Long lifetime air plasma channel generated by femtosecond laser pulse sequence

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Abstract: Lifetime of laser plasma channel is significantly prolonged using femtosecond laser pulse sequence, which is generated from a chirped pulse amplification laser system with pure multi-pass amplification chain. Time-resolved fluorescence images and electrical conductivity measurement are used to characterize the lifetime of the plasma channel. Prolongation of plasma channel lifetime up to microsecond level is observed using the pulse sequence.

OCIS codes: (260.5950) Self-focusing; (320.2250) Femtosecond phenomena; (320.7110) Ultrafast nonlinear optics; (350.5400) Plasmas.

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1. Introduction

Lifetime of plasma channel generated by femtosecond (fs) laser pulse in air [1–4] is one of the key parameters for conductivity based applications, such as guiding high-voltage (HV) discharge and controlling the lighting [5–11]. Much effort has been paid on the prolongation of the plasma channel lifetime since fs laser plasma channel was observed [12–18]. One of the possible ways is to add supporting laser pulses following the lead fs laser pulse which generates the plasma channel. Prolonging of the channel lifetime by adding a delayed long laser pulse has been investigated and practiced in filament triggered HV discharge experiment [12–15]. However the long supplemental pulse is difficult to hold ionization of the plasma channel over long distance, because generally long laser pulse is not suitable to form the self-guided propagation as an fs pulse does. Recently, multiple fs laser pulses have been used in the experiment to further prolong the lifetime of the plasma channel [16,17]. Zhang et al. demonstrated that the lifetime of plasma channel can be doubled using dual fs pulses [16]. Ji et al. investigated the lifetime of the plasma channel produced by fs laser pulse sequence, generated by adjusting the regenerative amplifier in the traditional chirped pulse amplification (CPA) system. They generated a sequence of about 6 pulses and prolonged the lifetime of the plasma channel up to about 90 ns [17].

In this letter, a pure multi-pass amplification chain was used to directly amplify the pulse sequence from the fs oscillator. The sequence which contains 17 pulses with mJ level energy was obtained after the final compression. Time-resolved fluorescence measurement and electrical conductivity measurement were used to characterize the lifetime of the generated plasma channel. A study of lifetime of the plasma channel generated by laser sequence and single fs laser shows that use of the pulse sequence can significantly prolong the lifetime of the plasma channel.

2. Experiment setup

The experiments were carried out using a modified Ti: sapphire CPA laser system (XL-II facility) which used pure multi-pass amplification chain. Detailed description of the XL-II facility can be found in Ref [19]. It is a typical CPA laser system which consists an oscillator, a stretcher, two amplification chain (a regenerative preamplifier and a multi-pass main amplifier) and a compressor. In our work, we replaced the regenerative resonator by a nine-pass preamplifier. The seed pulse sequence with a time interval of 14.8 ns from the oscillator was stretched and amplified by the nine-pass preamplifier without pulse selection. The photodiode signal of the sequence with 40 pulses after the preamplifier is shown in Fig. 1(a). The total energy of the pulse sequence was about 0.8 mJ. After the first amplification, the pulses in the sequence were further amplified by a six-pass main amplifier and then

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compressed to pulse duration of 60 fs. Finally, about 17 pulses were efficiently amplified and their photodiode signal is shown in Fig. 1(b). The total energy of the output pulse sequence was measured to be 60 mJ. The signal shown in the oscilloscope was measured in linear region so that the energy of each pulse in the sequence can be estimated. The highest and lowest energies in the “visible” sequence from Fig. 1(b) are 11 mJ and 0.7 mJ respectively.

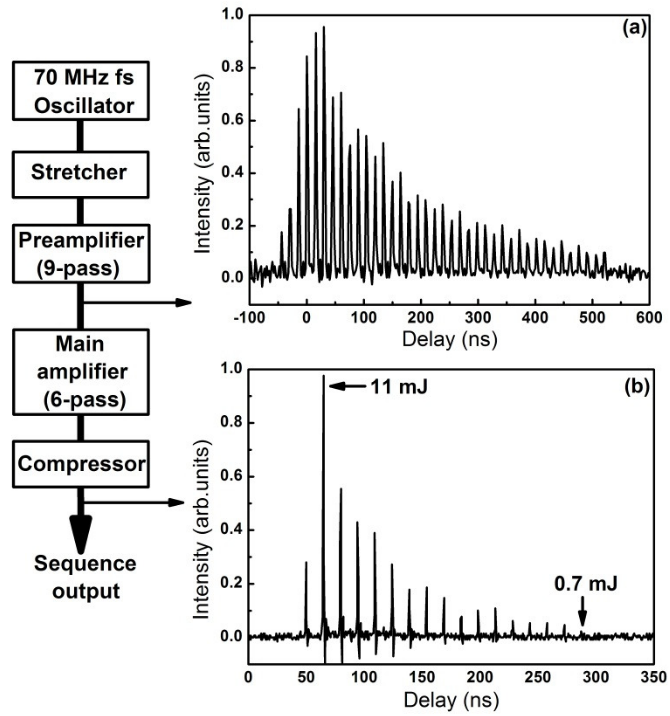

Fig. 1. Photo diode signal of laser sequence after the preamplifier (a) and the final compression (b).

The output pulse sequence is focused by a lens to generate plasma channel in air. An intensified charge coupled device (ICCD) is used to take fluorescence images of the filaments from the side, as shown in Fig. 2(a). The shutter width of ICCD is set to be 2 ns. Time evolution of fluorescence images is recorded by manipulating the delay time between the laser pulse sequence and the gate of ICCD by a step of 2 ns. On the other hand, electrical conductivity measurement is also performed to evaluate the conducting time of plasma channel, as shown in Fig. 2(b). DC voltage of 200 V is applied to the electrodes through a resistor of 1 kΩ. The electrodes are two cylinders with 5 mm diameter and 1 mm gap between them. The strongest part of the plasma channel passes through the gap between the electrodes without contacting with them. If ionization in the gap exists, the voltage signal can be detected by the oscilloscope and it can reflect the conductivity of the plasma channel.

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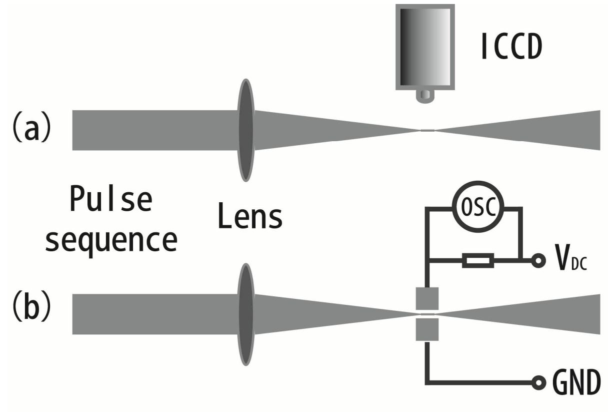

Fig. 2. Experiment setup. (a) Fluorescence measurement. (b) Electrical conductivity measurement.

3. Experiment results and discussions

The pulse sequence with 60 mJ total energy is focused by an f = 300 mm lens in air to form a plasma channel. Figure 3 shows typical time-resolved fluorescence images of plasma channel generated by pulse sequence (a) and 60 mJ single fs laser pulse with the same focal length (b). Existence of the fluorescence images is more than 1 μs for the pulse sequence while that for the single fs pulse is only 80 ns. From Fig. 3, we can see that fluorescence lifetime of the plasma channel is greatly prolonged using the pulse sequence configuration.

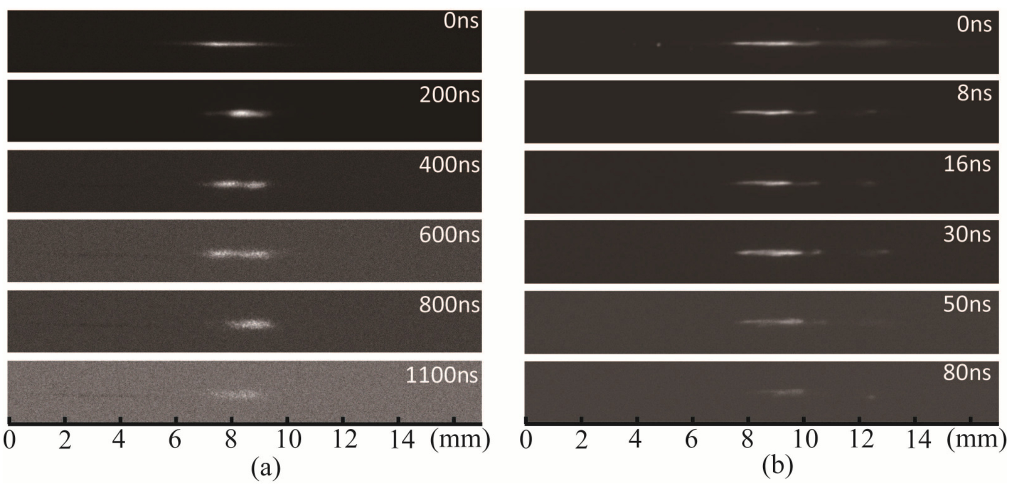

Fig. 3. Time-resolved fluorescence images for laser pulse sequence (a) and single pulse (b).

Figure 4(a-c) shows time evolution of the maximum fluorescence intensity from plasma channel using laser pulse sequence for different initial focusing conditions ((a)f = 1000 mm, (b)f = 500 mm, (c)f = 300 mm). We find that the fluorescence lifetime is sensitive to the external focusing condition. When loose focusing (f = 1000 mm) is applied, the plasma density in channel is lower and the lifetime of fluorescence is only about 5 ns, which is shorter than the separation between two neighboring pulses. In this case, each pulse in the sequence works independently and only several separated peaks can be seen. But for tight focusing condition, the fluorescence lifetime of plasma channel generated by the first strong pulse becomes longer than the time interval of the sequence (14.8 ns). So the uninterrupted fluorescence signal is observed, as shown in Fig. 4(b,c). For comparison, the time evolution of fluorescence intensity of plasma channel generated by single 60 mJ pulse with f = 300 mm

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initial focusing is also presented in Fig. 4(d). It is shown that even with such high pulse energy, the fluorescence lifetime by single pulse is only tens of nanoseconds, which is much shorter than that generated by pulse sequence with the same total energy.

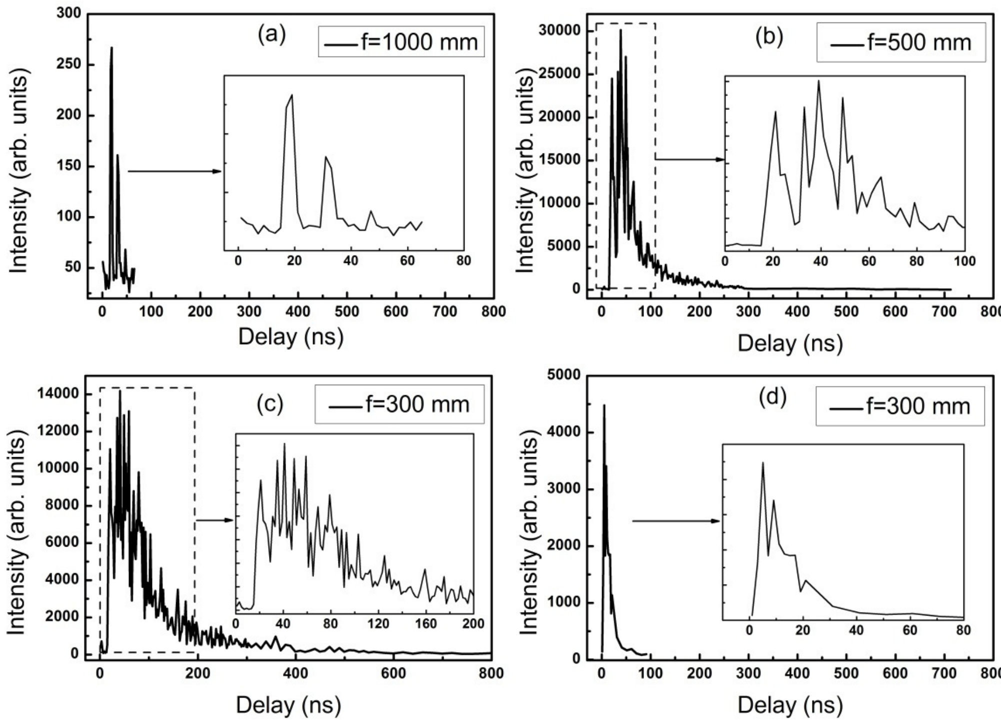

Fig. 4. Maximum intensity of the fluorescence images as a function of the time delay for laser sequences: (a)f = 1000 mm, (b)f = 500 mm, (c)f = 300 mm and for single laser pulse: (d) f = 300 mm.

Actually, fluorescence signal reflects the lifetime of excited states of molecules and ions in air. The existence of plasmas can be directly observed from the electrical conductivity measurement. Figure 5 shows comparison of electrical signal generated by pulse sequence and single laser pulse with the same total energy of 60 mJ and the same initial focusing of f = 300 mm. The FWHM width of electrical signal generated by the pulse sequence is 150 ns, which is much longer than that generated by the single laser pulse (8 ns). Besides, there is a long tail extended up to 700 ns for the electrical signal generated by the pulse sequence.

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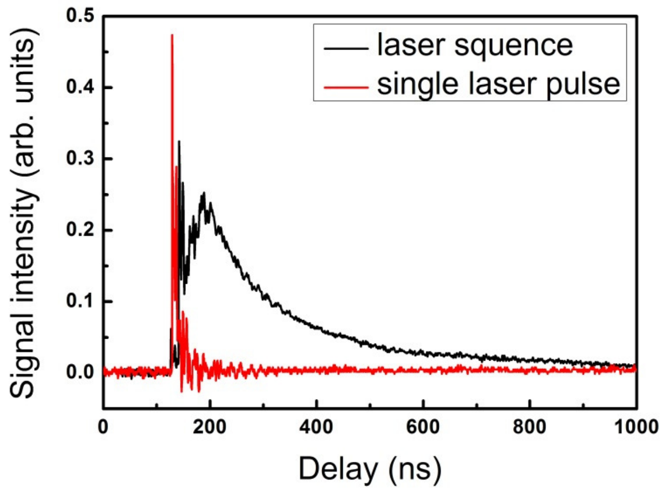

Fig. 5. (color online) Electrical signal of the plasma channel generated by pulse sequence (black line) and single pulse (red line) with the same total energy.

The experimental results from both fluorescence images and electrical conductivity measurement demonstrate that lifetime of the plasma channel can be greatly prolonged using the pulse sequence. It is well known that the critical power for self-focusing effect is about 3.2 GW in air for 800 nm laser pulse [4]. Thus all the “visible” pulses in the sequence shown in Fig. 1(b) can form plasma channel between the electrodes. In the case of tight focusing, the pulses arrive when the channel does not completely decay, so the following pulses can induce stronger ionization than that in ground state air. As a result, the time accumulation effect takes place. After the 17 strong pulses, the peak power of the pulses in the sequence becomes comparable or lower than the critical power. But the intensity in the geometric focus can be higher than the ionization threshold of air if the pulse energy is higher than tens of μJ. When the pulse energy in sequence reduces to the value which is unable to ionize air molecule, they can still detach the electrons from negative molecules and hold conductivity of air in the gap [20]. Therefore, the weak part of the pulse sequence can also contribute to the generation of air plasma. The long tail in Fig. 5 is the evidence of the re-ionization and detachment effect.

4. Conclusion

Long lifetime plasma channel was generated using fs pulse sequence in the experiment. The pulse sequence was produced by a modified Ti: sapphire CPA fs laser system with pure multi-pass amplification chain. Time-resolved fluorescence images and electrical conductive measurement were used to characterize the lifetime of plasma channel. It is found that the lifetime of the plasma channel can be prolonged up to μs level using the pulse sequence. Both the repeated ionization and the detachment effect by pulse sequence contribute to the prolongation of the plasma channel lifetime. Our experiment demonstrates new possibilities in principle to produce pulse sequence with plenty of pulses for better utilization of the filamentation. Further prolonging of the channel lifetime and improving of its quality can be achieved by increasing the amount of energetic pulses in sequence and reducing the time interval between pulses to several nanoseconds.

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