Comparative investigation of the resistance and ability to trigger high voltage discharge for single and multiple femtosecond filaments in air*

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(Received 26 May 2012; revised manuscript received 5 November 2012)

A comparative investigation of the resistance and ability to trigger high voltage (HV) discharge for a single filament (SF) and multiple filaments (MFs) has been carried out. The experimental results show that the trend of the breakdown threshold of the SF exactly follows that of its resistance, but this is not the case for the MF. The MF's resistance is much smaller than the SF's. However, the MF shows a slightly higher HV breakdown threshold than the SF. The underlying physics is that the measured resistance of the MF is collectively contributed by every filament in the MF while the HV breakdown threshold is determined by only one single discharging path.

Keywords: femtosecond filament, resistance, high voltage breakdown threshold

PACS: 52.38.Hb **DOI:** 10.1088/1674-1056/22/3/035203

1. Introduction

A long self-guided plasma filament is formed as an intense ultra-short laser pulse propagates in air,[1] which results from the dynamic equilibrium between the self-focusing effect and the generated plasma defocusing effect. The electron density of the laser filament is in the range of 10^{15}–10^{16} cm^{-3}, and the measured resistance of the filament varies from 3.6×10^{5} $\Omega\cdot$m^{-1} to 6.4×10^{7} $\Omega\cdot$m^{-1}, which depends on the laser pulse energy and the f number of the focusing optics.[2] Because of the great reduction in resistance over the free space, the plasma filament may find wide potential applications in lightning control,[3–6] fast switching for high voltage (HV) connection, and so on.

The resistance of the filament is a basic physics parameter that determines the filament's characteristics and influences many potential applications. Therefore it has been extensively studied by using various measurement methods over the years. In 1999, the resistance of the plasma filament was measured for the first time using different methods. The value varied from 4×10^{5} $\Omega\cdot$m^{-1} to 1×10^{7} $\Omega\cdot$m^{-1}.[7–9] Most the measurements were operated in the multiple-filament (MF) mode since the femtosecond laser pulse energy employed ranged from tens to hundreds mJ.[7–13] In the meantime, the HV triggering ability of the filament has also been intensively investigated,[4] as it is the key to some filament applications. The ability to trigger HV discharge by the filament was first demonstrated by Zhao *et al.* in 1995.[4] The plasma filament provides a preferred channel that allows the leader to propagate along it.[14] The resistance of the filament is a critical parameter for triggering and guiding the HV discharge. However, up to now, there is no report on the relationship between the resistance of the filament and its ability to trigger the HV discharge. In this paper, we make a comparative investigation of the resistances of single filament (SF) and MF, and the relationship between the HV breakdown threshold and the resistance. We find that the resistance of the MF is much smaller than that of the SF; however the MF's smaller resistance does not lead to a lower HV breakdown threshold. Those findings are very important to the understanding of the underlying physics in the process of filament triggered HV discharge.

2. Experimental setup

A chirped-pulse amplified Ti:sapphire laser system (Hidra-25, Coherent Inc.), which operates at 800 nm with a repetition rate of 10 Hz and a pulse duration of 100 fs, is employed to generate filaments in air. The laser pulse is focused by a lens with a focal length of 350 cm. The experimental setup for resistance and HV discharge measurements is shown in Fig. 1. Figure 1(a) shows the setup for the measurement of the filament resistance, in which a voltage of 960 V is applied to a pair of molybdenum (Mo) electrode plates with a gap of 1 cm. The laser pulse generates a self-guided filament before it enters the gap region of the electrodes. The pair of electrodes can be moved along the beam propagation

*Project supported by the National Natural Science Foundation of China (Grant Nos. 11074027, 60978014, 61178022, 11274053, and 11211120156), and the Funds from Sci. & Tech. Deparment of Jilin Province, China (Grant No. 20111812).

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axis. The beam is kept passing through two 0.5-mm-diameter pinholes centered on the two electrodes respectively. The signal from a sampling resistor of $R_s = 100\ \Omega$ is recorded by using a digital oscilloscope (TDS254B, Tektronix Inc.). The setup for the measurement of breakdown threshold is shown in Fig. 1(b). The high-voltage source, which can provide a static high voltage up to 100 kV, is connected to a sphere-plate electrode pair. The laser filament passes the sphere-plate electrode pair through two 2.5 mm diameter holes drilled on the sphere and the plate, respectively. The electrode pair is kept at a fixed distance of 1 cm, and they can be moved together along the propagation axis. Spatially-resolved measurements of the resistance and the HV breakdown threshold are performed by moving the electrode pair with a step of 1 cm. In our experiments, 2 mJ and 30 mJ pulses are used to generate SF and MF, respectively. Our experiments are performed under the conditions of 1 atm, 22 °C, and 13% relative humidity.

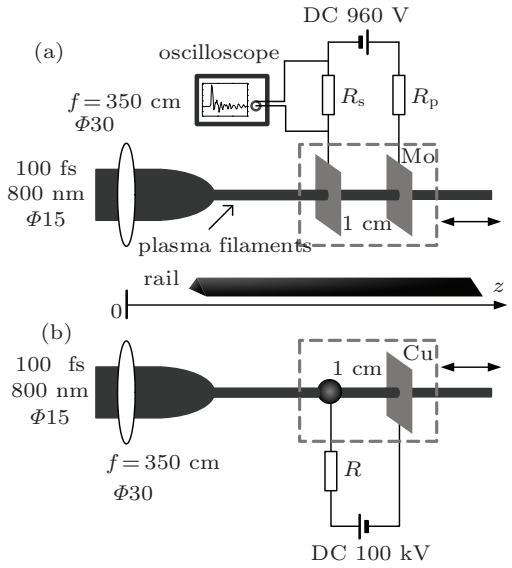


Fig. 1. Experimental setups for measurements of (a) resistance and (b) HV breakdown threshold, here $R = 25$ MΩ.

3. Results and discussion

Firstly, the resistances of SF and MF are measured respectively. The results are plotted in Fig. 2, which reveals the evolutions of the resistance along the propagation distance. In the SF case shown in Fig. 2(a), the resistance changes significantly along the beam propagation direction, and has a relatively flat region with a length of around 4 cm around the focus. The resistance in this region varies from 500 kΩ to 600 kΩ. In the MF case shown in Fig. 2(b), the plateau region of resistance extends to a length about 150 cm with typical values from 45 kΩ to 200 kΩ, which is in agreement with the values measured by other groups.[8,10,11] The resistance of the SF is several times bigger than that of the MF. We note that in our experiments, the contact resistance between the filaments and the electrodes is not taken into account due to its much lower value compared with the typical value of the filaments.[11]

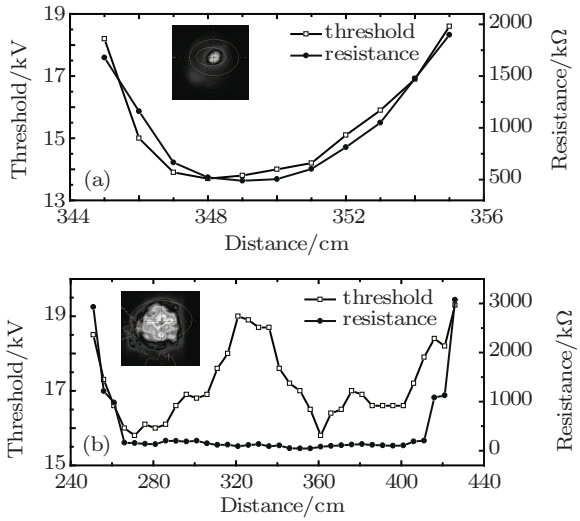


Fig. 2. Resistances and HV breakdown thresholds of (a) the SF and(b) the MF each as a function of distance from the lens along the laser propagation axis. The electrode gaps are fixed at 1 cm in both experiments. The inset images are cross section images of the laser beam obtained at a propagation distance of 450 cm showing SF and MF modes, respectively. The pulse energies used are 2 mJ and 30 mJ, respectively.

The HV breakdown thresholds of SF and MF each as a function of the propagation distance are also plotted in Fig. 2. In the SF case, the evolution of the threshold along the distance coincides with that of the resistance (Fig. 2(a)). The minimal value is 13.7 kV, and this value is approximately 50% of that of the spontaneous breakdown threshold, which is about 28 kV under our laboratory conditions. In the MF case, the HV breakdown thresholds exhibit quite large fluctuation along the propagation distance compared with the evolution of the resistance, which is totally different from that for the SF. The fluctuation should be connected to the properties of the MF, indicating some dynamic processes including random filamentation, modulation instabilities, filament breakup and fusion, focusing and defocusing effects, and so on. In the MF case, the minimal breakdown threshold is in the range from 55% to 66% of the spontaneous breakdown threshold. It is a little higher than that for the SF.

As shown in Fig. 2, the much lower resistance of the MF does not result in a lower HV breakdown threshold. This should be attributed to the difference in the physical processes that occur on the filament. The resistance measurement is under the condition that there is no breakdown between the electrodes. For the MF, the resistance is simultaneously contributed by all filaments in the bundle, like the measurement of a combined resistance of resistors connected in parallel in an electric circuit. Therefore the measured MF resistance reflects the macroscopic feature of the filament bundle without considering the details of the MF, such as the number of filaments, discontinuity, resistivity of each filament, and spacing

among filaments. However this does not apply to the case of the HV breakdown threshold measurement using the MF. Our previous research has already shown that in the HV discharge triggered and guided by the MF, only one path of the discharge is activated, i.e., the HV discharge follows a single path, similar to the case of the single filament, rather than activating multiple paths even though many filaments are contained in the bundle.[15] From this point of view, the discharge triggered and guided by the MF is comparatively much more microscopic, and this process is strongly connected to the internal structure of the filaments in the bundle.

Furthermore, even though the discharge in both the SF and the MF cases follows a single path, the minimal breakdown threshold for the MF case is slightly higher than that for the SF case (see Fig. 2). The difference of the minimal breakdown threshold for the SF and the MF should be attributed to their different ways of discharging. Figure 3 shows typical photos of HV discharge in the cases of SF (Fig. 3(a)) and MF (Fig. 3(b)). In the SF case, the HV discharge simply follows the filament, and the discharge path is a straight line without any discontinuity. However, in the MF case, discharging often jumps from one filament to another. This jumping is a reflection of the filament breakup or the fusion and modulation instabilities during the filamentation, which is a common phenomenon in the MF.[16,17] The discharge photos in Fig. 3 provide clear evidence for the difference of the minimal breakdown threshold for the SF and the MF. We believe that the jumps in the case of MF could bring extra resistance to the path followed by the discharge and must be responsible for the relatively higher minimal HV breakdown threshold compared with that of the SF case.

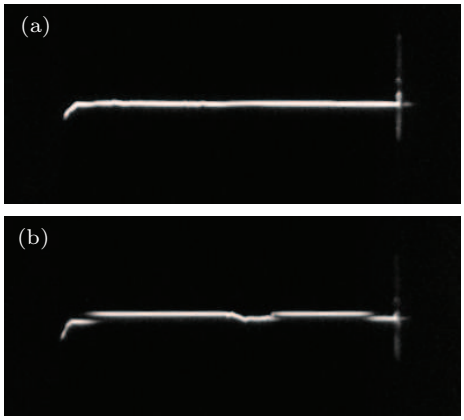


Fig. 3. Typical images of HV discharge path guided by (a) SF and (b) MF over a 1-cm gap. The exposure time of the camera is set to 1/15 s to ensure that the discharge is induced by a single laser pulse.

4. Conclusion

In summary, we comparatively study the resistance and the ability to trigger HV discharge of the SF and the MF. The results show that the resistance of the MF is much smaller than that of the SF; however, the HV breakdown threshold in the MF case is higher than that in the SF case. This is due to the different physical processes in the measurements of resistance and HV breakdown threshold. The resistance of the MF is a macroscopic reflection of the bundle and includes contributions from all the individual filaments. However, the HV discharge strongly depends on the details of the MF's structures, and it is microscopically connected to the specific path that the discharge travels along.

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