Triggering and guiding of megavolt discharges by laser-induced filaments under rain conditions

R. Ackermann
Teramobile, LASIM, UMR CNRS 5579, Université Lyon 1, 43 bd du 11 Novembre 1918, F-69622 Villeurbanne Cedex, France

K. Stelmaszczyk and P. Rohwetter
Teramobile, Institut für Experimentalphysik, FU Berlin, Arnimallee 14, D-14195 Berlin, Germany

G. Méjean, E. Salmon, J. Yu, and J. Kasparian[a)]
Teramobile, LASIM, UMR CNRS 5579, Université Lyon 1, 43 bd du 11 Novembre 1918, F-69622 Villeurbanne Cedex, France

G. Méchain
Teramobile, LOA, UMR CNRS 7639, ENSTA-Ecole Polytechnique, Centre de l'Yvette, Chemin de la Hunière, F-91761 Palaiseau Cedex, France

V. Bergmann, S. Schaper, B. Weise, T. Kumm, K. Rethmeier, and W. Kalkner
Institut für Energie- und Automatisierungstechnik, TU Berlin, Einsteinufer 11, D-10587 Berlin, Germany

L. Wöste
Teramobile, Institut für Experimentalphysik, FU Berlin, Arnimallee 14, D-14195 Berlin, Germany

J. P. Wolf
Teramobile, LASIM, UMR CNRS 5579, Université Lyon 1, 43 bd du 11 Novembre 1918, F-69622 Villeurbanne Cedex, France

(Received 1 July 2004; accepted 5 October 2004)

We demonstrate laser control of high-voltage discharges over a gap of 1.2 m filled with a dense water cloud. Self-guided filaments generated by ultrashort laser pulses are transmitted through the cloud and ionize a continuous plasma channel. The cloud typically reduces the discharge probability in given experimental conditions by 30%, but has almost no influence on the threshold required to trigger single discharge events, both in electrical field and laser energy. This result is favorable for real-scale lightning control applications.
[DOI: 10.1063/1.1829165]

The possibility of triggering and guiding lightning by means of pulsed laser beams has been debated for more than 30 years.[1] The main motivation is to protect sensitive sites, like electrical installations or airports, from direct strikes and electromagnetic perturbations. Studies using nanosecond lasers[2] exhibited severe limitations due to the lack of connected plasma channels. However, high-power fentosecond lasers, which produce ionized plasma channels, have opened new opportunities in this domain.[3] Two approaches have been investigated. In the first approach, strongly focused ultrashort laser pulses produce strongly ionized plasma channels near to the focus.[4–6]

In the second approach, long self-guided filaments generated by a slightly focused or parallel laser beam are used to ohmically bridge (i.e., to short-circuit) the electrodes and trigger and guide the high-voltage pulses.[7,8] Filaments[9–11] arise from a nonlinear propagation of ultraintense laser pulses, when Kerr-lens focusing dynamically balances defocusing by the ionized plasma produced within the filaments. Filaments can propagate over several hundreds of meters,[12] up to the kilometer range.[13,14] Moreover, the filaments survive the interaction with aerosol particles, even of large diameter.[15,16] This makes them suitable candidates for real-scale atmospheric applications[17] such as lightning control, where conducting over long distances in raining conditions is necessary.

Such outdoor experiments require knowledge about the influence of rain over laser triggering of high-voltage discharges. On one hand, even though self-guided filaments can survive the interaction with droplets,[15,16] the aerosol induces losses in the photon bath and perturbs the laser propagation. On the other hand, a water aerosol is generally considered to reduce the breakdown voltage due to a lower ionization potential. Water or ice particles are also necessary not only to generate the charge within the cumulo-nimbus cloud when they collide, but also to initiate natural lightning discharges.[18] However, due to the technical difficulty of both high-voltage and laser operation in humid conditions, the effect of rain and clouds on laser-triggered discharges has only been investigated with CO_2 lasers,[19] and is mostly focused on fog rather than rain. In this letter, we investigate the effect of rain on discharge guiding by ultrashort self-guided filaments.

The main parts of the experimental setup have been described in detail elsewhere.[8] Briefly, the *Teramobile*[20] laser system provided 170 fs pulses of 230 mJ centered at 800 nm, fired typically 5 μs after the peak voltage of a Marx shock generator (1.2 μs voltage rise time). We used a tip-plane electrode configuration with a gap of 1.2 m.

On demand, we sprayed water droplets before and in the gap between the electrodes, at a flow corresponding to a heavy rain (1.4 mm/min). The cloud extinction coefficient

[a)]Author to whom correspondence should be addressed; electronic mail: jkaspari@lasim.univ-lyon1.fr

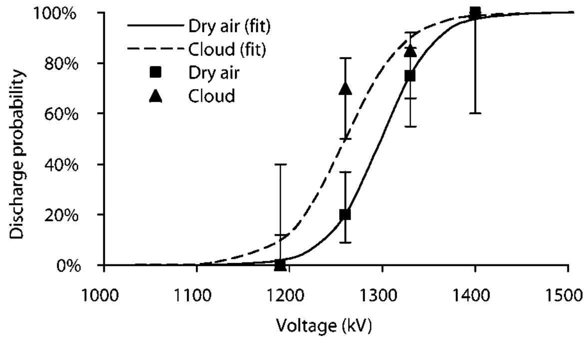

FIG. 1. Influence of a water cloud on free discharges. The solid lines are hyperbolic tangent fits used to determine the U_{50} values.

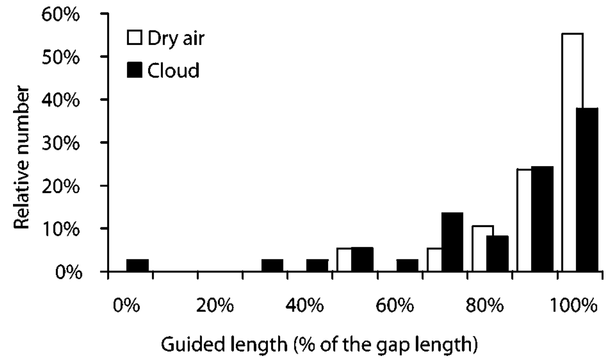

FIG. 3. Guided length (expressed as a fraction of the 1.2 m gap) in dry air and in cloud condition for triggered discharges.

was 0.14 m^{-1} over 3 m, corresponding 0.3 droplets/cm^{-3}, with a mean diameter of 0.5 mm. The beam profile on the ground electrode confirmed that filaments survive the interaction with water droplets, as previously demonstrated on a shorter scale.[15,16] The relative humidity (RH) within the aerosol cloud was 48% at a temperature of 19 °C (1% volume mixing ratio, VMR). Reference measurements have been conducted in dry air (34 % RH at 22 °C, corresponding to 0.9% VMR).

Since the occurrence of discharges in given conditions is stochastic, the estimation of the confidence interval is crucial to assess for significant effects when comparing different experimental conditions. Each data point is assigned a confidence interval at $\alpha=10\%$, which was calculated using a binomial probability law, based on the assumption that successive shots are independent from each other.

We first characterized the effect of the cloud on free discharges: the cloud reduces the 50% flashover voltage, i.e., the voltage yielding 50% probability of free discharges (U_{50}) by 3% (Fig. 1). This statistically significant positive contribution of water aerosol may be qualitatively understood as the effect of the lower ionization potential of water, compared to oxygen and nitrogen. The low RH in the cloud excludes effects of the water vapor itself.

While a cloud slightly reduces the free breakdown voltage, it does not prevent the filaments from triggering high-voltage discharges (Fig. 2). Triggered discharges have been observed down to 910 kV in cloudy conditions, compared to 850 kV in dry air and 1260 kV without laser. Conversely, the triggered discharge probability decreases by typically 30% in the cloud. However, once triggered, the discharges are guided almost as efficiently as in dry air. Figure 3 displays statistics about the guided length for voltages below 1260 kV, where only triggered discharges can occur. While a dense cloud slightly decreases the number of fully guided discharges and allows guiding over less than 70% of the gap, 90% of the triggered discharges are guided over at least 50% of their length, and 60% of them over more than 90% of their length.

The maintained triggering and guiding effect can be understood by the fact that a cloud with the same transmission (65%) as that of our experiment is known to transmit self-guided filaments.[15] Moreover, considering the droplet size and density, only half of the filaments hit a droplet. They are then replenished by the photon bath acting as an energy reservoir around them. Therefore, the linear extinction of the photon bath within the cloud plays an important role, especially over the long distances required for real-scale lightning control applications.

To quantify the effect of this extinction, we varied the laser pulse energy, at a fixed voltage (1050 kV) well below U_{50} for natural discharges. Reducing the laser energy decreases the triggering efficiency in both dry air and in a cloud, but the decrease is faster in the cloud (Fig. 4). However, even in the cloud, pulse energies as low as 60 mJ are sufficient to trigger discharges, although with a low probability. But in the context of real-scale lightning control, such low probability for single shots is balanced by the 10 Hz repetition rate of the laser (or by the kilohertz repetition rates of lasers which can be expected in the future). Hence, reasonable event occurrences can be expected for applications such as studies of lightning strikes as long as the energy threshold is not strongly affected by the cloud.

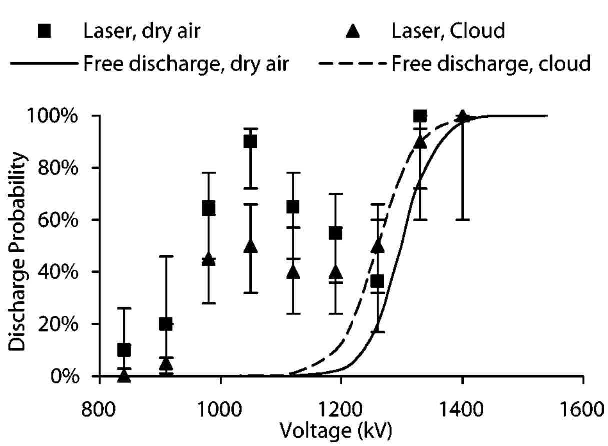

FIG. 2. Discharge probability as a function of voltage, for both dry and cloudy atmosphere. The fitted transition curves for free discharges (see Fig. 1) are plotted for comparison.

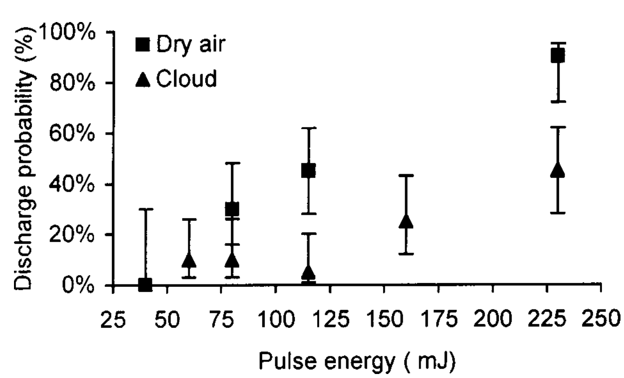

FIG. 4. Laser energy dependence of the triggering at 1050 kV voltage.

As a conclusion, we have demonstrated that self-guided filaments generated by ultrashort laser pulses can trigger and guide high-voltage discharges over a 1.2 m gap even in a dense cloud. The cloud reduces the discharge probability for given electrical field and laser energy conditions, and slightly favors free discharges. However, the presence of a cloud increases neither the electrical field nor the laser energy thresholds allowing single triggering and guiding events. Since real-scale applications can be performed with typical repetition rates of 10 Hz, or even in the kilohertz range in the near future, the reduced event probability near to the threshold should not be critical in applications.

This work has been performed within the *Teramobile* project, funded jointly by the CNRS, DFG, and French and German ministries of Research and of Foreign affairs. The Teramobile web site is www.teramobile.org. K.S. acknowledges support from Humboldt Foundation. We acknowledge the help of L. Gras (Ineris, Verneuil en Halatte, France) in measuring the droplet size distribution.

[1] D. W. Koopman and T. D. Wilkerson, J. Appl. Phys. **42**, 1883 (1971).
[2] M. Miki, Y. Aihara, and T. Shindo,J. Phys. D **26**, 1244 (1993).
[3] H. Pépin, D. Comptois, F. Vidal, C. Y. Chien, A. Desparois, T. W. Johnston, J. C. Kieffer, B. L. Fontaine, F. Martin, F. A. M. Rizk, C. Potvin, P. Couture, H. P. Mercure, A. Bondiou-Clergerie, P. Lalande, and I. Gallimberti, Phys. Plasmas **8**, 2532 (2001).
[4] D. Comptois, C. Y. Chien, A. Desparois, F. Gérin, G. Jarry, T. W. Johnston, J. C. Kieffer, B. L. Fontaine, F. Martin, R. Mawassi, H. Pépin, F. A. M. Rizk, P. Couture, H. P. Mercure, C. Potvin, A. Bondiou-Clergerie, and I. Gallimberti, Appl. Phys. Lett. **76**, 819 (2000).
[5] D. Comtois, H. Pépin, F. Vidal, F. A. M. Risk, C.-Y. Chien, T. W. Johnston, J.-C. Kieffer, B. La Fontaine, F. Martin, C. Potvin, P. Couture, H. P. Mercure, A. Bondiou-Clergerie, P. Lalande, and I. Gallimberti, IEEE Trans. Plasma Sci. **31**, 377 (2003).
[6] D. Comtois, H. Pépin, F. Vidal, F. A. M. Risk, C.-Y. Chien, T. W. Johnston, J.-C. Kieffer, B. La Fontaine, F. Martin, C. Potvin, P. Couture, H. P. Mercure, A. Bondiou-Clergerie, P. Lalande, and I. Gallimberti, IEEE Trans. Plasma Sci. **31**, 387 (2003).
[7] B. La Fontaine, D. Comptois, C. Y. Chien, A. Desparois, F. Gérin, G. Jarry, T. W. Johnston, J. C. Kieffer, F. Martin, R. Mawassi, H. Pépin, F. A. M. Rizk, F. Vidal, C. Potvin, P. Couture, and H. P. Mercure, J. Appl. Phys. **88**, 610 (2000).
[8] M. Rodriguez, R. Sauerbrey, H. Wille, L. Wöste, T. Fujii, Y.-B. André, A. Mysyrowicz, L. Klingbeil, K. Rethmeier, W. Kalkner, J. Kasparian, E. Salmon, J. Yu, J.-P. Wolf, Opt. Lett. **27**, 772 (2002).
[9] G. A. Askar'yan, Sov. Phys. JETP **15**, 1088 (1962).
[10] R. Y. Chiao, E. Garmire, and C. H. Townes, Phys. Rev. Lett. **13**, 479 (1964).
[11] A. Braun, G. Korn, X. Liu, D. Du, J. Squier, and G. Mourou, Opt. Lett. **20**, 73 (1995).
[12] B. La Fontaine, F. Vidal, Z. Jiang, C. Y. Chien, D. Comtois, A. Desparois, T. W. Johnson, J.-C. Kieffer, and H. Pépin, Phys. Plasmas **6**, 1615 (1999).
[13] M. Rodriguez *et al.*, Phys. Rev. E **69**, 036607 (2004).
[14] G. Méchain *et al.*, Appl. Phys. B: Lasers Opt. **79**, 379 (2004).
[15] F. Courvoisier *et al.*, Appl. Phys. Lett. **83**, 213 (2003).
[16] M. Kolesik, J. V. Moloney, Opt. Lett. **29**, 590 (2004).
[17] J. Kasparian *et al.*, Science **301**, 61 (2003).
[18] M. Baker and J. Nelson, C. R. Phys. **3**, 1293 (2002).
[19] T. Shindo *et al.*, IEEE Trans. Power Deliv. **8**, 2016 (1993).
[20] H. Wille *et al.*, Eur. Phys. J.: Appl. Phys. **20**, 183 (2002).