Deformation of density profile and efficiency of resonant absorption of laser radiation in an inhomogeneous plasma

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The optimal conditions (the incidence-angle region) and the maximum efficiency of resonant absorption of an intense p-polarized wave in a laser plasma are determined.

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The investigation of resonant absorption of high-power optical radiation in an inhomogeneous plasma is an important aspect of the general problem of energy transfer to the plasma in laser-mediated controlled thermonuclear fusion. In this paper we estimate the efficiency of this absorption with account taken of the strong deformation of the plasma density profile, which occurs at high power under the influence of the ponderomotive force. A very simple one-dimensional stationary model makes it possible to reveal and describe the physical effects that are typical of this problem and the relations that determine the optimal conditions and the efficiency of the absorption in a wide range of values of the laser-radiation power. The derived relations are in good agreement with the results of recent experiments,[1-3] in which a strong dependence of the efficiency of laser-radiation absorption in flat targets on the polarization and on the incidence angle of the wave was observed, as well as with the results of numerical simulation.[4]

We consider oblique incidence of a plane wave of amplitude E_0 and frequency ω on an inhomogeneous plasma layer with a stationary density profile $n(z)$. The wave vector of the wave lies in the xz plane and makes in vacuum an angle θ with the z axis; the electric-field vector (E_x,E_z) lies in the same plane; the magnetic field has a single component H_y. We are interested in the value of the additional resonant absorption which the considered p-polarized wave undergoes as a result of generation of longitudinal waves in the region of the plasma resonance under the influence of the E_z component of the electric field.

The density distribution produced by the averaged ponderomotive force can be represented in the form (under the condition that $|E|^2 \ll E_p^2$)

$$n = n_0(z) - n_c \frac{|E|^2}{E_p^2}, \tag{1}$$

where $E_p^2 = 4(T_e + T_i)m\omega^2/e^2$ is the characteristic plasma field,[1)] and $n_0(z)$ is the unperturbed density profile and is characterized by a certain sufficiently large inhomogeneity scale l:

$$n_0(z) = n_c(1 + z/l),\; n_c = m\omega^2/4\pi e^2,\; k_0 l >> 1,\; k_0 = \omega/c. \tag{2}$$

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Noticeable deformations of the density profile $n(z)$ occur primarily in the field-enhancement regions, namely, near the plasma-resonance point ($n = n_c$) and near the turning point ($n = n_c \cos^2\theta$).

The deformation with the lowest threshold is possessed by the deformation of the profile in the plasma-resonance region. If the condition

$$(V_{Te}/c)^2 << (E_0/E_p)^2 k_0 l << 1 \tag{3}$$

is satisfied, then at angles close to the optimal[2] $\theta_0 \approx (k_0 l)^{-1/3}$, a jump-like transition takes place through the point $n = n_c$,[6] but the plasma remains still practically unperturbed near the turning point, so that the region of reflection and the region of transformation remain separated by an opaque barrier. In an unperturbed plasma, the energy flux density generated by the runaway longitudinal wave is $S = (1/8)\omega l D^2$, where $D = D_z = H_y \sin\theta$ is the electric induction in the resonance region; at the optimal angle we have $D \approx E_0(2\pi k_0 l)^{-1/2}$. In the presence of noticeable deformation, the efficiency of the transformation into the runaway wave decreases like E_0^{-1}:

$$a = S/S_0 = 2\sqrt{3}(V_{Te}/c)(DE_p/E_0^2), \tag{4}$$

S_0 is the energy flux density in the incident wave, and $V_{T_e} = (T_e/m)^{1/2}$ is the thermal velocity of the electrons. At the same time, with increasing E_0, a noticable role can be played by the additional collisionless absorption due not to the outflow of the energy from the resonance region, but to the acceleration of the electrons directly in this region where the quasi-standing Langmuir solitons are modulation-excited and the spectrum of the electric field is enriched with slow harmonics. Estimates show that because of this additional loss mechanism, on the upper boundary of the amplitude, which is determined by the conditions (3), the fraction of the absorbed power is just as high as in the linear case ($\approx 50\%$ of the incident power).[3]

Under the condition

$$(E_0/E_p)^2 k_0 l > 1 \tag{5}$$

(which is certainly satisfied for a neodymium laser at a flux density $S_0 \gtrsim 10^{14}$ W/cm^2) the deformations of the profile cover already a rather wide region, so that the turning point practically coincides with the plasma resonance point. This produces favorable conditions for increasing the efficiency of the energy transformation into a longitudinal wave. The parameters of the large-scale plasma deformation that leads to such an appreciable shift of the turning point into the interior of the plasma can be easily determined under the condition $(E_0/E_p)^{2/3} \gg \sin\theta$, which makes it possible, when calculating the shift, to neglect the longitudinal field component E_z. In the WKB approximation the boundary of the transparency region can be determined from the equation for the slow amplitude $E = E_0[\epsilon(E^2) - \sin^2\theta]^{-1/4}$ (for an exact solution of the problem for an s-polarized wave see Ref. 7). It turns out that the dielectric constant of the plasma $\epsilon = 1 - (n/n_c)$ increases in the transparency region in this case on the average to a level $\bar{\epsilon} \approx (E_0/E_p)^{4/3}$, and the transition through the point $\epsilon = 0$ (from $\epsilon \approx \bar{\epsilon}$ to $\epsilon \approx -\bar{\epsilon}$) shifts into the region $z \approx l(E_0/E_p)^{4/3}$. The characteristic scale Λ_e of this transition is of the order of the length of the electromagnetic wave at $\epsilon = \bar{\epsilon}[\Lambda_e \approx c/\omega(\bar{\epsilon})^{1/2}]$.

To investigate the transformation of an electromagnetic wave into a plasma wave in the presence of such a strong deformation of the density profile it is possible, as before,[6] to use a quasi-static model, since the characteristic dimension of the transformation is small compared with Λ_e. It turns out that against the background of the "electromagnetic" transition there is formed a much steeper "plasma" transition ("jump") with a characteristic scale of the order of the plasma wavelength $\Lambda_p \approx V_{T_e}/\omega(\epsilon_c)^{1/2}$, in which the dielectric constant changes from a value $\epsilon \approx -\epsilon_c = (\bar{\epsilon}\sin\theta)^{1/3}$ to a value $\epsilon \approx -\epsilon_c$. The efficiency of generation of the runaway longitudinal wave can be estimated with the aid of relation (4), but with a different value of the induction $D \approx {}^4\sqrt{\bar{\epsilon}}E_0 \sin\theta$. As a result we have

$$a = S/S_0 \approx 2\sqrt{3}(V_{Te}/c)(\sin\theta/\sqrt{\bar{\epsilon}}). \tag{6}$$

The volume losses can be neglected in this case, since the presence of a strong inhomogeneity of the plasma hinders the modulation excitation of the Langmuir oscillations.

Insamuch as at large incidence angles $\sin^2\theta \gg \bar{\epsilon}$ the field in the resonance region is exponentially small, the optimum incidence-angle value corresponding to the maximum of the absorption lies obviously in the region

$$\sin\theta_{\rm opt} \approx \sqrt{\bar{\epsilon}} \approx (E_0/E_p)^{2/3} \tag{7}$$

whose width is $\Delta\theta \approx \theta_{\rm opt}$.

If the absorption on one jump is not large enough, the electromagnetic wave is close to a standing wave and a quasiperiodic structure is produced in the plasma, with several passages through the resonance region. The total absorbed power turns out to be in this case of the order of the incident power.

The relation (6) determines the value of the additional absorption $\alpha_{\max} = (S_{\max}/S_0) \approx 2(3)^{1/2}(V_{T_e}/c)$ for p-polarized radiation. It is clearly important that $\alpha_{\max}$ does not decrease with increasing wave power, whereas the efficiency of the absorption of s-polarized radiation decreases with increasing E_0 because of the onset of strong density gradients.[4] For a sufficiently hot plasma ($T_e \gtrsim 1$ keV) the efficiency of the additional absorption $\alpha_{\max}$ is several dozen percent, in good agreement with the results of experiments[1-3] and computer simulation.[4]

[1)] We consider for simplicity the case of a quiescent plasma. If the plasma has a stationary velocity profile $v(z)$ that conserves the flux density $nv = $ const, the obtained relations remain valid if we make the substitution $E_p^2 \to E_c^2 = 4Mm\omega^2 e^{-2}(v_s^2 - v^2)$, $v_s = [(T_e + T_i)/M]^{1/2}$ is the speed of the ion sound and M is the ion mass.

[2)] This angle corresponds to a maximum efficiency of the linear transformation in the case of small-amplitude waves.[5]

[3)] A detailed investigation of this question will be published in a separate article.

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