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Effect of Pulse Duration and Polarization on Momentum and Energy Transfer to Laser-Irradiated Targets

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Polished aluminum targets were irradiated with 1.06-μm laser pulses of 60-psec and 2.5-nsec duration and of π and σ polarization. The peak focused intensity was varied over the range 10^{14}–10^{16} W/cm^2. Clear evidence of resonant absorption for 60-psec pulses was obtained from target momentum measurements made with a torsion pendulum. *No* resonant absorption effects dependent on light polarization or angle of incidence were detected for long-pulse irradiations.

A necessary condition for successful laser-induced fusion is the efficient absorption of laser light in the coronal plasma surrounding the target. Equally important, however, is the coupling of this absorbed energy to the dense target material so that inward directed momentum will be imparted to compress and heat the fusion fuel.

Efficient laser-light absorption is believed to occur through the process of resonant absorption.[1] In experiments conducted with short-duration laser pulses ($\tau \leq 100$ psec), increased laser light absorption[2] and momentum transfer[3] have been observed with conditions optimized for the resonant absorption process. Current and planned laser fusion experiments, however, require much longer laser pulses ($\tau = 1$–10 nsec) and it is important to determine in this regime whether or not resonant absorption exists and if it will improve the efficiency of momentum transfer to the target.

This Letter deals with the experimental determination of the resonant-absorption contribution to the momentum imparted to targets irradiated with short (60 psec) or long (2.5 nsec) laser pulses. The targets, polished aluminum slabs, were irradiated at oblique incidence with high-focused-intensity (10^{14}–10^{16} W/cm^2), π and σ polarized, 1.06-μm wavelength laser light. (The target was always placed within the 10-μm-diam diffraction-limited focal spot of the $f/5$ convergent cone of light.[4]) The primary diagnostic was a torsion pendulum which measured the momentum imparted to the target.[5] Supporting data were provided by charge collectors (Faraday cups).

Figure 1 shows the experimental results. The ratio of momentum to incident energy (P/E) has been plotted as a function of incident intensity. Each point represents an average over 3 shots within an intensity bin extending $\pm 15\%$ from the plotted data point. Absolute calibrations for the momentum and energy measurements are accurate to $\pm 10\%$ and $\pm 5\%$, respectively. The lines are curve fits to the data obtained from equations of the form $P = AE^n$.

The ratio P/E provides a measure of the momentum coupling efficiency to the target. For 60-psec pulses, the coupling efficiency is 35% greater for π than for σ polarization. The coupling efficiencies are independent of focused intensity. For the 2.5-nsec pulses there is no difference between π and σ polarizations and the momentum coupling efficiency decreases with in-

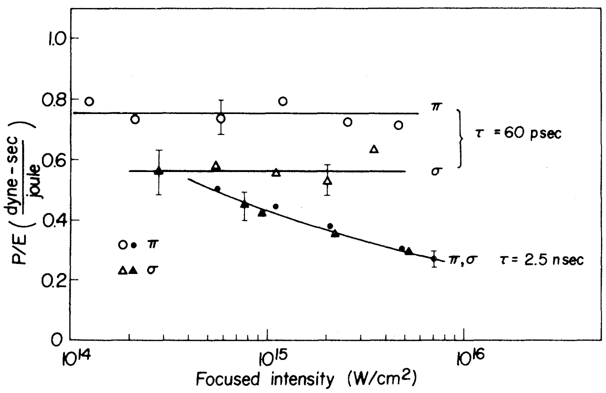

FIG. 1. Ratio of target momentum to the incident energy P/E (specific momentum) plotted as a function of focused intensity for π- and σ-polarized laser light incident at an angle of 17°, and pulse durations of 60 psec and 2.5 nsec.

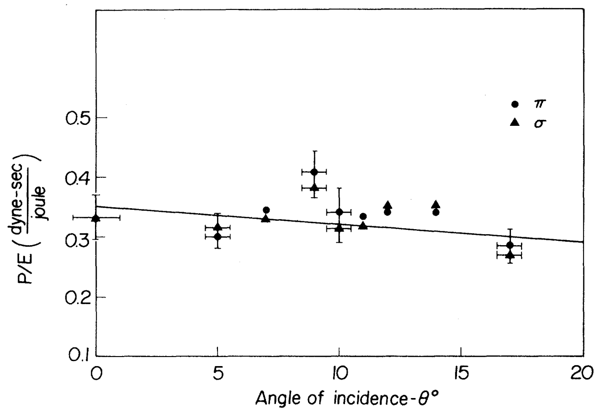

FIG. 2. Plot of specific momentum (P/E) as a function of the angle of incidence for both π- and σ-polarized light at a focused intensity of 8×10^{15} W/cm^2 and for a pulse duration of 2.5 nsec.

creasing intensity ($P/E \sim I^{-0.24}$). Above 3×10^{14} W/cm^2 the long-pulse momentum coupling efficiency is less than for short pulses. We note that the long-pulse scaling is similar to that previously observed with 0.5-nsec pulses over the range 10^{12}–4×10^{13} W/cm^2.[5]

Optimum resonant absorption occurs when $(l/\lambda_0)^{2/3}\sin^2\theta = 0.15$, where λ_0 is the laser light wavelength, l is the density scale length, and θ is the angle of incidence.[1] If l were larger for long pulses than for short pulses then the resonant absorption peak would occur at a smaller angle of incidence. Spatially resolved measurements made with an x-ray pinhole camera, an x-ray spectrometer, and a 2ω telemicroscope all indicated a plasma size of 30 μm. This gives an upper limit for the density scale length, i.e., $l \lesssim 30$ μm, and thus a lower limit to the angle for optimum resonant absorption $\theta \geqslant 7°$. A series of shots (sixty) were made at constant energy with the angle of incidence varied from 0° to 17°. The result is shown in Fig. 2. At no angle is there any difference between π and σ polarizations. The momentum coupling efficiency decreases slowly with increasing angle of incidence. It may be noted that since the incident laser beam had an effective f number of $f/5$, a range of angles was always incident upon the target. This angular spread did not, of course, obscure the short-pulse results. It should not have obliterated a long-pulse π-σ difference for the expected $\theta_{\text{optimum}} \gtrsim 7°$.

Charge-collector data may be used to determine which plasma component contributes to the target momentum. A typical charge-collector trace is shown in Fig. 3. The ion spectrum is divided into separate "fast" and "thermal" ion groups. The fast ions, although they may contain 50% of the observed ion energy, account for less than 10% of the observed ion mass. The momentum of an ion group P is related to the group's mass $\tilde{m}$ and its energy E_i by $P = (2\tilde{m}E_i)^{1/2}$.

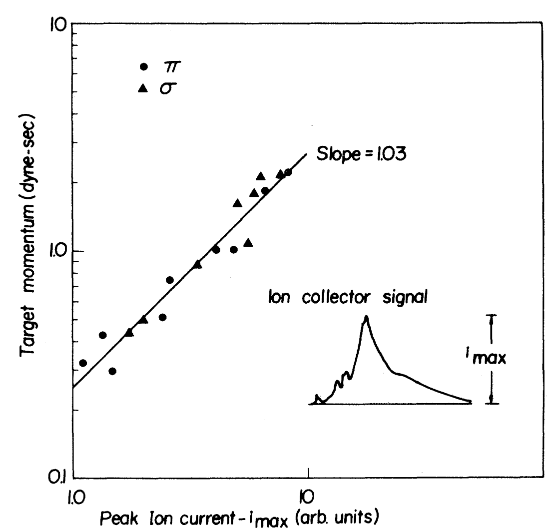

FIG. 3. Plot of the target momentum as a function of the peak ion current ($i_{\max}$) measured in the ion charge collectors for both π and σ polarizations. The pulse duration is 2.5 nsec and the angle of incidence is 17°. In the inset is a sketch of a typical ion-collector signal. The charge collector was located in the plane defined by the optical axis and the target normal, at an angle of 40° to the optical axis.

Thus, the greater part ($\gtrsim 80\%$) of the momentum should be contained in the thermal group.

Another indication of the thermal group's importance is obtained by cross-correlating pendulum and charge-collector results. By relating ion mass and velocity to the *peak* ion current i_{max}, and *its* effective ionization state Z, it can be shown that the ion momentum scales as $P \sim i_{max}/Z$. Since the current peak's velocity scales only weakly with incident laser energy ($\tilde{v} \sim E^{0.14}$ from our measurements), only a small Z variation is expected. In fact, the results of a systematic mass spectrometer study performed by Nicholson *et al.*[6] suggest a 20% variation for the current peak's charge state over our observed range of peak current ion velocities. P should be proportional to i_{max} and, as is shown in Fig. 3, the experimental cross correlation is linear. The charge-collector data, thus, indicate that the momentum is contributed mainly by the "thermal" component of the plasma.

A characteristic of resonant absorption is a larger velocity for the fast ion group.[2] Such a behavior was observed by us in the short-pulse experiments. The ratio of the velocities of the fast to thermal ion groups was found to be about 3 for π-polarized light and 2 for σ polarization with a thermal ion velocity of about 4×10^7 cm/sec at a laser intensity of 10^{15} W/cm^2. In the long-pulse regime, however, the fast-to-thermal ion velocity ratio equals 2 for both π and σ polarizations with the same thermal ion velocity and at the same light intensity. Thus the fast-ion data for long laser pulses also show no evidence of polarization-dependent resonant absorption.

It should be pointed out that since the targets were slabs, material vaporized with energy transported away from the laser-plasma interaction region may have contributed to the observed target momentum ("late effect"). By analyzing the results of experiments carried out with slabs and with thin foils mounted on a double pendulum device,[5] it was concluded that for the aluminum targets used in the experiment, the "late effect" contributed a maximum of 20% to the total momentum. (In plastic targets, half of the total momentum was found to be due to "late effects.")

The disappearance of polarization dependence during long-pulse irradiations might possibly result from (1) spherical expansion of the plasma, (2) long scale lengths, (3) ineffective coupling of suprathermal electrons to the dense target material, and (4) small-scale critical surface rippling or plasma turbulence. Spherical expansion of the plasma would cause the laser light to be normally incident on the plasma, independent of the angle of incidence on the target. Reflectivity measurements made during the experiments,[7] however, indicated a clear dependence of specular reflection on the angle of incidence, thus implying a planar geometry.

A long scale length would enhance absorption and stimulated backscatter in the underdense plasma so that the laser light might not reach the critical surface. 2ω light, emitted from points on the critical surface reached by laser light, was observed during the experiment.[7] From this it may be concluded that light did reach the critical surface. Furthermore, axial and transverse plasma dimensions were measured from spatially resolved 2ω-light and x-ray emissions. An upper limit for the density scale length of only 30 μm was obtained. This is too small to explain the absence of resonant absorption. We measured a 2ω emission region which had transverse dimensions of 12 ± 2 μm. This indicates that refractive broadening in the underdense plasma was not significant.

It is possible that resonant absorption occurred and that energy was deposited in suprathermal electrons, as in the short-pulse case, but they were trapped in the corona by their sheath potential and the lack of a cold-electron return current (because of flux inhibition[8]). The resonantly absorbed energy would not couple to the target but might produce fast ions in the corona. Charge collector data do not, however, show significant fast-ion dependence on polarization. It therefore does not appear that resonant absorption without corona-to-target coupling can explain the results.

Small-scale rippling or turbulence at the critical surface would tend to smear out any angle-of-incidence or polarization dependences. It would therefore be impossible to distinguish between resonant absorption and other absorption mechanisms. It would also mean that there is always some resonant absorption. Small-scale rippling has been observed for short pulses[9] but might have a growth rate slow enough to effect only the absorption of long pulses. Small-scale rippling or turbulence is not inconsistent with the experimental data. Specular reflection and stimulated backscatter would be observed but their angular distributions would be broadened. Such behavior has been observed by us and at other laboratories.[7,8,10]

Finally, the decrease of momentum coupling efficiency with intensity for long laser pulses (see Fig. 1) may be attributed to two effects, an increase in the plasma temperature and a decrease in the fractional absorption. The plasma momentum, P, can be expressed by $P = 2\eta E/\tilde{v}$, where η is the fraction of energy absorbed and $\tilde{v}$ is the characteristic blowoff velocity. For short pulses, our experiments indicate that both P/E and $\tilde{v}$ are constant as a function of laser intensity, thus implying that η is independent of laser intensity. For fixed focusing geometry and light polarization, η has indeed been observed to be independent of intensity for short laser pulses. For long pulses, however, our results show that for an angle of incidence of 17°, $P/E \sim E^{-0.24}$, while $\tilde{v}$ (as measured by the charge collectors) varies as $E^{0.14}$, thus implying that the fractional absorption decreases as $E^{-0.10}$. For normal incidence $P/E \sim E^{-0.14}$ and $\tilde{v} \sim E^{0.17}$ so that $\eta \sim E^{0.03}$. It would therefore appear that the decrease of P/E with laser intensity for long pulses is due mainly to an increase in the plasma temperature (at the expense of increased mass ablated) rather than in a pronounced decrease in the fractional absorption.

In conclusion, the resonant-absorption contribution to the momentum imparted to targets irradiated with high-intensity laser light was measured for laser pulses of 60-psec and 2.5-nsec duration. Resonant-absorption contributions were clearly observed for the short pulses. No polarization-dependent effects were observed for the long pulses. The disappearances of π-σ and angle-of-incidence dependences for long pulses may be the result of small-scale rippling or turbulence at the critical surface. In addition, the momentum coupling efficiency was found to be independent of intensity for short pulses and was found to decrease for long pulses. This behavior appears to be a consequence of corona temperature variations with incident light intensity.

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