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Density Cavitons and X-Ray Filamentation in CO_2-Laser-Produced Plasmas

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Measurements of electron density and x-ray emission have been made on a C VII plasma, generated by a 9×10^{12}-W-cm^{-2} CO_2 laser beam. A density cavity and x-ray filamentation are observed. The relevance of these results to theories of resonance absorption, soliton formation, self-modulation, and filamentation of laser light is noted.

The interaction of an intense electromagnetic field with the critical-density layer in a nonuniform plasma is a problem of topical interest in laser-heating and -compression experiments. Microwave experiments in a tenuous plasma[1] have demonstrated resonant enhancement of electric fields at this layer, and a density cavity, or caviton, was observed for times of order $10^5(\omega_{pe})^{-1}$. Relativistic computer simulations of such interactions have been undertaken[2,3] and the importance of resonance absorption,[4] its relation to self-generated magnetic fields[5] and second-harmonic generation,[6] its enhancement at sharp gradients near the critical surface, self-consistent modifications to the density profile,[2] and the influence of density scale length on parametric instability thresholds[7] have been widely discussed. The relationship between these instabilities, self-modulation and filamentation instabilities,[8] and soliton formation[9-12] have been active areas of related research. This paper describes the first observation of a density caviton in a *laser-produced plasma*; a preliminary description of the technique has been presented elsewhere.[13]

Measurements were made on plasma generated by an unpolarized 1.5-GW CO_2 laser pulse focused onto plane carbon targets at an intensity of 9×10^{12} W cm^{-2}, with a 50-nsec (full width at half-maximum) pulse duration and an energy of 75 J.[13] A holographic interferometer[14] was used to measure $\int n_e dl$, using a ruby oscillator which generated 100-MW, 10-nsec pulses to probe the plasma at 90° to the CO_2-laser axis. The interferograms were recorded on Agfa 10E 75 plates 25 nsec after initiation of the CO_2-laser pulse; the object resolution was 40 μm. Line densities deduced from fringe shifts were converted to radial density profiles by Abel inversion (Fig. 1). Mea-

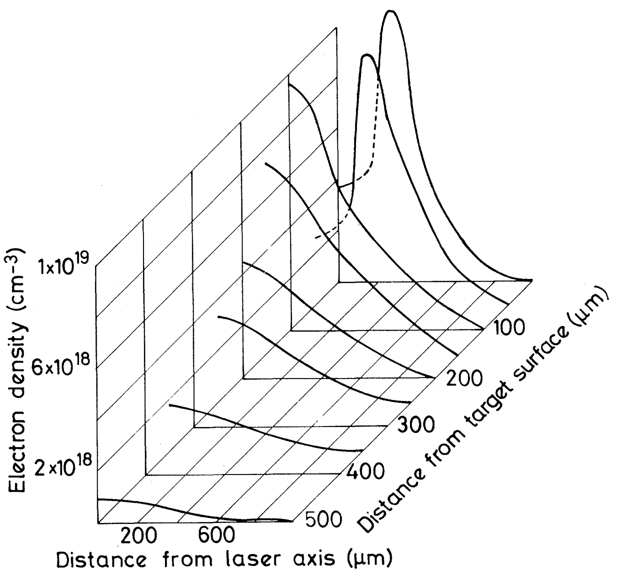

FIG. 1. Radial density profiles at $t = 25$ nsec.

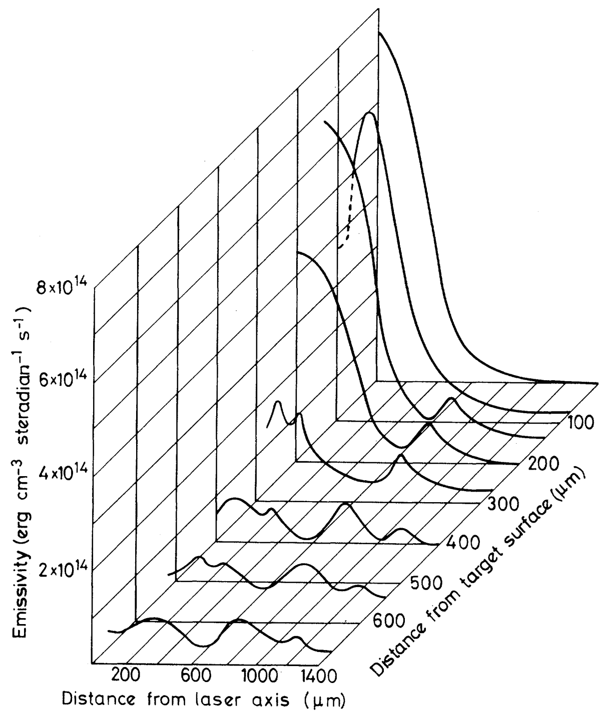

FIG. 2. Time-integrated radial x-ray emissivity profiles, after transmission through 0.564 mg cm^{-2} of Al filter.

surements were accurate to ±10% at peak density, and proportionately greater elsewhere. Each density measurement was made on a freshly irradiated target; microscopic examination showed depth and diameter of cratering less than 30 and ~1000 μm, respectively.

Indirect measurements of electron density[15] were made from x-ray pinhole photographs. A 25-μm pinhole, covered by a transmission filter, was located 2.75 cm from the plasma and the x-ray image, magnified 1.5×, was recorded on SC7 film with a resolution of 40 μm. Aluminum foils of 1.13, 0.846, and 0.564 mg cm^{-2} were used as filters. Film density was converted to intensity using an SC7 calibration.[16] The resulting intensity profiles were converted to energy emitted per unit volume per steradian (Fig. 2) by Abel inversion, after correcting for magnification and acceptance angle. Two views of the plasma are shown in Fig. 3.

In Fig. 1 density cavitation, and in Figs. 2 and 3 filamentation of the x-ray intensity, are apparent. Preliminary measurements of the laser-driven density caviton have already been reported.[13] Comparison of the axial variation of x-ray emissivity and electron density shows the plasma expansion to be isothermal between 50 μm and 1 mm from the target, since the x-ray intensity is seen to be only dependent on density squared (c.f. Fig. 4). The cavity seen in x-ray emission close to the target surface is qualitatively similar to the density cavity inferred from interferometry (Fig. 4). Fine structure is observed in the x-ray photographs, as filaments of ~100 μm diam extending several millimeters along the laser axis [c.f. Fig. 3(a)]. Measurements by the foil-ratio technique show the elec-

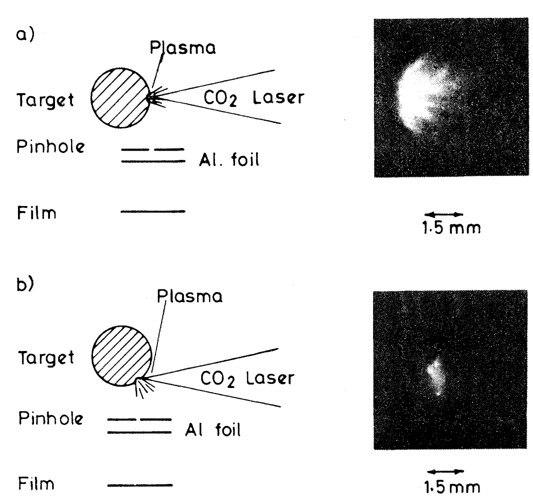

FIG. 3. X-ray pinhole photographs, taken with 0.564 mg cm^{-2} of Al filter, with the geometries indicated.

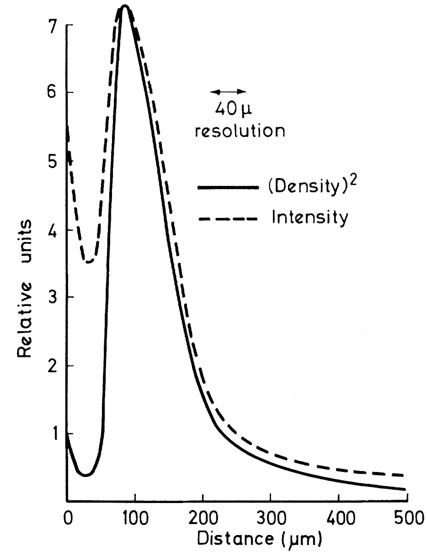

FIG. 4. Axial variation of x-ray emissivity and n_e^2, normalized at peak signal ~ 100 μm from target.

tron temperature of these filaments to be comparable to the ambient plasma (~1.6 keV) so that their density must be relatively higher. These filaments are only resolved in the outer regions of the plasma, where fine-scale density variations are too weak to be detectable by the interferometric technique. On the basis of these measurements the filaments are interpreted as isothermal plasma flowing along slowly diverging channels. Interaction of thermal and ponderomotive forces due to cavitons at the critical surface may compress plasma locally at discrete positions, with subsequent expansion in filaments. Channeling is more obvious when the pinhole camera views plasma along its expansion direction [c.f. Fig. 3(b)]. Filaments were not observed below an incident intensity of ~ 2×10^{12} W cm^{-2}. (The temperature deduced from these pinhole pictures is comparable to the peak, time-resolved value of 1.3 keV obtained previously.[13])

The measured "temperature" fits a $T_e \propto I^{2/3}$ steady-state flux-limited scaling law[17] and an upper limit of ≲55% can thus be deduced for the absorption coefficient, at the incident intensity of $I \sim 9\times10^{12}$ W/cm^2. (A volumetric energy balance supports this estimate, but direct measurements of reflection have yet to be made.) Empirically, the absorption is thus much stronger than the 2–8% due to inverse bremsstrahlung.[13] However, strong *resonant* absorption is expected, since the electric field of the focused beam has a component parallel to the density gradient which drives electrostatic waves interacting nonlinearly with the laser field (vacuum wavelength λ_0). Intense electric fields are thus localized near the critical surface. At the density scale lengths (L) shown in Fig. 1, maximum resonance[18] occurs when the angle of incidence $\theta = \pm \sin^{-1}[0.6(2L/\lambda_0)^{1/3}] \sim 8^\circ$, a value close to the $f/4$ semicone angle used in the experiment. Resonant absorption of order 60% may be expected[3] for the appropriate plane of polarization, giving a predicted absorption for the (unpolarized) beam of 32–68%. A density modulation of order 100% is expected from an analytic (warm-plasma) analysis.[3] [The modulation, taking into account the swelling factor, is given by

$$\delta n_e/n_e \simeq |V_0/V_t|^2(\lambda_0^3 L/\lambda_{De}^4)^{1/3}\varphi^2(\tau)/(6^2),$$

where n_e is the mean electron density, δn_e is the density depression, $|V_0/V_t|$ is the ratio of electron quiver to thermal velocities, $\varphi(\tau)$ is a resonance function $\varphi(\tau) \sim 1.2$, and λ_{De} is the Debye length at the critical layer.] This prediction is in agreement with one- and two-dimensional computer simulations of limited duration (times less than about $1000\omega_{pe}^{-1}$), and the experimental measurements of Figs. 1 and 2. (Note that $E_0^2/8\pi n_e kT_e \sim 0.16$, where E_0 is the vacuum electric field.) The forces exerted by the enhanced electric fields, and concomitant localized temperature gradients, are predicted analytically and computationally to produce a caviton having a limiting density scale-length of $(12-20)\lambda_{De}$ (see Refs. 12 and 3). In the experiment radial and axial scale lengths are ~200 and ≲50 μm, respectively, i.e., many hundred Debye lengths; however, the 40-μm interferometric resolution, and plasma motion during the exposure, may account for this discrepancy. Both laser pulse and caviton exist for times of order $10^6\omega_{pe}^{-1}$, and quasi-steady-state conditions are established; the experiment is therefore perhaps more closely related to Nd-laser-interaction experiments giving indirect evidence of fine-scale density modulations,[6,19] and resonance absorption,[6] than to the microwave caviton-decay experiment.[1]

Cavitons can be created by mechanisms other than resonance absorption; in particular the focused laser beam can self-modulate into filaments parallel to the laser propagation vector[8,20] (calculated threshold greater than 3×10^{10} W cm^{-2}) or form troughlike modulations at 90° to this vector by interaction of incident and reflected beams near the critical surface.[21] In both cases modulation is accompanied by a reduction of electron density due to ponderomotive forces in the region of the electric field maxima and is unstable to perturbations, undergoing longitudinal collapse.[21]

It is concluded that the observation of a caviton near the critical layer, localized heating of plasma in this region, and an empirical absorption greater than classical are consistent with resonance absorption of the laser radiation. It should be stressed that in the present experiment a highly developed level of plasma turbulence is expected theoretically. Under such conditions quasilinear analytic theories are illustrative rather than quantitative in nature, and multidimensional simulation "experiments" require the extensive use of computers. Further experiments are planned to resolve the dominant physical interactions.

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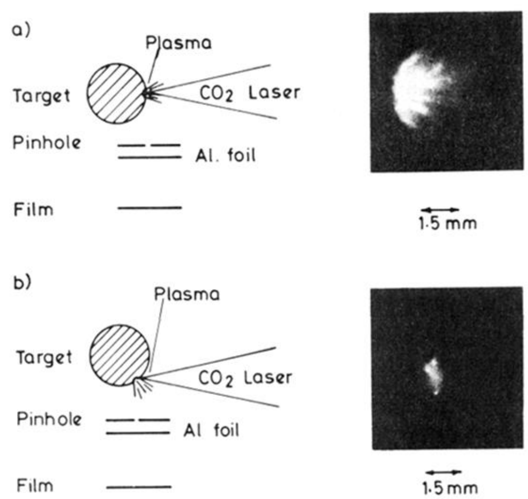

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