Long connected plasma channels in air produced by ultrashort UV laser pulses

S. Tzortzakis, S. D. Moustaizis*, M. Franco, A. Chiron, B. Lamouroux, B. Prade, and A. Mysyrowicz
Laboratoire d'Optique Appliquée, CNRS UMR 7639, Ecole Nationale Supérieure de Techniques Avancées – Ecole Polytechnique, Chemin de la Hunière, F-91761 Palaiseau Cedex, France
** Foundation for Research and Technology Hellas, Institute of Electronic Structure and Laser, P.O. Box 1527, Heraklion 711 10, Greece*
stzortz@enstay.ensta.fr, mysy@enstay.ensta.fr

Abstract: Sub-picosecond UV-laser pulses (248nm, 450fs) with only mJ energy propagating in atmosphere lead to the formation of connected plasma channels over several meters. Optical and electric diagnostics and simulations allow characterization of the plasma channel.

OCIS codes: 350.5400 Plasmas, 320.7120 Ultrafast phenomena

1. Introduction

Several studies have shown recently that ultrashort infrared laser pulses propagating through atmosphere may create long plasma filaments [1-3]. This effect may have important applications in laser-controlled discharges [4], long-range deposition of high laser intensities, new LIDAR monitoring [5], etc. We present an investigation of the nonlinear propagation of ultrashort UV laser pulses in air. We show, for the first time, that it is possible to form connected plasma channels extending over several meters by using as little as 1.7 mJ per pulse having a duration of 450 fs.

2. Experimental technique, and results

The UV laser pulse is obtained by an Excimer pumped femtosecond dye laser. Its characteristics are: maximum energy per pulse: 8 mJ; central emission wavelength: 248 nm; pulse duration: 450fs. The pulses were launched through atmosphere in a converging beam geometry. The low power focal distance of the beam was 9.5 m. At high intensities, a displacement of the focus towards the lens was observed. About 10% of the initial beam energy propagated further in the form of a narrow beam of constant diameter of 100 µm, 50% of the beam energy was lost in the focal region, and 40% contained in a diverging conical beam surrounding the filament.

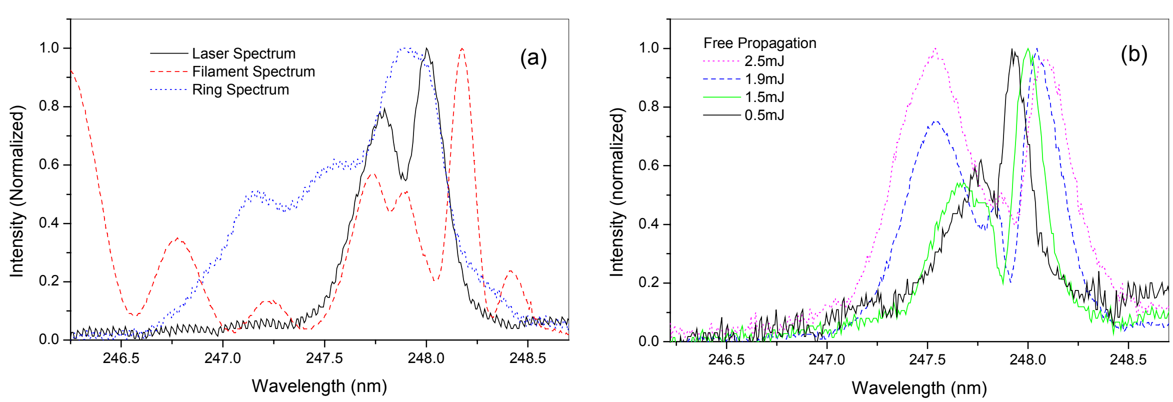

Fig. 1. (a) Spectra of the filament (dashed line) and of the conical ring around the filament (dotted line), recorded 1 m beyond the geometric focus. The input pulse energy is 1.7 mJ. Also shown is the unfocused laser spectrum. Note the strong blue shift in the filament. (b) Spectrum of the unfocused laser beam for different pulse energies, after 30 m propagation. No global blue shift is observed.

The laser spectrum was measured at different locations, as shown in the Fig. 1(a). For comparison, spectra of a non-converging laser beam were also recorded as a function of distance and pulse energy (Fig. 1(b)). The spectrum of the filament reveals a large bleu shift showing that its intensity is high enough to ionize air molecules by multiphoton processes. Laser beam profiles were correlated to the formation of a plasma filament by measuring the electric conductance of air as a function of distance after passage of the pulse [3]. As shown in the Fig. 2, a connected plasma filament extending over 6 m could be readily achieved with pulse energy of only 1.7 mJ. Connected plasma channels of such length could not be achieved with ultrashort IR pulses of similar energy.

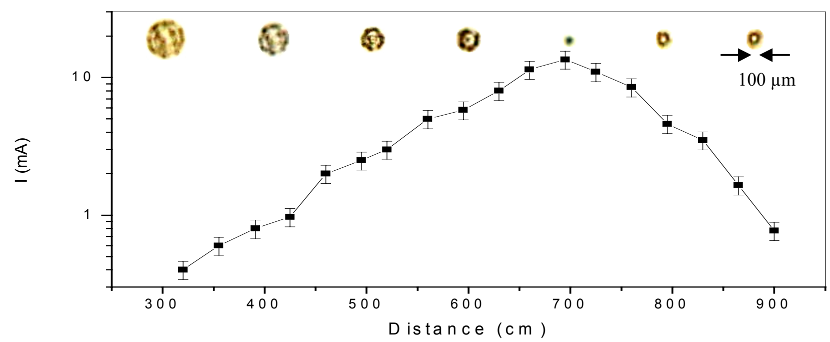

Fig. 2. Current measured across 2 electrodes separated by 1.5 cm, as a function of distance from the focusing lens. The laser pulse forms a plasma channel, which short-circuit the electrodes. Also shown is the approximate spatial dimension of the filament with distance.

3. Discussion

The results may be understood by considering the combined effects of nonlinear beam self-focussing due to the optical Kerr effect, beam defocusing due to multiphoton ionization of atoms and normal beam diffraction. A numerical simulation of the beam propagation was performed using a 3-Dimensional code with axial symmetry [6]. The value of the instantaneous nonlinear Kerr index was extracted from the literature and verified by fits of the spectra before and after propagation using a substitution algorithm. The importance of the retarded Kerr effect was obtained from the first spectral moment of the pulses in a parallel geometry as a function of laser power (Fig. 1(b)). The formation of the plasma was modeled by single ionization of oxygen and nitrogen atoms with a corresponding ionization potential of 12 and 15.5 eV, involving the simultaneous absorption of 3 and 4-UV photons respectively.

4. Conclusion

The simulation reproduces a large part of the experimental results. About 10% of the beam energy is transferred beyond the geometric focus in the form of an incipient self-guided pulse. The calculated plasma density yields a mean value of about 10^{16} cm^{-3} along the ionized path. This compares well with values extracted from the measurements of the ionized air channel conductivity. However our simulations presently do not predict self-guiding beyond 70 cm, a distance shorter than the one inferred from the experiment.

5. References

[1] H. Schillinger, and R. Sauerbrey, “Electrical conductivity of long plasma channels in air generated by self-guided femtosecond laser pulses”, Appl. Phys. B **68**, 753 (1999).

[2] B. La Fontaine, F. Vidal, Z. Jiang, C. Y. Chien, D. Comtois, A. Desparois, T. W. Johnston, J.-C. Kieffer, H. Pépin, and H. P. Mercure, “Filamentation of ultrashort pulse laser beams resulting from their propagation over long distances in air”, Phys. Plasmas **6**, 1615 (1999).

[3] S. Tzortzakis, M. A. Franco, Y.-B. André, A. Chiron, B. Lamouroux, B. S. Prade, and A. Mysyrowicz, “Formation of a conducting channel in air by self-guided femtosecond laser pulses”, Phys. Rev. E **60**, R3505 (1999).

[4] X. M. Zhao, J.-C. Diels, C. Y. Wang, and J. M. Elizondo, “Femtosecond Ultraviolet Laser Pulse Induced Lightning Discharges in Gases”, IEEE J. Quantum Electron. **31**, 599 (1995).

[5] L. Wöste, C. Wedekind, H. Wille, P. Rairoux, B. Stein, S. Nikolov, C. Werner, S. Nierdermeier, F. Ronneberger, H. Schillinger and R. Sauerbrey, “Femtosecond Atmospheric Lamp”, Laser Optoelektron **29**, 51 (1997).

[6] A. Chiron, B. Lamouroux, R. Lange, J.-F. Ripoche, M. Franco, B. Prade, G. Bonnaud, G. Riazuelo, and A. Mysyrowicz, “Numerical simulations of the nonlinear propagation of femtosecond optical pulses in gases”, Eur. Phys. J. D **6**, 383-396 (1999).