Parametric modulation of the density of a laser plasma near the critical surface

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We investigate the mechanism of the onset of a periodic structure in the vicinity of the critical surface of a laser plasma as a result of parametric excitation of trapped standing electromagnetic oscillations that are radiated into the region of the rarefied plasma.

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The formation of a periodic structure in the vicinity of the surface was recently observed under laboratory conditions[1] and in numerical experiments on the interaction of powerful radiation with a laser plasma[2–4]; this interaction has not found a satisfactory explanation within the framework of the prevailing concepts. The present communication is devoted to the establishment of the connection between the periodic modulation of the density along the plasma boundary, and the parametric excitation of standing electromagnetic waves with frequency Ω close to the frequency ω_0 of a powerful pump field. It is shown that the buildup of the emitted natural oscillations leads to formation of structures that are periodic in a direction transverse to the external field $\mathbf{E}_0$, with characteristic dimensions that exceed half the pump wavelength.

We consider a plasma that is inhomogeneous along the OX axis and has a density profile $n_0(x)$ connected with the distribution of the field $\mathbf{E}_0(r,t) = \mathbf{E}_0(x)\cos\omega_0 t$ of a powerful s-polarized electromagnetic wave propagated along the OX axis by the relation

$$n_0(x) = n_0 \exp\{-V_E^2(x)/2V_{Te}^2\},$$

$$V_{Te} = (T_e/m_e)^{1/2}; \quad \mathbf{V}_E(x) = e\mathbf{E}_0(x)/m_e\omega_0,$$

where the amplitude of the field $\mathbf{E}_0(x)$ satisfies the equation

$$\left[\frac{\partial^2}{\partial x^2} + \frac{\omega_0^2}{c^2}\epsilon(\omega_0, x)\right]\mathbf{E}_0(x) = 0, \tag{1}$$

$$\epsilon(\omega, x) = 1 - \frac{\omega_{Le}^2(x)}{\omega^2}\left(1 - i\frac{\nu(x)}{\omega}\right) \equiv \epsilon'(\omega, x) + i\epsilon''(\omega, x);$$

$$\omega_{Le}^2(x) = \frac{4\pi e^2 n_0(x)}{m_e}.$$

When the intensity of the incident wave is large enough, a region is produced in the plasma (cf. Ref. 3) in which the density distribution corresponds to the possible existence of s-polarized natural trapped potential oscillations (see Fig. 1), which are weakly damped because of the inverse bremsstrahlung as well as a result of their emission from the de-excitation point $x_0 : \Omega^2\epsilon'(\Omega, x_0) = k_{\parallel}^2 c^2$ ($\mathbf{k}_{\parallel}$ is the wave vector of the perturbations and is directed along the critical surface). The damping of the trapped wave, in the absence of an external field, is characterized by a decrement $\tilde{\gamma}$

$$\tilde{\gamma} = \frac{1}{W}\left\{\int_{x_0}^{\infty} dx \frac{\nu(x)\omega_{Le}^2(x)}{\Omega^3}\left|E^{(0)}(x)\right|^2 + \frac{c^2}{\Omega^2}\left|E^{(0)}(x_0)\right|^2 \operatorname{Im}\frac{\partial \ln E^{(0)}}{\partial x}\bigg|_{x_0}\right\},$$

$$W = \int_{x_0}^{\infty}\frac{dx}{\Omega^2}\frac{\partial}{\partial\Omega}\left(\Omega^2\epsilon'(\Omega)\right)\left|E^{(0)}(x)\right|^2. \tag{2}$$

The electric field intensity amplitude $\mathbf{E}^0(x)$ which enters in (2) satisfies the equation

$$\left[\frac{\partial^2}{\partial x^2} - \frac{\Omega^2}{c^2}\epsilon(\Omega, x) + k_{\parallel}^2\right]\mathbf{E}^{(0)} = 0 \tag{3}$$

with the boundary condition that requires that the obtained solutions go over into a wave propagating into the vacuum (in the direction $x \to -\infty$) to the left of the point

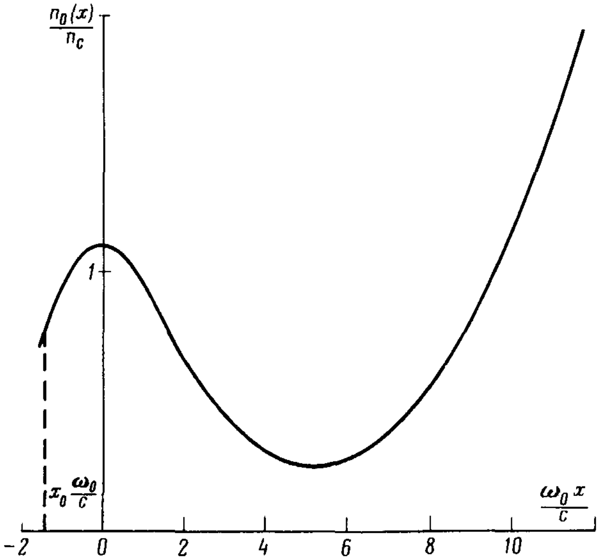

FIG. 1. Self-consistent profile of the plasma density in the field of a powerful wave $[V_E(x\to-\infty)/V_{Te}=2.5,\ V_{Te}/c=0.016]$, in which trapped natural electromagnetic oscillations can exist $[n_c\equiv n_0(X_c);\omega_{Le}(X_c)=\omega_0]$.

x_0. In the region of the plasma with the densities shown in Fig. 1, there can exist two modes of natural trapped oscillations with frequency close to ω_0, the spatial distribution of whose electric field amplitudes is shown in Fig. 2.

In the pump field, the indicated oscillations are excited with a wave vector ($\mathbf{k}_\parallel$ orthogonal to the direction of the intensity $\mathbf{E}_0$. Simultaneously, low-frequency perturbations with frequency $\omega\ll\omega_0\approx\Omega$ are excited. The dispersion equation obtained neglecting the interaction of the trapped oscillations with the external field in the region $x<x_0$ is of the form (cf. Ref. 5)

$$(\omega+i\gamma)^2+\frac{\Delta\omega_0\,\Lambda}{[\omega+i(\gamma+\tilde{\gamma})^2]^2-(\Delta\omega_0)^2}=0. \tag{4}$$

Here γ is the instability decrement and Λ is the coefficient of the coupling of the high-frequency trapped oscillations with the external field

$$\Lambda=\frac{\gamma_0^2}{W}\int_{x_0}^{\infty}dx\,\frac{\omega_{Le}^2(x)}{\omega_0^2}\left\{\left|\mathbf{E}^{(0)}(x)\mathbf{r}_E(x)k_\parallel\right|^2+\left|\frac{d}{dx}\mathbf{E}^{(0)}(x)\mathbf{r}_E(x)\right|^2\right\},$$

$$\Delta\omega_0=\omega_0-\Omega(\mathbf{k}_\parallel);\qquad \gamma_0=\omega_0\sqrt{\frac{m_e}{2m_i}};\qquad \mathbf{r}_E(x)=\mathbf{V}_E(x)/\omega_0$$

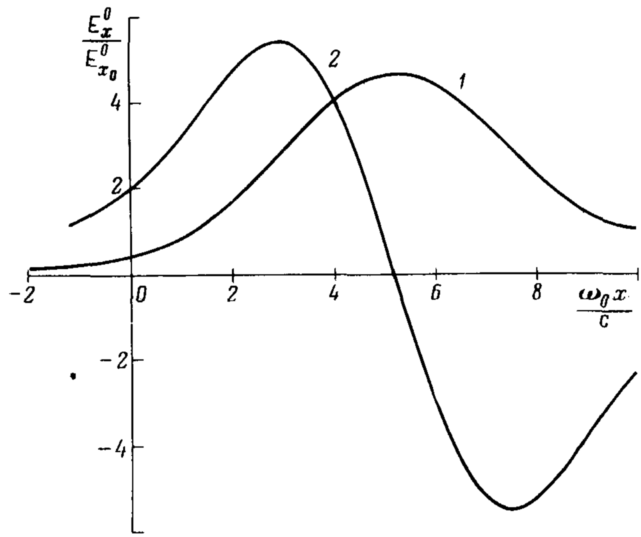

FIG. 2. Spatial distribution of the amplitude of the intensity of the electric field of the natural trapped oscillations with wave numbers $k_{\parallel} = 0.75\omega_0/c$ (1) and $k_{\parallel} = 0.4\omega_0/c$ (2).

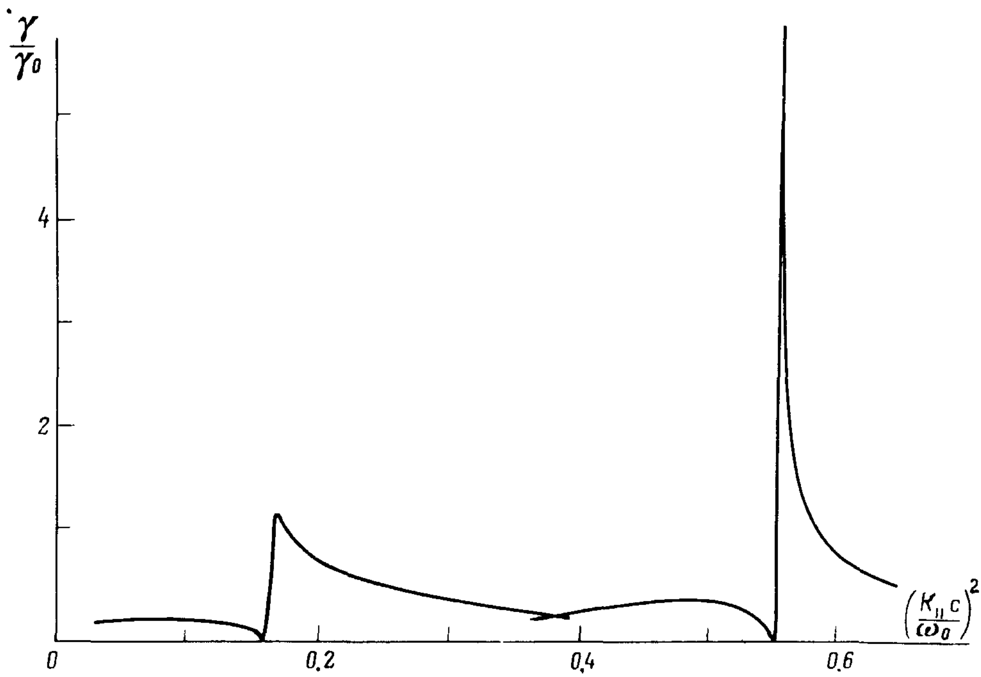

FIG. 3. Dependence of the increment of the parametrically unstable mode on the wave number of the perturbations along the critical surface when standing trapped electromagnetic oscillations are excited $[\gamma_0 = \omega_0(m_e/2m_i)^{1/2}]$.

The results of a numerical analysis of the increment γ, determined from Ref. 4, are given in Fig. 3 for the plasma parameters used to obtained Figs. 1 and 2. In addition, it was assumed that $\nu(x_c) = 10^{-3}\omega_0$. It is seen from Fig. 3 that the instability increment has two sharp maxima for oscillations whose wavelengths agree with the corresponding values of the trapped natural waves. This means that a periodic structure with two characteristic oscillations $l_1 = 0.67\lambda_0$ and $l_2 = 1.25\lambda_0$ ($\lambda_0 = 2\pi c/\omega_0$) is produced along the plasma boundary in a direction perpendicular to $\mathbf{E}_0$. This structure was observed in the numerical experiment[3] and previously recieved no satisfactory physical explanation.

Thus, when powerful radiation acts on an inhomogeneous plasma, the latter turns out to be unstable to buildup of standing trapped electromagnetic perturbations. The development of this instability is accompanied by the onset of modulation of the density in the vicinity of the critical surface, with characteristic dimensions equal to half the wavelength of the excited waves. Simultaneously with the indicated phenomenon, waves should be emitted at the pump frequency, propagating perpendicular to $\mathbf{E}_0$ and making an angle with the normal to the critical surface.

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