The possibility of triggering and guiding lightning by means of pulsed laser beams has been debated for more than 30 years. The main motivation is to protect sensitive sites, like electrical installations or airports, from direct strikes and electromagnetic perturbations. Studies using nanosecond lasers exhibited severe limitations due to the lack of connected plasma channels. However, high-power femtosecond lasers, which produce ionized plasma channels, have opened new opportunities in this domain. Two approaches have been investigated. In the first approach, strongly focused ultrashort laser pulses produce strongly ionized plasma channels near to the focus. 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. Filaments 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, up to the kilometer range. Moreover, the filaments survive the interaction with aerosol particles, even of large diameter. This makes them suitable candidates for real-scale atmospheric applications 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, 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. 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 CO2 lasers, 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. Briefly, the Teramobile 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...
is 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.\textsuperscript{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.\textsuperscript{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.
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.

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