# Polarization-Dependent Absorption of Laser Radiation Incident on Dense-Plasma Planar Targets*

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Polarization-dependent absorption of obliquely incident laser radiation by dense plasmas has been observed. Irradiation of a planar plasma with a nearly collimated $p$-polarized laser beam shows an enhancement in absorption by a factor of 2 to 2.5 over $s$-polarized irradiation. Theoretical estimates of the effect of resonance absorption under the present conditions show agreemwnt with the experimentally observed results.

We report here the first direct evidence of polarization-dependent absorption of laser light by dense-plasma planar targets. For several years, theoretical models for laser absorption at high intensities have predicted a polarization-dependent absorption due to the process called resonance absorption.[1,2] The existence of such an effect has been previously inferred by indirect methods.[3] In the present work, we present direct evidence and a quantitative evaluation of polarization-dependent laser absorption on planar targets. Four independent measurements lead to the inference of polarization-dependent abosrption—that is, changes in (1) the energy of the fast plasma ions, (2) the total plasma energy as deduced from Faraday-cup currents, (3) the maximum proton energy, and (4) the size of the hole burned through the thin-slab targets.

Resonance absorption is thought to be the dominant collisionless absorption mechanism in the present experimental regime ($I \gtrsim 10^{14}$ W/cm$^2$). It is a particularly interesting phenomenon from a practical point of view in that it is predicted to have a high absorption efficiency, reaching ~ 55% at moderate angles of incidence. If an electromagnetic wave is incident on a planar plasma density gradient at a nonzero angle of incidence, $\theta$, and has electric polarization vector $\vec{E}$ lying in the plane determined by $\vec{k}$ and $\nabla n$, the electric vector of the wave points locally in the direction of $\nabla n$ when it reaches its turning point; here $\vec{k}$ is the free-space wave vector and $n$ is the plasma density. If the turning-point density ($n = n_c \cos^2\theta$) is not too far spatially from the critical density ($n_c$), the electric field of the wave can tunnel in to $n_c$ and drive resonant plasma oscillations there. Damping of these driven Langmuir oscillations provides an absorption mechanism for the incident light wave. The polarization for which resonance absorption occurs is frequently described as "$p$ polarization." In the opposite case ("$s$ polarization"), $\vec{E}$ is perpendicular to the plane defined by $\vec{k}$ and $\nabla n$ and the resonance absorption phenomenon does not occur.

Since resonance absorption is a polarization-dependent phenomenon, an experiment was designed to evaluate changes in the plasma absorption with changes in the incident laser polarization. Planar 1000-Å-thick polystyrene targets were irradiated at an angle of 17° with 50-psec, 1.06-$\mu$m laser pulses at flux levels of $10^{14}$ W/cm$^2$. The focal spot of 100 $\mu$m contains 60% of the incident laser energy. The experimental configuration is shown in Fig. 1. Since resonance absorption is predicted to be dependent on the angle of incidence,[1,2] the laser beam was focused with $f/9$ coated optics so that the incident laser beam was nearly collimated (± 3°) and therefore had a well-defined angle of incidence with respect to the tar-

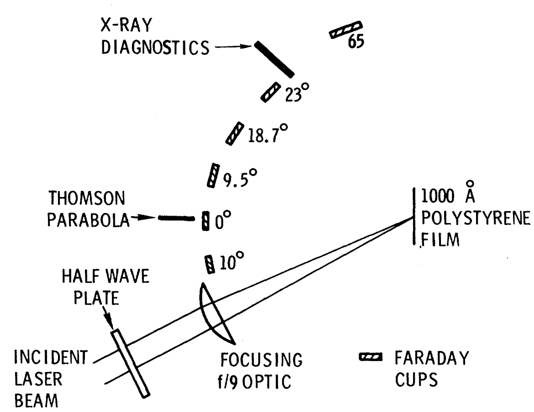
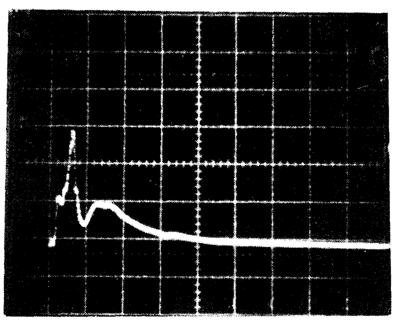



FIG. 1. Experimental configuration for study of polarization dependence.

get. In the power regime employed, the laser output was a reproducible high-quality Gaussian spatial distribution, as diagnosed by pinhole transmission[4] and bismuth-plate irradiation.[5] The incident polarization was changed from $p$ (resonance absorption) to $s$ (no resonance absorption) by rotating a half-wave plate in front of the focusing lens. The incident radiation had a polarization of at least 97%. The results discussed below are based on a series of sixteen data shots at nearly identical irradiation conditions, eight for each polarization.

The plasma expansion characteristics were evaluated to monitor the effects of changing incident polarization. Several Faraday cups of a new design[6] were placed at different angles with respect to the target normal. A Thomson parabola measured the ion-energy and -species distribution. Typical Faraday-cup traces detected by a cup at 18.7° with respect to target normal for different incident laser polarizations are shown in Fig. 2. Figure 2(a) shows the ion current with $p$-polarized incident radiation and Fig. 2(b), that with $s$-polarized radiation. They are both seen to consist of a double-peaked current profile in which the first peak is representative of a fast ion component and the second is characteristic of a thermal component.[7] An energy corresponding to the time of arrival of maximum Faraday-cup current of the fast component can be derived by using the target to diagnostic distance, the time of arrival, and the ion mass (carbon ions). This energy with $p$-polarized incident irradiation is 30 keV and that with $s$-polarized light is 13 keV, showing approximately a factor-of-2 difference. This result is characteristic of all the data shots (sixteen) at this angle of incidence and energy. The second peaks appear not to be significantly affected by changes in incident polarization.

(a)



(b)

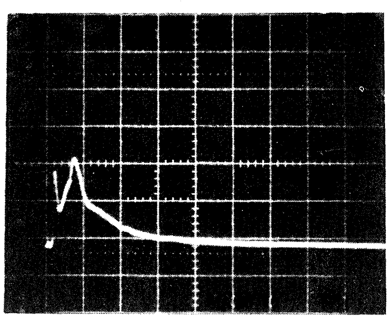


FIG. 2. (a) Upper: Time history of Faraday-cup current for $p$-polarized laser irradiation. (b) Lower: Time history of Faraday-cup current for $s$-polarized laser irradiation.

The ion number can be evaluated from the Faraday-cup trace by deconvoluting the current magnitude with a time-dependent average charge distribution obtained from the Thomson parabola. This information, coupled with the time of flight for a known target to diagnostic distance, gives the time-dependent energy content of the blowoff. The time-dependent ion number and energy can be used to obtain the number of ions per unit energy, i.e., a velocity distribution function. Evaluating the Faraday-cup traces in Fig. 2 and many others resulting from similar irradiation conditions, the total plasma energy observed with the cup is 2.0 times larger for $p$ polarization than with $s$ polarization. The error in the relative measure is approximately 15%.

The Thomson parabola yields a third piece of evidence for polarization dependence. The proton energy distribution is detected to have a sharply defined maximum on each shot which is roughly a factor of 2 larger for $p$ polarization than for $s$ polarization. For example, for the data shown in Fig. 2, the maximum hydrogen energies are 75 and 37 keV for $p$ and $s$ polarizations, respectively. This ratio indicates an enhanced plasma expansion energy with $p$-polarized irradiation.

Another measure of the laser energy absorbed by a target is the size of the hole left in the thin film after irradiation. Although this diagnostic is difficult to relate in detail to microscopic plasma phenomena, it is nevertheless attractive in its directness and simplicity. Figure 3 shows the hole size burned in the target as a function of incident energy and polarization. To burn the same hole size, say 35 mm in diameter, twice as much incident laser energy is required for $s$-polarized radiation as for $p$ polarization.

A summary of all the diagnostic results is shown in Table I. All indications are that the plasma expansion energy is higher by a factor between 2 and 2.5 for $p$-polarized incident radiation, indicating a statistically significant polarization-

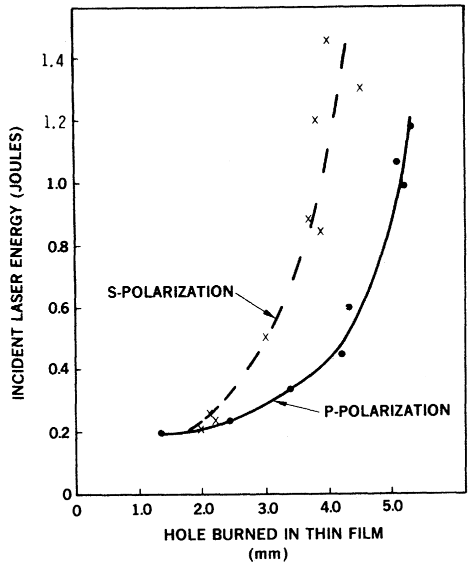



FIG. 3. Diameter of hole burned in thin-film target as a function of incident laser energy for a 50-ps full width at half-maximum laser pulse.

dependent absorption process.

In considering the laser-plasma interaction, the laser-radiation absorption is thought to be due to inverse bremsstrahlung, resonance absorption, and parametric instabilities. In order for the latter to be important, the light must pass quite close to the critical density. However, at 17° the maximum density reached by the light is $n_c \cos^2 17° = 0.91 n_c$; therefore, parametric instabilities are expected to be an unimportant process.

The fractional absorption due to inverse bremsstrahlung ($f_{\rm ib}$) may be calculated by

$$f_{\rm ib} = 1 - \exp[-2kL(\nu/\omega)\cos^5\theta],$$

where $\nu$ is the collision frequency at $n_c$, $\omega$ is the laser frequency, and $k$ is the magnitude of the incident wave vector. For numerical evaluation, the scale length $L$ and temperature $T$ are required. The latter (from x-ray data)[8] is ~200–300 eV. The scale length can be estimated from an isothermal plasma expansion model, which agrees well with the experimental data.[8] With use of this model, the scale length is 2.7 $\mu$m at peak power, giving $f_{\rm ib} = 30\%$. With $s$ polarization, this is the total absorbed power. With $p$ polarization, resonance absorption is added for which the fractional absorption is

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

where $\varphi(\tau)$ is a resonance function[1]; $\tau = (kL)^{1/3} \times \sin\theta$. For $L = 2.7$ $\mu$m, $\tau \cong 0.75$ and $f_{\rm ra} \cong 37\%$; therefore, total absorption is around 67%. Under the present experimental conditions, if there is profile steepening,[2] inverse bremsstrahlung and resonance absorption will both decrease. For example, if $L = 1$ $\mu$m, $f_{\rm ib} \cong 13\%$, $f_{\rm ra} \cong 30\%$, and the total absorption is about 43%. These results are in qualitative agreement with the observed absorption ratio of 2 to 2.5 between $p$ and $s$ polarizations.

TABLE I. Comparison of $p$- and $s$-polarized irradiation of planar targets.

| Diagnostic | Polarization $p$ (keV) | $s$ (keV) | Ratio $p/s$ |
|---|---|---|---|
| Faraday-cup current peak | 30 | 13 | 2.3 |
| Ion energy measured with Faraday cup | 2.0[a] | 1.0 | 2.0 |
| Thomson parabola | 74 | 37 | 2.0 |
| Hole in target | 2.1[a] | 1.0 | 2.1 |

[a]Normalized to value with $s$ polarization.

It is also of interest to compare these results with a calculation by Malone and Morse[9] using a hydrodynamics computer code including a resonance absorption function, $\varphi(\tau)$. With a power of $10^{14}$ W/cm$^2$ and a pulse length of 100 ps, these authors find for $s$ polarization at 17°, $f_{\rm abs} \cong 20\%$, and for $p$ polarization $\simeq 38\%$, again in general agreement with our observations.

In summary, polarization-dependent absorption of laser radiation by dense plasmas has been observed directly for the first time. A twofold enhancement of absorption in the presence of $p$-polarized incident light at 17° angle of incidence suggests the existence of resonant absorption processes. Theoretical estimates of the impact of resonance absorption agree qualitatively with the observed twofold enhancement of plasma absorption.

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# Plasma Heating in a High-Voltage Toroidal $\theta$ Pinch*

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Rapid heating of ions and electrons to keV temperatures in $\lesssim 1$ $\mu$sec has been observed at densities of $1\times10^{14}$ cm$^{-3}$. This is to be compared with experiments in which energy losses along the magnetic field limit the electron temperature. The most striking difference is in the ratio of electron to ion temperature which is now $\lesssim 0.3$ as in comparable open-ended $\theta$ pinches.

One of the major problems in controlled-fusion research is the achievement of sufficiently high ion temperatures. Among the various plasma heating devices, $\theta$ pinches have relatively high efficiencies, especially those driven by fast, high-voltage pulses. However, in such experiments[1-5] electron energy transport along the lines of the solenoidal magnetic field is very fast[6,7] so that average electron temperatures have been relatively low. The question therefore arises whether the various ion heating mechanisms based on microinstabilities[8-10] remain sufficiently strong when the energy is confined, as required for fusion research.

In order to address this question, a high-power[11] ($\lesssim 10^{12}$ W), pulsed ($\approx 1$-$\mu$sec rise time), high-voltage ($\lesssim 600$ kV) toroidal $\theta$ pinch (20-cm minor radius, 50-cm major radius), "Thor," has been constructed (see Fig. 1). The initial experiments described here were performed with ~2 mTorr $D_2$ in an acrylic vacuum vessel. Breakdown and preheating are achieved by discharging capacitors (in parallel) through the toroidal field coils. Further preheating and toroidal current generation are accomplished by capacitor discharges through the primary of an (air core) transformer situated in the center of the machine. These ringing circuits have a period of 17 $\mu$sec. Another slower circuit with a 640-$\mu$sec period, fired first, generates a quasistatic toroidal bias field of 100 G, which is less than the preheating field.

Most of the measurements presented here were taken using $\frac{1}{4}$ of the peak design power, i.e., with a 280-kV charging voltage and a toroidal compression field rising to ~6 kG in 0.9 $\mu$sec. Figure 2(a) shows the corresponding current trace. The current is crowbarred (i.e., the capacitors are shunted) at ~1.2 $\mu$sec from its initiation and then falls with an $L/R$ time constant of ~30 $\mu$sec.

Neutron emission is observed, by using lead-shielded fast-scintillator–photomultiplier combinations, before and near the current peak [see Fig. 2(b)]. The total neutron yield, measured

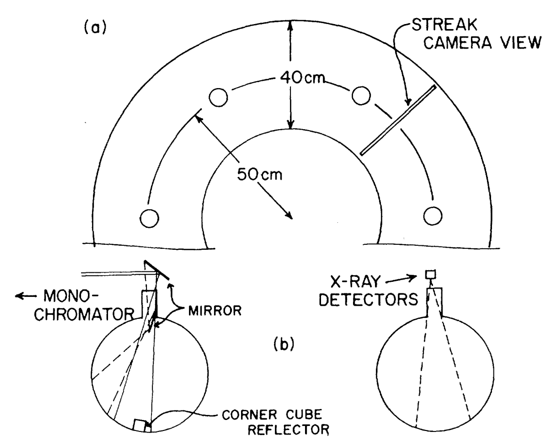
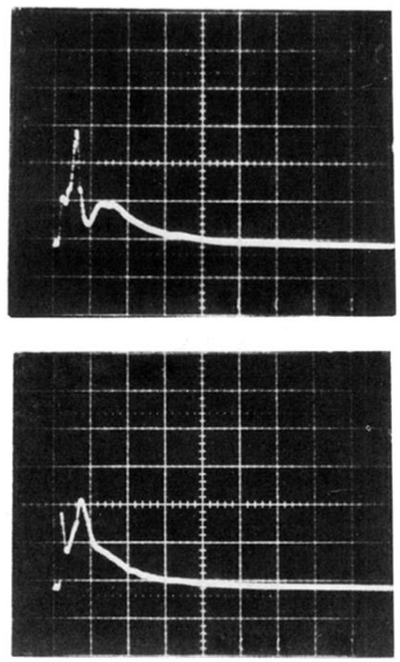



FIG. 1. (a) Top view and (b) cross-sectional side view of toroidal vacuum vessel. Various diagnostics are indicated.

(a)

(b)



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