Influence of relativistic effects on the penetration of a wave beam into a dense plasma

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The absorption of an intense wave beam in a dense plasma is analyzed. Relativistic effects are considered. Absorption in a plasma with a density above the critical value may be increased substantially by the relativistic nonlinearity even after a brief time.

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A wave beam, even of comparatively low intensity, can penetrate into an opaque medium, and the collisional absorption increases significantly.[1,2] The electrostrictive nonlinearity was studied in Refs. 1 and 2, and the condition for the penetration of the radiation was found to be $W/nT > \lambda/L$, where W is the initial energy density of the beam, n and T are the beam density and temperature, λ is the wavelength, and L is the characteristic dimension of the inhomogeneity of the medium. In order to take the "slow" electrostrictive nonlinearity into account, however, it is generally necessary to solve the problem incorporating (in addition to the incident wave) the reflected front, which has time to form. This circumstance causes serious analytic difficulties. With increasing wave energy, the "fast" relativistic nonlinearity comes into play, and W/nT, for example, loses its meaning at short times, before the density profile can be deformed.

In this letter we take the relativistic nonlinearity into account, and we show that the absorption in a transcritical plasma can increase substantially even in a short time.

We consider the normal incidence of a three-dimensional axisymmetric wave beam of high energy (the plasma electrons acquire relativistic velocities in this beam) on a plasma with a linear density profile $n = n_0(1 + z/L)$. We work from the standard wave equation for the complex amplitude of the electric field of the beam,[1,2]

$$\Delta E + \frac{\omega^2}{c^2}\left(1 - \frac{\omega_p^2}{\omega^2}\right)E = 0, \tag{1}$$

where $\omega_p^2 = \omega_e^2(1 + (e^2E^2)/(m_{0e}^2\omega^2c^2))^{-1/2}$ is the electron plasma frequency.

We seek a solution of Eq. (1) in the form

$$E = A(z, r)\left(\frac{k_0}{k(z)}\right)^{1/2} \exp\left\{-i\int^{z} k(z')dz'\right\}. \tag{2}$$

We assume that the longitudinal wave number $k(z)$ includes terms with both the linear and nonlinear parts of the dielectric function. Denoting by a the characteristic transverse dimension of the beam, we can study Eq. (1) by the geometric-optics approach under the condition $|k(z)a| \gg 1$. Adopting a Gaussian field distribution A

$= (A_0/f)e^{-(r^2/a^2f^2)}$ in the beam, and discarding terms of order $1/k^2(z)a^2$, we find, for the axial region,

$$\frac{d^2f}{dz^2} + \frac{d}{dz}\ln k(z)\frac{df}{dz} = \frac{4}{k^2(z)a^4f^3} - \frac{\gamma^2}{\left(1+\gamma^2\frac{k_0}{k(z)}\frac{1}{f^2}\right)^{3/2}}\frac{1}{f^3a^2}\frac{k_0}{k(z)}\frac{\omega_e^2}{k^2(z)c^2}, \tag{3}$$

$$k^2(z) = \frac{\omega^2}{c^2}\left(1 - \frac{\omega_e^2}{\omega^2}\frac{1}{\left(1+\gamma^2\frac{k_0}{k(z)}\frac{1}{f^2}\right)^{1/2}}\right), \qquad \omega_e^2 \equiv \frac{4\pi n e^2}{m_{0e}} \tag{4}$$

where f is the dimensionless beam width, and $\gamma^2 = e^2A_0^2/m_{0e}^2\omega^2c^2$ is the relativistic parameter.

In the slightly relativistic case ($\gamma^2 \ll 1$), Eqs. (3) and (4) describe a "fast" self-focusing of the wave beam, and they have the same form as the well-studied nonrelativistic equations for a medium with a cubic nonlinearity.[1,2]

Let us examine Eqs. (3) and (4) in the highly relativistic limit ($\gamma^2 \gg 1$). In this case we have $k(z) \approx k_0$, and by ignoring the diffraction term in (3) we find the focal length to be $F \approx a\gamma^{1/2\omega}/\omega_e \gg a$ (i.e., the parabolic approximation is not violated).

Beyond the focus the beam undergoes a quasichanneling with

$$f \approx (4\gamma)^{1/3}\left(\frac{\lambda}{a}\right)^{2/3}, \quad \frac{\lambda}{a} \ll 1. \tag{5}$$

The length of the channel is

$$l \approx \gamma^{2/3}\left(\frac{a}{\lambda}\right)^{2/3} L \gg L. \tag{6}$$

Let us examine the absorption of beam energy. In the channeling regions, $\omega_e < \omega$, we find, using the length of these region found above,

$$Q = 1 - \exp\left[-\frac{\nu}{c}L\left(\frac{a}{\lambda}\right)^{2/3}\gamma^{2/3}\right]. \tag{7}$$

We see that in the relativistic case the fraction Ω of the energy absorbed in the channeling regions due to collisions in the case $\nu = \text{const}$ is much higher than the collisional absorption in the nonrelativistic case (with an electrostrictive nonlinearity). Near the focus the collisional absorption is weak, but a parametric instability may occur there. It should be noted that a factor of decisive importance for the onset of these instabilities is the relativistic dependence of the electron mass on the amplitude of the pump wave.[3–6] A third dissipation mechanism is the conversion of beam energy into plasma waves at the density jump in the region where the dielectric function is approximately zero. Estimating the energy loss at the boundaries of the channel corresponding to this conversion, we find that the energy of the incident laser beam is absorbed over a distance

$$l \simeq a \frac{W}{nT} \frac{c}{v_e}, \quad (8)$$

where W/nT is an average value of the parameter along the side walls of the channel.

For these relativistic effects to occur, the power density of a CO_2 laser would have to be on the order of or greater than 10^{16} W/cm^2. An experimental team at Los Alamos[7] recently observed a pronounced increase in the absorption of a laser beam, from 25–30% at 10^{14} W/cm^2 to 50–60% at 10^{16} W/cm^2. This effect can apparently be attributed to relativistic effects.

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