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Influence of negative leader propagation on the triggering and guiding of high voltage discharges by laser filaments

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Abstract The triggering and guiding of negative discharges using filaments induced by a femtosecond-terawatt laser pulse have been studied in sphere-plane gaps up to 4.5 meters. Fast-frame camera pictures allow the evaluation of the influence of the negative leader propagation on the triggering and guiding process. We show that the plasma channel can either trigger a space-leader discharge or act as a guiding path for the negative leader head. For the latter case the results suggest a linear dependence of the guided lengths up to 2.4 m, while the formation of a space-leader reduces this guided length by up to 50 %. This effect is explained by the limited plasma lifetime of the filament that is measured to be about 1 μs.

Introduction Lightning control by lasers has been a dream of scientists since the 1970's. Early approaches focussed on powerful CO_2-lasers [1,2], but as the air plasma is opaque at the laser-wavelength $\lambda = 10.6$ μm (critical density $n_c \approx 10^{19}$ cm^{-3}), large plasma extensions are hardly achievable. Therefore, the application of ultrashort laser pulses has become more popular in recent years, as they provide plasma generation via Multi-Photon-Ionization at moderate pulse energies [3–7]. The opacity problem is avoided by typical laser wavelengths in the NIR or UV [8], e. g. $n_c \approx 2 \times 10^{21}$ cm^{-3} at 800 nm.

The first approach to trigger lightning was to replace or extend an existing lighting rod by the laser filament near to the ground. As in this case the last step of lightning is the emergence of an upward moving positive leader, most of the investigations have focussed on this type of leaders, e. g. using a bi-foci lens to produce a 2 m long plasma channel [5,9]. However, in weakly focussed beams a dynamic balance of the nonlinear Kerr-effect and plasma generation [10–13] allows plasma channels at distances up to several kilometers [14]. Such filaments may be in contact with lightning leaders, 90 % of which have negative polarity [15]. Therefore, negative discharges have raised much attention in the last years [6,16,17,4].

In laboratory experiments the main property of negative discharges compared to the positive polarity is the existence of the so called space-stem, a propagating plasma that originates from negative streamers [18–21]. The space-stem acts as a source for both negative and positive streamers, branching towards both electrodes, and propagates towards the ground electrode in a self-reproducing way. When the space-stem has reached the ground electrode, the breakdown is initiated. For gaps greater than about 2 m the space-stem can transform itself into a space-leader whose positive leader head propagates towards the cathode [18,20]. Therefore, the negative discharge develops stepwise by the connection of the space-leader to the electrode-leader. A stepped propagation is also observed for negative lightning leaders which exhibit similar mechanisms to laboratory discharges [20].

Previous experiments have shown that negative discharges can be guided and triggered by laser filaments in long air gaps up to 3.8 m [6]. Triggering is characterized by the reduction of the voltage inducing 50 % breakdown probability (U_{50}). Besides, negative and positive streamers have been observed at the borders of a 5 cm long plasma channel in a 30 cm gap under negative voltage pulses [4,22]. In this paper we present new experimental results about the triggering and guiding of negative discharges in gaps up to 4.5 m. Fast-frame camera pictures show the space-leader formation and the negative leader propagation for different configurations. Finally, taking into account earlier results obtained in [6], the influence of the space-leader formation on the achievable guided lengths will be discussed.

Experimental Setup The experiments were conducted using the Marx high-voltage generator of the Centre d'Essais Aéronautiques de Toulouse, France. This device delivered a voltage pulse of negative polarity up to 2.7 MV. Its rise time was 2 μs, and the fall time was about 50 μs. A plane (5 m height and 10 m width) ground electrode was placed perpendicular to the beam axis, while the high voltage electrode was a sphere with 8 cm diameter. The distance between both electrodes was adjusted from 2.3 m to 4.5 m.

Discharges were guided using the Teramobile [23,24], a mobile laser system delivering pulses of 250 mJ energy with pulse durations down to 100 fs. The center wavelength was 800 nm and the repetition rate 10 Hz. The laser was installed inside the high-voltage facility, with its beam aligned with the electrodes. The laser beam was tangent to the HV electrode and went through a small hole drilled into the ground electrode to avoid ablation. The beam was slightly focussed (f $\approx$ 23 m) by a telescope so that the filaments covered the whole gap. The number of filaments was estimated to be 25 by applying a resistivity measurement technique as reported in [25]. This filament number is consistent with the observation of the beam profile on a screen [26]. The peak electron density is estimated to be 3×10^{16} cm^{-3} [25]. Typically, the filamentation started 1 m upstream from the high voltage electrode. A negative chirp was applied resulting in an initial pulse duration of 500 fs, as this led to the maximum triggering efficiency. The delay of the laser was varied between 1 μs before and 2.6 μs after the beginning of the high voltage pulse.

Fast-frame camera pictures and records of the voltage and current at the high voltage electrode were used to investigate the different steps of the discharge development, while still photographs allowed the determination of their geometrical characteristics.

Experimental Results and Discussion We first characterized the regime far above the distance threshold for the formation of space-leaders [18–20] at a gap distance of 4.5 m. Figure 1 shows a set of fast-frame camera pictures (a), the corresponding records of the voltage and current (b) and a still picture (c) of a partially guided discharge triggered by the laser under these conditions. The peak voltage was 2.2 MV, and the laser was shot 1.2 μs after the beginning of the high voltage pulse. We checked that only triggered discharges could occur. No free discharge could be observed up to 2.7 MV, which was the limit of the generator performance. On the first fast-frame camera picture in figure 1(a) one can see that a space-leader has developed about 1 m away from the high voltage electrode, and its positive leader head propagates towards the cathode. The propagation velocity of the positive leader, averaged from 11 picture series, amounts to $(2.4 \pm 0.5) \times 10^6$ m/s independent of the gap length. This is in line with previous measurements on guided leaders [5,6]. After the connection of the space-leader to the electrode leader the new leader head at the position of the space-leader continues its propagation towards the ground electrode, at first guided over some distance and then in a free propagation. The delay between the laser pulse and the first occurence of the space-leader on the fast-frame pictures has been measured to be (800 ± 300) ns, averaged over 7 shots at this gap distance.

The current oscillograms show that the connection of the space-leader to the electrode leader causes a strong current pulse of about 1 kA, followed by a current rise lasting about 2 μs, until the final jump occurs [20,21]. The corresponding charge consumption reached up to 400 μC m^{-1} before breakdown for guided space-leader discharges. This value is twice as much as for free discharges without space-leader formation, for which we measured $(150 \pm 30)\ \mu\mathrm{C\ m}^{-1}$ at 3.4 m gap distance and a peak voltage of 2.3 MV $\approx$ U_{50}, in line with the value of 158 $\mu\mathrm{C\ m}^{-1}$ reported elsewhere [19].

As described above, space-leaders require gaps of about 2 m [18,20]. In order to investigate the guided space-leader formation near to this threshold, the gap distance was reduced to 2.3 m. The peak voltage level was set to 2.0 MV $\approx 1.2 \times U_{50}$ leading to a breakdown probability of 100 % even without laser. The laser delay was set to 1.2 μs after the start of the voltage pulse. Under these conditions both unguided and guided discharges occured, and we observed two competing processes with respect to the occurrence of space-leaders.

The first case (figure 2) is similar to the mechanism described above for the 4.5 m gap. However, probably due to the stronger electric field, the space-leader frequently starts to propagate towards the ground electrode, before the connection to the electrode leader has been established. Although the space-leader formation lies out of the limited time-window of the fast-frame camera, the delay between the laser pulse and this formation appears to be shorter than in the 4.5 m gap determined above, since it is below 450 ns.

In the second case (figure 3) the streamers and the space-stem entirely bridge the gap leading to the initiation of the final jump. This can be identified by the positive leader starting at the ground electrode (see figure 3(a)) and the increasing current marked in figure 3(b). The negative electrode leader appears about 2.5 μs after the start of the voltage pulse on the fast-frame pictures (not shown). No space-leader develops in this case, but the leader can still be partially guided, as can be seen on the last but one camera picture in figure 3(a).

Comparing the time scales in figure 2(a) and 3(a), one notices that the space-leader occurs about 1.5 μs before the initiation of the final jump in the case of the guided electrode leader. This suggests that the space-stem and streamers interact with the plasma channel generated by the laser during their propagation to the ground electrode. The streamer to leader transition of a natural discharge is generally considered to result from electron detachment and heating of the electrons transported into the gap by the streamers [21,27]. Therefore, the triggering of a space-leader could be explained by a contribution of the electrons of the filament to this process in the vicinity of the space-stem and its streamers. This may result in a thermal expansion of the filament during the first hundreds of nanoseconds after the laser, as reported on a smaller scale [28]. The smaller delay between the laser pulse and the space-leader formation at 2.3 m compared to the 4.5 m gap would then be explained by the higher level of the electric field. However, since the streamers are less luminous than the leader head, a camera with a higher dynamic range and spatial resolution would be required to reveal an interaction of the filament with the space-stem and streamers.

Also shown in figure 2(b) and 3(b) are the voltage and current records for both types of discharges indicating the different time scales and the absence of the current peak in the case where the electrode leader is guided.

The above results show that the laser is able to provoke a space-leader discharge if it is shot, before the final jump is initiated. In contrast to the observations on a small scale [4] the position of the space-leader does not necessarily correpond to the position of the guided part of the discharge (see figure 2).

Besides the streamer and leader propagation, the plasma lifetime [29, 30] is a key parameter for extrapolating the laboratory results to real-scale lightning control, because it limits the effective length of the plasma channel. This lifetime was estimated in two ways. Changing the laser delay relative to the voltage pulse in a 2.3 m gap (figure 4), we observed no triggered or guided event if the laser was shot more than 1 μs *before* the beginning of the voltage pulse, showing that the plasma channel has vanished within a few microseconds, before a sufficient electric field can be reached.

The second approach is based on the evaluation of the fast-frame camera pictures of the 4.5 m gap. As can be seen on figure 1(a) the space-leader propagates in the plasma channel first towards the high voltage electrode, until it connects to the electrode leader and then towards the ground electrode. This propagation begins $t_d = 800$ ns after the laser pulse and occurs at a speed of $v_g = 2.4 \times 10^6$ m/s. Therefore, the guided length, which corresponds to the path propagated by the space-leader before the plasma channel has vanished, is $x_g = v_g(t_p - t_d)$ where t_p is the plasma lifetime. It has been measured to be $t_p = (1.3 \pm 0.4)$ μs from an average over 7 events. The obtained plasma durations are much shorter than the 10 μs lifetime of the ionzed channel observed for a stronger focus (f $\approx$ 5 m) [5].

However, figure 3(a) shows that the electrode leader can still be guided, although it develops more than 2.5 μs after the laser pulse, i. e. at a time beyond the free plasma lifetime. In fact, the leader follows the guided path of the streamer, which has propagated earlier, first freely, before the laser was shot, then guided by the filament. The statistics over 13 shots of guided electrode leaders show that the end of the guided part does not exceed a distance of 1.5 m downstream from the high voltage electrode. The streamer velocity can be estimated from the fast frame pictures to be not less than 0.7×10^6 m/s. When the laser arrives 1.2 μs after the start of the voltage pulse, the streamers have propagated at least 80 cm into the gap. At this point, the streamer generated plasma is heated. If the heating is sufficient, a space-leader could be initiated. This is consistent with the fact that the space-leader is located at (1.0 ± 0.2) m downstream from the high-voltage electrode (averaged over 10 shots) independently from the gap length. If no space-leader is initiated, the streamers can interact with the laser filament during additional 70 cm on their way to the ground electrode if one considers a plasma lifetime of 1 μs as determined above. This leads to the observed limitation of 1.5 m for guided electrode leaders.

Figure 5 shows the guided lengths as a function of the gap length for laser delays between 0 and 2.6 μs. The data are averaged over all shots for which a space-leader can be seen on the fast-frame pictures. The guided length reaches 1.6 m for the 2.3 m gap and drops to about 1.2 m at 4.5 m gap length. The longer guiding for the 2.3 m gap can be explained by the reduced delay before space-leader formation, as described above (450 vs 800 ns). Figure 5 also displays results from earlier experiments with a laser delay between 2.4 and 5 μs in a sphere-plane gap with distances between 1.2 m and 3.8 m under negative voltage pulses with a rising time of 1.2 μs [6]. This shorter rising time further increases the delay between the high voltage maximum and the laser pulse. The experiments had been performed at moderate voltage levels so that all observed discharges were triggered by the laser. In these conditions the guided length increases linearly up to 2.4 m where a saturation seems to occur. Considering the plasma lifetime of 1 μs determined above, this suggests that the emerged electrode leader connects to the plasma channel without a delay as was observed for guided positive leaders [31]. The above condition of moderate voltage levels is essential to achieve optimum guided lengths, since at higher voltages the electrode leader is initiated before the laser. Therefore, the propagating electrode leader would connect to the filament at some point between the electrodes (see figure 3(a)): Then the discharge would be guided only from this point on.

Conclusion We have studied the triggering and guiding of negative discharges with long plasma filaments in sphere-plane gaps from 2.3 m to 4.5 m. The laser is able to provoke a space-leader if it is shot, before the final jump is initiated. The plasma lifetime relevant for triggering and guiding of discharges is about 1 μs. In the case of space-leader formation this lifetime limits the guided length to the meter range due to a delay of several hundreds of nanosends between the laser pulse and the occurence of the space-leader. If the electrode leader is guided by the plasma channel, the results suggest that the guided lengths are limited to 2.4 m due to the plasma lifetime and a measured leader velocity of 2.4×10^6 m/s.

However, in view of real scale lightning applications of this technique, numerical modeling [8] as well as recent experimental results [32, 17] show that the plasma lifetime can be enhanced by propagating a second laser pulse along the filament, improving the effective length of the filament for guiding.

With regard to a fundamental understanding of the negative discharge development, further investigation, based on more statistical accumulation and sensitive camera devices, could help to reveal the processes leading to the occurrence of a space-leader, especially to observe directly an interaction of the space-stem and streamers with the laser produced plasma channel.

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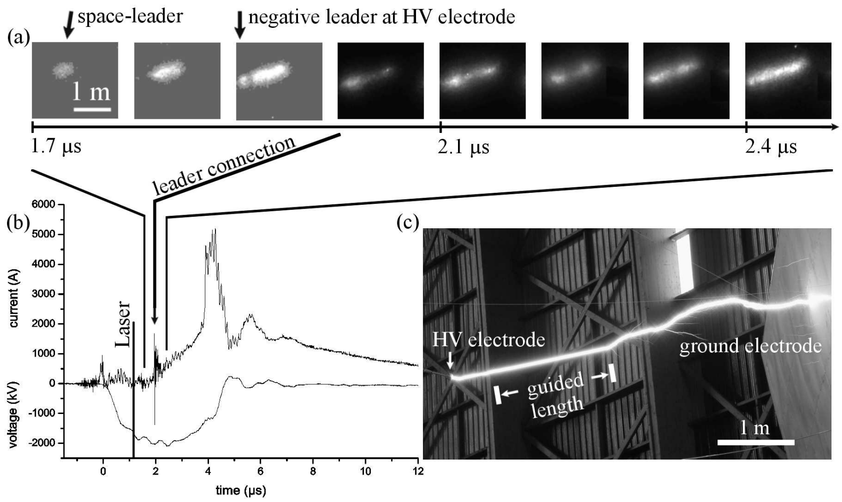

Fig. 1 (a) a sequence of fast-frame camera pictures zoomed into the first part of the gap to show space-leader formation, (b) the corresponding records of the high voltage and current and (c) a still photograph of a partially guided discharge in a 4.5 m gap. The exposure time of each fast-frame picture was 40 ns with a delay of 50 ns between each.

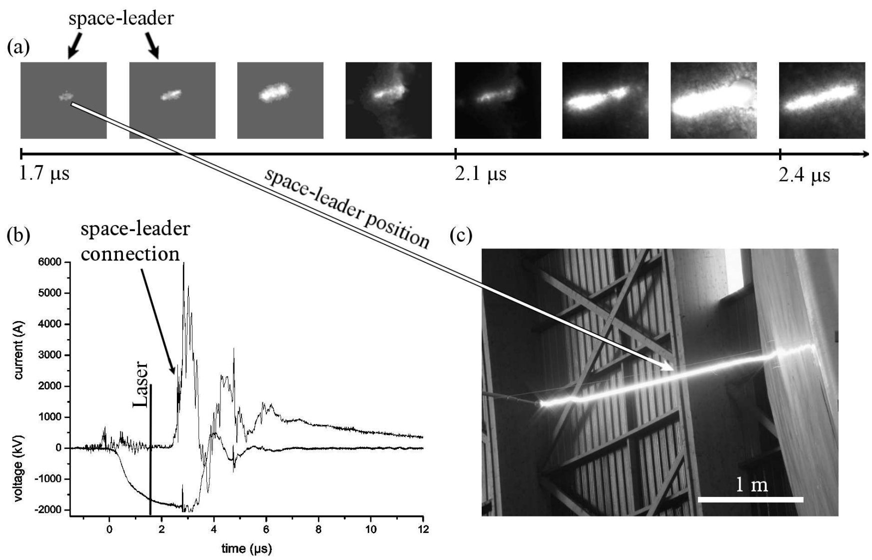

Fig. 2 (a) a sequence of fast-frame camera pictures for a triggered space-leader in a 2.3 m gap, (b) oscillograms of a space-leader discharge under similar conditions for a laser delay of 1.7 μs and (c) a still photograph of the discharge.

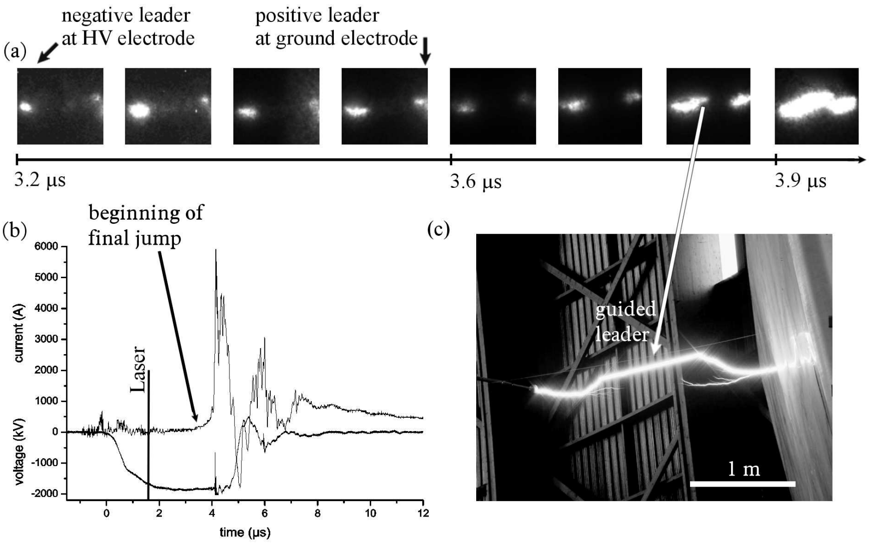

Fig. 3 (a) a sequence of fast-frame camera pictures for a guided electrode leader in a 2.3 m gap, (b) oscillograms of a discharge with a guided electrode leader under similar conditions for a laser delay of 1.7 μs and (c) a still photograph of the discharge.

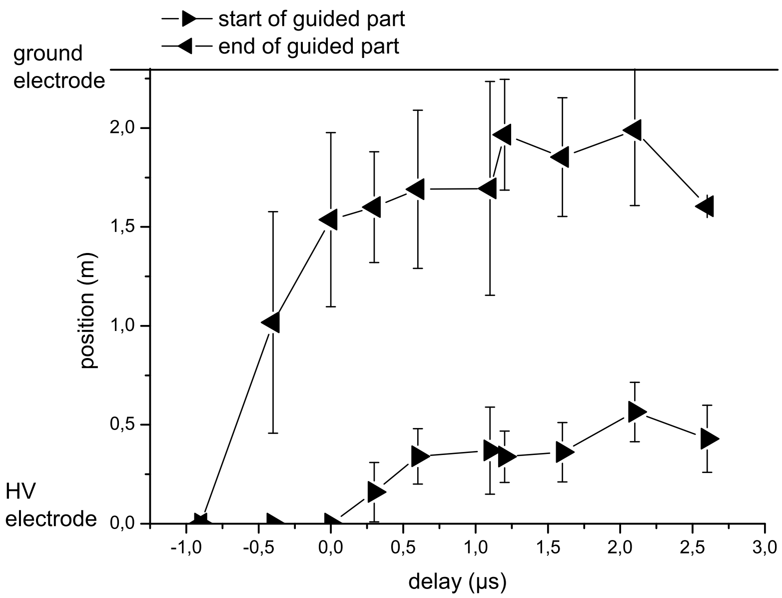

Fig. 4 Parameters of the guided parts of the discharge in a 2.3 m gap at voltage levels of about 2.0 MV. The error bars indicate the standard deviation.

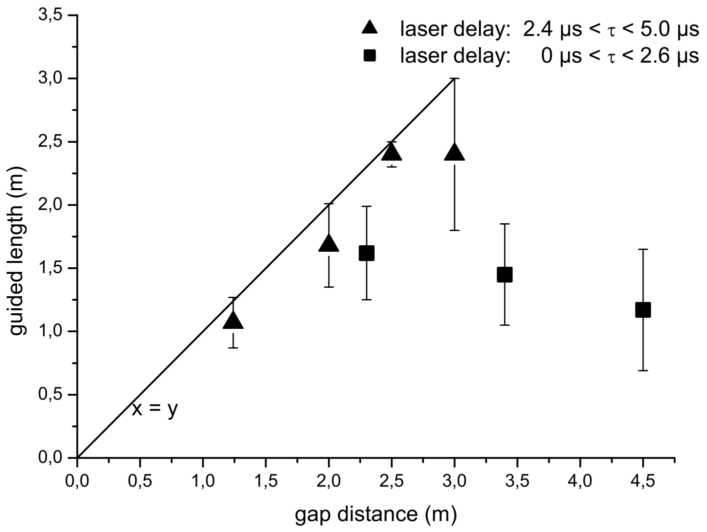

Fig. 5 The mean values of the total guided lengths as a function of the gap distance. τ denotes the time delay between the laser and the beginning of the voltage pulse, and the error bars indicate the standard deviation. The results for laser delays between 2.4 and 5.0 μs were obtained in an earlier experiment [6].