

# The Future of the Laser Lightning Rod

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## Abstract

The recent development of high average, high peak power lasers has revived the effort of using lasers as a potential tool to influence natural lightning. Although impressive, the current progress in laser lightning control technology may only be the beginning of a phase involving a positive feedback between powerful laser development and atmospheric research. In this review paper, we critically evaluate the past, present and future of the Laser Lightning Rod Technology (LLRT) approach, considering both technological and scientific significance in atmospheric research.

## 1. Introduction

Lightning is a spectacular natural phenomenon that has evoked both fear and wonder in humanity. Among the one billion lightning strikes that occur annually on Earth [Gowlett2016], many lead to natural fires, casting no doubt that the human fascination by lightning is closely intertwined with our history of mastering fire [Gowlett2016, Roebroeks2011]. Lightning has thus naturally fascinated generations after generations since the dawn of humanity.

The era of modern lightning science started with Benjamin Franklin's famous experiment in the 18<sup>th</sup> century that identified the electrical nature of the phenomenon. Alongside with this fundamental discovery, Franklin's work provided the first efficient protection technique against lightning: the lightning rod [Franklin1752]. With minor enhancements, this technique still forms the foundation of the state of the art lightning protection today [Uman2008]. A lightning rod primarily functions by diverting the lightning current to the ground through a safe conductor, thus preventing it from flowing through vulnerable structures. However, in spite of this simple and affordable protection means and its ubiquitous use, the total number of lightning-related fatalities worldwide is still estimated to range from 6000 to 24000 per year [Holle2016, Holle2023]. Death rates in developed regions are estimated to be around ~0.3 fatalities per million people per year, but they are significantly higher in less developed regions [Holle2008, Singh2015]. Damages caused by lightning amount to billions of dollars every year [Uman2008, Mills2010, Holle2014, Holle2023, Rudden2023]. Over recent decades, the range of risks associated with lightning has expanded significantly. Initially, the risks associated with lightning primarily included human and livestock fatalities, transportation disruption and structural damage.

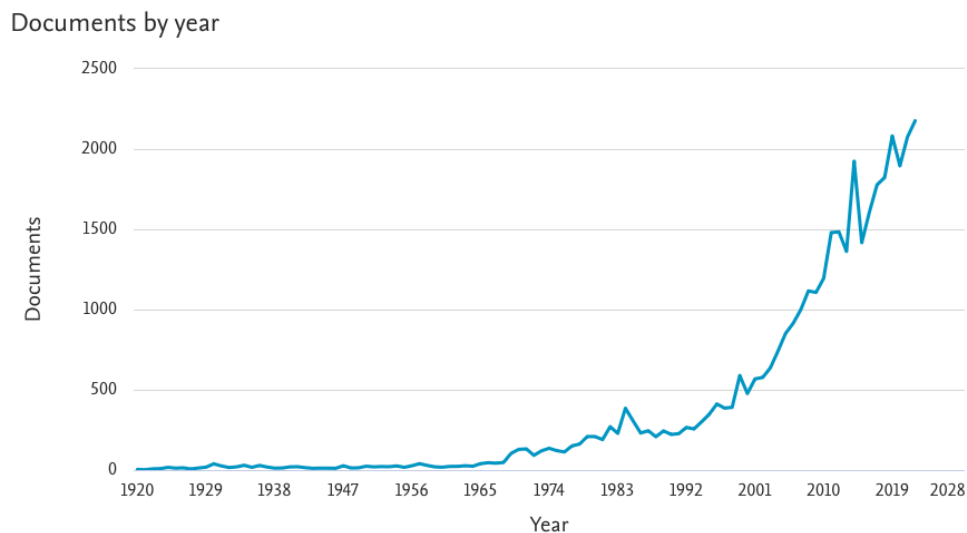


Figure 1: Number of scientific publications in the last 100 years in which the word 'lightning' appears either in the title, the abstract or the keywords. Source: Scopus (September 6, 2023)

However, as our society and economy have become more dependent on electricity, sensitive electronic, and digital control systems, new vulnerabilities have emerged [DataReportal]. The emergence of new risks associated with power outages as well as the disruption or damage to electronically or computer-controlled systems can in turn affect critical infrastructure, facilities, or services.

As a result, research efforts have intensified over time to enhance our understanding of lightning and to develop better protection against its adverse effects. This is evidenced by the significant rise in the number of scientific and technical articles on the subject, along with the corresponding increase in the citations to those articles (Figure 1). In spite of these efforts of the scientific community, the detailed physical mechanisms underlying the lightning initiation and associated phenomena like Transient Luminous Events (including Red Sprites, Blue Starters, Blue Jets, Gigantic Blue Jets, and Sprites) remain only partially understood [Franz1990, Surkov2012, Dwyer2014], calling for further fundamental studies. However, conducting such studies require adequate tools, including the ability to trigger lightning on demand, a task primarily achieved today through Rocket-Triggered Lightning (RTL), with minimal disturbance to its natural development.

The present article presents a review of past scientific efforts involving the use of lasers for lightning research. Additionally, it explores future directions with a special emphasis on the emergence of a new technology called Laser Lightning Rod Technology (LLRT).

We review the scientific questions and technical challenges that lie ahead, in view of a deeper understanding of both laser physics, laser technology, and the physics of lightning. Furthermore, we discuss the requirements for realistic full-scale experiments representative of typical use cases, in order to provide a clear assessment of the relevance of LLRT in lightning research, effective lightning protection, and other potential applications.

## 2. High-power laser propagation applied to lightning protection

### 2.1 Filamentation physics

When the peak power of a laser pulse exceeds a critical value  $P_{cr}$ , its propagation in a transparent medium becomes non-linear. In particular, self-actions like self-focusing and self-trapping ('filamentation') of light arise. Although these phenomena were already described in the early 1960s in solids and liquids [Askaryan1962, Chiao1964, Hercher1964, Lallemand1965, Shen1965, Talanov1965, Javan1966], filamentation in air, requiring femtosecond lasers, was only observed 30 years later [Braun1995]. This breakthrough was achieved thanks to the development of the laser Chirped Pulse Amplification (CPA) technique, which was invented by the 2018 Nobel laureates G. Mourou and D. Strickland [Strickland1985]. More precisely, at high laser intensity, the refractive index  $n$  of the air is modified by the electric field of the laser, a process known as the Kerr effect [Boyd2020]:  $n = n_0 + n_2 I$ , where  $I$  is the incident intensity and  $n_2$  is the nonlinear refractive index. As the intensity in a cross-section of the laser beam is not uniform and  $n_2$  in air is positive, the refractive index in the center of the beam is larger than on the edge. This induces a radial refractive index gradient equivalent to a converging lens (called 'Kerr lens'). If the beam power exceeds a critical power  $P_{cr}$  of a few GW in air in the NIR, this Kerr effect overcomes diffraction and the beam is focused by this lens, which continuously increases the intensity and shortens the Kerr focal length. The whole beam would therefore tend to collapse at a distance which depends on the initial beam power [Couairon2007, Bergé2007]. Kerr self-focusing could therefore be expected to prevent propagation of high power lasers in air if it was the only process at play.

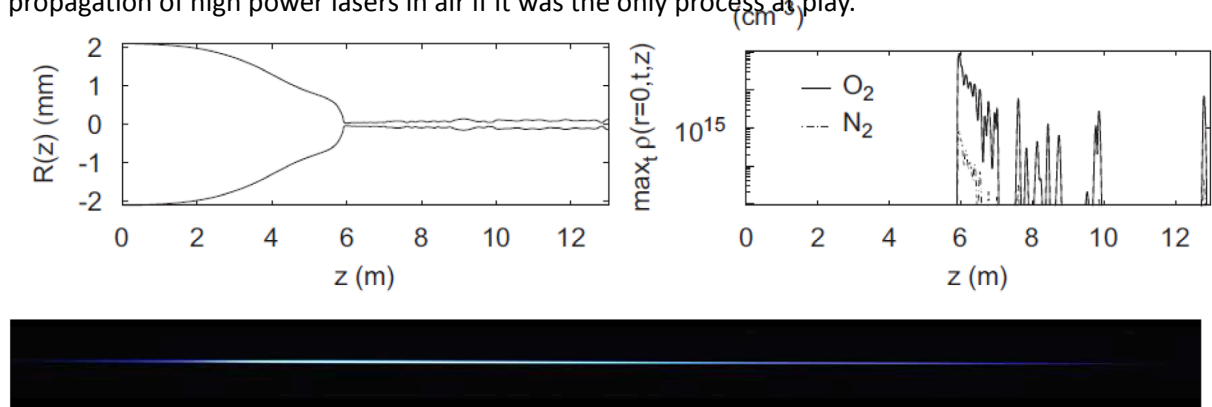


Figure 2: Upper left: Radius of a filamenting 800 nm ultrashort (50 fs) laser beam as a function of its propagation distance. Upper right: Associated estimated upper bound of the electron density. Both reprinted with permission from [Couairon2002]. Copyright by the American Physical Society. Lower center: Side view of the  $\sim 1$  m long characteristic blue sideward luminescence of the ionized channel associated with laser filamentation. Adapted from [Wolf2018].

However, as the laser self-focuses, the intensity rises to  $10^{13}$ - $10^{14}$  W/cm<sup>2</sup> and starts to *ionize* the air molecules. The produced electron density  $\rho$  induces a negative variation of the refractive index, and accordingly, a negative refractive index gradient. This acts as a diverging lens, which defocuses the laser beam and counteracts Kerr self-focusing. The consequent dynamic balance between Kerr effect and plasma generation leads to the formation of stable structures called "filaments" (Figure 2), bearing high intensities on a few hundred micrometres diameters, and spanning over tens of metres. Typical electrical carrier densities in filaments range from  $10^{15}$  to  $10^{17}$  cm<sup>-3</sup>, making the air suddenly *conductive*. If the laser carries a power  $P_0$  much beyond the critical power, typically some tens of GW or more, the whole beam splits into a bundle of filaments, the number of which scales with the ratio of  $P_0/P_{cr}$ , a phenomenon called *multi-filamentation* or *multiple filamentation*.

## 2.2 Ultrashort laser development for atmospheric applications

Most of the high intensity lasers used for large scale filamentation studies, hence most adapted for atmospheric applications, have been relying on the Ti:sapphire technology, pumped by Nd:YAG lasers. The first mobile system dedicated to atmospheric applications was the Teramobile in 1999 [Wille2002]. The Teramobile project set the ground for many disruptive atmospheric applications of ultrashort lasers capable of TW peak powers like multi-pollutant Lidar detection [Kasparian2003, Bourayou2005], remote filament based Laser Induced Breakdown Spectroscopy (LIBS) analysis [Stelmaszczyk2004, Rohwetter2005], remote lidar detection of bioaerosols [Méjean2004, Kasparian2003], laser induced water condensation in clouds [Rohwetter2010, Petit2010, Rohwetter2011, Henin2011, Staathoff2013, Joly2013], and lightning control [Kasparian2008]. Several similar platforms were also developed, like the ENSTAmobile at the LOA [Brelet2012], the T&T at DRDC in Canada [Kamali2009, Durand2013], the MU-HELF at CREOL in Florida [Richardson2020, Thul2021], and at SIOM in Shanghai [Wang2015, Wang2020b]. For more details on the recent advancement in high power lasers in general, the reader is referred to the recent review by Zuo *et al.* [Zuo2022].

The main disadvantage of Ti:Sapphire lasers for field experiments is the lack of direct diode-pumping. Rather, diode-pumped Nd:YAG lasers, which are frequency doubled in a non-linear crystal, are required. This significantly limits the efficiency of the laser chain and induces prohibitive energy consumption for high average power laser systems ( $> 100$  W).

Thin disk Yb based laser (TDL) systems, first demonstrated in 1994 [Giesen1994], became game changers, thanks to their direct diode pumping capability and efficient heat extraction, allowing to aim for higher average power laser systems. These lasers have seen massive improvement in the last decade [Saraceno2019, Drs2023], as reviewed specifically in the review by Saraceno *et al.* [Saraceno2019]. However, TDL systems providing simultaneously high average powers and high pulse energy/peak power are required for Laser Lightning Rod Technology and such requirement remains challenging.

A remarkable laser development was recently achieved within the European Laser Lightning Rod (LLR) project [Produit2021, Produit2021a, Houard2023] by the German company Trumpf Scientific [Herkommer2020]. Using a regenerative amplifier followed by a multipass involving 4 thin disk heads, they achieved pulse energies as high as 0.72 J within 920 fs pulse duration at 1 kHz repetition rate [Herkommer2020].

This achievement constitutes a real milestone, as this laser is the first TW-class peak power, kW-class average power laser system. This high average power and high pulse energy/peak power laser also showed excellent conversion efficiencies when generating SHG at 515 nm (using a LBO 50 mm diameter LBO crystals of 1.8 mm) and THG (using a second 50 mm diameter LBO crystal of 2 mm thickness) at 343 nm. Energies as high as, respectively, 300 mJ at 515 nm (59% efficiency) and 120 mJ at 343 nm (27% efficiency) were achieved in this configuration [Andral2022].

As compared to a TW laser based on Ti:sapphire, the pulse duration is significantly longer: ( $\sim 1$  ps as compared to  $\sim 50$ -100 fs) reflecting the narrower bandwidth (few nm around 1030 nm as compared to few tens of nm around 800 nm). Very recent developments using a 24-passes Herriott spectral broadening cell (filled with Ar or He) and recompression demonstrated pulses as short as 32 fs for 64 mJ pulse energy and a compressibility down to 45 fs for 200 mJ, at 5 kHz repetition rate [Pfaff2023].

## 2.3 Safety and side effects of high-power lasers

Although producing only limited damages on solid surfaces for transient exposures, TW lasers must be implemented in the field with caution. In particular, in the filamentary region, eye safety requirements (e.g., IEC-60825-1, EN 207, EN 208 and EN 60825 in Europe, and ANSI Z136 in the US) are never fulfilled at any wavelength. Beyond the filamentary region, the intensity decreases and international standards can be used to define the most favorable experimental conditions (in particular the wavelength of the laser). Pointing vertically in a fixed, near-vertical direction is also favorable, because it prevents the risk of direct illumination to the pilots' eyes. However, for any safe implementation of LLRT, a no-flight zone of some kilometers radius around the laser has to be requested by the air traffic control administration, requiring the emission of a NOTice To AirMen (NOTAM). Although relatively common, these requests can sometimes take several months or more until final acceptance and hence increase the administrative preparation of LLRT campaigns. Risk management should also involve the implementation of additional measures like real-time monitoring of the air traffic by transponder communications (ADS-B), and coordination with the nearest airport.

In the case of vertical pointing and scanning over a cone, the no-flight zone has to be widened accordingly, so that eye safety regulations for air traffic are fulfilled. Particular care has to be brought to light aircrafts, paragliders and similar activities, which do not use transponders and may miss the NOTAM announcing the no-flight zone. It is therefore strongly advised to add surveillance cameras with AI-based real-time detection of moving objects in the sky for steering laser interlocks. This is also advised for the protection of the fauna, like birds. In the case of the laser system described here, the beam can be switched on and off with a reaction time of a millisecond, i.e., during the time interval between two pulses.

An important aspect, in the case of lightning research, is that the laser is used only during thunderstorms and lightning periods, which reduces the probability of interacting with flying objects during the laser operation.

Laser filaments have also been observed to generate NO<sub>x</sub> and Ozone [Petit2010] and produce nanoscopic condensation nuclei that can turn into cloud condensation nuclei and lead to water droplet condensation if the meteorological conditions are favorable [Rohwetter2010, Rohwetter2011, Henin2011]. Although these productions are very modest as compared to similar effects induced by the lightning themselves, it is worth keeping these side effects in mind when long term implementation of LLRT is planned at the same location.

## 3. Laser Lightning Rod Technology (LLRT) development

### 3.1 Laboratory work

The discovery and experimental demonstration of the ability of powerful lasers to control electric discharges were provided soon after the invention of the laser itself [Vaill1970, Koopman1971, Saum1972, Diels1992] and led very early to operational propositions [Ball1974, Ball1977, Lippert1978, Schubert1978, Schubert1979]. The interest was renewed by the advent of femtosecond UV pulses, [Zhao1995, Rambo2001]. However, the first experiments were performed at the centimeter-scale. While this scale is relevant for technological applications like fast high-current switching, its mechanism consists in the generation of a single electron avalanche. In the context of lightning though, the much more complex streamer-leader mechanism has to be considered [Cooray2015]. The first demonstration of discharge guiding and triggering at the meter-scale by ultrashort laser filaments occurred at the turn of the 21st century.



Figure 3: Picture of a laser-guided negative discharge. Adapted with permission from [Rodriguez2002]  
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The first results were obtained with positive discharges [Pepin2001, Comtois2000], where near-infrared (800 nm) femtosecond pulses reduced the leader inception voltage by 50% and guided discharges over up to 2.3 m, with a 10-fold acceleration of the leader velocity [LaFontaine2000]. Numerical modelling [Bondiou1994] allowed the effect of the laser filaments to be understood as a combination of the release of free charges in the plasma and a local air depletion favoring their acceleration in the electric field [Vidal2000].

Similar results were observed in the case of negative discharges [Vidal2002, Rodriguez2002]. The breakdown voltage was reduced by 30% up to a 3.8 m inter-electrode gap, and fully guided discharges were recorded (Figure 3), even in the presence of artificial rain [Ackermann2004]. The Teramobile group also observed laser triggered space-leader discharges [Ackermann2006]. Later, the deviation of discharges from their natural path, switching their trajectory from one ground electrode to another, illustrated the versatility of near-infrared laser filaments and allowed considering new lightning protection schemes [Forestier2012].

Subsequent efforts aimed at approaching the conditions of real thunderstorms [Comtois2003a, Comtois2003b] and included upscaling the experimental setup with a 5-m wide planar electrode facing, at a distance of 5 m, a 2-m long lightning rod in the middle of a 15-m planar grounded electrode.

Using a DC voltage combines the fast, electronic breakdown mode already observed with pulsed voltage, and a slow process related to ionic mobility [Fujii2008]. Due to the higher electric field and energy required to accelerate the ions, this slower mechanism is only observed when the voltage approaches the laser-free breakdown threshold.

In contrast to the leader-streamer mechanism of pulsed or DC voltages, AC voltages [Henrikson2012, Brelet2012, Daigle2013, Arantchouk2016] generated e.g., by Tesla coils rely on a purely leader regime [Daigle2013]. This regime allows repeated discharges up to the repetition rate of the laser, i.e., 10 Hz in these experiments [Arantchouk2016, Walch2023b], facilitating the use of fast imaging to elucidate the development of the discharges [SchmittSody2015] for various temporal shapes (duration, chirp) of the laser pulse.

Besides fully developed discharges, laser filaments were found to strongly influence corona discharges, even with low-energy laser pulses in the 10 mJ range. They can divert the corona discharge away from an electrode towards the filament tip, while increasing their lifetime by a factor of 1000 [Wang2015].

It was also discovered that at an increased laser repetition rate, usually above 100 Hz and more (typically around 1000 Hz), laser filamentation would locally heat the air in its wake and leave a depleted air density [Lahav2014, Jhajj2014, Houard2016, Higginson2021]. This effect was shown to significantly enhance the laser effect on electric discharge [Houard2016, Walch2021, Loscher23] mostly through Paschen's law [Tirumala2010]. Moreover, it was also shown that ultracorona-like discharges [Uhlir1956, Rizk2010] were able to discharge a HV capacitor without triggering any spark between electrodes [Schubert2015]. The interaction of the laser filaments with the corona discharges also produces UV bursts [Sugiyama2010, Sasaki2010] indicating the generation of runaway electrons. These fast electrons feature longer mean free paths in air and produce the fast avalanches that are considered key in the development of lightning [Gurevich1992, Gurevich2005, Dwyer2005]. Paradoxically, the same group observed that laser filaments perpendicular to the laser axis can quench the same runaway electrons up to 1 MeV [Eto2012].

Following laboratory experiments demonstrating the triggering and/or guiding of discharges with lasers, and considering the multi-meter scale of the leader-streamer mechanism of lightning initiation, the need for field experiments appeared very early.

### 3.2 Field experiments

Even before the laboratory experiments described in the previous section, the possibility of influencing natural lightning with lasers, and its potential for lightning protection, were discussed in the scientific community [Vaill1970, Saum1972, Ball1974, Ball1977, Lippert1978, Schubert1978, Schubert1979, Diels1992].

One failed attempt was reported by [Lippert1978] in which, during one thunderstorm event with no cloud-to-ground lightning discharge, they tried, unsuccessfully, to trigger lightning. The first reported successful field experiment did not occur until 1999 [Uchida1999] after long preparatory works [Wang1994, Wang1995]. Pre-dating large-scale laboratory experiments using ultrashort laser filaments, it relied on a set of 3 lasers. A first CO<sub>2</sub> laser (10  $\mu$ m wavelength) providing 1 kHz pulses was focused on a dielectric hard target at the apex of a 50 m tower installed on a 200 m high hill. It produced an ablation plume in which a second CO<sub>2</sub> laser produced a 2-m long plasma spark. Finally, an ionized plasma channel was produced by a UV laser slightly aside of the tower apex, in order to guide the leader to the cloud. The setup was triggered based on the intra-cloud activity, considered as a precursor of the cloud-to-ground discharges. Unfortunately, only two discharges were reported, preventing a statistical assessment of the laser effect. No other attempts were reported in this configuration and hence other limitations like the short (2 m) reported plasma length or the scalability of the technique still stood unanswered.

The first attempt based on laser filaments was performed at the top of the South Baldy Peak (New Mexico, USA), 3200 m above sea level, in a very different configuration. The 4 TW Teramobile laser [Wille2002] was fired at a repetition rate of 10 Hz as soon as the electric field at ground exceeded 5 kV/m, regardless of the actual lightning activity. The beam, leaning 70° above horizontal, produced multiple filamentation at several hundred meters above ground, over a length of typically 100 m. A lightning mapping array (LMA) [Rison1999] tuned at a frequency of 63 MHz monitored the radiofrequency emission from the atmospheric electric activity.

The time-of-arrival differences of such pulses, detected by 5 antennas synchronized by GPS clocks, allowed to locate the development of the radiation source in three dimensions with an accuracy of ~100 m [Kasparian2008]. Only two thunderstorms occurred during the measurement time and no lightning strike was triggered to the ground. However, in the simultaneous presence of a ground electric field exceeding 10 kV/m and of the laser filaments, an electromagnetic activity was detected, which was both co-located with the filament position and synchronized at the same rate of 10 Hz.

The fact that the laser filaments did not trigger fully developed lightning in conditions where rockets would expectedly have done so was interpreted as the triggering of corona discharges at the upper end of the laser filaments [Kasparian2008]. Such a limited effect was attributed to the short ( $\mu\text{s}$  or shorter) lifetime of the laser-generated plasma, which together with the  $10^6$  m/s velocity of the leaders limits the laser effect to an effective length of a few meters.

Overcoming this limitation requires taking advantage of Paschen's law, which is the second physical mechanism playing a significant role in laser-induced effects on electric discharges. Indeed as already pointed out in Section 2.1, in the wake of filamentation a density depletion of air is formed and can be sustained virtually forever by cumulative effects of the filamentation at a repetition rate above several hundred Hz. Keeping such an air-depleted channel open requires high average power lasers, in the kW range. This high average power can only be achieved in lasers based on the latest thin-disk laser technology (TDL), as described in Section 2.2.

The European Laser Lightning Rod (LLR) project [Produit2021, Produit2021a, Houard2023] designed such a high-average power (kW) high-peak power laser (GW) at a repetition rate of 1 kHz [Herkommer2020]. This laser was installed in the telecom station located at the top of the Säntis mountain ( $47.24944^\circ$  N,  $9.34369^\circ$  E, 2481 m altitude) in North-Eastern Switzerland [Produit2021, Produit2021a]. The 124 m tall tower at the top of this mountain is known to be one of Europe's most struck by lightning, with about 100 events/year, mostly negative upwards [Romero2013, Rachidi2022]. The laser was fired continuously as soon as the weather forecast involved possible thunderstorm activity.

Out of the 16 discharges recorded on the tower during the measurement campaign (July and August 2021), 4 were guided over  $\sim 50$  m, as assessed from VHF interferometry, as well as, for one event with a cloud ceiling above the tower apex, fast imaging from two locations with viewing angles  $45^\circ$  apart (Figure 3). These four guided lightning strikes were all positive upward strikes, while all but one unguided flashes that were detected during the campaign were negative, like 90% of the strikes on the tower over the previous years. Furthermore, the unguided flashes exhibited much less branching, as well as a higher number of X-ray bursts. These results, which due to the strong contrast, are statistically significant in spite of the limited number of events, provided the first evidence of laser-guided lightning [Houard2023].

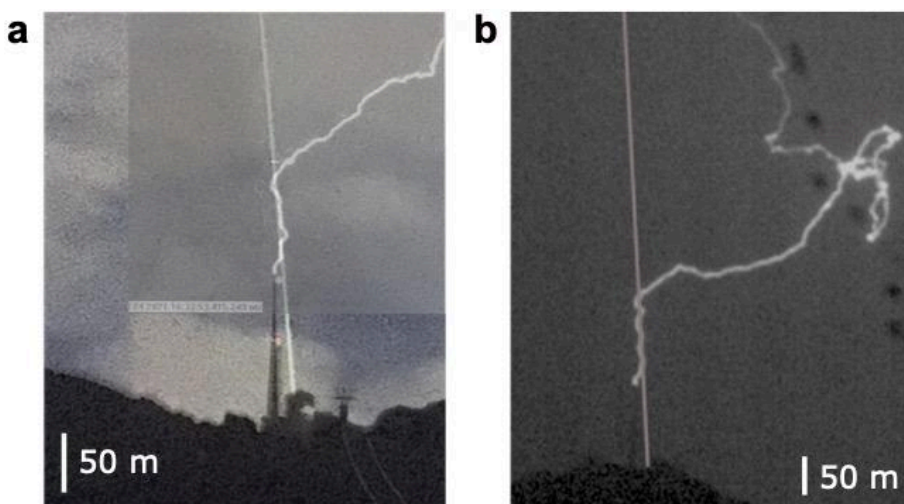


Figure 4: Image of the laser guiding lighting flash recorded by two fast cameras on Mount Säntis, Switzerland. From [Houard2023]  
CC BY 4.0



## 4. Future progress path of Laser Lightning Rod Technology

### 4.1 Relevance of Laser Lightning Rod Technology in lightning research

Studying lightning presents challenges due to its inherently random nature. Because it is impossible to predict exactly when and where lightning will strike, direct experimental data have to be gathered either from instrumented tall human-made objects such as telecommunications towers or skyscrapers that are struck by lightning several times a year, or by initiating lightning artificially. Currently, the only reliable means of artificially triggering lightning discharges is the use of small rockets trailing grounded wires that, under appropriate conditions, can initiate lightning [Rakov2009]. Both the use of tall structures and the rocket-and-wire lightning initiation technique are relatively inefficient, expensive to implement and to operate. Moreover, in the case of rocket-triggered lightning, there is a risk of danger when debris from the rocket or the Kevlar or metal wire fall to the ground.

In contrast, the use of high-power lasers for initiating and guiding lightning discharges, the Laser Lightning Rod Technology, offers several advantages over rockets. Firstly, triggering lightning with high-power lasers eliminates the need for launching small rockets and wires, thereby reducing hazards associated with falling debris. Additionally, high-power lasers afford greater control, as they can be activated and deactivated at will, and precisely steered by orienting the beam, unlike rockets where operators only control launch time and direction. For research purposes, this system could be deployed in different geographical locations and the beam could in principle be aimed, potentially in real-time, at specific locations in the cloud for lightning initiation (e.g., the most active ones), facilitating data collection for testing specific scenarios of interest.

Unlike the rocket-and-wire technique, which produces environmental pollution, the laser technique has minimal environmental impact apart from its energy consumption, manufacturing process, and disposal at the end of its lifespan. This promotes sustainable research practices that strives towards reducing the ecological footprint of research activities. In addition, implementing high-power lasers as a means to trigger lightning could potentially lead to long-term cost savings. Indeed, while the initial investment in laser technology may be substantial, the technique is likely to be more economical compared to the maintenance required for instrumented tall structures or rocket launchers, specialized rockets, and repeated rocket launches.

A further advantage of high-power lasers over small rockets is the ability to operate remotely, allowing researchers to trigger lightning from a distance.

From an experimental lightning science standpoint, laser-triggered lightning experiments would be more repeatable under similar conditions due to better control of the laser path compared to the trajectory of rockets. Furthermore, the plasma channel left behind by laser filaments causes much less disturbance to the local electric field than the highly conductive wires pulled by rockets. This repeatability is essential for data analysis and validating research findings. An indirect benefit of using high-power lasers for discharge initiation, with broader applications beyond lightning research, is that it would drive technological innovation and advancements in laser and optics technologies. Laser-triggered lightning experiments offer unique insights into lightning initiation processes, leader development, and other lightning processes, thereby enhancing our understanding of the phenomenon. This enhanced understanding contributes to advancements in atmospheric science and lightning protection strategies. Yet another strength of lightning initiation using high-power lasers is that it could be used in conjunction with tall structures to initiate upward lightning, which is of great importance for investigating the mechanisms of lightning initiation in wind turbines.

Finally, the portable and versatile nature of laser-triggering technique enables lightning research experiments to be conducted in diverse settings, including rural and urban areas, different latitudes, under different topographical conditions, and in the vicinity of critical infrastructure requiring enhanced lightning protection. Considering its described attributes, the utilization of high-power lasers for initiating and guiding lightning clearly holds the promise of transforming the landscape of lightning research. Typical potential use-cases will be reviewed in Section 5.

#### 4.2 Laser Lightning Rod Technology in the context of non-conventional lightning protection systems

The ongoing research effort reviewed in this paper focuses on the use of high-power lasers for LLRT. Note that the approach presented here is not to be confused with existing non-conventional lightning protection systems, specifically those called Early Streamer Emission (ESE) that have long been under scrutiny for their unproven claims of lightning prevention and control [Zipse1994]. Early streamer emission systems have been reviewed in several articles over the past 25 years [Mackerras1997, Chalmers1999, Uman2002, Beccera2007, Cooray2008, Beccera2008]. Note that [Uman2002] also reviewed other non-conventional lightning protection systems. A recent comparison of ESE and conventional Franklin rods, also including other non-conventional systems, is given by [Ozdemir2023].

We argue that LLRT is different from ESE in the following fundamental aspects:

1. Unlike ESE systems, whose purported operation attempts to provide a larger zone of protection, the principle of operation of the LLRT is to actively control lightning through guiding or initiation using laser-generated ionized filaments.
2. ESE systems aim to mitigate the impact of lightning strikes, whereas LLRT explores the potential to guide lightning away from sensitive areas or initiate controlled lightning for protection and scientific purposes. In that respect, LLRT is more akin to the commonly used rocket-and-wire technique for lightning initiation in the context of lightning research.
3. As demonstrated in the reviews of ESE in the literature, theoretical and experimental observations have raised doubts about the effectiveness of ESE systems. In contrast, LLRT research is driven by experimental evidence and aims to explore new possibilities in lightning control. In particular, we give an extensive review of the past research efforts of the LLRT community in Section 2.3; essentially, the ability of high repetition rate, high power lasers in guiding the discharge under real conditions was recently demonstrated in the LLR group, in a 2021 field experiment [Houard2023].

### 4.3 Open scientific questions

Real scale experiments like the recent one at the Säntis tower in Switzerland by Houard *et al.* [Houard2023] were impressive demonstrations of LLRT and clearly demonstrated the potential of ultrashort laser filaments for lightning research and application purposes. Moreover, these indications are supported by theoretical modelling of the lightning initiation threshold in terms of electric field, with and without the laser filaments [Houard2023].

However, these observations are only the beginning of the LLRT journey and further experiments are required to explore the full potential of this technology. Indeed, all real scale experiments published to date suffer from shortcomings. Therefore, beyond the very spectacular and encouraging demonstration, challenges remain ahead. Here, with the aim of encouraging the community to take the next step, we list the shortcomings of previous experiments as well as the open scientific questions to address in future LLRT experiments.

#### ***Shortcomings of previous experiments***

In the recent demonstration by Houard *et al.* [Houard2023], the guided lightning flashes were all of the positive type. While improving the statistical significance of their results, this peculiarity corresponds to an asymmetry in the laser-lightning interaction, which has been described by their modelling.

As a reminder, the atmospheric electricity sign convention is that a *positive* lightning flash is produced by a *positively* charged cloud, generating a *positive* background electric field around the tower and inducing *upward negative* leaders in the case of a tall structure. The fact that only positive strikes were guided while negative ones are much more frequent in Europe, including at the Säntis, challenges the applicability of the results to the bulk of the lightning strikes, and calls for a more efficient laser configuration.

The configuration of a tall tower on a high (2500 m) and relatively isolated mountain is pretty specific, and not representative of most use cases for applications (See Section 5) on, e.g., buildings or airports in plains or protecting of wide-area flat facilities.

Finally, the biggest shortcoming in our view is *reproducibility*: each of the previous real scale LLRT experiments [Uchida1999, Kasparian2008, Houard2023] was conducted during one measurement campaign and hence all suffered from sparse data. Uchida *et al.* reported two laser-triggered events, Kasparian *et al.* reported two thunderstorm events with statistical significant laser effect and Houard *et al.* reported 16 lightning strikes, 4 of which were laser guided over ~50 m, over the course of their single experimental campaign (July and August 2021). No ulterior replication of their respective experiments were published.

Since lightning is intrinsic of random nature, a permanent LLRT station would be very valuable to advance lightning research, and to investigate in greater detail the physics and the use-case applicability of LLRT technology by providing long data series in a wide range of conditions, including wind, cloud altitude, season, etc.

	Laser filament	Streamer	Leader
Electron density	$10^{15} - 10^{17} \text{ cm}^{-3}$ [Th��berge2006]	$10^{14} \text{ cm}^{-3}$ [Bazelyan2000]	$10^{13} \text{ cm}^{-3}$ [Popov2003]
Electron temperature	0.5 - 1 eV [Bodrov2013]	2 eV [DaSilva2013]	2 eV [DaSilva2013]
Air temperature	400-1'000 K [Point2015]	1'500-2'000 K . Transition to leader around 5000 K [Popov2003]	> 5 000 K [Bazelyan2000, Popov2003]  ~15'000 K / >20'000 K (stepped / dart leader) [Chang2017]
Depleted air density ( $\rho/\rho_0$ )	0.5 - 0.99 [Cheng2013, Walch2021]	0.9 [Woolsey1986]	0.1 [Popov2003]
Propagation velocity	$\sim c$ ( $2.99 \times 10^8 \text{ m.s}^{-1}$ )	Typically between $10^5$ $\text{m.s}^{-1}$ and $10^6 \text{ m.s}^{-1}$ [Nijdam2020]	$\sim 10^5 \text{ m.s}^{-1}$ [Bazelyan2000]

Table 1. Comparison of typical characteristics of ultrashort laser filaments, streamers, and leaders generated in atmospheric air.

### ***Physical mechanism of laser-assisted lightning guiding and initiation***

The physical effect of the laser filament on the lightning discharge propagation and initiation and their complex interplay remains unclear, since three effects concurrently play a role:

- The free electrons generated in the filament increase the channel conductivity and are responsible for the suppression of natural spark observed with a kHz laser [Schubert2015]. But their very short lifetime ( $\sim \text{ns}$  to  $\mu\text{s}$  lifetime [Walch2023]) and their relatively low electron density (typically  $< 10^{13} \text{ cm}^{-3}$  after  $\sim 1 \text{ us}$  [Tzortzakis2000]) does not allow by itself to explain the guiding of long spark discharges in laboratory with lasers working at 10 Hz, or in lightning experiments [Tzortzakis2001, Forestier2012].
- The long-lived ( $\sim \mu\text{s}$ -range) negative ions created by electron attachment on  $\text{O}_2$  molecules can also accelerate the leader development [Raizer2000] but this effect has never been quantified or demonstrated experimentally except in cm scale discharges [Walch2021]. Furthermore, its understanding and modelling is highly dependent on the external electric field.

- The air density depletion induced by the energy deposition in the filament creates a preferable path for the free streamers and leaders [Tzortzakis2001, Gordon2003] and hence can be beneficial for electric arc guiding [Saum1972], as described by the Paschen's law [Tirumala2010]. In the long-lived low density channel formed by the filament, the breakdown voltage is proportional to the gas density, down to  $\sim 0.1$  atm. Depending on the laser intensity a permanent reduction by a few % [Walch2021, Löscher2023], and transiently up to 10% to 90%, can be achieved [Tzortzakis2001, Clerici2015].

These processes are of course active simultaneously and can even act in synergy. In particular, releasing free electrons in an air density-depleted channel provide both free charges and favorable conditions for their acceleration. As detailed in Table 1, the conditions (temperature, free electron density, etc.) in plasma filaments are close to those of streamers [Bazelyan2000, Popov2003]. Therefore, it is not surprising that the limited understanding of the laser-lightning interaction is deeply related to the lack of comprehensive modelling of lightning covering all scales from microphysics of, e.g., aerosol particle electrification to the km scale of the thunderclouds and of the lightning discharges themselves. The same applies to time scales, where quasi-static processes like the slow rise of the macroscopic electric field are interconnected with processes like the stepped leader propagation and the lightning discharge itself, requiring a high amount of both conceptual work and computational power.

In that regard, though impressive and insightful, the use of a rather simplistic empirical model to interpret the results of [Houard2023] is quite representative of the state of the art of the limited conceptual understanding of the interplay between lightning and laser filaments.

Another major interrogation resides in the ability of the laser filament to **trigger lightning** or to **initiate leaders**. While the ability of near-IR filaments to guide lightning leaders over tens of meters has been clearly demonstrated in [Houard2023], initiating lightning is more difficult to obtain and to demonstrate experimentally. Kasparian *et al.* experiments [Kasparian2008] gave interesting insights in that regard and further experiments could be done by either connecting an ascending leader with a descending one in conditions where the ambient field does not allow them to connect, or by initiating an upward leader like a rocket would do [Rakov2005]. The first case would correspond to conditions in the Săntis experiment, where many positive flashes were observed in the presence of the laser. Inducing an upward leader with the filament would require the generation of a highly conductive channel during several microseconds to allow the polarization of the channel in the presence of the external field [Bazelyan2000]. This appears to be difficult to realize with a single ultrashort pulse. Solutions have been proposed based on the heating of the filament by a second energetic pulse [Scheller2014, Papeer2014] but the required energy of  $\sim 15$  J/m and the use of multiple lasers make it difficult to implement on real scale with a sufficient repetition rate.

### ***Optimal laser parameters and geometries***

Though impressive, the experiment by Houard *et al.* did not explore all the possibilities given by their LLRT schemes. Besides their scientific interest, exploring various laser configurations is crucial for optimising applications. Indeed, we identify several parameters to explore in future LLRT experiments:

- The parameters of the laser filaments (air density, ionization, temperature, lifetime, diameter...) depend directly on the **laser wavelength**. While a UV laser would be more efficient to ionize air, generating denser plasma channels [Rambo2001, Rastegari2021], an IR laser can better propagate in the air and produce very long and wide mono-filaments containing energy up to the Joule level [Tochitsky2019]. These options are promising, but the only available technologies allowing routinely TW peak power with a high repetition rate are working in the near-IR range, at 800 nm or 1030 nm. It explains why most of the experiments of meter-scale laser guiding were made at these wavelengths. Shorter wavelengths therefore require frequency conversion, hence the use of nonlinear crystals that imply slightly more complex setup and careful alignment.
- It has been suggested to use **bi- and tri-colour schemes** using the second and the third harmonic of a near-IR laser [Produit2019]. Though the same authors report the production of SHG and THG with the same laser [Andral2022], this technique was not used in the experimental campaign in Sântis due to time constraints [Houard2023]. As indicated by [Produit2021, Produit2019, Schubert2017] multi-color schemes might provide a boost to the efficiency of existing LLRT schemes.
- The **laser repetition rate** is an important aspect in the choice of the laser for two main reasons: First, using a laser with a repetition rate higher than 1 kHz has been shown to increase the guiding effect of the filament on small discharges [Walch2021, Löscher2023] and to allow the formation of a permanent low density channel [Vidal2000, Lahav2014, Jhajj2014, Walch2021, Cheng2013, Jhajj2013, Walch2021, Isaacs2022]. Second, the timescale for the development of a lightning flash is typically in the millisecond timescale. A kHz repetition rate, at least, is therefore necessary to maximize the temporal interaction between the laser and the lightning precursors, since their appearance remains largely unpredictable.
- The **filamentation length** is obviously an important parameter. However, the need to use focused laser filaments seems to be needed for LLRT [Walch2023]. Focusing inherently limits the filament length [Wille2002]. Schemes to enhance the laser filament length include the use of a telescope with an actively shifting focus, multiple beams focused at different distances [Papeer2015, Polynkin2017] or pulse shaping with deformable mirrors or diffractive waveplates. Comparative works gauging their applicability for LLRT remains to be done.
- The **location of the filamenting region** is another obvious important parameter. Indeed, Houard *et al.* reported in their model that the distance between the tip of the tower and the filamentation region was of critical importance for lightning initiation and development. Using beam steering technique to induce angle movement but also longitudinal focus shift (for instance by geometrical focus change or chirping), could be interesting to compare dynamic schemes LLRT to static LLRT schemes.
- **Spatial and Temporal shaping** of the laser filamentation like pulse trains [Liu2012, Wolf2018] and quantum wake effect [Schroeder2020] as well as **spatial shaping** like self-healing Airy laser modes [Zou2023] might be of interest for LLRT and remain for now barely explored at real scale.

### ***Related physical mechanisms***

It was shown that the shockwaves initiated by the energy deposition in laser filaments are able to opto-mechanically push water droplets. Laser filamentation at kHz repetition rate can thus keep such particles out of the beam at a rate sufficient to compensate for their drift back into the laser path. Hence, it is able to drill a hole through clouds, thanks to the radial pressure wave generated by the filament [DelaCruz2015, Schimmel2018, Schroeder2022, Schroeder2023]. This interaction and the scattering due to the presence of the water droplets on the laser path should also modify the filamentation process. One could imagine that this could have a significant effect in the microphysics of cloud electrification when laser filament propagates through thunderstorm clouds. Though there is a renewed interest in long-range filamentation physics [Isaacs2022], these physical processes remain relatively unexplored and might be of great interest for LLRT. An important discovery of the field measurements is that laser guiding of lightning [Houard2023] was also observed in fog conditions by the VHF interferometer, and over the same distance as in a clear atmosphere. This is a strong hint that filamentation-induced cloud clearing occurred at atmospheric scale, as already characterized in the laboratory [DelaCruz2015, Schimmel2018, Schroeder2022, Schroeder2023].

#### **4.4 Locations for future Laser Lightning Rod Technology experiments**

As mentioned above, a permanent station equipped with LLRT capabilities would be highly desirable from a scientific but also from a use-case assessing point of view.

The site(s) selected to conduct lightning studies should ideally allow for testing the influence of a spectrum of parameters as wide as possible, including, for instance, the effect of the local ground flash density (i.e., the average number of lightning flashes per square kilometer and per year), the field topography, the altitude, the latitude, the season, the type of soil, the presence or absence of a tall structure, etc. Since no single site allows to test all those conditions (as some of them are geographical location dependent), at least two approaches can be utilized:

- The laser system could be installed on a permanent or long-term basis at an appropriate location with a testable subset of conditions relevant for lightning research, or
- a mobile test setup could be used to investigate the lightning protection capabilities at different locations in the vicinity of sensitive installations or relevant lightning active locations.

Another criterion for the choice of the experimental test location is the availability of power supply and other services, infrastructure and/or logistics required to set up and run experimental campaigns with a heavy and sensitive device like a high-power laser and its need for a clean and controlled operating environment. Whatever the approach, it may still be desirable, if possible, to conduct the experiment at sites whose topography includes mountains or high towers, since this will increase the lightning incidence including the number of upward lightning flashes. In the following section we have listed possible sites around the world presenting a high lightning activity and we assess them according to the criteria above. Moreover, we also review the relevant available laser systems and discuss the criteria for their applicability for LLRT.

### ***Tall structures and dedicated lightning and atmospheric facilities***

The location where LLRT integration would be most straightforward is in already existing facilities dedicated to lightning studies. In Table 2 and Table 3, we tabulate and discuss a curated list of facilities, which to our knowledge would benefit greatly from LLRT and where we envision reasonably a possible integration of LLRT.



Table 2. Curated list (in no particular order) of instrumented towers dedicated to lightning research which would be suitable for Laser Lightning Rod Technology (LLRT) experiments. Active sites by the time of writing have their name bolded.

Infrastructure name	Location (name, coordinates)	Geographical characteristics (altitude, elevation over neighborhood)	Lightning characteristics (spatial density, seasonality, polarity)	Existing equipment (laser facility, diagnostics, access)	Suitability for LLRT integration
<b>Säntis tower</b>	47.24944°N, 9.34369°E, Säntis, Switzerland	124 m tall tower at the top of the Säntis mountain at an altitude of 2502 m above sea level (ASL) near Urnäsch, Switzerland	On average, about 100 flashes/year strike the tower annually [Romero2013, Rachidi2022]. About 90% of the flashes are negative and almost 100% of the flashes are of the upward type.  Ground Flash Density in the region: about 3 flashes/km <sup>2</sup> /year [Manoochehrnia2008]	Multiple lightning measurement instruments located at different stations, as described in [Rachidi2022]. Ultrashort laser was installed in 2021 but is not there anymore	Already proven its suitability for LLRT, see [Produit2021, Produit2021a, Houard2023]. However, the laser facility was dismantled from the Säntis tower. But a new installation with permanence in sight could be planned. Access only via cable car
Monte San Salvatore tower	45.97673°N, 8.94621°E, Monte San Salvatore, Switzerland	70 m tall TV tower at the top of Mount San Salvatore at an altitude of 912 m ASL near Lugano, Switzerland	Ground flash density in the Lugano Lake region : 3.8 flashes/km <sup>2</sup> /year [Smorgonskiy2013]	No longer used for lightning research. The pioneering experimental characterization of lightning performed by the late Prof. Berger and co-workers was carried out here [Berger1967]	Easy access (road and funicular). Already proven its suitability for lightning studies but may be lacking shelter and power access for lasers

<b>Gaisberg tower</b>	47.805°N, 13.112°E, Mount Gaisberg, Salzburg, Austria	100 m tower located on the top of a 1287 m mountain (Mount Gaisberg) near Salzburg, Austria. The mountain top is approximately 800 m ASL above the city of Salzburg	The tower is struck by lightning about 60 times a year on average, with very large year-to-year variations. Almost 100% of the lightning to the Gaisberg tower is of the negative upward type. Ground flash density in the region of Salzburg: 3.8 flashes/km <sup>2</sup> /year [Smorgonskiy2013]	Multiple lightning diagnostics as described in [Diendorfer2009]	Very similar to the Sântis tower location in terms of lightning statistics. Hence LLRT implementation can be envisioned. Has road access
Fukui chimney	36.2109°N, 136.1346°E, Mikuni-chō (三国町), Fukui (福井県) Prefecture, Japan	200 m high chimney of the Mikuni cooperative power station located at the Fukui (Mikuni) Thermal Power Station near Fukui, Japan	Experimental site selected to maximise the possibility of being hit by Japanese winter thunderstorms, which are prone for lightning [Miki2005]	Multiple lightning diagnostics as described in [Miki2005]	Close to Mikuni-chō and has easy road access easing logistics. This site was already used as an experimental site for lightning research [Miki2005], hence implementation of permanent LLRT capabilities can be envisioned
Mihama tower	35.62081°N, 135.90013°E Mihama-chō (美浜町), Fukui (福井県) Prefecture, Japan	Lightning tower on the top of a ~180 m hill near the coast of the Wakasa bay (若狭湾), Japan	Experimental site selected to maximise the possibility of being hit by Japanese winter thunderstorms, which are prone for lightning [Uchida1999]	Multiple lightning diagnostics as described in [Uchida1999] were installed but are now dismantled	Close to Mihama-chō and has easy road access easing logistics. This site was already used as an experimental site for [Uchida1999], hence implementation of permanent LLRT capabilities can be envisioned

<b>Peissenberg tower</b>	47.80113°N, 11.02453°E, near Peißenberg, Bavaria, Germany	160 m tower on top of the Hoher Peißenberg ridge at about 950 m located near Munich, Germany	118 lightning strikes were recorded on the tower between 1992 and 1998. Nearly all lightning strikes to the tower are of negative polarity (negative charged cloud) [Fuchs1998].  Ground Flash Density in Southern Germany: 2.8 flashes/km <sup>2</sup> /year [Finke1996]	Multiple lightning diagnostics as described in [Fuchs1998]	Very similar to the Sântis tower location in terms of lightning statistics. Hence, implementation of permanent LLRT capabilities can be envisioned. Has road access
<b>Shenzhen Meteorological Gradient Tower (SZMGT)</b>	Shí yán (石岩) Residential District, Bǎo'ān Qū (宝安区), north of Shēnzhèn (深圳), People's Republic of China	356 m tall tower for meteorological studies north of Shēnzhèn (深圳)	Total flash density : >15 flashes/km <sup>2</sup> /year [Qiu2015]	Lightning observation site located 440 m away from the tower base [Gao2020]	This location is already equipped for meteorological studies and already has some basic lightning observation capabilities. Hence, implementation of permanent LLRT capabilities can be envisioned, subject to adding some lightning detection capabilities
<b>Sentech Tower (Brixton tower)</b>	26.19245°S, 28.00687°E, Johannesburg, South Africa	250 m tall tower in Johannesburg	Between 2009-2013, 66 flashes have been photographed attaching to the Brixton tower [Hunt2014]  Ground Flash Density in Johannesburg: 11-18 flashes/km <sup>2</sup> /year [Smit2023]	Multiple lightning diagnostics maintained by the Johannesburg Lightning Research Laboratory and described in [Hunt2014, Smit2023]	Implementation of permanent LLRT capabilities can be envisioned as this tower is already used for lightning research purposes. This location has a road access

<b>Morro do Cachimbo</b>	20.000°S, 43.580°W, Belo Horizonte, Minas Gerais, Brazil	60 m tall tower, 1430 m ASL	Between 2010 and 2014, 61 flashes were recorded, including 9 upward flashes [Guimarães2014]  Ground Flash Density in Brazil: 7 flashes/km <sup>2</sup> /year [Pinto2008]	Current measurements, high-speed camera [Visacro2004, Guimarães2014]	Implementation of permanent LLRT capabilities can be envisioned as this tower is already used for lightning research purposes. This location has road access
<b>Eagle Nest</b>	42.321° N, 1.892° E, Catalonia, Spain	25 m tall tower, located, 2537 m ASL	Ground Flash Density in the region: 1.8 flashes/km <sup>2</sup> /year [Shindo2015]	Current, High speed camera, two high energy detectors, a E-field antenna and a VHF antenna [Montanyà2012]	Implementation of permanent LLRT capabilities can be envisioned as this tower is already used for lightning research purposes. A cable car arrives very close to the site, which is also accessible by car except in snow conditions
<b>Tokyo Skytree</b>	35.71004°N, 139.8107°E, Tōkyō (東京), Kantō-chihō (関東地方), Japan	634 m tall freestanding broadcasting tower, 37 m ASL	35 flashes recorded in 2012 and 2013 (11 upward flashes) [Shindo2014]  Ground Flash Density in Tokyo: 2 flashes/km <sup>2</sup> /year [Miki2012]	Lightning current, high-speed camera, electric fields [Miki2012]	Implementation of permanent LLRT capabilities can be envisioned as this tower is already used for lightning research purposes. The dense city area location might complicate logistical ease and eye safety for LLRT implementation
<b>CN Tower</b>	43.6426°N, 79.3871°W Toronto, Ontario, Canada	553 m tall telecommunications tower, 76 m ASL	During the 1991 lightning season, the tower was hit with 72 flashes, 24 of which occurred within 100 min during the early morning of July 7. [Hussein2004]  Ground Flash Density in Toronto: 2 flashes/km <sup>2</sup> /year [Hussein2010]	Lightning current measurements at two different heights (509 m and 474 m), electromagnetic fields at different distances, two high-speed cameras [Hussein2004, Shindo2015]	Implementation of permanent LLRT capabilities can be envisioned as this tower was already used for lightning research purposes. The dense city area location might complicate logistical ease and eye safety for LLRT implementation

Empire State Building	40.7484° N, 73.9857°W New York, New York State, United States of America	410 m tall building, 10 m ASL	Annual number of flashes to the structure: 22-6 [Shindo2015]  Ground Flash Density in the region: 2.9 flashes/km <sup>2</sup> /year [Shindo2015]	Lightning current and photographic observations were obtained for more than a decade from 1935 to 1949 [Hagenguth1952]  Site of the first characterization of upward lightning [McEachron1939, McEachron1941, Hagenguth1952]	Implementation of permanent LLRT capabilities can be envisioned as this tower was already used for lightning research purposes. The dense city area location might complicate logistical ease and eye safety for LLRT implementation
St. Crischora	47.571944°N, 7.687222°E Bettingen, Basel-Stadt, Switzerland	250 m tall communications tower on Mount St. Chrischora, 493 m ASL	Relatively low incidence: about 10 flashes per year [Manoochehrnia2008].  Ground Flash Density in the region: about 2 flashes/km <sup>2</sup> /year [Manoochehrnia2008]	Two current loop antennas at 248 and at 175 m, and an additional current probe at the top	Implementation of permanent LLRT capabilities can be envisioned as both towers were used for lightning research purposes. Has road access but is situated in the middle of a village complicating an eye safe implementation.
Monte Sasso di Pale, Monte Orsa	Sasso di Pale, near Foligno, central Italy and Monte Orsa, near Varese, northern Italy	Two TV towers respectively at the top of Monte Sasso de Pale (980 ASL) and Monte Orsa (998 ASL)	Most of the flashes were of upward type [Garbagnati1974] [Garbagnati1982]  Ground Flash Density in northern Italy: about 4 flashes/km <sup>2</sup> /year [Bernardi2004]	Lightning current and photographic observations	Implementation of permanent LLRT capabilities can be envisioned as both towers were already used for lightning research purposes. Monte Orsa has a road access reaching to the top.

Eriksson Tower	Pretoria, South Africa	60 m tall tower on a hill 80-m above surrounding terrain, 1400 m ASL	<p>More than 50% of the measured flashes are downward negative. [Eriksson1978]</p> <p>Ground Flash Density in Pretoria: 7 flashes/km<sup>2</sup>/year [Eriksson1979]</p>	Rogowski coil at the bottom of the tower	Implementation of permanent LLRT capabilities can be envisioned as this tower was already used for lightning research purposes. The dense city area location might complicate logistical ease and eye safety for LLRT implementation
Ostankino Tower	55.8197° N, 37.6117° E Moscow, Russia	540 m tall telecommunications tower in a flat region, 124 m ASL	<p>A total of 90 upward flashes in a span of two years of observation. [Gorin1984]</p> <p>Annual number of flashes to the structure: 30 [Shindo2015]</p>	<p>Lightning current installed at three different locations (533 m, 272 m and 47 m. Two optical cameras were installed at 385 m and 550 m from the tower. [Gorin1975, Gorin1977, Gorin1984]</p>	Implementation of permanent LLRT capabilities can be envisioned as this tower was already used for lightning research purposes. The dense city area location might complicate logistical ease and eye safety for LLRT implementation
Euskalmet Tower (M)	42.766° N, 2.538° W Basque Country, Spain.	50-m tall tower on top of the Kapildui Mountain, 1169 m ASL	Severe weather conditions are usual as described in [López2012]	The Euskalmet tower lightning initiation was monitored using the meteorological and lightning characteristics inferred from these data, as described in [López2012].	The tower is not directly instrumented for lightning research and some upgrades would be necessary to make it a proper lightning research station. Nevertheless, implementation of permanent LLRT capabilities can be envisioned. Logistically complicated since there is no direct road access to the top.

Table 3. Curated list of launch pads for lightning triggering rockets and other sites which would be suitable for Laser Lightning Rod Technology (LLRT) experiments. Active sites have their name bolded.

Infrastructure name	Location (name, coordinates)	Geographical characteristics (altitude, elevation over neighborhood)	Lightning characteristics (spatial density, seasonality, polarity)	Existing equipment (laser facility, diagnostics, access)	Suitability for LLRT integration
<b>Langmuir laboratory</b>	South Baldy, New Mexico USA	133.5 km <sup>2</sup> (33000 acres) wide research area (Langmuir Research Site) in the middle of the Cibola National Forest located at an elevation of 3240 m (10630 ft) in the Magdalena Mountains near South Baldy, New Mexico USA	Ground flash density : up to 0.55 flashes/km <sup>2</sup> /year [Fosdick1995]	Multiple lightning diagnostics as balloons, rockets, Doppler radar, aircraft, lighting instruments and ground-based electric field mills [LangmuirWebsite].	Already proven its suitability for LLRT see [Schubert1979, Kasparian2008]. No tower or specific lightning hotspot. Would require a mobile LLRT facility like the Teramobile experiment [Kasparian2008].
Lightning Center for Lightning Research and Testing (ICLRT) of the University of Florida	Camp blandig near Starke, Florida, USA	Rocket-triggered lightning centre over mostly flat ground.	10 to 12 flashes/km <sup>2</sup> /year [Hodanish1997]	Fully equipped rocket triggering facility but facilities have been closed since 2017.	Studies of lightning triggering with rockets have been performed from 1994 on [Rakov2005] but the facility has been closed since 2017. Hence, LLRT implementation can be envisioned. Has road access.
St Privat d'Allier	St Privat d'Allier, France	Mounted 24m tower over a flat region at 1100 m above sea level	Selected location fulfilling certain security criterions (at least 500 m from any dwelling or road or power and telephone lines) and situated on a plateau where the local keraunic level is high (> 30 thunderstorm days/year)	Fully equipped rocket triggering facility described in [Fieux1978], closed in 1993.	This location already showed suitability for rocket-triggering capabilities and could be potentially interesting for LLRT applications.

<b>VEGA and SOYUZ rocket launch pads</b>	5.23°N, 52.76°W, Centre spatial guyanais (CSG), northwest of Kourou, French Guiana, France	Rocket launch pad on flat ground with high buildings and infrastructure	Total lightning density: 3.3 flashes/km <sup>2</sup> /year [VaisalaInteractiveMap]	Tested for lightning strikes, hence some lightning recognition capabilities [Bachelier2012, Issac2012].	Location might be interesting due to logistical ease but launch pad activities might hinder smooth LLRT activities.
<b>Mobile Ultrafast High-Energy Laser Facility (MU-HELFF)</b>	Townes Institute Science and Technology Experimentation Facility (TISTEF), Merritt Island, Florida, USA		7 to 9 flashes/km <sup>2</sup> /year [Roeder2017].  The region over the John F. Kennedy Space Center is well studied in terms of lightning characteristics see for instance [Fisher1993, Willett1999, Roeder2017]	Ultrashort laser dedicated for outdoor physics.  Ultrashort laser dedicated to atmospheric laser propagation studies.	Various rocket-triggered lightning experiments have already been conducted at the John F. Kennedy Space Center [Fisher1993, Willett1999] meaning that lightning studies capabilities are already onsite. Moreover, the MU-HELFF facility [Thul2021, Richardson2020] could be adapted to host a LLRT capable laser.
<b>GCOELD rocket-triggering facility</b> also named <b>Guangzhou Field Experiment Site for Lightning Research and Testing (GFESLRT)</b>	North of Cónguà (从化), Guǎngzhōu (广州) province, People's Republic of China	Rocket triggering facility on flat ground	77 thunderstorm days per year on average in Guǎngzhōu (广州) province [Zhang2014]. Total lightning density: 34.4 flashes/km <sup>2</sup> /year [VaisalaInteractiveMap].	Rocket-triggering capabilities [Zhang2014, Zhang2016, Qie2019, Wang2022] and many lightning research equipment.	Studies of lightning triggering with rockets have been performed here. Hence, a LLRT implementation can be envisioned.
<b>SHATLE rocket-triggering facility</b>	37.7°N, 117.8°E, north of Bīnzhōu (滨州), Shandong (山东) province, People's Republic of China	Rocket triggering facility on flat ground	50 thunderstorm days per year on average near Bīnzhōu (滨州) [Qie2009].  Total lightning density: 11.7 flashes/km <sup>2</sup> /year [VaisalaInteractiveMap].	Rocket-triggering capabilities [Qie2009, Qie2017, Qie2019] and many lightning research equipment.	Studies of lightning triggering with rockets have been performed here. Hence, a LLRT implementation can be envisioned. Has road access.



Cachoeira Paulista test facility	22.683°S, 44.983°W, near Cachoeira Paulista, São Paulo, Brazil	625 m altitude. 120 m x 70 m flat area of a hilltop. This location inside the meteorological observation area of the Brazilian National Institute for Space Research (Instituto Nacional de Pesquisas Espaciais - INPE) near Cachoeira Paulista, São Paulo, Brazil	<p>Keraunic level: 80 thunderstorm days/year [Saba2005]</p> <p>Total lightning density: 19.8 flashes/km<sup>2</sup>/year [VaisalaInteractiveMap].</p>	Fully equipped rocket triggering facility described in [Saba2005] as well as various meteorological equipment on site.	Dedicated natural and triggered lightning test facility as described in [Saba2005]. Lightning triggering tests performed in 1998-2003. The area already hosts various meteorological measuring equipment. Hence, a LLRT implementation can be envisioned.
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## Lightning hotspots

The second strategy to augment LLRT capabilities would be to focus on mobile and transportable laser systems, in the same vein as the Teramobile project [Wille2002], and use it along with lightning measurement diagnostics in lightning prone regions.

Lightning hotspots on Earth, as reported in Figure 5, could then be explored more thoroughly.

This way, previously inaccessible lightning prone locations could become more reachable for lightning studies. The main challenge of this approach though is the logistics. Even with a transportable laser system like the Teramobile laser [Wille2002, Kasparian2008] or semi-transportable system like the European LLR laser system [Produit2021, Produit2021a, Houard2023], logistical challenges like power delivery and transportation have still to be overcome for successful experimental campaign as many of the lightning prone regions are situated in remote locations.

In Table 4, we tabulate and discuss a curated list of lightning hotspots on Earth, where we envision reasonably a possible integration of mobile LLRT for fundamental and applied lightning research purposes.

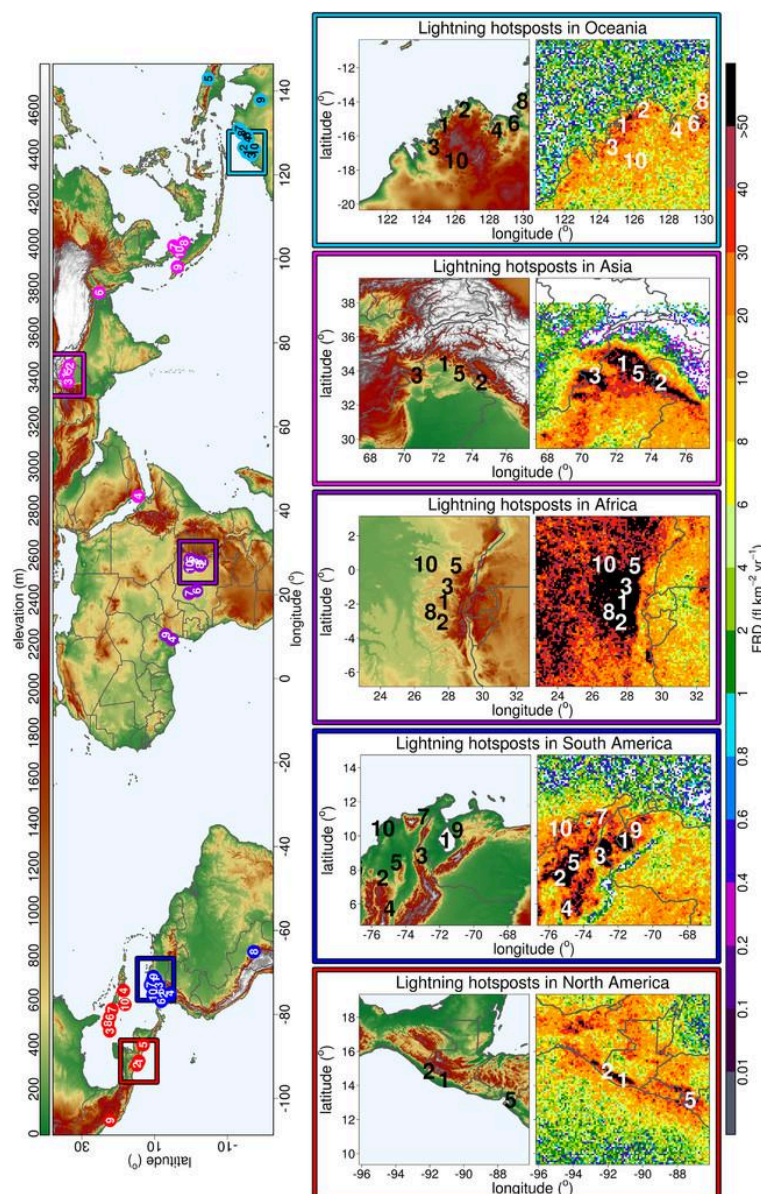


Figure 5: Top lightning hotspots per major continental landmasses. Adapted from [Albrecht2016]. © American Meteorological Society. Used with permission.

Table 4: Curated list lightning hotspot promising for LLRT, ordered by descending total lightning density.

Location (name, coordinates)	Lightning characteristics	Accessibility	Suitability for LLRT integration
Relámpago del Catatumbo (9.75°N, 71.65°W)	First lightning hotspot on Earth. Total lightning density of 232.52 flashes/km <sup>2</sup> /year [Albrecht2016].	This lightning hotspot region is easily accessible due to its proximity to the second-largest city in Venezuela, Maracaibo. The central part of the hotspot however is situated approximately in the center of the lake of Maracaibo, potentially augmenting the logistical burden of experimentation.	Due to the predictable nature of the <i>Relámpago del Catatumbo</i> phenomenon [Muñoz2016], it could be an interesting location for mobile LLRT. The proximity of the La Chinita International Airport ensures good quality weather forecasts as well as natural candidate location for LLRT operationalization experiments, tailored e.g., to diminish operational shutdown of the international airport due to lightning, as suggested by [Arnold2023] and described later in subsection 5.2. Moreover, the proximity of various scientific universities (like for instance University of Zulia ( <a href="http://www.luz.edu.ve">http://www.luz.edu.ve</a> ) in Maracaibo or Universidad de Los Andes ( <a href="http://www.ula.ve/">http://www.ula.ve/</a> ) in Merida) could play a key role to coordinate all the actors and drive the scientific relevancy of these proposed deployed LLRT experiments.
Kabare (1.85°S, 27.75°E)	Second lightning hotspot on Earth. Total lightning density of 205.31 flashes/km <sup>2</sup> /year [Albrecht2016].	Situated ~150 km north-west of the city of Bukavu, Sud-Kivu, Democratic Republic of Congo (DRC) with no direct road access.	The proximity of the city of Bukavu, Sud-Kivu, Democratic Republic of Congo (DRC) could serve as a logistical centrepiece. Moreover, this city is also situated ~150 km from the third lightning hotspot on Earth (Kampene) and hence Bukavu could become an interesting lightning research convergence point. For instance, there is recent interest in the literature investigating more in depth lightning activities in this region [KaserekaKigotsi2018, KaserekaKigotsi2022, Emmanuel2022]. At time of article writing though, a conflict in neighbouring North Kivu (Nord-Kivu) province could, in the short-term, constrain the accessibility of the region.
Kampene (3.05°S, 27.65°E)	Third lightning hotspot on Earth. Total lightning density of 176.71 flashes/km <sup>2</sup> /year [Albrecht2016].	Situated ~150 km away from the city of Bukavu, Sud-Kivu, Democratic Republic of Congo (DRC) with no direct road access.	The proximity of the city of Bukavu, Sud-Kivu, Democratic Republic of Congo (DRC) could serve as a logistical centrepiece. Moreover, this city is also situated ~150 km from the second lightning hotspot on Earth (Kabare) and hence Bukavu could become an interesting lightning research convergence point. For instance, there is recent interest in the literature investigating more in depth lightning activities in this region [KaserekaKigotsi2018, KaserekaKigotsi2022, Emmanuel2022]. At time of article writing though, a conflict in neighbouring North Kivu (Nord-Kivu) province could, in the short-term, constrain the accessibility of the region.
Cáceres (7.55°N, 75.35°W)	Fourth lightning hotspot on Earth. Total lightning density of 172.29 flashes/km <sup>2</sup> /year [Albrecht2016].	Situated ~150 km away from Medellín, Antioquia, Colombia, which is the second-largest city in Colombia and only ~3 km away from the city of Cáceres, Antioquia, Colombia.	The proximity of the city of Cáceres, Antioquia, Colombia (30'000 inhabitants) makes this lightning hotspot very interesting for a LLRT implementation. Indeed, the proximity ensures logistical ease and since the region is not very dense this could also help for an eye-safe implementation.

Singapore (1.36 °N, 103.78°E)	Total lightning density of 127.6 flashes/km <sup>2</sup> /year [VaisalaInteractiveMap]	Situated in the city-state of Singapore.	Singapore is a good candidate for LLRT since an unpublished LLRT experiment has been conducted by one of the authors (A. Houard) in 2011. This location was selected due to its high lightning activity as well as proximity to a big city infrastructure. Moreover, the exact location chosen ensured an eye-safe operation despite the dense area around. The proximity of the La Chinita International Airport ensures good quality weather forecasts as well as natural candidate location for LLRT operationalization experiments, tailored e.g. to diminish operational shutdown of the international airport due to lightning, as suggested by [Arnold2023] and described later in subsection 5.2. Moreover, the proximity of various scientific universities (like for instance National University of Singapore ( <a href="https://nus.edu.sg/">https://nus.edu.sg/</a> ) or Nanyang Technological University ( <a href="https://www.ntu.edu.sg/">https://www.ntu.edu.sg/</a> ) could play a key role to coordinate all the actors and drive the scientific relevancy of these proposed deployed LLRT experiments.
Rodas (22.35°N, 80.65°W)	Total lightning density of 98.22 flashes/km <sup>2</sup> /year [Albrecht2016].	Situated ~30 km from Cienfuegos, provincia de Cienfuegos, Cuba,	This is situated at ~30 km from Cienfuegos, provincia de Cienfuegos, Cuba, which might be of interest for LLRT. Indeed, Cienfuegos is a relatively big city (180'000 inhabitants) and possesses good infrastructure and at the same time the area around is not very densely populated, which would allow for an eye-safe LLRT implementation. Moreover the proximity of an international airport, the Aeropuerto Internacional Jaime González ensures good quality weather forecasts as well as natural candidate location for LLRT operationalization experiments, tailored e.g., to diminish operational shutdown of the international airport due to lightning, as suggested by [Arnold2023] and described later in subsection 5.2.
Kuala Lumpur (3.15°N, 101.65°E)	Total lightning density of 93.96 flashes/km <sup>2</sup> /year [Albrecht2016].	Situated just 5km from the capital city of Malaysia, logistical accessibility is ensured. Nevertheless, the dense city area location might complicate eye safety for LLRT implementation.	We expect this hotspot to be highly interesting for LLRT. Indeed, it is reported that more than 70% of power outages are due to lightning in Malaysia [Leal2021]. Hence, there is a great interest in this region to mitigate lightning induced damages. The proximity of Kuala Lumpur International Airport ensures good quality weather forecasts as well as natural candidate location for LLRT operationalization experiments, tailored e.g. to diminish operational shutdown of the international airport due to lightning, as suggested by [Arnold2023] and described later in subsection 5.2. Moreover, the Centre for Electromagnetic and Lightning Protection Research (CELP) at the nearby University of Putra Malaysia could play a key role to coordinate all the actors and drive the scientific relevancy of these proposed deployed LLRT experiments.
Derby (15.35°S, 125.35°E)	Total lightning density of 92.15 flashes/km <sup>2</sup> /year [Albrecht2016].	Situated at ~300 km from Derby, Western Australia, Australia	The Kimberley region of Western Australia, especially the area west of Kununurra and east of Derby is host to most of Oceania's lightning hotspots. Since the region is sparsely inhabited it could be interesting in terms of eye safety but challenging in terms of logistics for an LLRT implementation.

## 4.5 Relevant laser systems

Regenerative thin-disk amplifier (RTDA) geometry was one of the main drivers of LLRT development. Here, we shortly describe the required laser specification needed for a LLRT capable laser system. Moreover, we list in Table 5 and in Figure 6 laser systems already used for LLRT experiments or which fulfill these criteria .

Ideally, a LLRT-capable laser system should be able to produce multiple filamentation to ensure a sufficient amount of generated free charges. This requires a peak power well above the critical power  $P_{cr}$ , where  $P_{cr} \sim 3$  GW at 800 nm [Couairon2007, Bergé2007] and  $P_{cr} \sim 5.3$  GW at 1030 nm [Houard2016]. Realistically, we estimate that a LLRT-capable laser should have at least the capability of producing tens of filaments and hence have a peak power above  $\sim 200$  GW, which was indeed the case in the latest experiments [Houard2023]. This amounts to pulse energies of 10 mJ for  $\sim 100$  fs pulses, and in the  $\sim 100$  mJ range for  $\sim 1$  ps pulses, typical for TDL lasers. It has to be kept in mind, however, that the pulse duration will change while propagating in the atmosphere, by e.g. dispersion and non-linear self-steepening.

This multiple filamentation should be generated at a sufficient repetition rate to fully take advantage of the cumulative air density depletion arising in the wake of filamentation, which have been shown to be beneficial for electrical purposes [Vidal2000, Lahav2014, Jhajj2014, Walch2021, Cheng2013, Jhajj2013, Walch2021, Isaacs2022] through Paschen's law [Tirumala2010]. Repetition rates of at least  $\geq 100$  Hz or even 1 kHz are hence desirable. Recent works indicate that an even higher repetition rate up to 100 kHz could push these benefits even further [Löscher2023].

The choice of laser wavelength is mostly driven by the available laser technology advancement, which for the latest experiments, relied on TDL technology at  $\sim 1030$  nm. However many works indicate (see Section 3.3) that shorter wavelengths would be favourable for LLRT purposes due to the higher photon energy and therefore higher ionization efficiency. Conversely, promising results have also been obtained in the Long-Wavelength Infrared (LWIR), which maximizes the energy per filament [Kartashov2013, Tochitsky2019, Welch2021].

From a more technical point of view, the wall-plug efficiency is key for high power and high repetition rates lasers, as progress in average optical power translates into a growing energy demand. As an example, the laser system used by Houard *et al.* had an optical average power of  $\sim 720$  W ( $720$  mJ \*  $1$  kHz) and an optical-to-optical efficiency of LLR laser 8% ( $720$  W /  $9$  kW diode pumping)[Herkommer2020]. Considering a typical wall-plug total efficiency of  $\sim 1\%$  yields an electrical power demand in the  $\sim 70$  kW range. Recently, more efficient Yb:YAG thin-disk laser oscillator with optical-to-optical efficiency of 26% [Fischer2021] or even 33% [Radmard2022] allowed a demonstrated wall-plug efficiency of 7.3% [Braesselbach1997], leaving the hope for 10% or more wall-plug efficiency at technology maturity.

Finally, the ability to transport the laser system to lightning-prone locations is another key requirement for LLRT purposes, as reviewed in the previous section.

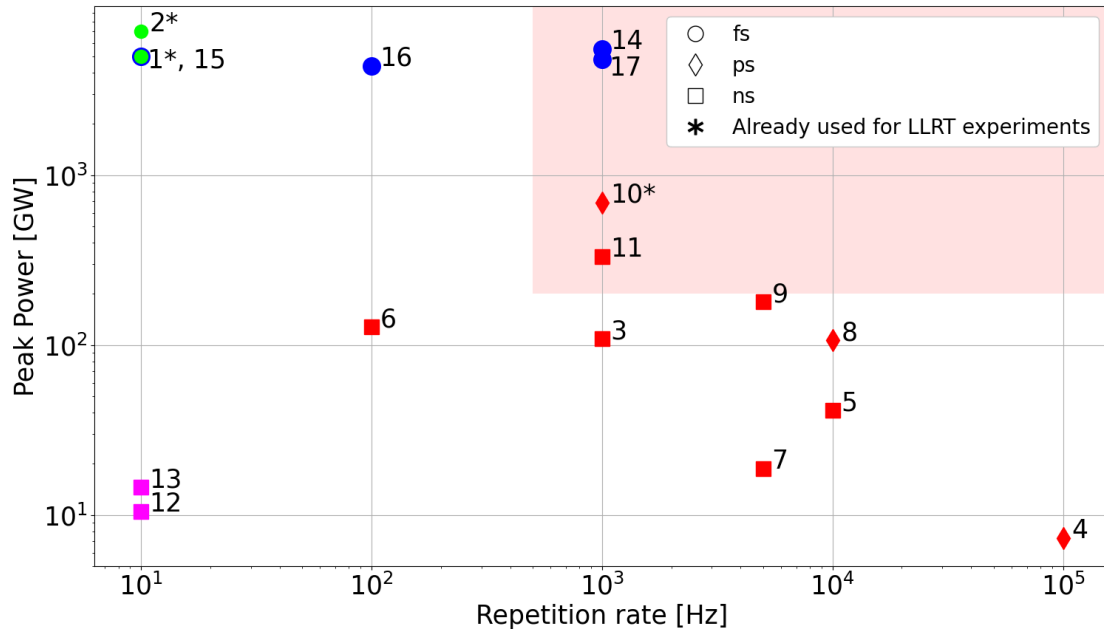


Figure 6: Curated list of laser sources relevant to LLRT. All the lasers are listed in Table 3. Only published laser sources with a repetition rate greater or equal to 10 Hz and a peak power between 5 GW and 500 TW are reported.

Blue marker: OPCPA, Green marker: Ti:Sapphire, Magenta marker: Slab, Red marker: Thin-disk.

Round marker: Pulse duration < 100 fs, Diamond shaped marker: 100 fs < Pulse duration  $\leq$  1 ps, Square marker: Pulse duration > 1 ps.

The region in pink represents the target region: Peak power > 200 GW and repetition rate > 1000 Hz.

The laser systems marked with an asterisk were already used for LLRT experiments.

Nr	Name	Peak power	Pulse duration	Energy per pulse	Repetition rate	Average power	Technology	Reference
1	Teramobile	5 TW	70 fs	350 mJ	10 Hz	3.5 W	Ti:sapphire	[Wille2002]
2	ENSTAmobile	7 TW	50 fs	350 mJ	10 Hz	3.5 W	Ti:sapphire	[Brelet2012]
3	TRUMPF 1	108.8 GW	1.9 ps	220 mJ	1 kHz	220 W	Thin-disk	[Klingebiel2015]
4	TRUMPF 2	7.3 GW	210 fs	2 mJ	100 kHz	200 W	Thin-disk	[Ueffing2016]
5	TRUMPF 3	41.23 GW	1.14 ps	50 mJ	10 kHz	500 W	Thin-disk	[Schultze2016]
6	Max Born Institute RTDA	127.5 GW	1.77 ps	240 mJ	100 Hz	24 W	Thin-disk	[Jung2016]
7	Max-Planck Institut für Quantenoptik RTDA	18.8 GW	1 ps	20 mJ	5 kHz	100 W	Thin-disk	[Fattahi2016]
8	TRUMPF 4	106.6 GW	970 fs	110 mJ	10 kHz	1.1 kW	Thin-disk	[Wandt2017]
9	TRUMPF 5	179.3 GW	1.08 ps	206 mJ	5 kHz	1.03 kW	Thin-disk	[Nubbemeyer2017]
10	LLR	689 GW	920 fs	720 mJ	1 kHz	720 W	Thin-disk	[Herkommer2020]
11	Colorado State University laser	332.65 GW	2.91 ps	1.1 J	1 kHz	1.1 kW	Thin-disk	[Wang2020]
12	DiPOLE100 amplifier chain	10.5 GW	10 ns	105 J	10 Hz	1.05 kW	Slab	[Mason2017]
13	UK Central Laser Facility (CLF)	14.5 GW	10 ns	145 J	10 Hz	1.45 kW	Slab	[UKLaserRecord2021]
14	Vilnius University Laser Research Center OPCPA	5.5 TW	8.8 fs	53.8 mJ	1 kHz	53.8 W	OPCPA	[Budriūnas2017]
15	Max-Planck-Institut für Quantenoptik OPCPA	5 TW	6.9 fs	42 mJ	10 Hz	0.42 W	OPCPA	[Kessel2018]

16	Max Born Institute for Nonlinear Optics and Short Pulse Spectroscopy OPCPA	4.4 TW	8.3 fs	42 mJ	100 Hz	4.2 W	OPCPA	[Kretschmar2020]
17	SYLOS	4.8 TW	6.6 fs	32 mJ	1 kHz	32 W	OPCPA	[Toth2020]

Table 5: Curated list of laser sources relevant for LLR purposes, sorted by technology and publication date. Peak power and pulse duration are calculated similarly as in [Zuo2022]. The average power is obtained by multiplying the repetition rate with the pulse energy. Numbers refer to those of Figure 6.



## 5. Outlook: potential use-cases

Beyond the scientific case *stricto sensu*, and on-demand lightning triggering for scientific research purposes, several applications have been proposed or envisioned for the control of lightning using lasers. In this section, we briefly review these use cases and briefly discuss both their feasibility and relevance in terms of LLRT.

### 5.1 Protection of critical facilities

#### **Power lines**

In Canada, Japan, or Malaysia, most of the power outages affecting the distribution network are due to lightning [Leal2021]. The cost of these lightning-caused outages in Canada is estimated to 350 million CAD each year [Mills2010].

The study of lightning-induced damages on power lines, and lightning protection motivated the constructions of large lightning test facilities by national electrical energy supply companies. In the 1970s, the French electric company EDF founded the first laboratory studies of long air gap discharges, analyzing the development of lightning leaders at the research center “Les Renardières” [Renardières1977]. In Canada, the electric company Hydro-Quebec launched the first project on the control of lightning using femtosecond lasers with INRS in the late 90s [Vidal2002].

In recent years, there has been a reassessment of the challenge of lightning protection for both overhead and buried power lines. This reconsideration is prompted by the growing demand from customers for high-quality power supply [Nucci2022]. Direct lightning strikes pose a significant threat to high-voltage transmission networks. However, in medium-voltage distribution networks, overvoltages induced by nearby lightning are a notable factor contributing to flashovers and disruptions [Chowdhuri2001].

#### **Effect on power plants**

The damages produced by lightning on *nuclear power plants* are generally due to indirect effects. A ground potential rise, or the loss of transmission lines can cause equipment damage or misoperation, but they do not appear as a significant risk for the power plant safety [Rourke1994].

On the contrary, *photovoltaic power plants* are much more sensitive to the effect of lightning strikes. Besides material degradation by direct lightning strikes, overvoltage can damage the electronic system, and repeated impulse current stresses reduce the efficiency of the photovoltaic detectors [Ahmad2018, Omar2022]. In the case of a large photovoltaic power plant, redirecting the lightning with a LLRT at a distance from the strike could therefore be very useful.

#### **Refineries, and explosive storage structures**

Storage tanks for fuel, or explosives warehouses are particularly vulnerable to lightning strikes. Lightning can ignite tank fires, produce toxic releases or explosions. Oil, diesel and gasoline are the substances most frequently released during lightning-triggered Natech accidents (NAtural-hazard triggered TECHnological accidents) [Renni2010]. A recent event occurred in October 2023 at a recycling power plant near Oxford, where a massive explosion of a biogas tank was ignited by lightning.

### **Rocket launch pads**

Rockets and launching infrastructures are highly sensitive to lightning, due to the use and transport of highly flammable/explosive fuels, sensitive electronic equipment, and their exposure, being tall structures in flat environments, often in tropical regions (Florida, French Guiana, etc.). Lightning strikes can occur during the transport of large rocket elements from the storage hangars to the launchpad, mounting and parking on the launch pad, and even after take-off, in flight, as experienced for example by the NASA Apollo 12 missions [NASALightningStrike]. A major difference between the take-off or transport on the ground and the parking on the launch pad is the duration of the risk. Some launchers remain parked on the pad for several days, limiting the accuracy of risk assessment based on the weather forecasts. As for airports, launch pads are equipped with field mills, radiofrequency antenna arrays, and weather radar. To secure the rockets during the parking phase, several arrangements using arrays of tall lightning rods are used [Bachelier2012].

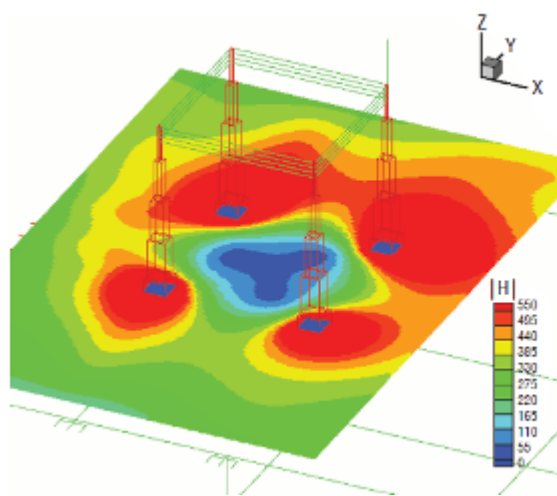


Figure 7: Typical spatial distribution of the magnetic field around the typical arrangement of Franklin-type lightning rods used on rocket launch pads. [Reproduced from Issac2012].

As exemplified by the Soyouz Launch Complex (Figure 7) at the French Guiana Space Center, a typical protecting system is formed by a square network of 4 metallic pylons of 90 m height, separated by 60 m, and connected by conductive wires at their tips. This geometry was optimized not only to avoid direct strike to the fuselage, but also to reduce electromagnetic noise. A strike on one of the pylons could induce a current of up to 200 kA [Rakov2003], and a current variation  $dI/dt$  of the order of  $10^{10}$ – $10^{11}$  A/s [Leteinturier1991], leading to very high magnetic field transients. In turns these magnetic fields can damage the sensitive electronics of the launcher and the payload. The simulated distribution of the magnetic field at ground (Figure 7) shows the protected region around the rocket. A laser-based lightning rod could potentially have several advantages as compared to this fixed protection infrastructure: (1) it could be deployed at will, and thus providing more flexibility on the localisation of the launching equipment, (2) it could be significantly more cost-effective than a massive infrastructure made of concrete and tall metallic towers, and (3) if mobile on a trailer, it could be used for all the three critical phases mentioned above, i.e., transport to the pad, waiting phase and after take off. As launch pads are located in no-flight zones by nature, eye-safety and air traffic control constraints to open-air laser use would be less stringent.

### ***Offshore oil rigs, Offshore wind farms***

Offshore oil rigs and wind farms, often consisting of large metal structures (and/or carbon fiber composite in the case of windmills) grounded to the ocean, are typically situated at varying distances from the coast, ranging from a few hundred meters to several hundred kilometers. While the density of lightning flashes is lower over oceans than over land [Boccippio2000], the height of these structures increases their susceptibility to lightning strikes. This risk is more pronounced in tropical regions due to a higher frequency of storms, a factor that is expected to be further increased by global warming.

New wind power generation units feature increasingly taller turbines, with blades extending to lengths of 60 meters and beyond. Consequently, modern turbines are facing greater exposure to lightning strikes. They are also triggering a significant number of upward lightning flashes. Furthermore, carbon fiber composite materials are now extensively used to reinforce the blades [IECWindTurbines2019]. The inclusion of these composite materials will impact the effectiveness of the lightning protection system (LPS) and thus must be considered during the design phase [Rachidi2012]. The integration of a laser-based lightning rod system could be difficult due to the need to transport the laser to remote offshore structures. A possible solution would be the permanent installation of LLRT protection on the platform itself or, if technically possible, on a moored barge nearby. Alternatively, for platforms or wind farms located closer to the coast, the system could be operated from the shore, pointing the laser in the direction of the structure.

See also section 5.3 ***Protection against indirect (electromagnetic perturbation) effects of lightning***

## **5.2 Protection of wide-area flat facilities**

### ***Airports***

Lightning is a major concern for airports, especially ground handling personnel, interrupting all departures and arrival operations for the whole duration of the thunderstorm [Bloom2008]. As a result, aviation operators have to find the right balance between personnel safety and operational efficiency. The costs of flight delays to the airline industry amounts over 8 billion USD a year (FAA Report 2010), which put airport professionals under pressure. Lightning impacts also set fire to buildings at airports, damage aircrafts at ground, strike and knock out air traffic control towers, and directly or indirectly hit ground crew workers.

Decision making is usually based on lightning detection systems (e.g., RF antennas, local field mills) and meteorological data, but also risk assessments involving insurances. 61.4 % of all flight delays in the USA are produced by weather conditions [FAAReport2023], and among them the majority are thunderstorms. There are no requirements for airports or airlines in the USA to follow specific lightning alerting rules [UltimateLightningGuide], but the FAA recommendations are issuing an alert to the operations team when at 11 km, stopping fueling and ramp operations at 8 km, resuming operations after 15 minutes all clear.

For these reasons and as cloud-to-cloud lightning strikes are often detected before cloud-to-ground, a total lightning detection system rather than forecast is required, with automated alerts.

The occurrence of lightning on airfields depends on their geographical locations and meteorological conditions. Airports in tropical regions are more strongly affected by lightning than others. As an example, the Tampa airport in Florida was struck by 283 cloud-to-ground strikes in 2017, and experienced 4423 cloud-to-cloud lightning strikes above it during the same year.

Hence, avoiding to close an airport during thunderstorms or reducing the time of closure could generate a financial incentive that could make LLRT an attractive option to consider [Arnold2023].

State-of-the-art lightning detection systems are able to provide warning information some 15 km away from the airfields. This information could thus be used as a trigger for starting laser-lightning protection operational phases. In the context of the possible implementation of laser lightning rods at airfields, several deployment options could be considered.

Flat, extended facilities like airports are difficult to protect due to their wide area, as well as crowded airspace that prevents using permanent masts and towers as lightning rods. Thunderstorms are however a key constraint to airport operations, as a high risk of lightning imposes a pause in operation to ensure airplane safety at ground and in take-off phases.

Laser-based protection would potentially provide wide-area coverage by the combination of the filament length and the sweeping of the beam, controlled by a real-time measurement of the electric field at and close to the ground. For the same reason, they can protect areas from the side, which is especially relevant for runways and taxiways. Furthermore, lasers do not impact airplane movements as they can be switched off as needed while airplanes move in their vicinity.

Such application depends on the ability of lasers to initiate upward or downward lightning preventively or to intercept and guide dissenting leaders, which at this stage requires further investigation, as discussed in Section 4.2 above.

A key advantage of LLRT is that lasers can be switched on and off at will, and with a response time of a millisecond. Tall metallic rods are clearly to be avoided on an airfield and virtual lightning rods that can disappear in such short times open new possibilities. Vertical pointing lasers could be deployed around airplanes parking lots, or even made mobile on vehicles that could be moved between different places depending on the risk. Clearing the airport from lightning strikes by switching on the rod for reducing the dead time might also be possible: Control tower operators can make decisions based on information from the aircrafts and from the lightning detection system, and control the laser to avoid any disturbance to the air traffic. First, the action could be beneficial both for reducing damage costs on airport infrastructures and landed aircrafts and for reducing the delays in flight schedules. Depending on the performances of the future laser lightning rod, one could consider either a network of vertical pointing lasers or a single laser that scans the sky over a large area above the airport. Fast scanning over a defined solid angle has the advantage of probing essentially the whole charged cloud over the airport. Again, the laser would then be switched off for planes scheduled to take off or to safely land. Finally, laser lightning rods could also be interesting for defense purposes, where a fixed metal infrastructure is impractical. That could be the case for helicopters landing or taking off, as well as aircraft carriers on the sea.

### ***Protection of large crowds of people in open areas***

Several spectacular incidents or accidents causing tens of injured or even casualties are regularly reported in large crowds gathered in open areas for music festivals [Arnold2023], popular official events [Horváth2007], sport events at stadions [Makdissi2002] or in the outdoor [Cherington2001]. Prevention resides in lightning monitoring, stopping or cancelling the event, and evacuating of the public if an active thunderstorm approaches [Walsh2000]. Large crowds impose specific constraints, with the need of pre-identified shelters of large capacity as well as long evacuation time [Makdissi2002] which in turn increases both the time for the event interruption and distance range to monitor around the event venue, increasing the risk of occurrence of a thunderstorm activating the evacuation plan. Indeed, for large stadiums, current recommendations (the so-called 30/30 rule) ask to suspend the event from flash-to-bang time of 30 s (i.e., approximately occurrence of a lightning strike within 10 km of the area to be protected) until 30 min after the end of the last flash [Walsh2000, Makdissi2002]. In such a situation, lightning protection should cover a wide open area.

The crowd itself should be protected against electrification; The buildings and equipment (lighting masts, trees) surrounding the crowd should also be considered since they could cause injuries if they burn or fall after being damaged by a lightning strike. The typical dimension of a stadion (~100 m) is commensurate with the typical length of laser filamentation, allowing a single laser (or a reduced number thereof) to cover the whole area at risk. However, the main open question remains the ability of lasers to offer a very high level of protection without being complemented by a classical lightning rod, to avoid the event suspension or cancellation.

### ***Prevention of lightning-ignited wildfires***

Another raise in vulnerability regards forest. Though the sensitivity to climate change on the occurrence of lightning-induced wildfire is uncertain [Pérez-Invernón2023], hotter conditions could increase the risk that lightning strikes trigger wildfires [Canadell2021, Jones2022]. Other studies report that climate change is expected to decrease the occurrence frequency of lightning [Finney2018]. Typically, one out of 1,000 cloud to ground strikes triggers a forest fire, with a highest risk in low-intensity precipitationless thunderstorms [Soler2021]. Furthermore, human exposure is also increasing due to the growing entanglement of habitation zones with fire-vulnerable forests. The main challenge posed by forest protection is their spatial extension, while a dense network of high lightning rod towers would severely impact landscapes and therefore raise questions about their acceptability by populations. However, even a sparser network of lasers would require a dense infrastructure for both access and power supply, let alone the cost. A laser could attract lightning to a firewall or a clearing. The need would however be a mobile LLRT reaching the sections of the forest most at risk according to weather forecasts, which would pose access issues.

## **5.3 Other use-cases**

### ***Protection against indirect (electromagnetic perturbation) effects of lightning***

Current protection techniques relying on lightning rods are highly efficient against direct (thermal) effects of lightning as they lead the lightning current to ground through a down-conductor of adapted cross-section. However, the high-intensity, fast-varying lightning return stroke currents are the source of strong electromagnetic radiation that can induce overvoltages on power lines and unwanted voltages and currents on electrical and electronic equipment. These impacts are collectively known as indirect effects of lightning. Since the electromagnetic field decays rapidly with distance from the lightning channel [Rubinstein1989], shifting the transient current away from the facility to be protected will considerably reduce its indirect effects. For example the four lightning rods protecting the Ariane 5 launchpad are located 25 m away from the vehicle, a distance that could be easily doubled or tripled by guiding the lightning strike away. Such an approach may also apply to large buildings, or to wind turbine protection [IECWindTurbines2019], whereby the earthing conductor has to cross the turbine head, and therefore has a distance to the sensitive parts limited to the meter range.

In either case, the key parameter is the competition between the elevated point (lightning rod, arm of the wind turbine) and the laser launched above it. Neither available experimental data nor existing models are sufficient to date to assess the potential success rate, i.e., the fraction of flashes of either polarity that would be intercepted and deviated or missed in a specific configuration, characterized by tower/lightning rod height, the surrounding topography, as well as by the laser location, elevation angle and filament length. Further investigation in that direction is therefore crucial, as discussed in Section 4.1.

### ***Clouds discharge***

Actively initiating lightning before its natural occurrence, in order to better control and let the cloud charge flow to the ground [Brunt2000], is often expected to unload clouds. However the typical charge density in thunderclouds amounts to some  $\mu\text{C}/\text{m}^3$  [Amoruso2002] while a typical lightning strike drives to the ground a total charge of some tens of Coulomb. A single strike is therefore able to discharge a typical volume of  $10^7 \text{ m}^3$ , i.e., a typical cloud region of  $200 \times 200 \times 200 \text{ m}^3$ . This constitutes a negligible fraction of the active thunderstorm volume.

With typical radii of a few tens of km, the thunderstorm has a volume of at least  $10^{12} \text{ m}^3$  [Rakov2003]. Reasoning from a temporal rather than volumic point of view yields comparable results. Indeed, typical lightning strikes often give rise to re-illumination, i.e., repeated lightning strikes originating from the same location in the cloud, and following the same path through the cloud. A typical delay between re-illuminations lies in the second range [Rakov2003], indicating that the charge-depleted volume due to the original lightning strike has been replenished within less than 1 s [Rakov2003]. Indeed, the typical charge buildup in a thundercloud is in the range of  $1 \text{ C}/\text{km}^3/\text{min}$  [Ávila2011] would require several lightning strikes per  $\text{km}^3$  per minute. If considering a 10 km-high thundercloud, typically one discharge/ $\text{km}^2/\text{s}$  would be needed to drain charge to the ground at a rate comparable with its generation. Further investigation is necessary to assess the ability of LLRT to offer this rate having an improved effect, if at all.

### ***Lightning energy collection***

A single lightning flash to ground has a total energy of the order of  $10^9$  to  $10^{10} \text{ J}$  [Rakov2003]. This is equivalent, for example, to the consumption of a single average Swiss household for about one month only (at  $\sim 5000 \text{ kWh}/\text{year}/\text{household}$  in 2021 [ConsommationSuisse2021]). Moreover, we expect lightning energy collection to be difficult for at least three main reasons. The first difficulty stems from the fact that all this energy ( $10^9$  to  $10^{10} \text{ J}$ ) is concentrated during the very short duration of the lightning strike, i.e., of the order of hundreds of  $\mu\text{s}$ , bringing the power to tame to an unreasonable amount in the  $\sim$ hundreds of TW range. Second, it is well known that lightning does not always strike the apex of structures, even for high structures [Shindo2018], complicating further the hypothetical energy flow capture. Third, most energy is dissipated in the atmosphere during the propagation of the lightning strike, so that only a small fraction, roughly 1% of the total energy from a cloud-to-ground lightning flash reaches the strike point where the energy could be harvested. Finally, capturing a significant number of lightning strikes would necessitate numerous tall towers (or LLRT facilities), rendering it impractical as a means of energy collection. All these limitations are related to lightning itself rather than to a specific collection technology, so that LLRT would not fundamentally change their scope.

## 6. Conclusion

While being considered for over 30 years, lightning control by lasers has long been restricted to speculations based on the extrapolation of small to medium-scale laboratory experiments and rough theoretical arguments. However, the relevance of cm-scale to meter-scale laboratory experiments is limited due to the leader-streamer mechanism that drastically modifies the behavior of a discharge beyond the length of a single leader step, i.e., several meters. On the other hand, integrating the effect of a high-power laser pulse, inherently transient, onto lightning initiation and propagation theories that must accommodate a wide range of scales ranging from micrometer to hundreds or thousands of meter scale, is out of reach of current models, especially when transient effects have to be taken into account. Furthermore, arguments based on the limited amount of energy deposited by ultrashort laser filaments in the air have been considered to explain the lack of laser initiation [Kasparian2008] or of inconclusive nature [Miki2005] of previous field experiments aiming at lightning control using lasers.

The advent of kHz-repetition rate, high-power lasers based on Yb thin-disk technology changed this context by offering for the first time the opportunity to deposit high energy and average power densities in the air, at a rate sufficient to imprint a permanently depleted region prone to discharge propagation due to the Paschen effect.

Furthermore, the ability of such a class of lasers to produce filaments over more than 100 m was confirmed. This progress provided the basis for a field campaign at a particularly well-instrumented site enjoying a very high local density of lightning strikes: Mount Säntis and its telecommunications tower, where guided lightning strikes were stereo-imaged by fast cameras, located and tracked via their radio-emission, and produced in a sufficient amount to ensure statistical significance. The positive polarity of the guided discharges, which contrasts with the negative polarity of discharges occurring when the laser was not fired, might even suggest a possible triggering by the laser. This interpretation was further supported by a model indicating that the observed electric field during these strikes exceeds the threshold for positive laser-triggered events but not that for negative ones [Houard2023].

This demonstration, however, calls for further investigation. A better elucidation of the triggering and guiding mechanism is needed, as well as an assessment of the optimal laser conditions, including repetition rate, wavelength, and focusing geometry. Furthermore, assessing the LLRT technology beyond the specific scenario of upward lightning initiated from a tower is key for most application use cases, such as protecting critical facilities and large, open areas. In the longer term, these applications will require specific assessments, in comparison with the existing state-of-the-art lightning protection measures tailored to each case. Apart from offering protection in areas that cannot be covered by classical lightning rods, the expected advantage of the laser system lies in diverting lightning and associated electromagnetic disturbances away from critical and sensitive systems, such as control-command circuits or other key electronic or digital devices.

## 7. References (in alphabetical order)

- [Ávila2011] E. E. Ávila *et al.*, "[Charge separation in low-temperature ice cloud regions](#)", Journal of Geophysical Research Atmospheres **116**, D14 (2011).
- [Ackermann2004] R. Ackermann *et al.*, "[Triggering and guiding of megavolt discharges by laser-induced filaments under rain conditions](#)", Applied Physics Letters **85**, 5781 (2004).
- [Ackermann2006] R. Ackermann *et al.*, "[Influence of negative leader propagation on the triggering and guiding of high voltage discharges by laser filaments](#)", Applied Physics B **82**, 561 (2006).
- [Ahmad2018] N.I. Ahmad *et al.*, "[Lightning protection on photovoltaic systems: A review on current and recommended practices](#)", Renewable and Sustainable Energy Reviews **82**, 1611 (2018).
- [Albrecht2016] R. I. Albrecht *et al.*, "[Where Are the Lightning Hotspots on Earth?](#)", Bulletin of the American Meteorological Society **97**, 2051 (2016).
- [Amoruso2002] V. Amoruso and F. Lattarulo, "[Thundercloud pre-stroke electrostatic modeling](#)", Journal of Electrostatics **56**, 255 (2002).
- [Andral2022] U. Andral *et al.*, "[Second and third harmonic generation from simultaneous high peak- and high average-power thin disk laser](#)", Applied Physics B **128**, 177 (2022).
- [Arantchouk2016] L. Arantchouk *et al.*, "[Prolongation of the lifetime of guided discharges triggered in atmospheric air by femtosecond laser filaments up to 130  \$\mu\$ s](#)", Applied Physics Letters **108**, 173501 (2016).
- [Arnold2023] C. L. Arnold *et al.*, "[Lightning protection by laser](#)", Nature Photonics **17**, 211 (2023).
- [Askaryan1962] G. A. Askar'yan, "[Cerenkov Radiation and Transition Radiation from Electromagnetic Waves](#)", Soviet Physics JETP **15**, 943 (1962).
- [Bachelier2012] E. Bachelier *et al.*, "[Lightning protection of SOYUZ and VEGA launching pads](#)", 2012 International Conference on Lightning Protection (ICLP), pp. 1-6 (2012).
- [Ball1974] L. M. Ball, "[The Laser Lightning Rod System: Thunderstorm Domestication](#)", Applied Optics **13**, 2292 (1974).
- [Ball1977] L. M. Ball, "[Laser lightning rod system](#)", US Patent US4017767A (1977).
- [Bazelyan2000] E. M. Bazelyan and Y. P. Raizer, "[The mechanism of lightning attraction and the problem of lightning initiation by laser](#)", Physics-Uspekhi **43**, 701 (2000).
- [Beccera2007] M. Beccera and V. Cooray, "[The Early Streamer Emission Principle Does Not Work Under Natural Lightning](#)", Proceedings of the IX International Symposium on Lightning Protection, Foz do Iguaçu, Brazil, 26-30 November 2007
- [Beccera2008] M. Beccera and V. Cooray, "[Laboratory experiments cannot be utilized to justify the action of early streamer emission terminals](#)", Journal of Physics D: Applied Physics **4**, 085204(2008).
- [Berger1967] K. Berger, "[Novel observations on lightning discharges: Results of research on Mount San Salvatore](#)", Journal of the Franklin Institute **283**, 478 (1967).
- [Bergé2007] L. Bergé *et al.*, "[Ultrashort filaments of light in weakly ionized, optically transparent media](#)", Reports on Progress in Physics **70**, 1633 (2007).
- [Bernardi2004] M. Bernardi and D. Ferrari, "[Evaluation of the LLS efficiency effects on the ground flash density, using the Italian lightning detection system SIRE](#)", Journal of Electrostatics **60**, 131 (2004).
- [Bloom2008] K. Bloom, "[Lightning Detection in Support of Airport Authority Decision Making](#)", Aerodrome Meteorological Observation and Forecast (AMOFSG) Seventh Meeting, AMOFSG/7-SN No. 17 (2008).
- [Bodrov2013] S. Bodrov *et al.*, "[Effect of an electric field on air filament decay at the trail of an intense femtosecond laser pulse](#)", Physical Review E **87**, 053101 (2013).
- [Boccippio2000] D. J. Boccippio *et al.*, "[Regional Differences in Tropical Lightning Distributions](#)", Journal of Applied Meteorology and Climatology **39**, 2231 (2000).



- [Bondiou1994] A. Bondiou and I. Gallimberti, "[Theoretical modelling of the development of the positive spark in long gaps](#)", Journal of Physics D: Applied Physics **27**, 1252 (1994).
- [Bourayou2005] R. Bourayou *et al.*, "[White-light filaments for multiparameter analysis of cloud microphysics](#)", Journal of the Optical Society of America B **22**, 369 (2005).
- [Boyd2020] R. W. Boyd, "[Nonlinear Optics](#)", 4th Edition Elsevier Science, ISBN 978-0-12-811002-7 (2020).
- [Braesselbach1997] H. Braesselbach *et al.*, "[Side-pumped Yb:YAG Rod Laser Performance](#)", OSA Technical Digest (Optica Publishing Group) Vol. 11, CPD34 (1997).
- [Braun1995] A. Braun *et al.*, "[Self-channeling of high-peak-power femtosecond laser pulses in air](#)", Optics Letters **20**, 73 (1995).
- [Brelet2012] Y. Brelet *et al.*, "[Tesla coil discharges guided by femtosecond laser filaments in air](#)", Applied Physics Letters **100**, 181112 (2012).
- [Brunt2000] R. J. Van Brunt *et al.*, "[Early streamer emission lightning protection systems: An overview](#)", IEEE Electrical Insulation Magazine **16**, 5 (2000).
- [Budriūnas2017] R. Budriūnas *et al.*, "[53 W average power CEP-stabilized OPCPA system delivering 5.5 TW few cycle pulses at 1 kHz repetition rate](#)", Optics Express **25**, 5797 (2017).
- [Canadell2021] J. G. Canadell *et al.*, "[Multi-decadal increase of forest burned area in Australia is linked to climate change](#)", Nature Communications **12**, 6921 (2021).
- [Chalmers1999] I. D. Chalmers *et al.*, "[Considerations for the Assessment of Early Streamer Emission Lightning Protection](#)", IEE Proceedings - Science, Measurement and Technology **146**, 57 (1999).
- [Chang2017] X. Chang *et al.*, "[Variation of the channel temperature in the transmission of lightning leader](#)", Journal of Atmospheric and Solar-Terrestrial Physics **159**, 41 (2017).
- [Cheng2013] Y.-H. Cheng *et al.*, "[The effect of long timescale gas dynamics on femtosecond filamentation](#)", Optics Express **21**, 4740 (2013).
- [Cherington2001] M. Cherington, "[Lightning injuries in sports: situations to avoid](#)", Sports Medicine **31**, 301 (2001).
- [Chiao1964] R. Y. Chiao *et al.*, "[Self-Trapping of Optical Beams](#)", Physical Review Letters **13**, 479 (1964).
- [Chowdhuri2001] P. Chowdhuri, "[Parameters of lightning strokes and their effects on power systems](#)", 2001 IEEE/PES Transmission and Distribution Conference and Exposition. Developing New Perspectives (Cat. No.01CH37294), 1047 (2001).
- [Clerici2015] M. Clerici *et al.*, "[Laser-assisted guiding of electric discharges around objects](#)", Science Advances **1**, e1400111 (2015).
- [Comtois2000] D. Comtois *et al.*, "[Triggering and guiding leader discharges using a plasma channel created by an ultrashort laser pulse](#)", Applied Physics Letters **76**, 819 (2000).
- [Comtois2003a] D. Comtois *et al.*, "[Triggering and guiding of an upward positive leader from a ground rod with an ultrashort laser pulse. I. Experimental results](#)", IEEE Transactions on Plasma Science **31**, 377 (2003).
- [Comtois2003b] D. Comtois *et al.*, "[Triggering and guiding of an upward positive leader from a ground rod with an ultrashort laser pulse. II. Modeling](#)", IEEE Transactions on Plasma Science **31**, 387 (2003).
- [ConsommationSuisse2021] <https://pubdb.bfe.admin.ch/fr/publication/download/10559>, accessed on the 08.02.2024
- [Cooray2008] V. Cooray and N. Theethayi, "[Laboratory Experiments Cannot Be Utilized to Justify the Action of Early Streamer Emission Terminals](#)", Journal of Physics D: Applied Physics **41**, 085204 (2008).
- [Cooray2015] V. Cooray, "[Basic Physics of Electrical Discharges](#)", In: An Introduction to Lightning, ISBN 978-94-017-8938-7, Springer Dordrecht (2015).

- [Couairon2002] A. Couairon and L. Bergé, "[Light Filaments in Air for Ultraviolet and Infrared Wavelengths](#)", Physical Review Letters **88**, 135003 (2002).
- [Couairon2007] A. Couairon and A. Mysyrowicz, "[Femtosecond filamentation in transparent media](#)", Physics Reports **441**, 47 (2007).
- [Daigle2013] J.-F. Daigle *et al.*, "[Dynamics of laser-guided alternating current high voltage discharges](#)", Applied Physics Letters **103**, 184101 (2013).
- [DaSilva2013] C. L. da Silva and V. P. Pasko, "[Dynamics of streamer-to-leader transition at reduced air densities and its implications for propagation of lightning leaders and gigantic jets](#)", Journal of Geophysical Research: Atmosphere **118**, 13561 (2013)
- [DataReportal] <https://datareportal.com/reports/digital-2023-global-overview-report>
- [DelaCruz2015] L. de la Cruz *et al.*, "[High repetition rate ultrashort laser cuts a path through fog](#)", Applied Physical Letters **109**, 251105 (2016).
- [Diendorfer2009] G. Diendorfer *et al.*, "[Some Parameters of Negative Upward-Initiated Lightning to the Gaisberg Tower \(2000-2007\)](#)", IEEE Transactions on Electromagnetic Compatibility **51**, 443 (2009).
- [Diels1992] J.-C. Diels *et al.*, "[Discharge of lightning with ultrashort laser pulses](#)", US Patent US5175664A (1992).
- [Durand2013] M. Durand *et al.*, "[Kilometer range filamentation](#)", Optics Express **21**, 26836 (2013).
- [Drs2023] J. Drs *et al.*, "[A Decade of Sub-100-fs Thin-Disk Laser Oscillators](#)", Laser & Photonics Reviews **17**, 2200258 (2023).
- [Dwyer2005] J. R. Dwyer, "[The initiation of lightning by runaway air breakdown](#)", Geophysical Research Letters **32**, L20808 (2005).
- [Dwyer2014] J. R. Dwyer and M. A. Uman, "[The physics of lightning](#)", Physics Report **534**, 147 (2014).
- [Emmanuel2022] N. K. Emmanuel *et al.*, "[Study of the correlation between lightning activity and convective rain over Equatorial Africa](#)", 36th International Conference on Lightning Protection (ICLP), Cape Town, South Africa, 354 (2022).
- [Eriksson1978] A.J. Eriksson, "Lightning and Tall Structures", Transactions of the South Africal Institute of Electrical Engineers, pp. 238-252, August 1978.
- [Eriksson1979] A.J. Eriksson, "The Lightning Ground Flash: An Engineering Study", PhD. Thesis, University of Natal, Pretoria, South Africa, 1979.
- [Eto2012] S. Eto *et al.*, "[Quenching electron runaway in positive high-voltage-impulse discharges in air by laser filaments](#)", Optics Letters **37**, 1130 (2012).
- [FAAReport2023] Federal Aviation Administration, "[Air Traffic By the Numbers](#)", April 2023
- [Fattahi2016] H. Fattahi *et al.*, "[High-power, 1-ps, all-Yb:YAG thin-disk regenerative amplifier](#)", Optics Letters **41**, 1126 (2016).
- [Finke1996] U. Finke and T. Hauf, "[The Characteristics of Lightning Occurrence in Southern Germany](#)", Beiträge Zur Physik Der Atmosphäre, 361 (1996).
- [Finney2018] D. L. Finney *et al.*, "[A projected decrease in lightning under climate change](#)", Nature Climate Change **8**, 210 (2018).
- [Forestier2012] B. Forestier *et al.*, "[Triggering, guiding and deviation of long air spark discharges with femtosecond laser filament](#)", AIP Advances **2**, 012151 (2012).
- [Fosdick1995] E. K. Fosdick and A. I. Watson, "[Cloud-to-ground lightning patterns in New Mexico during the summer](#)", National Weather Digest **19**, 17 (1995).
- [Fieux1978] R. P. Fieux *et al.*, "[Research on Artificially Triggered Lightning in France](#)", IEEE Transactions on Power Apparatus and Systems **3**, 725 (1978)
- [Fischer2021] J. Fischer *et al.*, "[Efficient 100-MW, 100-W, 50-fs-class Yb:YAG thin-disk laser oscillator](#)", Optics Express **29**, 42075 (2021).
- [Fisher1993] R. J. Fisher *et al.*, "[Parameters of triggered-lightning flashes in Florida and Alabama](#)", Journal of Geophysical Research: Atmospheres **98**, 22887 (1993).

[Franklin1752] [“The Kite Experiment. 19 October 1752”](#), Founders Online, National Archives, USA.

[Franz1990] R. C. Franz *et al.*, [“Television Image of a Large Upward Electrical Discharge Above a Thunderstorm System”](#), *Science* **249**, 48 (1990).

[Fuchs1998] F. Fuchs *et al.*, [“Lightning Current and Magnetic Field Parameters Caused by Lightning Strikes to Tall Structures Relating to Interference of Electronic Systems”](#), *IEEE Transactions on electromagnetic compatibility* **40**, 444 (1998).

[Fujii2008] T. Fujii *et al.*, [“Leader effects on femtosecond-laser-filament-triggered discharges”](#), *Physics of Plasmas* **15**, 013107 (2008).

[Gao2020] Y. Gao *et al.*, [“The spatial evolution of upward positive stepped leaders initiated from a 356-m-tall tower in Southern China”](#), *Journal of Geophysical Research: Atmospheres* **125**, e2019JD031508 (2020).

[Garbagnati1974] E. Garbagnati *et al.*, “Survey of the characteristics of lightning stroke currents in Italy – results obtained in the years from 1970 to 1973”, ENEL Report R5/63-27 (1974).

[Garbagnati1982] E. Garbagnati *et al.*, “Results of 10 years investigation in Italy”, In: *Proceedings of the International Aerospace Conference on Lightning and Static Electricity*, Oxford, UK, paper A1, (1982).

[Giesen1994] A. Giesen *et al.*, [“Scalable concept for diode-pumped high-power solid-state lasers”](#), *Applied Physics B* **58**, 365 (1994).

[Gordon2003] D. F. Gordon *et al.*, [“Streamerless guided electric discharges triggered by femtosecond laser filaments”](#), *Physics of Plasmas* **10**, 4530 (2003).

[Gorin1975] B. N. Gorin *et al.*, “Results of studies of lightning strikes to the Ostankino TV tower”, *Trudy ENIN* **43**, 63 (1975).

[Gorin1977] B. N. Gorin *et al.*, “Lightning strikes to the Ostankino tower”, *Elektrichestvo* **8**, 19 (1977).

[Gorin1984] B. N. Gorin and A. V. Shkilev, “Measurements of lightning currents at the Ostankino tower”, *Elektrichestvo* **8**, 64 (1984).

[Gowlett2016] J. A. J. Gowlett, [“The discovery of fire by humans: a long and convoluted process”](#), *Philosophical Transactions of the Royal Society B* **371**, 20150164 (2016).

[Granget1995] F. Granget *et al.*, [“Numerical and experimental determination of ionizing front velocity in a DC point-to-plane corona discharge”](#), *Journal of Physics D: Applied Physics* **28**, 1619 (1995).

[Guimarães2014] M. Guimarães *et al.*, [“Lightning Measurements at Morro do Cachimbo Station: new results”](#), 2014 International Conference on Lightning Protection (ICLP), Shanghai, China, 1695 (2014).

[Gurevich1992] A. V. Gurevich *et al.*, [“Runaway electron mechanism of air breakdown and preconditioning during a thunderstorm”](#), *Physics Letters A* **165**, 463 (1992).

[Gurevich2005] A. V. Gurevich and K. R. Zybin, [“Runaway Breakdown and the Mysteries of Lightning”](#), *Physics Today* **58**, 37 (2005).

[Henin2011] S. Henin *et al.*, [“Field Measurements Suggest Mechanism of Laser-Assisted Water Condensation”](#), *Nature Communications* **2**, 456 (2011).

[Hagenguth1952] Hagenguth, J.H., and Anderson, J.G. 1952. Lightning to the Empire State Building. *AIEE Trans.* 71(3): 641–9.

[Henriksson2012] M. Henriksson *et al.*, [“Laser guiding of Tesla coil high voltage discharges”](#), *Optics Express* **20**, 12721 (2012).

[Hercher1964] M. Hercher, [“Laser-induced Damage in Transparent Media”](#), *Journal of the Optical Society of America* **54**, 563 (1964).

[Herkommer2020] C. Herkommer *et al.*, [“Ultrafast thin-disk multipass amplifier with 720 mJ operating at kilohertz repetition rate for applications in atmospheric research”](#), *Optics Express* **28**, 30164 (2020).

- [Higginson2021] A. Higginson *et al.*, "[Wake dynamics of air filaments generated by high-energy picosecond laser pulses at 1 kHz repetition rate](#)," Optics Letters **46**, 5449 (2021).
- [Hodanish1997] S. Hodanish *et al.*, "[A 10-yr monthly lightning climatology of Florida: 1986-95](#)", Weather and Forecasting **12**, 439(1997).
- [Holle2008] R. L. Holle, "[Annual rates of lightning fatalities by country](#)", 20th International lightning detection conference, 2425. (2008).
- [Holle2014] R. L. Holle, "[Some aspects of global lightning impacts](#)", 2014 International Conference on Lightning Protection (ICLP), 1390 (2014).
- [Holle2016] R. L. Holle, "[The number of documented global lightning fatalities](#)", 24th International Lightning Detection conference (ILDC 2016) (2016).
- [Holle2023] R. L. Holle & D. Zhang, "[Human Impacts, Damages, and Benefits from Lightning in Arizona](#)", In: Flashes of Brilliance: The Science and Wonder of Arizona Lightning 97, Springer International Publishing (2023).
- [Horváth2007] Á. Horváth *et al.*, "[The Constitution Day storm in Budapest: Case study of the August 20, 2006 severe storm](#)", Időjárás/Quarterly Journal of the Hungarian Meteorological Service **111**, 41 (2007).
- [Houard2011] Aurélien Houard, personal communication to Thomas Produit, 30 November 2022.
- [Houard2016] A. Houard *et al.*, "[Study of filamentation with a high power high repetition rate ps laser at 1.03  \$\mu\text{m}\$](#) ", Optics Express **24**, 7437 (2016).
- [Houard2023] A. Houard *et al.*, "[Laser-guided lightning](#)", Nature Photonics **17**, 231 (2023).
- [Hunt2014] H. G. P. Hunt *et al.*, "[Evaluation of the South African Lightning Detection Network using Photographed Tall Tower Lightning Events from 2009 - 2013](#)", 2014 International Conference on Lightning Protection (ICLP), 1746 (2014).
- [Hussein2004] A. M. Hussein *et al.*, "[Current waveform parameters of CN tower lightning return strokes](#)", Journal of Electrostatics **60**, 149 (2004).
- [Hussein2010] A. M. Hussein *et al.*, "[Influence of the CN Tower on the lightning environment in its vicinity](#)", In Proceedings of the International Lightning Detection Conference (ILDC), 1 (2010).
- [IECWindTurbines2019] IEC 61400-24:2019, "[Wind turbine generator systems - Part 24: Lightning protection](#)", International Electrotechnical Commission (IEC), Geneva, Switzerland, (2019).
- [Ioannidis2023] A. I. Ioannidis and T. E. Tsovilis, "[Introducing the Concept of the Volume Lightning Strike Density](#)", IEEE Transactions on Power Delivery **38**, 2973 (2023).
- [Isaacs2022] J. Isaacs *et al.*, "[Modeling the propagation of a high-average-power train of ultrashort laser pulses](#)", Optics Express **30**, 22306 (2022).
- [Issac2012] F. Issac *et al.*, "[Space Launching Site Protection against Lightning Hazards](#)", Aerospace Lab **5**, 1 (2012).
- [Javan1966] A. Javan and P. L. Kelley, "[6A5 - Possibility of self-focusing due to intensity dependent anomalous dispersion](#)", IEEE Journal of Quantum Electronics **2**, 470 (1966).
- [Jhajj2013] N. Jhajj *et al.*, "[Optical beam dynamics in a gas repetitively heated by femtosecond filaments](#)", Optics Express **21**, 28980 (2013).
- [Jhajj2014] N. Jhajj *et al.*, "[Demonstration of Long-Lived High-Power Optical Waveguides in Air](#)", Physical Review X **4**, 011027 (2014).
- [Jones2022] M. W. Jones *et al.*, "[Global and Regional Trends and Drivers of Fire Under Climate Change](#)", Reviews of Geophysics **60**, e2020RG000726 (2022).
- [Joly2013] P. Joly *et al.*, "[Laser-induced Condensation by Ultrashort Laser Pulses at 248 nm](#)", Applied Physics Letters **102**, 091112 (2013).
- [Jung2016] R. Jung *et al.*, "[Regenerative thin-disk amplifier for 300 mJ pulse energy](#)", Optics Express **24**, 883 (2016).

- [Kamali2009] Y. Kamali *et al.*, "[Remote sensing of trace methane using mobile femtosecond laser system of T&T Lab](#)", Optics Communications **282**, 2062 (2009).
- [Kartashov2013] D. Kartashov *et al.*, "[Mid-infrared laser filamentation in molecular gases](#)", Optics Letters **38**, 3194 (2013).
- [KaserekaKigotsi2018] J. Kasereka Kigotsi, "[Analyse de l'activité d'éclairs des systèmes orageux dans le bassin du Congo](#)", Doctoral dissertation, Université Toulouse 3 Paul Sabatier, France (2018).
- [KaserekaKigotsi2022] J. Kasereka Kigotsi *et al.*, "[Contribution to the study of thunderstorms in the Congo Basin: Analysis of periods with intense activity](#)", Atmospheric Research **269**, 106013 (2022).
- [Kasparian2003] J. Kasparian *et al.*, "[White Light Filaments for Atmospheric Analysis](#)", Science **301**, 61 (2003).
- [Kasparian2008] J. Kasparian *et al.*, "[Electric events synchronized with laser filaments in thunderclouds](#)", Optics Express **16**, 5757 (2008).
- [Kessel2018] A. Kessel *et al.*, "[Relativistic few-cycle pulses with high contrast from picosecond-pumped OPCPA](#)", Optica **5**, 434 (2018).
- [Klingebiel2015] S. Klingebiel *et al.*, "[220mJ Ultrafast Thin-Disk Regenerative Amplifier](#)", in CLEO: 2015, OSA Technical Digest (online) (Optica Publishing Group), paper STu4O.2 (2015).
- [Koopman1971] D. W. Koopman and T. D. Wilkerson, "[Channeling of an Ionizing Electrical Streamer by a Laser Beam](#)", Journal of Applied Physics **42**, 1883 (1971).
- [Kretschmar2020] M. Kretschmar *et al.*, "[Thin-disk laser-pumped OPCPA system delivering 4.4 TW few-cycle pulses](#)", Optics Express **28**, 34574 (2020).
- [LaFontaine2000] B. La Fontaine *et al.*, "[Guiding large-scale spark discharges with ultrashort pulse laser filaments](#)", Journal of Applied Physics **88**, 610 (2000).
- [Lahav2014] O. Lahav *et al.*, "[Long-lived waveguides and sound-wave generation by laser filamentation](#)", Physical Review A **90**, 021801 (2014).
- [Lallemant1965] P. Lallemant and N. Bloembergen, "[Self-Focusing of Laser Beams and Stimulated Raman Gain in Liquids](#)", Physical Review Letters **15**, 1010 (1965).
- [LangmuirWebsite] <https://www.nmt.edu/research/organizations/langmuir.php>, accessed on 08.01.2024
- [Leal2021] A. F. R. Leal, "[Frontiers in Lightning Research and Opportunities for Scientists from Developing Countries](#)", In: Gomes, C. (eds) Lightning. Lecture Notes in Electrical Engineering, vol 780. Springer, Singapore. (2021).
- [Leteinturier1991] C. Leteinturier *et al.*, "[Submicrosecond characteristics of lightning return-stroke currents](#)", IEEE Transactions on Electromagnetic Compatibility **33**, 351 (1991).
- [Lippert1978] J. R. Lippert, "[A Laser-Induced Lightning Concept Experiment](#)", Defense Technical Information Center, Technical report AFFDL-TR-78-191, Accession Number ADA065897 (1978).
- [Liu2012] X.-L. Liu *et al.*, "[Long lifetime air plasma channel generated by femtosecond laser pulse sequence](#)", Optics Express **20**, 5968 (2012).
- [Löschner2023] R. Löschner *et al.*, "[High-power sub-picosecond filamentation at 1.03  \$\mu\text{m}\$  with high repetition rates between 10 kHz and 100 kHz](#)", APL Photonics **8**, 111303 (2023).
- [López2012] J. López *et al.*, "[Lightning initiation from a tall structure in the Basque Country](#)", Atmospheric Research **117**, 28 (2012).
- [Mackerras1997] D. Mackerras *et al.*, "[Review of Claimed Enhanced Lightning Protection of Buildings by Early Streamer Emission Air Terminals](#)", IEE Proceedings - Science, Measurement and Technology **144**, 1 (1997).
- [Makdissi2002] M. Makdissi and P. Brukner, "[Recommendations for lightning protection in sport](#)", The Medical Journal of Australia **177**, 35 (2002).



- [Manoochehrnia2008] P. Manoochehrnia *et al.*, "[Lightning statistics in the regions of Saentis and St. Chrischona towers in Switzerland](#)", In 29th International Conference on Lightning Protection (ICLP) **1**, 2 (2008).
- [Mason2017] P. Mason *et al.*, "[Kilowatt average power 100 J-level diode pumped solid state laser](#)", *Optica* **4**, 438 (2017).
- [McEachron1939] K.B. McEachron, "[Lightning to the Empire State Building](#)", *Journal of the Franklin Institute* **227**, 149 (1939).
- [McEachron1941] K.B. McEachron, "[Lightning to the Empire State Building](#)", *Transactions of the American Institute of Electrical Engineers* **60**, 885 (1941).
- [Méjean2004] G. Méjean *et al.*, "[Remote Detection and Identification of Biological Aerosols using a Femtosecond Terawatt Lidar System](#)", *Applied Physics B* **78**, 535 (2004).
- [Miki2005] M. Miki *et al.*, "[Initial stage in lightning initiated from tall objects and in rocket-triggered lightning](#)", *Journal of Geophysical Research* **110**, D02109 (2005).
- [Miki2012] M. Miki *et al.*, "[Measurement of lightning currents at TOKYO SKYTREE® and observation of electromagnetic radiation caused by strikes to the tower](#)", In 2012 International Conference on Lightning Protection (ICLP), 1 (2012).
- [Mikropoulos2019] P. N. Mikropoulos and T. E. Tsovilis, "[Estimation of Lightning Incidence to Telecommunication Towers](#)", *IEEE Transactions on Electromagnetic Compatibility* **61**, 1793 (2019).
- [Mills2010] B. Mills *et al.*, "[Assessment of lightning-related damage and disruption in Canada](#)", *Natural Hazards* **52**, 481 (2010).
- [Mongin2015] D. Mongin *et al.*, "[Non-linear Photochemical Pathways in Laser induced Atmospheric Aerosol Formation](#)", *Scientific Reports* **5**, 14978 (2015).
- [Montanyà2012] J. Montanyà *et al.*, "[Two upward lightning at the Eagle Nest tower](#)", 2012 International Conference on Lightning Protection (ICLP), Vienna, Austria, 1 (2012).
- [Muñoz2016] Á. G. Muñoz *et al.*, "[Seasonal prediction of lightning activity in North Western Venezuela: Large-scale versus local drivers](#)", *Atmospheric Research* **172**, 147 (2016).
- [NASALightningStrike] <https://www.nasa.gov/history/afj/ap12fj/a12-lightningstrike.html>, accessed on the 15.02.2024
- [Nelson2003] F. Nelson *et al.*, "[Microfísica del Relampago del Catatumbo](#)", *Revista del Aficionado a la Meteorología*, 10.05.2003
- [Nijdam2020] S. Nijdam *et al.*, "[The physics of streamer discharge phenomena](#)", *Plasma Sources Science and Technology* **29**, 103001 (2020).
- [Nucci2022] C. A. Nucci *et al.*, "[Interaction of lightning-generated electromagnetic fields with overhead and underground cables](#)", *Lightning Electromagnetics. Volume 2: Electrical processes and effects*, 2nd ed., Chap. 8, 291-324, (2022).
- [Nubbemeyer2017] T. Nubbemeyer *et al.*, "[1 kW, 200 mJ picosecond thin-disk laser system](#)", *Optics Letters* **42**, 1381 (2017).
- [Omar2022] A. I. Omar *et al.*, "[Induced Overvoltage Caused by Indirect Lightning Strikes in Large Photovoltaic Power Plants and Effective Attenuation Techniques](#)", *IEEE Access* **10**, 112934 (2022).
- [Ozdemir2023] A. Ozdemir and S. Ilhan, "[Experimental Performance Analysis of Conventional and Non-Conventional Lightning Protection Systems – Preliminary Results](#)", *Electric Power Systems Research* **216**, 109080 (2023).
- [Papeer2014] J. Papeer *et al.*, "[Extended lifetime of high density plasma filament generated by a dual femtosecond–nanosecond laser pulse in air](#)", *New Journal of Physics* **16**, 123046 (2014).
- [Papeer2015] J. Papeer *et al.*, "[Generation of concatenated long high density plasma channels in air by a single femtosecond laser pulse](#)", *Applied Physics Letters* **107**, 124102 (2015).

- [Pepin2001] H. Pepin *et al.*, "[Triggering and guiding high-voltage large-scale leader discharges with sub-joule ultrashort laser pulses](#)", *Physics of Plasmas* **8**, 2532 (2001).
- [Pérez-Invernón2023] F. J. Pérez-Invernón *et al.*, "[Variation of lightning-ignited wildfire patterns under climate change](#)", *Nature Communications* **14**, 739 (2023).
- [Petit2010] Y. Petit *et al.*, "[Production of Ozone and Nitrogen Oxides by Laser Filamentation](#)", *Applied Physics Letters* **97**, 021108 (2010).
- [Pfaff2023] Y. Pfaff *et al.*, "[Nonlinear pulse compression of a 200 mJ and 1 kW ultrafast thin-disk amplifier](#)", *Optics Express* **31**, 22740 (2023).
- [Pinto2008] O. Pinto Jr, "[An overview of cloud-to-ground lightning research in Brazil in the last two decades](#)", In 20th International Lightning Detection Conference (2008).
- [Point2015] G. Point *et al.*, "[Generation of long-lived underdense channels using femtosecond filamentation in air](#)", *Journal of Physics B* **48**, 094009 (2015).
- [Polynkin2017] P. Polynkin, "[Multi-pulse scheme for laser-guided electrical breakdown of air](#)", *Applied Physics Letters* **111**, 161102 (2017).
- [Popov2003] N. A. Popov, "[Formation and Development of a Leader Channel in Air](#)", *Plasma Physics Reports* **29**, 695 (2003).
- [Produit2019] T. Produit *et al.*, "[HV discharges triggered by dual- and triple-frequency laser filaments](#)", *Optics Express* **27**, 11339 (2019).
- [Produit2021] T. Produit *et al.*, "[The laser lightning rod project](#)", *European Physical Journal - Applied Physics* **93**, 10504 (2021).
- [Produit2021a] T. Produit, "[De la réalisation d'un paratonnerre laser](#)", Doctoral dissertation nr. 5555, Université de Genève, Switzerland (2021).
- [Qie2009] X. Qie *et al.*, "[Characteristics of triggered lightning during Shandong artificial triggering lightning experiment \(SHATLE\)](#)", *Atmospheric Research* **91**, 310 (2009).
- [Qie2017] X. Qie *et al.*, "[Bidirectional leader development in a preexisting channel as observed in rocket-triggered lightning flashes](#)", *Journal of Geophysical Research: Atmospheres* **122**, 586 (2017).
- [Qie2019] X. Qie and Y. Zhang, "[A Review of Atmospheric Electricity Research in China from 2011 to 2018](#)", *Advances in Atmospheric Sciences* **36**, 994 (2019).
- [Qiu2015] Z. Qiu *et al.*, "[Lightning parameters measurement systems and Instrumentation on meteorological gradient observation tower in Shenzhen China](#)", 2015 International Symposium on Lightning Protection (XIII SIPDA), pp. 306-308 (2015).
- [Rachidi2012] F. Rachidi *et al.*, "[Lightning Protection of Large Wind-Turbine Blades](#)", In: *Wind Energy Conversion Systems: Technology and Trends*, 227 (2012).
- [Rachidi2022] F. Rachidi and M. Rubinstein, "[Sântis lightning research facility: a summary of the first ten years and future outlook](#)", *Elektrotechnik und Informationstechnik* **139**, 379 (2022).
- [Radmard2022] S. Radmard *et al.*, "[400 W average power Q-switched Yb:YAG thin-disk-laser](#)", *Scientific Reports* **12**, 16918 (2022).
- [Raizer2000] E. M. Bazelyan and Y. P. Raizer, "[Lightning Physics and Lightning Protection](#)", 1st edition CRC Press (2000).
- [Rambo2001] P. Rambo *et al.*, "[High-voltage electrical discharges induced by an ultrashort-pulse UV laser system](#)", *Journal of Optics A: Pure and Applied Optics* **3**, 146 (2001).
- [Rakov2003] V. A. Rakov and M. Uman, "[Lightning: Physics and Effects](#)", Cambridge University Press (2003).
- [Rakov2005] V. A. Rakov *et al.*, "[A review of ten years of triggered-lightning experiments at Camp Blanding, Florida](#)", *Atmospheric Research* **76**, 503 (2005).
- [Rakov2009] V. A. Rakov, "[Triggered Lightning](#)", In: Betz, H.D., Schumann, U., Laroche, P. (eds) *Lightning: Principles, Instruments and Applications*. Springer, Dordrecht (2009).

- [Rastegari2021] A. Rastegari *et al.*, "[Investigation of UV filaments and their applications](#)", APL Photonics **6**, 060803 (2021).
- [Renardières1977] Les Renardières Group, "Positive discharges in long air gaps at Les Renardières – 1975 results and conclusions", Electra, 53 (1977).
- [Renni2010] E. Renni *et al.*, "[Industrial accidents triggered by lightning](#)", Journal of Hazardous Materials **184**, 42 (2010).
- [Richardson2020] M. Richardson *et al.*, "[Mobile Ultrafast High Energy Laser Facility \(MU-HELFI\)](#)", Technical Report, Accession Number AD1110950, University of Central Florida (2020).
- [Rison1999] W. Rison *et al.*, "[A GPS-based three-dimensional lightning mapping system: Initial observations in central New Mexico](#)", Geophysical Research Letters **26**, 3573 (1999).
- [Rizk1994] F. A. M. Rizk, "[Modeling of lightning incidence to tall structures. II. Application](#)", IEEE Transactions on Power Delivery **9**, 172 (1994).
- [Rizk2010] F. A. M. Rizk, "[Analysis of Space Charge Generating Devices for Lightning Protection: Performance in Slow Varying Fields](#)", IEEE Transactions on Power Delivery **25**, 1996 (2010).
- [Rodriguez2002] M. Rodriguez *et al.*, "[Triggering and guiding megavolt discharges by use of laser-induced ionized filaments](#)", Optics Letters **27**, 772 (2002).
- [Roebroeks2011] W. Roebroeks and P. Villa, "[On the earliest evidence for habitual use of fire in Europe](#)", Proceedings of the National Academy of Sciences **108**, 5209 (2011).
- [Roeder2017] W. P. Roeder, "[A new lightning climatology for Cape Canaveral Air Force Station and NASA Kennedy Space Center](#)", 18<sup>th</sup> Conference on Aviation, Range, and Aerospace Meteorology. (2017).
- [Romero2013] C. Romero *et al.*, "[Statistical Distributions of Lightning Currents Associated With Upward Negative Flashes Based on the Data Collected at the Sântis \(EMC\) Tower in 2010 and 2011](#)", IEEE Transactions on Power Delivery **28**, 1804 (2013).
- [Rohwetter2004] P. Rohwetter *et al.*, "[Remote LIBS with Ultra-Short Pulses: Characteristics in Picosecond and Femtosecond Regimes](#)", Journal of Analytical Atomic Spectrometry **19**, 437 (2004).
- [Rohwetter2005] P. Rohwetter *et al.*, "[Filament-induced Remote Ablation for Long Range LIBS Operation](#)", Spectrochimica Acta B **60**, 1025 (2005).
- [Rohwetter2010] P. Rohwetter *et al.*, "[Laser-induced Water Condensation in Air](#)", Nature Photonics **4**, 451 (2010).
- [Rohwetter2011] P. Rohwetter *et al.*, "[Modelling of HNO<sub>3</sub>-Mediated Laser-Induced Condensation: A Parametric Study](#)", The Journal of Chemical Physics **135**, 134703 (2011).
- [Rourk1994] C. Rourk, "[A review of lightning-related operating events at nuclear power plants](#)", IEEE Transactions on Energy Conversion **9**, 636 (1994).
- [Rubinstein1989] M. Rubinstein and M. A. Uman, "[Methods for Calculating the Electromagnetic Fields from a Known Source Distribution: Application to Lightning](#)", IEEE Transactions on Electromagnetic Compatibility **31**, 183 (1989).
- [Rudden2023] J. Rudden, "[Homeowner insurance claims paid out due to lightning losses in the United States from 2006 to 2021](#)", Statista (2023).
- [Saba2005] M. M. F. Saba *et al.*, "[Lightning current observation of an altitude-triggered flash](#)", Atmospheric Research **76**, 402 (2005).
- [Saraceno2019] C. Saraceno *et al.*, "[The amazing progress of high-power ultrafast thin-disk lasers](#)", Journal of the European Optical Society-Rapid Publications **15**, 15 (2019).
- [Sasaki2010] A. Sasaki *et al.*, "[Percolation Simulation of Laser-Guided Electrical Discharges](#)", Physical Review Letters **105**, 075004 (2010).



- [Saum1972] K. A. Saum and David W. Koopman, "[Discharges Guided by Laser Induced Rarefaction Channels](#)", *The Physics of Fluids* **15**, 2077 (1972).
- [Scheller2014] M. Scheller *et al.*, "[Externally refuelled optical filaments](#)", *Nature Photonics* **8**, 297 (2014).
- [Schimmel2018] G. Schimmel *et al.*, "[Free space laser telecommunication through fog](#)", *Optica* **5**, 1338 (2018).
- [SchmittSody2015] A. Schmitt-Sody *et al.*, "[The importance of corona generation and leader formation during laser filament guided discharges in air](#)", *Applied Physics Letters* **106**, 124101 (2015).
- [Schroeder2020] M. C. Schroeder *et al.*, "[Molecular quantum wakes for clearing fog](#)", *Optics Express* **28**, 11463 (2020).
- [Schroeder2022] M. C. Schroeder *et al.*, "[Opto-mechanical expulsion of individual micro-particles by laser-induced shockwave in air](#)", *AIP Advances* **12**, 095119 (2022).
- [Schroeder2023] M. C. Schroeder, "[Optomechanical Clearing of Aerosols for Free-Space Optical Telecommunication](#)", Doctoral dissertation nr. 5724, Université de Genève, Switzerland (2023).
- [Schubert1978] C. W. Jr., Schubert, "[The Laser Lightning Rod System: A Feasibility Study](#)", Defense Technical Information Center, Technical report AFFDL-TR-78-60, Accession Number ADA063847 (1978).
- [Schubert1979] C. W. Jr., Schubert and J. R. Lippert, "[Investigation into triggering lightning with a pulsed laser](#)", 2nd IEEE international pulsed power conference, Digest of technical papers, Reference number 16074393 (1979).
- [Schubert2015] E. Schubert *et al.*, "[Remote electrical arc suppression by laser filamentation](#)", *Optics Express* **23**, 28640 (2015).
- [Schubert2017] E. Schubert *et al.*, "[HV discharge acceleration by sequences of UV laser filaments with visible and near-infrared pulses](#)", *New Journal of Physics* **19**, 123040 (2017).
- [Schultze2016] M. Schultze *et al.*, "[Toward Kilowatt-Level Ultrafast Regenerative Thin-Disk Amplifiers](#)", in Lasers Congress 2016 (ASSL, LSC, LAC), OSA, Boston, Massachusetts, paper ATu4A (2016).
- [Shen1965] Y. R. Shen and Y. J. Shaham, "[Beam Deterioration and Stimulated Raman Effect](#)", *Physical Review Letters* **15**, 1008 (1965).
- [Shindo2014] T. Shindo *et al.*, "[Lightning observations at Tokyo Skytree](#)", 2014 International Symposium on Electromagnetic Compatibility, Gothenburg, Sweden, 583 (2014).
- [Shindo2015] T. Shindo *et al.*, "[Lightning striking characteristics to very high structures](#)", Technical Brochure 633, CIGRE C4.410 (2015).
- [Shindo2018] T. Shindo, "[Lightning Striking Characteristics to Tall Structures](#)", *IEEJ Transactions on Electrical and Electronic Engineering* **13**, 938 (2018).
- [Singh2015] O. Singh and J. Singh, "[Lightning fatalities over India: 1979-2011](#)", *Meteorological Applications* **22**, 770 (2015).
- [Smit2023] J. R. Smit *et al.*, "[The Johannesburg Lightning Research Laboratory. Part 1: Characteristics of lightning currents to the Sentech Tower](#)", *Electric Power Systems Research* **216**, 109059 (2023).
- [Smorgonskiy2013] A. Smorgonskiy *et al.*, "[On the relation between lightning flash density and terrain elevation](#)", In 2013 International Symposium on Lightning Protection (XII SIPDA), 62 (2013).
- [Soler2021] A. Soler *et al.*, "[Characterisation of thunderstorms that caused lightning-ignited wildfires](#)", *International Journal of Wildland Fire* **30**, 954 (2021).
- [Staathoff2013] H. Staathoff *et al.*, "[Laser Filament-Induced Aerosol Formation](#)", *Atmospheric Chemistry and Physics* **13**, 4593 (2013).

- [Stelmaszczyk2004] K. Stelmaszczyk *et al.*, "[Long-distance Remote LIBS using Filamentation in Air](#)", Applied Physics Letters **85**, 3977 (2004).
- [Strickland1985] D. Strickland and G. Mourou, "[Compression of amplified chirped optical pulses](#)", Optics Communications **55**, 447 (1985).
- [Sugiyama2010] K. Sugiyama *et al.*, "[Submicrosecond laser-filament-assisted corona bursts near a high-voltage electrode](#)", Physics of Plasmas **17**, 043108 (2010).
- [Surkov2012] V. V. Surkov and M. Hayakawa, "[Underlying mechanisms of transient luminous events: a review](#)", Copernicus GmbH, Annales Geophysicae **30**, 1185 (2012).
- [Talanov1965] V. I. Talanov, "[Self Focusing of Wave Beams in Nonlinear Media](#)", JETP Letters **2**, 138 (1965).
- [Théberge2006] F. Théberge *et al.*, "[Plasma density inside a femtosecond laser filament in air: Strong dependence on external focusing](#)", Physical Review E **74**, 036406 (2006).
- [Thul2021] D. Thul *et al.*, "[The mobile ultrafast high energy laser facility - A new facility for high-intensity atmospheric laser propagation studies](#)", Optics and Lasers in Engineering **140**, 106519 (2021).
- [Tirumala2010] R. Tirumala and D. B. Go, "[An analytical formulation for the modified Paschen's curve](#)", Applied Physics Letters **97**, 151502 (2010).
- [Tochitsky2019] S. Tochitsky *et al.*, "[Filamentation of long-wave infrared pulses in the atmosphere](#)", Journal of the Optical Society of America B **36**, G40 (2019).
- [Toth2020] S. Toth *et al.*, "[SYLOS lasers – the frontier of few-cycle, multi-TW, kHz lasers for ultrafast applications at extreme light infrastructure attosecond light pulse source](#)", Journal of Physics: Photonics **2**, 045003 (2020).
- [Tzortzakis2000] S. Tzortzakis *et al.*, "[Time-evolution of the plasma channel at the trail of a self-guided IR femtosecond laser pulse in air](#)", Optics Communications **181**, 123 (2000).
- [Tzortzakis2001] S. Tzortzakis *et al.*, "[Femtosecond laser-guided electric discharge in air](#)", Physical Review E **64**, 057401 (2001).
- [Uchida1999] S. Uchida *et al.*, "[Laser-triggered lightning in field experiments](#)", Journal of Optical Technology **66**, 199 (1999).
- [Ueffing2016] M. Ueffing *et al.*, "[Direct regenerative amplification of femtosecond pulses to the multimillijoule level](#)", Optics Letters **41**, 3840 (2016).
- [Uhlig1956] C. A. E. Uhlig, "The ultra corona discharge, a new phenomenon occurring on thin wires", High voltage symposium, National Research Council of Canada, Ottawa, Canada (1956).
- [UKLaserRecord2021] <https://www.ukri.org/news/new-world-record-for-uk-built-laser-technology/>, accessed on 14.02.2024
- [Uman2002] M. A. Uman, M. A. and V. A. Rakov, "[A Critical Review of Nonconventional Approaches to Lightning Protection](#)", Bulletin of the American Meteorological Society **83**, 1809 (2002).
- [Uman2008] M. A. Uman, "[The Art and Science of Lightning Protection](#)", ISBN: 9780511585890, Cambridge University Press (2008).
- [UltimateLightningGuide] <https://www.earthnetworks.com/the-ultimate-lightning-guide-for-airport-operations/>, accessed on 08.02.2024
- [Vaill1970] J. R. Vaill *et al.*, "[Propagation of High-voltage Streamers along Laser-induced Ionization Trails](#)", Applied Physics Letters **17**, 20 (1970).
- [VaisalaInteractiveMap] <https://interactive-lightning-map.vaisala.com/>, accessed on 16.01.2024
- [Vidal2000] F. Vidal *et al.*, "[Modeling the triggering of streamers in air by ultrashort laser pulses](#)", IEEE Transactions on Plasma Science **28**, 418 (2000).

- [Vidal2002] F. Vidal *et al.*, "[The control of lightning using lasers: properties of streamers and leaders in the presence of laser-produced ionization](#)", *Comptes Rendus Physique* **3**, 1361 (2002).
- [Visacro2004] S. Visacro *et al.*, "[Statistical analysis of lightning current parameters: Measurements at Morro do Cachimbo Station](#)", *Journal of Geophysical Research: Atmospheres* **109**, D1 (2004).
- [Walch2021] P. Walch *et al.*, "[Cumulative air density depletion during high repetition rate filamentation of femtosecond laser pulses: Application to electric discharge triggering](#)", *Applied Physical Letters* **119**, 264101 (2021).
- [Walch2023] P. Walch *et al.*, "[Long distance laser filamentation using Yb:YAG kHz laser](#)", *Scientific Reports* **13**, 18542 (2023).
- [Walch2023b] P. Walch *et al.*, "[Study of consecutive long-lived meter-scale laser-guided sparks in air](#)", *Physics of Plasmas* **30**, 083503 (2023).
- [Walsh2000] K. M. Walsh *et al.*, "[National athletic trainers' association position statement: lightning safety for athletics and recreation](#)", *Journal of Athletic Training* **35**, 471 (2000).
- [Wandt2017] C. Wandt *et al.*, "[1 kW Ultrafast Thin-Disk Amplifier System](#)", in *Conference on Lasers and Electro-Optics*, OSA, San Jose, USA, paper STh1L. 1 (2017).
- [Wang1994] D. Wang *et al.*, "[A preliminary study on laser-triggered lightning](#)", *Journal of Geophysical Research* **99**, 16907 (1994).
- [Wang1995] D. Wang *et al.*, "[A possible way to trigger lightning using a laser](#)", *Journal of Atmospheric and Terrestrial Physics* **57**, 459 (1995).
- [Wang2015] T. J. Wang *et al.*, "[Direct observation of laser guided corona discharges](#)", *Scientific Reports* **5**, 18681 (2015).
- [Wang2020] Y. Wang *et al.*, "[1.1 J Yb:YAG picosecond laser at 1 kHz repetition rate](#)", *Optics Letters* **45**, 6615 (2020).
- [Wang2020b] T. J. Wang *et al.*, "[Femtosecond laser filament guided negative coronas](#)", *AIP Advances* **10**, 035128 (2020).
- [Wang2022] J. Wang *et al.*, "[Two successive bidirectional leaders propagated in triggered lightning channel](#)", *Scientific Reports* **12**, 9235 (2022).
- [Welch2021] E. C. Welch *et al.*, "[Study of the Physical Mechanism of Air Breakdown Using Picosecond Long-Wavelength Infrared Laser Pulses](#)", Abstract CP11.00009, 63rd Annual Meeting of the APS Division of Plasma Physics, Pittsburgh, USA, (2021).
- [Wille2002] H. Wille *et al.*, "[Teramobile: A mobile femtosecond-terawatt laser and detection system](#)", *European Physical Journal - Applied Physics* **20**, 183 (2002).
- [Willett1999] J. C. Willett *et al.*, "[An experimental study of positive leaders initiating rocket-triggered lightning](#)", *Atmospheric Research* **51**, 189 (1999).
- [Wolf2018] J.-P. Wolf, "[Short-pulse lasers for weather control](#)", *Report on Progress in Physics* **81**, 026001 (2018).
- [Woolsey1986] G. A. Woolsey *et al.*, "[A quantitative laser Schlieren analysis of positive streamers in atmospheric air](#)", *Proceedings of the Royal Society of London. A. Mathematical and Physical Sciences* **405**, 355 (1986).
- [Zhang2014] Y. Zhang *et al.*, "[Experiments of artificially triggered lightning and its application in Conghua, Guangdong, China](#)", *Atmospheric Research* **135**, 330 (2014).
- [Zhang2016] Y. Zhang *et al.*, "[A review of advances in lightning observations during the past decade in Guangdong, China](#)", *Journal of Meteorological Research* **30**, 800 (2016).
- [Zhao1995] X. M. Zhao *et al.*, "[Femtosecond ultraviolet laser pulse induced lightning discharges in gases](#)", *IEEE Journal of Quantum Electronics* **31**, 599 (1995).
- [Zipse1994] D. W. Zipse, "[Lightning protection systems: advantages and disadvantages](#)", *IEEE Transactions on Industry Applications* **30**, 1351 (1994).

[Zou2023] L. Zou *et al.*, “[Laser energy deposition with ring-Airy beams beyond kilometer range in the atmosphere](#)”, *Physical Review A* **108**, 023524 (2023).

[Zuo2022] J. Zuo and X. Lin, “[High-Power Laser Systems](#)”, *Laser & Photonics Reviews* **16**, 2100741 (2022).