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Abstract

Electron heating in a single-ended Q-machine was tried out by two different techniques: (1) by application of μ-wave power at the electron cyclotron frequency and (2) by insertion of a positively biased grid close to the hot plate. The electron temperature T_e was measured with a Langmuir probe. By means of the first method the electron temperature was increased by a factor of 2 without any significant disturbance of the ion distribution function. By the other method T_e was increased by a factor of 4. This heating was accompanied by a severe distortion of the ion distribution function which could be remedied by charge exchange cooling of the ions.

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Introduction

A high electron - ion temperature ratio, T_e/T_i, is necessary for a plasma to show strong collective interactions. In a Q-machine operated in the normal mode this ratio is close to 1. Therefore it will be desirable to heat the electrons.

It is possible to raise the temperature ratio by applying r.f. power to a grid inserted in the plasma[1]. We tried to heat the electrons with μ-wave power at the electron cyclotron frequency and by inserting a positively biased grid close to the hot plate.

The μ-wave heating has the advantage that it is possible to raise the electron temperature without any severe increase of the noise level.

Electron Heating by Cyclotron Resonance

The experiment was performed in a single-ended Q-machine; a diagram of the experimental set-up is shown in fig. 1. The density was of the order $10^9\ cm^{-3}$, and the temperature of the hot plate was 2200 K. The magnetic field was about 0.6 T, giving an electron cyclotron frequency close to 10 GHz, i.e. in the X-band. The plasma column was terminated by an electrostatic ion energy analyser[2]. The front grid of the analyser was biased to -15 V in order to reflect all the electrons, and the hot plate was d.c. grounded.

The electron temperature, T_e, was measured with a Langmuir probe consisting of a 0.2 mm wire made of wolfram. The wire was bent into a loop with an area of 3 mm^2 perpendicular to the B-field. Just before each measurement the wire was heated to about 1500^{o}C by a d.c. current in order to produce a clean surface.

The temperature ratio T_e/T_i is often determined by measuring of the phase velocity and damping of a grid-excited, low-frequency ion acoustic wave. This kind of measurement does not necessarily give a correct value for the electron temperature for the following reasons:

If the grid voltage oscillates with a frequency ω_o, then the ions within a certain distance, l, from the grid are perturbed by the oscillating potential. Some of the ions will be absorbed, while the rest will be accelerated and decelerated. As long as $v/l \gg \omega_o$ (v is a characteristic ion velocity, i.e. the ion drift velocity), the ions that are not absorbed will be accelerated and decelerated by an equal amount. This means that the potential variation is vanishing within the time it takes an ion to move through the grid. v/l is generally of the order $10^6 \cdot s^{-1}$. The absorption of the ions takes place when the grid is biased below the plasma potential. Therefore the problem of grid-excited waves should rather be considered as a boundary perturbation than as a "test-charge" problem[3]. Calculations[4] show that the velocity distribution of the absorbed ions plays a dominant role in the former case. This distribution is measurable in certain cases[5], but usually not in the case of high electron temperature because of the increased noise level.

The μ-wave power was fed into the plasma through (1) a μ-wave horn, (2) a resonator consisting of a tube with the axis parallel to the B-field and covered at the ends by grids in order to allow the plasma to flow freely through the tube. The μ-wave power could be varied within the range 50-250 mW.

The B-field had a small longitudinal gradient in the region where the μ-wave power was fed into the plasma. This was necessary in order to get a good coupling to the plasma as the following simple calculation will show:

We assume that the B-field is constant and pointing in the z-direction. We now consider a single electron moving in this B-field and with an oscillating E-field in the x-direction. The equation of motion for the electron is

$$m(\dot{\underline{v}} + \nu\underline{v}) = e(\underline{E} + \underline{v} \times \underline{B}),$$

where collisions have been taken into account by the collision frequency ν. If the electron density is n, a simple calculation shows that the current is given by

$$j_p = \sum_q \sigma_{pq} E_q \qquad p = x, y, z$$

where

$$\sigma_{pq} = \frac{ine^2}{(\omega + i\nu)m} \begin{bmatrix} \frac{(\omega + i\nu)^2}{(\omega + i\nu)^2 - \omega_c^2} & \frac{i\omega_c(\omega + i\nu)}{(\omega + i\nu)^2 - \omega_c^2} & 0 \\ \frac{-i\omega_c(\omega + i\nu)}{(\omega + i\nu)^2 - \omega_c^2} & \frac{(\omega + i\nu)^2}{(\omega + i\nu)^2 - \omega_c^2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

In a plasma of density $n = 10^{12}\ cm^{-3}$ and in the temperature range 2000 - 2500°C the electron - electron collision frequency is of the order $10^4 - 10^5\ s^{-1}$. From the expression for σ_{pq} we see that the resonance is rather sharp. Therefore, in order to get an effective μ-wave coupling to the plasma, it is necessary to introduce a gradient in the B-field.

At resonance the electrons will obtain an increased velocity perpendicular to the B-field, while the velocity parallel to the B-field is unaffected. Thereby we get $T_\perp > T_{\parallel}$. A distribution with this property is known to be unstable[6], and this instability may cause a Maxwellization of the electrons. At the same time the gradient in the B-field will cause a conversion of the high perpendicular velocity into parallel velocity since the magnetic moment is conserved. However, this effect is small since it is only possible to obtain a small gradient in the B-field.

By introducing different inert gases instead of caesium and measuring the density of the ions produced by electron - neutral collisions one gets a crude estimate of the electron energy, since the ionization potentials of the various gases are known[7]. During these measurements the only function of the hot plate was to produce free electrons, since the inert gases could not be ionized by surface ionization. When using argon one gets a considerable ionization, and we conclude that the electrons have energies of at least 15 eV (the energy necessary for single ionization of Ar is 15.68 eV).

In the experiment we adjusted the klystron frequency to about 10-12 GHz and then varied the B-field until resonance was obtained. The resonance was accompanied by an increase in the density by a factor of 1.5 - 2. We believe that this is due to ionization of neutral Cs (with a background pressure of 10^{-5} torrs, the density of Cs is $10^{12}\ cm^{-3}$).

In fig. 2 is shown measurements of the ion distribution function with and without μ-wave heating. The ions were cooled by charge exchange during these measurements. The ion distribution is slightly distorted by the electrons owing to ionization of neutral Cs and second ionization of Cs^+. (The corresponding ionization potentials are 3.87 eV and 23.4 eV respectively). In fig. 3 are shown differentiated Langmuir probe characteristics. These measurements were obtained by using the resonator described above. Differentiated Langmuir probe characteristics are shown in fig. 4 where the μ-waves are fed in through a conventional horn. In this case the heating turned out to be less effective, and the noise level was somewhat higher compared with the former case. In both cases the heating was independent of the length of the plasma column.

The heated electrons cause an increased electron flux from the plasma to the hot plate. Therefore the plasma potential will be slightly increased (i.e. it becomes less negative) in order to maintain a balance between the incoming and outgoing electron flux at the hot plate. This is in agreement with our measurements.

In fig. 5 is shown interferograms of a 100 kHz grid-excited wave. The electron temperature is determined from

$$\frac{T_{e,\ \text{heated}}}{T_{e,\ \text{unheated}}} = 2\left(\frac{v_{pn,\ \text{heated}} - v_d}{v_{pn,\ \text{unheated}} - v_d}\right)^2 - 1,$$

which is obtained from the following formula:

$$v_{pn} \simeq v_d + \sqrt{\frac{\kappa T_i + \kappa T_e}{m_i}} \ ,$$

where v_p is the phase velocity and v_d the drift velocity[1]. These measurements are in fair agreement with the electron temperature measured with the Langmuir probe in spite of our reservation earlier in this section.

Measuring the flux in the propagation of step-like initial perturbations[8] we also find good agreement with calculations in which we have used $T_e/T_i = 2$, measured with the Langmuir probe. (The plasma is perturbed by means of an absorbing grid). Fig. 6a shows the flux in the perturbation for two temperature ratios. Fig. 6b shows the calculated curves. We therefore conclude that, at low temperature ratios, $T_e/T_i \leq 4$, the ion distribution is only weakly perturbed, and the grid/plasma interaction mechanism is independent of T_e. (In other words, the distribution in the perturbation is virtually the same).

We conclude that by using a resonator we can get a reasonable electron heating at a low power level by cyclotron resonance. The efficiency is expected to increase if the resonator is supplied with coils for fine-adjustment of the magnetic field in the resonant region. Especially, it will be desirable to superimpose small spatial ripples of the B-field gradient in order to produce more points where the electrons are in resonance with the μ-waves. Related experiments have been carried out by D. Baker and J.J. Balliardo[9].

Turbulent Heating

In this experiment we perturbed the plasma by inserting a coarse-meshed tantalum grid 1 cm from the hot plate, perpendicular to the B-field (see fig. 1). The grid was biased 50 - 180 V above the plasma potential. The current drawn from the plasma was of the order 250 mA. The electron temperature, measured with a Langmuir probe, could be increased by a factor of 2-3 (see fig. 6). At the same time the plasma density was decreased by a factor of 2-3. The electron temperature was found to be independent of small variations of the distance between the grid and the hot plate. In fig. 7 the electron temperature is shown as a function of the grid voltage.

Independent measurements of the plasma potential, φ_{pl}, by the charge exchange method[2] showed only a slight decrease in φ_{pl} with an increased grid voltage. We therefore believe that the electron distribution function is anisotropic. This indicates that the grid causes an electron beam to pass through the plasma. The distribution would be symmetric with respect to $v = 0$ if we had a "mirror" refelction of the electrons at the analyser, but this need not be the case.

The heating was accompanied by a considerable increase in the noise level. Measurements showed that the ion distribution function was severely distorted. This could be somewhat remedied by cooling the ions by charge exchange processes, which also helped to decrease the noise level. The ion distribution is shown in fig. 8.

The mechanism for this electron heating is not known, but we surmise that a two-stream electron instability is excited between the hot plate and the grid. Non-linear decay of the unstable electron oscillations then causes the heating of the electrons. If we consider the high-frequency oscillation as a gas of quasiparticles, this plasmon gas is known to be unstable with respect to decays of the type $(\omega_o, k_o) \rightarrow (\omega, k)_{pl} + (\Omega, q)_{i.a.}$ where pl stands for plasmon, and i.a. for ion acoustic wave[10]. We suggest that this effect accounts for the distortion of the ion distribution.

Although the electron heating described in this section is more effective than heating by means of cyclotron resonance, the latter method is preferable, since the temperature ratio T_e/T_i can be further increased by heavy cooling of the ions by charge exchange and the former method has the disadvantage of a high noise level.

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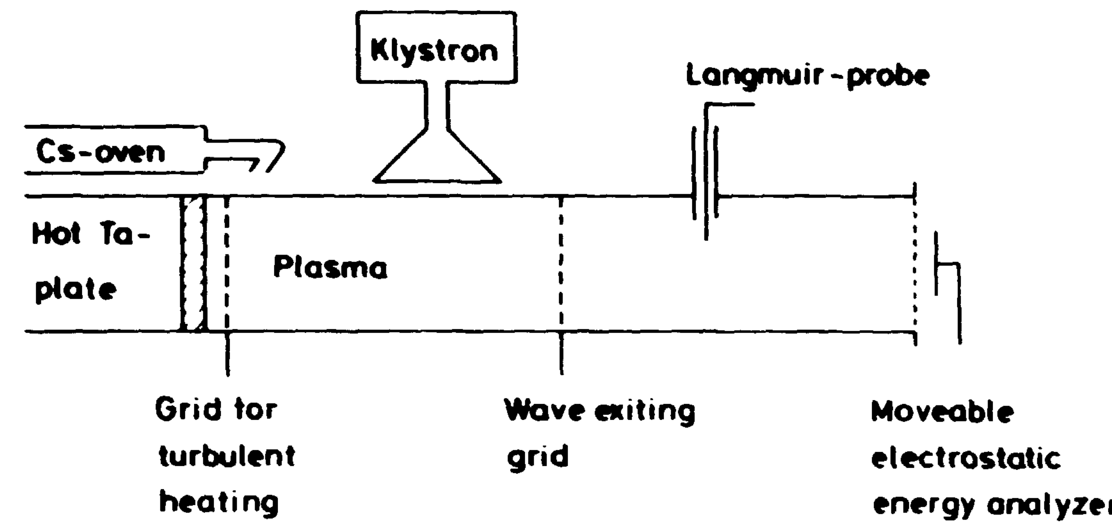

Fig. 1. Schematic diagram of the Q-machine.

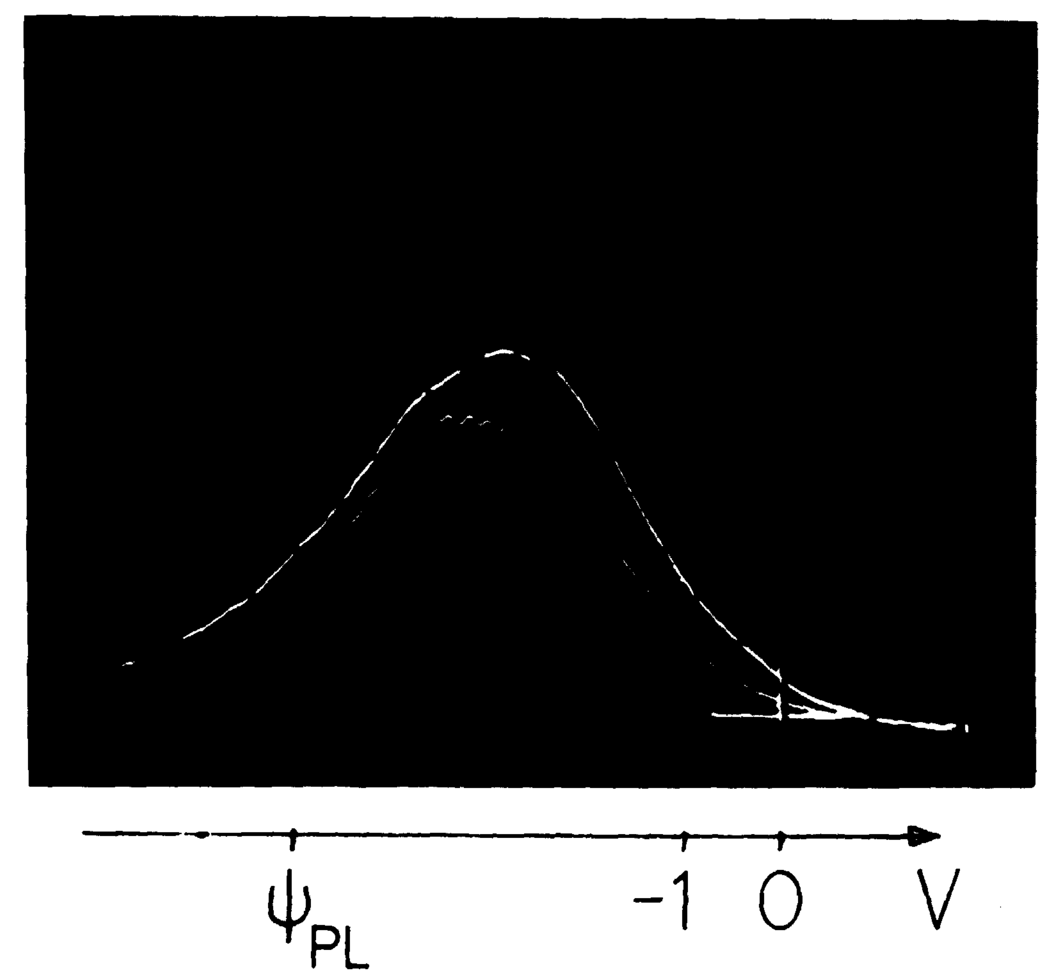

Fig. 2. The ion energy distribution measured with the electrostatic energy analyser. Upper trace: The electrons unheated
Lower trace: The electrons heated by cyclotron resonance.

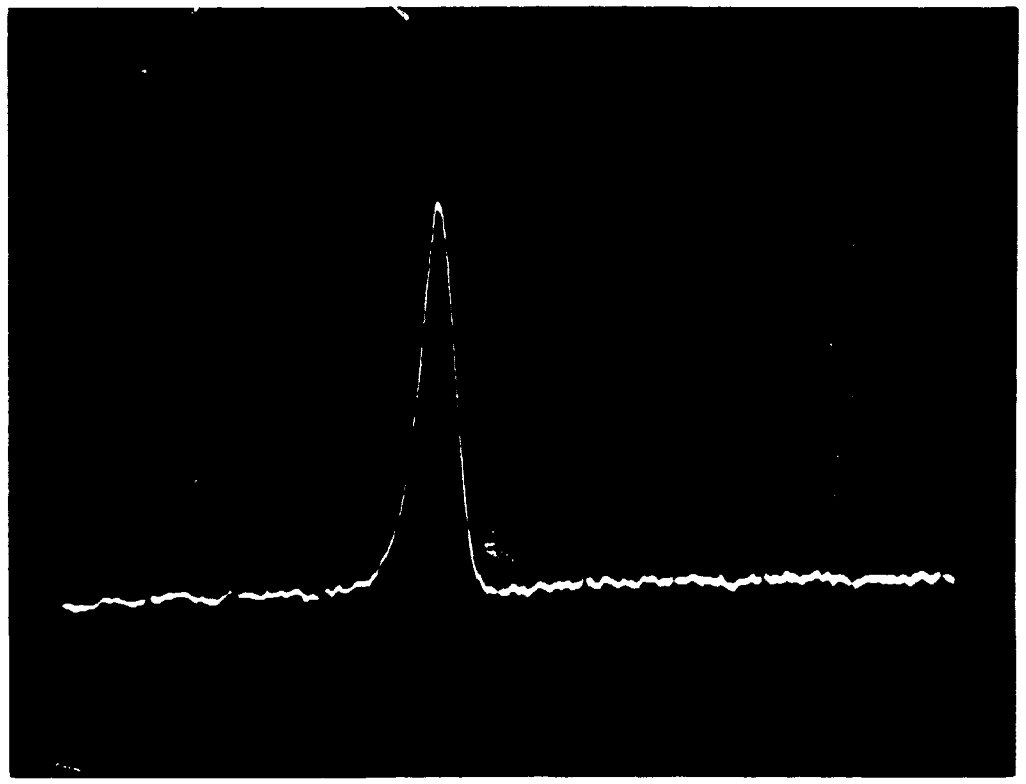

FIG. 3a

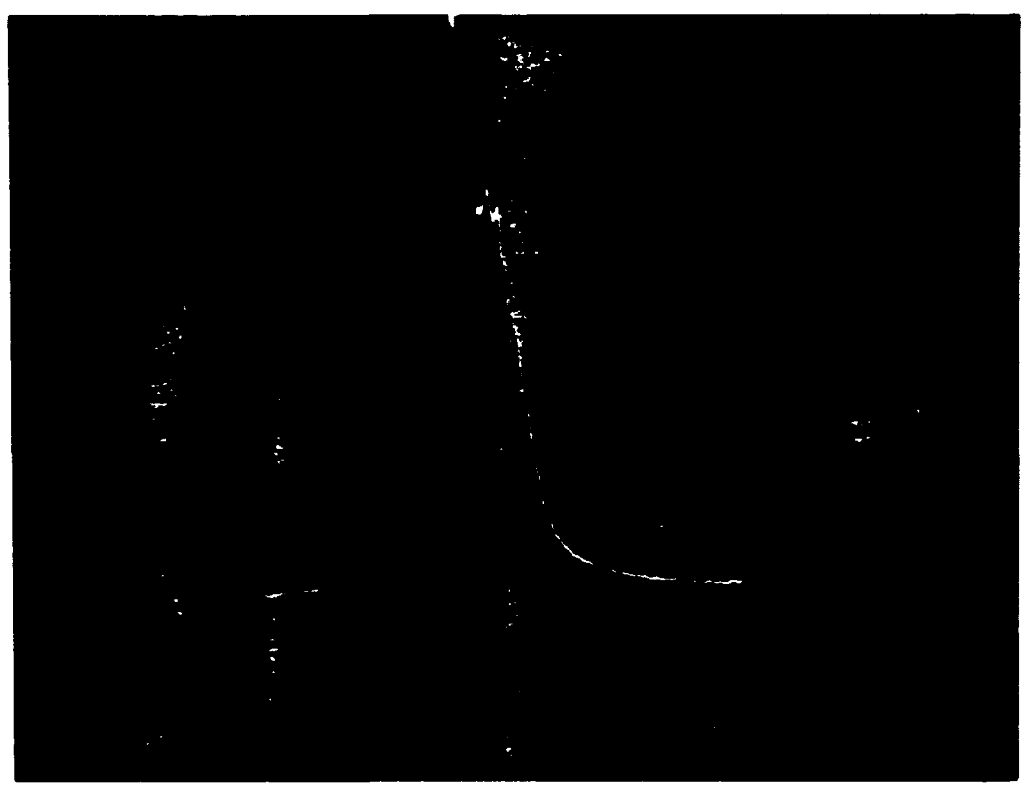

FIG.3b

Fig. 3a. **The** electron energy distribution for unheated electrons. The **figure shows** the differentiated Langmuir probe characteristic.
b. **The** electron energy distribution when the electrons are heated by **cyclotron** resonance, using the resonator.

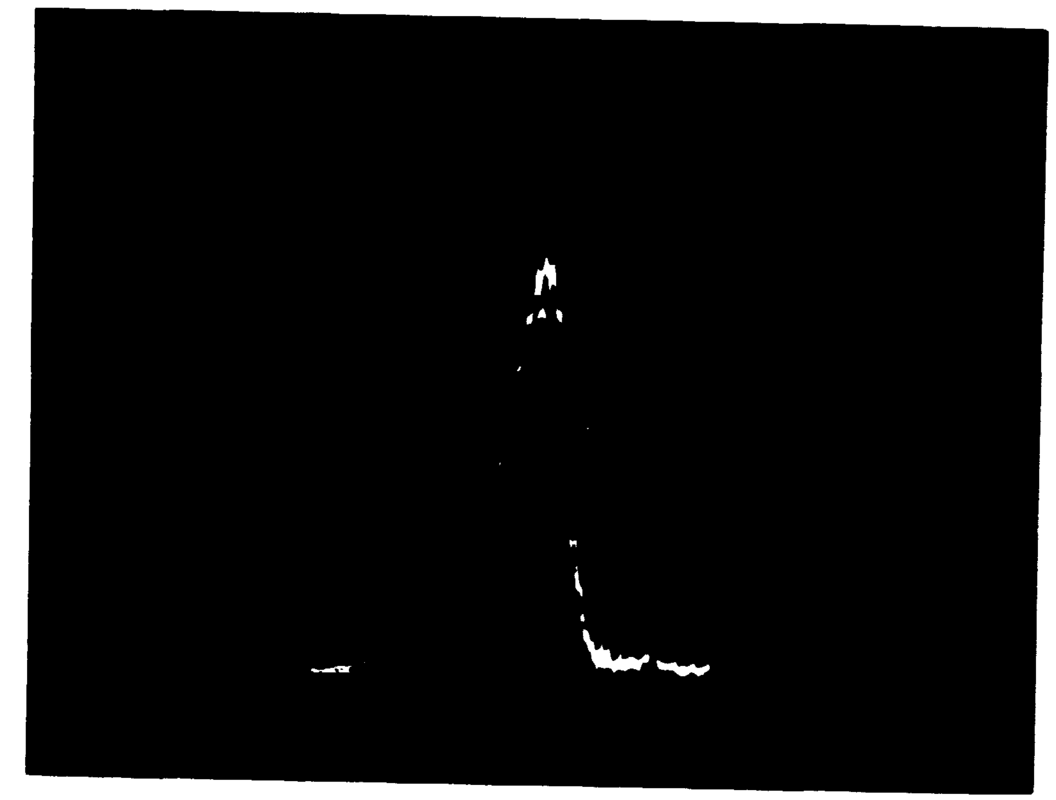

Fig. 4. Electron energy distribution.
Upper trace: The electrons heated by cyclotron resonance, using a conventional μ-wave horn.
Lower trace: The electrons unheated.

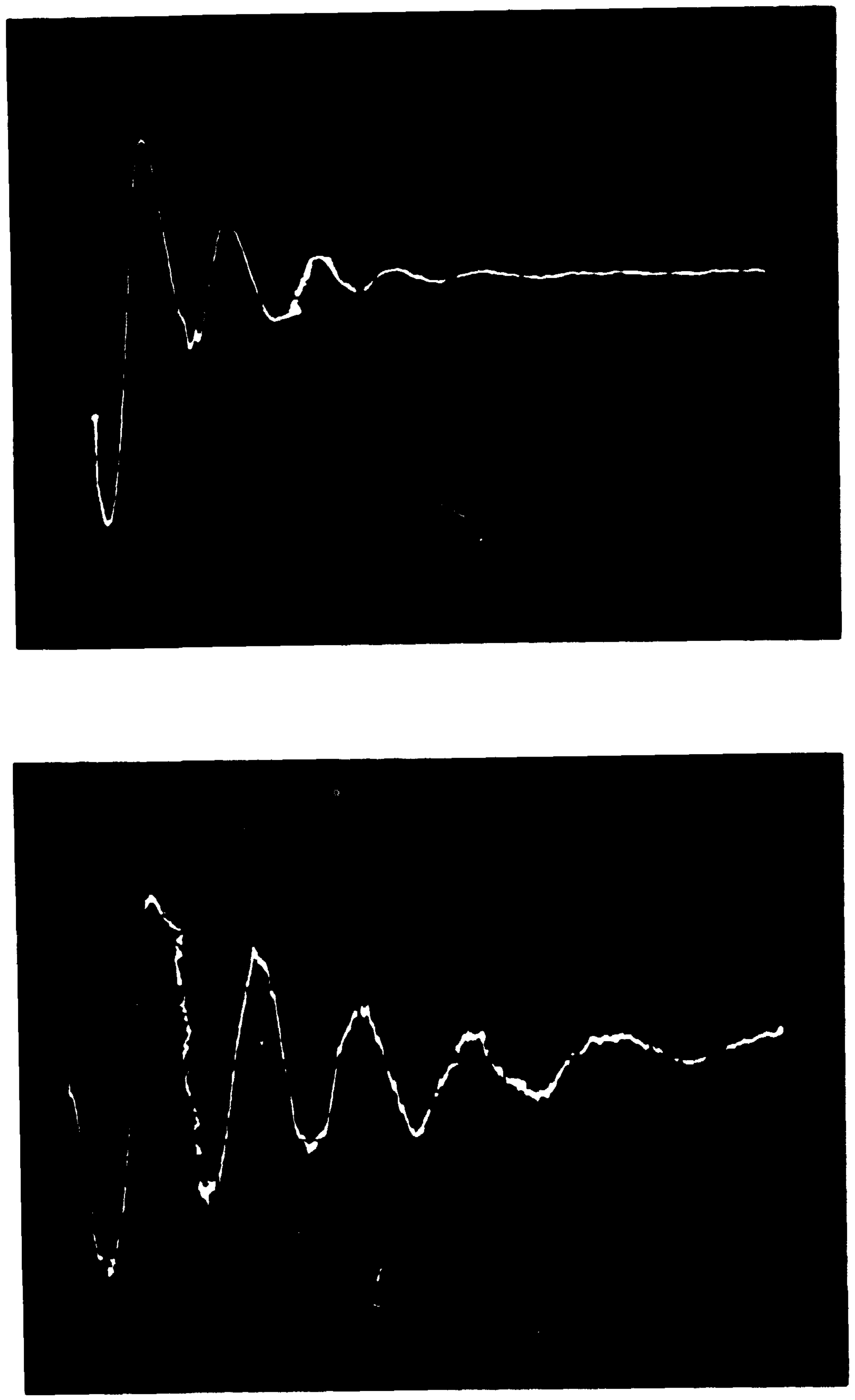

Fig. 5. Interferogram of a grid-excited, 100 kHz wave.

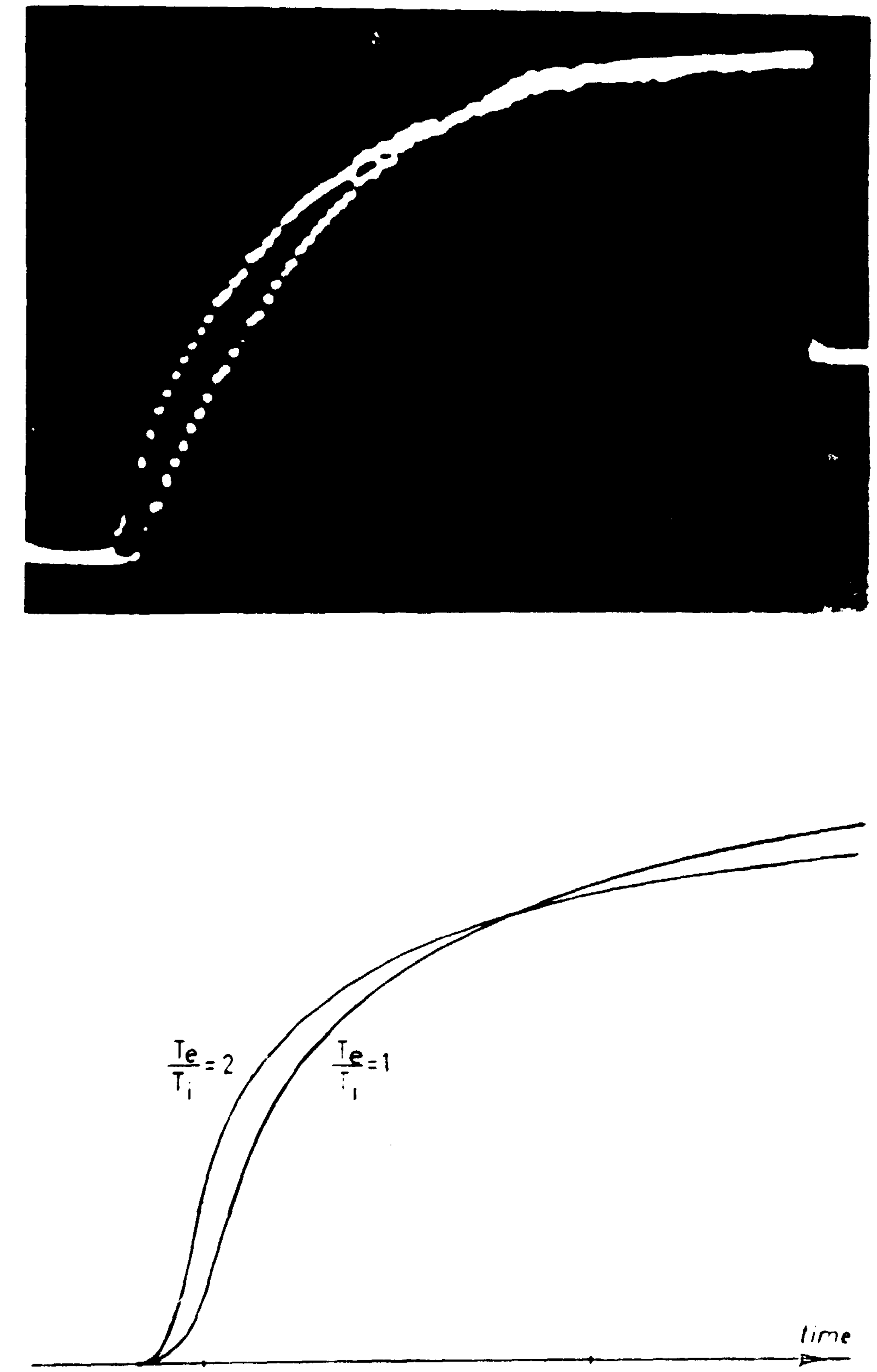

Fig. 6a. The ion flux as a function of time in the case of a step-like initial perturbation. The two traces correspond to two different electron temperatures.
b. Calculated curves where the ion distribution in the perturbation is the same.

Fig. 7. Differentiated Langmuir probe characteristics corresponding to heated and unheated electrons.

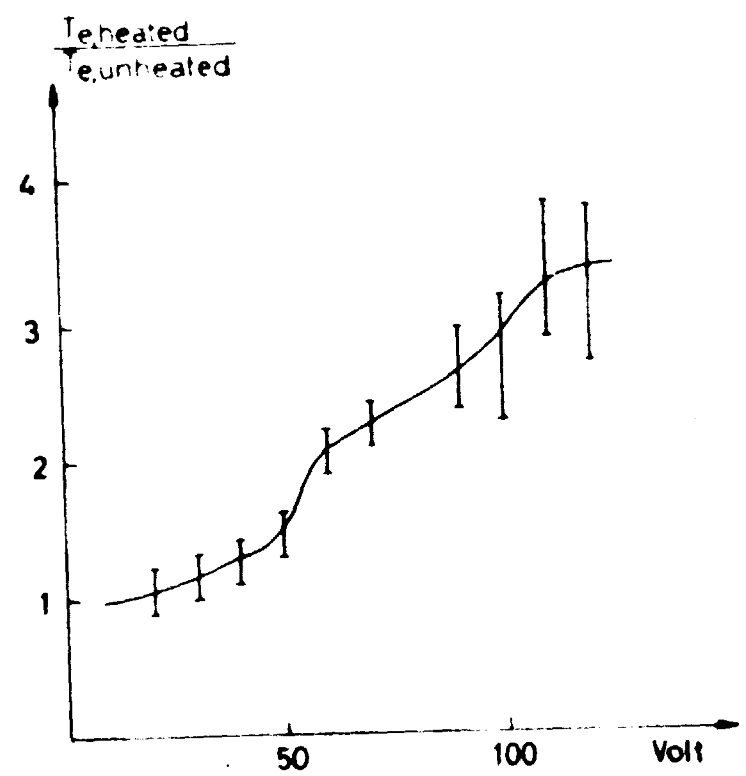

Fig. 8. The electron temperature measured with a Langmuir probe as a function of the grid voltage.

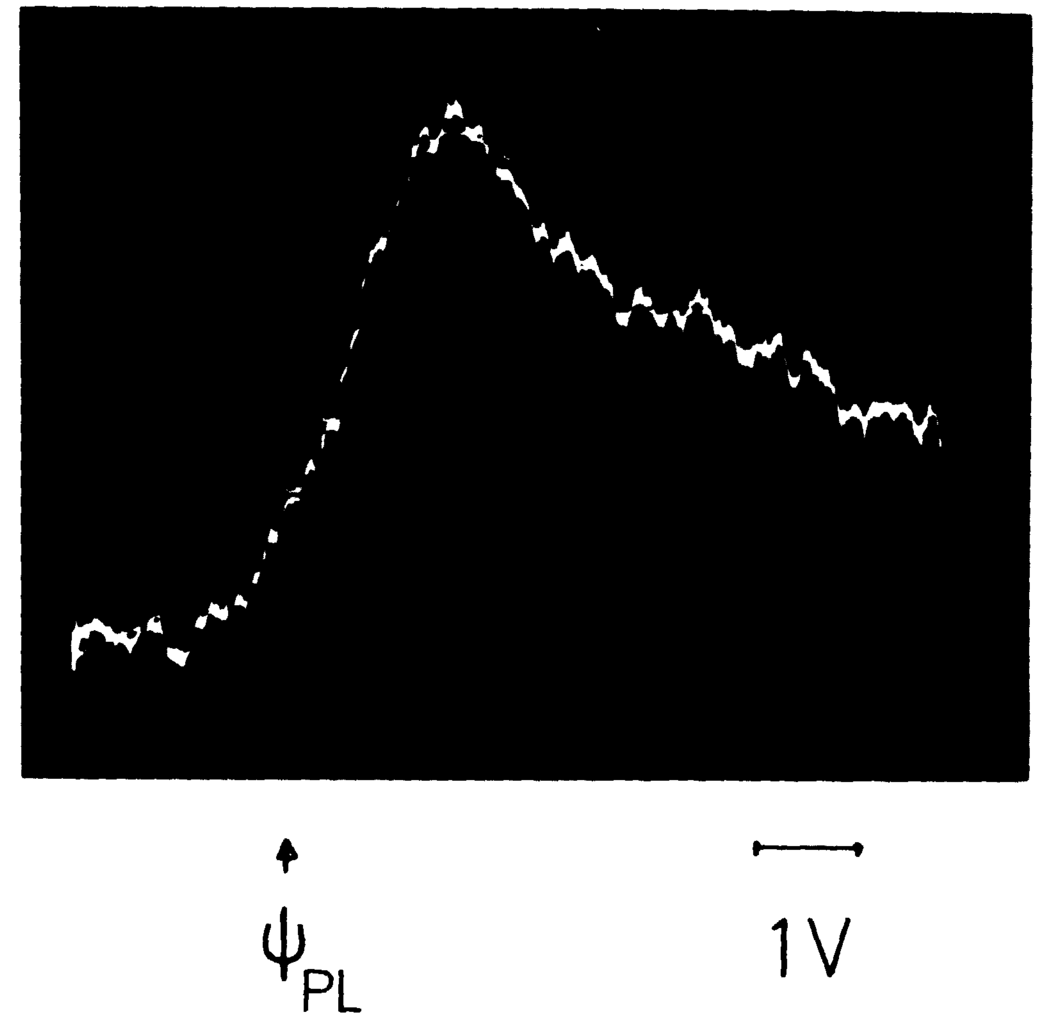

Fig. 9. Ion energy distributions obtained with the electrostatic energy analyser. The two traces correspond to heated and unheated electrons. The ions were cooled by charge exchange during these measurements.