# Measurements of Short-Pulse Backscatter from a Gas Target

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Measurements are reported of short-pulse (100 psec), 1.06-$\mu$m laser backscatter from a high-pressure nitrogen gas target. Spectral measurements clearly show the expected Brillouin red shift. The backscatter fraction saturated at ~40% at $2\times10^{15}$ W/cm$^2$ and what appears to be multiple Brillouin scattering in a long-gradient-length plasma is observed.

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The Brillouin backscatter mechanism[1-3] has been recognized as a possibly severe problem for some laser fusion schemes, as it could strongly reduce laser-energy deposition in fusion targets. Recent laser-target interaction experiments[4,5] have produced strong evidence that stimulated Brillouin backscatter is playing a role in longer-gradient-length plasma experiments. Laser-plasma interaction experiments using $CO_2$ lasers and gas targets[6,7] have produced clear evidence of Brillouin backscatter since a direct measure of the ion acoustic frequency shift was obtained. We were motivated by these experiments to examine the backscatter from a gas target using the Nd:glass laser which, operating with a short pulse, could perhaps minimize plasma motion effects, e.g., Doppler shift in short-pulse solid-target experiments, and ionization-wave effects in long-pulse $CO_2$-laser gas-target experiments. We were interested in (1) obtaining a clear signature of Brillouin backscatter in spectral measurements, (2) observing saturation of the backscattered energy with laser power, and (3) observing any systematic spectral changes with increasing laser power.

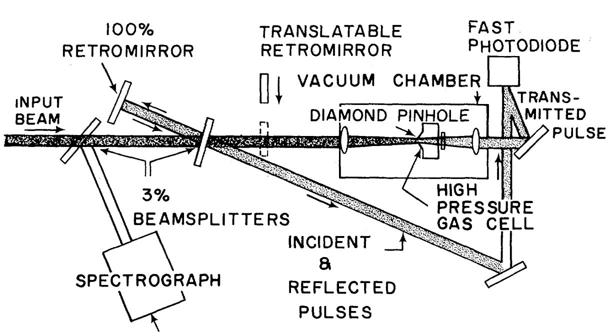


FIG. 1. Experimental configuration of the gas-target reflection and spectral measurements.

In this Letter, we report clear observations of stimulated Brillouin backscatter of a short (100 psec) pulse from a long-gradient-length (~50 $\mu$m) gas-target plasma. The backscatter fraction saturates at about 40% and we have observed what may be multiple Brillouin scattering at our highest laser powers.

Our experimental setup, shown in Fig. 1, is quite simple. We have made use of a puffed nitrogen-gas jet as the laser target. High-pressure nitrogen (about 10 atm) is allowed to leak through a 100-$\mu$m-diam pinhole producing supersonic nozzle flow into a vacuum chamber. The gas density falls off approximately as $\rho\sim\rho_0(r_a/r)^2$ in this free expansion.[8] Here $r_a$ is the pinhole radius, $\rho_0$ was high enough to produce a critical-density surface if the nitrogen was partially ionized. The laser beam was directed on axis, up the density gradient, and the focal position could be shifted axially. The electron density at the lens focus was not measured, and is only crudely estimated at about $10^{21}$ cm$^{-3}$. The experiments were performed at a focal position which maximized backscatter.

The Nd:glass laser had an approximately square pulse shape of 100 psec duration, maximum energy of 700 mJ, and a beam diameter of 40 mm. The laser energy was focused onto the gas jet with an $f/3.5$ lens. We made measurements of prepulses (less than $10^{-6}$ of the main pulse) and measured both the incident- and reflected-beam energy with the same fast calibrated photodiode. A retromirror provided reflection calibration of the photodiode. Spectral measurements of the backscattered light were made with a Czerny-Turner grating spectrograph having 1.2-Å resolution. Far-field focal-spot measurements showed that 90% of the energy was contained with-in a 20 $\mu$m diameter which gave a peak focused intensity of $2\times10^{15}$ W/cm$^2$.

Figures 2(a)–2(d) show the backscattered spectra obtained as the incident pulse energy is increased from 50 to 700 mJ, corresponding to peak focused intensities from $1.6\times10^{14}$ W/cm$^2$ to $2.2\times10^{15}$ W/cm$^2$. The backscattered energy in Fig. 2(a) is seen to be red shifted by about 4.5 Å with no energy at the incident frequency $\omega_0$. This shift is typical of all the backscattered spectra even at higher incident powers. The red shift clearly indicates the Brillouin backscatter mechanism, and is in qualitative agreement with the measurements of Offenberger.[6,7] For an inhomogeneous infinite plasma, the intensity threshold condition to be satisfied[9] for Brillouin backscatter is given by

$$(V_{os}/V_{th}) > (n_c/n)(8/k_0L_t), \tag{1}$$

where $L_t$ is the temperature-gradient length, $V_{os}$ is the electron oscillatory velocity in the electric field of the wave, $V_{th}$ is the electron thermal velocity, $n/n_c$ is the electron density relative to critical density, and $k_0$ is the vacuum wave number. For typical values of $n_c/n \approx 5$ and $L_t \approx 50$ $\mu$m, this threshold occurs at $(V_{os}/V_{th})^2 \approx 0.1$. This value is exceeded for all our intensities at the electron temperatures (~100 eV) estimated below from the spectral shift of the backscattered line, so that Brillouin backscatter should develop in these experiments.

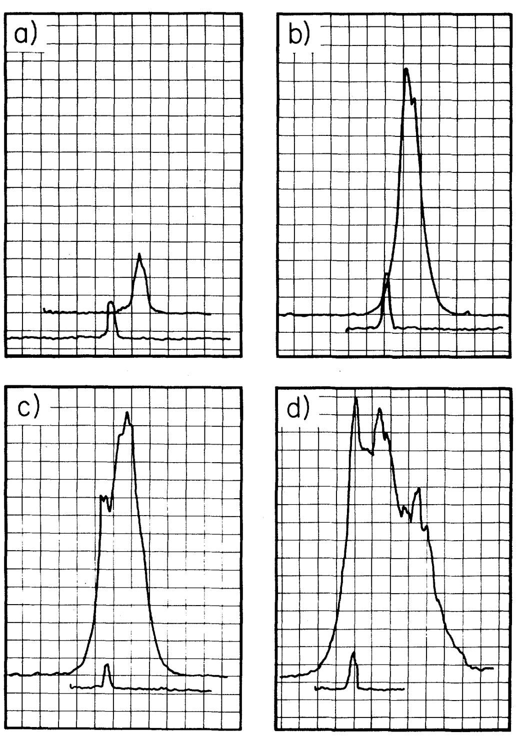


FIG. 2. (a)–(d) Microdensitometer traces of back-reflected spectra. Wavelength increases to the right. Note the location and the spectral width of the incident 1.06-$\mu$m-laser energy (the lower traces). The incident power increases from $2\times10^{14}$ W/cm$^2$ in (a) to $2\times10^{15}$ W/cm$^2$ in (d).

In Fig. 3, we present the backscattered energy fraction versus incident pulse energy (or power, since the pulse length is constant). The backscatter fraction increases with incident laser power and appears to saturate at about 40%. These results agree well with those of Ng *et al.*[7] We wish to indicate that a few anomalous shots gave backscattered fractions up to 60% as shown in Fig. 3. Because Brillouin backscatter (also sidescatter) could fall in angles outside our collection aperture (up to $f/2$), misalignment of the gas jet and optical axis may be responsible for the saturation levels being below the anomalous points. The saturation value of ~40% is also in agreement with the measurements of Ripin *et al.*[4] but, of course, this result depends on $L_t$.

From the measured shift of the backscattered line, we can roughly estimate $T_e$ and $T_i$ from the relationship between the frequency shift and the ion acoustic speed given by[2]

$$\frac{\omega_s}{\omega_0} = 2\left[\left(1-\frac{n}{n_c}\right)\frac{\bar{Z}T_e+3T_i}{m_ic^2(1+k^2\lambda_D{}^2)}\right]^{1/2}, \tag{2}$$

where $\bar{Z}$ is the ionization state, $T_e$ and $T_i$ are the

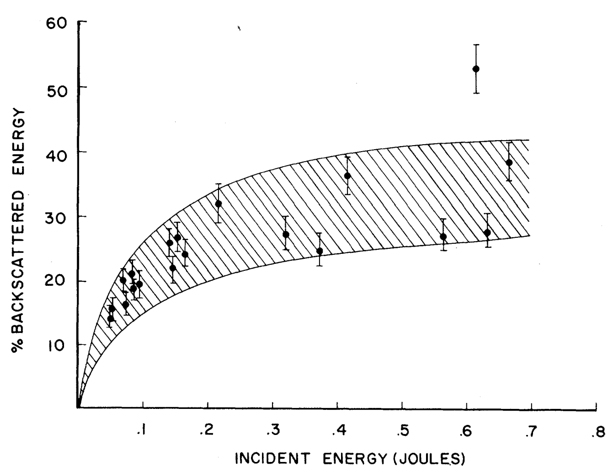


FIG. 3. The total back-reflected energy (Brillouin shifted plus unshifted) as a function of incident laser energy in joules.

electron and ion temperatures, $m_i$ is the ion mass, $c$ is the speed of light, and $k\lambda_D \ll 1$. Following Offenberger, we measure the width of the backscattered line, and assuming the line broadening is entirely due to ion Landau damping, we can determine the ratio of $\bar{Z}T_e/T_i$ from the measured ratio of the width to the line shift. Simulations confirm that the full width at half maximum (FWHM) is approximately equal to $\omega_i$, the ion Landau-damping frequency $\delta$ at constant density. We have assumed no other broadening mechanisms are operative, such as time-dependent temperatures, and collisions. Nonuniform density can also cause broadening [see Eq. (2)]. Figure 4 shows the measured line shifts and widths as a function of laser energy (or power). There is considerable data scatter; however, at the lower powers we have approximately, $\Delta\omega_{\mathrm{FWHM}}/\omega_s = \frac{1}{3}$ which corresponds to $\bar{Z}T_e = 1.3T_i$. Using this result in Eq. (2) along with the assumption that $n/n_c = 0.2$, we find $\bar{Z}T_e = 1.3T_i = 250$ eV. Simple ionization-rate estimates show that the plasma cannot be fully ionized ($\bar{Z} = 7$), but rather for our 100 psec pulse length, we estimate $\bar{Z} \approx 2$ at these low temperatures. Therefore, we have $T_e \approx 125$ eV and $T_i \approx 190$ eV. Notice that, as the laser power is increased, the shift of the backscattered line does not increase as might be expected. Apparently, as the power is increased backscatter, sidescatter, and critical-surface reflection increase so as to keep the energy absorbed nearly constant.

Figures 2(b) and 2(c) are typical spectra [the backscattered spectra was not time resolved as we would expect quite poor temporal resolution (~30 psec) given our high spectral resolution (~1 Å)] obtained as the laser power is increased. Some energy is being reflected at $\omega_0$, presumably from the critical-density surface which is not moving appreciably during the pulse or the line would be Doppler shifted. Also, the Brillouin red shift is not greater at higher power than at lower power, indicating that apparently the ion acoustic sound speed is not substantially increased as might be expected. We observe a further broadening of the backscattered feature at higher powers (see Fig. 4) indicating a decrease in $\bar{Z}T_e/T_i$. Qualitatively, the backscattered line is always skewed to the long-wavelength side. In some shots, Fig. 2(d), we observed a nearly periodic modulated structure on the long-wavelength side.[10] A qualitatively similar result has been observed in particle simulations studies of the stimulated Brillouin process[11] and has not been previously observed experimentally. In these simulations ($1\frac{1}{2}$ dimensional) the plasma was uniform at $n/n_c = 0.5$, 40 wavelengths deep, with a vacuum left boundary and a perfect conductor or perfect absorber at the right boundary. Other simulation parameters were $m_i/m_e = 100$, $V_{os}/V_{th} = 0.9$, and $\bar{Z}T_e/T_i = 30$. The kinetic simulation follows the electromagnetic wave (transverse $E_y$ and $B_z$) on the time and space scale of the laser light as well as the electrostatic electric field $E_x$. The current and charge density from the particles self-consistently feed back to the fields, $E_y$, $B_z$, and $E_x$. Figure 5 shows the Fourier spectrum of the incident- and reflected-light electric field for the case of a perfectly conducting boundary (solid lines) and perfectly absorbing boundary (dotted lines). The Brillouin reflection in both cases was about 60%. The cascade of lines, on the red side of $\omega_0$, are separated by the ion acoustic frequency. The light can also scatter off critical (solid lines) with no shift in this simple model. The significance of multiple scattering is as follows: (1) For each scattering the light has another chance to be absorbed by inverse bremsstrahlung; (2) each scattering off the critical surface gives the light another chance to be absorbed there; (3) each scattering heats the ions; and (4) each scattering increases the bandwidth, which acts to reduce Brillouin scattering.[12] We have not attempted to make a quantitative fit between the experimental spectra and those from simulations, but the observed periodic pattern on the red side of $\omega_0$, is in qualitative agreement

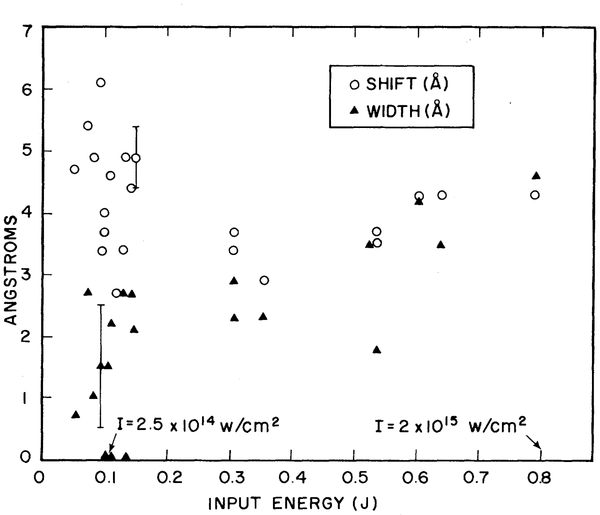


FIG. 4. The measured Brillouin shift and linewidth (FWHM) as a function of incident laser energy.

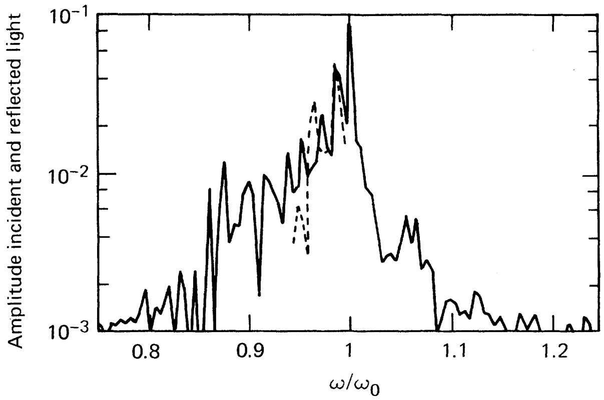


FIG. 5. Amplitude of incident and reflected spectrum (in frequency space) from the particle simulation code.

with the simulation results.

It is quite interesting that energy is reflected from the critical surface at the higher intensities because inverse bremsstrahlung, in our low-temperature plasma, ought to be nearly 100% efficient in absorbing the energy which is not Brillouin backscattered. We believe this reflected energy at $\omega_0$ is not stray light because in some shots at similar laser power but much reduced gas pressure (where there was insufficient gas density to produce a critical surface) we found no energy at $\omega_0$. Also, experiments with no puffed gas showed no reflection. From our measured backscatter shifts, we estimate $(V_{os}/V_{th})^2 \approx 2$ at higher powers. The appearance of the reflected light at $\omega_0$ is probably due to a combination of high-field inverse bremsstrahlung[13] and the ponderomotive force producing some profile steepening.[14] Either process can lower the overall absorption of the laser energy not Brillouin backscattered to a level sufficient to explain our observations.

In conclusion, we have observed the clear signature of the Brillouin backscatter in a nearly stationary, long-gradient-length plasma. We have found the backscatter to saturate at about 40%. At intensities of $10^{15}$ W/cm$^2$, we have observed reflection from the critical surface as well as the Brillouin-shifted backscatter; both may be the result of profile steepening at the critical surface. Finally, we observe increased ion heating and multiple Brillouin scattering at our highest intensities.

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