Nonlinear interaction between radiation and an expanding plasma

N. E. Andreev, V. P. Silin, and G. L. Stenchikov

P. N. Lebedev Physics Institute, Academy of Sciences of the USSR, Moscow
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The self-consistent equation set for nonlinear electrodynamics and hydrodynamics is investigated with allowance for the effect of the ponderomotive force, due to the electromagnetic field, on the hydrodynamic flow. The dissipation of the electromagnetic field is described by the electron collision frequency and the collisionless Landau damping. The redistribution of the electron velocity is described by a kinetic equation with a quasilinear diffusion coefficient. Both the Landau damping decrement and quasilinear diffusion coefficient are averaged over the spatial region of a strong internal plasma field. The variation of the density and hydrodynamic velocity of the plasma, the evolution of the internal plasma field, the time dependence of the absorption of the electromagnetic field energy by the plasma, and the partition of the energy among thermal and fast electrons are studied. The electron velocity distribution is investigated. Finally, generation of the second harmonic radiation is considered. All the processes differ qualitatively in two opposite limiting cases, for a plasma flow with a comparatively smooth velocity gradient in the vicinity of the critical density and a supersonic flow with a steep velocity gradient. In the case of the second regime of the plasma flow, the formation of cavitons—density pockets in the plasma filled by the high frequency internal field—is impeded. Cherenkov dissipation of the electromagnetic field is suppressed simultaneously and hence the generation of fast electrons in the plasma is suppressed.

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1. INTRODUCTION

The study of the interaction of powerful electromagnetic radiation with plasma is essential for the solution of important practical problems of laser controlled fusion and presents much fundamental interest because this interaction is characterized by a number of nonlinear phenomena. Firstly, the electromagnetic wave acts upon the plasma as a pump because the action of its non-linear ponderomotive force may deform the nonuniform plasma-density profile.[1] Secondly, the creation of intense electron Langmuir oscillations in the plasma may even more strongly expel the plasma from the volume of its localization. Under these conditions plasma waves become essentially non-linear (cavitons[2]), which also obviously changes the realization of radiation-absorption mechanisms.

Since the conditions for stimulation of intense electric fields in the plasma are most favored[3] in oblique incidence of p-polarized electromagnetic waves on the plasma, attention is concentrated in this work on the investigation of the absorption dynamics of p-polarized radiation near the critical plasma density. Under these conditions consistent account is taken of the change in the spatial distribution of the particles under the effect of the full ponderomotive force and also of the hydromagnetic effects connected with the plasma motion in the region of critical density, where the non-linear effect of profile deformation is especially important. We note that under the action of radiation of a neodymium laser on a plasma of temperature ~1 keV, power density of the p-polarized light component of several units of 10^{14} W/cm^2 leads to a significant ponderomotive force that deforms the inhomogeneous plasma density profile. The speed of motion of a plasma formed by the action of laser radiation on the matter of a solid target depends upon the evaporation conditions on the thermal wave-front and on the dynamics of the plasma corona in the body. In accordance with estimates of the stationary hydrodynamic corona model[4], satisfactorily in agreement with experimental data[5], near the critical plasma density the speed of plasma motion may be of the order of the local sound speed, and also may significantly exceed it, depending on the value of the laser flux density and on the dimensions of the solid target. Therefore below in our analysis of a relatively narrow layer of plasma near the critical density, one may consider the initial speed of the plasma flux flowing from the more dense layers of plasma given and determined by the global characteristics of the target hydrodynamic motion.

Our preceding investigations[6-8] have demonstrated the strong dependence of the radiation reflection coefficient on the rate of flow of the plasma through the critical-density region. It must be borne in mind here that a most important question in the problem of laser-driven fusion, besides the value of the absorption, is that of the redistribution of the radiation energy transferred to the plasma among the various particle groups. Thus the formation of an even relatively small number of hot electrons that prevent compression of the target core hinders greatly the initiation of the thermonuclear burning. Special attention is therefore paid here to a determination of the conditions under which collisional dissipation of the field, which leads to heating of the bulk of the electrons, predominates in the plasma.

For a detailed analysis of the possibility of suppression of the radiation energy transfer to fast electrons[7] under conditions of excitation of intense Langmuir oscillations, the present work uses a kinetic description of Cherenkov interactions of waves with particles and investigates in detail the peculiarities of the electron velocity distribution for various regimes of flux of matter in the region of the critical density. With this purpose the Landau damping of the field potential com-

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ponent in the equations of the electromagnetic field is computed; quasilinear theory is used for determination of the self-consistent relaxation of the electron distribution function. Under this condition the change in energy of the bulk of the electrons (temperature) is determined by the fraction of the absorbed electromagnetic field energy that is dissipated in the plasma as a consequence of the collisions.

2. BASIC EQUATIONS

Let's analyze a plane layer of fully ionized plasma with ion density $n(x)$ increasing along the x axis. A plane p-polarized electromagnetic wave with the wave vector

$$\mathbf{k}_0=\{\cos\theta_0, \sin\theta_0, 0\}\omega_0/c$$

is obliquely incident on the plasma from the region $x<0$ (c is the velocity of light; ω_0 is the electromagnetic wave frequency) at an angle θ_0 between the density gradient and the electric field vector

$$\mathbf{E}=\mathrm{Re}\left\{\mathbf{E}_0(x,t)\exp\left[-i\omega_0 t+i\left(\frac{\omega_0}{c}\right)\sin\theta_0 y\right]\right\},$$
$$\mathbf{E}_0(x,t)=\{E_x(x,t), E_y(x,t), 0\}.$$

The evolution of the electromagnetic wave in the plasma is determined by a system of Maxwell's equations shortened in time:

$$\left[2i\omega_0\left(\frac{\partial}{\partial t}+\hat{\Gamma}\right)+v_{Te}^2\left(3\frac{\partial^2}{\partial x^2}+\frac{\partial\varepsilon/\partial x}{1-\varepsilon}\frac{\partial}{\partial x}\right)+\omega_0^2(\varepsilon-\sin^2\theta_0)\right]E_x(x,t)=i\sin\theta_0 c\omega_0\frac{\partial E_y(x,t)}{\partial x},$$
$$\left[2i\omega_0\frac{\partial}{\partial t}+c^2\frac{\partial^2}{\partial x^2}+\omega_0^2\varepsilon\right]E_y(x,t)=i\sin\theta_0 c\omega_0\frac{\partial E_x(x,t)}{\partial x} \quad (2.1)$$

with the boundary conditions corresponding to incident and reflected waves for $x\to-\infty$ and a transmitted wave for $x\to+\infty$.

The plasma properties are characterized by the dielectric constant

$$\varepsilon=1-\frac{n(x,t)}{n_c}\left(1-i\frac{\nu}{\omega_0}\right), \quad (2.2)$$

by the masses m_e and M_i by the charge e and $Z|e|$ by the electron and ion temperatures and T_e and T_i, the electron thermal velocity $v_{Te}=(T_e/m_e)^{1/2}$; by the ion-sound velocity $v_s=[(ZT_e+T_i)/M_i]^{1/2}$, and by the critical plasma density $n_c=m_e\omega_0^2/4\pi e^2Z)$ determined from the equality of the frequency ω_0 of the external radiation to the electron Langmuir frequency $\omega_{Le}=(4\pi e^2n_e/m_e)^{1/2}$. The effective collision frequency ν determines the damping of the longitudinal and transverse field components, and the operator

$$\hat{\Gamma}E_x(x,t)=\frac{1}{2\pi}\int dk\,\gamma_L(k)\int dx'\,e^{ik(x-x')}E_x(x',t) \quad (2.3)$$

describes the Cherenkov interaction of the potential oscillations with the plasma electrons. The Landau-damping decrement

$$\gamma_L(k)=\frac{\pi}{2}\frac{\omega_0^3}{k^2v_{Te}}\left(\frac{\partial\bar{f}}{\partial v}\right)_{v=\omega_0/k} \quad (2.4)$$

appears in our analysis as a functional of the distribution function $f(x,v,t)$ averaged over the region of localization of the longitudinal electric field. In the quasilinear approximation this distribution function by the diffusion equation in the space of the velocities v

$$\frac{\partial f}{\partial t}+v\frac{\partial f}{\partial x}=\frac{\partial}{\partial v}D(v,t)\frac{\partial}{\partial v}f(x,v,t). \quad (2.5)$$

The diffusion coefficient, also averaged over the localization region of the longitudinal field, is defined by the relationship

$$D(v,t)=\frac{\pi e^2}{m_e^2}\sum_k|E_x(k,t)|^2\delta(\omega_0-kv), \quad (2.6)$$

where $E_x(k,t)$ is the spatial Fourier transform of the longitudinal component of the electric field.

The term df/dt in (2.5) is small in comparison with the convective term because of the small ratio $v_s/v_{Te}\ll 1$. Therefore for the description of the evolution of the electron distribution function it is advisable to use a stationary diffusion equation with boundary conditions corresponding to the entry of Maxwellian electrons with the temperature of the plasma near the critical density into the field localization region.

The deformations of the ion density $n(x,t)$ and of the hydrodynamic velocity profile $u(x,t)$ under the influence of the ponderomotive force of the high-frequency field and of the pressure gradient are determined by the equations of single-fluid hydrodynamics:

$$\frac{\partial n}{\partial t}+\frac{\partial nu}{\partial x}=0,\quad \frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}=-\frac{Ze^2}{4M_im_e\omega_0^2}\frac{\partial|\mathbf{E}_0|^2}{\partial x}-v_s^2\frac{1}{n}\frac{\partial n}{\partial x}, \quad (2.7)$$

which are valid under the assumption of small Debye radius and uniform temperatures of the ions and electrons. The latter assumption is connected with the fact that the equalization of the electron temperature distribution occurs in time significantly shorter than the hydrodynamic time ($v_s\ll v_{Te}$), and with the fact that the characteristic temperature non-uniformity scale corresponding to the electron mean free path $\lambda_{Te}\sim v_{Te}/\nu$, is greater than the dimensions of the field localization region where the basic energy dissipation occurs.

For investigation of the dynamics of absorption of powerful radiation in the region of critical plasma density and generation of fast electrons, the important question is the redistribution of the energy transferred to the plasma among the various groups of particles. In the present work the allowance for kinetic effects and for processes of energy redistribution in the plasma is self-consistent. The relaxation of the distribution function of superthermal electrons is described by the quasi-linear equation (2.5) with a diffusion coefficient (2.6) determined by the longitudinal electric field excited in the plasma. The damping (2.3) of the potential component of the field, in its turn, is determined by the Landau damping decrement (2.4) and therefore depends upon the electron distribution function. Under these conditions the fraction of the laser radiation energy flux Q_L absorbed in Cherenkov interaction of the potential component of the field with the electrons

$$Q_L=\left(\frac{c}{8\pi}|\tilde{\mathbf{E}}_0|^2\cos\theta_0\right)^{-1}\frac{1}{4\pi}\int dk\,\gamma_L(k)|E_x(k,t)|^2, \quad (2.8)$$

leads to the generation of fast particles. (Here $\tilde{\mathbf{E}}_0$ is the amplitude of the incident electromagnetic wave in vacuum.)

On the contrary, the fraction Q_T of the energy flux of the incident radiation absorbed as a result of collisions, leads to heating of the bulk of the electrons and is expressed by the relation

$$Q_T=\left(\frac{c}{8\pi}|\tilde{\mathbf{E}}_0|^2\cos\theta_0\right)^{-1}\int_{-\infty}^{\infty}dx\,\nu\frac{n}{n_c}|\mathbf{E}_0(x,t)|^2. \tag{2.9}$$

Under this condition the change in electron temperature is determined by the equation

$$\frac{d}{dt}\left[\frac{3}{2}T_e\int n\,dx\right]=Q_T\frac{c}{8\pi}|\tilde{\mathbf{E}}_0|^2\cos\theta_0-\alpha m_e n_c v_{Te}^3, \tag{2.10}$$

which is obtained with neglect of terms small in comparison with the thermal hydrodynamic energy flux. The last term on the right side of (2.10) with $\alpha=(2/\pi)^{1/2}$ describes the energy outflow from the region of critical density by the collisionless flux of Maxwellian electrons.

The solution of the electrodynamic Eqs. (2.1) for the field at the fundamental frequency ω_0 permits the determination of the non-linear current at the frequency $N\omega_0$, which causes the excitation of the N-th harmonics of the electromagnetic field in the plasma. In the discussed case of a plane-layered medium the N-th harmonic may be described by the z-component of the magnetic field:

$$\mathbf{B}_{N\omega_0}(x,y,t)=\{0,\,0,\,B_N(x,t)\exp[-iN\omega_0(t-(y/c)\sin\theta_0)]\}, \tag{2.11}$$

the equation for which has the following form:

$$\left\{\frac{\partial^2}{\partial x^2}+\frac{1}{\varepsilon_N}\frac{\partial\varepsilon_N}{\partial x}\frac{\partial}{\partial x}+\left(\frac{N\omega_0}{c}\right)^2(\varepsilon_N-\sin^2\theta_0)\right\}B_N(x,t)$$
$$=-\frac{4\pi}{c}\left\{\left(\frac{\partial}{\partial x}-\frac{1}{\varepsilon_N}\frac{\partial\varepsilon_N}{\partial x}\right)j_y^{(N)}-\frac{iN\omega_0}{c}\sin\theta_0 j_x^{(N)}\right\}, \tag{2.12}$$

where $\varepsilon_N=\varepsilon(N\omega_0,x,t)=1-\omega_{Le}^2(x,t)/(N\omega_0)^2[1-i\nu/(N\omega_0)]$.

Below we show the result on the generation of the second harmonic of the radiation ($N=2$). For this the vector of the non-linear current at the frequency $2\omega_0$ may be written in the following form:

$$\mathbf{j}^{(2)}=\frac{i}{8\pi}\frac{e}{m_e\omega_0}\left\{\mathbf{E}_0\operatorname{div}\mathbf{E}_0+\frac{\omega_{Le}^2}{4\omega_0^2}\operatorname{grad}|\mathbf{E}_0|^2\right\}, \tag{2.13}$$

where $\mathbf{E}_0=(E_x,E_y,0)$ is the solution of equations (2.1) through (2.10). Equation (2.12) with the non-linear current (2.13) must be supplemented with boundary conditions corresponding to free radiation in vacuum and to reflection of waves from the region of dense plasma ($n>4n_c$). The solution found in this manner permits the determination of the coefficient of transformation of energy of the incident radiation into the second harmonic:

$$K_2=(B_2/B_0)^2, \tag{2.14}$$

where B_2 and B_0 are the magnetic fields of the second harmonic and of the incident radiation in vacuum.

3. RESULTS

Below we discuss the solutions of the system of equations (2.1) through (2.10) for two different physical situations, which may appear as a result of the initial stage of evaporation of a solid target and which lead to different initial conditions for the hydrodynamic equations. In the case when the leading front of the radiation pulse leads to relatively fast and uniform heating of the plasma corona, the resulting flow of the plasma is characterized by density and material-velocity gradients and that are close in value, and may be described as a rarefaction wave that corresponds to the following spatial distribution of plasma density and velocity

$$n(x)=n_c\exp\{(x-x_c)/l\}, \tag{3.1}$$

$$v(x)=-v_c+(x-x_c)/l. \tag{3.2}$$

Here v_c is the absolute value of the plasma velocity at the point of critical density, x_c is its coordinate, and l denotes the characteristic dimension of the density and velocity change, which is proportional to the time measured from the beginning of the formation of the rarefaction wave: $l=v_s t$. We note that the rarefaction wave is the exact solution of the hydrodynamic equations (2.7) in the assumption of constant sound speed (i.e., temperature) and also with neglect of the ponderomotive force, a procedure justified for the initial stage of growth of the leading front of the radiation pulse, when the electric field pressure is negligibly small.

We first analyze the solution to the system of equations (2.1) through (2.13) using as initial conditions for the hydrodynamic equation (2.7) the relationships (3.1) and (3.2). A numerical integration of the system (2.1) through (2.13) has been carried out for parameters close to those realized in the experiments, when $v_E/c=0.015$, where $v_E=e\tilde{E}_0/m_e\omega_0$ is the velocity of electron oscillation in the field of the pump wave (in vacuum), and the initial value of the electron temperature is $T_{e0}=1.25$ keV, which means that $v_e/v_{Te}=0.3$. The initial scale of the non-uniformity in (3.1) and (3.2) was taken equal to $l=10\ c/\omega_0$, and corresponded to supersonic plasma flow with steep density and velocity gradients. The effective collision frequency is given by the ratio $\nu/\omega_0=5\times10^{-3}$; and the sine of the angle of incidence is $\sin\theta_0=0.29$ ($\theta_0=17°$).

On Fig. 1 is shown the time dependence of the absorption coefficient $A(t)=1-|R(t)|^2$ and the quantity $Q_T(t)$ (2.8), [Fig. 1(a)], and also the shape of the laser pulse $W_L(t)=\tilde{E}_0^2(t)/(4\pi m_c T_{e0})$ and the coefficient of transformation of radiation into the second harmonic K_2 (2.14) [Fig. 1(b)]. The initial decrease of the absorption A and the relatively large difference between the quantities

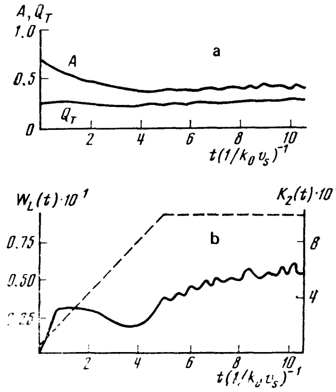

FIG. 1.

A and Q_T when the radiation incident on the plasma is turned on are determined by the increase of the energy of the potential component of the electric field in the region of the critical density and do not correspond to a large transfer of radiation energy to the plasma. The reason for the limit on the growth, proportional to the pump energy $W_L(t)$, of the coefficient $K_2(t)$ of the transformation into the second harmonic when $t \sim 1/k_0 v_s$ (Fig. 1b) is the onset of non-linear deformation of the plasma-density profile in the vicinity of the critical point under the influence of the ponderomotive force. Such a process is characterized by formation of a sharp transition (jump) through the point with the critical value of density, and becomes quasistationary at the time $t \geq 7/k_0 v_s$, as is shown by the evolution of the quantities A, Q_T, and K_2 (Fig. 1). One may directly be convinced of this by inspection of the spatial distributions of the density, velocity, and electric fields in the plasma, which are shown in Fig. 2 for the instant of time $t = 8/k_0 v_s$. The spatial relations presented in Fig. 2 correspond to a steady-state quasi-stationary interaction regime characterized by an average absorption $\overline{A} = 1 - \overline{|R(t)|^2} \approx 40\%$. Under this condition the fraction of radiation energy $\overline{Q_T}$ going into heating of the bulk of the electrons by collisions is shown to be of the order of 25%; correspondingly only 15% of the radiation energy incident on the plasma is transferred to the fast electrons.

The distribution function, corresponding to such an energy balance, of the electrons passing through the region of space in which intense Langmuir waves and electrons accelerated by the Cherenkov mechanism exist, is presented on Fig. 3, where the dashed line shows the Maxwellian distribution function $f_M = (2\pi)^{-1/2} \exp(-v^2/2v_{Te})^2$. An important peculiarity of this regime of radiation absorption by the moving plasma is not only the relatively small number of hot electrons, because of the small fraction of energy carried away by them, but also the sharp fall-off of the distribution function with the growth of particle energy. We note also the anisotropic character of the electron acceleration in the direction of the decrease in plasma density. These peculiarities are determined by the Langmuir field structure which corresponds to the formation of an abrupt transition through the critical point. We emphasize that the Langmuir oscillations excited in the region of the critical density are essentially non-linear since the ponderomotive force produced by them causes and maintains to a considerable degree the jump in density. However, the large plasma flow velocity gradient, which hinders the formation of cavitons[7,8] in the range of parameters analyzed, that can capture the Langmuir waves, leads to a monotonic density profile in the region of the critical point and correspondingly to unimpeded departure of the Langmuir oscillations to the region of the tenuous plasma. This is precisely the cause favoring the realization of laser controlled thermonuclear fusion, that the electron acceleration is ineffective and occurs only in the direction opposite to the density gradient; i.e., away from the target core where the electrons can make the target compression more difficult.

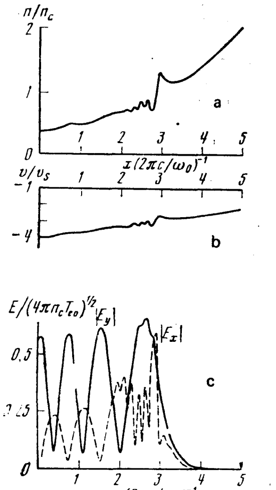

FIG. 2.

The absence of cavitons with an intense-stationary Langmuir field leads also to a smooth time-dependence of the coefficient $K_2(t)$ of transformation into the second harmonic after establishment of the density jump, when $t \geq 7/k_0 v_s$ (Fig. 1b). Under this condition the characteristic dimension L of the density change in the vicinity of the critical point may be estimated in order of magnitude from the effectiveness of the transformation into the second harmonic K_2 with the help of a formula that does not take into account the non-linear Langmuir waves[9,10]:

$$L \sim \frac{c}{\omega_0} \frac{1}{\Phi^2(\tau) \sin \theta_0} \frac{c}{v_E} K_2^{1/2}, \tag{3.3}$$

where $\Phi(\tau)$ is the resonance function of the angle of incidence θ_0.[3]

The quasi-stationary regime of the interaction of laser radiation with plasma leads to a temperature of the bulk of the electrons that varies weakly with time and is close to the stationary solution of equation (2.10). For the radiation energy fluxes discussed this stationary value is $T_e \approx 1$ keV.

We will briefly dwell upon the dependence of the results on the initial plasma density gradient. Computations conducted by us of the initial dimension of non-uniformity of density $l_n = 41\ c/\omega_0$, with the other parameters the same as for Figs. 1 through 3, showed that the very fact of formation of the density jump, its magnitude, and its time of formation do not depend on the

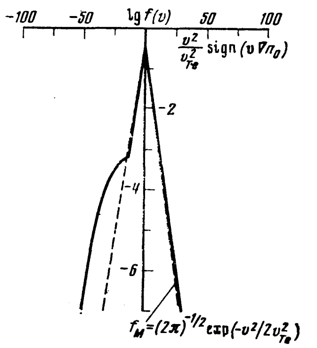

FIG. 3.

initial density gradient (of Fig. 2 of Ref. 7). However, the evolution of the damping coefficient becomes more non-monotonic with decrease of the initial gradient (especially in the period of formation of the density jump). The reason is the increase in the region of space with subcritical (but near-critical) density, where intense Langmuir waves exist. This circumstance increases somewhat, both the collisional and the Cherenkov dissipation of the radiation, without changing qualitatively the above-described picture of the interaction of radiation with a fast-moving plasma.

We turn now to the qualitatively different situation in which the plasma flow that arises as a result of the action of the leading front of the radiation pulse is characterized by a significantly more gently sloping velocity distribution than that which takes place in the isothermal rarefaction wave (3.1), (3.2). If the change of the velocity over the characteristic density scale, is small in the vicinity of the critical point in comparison with the local sound speed, then the plasma motion may be neglected. Results of the solutions of equations (2.1) through (2.13), corresponding to a plasma at rest at the initial time, are shown by Figs. 4 through 6. All other parameters (except the initial plasma velocity) of the solution discussed below are the same as those for Figs. 1 through 3.

Comparison of the results of the computations of the dynamics (Fig. 4a) of absorption and emission at the second-harmonic frequency $2\omega_0$ (Fig. 4b) with the corresponding dependences shown in Fig. 1 for the case of supersonic plasma flow demonstrates the qualitative influence of the velocity gradient of the material in the vicinity of the critical density on the interaction of the powerful radiation with plasma. For an explanation of the reason for the onset of absorption that can reach peaks to 100% and correlate with the bursts of second-harmonic generation (see Fig. 4) we turn to the spatial distributions of the density, velocity, and field in the plasma, shown in Fig. 5 for the moment of time $t=11.5/k_0v_s$. The significant difference of the density profile shown in Fig. 5a from that shown by Fig. 2a is due to the advent of cavitons—regions of space bounded on all sides by humps with supercritical values of density ($n>n_c$), where, as is obvious from Fig. 5c the Langmuir-oscillation field is captured and amplified. Precisely at this instant of time the absorption $A=1-|R|^2$ attains an especially large value ($A\approx 95\%$ at the time $t=11.5/k_0v_s$ corresponding to Fig. 5). However, under this condition over half of the absorbed energy goes into formation of hot electrons ($Q_L\approx 50\%$) and the lesser part ($Q_T\approx 40\%$) leads to heating of the bulk of the electrons as a consequence of ion-electron collisions.

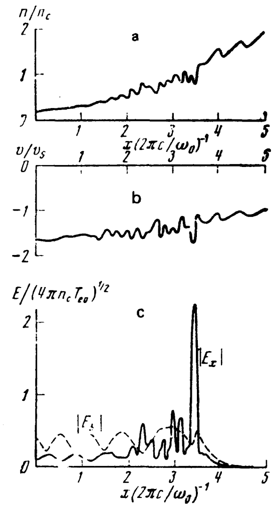

FIG. 5.

In the case we have analyzed, with a relatively steep initial density gradient ($k_0l_n=10$), the absorption process bears a clearly expressed dynamic character, characterized by the onset and destruction of cavitons. Under this condition not all of the energy contained in the caviton can be absorbed during its lifetime (i.e. before the disappearance of the left density hump that blocks the field). Thus, for example, for the moment of time $t=11.5/k_0v_s$ specified above the radiation energy dissipated in the plasma is $Q_T+Q_L\approx 90\%$, while at the same time the reflected energy is only 5%. The unabsorbed fraction of the field energy at the subsequent instants of time may be radiated from the plasma and by the same token the reflection coefficient exceeds unity (see Fig. 4a). This phenomenon, "super-reflectivity", by the dynamics of formation of regions with intense localized fields, arises also when sufficiently powerful radiation is normally incident plasma.[11]

We will now discuss how the excitation of an intense field of non-linear Langmuir oscillations captured in cavitons (Fig. 5c), manifests itself in redistribution of the energy absorbed in the plasma. Figure 6 shows the electron distribution function for the moment of time $t=11.5/k_0v_s$ corresponding to Fig. 5. This function

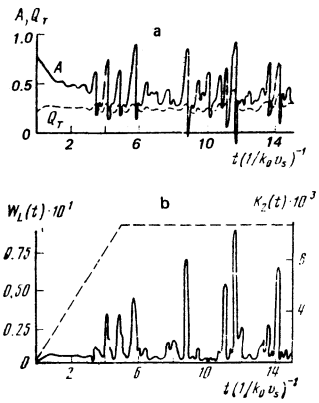

FIG. 4.

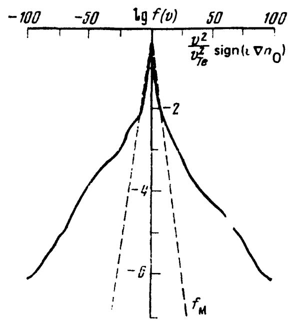

FIG. 6.

is qualitatively different from the function obtained in the previously considered absorption regime analyzed above in the case of supersonic plasma flow with a steep velocity gradient (see Fig. 3). The presence of cavitons that trap the non-linear plasma waves, besides increasing the energy carried away by the hot electrons ($Q_L \approx 50\%$), causes the electrons to be effectively accelerated practically equally along and against the density gradient. An essential property is also the significantly slower (than in Fig. 3) fall-off of the distribution function with the growth of the energy of accelerated particles. This fall-off can be characterized by a "temperature" T_{hot} approximately seven times higher (for the parameters considered) than the temperature T_e of the bulk of electrons. At the value $T_e \approx 1.25$ keV used in our computations this corresponds to a temperature of hot electrons $T_{hot} \approx 10$ keV (cf. Ref. 12). The generation of hot electrons with such a wide energy spectrum is due to the fact that in the process of dynamic compression and field amplification in a caviton the Langmuir-oscillation spectrum turns out to be strongly enriched with long-wave and short-wave components.

The non-linear amplification of the field in the caviton manifests itself in bursts of plasma radiation at higher harmonics. Figure 4 shows that the intensity of the second-harmonic generation grows by an order of magnitude at the instants of time corresponding to the maximum amplification of the field in the cavitons. Of course, the field of the second harmonic makes a negligibly small contribution to the overall energy balance of the interaction of the radiation with the plasma. However, our results allow us to state that the experimentally observed[13] sharp oscillation of the coefficient of transformation into higher harmonics of the radiation, on a picosecond time scale, may be directly shown to be processes of dynamic amplification of the field upon deformation of the plasma density profile.

The computations conducted at a larger initial value of the characteristic dimension of the density non-uniformity $l_n = 41\ c/\omega_0$ (which corresponds to a longer radiation pulse), for the case of slow plasma flow with a small velocity gradient, showed that with increasing volume of space occupied by the intense Langmuir oscillations (i.e. with increase of l_n) the process of caviton formation becomes quasi-stationary (cf. Fig. 1 in Ref. 7) and is characterized by values of absorption $\overline{A} \approx 90\%$, $\overline{Q}_T \approx 40\%$, $\overline{Q}_L \approx 50\%$, which correspond to the electron distribution function shown by Fig. 6.

A comparison of the distribution functions characterizing the absorption of radiation for various regimes of motion of the substance (see Figs. 3 and 6) clearly shows that supersonic plasma flow with a steep gradient of velocity in the vicinity of the critical density hinders the formation of cavitons and leads both to a smaller fraction of the energy transferred to superthermal electrons, and to a significant narrowing of the spectrum of the fast electrons. Both of these circumstances are extremely important for realization of laser-driven thermonuclear fusion and in our opinion point to a new possibility of finding the optimal, from the point of view of laser controlled thermonuclear fusion regime of interaction of laser radiation with plasma.

4. BRIEF CONCLUSIONS

The analysis conducted of the solutions of the dynamic equations describing the interaction of plasma with powerful electromagnetic radiation shows that there exists qualitatively different regimes of such interactions. In one of these limiting regimes, characterized by a relatively smooth velocity gradient in the vicinity of the critical density, there exist quite favorable conditions for formation of cavitons, for transfer of radiation energy to superthermal electrons via Cherenkov interaction and correspondingly for the generation of hot electrons. In the other limiting regime, corresponding to supersonic plasma flow with a relatively steep velocity gradient near the critical density, on the other hand, there exist conditions that hinder the formation of cavitons, decrease the possibility of Cherenkov transfer of radiation energy to fast electrons, and lead to the narrowing of the energy spectrum of these electrons. The observed fact of the existence of qualitatively different regimes of the interaction of powerful radiation with plasma opens further paths for optimization of the interaction of laser radiation with plasma under conditions of controlled laser-driven thermonuclear fusion.

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