Multiangle, Time-Resolved Spectroscopy of Laser-Light Scattering in Underdense, Inhomogeneous Laser Plasmas

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Multiangle, time-resolved, spectroscopic measurements of laser-light scattering from preformed, large, very underdense laser plasmas with finite inhomogeneous flow are reported. Absolutely calibrated spectra of the scattered light were recorded simultaneously at several angles. The variations in the scattering in time and angle indicate that ion-acoustic turbulence, rather than stimulated Brillouin scattering, is dominant in determining the scattering amplitudes.

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Laser light may be scattered from optical media by a number of mechanisms [1]. It may be reflected by surfaces and it may be scattered either by stimulated processes or from thermal or enhanced turbulent fluctuations in the medium. Filamentation of the laser light may alter the magnitude and direction of stimulated scattering in nonlinear media. In general, such scattering mechanisms place limits on the practical applications of various media. We are concerned here with scattering from plasmas, and specifically with scattering having small ($<1\%$) frequency shifts. Such scattering, when at levels well above those produced by thermal fluctuations, has generally been attributed either to reflections from the critical density n_c or to stimulated Brillouin scattering (SBS) [2], in which the laser resonantly excites scattered electromagnetic and ion-acoustic modes. By obtaining time- and wavelength-resolved data at several angles, under conditions that were designed to facilitate very clean studies of SBS, we are able to discriminate among the anticipated effects of acoustic turbulence, convectively amplified SBS, absolutely unstable SBS, and convective SBS modified by filamentation. We find evidence that acoustic turbulence is dominant in determining the scattering levels.

This topic is of some practical importance. SBS, in particular, could in principle degrade the implosion efficiency of laser-fusion targets or decrease the gain of some x-ray laser systems by nonlinearly heating the ions. Acoustic turbulence, if present, will increase laser-light absorption, reduce heat transport, and may impact the possibility of diagnosing temperatures by Thomson scattering.

Relatively little past work has been reported on acoustic turbulence in laser plasmas. In particular, while Thomson-scattering measurements at wave numbers much larger than those driven by the interacting lasers have successfully observed thermal ion waves (sometimes with anomalous enhancements [3,4]), no study of the structure of the acoustic turbulence at wave numbers near that of the laser has been reported to our knowledge. One implication of the present work is that such studies may well be crucial to an accurate comprehension of laser plasmas.

There have been many past studies of SBS, as reviewed by Kruer [5] and by Baldis, Campbell, and Kruer [6]. These have included experiments using non-laser-produced plasmas, plasmas produced by ionization of gas jets, ionization of foams or thin foils, or by ablation of solid matter. In most previous experiments using inhomogeneous plasmas, the observed spectrum and amplitude of SBS may have been affected by reflection [7] of laser light from the critical density (n_c), enhanced ion-wave noise produced at $n_c/4$ as a consequence of two-plasmon decay [8,9], or ion-wave noise resulting from turbulence driven by heat transport [10,11]. Other experiments were in strongly driven regimes [12–15] in which the growth rate of the instability in a homogeneous plasma γ_0 is much larger than the ion-acoustic frequency ω_{IA}, or in strongly perturbed regimes in which the electron oscillatory velocity $\mathbf{v}_{\mathrm{os}} = (e\mathbf{E}_0/m\omega_0)$ is much greater than the electron thermal velocity $v_{\mathrm{th}} = (T_e/m)^{1/2}$. Here e, m, and T_e are the electron charge, mass, and temperature (in energy units), and $\mathbf{E}_0$ and ω_0 are the laser electric field and frequency, respectively. These complications permit at best a tenuous comparison to the basic theory of SBS.

In contrast, the experiments discussed here were designed to unambiguously produce weakly driven SBS ($\gamma_0/\omega_{\mathrm{IA}} \sim 0.1$) in a weakly perturbed ($v_{\mathrm{os}}/v_{\mathrm{th}} \sim 0.05$), very underdense ($<n_c/4$) plasma having finite and inhomogeneous plasma flow, but without strong temperature gradients to drive heat transport. Had SBS been the dominant scattering mechanism, we should have obtained data that could be clearly compared to the theory, including spectral amplitude, angular variations, laser-intensity scaling, and time-dependent effects.

In these experiments we symmetrically illuminated thin (0.5 ± 0.025 μm thick), circular (1.65 ± 0.1 mm diameter) titanium foils, mounted on 1000^{+000}_{-200} Å Formvar supports, using eight laser beams of the NOVA laser facility [16] to preform the plasma, as is shown schematically in Fig. 1. Titanium was chosen to minimize the ion Landau damping by maintaining ZT_e/T_i large, where Z is the average ion charge state, and T_i is the ion temperature. These "preformed" beams, of wavelength 351 nm,

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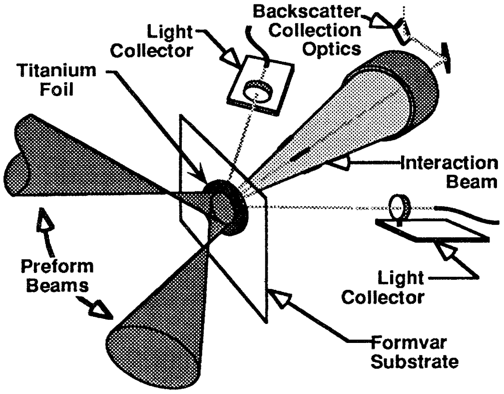

FIG. 1. Schematic of experiment. Only two of the eight preformed beams (four on each side of the foil) and two of the six collectors are shown.

were incident upon the foil at 50° from the target normal and were defocused (through $f/4.3$ optics) to produce a roughly uniform spot, 850 μm diameter full width at half maximum (FWHM), at the target plane. The total energy in the preformed beams was nominally 22 kJ, with energy balance between both sides of the foil within 5%. The laser pulse had a 2 ns FWHM, flat-topped shape, with 100 ps rise and fall times.

Approximately 200 ps prior to the end of the preformed beams, a 527 nm, 2 ns FWHM pump beam was focused at the center of the underdense plasma to a 175 ± 30 μm diameter spot containing 80% of the energy (based on measurements of other NOVA beams). For the data discussed here, the energy of the pump beam was 0.16 ± 0.05 kJ and the pump beam ramped up in intensity from 4×10^{13} W/cm^2 after the initial 100 ps onset to 4×10^{14} W/cm^2 at the end of the pulse. Other data, obtained with higher intensities or thicker targets, will be discussed elsewhere. The plasma parameters were inferred from simulations using the LASNEX [17] computer code, whose results were consistent with experimental observations. LASNEX predicted that at the start of the pump beam, the peak density was $0.05n_c$, $T_e = 3$ keV, the flow gradient was 7.7×10^8 s^{-1}, $Z = 20.5$, and the FWHM of the density profile was 1.2 mm. The details of the experiment, including results of simulations and comparison to measurements that characterize the evolution of the plasma, are reported separately [18,19].

We measured the scattered light at wavelengths near 527 nm using a diagnostic system consisting of seven optical light collectors, fiber optics, a 0.5 m Czerny-Turner spectrometer, and an optical streak camera [20,21]. Six of the collectors were each adjacent to a filtered, absolutely calibrated photodiode for calibration. The fibers, of varying lengths, are offset at the spectrometer to displace the signals in time and space, so a single streak camera can record all the data. Typical resolutions were 100 ps and 4 Å, and spectral peaks could be located to 1 Å.

Figure 2 shows the time-resolved spectra at four angles simultaneously from the experiment described above. Figure 2(a) shows contours of the scattered spectral intensity at four rearward angles. Figure 2(b) shows the evolution of the calibrated, absolute spectral intensity measured at the wavelength of maximum observed emission, and some theory results discussed below. However, the absolute intensities shown for direct backscatter (180°) are lower limits obtained by taking the reflectivity of the laser optics to be 1%, consistent with both the optical design and measurements during a dedicated calibration shot. [Attempts to directly measure the scattered energy with the calorimeter occasionally led to much larger inferred optics and plasma reflectivities, and it is likely that this resulted from the small fractional (~ 0.01) area of the backscattered beam over which the sample was collected.] Figure 2(c) compares the measured spectra with the Doppler width expected from the distributed plasma flow within the region of the beam waist. The observed spectra are typically twice this width, suggesting that the scattering is originating from locations somewhat beyond this region. Other, similar experiments produced similar spectra and ampli-

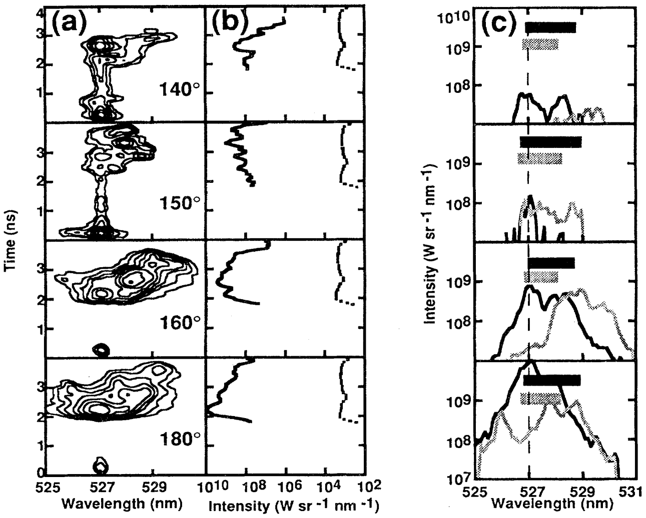

FIG. 2. Backscattered light at 140°, 150°, 160°, and 180° with respect to direct forward of the pump beam: (a) Spectral-intensity contours of time-resolved spectra, spaced by factors of 2, with the peak contour at each angle at 90% of the maximum; (b) measured and expected evolution of maximum spectral intensity. The measured intensities (solid lines) are averaged over approximately 3 Å around the peak and have an approximate temporal resolution of 100 ps. Signals from preformed beam reflections (before 1.8 ns) are not shown. The predicted intensities are shown as broken lines. The preformed pulses last from 0 to 2 ns, and the pump pulse lasts from 1.8 to 3.8 ns. (c) Measured spectra (averaged over ~ 120 ps) and beam-waist spectral widths at 2.25 ns (dark curves and bars, respectively) and 3.0 ns (light curves and bars, respectively). The broken vertical line represents the laser wavelength. The spectral widths show the range of frequencies implied by the range of Doppler shifts corresponding to the ends of the approximately 1 mm long beam waist.

tudes. The time dependences were also similar except that an initial brief burst of emission was often observed before a gradual increase in intensity such as that seen in Fig. 2.

By examination of these data, one can discriminate among possible scattering mechanisms. The additional curves in Fig. 2(b) show the predicted level of scattering by SBS, assumed to result from the convective amplification of thermal noise and calculated by established methods [2,20,22–24]. For this particular case, the predicted SBS does not significantly amplify the Thomson scattering from thermal acoustic noise. During the pump beam pulse, the thermal noise decreases by about twice as much as the SBS amplification increases. At all angles, the observed signals are many orders of magnitude larger than those anticipated from SBS.

The data also do not support the possibility that the observed signals are produced by absolutely unstable SBS. Absolutely unstable SBS should grow to a saturation level more quickly than the near-backscatter signals do, and should produce no signals at the near-sidescatter angles. In addition, it is not clear by what mechanism SBS could become absolutely unstable at the experimental intensities, which are far below the damping threshold for absolute instability in this very underdense plasma.

In contrast, much of the observed behavior is plausibly produced by Thomson scattering from acoustic turbulence. Beginning immediately at 1.8 ns, the signals at all four angles are about 5 orders of magnitude stronger than the Thomson scattering anticipated from thermal ion-acoustic waves. (The signals at 140° and 150° are filtered weakly enough that one can see the weak reflection from the target stalk during the preformed beams—no green light from the preformed beams reaches the target.) One may estimate the level of ion-acoustic turbulence, established by the preformed beams or other mechanisms, required to produce these signals by Thomson scattering [25]. Assuming these signals of about 10^8 W sr^{-1} nm^{-1} to be Thomson scattering, the inferred amplitude of the spectral density function is $\sim 10^{-8}$ sr^{-1} s^{-1}. Alternatively, if the signal scattered into 10^{-3} sr were produced by scattering from a single mode over a distance of 100 μm, then the mode amplitude ($\delta n/n$) would have been $\sim 10^{-4}$. Although well above thermal levels, these amplitudes correspond to relatively weak turbulent fluctuations.

Later in time, as the pump-laser intensity increases by an order of magnitude, the signals at 150° do not increase more than the laser intensity, and those at the other angles actually decrease significantly. This is consistent with the interpretation that the spectral density of acoustic fluctuations, throughout most of the region of phase space responsible for such scattering, decreases slowly with time after the preformed beams end. Such fluctuations could in principle be driven by the preformed beams, either by beating among them or by oblique forward SBS. However, while this hypothesis might explain the often seen, brief burst of emission mentioned above, it is unlikely to explain the longer-term emission discussed here, because the damping rate of such fluctuations is of order 10^{11} s^{-1}.

The signals at 160° and 180° increase by about 2 orders of magnitude over the first few hundred ps of the pump beam. This is slower than one would infer from the homogeneous SBS growth rate ($\sim 3 \times 10^{11}$ s^{-1}) or from the asymptotic time for convective amplification ($\sim$50 ps). However, the time scales and magnitudes are consistent with SBS enhanced by filamentation, which would require more time to develop than SBS would. If, for example, filamentation were to amplify 10% of the laser beam to 8 times the average intensity (at 2.5 ns), then the local gain would be 1000 and the total signal would increase to 100 times above the level of scattering from the initial enhanced noise level, which is indicated by the scattering in all directions. This is consistent with analytical predictions [26] and modeling of filamentation [27] and also with the observation of much stronger amplification for near backscatter than for near sidescatter [28].

It is useful to compare these data with those of Ref. [10], in which a preformed plasma was irradiated by a 10 ps, 1 μm laser pulse, which excludes any potential for filamentation [29]. In contrast to the present case, the pulse duration was much shorter than the asymptotic time for convective amplification. The (inferred) spectral intensity of the backscattering at low laser intensity was comparable to the initial level of scattering observed here at all angles, suggesting that the level of ion acoustic turbulence in the two preformed plasmas was comparable and was very far above thermal levels. The data in both cases suggest that SBS may play a role in amplifying the scattered light above this initial level.

Further work in light of these data could include the use of Thomson scattering to probe for the distribution of ion-acoustic turbulence produced by the preformed beams and variations of the target and laser-beam properties to vary the onset time of filamentation. Theoretical work might be aimed at identifying mechanisms that might drive such turbulence, one possibility being the damping of long-lived microshocks produced during plasma formation [30]. The present data show that the level of acoustic turbulence may be far above thermal levels and provide some useful constraints on possible future theories of acoustic turbulence.

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