Direct observation of laser beam filamentation in an underdense plasma

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By using optical Fourier-transform techniques, we have obtained photgraphs of plasma density striations in the focal region of a 350-MW CO_2 laser beam focused by an $f/7.5$ lens into a plasma with density $0.1n_c$. The observed spatial frequency and the estimated density change imply that the striated regions are also the regions of self-trapped radiation channels.

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Self-focusing of laser radiation in plasmas with subcritical densities is of current interest because underdense plasmas, hundreds of wavelengths long, ideal for filamentary break-up of the laser beam, will be created when break-even laser-fusion targets are irradiated. The self-focused filaments not only spoil the symmetry of energy deposition but may also trigger parametric instabilities that lead to back- and side-scattering of the beam and the production of hot electrons via the Raman and two-plasmon decay instabilities. Evidence for self-focused filaments in laser-produced plasmas[1] is available from hot spots in x-ray pinhole photographs, time-resolved x-ray emission, and Thomson scattering from plasma waves produced by two-plasmon decay in the filament walls; but until recently[2] there had been no direct evidence for the density perturbations produced by the filaments.

In this letter we report on an experimental investigation of self-focusing of 10.6-μm laser radiation in a totally underdense ($n_e \sim 0.1n_c$) hydrogen plasma. Direct evidence for the break-up of the CO_2 laser beam into self-trapped beamlets has been obtained by using optical Fourier-transform techniques to image the density filaments and by correlating them with the transmitted pulse shape.

The experimental investigation of self-focusing was carried out on an 8 cm long, 6×10^{16} cm^{-3}, 25-Torr, partially ionized hydrogen-arc plasma altered by focusing a 350-MW, 50-ns (FWHM) CO_2 laser pulse using an $f/7.5$ lens. The plasma density characteristics were monitored by ruby-laser interferometry. The detailed evolution of the plasma, as a laser-supported ionization wave bleaches its way across the preionized gas, is described in a previous publication.[3] At the peak of the CO_2 laser pulse the radial plasma density profile was as shown in Fig. 1 with an on-axis density of $0.1n_c$. At this time the axial extent of the laser altered plasma upstream of the best focus was about 1 cm with a density of $0.1n_c$ everywhere except at the ionization front where the density was up to $0.17n_c$. In addition, the transmitted pulse shape was monitored by focusing the entire transmitted beam onto a photon drag detector. The plasma temperature without the laser heating was measured spectroscopically (ratio of H_β line to continuum) to be 5 eV. The temperature of the laser-altered plasma was estimated from the spectrum of the Brillouin backscattered light to be 50 eV. To probe for the rarefied-density channels characteristic of self-focusing, the method of "dark-field"[4] was used (Fig. 2). A carefully spatially filtered, parallel ruby-laser beam, 1.5 mm in diameter and a few MW in power, traverses the plasma at right angles to the CO_2 beam. The phase of the intially plane wavefront is perturbed by regions of varying density. This phase perturbation is then transformed into amplitude perturbation in the Fourier transform (FT) plane by a lens. The trick in obtaining very high contrast images of the filaments lies in the fact that we can guess the far-field diffraction pattern or the FT of the filamentary density striations. This then enables not only the fundamental but also nearly all the other spatial frequencies except the FT of the density striations to be filtered out by placing a suitable mask in the FT plane. In

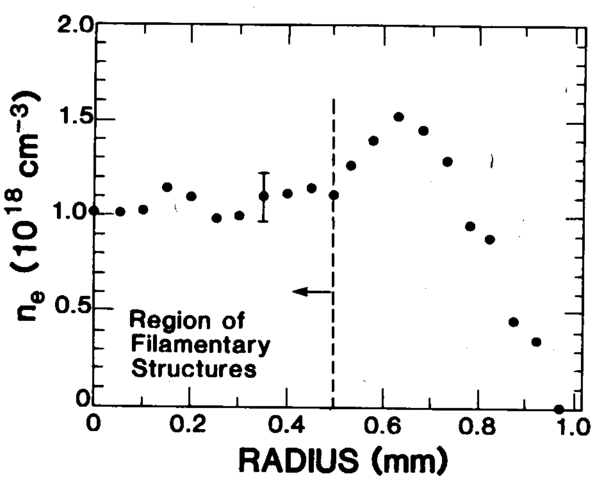

FIG. 1. Radial density profile of the laser-altered hydrogen plasma at the peak of the pulse. The density on axis is $0.1n_c$.

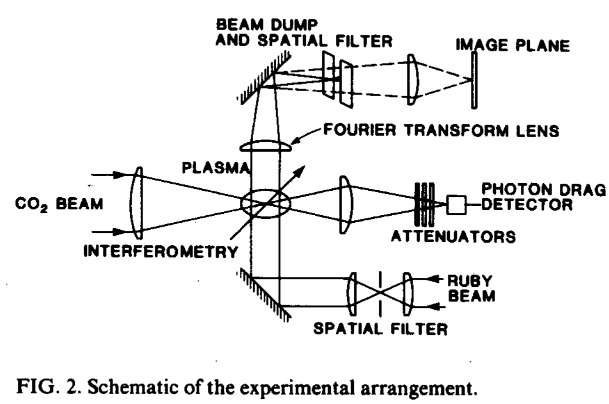

FIG. 2. Schematic of the experimental arrangement.

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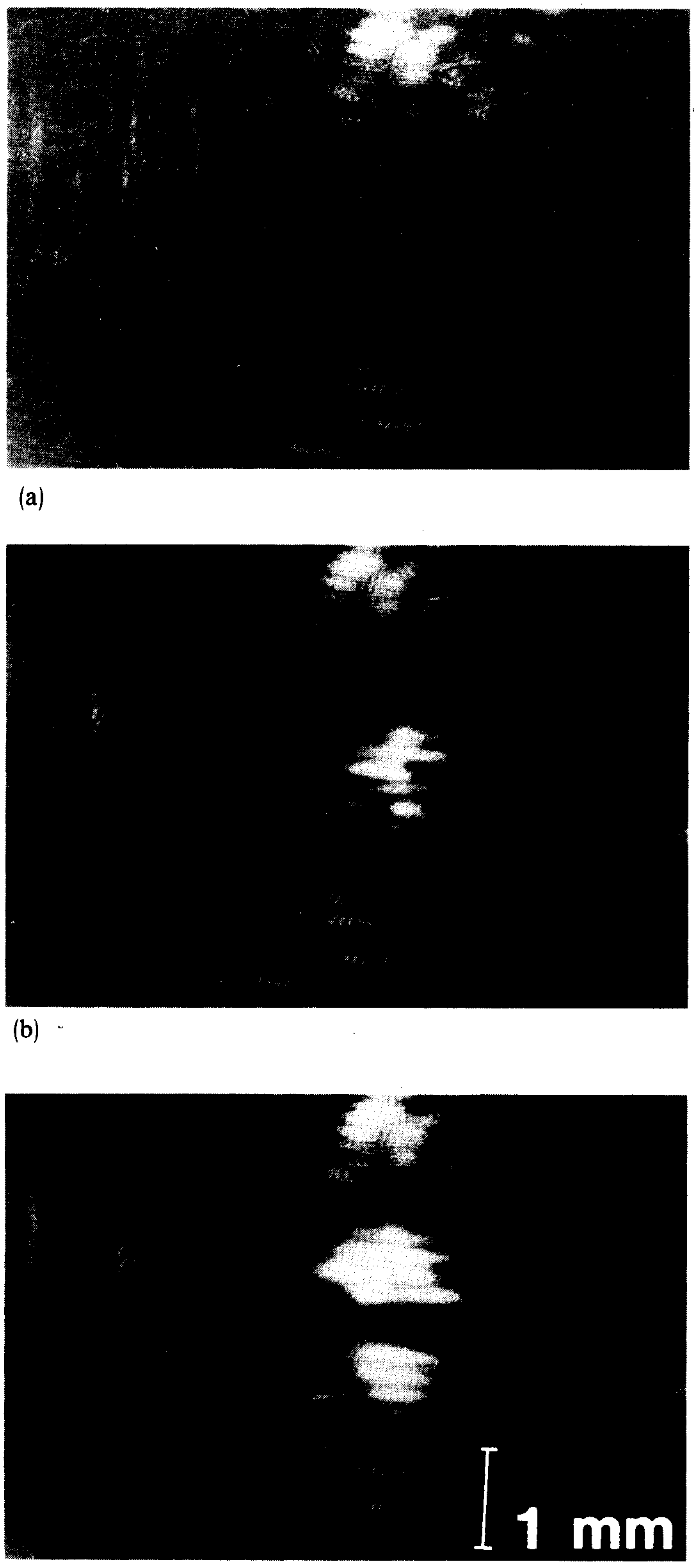

FIG. 3. Photographs of the image plane with (a) preionized plasma alone and (b) and (c) plasma plus CO_2 beam at the peak of the CO_2 laser pulse. The striations in (b) and (c) have $k = 250\ cm^{-1}$.

the present setup, highest contrast images are obtained when a 1 mm diameter beam block is used to dump the main beam (the fundamental frequency) and a 4 mm wide slit perpendicular to k of the CO_2 beam (to allow the diffraction pattern of the filaments to pass through it) is placed in the focal plane of the FT lens. Spatial filtering in this plane, followed by imaging the object plane (the plasma), then enables one to obtain photographs of the regions of the plasma causing the phase perturbation. Although, the phase change can be extremely small because $\omega \gg \omega_p$, this method allows them to be detected down to 0.01π rad if the intensity of the probe beam is high enough. In the present setup the spatial resolution of the optical system was found to be better then 20 μm by using a two-dimensional phase grating in place of the plasma.

Figure 3(a) shows a photographic result of the null test: the arc plasma with no CO_2 beam. The ruby-probe beam produces no significant exposure at the image position, which is located at the center of the photograph. The background exposure seen in this photograph is common to the subsequent photogaphs in Figs. 3(b) and 3(c), which do show clear evidence for filamentary density perturbations when the CO_2 beam is fired into the arc plasma. It should be noted that interferograms of the plasma at these times clearly show that the radial extent of the laser-altered arc plasma is greater than the size of the ruby-probe beam. The main feature of these photographs is that although the measured half-energy vacuum focal spot diameter was only 300 μm, density striations cover a region over 1 mm wide. If we assume that these striations are correlated with self-trapped radiation channels, then it would appear that the beam fails to focus down to its vacuum spot size when the preionized plasma is present. Instead, it breaks up into individual beamlets, $\leqslant 200$ μm wide, with $k = 250\ cm^{-1}$. Indeed, the spot size 1 cm upstream from the best focus, which is also roughly the axial extent of the laser-altered plasma, is about 1 mm. Also, the nearly constant width of the striations along their length would imply self-trapped radiation channels,[5] in which the individual beamlets are nondiffractiing, rather than self-focusing filaments. Another feature frequently observed was the beam breakup into two distinct lobes. This is attributable to the near-field beam profile, which because of the Cassegrain optics used on the final amplifier, also has a two-lobed structure. It should be noted, however, that the observed k of the structure within the lobes cannot be attributed to the near-field distribution since the beam is not similarly modulated. The phase change required to give the observed exposure in the image plane can be estimated to first order by assuming that the intensity of the light in the image plane is proportional to the square of the phase perturbation. For an estimated phase change of $0.16 + 0.08$ rad. we calculate a density change of $4 \pm 2 \times 10^{17}\ cm^{-3}$ if the striations are filaments 200 μm in diameter or of $8 \pm 4 \times 10^{16}\ cm^{-3}$ if the striations are rectangular slabs $200 \times 1000\ \mu$m in cross section. The density limit given below favors the latter interpretation.

In collisionless plasmas, ponderomotive self-focusing of the incident beam[6] can occur if $v_0^2/v_{th}^2 = 0(1)$, where v_0 and v_{th} are the electron oscillatory and thermal velocities, respectively. For the initial plasma conditions, assuming a beam diameter of 1 mm, we have $v_0^2/v_{th}^2 \simeq 0.36$; and the most unstable wavenumber[6] given by $k_\perp = (\omega_p/c)(v_0/2v_e)(1 + T_i/ZT_e)^{-1/2} = 196\ cm^{-1}$ is somewhat smaller than the

(a) (b) (c)

FIG. 4. (a) Incident laser pulse; (b) transmitted pulse at 50 MW input power; (c) sam: at 350 MW. The timescale is 20 ns per division.

experimentally observed value of 250 cm^{-1}. On the other hand, assuming the final plasma density of 10^{18} cm^{-3} and the heated temperature of $\simeq$50 eV, we obtain $k_{\perp} \simeq 350$ cm^{-1}, which is somewhat larger than the observed value.

Correlation of the transmitted pulse shape with the time of occurrence of the density striations shows that the latter occur during the high density, heated phase of the plasma. In Fig. 4 we show the incident and transmittted pulse shapes at two power levels. At low power, roughly 50% absorption occurs throughout the pulse. At high power, the transmitted signal shows that during the rise of the pulse strong ionization (leading to a rapid increase in the plasma density) results in almost total absorption of the beam. Then follows a 30–40 ns period of transparency, during which we observe strong density striations. This increase in transmission can be caused by the filamentation or can simply be explained by the reduction in classical absorption ($\propto T_e^{-3/2}$) as the plasma heats from 5–50 eV. Following this period, during which the laser beam is strongly transmitted, we observe a second period of strong ($\simeq$80%) absorption, which is not understood, unless the transparency is induced by filamentation, and the filaments collapse.

In the absence of absorption, the steady-state change in plasma density inside the filament is estimated from pressure balance to be 7×10^{16} cm^{-3}, assuming intensity $I \simeq 2\times10^{11}$ $\mathrm{W/cm}^2$, $T_e \simeq 50$ eV, and $T_i \simeq 15$ eV inside the filament. However, this number is very sensative to I, T_e, and T_i, and can be considered as an upper bound. It is reasonably consistent with the intepretation of the images as beam breakup into slabs with k in the direction along the wave E-vector. We speculate that the reason for beam break up into slabs (when the ponderomotive force is symmetric) is that filamentation is in competition with Brillouin sidescatter, which occurs preferentially in the direction perpendicular to **E**. Further work with simultaneous observations of Brillouin sidescatter and filamentation is necessary to resolve this issue.

Finally, we note that the thermal self-focusing cannot be ruled out in our present experiment. For the initial plasma conditions ponderomotive self-focusing is probably dominant, however as the plasma density increases from 6×10^{16} cm^{-3} to 10^{18} cm^{-3} both thermal and ponderomotive self-focusing may be occurring simultaneously.

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