Corrigendum: Extended lifetime of high density plasma filament generated by a dual femto–nanosecond laser pulse (2014 New J. Phys. 16 123046)

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The nanosecond laser intensity units on page 7 (second line from below) and all the units in the caption of figure 4 (page 8) should be TW cm⁻² instead of GW cm⁻².

In particular:

- Page 7, second line from below:
  '0.44 GW cm⁻²' should be corrected to '0.44 TW cm⁻²'

- Page 8, caption of figure 4:
  '0.44 GW cm⁻²' should be corrected to '0.44 TW cm⁻²'
  '0.22 GW cm⁻²' should be corrected to '0.22 TW cm⁻²'
  '0.11 GW cm⁻²' should be corrected to '0.11 TW cm⁻²'

These are unintentional typo errors. There are no implications whatsoever on the results or the conclusions within the article. The typo creates a contradiction within the article and points to unrealistic results. It might confuse the readers, and therefore should be corrected.
Extended lifetime of high density plasma filament generated by a dual femtosecond–nanosecond laser pulse in air

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Abstract
A substantially extended lifetime of a high-density plasma channel generated in the wake of an intense femtosecond pulse propagating in air is experimentally demonstrated. Free electron density above $10^{15}$ cm$^{-3}$ in the formed plasma filament is measured to be sustained for more than 30 ns. This high-density plasma lifetime prolongation of more than one order of magnitude is achieved by properly timed irradiation of the filament with a relatively low-intensity nanosecond laser pulse, in comparison with a filament without such irradiation. The experimental results are in good agreement with our theoretical model that follows the evolution of the temperature and density of various molecules, atoms, and ion species. The results point to the possibility of generating extremely long time duration, stable high-density plasma filaments in air.

Keywords: femtosecond filamentation, plasma filaments, high power lasers, air plasma, laser plasma interaction

1. Introduction

Filamentation of an ultra-short pulsed high-intensity laser beam in air takes place when nonlinear self-focusing due to the optical Kerr effect overcomes the natural diffraction of the
beams. Eventually the increasing intensity of the focusing beam reaches the ionization threshold of the medium, leading to plasma defocusing, which balances the focusing effect (see [1, 2] for detailed review). Left by itself, the laser filamentation process has a stochastic nature in the position and number of the produced filaments. Nevertheless, in each filament a plasma channel of about 100 μm in diameter is formed by the high-intensity laser pulse head. This conducting channel in air opens up the potential for many applications, such as THz radiation sources, spectral manipulations of the laser pulse, remote radiation sources, remote triggering and guiding of electrical discharges [1, 2], and generation of high-power optical waveguides [3]. However, control of the position and number of the filaments as well as maintaining a minimal electrical conductivity of the plasma channel over a relevant time are fundamental conditions for most of the possible applications. Introducing an intended astigmatism into the laser beam was demonstrated to increase shot-to-shot stability and to enable control of the number of the produced filaments [4]. Furthermore, using telescopic systems was shown to enable controlled remote generation of the filaments [5]. Typical laser intensities in a filament are on the order of $5 \times 10^{13}$ W cm$^{-2}$ [6], and peak density of free electrons in these plasma channels is on the order of $10^{16}$ cm$^{-3}$ [7–10]. These electrons are produced mostly by multiphoton ionization of oxygen molecules due to their lower ionization potential, 12.2 eV compared with 15.6 eV for nitrogen molecules. However, the lifetime of these high-density plasma channels is only a few nanoseconds. The electron density decreases by more than an order of magnitude in less than 3 nanoseconds due to recombination followed by much slower attachment [7–9]. These mechanisms introduce an inherent limitation on the length of the high-density plasma channel as its head propagates with the laser pulse, whereas the tail decays a few nanoseconds afterward, thus limiting the length of the channel with electron density above $10^{15}$ cm$^{-3}$ to a few tens of centimeters.

The key issue required to achieve elongated high-density plasma channels is to prolong the lifetime of the free electrons in the plasma filaments, i.e., to sustain electron densities on the order of $10^{15}$ cm$^{-3}$ or higher (for example [11]). In our earlier work [12] it was proposed that a combination of a high-intensity short pulse Ti-Sapphire laser and a low-intensity 100 ns-duration CO$_2$ laser pulse can be used to remotely produce a plasma-based source with its lifetime on the microsecond timescale. Numerical studies of femtosecond laser-generated plasma channels in an external electric field and irradiated by an additional laser pulse were also reported [13, 14]. Experiments aimed at increasing the lifetime of low-density plasma channels by detaching electrons from negatively charged oxygen molecules (produced by electron attachment) with a delayed ns laser pulse were reported [15, 16]. Recent experiments have demonstrated the increase in a time-integrated plasma signal attributed to optically driven avalanche ionization imposed by a femtosecond laser pulse combined with a co-propagating multi-Joule nanosecond pulse. Those experiments in air were always accompanied by fragmentation of the plasma channel into discrete plasma bubbles randomly scattered along the channel [17]. The length of an optical filament was shown to be extended by employing an additional weakly focused femtosecond pulse, which co-propagates with the optical filament and supplies energy to it [18].

In this paper we demonstrate experimentally for the first time plasma filaments with electron density above $10^{15}$ cm$^{-3}$ that are being sustained longer by an order of magnitude than a typical filament generated by a single femtosecond pulse. This substantial extension of the high-density plasma lifetime is achieved by irradiating the plasma channel with a 10 ns-duration
secondary laser pulse with energy of several hundreds of mili-Joules. In this scheme the plasma generated by the femtosecond pulse acts as seed target plasma to absorb energy delivered by the nanosecond pulse. The intensity of the secondary laser pulse is well below the breakdown threshold of air [19] and is not high enough to generate plasma bubbles. The secondary laser heats the plasma and keeps its density above $10^{15}\text{cm}^{-3}$ for a considerably extended time. This heating mechanism, which was not addressed in previous schemes using a delayed nanosecond laser [15, 16], is a key factor in our approach.

In the following section we describe the experimental setup and the density measurement technique. Our filament stabilization scheme [4, 5], enables us to reproduce the initial plasma channel conditions while altering the time delay of the second laser. We therefore can fully explore the influence of the second laser pulse on the plasma channel. The results of this study are presented in the third section followed by results of our detailed theoretical model. Finally we present a discussion and point to possible extensions of the current scheme.

2. Experimental setup and methodology

The temporal evolution of the plasma density was measured by monitoring the interaction of the plasma filament with a low-intensity continuous wave (CW) microwave (MW) propagating in a rectangular single-mode waveguide. This method enables a direct time-resolved measurement of free electron density in a single plasma filament. The electron density is obtained over the entire process of plasma evolution with spatial resolution along the filament of 0.5 cm and temporal resolution of 0.3 ns. This method was described in detail in our previous publication and was used recently to study temporal relaxation of a short-pulse-generated plasma filament [9, 10]. A brief summary of the measurement technique is presented here for completeness. The MW diagnostic system is composed of a 15 mW, 34.7 GHz circularly polarized CW MW source coupled by a horn antenna to a single-mode rectangular waveguide (Ka band). The MW radiation in the waveguide is monitored by a fast MW probe connected to a 3 GHz bandwidth oscilloscope. The plasma filament is introduced into the center of the waveguide, with its axis parallel to the direction of the electric field of the TE$_{10}$ mode. The wavelength of the MW radiation is two orders of magnitude larger than the dimensions of the plasma, but since the interaction is confined by a cavity of the single-mode waveguide, the filament affects the free propagation of the MW TE$_{10}$ mode and a reduced intensity is measured by a MW detector. A schematic of the experimental setup is presented in figure 1. The MW propagation along the waveguide is attenuated by the free electrons in the plasma filament. As the plasma density decays, the transmission improves, making it possible to monitor the history of the electron density. The temporal resolution of the measurements is 0.3 ns, determined by the bandwidth of the detecting electronics, and the spatial resolution is 3 mm, determined by the dimensions of the MW waveguide. This experimental technique enables an accurate and simple time-resolved derivation of the electron density in the plasma channel. It is non-interferent with the filament, easy to align, and not sensitive to small variations in the radial position of the filament.

The filament was generated by a 1 TW, 100 fs Ti:Sapphire laser system focused by an $f=2\text{m}$ lens. Without any intervention this laser is expected to produce multiple filaments. We gradually reduced the energy of the laser and tilted the lens to an angle of $\approx 5^\circ$, in concurrence with our previously developed technique [5], so that a single stable filament was produced. This method reduces shot-to-shot variations in the radial position of the filaments to spread less than
140 μm after 5-meter propagation. Filament stabilization is crucial for conducting repeatable single-shot experiments since it assures similar overlap conditions of the two pulses and therefore similar intensity of the secondary laser applied on the initial plasma filament.

The filament was irradiated by a second counter-propagating Nd:YAG (λ = 1.064μm) laser with 10 ns pulse duration and energy in the range of 50 to 800 mJ. The Nd:YAG laser was focused by an f = 1 m lens in such a way that temporal and spatial overlap of the two beams was made to occur within the area monitored by the MW diagnostics. The temporal delay between the two lasers was controlled electronically, with an accuracy of ±3 ns, and monitored by a fast photodiode placed in front of the MW diagnostics. To ensure spatial overlap, the two beams were aligned with a 100 μm pinhole placed at the location of the waveguide prior to the experiment. The intensity of the Nd:YAG laser was varied by controlling its energy by neutral density filters.

The experimental procedure was as follows: at first, a single stable filament was generated, and its plasma evolution was recorded by the MW diagnostics. Afterward, the Nd:YAG laser pulse was introduced and plasma evolution induced by both lasers was recorded. The experiment was repeated for various delays between the two lasers. By varying the temporal delay between the femtosecond and nanosecond lasers we demonstrated the preferential conditions for extension of high-density plasma lifetime in a filament. An additional measurement was conducted to assure that no signal was generated by the secondary laser alone. This procedure was repeated for various energy outputs of the secondary laser ranging from 50 to 850 mJ. Special care was given to prevent the lasers from irradiating any solids in the area of the MW system, in order to prevent ejecta that could obscure the measurements. Two delrin plates were placed in front of the waveguide from both sides to prevent the lasers from ablating the waveguide surface. All beams were aligned with a removable pinhole with diameter of 100 μm placed in front of the delrin plate (d1) prior to the experiment. The Nd:YAG beam was diverted by 0.6° of the optical axis to prevent the filament from damaging the f = 1 m
lens. This method [9] enables a direct time-resolved derivation of the electron density and is insensitive to the position of the plasma channel in the MW diagnostics.

3. Measurements of plasma lifetime

Highly reproducible results are presented in figure 2. The derived electron density at $t = 0$ shown in that case is $1.4 \times 10^{16}$ cm$^{-3}$, in good agreement with [9, 10]. The electron number density in the plasma channel left in the wake of a single Ti:Sapphire laser pulse with energy of 15 mJ is represented by the blue curve. The electron density drops by an order of magnitude in less than 3 ns. The red curve represents a measurement of plasma density in a similar filament, irradiated by the secondary Nd:YAG pulse, temporally centered 7 ns after the short pulse. The intensity of the Nd:YAG laser at the plasma channel in that case was $130 \text{GW cm}^{-2}$. This intensity is below the threshold of channel fragmentation, and no visible plasma bubble formations were observed. The effect of the channel’s lifetime extension is clearly seen by comparing both curves. The electron density remains above the value of $10^{15}$ cm$^{-3}$ for more than 30 ns.

The effect of the temporal delay between the two pulses is presented in figure 3. The experimental data are averaged over 10 laser shots to reduce the effect of electronic noise. It is seen that the temporal delay strongly affects the temporal profile of the plasma density. Best results for maintaining electron density above $10^{15}$ cm$^{-3}$ in the current setup are obtained by delay between the two pulses in the range of 4–10 ns.

4. Numerical modeling

The plasma temporal evolution measured in the experiment is compared with a numerical model that describes the interaction of the two laser pulses with air. We solved rate equations to calculate the electron and air density and temperature. The model includes multiphoton and impact ionization, recombination, attachment, detachment and dissociation, and electron Joule heating. The electrons are heated by inverse bremsstrahlung, and they further ionize, excite, and
dissociate air molecules. The air is heated due to energy transfer from the electrons through electronic and vibrational excitations of molecules. The additional ionization and electron heating generated by the nanosecond pulse is accompanied by vibrational excitation and heating of the air. A large number of air species are considered in the model, including the molecules O$_2$ and N$_2$ in ground states and vibrational excited states; O and N atoms; electrons; the positive ions O$_2^+$, N$_2^+$, O$^+$, and O$_4^+$; and the negative ions O$_2^-$ and O$^-$. The rates of the reactions among the above species were taken from reference [20] and CHMAIR [21, 22].

The energy balance in the air plasma in the model is described by the time evolution of the electrons, molecular vibrations, and air temperatures. The electrons are heated by the laser through Ohmic heating and are cooled by excitation of molecular vibrations and by direct air heating due to elastic electron–molecule and Coulomb collisions. The molecular vibrations are excited by collisions with the electrons and further heat the air by vibrational–translational (VT) relaxation. Therefore the time-dependent electrons, molecular vibrations, and air temperatures

Figure 3. Time-resolved experimental measurements of free electron density in plasma filament. Blue curves are the electron density in a filament generated by a single femtosecond laser pulse. Red curves correspond to a similar filament irradiated by a 12 ns-duration Nd:YAG laser temporally centered at different times. The gray shaded curve indicates the envelope of the Nd:YAG. The timing of the ns pulse is (a) $t=-2.6$ ns, (b) $t=0$, (c) $t=3.5$ ns, (d) $t=8$ ns, (e) $t=11$ ns, (f) $t=16$ ns.
are

\[
\frac{d}{dt} \left( \frac{3}{2} n_e k_B T_e \right) = J_L - \frac{3}{2} n_e k_B (T_e - T_i) v_{ce} - \frac{3}{2} n_e k_B (T_e - T_g) \frac{2m_e}{M} v_c
\]

\[
\frac{d}{dt} (E_v) = \frac{3}{2} n_e k_B (T_e - T_i) v_{cv} - \frac{E_v - E_{v0}}{\tau_v T} + \frac{E_v - E_{v0}}{\tau_v T}
\]

The electrons and air number densities are \(n_e\) and \(n_g\); \(k_B\) is the Boltzmann constant; \(m_e\) is the electron mass; \(c\) is the speed of light; and \(M\) represents an effective air molecule mass defined by 

\[
M = \frac{M_{N_2} \cdot M_{O_2}}{0.8 \cdot M_{N_2} + 0.2 \cdot M_{O_2}}
\]

where \(M_{N_2}\) and \(M_{O_2}\) denote the mass of the nitrogen and oxygen molecules. The Ohmic heating rate is given by 

\[
J_L = \frac{4 \pi e^2 n_e v_c}{m_e c^2} \omega^2 + \frac{v_c}{L}
\]

\(e\) is the electron charge, \(\omega\) is the laser frequency, \(I_L\) is the laser intensity, and the electron collision frequency \(v_c = v_{cn} + v_{ci}\) is the sum of the electron–neutral \(v_{cn}\) \([s^{-1}] \approx 10^{-7} n_g [cm^{-3}] \cdot T_e^{0.5} [eV]\) and the electron–ion \(v_{ci} [s^{-1}] \approx 10^{-5} n_e [cm^{-3}] \cdot T_e^{-1.5} [eV]\) contributions. The cooling frequency \(v_{ce} [s^{-1}] = \frac{Q_n}{5 k_B T_e}\) is related to the cooling rate \(Q_n\) due to all inelastic collisions and includes internal excitations of vibrational, rotational, and electronic states of air. The cooling rate as a function of electron temperature is taken from references [22, 23]. The vibrational energy of air \(E_v\), its equilibrium value \(E_{v0}\), and the VT-relaxation time \(\tau_v T\) are taken from [14].

The rate equations for the plasma channel electrons and air species density and temperature evolution were solved for a range of temporal delays between the short pulse and the long pulse lasers and for different long-pulse laser energies.

The temporal evolution of electron and vibration temperatures is shown in figure 4 for different nanosecond laser intensities. During the time scale considered here the air temperature \(T_g\) does not change; therefore, it is not displayed in the figure. To emphasize the role played by the excitation of the vibrations in the energy balance, the inset of figure 4 displays the calculated electron temperature for the same nanosecond pulse intensities without taking into account electron cooling by vibrational excitation. It is seen that for all three laser intensities considered, the electron temperature rises sharply, above 10 eV, in less than 1 nanosecond (figure 4, inset). For the case of air irradiation with the femtosecond pulse only, the electron temperature in the plasma filament increases sharply to a maximum of about 0.45 eV and outside it the cooling term remains constant (figure 4, inset, magenta curve). When accounting for the cooling term, in the case of air irradiation with the femtosecond pulse only, the electron temperature in the plasma filament increases sharply and then decreases to the ambient temperature on a time scale of a few nanoseconds due to the vibrational sink. The change in the temperature of the vibrations is less than \(3 \cdot 10^{-2} \text{ eV}\) (figure 4, dashed magenta line), and the energy absorbed by the electrons from the short-pulse laser is not sufficient to increase the temperature of the vibrations. For the dual-pulse case, the electron temperature increases to a maximum value, for example, 1.9 eV for a nanosecond laser intensity of 0.44 GW cm\(^{-2}\) (figure 4, solid red line), at a time corresponding to the peak of the long-pulse laser and then decreases on a time scale of the
duration of the long pulse due to transfer of energy to vibrations. The temperature of the vibrations rises (figure 4, dashed red line), and after about 25 ns following the plasma filament generation, the temperatures of the electrons and vibrations reach a common value of 0.4 eV. The electron temperature in that case remains elevated during the long laser pulse due to continuous transfer of energy from the laser to the electrons, which compensates for the energy lost to the vibrations. This is the main mechanism that allowed us to sustain electron density above $10^{15}$ cm$^{-3}$ for an extended time.

5. Discussion and summary

Our experimental results show that the lifetime of high-density plasma channels generated in the wake of optical filaments propagating in air can be increased by more than an order of magnitude by irradiation with a low-intensity nanosecond pulse. Our theoretical study of the experimental results points to the important role played by the vibrational states of the air molecules in enabling a prolonged high-density conducting channel. In agreement with our previous study [9], we find that the temperature of the free electrons at the end of the femtosecond pulse has a small effect on the temporal evolution of the free electron density in the formed channel. It is therefore concluded that further heating the electrons by the first pulse is ineffective because the electrons lose their energy to the vibrations in a short time. Compensating this energy transfer to the vibration sink by a properly timed illumination of the formed channel by a second nanosecond pulse is the main cause of the prolonged lifetime of the conducting channel. The temperature of the electrons follows the envelope of the second pulse, and they transfer energy to the vibration sink, effectively increasing its temperature (see figure 4). Thus the various decay processes are slower and the electrons can remain free for longer times. Upon termination of the second pulse, the temperature of the electrons drops to equilibrium with their surrounding vibrational heat bath. Running the simulations with impact...
ionization switched off showed similar results, pointing out the minor role played by avalanche ionization. Simulations performed at a YAG laser intensity greater than that used in the experiments here show that impact ionization becomes important, leading to electron density above its initial value, i.e., the electron densification effect and fragmentation of the beam into discrete plasma bubbles, as reported in [17]. Proper nanosecond-scale timing of the second pulse is crucial for the effectiveness of this mechanism, as can be deduced from our experimental results (see figure 3). Illuminating the second laser ‘too early’ is ineffective because the electrons are losing their energy to other competing mechanisms (figure 3(a)). On the other hand, using the second pulse ‘too late’ means that the free electron density is too low to be an effective energy carrier from the laser to the vibrations, thus impairing the effectiveness of the process (figure 3(f)). These conclusions open up the possible route of maintaining the conducting channel in air by further heating of the vibrational energy sink.

In conclusion, we have demonstrated experimentally that the lifetime of high-density plasma filaments generated by the self-focusing of an intense femtosecond laser pulse in air is extended by irradiating the plasma with a low-intensity nanosecond laser pulse. Typical relaxation time is extended from several nanoseconds by tens of times. The prolongation of the plasma filament lifetime results from energy absorption from the long-pulse laser and heating of the electrons to higher temperature, compared with the single-pulse case, inducing further impact ionization. The plasma evolution was measured by a non-intrusive diagnostic method that does not require prior knowledge of the filament size or its exact location within the MW waveguide or a simulation of the MW damping mechanism. The temporal evolution of the plasma filament is found to be in very good agreement with the results of a simulation model that solves rate equations for the temperatures and densities of various molecules, atoms, ions, and electrons of air plasma. The proposed approach can be extrapolated to larger distances and thus may be used in a broad range of applications where high-density long plasma filaments are required. The extension of plasma lifetime is particularly important for many potential applications since it opens up the potential for generation of long plasma channels with electron density above $10^{15}\text{cm}^{-3}$. For example, delaying the relaxation of the plasma to 35 ns would allow the front of the channel to propagate a distance of $\approx 10\text{m}$ before the erosion of the plasma tail, thus enabling the generation of a continuous long high-density plasma channel.

Acknowledgments

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