Lengthening the Lifetime of Long Plasma Channel in Air Generated by Femtosecond Laser Pulse *

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We theoretically investigate the lifetime of self-guided plasma channel in air by launching an auxiliary delayed long-pulsed laser beam following an ultrashort laser. A detailed model makes the electron–ion recombination, the attachment of electrons on neutral particles, and particularly the impact ionization and electron-detachment mechanism incorporate. The calculated results show that the temporal evolution of electron density is greatly flattened and broadened. When the auxiliary laser intensity exceeds the threshold $3.32 \times 10^4\ Wcm^{-2}$*, the channel lifetime is distinctly prolonged from nanosecond to microsecond, or even longer due to the electrical field enhancement. Furthermore, with the laser intensity up to* $10^9\ Wcm^{-2}$*, the impact ionization overwhelms the detachment in effect. Thus, it is an effective way to extend the channel lifetime and provides a real opportunity for applications.*

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Since Braun *et al.*[1] observed the remarkable phenomenon that infrared femtosecond laser pulses in air can channel themselves into filaments over 20 m in 1995, this effect has been widely studied.[2−5] It has been demonstrated that this narrow filament can propagate over distances of hundreds of meters, and even beyond 10 km.[6−10] The underlying mechanism that leads to the formation and stabilization of these plasma filaments is based on the dynamic balance between self-focusing, diffraction of the laser beam, and defocusing of the axial plasma filaments. Such long plasma filaments provide an opportunity in lightning control, remote sensing and so on.[6] By using electrical conductivity of the plasma channel, it is possible to artificially trigger and guide lightning to safe places and then to protect sensitive sites from direct strikes and electromagnetic perturbations.

In the application of the plasma channel, not only its propagation distance, but also the lifetime should be taken into consideration. Recent research has proven that due to the fast recombination of electron–ion and strong attachment of electrons to other neutral particles,[7−9,11] the lifetime of conductive channel only lasts several nanoseconds,[8,9] which leads to *discrete* plasma filament over a long distance. This restricts its applications, such as guide lightning over distances from clouds to ground. Therefore, how to maintain the electron density in the filament above the lightning initiation ($\sim 5 \times 10^{11}\ e^-/\mathrm{cm}^3$[12]) for longer duration (at least in the order of microsecond[11]) becomes an important issue. In 1995, Zhao *et al.*[11] first proposed a new method to prolong the channel lifetime by launching a weak visible long-pulse laser along the plasma channel. Due to the electrical field enhancement induced by the long-pulse laser, those attached electrons are partially detached from neutral molecules and the calculated lifetime is correspondingly extended. Later, Yang *et al.*[7] and Lu *et al.*[13] also investigated the detachment mechanism in theory. Furthermore, Hao *et al.*[14] first experimentally determined the decay time of the plasma fluorescence signal by injecting a delayed sub-nanosecond laser. He concluded that this prolongation is actually caused by the heating and further ionization through the inverse bremsstrahlung absorption of the post-pulse, not the detachment mechanism proposed by Zhao *et al.* In this Letter, we also study the lifetime of plasma channel in theory. The original model of decay kinetics of plasma channel is modified when the electron-detachment mechanism and the impact ionization both are taken into consideration. The influence of two mechanisms on the channel lifetime is discussed in detail.

When an ultrashort laser with pulse energy 40 mJ and width 100 fs is focused in air by a 2-m converging lens, a plasma filament over 60 cm long is generated as shown in Fig. 1. The filament contains free electrons, positive (negative) ions, neutral molecules and atoms. These components play different roles on the channel conductivity as illustrated in Fig. 2. Among them, both free electrons and ions contribute to the channel conductivity, whereas the electron–ion recombination reduces the channel conductance. In addition, the generated electrons in high density have a strong tendency to attach to neutral molecules, creating negative ions with low mobility. The substitution of slow

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negative ions for fast electrons is also detrimental to the channel conductivity. At the atmosphere pressure, O_2^- is the main negative ion formed from the electron attachment by three-body reaction.[15,16] The binding energy of the extra electron of O_2^- was reported ranging from 0.07 eV to 0.9 eV.[17] The weakness of the binding energy allows the ions to be broken easily into O_2 and e by collision detachment or by charge exchange. It can also be easily detached by the process of photon-excitation.[17] The interaction of a photon and a negative molecular ion may result in excitation of the ion by absorption of the photon,[17] or if the photon energy is sufficiently large, it may free the extra electron from the neutral molecule. In the case of O_2^-, photons in the visible-to-infrared range of wavelengths have enough energy to cause photodetachment.

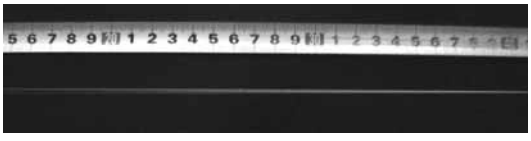


Fig. 1. Long plasma filament produced by ultrashort laser pulse in air.

According to Ref. [11], a complete form of a kinetic model for electron density n_e and the positive (negative) ion concentration n_p (n_n) in air is

$$\frac{dn_e}{dt} = \alpha n_e - \eta n_e - \beta_{ep} n_e n_p + \gamma n_n, \tag{1a}$$

$$\frac{dn_p}{dt} = \alpha n_e - \beta_{ep} n_e n_p - \beta_{np} n_n n_p, \tag{1b}$$

$$\frac{dn_n}{dt} = \eta n_e - \beta_{np} n_n n_p - \gamma n_n. \tag{1c}$$

Consider the electrical neutrality of the plasma

$$n_e + n_n = n_p.$$

The initial conditions imposed on the system of kinetic equations are

$$n_e(0) = n_p(0) = n_{e0}, n_n(0) = 0,$$

where $\alpha, \eta, be_{ep}, \beta_{np}$, and γ are the ionization, attachment, electron-ion recombination, ion–ion recombination and laser-induced detachment coefficients, respectively. Without an auxiliary laser, the ionization and detachment mechanisms for the plasma filament are neglected, namely $\alpha = \gamma = 0$. By assuming $\beta = \beta_{ep} = \beta_{np}$, the analytic solutions of electrons and ions density are deduced as follows:[13]

$$n_e(t) = \frac{n_{e0} e^{-\eta t}}{1 + \beta n_{e0} t}, \tag{2}$$

$$n_p(t) = \frac{n_{e0}}{1 + \beta n_{e0} t}, \tag{3}$$

$$n_n(t) = \frac{n_{e0}}{1 + \beta n_{e0} t}(1 - e^{-\eta t}). \tag{4}$$

When an auxiliary long pulse is launched into the channel, those free electrons remained in the channel as prime seeds will further induce particles ionization by collision, which leads to an increase of electrons. In addition, due to the electrical field enhancement by laser radiation, those attached electrons may partially detach from the negative molecules. Therefore, the temporal dependence of electron density in the channel can be obtained by numerical simulation. Table 1 lists the transport parameters used for calculation. The collision ionization rate provided by Shen[18] is expressed as $\alpha = (e^2|E|^2\tau)/[m\varepsilon_{\rm I}(1 + \omega^2\tau^2)]$, where E is the optical field at frequency ω; τ is the momentum transfer collision time, which is 1.1 ps for air at atmospheric pressure;[11] e and m are the electron charge and mass, respectively; ε_I is the ionization energy of atoms or molecules ($\varepsilon_I = 15.6$ eV for N_2[10]). The electron-attachment rate η is $6.84 \times 10^6\,{\rm s}^{-1}$ determined by experiment.[9] The detachment rate is equal to the rate of negative ion absorption of photons (single photon process at visible wavelengths), so the corresponding detachment coefficient is deduced as $\gamma(s^{-1}) = \sigma_{O_2^-} I/\hbar\omega$.[11] Here $\sigma_{O_2^-} = 1.3 \times 10^{-22}\,{\rm m}^2$ is the cross section for photodetachment at the laser wavelength 532 nm.[16] The recombination rates β_{ep} and β_{np} are $2.2 \times 10^{-13}\,{\rm m}^3{\rm s}^{-1}$, taken from Ref. [11].

Table 1. Typical parameters used in the calculation.

Auxiliary laser intensity (W cm^{-2})	Collision ionization (s^{-1})	e-O_2 Attachment (s^{-1})	e-p Recombination (m^3 s^{-1})	p-n Recombination (m^3 s^{-1})	O_2^- Photodetachment (s^{-1})
3.32×10^4	2.04×10^2	6.84×10^6	2.2×10^{-13}	2.2×10^{-13}	1.16×10^5
5.31×10^5	3.27×10^3	6.84×10^6	2.2×10^{-13}	2.2×10^{-13}	1.85×10^6
3.32×10^6	2.04×10^4	6.84×10^6	2.2×10^{-13}	2.2×10^{-13}	1.16×10^7
1.33×10^7	8.18×10^4	6.84×10^6	2.2×10^{-13}	2.2×10^{-13}	4.63×10^7
3.32×10^8	2.04×10^6	6.84×10^6	2.2×10^{-13}	2.2×10^{-13}	1.16×10^9
1.33×10^9	8.18×10^6	6.84×10^6	2.2×10^{-13}	2.2×10^{-13}	4.63×10^9

Figure 3 shows the free decay of electron, positive and negative ion densities as a function of time under the initial condition $n_{e0} = 10^{17}\,{\rm cm}^{-3}$. Due to the electron–ion recombination and electrons attachment to oxygen molecules, the electron density drops sharply to $10^{12}\,{\rm cm}^{-3}$ within 400 ns, which is barely above the lightning initiation threshold $5 \times 10^{11}\,{\rm cm}^{-3}$.[12] Considering the characteristic attach-

ment time $t = 1/\eta = 146$ ns, the decay mechanism initially is primarily determined by the recombination because this effect favoured at high particle density is proportional to the product of electrons and positive ion numbers. Furthermore, compared with the attachment effect, the recombination due to Coulomb attraction is a transient process, which depends on the electron–ion collision time. Therefore, for the electron density above $10^{15}\,\mathrm{cm}^{-3}$ and time less than 5ns shown in Fig. 3, the main mechanism involved in the plasma relaxation is the recombination process. When $t > 146$ ns, substantive electrons start to attach to neutral particles by two- and three-body collision to form the negative ion. Thus in the subsequent period, the attachment gradually becomes dominant, leading to the electron density in exponential damping ($\sim e^{-\eta t}$). For positive ions, they decay more slowly than electrons because they are not affected by the attachment. The negative ions experience a rapid increase to the maximum value $3\times10^{13}\,\mathrm{cm}^{-3}$ during the initial 4 ns and then a gradual decrease by the ion–ion recombination.

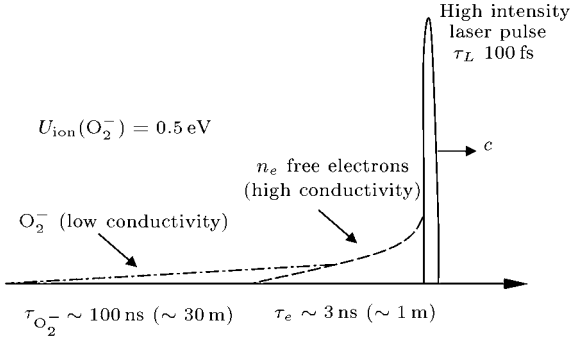


Fig. 2. Contribution of different components in plasma filament to the channel conductivity.

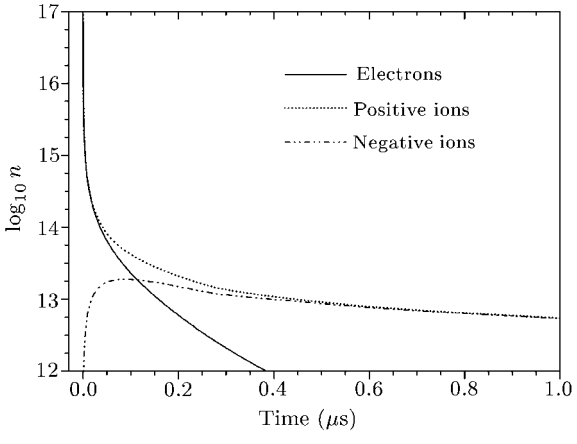


Fig. 3. The temporal evolution of densities of electrons, positive and negative ions without auxiliary laser in air.

When a sub-millisecond pulse is added in the filament, due to the enhancement of electrical field, the electron density will increase by the impact ionization and photodetachment. Figure 4 shows the temporal evolution of electron density with and without the auxiliary long-pulse laser under different laser intensities. When the auxiliary light intensity is lower than the threshold $3.32\times10^4\,\mathrm{Wcm}^{-2}$, the temporal decay of electron density is observed to be invariable. With the increasing intensity, the electron distribution is distinctly flattened and broadened. The corresponding electron lifetime is prolonged gradually from nanosecond to microsecond, even longer. With the intensity up to $1.33\times10^9\,\mathrm{Wcm}^{-2}$, the electron density almost keeps constant in a level of $3.72\times10^{13}\,\mathrm{cm}^{-3}$.

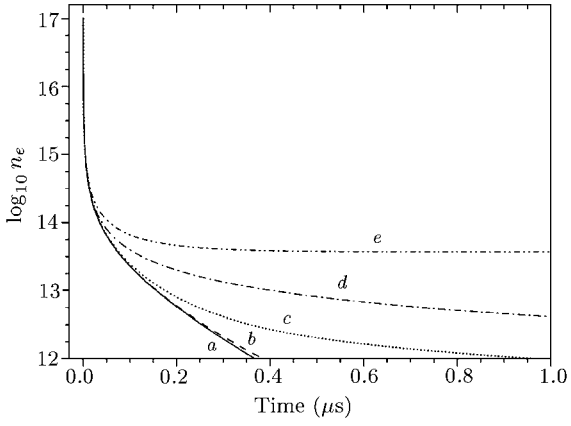


Fig. 4. The temporal evolution of electron density in channel. Curve a represents the free decay in channel. Curves b–e represent the temporal evolution of the electron density in channel with a long-pulse laser in intensities 3.32×10^4, 5.31×10^5, 1.33×10^7, $1.33\times10^9\,\mathrm{Wcm}^{-2}$, respectively, after a femtosecond laser.

The impact ionization and detachment as two primary factors influence the plasma duration. However, which one is more important? We first take the detachment mechanism into consideration and neglect the impact ionization, that is, $\gamma \neq 0$ and $\alpha = 0$, the corresponding analytic solution of Eq. (1) is rewritten as follows:[13]

$$n_e(t) = \frac{n_{e0}(\gamma + \eta e^{-(\eta+\gamma)t})}{(\eta+\gamma)(1+\beta n_{e0} t)}. \tag{5}$$

According to Eqs. (1) and (5), the calculation result of electron density evolutions with and without consideration of the impact ionization are shown in Fig. 5. It is found that if the incident intensity of long-pulse laser is lower than $3.32\times10^6\,\mathrm{Wcm}^{-2}$ as shown in Fig. 5(a), the decay tendency remains unchanged no matter whether the ionization mechanism is considered or not. The electron density decays to $2.8\times10^{12}\,\mathrm{cm}^{-3}$ within 1 μs. Thus, under this condition the detachment is the main attenuating factor. When the laser intensity is increased, the impact ionization comes to affect the electron density, until the density almost remains constant with the intensity up

to 1.33×10^9 Wcm^{-2} as shown in Fig. 5(c). In this case, the impact ionization overwhelms the detachment in effect. In addition, compared to the breakdown threshold of air ($10^{11} \sim 10^{12}$ Wcm^{-2} for ns laser[19]), the threshold in plasma channel greatly decreases due to the auxiliary laser in the long pulse duration[20] and the existence of abundant prime free electrons in the channel.[18] Considering that the threshold dependence of incident intensity on laser pulse duration is an inverse square ($I_{\rm th} \propto \tau^{-0.5}$[20]) relation, the effect of long pulse duration plays a dominant role in decreasing the breakdown threshold.

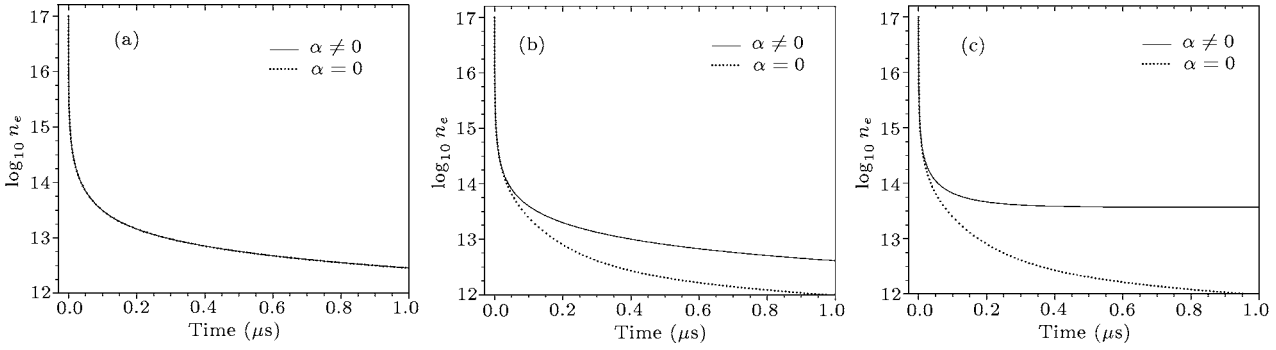


Fig. 5. The temporal decay of electron density in channel with and without consideration of impact ionization at the auxiliary light intensities (a) 3.32×10^6, (b) 3.32×10^8, (c) 1.33×10^9 Wcm^{-2}.

In summary, based on the decay kinetics of plasma filament, the time-resolved electron in the conductive channel generated by femtosecond laser pulses is short-lived. The electron density decays from 10^{17} cm^{-3} to 10^{12} cm^{-3} within 400 ns, which is dominated by the recombination of electron–ions and the attachment of electrons on neutral particles. With an auxiliary long-pulse laser beam in intensity greater than 3.32×10^4 Wcm^{-2} into the channel, the electron distribution is greatly flattened and broadened due to the impact ionization and detachment mechanism. The corresponding channel lifetime is prolonged from nanosecond to microsecond, even longer under the electrical field enhancement. In addition, when the succeeding laser intensity exceeds 10^9 Wcm^{-2}, the impact ionization overwhelms the detachment in effect. This result is encouraging for the further applications of femtosecond laser-induced light filaments.

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