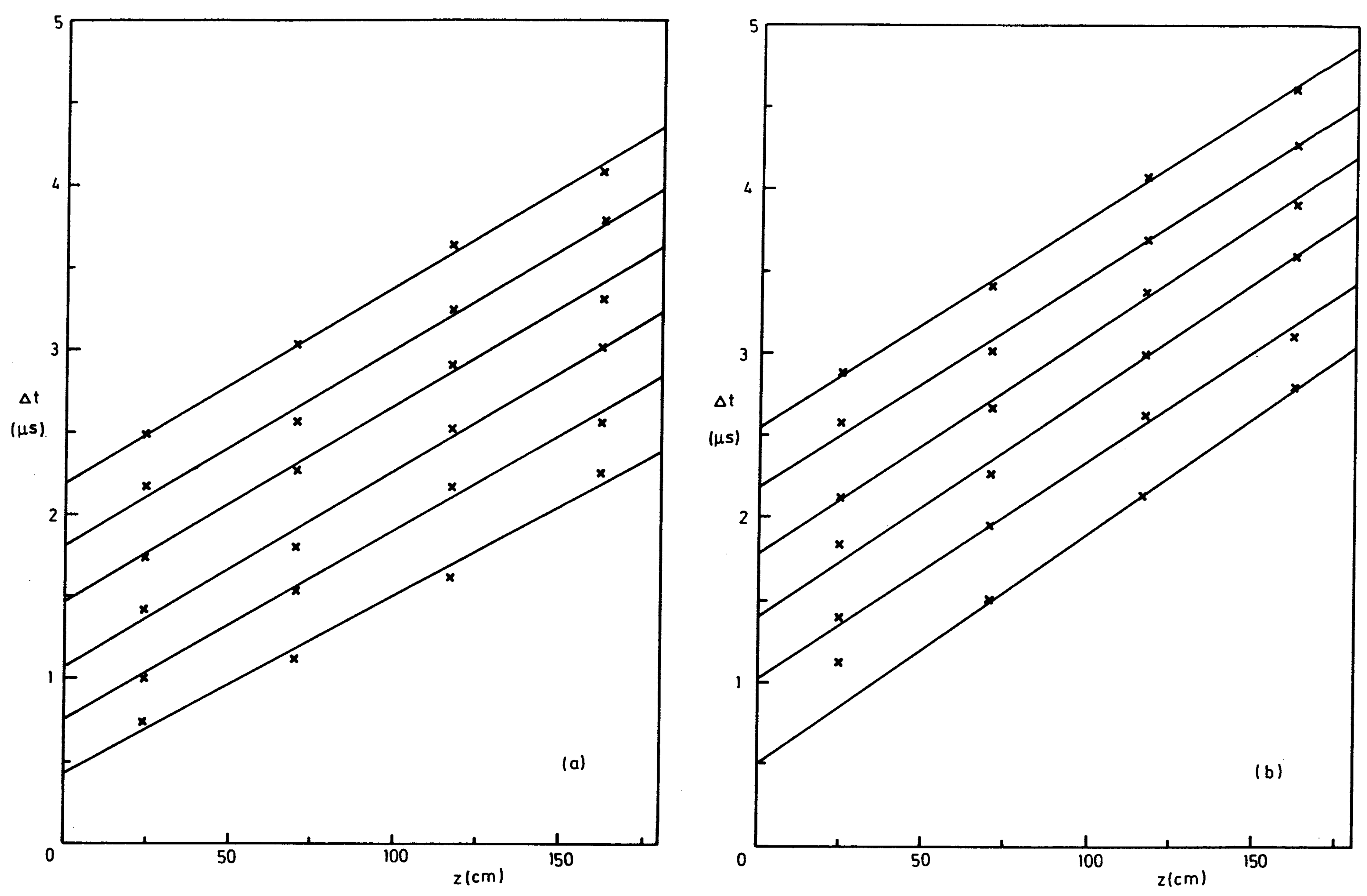


Figure 6.

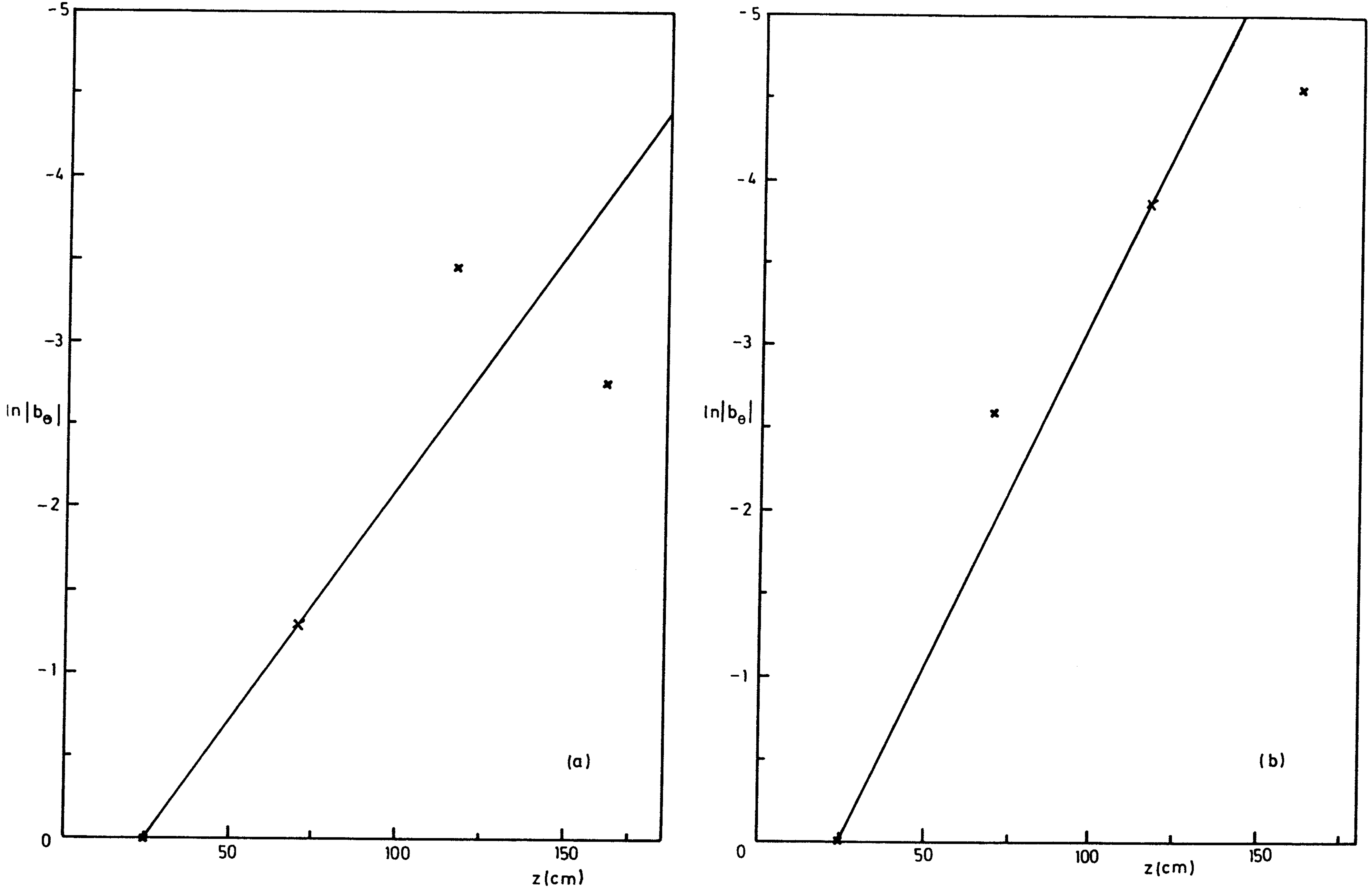
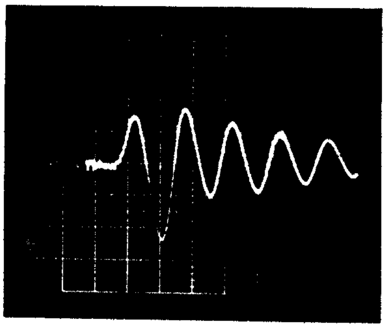
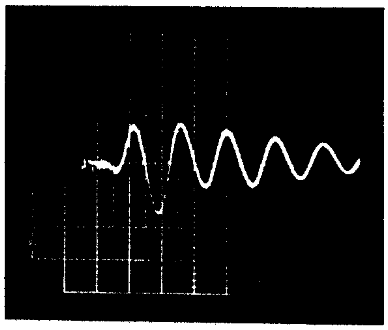


Figure 7.

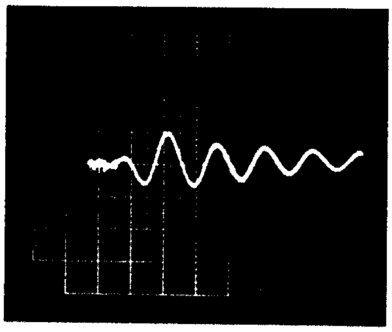


(i)

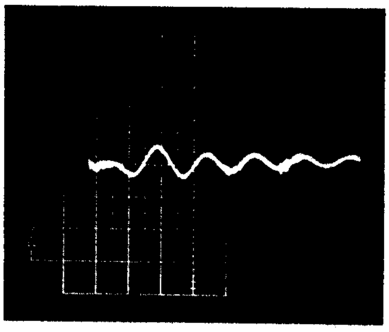


(ii)

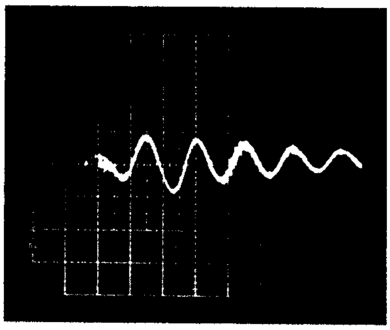
(a)



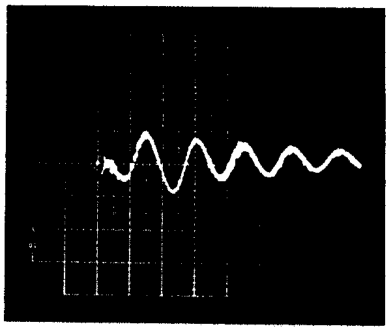
(iii)



(iv)

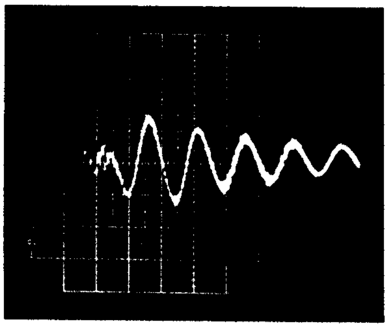


(i)

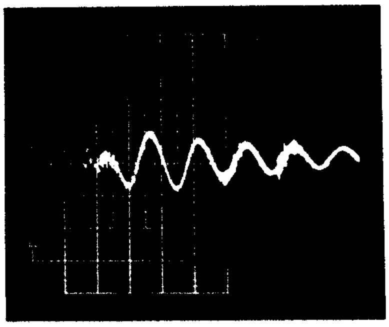


(ii)

(b)



(iii)



(iv)

Figure 8.

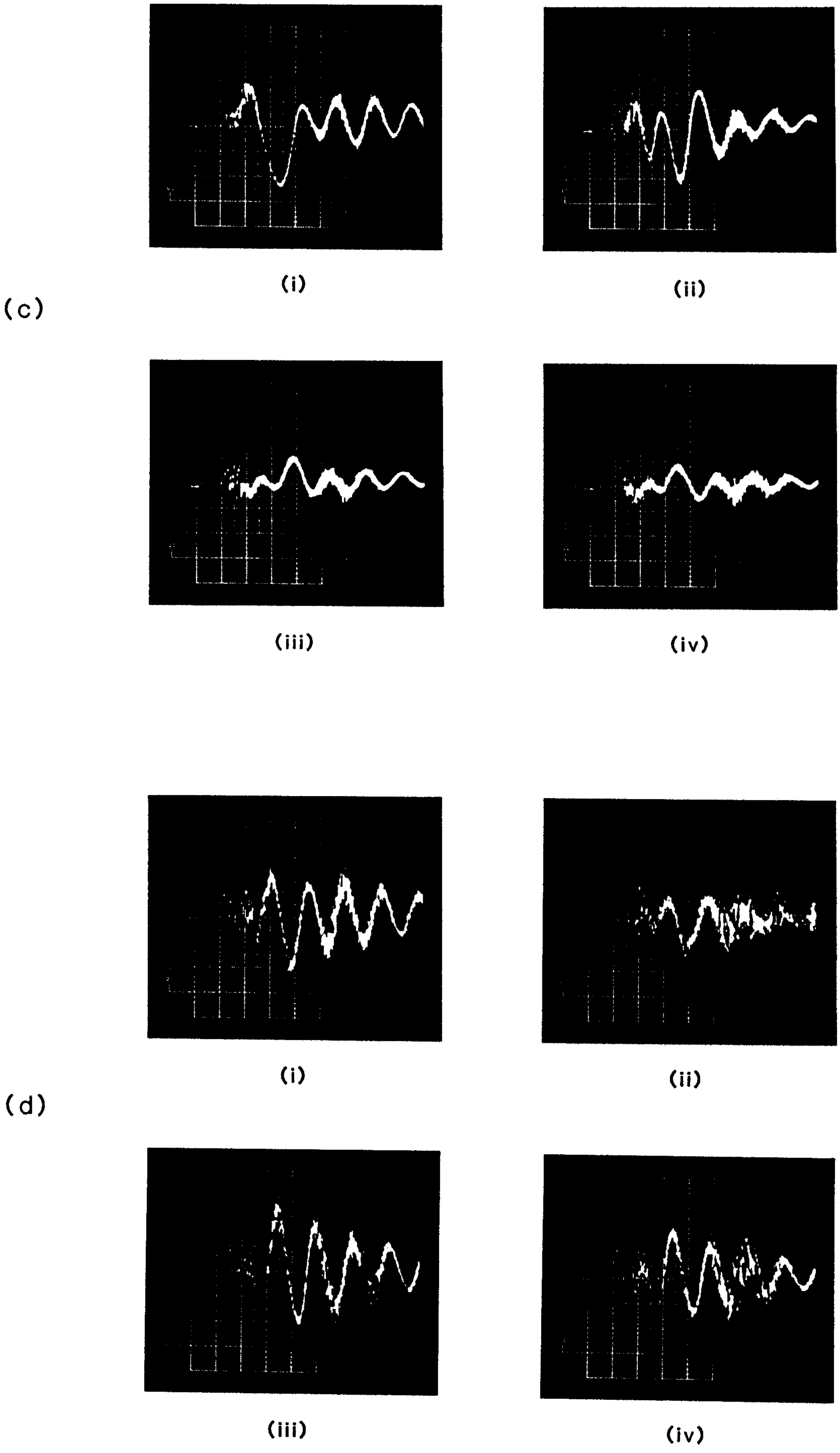
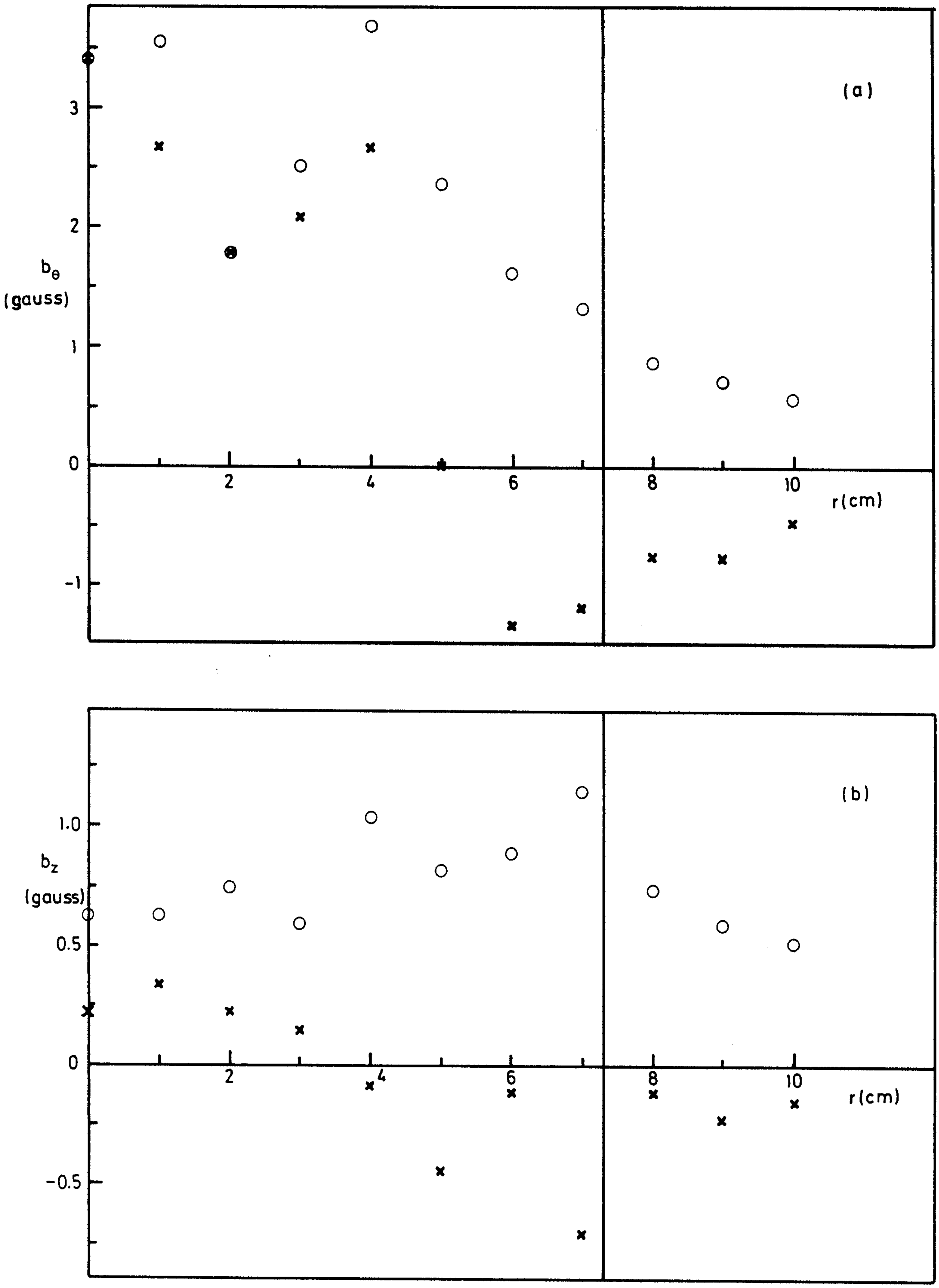


Figure 8.



3
2
1
0
-1
b_θ
(gauss)
2
4
6
8
10
r(cm)
(a)
1.0
0.5
0
-0.5
b_z
(gauss)
2
4
6
8
10
r(cm)
(b)

Figure 9.