Electric events synchronized with laser filaments in thunderclouds

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Abstract: We investigated the possibility to trigger real-scale lightning using ionized filaments generated by ultrashort laser pulses in the atmosphere. Under conditions of high electric field during two thunderstorms, we observed a statistically significant number of electric events synchronized with the laser pulses, at the location of the filaments. This observation suggests that corona discharges may have been triggered by filaments.

OCIS codes: (010.1300) Atmospheric propagation; (140.7090) Ultrafast lasers; (190.5940) Self-action effects; (190.7110) Ultrafast nonlinear optics; (350.5400) Plasmas; (999.9999) Lightning control

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1. Introduction

Lightning has always been considered as fascinating but hazardous. Extensive work has been dedicated to the quantitative understanding of this natural phenomenon, with only limited success. In particular, its randomness makes *in situ* measurements difficult, raising the need to trigger lightning strikes at predetermined times and locations where instruments are available. Small rockets pulling thin wires into the high-field regions below thunderclouds can achieve such triggering [1, 2]. But the number or available rockets is limited, and several seconds elapse between the launch of a rocket and the triggered lightning strike.

To overcome these drawbacks, the use of lasers has been considered since the 1970's although without success. [3] The hot and dense plasma produced by such lasers absorbs the trail of the laser pulse and prevents the formation of the long plasma channels required to guide lightning strikes. Even by focusing four laser beams at the top of a lightning tower and using a solid target to produce a dense plasma, Uchida *et al*. [4] observed only two lightning strikes when the lasers were shot. Moreover, these events cannot be unambiguously attributed to an effect of the laser because the laser pulses were triggered only upon detection of naturally initiated descending leaders.

The advent of high-power, ultrashort (~100 fs) lasers renewed the perspective of laser-controlled lightning. Such systems generate efficient multiphoton/tunnel ionization of the air even at moderate energy (typically a few mJ per pulse), while they are too short to induce cascading ionization. The balance between Kerr self-focusing and defocusing by this plasma results in self-guided filaments [5-10]. More powerful lasers generate multiple filaments, which start and end randomly within a filamentation bundle of length up to hundreds of meters [11, 12]. They form channels of cold and underdense plasma with an electron density $N_e \approx 10^{15}$ cm^{-3} [13], several orders of magnitude above the required free electron density for lightning initiation in the atmosphere ($N_{init} \approx 5 \times 10^{11}$ cm^{-3} [14]). We have recently shown that such conducting filaments can be generated away from the laser source [15], propagate in clouds or turbulent atmospheres [16-18], and trigger and guide high-voltage discharges even in artificial rain [9, 10].

In this paper, we report *in-situ* investigations of the effect of laser filaments on electric activity in a thunderstorm. The observation of a statistically significant number of radiofrequency (RF) pulses associated with electric events in clouds, collocated and synchronized with the filaments, suggests that the laser has induced electric activity in the thunderclouds.

2. Experimental methods

We investigated the effect of femtosecond plasma channels of moderate energy on thunderclouds during a field campaign at the Langmuir Laboratory (New Mexico, USA, See Fig. 1), which provides a fully equipped facility with high lightning occurrence.

The *Teramobile* femtosecond-terawatt laser [19] was fired from the ridge of South Baldy Peak, 3209 m above sea level, at coordinates N33.98° and W107.2°. The laser was triggered at a repetition rate $f = 10$ Hz (*i.e.* every $T = 100$ ms) by an internal clock, independently from the thunderstorm activity. It emitted a collimated (unfocused) beam, leaning southwards 70° above horizontal. The laser beam diameter was 3 cm, and the energy per pulse was 270 mJ at a center wavelength of 800 nm. The laser pulses, of 150 fs initial duration, were negatively chirped to 600 fs. Based on previous experiments with the same laser system [15] as well as control measurements performed at the campaign location [17] we determined that the above-described laser setup generates multiple filamentation with significant ionization over a typical length of 100 m, a few hundreds of meters above ground.

We investigated two thunderstorms (labelled T1 and T2, respectively) on September 24 (20:50 to 22:40 UTC) and September 25 (21:34 to 23:20 UTC), 2004. We focused the analysis on times when the electric field would have been sufficient to trigger lightning using rockets, *i.e.* exceeded 10 kV/m [20]. To account for the faster decrease of the electric field at ground level than a few meters above [21], we considered the maximum value of the electric

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field, measured at ground level by a field mill, over a running 20 s time interval rather than its instantaneous value. During T1, the high-electric field criterion was achieved during 135 s, corresponding to 1350 laser pulses, in several time frames between 21:23 and 21:28. During T2, the relevant times lasted for 115 s (1150 laser pulses) in 3 periods: 21:48-21:52, around 23:07, and 23:14-23:15.

We analyzed the raw data from five Lightning Mapping Array (LMA) [22] receivers located within 1 km distance from the laser (See Fig. 1). Such receivers detect radiofrequency (RF) pulses at 63 MHz, generated by the electric activity in the atmosphere, with a time accuracy of 40 ns. For each node of a 100 x 100 m grid within a 2 x 2 km area around the laser, we shifted the clock of each receiver in order to account for its distance to the considered location. Each electric event in the atmosphere is then characterized by a set of RF pulses detected simultaneously (within ±167 ns, *i.e.* 100 m horizontal resolution) by all of the 5 receivers. This data analysis technique allows to consider sets of RF sources with a delay mismatch corresponding to distances up to 100 m. Therefore, it is well suited to detect possible RF sources spreading over many tens of meters, as could be the case for events distributed along a filament, *i.e.* over a length up to 100 m. The delay mismatch between the times of arrival of the signals on the different receivers was evaluated for each event detected during T1.

Because the laser is fired independently from the electric activity in the clouds, temporal correlations of the electric events detected by the LMA with the laser operation can provide indications for an effect of the laser. At each location, we sought electric events temporally separated by entire multiples of $T = 1/f$ within an uncertainty of $t = 2$ ms. This 2 ms time delay has been chosen as a safe value to account for both the drift of the laser master clock over the duration of the thunderstorms, as well as possible delays between a laser pulse and an electric event it could trigger. In particular, typical discharge propagation speeds of 10^5-10^6 m/s [23] correspond to sub-ms to ms-range delays for the typical 100 m scale of the filaments.

Electric activity in clouds is a random process, so that a temporal correlation between the electric activity in the thunderclouds and the laser pulses may be obtained by chance. We therefore estimated, at each location within the investigated area, the probability α_{sync} that the observed number of synchronized events may have been obtained by chance among random events, rather than being due to an effect of the laser. This estimation yields the corresponding confidence level $1 - \alpha_{sync}$, where α_{sync} can be understood as the risk of error when concluding that the observed pulses are related with the laser pulses.

Alternatively, we periodically blocked the laser beam for $t_{\mathrm{OFF}} = 3$ to 10 s and recorded the ratio of the number of events while the laser was emitted and blocked, respectively. Comparing this ratio with the one that could be expected in the case of random pulses yields the confidence level $1 - \alpha_{excess}$ for this second observable.

The α values have been calculated as follows. Observing, at a given location, n selected events among N is likely to be due to an effect of the laser only if the corresponding single-sided confidence level $1-\alpha$ (where α is the *a priori* probability that at least n events are selected among N random ones) is high. If the *a priori* probability for an individual random event to be selected is p, then:

$$\alpha = \sum_{n'=n}^{N} p^{n'} \cdot (1-p)^{(N-n')} \cdot \frac{N!}{n'! \cdot (N-n')!} = \beta(n, N-n+1, p)$$

where β denotes the incomplete beta function. When observing n_{ON} events during the time t_{ON} with the laser firing, and n_{OFF} events in the time t_{OFF} without laser, the selection probability is $p = t_{ON} / (t_{ON} + t_{OFF})$, so that $1 - \alpha_{excess} = 1 - \beta(n_{ON}, n_{OFF} + 1, t_{ON} / (t_{ON} + t_{OFF}))$. Similarly, if n events among N are separated by entire multiples of T within $t = 2$ ms, the confidence level of the corresponding single-sided statistical test is the probability of detecting by chance n or

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more synchronized events among N random events: $1-\alpha_{sync}=1-\sum_{k=1}^{T/t}R_k$, where $R_k=R_1\cdot(1-R_{k-1})$, $R_0=1$ and $R_1=\beta(n,N-n+1,t/T)$. Here, the summation accounts for the fact that the absolute time of the train of laser pulses is unknown, so that any time delay should be considered.

3. Results and discussion

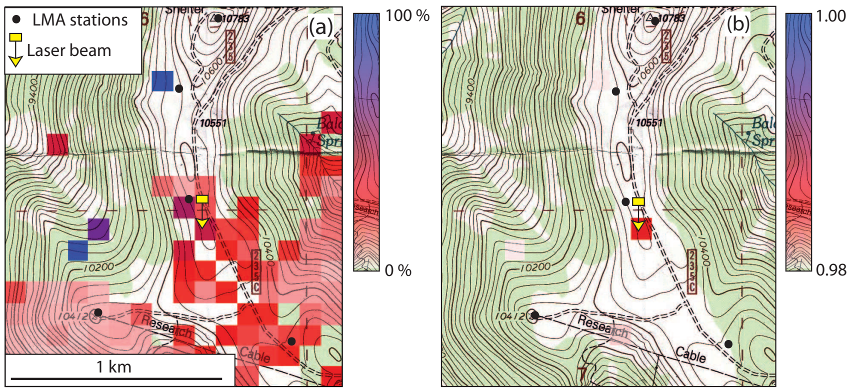

Fig. 1. Statistical analysis of the electric events detected during thunderstorm T1. (a) Rate of pulses synchronized with the laser repetition rate; (b) Corresponding statistical confidence level ($1 - \alpha_{sync}$, see text for details). The color scale is transparent below 98 % (*i.e.* for error risks above 2 %), leaving the topographical background uncovered.
The arrow head indicates the location of the laser-induced plasma channel, while its tail marks the laser emitter. Topographic background courtesy of US Geological Survey.

Fig. 1 displays the result of the statistical analysis of thunderstorm T1. At the location of the laser filaments (arrow head), 43 % (3 out of 7, Fig. 1(a)) of the pulses are synchronized with the laser repetition rate. This rate may appear pretty low, especially when considering that higher rates are observed at several other locations of the map. However, performing the statistical test described above at each location draws a fully different picture (Fig. 1(b)). The confidence level shows high statistical significance ($1 - \alpha_{sync} = 0.987$) only at the location of the laser filaments, suggesting that the laser did indeed induce the observed electric events. This statistical significance is achieved in spite of the limited number of events, especially if we compare with the 1350 laser pulses launched into the atmosphere during the considered 135 s time frame. This significance stems from the fact that the time jitter allowed between synchronized pulses is much shorter than the time between two consecutive laser pulses (2 ms *vs* 100 ms). Similar results are obtained for Thunderstorm T2 (3 synchronized pulses out of 10 in 115 s, $1 - \alpha_{sync} = 0.958$). In the latter case the effect is slightly shifted northwards due to a drift in the plasma filaments along the laser beam and the uncertainties in the triangulation algorithm. No effect was observed when the electric field was low or negative. Therefore, our results suggest that a small fraction (0.24 % of the laser pulses, *i.e.* ~1 event/minute) of the plasma filaments have initiated electric events in a strong positive (upward pointing) electric field.

Moreover, more electric events are observed when the laser is fired than when it is blocked (Fig. 2). During T1, 7 pulses are detected at the laser location during a total $t_{ON} = 135$ s, and none during $t_{OFF} = 72$ s when the laser is blocked, corresponding to a significant effect within a confidence level $1 - \alpha_{excess} = 0.95$. Again, similar results (10 pulses in $t_{ON} = 115$ s *vs* none in $t_{OFF} = 84$ s, $1 - \alpha_{excess} = 0.998$) are observed for T2.

The laser filaments do not extend to the ground, so that they can be compared with a rocket-pulled wire not connected to the ground. While the potential upward positive leader

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can be invisible to the LMA [24, 25], the associated negative downward leader propagating from the bottom of the wire (resp. filament) and dart leaders that later propagate from the cloud down to the initial positive leader channel, shall emit detectable pulses. However, the delay mismatch between the RF pulses detected on the different LMA detectors for some events correspond to some tens of meters. Such mismatches suggest spatially spread events, such as corona discharges at the tips of individual filaments within the bundle of multiple filamentation.

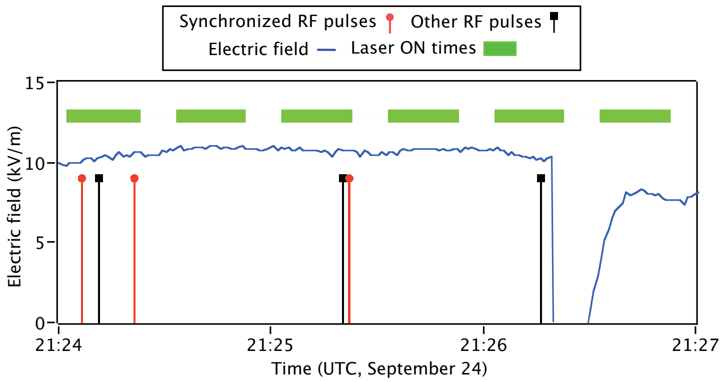

Fig. 2. Electric events during a high-field period of thunderstorm T1. Triggered events contribute to the excess of detected events when the laser is shot (green blocks)

The very limited effect of the plasma channel left behind by the filaments, which did not trigger full lightning strike, is due to their limited lifetime of ~1 µs [26, 27], corresponding to an effective length on the meter-scale for a leader propagating at a speed of a few 10^6 m/s [23]. Since wires of a few tens of meters are sufficient for rocket triggering of lightning, the plasma lifetime has to be enhanced up to several tens of µs. This could be achieved by a subsequent nanosecond, multi-Joule laser pulse [14, 28]. Recetly, we have even shown in the laboratory that a frequency-doubled YAG pulse of moderate energy (200 mJ) is sufficient to improve the ability of femtosecond filaments to trigger high-voltage discharges on the meter-scale [29]. Sequences of ultrashort pulses at 800 nm have also been proposed to improve the plasma lifetime [30, 31]. The definition of the optimal pulse sequence is still an open question, relying on throughout modeling of the temporal evolution of the plasma channel created by the laser in an electric field. [32] Other available parameters include the pulse energy and beam profile. While the latter is difficult to control over long distances in the highly perturbed propagation conditions encountered in thunderstorms, an increased pulse energy could yield more filaments over longer distances [33], thus possibly improving the effect of the laser on the electric field.

To implement and optimize such improved laser schemes in a field campaign, an observable is required to assess for the influence of each investigated parameter. In that purpose, a sensitive detection system with adequate spatial and temporal resolution, as was provided by the LMA, is a key element for such field experiments. The effect of the laser, as faint as it may be, can then be monitored as a function of each experimental parameter in order to drive the experimental work and optimize the laser effect. In that regard, our results constitute a step towards laser-controlled lightning.

4. Conclusion

As a conclusion, we have investigated the influence of ultrashort laser filaments on thunderclouds. Our results suggest that plasma filaments generated in the atmosphere by ultrashort laser pulses can trigger electric events in thunderclouds under high positive electric field, although the efficiency achieved in our experiment is low. This result constitutes a step towards laser-controlled lightning. The triggering of actual lightning strikes requires further development, in particular to enhance the plasma lifetime and density within the filament *e.g.* using sequences of laser pulses. Also, improving the laser repetition rate will enhance the time rate of triggered events. A factor of 10 could be achieved if using the TW-lasers with repetition rates of 100 Hz or more that are becoming available.

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