Intensity dependence of transmission of electromagnetic radiation through an overdense Z-pinch plasma[a]

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The interaction of a 10.6-μm-wavelength electromagnetic wave with an independently created overdense plasma has been investigated at incident intensities on either side of the field-strength condition $V_{\rm osc}/V_{\rm th} = 1$. An intensity threshold for transmission of the radiation through the overdense target plasma was observed near $V_{\rm osc}/V_{\rm th} = 1$. Temporal behavior of the transmitted radiation pulse was compared to that of the incident pulse over an intensity range $(0.1\text{–}4)\times 10^{11}$ W/cm^2.

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The interaction of an intense beam of electromagnetic radiation with a high-density plasma is a topic of current experimental and theoretical interest relevant to laser-induced thermonuclear fusion. At incident radiation intensities sufficient to provide a radiation pressure comparable to the kinetic pressure of the target plasma, a variety of effects, such as density profile modification,[1] critical surface burnthrough,[2] or parametric instabilities,[3] is expected to alter the transmission, absorption, and reflection characteristics of the plasma from the classical low-intensity prediction.

This investigation examined the intensity dependence of transmission of 10.6-μm laser radiation through an initially overdense plasma[4] created independently of the laser. The experimental arrangement has been described earlier[5] and is briefly reviewed here (Fig. 1). The plasma source was a small coaxial linear Z-pinch discharge[6] which produced a fully ionized helium plasma that reached a peak electron density of 4×10^{19} electrons/cm^3 (four times the critical density for 10.6-μm radiation) and an electron temperature of approximately 20 eV. Radially incident on this plasma column was 10.6-μm CO$_2$ laser radiation, delivered in a 38-nsec FWHM pulse focused to a diffraction-limited spot of 125-μm diameter. Any CO$_2$ laser radiation passing through the plasma column was collected by a lens and split between a pyroelectric monitor of pulse shape and a burn-image monitor of intensity distribution. Transmitted radiation was examined over a range of incident intensities from $(0.1 \text{ to } 4.2)\times 10^{11}$ W/cm^2. Incident intensity was varied by changing the pressure within a propylene-gas-filled attenuator cell. Over the intensity range reported here, the focal spot size remained constant. This range provided intensities on either side of the field-strength condition $V_{\rm osc}/V_{\rm th} = 1$, which was calculated to occur at an intensity of 2×10^{11} W/cm^2. $V_{\rm osc}$ is the peak quiver velocity of the electron oscillating in the laser field at the critical surface, $V_{\rm osc} = eE_{\rm max}/m\omega$, and $V_{\rm th}$ is the electron thermal velocity in the plasma prior to laser heating. In calculating $E_{\rm max}$ to determine $V_{\rm osc}$, the effects of field swelling, due to change in the plasma dielectric constant as critical density is approached, and field absorption, due to collisional damping, were included using a linear density gradient of 150-μm scale length.

Pulsed holographic interferometry at frequency-doubled ruby-laser wavelength ($\lambda = 347.2$ nm, 16 nsec FWHM) provided temporally and spatially resolved density profiles of the target plasma in the absence of the high-intensity laser at various times along the evolution of the Z-pinch discharge. As shown in Fig. 1, the object beam of the interferometer was incident perpendicular to both the axis of the CO$_2$ laser beam and the axis of the discharge column. The interferograms indicated that the plasma density profile remained relatively stationary during the 35 nsec immediately following the burst of optical continuum radiation from the discharge; it was during this time segment that all results discussed here were obtained. At this point, the plasma centerline density was about three times critical density, the critical scale length was between 100 and 200 μm, and the critical radius was approximately 1 mm.

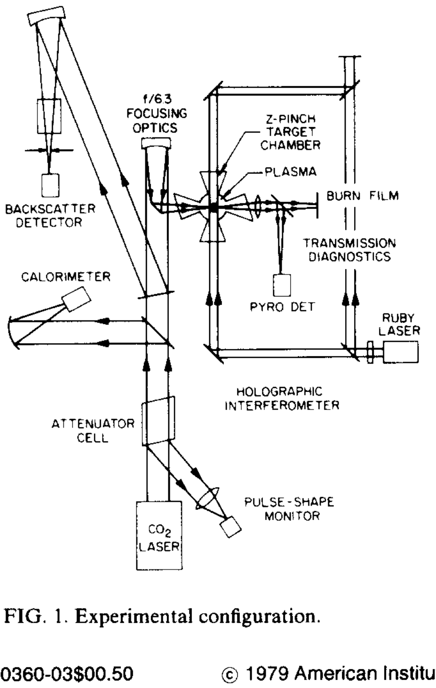

FIG. 1. Experimental configuration.

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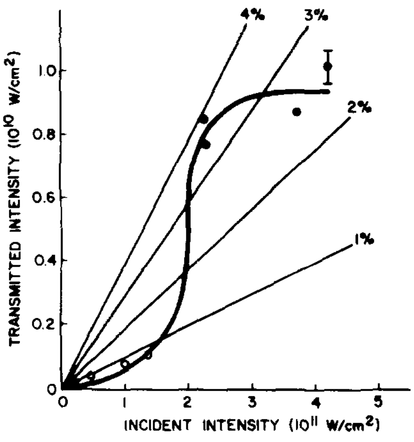

FIG. 2. Transmitted intensity versus incident intensity showing threshold at 2×10^{11} W/cm^2, initially overdense target plasma. Hollow circles — no transmission; solid circles — transmission. Lines of constant transmission fraction are shown.

In firing the CO_2 laser on the overdense plasma column at a variety of intensities, a threshold was seen for transmission of the 10.6-μm radiation through the plasma. In a plot of transmitted intensity versus incident intensity (Fig. 2), hollow circles indicate that no transmission was seen for laser intensities less than 2×10^{11} W/cm^2. Allowing for the limit of detectability of the diagnostics, this placed an upper bound on the transmission fraction of 0.8%. For a small change of a factor of 1.6 in incident intensity above the value of 2×10^{11} W/cm^2, a sharp increase of at least a factor of 5 in the transmission fraction was observed, as indicated by the solid dots.

As the incident laser intensity was further increased above this threshold, the width of the transmitted pulse was seen to decrease (Fig. 3) to a pulse width of 15 nsec, compared to the width of the incident pulse, 38 nsec. A plot of transmitted energy versus incident energy indicates the lower-energy transmission at the higher intensities (Fig. 4). The decrease in transmitted energy with increased intensity arises from the decrease in transmitted pulse width at intensitites well above threshold (Fig. 3) coupled with a peak transmitted intensity that varies little with intensity above threshold (Fig. 2).

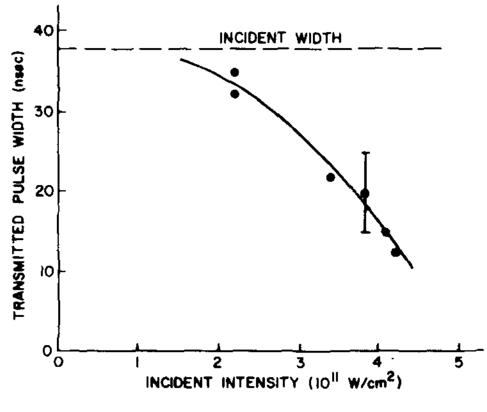

FIG. 3. Transmitted pulse width versus incident intensity.

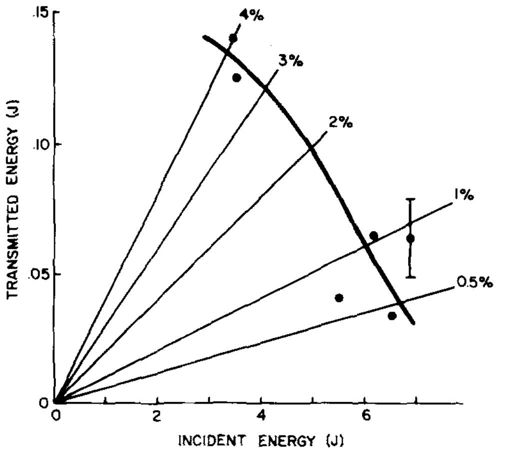

FIG. 4. Transmitted energy versus incident energy. Lines of constant transmission fraction are shown.

With incident intensity above threshold, the transmitted radiation was seen by coincidence measurements to derive from the later portion of the incident pulse. Figure 5 compares the incident and transmitted radiation pulse shapes at intensity well above threshold, showing the shortened pulse in transmission and the 30-nsec delay observed in the peak of the transmitted pulse relative to the peak of the incident pulse. Figure 5 also shows an enhanced modulation depth of the transmitted pulse over the 20% depth associated with laser self-model-locking on the incident pulse. In addition, the rapid turn-on of the transmitted pulse should be noted.

Holographic interferograms indicated the presence of a laser-driven shock wave, much larger than the laser focal spot, in the plasma column resulting from the incident CO_2 laser radiation.[5] By the assumption of rotational symmetry of the shock about the axis of the laser, density information

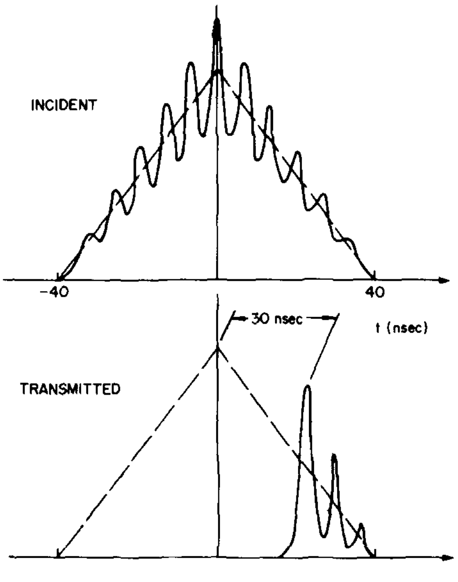

FIG. 5. Temporal pulse shape of incident and transmitted laser pulse; incident intensity $= 4\times10^{11}$ W/cm^2. Modulation on incident pulse due to laser self-mode-locking.

in the shock region was extracted and an estimate of energy absorption was made from hydrodynamic scale-length arguments in a manner detailed elsewhere.[7] The absorption fraction thus obtained was between 50 and 80% of the incident beam energy.

The intensity threshold requirement for transmission in the neighborhood of $V_{\mathrm{osc}}/V_{\mathrm{th}} = 1$ cannot be explained without including high-intensity nonlinear effects. The 30-nsec delay between the intensity peak of the incident radiation and the peak of the transmitted radiation, suggesting propagation of a disturbance across the plasma column, is similar to the acoustic transit time across the plasma. However, hydrodynamic motion alone cannot account for the transmission behavior with intensity. Holographic interferometry indicated that the laser-driven shock front exceeds critical density; thus, on the macroscopic hydrodynamic spatial scale ($> 160\,\mu$m), an overdense region is continually between the incident laser beam and the transmission diagnostics during the time of observed transmission.

Calculations indicate a means by which an inhomogeneous laser beam can penetrate an overdense plasma.[2] In this model, the focal volume in the plasma is illuminated by a transversely inhomogeneous intensity distribution, causing expulsion of plasma from the focal volume into a region around the beam. The outward transverse force arises from the center-peaked intensity distribution, which causes either an outward-directed ponderomotive force (in a collisionless plasma) or an outward-directed thermal expansion (in a collisional plasma).

The resulting density depression along the center line of the focal volume induces self-focusing of the laser beam. A threshold condition similar in magnitude to that seen in this experiment is obtained by relating the beam width to the difference of a divergence term due to diffraction and a convergence term due to self-focusing. The presence of a small stationary hole in the plasma, indicated by a ring pattern on the transmitted spot,[8] could point to such a hole-burning mechanism. Such a process would exhibit a "burn-through" time, delaying transmission until the hole had traversed the overdense region. The beam convergence term contains the product of beam intensity and plasma density; thus, at a higher intensity, the threshold condition, i.e., equality of self-focusing convergence and diffraction divergence, occurs at a lower density. For a cylindrical laboratory plasma, with a peak density on axis, this implies that self-focusing begins at a larger radius, i.e., closer to the beam entrance point. Thus, the higher-intensity beam must burn through a greater length of plasma, possibly accounting for longer burn-through time and the pulse shortening at high incident intensity.

The presence of a critical layer in the target plasma was a requirement for observation of the intensity threshold, temporal, and spatial pulse-shape modification in transmission. A series of experiments carried out on the Z-pinch plasma with laser incidence at an earlier stage of target evolution, before critical density was reached, indicated no intensity threshold, plasma "shutter" effect, or ring structure. For incidence on this underdense plasma, the transmitted pulse shape was preserved and was observed at incident intensities as low as 10^{10} W/cm^2.

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[1] Damon V. Giovanielli, Bull. Am. Soc. **21**, 1047 (1976).

[2] M.S. Sodha and V.K. Tripathi, Phys. Rev. A **16**, 2101 (1977).

[3] J.F. Drake, P.K. Kaw, Y.C. Lee, G. Schmidt, C.S. Liu, and Marshall N. Rosenbluth, Phys. Fluids **17**, 778 (1974).

[4] John G. Ackenhusen and David R. Bach, J. Appl. Phys. (to be published).

[5] P.D. Rockett, D.G. Steel, J.G. Ackenhusen, and D.R. Bach, Phys. Rev. Lett. **40**, 649 (1978).

[6] D.G. Steel, P.D. Rockett, D.R. Bach, and P.L. Colestock, Rev. Sci. Instrum. **49**, 456 (1978).

[7] John G. Ackenhusen and David R. Bach, J. Appl. Phys. (to be published).

[8] D.G. Steel, D.R. Bach, and P.D. Rockett, Bull. Am. Phys. Soc. **21**, 1140 (1976).