Improved laser triggering and guiding of megavolt discharges with dual fs-ns pulses

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We demonstrate that the capacity of ultrashort high-power laser pulses to trigger and guide high-voltage discharges can be significantly enhanced by a subsequent visible nanosecond laser pulse. The femtosecond pulse induces a bundle of filaments, which creates a conducting channel of low density and cold plasma connecting the electrodes. The subsequent laser pulse photodetaches electrons from O_2^- ions in the electrode leader. The resulting electrons allow efficient heating by Joule effect in a retroaction loop, resulting in a 5% reduction of the breakdown voltage. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2162430]

Triggering and guiding of lightning using laser beams has been considered for more than 30 years.[1] The main motivation is to protect sensitive sites, such as electrical installations or airports, from direct strikes and electromagnetic perturbations. Early studies in the 1970s and 1980s using nanosecond laser pulses of high energy (in the kJ range),[2] have shown severe limitations due to the lack of connected plasma channels and the large absorption of the laser pulse by the induced hot and dense plasma. In contrast, ultrashort (femtosecond) lasers can generate efficient multiphoton/tunnel ionization even at moderate energy (typically 0.1 J per pulse), while they are too short to induce cascading ionization. The weak absorption of the laser energy results in long channels of cold plasma with an electron density as low as $N_e \approx 10^{15}$ cm^{-3},[3] still several orders of magnitude above the required free-electron density for lightning initiation in the atmosphere ($N_{\mathrm{init}} \approx 5\times 10^{11}$ cm^{-3}).[4] This promising approach has been demonstrated in the ultraviolet (UV) over short scales (typically 30 cm),[4,5] as well as with infrared lasers, both focused to form a short plasma channel of 5 to 20 cm length[6,7] or longer, using multiple focusing,[8,9] and in the filamentation regime.[10,11] In the latter approach, collimated or slightly focused infrared (IR) femtosecond pulses generate long plasma channels (filaments) that ohmically connect the electrodes. Filaments[12] result from the dynamic balance between Kerr-lens focusing and the defocusing by the laser-induced plasma. In the atmosphere, filaments have been observed over several tens of meters, up to a few kilometers away from the laser source.[13] Therefore, they are good candidates to extrapolate laboratory results to the atmospheric scale (>100 m), especially since rain does not prevent the triggering effect of the filaments.[14]

A strong limitation for lightning control by filaments stems from the limited lifetime of the generated plasma, which amounts to only a few μs.[15,16] At a typical speed of 10^6 m/s,[17] the discharge can thus only propagate over a few meters,[9,11] which limits the effective guiding length to the meter scale and prevents a direct extrapolation of the laboratory results to the atmospheric scale. Hence, the key issue to trigger lightning discharges resides in increasing the plasma lifetime. For this purpose, it has been shown that the use of a train of ultrashort pulses[18] can prolong the plasma lifetime. Also, it has been suggested that a second, relatively long (ns) laser pulse of high energy (several tens of J),[4,5] referred to as the maintaining pulse, could sustain the plasma density through both photodetachement from O_2^- ions, and plasma heating by inverse bremsstrahlung. The absorption coefficient for inverse bremsstrahlung is $\alpha=\nu_{ei}\omega_p^2/c\omega^2$, where ω represents the laser frequency, $\omega_p=\sqrt{N_e e^2/m_e\varepsilon_0}$ is the plasma frequency, $\nu_{ei}=3\times 10^{-6} N_e \ln(\Lambda)/T_e^{1.5}$ is the electron-ion collision frequency, and a typical range for the Coulomb integral is $1<\ln(\Lambda)<10$.[5,8] Treating the plasma as an ideal gas and assuming that all the deposited energy heats it, an upper bound for the plasma heating is only 4 K per Joule of laser energy at $\lambda=532$ nm when considering an upper limit for the electron density $N_e=10^{21}$ m^{-3},[3] with ln $(\Lambda)=5$,[4,5]] and an electron temperature ($T_e=1$ eV), corresponding to the excess energy of the free electrons after photodetachment and multiphoton ionization. Therefore, the electron density in a filament is not sufficient for a maintaining a laser pulse of reasonable energy to significantly heat the plasma.

The main electron sink in the filaments is the attachment to O_2 molecules.[19] Since the photodetachment energy of O_2^- (0.54 eV) is well below the considered photon energies ($E_{\mathrm{photon}}=2.3$ eV at 532 nm), the single-photon photodetachment rate is $\gamma_l=\sigma_{O_2^-} I_l/\hbar\omega$, where I_l is the intensity of the maintaining pulse (in W/cm^2), $\sigma_{O_2^-,532}=1.5\times 10^{-19}$ cm^2, and $\sigma_{O_2^-,1064}=4.6\times 10^{-21}$ cm^2 at 532 and 1064 nm, respectively.[19] In standard conditions ($T=300$ K, $P=1$ atm), under an electric field $E=500$ kV/m, the attachment coefficient of electrons to O_2 molecules is $\eta=2.5\times 10^7$ s^{-1}. Therefore, pulse

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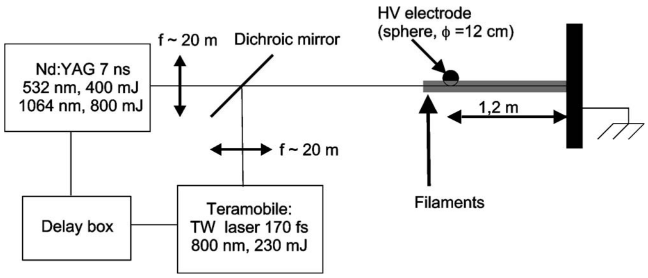

FIG. 1. Experimental setup for high-voltage discharges guiding and triggering with a double pulse configuration

energies as high as E_{532}=0.7 J and E_{1064}=2 J are required for the photodetachment to overcome attachment (i.e., $\gamma_l > \eta$). Detailed simulations based on a kinetic analysis show a maximum efficiency when the ns laser pulse is fired when the O_2^- concentration is maximum in the filaments, i.e., 10 ns after the ultrashort laser pulse.[15] However, in view of field experiments, efficiently coupling a high-energy laser on self-guided filaments may not be straightforward. In this letter, we show that a maintaining laser pulse of moderate (subjoule) energy is sufficient to significantly improve the triggering and guiding of the high-voltage discharges, because it improves the ohmic contact between streamers and filaments.

The experimental setup (Fig. 1) is similar to that of previous experiments.[11] The impulse generator (Marx multiplier circuit) of the high-voltage facility of the Technical University of Berlin provided up to 2 MV negative pulses with a rise time of 1.2 μs and an exponential decay time of 50 μs. We used a spherical high-voltage electrode of 12 cm diameter and a plane ground electrode of 3 m diameter, with a gap of 1.2 m. Prior to the experiments, the 50% flashover voltage (U_{50}) without laser has been measured to be 1300 kV.[14]

The *Teramobile* (Ref. 20) provided 100 fs pulses of 230 mJ centered at 800 nm at a repetition rate of 10 Hz. In order to optimize filamentation between the electrodes, the laser beam of 10 cm initial beam diameter was slightly focused ($f \sim 20$ m), and properly antichirped with an initial pulse duration of 170 fs. The high-voltage pulse was synchronized so that the laser was fired typically 5 μs after the maximum voltage was reached, on the voltage plateau. After an adjustable delay, the maintaining laser pulse of 7 ns duration was shot by a Nd:YAG laser (Spectra-Physics, Quanta-Ray) providing 800 mJ pulses at 1064 nm, or 400 mJ pulses at 532 nm. A telescope focused the YAG beam (initial beam diameter ~5 cm) to match its profile with that of the femtosecond beam between both electrodes. Both beams were shot onto the center of the ground electrode by passing very close to the tip electrode (1 cm, comparable with the beam diameter). The filament started some meters before the tip electrode and spanned over the whole gap. No triggered discharge could be observed with the nanosecond pulse only.

Since the occurrence of discharges in given conditions is stochastic, the effect of the lasers is characterized by accumulating statistics over 10 to 20 shots in each experimental condition. The confidence interval for the measured discharge probability is estimated by using a binomial law, based on the assumption that successive shots are independent from each other.

Figure 2 shows the discharge probability for a set of voltages well below the U_{50} for natural discharges, for both

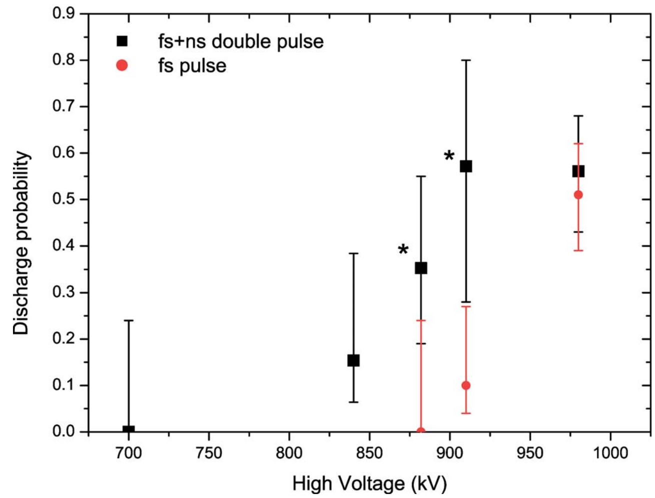

FIG. 2. Triggering probability of high-voltage discharges with both a single fs pulse alone and a dual (fs+ns) pulse with the maintaining pulse at 532 nm. The astrisk (*) denotes a statistically significant effect of the maintaining laser for individual points.

fs pulses alone, and dual pulses, with the maintaining pulse at λ=532 nm temporally overlapping the fs pulses.

The effect of the nanosecond pulse is greater for low voltages, at which the triggering probability of the femtosecond pulse alone falls down. At 880 kV and 910 kV, the effect of the YAG has a statistical significance higher than 98% even for individual points, with more than a five fold increase of the discharge probability at these voltages (Fig. 2). Moreover, the second pulse decreases the voltage required to trigger discharges by at least 40 kV, i.e., more than 5%, compared to the femtosecond laser alone. It allows discharge events at 65% of the natural U_{50}.

With the fundamental wavelength of the YAG, at 1064 nm, no significant effect could be observed although the pulse energy is twice (800 mJ) as high as the second harmonic. Also, the maintaining pulse has no significant effect when shot before the femtosecond pulse, nor when the pulses had no temporal overlap at all, i.e., when the maintaining laser pulse does not meet the plasma produced by the femtosecond pulse and cannot therefore have any action on it.

The effect of a maintaining pulse with moderate energy can be understood if considering that under similar conditions but without laser, no breakdown occurs and leaders propagate only a few centimeters within several μs.[21] Therefore, when arriving at the high-voltage electrode, the maintaining pulse crosses the leader head, with 10^{14}cm^{-3} O_2^- ion density[9] and atomic temperatures between 300 K and 1500 K. These elevated temperatures lead to significant drop of the attachment rate. For example, after 5 μs, the temperature amounts to 1200 K and the attachment rate drops by a factor of 2. Since the detachment rate is not affected by the atomic temperature, the reduced attachment rate does not balance thermal detachment any more, so that the *net* detachment rate of electrons from O_2^- ions rises by six orders of magnitude, from $\gamma_{\text{net,300K}} = 1.2 \times 10^{-6}$ s^{-1} to $\gamma_{\text{net,1200K}} = 2.7$ s^{-1}.[9] Therefore, the maintaining pulse is able to efficiently detach electrons from O_2^- ions, and the resulting higher electron density leads to more efficient heating by the Joule effect, which in turn favors photodetachment, launching a positive retroaction loop which lasts even after the end of the maintaining pulse. The resulting enhanced electron density within the streamer improves the electrical connection between the streamer and the filament. Due to the retroaction loop, the new maintaining mechanism described here is efficient at much lower laser pulse energies than those proposed earlier,[4,6] which rely on either photodetachment or heating.

In conclusion, we have demonstrated an improved triggering of high-voltage discharges by femtosecond laser pulses using a second, maintaining ns laser pulse of moderate energy. The effect is due to a positive retroaction loop involving photodetachment, improved Joule heating, and a better ohmic bridging, suggesting that the electron density keeps above 5×10^{11} cm^{-3} for a longer time. This longer lifetime could provide a way to circumvent the main limitation of the extrapolation of laboratory results to real lightning experiments. Together with recent demonstrations of high-voltage discharges triggered and guided under rain,[14] it improves the evaluation of the feasibility of a real-scale lightning control experiment. Besides increased energy for the maintaining pulse, further improvement can be reached by using a maintaining pulse of a shorter wavelength providing a more efficient photodetachment, and by optimally matching the profile of the maintaining pulse with that of the plasma channel. In that regard, the thermal expansion of the plasma channel generated by the laser[22] is favorable since it increases the active volume and reduces both the criticality of the alignment and the limitations induced by the diffraction on the propagation of a collimated maintaining pulse of small diameter.

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