Oxford, England, 1979, edited by R. J. Bickerton (Culham Laboratory, Oxford, England, 1979), p. 355.
[14]Y. Ngan *et al.*, Phys. Fluids 20, 1920 (1977).
[15]H. Kimura *et al.*, Nucl. Fusion 19, 1499 (1979).
[16]DIVA Group, Nucl. Fusion 18, 1619 (1978).
[17]K. Odajima *et al.*, to be published.

Self-Focusing of 10.6-μm Radiation in an Underdense Plasma

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Self-focusing filaments have been observed in a long-scale-length plasma irradiated with a 10.6-μm beam containing hot spots. Filaments were observed by use of Thomson scattering from electron plasma waves produced by two-plasmon decay in the walls of the filament, and Fresnel reflection of a visible probe beam from the density discontinuity at the filament boundary.

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In addition to its intrinsic interest, the self-focusing of laser radiation in subcritical density ($n<n_c$) plasmas may present severe problems for maintaining symmetry of energy deposition and implosion in laser fusion targets. Further, the undiagnosed presence of self-focusing filaments in experiments aimed at analyzing the basic physics of high-power laser-matter interactions can severely distort the conclusions drawn from these experiments. Self-focusing thresholds are predicted to be only 10^5 to 10^7 W for any pump wavelength in typical uniform plasmas.[1] Thus in many cases the threshold for self-focusing is less than that for other instabilities. However, self-focusing is much more difficult to observe since the dimensions of a self-focusing filament are expected to be on the order of a vacuum wavelength in diameter.[2] Perhaps the best experimental evidence of self-focusing to date comes from x-ray pin-hole photographs which show small regions emitting hot x-rays spatially correlated with, but smaller than hot spots in a pump beam.[3] These, however, have not been systematically studied. Other studies have been largely based on observing spatial structure in focused backscattered radiation.[4] This method, however, may not necessarily yield an image of the plasma.[5]

We report an experimental investigation of self-focusing using 10.6-μm radiation with the aid of a new diagnostic. Two intensity distributions were used, one containing three hot spots of about equal intensity and ~80 μm in diameter each (structured beam), and the other with an ~200-μm-diam Gaussian spatial profile (uniform beam). Within the limited dynamic range of Kalvar film (~3), no modulation was observed for the uniform beam.

We have directly observed self-focusing of the structured beam in two regions of the plasma: (i) in the low-density region $0.1n_c<n<0.5n_c$ ($n_c=10^{19}$ cm^{-3}) where it was observed by monitoring the Fresnel reflection of a probe (0.53 μm) beam from the density discontinuity, and (ii) in the high-density region $n_c>n>0.25n_c$ where it was observed by use of Thomson scattering from electron plasma waves generated at $n=\frac{1}{4}n_c$ ($\omega=\frac{1}{2}\omega_0$) and at $n=n_c$ ($\omega=\omega_0$), both from within the same scattering volume. No evidence of self-focusing of the uniform beam was found even at incident intensities up to $I=10^{13}$ W/cm^2.

In addition to the direct evidence listed above, other (indirect) evidence is consistent with the hypothesis of self-focusing in the structured beam. Qualitatively different behavior was observed between the structured pump and uniform pump cases in (1) the level of backscattered 10.6-μm radiation and, (2) the plasma temperature profile.

The experiment was performed on a long-gradient-scale-length carbon plasma [$L=(d\ln\chi/dx)^{-1}\simeq 300$ μm] described previously.[6] The 10.6-μm beam consisted of a train of 4-ns (full width at half maximum) pulses separated by 120 ns.[7] The pulses acted on the plasma independently and only the largest was probed.[6] Interferometry and Thomson-scattering data were taken simultaneously on every shot with a 1-ns probe pulse of 0.53-μm radiation. This provided a routine monitor of the electron and ion temperatures and the plasma density.

In the density range $0.1n_c < n < 0.5n_c$ we observed an anomalous component in the large-angle (135°) scattering signal in addition to the usual Thomson-scattering spectrum when and only when the structured 10.6-μm beam was incident upon the plasma with a power density $>10^{11}$ W/cm^2. This new component was unshifted from the probe-laser frequency and displayed a strong dependence on the incident 10.6-μm power density. The spectral width of the unshifted component was less than 0.5 Å and unresolved. The 10.6-μm power dependence of the unshifted signal, normalized to the thermal component of the spectrum, is shown in Fig. 1 for $n = 0.16n_c$ and $n = 0.4n_c$. At $0.16n_c$ a clear threshold and saturation behavior was observed while at densities $n > 0.5n_c$ the unshifted component was not observed.

The above characteristics of the anomalous signal cannot be accounted for by scattering from any of the normal modes of the plasma. Moreover, the anomalous signal was only present when the plasma was irradiated with the structured beam and then, only for $I \gtrsim 5 \times 10^8$ W/cm^2. Finally, since the frequency shift was less than 0.5 Å (the limit of our resolution), the velocity component of the anomalous source in the direction of the scattering k vector must be less than 1.5×10^6 cm/sec. This is less than $\frac{1}{3}$ of the measured thermal sound velocity of $\sim 4 \times 10^6$ cm/sec. These characteristics are consistent with the existence of self-focusing channels in the plasma leading to Fresnel reflection at a discontinuity in the electron density profile at the channel boundary. For $n \sim 0.2n_c$ and for an initial (measured)

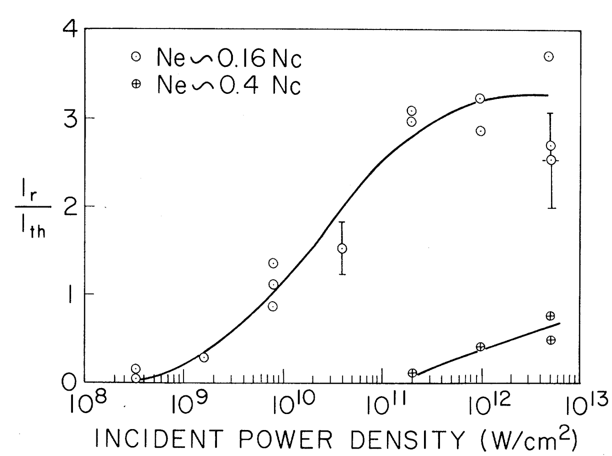

FIG. 1. The 10.6-μm power dependence of the unshifted scattered signal, normalized to the thermal component of scattered spectrum for $n = 0.16n_c$ and $n = 0.4n_c$.

electron temperature of $T_e \simeq 10$ eV, the laser power density required for the 10.6-μm-radiation pressure to balance the plasma pressure is $I \sim 0.8 \times 10^{11}$ W/cm^2. Including heating during the laser pulse (T_e reaches ~30 eV) the required intensity is $I \sim 2.5 \times 10^{11}$ W/cm^2. The threshold intensity implied by Fig. 1 corresponds to the predicted threshold $I \sim 10^9$ W/cm^2 for self-focusing[1] while saturation[2] is predicted to occur at intensities of $I \sim 10^{13}$ W/cm^2.

The above interpretation can qualitatively account for the relative signal strength of the shifted (thermal scattering) and nonshifted (reflected) component. Thomson scattering is observed from a plasma volume of $\sim 10^{-5}$ cm^3. As such, the signal strength at $n \sim 0.16n_c$, scattered into 4π sr, is $I_{\rm thres} \sim 3 \times 10^8 I_0$. Normal-incidence Fresnel reflection from an electron density discontinuity of 1.6×10^{18} cm^{-3} leads to a reflected intensity of $I_r \sim 2 \times 10^8 I_0$. If one makes the (over)simplification that the reflected signal is distributed equally over 4π sr, a remarkable qualitative agreement is found with experimental results. In practice, of course, a true density discontinuity is not possible. The observation of a significant reflected signal implies a minimum radial density scale length $l \lesssim 0.53$ μm$/2\pi \sim 0.1$ μm for the plasma. This is a surprising result and to our knowledge such scale lengths have never been predicted, nor measured in any laser-plasma-interaction experiment. It should be noted, however, that in the ambient plasma, the Debye length is only ~0.01 μm while a thermal electron entering a filament which is supported by a 10^{13}-W/cm^2, 10.6-μm beam with a radial intensity profile given by $\exp(2\pi/\lambda_{\rm pump})$ (characteristic of an evanescent wave in a metal) will be reflected in ~0.1 μm.

At higher electron densities the observed decrease in $I_r/I_{\rm thres}$ could be the result of (i) the background thermal-scattering level which must increase with increasing density, (ii) a decrease in the cross section of the filament (for $I \sim 10^{12}$ W/cm^2 and an 80-μm-diam focal spot, steady-state self-focusing is expected in ~240 μm),[8] and/or (iii) a change in the radial density scale length of the plasma.

The lack of an observed unshifted signal for $n > 0.5n_c$ may reflect the combined effects of the above and/or that the filament decays in the high-density region. Forward scattering provides strong evidence that the latter does not occur.

Forward (20°) Thomson scattering was used to monitor the collective behavior of the plasma.

Experiments carried out with the uniform pump beam have demonstrated that it is possible to observe the signal scattered from the nonlinearly enhanced electron plasma waves having a frequency $\omega = \frac{1}{2}\omega_0$ (a signature of the $n = \frac{1}{4}n_c$ region due to two-plasmon decay)[6] and a frequency $\omega = \omega_0$ (a signature of $n = n_c$ because of parametric decay instability and/or resonance absorption). In our plasma these regions are separated by $\gtrsim 1$ mm, or more than 7 times the spatial resolution of the scattering system. With the structured beam, however, we observed electron plasma waves $\omega = \frac{1}{2}\omega_0$ and $\omega = \omega_0$ within the same scattering volume (Fig. 2) throughout the electron density range $\frac{1}{4}n_c < n < n_c$. The presence of such strong signatures of the two distinct densities within the same scattering volume (diameter 150 μm) indicates a strong profile modification (scale length <40 μm). Such a dramatic change in the initial density profile, if it occurs over the whole pump beam profile, should be resolvable by use of interferometry. However, we find no evidence of it. (Filaments with diameter on the order of one or two vacuum wavelengths are unresolvable in an ambient density of $\lesssim n_c$ with visible interferometry.)

The signature of the $2\omega_p$ decay is observed at all (background) electron densities (measured interferometrically) between n_c and $\frac{1}{4}n_c$. This indicates the $2\omega_p$ decay takes place along the filament walls. Growth is possible in the long scale length presented along the direction of the beam path,[9] and $\frac{1}{4}n_c$ clearly represents an upper bound to the density inside the filament.

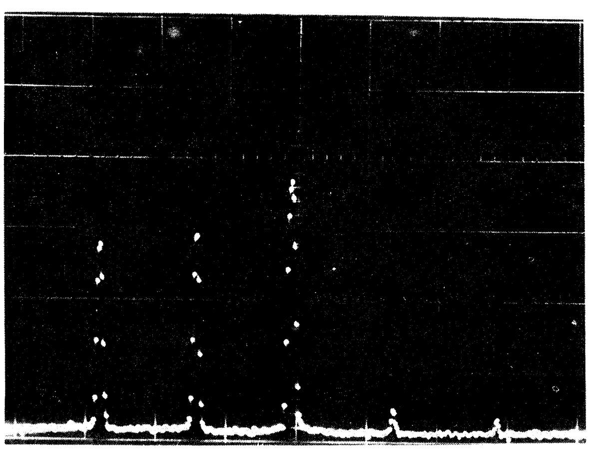

FIG. 2. Forward (20°) Thomson scattering at an ambient $n = n_c$. The scattered signal is composed of the ion feature (central peak) and two sets of electron satellites with shifts of approximately $\frac{1}{2}\omega_0$ and ω_0, respectively (ω_0 is the frequency of the pump 10.6-μm beam). The dispersion in the picture is approximately 100 Å per division.

The self-focusing of the structured beam is observed with a threshold of $\sim 10^9$ W/cm^2. However, we have found no evidence of self-focusing with the uniform beam up to a power density of $\sim 10^{13}$ W/cm^2. This different behavior can be explained by the length and/or time scales required for self-focusing for both configurations. For the structured and (unstructured) uniform beams the self-focusing scale lengths[8] are approximately 240 and 1800 μm, respectively. The self-focusing times are given by the acoustic transit time across radius of the filament[2] and these are, respectively, 1 and 3 ns. Furthermore, as the beams penetrate into higher electron densities, plasma pressure increases so that the effect of self-focusing is even less important for the uniform beam than the above estimates would indicate.

The conclusion that filamentation is occurring in the structured beam but not in the unstructured beam implies a number of observable consequences, of which we have chosen to verify two. The plasma profile as seen by the incoming 10.6-μm photons should be very different for the structured and unstructured beam. In the present experiment, with the uniform beam we observe $\sim 55\%$ reflectivity of the incident 10.6-μm light as monitored through the focusing optics. However, if filamentation occurs, the reflectivity must decrease due to the smaller value of $\int n\,dl$ along the path of the incident 10.6-μm beam, and/or saturation of Brillouin scattering which may occur due to the higher fluxes associated with self-focusing filaments. We observed with the structured beam that the 10.6 μm light reflected back through the focusing optics represents only (10–15)% of the incident energy, and, of course, a large portion of this may be due to much higher reflectivity early in the pump pulse, before the filament can be fully formed. The above result clearly implies that filamentation can yield misleading results in the interpretation of experiments showing saturation of Brillouin scattering where pulse durations are greater than hydrodynamic response time of the plasma, and/or the plasma dimensions greater than self-focusing scale length.

Finally, Thomson-scattering measurements have shown[10] that long-density-scale-length plasmas establish "inverse" electron and ion temperature profiles (i.e., higher temperature at n_e

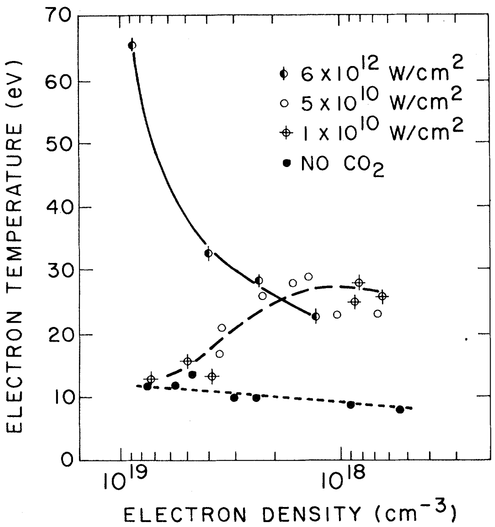

FIG. 3. Electron temperature vs ambient electron density measured by large-angle (135°) Thomson scattering, for different 10.6-μm intensities.

$\sim 0.1 n_c$ than at $n_e \sim n_c$) when pumped with a 10.6-μm beam (10^{12}–10^{13} W/cm^2) focused to a uniform 200-μm-diam focal spot. These inverse profiles appear to be due to the limited penetration (the result of Brillouin scattering) of the pump beam. In the present experiment, and with the structured beam, we observe the maximum temperature near n_c (Fig. 3) for incident powers above 10^{12} W/cm^2. In the presence of self-focusing an inverse temperature profile is only observed at incident power levels of $<10^{11}$ W/cm^2 as shown in Fig. 3. It, therefore, appears that self-focusing allows the laser radiation to penetrate to regions of higher density ($\sim n_c$) where it is effectively absorbed.

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[1]J. F. Drake, P. K. Kaw, Y. C. Lee, G. Schmidt, C. S. Liu, and M. N. Rosenbluth, Phys. Fluids 17, 778 (1974).

[2]P. Kaw, G. Schmidt, and T. Wilcox, Phys. Fluids 16, 1522 (1973); C. E. Max, Phys. Fluids 19, 74 (1976).

[3]R. A. Haas, M. J. Boyle, K. R. Manes, and J. E. Swain, J. Appl. Phys. 47, 1318 (1976); H. D. Shay *et al.*, Phys. Fluids 21, 1634 (1978).

[4]A. Ng, D. Salzmann, and A. A. Offenberger, Phys. Rev. Lett. 43, 1502 (1979); G. R. Mitchel, B. Grek, T. W. Johnston, H. Pepin, and J. C. Kieffer, Bull. Am. Phys. Soc. 24, 1105 (1979).

[5]The phase conjugate nature of Brillouin-scattered light is well documented in liquids, even in the presence of self-focusing. Evidence presently available, although not conclusive, suggests that Brillouin-backscattered radiation from plasmas may be also phase conjugated. If this is the case, the backscattered beam is the time reverse of the input beam and can carry no information about the transverse spatial profile of the plasma.

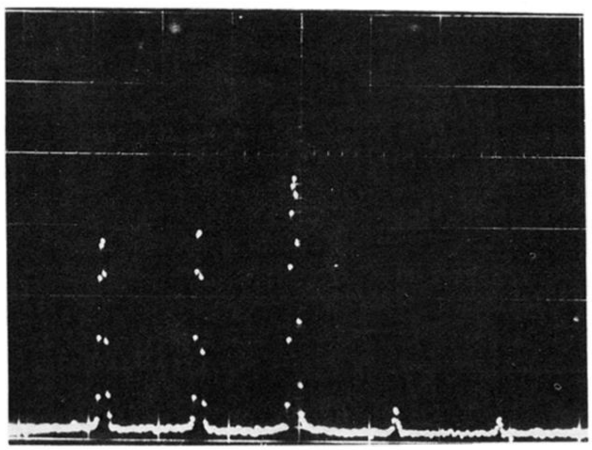
[6]H. A. Baldis, J. C. Samson, and P. B. Corkum, Phys. Rev. Lett. 41, 1719 (1978).

[7]P. B. Corkum and A. J. Alcock, Opt. Commun. 26, 103 (1978).

[8]R. E. Kidder, in *Proceedings of the Japan–U. S. Seminar on Laser Interaction with Matter, Kyoto, Japan, 1972,* edited by C. Yamanaka (Japan Society for the Promotion of Science, Tokyo, 1973).

[9]A. B. Langdon and B. F. Lasinski, Phys. Rev. Lett. 34, 934 (1975).

[10]H. A. Baldis, P. B. Corkum, and N. H. Burnett, in *Proceedings of the IEEE International Conference on Plasma Science* (IEEE, New York, 1979), Paper No. 5A6, p. 128.



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