

LASER-PLASMA FILAMENTATION IN ICF PLASMAS: WHAT CAN BE LEARNED FROM IMAGING FILAMENTED LIGHT?

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As remarked elsewhere [1], even though filamentation and self-focusing involving realistic laser beams and real plasmas can be quite complicated, there is considerable exploration utility [2,3] in a Ponderomotive potential version of the generalised Nonlinear Schrödinger Equation (= PNLSE). The PNLSE (which is relatively inexpensive to explore numerically) represents, in the paraxial approximation, a local inertia-less or equilibrium between light and plasma pressures. In normalised form (for details see [1] or [2]) the PNLSE is as given next. Here z is the distance (or time) following a transverse beam slice, ∇_{\perp}^2 is the transverse Laplacian operator, and the last term is the modification in refractive index from the plasma density reduction due to the ponderomotive potential from the normalised laser energy density uu^* .

$$\left(i \frac{\partial}{\partial z} + \nabla_{\perp}^2 + \left(1 - e^{-|u|^2} \right) \right) u = 0$$

For applications to Inertial Confinement Fusion the incoming light (which is far from being in a transversely coherent state in the first place) has had its transverse wave spectrum energy shifted to higher transverse wavenumbers by the use of Random Phase Plates (RPP). The transverse structure of an RPP beam (commonly referred to as “speckles”) varies with distance, each speckle having an effective length whose average length (the speckle length) is known, but whose details vary essentially randomly from one speckle to another. In contrast, therefore, to many theoretical studies of self-focusing where one begins with a light beam with a phase structure that is “flat” (i.e. spatially transversely uniform), here the beam phase is very nonuniform. Also the ICF-relevant transverse boundary conditions are not open as in the single-beam case (as in [2,3]), but two-dimensionally periodic [1]. The challenge here is to investigate what can be learned from the study of the light emerging, from where the filamentation has occurred, through a realistic gradually decreasing plasma density.

The two particular examples to be discussed next illustrate the general nature of the resulting behaviour. These are taken from a series of runs of a PNLSE code used previously [1] with uniform density. Here the density varies with z , and the density normalization is to the peak value (necessarily less than the critical value n_c) of electron density (here $0.125n_c$). The gradual rise is in the form of $\text{sine}^2[(z-z_R)\pi/2R]$ (here R is $300 \mu\text{m}$) in electron density. The fall in density is of a similar form (but with F replacing R), but simulation runs were examined with various values for R , ranging from essentially 0 to 300 wavelengths. The normalised values used in the cases discussed here correspond to a temperature of 1 keV, a (green) laser wavelength of $0.526 \mu\text{m}$ and a mean intensity of $3 \times 10^{15} \text{ W/cm}^2$ (a normalised intensity of about 0.081) and the dimensions on the Figures are given in μm .

The two cases shown here as examples both have rise length $R = 300 \mu\text{m}$ and the values of the fall length F were set to be (i) $50 \mu\text{m}$ and (ii) $300 \mu\text{m}$. In both cases, when the incoming light reaches the region where the maximum filamentation amplification [1] associated with high-field regions in the speckle ($\approx \exp(\int dz[(n/n_{\text{max}})(uu^*/\langle uu^* \rangle)]^{1/2})$) is significant. From there on speckle structure becomes intensified and quite different from the local speckle structure, up until the peak density ($z = 300 \mu\text{m}$). If the plasma density were then suddenly to be decreased to negligible values, re-imaging the far-field light would provide an exact image of this region, as shown in the upper left-hand frame in the Figures and marked “ $z = 300 \mu\text{m}$ ” in each. With a more gradual decay of plasma, this image is no longer accessible, as we will see in the Figures. After the plasma is left behind (at $z = (300 + F) \mu\text{m}$), the focusing out of the plasma by an external lens nonlinear term is emulated by putting the nonlinearity equal to zero, and propagating backwards, with the corresponding frames placed under their plasma counterparts. It is just this difference in refocusing (i.e. in optics terminology the “non-reciprocity” of the system) which makes it difficult to determine the state of the filamentation deep in the plasma.

Even a modest amount of plasma after the peak drastically reduces the accessibility by imaging. For even the lowest value of F used here, namely, $50 \mu\text{m}$, as shown in Fig. 1, the image of the $300 \mu\text{m}$ plane is completely misleading, showing little or no filamentation, which is in reality quite intense in the plasma. The best image match occurs at $z = 325 \mu\text{m}$, the half-way point, so to speak (where the density is $1/2 n_{\text{max}}$) and the correspondence of the two frames (plasma and image) is quite good. As expected, the vacuum image there, while clearly indicative of the structures in the plasma, the image structures being much less concentrated in the absence of self-focusing in the imaging system, and many filament candidates will be entirely missed.

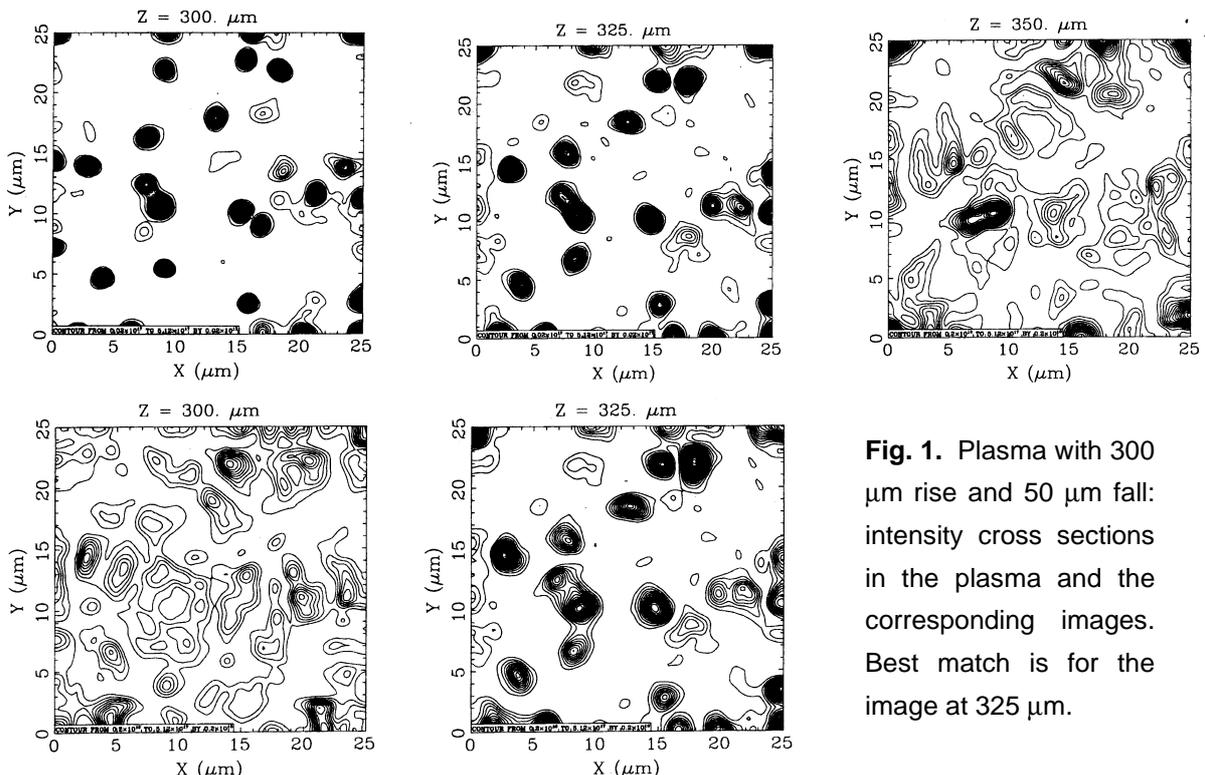


Fig. 1. Plasma with $300 \mu\text{m}$ rise and $50 \mu\text{m}$ fall: intensity cross sections in the plasma and the corresponding images. Best match is for the image at $325 \mu\text{m}$.

As one might expect, the diagnostic situation is much worse with a much slower drop in plasma density, such as shown in Fig. 2, where one now has $F = 300 \mu\text{m}$. Again the best image at $500 \mu\text{m}$ is fairly close to its plasma object, but the electron density at this plane is lower than for the previous case, and the best-focus structures are larger than the previous case. However this best image differs even more drastically than the previous best image from being a good representation of the strong filamentation deep in the plasma at $300 \mu\text{m}$.

From data such as these, some general conclusions are easily drawn. The more plasma one has after the peak to decompress filaments gradually from deep inside the plasma, the less one can know about conditions there. If one could store the light holographically one should choose the image in the plane with the most concentrated structures (which can automated via a spatial Fourier transform analysis). However it seems that one can only infer what might be going on deeper in the plasma by using detailed realistic modelling.

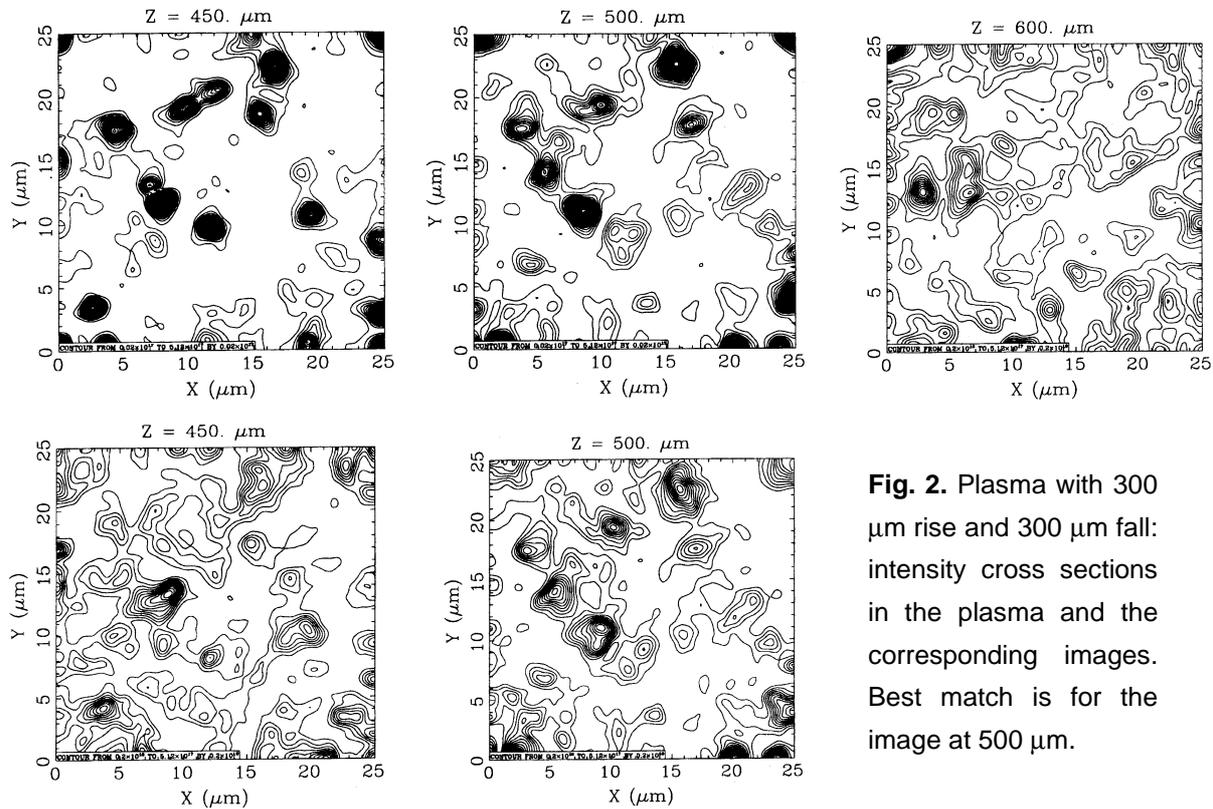


Fig. 2. Plasma with $300 \mu\text{m}$ rise and $300 \mu\text{m}$ fall: intensity cross sections in the plasma and the corresponding images. Best match is for the image at $500 \mu\text{m}$.

References

- [1] T.W. Johnston, F. Vidal and D. Fréchet: *Phys. Plasmas* **4**(5) 1434-1447 (1997).
- [2] F. Vidal and T.W. Johnston: *Phys. Rev. Lett.* **77**(7) 1282-1285 (*Errata* (23) 4852 (1996).
- [3] F. Vidal and T.W. Johnston: *Phys. Rev. E* **55**(3) 3571-3580 (1997)