Probing the effective length of plasma inside a filament

YAOXIANG LIU,1,2,3 TIEJUN WANG,2,5 NA CHEN,2 SHENGZHE DU,2,3 JINGJING JU,2 Haiyi Sun,2 CHENG WANG,2 JIANSHENG LIU,2,6 HAIHE LU,2 SEE LEANG CHIN,4 RUXIN LI,2,7 ZHIZHAN XU,2 AND ZHANSHAN WANG1

1MOE Key Laboratory of Advanced Micro-structured Materials, Institute of Precision Optical Engineering, School of Physics Science and Engineering, Tongji University, Shanghai 200092, China
2State Key Laboratory of High Field Laser Physics, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, No. 390, Qinghe Road, Jiading District, Shanghai 201800, China
3University of Chinese Academy of Sciences, Beijing, 100049, China
4Centre d’Optique, Photonique et Laser (COPL) and Département de physique, de génie physique et d’optique, Université Laval, Québec, Québec G1V 0A6, Canada
5tiejunwang@siom.ac.cn
6michaeljs_liu@siom.ac.cn
7ruxinli@mail.shcnc.ac.cn

Abstract: We present a novel method based on plasma-guided corona discharges to probe the plasma density longitudinal distribution, which is particularly good for the weakly ionized plasmas (~10^14 cm\(^{-3}\)). With this method, plasma density longitudinal distribution inside both a weakly ionized plasma and a filament were characterized. When a high voltage electric field was applied onto a plasma channel, the original ionization created by a laser pulse would be enhanced and streamer coronas formed along the channel. By measuring the fluorescence of enhanced ionization, in particular, on both ends of a filament, the weak otherwise invisible plasma regions created by the laser pulse were identified. The observed plasma guided coronas were qualitatively understood by solving a 3D Maxwell equation through finite element analysis. The technique paves a new way to probe low density plasma and to precisely measure the effective length of plasma inside a filament.

© 2017 Optical Society of America

OCIS codes: (280.5395) Plasma diagnostics; (190.7110) Ultrafast nonlinear optics; (260.5950) Self-focusing.

References and links


1. Introduction

When high peak-power ultrashort pulses propagate in transparent medium, a dynamic equilibrium appears between nonlinear Kerr self-focusing and laser ionized plasma defocusing. This dynamics is called filamentation [1, 2]. Through filamentation, high peak-power pulses will collapse along the plasma channel, accompanying by the phenomenon of intensity clamping [3, 4], broad band supercontinuum generation [5], conical emission [6], THz radiation [7] and etc. The ionization channel can persist over a distance of tens to hundreds of meters [8, 9] and has good conductivity with the electron density ranging from $10^{12}–10^{18}$ cm$^{-3}$ [10, 11]. Femtosecond laser filamentation has a wide range of applications, for instance, in remote sensing [12], lighting control [13], rain and snow precipitation [14, 15].

Knowing the longitudinal distribution of electron density is significant for the applications of the plasma channel. General categories of plasma characterization include electric and optical methods, for example, current method [16, 17], electrical conductivity [18], Schlieren...
and shadowgraphy techniques [19, 20], moiré deflectometry technique [21], longitudinal diffractometric technique [22], ionization induced fluorescence technique [23]. The reported plasma density measurement techniques have a poor sensitivity to weakly ionized plasma and besides that some are too complex [21–24] or have low precision [16–18].

In this work, we demonstrate a new electrical technique to probe the plasma, especially the weakly ionized plasmas. This technique is based on the conductivity of the plasma. Inside the plasma there are free electrons and ions which interact with the external electrical field leading to enhanced ionization [24, 25]. As a consequence an enhanced plasma emission in the visible region can be used to probe the weakly ionized plasmas. By this method, the longitudinal distribution of plasma density inside a filament was more precisely characterized.

2. Experimental setup

The experimental setup is presented in Fig. 1. Experiments were conducted using a Ti:sapphire chirped pulse amplification (CPA) laser system which delivered 1kHz/30fs laser pulses. The maximum laser pulse energy was 8 mJ with central wavelength at 800 nm. Laser pulses of various pulse energies were focused by a 30 cm focal length plano-convex lens to create weak ionization or stable air filaments in a grounded Faraday cage of $0.5 \times 0.5 \times 0.4$ m$^3$. A DC high voltage power supply with output up to 100 kV/1000 W was connected to a copper cylindrical electrode to ignite streamer type corona discharges. The electrode fixed on a plastic bracket was 5 cm in length and had a sharp tip with a tip radius of approximately 1 mm. The electrode axis and the light beam were in the same horizontal plane. The direction of laser propagation was perpendicular to the electrode and the distance between the tip and the focal axis was about 1 mm. The laser ionized plasmas (weak ionization or filament) formed a preferred conducting path when a high voltage was applied on the electrode and streamers could originate from the localized plasma sources. During the experiment a digital cameras (Nikon D7200) was used to take color fluorescence images simultaneously from above.

Fig. 1. Schematic of experimental setup. M1 and M2 are two high-reflection mirrors at 800 nm.
3. Results and discussion

3.1 Probe of the weakly ionized plasma

In order to demonstrate the capability to probe the low density plasma, the laser pulse energy was decreased to 0.18 mJ. This 0.18 mJ/100 fs pulse with beam diameter of 15 mm has a peak power of $1.8 \times 10^9$ W which is less than the critical power $P_{\text{cr}}$ for self-focusing ($P_{\text{cr}} \leq 5 \text{ GW}$ for pulses longer than 100 fs in air at the wavelength of 800 nm) [26]. At the focal region, a very weak ionization was created around the Rayleigh region of the geometrical focus. Figure 2(a) shows the real-color image of the typical corona discharge which was taken by the digital camera from the top. The corona discharging voltage was set at 50 kV. The fluorescence intensity of the laser induced plasma was too weak to be clearly detected by the digital camera (in Fig. 2(b)) although it still could be barely seen. When a high voltage of 50 kV was applied on the electrode, the phenomenon of laser guided corona discharge was observed [24, 25] as shown in Fig. 2(c).

In Fig. 2(c) a streamer type of corona discharges at both ends of the laser induced plasma region can be seen. In the same rectangle areas in Fig. 2(b) and Fig. 2(c) the invisible weakly ionized plasma created by the laser in Fig. 2(b) was revealed and detectable with the help of the electric field.

Figure 3 gives the fluorescence intensity distribution along laser induced plasma without voltage (Laser) and with voltage (eLaser). The results were obtained by integrating pixel intensity on each column in the same rectangle as shown in Fig. 2(b) and Fig. 2(c). The position of the geometrical focus of the lens indicated by the arrow in Fig. 2(b) is defined as “0”. The fluorescence signal intensity of the laser induced plasma (without high voltage) is very weak and almost close to the background (Fig. 3(Laser)). When the laser induced plasma...
was enhanced by the high voltage, the fluorescence signal intensity became much stronger, especially at both ends of the laser induced weak plasma (Fig. 3(eLaser)). This indicates that the ionization of low density plasma induced by laser was enhanced in the presence of the electrical field leading to detectable fluorescence radiation. The domain of integration contains the plasma and all the roots of streamers. Thus, in Fig. 3, the fluorescence intensity peaks indicate the generation of plasma guided streamer coronas or stream discharge from the electrode. From the positions where these peaks occurred, the spatial distribution of plasma density should have large curvatures. By using the coronas from two ends of plasma channel, the length of the weak plasmas could also be defined.

To estimate the plasma density inside this weak plasma, a 1 kHz/30 fs/0.5 mJ laser pulse (peak power of 16.7 GW, \(\sim 1.7P_{cr}\)) was focused by a lens of 20 cm to create a filament. According to Ref [23], the peak plasma density inside the filament could be \(10^{17}\) cm\(^{-3}\). Along the filament, the peak fluorescence signal intensity measured was three orders of magnitude higher than the weakly ionized region at ends of the filament. Thus, the plasma density in the weak plasma in Fig. 2(b) can be estimated to \(10^{14}\) cm\(^{-3}\) since fluorescence intensity is proportional to plasma density.

This method provides a sensitive and simple way to probe longitudinal distribution of the weakly ionized plasmas compared to the traditional methods.

### 3.2 Length characterization of plasma filament

The technique was applied to probe the spatial distribution of plasma density inside laser filaments. Figure 4(a) - Fig. 4(f) show typical fluorescence images of laser filament in air under different high voltages. The voltage applied on the electrode varied from 0 kV (in Fig. 4(a)) to 50 kV (in Fig. 4(f)) and the plasma channel was created by 1 kHz/28 fs/3.42 mJ laser pulses focused by a lens of 30 cm focal length. Femtosecond pulses propagated from the right to the left in the Fig. 4. The distance between the tip of the electrode and the filament was about 1 mm. These real-color images were taken by the digital camera from the top (at about 45 deg. to the vertical plane).
Figure 4(a) shows the typical fluorescence image of laser filament in air when the high voltage was 0 kV. As the high voltage applied on the electrode increased, the leader type of corona was observed at the end of the filament (indicated by the elliptical circles in Fig. 4(c) and Fig. 4(d)). The streamer type of corona discharges were also observed not only along the tip of the electrode but also on both ends of the laser filament [24, 25]. And the positions where the laser guided streamer coronas were stationary at fixed positions (Fig. 4(a) - Fig. 4(f)), except that new streamers were generated with voltage increasing. Compared to a conductor with a rough surface in an electric field, the streamers appeared at the positions with larger curvature along the filament. Thus, the plasma density spatial distribution of laser filament can be inferred by looking into the distribution of the laser guided corona discharges. In addition, the positions where the streamer appear are related to the spatial distribution of the plasma. In terms of a metallic conductor in a high voltage electric field, the surface roughness is one of the dominant parameters for the generation of streamers [27]. The accumulation of electric charges on the conductor’s surface prefer to concentrate more at the position with a larger curvature than the positions with a smaller curvature through the electrostatic process. Thus the electric field at the positions with a large curvature would be enhanced leading to the
breakdown of the air molecules by the strong electric field. Consequently, streamers will be generated.

In the rectangular areas as shown in Fig. 4(a), when the voltage was set at 50 kV, many isolated streamers were generated at both ends of the filament within these rectangles (Fig. 4(f)). These invisible low density plasma regions were revealed through filament guided streamer coronas under a high electric field. This is due to the enhanced ionization of the low density plasma created by laser pulses from the interaction of laser filament and high electric field [24, 25]. It provides a more precise approach to characterize the plasma length of a laser filament.

![Figure 5](image.png)

Figure 5(a) is part of Fig. 4(f) which was taken by the digital camera (D7200) from the top (at about 45 deg. to the vertical plane). Figure 5(b) gives the result of fluorescence intensity distribution along the plasma channel by integrating the pixel intensity on each column in the red rectangle as shown in Fig. 5(a). The domain of integration contains the filament and roots of steamers at the beginning and the end of the filament. The arrow indicates the position of the geometrical focus of the lens, which is defined as “0”. The position away from the tip of the electrode to the left, which was along the direction of laser propagation in Fig. 5(b), is positive. In the range between two dotted lines the fluorescence intensity of the filament reaches the saturated threshold of the digital camera, and the integrated pixel intensity cannot accurately reflect fluorescence intensity distribution along the filament because of saturation. But the significant ranges are in the two rectangles as shown in Fig. 5(b) which contain the leading and trailing ends of the filament, respectively. The camera worked in the linear range...
in these areas. The high voltage dependence of the fluorescence intensity in the two ranges are shown in Fig. 5(c) and Fig. 5(d), respectively. With an increase of the voltage applied on the electrode, the length of fluorescence was extended and the fluorescence intensity of the leading (in Fig. 5(d)) and trailing (in Fig. 5(c)) ends of the plasma channel increased.

The measured filament length under different voltages with laser pulse energy fixed at 3.42 mJ is shown in Fig. 6. When defining the filament length, the noise level (as shown in Fig. 5(c) and Fig. 5(d)) was defined as zero and the effective length of the filament was defined as the full width of the fluorescence intensity curve (Fig. 5(a)) at 3% of the maximum from the baseline (noise level). As the applied voltage increases, the length of the plasma channel increases. It approaches a constant value when the voltage reached a critical value (for example, ~35 kV in our case). In this experiment when the voltage was set at 35 kV, the length of the plasma channel was measured to be 35.7 mm. This length is about 1.3 times longer than that measured by typical fluorescence method without high voltage (27.3 mm). Without the high voltage, the molecules in the regions revealed by voltage at both ends of the filament were weakly ionized by the laser pulse. However, the fluorescent signals are too weak to be detected. In the presence of the high voltage electric field, the ionization in the weakly ionized region at both ends of the filament is enhanced [24], which results in the detectable fluorescence radiation. The electrons inside the filament are accelerated along the plasma channel with low pressure [28, 29] by the positive electric field. These accelerated electrons will collide with molecules, ions and electrons, which leads to enhanced ionization and fluorescence. More charges concentrate at the positions with large curvatures where streamers will be generated. Then, longer filament can be detected with increasing voltage due to the low density plasma at the beginning and trail ends of the filament. The spatial structure of laser plasma guided streamer coronas was totally different from the high voltage electrode induced streamer coronas (in Fig. 4(e)), which was used to safely characterize the length of filament. The length of plasma filament obtained by this method was more precisely compared to traditional methods [18–24] which are unable to detect weakly ionized region along the plasma channel.

![Fig. 6. Measured filament length as a function of the high voltage. The filamentsing laser pulse energy was fixed at 3.42 mJ. Without the high voltage, the length of the filament was 27.3 mm (point A). When the applied voltage increased to 35 kV, the length of the filament approached to a constant of 35.7 mm (point B).](image)

### 3.3 Simulation

In order to understand the mechanism of plasma-guided corona discharges, a calculation of electric field distribution in three dimension (3D) in air was performed by solving the following Poisson Equation and Maxwell equation (Eq. (1) and Eq. (2)):

\[ \nabla \cdot (\varepsilon_r \cdot \varepsilon_0 \nabla \phi) = -\rho_v \]  

(1)
where $\varepsilon_r$ is the relatively dielectric constant, $\varepsilon_0$ is the permittivity of vacuum, $\Phi$ is the electric scalar potential, and $\rho_r$ is the density of volume charges.

In the simulation the filament was considered as a plasma channel with length of 3 cm and radius of 50 $\mu$m. Considering the plasma density in the plasma channel at about $10^{18}$ cm$^{-3}$, the bulk conductivity of the plasma conductor is 100 siemens/m according to Ref [11]. As shown in Fig. 4, a phenomenon was observed that a short plasma channel appeared between the electrode and the filament because of tip discharge. However, no corona discharges were generated at the ends of the filament. With the voltage increasing, laser guided corona discharges began to appear. We have also changed the distance between the electrode and the filament under the same voltage of 50 kV. When the electrode moving away, there were less or even no laser guided corona discharges as the plasma connection disappeared gradually. In order to exclude the chosen geometry effect of sharp electrode, we also performed simulation and experiment using a spherical electrode to replace the sharp electrode. There was a channel through the center of the ball electrode, letting laser filament passing through it. Under the same conditions of laser filament and high voltage electric field, similar corona streamers were observed at the end of laser filament.

![Figure 7](image_url)

Fig. 7. (a) Static electric field distribution on horizontal plane when a plasma channel under an applied high voltage of 50 kV. (b) and (c) are the areas in rectangles A and B as shown in (a).

Figure 7 depicts the electric field distribution in horizontal plane. Figure 7(b) and Fig. 7(c) show the electric field distribution in rectangles A and B in Fig. 7(a). Under an applied high voltage of 50 kV, electric field on the plasma conductor surface is at least $10^7$ V/m. The simulation results showed that the electric field strength was stronger at tips of the plasma conductor where the curvature of plasma density distribution was larger. This illustrates that the electric field at both ends of filament are enhanced which results in an enhancement of ionization in weakly ionized region inside the filament. Applying an electric field upon a plasma channel, the unexplored region would be revealed. Then the filament length can be measured more precisely and low density plasma ($10^{14}$ cm$^{-3}$) can be detected.
3.4 Discussion

During the propagation of the femtosecond pulse in air assisted by a focusing optics, the laser intensity increases because of a joint effect of self-focusing and external focusing. When the peak intensity is sufficiently high, ionization of the air molecules takes place. Then the defocusing effect of plasmas, dispersion and diffraction will stop the increase of laser intensity. Before reaching the filamentation condition, a low density plasma can be generated through weak ionization around geometrical focus. When the peak power of the laser pulse is higher than the critical power for self-focusing, the competition between the defocusing and self-focusing effects would result in the formation of a laser filament. Before reaching the equilibrium (at the leading edge of the filament), the external focusing effect plays a dominant role and the laser intensity will weakly ionize the air molecules. At the trailing end of the filament, the defocusing effect prevails. Although the laser intensity decreases after the equilibrium, the intensity is still high enough to ionize some air molecules. As a consequence, there are low plasma density (weak ionization) regions on both ends of the filament.

The plasma density ionized by laser field ranges from \(10^{12} \text{ to } 10^{18} \text{ cm}^{-3}\) [10, 11] either before reaching filamentation or during femtosecond laser filamentation, which paves the way for conducting a high voltage electric field. When a high voltage electric field is applied onto the plasma region through an electrode, the laser freed electrons are accelerated and gain energy. As a consequence, enhanced ionization occurs through collision processes leading to more efficient conduction. Therefore a stronger fluorescence can be emitted making weakly ionized regions (~\(10^{14} \text{ cm}^{-3}\)) easily detectable. Following this idea, a low density plasma created by focusing non-filamenting 0.18 mJ/100 fs pulses through 30 cm focal length lens has been successfully revealed (Fig. 2). Using the detectable fluorescence as an indicator, low density region of plasma filament has also been detected leading to longer visible plasma length of a laser filament. In this work, ~1.3 times longer filament length was measured as compared to the typical fluorescence method without high voltage electric field (Fig. 6); i.e. the plasma filament length should be ~30% longer. Note that the longer filament length measured with a high voltage is not an artificial result from high electric field because the structure of the isolated streamer corona discharges at both ends of the filament is definitely different from the typical fan-shaped tip corona discharge from the anode (Fig. 4) indicating that the generation of these streamers only relies upon the original plasma created by laser rather than the high voltage field.

4. Conclusion

We have demonstrated a novel method based on plasma-guided corona discharges to probe weakly ionized plasma (~\(10^{14} \text{ cm}^{-3}\)). The technique was successfully applied to more precisely measure the effective length of plasma inside a laser filament. A 3D calculation of electric field distribution in air was performed to support the experimental observations. The results offer a new tool to probe the plasma density longitudinal distribution and may find a new opportunity on plasma based physics and applications.

Funding

National Natural Science Foundation of China (NSFC) (Grant Nos. 61221064, 11127901, 11404354), National 973 Project (Grant No. 2011CB808103), Strategic Priority Research Program (B) (Grant No. XDB16), Key Project from Bureau of International Cooperation Chinese Academy of Sciences (Grant No. GJHZ1759), State Key Laboratory of High Field Laser Physics, 100 Talents Program of Chinese Academy of Sciences.