Long-lived laser-induced arc discharges for energy channeling applications

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Laser filamentation offers a promising way for the remote handling of large electrical power in the form of guided arc discharges. We here report that it is possible to increase by several orders of magnitude the lifetime of straight plasma channels from filamentation-guided sparks in atmospheric air. A 30 ms lifetime can be reached using a low-intensity, 100 mA current pulse. Stability of the plasma shape is maintained over such a timescale through a continuous Joule heating from the current. This paves the way for applications based on the generation of straight, long duration plasma channels, like virtual plasma antennas or contactless transfer of electric energy.

Laser filamentation is a nonlinear optical phenomena that was discovered in the early days of the laser era, when damage tracks and thin fluorescent channels were witnessed in transparent condensed matter through which a powerful laser pulse propagated¹,². But it is only after the chirped pulse amplification technique was devised³ that filamentation could be witnessed in gases⁴.

This propagation regime results from the dynamic competition between the self-induced collapse of a powerful laser pulse due to the optical Kerr effect, on the one hand, and diffraction, group velocity dispersion, nonlinear absorption of the laser energy and photoionization-induced plasma defocusing, on the other hand. This yields the formation of thin and long channels - or filaments - in which the pulse is able to maintain a very high intensity seemingly without suffering from diffraction⁵⁻⁹.

A very interesting property of filaments is that while propagating in this regime, a laser pulse deposits a significant part of its energy in the propagation medium over the whole filament length. This nonlinear energy absorption occurs chiefly through high-field ionization, but also from rotational stimulated Raman scattering¹⁰. After a nanosecond-scale thermalization, this fast energy deposition is eventually converted into heat and leads to the formation and subsequent hydrodynamic expansion of a hot air cylinder along the filament, leaving a central air channel with reduced density¹¹⁻¹⁷. This in turn reduces the dielectric strength of air, meaning that a spark discharge can be induced at a voltage lower than the breakdown voltage by connecting two charged electrodes with filaments¹⁶,¹⁸. As such, laser filamentation was shown to be able to trigger and guide long sparks¹⁸⁻²¹, guide corona discharges²², and even deviate discharges from their natural path²³. Recently, Clerici et al. also demonstrated control of curved spark trajectories by means of Airy laser beams instead of the widely used Gaussian beam²⁴. Théberge and co-authors also showed that meter-sized, milliseconds duration guided discharges can successfully be developed using a double-circuit scheme²⁵,²⁶.

Filamentation-guided discharges have several interesting applications currently under active development. First, such straight and precisely controlled plasma columns can be used as a substitute for radio-frequency (RF) metallic antennas, sporting superior reconfigurability and stealth capabilities²⁷,²⁸. Laser-induced discharges have also been long envisioned as a means to transfer high intensity electrical energy. A filament lightning rod could be used to protect sensitive facilities by triggering the inception of downward leaders from lightning clouds²⁹⁻³⁰ or intercepting naturally-generated downward leaders before they reach the ground³¹⁻³⁴. They can also be used to channel electrical energy along a well-controlled path, with several pending technologies like the design of sturdy and reliable closing switches with a very low jitter³² or even a replacement for the pantograph on trains, leading to the suppression of mechanical friction with overhead power lines³³,³⁴.

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However several problems currently plague the development of such applications. Taking the example of the plasma antenna\textsuperscript{25}, the performance of these technologies directly depends on the ability of the discharge plasma to remain at the required conductivity level for as long as possible. A second problem, which is expected to become more and more important as the plasma lifetime is increased, is to be able to preserve the shape of the plasma column for the required time.

We have previously shown that the temporal evolution of electron density in filamentation-guided discharges is dictated by the discharge current waveform when the current time evolution is slow\textsuperscript{35}. From this finding we devised two different techniques to increase the plasma lifetime to a millisecond timescale, that we demonstrate in this Article:

- If a high electron density plasma is required, an oscillating current with high amplitude and low damping is best adapted. This scheme was tested using a homemade filament-triggered, 180 kV Marx generator\textsuperscript{36} to generate a 10 cm spark with \(\sim 10\) μs lifetime before injecting \(\sim 100\) A AC current in the resulting plasma to sustain it over a millisecond timescale.
- Conversely, when a lower electron density is required, a low-amplitude, long-lasting monopolar current pulse is the ideal solution. This scheme was tested using a very compact, strongly-damped 30 kV RC circuit delivering a \(\sim 10\) ms, 100 mA current pulse over a 10 cm gap.

We also show that in both cases the discharge spatial shape can be preserved over such long timescales through the continuous Joule heating of the plasma by the residual current.

**Results**

**Long duration, high current filamentation-guided discharges.** The generation of millisecond-duration, 100 A sparks was done using a slightly modified version of the double-circuit scheme already used by Arantchouk et al\textsuperscript{25}. This scheme was built around a filamentation-triggered Marx generator as the high-voltage source. Using a single laser pulse, it has previously been demonstrated that it was possible to trigger both the generator, and a guided discharge at its output up to 21 cm long with a 180 kV output voltage\textsuperscript{36}. In the present experiment the output voltage was reduced to 100 kV for practical purposes, while the gap was shortened to 85 mm to keep discharge jitter at a reasonable level. The double circuit is depicted in Fig. 1(a). It consists in two entangled RLC circuits. When gap breakdown occurs, the low energy (10 J) 5-stage Marx generator, starts to discharge in the first (R\(_2\)L\(_2\)C\(_2\)) circuit provided that L\(_2\) \ll L\(_1\). It results in damped sinusoidal oscillations at the high frequency \(f_{\text{HF}} = 156\) kHz. Once the spark is established, the capacitor C\(_2\), initially charged to U\(_2\) = 20 kV for a 32 J total energy, starts to discharge through the plasma. By carefully choosing the value of L\(_1\), with respect to the Marx generator’s impedance, almost no return current goes to the generator. This secondary (R\(_1\)L\(_1\)C\(_1\)) circuit is characterized by current oscillations with a much lower frequency \(f_{\text{LF}} = 4\) kHz. By keeping the ballast resistor R\(_2\) at a small value (10 Ω), current damping is low enough so that it oscillates for more than 1 ms (see Fig. 1(b)). We can see that \(i(t) \approx i_2(t)\) in this regime, showing the absence of return current in the Marx.

Guided discharges were characterized using three main diagnostics: electron and neutral air density profiles were recorded simultaneously by means of a two-color interferometer\textsuperscript{37}. A high speed camera was used to record time-resolved pictures of the plasma emission in the visible range for the whole duration of a given discharge. Finally current viewing resistors (shunts) were used to record the time evolution of the discharge current.

Results from the two-color interferometry are presented in Fig. 2. The simple study of interferograms (Fig. 2(a)) already brings useful information about the discharge physics, showing the formation of a steep optical index gradient propagating outwards at early times, leaving a perturbed cylinder at the center. This can be quite easily interpreted at the generation of a shock wave due to the sudden heating from the deposited energy in the plasma, which expels matter from the center of the discharge and leaves a tube of low density.

When looking at neutral and electron density radial profiles after the shock has left the field of view (Fig. 2(b)), one can see that free electrons are concentrated in the form of a narrow peak with a \(\sim 500\) μm half-width at half-maximum (HWHM). A secondary ring is also observed at a radial position corresponding to the neutral channel boundary. However, one must be cautious about the reality of this peak at the edge of the low density channel, because its position corresponds to sharp changes in the interferograms and could therefore correspond to a measurement artifact. The maximum electron density reached is on the order of \(10^{23}\) m\(^{-3}\). In the case of
standard density air, this would correspond to a ionization ratio of less than 1%. However, one can see that the corresponding neutral profile shows a much larger channel with a ~4 mm HWHM and a quasi-depleted density. Given the resolution of our instrument on the order of 10^2 m^{-3}, we therefore estimate that the residual air density in the underdense channel is below ~10% of the air density in normal pressure and temperature conditions n_0 = 2.47 \times 10^{25} m^{-3}. Consequently the real ionization ratio of the discharge plasma is at least one order of magnitude higher than previously estimated. It is even possible that the central plasma column could actually be fully ionized.

Figure 2(c) shows the time evolution of on-axis electron density, compared to that of the discharge current. At early times, when the current evolves in the high frequency regime, the electron density decays relatively quickly, almost reaching the detection threshold by 10 \mu s. However at later times, in the low-frequency regime, it is back to a level ~10^{23} m^{-3}. Interestingly, while the measurements performed at times corresponding to a local current extremum yield electron profiles, the electron density falls below the detection threshold when the current is near 0. It means that electron density starts to oscillate at twice the current frequency, as it was predicted in the case of a low frequency AC discharge current^{35}. Hint of this behavior was given by the dependence of plasma luminescence on the square of the current as recorded in reference^{25,26}, but our measurement is the first to show a direct dependence of the plasma electron density on the discharge current in the AC regime. Therefore the design of specific current waveforms could enable one to precisely control the plasma density and reach even longer discharge lifetimes. Surprisingly the plasma resistance seems not to share the oscillatory behavior of electron density. Indeed discharge current is well fitted by a double damped sine:

i(t) = I_1 \sin(2\pi f_1 t + \varphi_1)e^{(-t/\tau_1)} + I_2 \sin(2\pi f_2 t + \varphi_2)e^{(-t/\tau_2)},

which corresponds to a double RLC circuit with constant component values (Fig. 2(c)). The low frequency oscillatory component decays with a characteristic time:

\tau_2 = L_2/(R_2 + R_p) = 490 \mu s.

In this precise case, neglecting the contribution of the contact resistance between the electrodes and the spark, we find the plasma resistance to be:
Long duration, low current filamentation-guided discharges. Long-lived, low current discharges were investigated using a much simpler setup than previously. It consists in a simple RC circuit (Fig. 4(a)), in which the capacitor is charged to a voltage \(U_0\) before filaments are used to close the gap and generate a guided discharge. The goal here was to initiate a very long current pulse with a low amplitude, leading us to use a very high ballast resistor of \(230\, \text{k}\Omega\). In order to extend the gap to \(85\, \text{mm}\), like in the previous case, with a voltage as low as \(28\, \text{kV}\), we make use of an axicon lens instead of a spherical lens to generate laser filaments, a technique which proved able to decrease the breakdown voltage of air by one order of magnitude\(^{24}\). This result represents an even higher increase in discharge length than was observed with AC high voltage (~400\%\(^{41,42}\)). Since insulation constraints are much lower than in the case of the Marx generator, it is possible to continuously record the gap voltage using a simple high-voltage probe. This enables us to track the time evolution of the plasma resistance. As seen in Fig. 4(b), the current pulse generated by the gap closure has the characteristic shape of an exponential-decaying pulse from a RC circuit with a very long duration of more than \(30\, \text{ms}\) and a low peak amplitude of \(100\, \text{mA}\). Note that the total electric energy is equivalent to the one used with the double circuit (70 J vs. 42 J). The long current decay thus ensures that the low current pulse will result in a discharge with a much longer duration than with the Marx generator.

With such a simple setup, we therefore achieved a discharge duration one order of magnitude higher than the current record obtained for filamentation-triggered arcs\(^{24}\). The corresponding plasma resistance has a completely different behavior from that of long-lived, high current discharges. First, the order of magnitude of this parameter peaks at \(100\, \text{k}\Omega\), which is \(10^4\) times higher than previously. Such a high resistance is very uncommon for discharges, still it does not prevent the plasma from reaching an unprecedented lifetime. Second, the resistance...
also strongly varies with time, reaching a steady state by $\approx 50$ kΩ before sharply increasing at the end of the discharge, when plasma is starved of current, reaching 400 kΩ by 30 ms.

Compared to the Marx discharges, the current is $\sim 10^3$ lower (100 mA versus $\sim 10$ A at long times) and the plasma resistance is $\sim 10^4$ higher (100 kΩ versus $\sim 10$ Ω), meaning the Joule heating should stand at the same level in both cases. Therefore, as the discharge stability directly depends on this parameter as shown by Shneider\(^{38}\), plasma distortion in the case of low current discharges should remain at a level comparable to that of Marx discharges. Consequently we used the same diagnostic as before: films recorded using a fast camera. Figure 4(c) presents sample images of one such film, showing the discharge remains quite straight for a few milliseconds before irremediably distorting near the grounded electrode. Evaluating the normalized RMS distortion as in
the previous section yields the curve displayed in Fig. 4(d). One can see that the nRMSD equals 2% after 5 ms, increasing linearly with time and increasing well above 10% at the end of the discharge. Looking at the previous results (Fig. 3(c)), the 2% level was reached by only 800 μs with the oscillating high current. A continuous Joule heating therefore appears more favorable than an alternating one to ensure the discharge stability. This can be assessed by estimating the time evolution of the plasma temperature as it was done in the previous section: after a few hundred microseconds the plasma is back to atmospheric pressure, meaning that the temperature can be unambiguously extracted from a measurement of the plasma conductivity, which in turn can be readily extracted from the plasma resistance and the plasma section. The result in plotted in Fig. 4(d): plasma temperature keeps increasing for ~300 μs up to 4200 K before smoothly decaying, eventually reaching 3000 K after 30 ms as the current is unable to sustain the Joule heating of the discharge. Inevitably this results in a loss of stability.

Discussion
Two main facts can be assessed from these experiments: first, the discharge plasma from a previous, short duration spark can be sustained for a much longer time by channeling electric energy from another source. Second, this sustaining can be achieved using a very low current amplitude. The key parameter ensuring the discharge stability appears to be the plasma temperature. When the temperature decreases, a flow from the surrounding air will start to fill the low-density tube surrounding the plasma, eventually becoming turbulent and strongly disrupting the discharge straightness. Conversely if the temperature can be maintained through the Joule heating of the plasma, this deleterious effect can be prevented.

Therefore the lengthening of the discharge lifetime is an aspect that can be completely dissociated from the lengthening of the discharge gap. Indeed already exist methods based on filamentation-guided discharges that can be used to generate meter-long sparks using small-scale high-voltage sources. Once a well-guided spark is generated, only the external circuit supplying current to the plasma can play a role in the discharge stabilization. One has to be particularly careful to the current waveform used to make sure that the plasma temperature, and therefore the discharge stability, is maintained.

In these experiments we only used tabletop voltage sources and relatively small capacitors. With a larger power supply, one could extend the lifetime of a guided discharge by several orders of magnitude, at least until convection of the generated hot air finally disrupts the channel.

Methods
Guided discharge generation. The generation of guided discharges was done using a chirped pulse amplification Ti:sapphire laser chain able to deliver pulses as short as 50 fs and with an energy up to 200 mJ. In the case of the Marx generator, 200 mJ, 700 fs pulses were focused using a 5 m spherical lens, generating a ~2 m long multifilament bundle both in the discharge gap and through the whole Marx generator. For the low-current discharges, the spherical lens was replaced by an axicon lens with a 5° apex angle, yielding a much shorter plasma column with a ~20 cm length using a 100 mJ, 50 fs laser pulse. As both setup used gaps initially charged with a constant voltage, no synchronization was required between the laser system and the high-voltage circuits.
Discharge diagnostiscs.

- Films of discharges were made using a Fastcam SA-X2 ultrafast camera from Photron, Inc.
- The density of heavy species and of free electrons in the plasma was recorded using a two-color interferometer. This works by recording simultaneously the plasma refractive index at two different wavelengths. As the contribution of heavy species is almost independent of the wavelength, while it has a quadratic dependence for free electrons, one can then solve an equation system with two unknowns to finally retrieve plasma densities. Interferometry was performed transversely on the Marx generator discharges, followed by Abel inversion of the recorded phase shift profiles, enabling us to extract free electron density and neutral density with a 1 cm wide field of view, a 10 μm spatial resolution and a 10 time resolution, yielding a ~10²² m⁻³ resolution for electron density and a ~10²⁴ m⁻³ resolution for neutral density.
- For both low and high current discharges, current waveforms were recorded using current viewing resistors (shunts) from T & M Research Products.
- Gap voltage for low-current discharges was tracked using a PVM-1 high-voltage probe from North Star High Voltage.

Discharge shape stability indicator. We designed a scalar indicator to assess the shape stability of a guided discharge, based on time-resolved side pictures of the arc. These pictures can be described as two-dimensional \((y, z)\) luminescence maps, where \(z\) is taken along the discharge axis (Fig. 5). For each picture, taken at different times, the curve yielding the position \(y_{\text{\max}}(z, t)\), that is the luminescence ridge position (black curve on Fig. 5), is extracted. This curve is to be compared to a reference curve \(y_{\text{\ref}}(z)\) (light blue curve on Fig. 5), which is taken as the luminescence ridge curve \(y_{\text{\max}}(z, t = 0)\) estimated at the breakdown time. The indicator, dubbed root mean square distortion, or RMSD, is calculated at time \(t\) following:

\[
\text{RMSD}(t) = \sqrt{\frac{\sum_{i=1}^{N_{\text{pixels}}} (y_{\text{\max}}(z_i, t) - y_{\text{\max}}(z_i, t = 0))^2}{N_{\text{pixels}}}},
\]

\(N_{\text{pixels}}\) being the number of pixels along \(z\).

The normalized RMSD, or nRMSD, is just taken as:

\[
n\text{RMSD}(t) = \frac{\text{RMSD}(t)}{L_{\text{gap}}},
\]

where \(L_{\text{gap}}\) is the length of the discharge gap along \(z\). A null nRMSD means that the discharge has exactly the same shape as it has initially. A nRMSD equal to 1 means that the transverse distortions of the discharge with respect to the reference path are on the order of the gap length, a very high value.

Data availability. The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

Conclusion

In this Article we investigated two different schemes for increasing the lifetime of laser filamentation-guided discharges based on the design of the discharge current waveform. In the first one, a first electrical circuit was used to generate a first spark, before a second circuit started to discharge through the resulting plasma column, sustaining it for more than 1 ms, three orders of magnitude longer than with the first circuit alone. In the second scheme, a single, low amplitude and long duration current pulse was used directly from the inception of the filament-triggered discharge, yielding an even longer arc of 40 ms. In both cases, the discharge stability was maintained for ~1 ms by means of Joule heating from the current itself, preventing the turbulent decay of the low-density tube surrounding the plasma column. Although these experiments were performed with relatively small-scale discharges (85 mm), they can be easily transposed on larger setups because the initial spark generation
and the subsequent sustaining of the discharge are completely uncorrelated. In recent experiments we increased the gap length to the meter-scale without much difficulty. This will be reported later.

As such, these results represent a significant achievement for the development of technologies in need of a non-solid, long-lived and stable conductor like the virtual RF antenna or the contactless transfer of electrical energy.

References
1. Hercher, M. Laser-induced damage in transparent media. J. Opt. Soc. Am. 54, 563 (1964).
2. Shen, Y. R. & Shaham, Y. J. Beam deterioration and stimulated raman effect. Phys. Rev. Lett. 15, 1008–1010 (1965).
3. Strickland, D. & Mourou, G. Compression of amplified chirped optical pulses. Opt. Commun. 56, 219–221 (1985).
4. Braun, A. et al. Self-channeling of high-peak-power femtosecond laser pulses in air. Opt. Lett. 20, 73–75 (1995).
5. Couairon, A. & Mysyrowicz, A. Femtosecond filamentation in transparent media. Phys. Rep. 444, 47–189 (2007).
6. Berge, L., Skupin, S., Neter, R., Kasparian, J. & Wolf, J. P. Ultrafast light pulses of light in weakly ionized, optically transparent media. Rep. Prog. Phys. 70, 1633 (2007).
7. Kasparian, J. & Wolf, J.-P. Physics and applications of atmospheric nonlinear optics and filamentation. Opt. Express 16, 466–493 (2008).
8. Chen, S. L. et al. Advances in intense femtosecond laser filamentation in air. Laser Phys. 22, 1–53 (2012).
9. Milchberg, H. M. et al. The extreme nonlinear optics of gases and femtosecond optical filamentation. Phys. Plasmas 21, 100901 (2014).
10. Rosenthal, E. W. et al. Sensitivity of propagation and energy deposition in femtosecond filamentation to the nonlinear refractive index. J. Phys. B 48, 094011 (2015).
11. Vidal, F. et al. Modeling the triggering of streamers in air by ultrashort laser pulses. IEEE Trans. Plasma Sci. 28, 418–433 (2000).
12. Tzortzakis, S. et al. Femtosecond laser-guided electric discharge in air. Phys. Rev. E 64, 057401 (2001).
13. Cheng, Y.-H., Wahlstrand, J. K., Jhajj, N. & Milchberg, H. M. The effect of long timescale gas dynamics on femtosecond filamentation. Opt. Express 21, 4740–4751 (2013).
14. Wahlstrand, J. K., Jhajj, N., Rosenthal, E. W., Zahedpour, S. & Milchberg, H. M. Direct imaging of the acoustic waves generated by femtosecond filaments in air. Opt. Lett. 39, 1290–1293 (2014).
15. Lahay, O. et al. Long-lived waveguides and sound-wave generation by laser filamentation. Phys. Rev. A 90, 021801 (2014).
16. Point, G., Milián, C., Couairon, A., Mysyrowicz, A. & Houard, A. Generation of long-lived underdense channels using femtosecond filamentation in air. J. Phys. B 48, 094009 (2015).
17. Point, G., Thouin, E., Mysyrowicz, A. & Houard, A. Energy deposition from focused terawatt laser pulses in air undergoing multifilamentation. Opt. Express 24, 6271–6282 (2016).
18. Zhang, X. M., Diels, J. C., Wang, C. Y. & Eliondo. J. M. Femtosecond ultraviolet laser pulse induced lightning discharges in gases. IEEE J. Quantum Electron. 31, 599–612 (1995).
19. La Fontaine, B. et al. Guiding large-scale spark discharges with ultrashort pulse laser filaments. J. Appl. Phys. 88, 610–615 (2000).
20. Rambo, P., Schwarz, J. & Diels, J.-C. High-voltage electrical discharges induced by an ultrashort-pulse uv laser system. J. Opt. A 3, 146 (2001).
21. Rodriguez, M. et al. Triggering and guiding megavolt discharges by use of laser-induced ionized filaments. Opt. Lett. 27, 772–774 (2002).
22. Wang, T.-J. et al. Direct observation of laser guided corona discharges. Sci. Rep. 5, 18681 (2015).
23. Forestier, B. et al. Triggering, guidance and deviation of long air spark discharges with femtosecond laser filament. AIP Adv. 2, 012151 (2012).
24. Clerici, M. et al. Laser-assisted guiding of electric discharges around objects. Sci. Adv. 1, e1400111 (2015).
25. Aranchoth, L. et al. Prolongation of the lifetime of guided discharges triggered in atmospheric air by femtosecond laser filaments up to 130 μs. Appl. Phys. Lett. 108, 173501 (2016).
26. Théberge, F., Daigle, J.-F., Kieffer, J.-C., Vidal, F. & Châteauneuf, M. Laser-guided energetic discharges over large air gaps by electric-field enhanced plasma filaments. Sci. Rep. 7, 40063 (2017).
27. Dwyer, T. et al. On the feasibility of using an atmospheric discharge plasma as an rf antenna. IEEE Trans. Antennas Propag. 32, 141–146 (1984).
28. Belet, Y. et al. Radiofrequency plasma antenna generated by femtosecond laser filaments in air. Appl. Phys. Lett. 101, 264106 (2012).
29. Kasparian, J. et al. Electric events synchronized with laser filaments in thunderclouds. Opt. Express 16, 5757–5763 (2008).
30. Comtois, D. et al. Triggering and guiding of an upward positive leader from a ground rod with an ultrashort laser pulse-I: experimental results. IEEE Trans. Plasma Sci. 31, 377–386 (2003).
31. Comtois, D. et al. Triggering and guiding of an upward positive leader from a ground rod with an ultrashort laser pulse-II: modeling. IEEE Trans. Plasma Sci. 31, 387–395 (2003).
32. Aranchoth, L. et al. A simple high-voltage high current spark gap with subnanosecond jitter triggered by femtosecond laser filamentation. Appl. Phys. Lett. 102, 163502 (2013).
33. Klapis, D., Hackam, R. & Beanson, F. A. Electric arc power collection for high-speed trains. P. IEEE 64, 1699–1715 (1976).
34. Houard, A. et al. High current permanent discharges in air induced by femtosecond laser filamentation. Appl. Phys. Lett. 90, 171501 (2007).
35. Point, G., Aranchoth, L., Carbonnel, J., Mysyrowicz, A. & Houard, A. Plasma dynamics of a laser filamentation-guided spark. Phys. Plasmas 23, 093505 (2016).
36. Aranchoth, L. et al. Compact 180-kv Marx generator triggered in atmospheric air by femtosecond laser filaments. Appl. Phys. Lett. 104, 103506 (2014).
37. Point, G. et al. Two-color interferometer for the study of laser filamentation triggered electric discharges in air. Rev. Sci. Instrum. 85, 123101 (2014).
38. Shneider, M. N. Turbulent decay of after-spark channels. Phys. Plasmas 13, 073501 (2006).
39. Capitelli, M., Colonna, G., Gorise, C. & D’Angola. A. Transport properties of high temperature air in local thermodynamic equilibrium. Eur. Phys. J. D 11, 279–289 (2000).
40. Leonov, S. V., Isakmon, Y. I. & Shneider, M. N. Suppression of the turbulent decay of an afterspark channel with residual current. Phys. Plasmas 14, 123504 (2007).
41. Daigle, J.-F. et al. Dynamics of laser-guided alternating current high voltage discharges. Appl. Phys. Lett. 103, 184101 (2013).
42. Aranchoth, L. et al. Large scale tesla coil guided discharges initiated by femtosecond laser filamentation in air. J. Appl. Phys. 116, 013303 (2014).

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Author Contributions
A.H. and A.M. conceived and supervised the project. G.P., L.A. and J.C. built the experimental devices. G.P., L.A., E.T., J.C. and A.H. performed the experiments. G.P., E.T. and L.A. conducted the data analysis. G.P. wrote the manuscript. All authors contributed equally in discussing and interpreting results.

Additional Information
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