# Short-Pulse Laser Absorption in Very Steep Plasma Density Gradients

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We have measured the absorption of 1-ps laser pulses interacting with matter at intensities from $10^{10}$ to $10^{16}$ W/cm$^2$. The variations of absorption with incidence angle and polarization have been used to infer submicron plasma-density-gradient scale lengths. The results show a transition between a regime of laser interaction with sharply bounded dense cold matter ($I \le 5\times10^{12}$ W/cm$^2$), where absorption is by the usual skin depth effect, to a regime of interaction with a plasma of very steep density gradient ($L/\lambda \le 0.2$) ($5\times10^{12}$ W/cm$^2 \le I \le 10^{15}$ W/cm$^2$).

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The interaction of very short laser pulses with matter has become an important field of study with the recent development of intense picosecond and subpicosecond lasers, particularly in view of their many applications. These sources can produce, on an appropriate target, ultrashort x-ray pulses which can be used either as probes or as calibrating sources.[1] Short pulses can also be used to study ions in extremely high electromagnetic fields where line broadening[2] and multiphoton processes[3] are important. In addition, short laser pulses can heat the matter significantly before any expansion occurs, allowing the study of hot material at solid density.[4] Inversions of population between states of recombining ions may also be expected during the rapid plasma cooling[5] after the short pulse. For most of these applications, the nature of the laser-light absorption process must be determined.

Previous absorption data have been obtained with laser wavelengths ($\lambda$) of 1 $\mu$m or less and long pulses involving gradient scale length $L$ of a few wavelengths or more[6] (while results for $L/\lambda \le 1$ have been obtained with a 10-$\mu$m laser, the plasma gradients were nonlinearly steepened by the ponderomotive force and the absorption was dominated by complex nonlinear processes[7]).

In this Letter, we present the first absorption measurements for a short 1-$\mu$m laser pulse (1 ps) interacting with matter over a large intensity range ($10^{10}$–$10^{16}$ W/cm$^2$). We will show a transition between an interaction with dense cold matter ($I \le 5\times10^{12}$ W/cm$^2$) where absorption is by the usual skin depth effect, and an interaction with a plasma with a finite but rather steep density gradient ($5\times10^{12}$ W/cm$^2 \le I \le 10^{15}$ W/cm$^2$). The angular and polarization variations of absorption are used to infer a *submicron* density-gradient scale length $L$ ($L/\lambda \le 0.2$). At high intensities ($I \ge 10^{15}$ W/cm$^2$) nonlinear effects begin to dominate.

These experiments were carried out with the Table Top Terawatt laser at the Laboratory for Laser Energetics. A detailed description of this system is given elsewhere.[8] The laser (1.053 $\mu$m) delivers up to 300 mJ in a 1-ps pulse. The pulse width was measured with autocorrelators based on second- and third-harmonic generation.[9] In the conditions of our experiments, 85% of the laser energy was contained in the main 1-ps (FWHM) pulse with 5% in the low-intensity ($10^{-3}$) 30-ps prepulse, and 5% in a similar post pulse. A few percent of the energy was also found in a second 1-ps pulse which arrived 1 ns after the main pulse. The laser beam was focused by an $f/8$ lens on massive plane Cu, Al, and Teflon targets. At best focus, the focal spot diameter was found to be 100 $\mu$m from x-ray pinhole camera data and from measurements in the equivalent target plane. The plane of polarization of the beam was rotated (90°) with a half-wave plate. The laser light scattered outside the focusing optics was collected by an integrating Ulbricht sphere,[10] while light reflected back into the focusing lens cone was measured by a backscatter calorimeter. Each of these diagnostics was calibrated *in situ*.

The variations of the measured absorptions with the laser intensity $I$ at three angles of incidence for a copper target are plotted in Fig. 1. For $I \le 10^{11}$ W/cm$^2$ the target acts as a nearly perfect mirror, the energy being reflected back into the focusing lens. For normal incidence [Fig. 1(a)] absorption rapidly increases up to 40% between $10^{11}$ and $5\times10^{12}$ W/cm$^2$, and then remains between 40% and 50% for $5\times10^{12}$ W/cm$^2 \le I \le 10^{15}$ W/cm$^2$. At the highest intensities, absorption decreases somewhat, but remains high (30%). As expected for normal incidence, the results remain the same with $s$ and $p$ polarizations. Figures 1(b) and 1(c) show the absorptions obtained for incidence angle of 25° and 45°, respectively. For $I \le 10^{15}$ W/cm$^2$ and for $s$-polarized light (dots) the absorption decreases as the incidence angle increases. A significant polarization effect is only observed

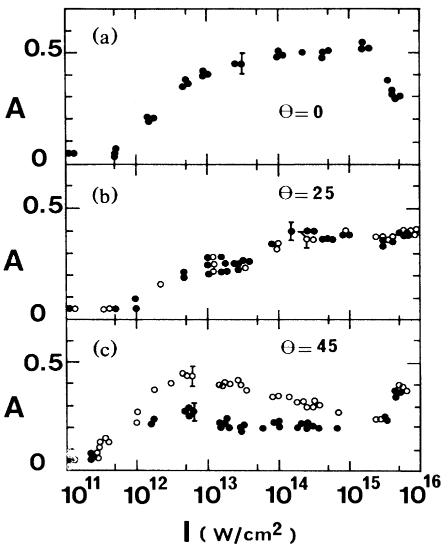


FIG. 1. Variations of the measured absorptions with the laser intensity for a Cu target. (The laser energy was between 0.2 and 300 mJ with focal spot diameters between 100 $\mu$m and several mm.) Dots are for $s$ polarization and circles are for $p$ polarization. (a) Normal incidence; (b) incidence angle of 25°; and (c) incidence angle of 45°.

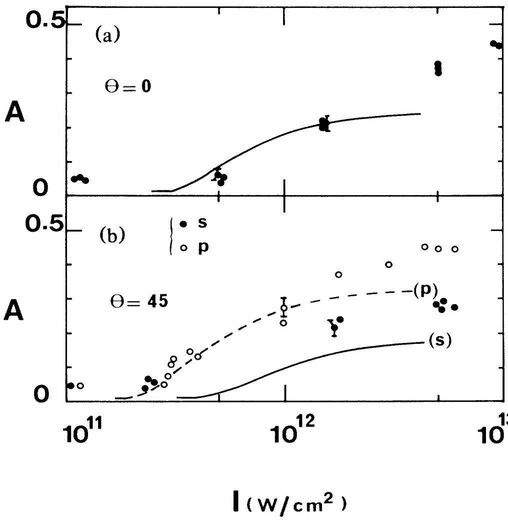


FIG. 2. Comparison between the measured absorption (dots) for Copper and the absorption calculated with a Drude model of conductivity (lines). (a) Normal incidence. The dots are experimental results taken from Fig. 1(a). (b) Incidence angle of 45°. The dots (circles) represent measured data [Fig. 1(c)] for $s$ ($p$) polarization. The solid (dashed) line is the calculation for $s$ ($p$) polarization.

at large incidence angle where the absorption is greater with $p$-polarized light than with $s$-polarized light. For $I \gtrsim 10^{15}$ W/cm$^2$, all the results are essentially polarization independent. It must be noted that at these high laser irradiances the prepulse ($\gtrsim 10^{12}$ W/cm$^2$) will have produced a plasma of long-gradient scale length before the main pulse arrives. Furthermore, in this high-intensity regime, we observe strong backscattering (up to 15% of the laser energy) even at large incidence angles and the second-harmonic backscattered emission appears and increases strongly with the laser irradiance. Hot electrons are also detected when $I \gtrsim 10^{15}$ W/cm$^2$ from comparison with x-ray diode signals with and without magnets. These last results are produced by nonlinear effects which are beyond the scope of this paper.

The time-integrated x-ray emission, obtained from a set of x-ray diodes also suggests the existence of three regimes depending on the laser intensity. Below $5\times10^{12}$ W/cm$^2$, sub-keV x-ray emission ($h\nu \gtrsim 100$ eV) is negligible indicating an interaction with solid density matter. Between $5\times10^{12}$ and $10^{14}$ W/cm$^2$ sub-keV emission and conversion efficiency drastically increase. This we attribute to a strong electron temperature increase from about 20 eV at $5\times10^{12}$ W/cm$^2$ to 200 eV at $10^{14}$ W/cm$^2$ based on a comparison of the measured x-ray spectra with the stationary model of Alaterre *et al.*[11] At higher intensities, sub-keV emission saturates and keV emission appears. We will analyze only the results obtained in the low and modest intensity regime ($I \lesssim 10^{15}$ W/cm$^2$). Higher irradiance results linked to nonlinear effects will be discussed elsewhere.

For intensities less than $5\times10^{12}$ W/cm$^2$, we analyze the absorption experimental results on the basis of a Drude model of conductivity.[12] The Fresnel formulas for absorption in a solid are used and an empirical formula for the collision frequency was chosen to fit recent experimental data[13] for resistivity between 1 and 100 eV. We take

$$\nu = \nu(T_0) T_i T_0^{-1} \epsilon_F^{1.5} / (\epsilon_F + T_e)^{1.5},$$

where $T_0 = 373$ K, $\epsilon_F$ is the Fermi energy, and $T_e$ ($T_i$) is the electron (ion) temperature. The correspondence between $T_e$ and $I$ is obtained by simply balancing the thermal conduction in the solid with the absorbed power.

Figure 2 presents a comparison between the absorption calculated with this model (assuming $T_i/T_e = 0.6$) and the experimental data for normal [Fig. 2(a)] and 45° incidence angles [Fig. 2(b)]. The model explains semiquantitatively the absorption dependence on intensity, polarization, and incidence angle, indicating clearly that at low irradiance the absorption is by skin depth effects in solid density matter. However, the measured fraction of absorbed energy in $s$ polarization is greater than the calculated one, and such a simple description is limited to a few times $10^{12}$ W/cm$^2$ [Fig. 2(b)], which roughly corresponds to $T_e \simeq \epsilon_F$.

At higher intensities ($I \gtrsim 5\times10^{12}$ W/cm$^2$), the interaction regime changes and the laser wave propagates into a plasma of steep gradient length. Absorption is now mainly by inverse bremsstrahlung, and by linear resonance absorption in $p$ polarization.[14,15] To analyze the experimental results, we look at two quantities chosen because of the well known behavior of the $p$-polarization absorption with the gradient length.[14] We first consider the ratio $R_{pp}$ of the absorption at $\theta = 45°$ in $p$ polarization to the $p$-polarization absorption at $\theta = 25°$ as a measure of angular behavior of $p$ polarization and we use this quantity to infer $L/\lambda$. We also consider $R_{sp}$, the difference between absorption in $p$ and $s$ polarizations, normalized to the absorption in $p$ polarization, at a given incidence angle, as a measure of the polarization dependence of absorption and as a complementary way to infer $L/\lambda$. We calculate the variations of $R_{sp}$ and $R_{pp}$ with the gradient scale length $L/\lambda$, by numerically solving the linear electromagnetic field equation with collisions. The collision frequency is taken as $\nu = \nu^* \omega (n/n_c)$, where $\nu^* = \nu_{ei}/\omega$ at the critical surface ($\nu_{ei}$ is the electron-ion collision frequency and $\omega$ is the laser frequency), which is equivalent to the assumption of a uniform temperature in the absorption region. We assume an exponential density profile, and calculate the field components (along and perpendicular to the density gradient) at each point of the density profile for various incidence angles. The calculated absorption range is bounded by values obtained for $\nu^* = 0.32$ and 0.04, which could reasonably represent the limits of variation of the plasma parameters over our large intensity range. These two values of $\nu^*$ correspond, for instance, to values of $Z = 3$, $T_e \simeq 10$ eV and $Z = 15$, $T_e \simeq 200$ eV, respectively. These simple calculations are limited to temperatures less than 200 to 300 eV, which correspond to the limit of a purely collisional regime. At higher temperatures, convection and wave breaking must be taken into account.

The experimental and calculated $R_{pp}$ and $R_{sp}$ values are shown in Fig. 3. We expect $L/\lambda$ to increase monotonically with laser intensity and indeed the qualitative agreement of calculated and experimental $R_{pp}$ and $R_{sp}$ values is quite striking, to the point that we feel justified in inferring $L/\lambda$ values from the observed $R_{pp}$ values. The variations of $R_{pp}$ with the laser intensity, as obtained from the experimental data of Figs. 1(b) and 1(c), appear in Fig. 3(a), while Fig. 3(b) presents the calculated ratio. These results show that $L/\lambda \le 0.2$ when $I \le 10^{14}$ W/cm$^2$. Figure 3(c) shows the experimentally obtained $R_{sp}$ ratio for an incidence angle of 45°. These values seem to be somewhat lower than the calculated ones [Fig. 3(d)] while following the same trend. This is because there is more absorption in $s$ polarization than predicted by the linear model (as in Fig. 2 for the lowest intensities). We suspect that this is produced by some transverse nonuniformity, probably because of laser and target inhomogeneities, which blurs the definition between $s$ and $p$ polarization.[16] Short-wavelength ion turbulence[17] may also reduce the angle and polarization dependence. Such a mechanism could be the main ab-

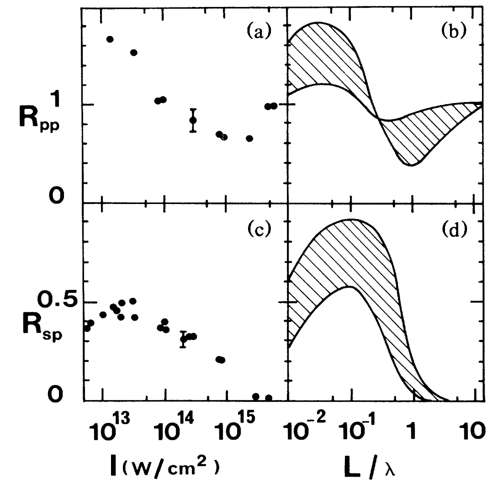


FIG. 3. Comparison between experimental data and electromagnetic wave propagation calculations. The limits of the hatched area correspond to $\nu^* = 0.32$ and 0.04. (a) Experimental ratio $R_{pp}$ of the absorption at 45° on absorption at 25°, in $p$ polarization vs laser intensity. (b) Calculated ratio $R_{pp}$ vs the normalized gradient scale length $L/\lambda$. (c) Experimental difference $R_{sp}$ between the absorption in $p$ and $s$ polarization normalized to the $p$-polarization absorption vs the intensity at 45°. (d) Calculated normalized difference $R_{sp}$ at 45° vs the normalized gradient scale length $L/\lambda$.

sorption process at the higher irradiances ($I \ge 10^{15}$ W/cm$^2$) where we observe no angle and polarization dependence and where the absorption remains large (30%). In this intensity range ($I \ge 10^{15}$ W/cm$^2$) the 30-ps prepulse can produce a plasma having a gradient scale length of several laser wavelengths. Then the 1-ps laser pulse strikes this plasma moving away from the surface. This could affect the absorption of the laser beam and could account for the observations at the higher intensities. It must also be noted that the post pulse could slightly reduce the $R_{sp}$ ratio by the post pulse interacting with a plasma with a longer-gradient scale length.

Turning now to the other materials, we have observed an absorption slightly higher with Al than with Cu. The data for both metals have the same dependences with laser intensity, incidence angle, and light polarization. Contrary to expectations, absorption measured with thick (200 $\mu$m) Teflon targets (around 40%) was independent of the angle of incidence and of the polarization over the whole intensity range considered here. The origin of this behavior is not clear, but the lighter ions move faster and could form a longer plasma gradient which can reduce the polarization dependence. Further investigations are needed to clarify these differences.

In summary, we report the first absorption measurements for short laser pulses (1 ps) interacting with matter. By analyzing the polarization and angular dependence of absorption, we have been able to obtain the density-gradient scale length ($L/\lambda \leq 1$) from a simple absorption model. Results show a transition from the usual skin depth absorption in solid matter to absorption in a plasma with a rather steep density gradient. At the highest intensities ($I \geq 10^{15}$ W/cm$^2$), nonlinear effects are dominant.

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