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Angle-Dependent Reflectance of Laser-Produced Plasmas

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The reflectance of planar targets irradiated by 400-mJ, 30-ps Nd : glass laser pulses was measured as a function of angle of incidence and polarization with an Ulbricht spherical photometer. At normal incidence we find reflectances > 0.6. The reflectance for p-polarized light has a minimum at an incidence angle of 20° to 30°; for angles greater than 60° total reflection occurs for both s- and p-polarized light. The results seem consistent with simulations.

Understanding the absorption of intense laser radiation incident upon solid targets is of basic importance in laser-fusion studies. Optical energy-balance measurements are the most direct means for gaining information. Recent measurements with planar targets[1-3] have shown reflectances of 0.5 and more at *normal* incidence. These observations have created renewed interest in reflectance measurements as a function of angle of incidence and polarization which should yield more information than do normal-incidence measurements. In particular, optical resonance[4-6] should enhance absorption of p-polarized light.

Measurements at normal incidence have indicated polarization effects in the scattered laser light, but these are rather indirect and difficult to correlate with theoretical models.[2] Ion-velocity measurements at a fixed angle of incidence give qualitative evidence for a polarization effect, but no quantitative measure of absorption.[7] In this Letter we report direct reflectance measurements as a function of angle of incidence and polarization which exhibit the polarization effects expected on the basis of optical resonance. In a previous experiment[8] these effects were not evident.

In laser-produced-plasma experiments a large fraction of the nonabsorbed laser light may be scattered in a rather diffuse manner.[1] Hence a reflectometer to be used in such experiments should have a 4π collection angle, especially if the target is tilted during the measurements. An Ulbricht spherical photometer[9] is ideal. It consists of a hollow sphere with its inner surface coated by a diffuse reflector. The attractive feature of such a device is that the measured intensity is independent of the angular radiation distribution of the source (in our case, the reflecting laser-produced plasma).

Our Ulbricht sphere was constructed by painting the inside of a 150-mm-diam plastic shell with Eastman white reflectance paint (see Fig. 1). Ap-

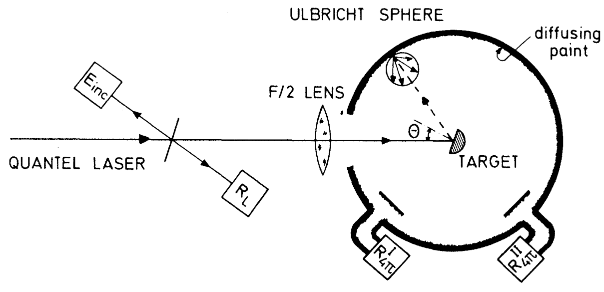

FIG. 1. Ulbricht spherical photometer adapted for use with laser-produced plasmas.

ertures (mainly for the focused laser beam) have an area less than 5% of an unblemished sphere. As shown in Fig. 1, silicon *p-i-n* photodiodes (screened to prevent viewing directly the laser target located at the center of the sphere) are positioned at angles of 45° and 135° with respect to the laser beam. They lie in a plane normal to the plane of incidence in the experiments to be described. Tests showed that our photometer provides a nearly constant signal intensity for a wide range of angular distributions for both 0.63- and 1.06-μm laser light.

A particular advantage of the Ulbricht sphere is the straightforward procedure for calibration relative to the detector labeled E_{inc}. Since the signal is independent of the angular distribution of laser radiation we can simply calibrate for 100% target reflectance into the sphere by removing the target and firing onto the rear wall. Two detectors, labeled $4\pi^{\text{I}}$ and $4\pi^{\text{II}}$, are used to average over remaining asymmetries of the sphere. A correction is made for that fraction (14%) of the laser light backscattered from the target which is returned to the sphere by reflection from the focusing optics. This correction is generally small and becomes negligible for angles larger than 15° where the specular reflection from the target is no longer intercepted by the focusing lens. The laser light itself which is backscattered through the lens is measured by the detector labeled R_L. It is calibrated by placing a 99.8-% dielectric mirror in front of the experimental chamber and correcting for the measured transmittance of the focusing lens and chamber window. Total reflectance R_T is calculated as the sum of reflectance into the sphere $R_{4\pi}$ and back through the lens R_L. Various tests indicate that the apparatus should be accurate to about 10%.

The laser is a mode-locked Quantel Nd–yttrium aluminum garnet laser ($\lambda = 1.06$ μm) delivering 400-mJ, 30-ps pulses onto the target. For these

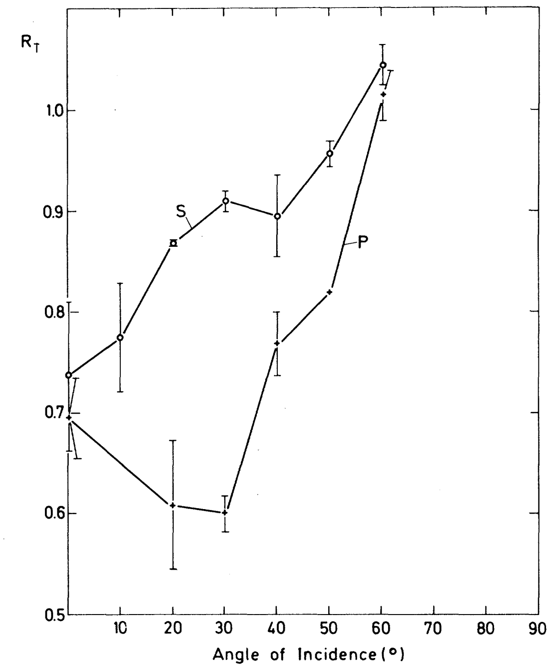

FIG. 2. Total reflectance R_T into 4π sr by a Cu target as a function of incidence angle. Focus 200 μm in front of the surface; *s* and *p* denote polarization perpendicular and parallel to the plane of incidence.

operating conditions measurements have shown that the four-element $f/2$ Zeiss lens concentrates half of the pulse energy into a focal spot with a diameter of 10 μm. Hemicylindrical targets prepared from glass and steel rods nominally 3 mm in diameter were used. The polished (diametrically cut) face of the rod was coated with Cu in the case of the steel rods. The center of rotation in the face of the rod was controlled to within 30 μm. A new surface was exposed for each shot. Measurements were made as a function of focal position (by varying the lens position), incidence angle, and polarization (by reversal of the current flow in a Faraday rotator).

We have measured the total reflectance for several types of targets and laser operating conditions. Figure 2 is a plot of the reflectance of a Cu-coated target for 400-mJ, 30-ps pulses as a function of angle for *s* and *p* light. At normal incidence ($\theta = 0°$) we have $R_T \simeq 0.7$ for both polarizations. With increasing angle the reflectance of *s* light steadily increases reaching $R_T \simeq 1$ at $\theta \simeq 60°$. The *p*-light reflectance first decreases with angle reaching a minimum at $\theta_m \simeq 20°$ to 30° and then approaches $R_T \simeq 1$ for 60°. Very similar curves were measured with 15-mJ, 30-ps pulses and a glass target.

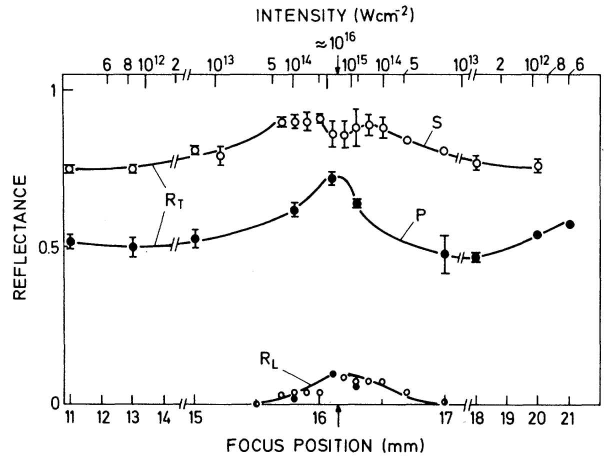

FIG. 3. Total reflectance R_T and lens backscatter R_L from a Cu target with an incidence angle of 25° as a function of focus position. At 16.15-mm, focus is at the target surface, for greater numbers inside. Upper scale gives intensity.

The data of Fig. 2 were taken with the beam focus about 200 μm in front of the target (corresponding to an intensity of 3×10^{14} W cm^{-2} and a spot size of ~75 μm). A similar curve was obtained with the focus 200 μm inside the target. With the focus at the target surface, the data displayed a less marked difference between s and p reflectance.

To clarify this point, measurements were made at constant angle of incidence (25°), but with the focus position relative to the surface being varied (Fig. 3). We find a typical enhancement in absorption for p light by a factor of 2 compared to s light apparently independent of intensity and target material. This observation is in agreement with less direct experiments.[7] In focus the two curves tend to merge and the difference between s and p light is less pronounced. This behavior is not unexpected, since recent measurements[1] using the same $f/2$ focusing lens have shown that only out of focus does a planar target act as a planar mirror. In focus the reflected laser light is diffusely scattered. The underlying "roughness" of the plasma layer which might have to do simply with the hydrodynamic motion of the pointlike heated target surface must be expected to smooth out the polarization effects. This may explain why no clear polarization effect was observed in Ref. 8 where only measurements in focus were performed.

We are interested here mainly in the behavior of the specularly reflected beam but it should be noted that the experiment shows a second lobe of scattering from the target. Backscatter through the focusing lens (R_L) in Fig. 3 is too large to be accounted for by diffuse scattering alone. Such directional scattering back into the lens is well known as so-called collimated backscatter, generally attributed to stimulated backscattering.[10] As far as the two components can be distinguished for incidence angles >15°, the specular component into the sphere is much stronger than the collimated one; for example, according to Fig. 3, the contribution of R_L to the total reflectance is at most ~10% in focus and decreases rapidly outside. Hence we have plotted total reflectivity R_T throughout this Letter. Nevertheless the relative insignificance of collimated backscatter may be true only for very short and clean pulses (prepulse energy <6 μJ in this investigation); occasional double pulsing of the laser sometimes leads to very strong collimated backscatter (R_L >0.5), possibly as a result of stimulated backscattering from a preformed plasma cloud. These observations need more detailed investigation.

In intense laser-plasma interactions many competitive instabilities may occur and quantitative, analytical predictions are difficult. We will briefly consider two-dimensional simulation results.[11,12]

Simulations identify resonant absorption as the major absorption mechanism. Even at a normal incidence on a collisionless plasma, gradient absorption remains finite (typically $A\simeq0.1$ to 0.2) due to an induced roughness of the critical density layer. We find experimentally at normal incidence (Fig. 2) and for oblique incidence of s light (Fig. 3) a somewhat larger absorption of $A\simeq0.3$. It is doubtful whether this deviation is significant, since plane-wave simulations are only an approximation to focused-beam experiments. For example, a finite-size focus leading to enhanced diffuse scattering,[1] the considerable range of incidence angles in the focused beam (the half-angle of $f/2$ lens is 15°), and possibly also collisional absorption in the lower-intensity range all tend to increase absorption in the experiment.

For obliquely incident p light the optimum absorption angle for resonance absorption is given by $(k_0L)^{1/3}\sin\theta_m\simeq0.8$, where k_0 is the free-space wave vector and L the local scale length at the critical density. The measured $\theta_m\simeq25°$ then implies $k_0L\simeq6$ or $L\simeq\lambda_0$. Such steep density gradients are, in fact, found in the simulations and are generally attributed to profile steepening due to light pressure. Our measured $A_{max}\simeq0.4$ at the optimum angle is consistent with simulation results of $A_{max} \simeq 0.4-0.6$.[11,12] In conclusion, reflectance measurements and plasma-simulation calculations exhibit similarities unexpected only a short time ago.

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Note added.—Since the original submission of this paper a related work has appeared.[13]

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Universal Jump in the Superfluid Density of Two-Dimensional Superfluids

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We observe that recent theories of phase transitions in the two-dimensional XY model predict a universal jump in the superfluid density of ^{4}He films as T_c is approached from below. Specifically, we find that $\lim_{T\to T_c^-} \rho_s(T)/T = 3.52\times10^{-9}$ g/cm^2 °K. Analogous results should hold for two-dimensional planar magnets and liquid crystals.

A number of theories have been advanced dealing with the critical properties of the classical two-dimensional XY model.[1-6] Although the lack of long-range order in such systems has been proven rigorously,[7] evidence from high-temperature-series expansions[8] suggests the possibility of a transition at finite temperature into a low-temperature phase without longe-range order. Indeed, the theories of Refs. 1-6 all predict a low-temperature region which can be characterized as a "phase" of critical points with continuously variable critical exponents. Within this phase, order-parameter correlation functions are expected to fall off at large distances as power laws with temperature-dependent exponents. There is considerable disagreement, however, on the predictions near the critical temperature T_c, above which correlations are expected to decay exponentially. Because *experimental* realizations of two-dimensional XY behavior may actually be available in ^{4}He films,[9] in planar magnets,[10] and in liquid crystals,[11] it seems desirable to have a simple criterion for determining which of the theories, if any, are correct.

In this Letter, we point out that the theories advanced in Refs. 2b and 5 predict a *universal* jump in the superfluid density of ^{4}he films. The size of the jump is related to the critical exponent $\eta(T_c)$, which governs the power-law decay of correlations at the critical temperature. This result