Self-focusing and energy absorption of a laser beam in an inhomogeneous plasma

N. S. Erokhin, S. S. Moiseev, V. V. Mukhin, V. E. Novikov, and R. Z. Sagdeev
Physicotechnical Institute, Academy of Sciences, Ukrainian SSR

(Submitted 23 March 1981)

Pis'ma Zh. Eksp. Teor. Fiz. **33**, No. 9, 451–454 (5 May 1981)

It is shown that a beam of sufficiently small transverse dimensions can penetrate into the opacity region to a depth that exceeds this dimension. The role of different laser energy absorption mechanisms are discussed. Specifically, a shift in the direction of increase of collisional absorption is shown.

PACS numbers: 52.25.Ps

There are three competing processes responsible for the energy absorption of a laser beam in the plasma of a target: Coulomb collisions, linear conversion of an obliquely incident, transverse wave to a longitudinal wave, and parametric mechanisms (see, for example, Ref. 1). The bulk of experimental data unfortunately could not be interpreted unambiguously until now, because at the attained parameters (laser power, collision frequencies, etc.) they lie in the border zone between the three indicated processes. Investigation of the energy absorption in the transition region, therefore, is of particular interest.

 0021-3640/81/09434-04$00.60

We show in this paper that allowance for the transverse dimension of the beam qualitatively changes the picture of its propagation and energy absorption in the plasma and also the relation between the competing processes. Specifically, the importance of the collision mechanism increases at moderate laser power.

In contrast to Ref. 2, in which the self-focusing of a *TE*-type beam was analyzed while ignoring the absorption processes, we shall examine the normal incidence of a three-dimensional, axisymmetric (radius a), *TM*-type wave beam (the most interesting in terms of absorption) on a plasma with a linear density profile $\epsilon_0 = 1 - z/L$. We shall seek a solution of the standard wave equation for the H_x component of the magnetic field in the form

$$H_x = A(z, r)\exp\left[-i\int_0^z k(z')dz'\right]. \tag{1}$$

Just as in Ref. 2, we shall assume that $k(z)$ includes the terms associated with the linear and the nonlinear parts of the dielectric constant ϵ. Assuming that the narrow-beam approximation $N_z \gg N_\perp$ is Gaussian (which simplifies the calculation but does not affect it materially), taking into account that the strictional effects reach the values necessary to brighten the plasma in the cases of practical interest, and requiring, therefore, that the WKB approximation is realized, we obtain in the axial region

$$N_z^2 = \epsilon_0(z) + \frac{W}{nT}\frac{N_z}{f^2|\epsilon|} - \frac{q^2}{f^2},$$

$$\frac{d^2f}{dz^2} = \frac{q^2}{N_z^2 a^2 f^3} - \left(\frac{df}{dz}\right)\frac{d\ln N_z}{dz} - \frac{2W}{nT}\frac{1}{N_z a^2 f^3|\epsilon|}, \tag{2}$$

$$\epsilon_r = \epsilon_0 + (W/nT)(N_z/f^2\sqrt{\epsilon_r^2 + \epsilon_i^2}).$$

Here ϵ_r and ϵ_i are the real and the imaginary parts of the dielectric constant, respectively, f is the dimensionless width of the beam, $N_z = ck/\omega$, $N_\perp = q/f$, $|\epsilon| = \sqrt{\epsilon_r^2 + \epsilon_i^2}$, W is the density of the initial beam energy, and $q = (2c/a\omega)$ is the diffraction parameter.

We present the results of the analysis (2). First, we shall mention that the density jump, which occurs near the plasma resonance of a plane wave[3] and which prevents it from penetrating into the plasma, is missing in the entire region of penetration of the beam beyond the linear reversal point. In our case, however, the plasma is ejected primarily at right angles to the motion of the narrow wave beam, since its transverse rf pressure is larger than the longitudinal pressure. Mathematically, the absence of a jump is illustrated by the behavior of $\epsilon_r(z)$ (Fig. 1). Further, we can identify two modes of behavior of a wave beam beyond the linear reversal point. If $(a/L)^{3/2} < (W/nT) \ll 1$, then the beam will contract to its minimum size beyond the linear reversal point at a distance of the order of a. Such a fast self-focusing of the beam in the opaque region is highly general and is based on the

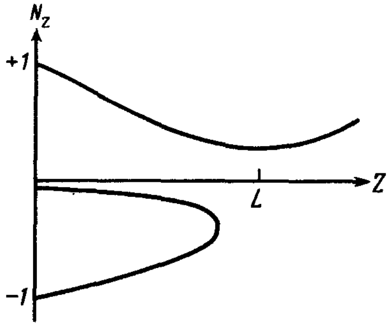

FIG. 1. Dependence of the longitudinal number on the coordinate directed through the bulk of the plasma.

fact that the beams cannot "escape" from the transparent channel (in contrast to the transparent medium in which the channel "confines" only the beams that have experienced a total internal reflection). We have obtained from (2) an approximate expression for the beam width near the region of the focus

$$\frac{z}{a\sqrt{3}} = \int_1^{F_0} \frac{x^2 dx}{\sqrt{1 - x^4/F_0^4}} + \int_F^{F_0} \frac{x^2 dx}{\sqrt{1 - x^4/F_0^4}}, \tag{3}$$

where

$$F = [f(z)]^{1/4}; \quad \frac{1}{F_0} = \left(1 - \frac{a^2}{3l^2}\right)^{1/4}; \quad l \equiv (df_0/dz)^{-1}.$$

Beyond the focus the beam goes into the quasi-tunneling mode with

$$f \sim (b/z)^{5/2}, \tag{4}$$

where $b = L\,(a/L)^{2/5}\,(W/nT)^{2/5}$. However, the diffraction term defocuses the beam at a distance $L\sqrt{(a/\lambda)}\;W/nT$ from the focus, and the WKB approximation breaks down. If, however, $(c/\omega L) < (W/nT) < (a/L)^{3/2}$, then the quasi-channeled regime similar to (4) occurs directly beyond the reversal point.

We shall now analyze the energy absorption of a beam. In the channeled sections $\omega_{pe}(r) < \omega$, allowing for the length of these sections that were traced above, we can see that the fraction of energy absorbed in them due to collisions $(\nu L/c)$ $(L/\lambda)^{1/5}$ $(a/L)^{4/5}$ can substantially exceed the collisional absorption in the transparent region. The absorption due to collisions is small ν/ω in the region of the focus; however, an absolute parametric instability can develop in this region ($t \to l + s$, see Ref. 4). Note that the Langmuir wave formed at the leading edge of the wave packet, just as in Ref. 5, transfers its energy to thermal electrons faster than the parametric instability mentioned above can be developed, if $1/\omega_s > a/v_T\sqrt{(aW/nT\lambda)}$ (ω_s is the frequency of the ion sound).

In conclusion, we note that, in addition to the diffraction effects, nonlinear energy absorption can also limit the wave amplitude in the region of the focus (see Ref. 6).

1. Lazery i termoyadernaya problema (Lasers and the Nuclear Fusion Problem), a collection of translated articles, Atomizdat, Moscow, 1973.
2. N. S. Erokhin, S. S. Moiseev, V. V. Mukhin, V. E. Novikov, and A. V. Tur, Soviet-French seminar on rf methods of heating a plasma, 17–21 June, 1974, Nauka, Leningrad, 1974; N. S. Erokhin, S. S. Moiseev, and V. E. Novikov, Zh. Tekh. Fiz. 48, 1769 (1978) [Sov. J. Techn. Phys. **23**, 1007 (1978)].
3. V. B. Gil'denburg, Zh. Eksp. Teor. Fiz. **46**, 2156 (1964) [Sov. Phys. JETP **19**, 1456 (1964)].
4. N. S. Erokhin, S. S. Moiseev, and V. V. Mukhin, Zh. Eksp. Teor. Fiz. **68**, 536 (1975) [Sov. Phys. JETP **41**, 262 (1975)].
5. R. Z. Sagdeev and V. D. Shapiro, Zh. Eksp. Teor. Fiz. **66**, 1651 (1974) [Sov. Phys. JETP 39, 811 (1974)].
6. V. I. Lugovoĭ and A. M. Prokhorov, Usp. Fiz. Nauk **111**, 203 (1973) [Sov. Phys. Uspekhi **16**, 658 (1973)].

Translated by S. J. Amoretty
Edited by Robert T. Beyer