Reflection Losses from Laser-Produced Plasmas

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Optical calorimetry of laser radiation reflected from plane targets irradiated by a 0.3 J/30 ps Nd-laser pulse ($\lambda = 1.06\ \mu$m) has been performed. A 2π-ellipsoidal mirror was used for scattered light collection. We find that scattering outside the solid angle of the focusing lens is a major reflection loss from the target. A maximum fraction of 0.5 of the incident pulse energy was absorbed in the target with only a very weak dependence on pulse energy and target material. We emphasize that measurements made with sharp focusing on the target surface are difficult to compare with theoretical models in the plane wave/plane target approximation.

1. Introduction

The interaction of intense laser radiation with a solid target has recently found considerable interest in the context of laser fusion. One of the problems concerns absorption of laser radiation in the dense plasma which is formed on the target surface under irradiation up to intensities of 10^{17} Wcm^{-2}. At such intensities the plasma is expected to reach such a high temperature that absorption by electron-ion collisions ("inverse bremsstrahlung") is no longer efficient. Furthermore, since the free-electron density may approach or exceed solid-state density, the plasma frequency is well above the frequency of the powerful lasers presently available. Hence the laser radiation may be completely reflected in much the same manner as from a metal.

In this paper we are concerned with experimental aspects of reflectance measurements on laser-produced plasmas. Irradiation experiments at $\lambda = 1.06\ \mu$m with plane targets have shown that at intensities $\Phi \simeq 10^{15}$ Wcm^{-2} a fraction of $\simeq 0.7$ of the incident laser energy may be reflected through the focusing lens[1,2]. At still higher intensities ($\simeq 10^{16}$ Wcm^{-2}) short pulse irradiation experiments show a drop of lens reflectance to low values (< 0.2)[2,3]. For the understanding of laser-plasma interactions it is important to know whether this behaviour indicates enhanced absorption at high intensity or simply a transition from directional to diffuse reflection outside the narrow solid angle of the lens. This open question has motivated the present investigation. The measurements are performed at a laser wavelength of $\lambda = 1.06\ \mu$m and at normal incidence.

During the course of this investigation[4] some measurements of total target reflectance have been reported[5,6]. The main difference compared to those investigations lies in our relatively low laser pulse energy/high repetition rate, which enabled us to make many measurements over a much more extended range of parameters. Besides new and more complete data, this approach provides new insight into the interpretation of such experiments and should be helpful in clarifying the confusing situation in this field. The mirror technique applied here is simpler and insures better target accessibility than box calorimeters[5] and is more accurate than the use of burn paper[6].

2. Experimental Arrangement

The basic arrangement is shown in Figure 1. Four detectors, each consisting of a diffuser: silicon PIN photodiode combination, measure the incident laser-pulse energy (E_{inc}), the energy backreflected through the lens (R_{L}), the energy transmitted by the target (T) and the energy of laser radiation scattered outside the solid angle of the focusing lens (R_{diff}). The plane target, adjusted accurately normal to the laser beam axis, and the detector R_{diff} are located in the foci of an ellipsoidal mirror of aluminum which collects the scattered laser radiation over 2π

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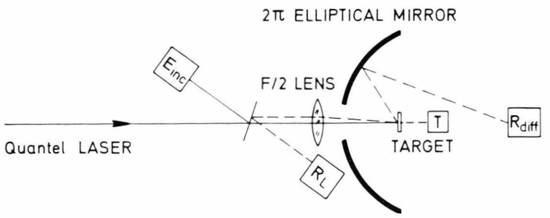

Fig. 1. Ellipsoidal mirror arrangement for measurement of scattering losses from a plane laser-irradiated target.

steradians. The light transmitted through the target is collected in a highly reflective tube and "piped" to the detector T. The collection angle for transmitted light slightly exceeds that of the beam divergence with no target.

The laser is a Quantel Nd-YAG laser ($\lambda = 1.06$ μm) consisting of a mode-locked YAG-oscillator, a Pockels cell pulse selector, a YAG preamplifier, a dye cell for prepulse suppression, a spatial filter, 16 mm and 25 mm diam. glass amplifiers, a Faraday rotator, a 45 mm diam. final glass amplifier and a second Faraday rotator. Whereas the system is guaranteed for a focusable 1.5 J/30 ps output, it was used in the present investigation at an output energy of only 300 mJ with a corresponding "B integral" of about 1 (i.e., we operated in a region where beam disturbances through nonlinear optical effects should be insignificant). The four element F/2 Zeiss lens, designed for diffraction limited focusing of a parallel laser beam, concentrates half of the pulse energy into a focal spot with a diameter less than 10 μm. This was measured at full power (300 mJ) by imaging the focus with a second lens of the same type at a manigfication of 200 × onto a circular aperture in front of a photodetector. The pulse duration of 30 ps, verified with an Electrophotonics streak camera, was held constant in this investigation. (The laser allows 30, 50, 100, 200 ps and 2 to 15 ns pulse duration.) The appearance of double pulses was monitored with a Tektronix 519 oscilloscope.

In the experiment the target was held fixed in the focus of the mirror whereas the distance between laser beam focus and target surface, and hence intensity, was changed by moving the focusing lens. (The micrometer readings of lens position with arbitrary zero point are given directly in Figs. 4—8.) Since the total position for a "warm" and "cold" amplifier chain was found to vary by about 120 μm, all measurements were made in a series of several tens of shots using the automatic timer of the laser (2 min interval at full power). By inspecting the crater shape in the target using an electron microscope it was verified that the optical focus apparent from Figs. 4—8 coincided with the position of most concentrated energy impact to better than $\pm 100\,\mu$m (Figure 2).

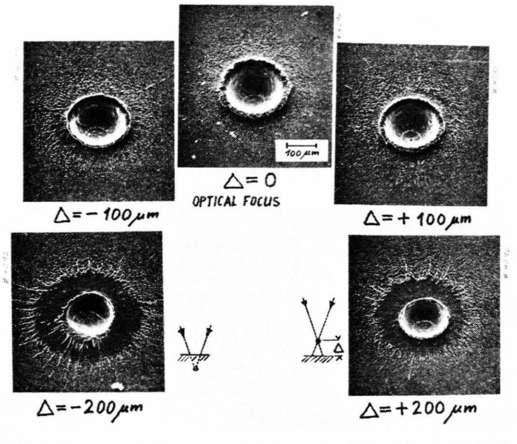

Fig. 2. Target crater shape as a function of beam focusing. Polished steel target, 0.4 J laser pulses.

An optical shutter and saturable dye cell (Kodak 9740 dye) in chlorobenzene attenuated prepulses relative to the main pulse by $\alpha = 2 \times 10^{-5}$, corresponding to ~ 6 μJ of prepulse energy. Tests with varying dye concentration in the range $2 \times 10^{-3} < \alpha < 2 \times 10^{-7}$ showed no dependence of reflectance on the contrast ratio. The detector R_{L} was calibrated by placing a 99.8% reflectance dielectric mirror in front of the chamber and correcting for measured window and focusing lens transmission. Calculation of ray paths and experimental tests showed that focusing could be varied by lens motion in the range 13 to 16 mm (focus at 15 mm, see figures) without interception of the backreflected laser light by the mounting of the beam-splitter. This effect must be considered since the back-reflected beam becomes convergent or divergent depending on focusing conditions. Calibration of the detector R_{diff} was more difficult due to scattering losses from concentric grooves left from machining in some zones of the mirror. Final calibration was done by diffusively scattering a defocused low-intensity pulse ($< 10^9$ Wcm^{-2}) from a target painted with Kodak White Reflectance Paint. This calibration should be accurate for broad angular distributions of scattered laser radiation such as those observed with the target in focus (see below). R_{L} and T are believed to be accurate to $\pm 5\%$, R_{diff} possibly not better than $+20\%$, -10%. Finally it should be noted that the detailed curves presented here were obtained only with targets of high surface quality, i.e. where diffuse scattering from the virginal surface is

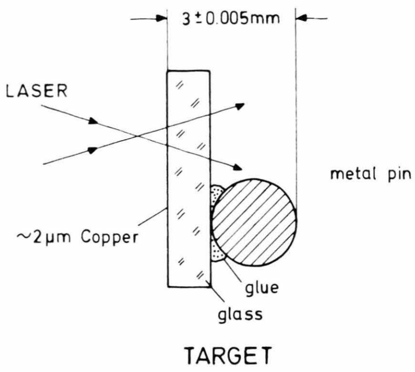

Fig. 3. Target construction.

negligible. We used 1 mm thick optical glass flats ($50 \times 5 \times 1$ mm), glued to a straight metal pin serving as a holder (Figure 3). The position of the rear surface of the pin was read with an accuracy of ± 10 μm from a 60 × projection. The targets were fabricated with a thickness tolerance (front surface to rear side of pin) of ± 5 μm. Either the bare glass surface (glass measurements) or a $\simeq 2$ μm, vapor deposited copper overcoat (copper measurements) was irradiated by the laser. Vertical, 1 mm motion between shots exposed a fresh surface at each shot. Usually 3 to 5 shots were averaged at full energy (300 mJ) and up to 10 shots at low energy (160 μJ).

3. Experimental Results

Figure 4 shows the reflectance of 140 μJ pulses from copper. At the lowest applied intensity of 5×10^9 Wcm^{-2} R_L approaches the metallic reflectance of copper (literature data are between 0.90 and 0.98 at 1.06 μm, depending on surface preparation). With the pulse focused more sharply on the target surface R_L decreases to a minimum value of 0.32. We see in this figure the characteristic behaviour found with all targets and at all pulse energies. When the pulse is sharply focused and R_L decreases to its minimum value, diffuse scattering sets in and limits absorption to lower values than deduced from reflectance back through the focusing optics. With $R_{\text{diff}} = 0.14$ we obtain $R_{\text{tot, min}} = 0.46$ or $A_{\text{max}} = 1 - R_{\text{tot, min}} = 0.54$, the highest absorption obtained in this series of experiments. Note that with a pulse energy of 140 μJ the intensity is only 6×10^{12} Wcm^{-2}. Total reflectance R_{tot} is defined as $R_{\text{tot}} = R_L + R_{\text{diff}} + T$ where $T = 0$ with the copper target.

At a pulse energy of 300 mJ (Fig. 5) this behaviour is more drastic. R_{diff} now increases to a maximum value of 0.41 and dominates reflection losses. The minimum value of R_L has further decreased to 0.16. A_{max} is still 0.50 though the pulse energy is 2×10^3 times higher than in the previous case. The intensity is now 1×10^{16} Wcm^{-2}. R_L seems to rise steadily towards metallic reflection with increasing spot size. Note that the reflection curves have broadened from low to high pulse energy.

Thus the effect of intense, point-like laser irradiation on copper is to decrease its nearly perfect metallic reflectivity to about 0.5. Glass, on the other hand (a transparent dielectric at $\lambda =$

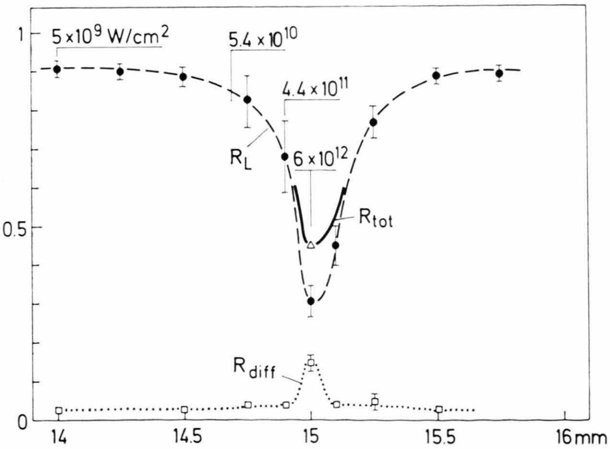

Fig. 4. Reflectance of 140 μJ/30 ps pulses from a copper target. Intensity is calculated from the geometry of the focused beam. The lens position (horizontal scale) has an arbitrary zero.

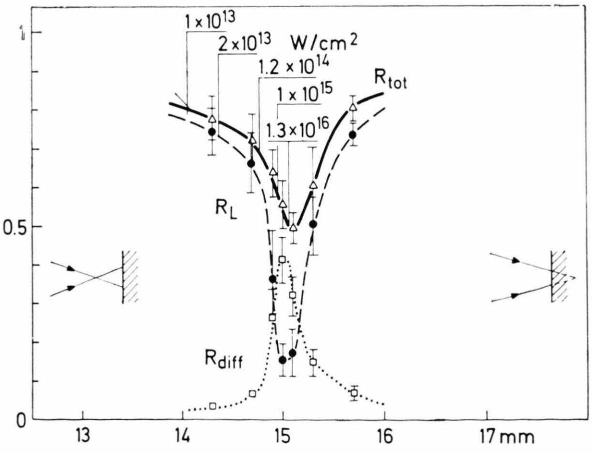

Fig. 5. Reflectance of 300 mJ/30 ps pulses from copper.

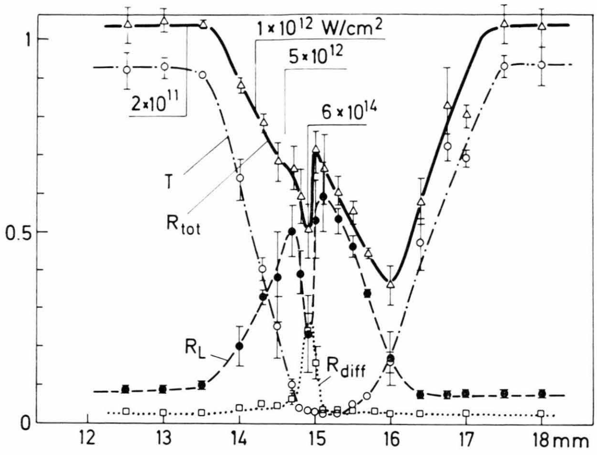

Fig. 6. Reflectance and transmittance of 14 mJ/30 ps pulses from a 1 mm thick glass flat.

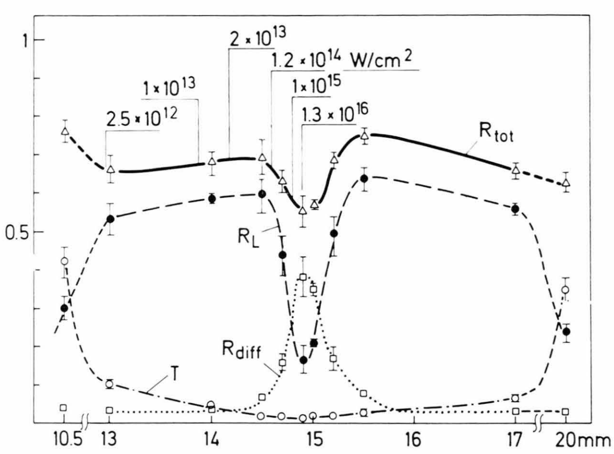

Fig. 7. Reflectance and transmittance of 300 mJ/30 ps pulses from a 1 mm thick glass flat.

1.06 μm), might be expected to become a metallic reflector on intense laser irradiation due to formation of a highly conducting plasma sheath on the surface.

To see the transition from the transparent to the reflecting state in the case of glass, we discuss first measurements made at an intermediate pulse energy (14 mJ, Figure 6). For a two-sided glass sheet one expects from Fresnel's formulas $R_{\mathrm{L}} = 0.08$, $T = 0.92$, $R_{\mathrm{diff}} = 0$ as is in fact observed for $\Phi < 2 \times 10^{11}$ W cm^{-2}. With increasing intensity the transmittance drops to zero whereas R_{L} reaches a maximum of 0.59. At focus, in a range of ~ 200 μm, R_{L} drops sharply to a much lower value of 0.23. In the same range R_{diff} rises strongly, in a manner similar to that for copper.

Figure 7 shows the behaviour at 300 mJ. The glass has become highly reflecting with R_{L} in the range 0.5 to 0.6 on both sides of the focus (note that for lens positions greater than 16 mm the detector R_{L} measures an anomalously low value due to geometrical cutoff). At focus R_{L} has an even deeper minimum and R_{diff} has become dominant as in the full-energy copper case; R_{tot} and hence absorption is very weakly dependent on intensity. In the flat minimum at focus the maximum absorption is 0.45. With plexiglass the maximum absorption was 0.37 under the same conditions.

With glass we found a peculiarity — surprising at first glance — which became prominent at reduced pulse energy (14 mJ and 160 μJ, Figs. 6 and 8), where the range of plasma reflection is bounded on both sides by the normal solid-state optics behaviour of glass. The curves R_{tot} in Figs. 6 and 8 (from left to right) drop from 1 to about 0.5 at focus (corresponding to the maximum absorption of $\simeq 0.5$ found under all conditions) and then tend to rise again. However, there is then a further drop to $R_{\mathrm{tot}} \simeq 0.3$. It is only at lens position 15.7 to 15.8 that R_{tot} rises steeply to one (Fig. 8; a similar behaviour is seen in Fig. 6). There is a natural explanation for this. When the focus is moved from the surface towards the interior of the glass target, the intensity on the surface is reduced and it begins to transmit laser light. Since the laser light comes to focus inside the glass (see symbols Fig. 5),

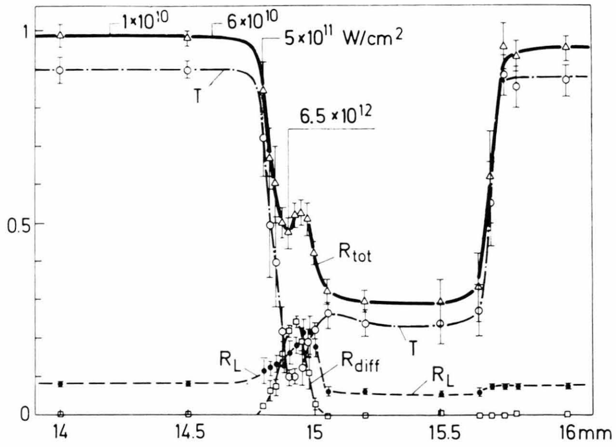

Fig. 8. Reflectance and transmittance of 160 μJ/30 ps pulses from a 1 mm thick glass flat.

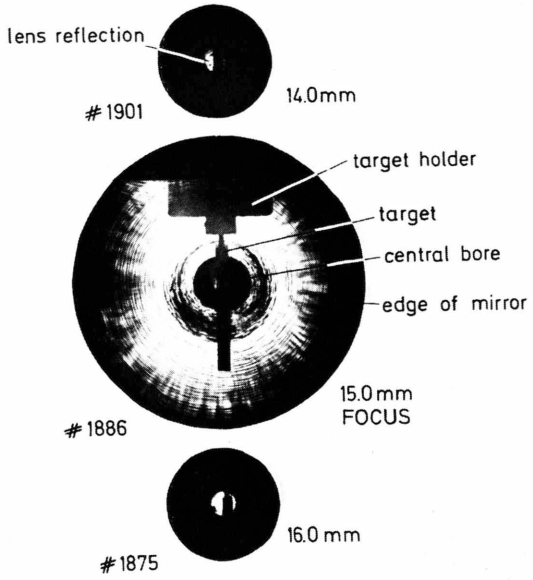

Fig. 9. Distribution of laser radiation scattered into the mirror with the target in focus. Concentric grooves come from machining of the mirror surface. Photographs taken at 14.0 mm and 16.0 mm show no diffuse scattering, therefore only their central part is shown. One may note that a lens reflection from the focusing lens becomes very bright at these positions indicating a high reflectivity back through the focusing lens.

it may become trapped in self-focusing filaments or simply refracted and is either absorbed or scattered into angles larger than covered by the detector T. It is only when the focus is beyond the rear surface of the 1 mm glass target that the radiation is fully transmitted. In fact, the width of R_{tot} should then be slightly larger than $d/n = 0.7$ mm; where d is the glass thickness (1 mm) and n is the index of refraction (1.4); in agreement with the measurements. In addition self-focusing traces have been observed with microscopic inspection. The possibly enhanced absorption in this range seems of no interest in the context of laser fusion.

An advantage of the ellipsoidal mirror is that it can be readily used to photograph the angular distribution of scattered radiation. For this purpose the detector R_{diff} is replaced by a camera focused onto the inner mirror surface. At the laser wavelength ($\lambda = 1.06$ μm) photographs were taken on Kodak IZ plates; for photographs at the second-harmonic wavelength ($\lambda = 0.53$ μm) Polaroid film was used.

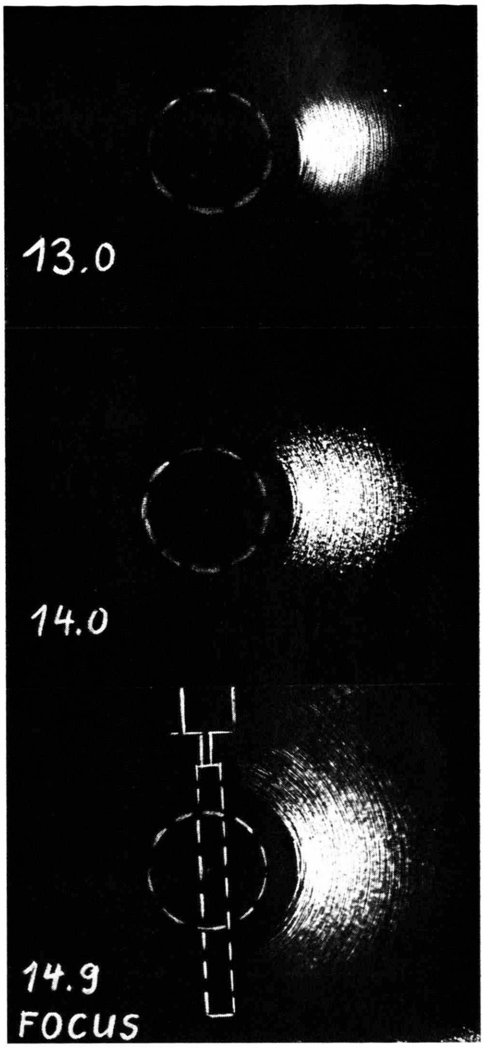

Fig. 10. Specular infrared beam reflected into the mirror from a tilted glass target at an angle of incidence of 17°. The position of the central bore and the target are marked. Note the broadening of the angular distribution as focus is approached.

Figure 9 shows the broad angular distribution of scattered radiation with the target in focus; out of focus only a bright lens reflection is seen in the central bore of the mirror, indicating strong reflection through the lens in agreement with the measurements in Figs. 4 to 8. With a tilted target out of focus a well defined specular beam is reflected into the mirror. The angular distribution broadens when focus is approached (Figure 10). We have also verified that for p-polarization (E-vector horizontal, target rotational axis vertical) the specular harmonic

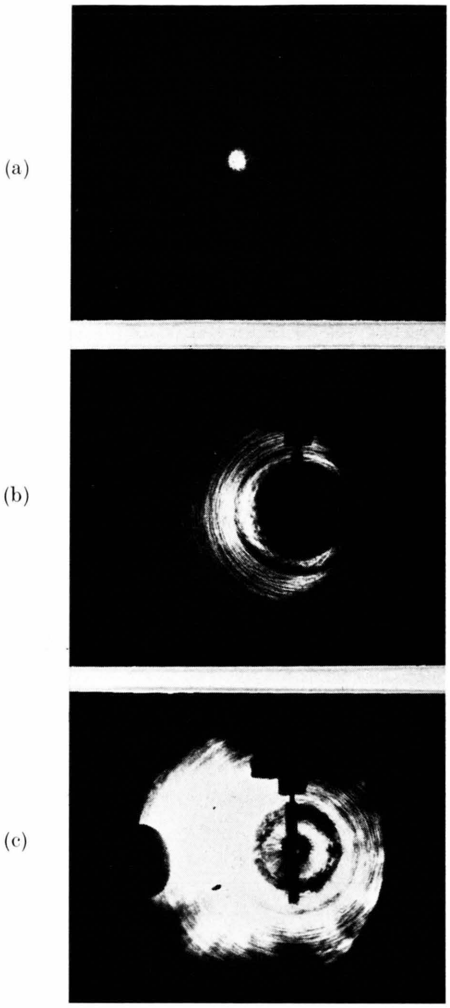

Fig. 11. A green beam of frequency doubled light is produced together with the specularly reflected laser beam. The target was tilted by 17° in the *opposite* direction compared to Figure 10. Photographs taken with a $\lambda = 0.53\ \mu m$ interference filter and infrared blocking filters on Polaroid film. As with the infrared beam, the frequency doubled beam becomes more and more diffuse near focus (at 14.6 mm in this case). a) 13.0 mm; b) 14.3 mm; c) 14.6 mm.

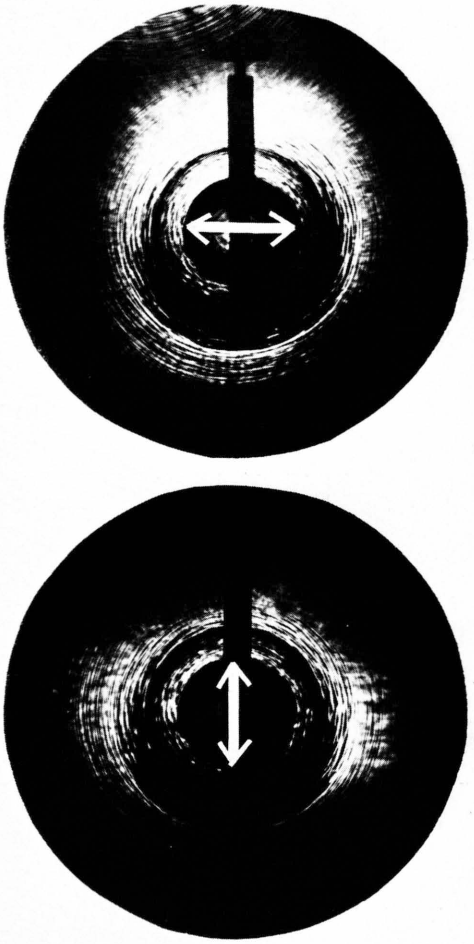

Fig. 12. Photographs of laser light scattered into the mirror (similar to Fig. 9). The arrows denote the direction of the electric field vector of the linearly polarized laser beam. Photographs taken at 15.3 mm, i.e. about 300 μm away from best focus.

is accompanied by a specular beam of frequency doubled light whose distribution broadens as well when focus is approached (Figure 11). This observation confirms the results on second harmonic production in laser-produced plasmas obtained previously with nanosecond pulses[7].

We were also interested in whether or not the intensity distribution of scattered laser radiation is rotationally symmetric around the laser axis or shows polarization effects related to the linearly polarized laser beam. In focus the photographs showed symmetric distributions; Fig. 9 is an example of this case. Weak polarization effects were observed a few hundred microns out of focus. In Figure 12, the photographs taken 300 μm out of focus, the distribution of scattered laser radiation is slightly elliptical and rotates with the E-vector of the laser beam (polarization rotation was achieved by reversing the current in a Faraday rotator). The orientation of the ellipses is such that absorption is stronger for scattered laser radiation with the E-vector in the plane of scattering (p-polarization). Similar observations were made in [5]. The effect may be attributable to resonance absorption [8, 9, 10]; the evidence obtained in this way is, however, rather indirect since theoretical models do not include diffuse scattering of laser light. Nevertheless recent experiments have verified much more directly the typical polarization effects of resonance absorption at oblique incidence [11]; hence such interpretations may be correct.

4. Discussion

On the basis of this investigation it is now clear that measurements of reflection losses outside the focusing optics are indispensable before any conclusions concerning absorption in laser-produced plasmas can be made. Such losses are particularly important with the target in focus where most measurements have been made so far.

It also became clear that meticulous care is required to perform such experiments. A controlled focal spot size unaffected by self-focusing in the laser up to full power, accurate and reproducible control over the focusing conditions, calibration and light transport to the detectors and surface quality of the target are very important. For example, misplacing the target by a distance of only ~ 100 μm can cause dramatic changes in lens reflectivity (see Figs. 4 to 8). We are no longer surprised that often quite contradictionary results have been reported in the literature.

Recent measurements of total reflectance have been collected in Figure 13. Curves 1 and 2 are R_{tot} from Fig. 1 and 2, curve 3 measurements made at Lawrence Livermore Laboratory with parylene discs with the intensity varied by changing focusing conditions in the manner as used in this work[5], curve 4 measurements made with our apparatus but with long (10 ns) pulses and curve 5 measurements made at Los Alamos with a CO_2 laser (10.6 μm) and the target in focus [12]. We emphasize the following points:

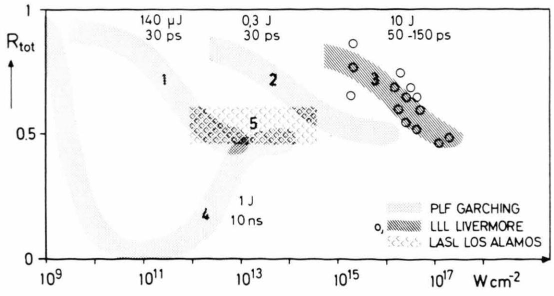

Fig. 13. Recent measurements of total reflectance made in several laboratories. For references see text.

(i) At intensities $10^{10}-10^{13}$ Wcm^{-2} we can have either complete reflection or absorption depending on pulse length! Collisional absorption in a cold, extended corona seems the most likely source for the strong absorption of the nanosecond pulses.

(ii) With intense, short pulses ($> 10^{13}$ Wcm^{-2}) maximum absorption does not exceed ~ 50%. The same absorption is observed at $\lambda = 10.6$ μm [12, 13].

(iii) Most fascinating is the universal behaviour observed with the target in focus. Reflection losses remain in the range $0.5 \lesssim R_{\text{tot}} \lesssim 0.7$ independent of intensity (for nearly five orders of magnitude), target material and wavelength! In all cases diffuse scattering is dominant indicating that the target does not remain plane under irradiation. This is really not surprising since simply the hydrodynamic motion of a point-like heated target could lead to deflection (scattering) of laser light. In any case measurements made at focus are difficult to interpret since a well defined geometry may not exist in such experiments. Linear coupling mechanisms such as resonance absorption may be able to account for the observed independence of intensity and wavelength.

(iv) The thusfar undisputed assumption that reflection is a unique function of intensity appears now doubtful. For example, at a constant intensity of $\Phi = 10^{13}$ Wcm^{-2} we can have in focus $R_{\text{tot}} \simeq 0.5$ (curve 1) or, under defocused conditions with larger spot size, $R_{\text{tot}} \simeq 0.8$ (curve 2) and similar for other conditions. Also, at constant intensity, diffuse scattering decreases strongly with increasing spot size (compare Figs. 4 to 8). This indicates that the results may not be directly comparable to theoretical models assuming plane waves of infinite lateral extent but rather that they are influenced by effects of the focal spot size. It would not be surprising if the „artificial'' roughness induced by the final spot size would also influence, for example, scattered light spectra, X-rays, the angular and energy distributions of emitted ions.

(v) If one extrapolates the present data — which are still rather incomplete and inaccurate for this purpose — towards a plane wave normally incident onto the target, the data show a trend towards $R_{\text{tot}} \gtrsim 0.8$. This result, if confirmed by improved measurements, would be consistent with computer simulations of a collisionless plasma gradient at normal incidence[14,15].

The realization that full-angle reflection measurements are necessary and the discovery of the importance of the focal spot size are the two main achievements of this investigation. They affect strongly the interpretation of the experiments performed in this field so far. Whereas care has been taken already for a complete reflection measurement in recent experiments[5,6,12,13], finite focus effects are more difficult to assess. Their consideration requires either full, multi-dimensional numerical simulations, or, ideally, more powerful lasers which allow experiments at increased spot size. It appears at first glance that with these results the interaction problem and the way to its understanding has become more complicated. On the other hand, it should not be overlooked that more complete investigations like this one, indicate that the underlying physics may be less complicated than was suggested by the confusing situation as recently as a year ago. The observed intensity and wavelength independence point into this direction.

[1] F. Floux, J. F. Benard, D. Cognard, and A. Salères, in Laser Interaction and Related Plasma Phenomena, Vol. 2, edited by H. J. Schwarz and H. Hora (Plenum Press 1972), p. 409; K. Eidmann and R. Sigel, ibid. Vol. 3B, p. 667; C. Yamanaka, T. Yamanaka, and H.-B. Kang, ibid. Vol. 3B, p. 629.

[2] M. Lubin, E. Goldman, J. Soures, L. Goldman, W. Friedman, S. Letzring, J. Albritton, P. Koch, and B. Yaakobi, in Plasma Physics and Controlled Nuclear Fusion Research 1974, Vol. II (International Atomic Energy Agency, Vienna, 1975) p. 459.

[3] P. Lee, D. V. Giovanielli, R. P. Godwin, and G. H. McCall, Appl. Phys. Lett. **24**, 406 [1974].

[4] C. G. M. van Kessel, J. N. Olsen, P. Sachsenmaier, R. Sigel, K. Eidmann, and R. P. Godwin, Max-Planck-Gesellschaft zur Förderung der Wissenschaften e.V., Projektgruppe für Laserforschung, D-8046 Garching, Laboratory Report IPP IV/94 (1976), unpublished, presented at the 10th European Conference on Laser Interaction with Matter, Ecole Polytechnique, Palaiseau, France, 18 to 22 October 1976.

[5] R. A. Haas, W. C. Mead, W. L. Kruer, D. W. Phillion, H. N. Kornblum, J. D. Lindl, D. MacQuigg, V. C. Rupert and K. G. Tirsell, Phys. Fluids **20**, 322 [1977].

[6] B. H. Ripin, Appl. Phys. Lett. **30**, 134 [1977].

[7] K. Eidmann and R. Sigel, Phys. Rev. Lett. **34**, 799 [1975].

[8] V. L. Ginzburg, The Propagation of Electromagnetic Waves in Plasmas, Pergamon, New York 1964, p. 214.

[9] J. P. Freidberg, R. W. Mitchell, R. L. Morse, and L. I. Rudsinski, Phys. Rev. Lett. **28**, 795 [1972].

[10] R. P. Godwin, Phys. Rev. Lett. **28**, 85 [1972].

[11] R. P. Godwin, P. Sachsenmaier, and R. Sigel, to be published.

[12] V. M. Cottles and D. V. Giovanielli, Los Alamos Scientific Laboratory, Report LA-UR-77-1096 [1977], unpublished.

[13] J. Martineau, M. Rabeau, J. L. Bocher, J. Ph. Elie, and C. Patou, Opt. Comm. **18**, 347 [1976].

[14] W. L. Kruer, R. A. Haas, W. C. Mead, D. W. Phillion, and V. C. Ruppert in Plasma Physics: Nonlinear Theory and Experiments, 36th Nobel Symposium Aspenäsgarden, Sweden, June 10—18, 1976, edited by H. Wilhelmsson (Plenum Press 1977).

[15] B. Bezzerides, D. F. Du Bois, D. W. Forslund, J. M. Kindel, K. Lee, and E. L. Lindman, in Plasma Physics and Controlled Nuclear Fusion 1976, Vol. I (International Atomic Energy Agency, Vienna, 1977) p. 123.