by Yu. V. Afanasiev *et al.*, Zh. Eksp. Teor. Fiz. 74, 516 (1978) [Sov. Phys. JETP (to be published)].

(a) Present address: Institute of Laser Engineering, Osaka University, Suita, Osaka, Japan.

[1] B. Yaakobi and T. C. Bristow, Phys. Rev. Lett. 38, 350 (1977).
[2] J. A. Stamper, K. Papadopoulos, R. N. Sudan, S. O. Dean, E. A. McLean, and J. M. Dawson, Phys. Rev. Lett. 26, 1012 (1971).
[3] J. J. Thomson, C. E. Max, and K. Estabrook, Phys. Rev. Lett. 35, 663 (1975).
[4] E. J. Valeo, Lawrence Livermore Laboratory Report No. UCRL-50021-76 (unpublished), pp. 4–101.
[5] D. A. Tidman and R. A. Shanny, Phys. Fluids 17, 1207 (1974); D. G. Colombant and N. K. Winsor, Phys. Rev. Lett. 38, 697 (1977).
[6] S. I. Braginskii, in *Reviews of Plasma Physics*, edited by M. A. Leontovich (Consultants Bureau, New York, 1965), Vol. 2, p. 65.
[7] J. N. Leboeuf, F. Tajima, and J. M. Dawson, to be published.
[8] A. Hasegawa and K. Mima, Phys. Fluids 21, 87 (1978).
[9] H. Okuda and J. M. Dawson, Phys. Fluids 16, 408 (1973).
[10] C. E. Max, W. M. Manheimer, and J. J. Thomson, Phys. Fluids 21, 128 (1978); J. R. Jokirii and E. N. Parker, Astrophys. J. 155, 777 (1969).
[11] K. A. Bruckner and S. Jorna, Rev. Mod. Phys. 46, 325 (1974).

Two-Plasmon Decay and Profile Modification Produced by 10.6-μm Radiation at Quarter-Critical Density

H. A. Baldis, J. C. Samson, and P. B. Corkum
National Research Council of Canada, Division of Physics, Ottawa, Ontario K1A 0R6, Canada

(Received 9 August 1978)

Two-plasmon decay of 10.6-μm radiation has been studied in a long density scale length (~300 μm) plasma using Thomson scattering and interferometry. Enhanced levels of both electron and ion plasma waves have been observed near $\frac{1}{4}n_c$ which are quenched during the CO_2-laser pulse. Profile modification localized at ~$\frac{1}{4}n_c$ has also been observed.

In this Letter, we present direct experimental observations of the decay waves generated by two-plasmon ($2\omega_p$) decay instability[1,2] in plasmas irradiated by intense CO_2-laser radiation, the modification of the electron density profile due to this instability, and the subsequent quenching of the decay wave during the evolution of the 4-ns CO_2-laser pulse. This has been carried out on a plasma with well-defined initial conditions, using for diagnostics interferometry and Thomson scattering. In many experiments the $2\omega_p$ decay has been observed indirectly through the $\frac{3}{2}\omega_0$ radiation,[3,4] while recently in a Thomson-scattering experiment on a gas target the first direct observation has been reported.[5]

To establish well-defined initial conditions, a target plasma was produced by irradiating solid carbon disks with a 4-J, 30-ns ruby-laser pulse, focused to a 600-μm spot. At approximately 5–15 ns after the peak of the ruby-laser pulse, the plasma had a scale length $L=[(1/n)dn/dx]^{-1}$ along the laser axis x equal to 300 μm at the electron density one-quarter critical ($\frac{1}{4}n_c$). This scale size is much larger than those encountered when irradiating solid targets with single CO_2-laser pulses.[6] Thomson scattering showed that both the ion temperature T_i and the electron temperature T_e were ~20 eV at $\frac{1}{4}n_c$.

The CO_2 laser consisted of an injection mode-locked 8-cm aperture TEA (transversely excited atomsphere) laser with an unstable resonator. The laser produced a train of 4-ns pulses with an interpulse separation of 40 ns and a main pulse energy of ~10 J. The beam was focused with a 50-cm–focal–length NaCl lens, giving a focal spot ~200 μm in diameter, and a maximum power density of ~5×10^{12} W/cm^2. The interpulse intensity of the CO_2 laser was monitored to a level of ~1.0×10^{10} W/cm^2.

Thomson scattering and optical interferometry were performed simultaneously on each shot. The folded–wave-front interferometer used two orthogonally polarized beams to give interferograms at two different times. The spatial resolution of the imaging optics of the interferometer was 10 μm. A 0.5-ns, 0.53-μm interferometer pulse and a 2.2-ns, 0.53-μm scattering pulse were both obtained by cutting two segments from the output of a single longitudinal- and transverse-mode Nd:glass laser, and frequency doubling. After passing through a spatial filter, the scattering beam was focused to a 200-μm-diam spot. The collecting optics had an $f/4$ aperture and a 200-μm-diam collecting volume, defined by a spatial filter after the collecting lens. Scattered spectra were analyzed with a 1-m–focal-length spectrograph and recorded on an optical multichannel analyzer.[7] The dispersion was varied between 7 and 0.7 channels/Å in order to resolve either the ion feature or to record a complete spectrum.

The electron and ion temperatures were measured using a scattering angle $\theta_s = 150°$ (direction B, Fig. 1). Over the density range monitored, the ion feature could be resolved in this scattering configuration during the time between CO_2-laser pulses ($I \lesssim 10^{10}$ W/cm^2) and during the main CO_2-laser pulse. The temperatures obtained before the arrival of the main CO_2-laser pulse indicated no effect due to the interpulse intensity. In all these configurations the total scattered intensities were consistent with Rayleigh scattering and the scattered spectra in good agreement with computed thermal spectra.

At $\frac{1}{4}n_c$ the temperatures T_i and T_e changed from 20 eV before the arrival of the CO_2-laser pulse, to $T_i = (60 \pm 10)$ eV and $T_e = (170 \pm 40)$ eV after the peak of the CO_2-laser pulse. These data imply that the scattering parameter $\alpha = (k\lambda_0)^{-1}$ ($\vec{k}$ is the scattering wave vector and λ_0 is the Debye length) varies from ~ 2.2 to ~ 1. As a result of the small values of $(k\lambda_0)^{-1}$, no enhanced scattering at $\sim \frac{1}{2}\omega_0$ is expected at this scattering angle θ_s. To observe enhanced scattering Landau damping should be small and $(k\lambda_0)^{-1}$ large. Furtheremore, for values of $k \gg k_0$ ($\vec{k}_0$ is the wave vector of CO_2) the maximum growth rate should occur in the direction midway between the electric field of the CO_2 and k_0.[1]

To probe for the $2\omega_p$ decay, the scattering angle was changed to $\theta_s = 20°$ (direction C, Fig. 1), with the scattering wave vector $\vec{k}$ in the plane of polarization of the CO_2-laser pulse, and at 35° to $\vec{k}_0$. In this configuration $(k\lambda_0)^{-1} \approx 11$ prior to the arrival of the CO_2-laser pulse. To ensure complete coverage of any regions of enhancement, scattering spectra were taken at densities ranging from above n_c to approximately $\frac{1}{10}n_c$.

A typical scattering spectrum taken at $\frac{1}{4}n_c$ before the arrival of the CO_2-laser pulse is shown in Fig. 2(a), where only the ion component of the spectrum is observed. The scattered intensity is consistent with Rayleigh-scattering calibration. If we calculate the thermal scattered spectra, the electron satellites are approximately 10^3 smaller than the ion peak. These intensities are too low to be detected.

Figure 2(b) shows a spectrum taken at $\frac{1}{4}n_c$ when the CO_2-laser pulse is incident on the plasma; the two electron satellites are now clearly visible. Using the spectra obtained before the arriv-

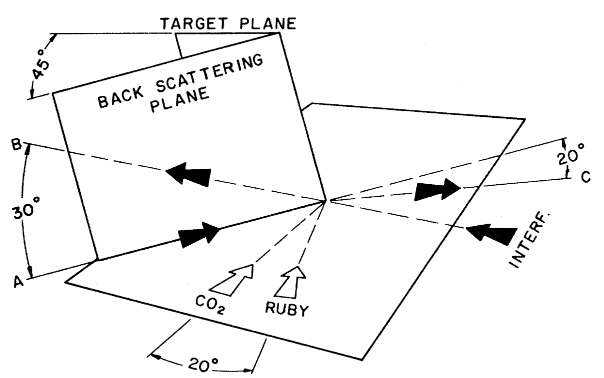

FIG. 1. Schematic of the incident laser and diagnostic beams. The scattering beam is incident along line A, and collected along directions B and C.

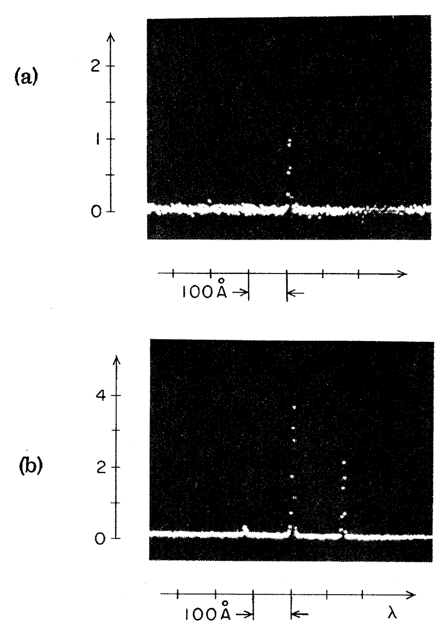

FIG. 2. Low-dispersion scattering spectra at $\frac{1}{4}n_c$ (please note the change in vertical scales): (a) before the CO_2-laser pulse and (b) during the CO_2-laser pulse.

al of the CO_2 laser as a reference, we observed (a) an enhancement in the ion peak of ~4 and, (b) electron satellite intensities corresponding to an enhancement from the thermal level (for $T_e \simeq 170$ eV) of at least 2×10^3 and 0.4×10^3 for the red and blue satellites, respectively. These values represent a lower limit due to the rapid temperature increase during the rising edge of the CO_2-laser pulse and to the large collecting volumes. The relative intensities of the red and blue satellites changed from spectrum to spectrum, but the red satellite was usually the largest. This preference for the red satellite might possibly be caused by Landau damping since waves propagating to lower densities (blue satellite) would be damped in a much shorter distance.

The blue and red electron satellites show a shift with respect to the central ion peak of 128 ± 2 Å and 136.5 ± 2 Å, respectively, a deviation of approximately 4.5 Å from the shift of 132.5 Å that corresponds to $\frac{1}{2}\omega_0$. The ion feature, on the other hand, shows no measurable shift.

When the plane of polarization of the CO_2 radiation was rotated by 90°, no measurable enhancement of the satellites was observed at $\frac{1}{4}n_c$. Since the enhancement due to the $2\omega_p$ decay should be predominantly in the plane of polarization of the CO_2 radiation, this observation and the localization of the enhancement near $\frac{1}{4}n_c$ give very strong evidence for the $2\omega_p$-decay-instability nature of the present observations.

Figure 3 shows the correlation between the intensity of the blue satellite and the timing of the CO_2-laser pulse. At the peak of the CO_2-laser pulse and thereafter, we observed a marked quenching that might be much greater than a factor of 10 as a result of the rapid temperature change during the evolution of the CO_2-laser pulse.

The enhancement is localized at densities near $\frac{1}{4}n_c$, since spectra taken at $0.5n_c$ and $0.2n_c$ show only the ion feature at a similar intensity before the arrival of the CO_2-laser pulse, and no evidence of the enhanced electron satellites. During the CO_2-laser pulse we observed strong scattering signals at $\pm\omega_0$ and an enhanced ion feature at densities near n_c. At densities $\sim\frac{1}{10}n_c$ an enhancement was observed only on the ion feature. These effects have not been fully studied yet.

Axial electron density profiles taken before and during the CO_2-laser pulse are shown in Fig. 4. Steepening of the profile at densities $\frac{1}{4}n_c$ and below is observed from the very beginning of the pulse. At $\frac{1}{4}n_c$ the scale length L de-

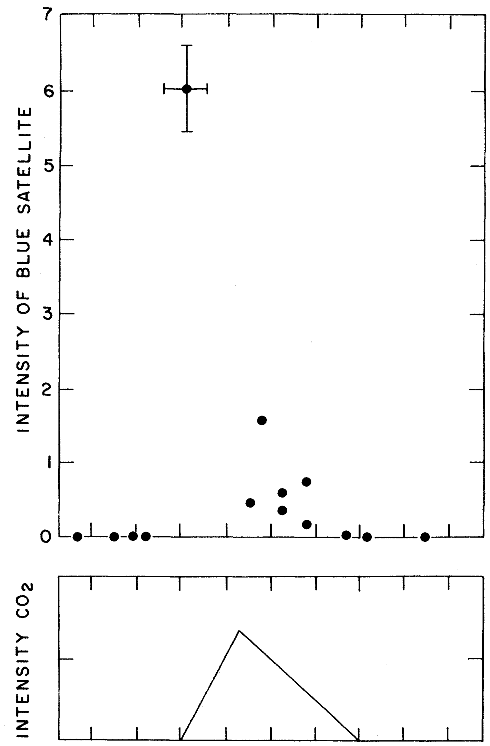

FIG. 3. Correlation between the intensity of the blue electron satellite and CO_2-laser pulse—horizontal scale 2 ns/division.

creased from ~300 μm before the CO_2-laser pulse to ~100 μm near and after the peak. The CO_2-laser pulse actually produced a density cavity just below $\frac{1}{4}n_c$, which was centered on the CO_2-laser beam axis, and has a transverse width of ~500 μm.

The profile steepening near $\frac{1}{4}n_c$ has been predicted by computer simulations,[8,9] but has not been observed before in laser-produced plasmas. The computer simulations indicate that the ponderomotive forces from the decay waves in the $2\omega_p$ instability can drive ion perturbations, causing the formation of a cavity and profile steepening near $\frac{1}{4}n_c$.

The profile steepening and the rise in the electron temperature at $\frac{1}{4}n_c$ are the most likely causes of the quenching of the $2\omega_p$ instability. If we assume that the axial electron density profile has the form $n(X)=n_0(1+X/L)$, then the threshold for the instability[2] is given by $\frac{1}{3}(v_0/v_{\rm th})^2 k_0 L > 1$, where v_0 and $v_{\rm th}$ are the laser-induced and thermal electron speeds, respectively. The profile steepening and rise in electron temperature observed in the experiment would indicate a required threshold of 8×10^{10} W/cm^2 at the begin-

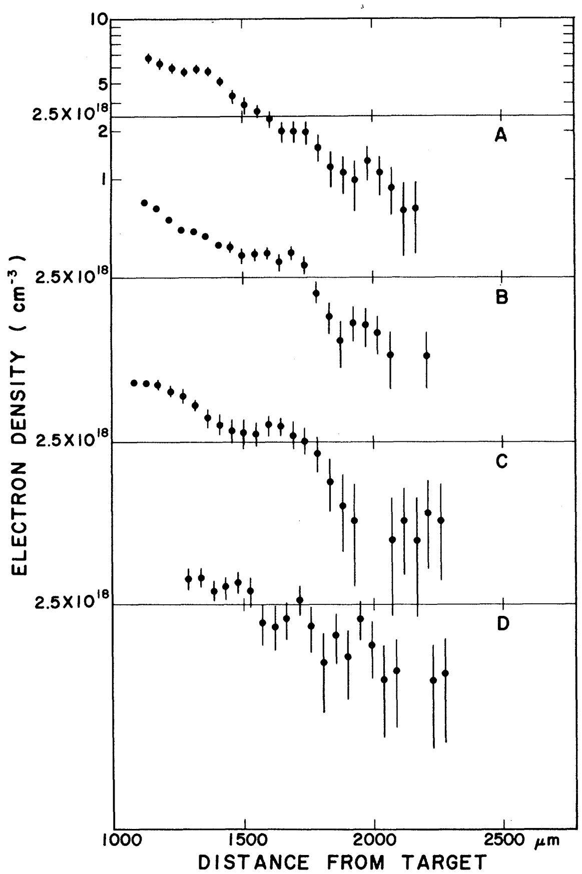

FIG. 4. Electron density profiles along the axis of the incident CO_2-laser beam: (a) 15 ns before the peak of the CO_2-laser pulse, (b) ~1.5 ns before the peak, on the rising edge, (c) ~1 ns after the peak, and (d) ~4 ns after the peak. The error bars are ~80% confidence limits.

ning of the CO_2-laser pulse, and 1.6×10^{12} W/cm^2 just after the peak of the pulse. The latter is marginally lower than the peak intensity of the CO_2-laser pulse in vacuum (5×10^{12} W/cm^2), although only a qualitative comparison can be made at this time since the actual intensity may be lower as a result Brillouin scattering at densities below $\frac{1}{4}n_c$.[10]

Two possible mechanisms for the enhanced ion fluctuations can be presented at this time: (i) the ponderomotive force from the superposition of various highly pumped, electron-plasma-wave-driven ion perturbations[8]; and (ii) a four-wave interaction[11] whereby a highly pumped plasma wave of frequency $\frac{1}{2}\omega_0$ and an incident photon ω_0 produce an ion acoustic wave ω_{ac} and a photon of frequency $\frac{3}{2}\omega_0-\omega_{ac}$. Although we have not yet had an opportunity to look for $\frac{3}{2}\omega_0$ radiation, this emission has been seen in interaction experiments.[3,7,12]

The results from this experiment agree with predicted characteristics of the $2\omega_p$ decay. Enhancements in the electron satellites at $\sim\frac{1}{2}\omega_0$ are localized near $\frac{1}{4}n_c$ and are not observed for $\vec{k}$ perpendicular to the plane of polarization of the CO_2-laser radiation. Furthermore, the heating of the electrons, and the steepening of the density gradient near $\frac{1}{4}n_c$ may account for the quenching of the observed enhancements.

We would like to thank Dr. A. J. Alcock for many helpful comments, and Mr. R. Benesch and Mr. D. Joines for valuable technical assistance.

[1]E. A. Jackson, Phys. Rev. 153, 235 (1967).

[2]C. S. Liu, in *Advances in Plasma Physics*, edited by A. Simon and W. B. Thompson (Wiley, New York, 1976), Vol. 6.

[3]S. Jackel, B. Perry, and M. Lubin, Phys. Rev. Lett. 37, 95 (1976).

[4]N. H. Burnett, H. A. Baldis, G. D. Enright, M. C. Richardson, and P. B. Corkum, J. Appl. Phys. 48, 3727 (1977).

[5]J. J. Schuss, T. K. Chu, and L. C. Johnson, Phys. Rev. Lett. 40, 27 (1978).

[6]R. Fedosejevs, I. V. Tomov, N. H. Burnett, G. D. Enright, and M. C. Richardson, Phys. Rev. Lett. 39, 932 (1977).

[7]Princeton Applied Research, Princeton, N. J.

[8]A. B. Langdon and B. F. Lasinski, in *Methods in Computational Physics*, edited by J. Killeen (Academic, New York, 1976), Vol. 16.

[9]B. F. Lasinski and A. B. Langdon, Bull. Am. Phys. Soc. 22, 1174 (1977).

[10]B. H. Ripin, F. C. Young, J. A. Stamper, C. M. Armstrong, R. Decoste, E. A. McLean, and S. E. Bodner, Phys. Rev. Lett. 39, 611 (1977).

[11]T. W. Johnston, private communication.

[12]J. L. Bobin, M. Decroisette, B. Mayer, and Y. Vitel, Phys. Rev. Lett. 30, 594 (1973).

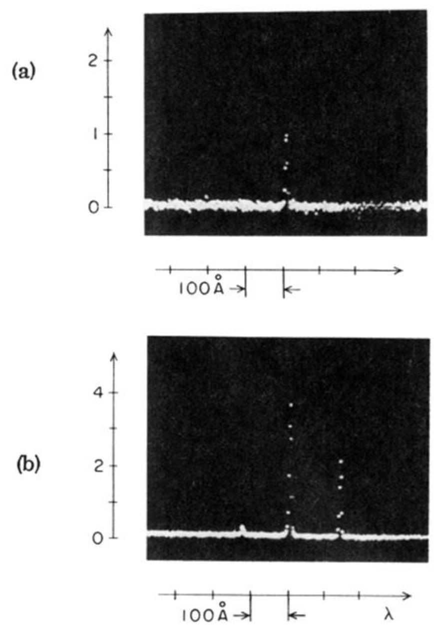

FIG. 2. Low-dispersion scattering spectra at $\frac{1}{4} n_c$ (please note the change in vertical scales): (a) before the CO_2-laser pulse and (b) during the CO_2-laser pulse.