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Triggering and guiding of high voltage discharge by using femtosecond laser filaments with different parameters*

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This paper demonstrates the triggering and guiding of the stationary high voltage (HV) discharges at 5–40 kV by using plasma filaments generated by femtosecond laser pulses in air. A significant reduction of the breakdown voltage threshold due to the pre-ionization of the air gap by laser filamentation is observed. The discharge experiments are performed by using laser pulses with different energy from 15–60 mJ. The electron density of filaments is detected by sonography method. The influence of the electron density of laser filaments on the triggering and guiding HV discharge is experimentally investigated. The results have shown that the behaviour of plasma filaments can strongly affect the efficiency of triggering and guiding HV discharge.

Keywords: laser filaments, HV discharge, triggering, guiding
PACC: 5150, 5250J

1. Introduction

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

In recent years, the ultra-short laser pulse has attracted great interest among scientists. When an ultra-intense femtosecond (fs) laser pulse propagates in air, long self-guiding plasma filaments can be generated as a result of the dynamic balance between the nonlinear Kerr self-focusing and plasma defocusing,[4] which is induced by the laser field ionization of air. Such a plasma filaments can propagate over a distance of hundreds[5] up to thousands[6] of meters and the fs laser plasma filaments are spatially continuous.[7] Consequently, the fs laser filaments could be more efficiently to trigger and guide a long gap discharge. Many laboratories have demonstrated HV discharges triggered by fs laser plasma filaments.[8−15] Wille *et al* have reported using the Teramobile system to trigger air discharge over 3.2 m.[7] It has been demonstrated that ultrashort laser pulse plasma filaments can reduce the discharge breakdown voltage efficiently and guide the discharge filaments along the laser propagation direction.

Many experimental studies on laser guided discharge have shown that the efficiency of triggering and guiding HV discharge is strongly depended on the characteristics of the plasma filaments. To our best knowledge, the relationship between the plasma

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density of filaments and the breakdown voltage of air gap has not been quantitatively studied yet. In this paper, we have experimentally investigated the influence of the electron density of filaments on the efficiency of triggering and guiding HV discharge. The fs laser pulses with energy from 15 mJ to 60 mJ are used to produce plasma filaments. The sonography method is used to detect the electron density in the filaments.[16,17] The triggering and guiding of HV discharge is demonstrated by using the filaments with different laser energies. The triggering and guiding of HV discharge using different part of the filaments is also studied as well.

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. The maximum output energy of this laser system is 640 mJ per pulse. For the experiment reported here the pulse duration is 50 fs, and the maximum energy is 60 mJ. The HV system can produce a static HV up to 40 kV. The fs laser pulse is 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, which is placed several centimetres away from the plate. There are two holes with 1 mm diameter in the centre of the plate and the sphere. The laser plasma filaments pass through the two holes and connect the two electrodes to trigger and guide a HV discharge, as shown in Fig.1.

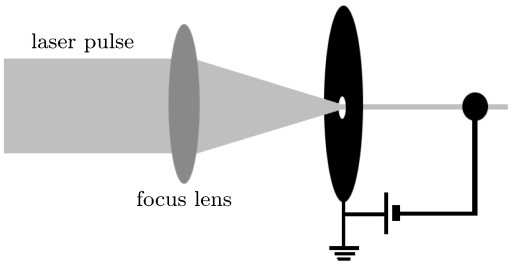


Fig.1. Experimental setup.

Both the ground plate and the cathode sphere can be moved along the laser propagation direction, in order to match different parts of the plasma filaments. The laser pulse propagation direction is from the ground plate to the sphere, just like from the ground to the cloud.

3. Results and discussion

In our experiment, the laser pulses with energy of 15, 30 and 60 mJ are used to generate plasma filaments. In the plasma filaments, the air molecules are partially ionized and plasma shock waves are formed. Then the plasma shock waves decay to plasma sound waves subsequently, which are the acoustic signals we detect. It has been found that the intensity of sound wave is related with the electron density in the plasma filaments.[18] A microphone is placed perpendicularly to the filaments at a distance of 1 cm from the laser axis. The acoustic signals are recorded by a digital oscilloscope after being amplified by an audio amplifier. The signals along the filaments are shown in Fig.2. According to the acoustic signals, we can indicate both the length and the relative electron density of the filaments. As shown in Fig.2, both the length and the electron density of the filaments increase with the laser energy.

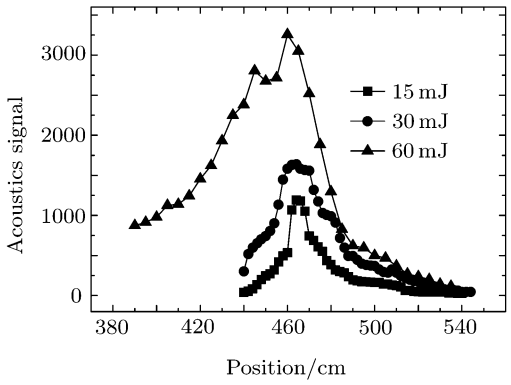


Fig.2. Acoustics signals along the propagation distance with laser energy 15, 30 and 60 mJ.

In order to identify the triggering ability of the laser filaments, we have first studied the reference case of a natural discharge without laser pulse. When HV has been applied to the cathode sphere, we move the ground plate close to the cathode sphere very slowly till the breakdown happened. As shown in Fig.3, for the voltage from 5 to 40 kV, the natural discharge gap length is from 1 to 30 mm.

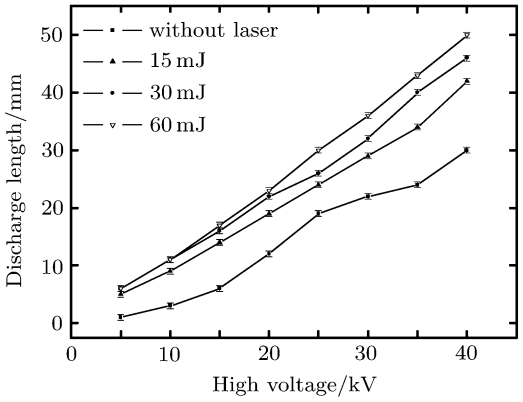
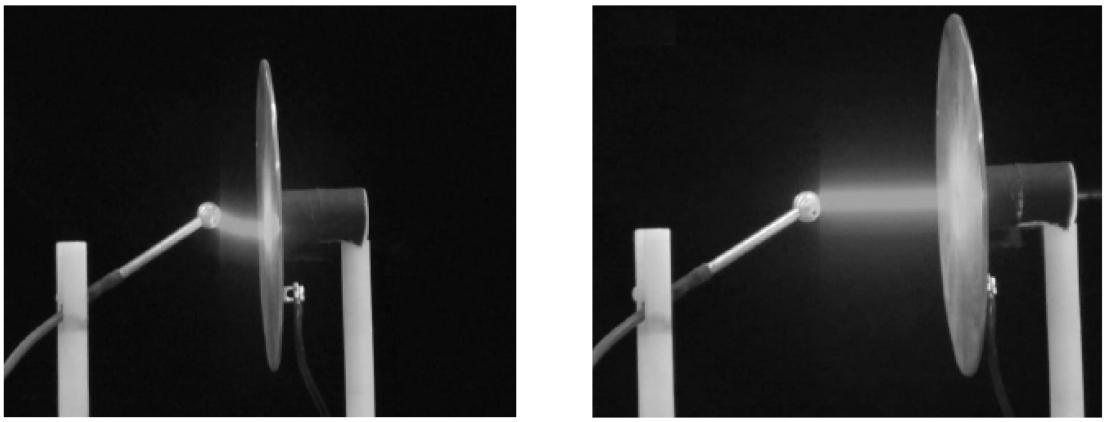


Fig.3. Breakdown voltage for natural discharge and laser triggering discharge.

Figure 4(a) is a typical image of the natural discharge in 19 mm air gap, a curly spark is observed. For the laser triggered discharge, the dependence of breakdown voltage on the air gap length is measured as follows. First we applied to the electrode a fixed HV and set the gap length a little longer than the critical distance, on which the natural discharge can happen. Then we switch on the laser filaments to connect the two electrodes. If the breakdown threshold voltage with laser filaments is less than the applied voltage, the discharge can be triggered. Then we prolong the air gap distance slowly step by step till the filaments are not able to trigger the discharge, and in this way we can find the dependence of breakdown threshold voltage on the air gap distance for laser triggered discharge. The discharge gaps are located on the filaments fragments with maximum electron density. From Fig.4(b), we can see that the triggered discharge spark in 50 mm is straight along the laser propagation direction.



(a) (b)

Fig.4. (a) The natural discharge spark in a 19 mm gap. (b) The laser triggered discharge spark in a 50 mm gap.

The electron density is a very important characteristic for the plasma filament's triggering ability.[10] The electron density of the filaments is strongly dependent on the energy of laser pulse. By increasing the pulse energy, higher density plasma filaments can be generated.[19] The dependence of laser triggered discharge length on the applied voltage is shown in Fig.3. The triggering ability of different laser pulse energies can be indicated by comparing the gap length of natural discharge with laser triggered discharge. For 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.3, the higher energy pulse has advantages on triggering air discharge especially for higher voltage. The triggered discharge lengths at 5 kV in the cases of 15, 30 and 60 mJ of laser pulse energies are almost the same, which is about 7 mm. When the applied voltage becomes higher, the triggered discharge length increases with laser energy more and more evidently. 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 60 mJ pulse, the discharge length increased by 53% and 66.7% respectively.

According to the acoustic signals, we know that the electron density along the propagation direction is not uniform. The electron density is higher in the middle and lower at the beginning and the ending parts of the filaments. As shown in Fig.2, when a pulse with 60 mJ energy is launched, the plasma filaments from 390 cm to 540 cm after the focus lens are created. The filaments generated here is about 0.5 m long, but due to the limitation of the HV source, we can only trigger a discharge in air gap of several centimetres. We move the ground plate and the cathode sphere along the plasma filaments, and use different parts of the filaments to trigger the discharge. The voltage applied on electrodes is fixed at 40 kV.

The dependence of the maximum length of discharge on the position of plate (or sphere) is shown in Fig.5. The dashed horizontal line indicates the natural discharge length at 40 kV, which is 30 mm. The

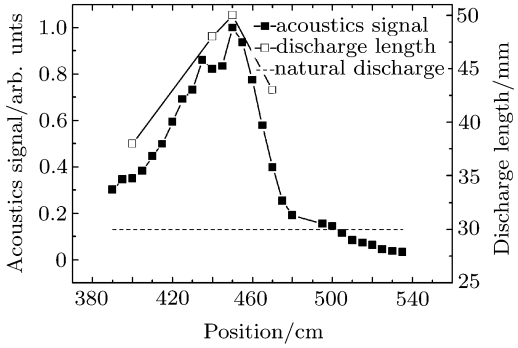


Fig.5. The acoustics signal and triggered discharge length along the propagation direction. The dashed horizontal line indicates the natural discharge length at 40 kV.

x axis indicates the distance after the focus lens. We have measured 4 positions along the plasma filaments. At 4 metres after the focus lens, the plasma filaments just begin to form and the electron density is low, only 38 mm discharge can be triggered. At 4.5 m after the lens, the plasma filaments reach the maximum electron density, and 50 mm discharge can be triggered. The maximum discharge gap length is well matched with the electron density of plasma filaments.

4. Conclusion

The triggering and guiding of the stationary HV discharges in 5–50 mm air gaps are demonstrated by using plasma filaments generated by fs laser pulse in air. A significant reduction of the breakdown voltage threshold due to the pre-ionization of the air gap by laser filamentation is observed. The triggering ability of laser filaments can be improved by the increase of laser energy. The prolongation of discharge length up to 1.67 times of natural discharge length is demonstrated at 40 kV HV by using 60 mJ laser energy. The triggering and guiding of HV discharge by different parts of the laser filaments have also been studied. The triggering and guiding by using the central part of filaments are much more effective than by using the beginning or the ending parts of filaments. Our experimental results indicate that the electron density and uniformity of the laser filaments are very important for the application of lightning control.

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