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1975

CLM-P 447

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ABSTRACT

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

(Submitted for publication in Physical Review Letters)

November 1975.

The absorption efficiency and interaction mechanisms of an intense electro-magnetic field with a critical-density layer, $\omega_o = \omega_p(z)$, in a non-uniform plasma is a problem of topical interest in laser-heating and compression experiments. Short-pulse microwave experiments in a tenuous plasma(1) have recently demonstrated resonant enhancement of electric fields localised at this layer, and the formation of a density cavity, or caviton, which was observed for times of order $10^5 (\omega_p)^{-1}$ after termination of the pulse. Two dimensional 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 density gradients near the critical surface, self-consistent modifications to the plasma density profile(2) and the influence of density scale length on parametric instability thresholds(7) have been widely discussed. The relationship between these instabilities and the electromagnetic self-modulation and filamentation instabilities(8) (and also soliton formation(9,10,11,12)) have been active areas of related theoretical research. The present 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).

The measurements were made on the plasma generated by an unpolarized 1.5 GW CO_2 laser-pulse focused onto plane carbon targets by a 30 cm focal length gold-coated spherical mirror. The cross section of the laser beam was 10 x 5 cm, its duration was 50 ns (FWHM) and its energy was varied between 19 and 75 J. A two beam holographic interferometer(14) was used to measure $\int n_e dl$, using as a holographic source a pulse-clipped ruby oscillator generating 100 MW, 10 ns pulses. The scene beam probed the plasma at 90°

to the CO_2 laser axis, and the interferograms were imaged onto high resolution Agfa 10E 75 plates by a 20 cm focal length lens. The magnification was 3 × and the system resolution 40 μm. Synchronized interferograms were recorded at 25 ns after initiation of the CO_2 pulse, and at 50 ns (when the gain-switched intensity was ~ 8% of the peak value occurring at 25 ns). Line densities were deduced from fringe-shifts of the scene beam, and converted to radial density profiles by Abel inversion(15), (Fig 1). Measurements of fringe shifts were accurate to $\lambda/2$, giving an estimated error of ± 10% at peak density, and proportionately greater elsewhere. Each density measurement was made on a freshly-irradiated target surface; subsequent microscopic examination showed that the depth and diameter of cratering was less than 30 μm and ~ 1000 μm respectively, per shot.

Indirect measurements of electron density(16,17) were made from pinhole photographs of X-ray emission. A 25 μm pinhole, covered by an X-ray 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. Aluminium foils of 1.13 mg cm^{-2}, 0.846 mg cm^{-2} and 0.564 mg cm^{-2} were used as X-ray filters. The X-ray photographs were scanned with a microdensitometer and film density converted to intensity using an SC7 film calibration(18). The resulting intensity profiles, integrated along a line of sight normal to the CO_2 laser axis, correspond to energy per unit area recorded on the film; they were converted to energy emitted by the plasma per unit volume per steradian (Fig. 2) by Abel inversion, after correcting for the camera magnification and the solid angle accepted by the pinhole. Two views of the plasma are shown in Fig. 3. In (a) the CO_2 laser was focused so that the pinhole viewed the plasma at 90° to its expansion direction and the laser direction while in (b) the CO_2 laser was focused so that the pinhole viewed the plasma along its expansion direction and at 90° to the laser direction.

In Fig. 1 cavitation of the plasma density, 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). Quantitative analysis of the X-ray profiles was made by computing the X-ray emissivity as a function of electron temperature and density, and comparing this with the measured emissivity at various foil thicknesses. Comparision of the axial variation of X-ray emissivity and the measured density profiles 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 dependent only on density squared, (c.f. Fig.4). The cavity seen in the 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 diameter extending several mm along the laser axis (c.f. Fig. 3a). Measurements by the foil ratio technique show the electron temperature of these filaments to be comparable to the rest of the plasma (i.e. approximately 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 less sensitive interferometric technique. On the basis of these measurements the observed filaments are interpreted as plasma confined to a constant temperature flow along slowly diverging channels. Interaction of thermal and ponderomotive forces due to cavitons at the critical surface may compress the plasma locally at discrete positions, with subsequent rapid isothermal expansion in filaments. Channelling is more clearly seen when the pinhole camera views the plasma along the expansion direction (c.f. Fig. 3b). The filaments were not observed when the incident intensity was lowered to $\sim 2 \times 10^{12}$ watts cm^{-2}. (The temperature of 1.6 keV deduced from the pinhole pictures is comparable to the peak, time-resolved, value of 1.3 keV obtained by a scintillator-foil technique(13)).

The measured electron "temperature" fits a $T_e \propto I^{\frac{2}{3}}$ steady-state flux-limited scaling law(19,20,21) and an upper limit of $\leqslant 55\%$ can thus be deduced for the absorption coefficient, at the incident (vacuum) intensity of $I \sim 9 \times 10^{12}$ W/cm^2. (A volumetric energy balance supports this absorption estimate, but direct measurements of reflection losses have yet to be made). Empirically, the absorption is thus much stronger than the 2-8% which can be ascribed to inverse bremmstrahlung(13). However, strong <u>resonant</u> absorption(22) is expected, since the electric field of the focussed laser beam has a component parallel to the density gradient vector which can drive electrostatic waves in the plasma. When the angle of incidence $\theta = \pm \sin^{-1}\ [0.6\ (k_oL)^{\frac{1}{3}}]$, non-linear interaction of these waves with the laser field (having wave number k_o) will generate very intense electric fields, localized near the critical surface. At density scale-lengths (L) appropriate to the conditions illustrated in Fig. 1, the angle of incidence inducing maximum resonance is calculated to be $|\theta| \leq 8^o$, a value close to the f/4 semi cone-angle used in this experiment. Under such conditions resonant absorption of order 60% may be expected(3) for the appropriate plane of polarization, giving a predicted gross absorption for the (unpolarized) beam of 32 - 68%. Following an analytic (warm plasma) analysis(3) it is also calculated that a density modulation of order 100% should be observed. (The density modulation, taking into account field enhancement effects, is given by $\delta n_e/n_e \simeq |V_o/V_t|^2 [\lambda_o^3 L/\lambda_D^4]^{\frac{1}{3}} \phi^2(\tau)/(6\pi^2)$ where n_e is the mean electron density, δn_e is the electron density depression, $|V_o/V_t|$ is the ratio of the electron quiver velocity to the thermal velocity, $\varphi(\tau)$ is a resonance function ~ 1.2, λ_o is the vacuum wavelength of the radiation and λ_D is the Debye length at the critical layer). This prediction is in agreement with 1D and 2D computer simulations of limited duration (ie times of $\leq 1000\ \omega_p^{-1}$), and the experimental measurements illustrated in Figs 1 and 2. (Note that $E_o^2/8\pi n_e k T_e \sim 0.16$, where E_o is the vacuum electric field). The forces exerted by the enhanced electric field, and concomitant localized temperature gradients, are predicted analytically and computationally to produce a caviton having a limiting density scale-length of 12(12) - 20(3) λ_{De}. In the present experiment the radial and axial scale lengths are $\sim 200\ \mu m$ and $\leqslant 50\ \mu m$ respectively, i.e. many hundred Debye lengths; however, the 40 μm resolution of the holographic system, and plasma motion during the exposure, may account for this discrepancy. Both the 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 recent Nd laser-interaction experiments which have given indirect evidence of fine-scale density modulations,(6,23) and resonance absorption(6), than to the microwave caviton-decay experiment(1).

It is noted that 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(8,24) (calculated threshold > 3×10^{10} watts cm^{-2}) or form trough-like modulations at 90° to the propagation vector by interaction of the incident beam with the beam reflected from the critical surface(25). In both these cases the modulation is accompanied by a reduction of electron and ion density due to ponderomotive forces in the region of the electric field maxima, and is unstable to perturbations, undergoing longitudinal collapse(25).

It is concluded that the observation of a caviton near the critical layer, localised 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 quasi-linear analytic theories are illustrative rather than quantitative in nature, and multi-dimensional simulation 'experiments' require the extensive use of computers. Further experiments are planned to resolve the dominant physical interactions.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge useful discussions with C. N. Lashmore-Davies and R. Bingham. T. P. Donaldson is on attachment from Queen's University, Belfast.

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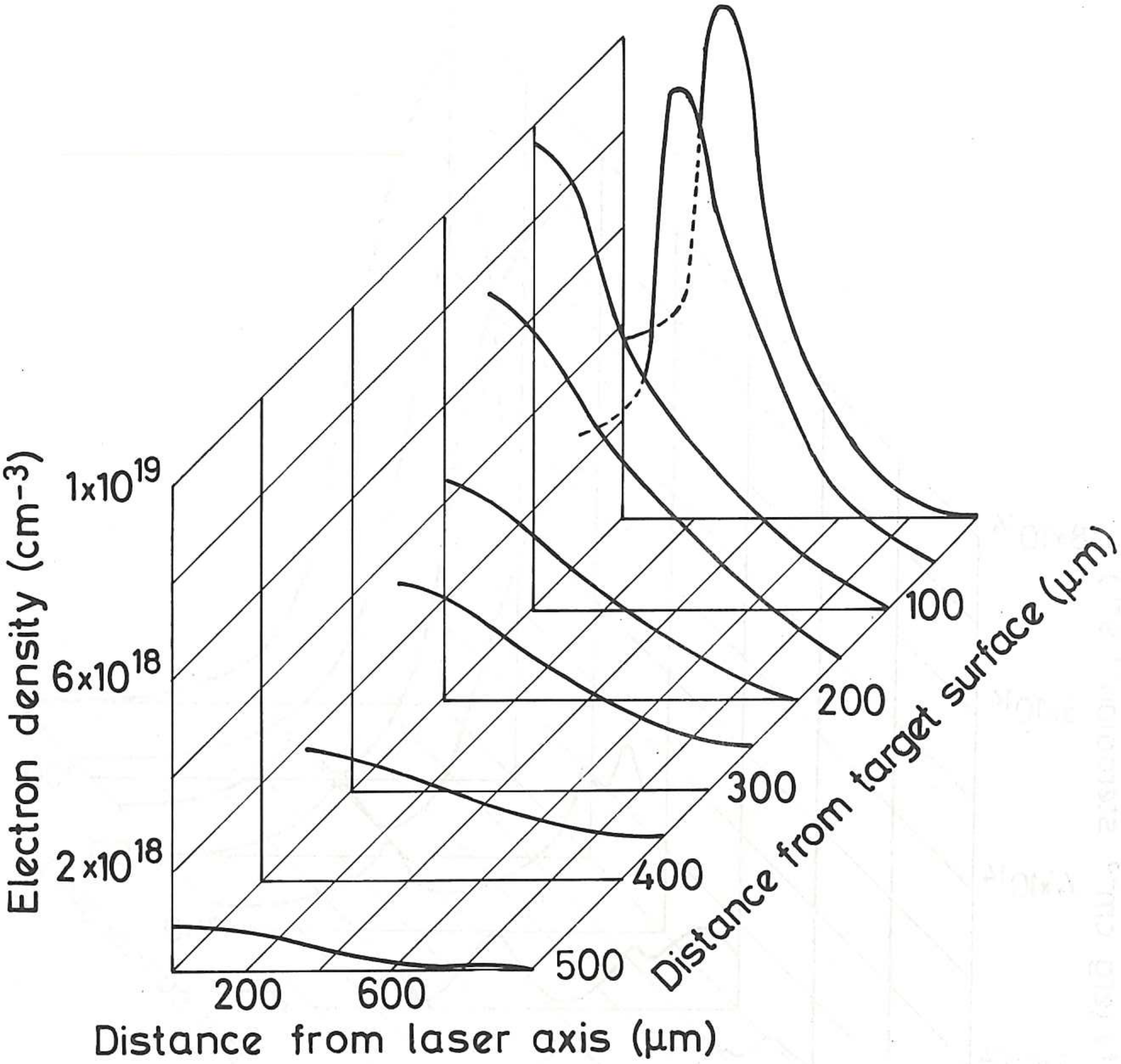

Fig.1 Radial density profiles at t = 25 ns.

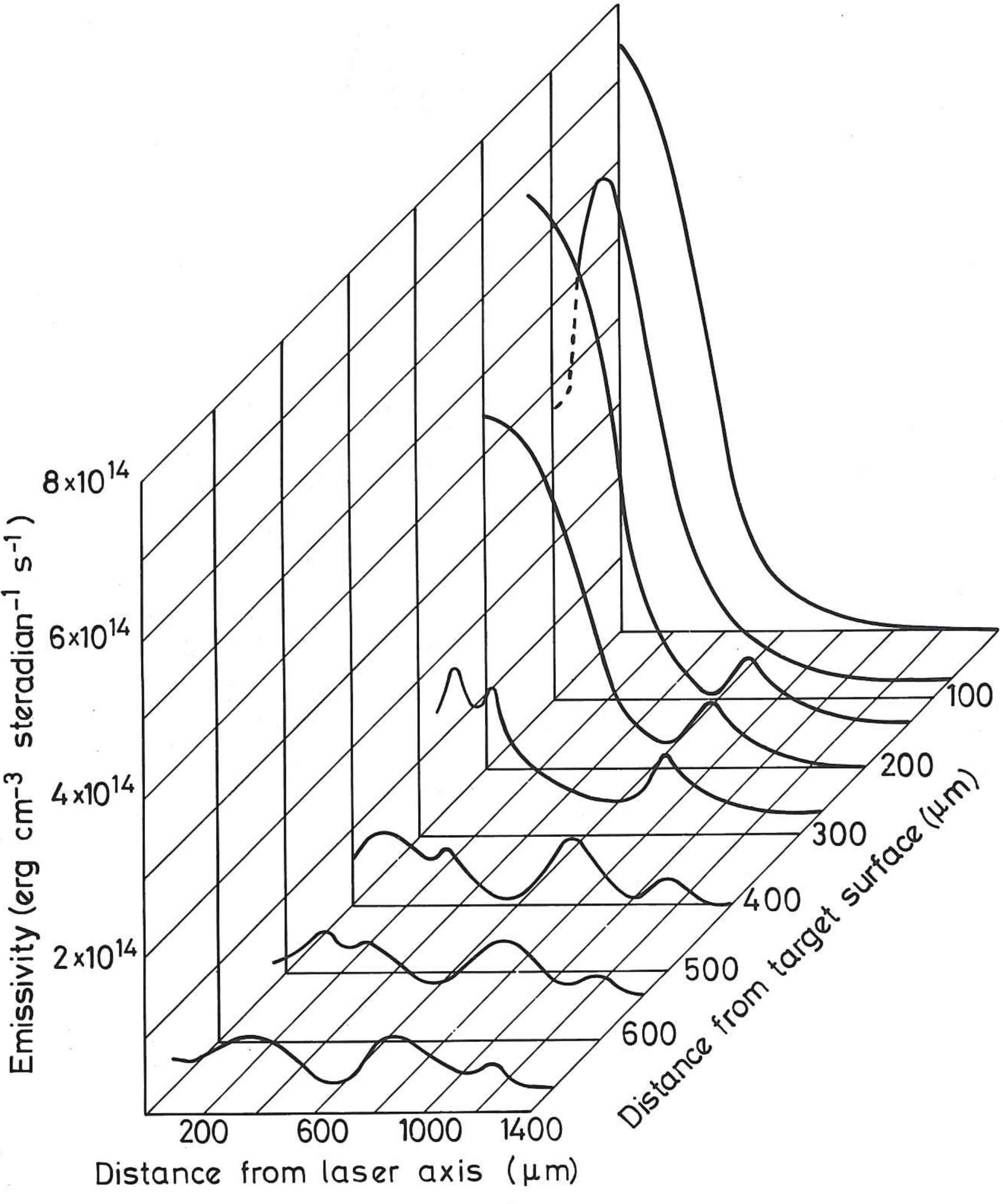

Fig.2 Time-integrated radial X-ray emissivity profiles, after transmission through 0.564 mg cm^{-2} of Al filter.

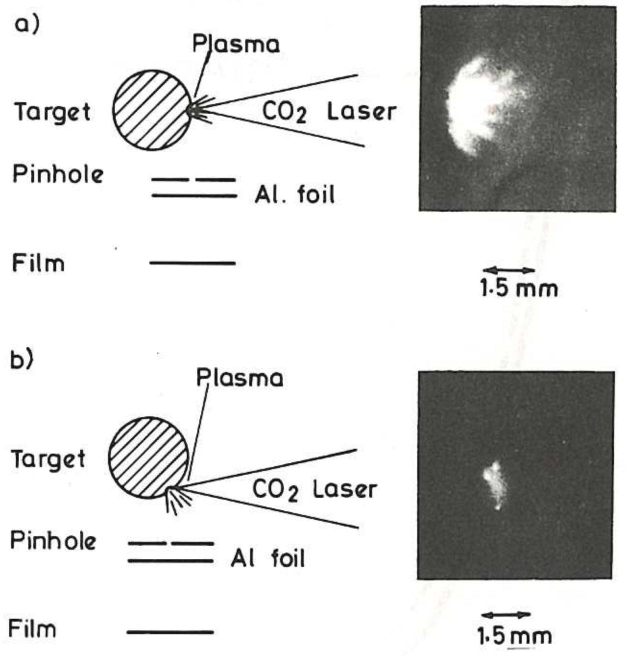

Fig.3 X-ray pinhole photographs, taken with 0.564 $\mathrm{mg\,cm^{-2}}$ of Al filter, with the geometries indicated.

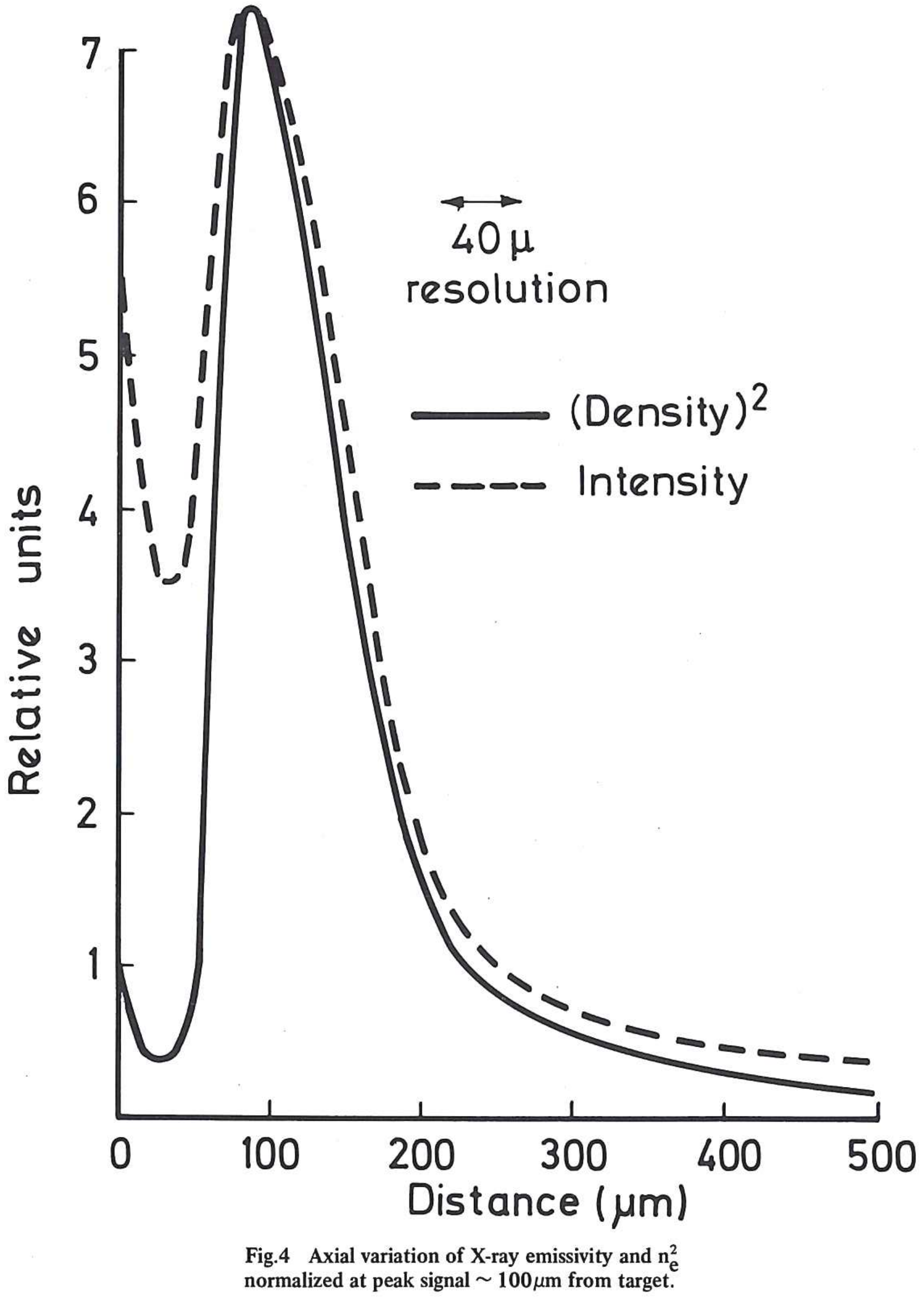

Fig.4 Axial variation of X-ray emissivity and n_e^2 normalized at peak signal ~ 100 μm from target.