Intensity-Dependent Absorption in 10.6-μm Laser-Illuminated Spheres

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An intensity dependence of the absorption of 10-μ m laser light on CO_2-laser–fusion targets has been observed. Absorption on gold spheres increases from 25%–30% at 10^{14} W/cm^2 to 50%–60% at 10^{16} W/cm^2, with most of the variation occurring above 10^{15} W/cm^2. Concurrently, hot-electron temperature scales as $T_{\rm hot} \propto I^{0.43}$ over the entire range. The absorption variation is interpreted as enhanced resonant absorption. It is suggested that as intensity is increased, the critical surface in the irradiated region becomes increasingly unstable, thereby permitting greater surface distortion and more favorable coupling conditions for resonant absorption.

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The absorption of laser energy is an important factor in the overall performance of a laser-fusion target capsule. At the 10.6-μm wavelength produced by CO_2 lasers, spherical-target absorption was previously shown to be in the range 20%–30% for intensities $\lesssim 10^{15}$ W/cm^2 and below.[1,2] We report here the observation of an increase in absorption to as high as 60% when intensity is increased to 10^{16} W/cm^2.

The experiments reported here were done on the Los Alamos National Laboratory eight-beam Helios CO_2 laser facility,[3] at energies up to 5 kJ. The targets were gold spheres mounted on slender glass stalks. The diameters were 0.3, 1, and 2 mm, with wall thickness between 0.3 and 31 μm. Absorption was measured with an array of fourteen calorimeters[4] deployed around the target chamber, each sensitive to particle flux as well as to x-ray photons; scattered 10-μm light is specifically rejected.

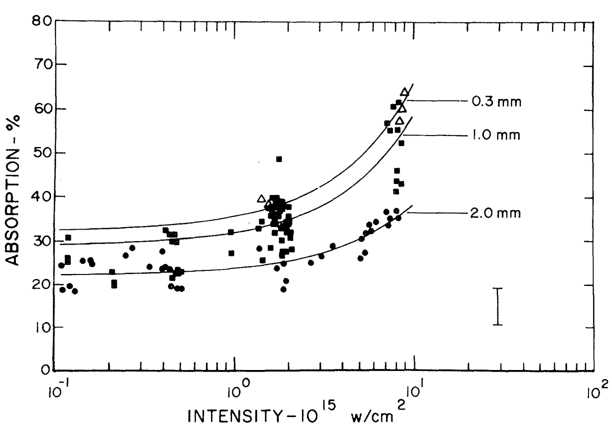

FIG. 1. Absorption vs intensity for gold spheres: triangles, 0.3 mm diam (9 shots); squares, 1.0 mm diam (82 shots); dots, 2.0 mm diam (43 shots). Error bar is average for all shots and includes the standard deviation of the various calorimeters. The curves are least-squares linear fits to the data.

Figure 1 shows the absorption as a function of intensity. The latter is varied primarily by defocusing and occasionally by total-energy variation. Individual beam intensity at best focus is computed with a 100-μm spot diameter containing 75% of the energy, and a pulse width of 0.75 ns (full width at half maximum). For all eight beams, an energy-weighted average is used to determine laser intensity. Defocused intensity is obtained from simple geometric considerations with an $f/2.4$ beam expansion from the waist.

The data show a very clear doubling in absorption for 0.3- and 1-mm-diam spheres as intensity is increased from 10^{15} to 10^{16} W/cm^2. The effect is not as dramatic with the 2-mm spheres, absorption increasing from 25% to only ~35% at 10^{16} W/cm^2. The variation with target diameter may be an instrumental effect. Measurements of the ion angular distribution on flat targets show the presence of an ion plume in the direction of the target normal. In the present experiments the normal is nominally toward the laser focusing mirrors. The ions involved are not collected by the calorimeter system and may represent an increasingly significant amount of undetected absorbed energy as the target radius increases. However, we cannot rule out the possibility that the diameter variation is real, a point which we will return to later.

Additional supporting evidence for the intensity variation has been obtained from scattered-light measurements under single-beam illumination on 1-mm-diam targets. The $f/2.4$ focusing optics from each of the eight Helios beam lines was used to collect large samples of scattered laser light at fixed angles from the single-beam axis. Figure 2 shows measured angular distributions for three different incident intensities. Integrated energies, under the assumption of azimuthal symmetry, clearly show a reduction in scattered light at high intensity, in agreement with the calorimeter results.

The calorimeter data have been examined for a possible separate correlation of absorption with laser spot size. At low intensity ($<10^{15}$ W/cm^2) no such correlation was found. At high intensity, a comparison was not possible since only small (surface-focused) spots were used. Also, no correlation of absorption with wall thickness or target atomic number was observed.

To test specifically the sensitivity of absorption to incident-beam wave-front shape, several identical targets were shot under conditions of equal spot size (~ 400 μm at 5×10^{14} W/cm^2), and with either positive or negative focal displacement. No differences in absorption were observed, indicating that the incident-beam wave front is not an important factor for absorption in spherical targets.

Also of interest is the spectrum of hot electrons

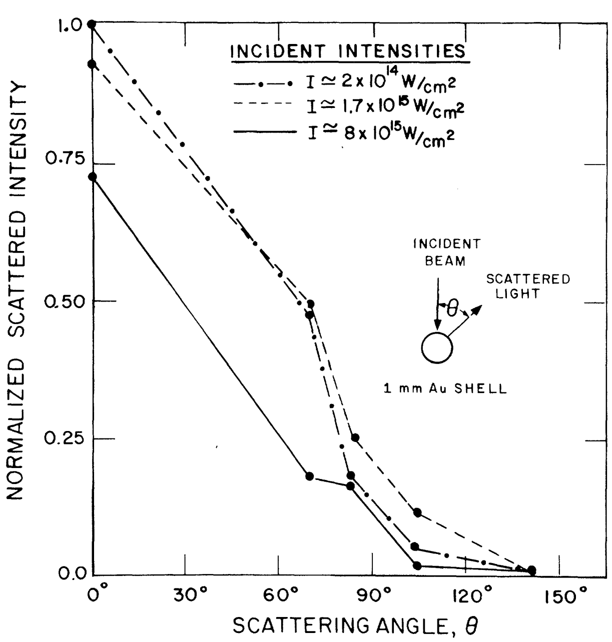

FIG. 2. Angular distribution of scattered laser light from single-beam irradiation of 1-mm-diam 10-μm-thick gold shell targets. Azimuthal symmetry about the incident beam is assumed, and direct backscatter corresponds to 0°.

generated during absorption. A multichannel bremsstrahlung measurement system,[5] viewing the entire target, was used to determine "hot-electron" temperature, $T_{\rm hot}$, on the assumption of an exponential spectrum. $T_{\rm hot}$ scales with intensity at $T_{\rm hot} = 100I^{0.43}$, with a $T_{\rm hot}$ of 100 keV at $I = 10^{15}$ W/cm^2. This scaling is in excellent agreement with that obtained previously.[5] Based on a crude yield analysis,[5] the fraction of absorbed energy collisionally deposited by hot electrons is between 7% and 50%, depending on intensity and assumed spectral dimensionality. Bremsstrahlung yield, and the larger questions of energy deposition and balance, are the subject of another paper currently in preparation.

There are four mechanisms by which absorption is believed to occur in laser-fusion plasmas. These are (1) inverse bremsstrahlung absorption,[6] (2) resonant absorption,[7] (3) ion acoustic turbulence,[8] and (4) stimulated Raman processes.[9,10] The relative importance of each is strongly influenced by density scale length and electron temperature in the underdense corona adjacent to the critical surface. Long scale lengths and low temperatures favor collisional processes,[6] while short scale lengths favor the resonant process.[7] Scale lengths as small as 2–5 μm, due to profile steepening, have been observed at intensities of 10^{12}–10^{14} W/cm^2,[11] and even smaller scale lengths are indicated at 10^{15}–10^{16} W/cm^2.[12] Theoretical and numerical calculations also predict short scale lengths for these plasmas.[12,13] Further, the production of copious high-energy electrons is consistent with resonant absorption.[5,14]

With both theory and experiment indicating resonant absorption as the dominant mechanism, the insensitivity of absorption to wave-front shape requires some discussion. An angular dependence of absorption has been repeatedly observed at lower values of $I\lambda^2$. This dependence has been attributed to resonant absorption on a smooth critical surface with moderately steepened density profile. Under these conditions, an optimum incidence angle exists, with no absorption at normal incidence.[7] We believe that in the present experiments, at values of $I\lambda^2$ up to 10^{18} W μm^2/cm^2, both extreme profile steepening and critical surface rippling occur. The former broadens the angular response, and the latter enables absorption at normal incidence.

Theoretical[15-20] and experimental[11,17] evidence suggests that distortion of the critical surface can be significant. Its effect on resonant absorption has been addressed by several authors.[10,15-18,20] There is general agreement that for light at near-normal incidence, surface ripples create regions of more favorable local incidence angle, thereby making possible substantial resonant absorption where otherwise none would occur. With both S and P polarization, as in the present experiments, we believe that the above description applies even at intensities of $\sim 10^{14}$ W/cm^2, with modest surface rippling generated by the S-polarized component.

Some understanding of the increased absorption as intensity increases can be obtained from two-dimensional plasma simulations using the WAVE code.[18] These simulations treat the time-dependent problem for either a focused laser beam or a plane wave. For P-polarized light at low intensity ($\sim 10^{14}$ W/cm^2), these simulations show an optimum absorption of $\sim 25\%$. An admixture of S-polarized light produces a modest amount of surface rippling.[17] These ripples couple to the P component, increasing its absorption but leaving the total absorption unchanged. Absorption is only weakly dependent on incidence angle.

For a more intense P-polarized pulse (10^{15}–10^{16} W/cm^2), the early-time absorption is the same, and produces a hot-electron temperature consistent with the lower intensity.[14] However, at a later time in the pulse a strong surface rippling instability develops, as shown in Fig. 3. Simultaneously, absorption increases by a factor of 3, and all of the increased absorbed energy goes into hot electrons.[18] As can be seen in Fig. 3, the wavelength of the excited ion waves along the surface is less than the wavelength of the incident light.

In simulations at even higher intensity ($> 10^{16}$ W/cm^2), steady-state electron-electron and electron-ion two-stream instabilities are observed which heat the background plasma, producing a highly turbulent critical surface and virtually complete absorption.[18] We thus have a picture of resonant absorption as transforming from what might be termed a "laminar" process at intensities $< 10^{14}$ W/cm^2 with little critical surface perturbation, to a fully stochastic process at 10^{16} W/cm^2, characterized by a totally incoherent critical surface and extensive background plasma heating.

The variation of absorption with diameter, if real, may also be interpreted in terms of critical surface deformation. We speculate that the plasma temperature at critical density may be lower in the larger targets, possibly resulting in a reduced surface roughness.

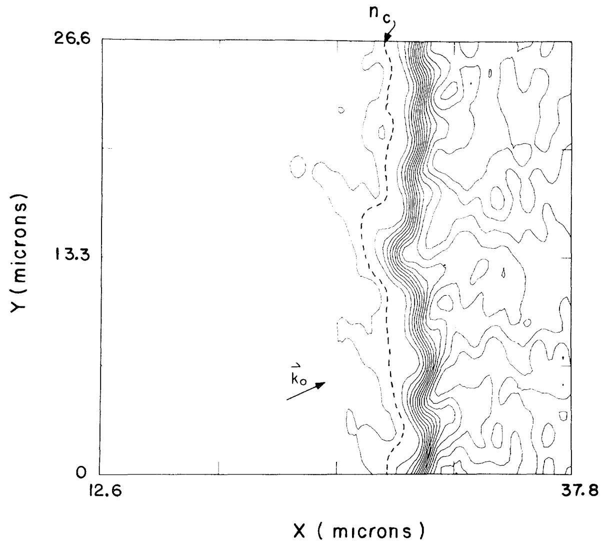

FIG. 3. Contour plot (from WAVE) of the ion density at 20 psec for $I = 2.5\times10^{15}$ W/cm^2. Note the roughness of the critical surface layer over a scale length of about 4 μm. The density gradient above critical is about 10^{20} per micrometer. Note also the fingers in the underdense plasma perpendicular to the incident wave vector, and the greatly reduced density gradient at and below the critical density.

Finally, it is of interest to compare these results with data obtained at other wavelengths. Measurements[21,22] at laser wavelengths of 1.06 and 0.53 μm generally show decreasing absorption as intensity is increased to $\sim 10^{15}$ W/cm^2. This has been attributed to reduced effectiveness of the inverse bremsstrahlung process, with a consequent drop in absorption to the resonant absorption levels of ~ 30. Further increase in intensity at $\lambda = 1.06$ μm has produced an observable increase in absorption.[22,23] This has been attributed to the effect of both coronal-density modulation and critical-surface deformation on resonant absorption. Whether or not the effect is the same at 1 and 10 μm is not clear at this time. Unfortunately, currently available experimental evidence does not permit identification of the mechanisms.

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