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Channeling the electrical breakdown of air by optically heated plasma filaments

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Femtosecond laser pulses with sufficiently high peak power leave tracks of dilute plasma in their wakes. Potential use of this plasma for channeling electrical discharges in the atmosphere has been discussed and demonstrated in laboratory-scale experiments. However, the electron density in femtosecond laser-generated plasma decays rapidly on the nanosecond time scale, due to recombination and electron attachment to air molecules. The finite plasma lifetime limits the maximum extent of the guided electrical breakdown to a few meters. Here, we experimentally demonstrate that the limitation associated with the short plasma lifetime can be overcome though optical heating of the plasma filaments by an auxiliary energetic laser pulse with a duration in the nanosecond range. We show that the breakdown electric field can be reduced by up to a factor of 4 with a heater fluence of about 1 kJ/cm^2. This approach could have applications in channeling long-range electrical discharges in the atmosphere and, potentially, in channeling lightning strikes.

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Using powerful laser beams for the guidance of the electrical breakdown of air and for channeling natural lightning has been discussed for many years. During the 1970s, the use of energetic *Q*-switched lasers with a nanosecond pulse duration has been investigated in this context [1]. Those investigations continued into the 1990s [2,3] but have not resulted in the development of a viable guiding technology. Nanosecond lasers can easily produce free electrons in air through optically driven avalanche ionization, but only under the condition of relatively tight focusing of the laser beam. Plasma channels created in air that way are dense but not very long; a large fraction of the laser energy is lost to scattering on the plasma.

The development of femtosecond laser systems and the demonstration of self-channeling of intense femtosecond laser pulses in 1996 [4] gave new hope to the idea of guiding long-range electrical discharges in air by laser beams. In the case of an intense femtosecond laser pulse, the combined effect of self-focusing, diffraction, and photoionization of air results in the propagation regime termed "laser filamentation" [5,6]. Plasma channels produced in air that way are dilute, and thus no excessive loss of laser energy to scattering on the plasma takes place. The guidance of electrical discharges with a length of up to 3.8 m by femtosecond laser filaments has been experimentally demonstrated [7].

The above-mentioned length of the guided breakdown is, however, very close to the maximum that can be attained. The key limitation of the approach is associated with the very short lifetime of plasma in femtosecond laser filaments, which is in the nanosecond range or even shorter [8,9]. Free electrons that are produced through photoionization of air molecules by the intense laser field disappear very rapidly due to recombination and attachment to neutral oxygen molecules. The plasma channel appears to be long, but in fact its instantaneous extent is not more than few meters.

It has been established that dilute filament plasma is not sufficiently conductive to channel an electrical discharge directly. Instead, the guidance involves three essential steps [7,10]: first, a column of free electrons is generated through photoionization of air by the laser field. Second, this weakly conductive path is ohmically heated by the applied DC electric field, resulting in the temperature elevation of the gas on the beam axis by about 100 K above ambient temperature [10]. Third, the heated air column radially expands, creating a reduced-density cylindrical channel between the electrodes. Only then does electrical discharge develop. It goes through the laser-defined low-density path, since, according to the

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Paschen's law [11], the strength of the threshold electric field for DC breakdown is approximately proportional to the gas density. This guidance mechanism relies on the existence of a continuous conductive path bridging the entire gap between the electrodes. If the conductive plasma channel is discontinuous or not long enough to connect the electrodes, no ohmic heating of the weakly ionized air takes place and thus no guidance of electrical discharge happens. Thus, a nanosecond-scale plasma lifetime in femtosecond laser filaments fundamentally limits the maximum length of guided electrical breakdown to a few meters.

In this Letter, we report an experimental demonstration of an approach to overcome the above range limitation. Instead of relying on ohmic heating of the conductive plasma channel by the applied DC electric field, we directly heat the plasma by an auxiliary laser pulse with multijoule pulse energy and with a duration in the nanosecond range [12–14]. Following the terminology used in the laser particle acceleration community, we refer to the approach based on the joint application of femtosecond and nanosecond laser pulses as the igniter–heater excitation scheme [15]. Free electrons in the femtosecond laser filament absorb energy from the nanosecond heater pulse through an inverse bremsstrahlung process. Then, just like in the scenario of guidance by the femtosecond filament alone, the heat is transferred from the electrons to the gas molecules, and the gas radially expands, creating a preferred low-density path for electrical discharge to go through. The existence of a continuous conductive path bridging the entire gap between the electrodes is no longer necessary. The lifetime of the low-density guide thus produced is determined by thermal diffusion and is in the millisecond range [16], which is much longer that the lifetime of plasma in the channel.

We point out that our approach does not rely on the maintenance of conductivity in the plasma channel through detachment of electrons from the negatively charged O_2^- complexes by the heater pulse, which is the basis of the approach suggested earlier [17]. In that case, the maximum extent of the guided electrical breakdown is limited by the duration of the heater pulse. The technique proposed here is free from such a limitation. In our case, the nanosecond laser pulse simply acts as a source of heat.

For experimental demonstration of our approach, on a laboratory scale, we make use of a setup schematically shown in Fig. 1. The demonstration utilizes all-solid-state, commercially available laser sources. The DC voltage source available to us has a maximum output of 35 kV. This source is connected to two ball-shaped metal electrodes. A dilute femtosecond plasma filament is produced by a 100 fs long laser pulse at an 800 nm wavelength, with pulse energy of 15 mJ. The filament plasma is heated by a copropagating pulse from a different laser operating at a wavelength of 1.064 μm and generating pulses of 6 ns duration, with up to 3.3 J of energy per pulse. Both lasers produce 10 pulses/s, and the pulse trains from the two lasers are synchronized in time through a common electronic triggering. The delay between the femtosecond and nanosecond pulses is adjusted to maximize the effect of heating of the filament plasma. The heater pulse slightly lags behind the igniter in time. The time delay has to be shorter compared to the characteristic decay of plasma density in the igniter filament. The optimum igniter–heater delay is in the nanosecond range. The two laser beams have input diameters of about 2 cm. The beams are spatially overlapped using a dichroic mirror and focused by a common conical lens (axicon) with an apex angle of 175°. Thus the created linear focus zone for the beams has a length of about 30 cm. The linear focus is positioned about 5 mm above the ball electrodes, so that the electrodes are not directly exposed to the intense laser field. The estimated peak intensity of the igniter pulse in the interaction zone, assuming linear focusing by the axicon, is 75 $\mathrm{TW/cm^2}$, which is close to the typical value of clamped intensity inside femtosecond laser filaments in air [18].

In Fig. 2, we show experimental results for the threshold breakdown voltage versus distance between the electrodes, for the case of unguided electrical breakdown. The slope of the data curve, at a particular interelectrode separation, approximately equals the threshold breakdown electric field for that separation. For millimeter-scale separations between the electrodes, the breakdown is dominated by the Townsend mechanism, in which no significant local charge separation occurs anywhere between the electrodes. Avalanche ionization is seeded by a secondary emission from the cathode and is driven by the externally applied electric field with a breakdown threshold strength of about 30 kV/cm. As the electrode separation is increased into the several-centimeter range, the

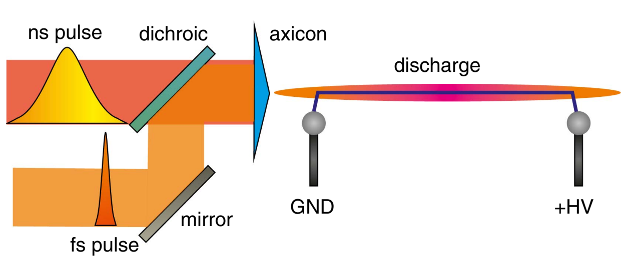

Fig. 1. Schematic of the experimental setup. Femtosecond and nanosecond laser beams are temporally and spatially overlapped and focused by a conical lens. Two ball electrodes are placed close to the beam axis. The electrical breakdown voltage is measured for different interelectrode separations and under various illumination conditions.

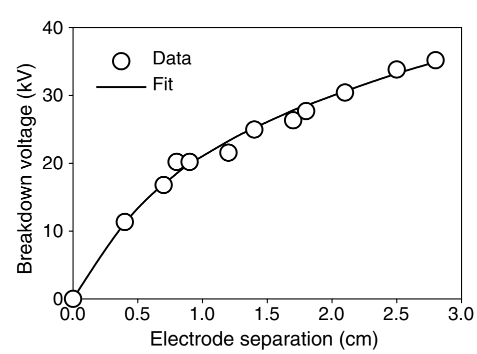

Fig. 2. Threshold breakdown voltage versus interelectrode separation for the case of unguided breakdown. The threshold breakdown field (which is the slope of this curve) decreases as the distance between the electrodes is increased, as a result of the transition from the Townsend to the streamer breakdown mechanism. Data points are shown with circles; the line is a polynomial fit.

streamer mechanism of breakdown starts to dominate, and the average breakdown field reduces to several kilovolts per centimeter. The formation of streamers relies on the local enhancement of the electric field due to charge separation in the streamer head [11]. For the case of very long breakdown sparks, including natural lightning, the average breakdown threshold field can be as low as several hundred volts per centimeter. In that case, the discharge is preceded by the formation of a breakdown leader that involves the development and merging of multiple streamers.

In Fig. 3, we show experimental data for the threshold breakdown voltage, as a function of interelectrode separation, for the cases of breakdown guided by the femtosecond laser filament alone and guidance by the filament heated by a nanosecond heater pulse, with two different heater-pulse energies. The apparent vertical offset of these curves by about 10 kV is because the 5 mm wide gaps between the electrodes and the plasma channel have to be jumped by unguided short streamers, without any help from channeling either by the laser plasma or by the reduced-density air channel. The intensity of the Bessel heater beam along its 30 cm long linear focus zone is higher in the center of the zone and declines toward its ends. Therefore, plasma heating is more intense in the middle of the channel. For the case of intermediate heater fluence of 1.0 kJ/cm^2, that results in the apparent increase of the slope of the breakdown voltage for interelectrode separations above 15 cm.

In the top part of Fig. 4, we show results for the breakdown threshold electric field versus peak fluence of the nanosecond heater pulse in the interaction zone. The energy of the femtosecond igniter pulse is fixed at 15 mJ. It is evident that the breakdown threshold field drops continuously as the fluence of the heater pulse is increased. In the bottom part of Fig. 4, we show the plasma density in the middle of the channel, on an arbitrary unit scale, versus fluence of the heater pulse. The plasma density is measured using a capacitive plasma probe described in detail elsewhere [19]. The curve shows the onset of an optically driven avalanche ionization of air at a heater fluence of about 1 kJ/cm^2. Below that level of fluence, only

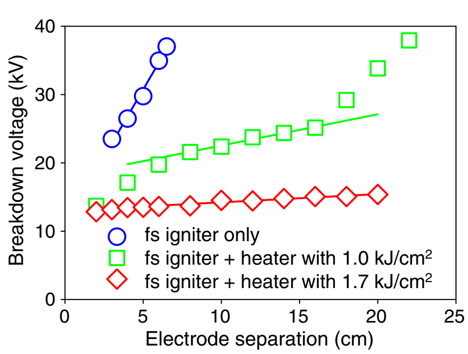

Fig. 3. Threshold breakdown voltage versus interelectrode separation, for the cases of electrical breakdown channeled by the femtosecond laser filament alone and by the filament heated by an auxiliary nanosecond laser pulse, with two different values of peak laser fluence. Optical heating of the filament plasma causes significant reduction of the breakdown threshold electric field.

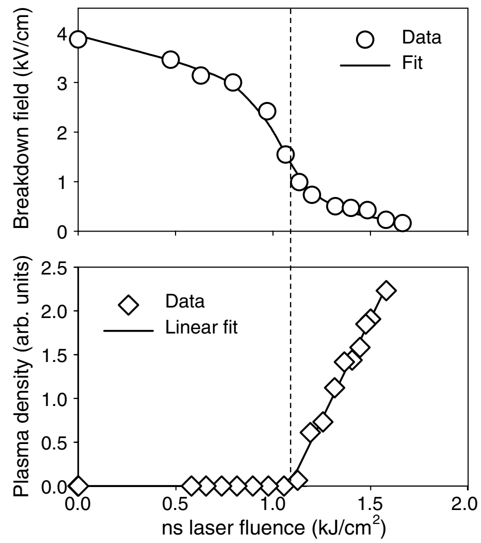

Fig. 4. Top: breakdown threshold electric field versus peak fluence of the nanosecond heater pulse in the interaction zone. The energy of the femtosecond igniter pulse is fixed at 15 mJ. The line is a polynomial fit to the data points. Bottom: corresponding plasma density in the channel on an arbitrary unit scale. The onset of optically driven avalanche ionization at the peak heater fluence of about 1 kJ/cm^2 is evident. Even below the threshold for an optical avalanche (the area to the left of the vertical dashed line), heating of the plasma channel by the nanosecond laser pulse results in significant reduction of the breakdown threshold electric field relative to the unguided case.

dilute plasma produced by the femtosecond igniter pulse is present. Its density is too low to show on the same scale with the density of dense plasma produced by an optically driven avalanche. Above the threshold for an optical avalanche, the heated channel continues to effectively channel electrical breakdown. However, the densified plasma in that case is fragmented into discrete bubbles [13,14]. Although channel fragmentation appears to be not much of a problem in our laboratory demonstration, in which both igniter and heater beams are focused by a common axicon lens, it may be undesirable in long-range applications of our approach. Producing an extended linear focus with a length above ∼10 m is very difficult, as that imposes very stringent requirements on the phase flatness of the laser beam front. Thus, in long-range implementations, the use of collimated igniter and heater beams will be more appropriate. The fragmentation of the plasma channel into discrete bubbles will cause excessive scattering losses for the heater beam. Therefore, the practically useful range of heater fluence will be that below the threshold for an optically driven avalanche, which is the region to the left of the vertical dashed line in Fig. 4. Remarkably, even below the threshold for optical avalanche ionization, the breakdown electric field can be reduced by up to a factor of 4 relative to the case of guidance by the femtosecond filament alone, with no range limitation related to the short plasma lifetime.

In order to estimate how the proposed channeling approach scales to realistic long-range situations, consider the case with an interelectrode separation of 20 m. Such a range could be practically relevant, e.g., for the remote detonation of land mines. In our laboratory-scale demonstration, a noticeable reduction of the breakdown threshold electric field relative to that for an unguided breakdown was achieved with a nanosecond pulse with a fluence in the range of 1 kJ/cm^2. A collimated Gaussian beam with a wavelength of 1 μm and Rayleigh length of 20 m will have a diameter of 5 mm. At the above-mentioned level of fluence, that beam size will correspond to a total heater pulse energy of about 200 J. Such laser energies are certainly achievable with modern solid-state laser technology.

We point out that if the 200 J heater pulse discussed above had a pulse duration of 6 ns, as in our laboratory-scale demonstration, the peak pulse power would be above the critical power for self-focusing in air, potentially causing problems associated with self-focusing of the heater beam. Thus a longer heater pulse with a duration in tens of nanoseconds would be preferred, as the optical heating effect scales not with the peak laser intensity but with the fluence [13]. For heater pulses that are longer than the lifetime of free electrons in the femtosecond igniter filament, a heater beam of sufficient intensity will cause detachment of electrons from O_2^- complexes and will continue to deposit heat into the gas [20]. Thus the maximum pulse duration of the heater pulse will not be limited by the lifetime of the igniter plasma. Alternative heater sources including powerful microwave beams may be also considered.

To summarize, we have demonstrated that the application of optical heating of dilute plasma in femtosecond laser filaments in air creates an extended low-density guide capable of channeling the electrical breakdown of air and thus leads to a significant reduction in the electrical breakdown threshold. This approach to laser guidance of electrical discharges in air alleviates the limitation on the maximum range of guidance associated with the nanosecond-scale lifetime of free electrons in femtosecond laser filaments.

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