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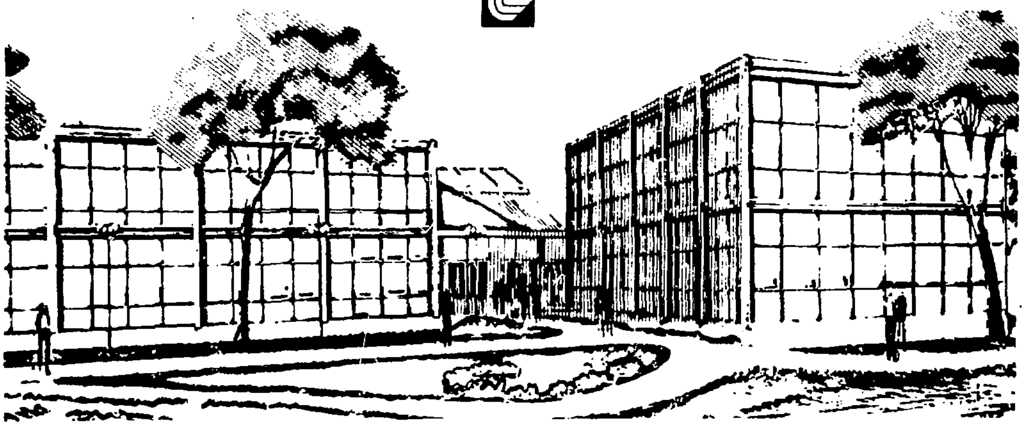

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BRILLOUIN SCATTER IN LASER-PRODUCED PLASMAS[*]

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Abstract

The absorption of intense laser light is found to be reduced when targets are irradiated by 1.06 μm light with long pulse widths (150-400 psec) and large focal spots (100-250 μm). Estimates of Brillouin scatter which account for the finite heat capacity of the underdense plasma predict this reduction. Spectra of the back reflected light show red shifts indicative of Brillouin scattering.

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In laser fusion applications it is important to understand the absorption of laser light with intensity $\gtrsim 10^{15}$ W/cm^2 (1.06μ light). In such experiments,[1-7] it was generally found that Brillouin scatter[8-10] limits at a low level, an effect which has been attributed theoretically[9,10] to the small mass and heat capacity of the small underdense plasma. With the advent of more powerful lasers, it is becoming common to investigate the absorption of intense light in experiments with long pulses and large focal spots. These experiments, characterized by a much larger region of underdense plasma, more closely approximate future experiments with shaped pulses. For example, a simple estimate shows that $L \simeq R$, where R is the radius of the focal spot, provided the pulse length is long enough for plasma to expand that far.

With large regions of underdense plasma, stimulated scattering of the incident laser light becomes a concern. First we briefly present a simple estimate for Brillouin scattering, which takes into account the finite heat capacity of the underdense plasma. Although crude, this model suffices to estimate magnitudes and also to emphasize the strong ion heating concomitant with the scatter. Then we present results of experiments in which discs are irradiated with intense, 1.06μ light using long pulse lengths and large focal spots. The absorption is found to be significantly degraded, as predicted.

At very high intensities such that the light pressure is much greater than the plasma pressure, the induced reflectivity can self-limit by simply pushing the underdense plasma aside.[10] However, in general we must consider the complementary regime in which the light pressure is less than the plasma pressure. For example, this regime is obtained when $I_L \sim 3 \times 10^{15}$ W/cm^2 and the plasma with density $\lesssim 1/3 - 1/2\ n_{cr}$ is rather hot ($\theta_e \sim 3$-5 keV, as indicated by the high energy x-rays). Some simple estimates of the induced reflectivity can then be obtained by postulating that long-term ion heating controls the level of the scatter. In the scattering, a small fraction of the incident light energy is transferred to an ion wave and then damped into the ions. Since the massive ions transport energy slowly, even a small energy deposition drives them to a high temperature; i.e., $\theta_i \sim O(\theta_e)$. This heating, in turn, reduces the reflectivity by making the ion waves heavily damped.

A simple description illustrates the numbers. Assuming that the intensity is well above the threshold set by gradients, we model the underdense plasma as uniform with size L. We consider only backscatter and anticipate that strong ion heating will lead the ion waves to be heavily damped in the final state. Then an analytic solution of the coupled wave equations gives for the induced reflectivity r:[9,11]

$$\frac{B}{r} = \frac{1-r}{\exp\,[x(1-r)]} \quad , \tag{1}$$

where

$$x = 1/4 \left(\frac{n_p}{n_{cr}}\right) k_o L \left(\frac{v_L}{v_e}\right)^2 \Bigg/ \frac{\nu_i}{\omega_i} \left(1 + \frac{3\theta_i}{\theta_e}\right) .$$

Here B is the noise level of the back-scattered wave, $n_p(L)$ is the plasma density (size), v_L is the oscillation velocity of electrons in the incident light wave with free-space wavenumber k_o, and v_e is the electron thermal velocity. $\theta_e(\theta_i)$ is the electron (ion) temperature, and ν_i (ω_i) is the ion wave damping (frequency).

To close this description, we need to estimate the ion temperature. The simplest assumption is that all the ions are heated and that they carry away energy as rapidly as possible; i.e. in a free-streaming limit. We balance this energy flux with that deposited into ion waves, giving

$$r\, I_L \frac{\Delta\omega}{\omega_o} = n_p\, \theta_i\, v_i \quad , \tag{2}$$

where $\frac{\Delta\omega}{\omega_o} = 2k_o v_s/\omega_o$ is the fraction of the reflected light energy given to the ion waves, and v_s is the ion sound velocity.

The solid lines in Fig. 1 show θ_i and r as a function of plasma size from this simple model. In this example $(v_L/v_e)^2 = 0.4$, which corresponds to $I_L = 3 \times 10^{15}$ W/cm^2 and $\theta_e = 3$ keV. Note from Fig. 1a the strong ion heating as anticipated. Even a modest reflectivity deposits sufficient energy into the ions to drive them to a mean temperature comparable to the electron temperature. Fig. 1b provides an estimate for the magnitude of the induced reflectivity. For $L \simeq 10\ \lambda_o$, $r \simeq 10\%$. For $L \simeq 50$-$100\ \lambda_o$, $r \simeq 50\%$. Note that r does not increase very rapidly with L in this model. As r increases, the ion heating increases, which acts to reduce the increase in r.

Improved models for the ion heating give similar results. Simulations[9-10] have shown that in general only a fraction of the ions are heated (via trapping in the ion waves). To model this effect, we balance the energy deposition into ion waves with that carried off by a fraction of the ions (n_h/n_p) heated to an effective temperature $\theta_h \simeq Mv_s^2$, where M is the ion mass. The dashed line in Fig. 1b shows the reflectivity then obtained. Note the magnitudes are similar. Finally we carried out some simulations of this model using a code with particle ions and fluid electrons. These simulations account for the microscopic nature of the heating as well as its spatial dependence. The calculated reflectivities in the heated state are denoted by the crosses in Fig. 1b.

These one-dimensional estimates are probably conservative since several effects are overlooked. First both back and side-scatter occur. Well above threshold, the scattered light is expected to come back in a broad range of angles as the side-scattered light refracts out of the plasma. This side-scatter occurs primarily out of the plane of polarization, which is another signature for Brillouin scatter. Secondly, it takes some time for the ions in the underdense plasma to heat to a steady state. During this time, the reflectivity is larger than that shown in Fig. 1b.

Experiments were carried out at the Argus[12] laser facility with 1.064 μm light focused by f/1 lenses. The pulses were Gaussian with a duration of 150 ps - 400 ps measured between half intensity points and had little sub-structure. The laser beam was only a few times diffraction-limited, and little aberration was visible at the spot sizes used in these experiments. The minimum detectable energy in any pre-pulse is 70 to 73 dB lower than the main pulse energy. No pre-pulse was detected on any shot for which data is presented here, although for a couple of the shots in Fig. 2, no pre-pulse photo was obtained. The spot diameters (100-250 μm) are measured between half-intensity points, which in the near field corresponds to the ray cone having 18° half-angle. Roughly 60% of the laser energy was contained within this half-angle, while 90% of the beam energy was contained within the ray cone of 24.5° half-angle. The targets were Parylene disks (C_8H_8, 22 μm thick, 300 μm diameter), which were oriented normal to the beam.

The light absorption was measured in two independent ways. One technique was to measure the non-absorbed light using a box calorimeter.[13] An innermost glass box, which was thermally isolated from the rest of the calorimeter, just transmitted the scattered light, not x-rays or particles. Calorimeters measured both the incident light and the light collected by the focusing lenses. Even though the box calorimeter was rotated by 15° from perfect alignment with the laser electric field, the two side panels out of the plane of polarization saw almost twice as much energy as the other two side panels. On similar shots with the box calorimeter not in place, an array of photodiodes confirmed this strong polarization dependence, which is expected of Brillouin scattering.

The second technique was to measure the energy in the plasma blowoff and x-rays using an array of plasma calorimeters.[13] These calorimeters were positioned both in and out of the plane of incidence; however no polarization dependence in the ion blowoff was observed. Since no plasma calorimeter could be placed closer than 52.5° to the incident beam direction due to mechanical interference with the focusing lens assembly, the general shape of the plasma blowoff energy distribution must be known. To obtain this information, on one shot the parylene disk was tilted 26° from the normal and the distribution was mapped by a ring of calorimeters in the plane of incidence. Assuming the plasma blow-off to have remained symmetric about the normal, we found the form A+Bcos^5 to fit the data for the blowoff to the front. The angle θ is measured away from the target normal. To obtain the energy in the blowoff to the back, the calorimeter measurements there were averaged and multiplied by 2π solid angle.

Fig. 2 shows the measured absorption efficiency as a function of focal spot diameter. The results are grouped into two intensity regimes - one in the 2-7 $\times 10^{15}$ W/cm^2 intensity range and the other in the 1-5 $\times 10^{16}$ W/cm^2 range. In each case the circles are previous results[4] obtained with the Janus laser using 80 ps pulses of 1.06μ light. The data at the large spot sizes are those obtained with the Argus laser. Note that in each intensity regime, the absorption is degraded by a factor of ≈ 2 in the experiments with larger spots and longer pulses. As expected, in the higher intensity regime this factor of 2 reduction takes place at smaller spot diameters.

In the Argus experiments, a large fraction of the incident light ($\sim$30-50%) is reflected back into the f/1 focusing lens. The frequency spectrum of this light provides additional evidence for the role of stimulated scattering. Fig. 3a shows the spectrum obtained for a 140 μm diameter glass ball irradiated by two opposing beams (north beam: 220 ps FWHM, 220 J and south beam: 150 ps FWHM, 198 J). The light collected by the north focusing lens was imaged onto the 25 μm slit of a 5/4-meter Czerny-Turner type spectrograph. The spectrum was recorded by an optical multichannel analyzer with a resolution of about one angstrom. At least 85% of the back-reflected light was shifted to the red side of the laser line. If the critical density surface moved outward during most of the laser pulse, this result implies almost all this light was Brillouin scattered. As additional support for this conclusion, the light absorption was measured to be only 12 ± 5% by an array of calorimeters measuring the energy in the particle blowoff and x-ray emission.

In general, the doppler shift due to plasma expansion can overcome that due to the ion waves. This is the case with the disk experiments. In Fig. 3b the spectrum for a parylene disk shot (100μ diameter spot, 148 J, 198 ps FWHM) is shown. Note the reflected line is rather broad and extends only partially to the red. The line has a width of $\sim 2\, k_o v_s$ as expected, since the ion waves are heavily damped. In contrast, in a disk experiment in which little Brillouin scatter was expected (28 ps pulse length, ∼ 50μ diameter focal spot), the back-reflected line was more narrow (11 Å wide) and had its center shifted farther (23 Å) to the blue. We therefore regard the broad spectrum in Fig. 3b, which is in part red-shifted, as evidence for Brillouin scatter.

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FIGURE CAPTIONS

Fig. 1 Estimates for a) the mean ion temperature and b) the induced reflectivity versus plasma size. $n_p/n_{cr} = .5$ and $B = 10^{-4}$.

Fig. 2. Absorption fraction f_{ABS} for parylene disk targets. ○ - box calorimeter, Janus laser facility, □ - plasma calorimeters, Argus, △ - box calorimeter, Argus.

Fig. 3. Spectrum of the back-reflected light for a) a glass microshell and b) a parylene disk irradiated by the Argus laser.

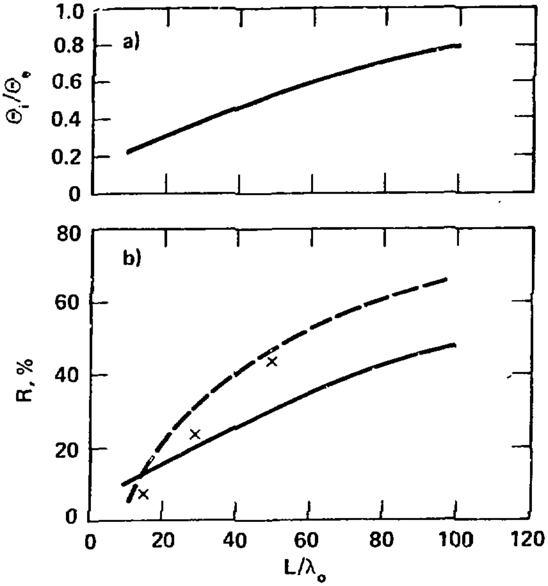

a)
b)
Θ_i/Θ_e
1.0
0.8
0.6
0.4
0.2
0
R, %
80
60
40
20
0
0
20
40
60
80
100
120
L/λ_o

Fig. 1

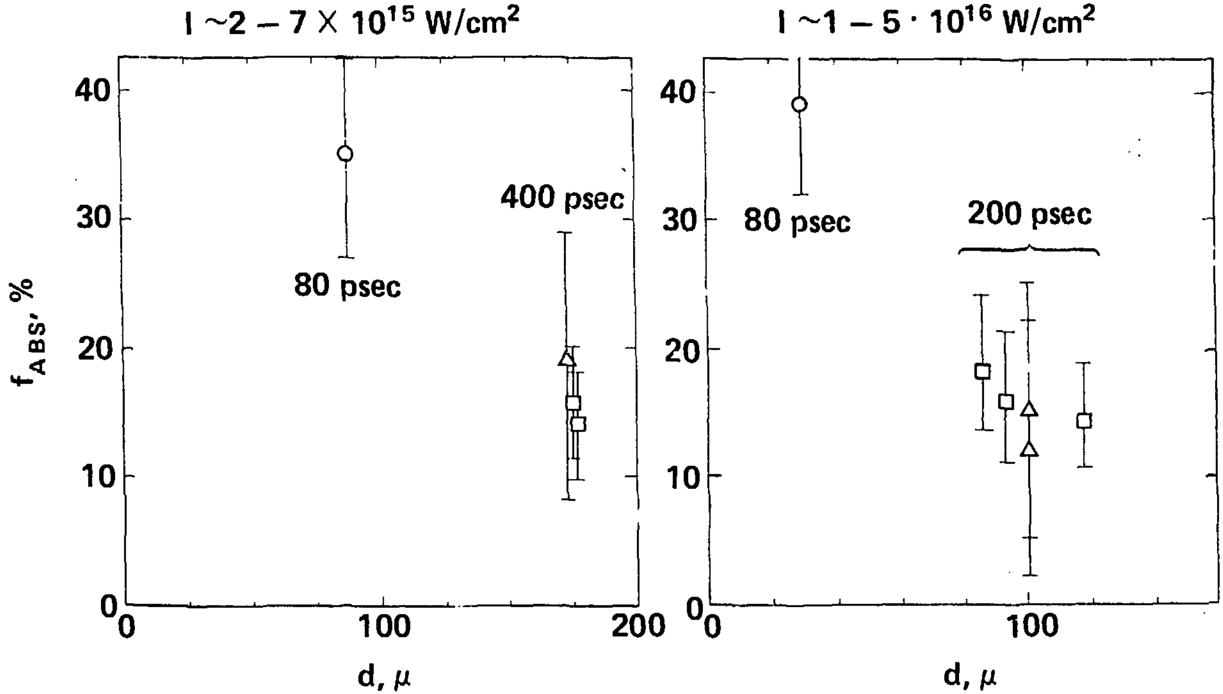
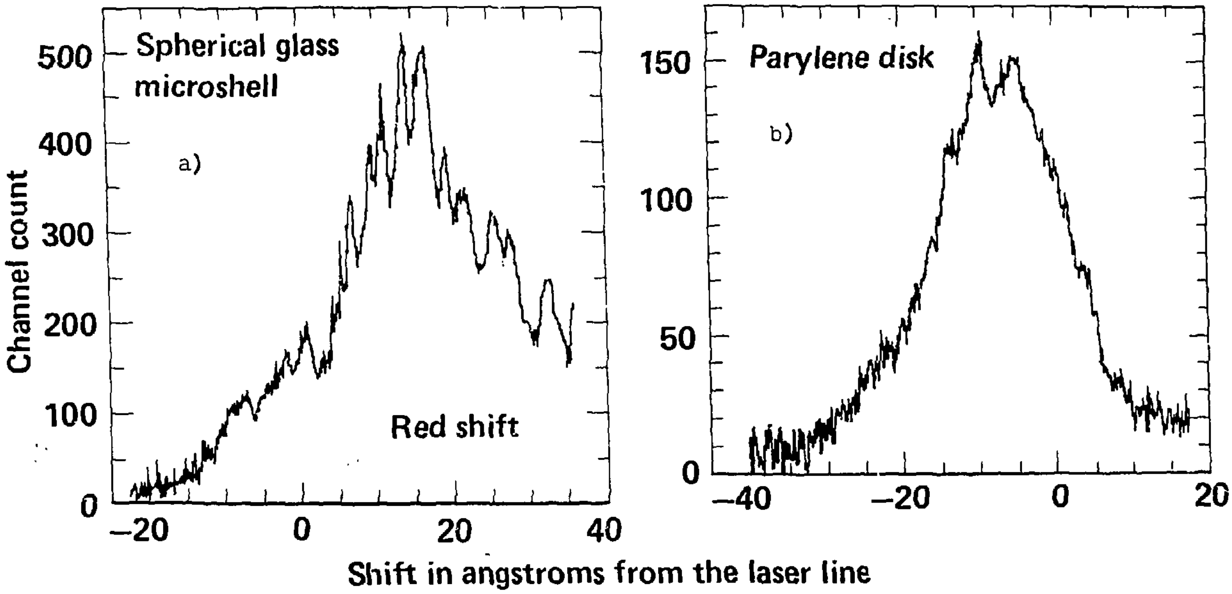

I ~2 – 7 X 10^15 W/cm^2
I ~1 – 5 · 10^16 W/cm^2
f_ABS, %
40
30
20
10
0
80 psec
400 psec
80 psec
200 psec
0
100
200
d, μ
d, μ

Fig. 2



Channel count
0
100
200
300
400
500
Spherical glass microshell
a)
Red shift
−20
0
20
40
0
50
100
150
Parylene disk
b)
−40
−20
0
20
Shift in angstroms from the laser line

Fig. 3