Triggering and guiding HV discharge in air by filamentation of single and dual fs pulses

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Abstract: The triggering and guiding of the stationary high voltage (HV) discharges at 5-40 kV are demonstrated by using plasma filaments generated by single and dual femtosecond(fs) laser pulses in air. A significant reduction of the breakdown voltage threshold due to the pre-ionization of the air gap by laser pulse filamentaion was observed. The amount of free electrons of filaments generated by different pulse configurations was compared by sonography method. The lifetime of filaments is measured by using time-resolved fluorescence spectrum, and the lifetime of filaments generated by dual fs laser pulses was doubled due to the re-ionization by the succeeding pulse. The triggering ability of dual fs laser pulses was demonstrated to be enhanced due to the longer lifetime of filaments.

OCIS codes: (140.7090) Ultrafast lasers; (190.7110) Ultrafast nonlinear optics; (350.5400) Plasmas; (999.9999) Lightning control

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1. Introduction

The triggering and guiding of lightning using high intensity laser beams has been considered since 1970s[1]. The main conception is to trigger the lightning and to guide the stroke to safe places using plasma channels, which is produced by ultra -intense laser beam. The physical mechanism of laser triggered lightning is very complicated and still not clearly understood till present time. The basic researches on the laser lightning control are mainly carried out in laboratories using artificial HV, because of the randomness and danger of the natural lightning. Since 1980s, Japanese scientists have done many works on laser-triggered HV discharge using high power CO_2 laser[2, 3]. The CO_2 laser produces a discontinuous plasma channel composed by serials of separated breakdown sparks, and large amount of laser energy was needed to trigger a long gap discharge.

In recent years, the ultra-short laser pulse filamentation has attracted a great interest of scientists[4, 5]. When ultra-intense fs laser pulses propagate in air, long plasma filaments can be generated in the results of the dynamic balance between the nonlinear Kerr self-focusing and

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plasma defocusing, which is induced by the laser field ionization of air. Such plasma filaments can propagate over a distance of hundreds of meters[6, 7], so the fs laser filaments could trigger and guide a long gap discharge more efficiently. Many laboratories have demonstrated HV discharges triggered by fs laser plasma filaments[8, 9, 10, 11, 12, 13, 14, 15, 16]. H. Wille et al. have reported using Teramobile system to trigger air discharge over 3.2 m[17]. It has been demonstrated that ultrashort laser pulse plasma filaments can reduce the discharge breakdown voltage efficiently and guide the discharge streamer along the laser propagation direction. A recent research has observed a statistically significant number of electric events synchronized with the laser pulses, at the location of the filaments during two thunderstorm[18]. This research result can investigate the possibility to trigger real-scale lightning using filaments generated by ultrashort laser pulses in the atmosphere.

Many experimental study on laser guided discharge have shown that the efficiency of triggering and guiding HV discharge is strongly dependent on the characteristics of the plasma filaments. For a centimeters scale discharge, the mechanism of triggering is the electron avalanche, which is caused by the ohmic heating of the filaments[19]. For meters scale or longer triggered discharge, the plasma filaments will first cause an electric field enhancement[20] and then guide the streamer or the discharge leader. Both the electron avalanche and the propagation of streamer or leader need plenty of time. The typical speed of the laser triggered leader is about 10^6 m/s[10, 13]; which means to propagate a distance of several meters, it needs a few μs. But the lifetime of filaments generated by single fs pulse is only several ns. Prolonging the plasma channel's lifetime by adding a delayed laser pulse has been suggested by Yang et al[21] and experimentally investigated by Hao et al[22]. A research group from Europe has studied the triggering and guiding ability using dual fs+ns pulses. The lifetime of the plasma filaments is prolonged by the succeeding nanosecond pulse and the capacity of fs laser pulses to trigger and guide HV discharges is enhanced significantly[15]. The mechanism of prolonging filaments' lifetime by adding a nanosecond succeeding pulse is the detachment effect, which can hold the electron density in 10^{12-13} cm^{-3} level. In order to produce long-life filaments with higher electron density, the re-ionization of filaments is necessary. Such filaments can be formed by multiple fs laser pulses. In this paper, we experimentally investigate the properties of light filaments generated by dual 15 mJ with 7 ns delay time. The enhancement of triggering ability due to long life time of filaments is demonstrated by the triggering and guiding of HV discharge using filaments generated by the dual fs+fs laser pulses.

2. Experimental setup

The laser system is a home-made Ti:sapphire chirped-pulse amplification system with a repetition rate of 10 Hz, a pulse duration of 30 fs, and a central wavelength of 800 nm. For the experiment reported here, the light filaments were generated by dual fs+fs pulses with 15 mJ energy for each and also single pulse with 15 mJ or 30 mJ energies. The dual fs+fs laser pulses are generated in the regen-amplifier, and the delay time is fixed at 7 ns according to the length of the regen-amplifier cavity. There is a series of laser pulses in the regen-amplifier and we just choose two of them by the Pockels cell. The high-voltage source can produce a static high voltage up to 40 kV. The fs laser pulses are focused with a thin lens with focal length $f = 4$ m to produce the plasma filaments. The grounded anode is a vertically placed circular plate with 100 mm diameter. This plate is fixed on a motorized stage, and its position can be controlled remotely. The cathode is a sphere with 10 mm diameter, and it is placed several centimeters away from the plate. There are two holes with 1 mm diameter in the center of the plate and the sphere. The laser plasma filaments pass through the two holes and connect the two electrodes to trigger and guide an HV discharge, as shown in Fig. 1. The electrodes are placed at the strongest part of the filaments, where the size of the filaments bundle is smallest. The gap between two

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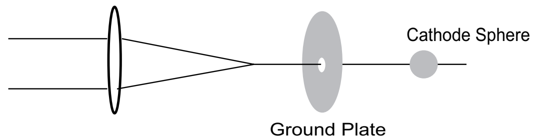

Fig. 1. Discharge setup

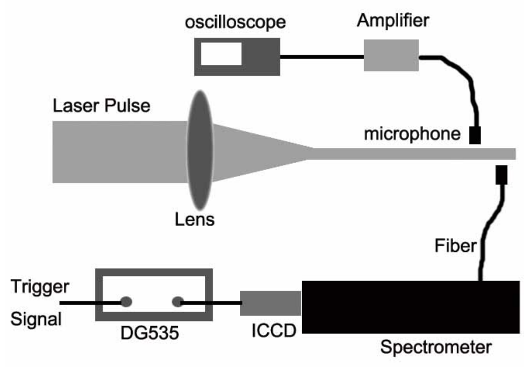

Fig. 2. The experiment setup for filaments diagnostics

electrodes is several centimeters and the size of the filaments bundle varies very little through this distance. So the filaments can fully pass through the two holes. The laser pulse propagation direction is from the ground plate to the sphere, just like from the ground to the cloud.

In order to understand the characteristics of the triggering ability, we performed preliminary diagnostics of filaments. The length and the amount of free electrons of filaments produced by different pulse configurations is compared by sonography method[23, 24]. In the plasma filaments, the air molecules are partially ionized and sound waves are formed. It has been found that the intensity of sound waves is related with the amount of free electrons in the plasma filaments. A microphone is placed perpendicularly to the filaments at a distance of 1 cm from the laser axis, as shown in Fig. 2. The acoustics signals are recorded by a digital oscilloscope after being amplified by an audio amplifier.

The lifetime of filaments is manifested by the temporal evolution of the fluorescence spectrum from the electron-ion recombination in the filaments[25]. The spectrum emitted from the filaments is collected by an ICCD+spectrometer system. The gate of the ICCD is set to be 2 ns. The synchronize trigger signal for ICCD comes from the laser system, as shown in Fig. 2. The jitter time between the trigger signal and the laser pulse is less than 500 ps. With the digit signal generator(DG535), we can manipulate the delay between the trigger signal and the laser pulse precisely. By changing the delay time of the trigger signal, we can obtain the temporal evolution of the spectrum intensity. Consequently, the lifetime can be deduced.

3. Results and discussion

The acoustic signal along the filaments generated by different pulse configurations is shown in Fig. 3. The amplified ratio for all measurements is constant. According to the acoustic signals, we can find that the amount of free electrons of filaments generated by a 15 mJ single pulse and by the dual fs+fs pulses is almost the same, which is significantly lower than that by a 30

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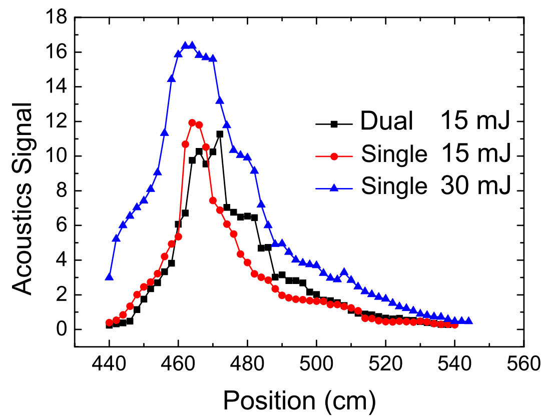

Fig. 3. Acoustics signals along the propagation distance with laser energy 15 mJ, 30 mJ and the dual fs+fs pulse.

mJ pulse. The length of filaments is about 1 m, which is many times longer than the Rayleigh length.

A sample of the fluorescence spectrum of filaments is shown in Fig. 4. There are many spectral lines from 300 nm to 400 nm assigned to two band system, which is corresponded to the $N_2 : C^3\Pi_u - B^3\Pi_g$ transition and the $N_2^+ : B^2\Sigma_u^+ - X^2\Sigma_g^+$ transition. We choose the spectral line of 383.8 nm$(N^+ : 4s(^3P^0) - 3p(^3P))$ to describe the lifetime of plasma filaments. The temporal evolution of the spectrum intensity is shown in Fig. 5. The spectral intensity is counted by averaging 10 laser pulses. The long rise time of the fluorescence spectrum is caused by the detection method. The fluorescence signal is time-integrated in 2 ns, so when the ICCD is triggered a little earlier than the filamentation, some signals can still be detected. This is the reason of the slow rise time about 2-3 ns of the fluorescence spectrum. Actually, the fluorescence occurs suddenly after the laser pulse. In order to retrieve the lifetime of the spectrum, we have deconvoluted these profiles with the true ICCD gate and the delay time. The dashed line in Fig. 5 is the deconvolution results. The rise time of the signal is still longer than the real signal because there is a time jitter between the trigger signal and the laser pulse. From deconvolution results, we can see that the lifetime of filaments generated by a single pulse is about 5 ns(bottom width), the fluorescence signal rise again after 7 ns delayed succeeding fs pulse, and the total lifetime of filaments is prolonged.

In order to identify the triggering ability of the laser filaments, we have firstly studied the threshold voltage of natural discharge without laser guiding as a reference. When high-voltage had been applied to the cathode sphere, we move the ground plate close to the cathode sphere very slowly till the breakdown happens. As shown in Fig. 6, for the voltage from 5 to 40 kV, the natural discharge gaps length is from 1 to 30 mm. For the laser triggered discharge, the dependences of breakdown voltage on the air gap length is measured as follows. First we apply a fixed high voltage to the electrode and set the gap length longer than the critical distance, on which the natural discharge can happen. Then we switch on the laser filaments to connect the two electrodes and trigger the air discharge. After this discharge finished, we prolong the air gap distance and then apply the high voltage again to the electrode. Then we switch on the laser filaments to trigger the air discharge. The air gap distance is prolonged slowly step by step till the filaments are not able to trigger the discharge, and in this way we can find the dependences of breakdown threshold voltage on the air gap distance for laser triggered discharge. In the laser triggering case, we use the single shot laser pulse (not 10 Hz) and the discharge probability is

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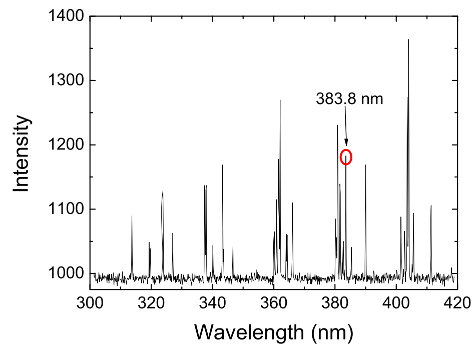

Fig. 4. A sample of the fluorescence spectrum at the focal point with laser energy 15 mJ, delay time 2 ns.

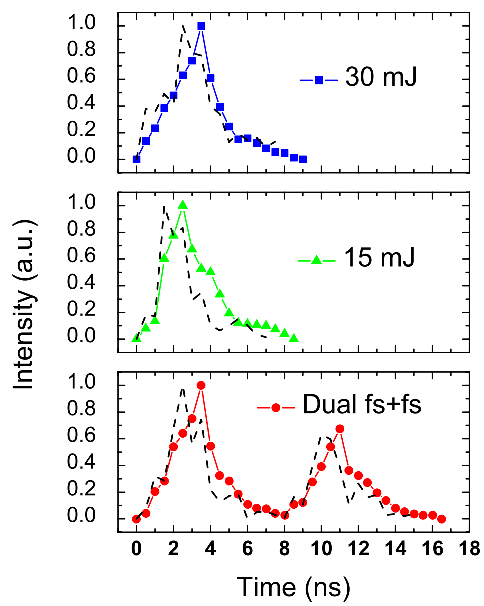

Fig. 5. The temporal evolution of the spectral line 383.8 nm, the dashed line is the deconvolution results with the ICCD gate and delay time.

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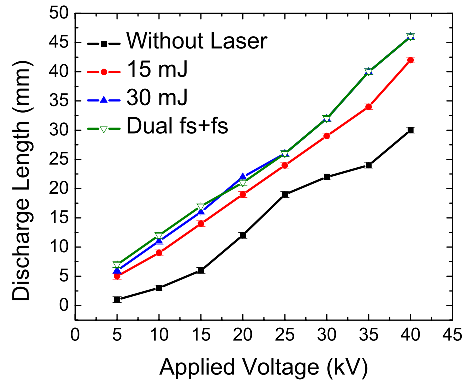

Fig. 6. Breakdown voltage for natural discharge and laser triggering discharge.

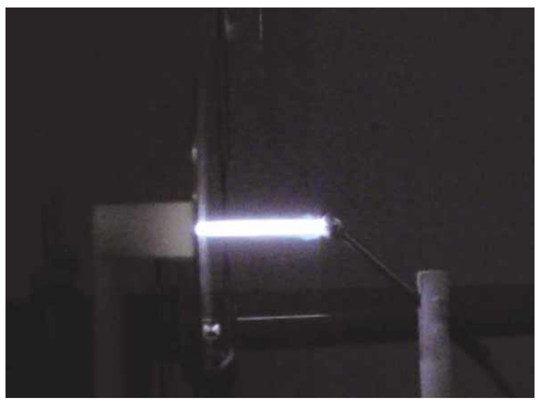

Fig. 7. The laser triggered discharge spark in a 45 mm gap.

more than 70%. The discharge gaps are located on the filaments fragments with maximum amount of free electrons. Figure. 7 shows a discharge spark triggering by 30 mJ laser pulse with 40 kV applied high voltage. From Fig. 7 we can see the discharge is guided to be straight along the laser propagation direction.

The dependence of laser triggered discharge length on the applied voltage is shown in Fig. 6. The triggering ability of different laser pulse configurations can be illustrated by comparing with the case of natural discharge. For single pulse energy of 15 mJ, the air discharge over a distance from 7-42 mm can be triggered at 5-40 kV, while the natural discharge length is only from 1-30 mm. As shown in Fig. 6, the 30 mJ single pulse and the dual 15 mJ fs+fs pulses show almost the same triggering ability. For example at 40 kV, the 15 mJ pulse has prolonged the discharge length by 40% than the natural discharge length; while for the 30 mJ pulse and the dual fs+fs pulses, the discharge length increased by 53%.

From the experimental results we can find that the triggering and guiding ability of filaments can be improved by increasing the initial electrons or lifetime of plasma filaments. For the triggered discharge in the scale of centimeters, the main contribution of the plasma filaments is the ohmic heating[19]. The model in Ref. [19] has shown that the ohmic heating persists over long

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time scales after the laser pulse and the rise of electron temperature causes the avalanche rate to increase to the point where breakdown occurs. In the case of dual fs+fs pulses configuration, the plasma inside the filaments, which are generated by the first pulse, can be re-ionized by the succeeding fs pulse, and the amount of free electrons can rise again. Consequently, the avalanche rate can be further increased with the electron temperature. In this way, the triggering ability is improved by the succeeding fs pulse.

4. Conclusion

The triggering and guiding of the stationary HV discharges in 5-46 mm air gaps are demonstrated by using plasma filaments generated by single and dual fs laser pulse in air. The characteristics of filaments are studied firstly in terms of relative amount of free electrons and lifetime. The amount of free electrons in filaments is compared by using the sonography method. The maximum amount of free electrons is almost the same for the single 15 mJ pulse and the dual 15 mJ pulses, which is much lower than a single 30 mJ pulse. The lifetime of filaments is demonstrated by the time-resolved fluorescence spectrum, and the results have shown that the lifetime can be prolonged by adding a succeeding fs pulse. The lifetime of the plasma filaments generated by the single 15 mJ or 30 mJ pulses is about 5 ns, and the lifetime of filaments can be prolonged by a 7 ns delayed succeeding fs pulse. The triggering and guiding ability of filaments is demonstrated by measuring the HV discharge length. The prolonging of discharge length up to 1.53 times of natural discharge length is demonstrated at 40 kV HV by using single 30 mJ pulse or the dual 15 mJ fs+fs pulses. The triggering ability of laser filaments can be improved by increasing the lifetime of the plasma filaments with dual fs+fs pulses. So the lifetime, consequently the triggering ability, is possible to be further increased by using a series fs pulses.

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