Measurement of short-wavelength ion turbulence in a CO_2-laser-heated plasma

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Strong ion turbulence generated in a CO_2-laser-heated gas-target plasma has been studied using ruby-laser Thomson scattering. Spectral and temporal features along with fluctuation levels which have been determined appear to account for the anomalous absorption previously observed.

Ion turbulence is of considerable importance to heating and energy transport for both high current magnetically confined plasma and high-intensity laser-plasma interaction. Large nonthermal density fluctuation levels have been experimentally inferred or measured for high current linear Z pinches,[1] high-voltage θ pinches,[2] toroidal devices,[3] and laser produced plasma.[4] Such fluctuations may arise from a current driven ion-wave instability when the electron drift speed exceeds the ion sound speed, from heat flux driven ion turbulence or from laser-induced parametric instabilities. In one of the earliest experiments, Daughney *et al.*[1] were able to show that the measured ion fluctuation levels could account for the required anomalous heating of a collisionless shock in a linear Z pinch. More recently, in a very careful and elegant study, Gray and Kilkenny[5] investigated the possible role of ion turbulence in reducing thermal conductivity in a Z-pinch plasma heated by moderate-intensity CO_2 laser radiation.

We have been studying a variety of phenomena induced by high-intensity CO_2-laser irradiation of gas targets with particular emphasis on parametric instabilities and accompanying density fluctuations. It was observed in target transmission experiments that anomalous collisions arising from enhanced short-wavelength ion fluctuations ($k\lambda_D \sim 0.5$, where k is the wave number of fluctuation; λ_D is the Debye length) could account for the variance between classical absorption expected and that measured.[4] The required fluctuation level $\sum_{k_i}(\delta n_{k_i}/n_c)^2 \simeq 0.03-0.06$.

We now report measurements of the ion fluctuation level for $k\lambda_D \sim 0.5$ using ruby-laser Thomson scattering which confirm three important details of the turbulence: (a) spectrally resolved measurements show the enhanced ion feature, (b) temporally resolved measurements show enhanced fluctuations for $t \sim 10$ nsec consistent with the period of strong absorption, and (c) measurements of the scattering form factor $S(k) = \int S(\vec{k},\omega)\,d\omega$, where $S(\vec{k},\omega) = \langle \delta n_e^2(\vec{k},\omega) \rangle$, for $\vec{k}$ both in and out of the nominal plane of the electric field of the focused CO_2-laser beam show the same enhancement.

The scattering geometry is shown schematically in Fig. 1. The nominal CO_2 laser (frequency ω_L) and plasma parameters are[4] focused intensity of the unpolarized CO_2-laser radiation $\leq 10^{13}$ W/cm^2, supersonic laminar oxygen gas target ionized to average $Z = 6$, approximately linear electron density profile $n_e \leq n_c$ (where $n_c = m_e\omega_L/4\pi e^2$) of scale length $L \sim 100$ μm (for early time), electron temperature $T_e \simeq 160$ eV. The Q-spoiled 8-MW ruby-laser probe beam (frequency ω_0, wave number k_0) is incident parallel to the plane of the gas target and perpendicular to the

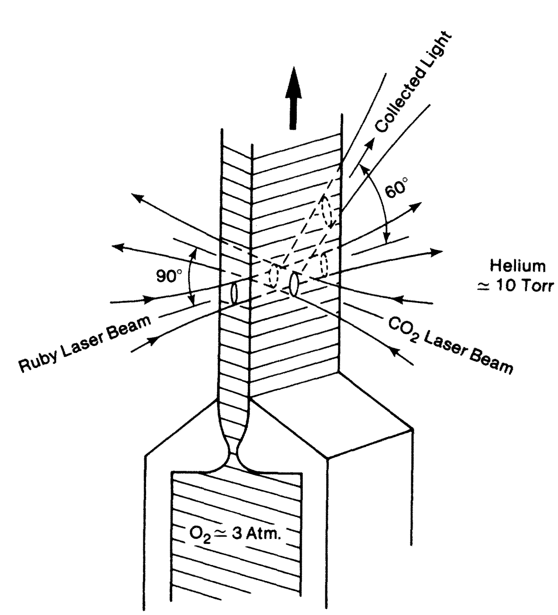

FIG. 1. Ruby-laser Thomson-scattering geometry for probing ion fluctuations induced by the high-intensity CO_2 laser. Scattering was measured both in and out of the plane of the target.

direction of the focused CO_2-laser beam.

Scattered light was detected at an angle $\theta = 60°$, with respect to the incident ruby-laser direction either in the plane of the target (case I) or in a plane defined by the ruby- and CO_2-laser propagation directions (case II). This determined the wave number $\vec{k}$ of the ion fluctuation in terms of the scattered and incident ruby-laser wave numbers, $\vec{k} = \vec{k}_s - \vec{k}_0$, $|k| = 2k_0 \sin\frac{1}{2}\theta = 9.05 \times 10^4\ \mathrm{cm}^{-1}$ for $\theta = 60°$. The scattered light collected with $f/5$ optics was detected simultaneously with a photomultiplier for temporal behavior (resolution 2 nsec) and an optical multichannel analyzer-monochromator system for (time integrated) spectral measurements (resolution 0.4 Å).

The range of $k\lambda_D$ defined by the scattering geometry and density appropriate to enhanced collisionality, $\frac{1}{4} n_c \leq n \leq n_c$, varies from $0.54 \geq k\lambda_D \geq 0.27$. We shall refer briefly to scattering at $\theta = 90°$ in the target plane as well, for which $0.76 \geq k\lambda_D \geq 0.38$. Since the scattering volume observed ($100 \times 100 \times 150\ \mu\mathrm{m}^3$) includes a wide variation in density, necessarily the signal will be an average over (the restricted range of) $k\lambda_D$.

Real-time temporal characteristics of the enhanced scattering in relation to the incident CO_2 laser and strong stimulated Brillouin backscattering (SBS) are shown in Fig. 2. This behavior is important in identifying (a) that the ion turbulence follows rather than occurs simultaneously with strong parametric interaction such as SBS, and (b) that the duration of enhanced ion fluctuations (~ 10 nsec) is consistent with the observed period of anomalous absorption. The first observation clearly shows that while subsequent mode-coupling or other plasma transport mechanisms may be responsible for ion turbulence, the fluctuations driven up during prompt Brillouin backscatter are not directly responsible. Other parametric processes such as two-plasmon decay and second harmonic generation are likewise coincident with SBS.

The magnitude of the signal is many orders of magnitude greater than scattering from thermal fluctuations could provide. A simple calculation shows that refraction of the ruby-laser beam by electron density gradients cannot account for the enhanced scattering since the deflection angle is small compared to the scattering angles used. The deflection angle, given by $\Delta\alpha = \int (1/n) \vec{\nabla} n \cdot d\vec{s}$, where the refractive index $n \simeq 1 - 2\pi n_e e^2 / m_e \omega_0^2$, is $\sim 10^{-3}$ rad for our plasma conditions.

Spectral measurements of the scattered ruby light are summarized in Fig. 3 for $\theta = 60°$ scattering either in or out of the target plane (cases I and II). Since these spectra correspond to time-integrated scattering, precise structure is lacking because of frequency-smearing effects associated with time-varying plasma conditions. Nevertheless, considerable information can be obtained from these representative spectra. The lower two spectra (case I) show a symmetric behavior with respect to λ_0, i.e., no discernable Doppler shift due to a superimposed plasma drift. This is perhaps to be expected for ion waves $(\vec{k}, \omega)$ propagating perpendicular to the CO_2-laser direction. On the other hand, the upper spectrum (case II) shows a distinct red shift for the case of $\vec{k}$ lying in the plane containing the incident CO_2-laser beam. The magnitude and direction of this shift $\Delta\lambda/\lambda_0 = -\Delta\omega/\omega_0 = -(\vec{k} \cdot \vec{u})/\omega_0$ implies a motion $\vec{u}$ in the direction of propagation of the incident CO_2-laser beam of magnitude $u = 5 \times 10^6$ cm/sec. This may suggest a heat-flux driven source of ion turbulence.

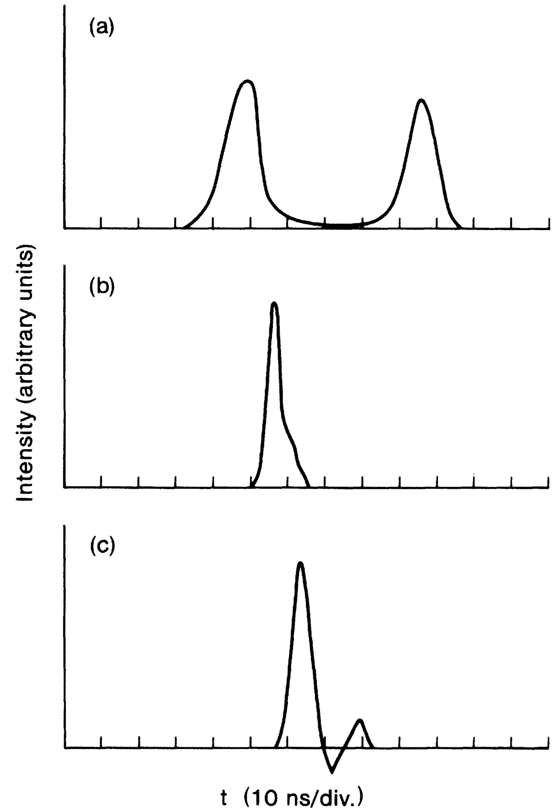

FIG. 2. Temporal behavior of (a) CO_2-laser transmission in the forward direction, (b) prompt Brillouin backscatter following gas-target breakdown, and (c) scattered ruby light from ion turbulence.

The peak of the scattered spectrum for Fig. (c) at $\Delta\lambda \simeq 1.7$ Å corresponds to an ion-wave frequency $\omega = 6.6 \times 10^{11}\ \mathrm{sec}^{-1}$. This value agrees quite well with that predicted by the ion-wave dispersion relation

$$\omega = \frac{\omega_{pi} k \lambda_D}{(1 + k^2 \lambda_D^2)^{1/2}} = 6.7 \times 10^{11}\ \mathrm{sec}^{-1} \ ,$$

for ion plasma frequency $\omega_{pi} = 1.8 \times 10^{12}\ \mathrm{sec}^{-1}$ and

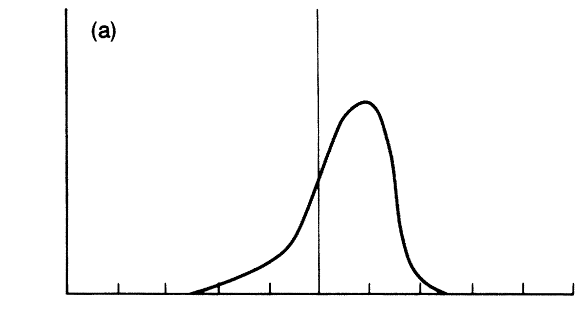

FIG. 3. Spectra of scattered ruby-laser light ($\lambda_0 = 6943$ Å) showing (a) *shifted* spectrum for scattering when measured at $\theta = 60°$ in the plane containing the ruby- and CO_2-laser beams and (b), (c) *unshifted* spectra when $\theta = 60°$ in the target plane. Both (b) and (c) are typical spectra which may be related to time varying plasma scattering conditions.

$k\lambda_D = 0.4$ for the assumed average plasma density $n = 5 \times 10^{18}$ cm^{-3}. In addition, from the spectral width $\Delta\lambda \simeq 2$ Å we can estimate an ion-wave damping rate of $\sim 4 \times 10^{11}$ sec^{-1} which implies a mode lifetime of 8 psec. Numerical simulations of current-driven ion turbulence by Dum *et al.*[6] show that enhanced ion fluctuations rapidly build up and decay, accompanied by electron heating, ion tail formation, and Landau damping of the instability. Thus if quasilinear effects are important in stabilizing the ion instability in this experiment, many periods of growth and decay of ion fluctuations are occurring, as is indeed inferred by the short mode lifetime.

We now turn to the determination of $S(k)$ from which the fluctuation level $(\delta n/n)$ can be calculated. 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 cross section, V is the scattering volume, $\Delta\Omega$ is the solid angle, and T is the transmission—was calibrated by comparing the Thomson-scattering signal with that due to the emission from a blackbody source. Thus the ratio of scattered powers for nonthermal and thermal fluctuations yields

$$S_{NT}(k) = (P_S^{NT}/T\Delta\Omega)/(In_e\sigma_e V) \quad .$$

Since the stray light levels were too large to calibrate $P_S^{TH}/T\Delta\Omega$ by Rayleigh scattering, it was necessary to accurately determine the other parameters. The intensity I was determined by measuring the laser power time profile, energy, and spatial distribution using a pinhole and long focal length lens. The volume was determined from the intersecting dimensions of the focused ruby- and CO_2-laser beams, the latter measured independently. We take the average density to be $n_e = 0.5 n_c$.

We calculate $S_{NT}(k)$ values of $\sim 10^3 \rightarrow 2 \times 10^3$ for the two 60° scattering directions as well as for $\theta = 90°$ scattering in the target plane. Now the fractional ion density fluctuation $(\delta n/n)$ is given by[5]

$$\left(\frac{\delta n}{n}\right)^2 = \frac{1}{(2\pi)^3}\frac{2}{n}\int_0^\infty S(k)k^2\,dk \simeq \frac{2}{3}\frac{S(\langle k\rangle)}{n\langle\lambda\rangle^3}$$

for $\langle k\rangle = 2\pi/\langle\lambda\rangle$ and spectral width $\Delta k \simeq \langle k\rangle$ which is suggested by the simulations of turbulent heating by Dum *et al.*[6] The corresponding $(\delta n/n) \simeq 0.02$. Finally, from Faehl and Kruer's expression for the anomalous collision frequency,[7] $\nu^* \sim \sum_{k_i}(\delta n_{k_i}/n_c)^2$, we find, assuming a broad isotropic turbulent spectrum, that $\sum_{k_i}(\delta n_{k_i}/n_c)^2 \simeq 0.04$ which is the required magnitude to account for the enhanced absorption.

In conclusion, we have measured the ion fluctuation spectrum induced by the interaction of high-intensity CO_2-laser radiation with a gas-target plasma and find strong ion turbulence which appears to quantitatively account for the observed anomalous absorption.

[1]C. C. Daughney, L. S. Holmes, and J. W. M. Paul, Phys. Rev. Lett. 25, 497 (1970).

[2]N. L. Bretz and A. W. DeSilva, Phys. Rev. Lett. 32, 138 (1974).

[3]A. Hirose and H. M. Skarsgard, Plasma Sci. 5, 66 (1977); with Y. Nishida, Phys. Rev. Lett. 38, 653 (1977).

[4]A. A. Offenberger and A. Ng, Phys. Rev. Lett. 45, 1189 (1980).

[5]D. R. Gray and J. D. Kilkenny, Plasma Phys. 22, 81 (1980).

[6]C. T. Dum, R. Chodura, and D. Biskamp, Phys. Rev. Lett. 32, 1231 (1974).

[7]R. J. Faehl and W. L. Kruer, Phys. Fluids 20, 55 (1977).