Angular Dependence of Polarization-Related Laser-Plasma Absorption Processes[(a)]

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We have measured the incidence-angle dependence of the absorption of p-polarized and s-polarized laser radiation by dense plasmas. A significant absorption peak at nonnormal angles of incidence is observed which is attributed to resonance absorption.

We report the first direct observation of the angular dependence of the absorption of p- and s-polarized laser radiation by dense plasmas. Independent measurements of the plasma expansion characteristics, the x-ray temperature, and the hole size burned in 1000-Å-thick polystyrene targets all show maximum absorption occurring at nonnormal angles of incidence. This characteristic, in conjunction with the polarization dependence of the absorption,[1] gives further evidence for the existence of resonance absorption.

There are several processes which transfer laser radiation into plasma energy. Under our experimental conditions, inverse bremsstrahlung and resonance absorption[2-4] are thought to be the dominant mechanisms. Parametric processes[5] are thought to be unimportant because, at a nonnormal angle of incidence θ, the laser radiation is reflected at an electron density $n = n_c \times \cos^2\theta$ and therefore does not reach the critical surface ($n = n_c$) where parametric effects can be significant.

The resonant absorption process is of great interest because of its predicted high efficiency for conversion of incident radiation to plasma energy (> 50%). If a p-polarized electromagnetic wave impinges upon a plasma at nonnormal angles of incidence, the electric-field vector is parallel to the density gradient near the point of reflection. The electric field drives Langmuir oscillations which undergo Landau damping, resulting in the transfer of wave energy into the plasma. Resonance absorption is angle dependent.[2] The fraction of energy absorbed by resonance absorption, f_{ra}, is given[4] by

$$f_{ra} = (1 - \tfrac{1}{2} f_{ib})\varphi^2(\tau)/\pi,$$

where f_{ib} is the fraction absorbed by inverse bremsstrahlung and $\varphi(\tau)$ is the absorption function. In Fig. 1, we plot $\varphi^2(\tau)/\pi$ as a function of the dimensionless parameter τ, which is defined by

$$\tau = (kL)^{1/3} \sin\theta,$$

where k is the magnitude of the incident wave vector and L is the density scale length. The angle of maximum absorption, θ_m, occurs in the neighborhood of $\tau = 0.7$. For illustrative purposes, we chose $k = 2\pi/(1.06\ \mu\text{m})$ and $L = 2.3\ \mu\text{m}$. Then $\theta_m = 17$ deg, as is shown by the θ abscissa in Fig. 1. Since inverse bremsstrahlung has a maximum absorption when the irradiation is normal to the target plane,[1] the observation of maximum absorption at a nonnormal angle of incidence suggests resonance absorption.

To evaluate the angular dependence, an experiment was designed to permit a well-defined angle of laser-plasma interaction with the minimum possible perturbation of the plasma from its initial planar geometry. A laser pulse of 50 psec full width at half-maximum was focused with $f/9$ optics (± 3 deg angular spread) onto a planar 1000-Å-thick target. The focal spot contained 60% of the laser energy in a diameter of 100 μm, corresponding to an irradiant flux of 1.5×10^{14} W/cm^2. It is inferred that the laser prepulse did not cre-

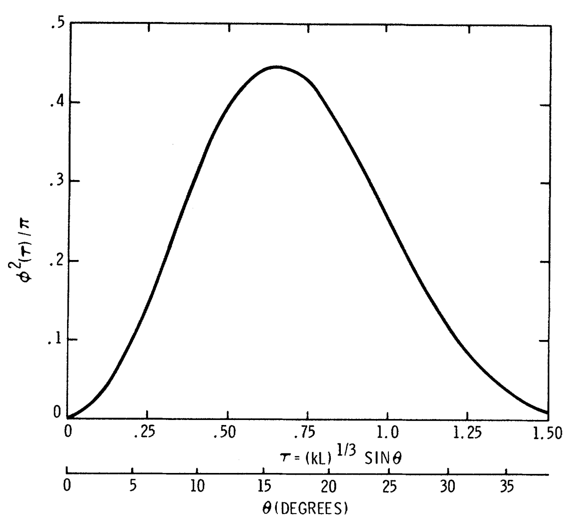

FIG. 1. Plot of $\varphi^2(\tau)/\pi$ vs τ and angle of incidence, θ, for a density scale length of 2.3 μm and 1.06-μm incident radiation.

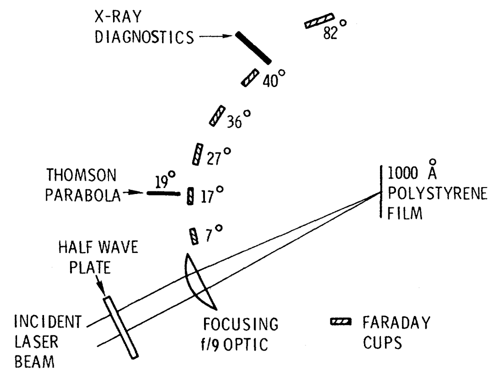

FIG. 2. Schematic of the experimental configuration.

ate a precursor since the target film remained intact when the laser system was fired but a pulse was not selected from the mode-locked oscillator pulse train. The angle of incidence was changed by rotating the target while maintaining the focusing optics and diagnostics in fixed spatial positions. Four angles of incidence were investigated: 8, 17, 26, and 36 deg. The diagnostics used to monitor the degree of laser absorption were Faraday cups, a Thomson parabola, K-edge filter x-ray diagnostics, and the target condition after irradiation.

A schematic of the experimental configuration is shown in Fig. 2. Faraday cups of a new design[6] were placed at angles of 7, 17, 27, 36, 40, and 82 deg from the lens. In addition, two Faraday cups (not shown) were placed out of the plane of incidence to more fully evaluate the plasma expansion characteristics. A Thomson parabola, placed at 19 deg, measured the ion energy and species charge-to-mass distribution. The Thomson-parabola traces permitted determination of a time-dependent average charge,[7] which in turn was convoluted with the Faraday-cup currents to give the time-dependent ion number and energy (assuming carbon ions). These quantities were used to evaluate the plasma absorption characteristics. In particular, for resonance absorption, the ratio of the total ion number and the ratio of the total ion energy for p- to s-polarized incident radiation are of interest. The upper curve in Fig. 3 gives the ratio of ion expansion energy for p-polarized to s-polarized irradiation. Each datum point represents the mean of ten or more shots and the error bar is the standard deviation from the mean. A peak in the energy ratio occurs at an angle of incidence between 17 and 26 deg. The lower curve of Fig. 3 shows a similar

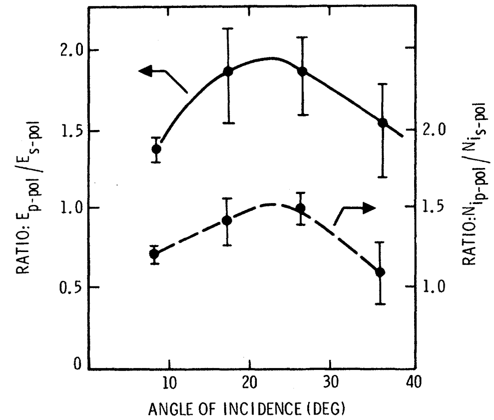

FIG. 3. Ratio of ion energy for p- and s-polarized irradiation (solid line) and ratio of ion number for p- and s-polarized irradiation (dashed line) as a function of the angle of incidence.

peak when the ratio of the ion numbers is plotted. From the energy ratio, a significantly higher plasma energy in the presence of p-polarized (resonantly absorbed) laser radiation can be inferred with the maximum absorption occurring at a nonnormal angle of incidence.

The other plasma diagnostics also show an angle-of-incidence dependence similar to that of the plasma expansion characteristics. The electron temperature derived from fitting the x-ray data is shown in Fig. 4 for p and s polarization. A significant angular dependence is observed with p-polarized incident radiation with a maximum temperature of approximately 475 eV occurring near 26 deg. The angular dependence observed with s polarization is in contrast to the predictions for a simple laser–planar-target interaction model but may result from nonplanar expansion of the thin-film target even on the 50-psec time scale

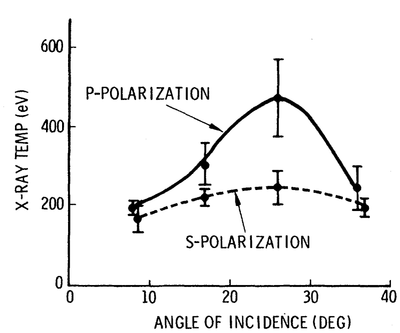

FIG. 4. Angular dependence of the plasma electron temperature determined from x-ray measurements for p-polarized and s-polarized irradiation.

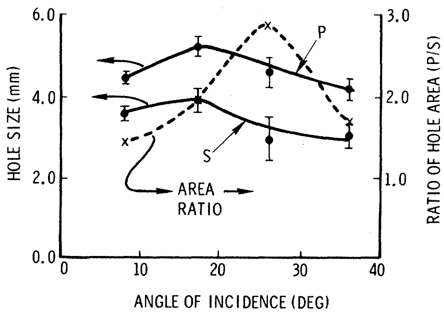

FIG. 5. Polarization dependence of the hole burned in thin-film targets as a function of the angle of incidence. The ratio of the hole area for p and s polarization is given by the dashed line.

or from profile modification. Both of these are discussed in more detail below.

The size of the hole burned in the 1000-Å-thick film can also be correlated with the angle of incidence and laser polarization. Though it is difficult to diagnose the microscopic target physics from the hole diameter, this measure is attractive in that it provides a direct and simple means of observing trends in the laser-target interaction process. The experimental results are shown in Fig. 5. The largest hole diameter occurs near 17 deg for both p and s incident polarization. The ratio of hole area for p- to s-polarized laser light (dashed line in Fig. 5) has a maximum near 26 deg. This is consistent with the other diagnostics.

The agreement between all the measurements is good and shows an enhancement of absorption with p polarization by a factor of 2 over that with s-polarized radiation. The peak in absorption occurs at an angle of incidence between 17 and 26 deg. If this range is utilized in the formula for θ_m, the plasma-density scale length is estimated to be between 0.7 and 2.3 μm. This can be compared to a scale length of 2.7 μm predicted by assuming an isothermal expansion.[7] The scale length is expected to be a function of position in the plasma because of spatial variations in the incident laser beams.

The scale length determined from the experimental data is an average over the focal-spot area. A steepening of the plasma density gradient is expected to occur when the plasma pressure is equal to the incident radiation pressure This threshold is 0.6×10^{14} W/cm^2 for an electron temperature of 500 eV.[8] This flux is exceeded near the center of the focal spot and thus some profile modification is expected locally. The modification, which creates a concave critical surface around the region of maximum laser-beam intensity, may account for the angular dependence of the s-polarized incident radiation. Perturbations of the plasma from planarity due to expansion should also be considered. The plasma expansion from the initial planar configuration generates a "coin shaped" plasma profile which has rounded edges. For example, under the assumption in our experiment of a critical surface velocity of 10^7 cm/sec, the surface moves a distance of approximately 5 μm normal to the original surface during the laser pulse as compared to a spot size of 100 μm diam. However, nonplanarity near the edges should not have a significant effect on the experimental results because the deviation occurs in regions of very low incident laser intensity.

In summary, the angular distribution of polarization-dependent absorption has been observed directly for the first time. The absorption is found to peak at an angle between 17 and 26 deg with a twofold maximum enhancement of energy deposition in the presence of p-polarized irradiation. These results suggest a resonant absorption process in the laser-plasma interaction.

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