Triggering and guiding megavolt discharges by use of laser-induced ionized filaments

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We have demonstrated the ability to trigger and guide high-voltage discharges with ionized filaments generated by femtosecond terawatt laser pulses. The plasma filaments extended over the whole gap, providing a direct ohmic connection between the electrodes. Laser-guided straight discharges have been observed for gaps of as much as 3.8 m at a high voltage reduced to 68% of the natural breakdown voltage. The triggering efficiency was found to depend critically on the spatial connection of the laser filaments to the electrode as well as on the temporal coincidence of the laser with the peak of the high voltage. © 2002 Optical Society of America

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The possibility of triggering and guiding lightning by using laser beams has been discussed for more than 25 years.[1,2] The main motivation for manipulating lightning is to protect sensitive installations such as strategic sites, including nuclear, biological, and chemical plants and airports from direct strikes and electromagnetic perturbations. Whereas early studies in the 1970s and 1980s with nanosecond lasers[3,4] suffered from severe limitations, the advent of high-power femtosecond lasers has opened new perspectives in this research. In particular, recent studies demonstrated that high voltage (HV) discharges can be triggered and guided over distances of as much as 3 m by use of ultrashort laser pulses (0.3 TW, 600 fs) focused between two electrodes and creating a local plasma at the focus.[5] Similar experiments have been conducted in the UV,[6] in which multiphoton ionization was significantly enhanced by the shorter wavelength. In those experiments the laser produced a medium-density plasma (typically 10^{17} cm^{-3}), from which ionization waves (streamers), accelerated by the electric field, propagated toward the electrodes.

A remarkable property that has been observed in high-power femtosecond pulse propagation is filamentation. For a pulse propagating in air, a dynamic equilibrium between Kerr self-focusing and plasma-induced diffraction yields a narrow ($\sim$100 μm in diameter[7,8]), low-impedance[9,10] ionized filament that can be as much as 200 m long.[11] Such long plasma filaments provide a real possibility of triggering and guiding lightning. Experiments that exploited the potential of the laser-induced filaments for HV discharge control without focusing the laser between the electrodes were recently conducted with 600-fs pulses.[12] Discharges guided by filaments have been successfully demonstrated over a gap of 2 m between two plane electrodes. However, these discharges were not triggered, in the sense that the breakdown voltage was not reduced by the presence of filaments.

In this Letter we report, for the first time to our knowledge, triggering and guiding of HV discharges by laser-induced filaments over large gaps (as long as 3.8 m). Our experiments showed that aiming the laser beam in the vicinity of two charged electrodes allows filaments to ohmically bridge the electrodes,

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trigger the electric discharge, guide it along a straight way, and reduce the buildup time of the discharge.

In our experiments a standardized negative HV lightning pulse (as much as 2 MV; rise time, 1.2 μs; decay time to half-maximum, 50 μs) created by a pulsed voltage generator (Marx multiplier circuit) was applied to a 12-cm-diameter spherical electrode. A plane electrode with a diameter of 3 m was used as ground. Other electrode geometries, such as torus–torus, were tested and yielded similar results. The HV pulses were synchronized to the laser with an adjustable delay.

The laser used for this experiment was the Teramobile system,[13] a container-integrated mobile femtosecond Ti:sapphire laser system. During this experiments the laser provided 150-fs pulses with as much as 300 mJ of energy at 790 nm and 10 Hz. We could vary the output energy continuously by detuning the pulse extraction from the regenerative amplifier. Its unique mobility feature permitted us to locate the laser system inside the HV laboratory, with its horizontal output beam in line with the electrodes, at a distance of 20 m from the HV electrode (Fig. 1). The laser beam was expanded to an initial diameter of 15 cm and slightly focused ($f \sim 15-20$ m) with an adjustable telescope. Typically, with 300 mJ we observed a filament bundle with a length of 4–5 m, a 0.5–1-cm diameter, and ~15 filaments at the HV electrode. In most of the experiments the filaments started before the HV electrode and spanned the whole gap, as was verified on a screen. To ohmically bridge the electrodes with the filaments we shot the laser beam close to the HV electrode, at a typical distance of 1 cm and against the ground electrode.

We investigated the influence of the delay between the HV and the laser pulses. No successful event was observed for laser pulses before the HV (negative delay), whereas successful triggering and guiding over the whole gap was observed for laser pulses from 0 to 15 μs after the maximum of the HV pulse. These results are in contrast to those of La Fontaine *et al.*,[12] who observed laser-guided discharges for a negative delay as long as 15 μs.

We checked the importance of the ohmic contact between the plasma filaments and the electrodes in two ways. First, we observed qualitatively, in a torus–torus configuration, that the discharge could not be triggered if the laser beam was moved several centimeters away from the HV electrode. This result is consistent with recent observations with a 1.5-cm-long gap.[10] Moreover, we moved the starting position of the filamentation axially over some meters by adjusting the focus of the sending telescope. The laser-induced breakdown (LIB) smoothly decreased to 0 if the starting point of the filament was moved inside the gap between the electrodes. When we moved the filamentation starting point a few meters in the opposite direction from the HV electrode, the end of the filament bundle no longer reached the ground electrode, and the probability of breakdown decreased as well. The optimal filament's starting position was found to be ~1 m upstream of the HV electrode, with the filaments spanning the whole gap.

The HV-discharge triggering ability was demonstrated by systematic measurement of the breakdown voltage with and without the laser for several electrode gap distances (L), as shown in Fig. 2. U_{50} values are those of the voltages at which the breakdown probability occurs for 50% of the events tested. Some single LIB events, corresponding to the lowest observed voltages, are also displayed. These results demonstrate that laser-induced filaments do trigger the HV discharge over distances up to 3.8 m: The laser significantly reduced the breakdown voltage. The reduction ratio $[(U_{50,\mathrm{free}} - U_{50,\mathrm{laser}})/U_{50,\mathrm{free}}]$ was typically 32(±1)%.

Some discharges were guided over only a fraction η of the gap and continued with an irregular path as in the case of a natural discharge [Fig. 1, inset (b)]. To get insight into the mechanism of the laser-triggered HV discharge we measured breakdown delay τ between the arrival of the laser pulse and the actual breakdown as a function of η. For these measurements the laser pulses passed the electrodes typically 1–2 μs after the HV pulse reached its maximum level, and we used a 2-m gap and four HV values, as shown in Fig. 3. The τ values do not significantly depend on the HV (which is kept sufficiently below the natural breakdown voltage) when the dispersion in the experimental data is taken into account, especially for small values of η.

For a setup such as ours (negative tip/plane, 1.2/50-μs HV pulse) the literature predicts free discharges without a laser with U_{50} of 700–1000 kV/m

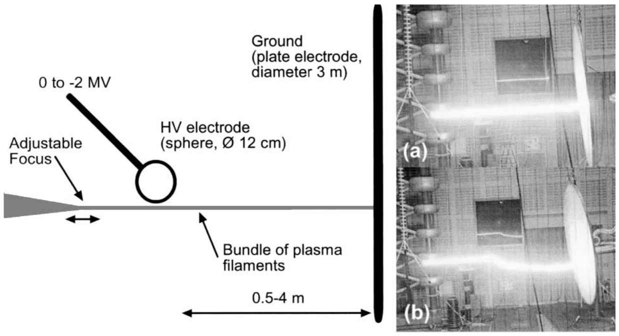

Fig. 1. Schematic of the experimental setup. (a) Photo of a guided discharge, (b) photo of a partly guided discharge.

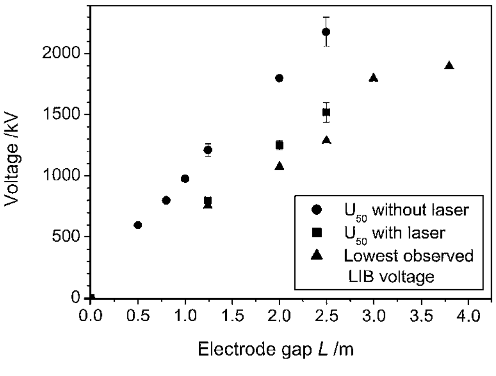

Fig. 2. U_{50} as a function of the electrode gap. Circles, natural breakdown; squares, laser-triggered discharge; triangles, single LIB events, the lowest observed voltage at each distance.

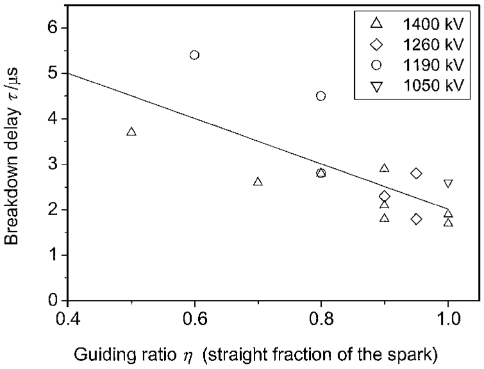

Fig. 3. Breakdown delay τ as a function of the guided fraction of spark η measured with an electrode gap of 2 m. The linear fit yields a velocity $v_g = (1.0 \pm 0.2) \times 10^6$ m/s for the guided propagation and a velocity $v_f = (2.9 \pm 0.5) \times 10^5$ m/s for free streamer propagation.

(consistent with our results in Fig. 2) conducted by a negative streamer that propagates toward the plane electrode at a velocity v_f of approximately 10^5 m/s.[14] Modification of this process by the laser can be explained as follows: The laser-induced plasma filaments (impedance in the range 10^5–10^6 Ω for a gap of several meters[9,10]) connect with the corona near the HV sphere electrode. The available free charges enhance the electric field locally and initiate electron avalanches along the plasma filaments. Therefore the avalanche threshold of ~25 kV cm^{-1} atm^{-1} is reached with a reduced voltage between the electrodes. At a velocity v_g the discharge channel grows straight, guided by the laser plasma along a fraction η of the gap. Thereby η fluctuates from 100% to lower values. Finally, if $\eta < 100\%$, a dominant streamer leaves the laser channel and propagates freely toward the ground electrode at velocity v_f, causing a spark. No LIB has been observed with η less than one third, which suggests that a certain guiding length is needed for free bridging of the remaining gap.

This simple model leads to an estimation for the breakdown delay of $\tau = L[\eta/v_g + (1 - \eta)/v_f]$. A linear fit to the experimental data shown in Fig. 3 yields $v_g = (1.0 \pm 0.2) \times 10^6$ m/s and $v_f = (2.9 \pm 0.5) \times 10^5$ m/s. These values are of the same order of magnitude as those found by La Fontaine *et al.*[12] Furthermore, our guiding velocity is similar to the observed velocities of afterstrikes passing through the same path as a preceding negative cloud-to-ground discharge,[14] which suggests that the laser filaments replace the initial creation of free charges in a natural discharge process.

In conclusion, we have successively triggered and guided HV discharges by using laser filaments ohmically bridging gaps as large as 3.8 m between two electrodes. The sphere–plane electrode configuration that we used provides a laboratory model of real-scale lightning control experiments. In such experiments a classic lightning conductor installed near the laser system will act as an electrode, which will allow a corona to develop at the conductor's tip as a reaction to a highly charged cloud. With the mobility of our terawatt laser system taken into account, these results promise to be useful in field experiments.

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