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Multiple filamentation of non-uniformly focused ultrashort laser pulses

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Abstract We propose the impingement of non-uniform wavefront curvature as a simple way to improve the longitudinal homogeneity of the plasma density along filaments generated by ultrashort laser pulses. We characterize multiple filamentation of a multiterawatt beam with different wavefront curvatures applied to specific regions in the transverse beam profile. In adequate conditions, the filamenting region is more homogeneously ionized, in the longitudinal direction, than in the case of uniform focusing. Moreover, the ionization maximum is located between the middle and the two thirds of the filaments in all investigated chirps and focus configurations.

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1 Introduction

There is great interest in the filamentation of ultra-intense femtosecond laser pulses propagating in the atmosphere [1–5] and its potential applications [5, 6], such as lightning control [7, 8], pulse self-compression [9, 10], remote laser-induced breakdown spectroscopy (LIBS) [11, 12], or remote sensing [13–15]. Filamentation arises from a dynamic balance between Kerr self-focusing and defocusing by the laser-generated plasma in the propagation medium. When the beam power exceeds the critical power for filamentation ($P_{cr} \sim 3$ GW in air at 800 nm), multiple filaments are generated at distances up to some kilometers away from the laser source [16] and can propagate over hundreds of meters [17].

Extensive efforts have been dedicated to the control of filamentation, in particular in view of increasing the filamentation length, distance, and the ionization efficiency within them, as is required for most of the above-cited applications. Several parameters have been investigated, including the pulse chirp, expanding and focusing the beam by a telescope [18], the pulse energy [19], beam ellipticity [20] and astigmatism [21], polarization [22], pulse shaping [23] or wavefront control using a deformable mirror [24], a pinhole [25] or a mesh [26]. In this paper, we propose non-uniform focusing of the beam as a simple way to improve the longitudinal homogeneity of long filaments. We show that the filamentation from transverse beam regions with different wavefront curvatures can interact and sustain each other, resulting in adequate conditions in long filaments with a longitudinally more homogeneous ionization than would be obtained with uniform beam focusing.

2 Experimental setup

The experiments were conducted with the Teramobile system [18] emitting 300 mJ pulses centered at 800 nm. We investigated positively and negatively chirped pulses, respectively anticompensating and compensating group velocity

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dispersion (GVD) in air. The typical second-order dispersion terms up to $k'' = 2 \times 10^4$ fs^2 yield durations ranging from 100 to 460 fs. These values, respectively, correspond to 190 to 1000 P_{cr} for 260–300 mJ energy per pulse. An all-reflective telescope of adjustable focus expanded the beam diameter to 15 cm at $1/e^2$ and allowed to adjust its focusing before transmitting it horizontally into 130 m of free atmosphere. Two geometries were investigated. In the first one, one side of the beam was focused by a semi-circular lens of focal length $f_{1/2} = 35$ m. In the second one, the central portion of the beam was focused by a $f_c = 30$ or $f_c = 40$ m lens of 5 cm diameter, typically enclosing 20% of the beam energy for an assumed Gaussian profile. The average intensity of the beam region concerned by the central lens was twice that of the beam edge. In both cases, the lens was inserted at the output of the expanding telescope. The other side (respectively, the outer ring) of the beam profile was left unaffected, i.e., it was governed only by diffraction and the focus f_T of the expanding telescope. Filamentation in each condition was characterized by the cracking noise of the beam on a paper screen [27]. This criterion is representative of the ionization density which is a highly relevant parameter in view of lightning control applications. It is more demanding than, e.g., the observation of bright hot spots in the beam profile, so that the filament lengths given below may appear underestimated as compared with other works [28]. In each condition, the begin and end position of the filamenting region were recorded, as well as the position of the most intense sound emission on the target, which is representative of the highest plasma density.

3 Results and discussions

Figure 1 displays, as a reference, the typical extension of the filamenting region generated by the beam of uniform wavefront curvature, with three foci ($f_T = 30$, 40 and 150 m, respectively) of the emitting telescope, and several chirps. As is well known [18], the location of the filamentation onset depends on the initial chirp value through both the compensation of group-velocity dispersion (GVD) and the initial peak power. It is also constrained by the geometrical term arising from the emitting telescope. Stronger focusing results in less chirp dependence because it corresponds to a higher relative contribution of the geometrical term in the Marburger formula [29]. More focused beams also generate a shorter filament bundle. Moreover, the geometrical focus of the emitting telescope defines the location of the highest plasma concentration within a few meters. The almost parallel beam ($f_T = 150$ m) generates a longer filamenting region, which is limited by the available propagation field. Therefore, in the following, we mainly focus on the situation where $f_T = 40$ m, where the effect of non-uniform wavefront curvature is more likely to be significant.

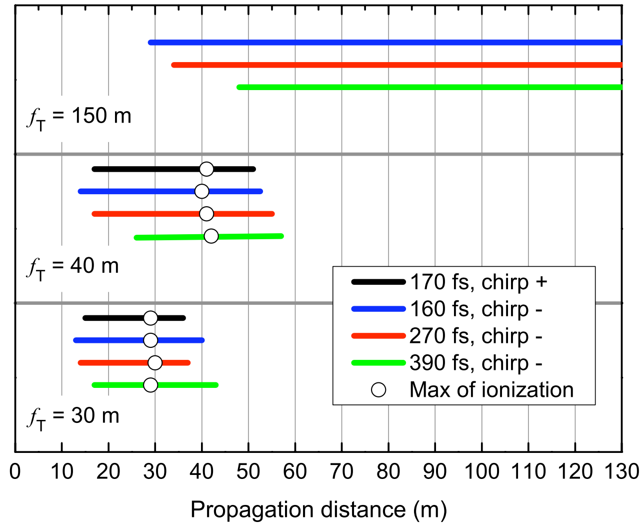

Fig. 1 Filamentation range and position of strongest ionization of the full beam ($E = 300$ mJ) as a function of chirp and initial focusing. Positive and negative chirps, respectively, correspond to the anticompensation and compensation of the group velocity dispersion of air

The effect of focusing ($f_{1/2} = 35$ m) one side of the beam superimposed over the uniform focusing by the emitting telescope ($f_T = 40$ m), for 260 mJ pulses, is shown in Fig. 2. The observation of the beam profile (see the inset in Fig. 2) in the filamenting region permits to unambiguously assign each filament to a given half of the beam. Surprisingly, the sharp phase jump induced by the edge of the semi-circular lens along the beam diameter does not couple the two beam sides through diffraction, nor generates a line of filament at the border between the two wavefront curvature domains. The side that is only focused by the emitting telescope generates a shorter filament bundle than the whole beam with the same wavefront curvature and energy (260 mJ), as plotted in the upper part of the figure. This reduced length is due to the fact that it only carries half of the total beam energy. The position of the ionization maximum, however, is very little affected, and lies shortly after the middle of the filamenting region. This observation confirms that the location of the highest plasma density is mainly governed by geometrical focusing considerations rather than by self-focusing. The beam side with the supplementary focusing generates an even shorter filament bundle, with a shorter self-focusing distance. Depending on the chirp, these two filamenting regions can overlap, providing a long ionized region. Moreover, since the filament bundle is focused, it converges towards the center of the beam. Therefore, filaments from both beam sides overlap and cannot be distinguished any more, as indicated by the dotted sections in Fig. 2. They can be considered as one single plasma bundle. In particular, the longitudinal and transverse gap between the two bundle sections is small compared to the typical scales of high-voltage discharges to be considered in

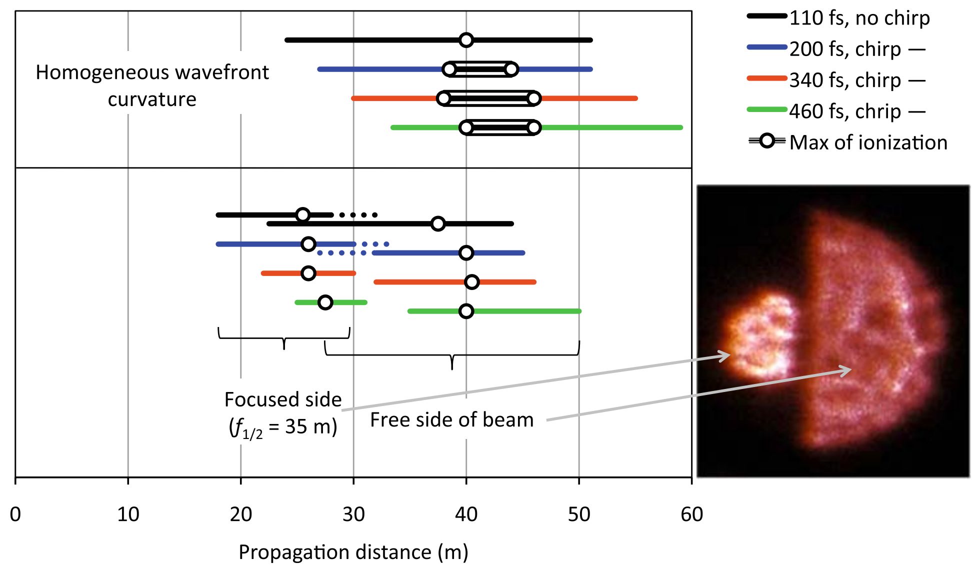

Fig. 2 Effect on the filamenting range and position of the maximum of ionization frequency of a supplementary focusing ($f_{1/2} = 35$ m) of one half of the beam profile, on top of the focusing by the emitting telescope ($f_T = 40$ m). Negative chirps correspond to the compensation of the group velocity dispersion of air. The total energy per pulse is 260 mJ. *Inset*: beam profile on a screen at a propagation distance $z \sim 25$ m

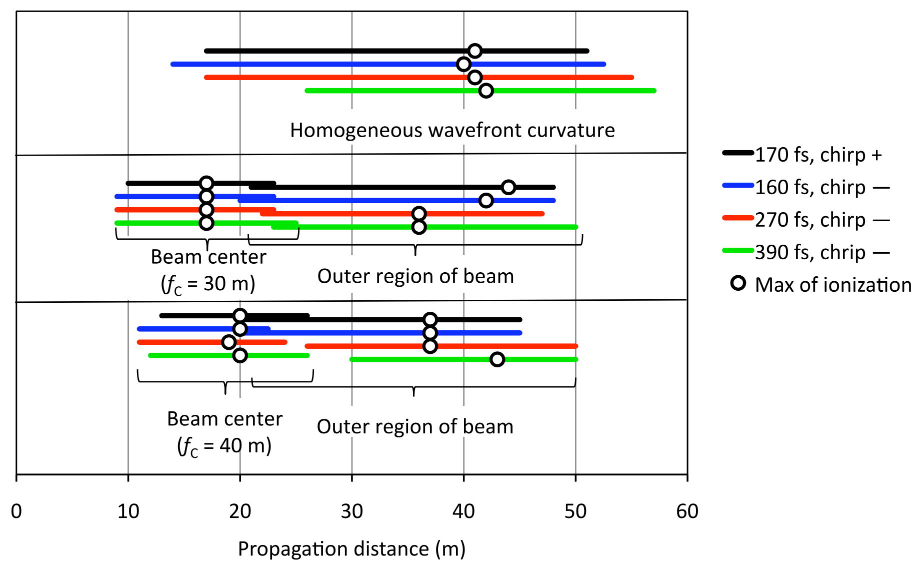

Fig. 3 Effect on the filamenting range and position of the maximum of ionization frequency of a supplementary focusing ($f_c = 30$ m and $f_c = 40$ m) of the center of the beam profile, on top of the focusing by the emitting telescope ($f_T = 40$ m), for a pulse energy of 300 mJ. Positive and negative chirps, respectively, correspond to the anticompensation and compensation of the group velocity dispersion of air

applications. The longitudinal ionization profile in this filamenting region has two maxima, each being governed by the initial wavefront curvature of one side of the initial beam profile. Such two-maxima structure results in a more homogeneous ionization along the length of the filament bundle, than would be obtained with a single maximum related to a uniform wavefront curvature. Similar results are obtained for a more focused beam ($f_T = 30$ m) as well as for an almost collimated beam ($f_T = 150$ m). The strong influence of the non-uniform wavefront curvature applied to the beam contrasts with that of classical astigmatism, which only marginally influences the location of the filamenting region of the beam [21].

Figure 3 displays the effect of central lenses of 5 cm diameter with focal lengths $f_c = 30$ m and $f_c = 40$ m placed in the center of an already focused beam ($f_T = 40$ m) with 300 mJ per pulse. Visual observation of the beam profile on a screen during its propagation confirms that filaments are first initiated in the inner (more focused) region of the beam, and later on the edges of the beam, which is less focused and intrinsically carries less intensity than its center. The locations of the filamentation onset and of the ionization maximum depend very little on the initial pulse chirp. Moreover, the filament bundles respectively generated by the external and inner part of the profile overlap well for all investigated chirps. The overall beam self-focusing and the focused geometry together lead the filament bundle from the beam edge to converge toward the beam center [30]. Its energy reservoir therefore merges with that of the central bundle. The resulting common photon bath re-feeds both central and peripheral filaments. Such process contributes to the observed improved longitudinal homogeneity of the plasma generated by the filaments over several tens of meters.

The overlap between the filament bundles generated in the inner and outer beam regions critically depend on the ability of the outer region to reach the beam center before the inner filaments vanish. The focal length of the central part of the beam contributes to this matching through (i) the length of the filamenting region in the center of the beam and (ii) the offset that it imposes to the filament onset, as compared with that of the outer region. The wavefront curvature of the outer region and the beam power also contribute to this match since they govern the onset position of the outer filament bundle. This need for interaction of the photon baths of both inner and outer regions of the beam profile explains the difference between the effects of transverse and radial variations of the wavefront curvature. While in the former case the two sides of the beam interact very little, they are geometrically forced to merge after some propagation distance in the concentric configuration. Therefore, the latter is more favorable to generate a long ionized section with higher longitudinal homogeneity.

When the respective wavefront curvatures of the outer ring and the center of the beam are far off (e.g., $f_T = 150$ m and $f_c = 40$ m, not shown), self-focusing of the outer part is not sufficient to focus a significant energy on the beam axis before the end of the strongly focused central filament bundle. Therefore, its power cannot contribute to the photon bath in the beam center. As a result, no extension of the filamenting length is observed.

4 Conclusions

A non-uniform wavefront curvature of ultrashort, ultra-intense laser pulses propagating in air significantly affect the location, length of the generated filament bundles, as well as the longitudinal homogeneity of their plasma density. Adequate laser parameters almost connect the filament bundles, providing a more homogeneous ionization than for a uniformly focused beam. While the precise result depends on the initial focus and chirp of the beam, this improved plasma longitudinal homogeneity is qualitatively observed over a wide range of energy and chirp. It is of high interest for applications requiring long plasma channels, as is the case for lightning control [8]. By applying a different wavefront curvature on different regions of the beam profile, it can also be seen as an easy technique for rough spatial pulse shaping [24, 31], allowing a better use of the energy reservoir [25, 30] of the beam.

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References

1. A. Braun, G. Korn, X. Liu, D. Du, J. Squier, G. Mourou, Self-channeling of high-peak-power femtosecond laser pulses in air. Opt. Lett. **20**, 73–75 (1995)
2. S.L. Chin, S.A. Hosseini, W. Liu, Q. Luo, F. Theberge, N. Akozbek, A. Becker, V.P. Kandidov, O.G. Kosareva, H. Schroeder, The propagation of powerful femtosecond laser pulses in optical media: physics, applications, and new challenges. Can. J. Phys. **83**, 863–905 (2005)
3. L. Bergé, S. Skupin, R. Nuter, J. Kasparian, J.-P. Wolf, Ultrashort filaments of light in weakly-ionized, optically-transparent media. Rep. Prog. Phys. **70**, 1633–1713 (2007)
4. A. Couairon, A. Mysyrowicz, Femtosecond filamentation in transparent media. Phys. Rep. **441**, 47–189 (2007)
5. J. Kasparian, J.-P. Wolf, Physics and applications of atmospheric nonlinear optics and filamentation. Opt. Express **16**, 466–493 (2008)
6. J. Kasparian, M. Rodriguez, G. Méjean, J. Yu, E. Salmon, H. Wille, R. Bourayou, S. Frey, Y.-B. André, A. Mysyrowicz, R. Sauerbrey, J.-P. Wolf, L. Wöste, White-light filaments for atmospheric analysis. Science **301**, 61 (2003)
7. H. Pépin, D. Comtois, F. Vidal, C.Y. Chien, A. Desparois, T.W. Johnston, J.C. Kieffer, B. La Fontaine, F. Martin, F.A.M. Rizk, C. Potvin, P. Couture, H.P. Mercure, A. Bondiou-Clergerie, P. Lalande, I. Gallimberti, Triggering and guiding high-voltage large-scale leader discharges with sub-joule ultrashort laser pulses. Phys. Plasmas **8**, 2532–2539 (2001)
8. J. Kasparian, R. Ackermann, Y.-B. André, G. Méchain, G. Méjean, B. Prade, P. Rohwetter, E. Salmon, K. Stelmaszczyk, J. Yu, A. Mysyrowicz, R. Sauerbrey, L. Wöste, J.-P. Wolf, Electric events synchronized with laser filaments in thunderclouds. Opt. Express **16**, 5757–5763 (2008)
9. A. Couairon, M. Franco, A. Mysyrowicz, J. Biegert, U. Keller, Pulse self-compression to the single-cycle limit by filamentation in a gas with a pressure gradient. Opt. Lett. **30**, 2657 (2005)
10. P. Béjot, J. Kasparian, J.-P. Wolf, Cross-compression of light bullets by two-color co-filamentation. Phys. Rev. A **78**, 043804 (2008)
11. K. Stelmaszczyk, P. Rohwetter, G. Méjean, J. Yu, E. Salmon, J. Kasparian, R. Ackermann, J.P. Wolf, L. Wöste, Long-distance remote laser-induced breakdown spectroscopy using filamentation in air. Appl. Phys. Lett. **85**, 3977 (2004)
12. J.-F. Daigle, G. Méjean, W. Liu, F. Théberge, H.L. Xu, Y. Kamali, J. Bernhardt, A. Azarm, Q. Sun, P. Mathieu, G. Roy, J.-R. Simard, S.L. Chin, Long range trace detection in aqueous aerosol using remote filament-induced breakdown spectroscopy. Appl. Phys. B **87**, 749 (2007)
13. G. Méjean, J. Kasparian, J. Yu, S. Frey, E. Salmon, J.-P. Wolf, Remote detection and identification of biological aerosols using a femtosecond terawatt lidar system. Appl. Phys. B **78**, 535–537 (2004)
14. G. Méjean, J. Kasparian, E. Salmon, J. Yu, J.-P. Wolf, R. Bourayou, R. Sauerbrey, M. Rodriguez, L. Wöste, H. Lehmann, B. Stecklum, U. Laux, J. Eislöffel, A. Scholz, A.P. Hatzes, Towards a supercontinuum-based infrared Lidar. Appl. Phys. B **77**, 357 (2003)
15. R. Bourayou, G. Méjean, J. Kasparian, M. Rodriguez, E. Salmon, J. Yu, H. Lehmann, B. Stecklum, U. Laux, J. Eislöffel, A. Scholz, A.P. Hatzes, R. Sauerbrey, L. Wöste, J.-P. Wolf, White-light filaments for multiparameter analysis of cloud microphysics. J. Opt. Soc. Am. B **22**, 369 (2005)
16. M. Rodriguez, R. Bourayou, G. Méjean, J. Kasparian, J. Yu, E. Salmon, A. Scholz, B. Stecklum, J. Eislöffel, U. Laux, A.P. Hatzes, R. Sauerbrey, L. Wöste, J.-P. Wolf, Kilometer-range nonlinear propagation of femtosecond laser pulses. Phys. Rev. E **69**, 036607 (2004)

17. B. La Fontaine, F. Vidal, Z. Jiang, C.Y. Chien, D. Comtois, A. Desparois, T.W. Johnson, J.-C. Kieffer, H. Pépin, Filamentation of ultrashort pulse laser beams resulting from their propagation over long distances in air. Phys. Plasmas **6**, 1615–1621 (1999)
18. H. Wille, M. Rodriguez, J. Kasparian, D. Mondelain, J. Yu, A. Mysyrowicz, R. Sauerbrey, J.-P. Wolf, L. Wöste, Teramobile: a mobile femtosecond-terawatt laser and detection system. Eur. Phys. J. Appl. Phys. **20**, 183–190 (2002)
19. G. Méchain, C. D'Amico, Y.-B. André, S. Tzortzakis, M. Franco, B. Prade, A. Mysyrowicz, A. Couairon, E. Salmon, R. Sauerbrey, Range of plasma filaments created in air by a multi-terawatt femtosecond laser. Opt. Commun. **247**, 171 (2005)
20. A. Dubietis, G. Tamošauskas, G. Fibich, B. Ilan, Opt. Lett. **29**, 1126 (2004)
21. S. Eisenmann, E. Louzon, Y. Katzir, T. Palchan, A. Zigler, Y. Sivan, G. Fibich, Multiple filamentation induced by input-beam ellipticity. Opt. Express **15**, 2779 (2007)
22. G. Fibich, B. Ilan, Multiple filamentation of circularly polarized beams. Phys. Rev. Lett. **89**, 013901 (2002)
23. R. Ackermann, E. Salmon, N. Lascoux, J. Kasparian, P. Rohwetter, K. Stelmaszczyk, S. Li, A. Lindinger, L. Wöste, P. Béjot, L. Bonacina, J.-P. Wolf, Optimal control of filamentation in air. Appl. Phys. Lett. **89**, 171117 (2006)
24. Z. Jin, J. Zhang, M.H. Xu, X. Lu, Y.T. Li, Z.H. Wang, Z.Y. Wei, X.H. Yuan, W. Yu, Control of filamentation induced by femtosecond laser pulses propagating in air. Opt. Express **13**, 10424 (2005)
25. W. Liu, J.F. Gravel, F. Théberge, A. Becker, S.L. Chin, Background reservoir: its crucial role for long-distance propagation of femtosecond laser pulses in air. Appl. Phys. B **80**, 857–860 (2005)
26. H. Schroeder, J. Liu, S.L. Chin, From random to controlled small-scale filamentation in water. Opt. Express **12**, 4768 (2004)
27. G. Fibich, S. Eisenmann, B. Ilan, A. Ziegler, Control of multiple filamentation in air. Opt. Lett. **29**, 1772 (2004)
28. G. Méchain, A. Couairon, Y.-B. André, C. D'Amico, M. Franco, B. Prade, S. Tzortzakis, A. Mysyrowicz, R. Sauerbrey, Long-range self-channeling of infrared laser pulses in air: A new propagation regime without ionization. Appl. Phys. B **79**, 379 (2004)
29. J.H. Marburger, E.L. Dawes, Dynamical formation of a small-scale filament. Phys. Rev. Lett. **21**, 556 (1968)
30. S. Skupin, L. Bergé, U. Peschel, F. Lederer, G. Méjean, J. Yu, J. Kasparian, E. Salmon, J.P. Wolf, M. Rodriguez, L. Wöste, R. Bourayou, R. Sauerbrey, Filamentation of femtosecond light pulses in the air: Turbulent cells versus long-range clusters. Phys. Rev. E **70**, 046602 (2004)
31. P. Rohwetter, M. Queisser, K. Stelmaszczyk, M. Fechner, L. Wöste, Laser multiple filamentation control in air using a smooth phase mask. Phys. Rev. A **77**, 013812 (2008)