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THE DISPERSION RELATION OF ELECTROTHERMAL WAVES IN A NONEQUILIBRIUM MHD PLASMA

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Contents

Abstract

The work described concerns the experimental verification of the dispersion relation of electrothermal waves. The theoretical derivation of this relation differs from the usual approach because the experiment requires an analysis in terms of real frequency and complex wave number. In the experiment values of electron temperature up to 2400 K and electron density up to $7 \times 10^{19}\ m^{-3}$ can be realized. The properties of the heavy particle gas do not have to be characteristic for the situation in a closed cycle MHD generator because electrothermal waves are essentially a property of the electron gas only. The waves are excited artificially in the stable regime so that they are damped which sets high requirements on the measuring technique. The ratio of the amplitudes at two successive double probes is measured as well as the phase shift between the two signals. The experimental results are discussed and compared with the theoretical predictions.

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Nomenclature

A	electron energy loss due to elastic collisions
$\vec{B}$	magnetic induction
$\vec{E}$	electric field
E_i	ionization energy
e	electronic charge
i	$= \sqrt{-1}$
$\vec{j}$	total electric current density
$\vec{j}_e$	electric current density carried by electrons
$\vec{k}$	complex wave number vector
k_B	Boltzmann's constant
k_f	ionization rate coefficient
k_r	recombination rate coefficient
m	mass
n	number density
p	partial pressure
Q	collision cross section
R	radiation loss
T	temperature
t	time
$\vec{u}$	flow velocity
x, y	cartesian coordinates
$\delta(x)$	Dirac delta function
$\vec{\vec{\chi}}$	heat conductivity tensor
$\nu_{in} = \frac{1}{\tau_{in}}$	= collision frequency of ions with neutrals
σ	electrical conductivity
Φ	angle between $\vec{k}$ and unperturbed current density $\vec{j}$
$\omega_e \tau_{en}$	Hall parameter for electrons
$\omega_i \tau_{in}$	Hall parameter for ions
ω_o	frequency of artificially excited perturbations

Subscripts

e	electrons
i	ions
g	heavy particles

Superscripts

$\tilde{}$	perturbed quantity
$*$	complex amplitude of perturbed quantity (see equation 6)

1. Introduction

Fluctuations in electron density n_e and electron temperature T_e coupled with electrothermal waves are a serious limitation for enthalpy extraction in closed cycle MHD generators. Although the general philosophy at this moment is that we will have to live with electrothermal instabilities, the profit that can be obtained by their suppression is great, and we should thus continue basic research into their fundamentals. This paper describes an investigation of the dispersion relation of electrothermal waves, because their wave character is peculiar since they propagate according to theory in only one half plane. This property might be important for some of the possibilities of stabilization that are given in the literature [1-5] . Verification of this property, which has not been described in the literature , is the main goal of the investigation described below.

2. Theoretical derivation of the dispersion relation

As is well known from the literature a reasonable assumption in the analysis of electrothermal waves is that the heavy particle properties do not fluctuate [6,7] . This implies that only the equations of the electron gas have to be considered. These equations are well known and can be written in the following general form [8,9]

$$\frac{\partial n_e}{\partial t} + \nabla . (n_e \vec{u}_g) + \frac{1}{e} (\nabla . \vec{j}_e) = k_f n_e n_{aC} - k_r n_e^3 \quad (1)$$

$$\vec{j} = \sigma \left(\vec{E} + \vec{u}_g \times \vec{B} + \frac{\nabla p_e}{e n_e}\right) - \frac{\omega_e \tau_{en}}{B} \vec{j} \times \vec{B}$$

$$- \frac{\omega_e \tau_{en} \omega_i \tau_{in}}{B^2} [\nabla p_e \times \vec{B} - (\vec{j} \times \vec{B}) \times \vec{B}] \quad (2)$$

$$\frac{\partial}{\partial t} \left[n_e \left(\frac{3}{2} k_B T_e + E_i\right)\right] + \nabla . \left[\left(\frac{3}{2} k_B T_e + E_i\right) n_e \vec{u}_g\right]$$

$$+ \frac{1}{e} (\vec{j}_e . \nabla) \left(\frac{3}{2} k_B T_e\right) + \left(\frac{3}{2} k_B T_e + E_i\right) \frac{1}{e} (\nabla . \vec{j}_e) =$$

$$- p_e(\vec{j}_e.\nabla) \left(\frac{1}{en_e} \right) - \frac{p_e}{en_e} (\nabla.\vec{j}_e) + \frac{j^2}{\sigma} - A + \nabla.(\vec{\chi}\nabla T_e) - R \qquad (3)$$

For a description of electrothermal waves these equations have to be supplemented by relations following from the low magnetic Reynolds number MHD approximation of Maxwell's equations [6]

$$\nabla.\vec{j} = 0 \qquad \nabla \times \vec{E} = 0 \qquad (4)$$

In equation (2) the electron inertia term has been neglected but apart of that the equations (1) to (3) have been written in a generally valid although not in the simplest form. The reason is that we want to show clearly the additional assumptions that are made. These are necessary since we want to take into account ambipolar diffusion in the calculations although at our plasma conditions the Hall parameter for the ions $\omega_i\tau_{in}$ is negligibly small compared to one. Because of this the last term in Ohm's law, equation (2), which describes the ion slip effect, can be neglected. It should be noted that the set of equations above is not yet complete since we still need the relation between $\vec{j}_e$ and $\vec{j}$ [10]

$$\vec{j}_e \equiv en_e (\vec{u}_e - \vec{u}_g) = - \vec{j} + \frac{e}{m_i\nu_{in}} (\vec{j} \times \vec{B}) - \frac{e}{m_i\nu_{in}} \nabla (p_i + p_e) \qquad (5)$$

Equation (5) is valid for a weakly ionized plasma and shows that $(\nabla.\vec{j}_e)$ is unequal to zero; the effect of this in equation (1) is called the ambipolar diffusion which is usually derived only for the situation that the electric current density $\vec{j}$ is zero [9].
It should be noted that because $\omega_i\tau_{in} << 1$ we can simplify the energy equation (3) since $\vec{j}_e$ can be replaced by $- \vec{j}$ in the terms $(\vec{j}_e.\nabla)\ T_e$ and $(\vec{j}_e.\nabla)\ n_e$.

In deriving the dispersion relation for electrothermal waves we start from a steady and homogeneous plasma state and introduce the perturbed quantities $\tilde{n}_e$, $\tilde{T}_e$, $\tilde{\vec{j}}$ and $\tilde{\vec{E}}$. The method of deriving the perturbed, linearized equations relating these quantities and the analysis in terms of plane waves have been described before [6,8]. In an experiment, however, it is difficult to create perturbations that grow and propagate only in time (and not in space) but a situation in which the perturba-

tions evolve only in space (and not in time) can easily be realized. Therefore in stead of the usual assumption of complex frequency ω and real wave number $\vec{k}$, we will analyse the perturbations in terms of plane waves with real ω and complex $\vec{k}$. If we take as the primary disturbance a source term approximated by $\delta\ (x - x_o)\ \delta\ (y - y_o)\ \vec{I}\ e^{-i\omega_o t}$, which we can easily realize experimentally by applying the frequency ω_o to a small double probe then we find as a solution a complicated superposition of plane waves. This has the disadvantage that the influence of the angle between $\vec{k}$ and $\vec{j}$ on the wave propagation cannot anymore be distinguished. Since the study of this influence is an essential part of our investigation we have decided to put much effort into exciting experimentally initial perturbations closely resembling plane waves. For the theoretical analysis we then approximate the initial disturbance by $\delta(x - x_o)\ \vec{I}\ e^{-i\omega_o t}$ which enters as a source term into the perturbed Ohm's law.
We look for solutions of the perturbed quantities of the form

$$\tilde{\vec{E}} = \int_{-\infty}^{\infty}\int \vec{E}^{*} e^{i(kx - \omega t)}\,dk\,d\omega \tag{6}$$

and use the relations

$$\frac{\partial}{\partial t} \rightarrow -\,i\omega,\quad \frac{\partial}{\partial x} \rightarrow ik,\quad \frac{\partial}{\partial y} = 0 \tag{7}$$

From this we get algebraic equations relating the complex amplitudes $\vec{E}^{*}$, $\vec{j}^{*}$, n_e^{*} and T_e^{*} and straightforwardly find for instance

$$\tilde{E}_x = I_y e^{-i\omega_o t} \int_{-\infty}^{\infty} \frac{D_1}{D}\, e^{ikx}\, dk \tag{8}$$

In this relation D_1 and D are fourth order algebraic equations in k with complex coefficients. D = 0 is the dispersion relation in terms of the complex wave number k. We only look for solutions in the half plane x > 0; for the contour integration of equation (8) in the complex k plane we therefore close the contour in the upper half plane. We call the dominant pole of the dispersion relation D = 0 in the upper half plane (the only pole which can cross the real axis when $\omega_e\tau_{en}$

increases) $k = k_1 = p + iq$ and get the result

$$\tilde{E}_x = W\, I_y\, e^{i(k_1 x - \omega_o t)} \tag{9}$$

where W is a complex number.
In the experiment we have small double probes to pick up the $\tilde{E}_x$ signal at $x = x_1$ and at $x = x_2$ ($> x_1$). We then find from equation (9) as the ratio of amplitudes R.A. of the signals at x_1 and x_2

$$\text{R.A.} = e^{-q(x_2 - x_1)} \tag{10}$$

For the phase shift P.S. between the signals at x_1 and x_2 we find

$$\text{P.S.} = p\,(x_2 - x_1)\ \text{rad.} \tag{11}$$

The results of the theoretical calculations are presented in the figures 2.1 to 2.3 at the following conditions, corresponding with the experimental values

$T_g = 1000$ K, $T_e = 2300$ K,
$n_{Ar} = 1.45 \times 10^{24}\ m^{-3}$ ($p_g = 0.2$ bar)
$n_{Cs} = 1.45 \times 10^{21}\ m^{-3}$

For the calculation of the value of ν_{in} the following values for the cross sections have been taken from [11]

$$Q_{Cs^+ - Cs} = 3 \times 10^{-18} m^2,\ Q_{Cs^+ - Ar} = 10^{-19}\ m^2.$$

It should be mentioned that the perturbed radiation term has only approximately been taken into account in the calculations. In the analysis with complex ω and real $\vec{k}$ it has been shown that $\tilde{R}$ is proportional to $\sqrt{|\vec{k}|}$ [7] but a similar result is not available when $\vec{k}$ is complex. In our calculations we have assumed $\tilde{R}$ to be proportional to $\sqrt{p}$ which is strictly valid only at small damping ($q \ll 1$). This implies also that k_1 has to be known before $\tilde{R}$ can be calculated so that the calculations have to be performed iteratively.

Considering the results shown in the figures 2.1 to 2.3 and comparing with the results already known from the literature the following remarks can be made. Figure 2.1 shows the ratio of amplitudes as a function of the angle Φ between the wave number vector and the unperturbed current density vector. The different curves show the usual result that the ratio of amplitudes increases with increasing Hall parameter. The angle at which the smallest damping occurs is $\Phi = -45^{\circ}$ which agrees with the value found in the literature [6]. The range of angles Φ where the ratio of amplitudes differs from zero is larger than the range from - 90 to + 90 degrees found in the literature. This may be due to the effects of ambipolar diffusion, heat conduction and radiation which tend to smear out sharply defined boundaries. Figure 2.2 shows that the maximum ratio of amplitudes decreases when the frequency increases keeping the Hall parameter constant. Before explaining this effect it is more convenient to consider first the results given in figure 2.3. This figure shows the influence of frequency on the phase shift as a function of the angle Φ. It appears that the phaseshift increases with increasing frequency which agrees with previous results [6] since the phaseshift is proportional to the real part of the wave number (see equation 11). Furthermore it is known from the literature that the magnitude of the damping terms describing ambipolar diffusion, heat conduction and radiation will increase when the wavelength decreases [6]. Since the real part of the wave number is proportional to the inverse of the wavelength this implies an increasing magnitude of the mentioned damping terms with increasing frequency. Therefore the trend shown in figure 2.2, also agrees with results known from the literature.

3. Description of the experimental facility and of the measuring technique

As we have mentioned before the electrothermal wave can be considered as a property of the electron gas only. Therefore we only have to simulate in the experiment the properties of the electron gas in a closed cycle MHD generator. The gas temperature and gas pressure have been mentioned before; the gas velocity in the experiment is negligibly small.

From the cross section drawn in figure 3.1 it appears that the experiment is contained within a vacuum vessel 1 in which is situated an aluminum oxyde heating cylinder 2 surrounded by radiation shields 3. In the center of the heating cylinder is situated the discharge chamber 4 which is also shown separately in figure 3.2. Through the tubes 5 in figure 3.1 the argon plus cesium mixture is transported to and from the discharge chamber. These tubes are also visible in figure 3.2 behind the walls of the discharge chamber which is practically perpendicular in shape with dimensions 8 x 8 x 4 cm^3. Along every wall of this chamber five electrodes are situated each of which is connected to an independent current source so that the distribution of electric potential within the discharge chamber can be adjusted by the plasma itself. Moreover this gives us the possibility of rotating the direction of the electric current density within the plasma.
The maximum current per electrode is 6 A; the corresponding maximum electron temperature is 2400 K and the electron density is then $7 \times 10^{19}\ m^{-3}$. These values have been determined experimentally from the measured intensities of the two particle recombination radiation at the wavelengths of 4452 and 4915 Å [see 12]. The electron density can also be determined by transmitting microwaves through the windows at the extreme left and right in figure 3.1 and by measuring the phase shift due to the presence of the plasma. In the figures 3.3 and 3.4 the complete experimental facility is shown; the cesium vessel is situated inside the oil bath at the background. The temperature of the oil bath determines the cesium vapor pressure in the cesium vessel and thus also the partial cesium pressure inside the discharge chamber.
Since the purpose of the experiment is to verify the linearized theory of small perturbations it is not possible to work in the unstable regime. Thus the perturbations have to be excited artificially for which purpose the two planes of grid wires parallel to the horizontal diagonal in figure 3.2 have been installed. During the excitation of the perturbations the grid wires of the upper plane are electrically coupled by means of capacitors and the same is done with the wires of the lower plane. These planes of grid wires therefore act for oscillating fields as equipotential planes without affecting the stationary conditions.

Between the upper and lower plane a fluctuating voltage is applied and in this way the excited perturbations closely resemble plane waves. It should be noted that the grid wires are parallel to the direction of the magnetic field so that only wave propagation perpendicular to this direction can be studied. There is general agreement upon the fact that this is the preferred direction for the waves with the weakest damping [6].
The fluctuations that propagate through the plasma are picked up again by probes placed at regular intervals along the vertical diagonal in figure 3.2. In the final configuration these probes have been replaced by double probes and the wires leading to the probes (# 6 in figure 3.1) come from the opposite direction as the wires leading to the transmitting antenna (# 8) in order to minimize direct electromagnetic coupling. Another difference with the discharge chamber shown in figure 3.2 is that in later configurations this chamber has been constructed completely from aluminum oxyde and small sapphire windows.
It should be mentioned that the discharge is operated in a pulsed mode in order to avoid that the plasma is pushed to one side under the influence of the Lorentz force. It has been verified that this precaution is sufficient by measuring the plasma potential along the diagonal of the discharge chamber by using pairs of transmitting antenna wires as double probes. Up till the maximum value of the magnetic field of 0.08 T no inhomogeneities in plasma potential have been observed.

Since the fluctuations are excited in the stable regime they are damped and will thus have a very small amplitude when they reach the double probes. Therefore very strong requirements have to be met in reproducing the unperturbed plasma condition. In connection with this a fast method of measuring the ratio of amplitudes or the phase-shift of the signals at two double probes showed to be the most satisfactory in practice. Because of this the variation of the unperturbed plasma condition over a series of measurements at forty different directions of the unperturbed electric current density is small. Moreover the measurement can be repeated several times in order to determine a good average value. For the measurement a sinusoidal voltage

at a fixed frequency is obtained from a battery operated function generator and is connected to the grid wires acting as the transmitting antenna. The signal which is received at a double probe is led via an opto-coupler to an oscilloscope amplifier. After this the signal passes a band filter which has been adjusted at the selected frequency and is led to a second oscilloscope amplifier. A large amplification is necessary because the amplitude of the signal at the first double probe is of the order of 10 μV although the amplitude of the input signal is of the order of 1 V. It should be mentioned that when we measure the double probe signal of the complete transmitting antenna we have reached the non linear part of this characteristic when the amplitude is 1 V.
In order to measure the ratio of amplitudes the signals are rectified and stored in a capacitor. The signals at two successive probes are measured alternately, the two amplitudes are divided electronically and the average result of several measurements is plotted on a strip chart recorder. In order to measure the phaseshift the signals are led to an overranged amplifier which makes a block out of the sinusoidal function. From the positive zero crossings sharp peaks are derived which are led to a logical electronic circuit so that the time that the output of this circuit is positive is determined by the phase shift between the two signals. The output is integrated and thus averaged over a series of measurements and the result is plotted again on a strip chart recorder.

4. Discussion of the experimental results

The ratio of amplitudes at two successive double probes as a function of the angle Φ between the wave vector $\vec{k}$ and the unperturbed electric current density $\vec{j}$ is shown in figure 4.1. This result has been obtained at a frequency of 1300 Hz and at three values of the Hall parameter for the electrons. It has been verified that the results can be reproduced when we take the signals at the second and third double probe instead of at the first and second double probe. Comparing figure 4.1 with the theoretical result in figure 2.1 we observe the same tendency namely that the peak in the ratio of amplitudes increases with increasing Hall parameter. This fact is a strong confirmation that we are actually observing electrothermal waves. The main point of criticism on the result in figure 4.1 is that the maximum ratio of amplitudes is larger than one although all these measurements have been taken at a value of the Hall parameter corresponding to the stable regime. This fact can easily be verified by checking that the signal at the double probes becomes negligibly small when we reduce the initial perturbation on the transmitting antenna to zero. After realizing this we have succeeded in showing that this fact has apparently been caused by pollution of the vacuum system and thus possibly by very thin cesium layers on the walls of the discharge chamber. The results of figure 4.1 have namely been obtained after many successive days of measuring without evacuating the system in between. When we switched over to the procedure of taking measurements only after evacuating the system during a couple of days we obtained the more reliable result of figure 4.2. This figure shows the influence of the frequency on the curve of the ratio of amplitudes as a function of the angle Φ. Just as in figure 4.1 we observe a maximum in the ratio of amplitudes at a certain angle of preference ($\Phi = 356^{\circ}$). This is seen most clearly at the frequency of 600 Hz since the ratio of amplitudes at $\Phi = 356^{\circ}$ increases with decreasing frequency. The agreement between experimental and theoretical results (compare with figure 2.2) is now reasonably good especially when we consider the maximum ratio of amplitudes. A distinct difference is that the angle of preference is found experimentally as $\Phi = 356^{\circ}$ although theory predicts a value of $\Phi = 315^{\circ}$. For this fact we cannot give a good explanation but it might be connected with the finite dimensions of the discharge chamber and with the orientation of the transmitting antenna with respect to the walls of this chamber.

Besides the ratio of amplitudes we have also measured the phase shift that exists between signals at two successive double probes in the plasma. The results of these measurements are difficult to interpret and show little agreement with the theoretical predictions as shown in figure 2.3. The absolute value of the measured phase shift never exceeds 30° and the maximum value reacts only very weakly upon the value of the frequency of excitation. The measurements don't show either that the phase difference is negative in a restricted range of angles Φ where the ratio of amplitudes is small as might be expected from theory. For the fact that the measurements of the phase shift cannot support the measurements of the ratio of amplitudes no clear explanation is available but it might be connected with the fact that the initial perturbation is only approximately a plane wave.

5. Conclusions

1. Measurements of the ratio of amplitudes show reasonably good agreement with theoretical results as far as the influence of the Hall parameter and the frequency on the maximum ratio of amplitudes is concerned.

2. There is, however, a discrepancy with respect to the value of the angle Φ at which the maximum ratio of amplitudes occurs.

3. Measurements of the phase shift show little agreement with theoretical predictions for which fact we cannot give a clear explanation.

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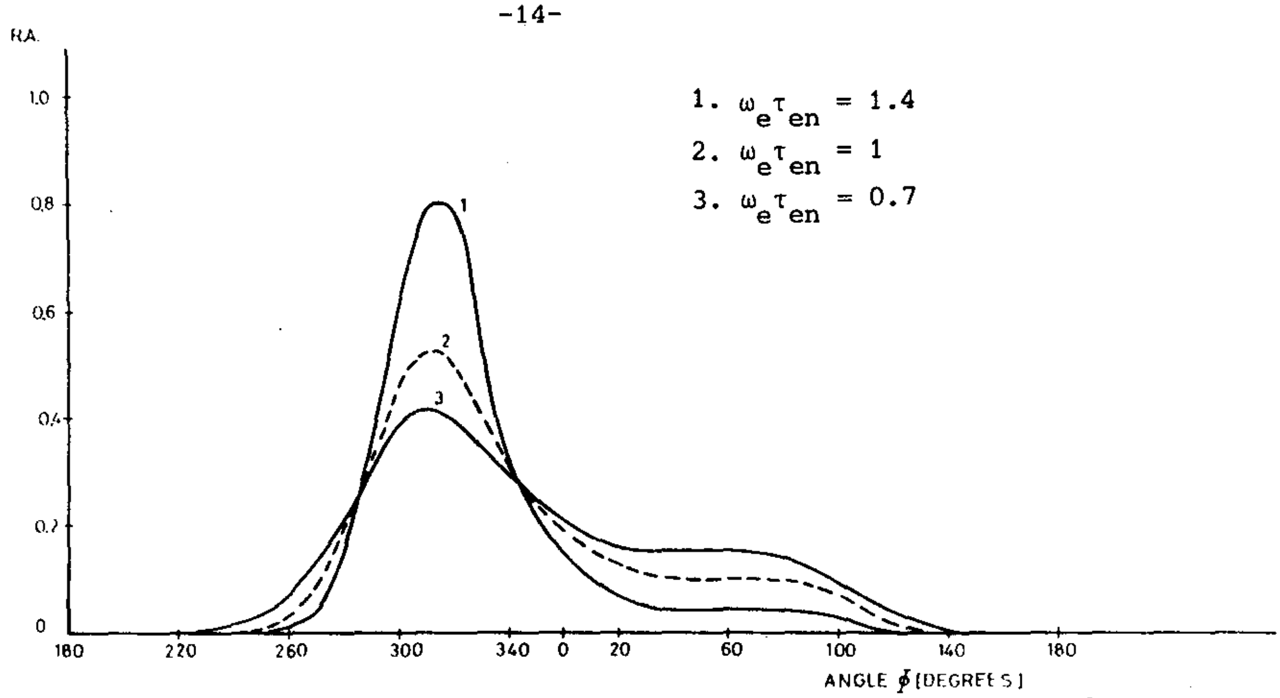

Figure 2.1 Ratio of amplitudes (R.A.) at different values of the Hall parameter as a function of the angle Φ; frequency = 1040 Hz.

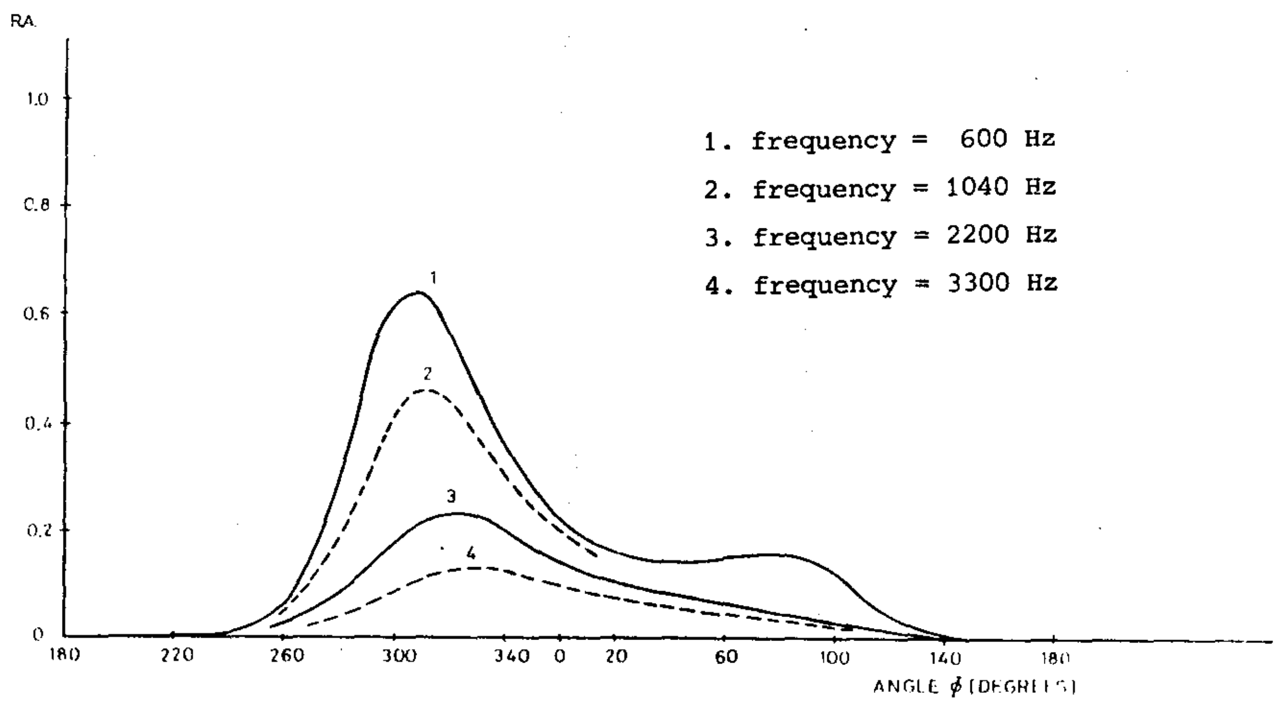

Figure 2.2 Ratio of amplitudes (R.A.) at different values of the frequency as a function of the angle Φ; Hall parameter $\omega_e\tau_{en}$ = 0.84.

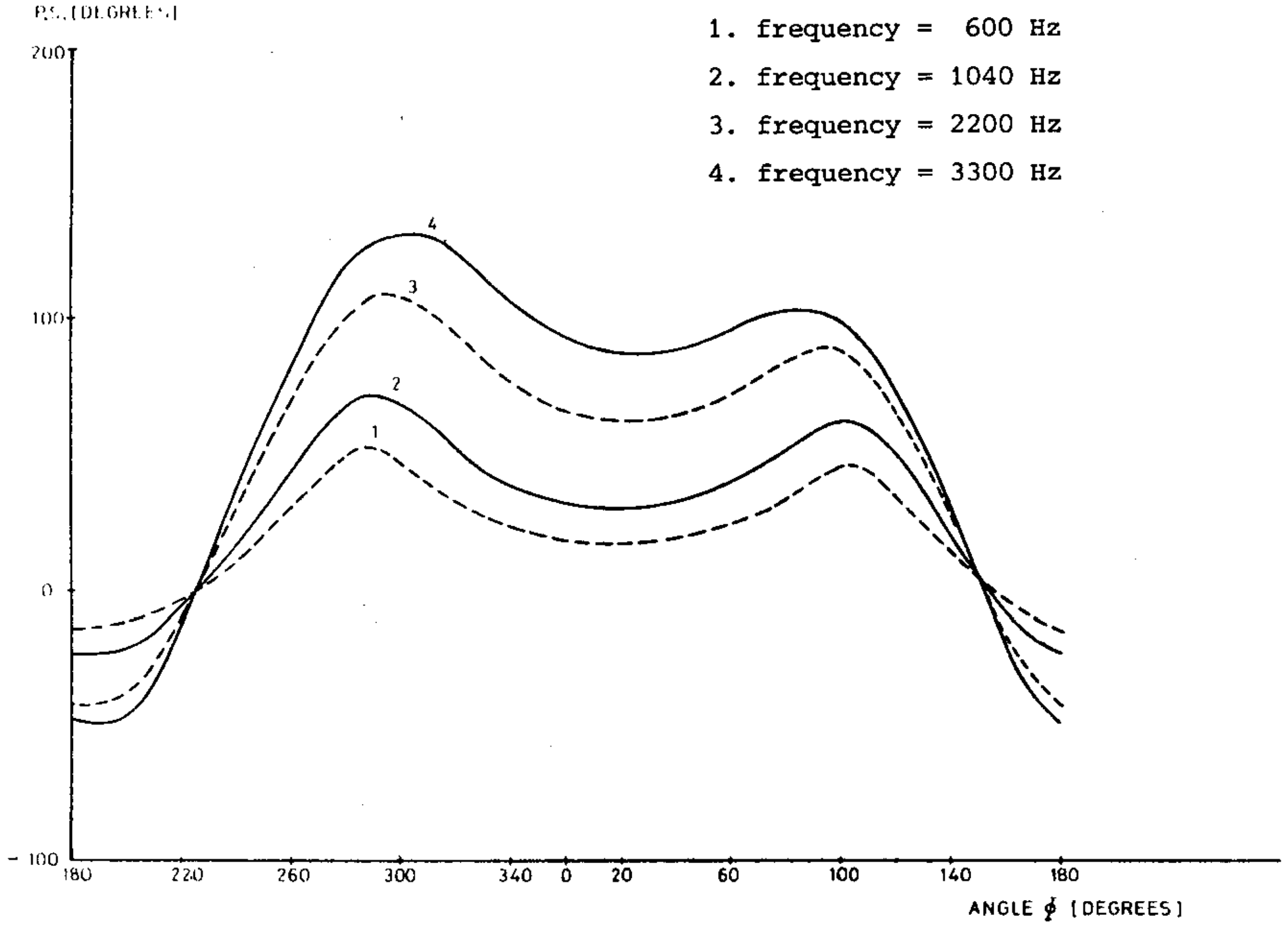

Figure 2.3 Phaseshift (P.S.) at different values of the frequency as a function of the angle Φ; Hall parameter $\omega_e \tau_{en} = 0.84$.

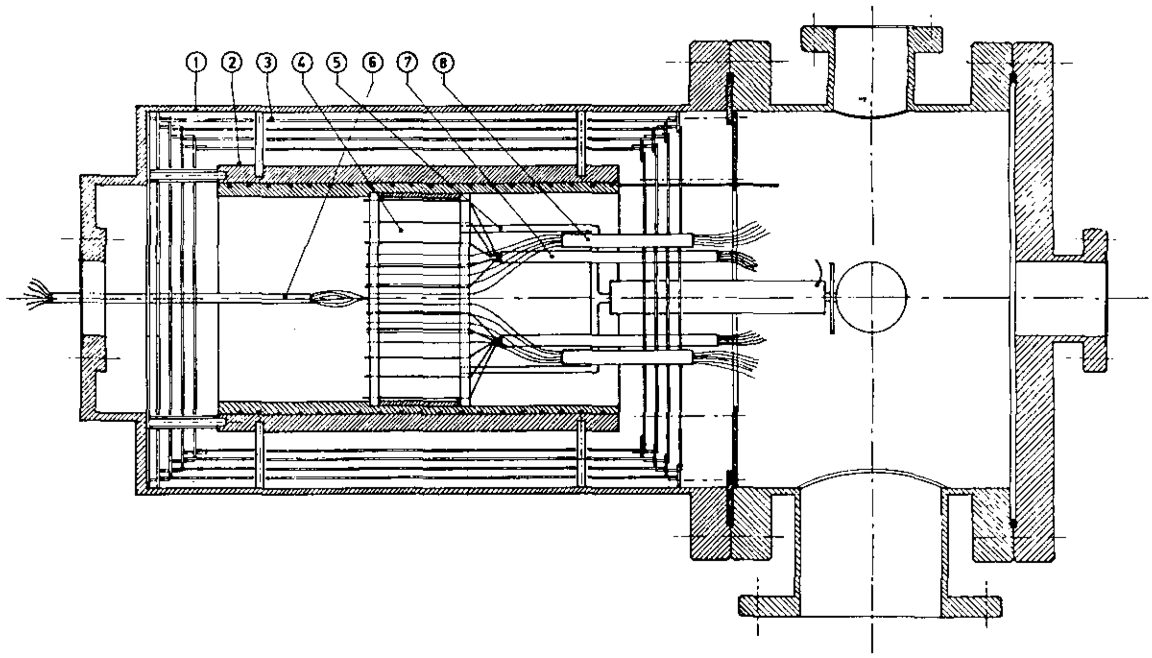

Figure 3.1 Cross section of the experimental set up.

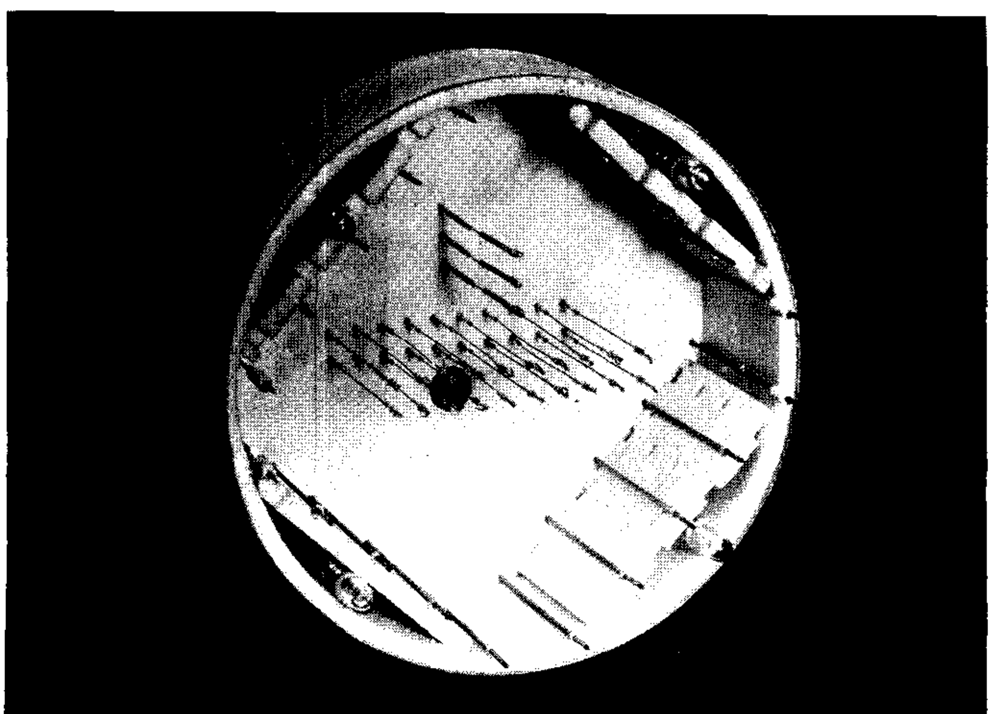

Figure 3.2 The discharge chamber.

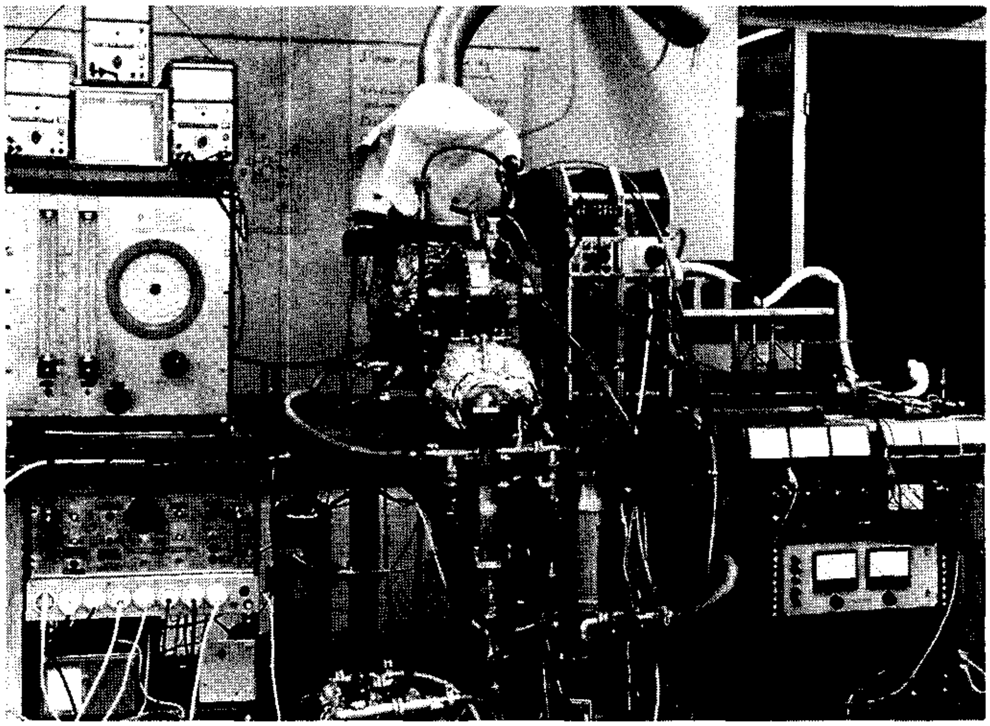

Figure 3.3 Total view of the experimental set up with auxiliary equipment.

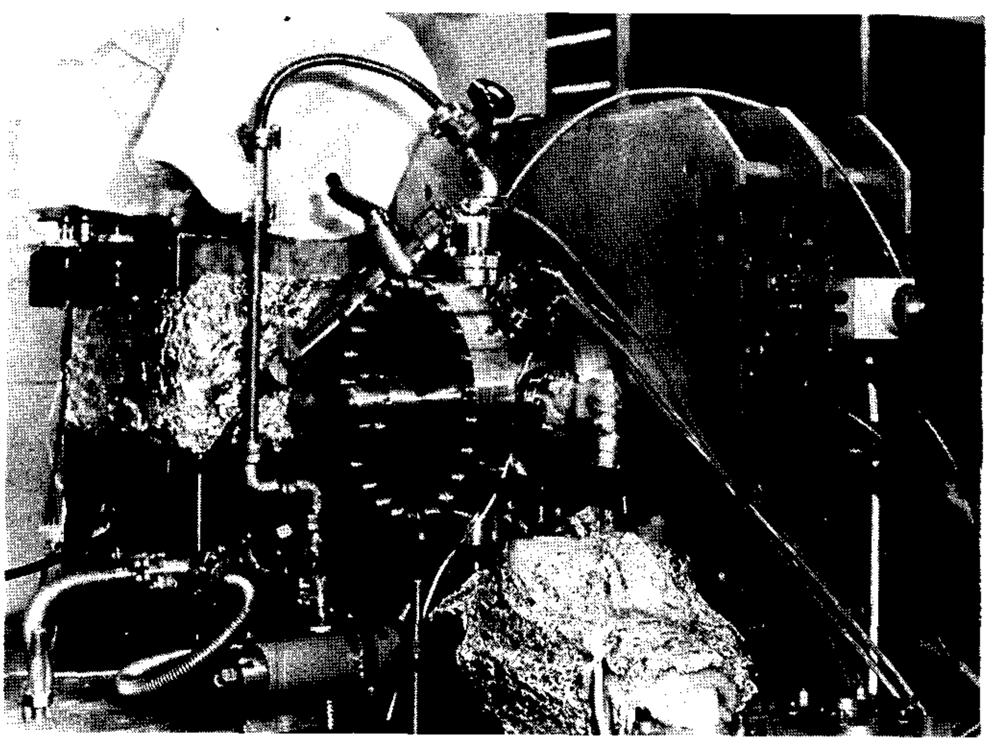

Figure 3.4 Close up of the experimental set up.

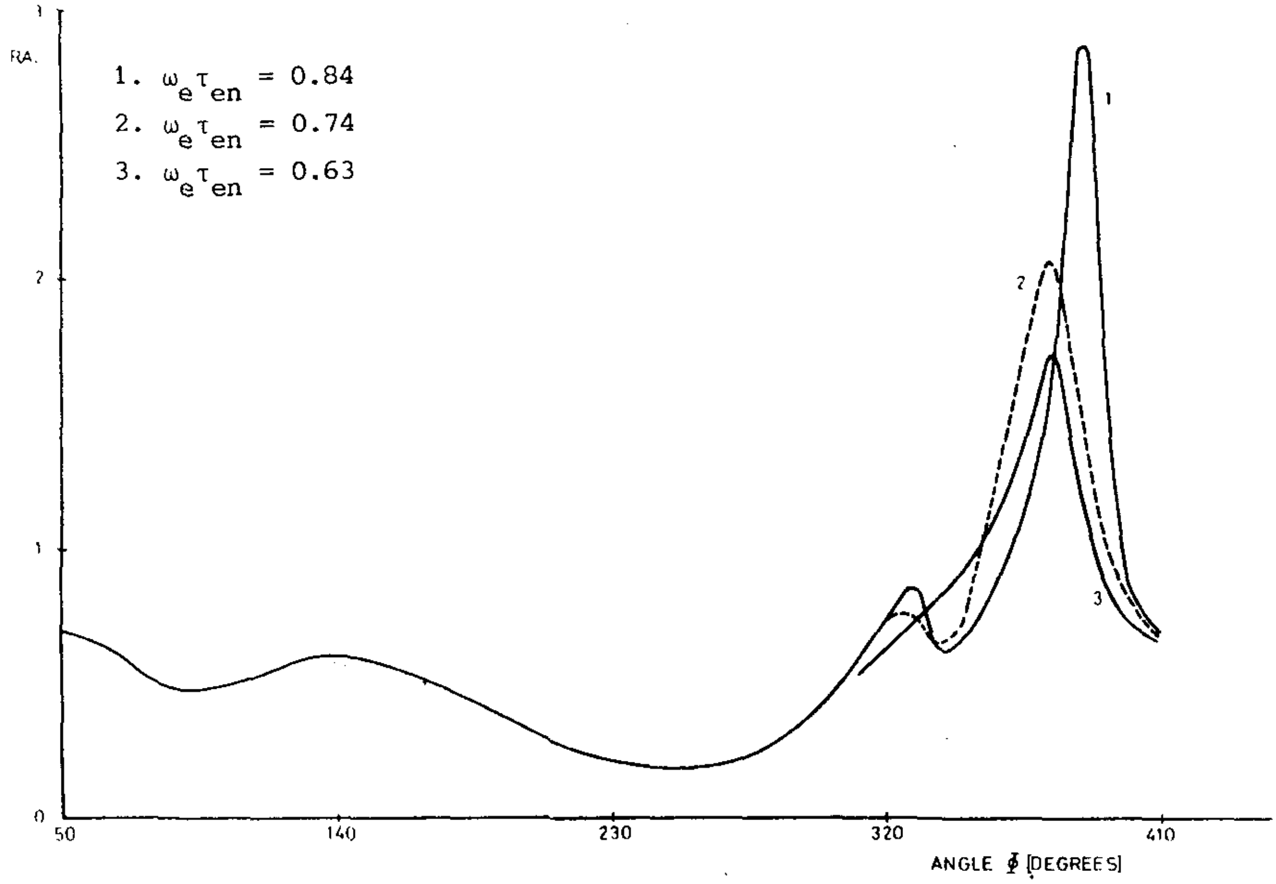

Figure 4.1 Experimentally determined ratio of amplitudes (R.A.) at different values of the Hall parameter as a function of the angle Φ; frequency = 1300 Hz.

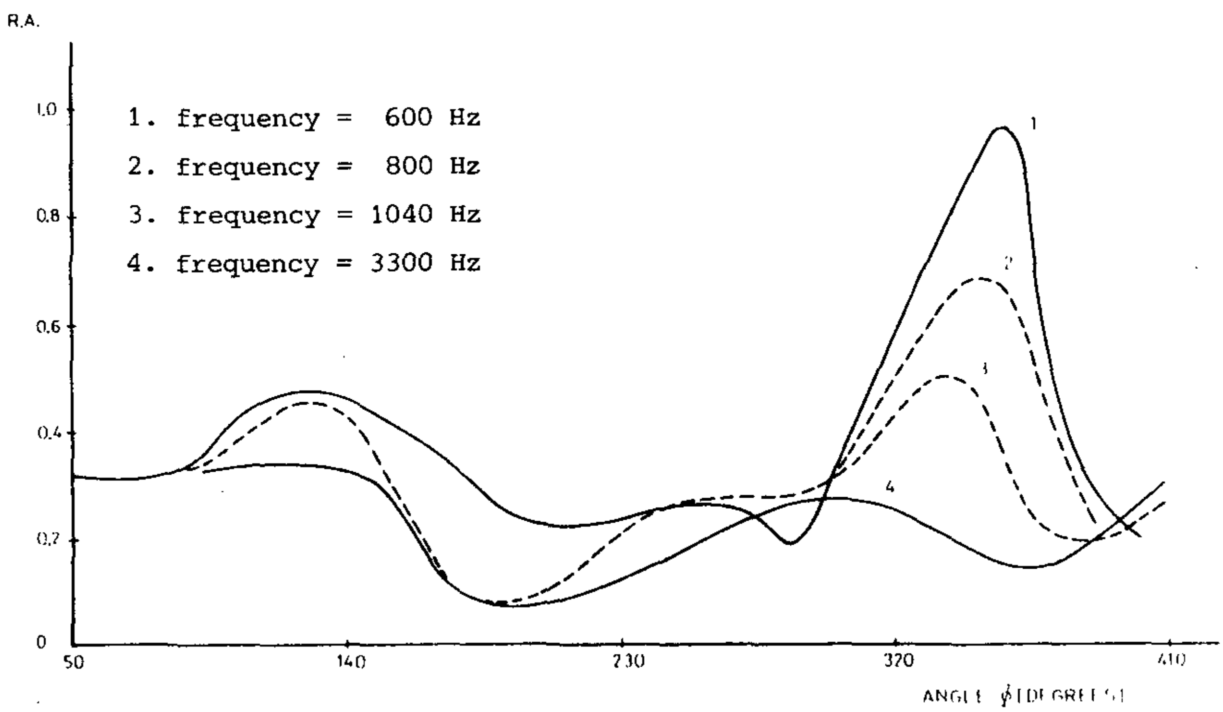

Figure 4.2 Experimentally determined ratio of amplitudes (R.A.) at different values of the frequency as a function of the angle Φ; Hall parameter $\omega_e\tau_{en}$ = 0.84.

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