Spatial evolution of multiple filaments in air induced by femtosecond laser pulses

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Abstract: The spatial evolution of plasma filaments in air induced by femtosecond laser pulses is investigated experimentally. Several major filaments and small scaled additional filaments are detected in the plasma channel. The complicated interaction process of filaments as splitting, fusion and spreading is observed. The major filaments propagate stably, and the small scaled additional filaments can be attracted to the major filaments and merged with them. The major filaments are formed due to the perturbation of initial beam profile and the small scaled filaments are mainly caused by the transverse modulational instability.

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1. Introduction

Since the first observation of long propagation of femtosecond (fs) laser pulses in air by Braun *et al*, [1] there has been great interest in the formation of long plasma filaments in air induced by fs laser pulses [2-15]. The filaments can propagate over hundreds of meters, exceeding many Rayleigh lengths of the laser beam. The filaments result from the dynamic balance between the nonlinear Kerr self-focusing due to the nonlinear intensity-dependent refractive index and the plasma defocusing due to the high-order multiphoton ionization (MPI) and diffraction effects of the laser pulses in air. If the laser power exceeds the critical power for self-focusing

$$P_{crit} = \lambda^2 / 2\pi\, n_0 n_2 \qquad (1)$$

of about 3.2 GW in air for the laser wavelength λ=800 nm, where $n_2 = 3.2 \times 10^{-19}\, cm^2 / W$ in air [2], then the laser beam is self-focused before the geometrical focus. The increased laser intensity due to the self-focusing generates free electrons by the MPI process, and the electrons contribute negatively to the index of refraction of air:

$$n_{plasma} = -\omega_p^2(r)/2\omega^2, \qquad\qquad (2)$$

where $\omega_p = (4\pi e^2 n_e / m_e)^{1/2}$ is the plasma frequency and n_e is the electron density [1]. The self-focusing and defocusing processes repeat again and guide laser pulses to propagate over long distance. Many interesting nonlinear phenomena have been observed within the filaments of fs laser pules, such as supercontinuum radiation [3], third-harmonic generation [6-8], conical emission [9, 10], and electrical conductivity of plasma channels [11, 12]. The characteristics of filaments enable many applications such as remote sensing, lightning control, Lidar, etc.

The dynamics of filamentation is complicated and the physics mechanism of multiple filaments (MF) evolution in air is still not well understood. The experimental research on the detailed process of filaments evolution is also insufficient. As to the free propagation of the collimated laser beam in air, Mlejnek et al. [16-18] proposed a model of optical turbulent light guiding to explain the breakup and fusion of filaments. In his simulations, the filaments propagate in the form of filamentation recurrence. The plasma defocuses a part of energy of filaments to energy background, which is made available for further nucleation of filaments. Bergé et al. [19] obtained MF patterns by launching a collimated laser pulse into the air and found that some major filaments persisted over several meters, whereas others randomly nucleated over shorter longitudinal scales. Energy evacuation from primary filaments supports the random nucleation. Tzortzakis et al. [20] believed that the modulational instability of laser pulses is the main mechanism of filaments evolution. Some experimental results indicate that the filament formed by free propagating laser pulse has mm size diameter and the intensity inside the filament is around the ionization threshold of air. However, as to the prefocused laser pulses in air with a high intensity level, the intensity inside the filaments is about 4×10^{13} $\sim 1\times10^{14}$ W/cm^2 [2, 21], the electron density in the filaments is about $10^{16} \sim 10^{18}$ cm^{-3} [1, 2, 22]. Therefore, the nonlinear effects and the interaction between filaments are extremely stronger, and consequently, the filamentation and its evolution are complex. The behaviors of the filaments should be different in some respects from the case of free propagation of collimated laser pulse. In this paper, we present our experimental investigations on the spatial evolution of filaments in air generated by prefocused fs laser pulse. The forming, splitting, fusing and spreading of the filaments in air are observed clearly in experiments. The random nucleation is not observed in our experiments. The small filaments are quickly attracted and join the major filaments along the laser propagation direction. The major filaments persist from beginning to end supported by the energy background and small filaments around it. We suggest that the local unbalance of the laser beam profile introduce the formation of primary filaments, the transverse modulational instability and strong interactions in the diffraction plane are mainly responsible for the complicated spatial evolution of filaments.

2. Experimental setup

The laser system used in our experiments is the extreme light laser system (XL)-II with an output energy up to 640 mJ in 30 fs pulses at a central wavelength of 800 nm. The repetition rate is 10 Hz. The input beam spatial profile was noisy as shown in Fig.1. The whole spatial profile is almost circular, however, the center region with much higher intensity is elliptical with an eccentricity of b/a = 2.12 (a=0.82 cm, b=1.74 cm; see the ellipse in Fig.1). The laser pulses are focused by an f = 4 m lens with a geometrical focal length of 5.05 m in air because the laser beam we used in experiments has a divergence angle. The experimental setup is shown in Fig.2. The laser beam is focused in air and forms a long plasma channel that can be seen directly by naked eyes. A glass plate is inserted at a 57° angle in the aim to sample the cross section of the channel. A lens images the channel onto a charged-coupled device (CCD) camera (512×512 pixels) with a pixel size of 24 μm. A high-speed shutter is used to take single shot image of the filaments on the plate. The glass plate is placed on a translation stage, which can move in parallel with the CCD. This ensures that each laser pulse shoots a new

place of the plate. The imaging system is setup on a small stage that moves along the laser propagation axis to obtain the images at different positions.
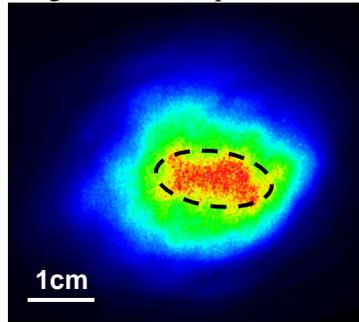
Fig. 1. Profile of the initial laser beam. Intensity recorded at the output of the compressor.
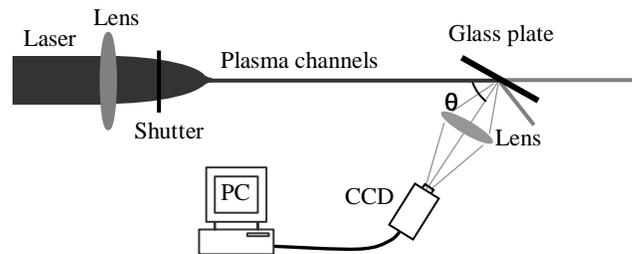
Fig. 2. Schematic diagram of the experimental setup.

3. Experimental results and discussion

In our experiments, 22 mJ and 50 mJ of laser pulse energy are used, corresponding to peak power values of about 0.7 TW and 1.7 TW respectively. This power is significantly higher than the critical power for self-focusing. We track the profile of filaments in detail along the direction of propagation. The plasma channel is stable, and the filaments image is reproducible from shot to shot. We owe the reproducible MF pattern to the input beam ellipticity. Several experimental studies have demonstrated that the input beam ellipticity can induce a deterministic MF pattern in ultrashort pulses in water [23], glass [24], and air [25]. Several representative profiles of filaments at 22 mJ laser energy are depicted in Fig.3. Since the glass plate forms an angle of 57° with the beam axis, a correction factor of 0.54 for the *x* coordinate is taken into account. A single filament is formed before 4.60 m. At 4.75 m, the single filament begins to breakup into a double structure; meanwhile, some small filaments appear in the low intensity background. The double filaments propagate stably from 4.85 m to 5.00 m, while a small filament neighboring the primary filaments evolutes quickly and unstably, but its onset position is relatively stable. The separation distance between these small filaments and primary filaments becomes closer, and eventually, some small filaments fuse with the primary filaments. It is clear that small-scaled filaments are attracted by the major filaments. From 5.10 m to 5.23 m, there are no obvious small filaments around the double filaments. The double filaments seem to propagate independently, however, the intensity and diameter of the two filaments transform dynamically. The diameter of a single filament varies around 95~150 μm, which is the typical filament diameter [1, 22]. After about 5.23 m propagation distance, the double major filaments begin to spread, and their separation distance becomes increasingly larger, and finally, the double filaments disappear beyond 5.70 m. The two filaments do not merge into a single one because the separation distance between the two filaments is too far away to coalesce [20]. Furthermore, some small filaments appear again when the double filaments spread after about 5.23 m. The reason should be that the energy in the background reservoir becomes larger because it does not need to feed major

filaments and a part of energy in filaments transfers to the reservoir due to the filaments dissipation. This will excite new sequences of small filaments.
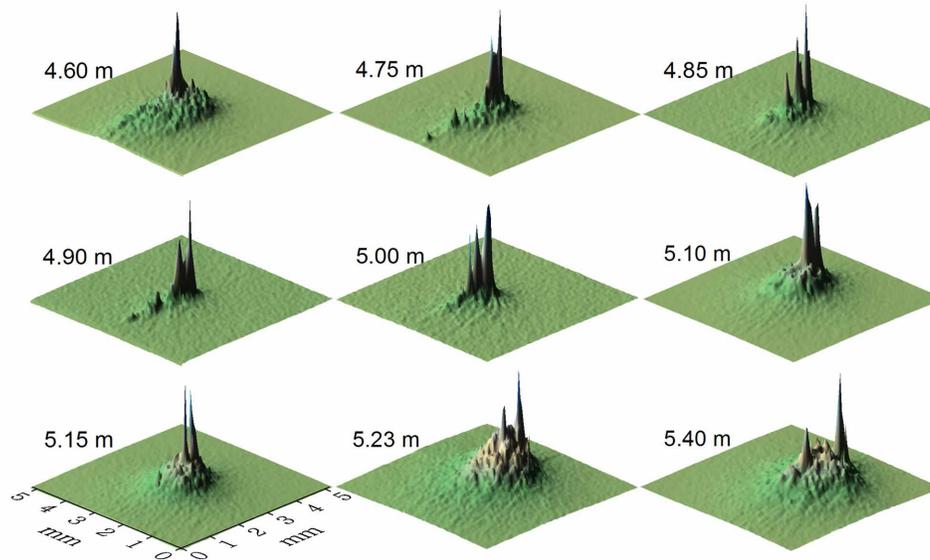
Fig. 3. Typical normalized profiles of filaments in plasma channels with a laser energy of E_{laser} = 22mJ. Frame size: 5.18×5.18 mm^2.

Furthermore, in the beam cross section, the onset position of the filament deviates from the beam center. The input laser profile is inhomogeneous, which is amplified by modulational instability during the propagation, and the filament forms at a position where the power exceeds the critical power for self-focusing. Furthermore, the intensity distribution of initial laser beam has an elliptical shape (see Fig.1), resulting in the MF along the long axis, as shown in Fig.3. However, the filamentation pattern evolves to a specific circularly symmetric shape, known as the Townes profiles [26], as can be seen more clearly from the beam profile at 5.40 m in Fig.3.

It is easier to form MF at a higher energy (50 mJ). We measured the sound signal along the plasma channel using the sonographic method [27-29]. The 50 mJ laser pulse undergoes higher complicated evolution compared to the case of 22 mJ. The detail can be found in Ref. (28, 29). The jump on the sound signal indicates the starting of the plasma channel, and the rapid decrease of the signal denotes the ending of it. The channel length at 50 mJ is about 30 cm longer than that at 22 mJ in the experiments.

It is note that the random nucleation which is found in the case of the collimated laser beam free propagation [19] is not observed in our experiments. The reason may be the great differences of the diameter, intensity, and the degree of modulational instability of laser beam between the two cases of prefocused and collimated laser pulses [30, 31]. The size of the background reservoir is also different, about several millimeters in our experiments versus tens of centimeters in the case of free-propagating laser pulses. As the result, the nonlinear effects including the self-focusing, plasma defocusing, self-phase modulation, and modulational instablility, have different degree and different influences. Therefore, the random nucleation has no chance to develop itself in our experimental condition.

The major filaments are formed from the local unbalance of beam and the beam perturbation due to modulational instability [20]. Then the plasma filaments cause strong defocusing, leading to a part of energy of filaments releasing into the background, which contributes to subsequent formation of new filaments [16-19]. As a result, the complicated interactions and some other nonlinear processes lead to the forming, splitting, fusing and

spreading of filaments. In experiments, the filaments are asymmetrical. They have different intensity, position, direction, and diameter. As the result, the interference, the energy flow, and other nonlinear interactions entangle each other, leading to the complicated evolution of filaments.

4. Conclusions

In conclusion, the spatial evolution of the filaments in plasma channels induced by intense fs laser pulses in air is investigated. The propagation of the filaments in the channel shows very complicated process including the evolution from a single filament into two and three and even more distinct filaments periodically, and the multiple filaments merge into two filaments and propagate stably and fade away eventually. We also find that the length of the filaments increases with the input laser energy. Moreover, the higher the initial laser power is, the more complicated phenomena appear due to the stronger modulational instability. The non-uniform intensity profile of the initial laser beam, modulational instability, and dynamic spatial replenishment mechanism are the main reasons for the filamentation and the complicated spatial evolution of fs laser pulses in air.

Acknowledgments