Appl Phys B (2009) 94: 249–257
DOI 10.1007/s00340-008-3270-5

Applied Physics B
Lasers and Optics

A simple method to significantly increase filaments' length and ionization density

J.-F. Daigle · O. Kosareva · N. Panov · M. Bégin · F. Lessard · C. Marceau · Y. Kamali · G. Roy · V.P. Kandidov · S.L. Chin

Received: 29 July 2008 / Revised version: 12 October 2008 / Published online: 31 October 2008

Abstract A simple method to produce longer filaments with higher ionization density in air by controlling the diameter of an aperture in the laser beam path is studied via an analysis of the backscattered N_2 fluorescence collected by LIDAR. Significant increase in the fluorescence signal (approximately by a factor of five depending on the conditions) and an increased filament length was observed at an optimum diameter. 3D + time stochastic numerical simulations have shown that the optimum aperture size corresponds to the case of multiple filament 'squeezing' around the propagation axis forming the regularized elongated structure with higher overall amount of plasma. The optimum range of aperture sizes is the same for the initial transverse perturbation scale variation at least within a factor of three.

PACS 42.62.Fi · 42.68.Wt · 42.65.-k

J.-F. Daigle (✉) · M. Bégin · F. Lessard · C. Marceau · Y. Kamali · S.L. Chin
Centre d'Optique, Photonique et Laser (COPL) et le Département de Physique, de Génie Physique et d'Optique, Université Laval, Québec, Québec, G1V 0A6, Canada
e-mail: jean-francois.daigle.2@ulaval.ca

O. Kosareva (✉) · N. Panov · V.P. Kandidov
International Laser Center, Physics Department, M.V. Lomonosov Moscow State University, Moscow 119991, Russia
e-mail: kosareva@phys.msu.ru

G. Roy
The Sensing (Air & Surface) & Optronics Section of the Defense Research and Development Center, Valcartier, QC, G3J 1X5, Canada

1 Introduction

When propagating in a transparent medium, intense ultrashort laser pulses tend to collapse into long plasma channels nowadays called filaments [1]. Because of its extraordinary properties (white light source [2], hundreds of meters range plasma channels [3]), filamentation [4–6] represents an ideal candidate for atmospheric studies [7], such as remote sensing of pollutants [8] and triggering/guiding of lightning discharges [9]. It is also investigated as a new method to remotely produce terahertz waves [10] and generate few cycle pulses via recompression of the broadened pulse spectrum occurring during filamentation [11].

This attractive tool is a result of a dynamic interplay between Kerr self-focusing induced by the medium's nonlinear intensity dependent refractive index and defocussing by the low-density plasma generated through multiphoton/tunnel ionization [5]. In air, this balanced propagation regime stabilizes and limits the light intensity contained in the filament core to an approximate value of 5×10^{13} W/cm^2 [12, 13], which is sufficiently high to ionize any atmospheric molecule. This rather simplified model gives an intuitive view of how a filament behaves. In reality, it is formed from the continuous succession of self-foci arising from the various longitudinal slices of a short pulse [14]. The process starts with the most intense slice at the peak of the pulse, and as it focuses, its intensity increases up to a point where it is sufficiently high to ionize the air molecules. The slice is then diffracted out by the generated plasma and dynamically replenishes [15] the surrounding photon bath for successive refocusing. Depending on their individual power [16], each slice of the pulse will collapse at a specific position and create the localized plasma. Because of the smooth intensity distribution of the pulse, this slice-by-slice self-focusing leads to the

formation of a continuous plasma column aligned along the propagation axis.

However, this explanation stands for a laser pulse whose transverse intensity distribution is perfectly Gaussian. In fact, such perfectly smooth laser pulses would almost never exist in practice. They are usually formed from the superposition of many spatial modes and present irregularities such as aberrations and hot spots that tend to generate off-axis multiple filaments. As a result of energy competition inside the limited reservoir of the laser pulse, each filament will collapse into a low-energy structure that cannot perform much ionization. This process makes the overall plasma generated by the whole pulse rather weak [17].

More recently, it has been observed that, because of self-focusing, the laser pulse undergoes a self-spatial-filtering process [18, 19], which leads to the formation of a unimodal, axially symmetric structure in the filament core. This core is surrounded by the energy reservoir [15] that feeds the filament. The self-spatial-filtering mechanism ensures high quality of the transverse intensity and fluence distributions in the filament. However, the presence of intensity and phase perturbations in the initial beam profile and excess peak power over 6 to 10 critical powers for self-focusing in the medium would induce multiple filament competition. This multifilamentary structure distorts the unimodal fluence distribution and results in the decrease of the filament bunch energy [20].

In the present work, we reduce multiple filament competition by blocking a wide outer part of the beam with a circular iris having a variable aperture. We have found the optimum iris opening size in the case of 7.2 mJ/100 fs pulses propagating in air, which maximizes the ionization density and filaments' length. For this optimum aperture size, the energy transmitted through the iris is 60% of the initial pulse energy, while the molecular nitrogen backscattered fluorescence signal experiences at least five-times increase as compared with the propagation where no iris is installed. Three-dimensional nonstationary numerical simulations demonstrate that the optimum aperture size corresponds to the largest opening for which multiple filaments can be still squeezed together into a stable structure centered on the beam axis. The simulated integrated plasma density is in good qualitative agreement with the N_2 fluorescence signal registered in the experiment.

Spatial regularization of femtosecond light filaments has been suggested earlier in Refs. [21, 22]. Recently, Hao et al. [23] found that filaments formed from focused pulses could be elongated and stabilized when an aperture was appropriately placed around the plasma core. Moreover, Chen et al. [11] improved their pulse compression technique via cascading filamentation by inserting a soft aperture before the focusing lens and obtained compressed pulses of higher stability and peak power. In this paper we analyze the longitudinal distribution of the plasma for different apertures and show the criterion to be used for the optimum choice of the aperture size, which is independent of the natural intensity perturbations of the pulses at the laser system output.

2 Experiment

In this experiment, the filaments are characterized via the fluorescence of N_2 present in the medium, namely air. The filaments are produced from negatively chirped laser pulses emitted at a 10 Hz repetition rate by a commercial Ti:Sapphire CPA laser system. The collimated pulses propagate through a 5 m distance before hitting an on-axis circular aperture of variable diameter.

A LIDAR [24] system, looking at the filaments formed in a 20 m long corridor, is used to collect the plasma's fluorescence on the sensitive surface of a photomultiplier tube (PMT, Hamamatsu R7400P). An UG11 filter [25] and a dielectric mirror coated for high reflectivity at 800 nm at perpendicular incidence, are used as a band pass filter for optimal detection of the molecular fluorescence of N_2. Because of the known speed of light, the temporal traces from the oscilloscope could be converted to a spatial scale which allows positioning of the produced signal. Considering that the lifetime of the N_2 fluorescence signal is around 1–2 ns [26], the resolution of this detection system, and hence, the longitudinal error in the starting and ending positions of the filament is around 30–60 cm for a single-shot pulse.

Before the aperture, the pulses are characterized with a negatively chirped duration of 100 fs FWHM and energy of 7.2 mJ. The initial beam diameter, measured where the intensity is decreased by a factor e^{-1} with respect to the signal's peak value, is 5.2 mm. For each opening diameter, the energy transmitted and the backscattered signal are measured. Figure 1a presents the experimental backscattered signal traces measured by the PMT for various aperture diameters. Each experimental trace is the result of averaging over 25 shots. As the aperture closes from $d = 6$ mm to $d = 4.5$ mm, the maximum of the backscattered signal amplitude increases approximately by a factor of 20 and the filament longitudinal extension by a factor of 2. With further iris closing until $d = 3.75$ mm, both the fluorescence signal and the filament length go down. This suggests the existence of an optimal aperture diameter.

Figure 2 (curve marked by squares) shows the fluorescence signal as a function of the aperture diameter d where each point on the curve is an integral over the longitudinal extension of a backscattered trace. Averaging is performed over 200 shots. As the aperture is closing on the beam, the fluorescence signal remains rather constant until the aperture size reaches $d \approx 5$ mm, and the corresponding transmitted energy decreases down to approximately 60% that of the initial pulse. In the aperture range between 4 to

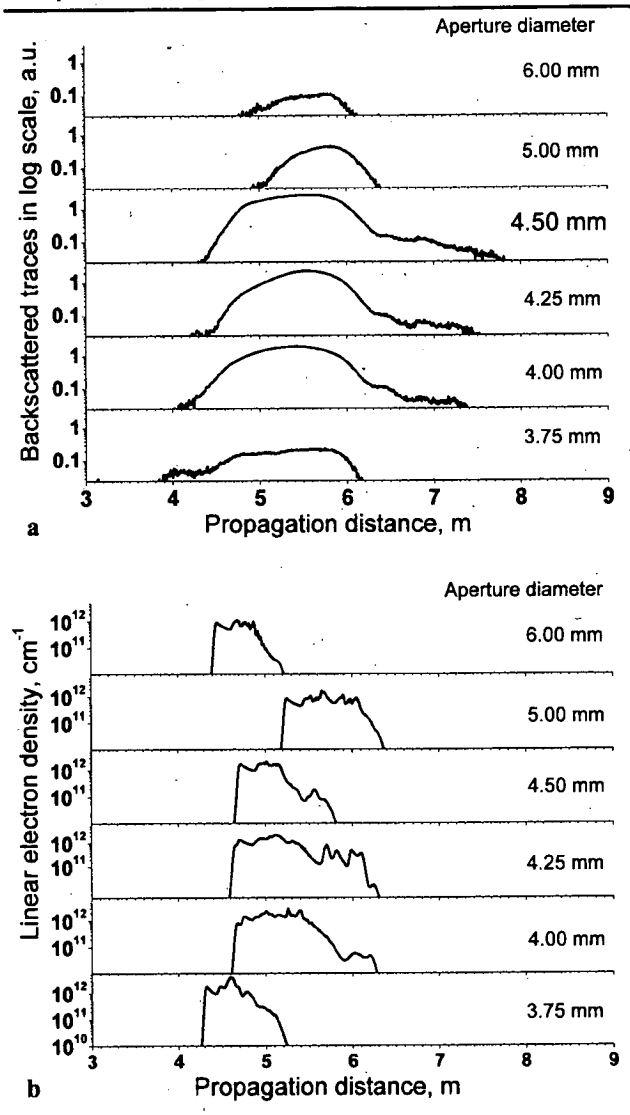

Fig. 1 (**a**) The traces of the backscattered molecular nitrogen fluorescence signal registered in the course of filamentation of 100 fs 7.2 mJ laser pulse transmitted through the aperture. Each trace is a 25 shot average. The opening diameter d is indicated for each *curve*. Note the logarithmic scale along the vertical scale. (**b**) The simulated electron density integrated over the transverse direction for the filaments obtained in the conditions similar to the experimental ones. The iris opening diameter d is indicated for each curve in both panels (a) and (b). Note that all the plots in panel (a) are calibrated identically so that "unity" corresponds to the same energy density of the fluorescence signal

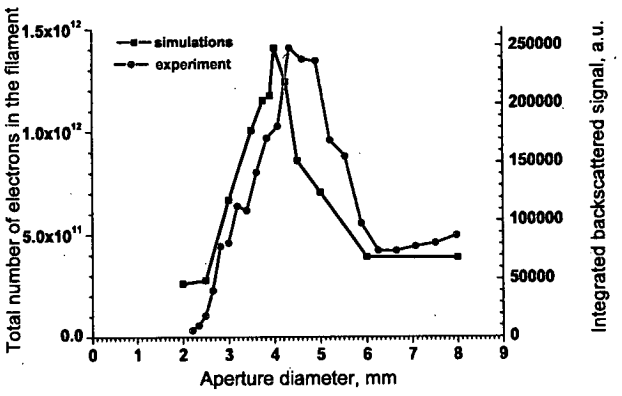

Fig. 2 The nitrogen fluorescence signal integrated over the whole extension of the filament in the experiment (*circles*) and the overall amount of electrons born in the simulations (*squares*) for each iris opening given by (8). Pulse duration is 100 fs, and the energy is 7.2 mJ. In the experiment each data point is the result of averaging over 200 shots

5 mm, the signal sharply rises to a maximum before it decays down. The maximum signal is reached for the aperture of $d = 4.3$ mm, and it exceeds the signal received with the fully opened iris approximately by a factor of five. This result suggests the interplay between the amount of energy transmitted through the aperture and the energy deposited into a single or a bunch of filaments [20] created after the aperture. Indeed, if the aperture is small ($d \approx 2.5$ to 3.5 mm), a perfect single filament centered on the propagation axis is created. However, due to the small energy contained in this filament, the overall amount of free electrons in the channel is small, and the longitudinal extension of the plasma region is very limited. With increasing aperture sizes, the energy increases and multiple filaments are created. As long as the aperture transmits the high-intense "top-hat" part of the beam, the filaments are born almost simultaneously and create an extended plasma region. This case corresponds to the maximum fluorescence signal. With increasing aperture diameter, multiple filaments are born stochastically, some earlier, some later in the propagation, the regularization influence of the aperture decreases. Accordingly, we also observe the decrease in both the amplitude and the longitudinal extension of the fluorescence signal in the experiment.

From Figure 1a we can see that the start of the filament, characterized by the fluorescence signal, changes very little in the vicinity of the aperture size range $d = 4$ to 4.75 mm. The analysis of the filament starting and ending position is shown in Fig. 3 (the two curves marked by circles), where the length of the filament is defined at 0.02 level of the global maximum of the fluorescence signal. From the curve corresponding to the onset of filamentation in the experiment (circles) we can see that within the range $d = 3.75$ to 4.75 mm the start of the filament moves slowly further in the propagation and saturates by $d = 5$ mm. For the same aperture size range 3.75 to 4.75 mm, the filament ending position exhibits the clearly pronounced maximum, then moves back to the laser system output and saturates by the same diameter value $d = 5$ mm. As the aperture size decreases from $d = 3.75$ mm to $d = 2$ mm, the onset of filamentation moves away from the laser system output until no signal is observed. Moving of the filament starting and ending positions in the forward and backward directions is due to the interplay between the whole beam self-focusing, which is the case for the smaller