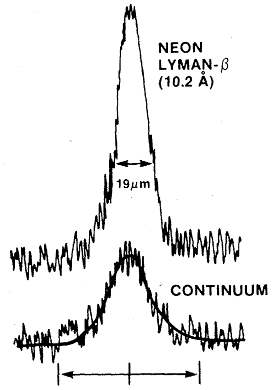

FIG. 5. Spatial profile of the Lyman-β line of neon (10.24 Å), and the nearby continuum. The bar indicates the compressed neon diameter as inferred from spectral profiles analysis.

target. Neon doping in future laser fusion targets may be interesting not only as a diagnostic probe but also as a means of controlling the implosion dynamics.[5] At low enough impurity content the dominant effect would be the inhibition of heat loss from the fuel to the tamper; at higher impurity content the dominant effect would be the cooling of the fuel by radiation losses, thereby enabling a higher compression.

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[(a)]On assignment from Exxon Research and Engineering Company.

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Brillouin Scatter in Laser-Produced Plasmas

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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 ps) 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.

In laser fusion applications it is important to understand the absorption of laser light when the product of intensity and the square of the wavelength exceeds $\sim 10^{15}$ W μm^2/cm^2. In such experiments,[1-7] it was generally found that Brillouin scatter[8-10] is limited 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 the size of the underdense plasma $L \approx R$, where R is the radius of the focal spot, provided that 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 Parylene disks are irradiated with intense, 1.06-μm 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 $I_L \sim 3\times10^{15}$ W/cm^2 and the plasma with density $\lesssim(\frac{1}{3}-\frac{1}{2})n_{\rm cr}$ 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]

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

where

$$x = \frac{1}{4}\left(\frac{n_p}{n_{\rm cr}}\right)k_0 L\left(\frac{v_L}{v_e}\right)^2\left[\frac{\nu_i}{\omega_i}\left(1+\frac{3\theta_i}{\theta_e}\right)\right]^{-1}.$$

Here, B is the noise level of the backscattered wave, relative to the incident intensity; n_p (L) is the plasma density (size); v_L is the oscillation velocity of electrons in the incident light wave with free-space wave number k_0; and v_e is the electron thermal velocity. θ_e (θ_i) is the electron (ion) temperature, and ν_i (ω_i) is the ion wave damping (frequency). ν_i is assumed to be given by ion Landau damping and so is a function of θ_e/θ_i.

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

$$rI_L\Delta\omega/\omega_0 = n_p\theta_i v_i, \tag{2}$$

where $\Delta\omega/\omega_0 = 2k_0 v_s/\omega_0$ 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 $I_L = 3\times10^{15}$ W/cm^2 and $\theta_e = 3$ keV. Note from Fig. 1(a) 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. Figure 1(b) provides an estimate for the magnitude of the induced reflectivity. For $L\simeq 10\lambda_0$, $r\simeq 10\%$. For $L\simeq(50-100)\lambda_0$, $r\simeq 50\%$. 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. 1(b) shows the reflectivity then obtained. Note that the magnitudes are similar. Finally, we

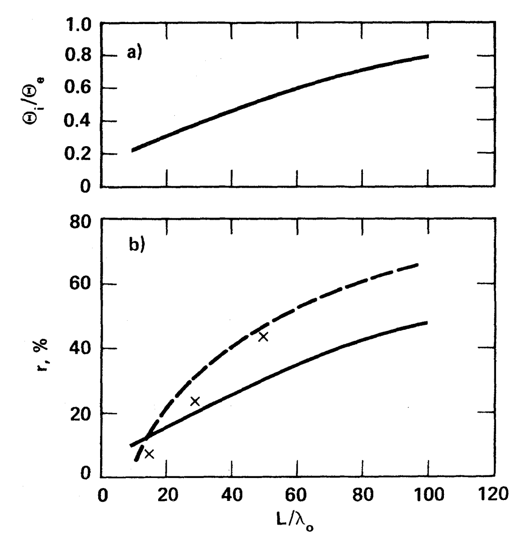

FIG. 1. Estimates for (a) the mean ion temperature and (b) the induced reflectivity vs plasma size. $n_p/n_{\rm cr} = 0.5$ and $B = 10^{-4}$.

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 (with $n_p = \frac{1}{3}$ the critical density) are denoted by the crosses in Fig. 1(b).

These one-dimensional estimates are probably conservative since several effects are overlooked. First both backscatter and side scatter occur. Well above threshold, the scattered light is expected to come back in a broad range of angles as 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. 1(b). Finally we have assumed a rather modest noise level ($B \simeq 10^{-4}$); but the estimated reflection length is only logarithmically sensitive to this value.

Experiments were carried out at the Argus[12] laser facility with 1.06-μm light focused by $f/1$ lenses. The pulses were Gaussian with a duration of 150–400 ps measured between half-intensity points and had little substructure. 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 prepulse is 70–73 dB lower than the main pulse energy. No prepulse was detected on any shot for which data are presented here, although for a couple of the shots in Fig. 2, no prepulse photo was obtained. The spot diameters (100–250 μm) are measured between half-intensity points, which in the near field correspond to the ray cone having 18° half-angle. 90% of the energy is within the ray cone of 24° half-angle, while the average intensity near the axis is correctly given if one assumes a uniform beam of 20° half-angle. The targets were Parylene disks (C_8H_8, 22 μm thick, 300 μm diameter) oriented normal to the beam.

The light absorption was measured in two independent ways. One technique was to measure the nonabsorbed 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.

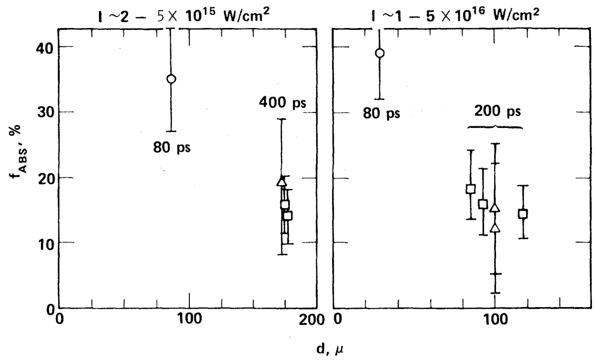

FIG. 2. Absorption fraction f_{ABS} for Parylene disk targets. Circles, box calorimeter, Janus laser facility; squares, plasma calorimeters, Argus; triangles, box calorimeter, Argus. In the Argus experiments the intensities were $(2.5-5)\times 10^{15}$ W/cm^2 (400 ps) and $(1-2)\times 10^{16}$ W/cm^2 (200 ps). In the Janus experiments the intensities were 2×10^{15} W/cm^2 and $(4-5)\times 10^{16}$ W/cm^2.

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 because of 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 blowoff to have remained symmetric about the normal, we found the form $A + B\cos^5\theta$ 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.

In Fig. 2 we compare the measured absorption efficiencies with those observed in previous experiments with shorter pulse lengths and smaller focal spots (and hence smaller regions of underdense plasma). The results are grouped into two intensity regimes—one in the $(2-5)\times10^{15}$-W/cm^2 intensity range and the other in the $(1-5)\times10^{16}$-W/cm^2 range. In each case the circles are previous results[4] obtained with the Janus laser using 80-ps pulses of 1.06-μm 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 longer pulses and larger spots (and hence larger regions of underdense plasmas). The reduction in absorption is not just a function of focusing. The data in Fig. 2 indicate that at a fixed spot size (~90 μm diam), the absorption degrades with increasing pulse length.

In the Argus experiments, a large fraction of the incident light [~(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. Figure 3(a) shows the spectrum obtained for a 140-μm-diam glass ball irradiated by two opposing beams [north beam; 220 ps full width at half-maximum (FWHM), 220 J; south beam, 150 ps FWHM, 198 J]. The light collected by the north focusing lens was imaged onto the 25-μm slit of a $\frac{5}{4}$-m Czerny-Turner–type spectrograph. The spectrum was recorded by an optical multichannel analyzer with a resolution of about 1 Å. 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 plasma calorimeters.

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. 3(b) the spectrum for a Parylene-disk shot (100-μm-diam spot, 148 J, 198 ps FWHM) is shown. Note that the reflected line is rather broad and extends only partially to the red. The line has a width of $\sim 2k_0v_s$ 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, ~50-μm-diam 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. 3(b), which is in part red shifted, as evidence for Brillouin scatter.

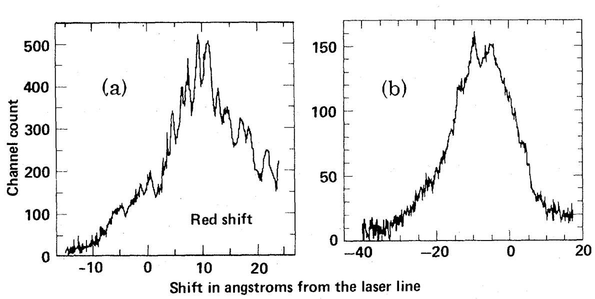

FIG. 3. Spectrum of the back-reflected light for (a) a glass microshell and (b) a Parylene disk irradiated by the Argus laser.

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Interaction of 1.06-μm Laser Radiation with Planar Targets

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Parylene and tungsten-glass disks have been irradiated with a 1.06-μm laser at fluxes of 10^{13}–10^{15} W/cm^2. Analysis of the experimental results indicates that the laser-plasma interaction was characterized by critical surface steepening, rippling and/or filamentation, polarization-dependent scattering, and efficient generation of superthermal electrons. These effects were significantly stronger in the tungsten-glass experiments.

Extensive experimental studies[1] of the interaction of laser radiation with low $\bar{Z}$ ($\lesssim 3.5$) targets, covering a wide range of intensities ($I_l \gtrsim 10^{12}$ W/cm^2) and wavelengths ($\lesssim 10.6$ μm), indicate that the interaction process is generally strongly influenced by collective plasma processes. This Letter presents the results of 1.06-μm laser-irradiation experiments[2] with the Cyclops laser[3] in which $\bar{Z}$ was varied significantly by using disk targets of Parylene (C_8H_8) and W glass (0.75 W_2O, 0.25 P_2O_5). Detailed measurements of the scattered laser light and x-ray and charged-particle emission characteristics show strong evidence that the interaction process was dominated by critical surface steepening, rippling and/or filamentation, polarization-dependent scattering, and efficient generation of superthermal electrons. Furthermore, the strongest noncollisional behavior occurred in the high-$\bar{Z}$ W-glass irradiations. Analysis suggests that the observed behavior of the two target types can be unified by the parameter $\eta = V_o/V_T$, the ratio of the electron oscillatory and thermal velocities.

The planar (650–950 μm diam $\times$ 7 μm thick) disks were located $\sim 10^3$ μm inside the focal waist in the near field of an f/2.5 aspheric lens. The flux level (10^{13}–10^{15} W/cm^2) was varied by changing the laser pulse length (150–400 ps) and energy (5–75 J). Target damage due to amplified spontaneous emission and prepulses was found to be unimportant. An extensive array of diagnostics[1,2] observed laser and plasma behavior during each experiment. The time-integrated laser energy distribution in the target plane was measured during each experiment with an equivalent-lens-multiple-image camera system. The focused laser beam, 250–300 μm FWHM (full width at half-maximum) in diameter, exhibited a ring structure, rising (50–100)% above the central minimum. Small-scale fluctuations, 30–40 μm in diameter and (30–50)% in relative I_l, were superimposed on these gross features.

Figure 1 shows the measured absorption η_a vs I_l. Both target types absorbed comparable fractions. For the ~200-ps experiments, η_a for W glass (Parylene) varied from ~38% (~30%) at 5×10^{13} W/cm^2 to ~30% (~25%) at 5×10^{14} W/cm^2. The discrepancy between the photodiode and box calorimeter measurements should be taken as indicative of the accuracy of the energy balance

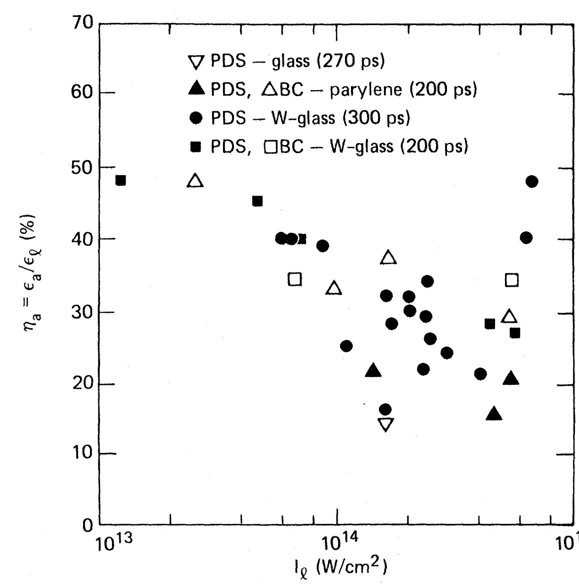

FIG. 1. Fractional laser-light absorption measurements: photodiodes (PDS) and "box" calorimeter (BC).