Active stabilization of filamenting high-power laser pulses propagating in low-density plasmas

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Abstract

The stability and nonlinear evolution of a long, low-intensity laser filament (τ_L=400ps, I~10^{10-12} Wcm^{-2}) propagating in an underdense plasma (n_e=10^{19}~10^{20} cm^{-3}) are studied. A 2-D time-resolved sampling diagnostic monitors the beam dynamics. It is found that the filament is not stable as a function of time even for beam power that is few orders of magnitude below the ponderomotive self-focusing threshold. Such instabilities can be reduced by propagating another laser pulse, at similar pulse energy, ahead of the laser pulse.

Introduction

Stable propagation of intense laser pulses through long underdense plasmas is a crucial requirement for laser plasma acceleration schemes, x-ray lasers, high harmonic generation, and inertial confinement fusion (ICF). The effectiveness of all these schemes is reduced when the interaction length is shortened by spatial or angular redistribution of the laser pulse power due to various instabilities taking place in the coupling between the laser and the plasma. For long (~ns), high-power laser pulses, this can take place due to thermal or ponderomotive filamentation, leading to a shortening of the effective propagation length below the Rayleigh length. Here we show (i) that filamentation of high-power pulses is unexpectedly observed at power much lower than predicted, (ii) however stabilization of such filamentation can be obtained using a preceding lower-intensity pulse. This is observed for the first time using a novel technique that allows unprecedented access to the transverse spatial dynamics of high-power laser pulses propagating in plasmas. This method of stabilizing filamentation could be an interesting alternative to the existing techniques since it requires only, in the form

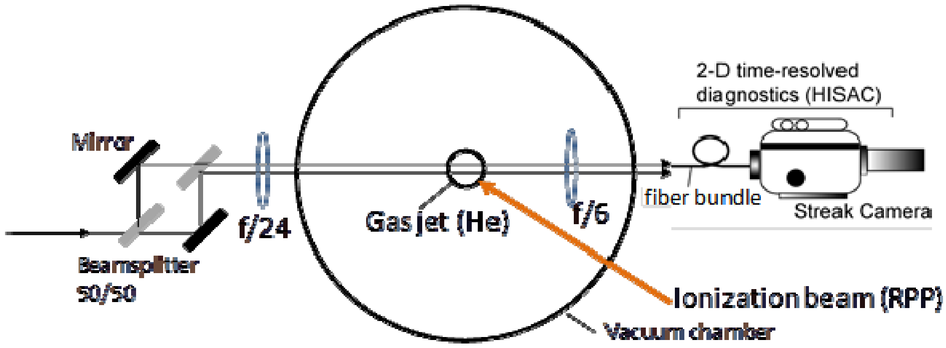

Figure 1 Experimental setup.

of a preceding pulse, a small fraction of the main laser pulse power.

Experimental setup

The experiment was performed using the 100 TW-ELFIE laser facility at the Laboratoire pour l'Utilisation des Lasers Intenses (LULI). A laser pulse of 0.5 - 100 mJ (λ = 1.05 μm, τ_L = 400 ps FWHM duration, horizontally polarized) was focused at a maximum intensity of few 10^{12} $W.cm^{-2}$ onto a supersonic Helium jet with a 1 mm diameter opening. As shown in fig. 1, before focusing, the 90 mm diameter interaction laser beam was split evenly in a Mach-Zender interferometer to produce two replicas of the beam with slight angular separation of at most 0.15 mrad. When focused, this resulted in two spots separated by a variable and controllable distance. The Mach-Zehnder was set to adjust as well the temporal delay between the two replicas of the beam. The beams were focused using an f/24 (f= 2.1 m) lens that produced a focal spot of 60 μm FWHM for each beam. The Rayleigh length of 1.9 mm was larger than the interaction length in the jet (~ 1.5 mm). The on-axis transmitted light was collected through an f/6 large aperture lens. The focal point of the laser was imaged onto a high-speed 2D spatially resolved sampling camera (HISAC) composed of a fiber optics bundle coupled to an optical streak camera [1]. This diagnostic obtained a sequence of time-resolved 2D images with a temporal resolution of ~30 ps. The He-gas was fully ionized 1 ns ahead of the main laser pulse using a spatially incoherent auxiliary beam by means of random phase plates (RPP). This beam produces a 180 × 430 μm spot containing speckles with typical size of 23 μm.

Experimental results - Single beam dynamics

Fig. 2(a) shows the time-resolved 2D transverse profile of the laser beam observed for various

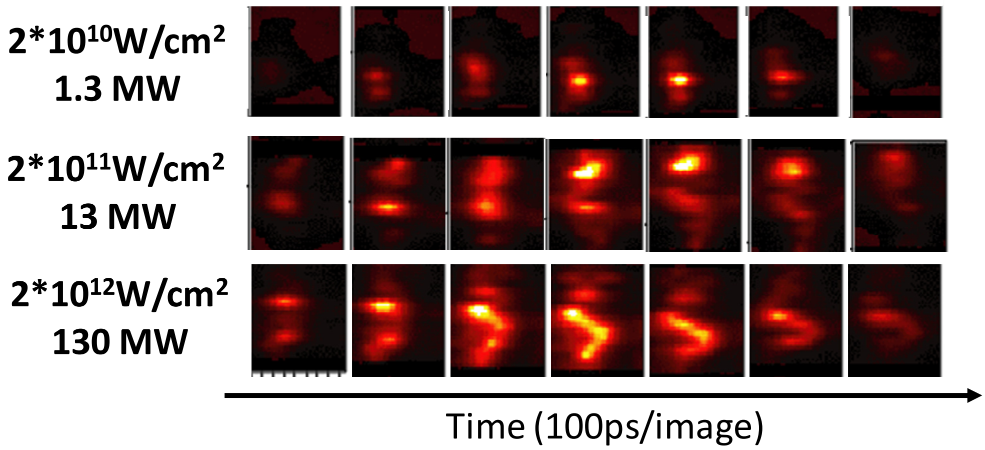

Figure 2 Temporal snapshot of the transverse profile of the laser beam observed by the HISAC diagnostic for various laser intensities. Each image is integrated over 100 ps. Plasma density is 0.032 n_c.

laser intensities. The plasma density through which the beams propagate is 0.015 n_c (at the temporal peak of the interaction pulse), where $n_c = 10^{21}$ cm^{-3} is the critical density of plasmas at the laser wavelength. One can observe that the overall size of the beam depends strongly on the laser intensity (or power), implying a strong nonlinear coupling between the laser and the plasma. The so-called ponderomotive self-focusing threshold P_c is

$$P_c = 32T_{keV}\left(\frac{n_c}{n_e}\right)\sqrt{1-\frac{n_e}{n_c}}\ \text{MW}.$$

where T_{keV} is electron temperature in keV. Under our experimental conditions (0.2keV, n_e=0.015n_c), P_c ~ 200 MW. The phenomena observed in Figure 2 are thus all below the filamentation threshold. The transmittance of the beam at 1- 10 MW was measured to be 80%.

Experimental results - Double beam dynamics

Figure 3 shows the dynamics of laser beams having a temporal separation of 600 ps (peak to peak). Each laser filament has the same laser energy and the same laser power (13 MW, 2 × 10^{11} W cm^{-2} in vacuum) and propagates into a pre-ionized 0.015n_c plasma. Fig. 3(a) shows the vacuum focal spot image that shows a ~70 μm FWHM focal spot.

When the pulses interact with the plasma, the earlier pulse is strongly filamented as has been already seen in fig. 2. However, the trailing pulse exhibits a collimated transverse intensity pattern (see Fig. 3(d)). The spot size of the secondary beam (~55μm FWHM) is even smaller than the vacuum focal spot size (~70μm FWHM). The peak intensity of the secondary beam is approximately 3 times higher than that of the primary beam.

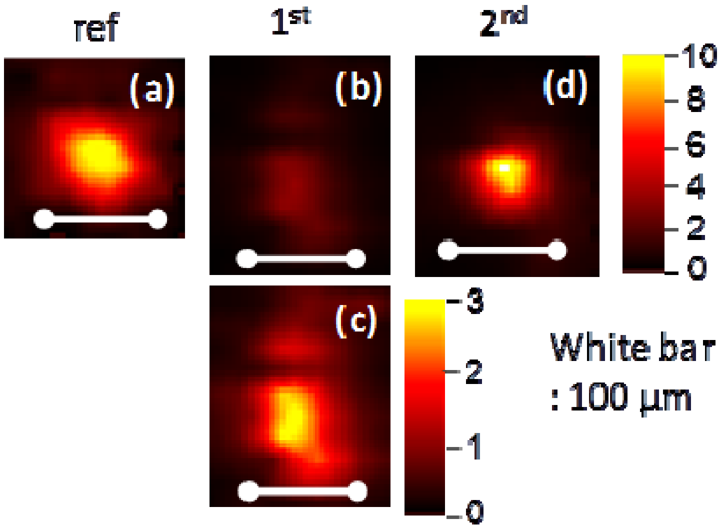

Figure 3 Temporal snapshot of two 5 mJ, 13 MW lasers propagating through a 0.032 n_c plasma with 600 ps temporal delay between them. (a) Spatial distribution of the lasers propagating in vacuum (reference shots). (b)(c) Same as in (a), but for a beam propagating through a 0.032 n_c plasma. (d) Same as (b)(c) but for a trailing beam coming 600 ps (peak to peak) after the first beam. The absolute color scale between (b) and (d) is the same. Each image was integrated over 30 ps. All horizontal bars indicate 100 µm. (c) represent the same image as (b) but the contrast of the image is adjusted to better show the filamented beam pattern. All snapshots are taken around the peak of the pulse.

Discussion and conclusion

We observed unexpected filamentation and active stabilization of laser pulses having power below the ponderomotive filamentation threshold. A 2D/3D hydrodynamic radiation code doesn't show any filamentation under our intensity regime when the beam propagates in a homogeneous plasma. The instability is thus likely liked to plasma inhomogeneities triggered by the auxiliary RPP beam which pre-ionized the He gas 1 ns before the interaction laser. It should be stressed that the observed filementation is not just related to the refraction, as the the filamentation was strongly dependent on the laser power as seen in fig. 2. Further work is required to clarify the underlying physics.

References

[1] M. Nakatsutsumi et al., Nat. Phys. 6, 1010 (2010).