Effect of suppression of the possible generation of fast electrons in a plasma

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It is shown that a transition to relatively high supersonic velocities of an inhomogeneous plasma stream going through the critical-density region suppresses the transfer of laser energy to the fast electrons.

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According to contemporary theoretical premises, when laser radiation interacts with a plasma an appreciable fraction of the absorbed radiation should be transferred to the fast electrons (see. e.g., Ref. 1). It is well known that the onset of fast electrons can greatly hinder the realization of the idea of laser-mediated thermonuclear fusion. We regard it therefore as extremely important to search for effects that can suppress the generation of fast electrons when electromagnetic waves are absorbed in a plasma. We call attention in the present communication to one such effect.

Generation of fast electrons is particularly effective under the influence of p-polarized radiation, for which the electromagnetic-field equations are

$$\left[2i\omega_0\frac{\partial}{\partial t}+c^2\frac{\partial^2}{\partial x^2}+\omega_0^2\epsilon\right]E_y(x,t)=i\sin\theta_0\, c\,\omega_0\frac{\partial E_x(x,t)}{\partial x},$$

$$\left[2i\omega_0\left(\frac{\partial}{\partial t}+\hat{\Gamma}\right)+v_{Te}^2\left(3\frac{\partial^2}{\partial x^2}+\frac{\partial\epsilon/\partial x}{1-\epsilon}\frac{\partial}{\partial x}\right)+\omega_0^2\epsilon\right]E_x(x,t)$$

$$=i\sin\theta_0\, c\,\omega_0\frac{\partial E_y(x,t)}{\partial x}, \tag{1}$$

where θ_0 is the incidence angle, ω_0 is the frequency of the incident electromagnetic wave, $v_{Te}^2=T_e/m_e$ is the square of the thermal velocity of the electrons, c is the speed of light

$$\epsilon=1-\frac{n(x,t)}{n_c}\left(1-i\frac{\nu_0}{\omega_0}\right),$$

$n(x,t)$ is the ion-number density, n_c is the critical density, ν_0 is the frequency of the electron collisions, and

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

where

$$\gamma_L(k)=\sqrt{\frac{\pi}{8}}\frac{\omega_0^4}{(kv_{Te})^3}\exp\left(-\frac{\omega_0^2}{2k^2v_{Te}^2}\right).$$

The operator $\widehat{\Gamma}$ determines the fraction of the energy transferred from the field to the fast electrons.

Since generation of fast electrons occurs under conditions when strong electric fields are realized and deform the plasma density by producing ponderomotive forces, it follows that the field equations must be supplemented by the hydrodynamic equations

$$\frac{\partial n}{\partial t} + \frac{\partial n v}{\partial x} = 0, \quad \frac{\partial n v}{\partial t} + \frac{\partial}{\partial x} n (v^2 + v_s^2) + \frac{1}{4} \frac{z e^2 n}{M_i m_e \omega_0^2} \frac{\partial}{\partial x} |\mathbf{E}|^2 = 0. \tag{3}$$

Here Z is the ion charge, M_i is the ion mass, and $v_s^2 = (ZT_e + T_i)/M_i$ is the square of the ion-sound velocity. Equations (3) take into account the influence of the ponderomotive forces on the motion of the plasma material.

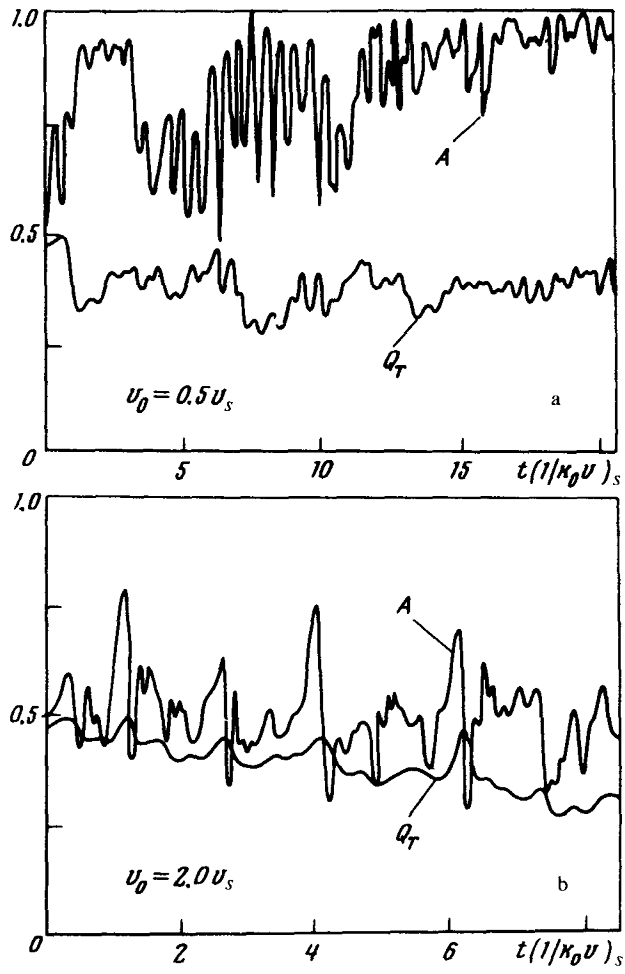

FIG. 1.

The system (1)–(3) was used by us to analyze the problem of incidence of p-polarized radiation on a planar layered structure with inhomogeneity along the x axis. At the initial instant, the density distribution was linearly inhomogeneous $\sim x/L$ and the plasma velocity corresponded to a constant flow $n(x,t=0)v(x,t=0) = \text{const}$. The system of equations was numerically integrated on a segment $[0,D]$ of length equal to several vacuum wavelengths of the radiation ($D = a2\pi c/\omega_0, a \gtrsim 5$). The boundary conditions set the rate $v(x = D,t) = -v_0$ of plasma flow from the thick layers towards the critical point.

The results of the solution of the system (1)–(3) have made it possible, in particular, to determine the absorption coefficient $A = 1 - |R|^2$, where R is the reflection coefficient of the wave incident on the plasma, as well as the fraction Q_T of the field energy absorbed by the plasma and determined by the electron collisions

$$Q_T = \frac{\omega_0}{c E_0^2 \cos\theta_0} \int_0^D dx \frac{\nu_0}{\omega_0} \frac{n(x,t)}{n_c} |\mathbf{E}|^2 .$$

Figure 1 shows the time dependences of A and Q_T, obtained at $\nu_0/\omega_0 = 5\times 10^{-3}$ sec^{-1}, $T_e = 1.25$ keV, and $\sin\theta_0 = 0.29; v_E/v_T = 0.3$, where $v_E = eE_0/m_e\omega_0$ is the electron oscillation velocity in the pump field in vacuum and $m_e v_T^2 = T_e + T_i/Z$. These parameters agree with those realized in experiment.

In the case of slow plasma flow ($v_0 = 0.5 v_s$), Fig. 1(a) demonstrates the feasibility of 100% absorption of the electromagnetic energy, due in particular to the onset of cavitons under these conditions.[2] At the same time, according to Fig. 1(a), only approximately half of the absorbed energy goes to heating of the bulk of the electrons,

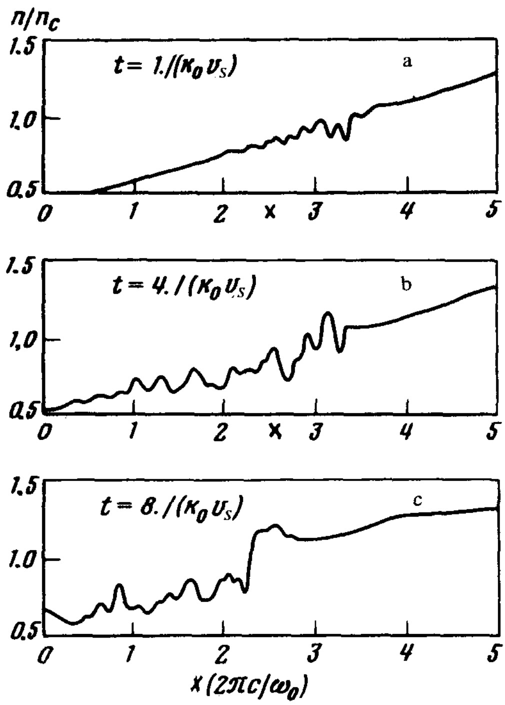

FIG. 2.

and the remainder is dissipated by Cerenkov interaction and is consumed in generation of fast electrons. In the opposite case of fast flow ($v_0 = 2v_s$) [Fig. 1(b)], the total absorbed energy is decreased somewhat, but at the same time almost all the absorbed energy goes to heating of the bulk of the electrons, and then only a small fraction is transferred to the fast electrons. According to Fig. 2, the formation of a caviton with a significant depth and long life is hindered, as is therefore the formation of the short-wave component of the potential field that leads to a generation of the fast electrons.

These results demonstrate the qualitative influence of the rate of flow of the plasma stream on the interaction of radiation with a plasma, and uncover a possibility of suppressing the fast-electron generation. We regard it as correct to attribute the fact that this influence manifests itself at velocities much lower than the group velocity of the linear electron Langmuir waves, but higher than the sound velocity, to the need for dispersing the ions when the plasma density is deformed by the field, since nonlinear potential waves cannot exist in the plasma without this deformation.

[1]K. Estabrook and W.L. Kruer, Phys. Rev. Lett. **40**, 42 (1978).
[2]A.Y. Wong, J. Phys. (Paris) Colloque **C6**, Supplement **38**, C6-27 (1977).