Enhanced Ion Fluctuations Generated in a CO_2-Laser–Heated Plasma

Y. S. Al-Shiraida, A. A. Offenberger, and W. Rozmus
Department of Electrical Engineering, University of Alberta, Edmonton, Alberta T6G 2G7, Canada

and

A. Ng
Department of Physics, University of British Columbia, Vancouver, British Columbia V6T 1W5, Canada
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Ion turbulence generated in a CO_2-laser–heated plasma has been studied by means of ruby-laser Thomson scattering. The first general measurement of the ion fluctuation spectrum, $S(k)$, induced in the plane of the laser electric field has been made and is reported here. High-speed streak measurements of Thomson-scattered light indicate very short-duration ($\lesssim 3$ ns) and very fast-rise-time (~ 10 ps) features in the enhanced ion fluctuations.

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It has been shown theoretically and experimentally that the presence of short-wavelength ion-acoustic fluctuations can result in enhanced laser-light absorption by plasmas.[1-7] Ion-acoustic turbulence may also play an important role in explaining the inhibited thermal transport observed in laser-produced plasmas.[8-10] The source and magnitude of the ion turbulence which may be generated in laser-produced plasmas, however, is not generally well understood. Manheimer and coworkers[3,9,11] have suggested that the turbulence may be produced by heat-flow–driven ion-acoustic instabilities. Faehl and Kruer[2] have postulated that ion-ion streaming instabilities could create a high level of fluctuations.

While ion fluctuation levels associated with Brillouin scattering have been directly measured,[12,13] no general measurement of the fluctuation spectrum $S(k) \propto |\delta n|^2$ has been made for plasmas produced by high-intensity lasers and, in particular, for k parallel to the direction of the incident electric field which is of importance for enhanced absorption. Moreover, there is only limited theoretical knowledge of the ion fluctuation spectra which may be generated by instabilities other than the current-driven ion-wave instability.

In this Letter we report experimental measurement of the $S(k)$ spectrum along with high-speed streak-camera measurements of the ion turbulence generated in a CO_2-laser–heated plasma using ruby-laser Thomson scattering. This study was motivated by earlier work which indicated anomalous absorption occurring in a high intensity CO_2-laser–plasma interaction experiment.[5-7]

Details of the experimental arrangement have been given in an earlier publication.[7] A schematic diagram of the scattering geometry along with the plasma electron-density profile is shown in Fig. 1. A supersonic, laminar, oxygen gas target is ionized to an average $Z = 6$ when irradiated with focused, 50-ns-long CO_2 laser pulses of intensities $\leqslant 5\times10^{12}$ W/cm^2 (laser power and

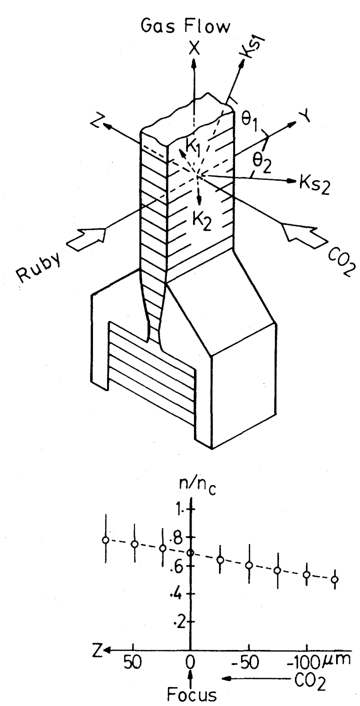

FIG. 1. Ruby-laser Thomson-scattering geometry for probing ion fluctuations induced by the high-intensity CO_2 laser. The electron density as a function of z measured at the center of the focal spot is also shown. K_{S1}, K_{S2}: wave vectors of the scattered light. K_1, K_2: wave vectors of the probed ion fluctuations. 1 and 2 stand for xy and yz planes, respectively.

energy are reproducible to ± 15%). The incident unpolarized, multi-transverse-mode laser beam is focused to a 100-μm-diam spot (limited by focusing aberrations) with a focal depth of 1 mm length (determined by measuring the intensity distribution). The average density, determined interferometrically, was $n_e = 0.7n_c$, where $n_c = 10^{19}$ cm^{-3} is the critical density, and the electron temperature, determined from x-ray measurements, was $T_e = 100 \pm 20$ eV.

With these conditions many laser-induced phenomena are expected to take place. Indeed, among the processes that have been detected previously are stimulated Brillouin and Compton scattering, filamentation, two-plasmon decay, and harmonic generation. In addition, the parameter v_0/v_{th} which characterizes the strength of the laser-plasma interaction can be as large as 2 [where $v_0 = eE_0/m\omega_0$ is the oscillating velocity of an electron in a pump wave field of amplitude E_0 and frequency ω_0 and $v_{th} = (T_e/m)^{1/2}$ is the electron thermal velocity]. This is high enough to induce parametric instabilities off resonance[14,15] for which the threshold pump strength varies in the range $0.05 \leq v_0/v_{th} \leq 2$ over the density range $0.5 \leq n_e/n_c \leq 0.9$.[16] Thus measurement of the spectral form factor, $S(k)$, of the ion fluctuations is essential if we wish to determine possible mechanisms for generating these fluctuations.

Ruby-laser Thomson scattering was used as the chief diagnostic technique for investigating ion turbulence generated by the focused CO_2-laser radiation. A Q-spoiled 8-MW ruby-laser probe beam was incident parallel to the plane of the target (xy plane) and perpendicular to the direction of the focused CO_2-laser beam. The scattered light was collected with two lenses, one fixed at 90° (for normalizing and monitoring purposes) and the other set at various angles $\theta = 10°$–$90°$ with respect to the incident ruby-laser beam in the xy plane, i.e., probing ion fluctuations in the plane of the electric field of the incident CO_2-laser radiation. Since unpolarized CO_2-laser light was employed, the fluctuation spectrum was assumed to be cylindrically symmetric in the xy plane. The wave vector $\vec{k}$ of the ion fluctuation is related to the incident and scattered wave numbers $\vec{k}_0$ and $\vec{k}_s$ through a simple relation, $\vec{k} = \vec{k}_s - \vec{k}_0$, $|\vec{k}| = 2k_0 \sin\frac{1}{2}\theta$. Thus we can scan fluctuations of wave numbers in the range 1.6×10^4 $cm^{-1} \leq k \leq 1.3 \times 10^5$ cm^{-1} or $0.045 \leq k\lambda_D \leq 0.36$ in the present experiment (assuming $n = 0.7n_c$), where λ_D is the Debye length. The scattered light was detected with two photomultipliers for time-integrated $S(k)$ measurements and a high-speed Hamamatsu streak camera for time-resolved behavior.

For $S(k)$ measurements, the scattered power $P_s = In_e\sigma_e V\Delta\Omega TS(k)$—where I is the focused ruby-laser intensity, σ_e is the Thomson scattering cross section, V is the scattering volume, $\Delta\Omega$ is the solid angle, and T is the optical transmission —was calibrated by comparison of the Thomson-scattered signal with that due to emission from a blackbody source. Because of the high stray-light levels detection of Rayleigh scattering was not possible; therefore, the parameters I, n_e, V, $\Delta\Omega$, and T were carefully determined. The intensity I was determined by measuring the ruby-laser power, energy, and spatial distribution with a pinhole and long-focal-length lens, the density n_e was measured with a Fresnel's bimirror interferometer illuminated by ruby-laser light, and the scattering volume was determined from the intersecting dimensions of the focused ruby laser, the CO_2 laser, and the collecting optics. The overall error in $S(k)$ due to the uncertainties in these parameters was estimated to be 25%.

The principal experimental result is the determination of the $S(k)$ spectrum. In Fig. 2, the time-integrated $S(k)$, as measured by a photomultiplier, is plotted as a function of $k\lambda_D$ with n_e taken to be the average density $= 0.7n_c$. As will be seen later there is considerable modulation in the structure of the scattered light; consequently, peak fluctuation levels can be higher than the average values shown. In the region $k\lambda_D < 0.2$, $S(k)$ is strongly dependent on k (almost exponentially); however, for larger $k\lambda_D$ it varies more slowly. Over the experimental range of $k\lambda_D$, the time-integrated turbulence level varies from as little as 2 to $\simeq 10^4$ times the thermal-fluctuation level. We should point out that, in general, this level is at least an order of magnitude below the previously reported value.[6,7] This is probably due to a number of changes in the operating conditions of the CO_2-laser–plasma interaction experiment, including focused laser conditions (a new focusing mirror with larger aberrations was used), ambient electron density, and electron temperature. It is apparent that no cutoff in the small-$k\lambda_D$ region such as that predicted for current-driven instability and seen by Slusher *et al.*[17] is found, at least for $0.045 \leq k\lambda_D \leq 0.36$.

We were unable to measure $S(k)$ in the xy plane for $\theta > 90°$ because of geometrical limitations that resulted in overlapping of focusing and collecting optics. However, no enhanced scattering

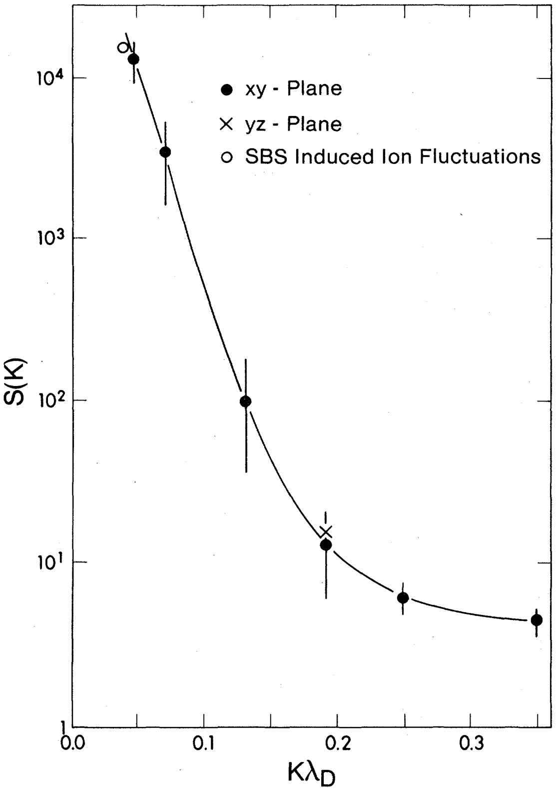

FIG. 2. Ion turbulence spectrum $S(k)$ as a function of $k\lambda_D$ assuming an average density $n_e = 0.7 n_c$ and temperature $T_e = 100$ eV. The error bars indicate the standard deviations for thirty shots at average focused CO_2-laser intensity of 5×10^{12} W/cm^2. The uncertainty in $k\lambda_D$ due to the uncertainty in the electron density is $\sim 20\%$.

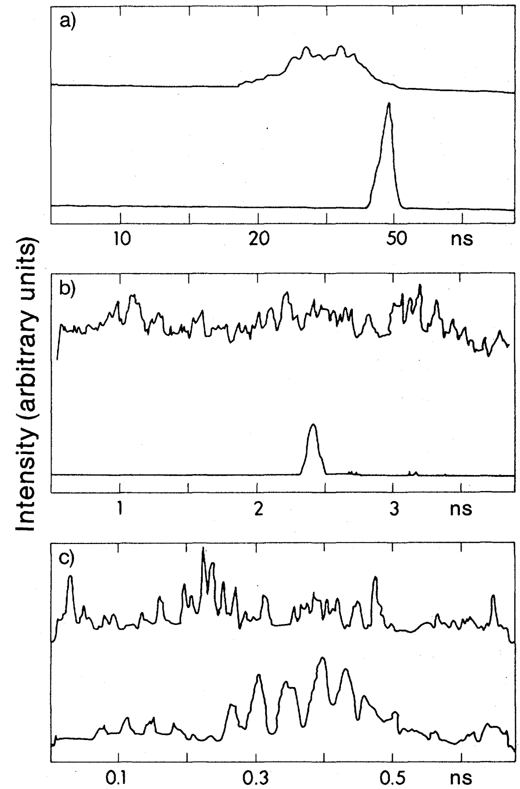

FIG. 3. Temporal behavior of the Thomson-scattered light (bottom) and the incident ruby-laser light (top) —monitored to establish real variations in scattered light—showing different features: (a) long-lived fluctuations (~ 3 ns) for $\theta = 16°$, (b) short-lived fluctuations (~ 250 ps) with no structure for $\theta = 30°$, and (c) structure ~ 0.7 ns long with fine structure for $\theta = 30°$. Highly modulated structure was observed in $\simeq 50\%$ of the shots and cannot be accounted for by the ruby fine structure.

over that expected from thermal fluctuations was seen for $\theta = 120°$ ($k\lambda_D \simeq 0.44$) in the yz plane. Furthermore, no change in the turbulence level was observed as we changed the direction of observation from the xy plane to yz plane for various angles. This suggests an approximately isotropic spectrum. Moreover, we probed $S(k)$ of the ion fluctuations induced by stimulated Brillouin backscattering (SBS) and the result, shown as a circle in Fig. 2, fits well on the curve. It is significant that, although the SBS-induced ion fluctuations (along the z axis) and the ion turbulence in the xy plane may be generated by different instability mechanisms, they are of comparable levels.

In order to follow the rapid temporal variations of the enhanced ion fluctuations a streak camera was employed to record the Thomson-scattered ruby-laser light. The temporal measurements are summarized in Fig. 3 for three different streak speeds. In general, the duration of the turbulence varied from approximately 3 ns [Fig. 3(a)] to as short as 250 ps [Fig. 3(b)]. The structure of the ion turbulence was observed to vary from shot to shot. Typically, it consists of fine structure of 50-ps duration and rise time of 10 ps [Fig. 3(c)] which is the instrumental resolution. Similar structure was seen in the scattered light of the ion fluctuations driven by SBS. In addition, changing the scattering direction from the xy plane to the yz plane showed no systematic change in the temporal behavior of the scattered light. Indeed, the observed changes were merely statistical.

The nanosecond duration of enhanced fluctuations is significantly shorter than the previously reported value, $T \lesssim 10$ ns, detected with a photomultiplier of $\simeq 2$-ns resolution.[6,7] Unfortunately, because of the change in focused laser intensity and the corresponding changes in laser-plasma interaction conditions, including the absence of a critical density layer, we cannot reproduce the old measurements with our present setup. On the other hand, we have obtained and present here a self-consistent set of experimental results for the existing laser-plasma interaction conditions.

In order to check one of the possible sources for generating ion turbulence in laser-produced plasmas we have numerically solved the general dispersion equation for ion waves in the presence of an electromagnetic pump wave.[14,15] These calculations show that the parametric decay instability off resonance can be excited in the density range $0.5 < n_e/n_c \lesssim 0.8$ with a threshold in the range $0.1 \leq v_0/v_{\rm th} \leq 1.1$. Likewise, the oscillating two-stream instability off resonance can be excited for $0.7 \leq n_e/n_c < 1.0$ with a threshold $0.2 < v_0/v_{\rm th} \leq 0.95$. With $v_0/v_{\rm th} = 2$ and $n = 0.7n_c$, for example, the growth rate of these instabilities can be as high as 10^{12} sec^{-1}, depending on the wave number k which covers the range $0.26 < k\lambda_{\rm D} < 0.45$. As the density increases the growth rate will increase and the $k\lambda_{\rm D}$ for maximum growth rate will be shifted towards lower values. Thus the qualitative trends of this theory and the quantitative values of γ may explain the range of observed rise times of the ion turbulence when the density values accessible and the variation in $v_0/v_{\rm th}$ (due to temporal modulation in CO_2 laser power) are taken into account. Therefore, it is more likely that our observations may be related to strong pump-induced ion-wave instabilities.[15,16] The current-driven ion instability, on the other hand, is less likely to be the source for the observed ion fluctuations for two reasons: (a) The $S(k)$ spectrum of Fig. 2 is not a Kadomtsev[18]-type spectrum nor is it similar to any of the modified spectra that the current-driven instability suggests[19]; (b) no hot electrons were observed in the present experiment which could provide a return-current source for a current-driven instability.

In conclusion, we have measured the $S(k)$ spectrum and the temporal behavior of the ion fluctuations generated in the plane of the electric field of a focused, high-intensity CO_2-laser beam interacting with underdense plasma. The observed spectrum does not correspond to the predictions of a current-driven ion-acoustic instability. On the other hand, parametric decay instability and oscillating two-stream instability off resonance, induced by the strong high-frequency field of the focused CO_2 laser, could be the principal source for directly driving the observed ion fluctuations.

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