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Experimental Study of Filamentation in Laser-Plasma Interactions

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Experimental study of filamentation in laser-plasma interactions

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Abstract

The filamentation instability can lead to regions of increased laser intensity when a spatially nonuniform laser beam interacts with a plasma. An experimental technique will be described which identifies the density perturbation produced by filaments. The growth of filaments has been investigated and, when the laser intensity is large enough, the transverse density profile of the filament can be measured. Evidence of filament growth influenced by plasma flow and density gradients is presented.

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I. INTRODUCTION

The filamentation instability can occur when an electromagnetic wave of sufficient intensity propagates through a plasma, and it results in the self-focusing of spatial nonuniformities in the electromagnetic wave front. Filamentation can occur in a variety of situations of interest to plasma physics among which are heating of the ionosphere with rf radiation,¹ microwave heating of tokamaks,² and implosion of inertial confinement fusion targets.³

The filamentation instability continues to be of particular concern to inertial confinement fusion plasmas for many reasons, among which are the requirement for a highly uniform driver for direct-drive implosions, and the potential for enhanced growth of parametric instabilities in the underdense corona. Recently, filamentation has been the subject of a number of computational studies,⁴⁻⁹ some of which have evaluated beam smoothing techniques which should minimize filamentation.^{10,11} Progress in understanding filamentation has been limited by the absence of quantitative experimental results.¹² A fundamental difficulty of previous experiments has been the lack of a well-characterized laser beam so one knows the location, spatial size and intensity fluctuation of the hot spots which seed the instability. The simplest comparisons between theory and experiment that can be made, that of measured and predicted thresholds, have only recently begun.^{3,13}

In this article we will discuss experimental observations of filamentation in laser-produced plasmas. We will focus here on the spatial density profile of filaments as measured by interferometry when the initial laser intensity is relatively high ($\sim 1 \times 10^{15}$ W/cm²). We

also have data demonstrating the growth and refraction of filaments in a density gradient and the influence of plasma flow on the filament growth.

Our technique has relied on several features: 1) direct measurement (by either interferometry or schlieren) of the density perturbation, 2) use of a line focus beam interacting with a preformed plasma, and 3) use of a $1\text{ }\mu\text{m}$ wavelength interaction laser. This technique has allowed us to identify filamentation and find threshold intensities for the instability,³ and identify filaments as a source of emission at the second harmonic of the incident laser frequency.¹³ In the future, we will report on the dependence of the filament growth on the initial perturbation size, and the lack of correlation between the level of stimulated Brillouin scattering and stimulated Raman scattering and the presence of filaments.

In Sec. II, we will describe the experimental technique used to identify filamentation. Instead of relying on secondary processes to identify filamentation, we look directly for the density perturbations produced by the instability. Since the density perturbation due to filamentation is usually small compared to the background density, we tailor the intensity profile of the filamenting beam in order to maximize the probe beam path through the filament.

In Sec. III, we will concentrate on two specific aspects of the filamentation experiment. In the first case, we use a high-intensity line focus to produce a density perturbation whose transverse dimension is large enough to resolve the center and walls of the filament. In the second case, we use a modulated intensity profile to investigate the change in the filament growth and direction in inhomogeneous plasmas. The paper is summarized in Sec. IV.

II. DESCRIPTION OF THE EXPERIMENT

A. Overview of the experiment

Our experiments to date have been set up similarly and have been designed to minimize the threshold for ponderomotive filamentation and maximize the threshold for thermal filamentation. The experiments have been performed on two laser facilities, the Phoenix laser facility at Lawrence Livermore National Laboratory and the Chroma laser at KMS Fusion.

First, a beam with circular focus and a wavelength of $1.06\text{ }\mu\text{m}$ irradiates a CH target. The target has been chosen to be low Z in order to help maximize the threshold for thermal filamentation which varies inversely with Z^2 . Also, for a given amount of laser energy, the plasma expansion velocity will be largest for low Z plasma and will provide the largest possible density gradient scale lengths. The target thickness is generally $1\text{ }\mu\text{m}$ or less, the thickness determines the burnthrough time of the foil which affects the peak plasma temperature and the size of the plasma.¹⁴

Once the plasma has been formed, a second beam irradiates the plasma to produce filamentation. The beam is Gaussian in time with a 100 ps FWHM and has a wavelength of $1.06\text{ }\mu\text{m}$. In some cases, the spatial intensity profile of the beam is modified using an etalon to interfere the beam with itself to produce a striated pattern. The distance between the striations can be varied by varying the angle between the etalon plates to change the wavelength of the perturbation which changes the filament growth. In order to achieve higher intensities ($> 5 \times 10^{13}\text{ W/cm}^2$), the beam is focused to a line.

The density perturbations produced by the interaction beam is detected using a short pulse (< 100 ps) probe beam which has been either $0.35\ \mu\text{m}$ or $0.23\ \mu\text{m}$ in wavelength. The probe beam is collimated and aligned tangential to the intensity striations in the interaction beam. Interferometry can detect the density perturbations, provided they are large enough, or schlieren can be used to detect rays refracted by the filaments.

B. Probing of the filament

In this section, we will further consider the probing of the slab filaments. The main points we wish to make are: 1) the probing method is more sensitive to slab filaments than to filaments which are cylindrical with respect to their direction of propagation (which grow from background noise), and 2) the background intensity fluctuations are generally smaller than the imposed perturbations, and have a wide distribution of spatial sizes, most of which should be below threshold or have growth rates too large to be observed in this experiment. There are also simple tests which we have made to look for growth of background fluctuations. It is important to point out that we have intentionally kept the filament-driving pulse length short in order to limit the number of modes which can grow.

The filamentation instability can, in principle, be identified by detection of either 1) the increase in laser intensity, or 2) the density depression, produced by the filament. Detection of the growth of the laser intensity due to filamentation is difficult in laser-produced plasmas. This is due to the non-uniform nature of such plasmas which contrasts sharply with the classic measurements of self-focusing in gases¹⁵ which act as an intrinsically uniform target medium. The non-uniformities of the laser-produced plasmas can distort

images of the laser intensity distribution imbedded in the plasma. With solid targets, of course, the laser intensity profile is not directly accessible.

A more promising method of detecting filaments is by detecting the effects of the density perturbations produced by filamentation with an optical probe beam which illuminates the plasma in a direction perpendicular to the laser beam and tangential to the line focus or striation in the intensity profile. For instance, the density perturbation can produce a phase shift of the probe beam wavefront relative to the phase shift produced by the background plasma. The relative phase shift is given approximately by

$$\delta\phi \simeq 9 \times 10^{-22} L_{p,\mu} \lambda_{p,\mu} \delta n \quad (1)$$

where $L_{p,\mu}$ is the probe beam path length through the filament (in μm), $\lambda_{p,\mu}$ is the probe beam wavelength (in μm), and δn is the density perturbation (in cm^{-3}). For a filament with a circular cross-section of $10 \mu\text{m}$ (for example), a probe beam wavelength of $0.24 \mu\text{m}$, and a density perturbation of $\delta n_e = 0.1 n_c = 1 \times 10^{20} \text{ cm}^{-3}$, one calculates a relative phase shift of only 0.03 radians compared to a total phase shift of 1.7 radians (if the plasma diameter is $500 \mu\text{m}$). A filament whose cross-section is extended along the probe beam path, however, can still produce a large phase shift regardless of its dimension perpendicular to the probe beam path. In other words, the dimension $L_{p,\mu}$ in Eq. 1 remains unchanged for the slab filament, even if it self-focuses to dimensions comparable to λ_0 .

As an experimental example, we compare the interferograms of plasmas in which the density perturbations are driven by a line focus (see Fig. 1a) and a circular focus (see Fig. 1b). In both figures, we see the interferograms of plasmas which have been produced by a beam which has irradiated a $0.35\text{-}\mu\text{m}$ -thick CH foil. The shadow of the washer that

supports the foil extends vertically in the center of each figure. On both sides of the target plane we see a series of fringes, each fringe represents a 2π phase shift of the probe beam relative to a reference beam. The total phase shift produced by the plasma at any point is calculated by adding up the number of fringes from the outside moving inward. A density depression is indicated by fringes indenting to the right (towards the target plane). Knowing the path length of the probe beam through the plasma we can reconstruct the density profile; in both of the cases shown, the peak density (which is at the target plane) is approximately $0.25n_c$.

We see that in the first case ($I \simeq 1 \times 10^{15} \text{ W/cm}^2$) the density perturbation is easily seen, and for an observed phase shift $\delta\phi \simeq 2\pi$, we find (from Eq. 2, using $L \simeq 300 \text{ }\mu\text{m}$) that $\delta n \simeq 9.3 \times 10^{18} \text{ cm}^{-3}$ which occurs in a background density of $n_e \simeq 1 \times 10^{20} \text{ cm}^{-3}$. In contrast, the perturbation produced by the circular focus is harder to see even though the initial laser intensity ($I \simeq 5 \times 10^{15} \text{ W/cm}^2$) is somewhat higher than in the case of the line focus and we expect it to produce a density perturbation as large (if not larger) than in the case of the line focus. Assuming the same δn in the two cases, we find (for $L_{p,\mu} = 10 \text{ }\mu\text{m}$), $\delta\phi \simeq 0.02$ compared to an observed $\delta\phi \simeq 0.1$.

The density gradients produced by the filaments will refract the probe beam rays and redistribute the intensity profile of the probe beam. In our earliest experiments, we used a dark-field imaging, or schlieren, technique to detect the refracted rays produced by filaments. Since the amount of refraction is also proportional to the probe beam path length through the filament, our arguments concerning interferometry and slab filaments is equally applicable to the schlieren technique.

III. EXPERIMENTAL DATA AND DISCUSSION

A. High intensity interaction beam

If we use a high intensity line focus to interact with a preformed plasma, the filament dimensions become large enough to resolve the walls of the filament, which are at a higher density than the background plasma density, and the center of the filament, which is at densities below the background plasma density. Such a case also shows how the dimensions of the filament change as the laser light propagates into the density profile.

One such case is illustrated in Fig. 2 which shows an interferogram of a plasma in which a prominent filament is driven in a preformed plasma. The plasma was formed with a 1-ns Gaussian, 110 J, $1.06 \mu\text{m}$ pulse which is illuminating a $1 \mu\text{m}$ thick CH foil with a circular spot of $450 \mu\text{m}$ diameter; in Fig. 2, this beam illuminates the left side of the target. The interferogram is taken at a time 300 ps after the peak of the plasma forming pulse. The interaction pulse is a 100 ps Gaussian, 30 J, focused to a line $350 \mu\text{m}$ long and $50 \mu\text{m}$ wide and propagates from the right side of the target.

The density perturbation produced by the interaction beam can be easily seen to the right of the target plane (see Fig. 2a). Refraction of the probe beam rays in the density gradients of the filament walls have redistributed the intensity profile in the image plane of the interferometer so that the higher density walls (indicated by the shift of the fringes to the right) appear to be brighter than the rest of the filament.

The peak density (neglecting the filament) in the plane labeled " $n(x)$ " is $0.1n_c = 1 \times 10^{20} \text{ cm}^{-3}$. Using Eq. 1, and setting $L_{p,\mu}$ equal to $300 \mu\text{m}$ (the length of the line focus), we can convert the perturbation phase shift, $\delta\phi$, to a density perturbation, δn . The

density in the walls of the filament is $1 \times 10^{19} \text{ cm}^{-3}$ higher than the background density; the walls are $7 \text{ }\mu\text{m}$ wide and are separated by $30 \text{ }\mu\text{m}$. The density minimum in the center of the filament is $3 \times 10^{19} \text{ cm}^{-3}$ lower than the background density. Analytic and simulation work is underway to theoretically predict the filament density profile under different stages of growth and for thermal or ponderomotive filamentation.¹⁶

Another interesting feature of the data shown in Fig. 2a is that the filament does not extend past the peak of the density profile, to the other side of the target. This is a common feature of most of our data in which the plasma is underdense, although recent data in which the peak density is low ($< 0.1n_c$) shows filaments which persist on both side of the density gradient. Finite axial extent of filaments might be produced by nonlinear effects at the focus of the filament. Another possible explanation depends on the presence of stimulated Brillouin scattering (SBS) which has been shown theoretically to lower the filamentation threshold in some cases¹⁷. Since the SBS gain is proportional to the density, most SBS should come from the peak of the density profile meaning that filaments would preferentially grow on the plasma facing the incident laser. Significant SBS levels are seen with $1.06 \text{ }\mu\text{m}$ lasers, and this would explain the dependence of the filament structure on the peak plasma density.

B. Low intensity interaction beam

We have also conducted a number of experiments in which the interaction beam has a circular outline but an intensity profile that has been intentionally modulated to produce a number of regularly spaced striations. This technique was used in an earlier report to

quantify conditions under which filaments grow. In this section, we want to look at how filaments evolve spatially in nonuniform plasmas.

Figure 3a shows the interferogram for a plasma which has been formed by irradiating a $1\text{ }\mu\text{m}$ thick CH foil with a $1.06\text{ }\mu\text{m}$ wavelength, 100 J, 1 ns FWHM Gaussian pulse. The interferogram is taken 200 ps after the peak of the plasma forming pulse. The fringes are fairly smooth and appears the same if the plasma is irradiated with an interaction beam which either has an intensity too low or a striation spacing too large, for filaments to grow.

Figure 3b shows the interferogram for a plasma produced under the same conditions as the previous figure. Now an interaction beam with a striation spacing of $40\text{ }\mu\text{m}$ is propagating through the plasma, producing density perturbations. As with the high intensity case discussed in the previous section, refraction of the probe beam leads to the filament walls appearing as high intensity regions in the interferogram. The filaments furthest from the laser axis appear to move away from the axis as they propagate towards the target; this could be explained in part by refraction of the laser in the density profile.

We also see interesting results when the interaction beam propagates at an angle to the plasma ablation flow. In Fig. 4 we see the interferogram for an experiment in which the target plane is approximately 30 degrees with respect to the direction of propagation of both the plasma forming and interaction beams. The plasma ablates primarily in the direction of the target normal which means that the interaction beam propagates at significant angles with respect to the plasma density gradients and the direction of flow.

Filaments are evident in this experiment (see Fig. 4) which bend in the direction of the density gradient which is primarily in the direction of the target normal. This is a

consequence of the refraction of the laser light in the nonuniform plasma.

Another interesting aspect of this experiment is the reduced growth of the filaments in the top half of the interaction beam. These are the filaments which are propagating nearly perpendicular to the plasma flow (those in the lower half are propagating nearly parallel to the plasma flow), because the plasma expansion is two dimensional (as confirmed by 2-D LASNEX¹⁸ simulations). It has been shown in earlier analysis¹⁹ that filaments cannot grow when the plasma flow perpendicular to the filament is greater than the sound velocity, c_s .

IV. CONCLUSIONS

We have described an experimental technique for investigating filamentation of laser light in a plasma. We have shown how this technique allows one to spatially resolve the density perturbation produced by filamentation and how plasma inhomogeneities can modify the propagation and growth of filaments.

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FIGURE CAPTIONS

1. Comparison of the density perturbation produced by a) a line focus beam of length $250\text{ }\mu\text{m}$ ($I_L = 1 \times 10^{15}\text{ W/cm}^2$), and b) a circular focus beam of $50\text{ }\mu\text{m}$ diameter ($I_L = 5 \times 10^{15}\text{ W/cm}^2$) interacting with a pre-formed plasma. The arrow to the left of each figure designates the direction of propagation and the location of the laser axis.
2. a) Interferogram of an experiment in which a high intensity ($I_L = 1 \times 10^{15}\text{ W/cm}^2$) line focus interacts with a preformed plasma. The density perturbation produced by the beam can be seen; in particular, walls with density higher than the background density are formed from the material pushed out from the center of the filament. ;The density perturbation along the ;section labeled $n(x)$ has been plotted in b).
3. Comparison of interferograms a) without and b) with a filament-driving beam incident normal to the target plane. In b) the solid lines to the right of the figure show the initial spacing of the intensity modulations on the interaction beam. The interaction beam has an intensity of $5 \times 10^{13}\text{ W/cm}^2$.
4. Interferogram of a plasma in which both the plasma forming and interaction beams intercept the target at an angle of 30 degrees with respect to the target normal. Both the laser axis and the spacing of the intensity modulations on the interaction beam are shown.

Figure 1

Figure 2

a)

↑
500
μm
↓

Plasma-
forming
beam

└─ Target plane

b)

— Filament
— driving
— beam
—

Figure 3

Figure 4

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