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A b s t r a c t

A summary of the results of numerical experiments (particle simulation) is given. The numerical experiment on studying one-dimensional Langmuir waves in collisionless plasma were performed in a wide range of parameters: $\frac{E_o^2}{8\pi nT} \sim 3\cdot 10^{-8} \div 10^2$; $\frac{V_{ph}}{V_T} \sim 2.5 \div 160$. The limits of validity of theoretical models describing a one-dimensional Langmuir wave were found for the theory of damping of the finite-amplitude Langmuir wave ($E_o^2/8\pi nT \le \frac{1}{2}(K_o r_d)^2$), for the linear (for $V_{ph}/V_T \geq 10$, $E_o^2/8\pi nT < 10^{-3}/(K_o r_d)^2$) and nonlinear (for $V_{ph}/V_T \geq 10$, $E_o^2/8\pi nT < K_o r_d$) theory of wave instability. The development of the instability and damping was investigate and the main processes were analysed.

Langmuir waves - one of the simplest phenomena in a plasma - have been carefully analysed in the theory. The theory of damping of the waves of small and finite amplitude, the linear and nonlinear theory of Langmuir wave instabilities have been constructed. However, the regions of validity of most of these theoretical models have not been clearly defined. Laboratory experiments have, for few exceptions, a qualitative character and do not permit to make conclusions about validity of the theory. The numerical experiment (particle simulation) gives a possibility to have some progress since it is equivalent to the complete solution of the kinetic equation. Such numerical experiment describes a plasma model whose region of validity is broader than that of mathematical models involving a small parameter, or using the hydrodynamic description (e.g., the models based on Zakharov equations /1/). Performing numerical experiments in a wide range of parameters, it is possible to find the limits of validity for theoretical models and to clear up what type of phenomena is essential in either range of parameters.

Numerical experiments /2-8/ devoted to a study of the damping and instability of Langmuir waves were performed in the range of initial parameters: $\frac{E_o^2}{8\pi nT} \sim 3\cdot10^{-8} \div 10^2$, $V_{ph}/V_T \sim 2.5 \div 160$, in a one-dimensional system with periodic boundary conditions. At the initial moment the Maxwellian velocity distribution was given for the ions and electrons. The ions were uniformly distributed over the length of the system. The Langmuir wave was given by the density and velocity perturbation of the electrons, which corresponds to a linear wave. The development of the wave was studied without external pumping. Reliability of the method and program was checked by comparison of the numerical experiment with the theory consistent with the laboratory experiment (damping of small but finite amplitude waves, interaction of the low density electron beam with plasma). The limits of validity of the numerical experiment are determined by noises and cut off of the distribution function due to the limited number of particles (in the numerical experiment under consideration, as a rule, $N_i = N_e = 10^4$, and the distribution function is cut off at $V \sim 2V_T$).

Damping of Langmuir waves.

"Boundary of electron nonlinearity" /4,7,8/

The region of small but finite amplitudes of the Langmuir waves has been studied thoroughly. For this region the theory was constructed /9/ under the condition $\omega/\omega_B >> \left(V_{ph}/V_T\right)^2$, that is equivalent to the conditions $\frac{e\varphi_0}{T} << \left(\frac{V_T}{V_{ph}}\right)^2$, $\sqrt{\frac{e\varphi_0}{m}} << V_T \cdot \frac{V_T}{V_{ph}}$, and $E_0^2/8\pi nT << \frac{1}{2}(K_0 r_d)^6$ ($\omega_B = k\sqrt{\frac{e\varphi}{m}}$ is the trapped particle oscillation frequency). The theory takes into account the motion of resonant electrons which are trapped at the initial time moment. The nonresonant part of the distribution function is assumed to be unperturbed. According to the theory /9/, at the initial stage, $t < \frac{T_B}{2}$, $T_B = \frac{2\pi}{\omega_B}$ the wave is damped with the Landau damping rate γ_L. At $t > \frac{T_B}{2}$ the wave amplitude oscillates with the period $\sim T_B$ (Fig.1). Theoretical results are in a good agreement with the results of the laboratory /10/ and numerical /11/ experiments performed in the region ($\frac{e\varphi_0}{T} << 1$, $\sqrt{\frac{e\varphi_0}{m}} << V_T$) somewhat broader than the region of validity of the theory /9/.

Our numerical experiment /4,8/ was performed in a wider range of initial wave parameters including the region from $\frac{e\varphi_0}{T} << 1$ up to $e\varphi_0/T >> 1$: $\frac{E_0^2}{8\pi nT} \sim 3\cdot10^{-4} \div 10^2$; $\frac{V_{ph}}{V_T} \sim 2.5 \div 20$; $(K_0 r_d)^2 \sim 2\cdot10^{-3} \div 3\cdot10^{-1}$; $\sqrt{\frac{e\varphi_0}{m}}/V_T \sim 0.2 \div 20$; $\frac{e\varphi_0}{T} \sim 4\cdot10^{-2} \div 4\cdot10^2$; $\sqrt{\frac{e\varphi_0}{m}}/V_\varphi \sim 0.1 \div 0.8$. The ions were taken immobile, $\frac{M}{m} = 10^{10}$, to exclude the wave instability (decay, modulational instability and so on).

In the region of low amplitude waves, where the perturbed velocity is less than the thermal one, $\sqrt{\frac{e\varphi_0}{m}} \lesssim V_T$ and $\frac{e\varphi_0}{T} \lesssim 1$ (in this region the range $V_{ph}/V_T \sim 2.5 \div 4.2$ was only studied), the numerical experiment results agree with theoretical results /9/, and the damping is described by the Landau damping rate (Fig.1) /4,8/. When the perturbed velocity becomes higher than a thermal one: $\sqrt{\frac{e\varphi_0}{m}} > V_T$ and $\frac{e\varphi_0}{T} > 1$, the damping rate becomes higher compared to γ_L. The ratio γ/γ_L increases exponentially with increasing the initial amplitude and phase velocity of the wave, so that the damping rate can exceed γ_L by many orders of magnitude (Fig.2). In this region the damping rate depends practically linearly on the number of electrons trapped by the wave. This number also increases exponentially with an increase of the amplitude and phase velocity of the wave. The mechanism of the phenomenon resulting in the increase of the damping rate is the trapping and acceleration of the electrons from the main, nonresonant part of the velocity distribution function (within the studied range of parameters these are electrons with unperturbed velocities $V < 2V_T$) due to its strong perturbation by the wave field /8/.

In construction of theoretical models it is usually assumed that the damping of Langmuir waves is described by the

Landau damping rate, so that in the region $V_{ph}/V_T \gg 1$, $k_o r_d \ll 1$ the damping is assumed to be negligibly small. The results of our numerical experiment show that the Langmuir wave damping can be described by the Landau damping rate only in the region $e\varphi_o/T \lesssim 1$, $E_o^2/8\pi nT \lesssim \frac{1}{2}(k_o r_d)^2$. In the region $e\varphi_o/T > 1$, $E_o^2/8\pi nT > \frac{1}{2}(k_o r_d)^2$ the damping rate can essentially exceed γ_L. Note, that the condition $E_o^2/8\pi nT > \frac{1}{2}(k_o r_d)^2$ coincides with the condition for exciting the supersonic modulational instability.

In Figs.3 and 4 are shown the curves of constant damping rate which correspond to the initial parameters of the waves damping with the same damping rate. In the region $e\varphi_o/T \lesssim 1$ they are vertical lines $\gamma = \gamma_L$; in the region $V_{ph}/V_T \gtrsim 10$ - the straight lines $\frac{E_o^2}{8\pi nT} \sim \frac{\alpha'}{(k_o r_d)^2}$ $(\alpha' \sim 3.8 \cdot 10^{-2} \div 2.3 \cdot 10^{-1})$, or $\sqrt{\frac{e\varphi_o}{m}}/V_T \sim \alpha'' \frac{V_{ph}}{V_T}$ $(\alpha'' \sim 0.54 - 0.82)$. The curves of constant damping rate may be used to characterize the validity limits of theoretical models which do not take into account the damping.

The region of validity of theoretical models is often determined by the condition that the effects due to electron nonlinearity are negligibly small. The numerical experiment allows the formulation of these conditions. The numerical experiment dealing with the study of electron nonlinearity /4, 7/ was carried out in the range of initial wave parameters: $\frac{E_o^2}{8\pi nT} \sim 10^{-8} \div 10^3$; $\frac{V_{ph}}{V_T} \sim 2.5 \div 160$; $(k_o r_d)^2 \sim 4 \cdot 10^{-5} \div 3 \cdot 10^{-1}$.

In a monochromatic wave the electron nonlinearity occurs when the perturbed electron velocity becomes close to the phase velocity. In this case, the electron is in the accelerating field phase for a longer time, so it gains a higher velocity in comparison with the linear case. This leads to an increase of the energy of oscillations of the electrons as compared to the field energy $\Delta W_e/W_E > 1$ and also to an increase of electron density in the accelerating field phases $\tilde{n}_+/\tilde{n}_- > 1$, so that the density perturbation is sharpened, while the wave field $E(x)$ is steepened. This is equivalent to the appearance of higher modes of the electric field and electron density with the same phase velocity as the basic ones. The case of strong electron nonlinearity is the trapping of electrons by the wave. In this case, the trapped electrons are accelerated up to $V \sim V_{ph} + 2\sqrt{\frac{e\varphi_o}{m}}$. Just this effect determines the high damping rate considered above.

The "boundary of electron nonlinearity" - the initial parameters of the waves at which electron nonlinearity becomes essential - was determined basing on the difference of the ratios $\Delta W_e/W_E$ and $\tilde{n}_+/\tilde{n}_-$ from unity (the difference of about 5-10% was assumed to be essential) /4,7/. The curve found is shown in Figs.3 and 4. In the region of high phase velocities $V_{ph}/V_T \gtrsim 10$ it is a straight line $E_o^2/8\pi nT \sim 10^{-3}/(k_o r_d)^2$, or $\sqrt{\frac{e\varphi_o}{m}}/V_T \sim 0.2\, V_{ph}/V_T$. The "boundary of electron trapping" with unperturbed velocities $\sim 2V_T$ was determined basing on a form of the phase plane. It appears to be close to the line of constant damping rate with $\gamma/\omega_{oe} \sim 3 \cdot 10^{-2}$. In the region of high V_{ph}/V_T it is a straight line $E_o^2/8\pi nT \sim \frac{6 \cdot 10^{-2}}{(k_o r_d)^2}$, or $\sqrt{\frac{e\varphi_o}{m}}/V_T \sim 0.6\, \frac{V_{ph}}{V_T}$.

Instability of travelling Langmuir waves - initial stage /6,7/

The instabilities of a one-dimensional Langmuir wave were intensively studied in the theory. It was found that the Langmuir wave is unstable, and the type of instability depends on the initial parameters of the wave. Most detailed theoretical analysis of the instabilities of a Langmuir wave, the review and analysis of the results available are given in Ref./12/. The scheme showing the regions of the instabilities of different types from Ref./12/ with some additions (A.M.Rubenchik, private communication) is presented in Fig.4.

I. Modulational (static) instability: $\varkappa < K_o$, $\lambda_m > \lambda_o$, $\varkappa$, λ_m - the wave vector and wavelength of a mode with maximum growth rate, K_o, λ_o - the same for a given wave.

II. Presonic modulational instability: $\varkappa > K_o$, $\lambda_m < \lambda_o$.

III. Supersonic (hydrodynamic) modulational instability: $\varkappa > K_o$, $\lambda_m < \lambda_o$.

IV. Modified decay instability: $\varkappa \sim 2K_o$, $\lambda_m \sim \frac{\lambda_o}{2}$.

V. Decay instability: $\varkappa \sim 2K_o$, $\lambda_m \sim \frac{\lambda_o}{2}$.

In Fig.4 are also shown the "boundary of electron nonlinearity" and the lines of constant damping rate. The "boundary of nonlinearity" shows the limit of validity of the linear theory. Note, that the boundaries of instability regions depend on the ratio $\frac{M}{m}$, whereas the "boundary of nonlinearity" and the lines of constant damping rate are independent of it, so the region of validity of the linear theory is varied with $\frac{M}{m}$. In Fig.4 the regions of instability for hydrogen ions, $\frac{M}{m}$ = 1836, are shown.

The numerical experiment on studying the initial stage of instability /6,7/ was performed in the range of initial wave parameters: $E_o^2/8\pi nT \sim 3\cdot10^{-8}\div10^2$, $V_{ph}/V_T \sim 3\div160$, $(K_o r_d)^2 \sim 4\cdot10^{-5}\div 2\cdot10^{-1}$, $\frac{M}{m} = 10^2$, in some cases $\frac{M}{m} = 10^3$, so that all of the instability regions are included. The region of instabili-

ties I-III from $\frac{E_o^2}{8\pi nT} \ll (K_o r_d)^2 < \frac{m}{M}$ to $\frac{E_o^2}{8\pi nT} \gg \frac{m}{M} > (K_o r_d)^2$ (variation in the amplitude $E_o^2/8\pi nT \sim 10^{-8}\div10^2$ at $V_{ph}/V_T = 16$, $(K_o r_d)^2 = 3.9\cdot10^{-3}$) is analysed in a considerable detail.

In the range of all parameters lying below the "boundary of trapping" and including the region of validity of the linear theory, and also all of the regions I-V, the instability of one type is observed. This instability is due to the perturbation of ion velocities and ion density by the electric field of the Langmuir wave, that stimulates the nonresonant decay $\ell_{K_o} \to \ell_{2K_o} - S_{K_o}$ with $\varkappa \sim 2K_o$ and $\lambda_m \sim \lambda_o/2$. The instability shows itself in the formation of the density cavity with $\lambda = \lambda_o$ and in the modulation of the wave with $\lambda_m < \lambda_o$ (in spectral description - in the growth of ion mode with $K = K_o$ and the Langmuir mode with $K = 2K_o$). This instability may be called the "stimulated decay". It differs from all of the instabilities found in the theory. This difference is especially clear in the region of modulational instabilities I-III where the wavelength of the mode with maximum growth rate (modulation length), according to the theory, must depend on the wave amplitude and must decrease with its increase. Note, that in the region I $\lambda_m > \lambda_o$, in the regions II and III - $\lambda_m < \lambda_o$. The modulation length observed in the numerical experiment does not depend on the wave amplitude and is always less than the initial wavelength. The reason of this difference from the theory consists, apparently, in that the theory does not take into account the ion perturbation by the initial wave field because of the averaging over time intervals $\sim 1/\omega_{oe}$, so the solution equivalent to the "stimulated decay" is lost. Of course, there is a question about the problem formulation. In the numerical experiment, at the initial moment the uniform distribution of the ions $n_i(x) = const$ and the electron density and velocity perturbations to set a Langmuir wave are given. Such a formulation of the problem seems reasonable because it corresponds to a real case when the Langmuir wave is excited during a short time in the homogeneous plasma in some way (e.g., by an electron beam).

Instability of travelling Langmuir waves -

nonlinear stage /2,3,4,6,8/

The difference of the instability observed in the numerical experiment from the theoretical one should show itself at the nonlinear stage of instability. Especially significant this difference can be in the region I $E_0^2/8\pi nT < (K_0 r_d)^2$, where theoretical instability must result in the wave modulation with $\lambda_m > \lambda_0$ and at the nonlinear stage - in formation of an envelope soliton with $\Delta X > \lambda_0$ /12/, whereas "stimulated decay" leads to the modulation with $\lambda_m < \lambda_0$. In the numerical experiment, in this region the nonlinear stage of instability was not studied because of high level of noises.

The difference can prove to be not so significant in the regions II and III, $E_0^2/8\pi nT > (K_0 r_d)^2$, where theoretical instability must lead to the wave modulation with $\lambda_m < \lambda_0$, and the ponderomotive force must play a main role. According to the theory, the development of instability in this region must result in formation of a quasi-stationary Langmuir soliton with parameters depending on the initial wave energy and $\Delta X < \lambda_0$

/12/. Following to /13,14/, the soliton field in the case when the group velocity is equal to zero is described by the formula

$$E(x,t) = \frac{E_m}{\operatorname{ch} \varkappa_0 x} \sin(Kx - wt)$$

where E_m is the maximum electric field. The soliton width at the level $1/e\ E_m$ is

$$\frac{\Delta X}{r_d} = \left(\frac{48}{E_m^2/8\pi nT}\right)^{1/2}; \quad \varkappa_0 = \frac{2}{\Delta X}$$

The maximum density perturbation is

$$\left(\frac{\tilde{n}}{n_0}\right)_m = \frac{1}{2}\,\frac{E_m^2}{8\pi nT}$$

The numerical experiment on studying the nonlinear stage of instability /2-4,6/ was carried out within the range of the initial wave parameters: $\frac{E_0^2}{8\pi nT} \sim 4\cdot10^{-2}-10^2$ at $\frac{V_{ph}}{V_T} = 16$, $(K_0 r_d)^2 = 3.9\cdot10^{-3}$, and also in the range $V_{ph}/V_T \sim 3\div160$, $(K_0 r_d)^2 \sim 3.9\cdot10^{-5}\div1.7\cdot10^{-1}$ at $\frac{E_0^2}{8\pi nT} = 1.6$; $\frac{M}{m} = 10^2$, and in some cases $\frac{M}{m} = 10^3$. Thus, the region $\frac{E_0^2}{8\pi nT} > \frac{m}{M} > (K_0 r_d)^2$ was studied.

At the initial stage of instability the "stimulated decay" leads to the formation of a density cavity and wave modulation with $\lambda_m < \lambda_0$. In the following development of instability, the Miller force (ponderomotive force) plays a main role, what results in carrying away the plasma from the region of maximum electric field intensity, in deepening the density cavity, and in further increasing the electric field intensity (Figs.5 and 6) /2,3,6/. So, at the nonlinear stage the development of instability is the same as that of modulational instability found theoretically (region III).

If the wave amplitude is low enough (case 6 /6,8/ - $E_0^2/8\pi nT = 4\cdot10^{-2}$; $V_{ph}/V_T = 16$; $E_0^2/8\pi nT = 0.5\, K_o r_d$), the development of instability leads to the formation of a quasi-stationary soliton with .quilibrium parameters (Fig.6, curve 6). This agrees with the theoretical result and confirms that, despite the difference at the initial stage, at the non-linear stage the instability is a modulational instability.

In the case of a higher amplitude (case 7 /6,8/: $\frac{E_o^2}{8\pi nT} = 10^{-1}$, $\frac{V_{ph}}{V_T} = 16$, $\frac{E_o^2}{8\pi nT} = 1.6\, K_o r_d$), the development of instability also leads to the formation of a soliton with equilibrium parameters (Fig.5; Fig.6. curve 7). But the soliton is not quasi-stationary in this case and is damped due to the trapping and acceleration of the electrons from the tail of the distribution function by short wavelength modes. Thus, this case shows the limit of validity of the nonlinear theory not taking account of damping.

In the case of a further increase of the amplitude (case 8 /2,3,6,8/: $\frac{E_o^2}{8\pi nT} = 3\cdot10^{-1}$; $\frac{V_{ph}}{V_T} = 16$; $\frac{E_o^2}{8\pi nT} = 4.8\, K_o r_d$), the equilibrium soliton is not formed but a fast growth of field intensity and a decrease of the field localization region are observed. The non-equilibrium soliton is here formed whose field $E(x,t)$ varies like a soliton field but the width Δx is more, and the depth of the density cavity is less than the equilibrium ones for the soliton with the same energy density. The non-equilibrium soliton continues to be compressed and begins to damp before it achieves the equlibrium soliton parameters. Therefore, in the range of parameters $\frac{E_o^2}{8\pi nT} > 1.6\, K_o r_d$ the collapse is observed.

If the initial parameters of the wave are higher than the

"boundary of electron nonlinearity", $\frac{E_o^2}{8\pi nT} > 10^{-3}/(K_o r_d)^2$, the development of modulational instability is limited by the damping (Fig.7, curves 9-11), and the collapse has no time to develop /4/.

If the initial parameters are in the region of strong damping, $E_o^2/8\pi nT > 4\cdot10^{-2}/(K_o r_d)^2$, ($\gamma/\omega_{oe} > 10^{-2}$), the wave is strongly damped from the very beginning, and the modulational instability does not develop (Fig.7, curves 12 and 13) /4/.

Thus, the numerical experiment shows that the nonlinear theory of modulational instability of a one-dimensional Langmuir wave, which results in the conclusion on soliton formation is valid only for a limited range of initial parameters of the wave: $\frac{E_o^2}{8\pi nT} < 1.6\, K_o r_d$.

To find the region of validity of the nonlinear theory is also possible with the help of simple arguments and the scheme from Fig.8 /8/. In this scheme in the coordinates $\frac{E^2}{8\pi nT} - (K r_d)^2$ the following curves are plotted: the curves of constant damping rate for $\gamma/\omega_{oe} \geqslant 10^{-2}$; the curve of equilibrium soliton parameters: $E_m^2/8\pi nT = 4.86\,(K r_d)^2$, $K = \frac{\pi}{\Delta x}$; and the curves of constant total wave energy: $\frac{E_o^2}{8\pi nT} = a\,(K_o r_d)$ (from $\frac{E_o^2}{16\pi nT}\lambda_o = \mathrm{const}$); the latter corresponds to different combinations of initial parameters E_o, V_{ph} at which the total energy of the waves is the same. On the other hand, at given initial parameters, such a curve roughly characterizes the variation in the parameters of the non-equilibrium soliton during its compression as practically the full wave energy is localized in this soliton. Intersection of the constant energy curve with the equilibrium soliton curve corresponds to soliton formation for the waves with any initial parameters but the same total energy.

If the constant energy curve intersects first the line of constant damping rate with fairly high γ, then for all the parameters with the same total energy, the collapse will be observed. In Fig.8 it is seen that the boundary curve is a line $\frac{E_o^2}{8\pi nT} \sim K_o r_d$, that is consistent with the results of the numerical experiment. Thus, the theory predicting the formation of a quasi-stationary soliton is only valid in the region of initial parameters of the wave $\frac{E_o^2}{8\pi nT} < K_o r_d$, and the known condition for its validity $E_o^2/8\pi nT << 1$ is insufficient.

The numerical experiment allows to analyse in detail the development of instability of a Langmuir wave and to investigat the phenomena playing a main role. We have already discussed the initial stage of instability - "stimulated decay" and the following stage - modulational instability - related to the action of the ponderomotive force.

In the development of instability an essential role also plays the process of wave conversion on the density perturbations. This process occurs when the density perturbations become large enough (in our range of parameters: $\tilde{n}/n_o \gtrsim 10^{-2}$). The conversion process $\ell_{K_o} + S_{K_i} \rightarrow \ell_{K_o \pm \beta K_i}$, $\beta = 1,2,3\ldots$, leads to the excitation of the backward waves and wave modes with shorter wavelengths, i.e. to the trapping of electric field in the density cavity and the formation of standing waves /2-4/.

The development of modulational instability leads to the formation of a non-equilibrium soliton which continues to be compressed. This soliton can be a Langmuir soliton (a bunch of travelling wave modes with definite relative phases), or a standing soliton (a bunch of standing wave modes) if the conversion becomes significant. The non-equilibrium soliton compression leads to the formation of a quasi-stationary soliton (Langmuir, or standing one), or to the damping /6/.

The damping results from the trapping of electrons by short wavelength modes excited during compression of the non-equilibrium soliton and the conversion. Due to intersection of the trapping regions of the modes, the trapped electrons are accelerated to high velocities, up to $V \sim V_{ph} + \sqrt{\frac{e\varphi}{m}}$ of the initial wave. If the initial wave parameters are far from the "boundary of trapping", the main part of the distribution function is perturbed slightly, so that the tail of accelerated electrons is only formed. The joint action of the conversion and trapping leads to a practically full absorption of field energy by plasma electrons /2-4/.

After damping of the electric field, the density cavities are filled with plasma, as a result of shock waves formation on the edges of the cavities. Their interaction leads to the development of ion turbulence and also to the appearance of accelerated ions /3/.

Thus, one can list the main processes playing a role in development of the instability and damping of a Langmuir wave in a one-dimensional system:

"Stimulated decay": $\ell_{K_o} \rightarrow \ell_{2K_o} - S_{K_o}$ related to the perturbation of ions by the initial field of a Langmuir wave;

Modulational instability associated with the carrying away of a plasma from the density cavity under the action of ponderomotive force;

Conversion of Langmuir waves on the density inhomogeneities: $\ell_{K_o} \pm S_{K_i} \rightarrow \ell_{K_o \pm \beta K_i}$, $\beta = 1,2,3\ldots$ resulting in excitation of backward waves and short wavelength modes;

Quasi-stationary soliton formation related to the equality of the ponderomotive force to plasma pressure;

Landau damping playing a role in the region $\frac{e\varphi}{T} < 1$, or $\frac{E^2}{8\pi nT} < \frac{1}{2}(kr_d)^2$;

Damping related to the trapping of nonresonant electrons by the wave due to a strong perturbation of the distribution function and playing a role in the region $\frac{e\varphi}{T} > 1$, or $\frac{E^2}{8\pi nT} > \frac{1}{2}(kr_d)^2$.

We have used the term "collapse" for the case when the instability due to the action of ponderomotive force leads to the damping of the field as, according to physical sense, this is just the same process which was found theoretically in the two-dimensional case /1/. However, if the term "modulational instability" is used not for a concrete instability acting within the regions I-III but in a broader sense, for any instability connected to the action of ponderomotive force (what is often done), the modulational instability seems to be the same physical process. Though, even in this case, it is reasonable to use the term "collapse" to denote the summary process - instability and damping.

Instability of standing Langmuir waves /3,5,6/

The numerical experiment on studying the instability of standing Langmuir waves /5,6/ was carried out in the range of the following wave parameters: $E_0^2/8\pi nT \sim 4\cdot 10^{-2} \div 10^{2}$ at $V_{ph}/V_T = \pm 16$, $(k_0 r_d)^2 = 3.9\cdot 10^{-3}$ and in the range: $V_{ph}/V_T = \pm(16-48)$, $(k_0 r_d)^2 \sim 3.9\cdot 10^{-3} \div 4.4\cdot 10^{-4}$ at $\frac{E_0^2}{8\pi nT} = 1.6$; $\frac{M}{m} = 10^2$. Thus, the region $\frac{E_0^2}{8\pi nT} > \frac{m}{M} > (k_0 r_d)^2$ was studied.

In the case of a standing wave, the electric field energy density is inhomogeneous from the very beginning, so that the position of density cavities is determined by the regions where the electric field is maximum. This is the main difference from the case of a travelling wave. In this case, the development of instability always leads to the formation of standing, equilibrium or non-equilibrium solitons. In other features, the development of standing wave instability does not qualitatively differ from the case of a travelling wave: in both cases, in the regions of the same parameters the same processes play a role. So, in the region $\frac{E_0^2}{8\pi nT} < k_0 r_d$ the quasi-stationary standing soliton is formed /6/, in the region $\frac{E_0^2}{8\pi nT} \gtrsim k_0 r_d$ - the equilibrium but damping standing soliton, in the region $E_0^2/8\pi nT > k_0 r_d$ the collapse occurs /6/, in the region $E_0^2/8\pi nT > 4\cdot 10^{-2}/(k_0 r_d)^2$ the wave damps from the very beginning /5/.

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FIGURE CAPTIONS

Fig.1 The dependence of wave amplitude on time $\frac{E}{E_0} = f(\gamma_L t)$ /4/. Solid curves - the theory /9/; a point - the numerical experiment /4/; $q = \gamma_L/\omega_B$; $\omega_B = k_0\sqrt{\frac{e\varphi_0}{m}}$

	V_{ph}/V_T	$E_0^2/8\pi nT$	q	$\sqrt{\frac{e\varphi_0}{m}}/V_T$
•	2.46;	$3\cdot10^{-4}$;	2.6	0.2
×	2.95;	$4\cdot10^{-2}$;	0.5	0.8
Δ	2.95	1.6	0.2	2.1

Fig.2a The dependence of damping rate on amplitude:

$\gamma/\gamma_L = f\left(\sqrt{\frac{e\varphi_0}{m}}/V_T\right)$ at $V_{ph} = const$ /8/;

	Δ	×	•	o
V_{ph}/V_T	2.46	2.95	4.2	6.9

Fig.2b The dependence of damping rate on phase velocity:

$\gamma/\gamma_L = f(V_{ph}/V_T)$ at $\sqrt{\frac{e\varphi_0}{m}} = const$ /8/;

	Δ	×	•	o	+	◇
$\sqrt{\frac{e\varphi_0}{m}}/V_T$	I	1.6	2.6	4.2	5.4	6.3

Fig.3 The lines of constant damping rate $\gamma/\omega_{oe} = const$ and the "boundary of nonlinearity" in the coordinates $\sqrt{\frac{e\varphi_0}{m}}/V_T - \frac{V_{ph}}{V_T}$ /8/. The line $\sqrt{\frac{e\varphi_0}{m}} = V_T \cdot \frac{V_T}{V_{ph}}$ - the boundary of validity of the theory /9/.

Fig.4 A scheme: the regions of instability of a one-dimensional Langmuir wave according to the theory /12/, the lines of constant damping rate, $\gamma/\omega_{oe} = const$, and the "boundary of nonlinearity" in the cooordinates $\frac{E_0^2}{8\pi nT} - (k_0 r_d)^2$ for $\frac{M}{m} = 1836$.

Fig.5 The distribution of field $E(x)$ and density perturbation $\frac{\hat{n}_i}{n_0}(x)$ at different time moments /6/. $T_{oe} = 2\pi/\omega_{oe}$ is the period of plasma oscillations. Case 7: $\frac{E_0^2}{8\pi nT} = 10^{-1}$; $\frac{V_{ph}}{V_T} = 16$.

Fig.6 The time dependence of maximum energy density $W_m/W_0(t)$ at different amplitudes and $V_{ph} = const$ /6/;

$W_m = E^2_{max}/8\pi n_{min} T$; $W_0 = E_0^2/8\pi n_0 T$

E_{max} is the field amplitude in the density cavity; n_{min} is the maximum density in the cavity. Numeration according to /7/. $V_{ph}/V_T = 16$.

Case	6	7	8
$\frac{E_0^2}{8\pi nT}$	$4\cdot10^{-2}$	10^{-1}	$3\cdot10^{-1}$

Fig.7 The time dependence of maximum energy density $W_m/W_0(t)$ at different amplitudes and $V_{ph} - const$ /4/. Numeration according to /7/. $V_{ph}/V_T = 16$

Case	8	9	10	11	12	13
$\frac{E_0^2}{8\pi nT}$	$3\cdot10^{-1}$	1.6	11	18	36	115

Fig.8 The lines of constant damping rate $\gamma/\omega_{oe} - const$; the lines of constant wave energy $\frac{E^2}{8\pi nT} = a k r_d$; the line of equilibrium soliton parameters and the initial wave parameters from /6/ in the coordinates $\frac{E^2}{8\pi nT} - (k r_d)^2$. Numeration according to /7/.

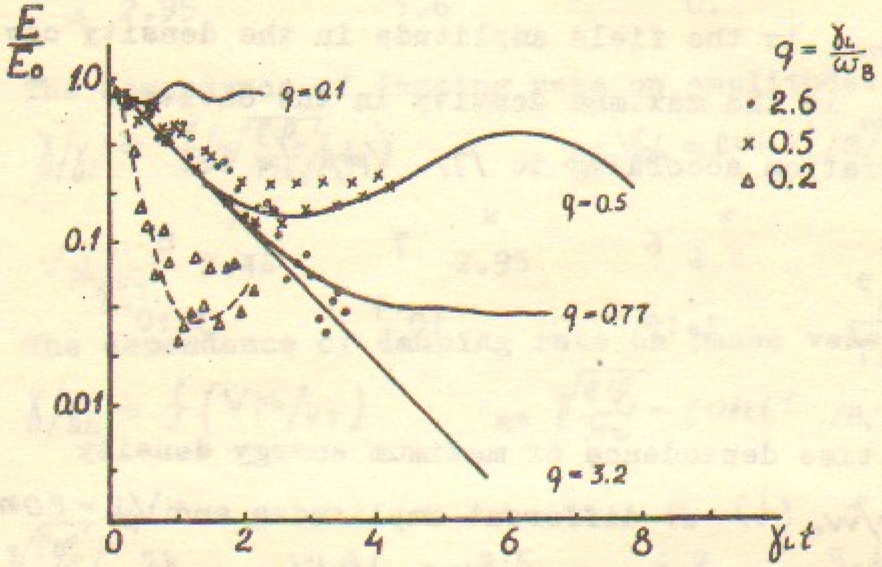

Fig.1

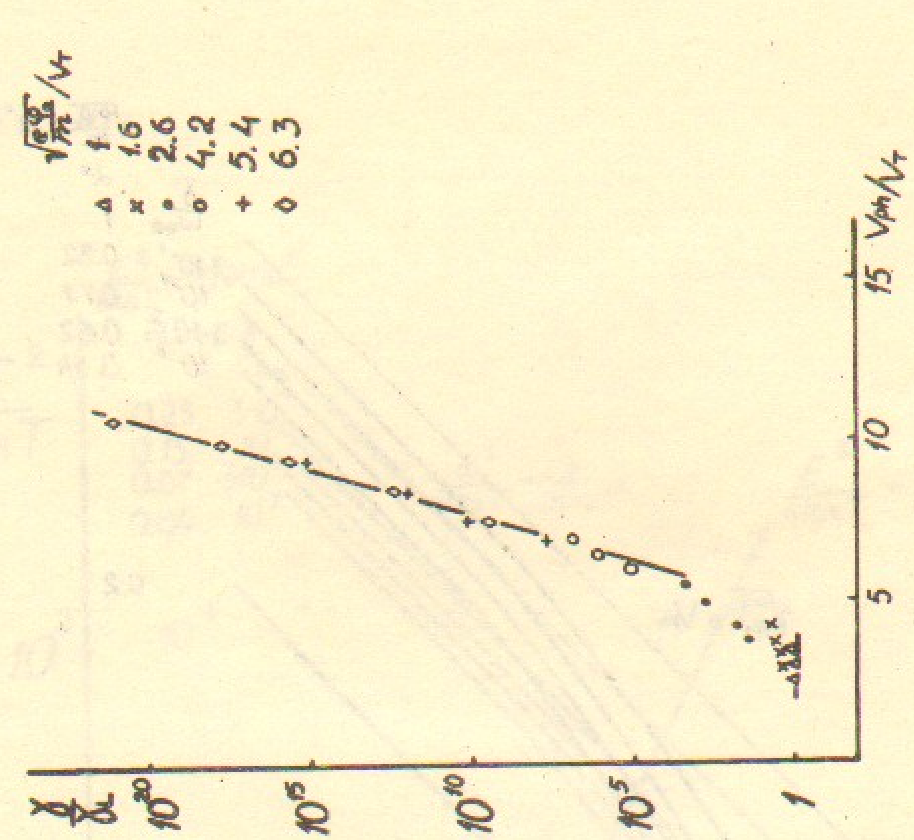

Fig.2b

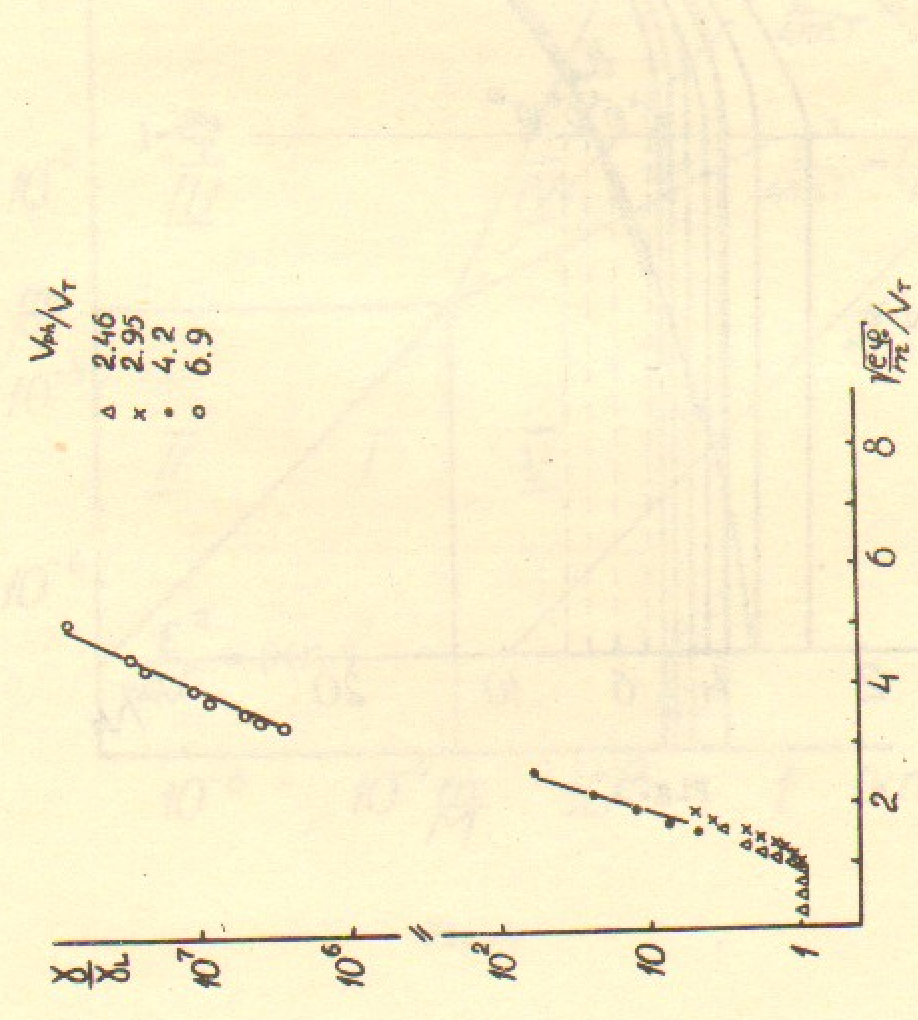

Fig.2a

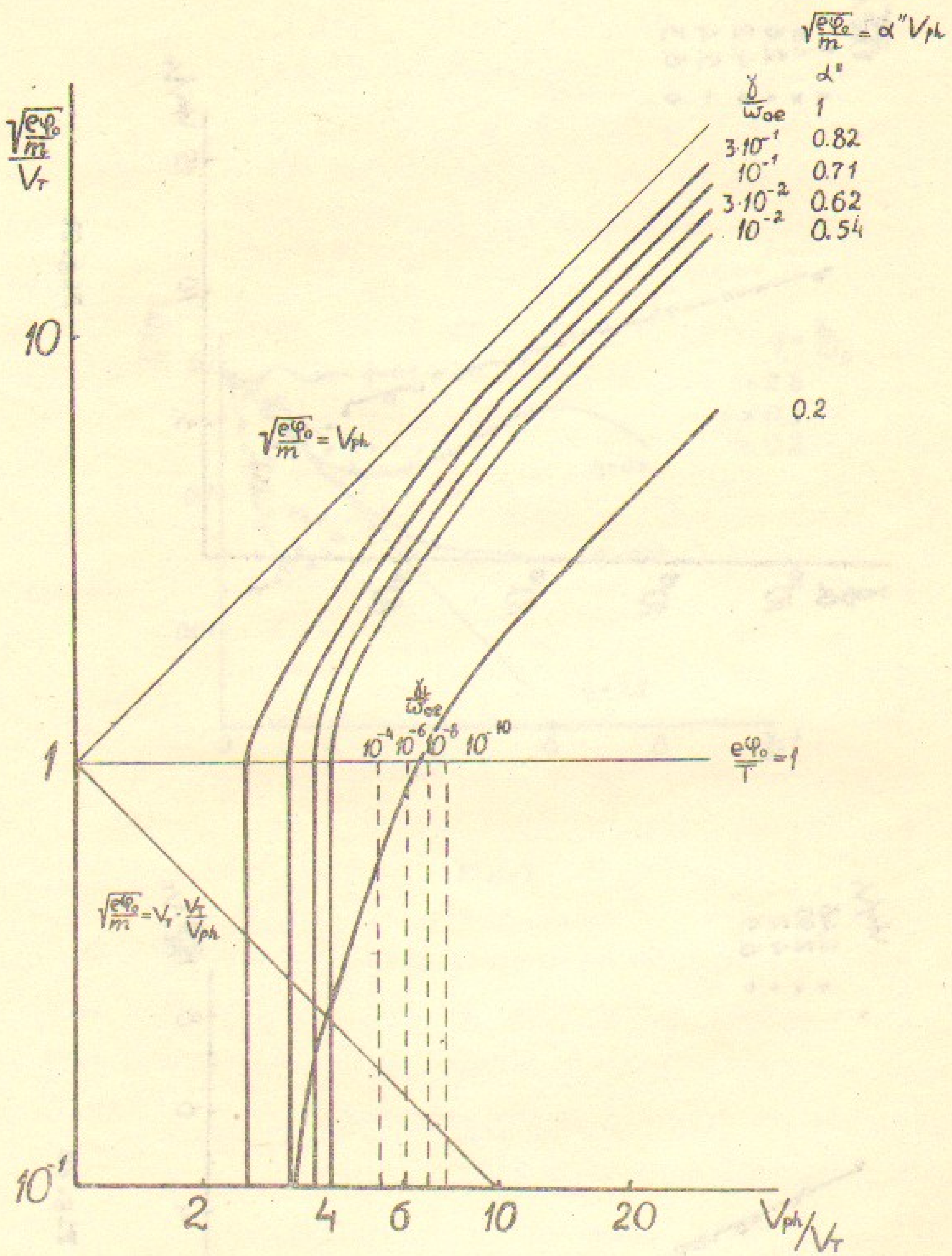
10
1
10^{-1}
2
4
6
10
20
V_{ph}/V_T
$\frac{e\varphi_0}{T}=1$
0.2

Fig.3

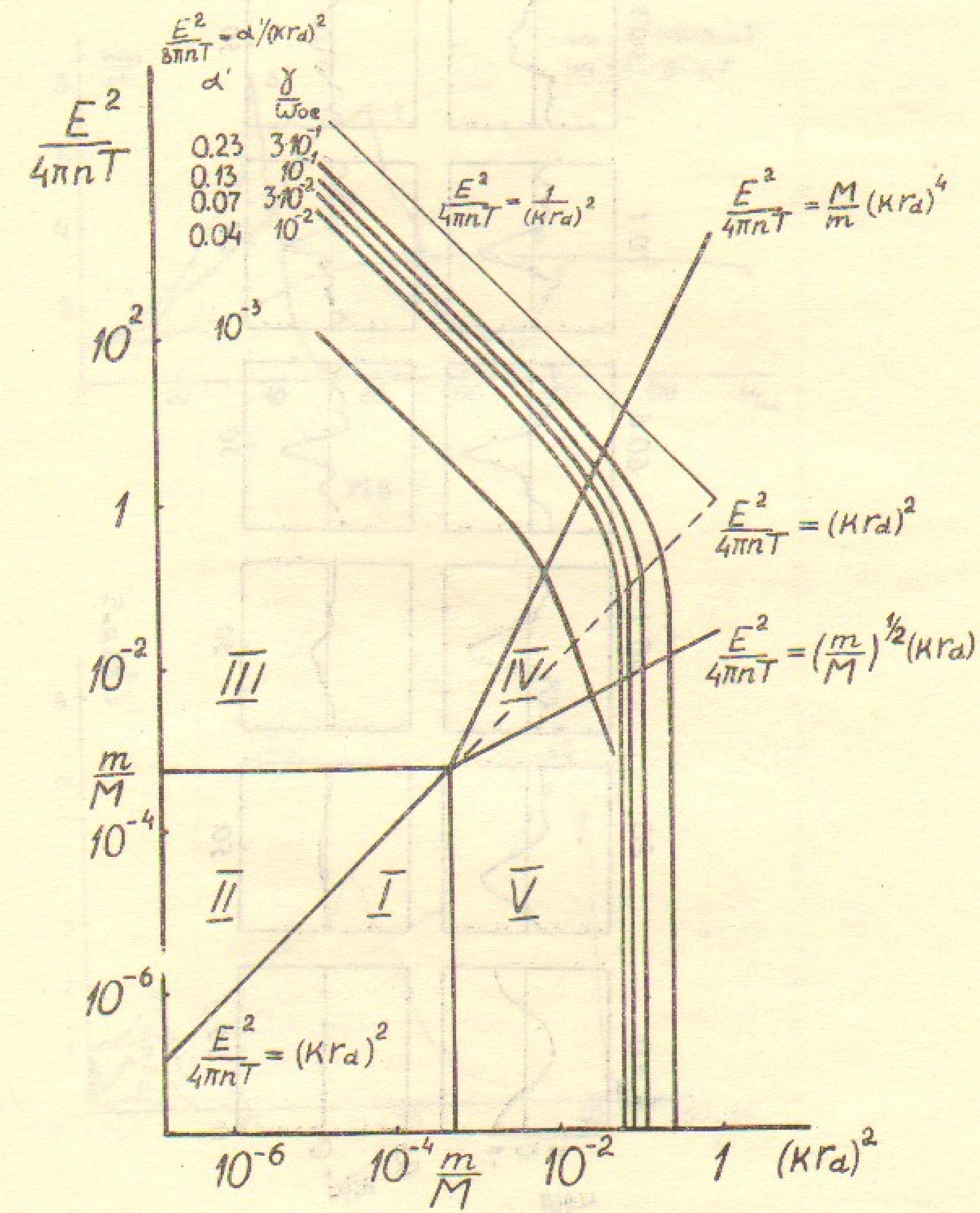
$\frac{E^2}{4\pi nT}$
$\frac{E^2}{4\pi nT}=\frac{M}{m}(\kappa r_d)^4$
$\frac{E^2}{4\pi nT}=(\kappa r_d)^2$
$\frac{E^2}{4\pi nT}=\left(\frac{m}{M}\right)^{1/2}(\kappa r_d)$
III
IV
II
I
V
$(\kappa r_d)^2$

Fig.4

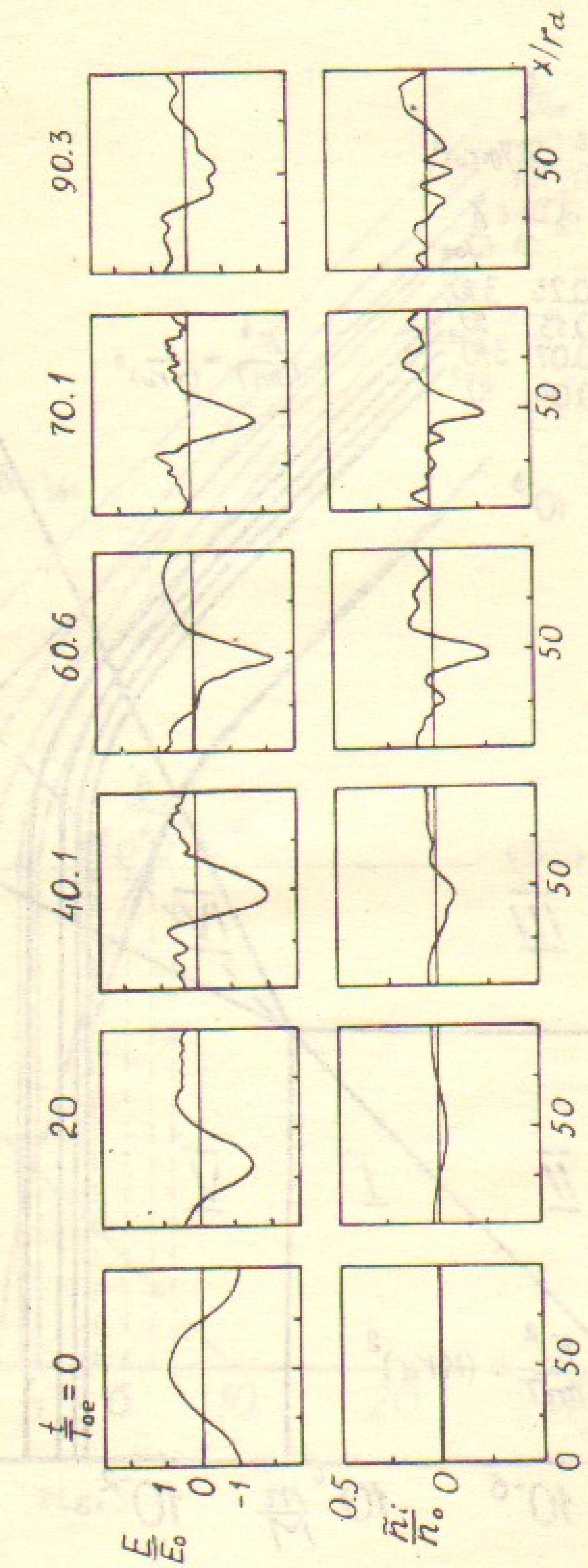

Fig.5

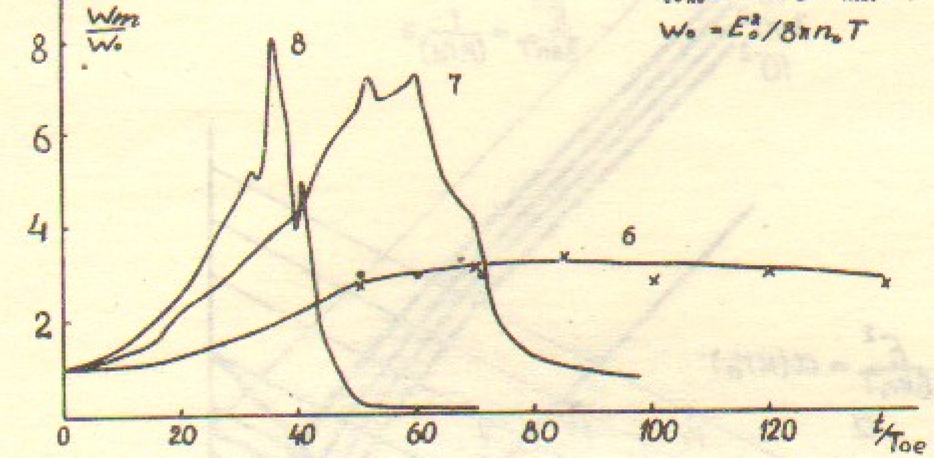

Fig.6

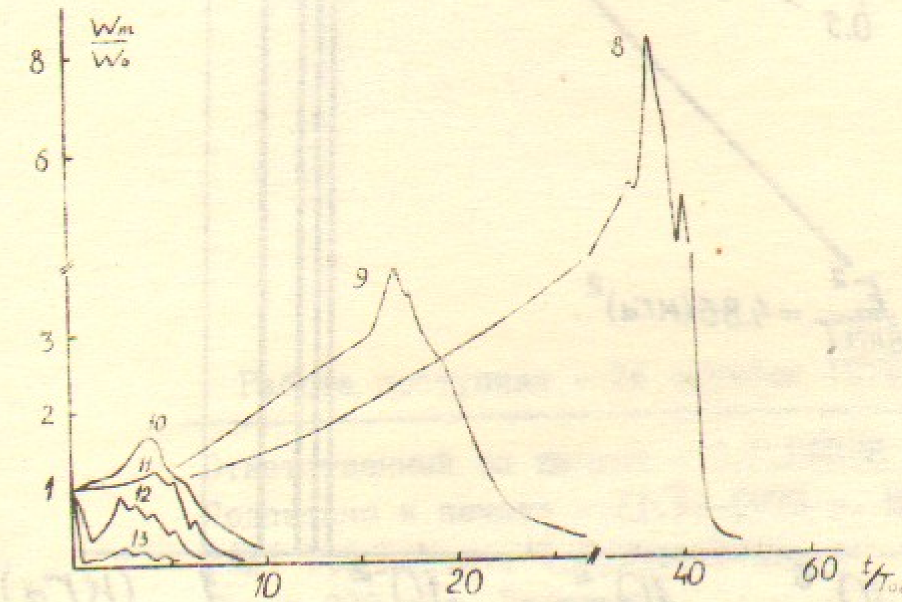

Fig.

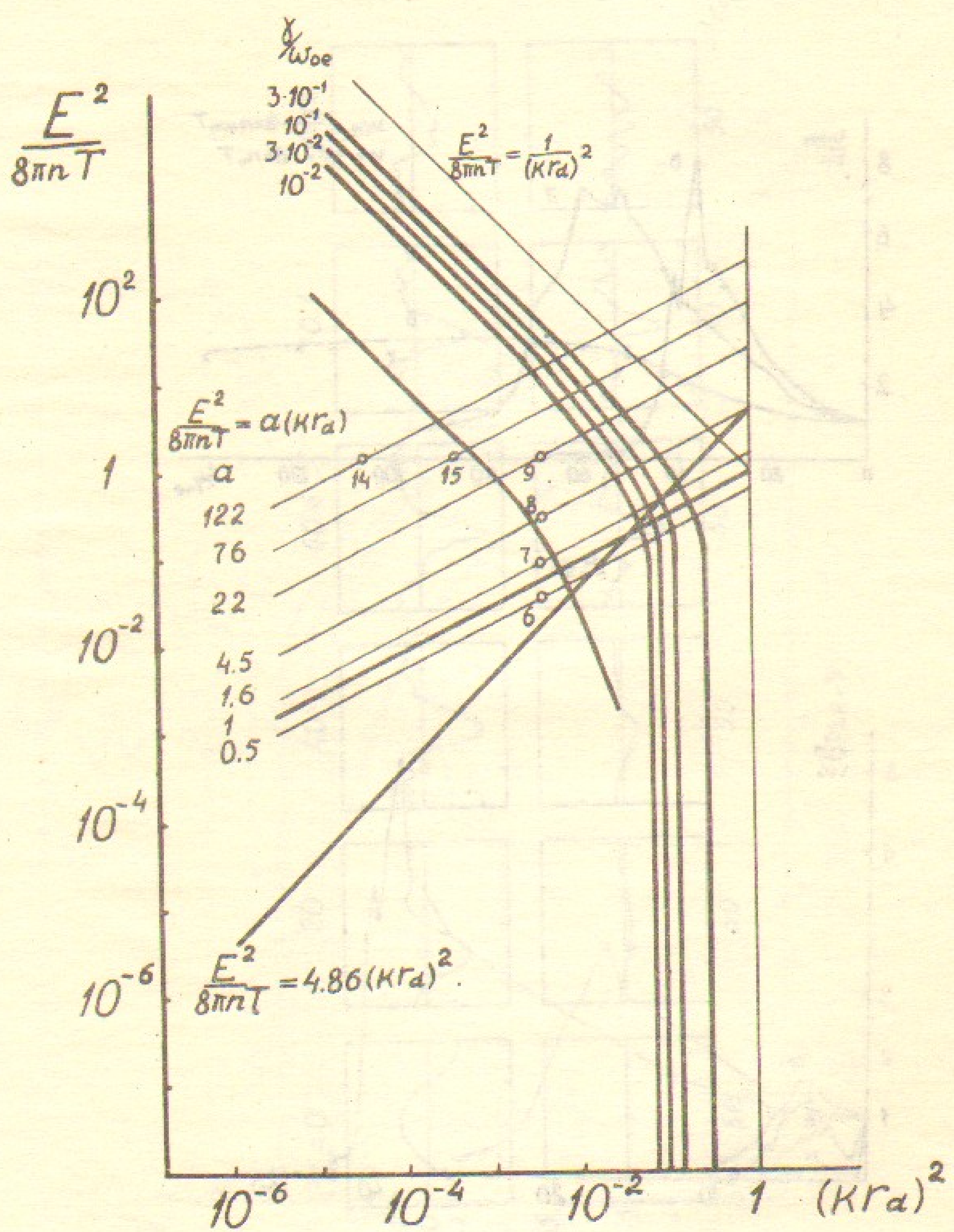

Fig.8

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