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Two-plasmon decay in a CO_2-laser–plasma interaction experiment

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Two-plasmon decay has been observed in a CO_2-laser–gas-target-plasma interaction experiment. The spectrum of 3/2-harmonic radiation has been measured and the threshold intensity for decay determined. An experimental value of $\sim 2\times10^{11}$ W/cm^2 is in reasonable agreement with theoretical predictions for an inhomogeneous plasma.

Radiation-induced instabilities are expected to play an important role in high-intensity laser beam coupling to a plasma, particularly in pellet-fusion schemes. When the focused laser intensity exceeds a threshold value, determined by damping or convective losses or loss of wave-matching conditions in an inhomogeneous plasma, a variety of longitudinal wave modes can build up from noise giving rise to stimulated scattering or noncollisional absorption of the incident radiation. One such process, to be reported on here, is the decay of an incident wave, frequency ω_0, into two longitudinal plasma oscillations, frequency ω_p, potentially important since for $\omega_0 = 2\omega_p$ coupling occurs in the underdense region near $\frac{1}{4}n_c$ (n_c being the critical density, i.e., where $\omega_0 = \omega_p$) thus leading to absorption in the outer plasma corona.

In the situation where the inhomogeneous plasma scale length determines threshold and growth of these waves, it is important to know how the greater plasma scale length associated with longer hydrodynamic times influences the two-plasmon decay. Experiments have been reported previously for Nd- and CO_2-laser interaction with solid targets.[1-3] Both Pant *et al.*[1] and Fabre *et al.*[2] found a threshold character for $\frac{3}{2}\omega_0$ emission, attributable to Raman scattering of laser radiation from plasmons with frequency $\frac{1}{2}\omega_0$. Spectral measurements in both cases showed blue-shifted as well as red-shifted components, characteristic of solid-target experiments where critical density is always obtained and reflection can occur from the rapid outward motion of the critical surface. It is difficult, in such experiments, to know the full spectrum of interacting waves giving rise to backscattered harmonics of the fundamental.

We wish to report measurements on CO_2-laser-induced two-plasmon decay in an underdense-gas-target plasma which does not have the added complication of a critical density layer expanding towards the incoming laser beam. This permits an unambiguous view of laser-plasma interaction at the $\frac{1}{4}$ critical density.

More complete details of the gas-target experiment which was devised to study all parametric instabilities from well underdense to $\frac{1}{4}$ critical to critical density will be reported elsewhere. Basically, as shown in the schematic diagrams of Figs. 1 and 2, CO_2-laser radiation is focused into a free-jet gas target formed at an orifice in a cell which has been puff-filled with hydrogen gas to any desired neutral density, thus predetermining the maximum electron-ion plasma density. The gain-switched CO_2 laser has a maximum multimode energy of 50 J in the initial 40-nsec FWHM pulse width, which when focused by a 10-cm focal length off-axis paraboloid mirror to a focal spot of 250-μm FWHM gives peak intensities $>10^{12}$ W/cm^2. Maximum intensities employed here were $\lesssim 10^{12}$ W/cm^2. The beam could be attenuated in a propylene cell to vary the incident laser intensity. Linearity of power and energy attenuation were checked separately.

Emission of $\frac{3}{2}\omega_0$ radiation (~ 7 μm) was collected by the input focusing optics, spectrally analyzed using a monochromator with effective instrumental width of 60 Å (set by the monochromator slits) and detected by a high-speed Ge:Cu infrared detector. Narrow-band filters centered at 7 μm and CaF_2 windows were used to provide additional discrimination against 10.6 μm and other wavelengths; rejection of 10.6 μm was greater than 5×10^7. The response time of the detection system was better than 2 nsec. Simultaneous detection of stimulated Brillouin-Compton scattering[4] (SBS) using a fast Ge:Au detector was used to monitor the interaction and provide a timing reference.

Temporal measurements gave the following results for $\frac{3}{2}\omega_0$ emission from underdense plasma with $n > \frac{1}{4}n_c$. The 7-μm radiation was found to be maximum nearly coincident (within our timing resolution of 10 nsec) with both the peak of the envelope of temporally modulated 10.6-μm backscatter and the (nonmodulated) incident laser power. In comparison with a 20-nsec FWHM for SBS, a characteristic width of 10 nsec was found for 7-μm emission which also showed temporal modulation as seen in Fig. 3. No direct correla-

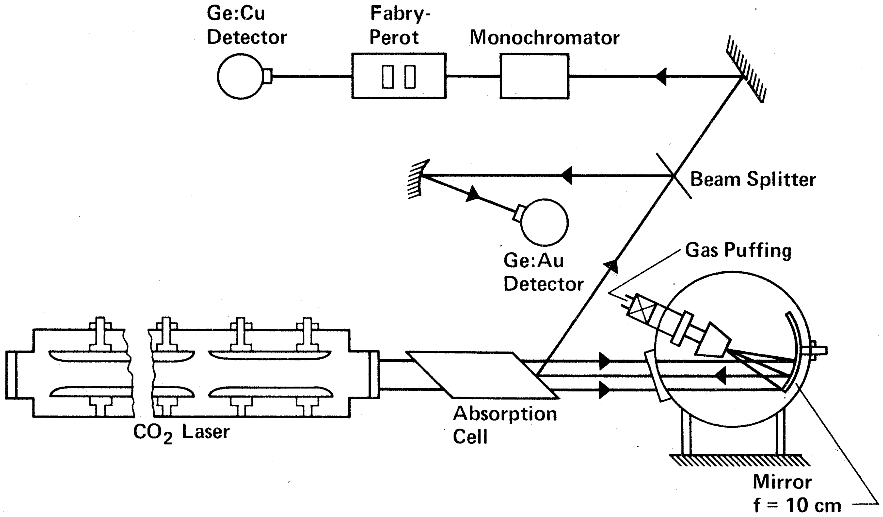

FIG. 1. Schematic diagram of CO_2-laser–gas-target and backscatter optical geometry.

tion of temporal modulation was found for the 7- and 10.6-μm signals which varied from shot to shot.

The absolute level of $\frac{3}{2}\omega_0$ emission collected by the focusing mirror was measured to be ~3×10^{-7} of the peak-incident laser power which can be compared with a $2\omega_0$ level of ~2×10^{-7} and scattered ω_0 level of ~0.2, though the instantaneous value of the latter is almost certainly higher since the detection bandwidth is not adequate to follow the short pulse spiking. In general the presence of $\frac{3}{2}\omega_0$ emission was found to be correlated with strong SBS.

The detailed spectrum of 7-μm radiation is shown in Fig. 4; it is entirely red-shifted with respect to $\frac{3}{2}\omega_0$ centered at 7.06 μm. This is to be contrasted with the blue-shifted component normally observed in addition to red-shift in solid-target interactions. In the present experiment, of course, only underdense plasma exists in the interaction region. Moreover, the hydrodynamic response time is much less than the 20-nsec rise time of the incident laser pulse which permits considerable radial expansion (leading to asymptotic density depression on axis in a time <10 nsec as shown by hydrodynamic simulation). In addition, streak photographs show a nearly stationary axial plasma column of $\simeq$600 μm in length at the time of maximum $\frac{3}{2}\omega_0$ signals which corresponds well with the calculated focal depth of 500 μm. Consequently, no blue-shifted emission is anticipated. The peak emission is shifted $\simeq+110$ Å or $\Delta\omega\simeq-4.2\times10^{11}$ sec^{-1}. This frequency shift at 7 μm is slightly greater than $2\omega_s$, where ω_s is the measured shift in the Brillouin backscatter at 10.6 μm, though the large instrumental width used for measuring the 7-μm spectrum limits the accuracy to perhaps 30%. Such a shift seems likely related to ion acoustic effects since strong Brillouin (and Compton) scattering is observed.

In addition to spectral measurements, the threshold intensity for decay was determined from the intensity dependence of backscattered $\frac{3}{2}\omega_0$ emis-

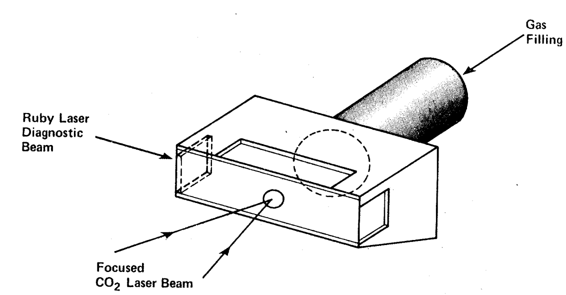

FIG. 2. Close-up view of the free-jet gas target. CO_2-laser focus is approximately 3 mm inside the iris.

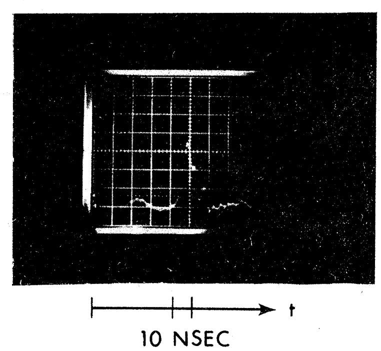

FIG. 3. Temporal structure of $\frac{3}{2}\omega_0$ emission.

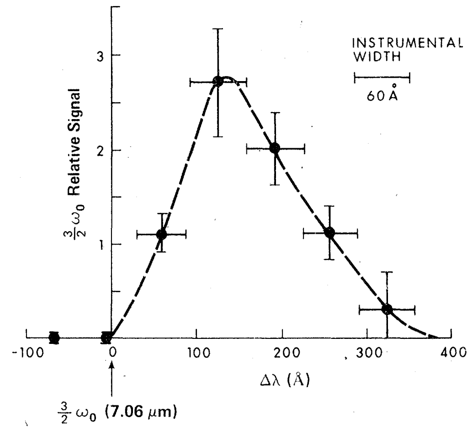

FIG. 4. Spectrum of $\frac{3}{2}\omega_0$ emission. Data is averaged over at least six shots per point for laser intensity of $\sim 5\times10^{11}$ W/cm^2.

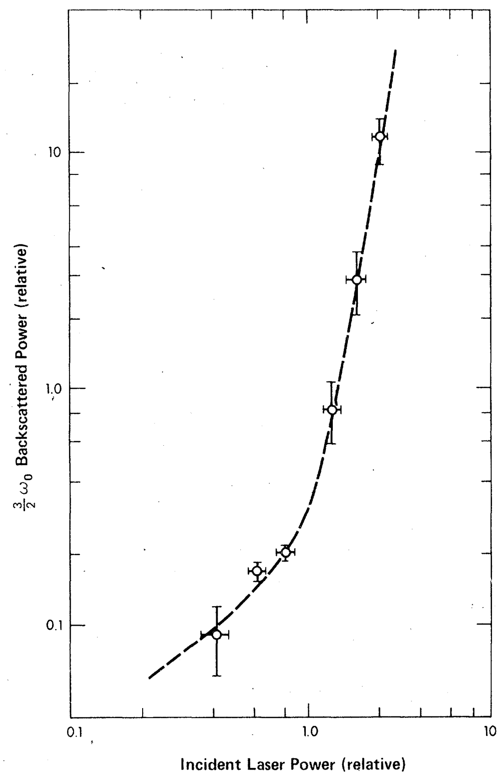

FIG. 5. Dependence of $\frac{3}{2}\omega_0$ emission on incident laser power. Unity on the abscissa corresponds to $\sim 2\times10^{11}$ W/cm^2.

sion. These measurements are summarized in Fig. 5. Two important features are discernible. At the lowest incident power for which 7-μm emission was detectable, the growth out of noise is not sharp—a feature also found in Nd experiments. This is to be anticipated for spatial growth prevailing over absolute instability. At higher power, the curve exponentiates though for the maximum intensity available the level of $\frac{3}{2}\omega_0$ is not fully developed, i.e., growth remains near threshold.

The estimated experimental threshold, subject to the usual uncertainties of power and focal dimensions, is $\sim 2\times10^{11}$ W/cm^2. For a finite length plasma (l) and inhomogeneity scale length L, the criterion given by Pesme *et al.*[5] for inhomogeneity to be more important than boundedness is given by $\gamma_0/|k'||V_1V_2|^{1/2}<l$, where k' is the slope in wave-number mismatch, V_1 and V_2 are group velocities of the decay-product waves, and γ_0 is the homogeneous growth rate. For our case this condition is well satisfied and thus inhomogeneity, even taking the scale length L to be the full axial plasma length, is thought to dominate wave growth. In such circumstances, Rosenbluth[6] gives a criterion for significant spatial growth as $2\pi\gamma_0^2/|k'||V_1V_2|\gg 1$. Since γ_0 and Landau damping are both increasing with wave number k, if we assume optimum growth for plasma waves satisfying $k\lambda_D\sim 0.2$, this criterion reduces to a threshold intensity slightly different from that given by Rosenbluth, chiefly through a $T^{1/2}$ versus linear temperature dependence. We find $I\gg 0.55\ T^{1/2}/L$, where T is in eV, L is in mm, and I is in 10^{10} W/cm^2.

For our experimental values of $T=115$ eV, $L=600$ μm, derived from analysis of stimulated Brillouin backscattering data,[4] a threshold intensity of 10^{11} W/cm^2 is obtained. There is, of course, some uncertainty in the position of the $\frac{1}{4}$ critical surface though it most certainly occurs within the 600-μm length of plasma which is emitting light. This would imply an uncertainty in focused intensity of a factor of 2. Within these limits agreement to within a factor of 2 between experiment and theory can be considered adequate. This experimental determination complements the measurements of Fabre *et al.*[2] and Sigel *et al.*[1] in that variations in pump frequency, temperature, scale length, and target have given similar results for predicted threshold intensities in two-plasmon decay.

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[2]E. Fabre *et al.*, in *Proceedings of Plasma Physics and Controlled Nuclear Fusion Research, Berchtesgaden* (IAEA, Vienna, 1976).
[3]J. L. Bobin, M. Decroisette, B. Meyer and Y. Vitel, Phys. Rev. Lett. 30, 594 (1973).
[4]A. A. Offenberger, A. Ng, and M. R. Cervenan, Can. J. Phys. 56, 381 (1978).
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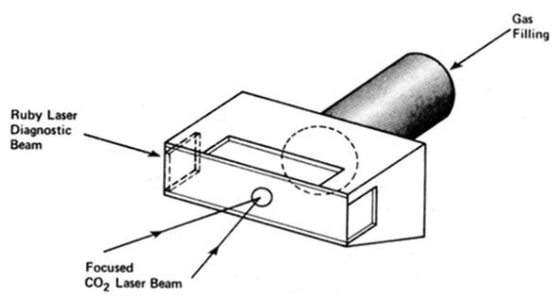

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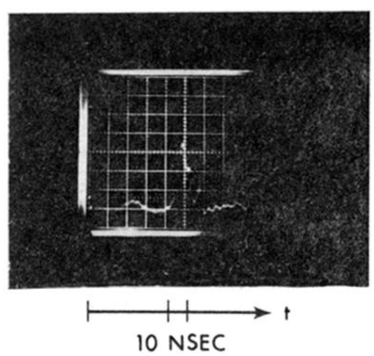

FIG. 3. Temporal structure of $\frac{3}{2}\omega_o$ emission.