The Influence of Gas Pressure, Voltage, and Frequency on Plasma Propagation in Tube

Article *in* IEEE Transactions on Plasma Science · September 2016

DOI: 10.1109/TPS.2016.2598551

The Influence of Gas Pressure, Voltage, and Frequency on Plasma Propagation in Tube

Yunhao Qiu, Lanlan Nie, Yubin Xian, Dawei Liu, *Member, IEEE*, Yuanfu Yue, and Xinpei Lu, *Senior Member, IEEE*

***Abstract*—The influence of gas pressure and electrical parameters on low-pressure plasma has been investigated in this paper. A fast intensified charge-coupled device (ICCD) imaging is utilized to examine the dynamics of plasma bullet and plasma plume length at different pressure and plasma parameters. The experimental results reveal that the gas pressure has great influence on both the length of the plasma and on the propagation velocity of the plasma bullet. By increasing the gas pressure from 15 to 15 000 Pa, both the length of the plasma jet and the velocity of the plasma bullet first increase and then decrease. The maximum value of plasma plume occurred at 100 Pa, in which the propagation velocity gets the maximum value of 5×10^6 m/s. Further increasing the gas pressure to 15 000 Pa results in decrease in both the plasma length and bullet velocity. Relative to voltage, the frequency of the applied pulse voltage has a different impact on the plasma propagation at different gas pressures. While a higher voltage induces a longer plasma plume and a faster propagation velocity at both 30 and 2000 Pa, increasing the frequency has little influence on plasma at 30 Pa but reduces the plasma length and propagation velocity observably at 2000 Pa. In addition, an exotic plasma plume structure is observed by ICCD. A possible hypothesis is discussed here to explain this phenomenon. These experiments may lead to a more precise control of the low-pressure plasma, warranted for advanced materials technologies.**

***Index Terms*—High-speed photograph, low-pressure plasma, nonequilibrium plasma.**

I. Introduction

RECENTLY, plasma has gained more and more attention due to its wide applications in many fields, such as material surface modification, biological industries, and for pollution treatment [1]–[7]. Most studies focus on the atmospheric pressure plasma [8]–[12]. Various plasma sources have been invented to satisfy the requirements [13], [14]. For example, a kind of atmospheric pressure nonequilibrium plasma (APNP) jet can be employed to sterilize wounds with no damage to tissues. As plasma contains plenty of ions, such as high-energy electrons and radicals like excited oxygen, reactions between particles are more likely to occur. Among the different configurations of plasma sources, APNP jets are much more applicable recently. APNP jets are being generated in a dielectric tube by a high voltage (HV) electrode, and then the plasma propagates into ambient air due to the flow of gases. Compared with the high temperature of direct current (dc) glow discharge, the temperature of APNP jets is close to room temperature. In addition, the power consumption of the APNP motivated by pulsed voltage is much less than dc glow discharge. Furthermore, as the plasma jet flows into the open space, there is no limit to the size of the objects to be treated.

Recently, many works have done on the APNP [15]–[19], which help to control the plasma for further application. Researches have revealed that the development of APNP jets is actually the propagation of a bullet-like plasma volume at a speed of 10^4–10^5 m/s [20], [21]. Photo-ionization plays an important role in the promotion of the plasma bullet [22].

However, despite the wide use of atmospheric pressure dielectric barrier discharge (DBD), it has some disadvantages. It cannot be easily controlled due to the open environments. The surrounding gases may affect the discharge of the working gas, and higher voltages are required for atmospheric pressure DBD. According to Paschen's law, breakdown can occur more easily at low pressure. Low-pressure plasmas that are sustained within a closed vessel are more controllable in comparison with APNP, as they do not contact with the ambient air. In addition, the energy consumption of the low-pressure plasma ignited by pulse voltage is much less than dc glow discharge. Low-pressure plasmas also have many applications due to these advantages, especially in material modification and decontamination of surfaces [23]–[27]. On the other hand, the dynamics of low-pressure plasmas in a closed vessel are not entirely clear. Investigation of the process of plasma propagation at low pressure can also help us in comprehending the mechanisms involved in plasma science. Few researches have been reported on the mechanism of the low-pressure plasma [28]–[30]. In this paper, studies of low-pressure plasmas may help to reveal what happens in the discharge by ICCD. The rest of this paper is as follows. In Section II, details of the experimental setup including the

Manuscript received January 26, 2016; revised June 5, 2016; accepted July 27, 2016. Date of publication September 26, 2016; date of current version November 7, 2016. This work was supported in part by the National Natural Science Foundation under Grant 51077063, Grant 51277087, and Grant 51477066, in part by the Research Fund for the Doctoral Program of Higher Education of China under Grant 20100142110005, and in part by the Chang Jiang Scholars Program through the Ministry of Education, China.
(Corresponding author: Xinpei Lu.)

Y. Qiu, L. Nie, Y. Xian, and Y. Yue are with the State Key Laboratory of Advanced Electromagnetic Engineering and Technology, Huazhong University of Science and Technology, Wuhan 430074, China.

D. Liu is with the State Key Laboratory of Advanced Electromagnetic Engineering and Technology, Huazhong University of Science and Technology, Wuhan 430074, China, also with the IFSA Collaborative Innovation Center, Shanghai Jiao Tong University, Shanghai 200240, China, and also with the State Key Laboratory of Electrical Insulation and Power Equipment, Xi'an Jiaotong University, Xi'an 710049, China.

X. Lu is with the State Key Laboratory of Advanced Electromagnetic Engineering and Technology, Huazhong University of Science and Technology, Wuhan 430074, China, and also with the IFSA Collaborative Innovation Center, Shanghai Jiao Tong University, Shanghai 200240, China (e-mail: luxinpei@hust.edu.cn).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TPS.2016.2598551

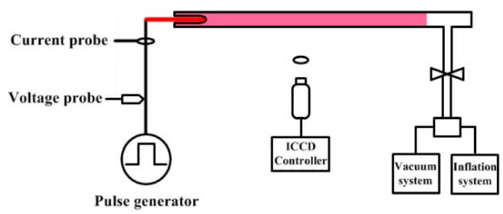


Fig. 1. Schematic of the low-pressure plasma device.

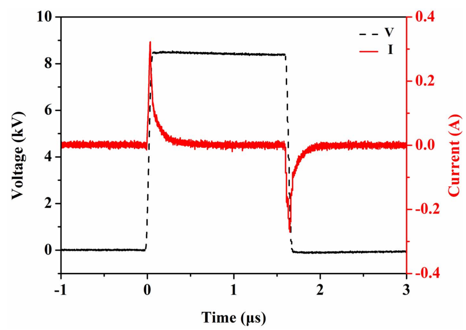


Fig. 2. Current–voltage characteristics of the discharge ($P = 100$ Pa, $U = 8$ kV, $f = 4$ kHz, and $T_w = 1.6$ μs).

power supply and equipment utilized for this study are presented. The experimental results and discussion are presented in Sections III and IV.

II. Experimental Setup

Fig. 1 shows the schematic of the devices. The setup comprises a power supply system, vacuum chamber, pumping system, inflation system, and pressure measurement system. Power supply is by an HV pulse generator that can produce HV pulses with amplitude up to 10 kV. The vacuum chamber is made of a quartz tube with an inner diameter of 6 mm and length of 1 m. The HV electrode is connected to the HV pulse generator and is inserted into the chamber to about 5 cm. The thickness of the quartz between the HV electrode and the inner space is about 1.5 mm. The pumping system consists of a rotary mechanical pump and a turbomolecular pump that can evacuate gas from the chamber till the gas pressure reaches 3×10^{-4} Pa. The inflation system and the pressure inspection system are used here to control the gas pressure and gas ingredients.

The inflation system supplies artificial air into the vacuum chamber after pumping the gas into it. The power supply system produces pulse voltage to the electrode when the pressure reaches a specified value. The frequency of the pulse voltage ranges from 100 Hz to 9 kHz. The pulsewidth is fixed at 1.6 μs. The voltage ranges from 3 to 9.5 kV with a rise time of 40 ns. Fig. 2 shows the current–voltage characteristics of the discharge at 100 Pa, $U = 8$ kV, $f = 4$ kHz, and $T_w = 1.6$ μs. As shown in the waveforms, the discharge current lasts for about 250 ns with a peak value of about 0.3 A when the pressure is 100 Pa.

III. Experimental Results

A. Photographs of the Discharge at Various Parameters

Figs. 3–5 show the images of the plasma taken at different gas pressures, voltages, and frequencies. The exposure time of all these photographs is 1/16 s. In Fig. 3, the voltage and frequency maintain at 8 kV and 4 kHz, respectively. The situation becomes interesting by changing the gas pressure from 15 to 15 000 Pa. By increasing the gas pressure, the length of the plasma plume increases up to nearly 100 cm, and then starts to decrease as the gas pressure is further enhanced to 15 000 Pa. The longest and brightest plasma observed at a pressure of 100 Pa is as shown in Fig. 3.

The length of the plasma is obviously affected by changing the voltage when the pressure is fixed at 30 Pa, as shown in Fig. 4(a). In the case of 5 kV, the plasma plume is shorter than 10 cm. By increasing the voltage to 9.5 kV, it becomes nearly 100 cm long. The influence of frequency on the plasma is visualized at the plasma brightness. The length of the plasma changes slightly when frequency increases from 500 Hz to 9 kHz.

In comparison, the impact of the electrical parameters is different when the pressure rises to 2000 Pa. In the case of 2000 Pa, the plasma becomes longer by increasing the voltage. The plasma length increases from 15 cm (at $U = 4$ kV) to nearly 80 cm (at $U = 9.5$ kV), as shown in Fig. 5(a). The influence of pulsed voltage on the plasma is similar to the case of 30 and 2000 Pa. Considering the pulse frequency, the plasma becomes brighter as the frequency of the pulse voltage increases, with little change in its length when the frequency is below 5 kHz. While further increasing the frequency results in decrease in the plasma length, which is different from the case of 30 Pa [Figs. 4(b) and 5(b)].

B. Influence of Gas Pressure on the Propagation of Plasma

To investigate the influence of the pressure, voltage, and frequency on plasma, a fast intensified charge-coupled device (ICCD) camera (Princeton Instruments, Model PIMAX2) has been used here to capture the image and measure the plasma propagation velocity. The exposure time is set to 5 ns for all the photographs taken at different times. The ICCD camera is triggered by the signal generator. Each photograph is an integrated picture of over 600 shots with the same delay time.

The method of measuring the plasma propagation velocity has been reported earlier [16]. The plasma propagation velocity at different pressures with the same voltage (8 kV), frequency (4 kHz), and pulsewidth (1.6 μs) are plotted versus the position of the plasma head in Fig. 6. The initial propagation velocity is around 10^6 m/s at each pressure. The propagation velocity increases with the rise of pressure below 100 Pa, and then decreases by increasing the pressure as shown in Fig. 6. In the case of 100 Pa, the propagation velocity reaches a peak value of nearly 6×10^6 m/s, where the longest and brightest plasma observed is as shown in Fig. 3.

C. Propagation Velocity at Gas Pressure 30 Pa

Fig. 7 shows the propagation velocity at pressure 30 Pa. In Fig. 7(a), the frequency is maintained at 4 kHz, but the voltage increases from 6 to 9 kV. When the voltage is set to 6 kV, plasma propagates with a velocity of 3×10^4 m/s as it is 25 cm away from the electrode. The propagation

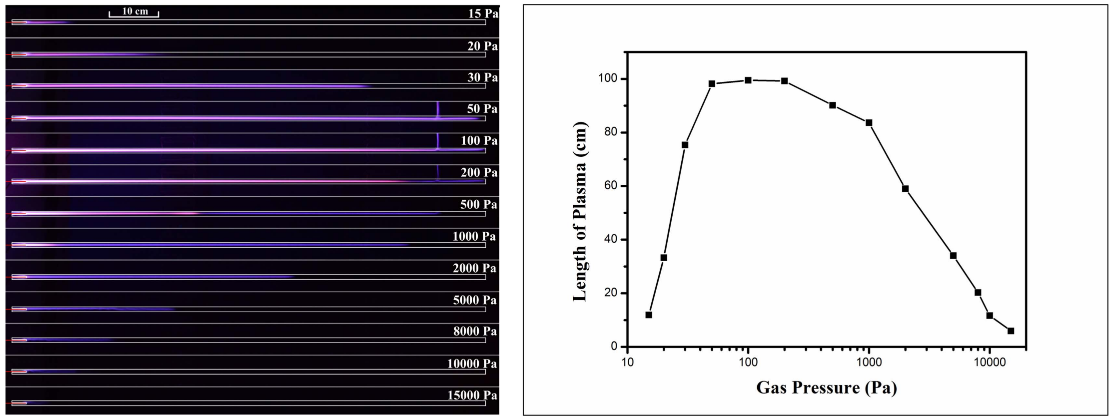
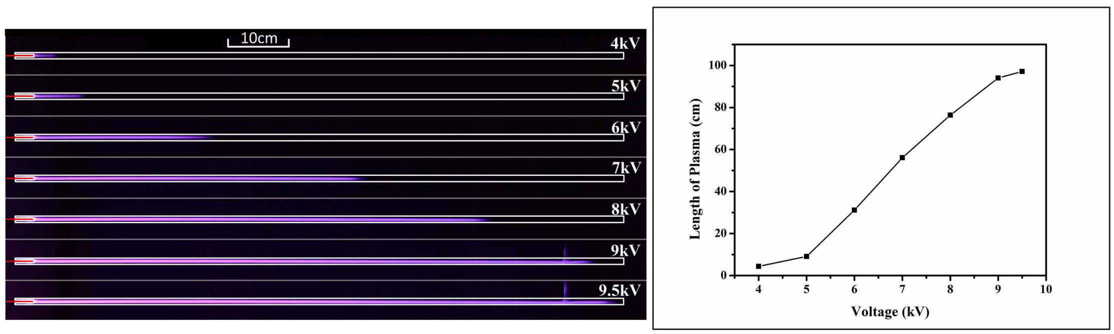
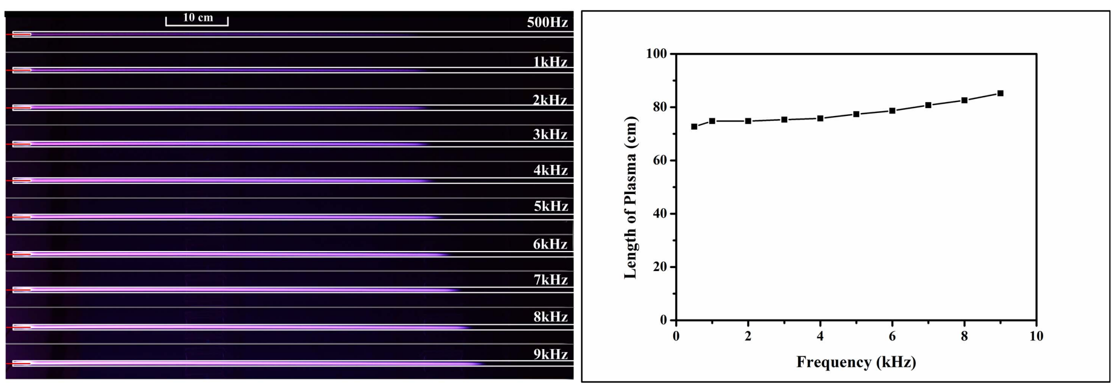


Fig. 3. Photographs of the plasma plume at various gas pressures. The voltage, frequency, and pulsewidth are fixed at 8 kV, 4 kHz, and 1.6 μs, respectively.



(a)



(b)

Fig. 4. Photographs of the plasma plume at various voltages and frequencies ($P = 30$ Pa and $T_w = 1.6$ μs). (a) Frequency of pulse voltage is fixed at 4 kHz and the voltage is increased from 4 to 9.5 kV. (b) Pulse voltage is fixed at 8 kV and the frequency is increased from 500 Hz to 9 kHz.

velocity is close to 1×10^6 m/s when the voltage is raised to 9 kV, which is over one order of magnitude higher than that of 6 kV. The influence of frequency on the velocity is much less than in the case of 30 Pa. Increasing the frequency from 1 to 8 kHz, the frequency makes little difference in the propagation velocity as shown in Fig. 7(b). The velocity decreases from 1×10^6 m/s to 2×10^5 m/s with the growth of plasma.

D. Propagation Velocity at Gas Pressure 2000 Pa

When the gas pressure increases to 2000 Pa, the effect of voltage on the propagation velocity is the same as 30 Pa. The velocity drops from 8×10^5 to 6×10^4 m/s at 6 kV and 1×10^5 m/s at 9 kV, respectively [Fig. 8(a)]. However, maintaining the voltage at 8 kV, the velocities decrease with the increase of frequency from 2 to 8 kHz as shown in Fig. 8(b). In the case of 8 kHz, the velocity drops to nearly 2×10^4 m/s at the end of the plume. In the case of 1 and 2 kHz, the velocities are almost the same.

E. Exotic Plasma Plume Structure

Fig. 9 shows the photographs of the propagation of the plasma bullet taken at different delay times in the case of 2000 Pa. The time labeled on each photograph corresponds to the time of rising edge of the applied voltage. Fig. 9(a)–(d) is taken at frequency 1, 2, 4, and 8 kHz,

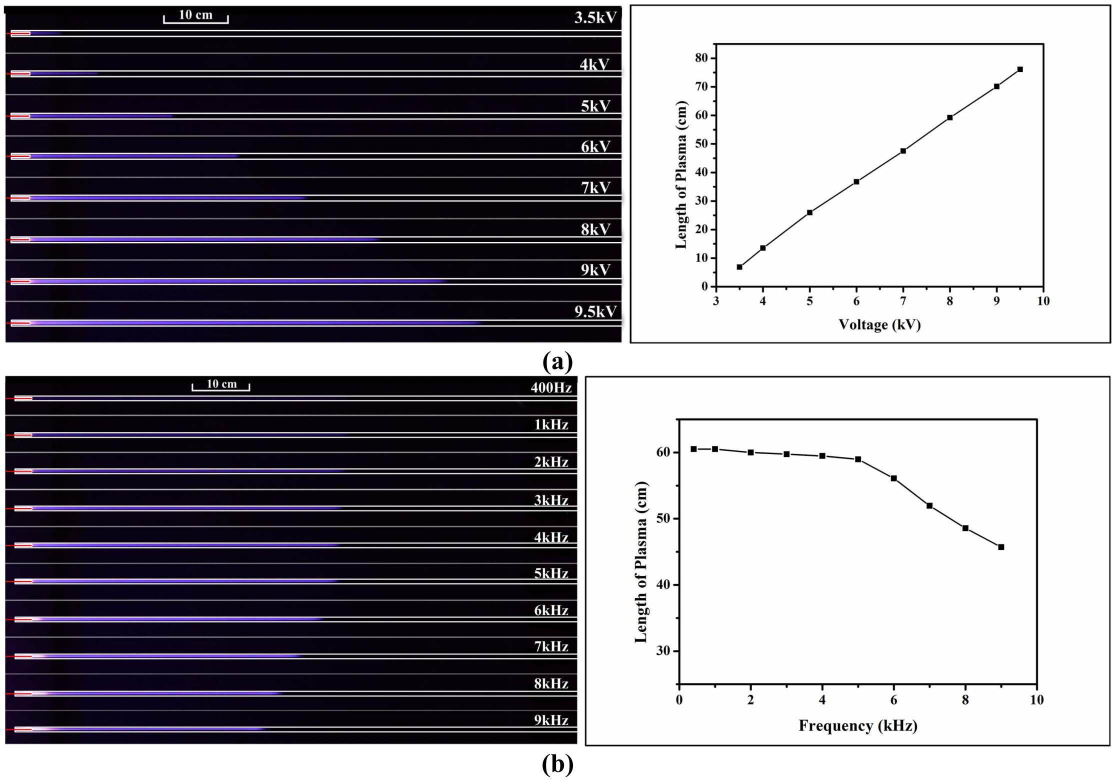


Fig. 5. Photographs of the plasma plume at various voltages and frequencies ($P = 2000$ Pa, and $T_w = 1.6$ μs). (a) Frequency of pulse voltage is fixed at 4 kHz and the voltage is increased from 3.5 to 9.5 kV. (b) Pulse voltage is fixed at 8 kV and the frequency is increased from 400 Hz to 9 kHz.

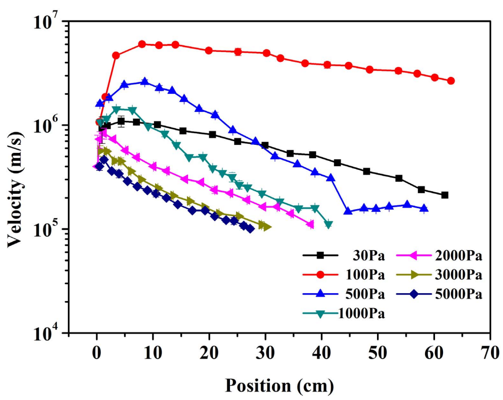


Fig. 6. Plasma propagation velocities versus the position of the head of discharge at different pressures ($U = 8$ kV, $f = 4$ kHz, and $T_w = 1.6$ μs).

respectively, with the same voltage 8 kV. When 1, 2, and 4 kHz are used, the plume dynamics [Fig. 9(a)–(c)] are typical of the plasma bullet propagation reported previously [15]. The bright plasma originates at the electrode at 50.7 ns and then separates from it. The plasma bullet propagates further at a speed of $\sim 10^5$ m/s, eventually slowing down and shrinking in size. The rest of the plasma plume darkens significantly when the bullet propagates further.

Fig. 9(d) shows a very different dynamics of the plasma plume generated when the frequency is set to 8 kHz. The plasma plume separates from the electrode at 50.7 ns. Then the plume propagates further to about 10 cm away from the front of the plume and the electrode at 350.7 ns. The length of the bright plasma channel is approximately 4 cm, and then the plasma bullet forms and detaches from the bright channel. As the plasma bullet propagates further with a speed lower than the plasma bullet in Fig. 9(a)–(c) (as shown in Fig. 8), a dark channel forms between the head of the bright channel and the plasma bullet. The luminosity of the bright channel decreases with the propagation of the plasma bullet. At 950.7 ns, the bullet is about 20 cm away from the electrode and stays almost static in rest time, so the velocity of the plasma bullet decreases sharply as shown in Fig. 8. The bright channel and the plasma bullet both become dimmer from 950.7 ns to the next discharge induced by the falling edge of the HV.

IV. Discussion

A. Gas Pressure and Voltage

Paschen's law can be utilized here to explain the gas pressure and the influence of voltage on the length of the plasma plume. The particle concentration in the chamber is relatively lesser at a lower gas pressure, which leads to a lower collision rate between the electrons and molecules. At high pressure, the mean free path of the electrons is too short for the electrons to gain enough energy to ionize the gas molecules. Hence, the pressure has a most appropriate value for an electron avalanche. According to the law, the statistic breakdown voltage Us is higher in both the low and high pressure cases. So as P increases, the breakdown voltage decreases at first, and then rises. The overvoltage $U - Us = \Delta U$ rises at first and then decreases at a fixed applied voltage, which results in that

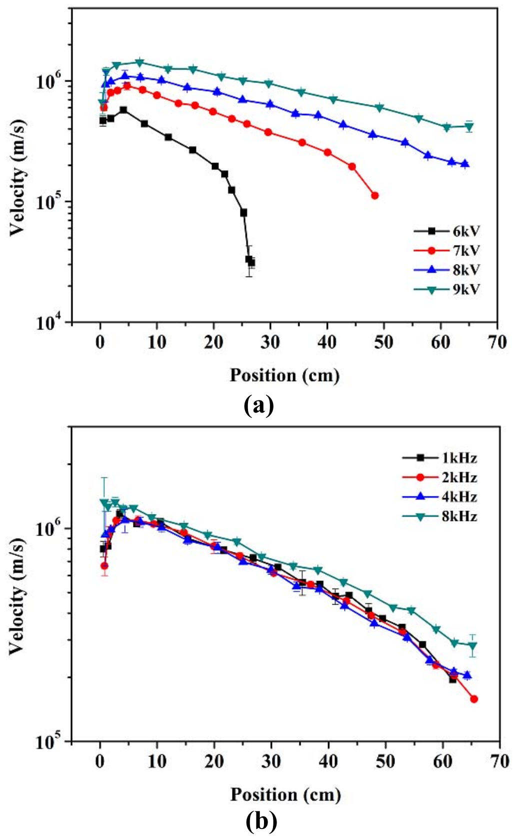


Fig. 7. Plasma propagation velocities versus the position of the head of discharge at various voltages and frequencies ($P = 30$ Pa and $T_w = 1.6\ \mu$s). (a) Frequency of pulse voltage is fixed at 4 kHz and the voltage is increased from 6 to 9 kV. (b) Pulse voltage is fixed at 8 kV and the frequency is increased from 1 to 8 kHz.

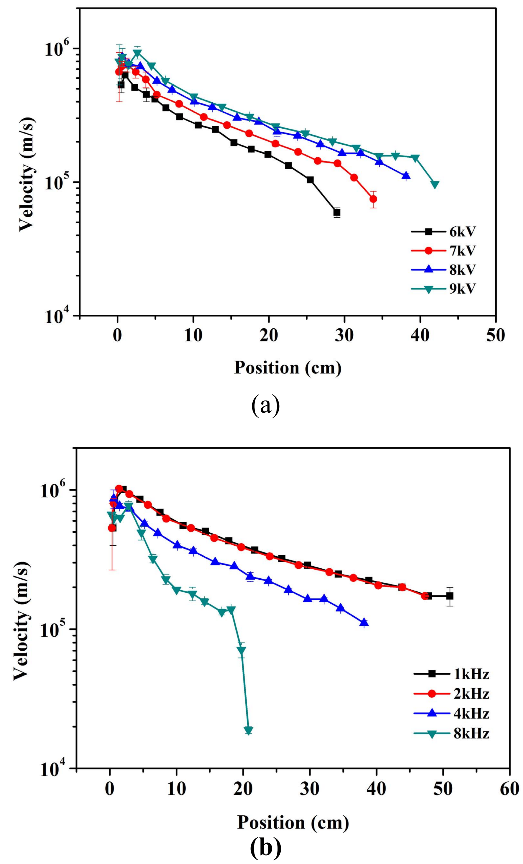


Fig. 8. Plasma propagation velocities versus the position of the head of discharge at various voltages and frequencies ($P = 2000$ Pa and $T_w = 1.6\ \mu$s). (a) Frequency of pulse voltage is fixed at 4 kHz and the voltage is increased from 6 to 9 kV. (b) Pulse voltage is fixed at 8 kV and the frequency is increased from 1 to 8 kHz.

the length of the plasma plume first increases and decreases afterward as the gas pressure increases. Similarly, setting the gas pressure at a specific value, such as 30 or 2000 Pa, increasing only the voltage leads to a larger ΔU, which results in the growth of the plasma plume. In addition to that, a larger ΔU means the electrons get more energy initially. Hence, the discharge can propagate at a higher velocity as shown in Figs. 6, 7(a), and 8(a).

B. Frequency

Considering the fixed voltage and gas pressure, how the frequency can affect the length and propagation velocity is still unknown. It is probably due to some reactive species, such as N_2 $W^3\Delta_u$ and $W^1\Delta_u$, which have lifetimes longer than 0.1 ms and, comparable to the duration of the pulse-OFF time, are accumulated in the chamber when the frequency increases. These reactive species with a positive charge may decrease the electric field, which induces the decrease in propagation velocity. At a relatively low pressure, the density of these reactive species is too low to influence the electronic field in the chamber, even if the frequency is increased to 8 kHz. However, we can predict that the propagation velocity will decrease if we keep increasing the frequency at a pressure 30 Pa. More experimental and simulation work are needed to explain this.

C. Unusual Bright Channel

The unusual propagation process shown in Fig. 9(d) is similar to a research reported by Xian *et al.* [19]. The dark channel-bright channel-plasma bullet structure also appeared in their work. However, there are many differences between these two works. Xian *et al.* [19] report that the bright channel forms locally and leaves about a 0.4-cm dark channel behind, whereas in this work, the bright channel is formed after the plasma plume propagates to a certain positon. According to [19], the forming of the exotic plasma structure is due to the asymmetrical distribution of residual electrons generated by the previous discharge of the falling edge of voltage. However, the voltage-OFF time between each pulse is approximately 124 μs, while the frequency is set to 8 kHz. The lifetime of the electrons will not be so long to affect the next discharge. So the appearance of this unusual propagation in this work may be due to the residual long lifetime of the reactive species.

The residual reactive species produced by the previous raising edge of pulse voltage distribute around the electrode. The concentration of these species near the electrode is relatively higher than that far from the electrode, based on the streamer theory. After the discharge of falling edge as shown in Fig. 9(d) at 1690.7 ns, the reactive species close to the electrode reduced due to intense recombination process.

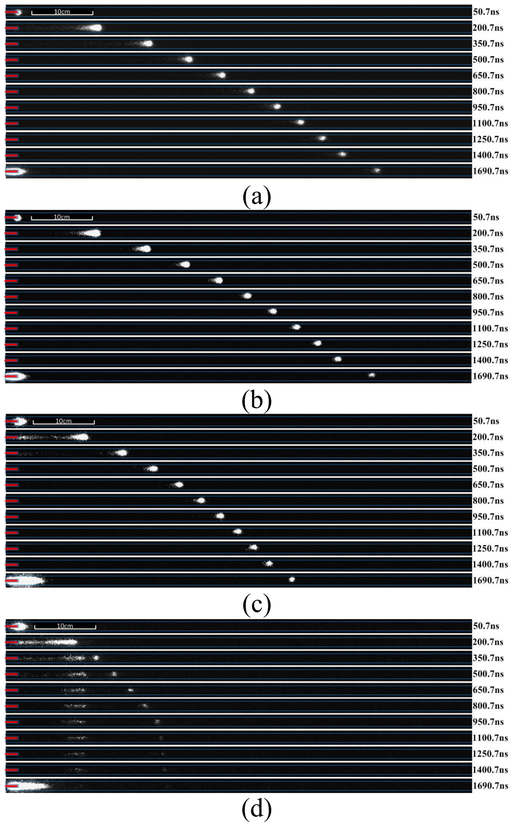


Fig. 9. High-speed photographs of the plasma plume. The exposure time is 5 ns. The time labeled on each photograph corresponds to the time of rising edge of the applied voltage. The pulse voltage applied in each picture is 8 kV with pulsewidth of 1.6 μs. The frequencies of (a)–(d) are 1, 2, 4, and 8 kHz, respectively.

The length of the discharge of fall-phase is about 5 cm, which is close to the length of the dark channel behind the bright channel, as shown in Fig. 9(d). Thus, it is reasonable to assume that the residual reactive species density near the electrode is relatively low. After going through an entire pulse voltage, the concentration of this species presents a low–high–low distribution. When the next pulse voltage comes, the residual long lifetime species still remains if the frequency is set to 8 kHz. The plasma plume propagates along the tube till 10 cm and leaves a 6-cm-long dark channel behind it in which the residual reactive species density is relatively low. The species close to the electrode are unable to sustain further discharge, which results in a dark channel at the end of the plasma. Considering the 6–10 cm part of the tube in which the concentration of reactive species may remain high, after the plume goes through this part, the reactive species sustain a certain degree of ionization and excitation. This is why the plasma of the bright channel remains stable for a relatively long time as shown in Fig. 9. The plasma plume continues propagating to the area in which the reactive species density is low. The electric field in the front of the plasma is still high enough to excite the gas molecule. So the plasma propagates in the form of a bullet and leaves a dark channel between the bright channel and the plasma bullet. Due to the residual reactive species, the electron density in the front of the plasma bullet reduces with its propagation. When the bullet reaches to 20 cm away from the electrode, both the electron density and the electric field are relatively low to sustain further propagation, which results in a sharp decrease in the velocity of the plasma bullet, as shown in Fig. 8(b). The bright channel and the approximate immobile bullet become dimmer from 950.7 ns, as shown in Fig. 9(d).

V. Conclusion

In this work, the influence of gas pressure and electrical parameters on the low-pressure plasma has been investigated by camera and ICCD. As the gas pressure increases, both the length of the plasma and the velocity of plasma bullet first increase and then decrease. At 100 Pa, the length of the plasma reaches the peak value at a propagation speed of approximate 5×10^6 m/s, as shown in Figs. 3 and 6. The influence of the voltage on the plasma is similar at 30 and 2000 Pa. The length of the plasma and the velocity of the bullet both increase with the increase in voltage from 6 to 9 kV. However, changing the frequency of the pulse voltage has little influence on the velocity of plasma bullet at 30 Pa, as the propagation velocity decreases obviously with the increase of frequency at 2000 Pa. From the high-speed photographs of the plasma plume (Fig. 9), we observe an exotic plasma structure. The distribution of residual long lifetime reactive species may explain this dark channel-bright channel-plasma bullet structure.

The precise control of the plasma bullet formation and propagation is promising in the application of plasma treatment. For delicate materials like graphene dispose, the concentration of various species makes a great difference in the process. The results clarify the influence of various parameters on low-pressure plasma streamers and can be used in improving the control of these types of nonequilibrium plasmas in nanotechnology applications. Further experimental and numerical techniques are still required to explain the propagation of the plasma bullet at low pressure.

References

[1] P. K. Chu, “Plasma-treated biomaterials,” *IEEE Trans. Plasma Sci.*, vol. 35, no. 2, pp. 181–187, Apr. 2007.

[2] T. Shao *et al.*, “Surface modification of polyimide films using unipolar nanosecond-pulse DBD in atmospheric air,” *Appl. Surf. Sci.*, vol. 256, no. 12, pp. 3888–3894, Apr. 2010.

[3] S. Zhao *et al.*, “Atmospheric pressure room temperature plasma jets facilitate oxidative and nitrative stress and lead to endoplasmic reticulum stress dependent apoptosis in HepG2 cells,” *PLoS ONE*, vol. 8, no. 8, p. e73665, Aug. 2013.

[4] P. K. Chu, J. Y. Chen, L. P. Wang, and N. Huang, “Plasma-surface modification of biomaterials,” *Mater. Sci. Eng. R, Rep.*, vol. 36, nos. 5–6, pp. 143–206, Mar. 2002.

[5] K. H. Becker, K. H. Schoenbach, and J. G. Eden, “Microplasmas and applications,” *J. Phys. D, Appl. Phys.*, vol. 39, no. 3, pp. R55–R70, Jan. 2006.

[6] A. Bogaerts, E. Neyts, R. Gijbels, and J. van der Mullen, “Gas discharge plasmas and their applications,” *Spectrochim. Acta. B, Atomic Spectrosc.*, vol. 57, no. 4, pp. 609–658, Apr. 2002.

[7] F. Iza *et al.*, “Microplasmas: Sources, particle kinetics, and biomedical applications,” *Plasma Process. Polym.*, vol. 5, no. 4, pp. 322–344, Jun. 2008.

[8] C. Tendero, C. Tixier, P. Tristant, J. Desmaison, and P. Leprince, “Atmospheric pressure plasmas: A review,” *Spectrochim. Acta B, At. Spectrosc.*, vol. 61, no. 1, pp. 2–30, Jan. 2006.

[9] D. Liu, F. Iza, and M. G. Kong, “Evolution of the light emission profile in radio-frequency atmospheric pressure glow discharges,” *IEEE Trans. Plasma Sci.*, vol. 36, no. 4, pp. 952–953, Aug. 2008.

[10] T. Shao *et al.*, “Diffuse discharge produced by repetitive nanosecond pulses in open air, nitrogen, and helium,” *J. Appl. Phys.*, vol. 113, no. 9, p. 093301, Mar. 2013.

[11] T. Shao *et al.*, "Diffuse discharge, runaway electron, and X-ray in atmospheric pressure air in an inhomogeneous electrical field in repetitive pulsed modes," *Appl. Phys. Lett.*, vol. 98, no. 2, p. 021503, Jan. 2011.

[12] S. Tao, L. Kaihua, Z. Cheng, Y. Ping, Z. Shichang, and P. Ruzheng, "Experimental study on repetitive unipolar nanosecond-pulse dielectric barrier discharge in air at atmospheric pressure," *J. Phys. D, Appl. Phys.*, vol. 41, no. 21, p. 215203, Nov. 2008.

[13] A. Schutze, J. Y. Jeong, S. E. Babayan, J. Park, G. S. Selwyn, and R. F. Hicks, "The atmospheric-pressure plasma jet: A review and comparison to other plasma sources," *IEEE Trans. Plasma Sci.*, vol. 26, no. 6, pp. 1685–1694, Dec. 1998.

[14] T. Shao *et al.*, "A compact repetitive unipolar nanosecond-pulse generator for dielectric barrier discharge application," *IEEE Trans. Plasma Sci.*, vol. 38, no. 7, pp. 1651–1655, Jul. 2010.

[15] X. Lu, G. V. Naidis, M. Laroussi, S. Reuter, D. B. Graves, and K. Ostrikov, "Reactive species in non-equilibrium atmospheric-pressure plasmas: Generation, transport, and biological effects," *Phys. Rep.*, vol. 630, pp. 1–84, May 2016.

[16] S. Wu, X. Lu, and Y. Pan, "On the mechanism of acceleration behavior of plasma bullet," *Phys. Plasmas*, vol. 21, no. 7, p. 073509, Jul. 2014.

[17] X. Lu, M. Laroussi, and V. Puech, "On atmospheric-pressure non-equilibrium plasma jets and plasma bullets," *Plasma Sour. Sci. Technol.*, vol. 21, no. 3, p. 034005, Jun. 2012.

[18] X. Lu, G. V. Naidis, M. Laroussi, and K. Ostrikov, "Guided ionization waves: Theory and experiments," *Phys. Rep.*, vol. 540, no. 3, pp. 123–166, Jul. 2014.

[19] Y. Xian *et al.*, "From short pulses to short breaks: Exotic plasma bullets *via* residual electron control," *Sci. Rep.*, vol. 3, Apr. 2013, Art. no. 1599.

[20] X. Lu and M. Laroussi, "Dynamics of an atmospheric pressure plasma plume generated by submicrosecond voltage pulses," *J. Appl. Phys.*, vol. 100, no. 6, p. 063302, Sep. 2006.

[21] Z. Xiong *et al.*, "Measurements of the propagation velocity of an atmospheric-pressure plasma plume by various methods," *IEEE Trans. Plasma Sci.*, vol. 38, no. 4, pp. 1001–1007, Apr. 2010.

[22] S. Wu, X. Lu, D. Liu, Y. Yang, Y. Pan, and K. Ostrikov, "Photo-ionization and residual electron effects in guided streamers," *Phys. Plasmas*, vol. 21, no. 10, p. 103508, Oct. 2014.

[23] B. T. Chiad, T. L. Al-Zubaydi, M. K. Khalaf, and A. I. Khudiar, "Characterization of low pressure plasma-dc glow discharges (Ar, SF_6 and SF_6/He) for Si etching," *Indian J. Pure Appl. Phys.*, vol. 48, no. 10, pp. 723–730, Oct. 2010.

[24] A. von Keudell *et al.*, "Inactivation of bacteria and biomolecules by low-pressure plasma discharges," *Plasma Process. Polym.*, vol. 7, nos. 3–4, pp. 327–352, Mar. 2010.

[25] A. D. Usachev *et al.*, "Formation of a boundary-free dust cluster in a low-pressure gas-discharge plasma," *Phys. Rev. Lett.*, vol. 102, no. 4, p. 045001, Jan. 2009.

[26] F. Rossi, O. Kylián, H. Rauscher, M. Hasiwa, and D. Gilliland, "Low pressure plasma discharges for the sterilization and decontamination of surfaces," *New J. Phys.*, vol. 11, no. 11, p. 115017, Nov. 2009.

[27] W. Petasch, B. Kegel, H. Schmid, K. Lendenmann, and H. U. Keller, "Low-pressure plasma cleaning: A process for precision cleaning applications," *Surf. Coatings Technol.*, vol. 97, nos. 1–3, pp. 176–181, Dec. 1997.

[28] D. M. Goebel and R. M. Watkins, "High current, low pressure plasma cathode electron gun," *Rev. Sci. Instrum.*, vol. 71, no. 2, pp. 388–398, Feb. 2000.

[29] K. Wagatsuma, "Emission characteristics of mixed gas plasmas in low-pressure glow discharges," *Spectrochim. Acta B, At. Spectrosc.*, vol. 56, no. 5, pp. 465–486, May 2001.

[30] S. Wu *et al.*, "Dynamics of mode transition in air dielectric barrier discharge by controlling pressures," *IEEE Trans. Plasma Sci.*, vol. 42, no. 10, pp. 2342–2343, Oct. 2014.

Yunhao Qiu received the B.S. degree in chemistry from the University of Science and Technology of China, Hefei, China, in 2010. He is currently pursuing the Ph.D. degree with the State Key Laboratory of Advanced Electromagnetic Engineering and Technology, Huazhong University of Science and Technology, Wuhan, China.

His current research interests include the diagnostics and applications of low-pressure nonequilibrium plasma sources.

Lanlan Nie received the M.S. degree in electrical engineering from Shandong University, Jinan, China, in 2014. She is currently pursuing the Ph.D. degree with the State Key Laboratory of Advanced Electromagnetic Engineering and Technology, Huazhong University of Science and Technology, Wuhan, China.

Her current research interests include the discharge mechanism of nonthermal plasma, plasma diagnostics, and applications of atmospheric pressure plasma jets.

Yubin Xian received the Ph.D. degree in electrical engineering from the Huazhong University of Science and Technology, Wuhan, China, in 2013.

He has been a Lecturer at the State Key Laboratory of Advanced Electromagnetic Engineering and Technology, Huazhong University of Science and Technology, since 2014. His current research interests include atmospheric pressure low temperature plasma sources and their applications.

Dawei Liu (M'09) received the B.Eng. degree from the China University of Geosciences, Beijing, China, in 2002, and the M.Sc. and Ph.D. degrees from Loughborough University, Loughborough, U.K., in 2005 and 2009, respectively.

He was with China Unicom Corporation, Beijing, from 2002 to 2004. Since 2009, he has been a Professor at the State Key Laboratory of Advanced Electromagnetic Engineering and Technology, Huazhong University of Science and Technology, Wuhan, China. His current research interests include numerical and experimental study on low temperature plasma, with special attention on plasma jet driven by radio frequency and pulse power supply for biomedical applications.

Yuanfu Yue received the B.S. degree from the School of Electrical and Electronic Engineering, Huazhong University of Science and Technology, Wuhan, China, in 2014, where he is currently pursuing the master's degree.

His current research interests include the diagnostics of atmospheric pressure plasmas, and the application in biomedical areas.

Xinpei Lu (M'06–SM'07) received the Ph.D. degree in electrical engineering from the Huazhong University of Science and Technology, Wuhan, China, in 2001.

He was with the Applied Plasma Technology Laboratory, Old Dominion University, Norfolk, VA, USA, for about five years. In 2007, he joined the Huazhong University of Science and Technology, where he is currently a Professor (Changjiang Scholar) with the College of Electrical and Electronic Engineering. He has authored or co-authored over 100 scientific articles. He holds eight patents. His current research interests include low-temperature plasma sources and their biomedical applications, modeling of low-temperature plasmas, plasma diagnostics, and pulsed power technology.

Dr. Lu was a Session Chair of the International Conference on Plasma Science for many times. He has served as a Guest Editor of the IEEE TRANSACTIONS ON PLASMA SCIENCE. He has also been invited to give plenary/invited talks in many international conferences, including the IEEE International Conference on Plasma Science.