On lightning control using lasers

JÉRÔME KASPARIAN[1,2] AND JEAN-PIERRE WOLF[1]

[1] *GAP, Université de Genève, 20 rue de l'École de Médecine, CH-1211 Genève 4, Switzerland*

[2] *Teramobile, Université Lyon 1; CNRS; LASIM UMR 5579, bât. A. Kastler,*
43 Bd du 11 novembre 1918, F-69622 Villeurbanne Cedex, France.

e mail: jerome.kasparian@physics.unige.ch
telephone: +41 22 379 68 44
fax: + 41 22 379 39 80

Abstract. After a quick review of historic lightning research, we discuss developments aiming at triggering and guiding lightning using lasers. We recall the limitations inherent to high-energy, nanosecond pulses and discuss the new perspective introduced by the advent of ultrashort, high-power laser pulses and the long ionized filaments they induce in air. After describing a recent field campaign where the triggering of electric activity in thunderclouds by ultrashort lasers was demonstrated for the first time, we discuss perspectives for improvements of both the sequence of laser pulses and the experimental configuration.

Introduction

Lightning, an unpredictable and frightening phenomenon has been associated with God's anger up to the Middle Ages. [1] Research for natural interpretations of lightning began in the 17th Century when René Descartes attributed it to collisions between clouds. However, lightning studies really developed in the 18th Century, in parallel with the development of knowledge about static electricity. In 1752, in Marly-la-Ville, near to Paris, Thomas François Dalibard observed sparks between a conducting stick pointed toward a thundercloud and isolated from ground on one side, and a grounded tip on the other side. This experiment, which had been proposed by Benjamin Franklin (1706-1790), confirmed that lightning is an electrical phenomenon. [2] On the next year, by grounding the conducting stick, Franklin invented the lightning rod. In the 20th Century, the advent of photography and of the cathodic ray tube oscilloscope allowed a precise characterization of lightning. Those techniques allowed to observe the trajectory of lightning strikes, and to measure the typical involved voltage (~ 100 MV) and intensity (~ 30 kA). Today's instruments and vectors, such as balloon, aircrafts or satellites, provide an even more precise view of the processes at play in the physics of lightning.

The lightning strike

The preliminary step for a lightning strike is the electric loading of clouds. Charges are generated by collisions between ice and/or water particles, and separated by vertical winds within clouds at speeds up to 20 m/s. Positively charged ice particles accumulate at the top of the cloud, while the bottom of the cloud is negatively charged. This charge separation generates an electric field of up to 10 to 15 kV/m at ground level, and 50 kV/m some hundreds of meters above ground.

The deformation of the charged water droplets of the cloud in this electric field forms ellipsoids which further increase the electric field and initiate corona discharges at their tip. These corona discharges develop into streamers, which connect and form a leader (Figure 1a). This ionized channel progresses by steps of some tens of meters, with rest times of 50 à 100 μs between two steps (Figure 1b). During its development, the leader splits into several branches. When one branch reaches close to ground, an upward leader is generated from an elevated point such as a tree, a building or a mountain ridge. The connection of the two leaders allows the flow of thousands to tens of thousands of Amperes from the ground to the cloud: This high current flow, or *return stroke* (Figure 1c), constitutes the visible part of the lightning strike and lasts from a fraction of a second to a few seconds, including re-illuminations when the same channel is used by subsequent current pulses.

Insert Figure 1 here

Attempts to trigger lightning using high-energy lasers

The electron avalanches of the streamer-leader mechanism typically need 10 m to develop. Such distance is generally not available in laboratory experiments because of the limitations in the available voltages and installation sizes. Field experiments on real-scale lightning are therefore necessary, but the random character of lightning limits its availability at the experiment location and prevents any synchronization of the instrumentation with the lightning strike itself. Therefore, several groups [3,4] developed techniques to trigger on-demand lightning with a rocket pulling a thin metallic wire, which initiates a lightning strike and guides it to the ground. Lightning strikes can even be triggered by short conducting wire sections, which perturb less the lightning mechanism than a continuous conducting wire does. However, the number of rockets available during one thunderstorm is limited to 5 to 10 in practice. Also, the rocket has to be launched with the right timing relative to the increase of the electric field in the cloud. Therefore, a continuously running lighting triggering system would be suitable.

Lasers have been identified as a candidate in this purpose as early as in the 1960's, as reviewed in [5]. Long laser spark were produced using neodymium or CO_2 lasers, with energies up to several kJ [6] and a typical pulse duration of 50 ns [7]. With such high energy, the channel can be heated to several thousands of degrees, which reduces the gas density by typically one order of magnitude. Since the rate of collisional ionization by electrons is inversely proportional to the gas density, such heating is highly favourable to the air ionization. Moreover, above a temperature of 4000 K, the associative ionization of radicals created by the laser pulse $N + O \rightarrow NO^+ + e^-$ contributes significantly to the ionization process, independently from the electric field. Heating also mostly suppresses the electron losses due to their attachment and recombination. However, by efficiently ionizing the air, the leading edge of the pulse generates a dense plasma, which is opaque to the trailing edge of the pulse. A large fraction of the pulse energy is therefore lost for further propagation, preventing the generation of a connected plasma channel beyond a length of a few meters. Even a geometrical focus tens to hundreds of meters away cannot generate connected plasma channels, but rather a series of localized plasma sparks.

In spite of these limitations, field experiments using high-energy lasers [8] were carried out to intercept lightning with lasers on the shore of the Sea of Japan. The experiments were conducted in a period of intense winter low-cloud thunderstorms, with electric fields up to 10 kV/m. A first CO_2 laser delivering 1 kJ was focused on a dielectric target at the top of a 50 m high tower constructed on a 200 m high hill. A second one was aimed near to the dielectric to form a 2 m long plasma spark. A third, ultraviolet laser was producing a weakly ionized plasma channel, slightly offset from the tower, to direct the leader to the cloud. The natural initiation of cloud discharges was considered as the precursor of the descending lightning strikes. Therefore, the lasers were triggered on the detection of such discharges. The authors reported two successful attempts, although the statistical significance of their result is not clear.

Control of high-voltage discharges using ultrashort lasers

In contrast to longer (nanosecond) pulses, ultrashort laser pulses in air can form plasma channels [9,10,11,12,13] with a length up to 100 m [14] at a distance of several kilometres. [15] This process named *filamentation* stems from a dynamic balance between the Kerr self-focusing on one side and the defocusing effect of the free electrons of the plasma generated at the non-linear focus on the other side (Figure 2). Moreover, steering the beam allows to aim the ionized plasma channel at the most active part of a thundercloud. Furthermore, we recently showed that filaments can propagate almost unperturbed in adverse conditions such as rain, [16] fog, [17] turbulence [18,19] or reduced pressure, [16] which makes them highly suitable for atmospheric applications.

Insert Figure 2 here

Insert Figure 3 here

The first demonstration of the ability of ultrashort laser pulses to trigger high-voltage discharges have been performed using focused infrared [20,21] or ultraviolet [22] lasers. Later, spectacular experiments with the *Teramobile* laser [23] installed in a high-voltage facility showed that laser filaments can trigger and guide 1.8 MV discharges over up to 4.5 m. The breakdown voltage is typically reduced by 30 % [24,25]. Moreover, triggered discharges are guided along the laser beam (Figure 3). Partly guided discharges also occur in some configurations, providing information about the mechanism of the initiation and propagation of laser-triggered discharges. [26] Even artificial rain does not prevent the laser filaments to trigger discharges. [27] Current work focuses on the possibility to extend the plasma lifetime using auxiliary lasers in order to increase the possible guiding length and improve the scalability to atmospheric scales. This approach relies on re-heating and photodetaching electrons of the plasma channel by subsequent pulses, either in the nanosecond [28] or in the femtosecond regime. [29] Although a high power of the subsequent laser pulse is generally considered necessary for efficiently photodetaching electrons from O_2^- ions in the plasma, it was recently demonstrated that a YAG laser pulse of moderate energy (sub-Joule) at 532 nm significantly increases the triggering effect of an infrared femtosecond laser near to the voltage threshold. [30] This effect was interpreted as resulting from a positive retroaction loop where Joule heating of the plasma channel enhances photodetachment, while the resulting higher electron density boosts the Joule effect.

Field experiments using femtosecond laser filamentation

Following the demonstration of both the capability of laser filaments to propagate in realistic atmospheric conditions and their ability to trigger high-voltage electric discharges, the effect of femtosecond plasma channels of moderate energy on thunderclouds was investigated during a field campaign [31] at the Langmuir Laboratory (New Mexico, USA, See Figure 4), which provides a fully equipped facility with high lightning occurrence.

The *Teramobile* femtosecond-terawatt laser [23] was fired from the ridge of South Baldy Peak, 3209 m above sea level, at a repetition rate $f = 10$ Hz. 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 central wavelength of 800 nm. The laser pulses, of 150 fs initial duration, were negatively chirped to 600 fs in order to generate multiple filamentation with significant ionization over a typical length of 100 m, a few hundreds of meters above the ground.

Two thunderstorms were investigated, focusing on the overall 250 s (*i.e.*, 2500 laser pulses) when the electric field would have been sufficient to trigger lightning using rockets. Five Lightning Mapping Array (LMA) [32] receivers located within 1 km distance from the laser (See Figure 4) detected radiofrequency (RF) pulses generated by the electric activity in the atmosphere, with a time accuracy of 40 ns. The comparison of the times of arrival of the RF pulses on the detectors yielded the location and time stamping of their origin. Sets of RF sources with delay mismatches corresponding to distances up to 100 m were included in the analysis, to account for events distributed along the laser beam, *i.e.* over a length up to 100 m.

Because the laser is fired independently from the electric activity in the clouds, and because natural electric activity in clouds is a random process, temporal correlations between the electric events detected by the LMA and the laser operation were used as an evidence for an effect of the laser. At each location, the events synchronized (within 2 ms) with the laser have been identified. The probability α_{sync} that these events may have been obtained by chance among random events, rather than being due to an effect of the laser, was estimated. α_{sync} can be understood as the risk of error when concluding that the observed pulses are related with the laser pulses. This corresponding confidence level is therefore $1 - \alpha_{sync}$.

Insert Figure 4 here

Figure 4 displays the result of this statistical analysis for one single thunderstorm. At the location of the laser filaments (arrow head), 43 % (3 out of 7) of the pulses are synchronized with the laser repetition rate, corresponding to a high statistical significance ($1 - \alpha_{sync} = 0.987$). The delay mismatch between the RF pulses detected on the different LMA detectors for some events correspond to some tens of meters, typical of spatially spread events, such as a series of simultaneous corona discharges at the tips of individual filaments within the bundle of multiple filamentation.

Similar results have been obtained during the second thunderstorm. In contrast, no effect was observed when the electric field was low or negative. Therefore, these 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. [31]

Plasma filaments generated in the atmosphere by ultrashort laser pulses therefore appear to be able to trigger electric events in thunderclouds under high positive electric field. This result constitutes a first step towards laser-controlled lightning.

Optimization of the filament effect in thunderstorms

Optimization of the plasma density and lifetime

The very limited effect of the plasma channel left behind by the filaments, which did not trigger lightning strikes to the ground, appears to be due to their low electron density as well as their limited lifetime of ~1 μs. [33,34] This duration corresponds to an effective length on the meter-scale for a leader propagating at a speed of a few 10^6 m/s. [24] Since wires of a few tens of meters are sufficient for triggering of lightning using rockets, 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. [35,36] Even 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. [37] Sequences of ultrashort pulses at 800 nm have also been proposed to improve the plasma lifetime. [38,39] The definition of the optimal pulse sequence is still an open question, which will require throughout modelling of the temporal evolution of the plasma channel created by the laser in an electric field. [40] 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, a higher pulse energy could yield more filaments over longer distances, [41] thus possibly improving the effect of the laser on the electric field.

Mechanism of the laser filament action in thunderclouds

The emission geometry can also be optimized. Such optimization first requires a clarification of the mechanism of the expected laser action on the thundercloud. Two mechanisms can be considered for the triggering of lightning by laser filaments. In a first scenario, The free electrons constitute a seed from which the filament, in the electric field, will turn into an ascending leader, and then into an ascending lightning strike. This scenario may appear realistic at first, since it requires an initial electron density of only $5\text{x}10^{11}$ cm^{-3}, [35] three to four orders of magnitude below the typical plasma densities in filaments. Also, the required filament length is that of a single step of a leader, *i.e.* a few tens of meters only. However, such filament-to-leader conversion process implies an electron avalanche, and therefore requires a local electric field of at least 26 kV/m. Such field can only be achieved if the filament starts from the top of a high tower (typically beyond 200 m). [1] Moreover, even at high towers, ascending lighting accounts for only 5-10 % of the lightning activity, which drastically restricts the number of potential events. Another limitation of this process is in the small number of electrons available in a filament, due to its reduced volume. A typical filament can be modelled as a cylinder or 30 μm diameter and 50 m length, providing a volume of 0.04 cm^3 only. In spite of its electron density of 10^{15} cm^{-3}, it therefore contains only 4 x 10^{13} electrons. In comparison, the electron density in the corona discharge at the tip of a metallic rod is only 10^{14} electrons/cm^3, [42] but its volume is orders of magnitude larger. Therefore, a filament cannot be expected to release more electrons in the atmosphere than a passive lightning rod does.

The following discussion will therefore focus on a second scenario, where the filament is considered as a passive conductor. This approach is consistent with the interpretation of the laser-triggered discharges in the laboratory as ohmic bridging. [24] The conducting filament suddenly emerges from the space charge accumulated around an elevated point such as the top of a tower, or near to the ground in a tower-free configuration. The sudden emergence of the filament acts like a rocket with a sufficient speed to precede the build-up of a space charge around its tip and avoid the screening of the electric field around itself.

The action of a plasma channel as a conductor is governed by the loading time of the corresponding RC circuit. The system formed by the ground, the filament and the cloud can be considered as a serial circuit including two tip-plane capacitors and one resistor. The two capacitors account for the gaps between the filament and the cloud, as well as between the filament and ground, each with a capacity $C = 4\pi\varepsilon_0 rS/(S + d \cdot r) \approx 4\pi\varepsilon_0 r$ where S is the surface of the bottom of the cloud, r = 100 µm is the radius of curvature of the « tip » at the end of the filament, d = 100 m is the distance between the filament end and the cloud (respectively, the ground). The filament itself is modelled a resistor $R = l \cdot r$, l = 50 m being the filament length and r = 1 MΩ/m its resistivity. [24] Under these assumptions, the loading time of the filament is $t = R \cdot C / 2 = 10^{-7}$ s. While this duration is longer than the picosecond timescale of electron attachment, it is much shorter than the microsecond lifetime of the plasma channel. We therefore neglect the transient and dynamical effects and handle the filament as a passive conductor inserted in the beam. Note that considering a bundle of N filaments yields $R = N \cdot l \cdot r$ and $C = 4\pi\varepsilon_0 NrS/(S + N \cdot d \cdot r) \approx 4\pi\varepsilon_0 Nr$, so that t is unaffected by the number of filaments in the bundle.

Since the filaments are considered as passive, the triggering of lighting depends on the ability of the filaments to intercept a descending leader. In the context of lightning protection engineering, it is common to consider that an object has an influence on leaders in its vicinity, within a distance $r = 10 \times I^{2/3}$, where r is expressed in meters and I the intensity (in kA) of the lightning strike that will occur. A typical value of $I = 30$ kA, yields $r = 96$ m. We consider that, once a filament interacts with the descending leader and generates an upward positive leader, the current increases in the plasma channel and stabilizes it. [43] Within this assumption, the filament intercepts all descending leaders that are within its area of influence r at the time of the laser pulse.

Influence of the geometric configuration

To illustrate the impact of several configuration parameters with and without tower, we performed phenomenological Monte-Carlo simulations of a descending leader above a flat ground. In each run, a stepped leader is launched from a random location in a cloud 2000 m above ground, and propagates in 10-m steps. The direction of each step is randomly chosen over 360° in azimuth and from 0 to -90° in elevation. When the leader reaches a distance smaller than r from the tower, filament or ground, the lightning strike is considered to hit the corresponding element. The simulation is conducted over a 3 x 3 km area. In this simple phenomenological model the filament is modelled as a permanently available conductor. We checked that the simulation results are almost insensitive to the topography provided reasonable landscape shapes are considered.

We investigated several geometries. In a first geometry (Figure 5a), the beam is aimed at the top of a 200-m high tower, extending its length vertically. Such a configuration is comparable to that of Uchida *et al*. [8] According to our simple model, a 200 m long filament on top of the tower only increases the number of lightning strikes on it by 10 to 20%. This increase hardly exceeds the 13% standard deviation for the number of strikes on the tower alone. Therefore, this first configuration is very unfavourable for field experiments because it will not allow to observe a statistically significant increase of the number of events for reasonable filament lengths.

In a second geometry (Figure 5b), the filament is launched vertically parallel to the tower, competing with it to attract lightning. If we consider the competition between a 200 m high tower and a filament located 30 m apart from each other, the main observable assessing for an effect of the laser would be the depletion of the number of lightning strikes on the tower as a function of the filament height.

The depletion becomes statistically significant (2 standard deviations, *i.e.* 26%) if the filament reaches a height of 175 m, which in principle can be practically achieved. However, the poor duty cycle of the filament has to be taken into account. A descending leader needs a time $t_{\text{transit}\neq}$ ~ 100 μs to go across the region of influence of the filament, with r = 100 m, at a typical propagation speed of 1 m/μs. [24] At 10 Hz (T = 100 ms), this corresponds to a duty cycle of 1/1000 which jeopardises the hope to observe a statistically significant effect within a finite time.

Insert Figure 5 here

The third geometry was that of the *Teramobile* team during their field campaign in New Mexico. [31] The filament is launched independently from any tower (Figure 5c). Again, very few descending leaders can be intercepted, independently on the filament altitude and length, especially when taking the duty cycle into account. Considering the occurrence of a few hundreds to thousands of natural descending leaders over the experimental area during a 3-month campaign, typical for a spot of high lightning occurrence, a few events at most can be expected. This could explain the very reduced number of events actually observed during the *Teramobile* field campaign. [31]

However, the low efficiency of the above-described strategies may be overcome by taking benefit of one of the most prominent advantages of the laser technique, namely its flexibility. In a fourth configuration, we assume that a real-time detector, as used by Uchida *et al.*, [8] is implemented to detect and locate the advent of descending leaders so as to trigger the laser and aim it at their origin, with or without a competing tower (Figure 5d and e). This approach improves the duty cycle by several orders of magnitude, since all laser shots are able to intercept a descending leader. Moreover, the steering capability drastically extends the volume of influence of the laser. Therefore, it increases the number of accessible descending leaders at least by a factor of 10, even for conservative filament heights of a few hundreds of meters. Intercepting several tens to a few hundreds of shots in one single campaign therefore appears accessible. This number of events would be sufficient to achieve the statistical significance required for such a campaign to be conclusive.

Although phenomenological and simplistic, these simulations show that the efficiency of laser triggering of guiding may be improved by orders of magnitude, provided the laser shots are triggered by electric activity in thunderclouds and kept oriented towards the most active regions of the clouds.

Conclusion

The 50-years old history of laser-assisted lightning has brought a wealth of laboratory development as well as field work, with mitigated success. While the potential of high-energy, nanosecond lasers appears to be limited, recent field results with the *Teramobile* ultrashort laser opened new prospects to reach the goal of triggering lightning with lasers.

Such an achievement will require to optimize the plasma channels generated during the filamentation of laser pulses. Emitting pulse sequences and increasing the pulse energy shall improve the electron density and the plasma lifetime. In parallel, optimized triggering and beam steering schemes, driven by real-time detectors locating the initial stages of descending stepped leaders, will greatly improve both the duty cycle and effective volume of influence of laser filaments. It should therefore increase by orders of magnitude the number of available events during field campaigns. This development is still in process. However, good hopes can be raised that laser triggering of lightning could be achieved in a near future.

Acknowledgements. This work has been performed in the framework of the *Teramobile* collaboration (www.teramobile.org), funded jointly by the CNRS, DFG, French and German ministries of Foreign affairs, Agence Nationale de la Recherche (ANR, grant # NT05-1_43175), Fonds national suisse de la recherche scientifique (FNS, grants #200021-111688/1 and 200021-116198/1), and the Swiss Secrétariat d'État à l'Éducation et à la Recherche (COST P18 action C06.0114). We would like to acknowledge all our collaborators within the Teramobile project for common work and constructive discussions.

References

1 C. Gary, *La foudre. Nature, histoire, risques et protection*. Dunod, Paris, 2004

2 E. Philip Krider, “*Benjamin Franklin and the First Lightning Conductors*”, Proceedings of International Commission on History of Meteorology **1** 1-13, 2004

3 R. Fieux, C. Gary, and P. Hubert, *Artificially Triggered Lightning above Land*, Nature **257**, 212-214 (1975).

4 V. A. Rakov, M. A. Uman, and K. J. Rambo, "*A review of ten years of triggered-lightning experiments at Camp Blanding, Florida*," Atmos. Res. **76**, 503-517 (2005)

5 E. M. Bazelyan, Yu P. Raizer, *The mechanism of lightning attraction and the problem of lightning initiation by lasers*, Physics - Uspekhi **43**, 701 (2000)

6 Apollonov V et al. AHPLA'99 Paper 3886-34

7 M. Miki, Y. Aihara, and T. Shindo, "*Development of long gap discharges guided by a pulsed* CO_2 *laser*," J. Phys. D: Appl. Phus **26**, 1244-1252 (1993).

8 S. Uchida, Y. Shimada, H. Yasuda, S. Motokoshi, C. Yamanaka, T. Yamanaka, Z. Kawasaki, and K. Tsubakimoto, "*Laser-triggered lightning in field experiments*," J. Opt. Technol. **66**, 199-202 (1999)

9 A. Braun, G. Korn, X. Liu, D. Du, J. Squier, and G. Mourou, "*Self-channeling of high-peak-power femtosecond laser pulses in air*," Opt. Lett. **20**, 73-75 (1995).

10 S. L. Chin, S. A. Hosseini, W. Liu, Q. Luo, F. Theberge, N. Akozbek, A. Becker, V. P. Kandidov, O. G. Kosareva, and H. Schroeder, "*The propagation of powerful femtosecond laser pulses in optical media: physics, applications, and new challenges*," Can. J. Phys. **83**, 863-905 (2005).

11 L. Bergé, S. Skupin, R. Nuter, J. Kasparian, and J.-P. Wolf, "*Ultrashort filaments of light in weakly-ionized, optically-transparent media*," Rep. Prog. Phys. **70**, 1633-1713 (2007).

12 A. Couairon and A. Mysyrowicz, "*Femtosecond filamentation in transparent media*," Phys. Rep. **441**, 47-189 (2007)

13 J. Kasparian and J.-P. Wolf, "*Physics and applications of atmospheric nonlinear optics and filamentation* M. Rodriguez, R. Bourayou, G. Méjean, J. Kasparian, J. Yu, E. Salmon, A. Scholz, B. Stecklum, J. Eislöffel, U. Laux, A. P. Hatzes, R. Sauerbrey, L. Wöste, and J.-P. Wolf, "*Kilometer-range non-linear propagation of femtosecond laser pulses*," Phys. Rev. E **69**, 036607 (2004).tion," Opt. Express **16**, 466-493 (2008).

14 B. La Fontaine, F. Vidal, Z. Jiang, C.Y. Chien, D. Comtois, A. Desparois, T.W. Johnson, J.-C. Kieffer, and H. Pépin, "*Filamentation of ultrashort pulse laser beams resulting from their propagation over long distances in air*". Physics of plasmas **6**, 1615-1621 (1999)

15 M. Rodriguez, R. Bourayou, G. Méjean, J. Kasparian, J. Yu, E. Salmon, A. Scholz, B. Stecklum, J. Eislöffel, U. Laux, A. P. Hatzes, R. Sauerbrey, L. Wöste, and J.-P. Wolf, "*Kilometer-range non-linear propagation of femtosecond laser pulses*," Phys. Rev. E **69**, 036607 (2004).

16 G. Méchain, G. Méjean, R. Ackermann, P. Rohwetter, Y.-B. André, J. Kasparian, B. Prade, K. Stelmaszczyk, J. Yu, E. Salmon, W. Winn, L. A. V. Schlie, A. Mysyrowicz, R. Sauerbrey, L. Wöste, and J.-P. Wolf, "*Propagation of fs-TW laser filaments in adverse atmospheric conditions*," Appl. Phys. B **80**, 785-789 (2005).

17 G. Méjean, J. Kasparian, J. Yu, E. Salmon, S. Frey, J.-P. Wolf, S. Skupin, A. Vinçotte, R. Nuter, S. Champeaux, and L. Bergé, "*Multifilamentation transmission through fog*," Phys. Rev. E **72**, 026611 (2005).

18 R. Ackermann, G. Méjean, J. Kasparian, J. Yu, E. Salmon, J.-P. Wolf, "*Laser filaments generated and transmitted in highly turbulent air*", Opt. Lett. **31**, 86-88 (2006)

19 R. Salamé, N. Lascoux, E. Salmon, J. Kasparian, and J. P. Wolf, "*Propagation of laser filaments through an extended turbulent region*," Appl. Phys. Lett. **91**, 171106 (2007).

20 H. Pépin, D. Comtois, F. Vidal, C. Y. Chien, A. Desparois, T. W. Johnston, J. C. Kieffer, B. La Fontaine, F. Martin, F. A. M. Rizk, C. Potvin, P. Couture, H. P. Mercure, A. Bondiou-Clergerie, P. Lalande, I. Gallimberti, "*Triggering and guiding high-voltage large-scale leader discharges with sub-joule ultrashort laser pulses*", Phys. Plasmas **8**, 2532-2539 (2001)

21 D. Comtois, C. Y. Chien, A. Desparois, F. Gérin, G. Jarry, T. W. Johnston, J. C. Kieffer, B. La Fontaine, F. Martin, R. Mawassi, H. Pépin, F. A. M. Rizk, F. Vidal, P. Couture, H. P. Mercure, C. Potvin, A. Bondiou-Clergerie, I. Gallimberti, "*Triggering and guiding leader discharges using a plasma channel created by an ultrashort laser*", Appl. Phys. Letters **76**, 819-821 (2000)

22 P. Rambo, J. Schwartz, J.-C. Diels, "*High-voltage electrical discharges induced by an ultrashort-pulse UV laser system*", J. Opt. A: Pure and Appl. Opt. **3**, 146-158 (2001)

23 H. Wille, M. Rodriguez, J. Kasparian, D. Mondelain, J. Yu, A. Mysyrowicz, R. Sauerbrey, J.-P. Wolf, and L. Wöste, "*Teramobile: a mobile femtosecond-terawatt laser and detection system*," Eur. Phys. J. - Appl. Phys. **20**, 183-190 (2002).

24 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, and J.-P. Wolf, "*Megavolt discharges triggered and guided with laser filaments*," Opt. Lett. **27**, 772-774 (2002).

25 J. Kasparian, M. Rodriguez, G. Méjean, J. Yu, E. Salmon, H. Wille, R. Bourayou, S. Frey, Y.-B. André, A. Mysyrowicz, R. Sauerbrey, J.-P. Wolf, and L. Wöste, "White-Light Filaments for Atmospheric Analysis" Science **301**, 61-64 (2003).

26 R. Ackermann, G. Méchain, G. Méjean, R. Bourayou, M. Rodriguez, K.Stelmaszczyk, J. Kasparian, J. Yu, E. Salmon, S. Tzortzakis, Y.-B. André, J.-F. Bourrillon, L. Tamin, J.-P. Cascelli, C. Campo, C. Davoise, A. Mysyrowicz, R. Sauerbrey, L. Wöste, J.-P. "*Wolf, Influence of negative leader propagation on the triggering and guiding of high voltage discharges by laser filaments*". Appl. Phys. B. **82**, 561-566 (2006)

27 R. Ackermann, K. Stelmaszczyk, P. Rohwetter, G. Méjean, E. Salmon, J. Yu, J. Kasparian, G. Méchain, V. Bergmann, S. Schaper, B. Weise, T. Kumm, K. Rethmeier, W. Kalkner, J.P. Wolf, and L. Wöste, "*Triggering and guiding of megavolt discharges by laser-induced filaments under rain conditions*". Appl. Phys. Lett. **85**, 5781-5783 (2004)

28 P. Rambo, J. Schwartz, J.-C. Diels, "*High-voltage electrical discharges induced by an ultrashort-pulse UV laser system*", J. Opt. A: Pure and Appl. Opt. **3**, 146-158 (2001)

29 Z. Hao, J. Zhang, Y.T. Li, X. Lu, X.H. Yuan, Z.Y. Zheng, Z.H. Wang, W.J. Ling, Z.Y. Wei, "*Prolongation of the fluorescence lifetime of plasma channels in air induced by femtosecond laser pulses*". Applied Phsics B 80, 627-630 (2005)

30 G. Méjean, R. Ackermann, J. Kasparian, E. Salmon, J. Yu, J.-P. Wolf, K. Rethmeier, W. Kalkner, P. Rohwetter, K. Stelmaszczyk, and L. Wöste, "*Improved laser triggering and guiding of megavolt discharges with dual fs-ns pulses*," Appl. Phys. Lett. **88**, 021101 (2006).

31 J. Kasparian, R. Ackermann, Y.-B. André, G. Méchain, G. Méjean, B. Prade, P. Rohwetter, E. Salmon, K. Stelmaszczyk, J. Yu, A. Mysyrowicz, R. Sauerbrey, L. Wöste, J.-P. Wolf, *Electric events synchronized with laser filaments in thunderclouds Opt. Express* **16**, 5757 (2008)

32 W. Rison, R. J. Thomas, P. R. Krehbiel, T. Hamlin, and J. Harlin, "*A GPS-based three-dimensional lightning mapping system: Initial observations in central New Mexico*," Geophys. Res. Lett. **26**, 3573-3576 (1999).

33 B. La Fontaine, F. Vidal, D. Comtois, C.-Y. Chien, A. Deparois, T. W. Johnston, J.-C. Kieffer, H. P. Mercure, H. Pépin, and F. A. M. Rizk, "*The influence of electron density on the formation of streamers in electrical discharges triggered with ultrashort laser pulses*," IEEE Trans. Plasma Sci. **27**, 688-700 (1999)

34 S. Tzortzakis, B. Prade, M. Franco, and A. Mysyrowicz, "*Time evolution of the plasma channel at the trail of a self-guided IR femtosecond laser pulse in air*," Opt. Commun. **181**, 123-127 (2000)

35 X. M. Zhao, J.-C. Diels, C. Y. Wang, and J. M. Elizondo, "*Femtosecond ultraviolet laser pulse induced lightning discharges in gase*s," IEEE J. Quantum Electron. **31**, 599-612 (1995).

36 P. Rambo, J. Schwarz, and J.-C. Diels, "*High-voltage electrical discharges induced by an ultrashort-pulse UV laser system*," J. of Opt. A: Pure Appl. Opt. **3**, 146-158 (2001).

37 G. Méjean, R. Ackermann, J. Kasparian, E. Salmon, J. Yu, J.-P. Wolf, K. Rethmeier, W. Kalkner, P. Rohwetter, K. Stelmaszczyk, and L. Wöste, "*Improved laser triggering and guiding of megavolt discharges with dual fs-ns pulses*," Appl. Phys. Lett. **88**, 021101 (2006)

38 H. Yang, J. Zhang, Y. Li, J. Zhang, Y. Li, Z. Chen, H. Teng, Z. Wei, and Z. Sheng, "*Characteristics of self-guided laser plasma channels generated by femtosecond laser pulses in air*," Phys. Rev. E **66**, 016406 (2002)

39 Z. Hao, J. Zhang, Y. T. Li, X. Lu, X. H. Yuan, Z. Y. Zheng, Z. H. Wang, W. J. Ling, and Z. Y. Wei, "*Prolongation of the fluorescence lifetime of plasma channels in air induced by femtosecond laser pulses*," Appl. Phys. B **80**, 627-630 (2005)

40 T. B. Petrova, H. D. Ladouceur, and A. P. Baronavski, "*Numerical modeling of the electrical breakdown and discharge properties of laser-generated plasma channels*," Phys. Rev. E **76**, 066405 (2007)

41 P. Béjot, L. Bonacina, J. Extermann, M. Moret, J. P. Wolf, R. Ackermann, N. Lascoux, R. Salamé, E. Salmon, J. Kasparian, L. Bergé, S. Champeaux, C. Guet, N. Blanchot, O. Bonville, A. Boscheron, P. Canal, M. Castaldi, O. Hartmann, C. Lepage, L. Marmande, E. Mazataud, G. Mennerat, L. Patissou, V. Prevot, D. Raffestin, and J. Ribolzi, "*32 Terawatt Atmospheric White-Light Laser*," Appl. Phys. Lett. **90**, 151106 (2007).

42 F. Grangé, N. Soulem, J.F. Loiseau, N. Spyrou, Numerical and experimental determination of ionizing front velocity in a DC point-to-plane corona discharge, J. Phys. D. Appl. Phys. **28** 1619-1629 (1995)

43 T. B. Petrova, H. D. Ladouceur, A. P. Baronavski, *Nonequilibrium dynamics of laser-generated plasma channels*. Phys. Plasmas **15**, 053501 (2008).

Figure captions

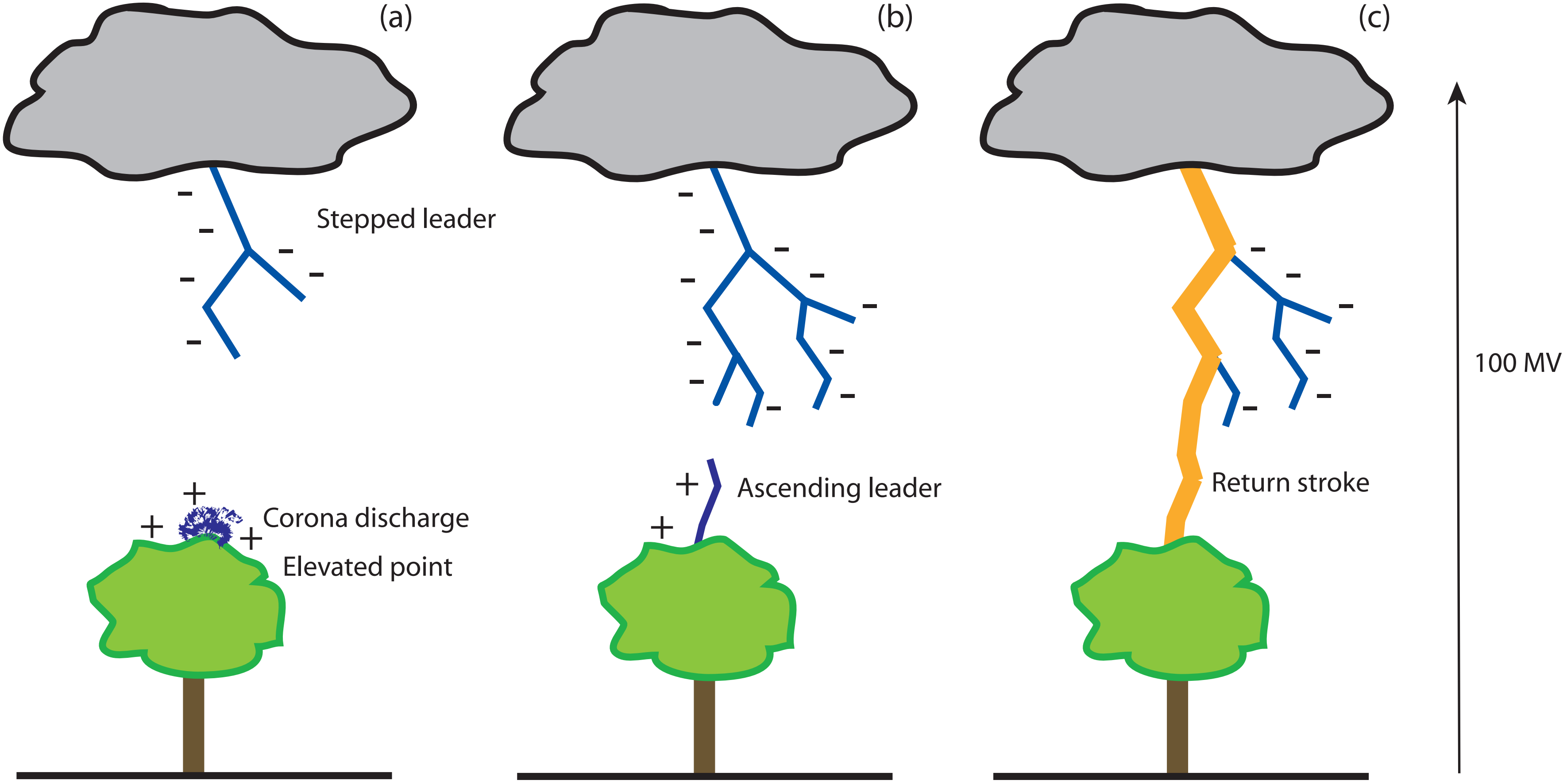
Figure 1. Mecanism of lightning initiation: (a) stepped leader formation; (b) initiation of an upward leader; (c) return stroke

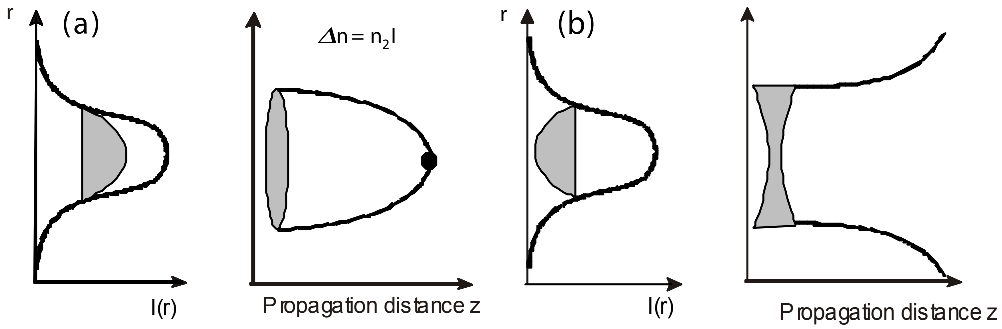
Figure 2. Mécanism of filamentation. (a) Kerr effect (self-focusing); (b) defocusing by the plasma

Figure 3. Laser control of high-voltage discharges. (A) Free discharge over 3 m, without laser filaments. Note the erratic path. (B) Straight discharge guided along laser filaments. [25]

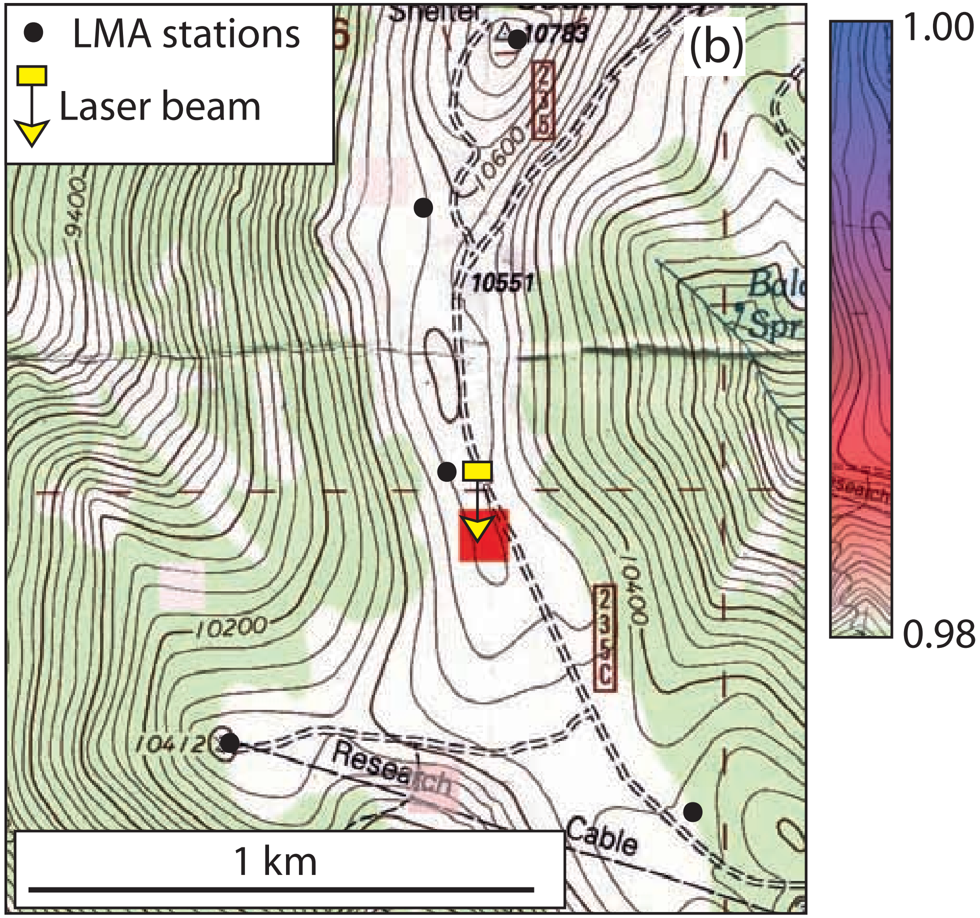
Figure 4. Statistical confidence level associated with the electric events synchronized with the laser pulses during a thunderstorm. The colour scale is transparent below 98 % (*i.e.* for error risks above 2 %), leaving the topographical background uncovered. Arrowhead: location of the laser-induced plasma channel; Arrow tail: laser emitter. Topographic background courtesy of US Geological Survey.

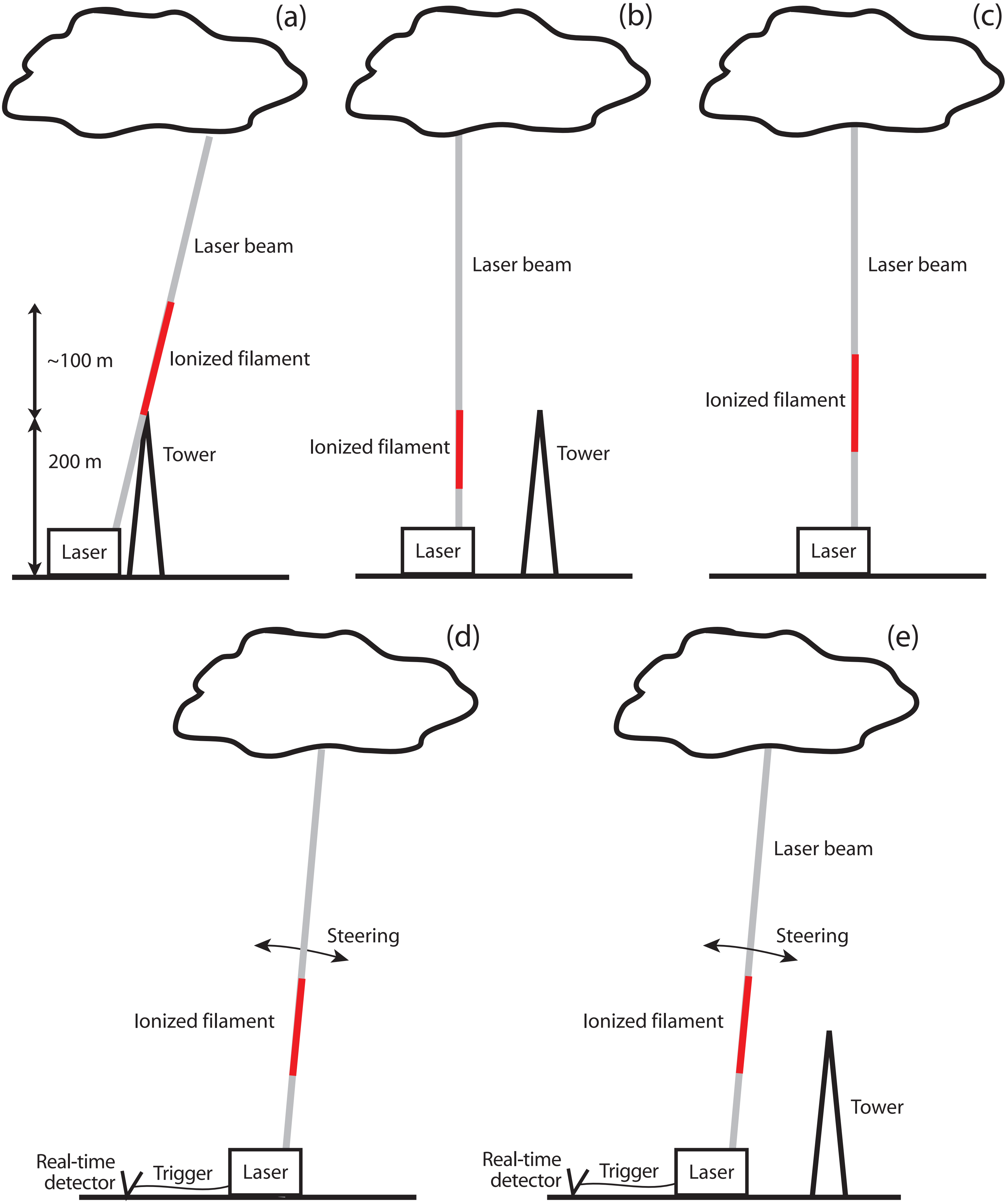
Figure 5. Schematic of the considered configurations. (a) Filament extending a tower; (b) Filament competing with a tower; (c) filament alone; (d) Filament with real-time triggering and aiming; (e) Filament with real-time triggering and aiming, competing with a tower.


(a)
(b)
(c)
Stepped leader
Corona discharge
Elevated point
Ascending leader
Return stroke
100 MV


r
(a)
I(r)
Δn = n₂I
Propagation distance z
r
(b)
I(r)
Propagation distance z


A
B


● LMA stations
Laser beam
(b)
1.00
0.98
1 km
Shelter
10783
10600
10551
9400
10200
10400
10412
Research
Cable
235
235C


(a)
Laser beam
~100 m
Ionized filament
200 m
Tower
Laser
(b)
Laser beam
Ionized filament
Tower
Laser
(c)
Laser beam
Ionized filament
Laser
(d)
Steering
Ionized filament
Real-time detector
Trigger
Laser
(e)
Laser beam
Steering
Ionized filament
Tower
Real-time detector
Trigger
Laser