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Space- and time-resolved observation of single filaments propagation in an underdense plasma and of beam coupling between neighbouring filaments

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Abstract
We have performed a systematic study of beam propagation (400 ps, \( I = 10^{10}–10^{14} \text{ W cm}^{-2} \)) in underdense plasmas \( (n_e = 10^{19}–10^{20} \text{ cm}^{-3}) \) at a level of reduced complexity compared with the smoothed beams currently used in inertial confinement fusion studies, using one or two well-controlled filaments. These experiments have been performed on the LULI 100 TW laser facility. The use of well-controlled, diffraction-limited single filaments is possibly due to the use of adaptative optics. We have used either a single filament or two filaments having variable distance, delay, intensity ratio and polarization. The single filament configuration allows to study basic beam propagation and reveals occurrence of filamentation at low intensity levels. The use of two filaments demonstrates the occurrence of beam coupling and merging, and the importance of cross-talk effects supported by the plasma.

(Some figures in this article are in colour only in the electronic version)
Figure 1. Layout of the wave front correction system implemented on the LULI 100 TW facility. The adaptive optic closed-loop system relies on (i) a 100 mm deformable mirror positioned mid-way in the final double pass disk amplifier of the laser chain section and (ii) an achromatic three-wave lateral shearing interferometer used as wave front sensors (SID 1).

measurement of individual filaments impossible. Recently, the use of ‘isolated filaments’ \cite{5,6} (or ‘single hot spots’), i.e. a beam limited by diffraction, made it possible to study the various phenomena related to the propagation of only one of the many filaments which compose a smoothed beam, but indirectly and with time-integrated diagnostics, by observing the angular or spectral distribution of the light in the exit plane of a plasma.

In this paper, we report on an experiment where we used one or two isolated filaments to track fundamental issues related to the propagation in a low density plasma in a regime of interest for ICF and to decipher potential coupling between individual filaments. These filaments are similar to the ones which compose the beams ‘smoothed’ by RPP, i.e. the smoothed beams used in ICF. In this study, we have varied the intensity of the produced filaments as in the beams smoothed by RPP, the speckles that compose the beam have a very broad distribution of intensities over the statistical ensemble.

The experiments were performed using the LULI 100 TW laser facility. As shown in figure 1, this laser includes wavefront correction using a deformable mirror coupled to a wavefront analyzer so that the focal spots can be diffraction limited \cite{7} (see figure 2). The chain can deliver ~60 J of total energy laser at a wavelength $\lambda = 1 \mu m$ and with a duration of 400 ps FWHM.

The general set-up of the experiment is shown in figure 3. The laser beam is horizontally polarized (i.e. in the plane of the figure). The main part of the laser beam is used uncompressed, as the interaction beam, the propagation of which is studied. Another fraction of the laser beam (~25 J) is recompressed in a vacuum compressor.

As shown in figure 3, the interaction beam was send through a Mach–Zender interferometer in order to be able, at will, to create one (by blocking one arm of the interferometer) or two filaments, to vary their separation at focus (see figure 4), their states of polarization and their intensities. The advantage of using the Mach–Zender is that we could split the laser beam
Figure 2. (Left) Azimuthally averaged radial profile of a measured focal spot with wavefront correction. The focusing is done by an f/24 diffraction-limited lens. (Right) Encircled energy for the same focal spot showing a Strehl ratio of 0.5. Here the spot has a 60 µm FWHM due to the f/24 focusing optics. Smaller (micrometre scale) spots, typical of random phase plate based smoothing technique, can be produced as well, provided that the shorter focal length optics are used.

Figure 3. Experimental set-up for analyzing the propagation of one or two filaments focused to the diffraction limit and the coupling of such two filaments. The beam injected into the Mach–Zender is the uncompressed beam (400 ps FWHM) of the LULI 100 TW laser.

We used two innovative diagnostics to analyze the modifications of a light filament that is self-induced by its propagation through the plasma. These two diagnostics are (1) proton...
radiography and (2) time-resolved 2D imaging of the filaments propagating through the plasma. Up to now the diagnostics of instabilities related to the propagation of a laser pulse in a plasma were analyzed using either emission diagnostics of the scattered light or diagnostics of the plasma waves (through Thomson scattering of a probe beam). To analyze the beam propagation, however, one relied on imaging the emission of harmonics (which does not allow time-resolved 2D images of the interaction to be obtained) or on measuring the density gradients induced by the laser–plasma coupling. A 2D image of these density gradients can be obtained over a short time by the use of a short duration optical probe.
The first diagnostic used in our experiment, time-resolved proton radiography, a recently developed technique [9,10], has unique advantages compared with other diagnostic techniques, allowing direct access to the temporal and spatial evolution of laser $E$-field structures with unprecedented precision. It exploits the deflections energetic (MeV) protons undergo when crossing electric fields (induced by the propagating laser pulse) within the plasma. Probing protons are accelerated [11] from the rear surface of a thin target by the compressed fraction of the laser pulse. Hot electrons are produced at the front side of the laser-irradiated target. They propagate through it and when they emerge at its rear side, they induce a space-charge field that ionizes the hydrogen layer at the back of the target and generates protons with a broad, Maxwellian-like, spectrum with energy ranging from 0 to 20 MeV in our experiment. Compared with the imaging of density gradients mentioned above, the advantage of proton deflectometry is that it gives a direct and quantitative access, at various times, to the $E$-fields generated in the plasma by the laser field of laser propagation and therefore represents the interaction more directly.

The second diagnostic exploits a 2D time-resolved transverse imaging technique (‘HISAC’) that has been developed at the University of Osaka [12]. As shown in figure 6, its operation principle is to image a 2D phenomenon on a square bundle of optical fibers. The bundle is tapered at its other end in a 1D line which is aligned onto the slit of a streak camera. In the output of the streak camera, the time-swept 1D image (i.e. each line of the swept signal) is, for each time, reorganized so that the 2D image is recomposed. Up to now, this diagnostic has not been used for the temporal analysis of long laser pulses (i.e. ns) propagation, although it performances are superior (except for the spatial resolution) to gated optical imagers which (1) have a minimum resolution of 80 ps, when the HISAC is limited by the time resolution of the streak camera (in our case, $\sim$30 ps), (2) provide only one or two time slices whereas the HISAC provides a quasi-continuous film of the observed phenomenon.

We first analyzed the structure of only one isolated filament, as a function of the filament intensity and as a function of the plasma density. Figure 7 shows the increase in beam spatial spreading at the end (output) of the plasma [13, 14] with both parameters, laser intensity
and plasma density. One thus observes that the effective beam size increases with both parameters, favoring the coupling between the neighbouring filaments. There are two possible coupling mechanisms, which can be classified as electromagnetic and hydrodynamic. The first stems from diffraction or scattering from a single beamlet that can couple to radiation emitted from another beamlet [15]. The other possible mechanism proceeds through a hydrodynamic coupling that is associated with ion density perturbations propagating between speckles [16]: each beamlet creates a density channel and the merging of the density channel allows for a single mode to propagate and the merging of the two beamlets to take place.

We have measured the coupling between close-by filaments, as a function of the distance between the filaments and of the background density of the plasma. The last factor is of importance since low intensity filaments are, within a beam RPP, statistically very close (about a filament diameter), whereas those which are the most intense, owing to the fact that they are less numerous, are more distant. The coupling that can be observed, depending on the interaction conditions, is illustrated in figure 8. While coupling is observed for close-by filaments, the two filaments remain independent for large separation. This is due to the fact that the two channels created by each filament do not have time to merge during the existence of the pulses in the case the two filaments separation is too large. We have observed that the maximum separation at which coupling still takes place is reduced with the filament intensity. Indeed, as the beam spreading reduces when the intensity decreases (see figure 7), the effective beam size reduces as well and thus the two filaments have to be initially closer for channel merging to take place.

Figure 9 shows a proton radiograph that allows one to study, complementary to the HISAC time-resolved transverse imaging, the spatial localization of the beam coupling but also to study a single filament propagation behavior. Indeed, it allows one to observe directly the zones of strong fields all along the propagation in the plasma. The interest of this last point is for the growth of parametric instabilities, these zones may play a more important role than the influence of the density gradients. For example, in figure 9, one can see clearly that the beam stay unperturbed for a third of their propagation length and do not undergo self-focusing or early filamentation that takes place only in the second part of the plasma. Towards the end of the plasma, the beam is seen to filament into many small-scale filaments. Electric fields
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Figure 8. Time- and space-resolved images of the evolution of two filaments separated by (left) 150 and (right) 300 µm for a 10 bars of the 1 mm diameter gas jet (the equivalent electron density is $10^{19}$ cm$^{-3}$). Top row shows the reference shot (without gas), the bottom row the actual shot in the gas jet. Each image is created by taking only a central lineout (through the two filaments) in all the 2D images obtained from the HISAC (see figure 6) with a 30 ps resolution and by stacking all the thus obtained lineouts. We clearly observe that the two filaments remain independent throughout their propagation when the separation between them is large (right image). However, when one reduces the separation (left image), we observe that the two filaments coalesce past the temporal peak of the pulses.

Figure 9. Proton radiograph (using 3 MeV protons) of the propagation of two filaments separated by 150 µm. The filaments are propagated from the left of the image over the 1 mm gas jet. The radiography is taken, with a magnification of 13, 150 ps after the temporal peak of the pulses that are propagated in a plasma of density $\sim 2 \times 10^{19}$ cm$^{-3}$. We can observe, complementarily to what is seen in figure 8, that the coalescence between the filaments in a large overall beam takes place towards the end of their propagation in the plasma.

developed in the first part of the plasma of a magnitude of $5 \times 10^7$ V m$^{-1}$ can be measured by simulating the proton modulation in the image. These observations are crucial in the sense that they are met in simulations of the interaction using the 3d non-linear hydrodynamic interaction code PARAX-MPL [17] only when (1) the ion viscosity due to ion--ion collisions and (2) the non-local heating of electrons are properly taken into account. Thus, such diagnostic is crucial and unique in analyzing the proper physics at play in this interaction regime, since no other measurement has yet proven to reach such level of details in the beam propagation analysis.

Our results underline the importance, for ICF predictive models, of taking into account properly the effects of the interaction between speckles within smoothed beams. This implies (i) improving present statistical modeling [18] which assumes the beamlets within the smoothed beams as independents [19] and (ii) having the required time and space resolution in numerical simulations [20], the applicability of which to full ICF however still faces computational limitations. Our study is also relevant for basic studies of beam interaction [21, 22] which are, e.g. of interest for lightning control and remote sensing. In the latter case, the beam interaction taking place through refractive index coupling within the medium is not induced by hydrodynamics, as in our case, but by the non-linear action of the high-power beams on the medium.
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