Experimental Transport Studies in Laser-Produced Plasmas at 1.06 and 0.53 μm

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Laser-irradiated thin-foil experiments at 1.06 and 0.53 μm show that heat penetration in the target is greater at shorter wavelengths as a consequence of larger ablation rate. Comparison of experimental and numerical results indicates that comparable flux inhibition occurs at both wavelengths.

The study of energy transport in laser-irradiated target experiments has recently received much attention in theoretical as well as experimental work.[1-8] The nature and the efficiency of the mechanisms contributing to energy transport are of fundamental importance in the characterization of a laser which will be an efficient driver in laser-driven, inertially confined fusion. In most of the experiments dealing with low-Z targets in the absorption region, the energy transport is mainly due to electrons having a thermal and a suprathermal distribution. The suprathermal electrons are known to give rise to a volume energy deposition in the target. The result is the explosive pusher mode in compression experiments. The thermal distribution is most important for the ablation mode. This paper deals with the study of heat conduction in thin-foil experiments as a function of the thermal-electron distribution and of laser wavelength. However, some aspects of the suprathermal-electron conduction have also been studied.

We used a glass-neodymium laser rod from Quantel, operating in the short-pulse mode at 10-J output energy in a 100-ps full width at half maximum pulse. The output can be frequency doubled with a potassium dihydrogen phosphate crystal. The energy is then 5 J in a pulse of approximately 80-ps duration. The laser beam is focused onto the target by a 180-mm–focal-length lens and the effective aperture of the focused beam is $f/2.5$.

The maximal light intensity on the target is 2.10^{15} W/cm^2 for the fundamental laser wavelength and 10^{15} W/cm^2 at 0.53-μm wavelength. The focal-spot diameter has been determined, by light transmission through pinholes, as 50 μm at half laser energy. Photographs of the second-harmonic emission and x-ray pinhole photographs of the plasma have not shown the presence of hot spots during the interaction. The irradiated targets are thin polystyrene films, with thicknesses ranging from 30 nm to a few microns. For convenient ion time-of-flight measurements along the direction perpendicular to the target, the angle of incidence was chosen to be 25°; P polarization was used.

The object of the measurements is to determine the foil thickness at which significant changes occur in transmission, reflection, x-ray emission, and ion time of flight, both in front of and behind the foil. These different foil thicknesses are then correlated with burnthrough depths (d) for heat penetration in the solid during the laser pulse. It is interesting to note that, although the diagnostics are different, the various burnthrough depths (d) have very comparable values. Moreover, these experimental measurements have been in all cases compared to numerical simulations by a one-dimensional (1D) Lagrangian hydrodynamic code. Before discussing the results, we discuss the methods for the determination of d.

The optical energy balance was obtained by monitoring with joulemeters the specularly reflected, backreflected, and transmitted laser light as a function of foil thickness. The transmitted laser light was collected by a $f/1$ lens whose aperture was larger than the focusing lens. In Fig. 1(a) we present typical results obtained at 1.06 μm for a laser intensity of 10^{14} W/cm^2. Curve 1 gives the variation of reflected light, and curve 2 the transmitted light. From curve 2, the burnthrough depth d_R is determined by taking the foil thickness for which the asymptotes to the ends of curve 1 intersect. The thickness d_T at 10% transmission was defined from the transmission curve. In fact, these determinations are not direct measurements of burnthrough but are affected by some plasma expansion before the foil becomes subcritical. Comparison with numerical simulations is necessary for a precise interpretation of the data. Figure 1(b) gives a comparison of foil transmission for the experiment at 1.06 μm and a laser intensity of 2×10^{15} W/cm^2 and at 0.53 μm for an intensity of 10^{15} W/cm^2. The figure demonstrates the larger heat penetration at 0.53 μm.

The second diagnostic was provided by the

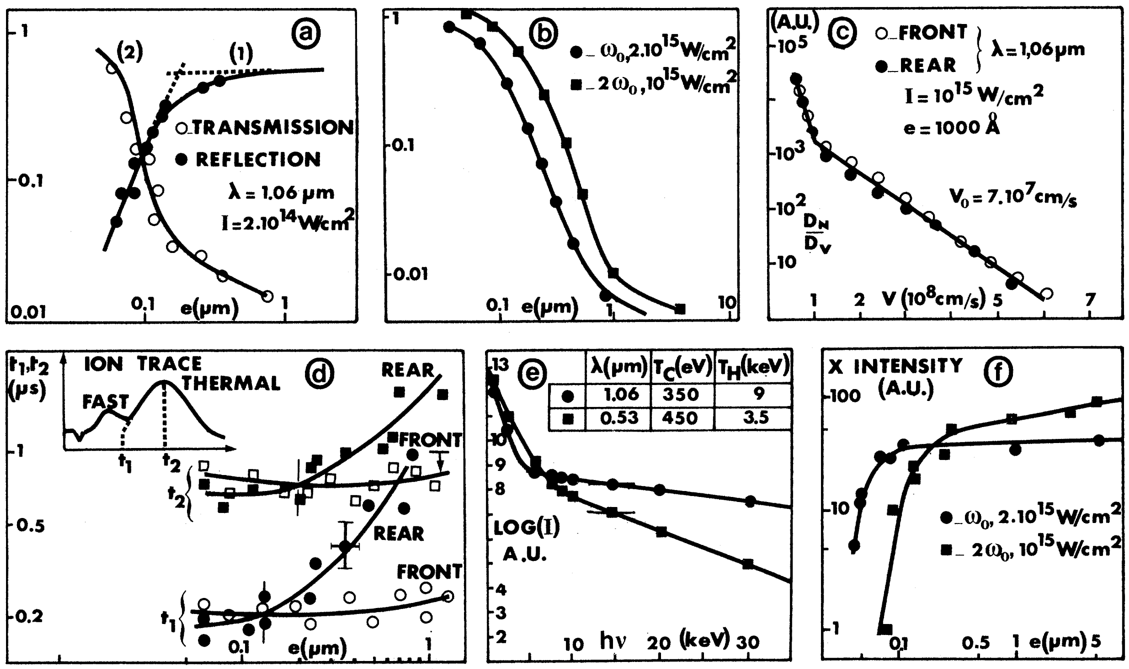

FIG. 1. (a) Reflection coefficient (curve 1) and transmission coefficient (curve 2) variation vs foil thickness. (b) Transmission-coefficient variation with foil thickness at ω_0 and $2\omega_0$. (c) Front and rear ion-velocity spectra shown for two symmetric charge collectors (A.U. : arbitrary units). (d) Front and rear ion times of flight t_1 and t_2 vs foil thickness. $\lambda = 1.06$ μm, $I = 2\times 10^{14}$ W/cm^2, and distance to target 45 cm. (e) X-ray spectra at 1.06 μm ($I = 2\times 10^{15}$ W/cm^2) and at 0.53 μm ($I = 10^{15}$ W/cm^2). (f) Relative intensity of x rays of 1–2-keV energy vs foil thickness for both wavelengths.

charge-collector analysis of the thermal ion time of flight in the front (t_f) and at the reat (t_r) of the foils (See Ref. 3). The ion collector signals were recorded on fast oscilloscopes, or digitized with Computer-Aided Measurement and Control units and processed with a Nova computer. The usual fast ions and thermal ions were observed. From the fast-ion signal we have deduced the isothermal expansion velocity v_0 and the temperature T_H by the analysis of the velocity distribution dN/dv which showed an exponential behavior $dN/dv \sim \exp(-v/v_0)$ with $v_0 = (ZkT_H/M)^{1/2}$ (see Campbell *et al.*[9]). Figure 1(c) gives a typical example for a thin foil showing an identical isothermal expansion velocity at the front and to the rear of the foil. This result does not mean that the fraction of energy in fast electrons is important but only that the mean free path of these electrons is longer than the thickness of the foil.

From thermal ion emission the criterion for burnthrough depth (d_i) was made as follows: d_i is the foil thickness for which the time of flight of ions emitted in the rear side of the foil begins to be larger than the time of flight of the corresponding ions emitted in the front side. This determination was made for two kinds of characteristic ions: The fastest thermal ions (d_{i1}) and the peak of the ion signal (d_{i2}). Figure 1(d) shows an example of this determination. We observe experimentally that $d_{i1} < d_{i2}$; this result is also obtained in the simulations when the heat flux is limited but not in the case of a nonlimited heat flux (see Table I).

The third diagnostic concerns x-ray emission from the plasma. X rays were detected by a nine-channel x-ray analyzer in the energy range between 1 and 30 keV. Figure 1(e) gives an example of the spectrum obtained for experiments at 1.06 and 0.53 μm, and laser intensities of 2×10^{15} and 10^{15} W/cm^2, respectively. A very interesting result is the much lower hot-electron temperature which occurs for the short-wavelength case. Figure 1(f) gives a plot of the x-ray intensity emission as a function of foil thickness for the 1–2-keV channel. After an increase in the x-ray emission, the saturation of the signal means that no more material is heated during the pulse. We define d_x as the thickness at which the asymptotic

TABLE 1. Experimental values of characteristic foil thicknesses d_T, d_{i1}, d_{i2}, and d_x (in microns). The values in parentheses represent the corresponding results obtained in simulations without fast electrons.

Laser intensity	d_T (μm)	d_{i1}(μm)	d_{i2}(μm)	d_x(μm)
	ω			
$(2-4)\times 10^{14}$ W/cm^2	0.11	0.12	0.20	0.11
	(0.22)[a]	(0.22)[a]	(0.22)[a]	
	(0.32)[b]	(0.67)[b]	(0.43)[b]	
	ω			
2×10^{15} W/cm^2	0.22	0.17	0.32	0.15
	(0.44)[a]	(0.46)[a]	(0.60)[a]	
	(0.70)[b]	(2.0)[b]	(1.5)[b]	
	2ω			
10^{15} W/cm^2	0.43	0.30	0.50	0.35
	(0.9)[a]	(0.75)[a]	(1.5)[a]	
	(1.4)[b]	(2.2)[b]	(2.0)[b]	

[a]With flux limit number $f = 0.05$.
[b]With flux limit number $f = 1.0$.

slopes of the curve intersect.

Experimental determination of the burnthrough depths by the different diagnostics and the corresponding results of numerical simulations are given in Table I. These simulations were performed with a 1D Lagrangian code derived from SUPER[10] which uses one-velocity, two-temperature formulation with a flux-limited plasma conductivity; suprathermal electrons are described by a multigroup model.[11] We can see that there is a systematic discrepancy between the magnitude of the experimental and the simulation values, even with a flux limit factor of 0.05. We do not think that it would be meaningful to increase the flux limit in order to obtain better agreement between the experimental and simulation values, because other effects such as two-dimensional behavior exist and are not included in the code. However, there is a good qualitative agreement on the scaling laws between experiment and simulation for parameter variation such as laser intensity φ and laser wavelength λ. The scaling law follows approximately in both cases: $d \sim \varphi^{1/3}\lambda^{-4/3}$.

The main results of our experiments are the following:

(i) The heat front penetrates deeper in the solid for the shorter wavelength: Ablation rate is larger in 0.53-μm experiments.

(ii) At 1.06 and at 0.53 μm, there seems to be a flux limitation which is comparable for both wavelengths.

(iii) By comparison between data at ω and 2ω, it is found that the contribution of fast electrons does not appreciably affect the results.

The first result has also been found numerically. Analysis of the code results leads to the conclusion that this is not a consequence of a smaller flux limitation at 0.53 μm, but the effect of a larger ablation rate at this wavelength. Indeed, comparison of numerical results with a flux limit factor f of 0.2 at 1.06 μm and 0.05 at 0.53 μm (same product fn_c) for identical absorbed laser fluxes gives better heat penetration in the solid for short wavelengths. Also, the first result is not explained because the critical layer at 2ω lies deeper in the material than at ω. In an experiment at 1.06 μm, the amount of matter contained between the layers $n_c(\omega)$ and $n_c(2\omega)$ is much smaller than the difference in the ablated matter in the two experiments. This leads to the conclusion that the better heat penetration in the solid for the 0.53-μm experiment is mainly due to a larger ablation rate at 0.53 μm as compared to that at 1.06 μm.

It is interesting to note that burnthrough depths determined by methods involving different physics give similar values. In fact, this is characteristic of strong flux limitation. Indeed, only in that case, the thermal front to which the x-ray and ion-time-of-flight diagnostics are sensitive is closely followed by the subcritical rarefaction region to which the transmission diagnostic is sensitive. In Table I, for the unihibited case ($f = 1$), the transmission determinations do not give the correct value of burnthrough depth which is given by the ion-time-of-flight diagnostic.

The second conclusion is that a flux limitation still exists in the 2ω experiment. The qualitative comparison between the numerical simulation and experiments shows that we have to include in both cases a strong flux limit if we want to obtain a reasonably good agreement between computed and observed results. However, the experimental uncertainties and the qualitative aspects of the comparison do not allow us to determine if the flux limit is significantly different between the 2ω and the ω experiments. More careful experiments with an appropriate interaction geometry, for instance, spherical,[12] must be undertaken in order to reduce the two-dimensional effects in these experiments.

The third point concerns the contribution of fast electrons to transport. In the present experiment, we have observed that at 0.53 μm, the hard x rays were decreased by several orders of magnitude and the fast-ion production was reduced, in comparison with experiments at 1.06 μm and comparable laser fluxes. This implies a strong reduction of fast-electron emission. Another confirmation of the reduction of fast-electron production in 2ω experiments is obtained by the observation for very thin foils of larger expansion velocity in the rear of the foil compared with the velocity in the front. This dissymetry is a consequence of a better ablation regime which results from the reduced contribution of fast-electron heating. However, the penetration depth is still larger at 2ω with less energetic suprathermal electrons. This leads us to the conclusion that in the focal-spot region the dominant contribution for energy transport comes from thermal electrons and not from suprathermal electrons. We have no measurement of the fraction of energy associated with fast electrons. Numerical simulations at 1.06 μm show that an assumption of 20% of the energy in fast electrons with T_H =10 keV, does not change significantly the penetration depths and the behavior of the foil expansion.

In conclusion, in laser interaction with solid targets conducted at 1.06 and 0.53 μm, our experimental results and comparison with numerical simulations show that the short wavelengths seem more favorable for energy penetration in the solid, mainly because of a larger ablation rate for shorter wavelengths. Flux limitations are observed for both wavelengths, but the hard-x-ray emission and, consequently, the fast-electron emission are significantly decreased for the 0.53-μm wavelength. The absorption is also increased at shorter wavelengths.[13] However, our results were obtained with a change in wavelength of a factor of 2. These preliminary results seem to be in favor of the use of short wavelengths in laser fusion: Core preheating by fast electrons will be reduced and, consequently, target design could be simplified. Therefore, for a more definitive conclusion it seems necessary to await results from experiments at shorter wavelengths such as 0.26 μm, which we are currently undertaking.

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