PHYSICAL REVIEW A VOLUME 18, NUMBER 4 OCTOBER 1978

Interpretation of the observed anomalous transmission of intense laser radiation through an overdense plasma

J. C. Sharma and V. K. Tripathi

Department of Physics and Astronomy, University of Maryland, College Park, Maryland 20742

(Received 27 April 1978)

An explanation is provided to the experimental results of Rockett *et al.* [Phys. Rev. Lett. **40**, 649 (1978)] on the anomalous transmission of a ring-shaped laser beam through an overdense plasma. The laser beam heats the electrons of the illuminated region which in turn heat the electrons of the central region through thermal conduction. In order to equalize the pressure everywhere, a density depletion of the spot size of the laser beam is created which paves the way for the beam to be transmitted.

Rockett, Steel, Ackenhusen, and Bach[1] have recently reported some interesting experimental results on the anomalous transmission of intense CO_2-laser radiation through an overdense ($n_e \gtrsim 10^{19}$ cm^{-3}), low-temperature (~20 eV) z-pinch plasma. The laser is incident on the z pinch from the transverse direction, viz., x axis, and possesses a ring-shaped intensity profile in the y-z plane.

$$E = E_0 \exp + i\left(\omega t - \int k\, dx\right),$$

$$E_0^2 = E_{00}^2 \frac{r^2/r_0^2}{\exp(-r^2/r_0^2)}, \quad r^2 = y^2 + z^2, \tag{1}$$

$$k = \frac{\omega}{c}\left(1 - \frac{\omega_p^2}{\omega^2} - i\frac{\nu}{\omega}\frac{\omega_p^2}{\omega^2}\right)^{1/2},$$

where ω_p is the local electron plasma frequency and ν is the electron-ion collision frequency. It is seen that the laser creates a depletion of the plasma over a circular spot of size slightly greater than r_0 and thus makes the way for its transmission. Had the electron-ion collisions been negligible, the ponderomotive force on the electrons should have created a density depletion[2,3] only on the ring ($r \approx r_0$) and a plasma accumulation at the center ($r \simeq 0$), contrary to the observation. As a matter of fact, the electron-ion collision frequency at $n_e \sim 10^{19}$ and $T_e \sim 20$ eV turns out to be[4,5] $\nu \simeq 10^{12}$ sec^{-1} which is very large. The electrons are heated nonuniformly by the laser around the ring $r = r_0$ through the collisions and a temperature gradient is set up. The hot electrons transfer their energy to the electrons in the central region ($r = 0$) through thermal conduction; a part of the energy flows outward away from the heated ring also. Besides this, the electrons lose a fraction ($\sim 2m/m_i$, m and m_i are the electron and ion mass) of their excess thermal energy to ions through collisions. Thus the energy balance equation for electrons would be[3]

$$\frac{d}{dt}\left(\frac{3}{2}T_e\right) = \frac{e^2|E|^2\nu}{2m\omega^2} - \frac{3}{2}\frac{2m}{m_i}\nu(T_e - T) - \frac{1}{n_e}\frac{1}{r}\frac{\partial}{\partial r}\left(x_e r \frac{\partial T_e}{\partial r}\right), \tag{2}$$

where x_e $(= 5n_e T_e/0.65m\nu)$ is the electron thermal conductivity and T is the ion temperature; the last term in Eq. (2) refers to thermal conduction. The ratio R of the energy loss in thermal conduction to that through collisions (i.e., third term to the second term on the right-hand side) comes out to be[2]

$$R \simeq \frac{m_i}{2m}\left(\frac{\lambda_m}{r_0}\right)^2, \quad \lambda_m = \frac{v_e}{\nu}, \quad v_e = \left(\frac{2T_e}{m}\right)^{1/2}.$$

For the parameters of the experiment ($T_e \simeq 20$ eV, $n_e \sim 10^{19}$ cm^{-3}, $m_i/m \simeq 7.3\times10^3$) $R \simeq 1$. However, as the electron temperature rises, R goes as $(T_e/T)^4$ and the thermal conduction predominates over the collisional energy loss. Taking the scale size of electron temperature variation as r_0, the time to achieve steady state (i.e., the time to heat the electrons of the central region, $r \simeq 0$) turns out to be $\tau_H \simeq m\nu r_0^2/5T_e$. For the parameters of the experiment $\tau_H \simeq 1$ nsec for $r_0 \simeq 10^{-2}$ cm, $T_e \simeq T$ and decreases rapidly as T_e rises. Thus the heating time is much smaller than the duration of the laser pulse ($\tau \sim 35$ nsec).

In the steady state all the electrons inside the circular spot of radius r_0 are heated (T_e being almost flat from $r = 0$ to $r \simeq r_0$ and then falling off sharply beyond r_0). The rise in temperature can be estimated to be

$$T_e - T \simeq e^2|E|^2\tau_H/2m\omega^2$$

$$\simeq (r_0^2 v_{0sc}^2/2v_{e0}^2\lambda_{m0}^2)(T_e/T)^{-4}T,$$

where v_{0sc} is the electron drift velocity owing to the laser, and v_{e0} and λ_{m0} are the electron thermal speed and mean free path at $T_e = T$. For the parameters of the experiment as the power density of the laser increases, i.e., v_{0sc}^2/v_{e0}^2 increases from 0.01 to 1.0, $(T_e - T)/T$ goes from 1 to 3.5. On increasing the power density further, the electron temperature rises slowly. For peak intensities of the experiment $T_e \simeq 4T$, i.e., the electron temperature rises four times its thermal equilibrium value.

The plasma in the hot spot must diffuse owing to a pressure gradient on a time scale $\tau_d \sim r_0/c_s$ $[c_s = (T_e/m_i)^{1/2}$ is the ion sound speed] which is ~5 nsec for the parameters of the experiment. Thus $\tau_d > \tau_H$ and the electron temperature attains steady state much before the diffusion takes place. In the steady state $(t \lesssim \tau_d)$ one would obtain, equalizing plasma pressure in the hot spot to that outside it,

$$n_e = [2T/(T_e + T)]\, n_0 ,$$

where n_0 is the electron density outside the spot. Thus a density depletion in the hot spot is created.

For power densities of ~10^{11} W/cm^2, $n_e \sim \frac{1}{3} n_0$. The critical density for laser radiation is $n_c \sim 10^{19}$ cm^{-3}. Thus the laser would be transmitted when $n_e \lesssim n_c$, i.e., the electron density is depleted below the critical density. For the density profile of the experiment, power threshold for transmission should be ~10^{11} W/cm^2 and the laser duration must be greater than the diffusion time ~5 nsec. The experimental values of power are greater than this, hence the transmission is observed.

(i) Experimentally the transmitted laser pulse is delayed by 10–20 nsec in the plasma. The delay according to the above-mentioned analysis, is owing to the time taken by the plasma for diffusion from the hot spot, i.e., a few τ_d ($\tau_d \sim 5$ nsec). This explains very well the delay. The front and tail portions of the pulse cannot create sufficient density depletion and are not transmitted. Subsequently the pulse width is reduced. The reduction for the parameters of the experiment should be ~15 nsec which is about the same as observed experimentally.

(ii) The incident beam possesses amplitude modulation of 20%. This creates density oscillations in the plasma cavity ($T_e \sim |E|^2$ oscillates and consequently $n_e \sim 1/T_e$ also oscillates). The density oscillations in the cavity sometimes allow more transmission and sometimes cut off the transmission. Thus the transmitted beam must possess more violent modulations. This is also in agreement with the experiment where 100% modulation of the transmitted beam has been observed.

(iii) On the basis of the linear theory of wave propagation, the wave is attenuated as $\exp[-(\int k_i\, dx)]$. A wave reaching up to the critical layer and then coming back after reflection should be attenuated (through collisional damping) more than 95% for the density profile of the experiment hence no reflected power. However, as the power is raised, the electrons are heated, collision frequency decreases (i.e., attenuation decreases), the wave gets transmitted owing to plasma depletion and the attenuation of the transmitted pulse is less than 95%. This speculation is quite well supported by the observed transmission of 4%.

(iv) The plasma possesses a sharp density gradient of $L_n \sim 70$ μm and a very large collision frequency (i.e., the large attenuation rate) consequently the power thresholds for Raman and Brillouin scattering as calculated by using the expressions given by Liu,[6] come out to be two orders of magnitude larger than those used in the experiment. This is why the parametric instabilities have not been observed in the experiment.

ACKNOWLEDGMENTS

The authors are grateful to Professor C.S. Liu for valuable discussions. This work was supported by Center for Theoretical Physics, University of Maryland, Department of Energy, and Office of Naval Research.

[1]P. D Rockett, D. G. Steel, J. G. Ackenhusen, and D. R. Bach, Phys. Rev. Lett. 40, 649 (1978).
[2]M. S. Sodha and V.K. Tripathi, Phys. Rev. A 16, 2101 (1977).
[3]M. S. Sodha, A. K. Ghatak, and V. K. Tripathi, Prog. Opt. 13, 169 (1976).
[4]I. P. Shkarofsky, T. W. Johnston, and M. P. Bachynski, *The Particle Kinetics of Plasmas* (Addison-Wesley, Reading, Mass., 1966).
[5]L. Spitzer, Jr., *Physics of Fully Ionized Gases* (Interscience, New York, 1962).
[6]C. S. Liu, Adv. Plasma Phys. 6, 121 (1975).