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ANOMALOUS DISSIPATION OF MICROWAVE ENERGY IN A COLLISIONLESS PLASMA

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A number of recent investigations [1 - 3] are devoted to various aspects of the anomalous interaction of microwaves with a collisionless plasma, namely, the heating of the electronic component [1], absorption of microwave energy in a plasma [2], and decay of a bounded plasma [3]. A common property of the foregoing phenomena was the fact that the frequency of the Coulomb collisions of the electrons with the ions, $\nu_{ei} \sim 10^5 - 10^6$ sec^{-1}, was lower by 3 - 4 orders of magnitude than the effective collision frequency ν_{eff} needed to give rise to the observed dissipative effects. Theoretical investigations of instability of a plasma in a microwave field [4 - 7] give grounds for assuming that the anomalous increase in the dissipation of the microwave energy is due to the onset of parametric instability in the plasma. Measurements [3] of the threshold value of the electric field of the wave in anomalous decay, as a function of the plasma density, have shown qualitative agreement with the theory of [5], viz., the threshold intensity decreased by 2 - 3 orders of magnitude when the plasma electron density n approached a critical value n_0 at which the Langmuir electron frequency equals the circular frequency of the external field, $\omega_{Le} = \omega_0$.

The purpose of the present investigation was to study simultaneously the effects of wave absorption and electron heating in a uniform plasma layer.

The experiment was performed with a plasma stream of uniform density [3] crossing a rectangular waveguide perpendicular to the broad wall, with an ion translational velocity 10^7 cm/sec. To this end, a length of 15 cm of one of the broad walls of the waveguide was replaced by a conducting grid. The waveguide was excited in the 10 cm band at the H_{10} mode, in which the direction of the electric-field force lines coincided with the direction of motion of the plasma stream through the waveguide. As is well known, the electric field intensity varies only along the broad wall of the guide: $E(x) = E_0 \cos(\pi x/a)$ (a is the dimension of the broad wall). Cutoff of wave propagation in the plasma-filled waveguide begins at a density $n = 0.6n_0$ (in the presence of anomalous dissipation). We note immediately that the concentration of the ions in the plasma stream remained unchanged even at high level of microwave energy dissipation in the plasma. The absence of anomalous decay under these conditions will be explained below. The duration of the microwave power pulse was 3×10^{-6} sec. The anomalous distribution assumed its steady-state value within a time $\Delta t \sim 10^{-7}$ sec.

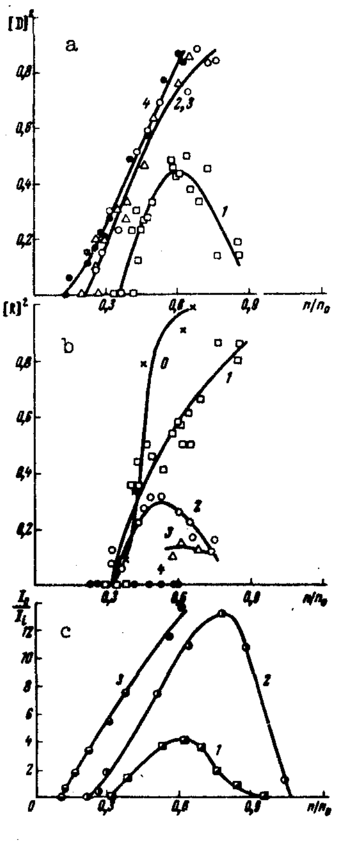

Fig. 1

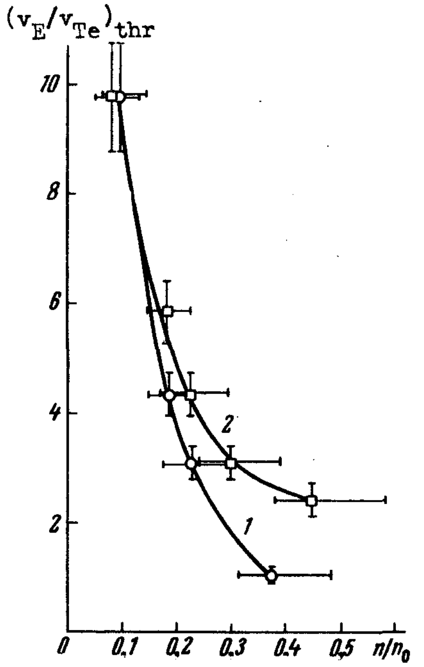

Fig. 2

Fig. 1. Absorption coefficient $|D|^2$, reflection coefficient $|R|^2$, and relative accelerated-electron current density I_e/I_i vs. the relative plasma density n/n_0. The numbers of the curves in Figs. 1a and 1b correspond to the following values of E_0: 0 - 3 V/cm, 1 - 0.7 kV/cm, 2 - 3.1 kV/cm, 3 - 4.2 kV/cm, 4 - 7 kV/cm. The curves of Fig. 1c were obtained at the following probe-collector potential U_k (in kV) and field inventity E_0 (in kV/cm): 1 - $U_k = 0.7$, $E_0 = 2.2$; 2 - $U_k = -0.7$ kV, $E_0 = -3.1$; 3 - $U_k = -2.0$, $E_0 = 7.0$.

Fig. 2. Threshold values of v_E/v_{Te} vs. the relative density n/n : 1 - for the start of the microwave power absorption, 2 - for the start of the accelerated current.

The dependence of the measured reflection coefficient $|R|^2$ of a wave of low intensity, $E_0 \sim 1$ V/cm, from a plasma having different concentrations corresponds to that calculated for a collisionless plasma (Fig. 1b - 0). It is obvious that the absorption coefficient $|D|^2$ is zero in this case. When the intensity increases to $E_0 = 0.7$ kV/cm and above, the dependence of $|R|^2$ on n becomes weaker, but strong absorption, $|D|^2 \to 1$, appears in the plasma.

At large values of E_0, the absorption started at lower densities (compare curves 1 - 4 in Fig. 1a). In the case corresponding to curves 1 of Figs. 1a and 1b, the dissipation was still weak and a decrease in the volume in which the plasma interacted with the microwave field, due to screening of the field at $n \geq 0.6n_0$, led to a decrease of absorption with increasing n. At larger values of E_0, the absorption of the microwave energy was practically complete. In the case $E_0 = 7$ kV/cm (curves 4 of Figs. 1a and 1b) there was no reflection, within the limits of measurement error, there was no reflection at any concentration. The nonmonotonic behavior of the reflection coefficient $|R|^2$ with increasing concentration (2 and 3 of Fig. b) can be attributed only to the sharp increase of absorption at $N \gtrsim 0.5n_0$).

The measurements have shown that simultaneously with the absorption of the wave microwave energy there is also "heating" of the electron plasma stream. Let us compare the obtained dependences of $|D|^2$ and $|R|^2$ on n/n_0 with dependence of the current density of the plasma electrons accelerated along the force lines of the wave's electric field, normalized to the density of the ion current in the plasma (in the same direction): $I_e/I_i = f(n/n_0)$ (Fig. 1c). In the absence of a microwave field the saturation electron current yielded a ratio $I_e/I_i \sim 5$. In the measurement of the dependence of I_e/I_i on n/n_0, a negative potential U_k was applied to the probe collector in order to block the secondary electrons from the waveguide walls with energy $W_{se} \lesssim 2e^2E_0^2/m\omega_0^2$.

The accelerated electron energies W_e measured with the aid of a multigrid probe had mean values 4 keV at E_0 = 8 kV/cm and $n/n_0 = 0.6$, with maximum values 11 keV. It is seen from curves 1 - 3 of Fig. 1e that at large E_0 the current is produced at lower densities and increases more rapidly with increasing density.

The data of Fig. 1 were used to plot the threshold field intensity against the plasma density in dimensionless form (Fig. 2): $(v_E/v_{Te})_{thr} = f(n/n_0)$, where $v_{E.thr} = eE_{0.thr}/m\omega_0$ and $v_{Te} = \sqrt{kT_e/m}$ is the thermal velocity of the electrons. The plot was constructed for both the start of the absorption (Fig. 1a) and for the start of the accelerated electron current (Fig. 1c). The observed discrepancies are due only to incorrect observation of the thresholds of the accelerated-electron current in the presence of high negative potentials U_k. Thus, the dependence of the threshold fields on the plasma density, determined from the start of the absorption and "heating" of the electrons is qualitatively the same as that determined from the plasma decay [3], but the values of the threshold fields turned out to be higher by one order of magnitude in the given geometry of the experiment.

The angular divergence of the beam of accelerated electrons relative to the direction of the field E did not exceed ±7°. Thus, owing to the anisotropic character of the "heating" of the electron, their pressure was applied to the waveguide walls and not on the free plasma boundaries. The escape of accelerated electrons should not charge the plasma, since they are replenished by secondary electrons from the waveguide walls. This explains why the plasma does not decay.

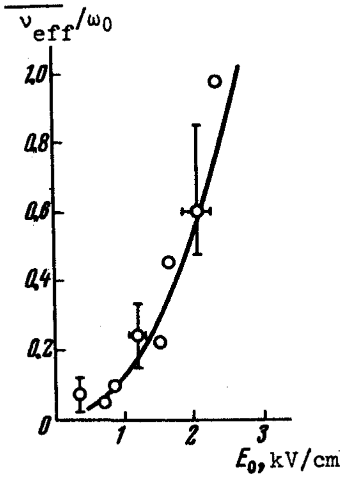

Fig. 3. Dependence of the relative values of the average effective collision frequency $\overline{\nu_{eff}}$ on the field intensity E_0, obtained for $n/n_0 = 0.6$.

The data of Fig. 1b were used to find the dependence of the mean effective collision frequency $\overline{\nu_{eff}}$, normalized to ω_0, on the field intensity E_0 at $n = 0.6n_0$ (Fig. 3). At $E_0 \sim 3$ kV/cm we have $\overline{\nu_{eff}}/\omega_0 \sim 1$. An estimate of the frequency of electron collisions with the waveguide walls, with energy $(W_{se})_{max}$, yielded a value smaller than $\overline{\nu_{eff}}$ by two orders of magnitude.

Conclusions: 1) Anomalous absorption of microwave energy in an isotropic plasma is accompanied by anomalous "heating" of the electrons; this "heating" has an unisotropic character and is maximal in the direction of $\vec{E}$.

2) The thresholds of both phenomena are the same and decrease when the concentration approaches n_0; this is in qualitative agreement with the theory of parametric instability [5].

3) The anomalous dissipation is characterized by large values of $\overline{\nu_{eff}}$, higher by not less than one or two orders of magnitude than the electron-wall collision frequency, and higher by three or

four orders than ν_{ei}. $\overline{\nu_{eff}}$ varies like E_0^2 with increasing E_0, and perhaps even more rapidly.

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INVESTIGATION OF THE CATAPHORESIS EFFECT IN A CADMIUM-VAPOR LASER

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When a dc discharge is excited in a mixture of gases having different atomic numbers and ionization potential, separation of the components - cataphoresis - is observed [1]. Goldsborough [2] used this effect to introduce cadmium vapor into the discharge gap in an He-Cd laser. The cadmium ions move in this case in the discharge gap from the anode to the cathode. Owing to the Doppler effect, the spectral emission lines of the ions, when observed in the direction of their motion and in the opposite direction, are shifted by an amount

$$\Delta\nu = 2\nu_0 \frac{V}{C}.$$

We have investigated experimentally the cataphoresis effect when an He-Cd dc discharge tube is placed in a traveling-wave generator.

The experimental setup is shown in Fig. 1. The resonator, made up of one spherical and two flat mirrors, has the form of an equilateral triangle of 50 cm on each side. The spectral composition of the laser radiation was analyzed with a ring scanning interferometer 2, placed past the photomixer 3. The use of a ring interferometer eliminates completely the influence exerted on the laser by the radiation reflected from the input mirror of the interferometer. The resonator length can be adjusted with the aid of an electrostrictor in a range ±1 μ.

The gas-discharge tube 1 has a discharge-gap length 200 mm and a channel diameter 1.8 mm. Cadmium (the isotope Cd^{114}) is placed near the anode. The tube was sealed off at a pressure 3 mm Hg.

Figure 2 shows and explains the spectrum obtained with a scanning interferometer, of oscillations produced in two opposing beams. When the perimeter of the ring resonator is rearranged and the pump level is suitably chosen, generation is observed in the first beam (a), then in two beams simultaneously (b), and eventually in the second beam (c). The distance between the frequencies of the generated oscillations equals 3C/L (600 MHz). The magnitude of the observed frequency shift between the generated oscillations is determined by the velocity of the ions along the tube axis and by the natural frequencies of the resonator. Distances of 600 MHz between the centers of the amplification