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# A cold plasma cross made of three bullet-like plasma plumes

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ABSTRACT

In contrast to other atmospheric pressure plasma jets, two perpendicular jet-like plasmas generated in ambient air by a special designed plasma device are reported. High-speed photographs taken by an ICCD camera with exposure time of 2 ns show that the horizontal part of the plasma is actually ignited by the vertical part of the plasma. Both the vertical and horizontal parts of the plasma are in fact a small bullet like volume of plasma traveling along different directions at high velocities. The horizontal plasma volume velocity is about half of the vertical plasma volume velocity at the same instant.

## 1. Introduction

Cold atmospheric pressure plasmas have recently received great attention due to several novel applications, such as surface and materials processing, aerodynamic drag reduction, shock-wave mitigation, synthesis of nano materials, and biological and chemical decontaminations of media [1–10]. However, due to relative high breakdown voltage of working gases under one atmospheric pressure, the discharge gaps are normally in a range from few millimeters to several centimeters, which limits the size of objects to be treated. One way to avoid this problem is to generate a plasma in an open space (surrounding air) rather than in a confined discharge gap only. However, due to the high electron collision frequency and attachment rate of electron to oxygen, where oxygen is from the ambient air, it is not easy to generate a large volume of cold atmospheric pressure plasma in the surrounding air. Fortunately, several different types of cold atmospheric pressure plasma jet (C-APPJ) devices have recently been developed [11–16].

In this paper, a plasma cross is generated in helium gas flow in the surround air by a special design plasma device. It is found that the horizontal part (secondary plasma) of the plasma cross is actually ignited by the vertical part (primary plasma) of the plasma cross, which can be directly contacted by a human finger without any harm. The rest of this paper is organized as follows. The experimental set-up is described in Section 2. Details of the experimental results, including the dynamics of the plasma cross are presented in Section 3. Finally, discussions are given in Section 4 and a brief summary of the work is presented in Section 5.

## 2. Experimental set-up

Fig. 1 is the schematic of the experimental set-up. The device consists of a plasma jet generator and two glass tubes for controlling the horizontal gas flow. The plasma jet generator has a high voltage (HV) wire electrode covered by a quartz tube with one end closed. The quartz tube along with the HV electrode is inserted into a hollow barrel of a syringe. The high voltage (HV) wire electrode, which is made of a copper wire with a diameter of 2 mm, is inserted into a 4 cm long quartz tube with one end closed. The inner and outer diameters of the quartz tube are 2 mm and 4 mm, respectively. The quartz tube along with the HV electrode is inserted into a hollow barrel of a syringe. The diameter of the hollow barrel is about 6 mm and the diameter of the syringe nozzle is about 1.2 mm. The distance between the tip of the HV electrode and the nozzle is 1 cm. Details on the plasma jet generator can be found in [16]. The two glass tubes have diameters of about 0.8 mm. They are about 1.4 cm away from the nozzle of the syringe. The distance between the gas exits of the two glass tube is about 1.2 cm. When HV pulsed DC voltage (amplitudes up to 10 kV, repetition rate up to 10 kHz, and pulse width variable from 200 ns to dc) is applied to the HV electrode, and helium gas is injected into the hollow barrel and the two glass tubes with flow rates of 2 L/min and 0.5 L/min, respectively, a plasma cross is generated in the surrounding air as shown in Fig. 1(b). The room temperature and the humidity are about 22 °C and 45%, respectively.

## 3. Experiment results

The current–voltage characteristics of the discharge are shown in Fig. 2, where the applied voltage is measured by a P6015 Tektronic HV probe and the current by a TCP202 Tektronix current probe. It should be mentioned that the current $I_{dis}$ is actual discharge current, which is obtained by subtracting measured displacement current $I_{no}$ from total

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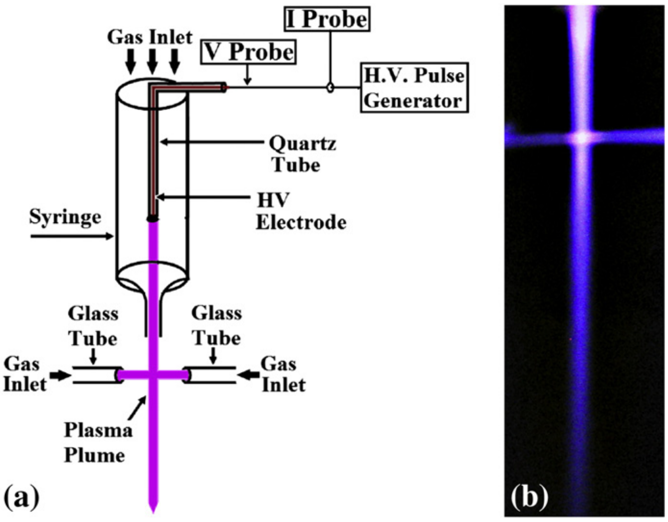

**Fig. 1.** (a) Schematic of the experimental setup. The inner and outer diameters of the quartz tube are 2 mm and 4 mm, respectively. The inner diameter of the hollow barrel of the syringe is 6 mm, and the diameter of the syringe nozzle is about 1.2 mm. The distance between the tip of the quartz tube and the nozzle is 1 cm. The inner diameters of the two glass tube are 0.8 mm. The vertical distances between the two glass tubes and the syringe nozzle are about 1.4 cm. The distance between the two glass tubes is about 1.2 cm. (b) Photograph of the plasma cross with the applied voltage $V_a$ of 9 kV, frequency of 4 kHz, pulse width of 800 ns, and helium flow rates of 2 l/min for the syringe and 0.5 l/min for each glass tube.

current $I_{tot}$. Two distinct discharge current pulses per applied voltage are observed. The second discharge ignites because of the voltage induced by the charges, which have accumulated on the surface of the quartz tube during the first discharge. This behavior is similar with that observed in the pulsed DBD discharge.

As shown clearly in Fig. 1(a), the plasma device has only one electrode, which is covered by the quartz tube. The two glass tubes are electrical floated and there is no electrode placed inside or outside the two glass tubes. They are used only for guiding the gas flow. Therefore the horizontal part of the plasma cross should be ignited by the plasma from the vertical part of the plasma cross. To investigate how the horizontal plasma is ignited, a fast intensified charge-coupled device (ICCD) camera (Princeton Instruments, Model: PIMAX2, exposure time down to 0.5 ns) is used to capture the dynamics of the discharge. The exposure time is set to 2 ns for all the photographs shown in this paper. Fig. 3 shows the photographs of the plasma plume taken at different delay time. Each picture was an integrated picture over 10 shots with same delay time. According to Figs. 2 and 3, the plasma exits the nozzle at about 200 ns after the discharge ignited inside the syringe. The plasma plume behaves like a "plasma bullet", which is similar with that were reported by Teschke et al. [11], Lu et al. [17], Sands et al. [18], and Shi et al. [19]. However, up to now, the bullet-like behavior is not well-understood.

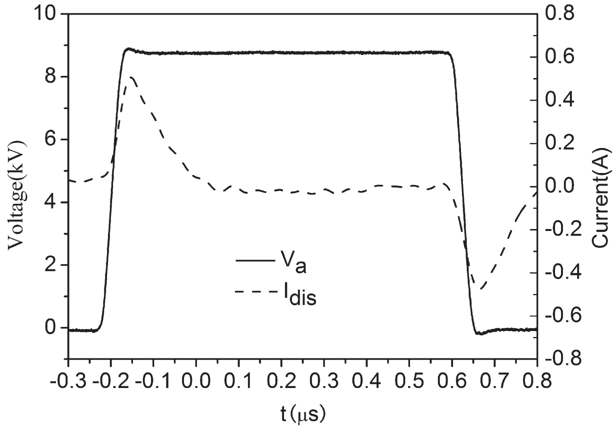

**Fig. 2.** Current–voltage characteristic of the discharge. $V_a$: applied voltage, $I_{dis}$: actual discharge current.

To have a more detailed discussion about the plume dynamics, the vertical plasma plume velocity versus time is plotted in Fig. 4. Because the plume location has a small fluctuation for the same delay time, the experiments were repeated six times. Fig. 4 clearly shows that the plume starts to accelerate as soon as it is launched from the nozzle of the syringe. It accelerates quickly and reaches about $2.2\times10^5$ m/s at a time corresponding to Fig. 3(e). Then it decelerates when it is passing through the horizontal flowing helium gas. It picks up speed again immediately after the horizontal plasma is ignited. Besides, the velocity of the horizontal plasma plume is estimated to be about $6\times10^4$ m/s, which is about half of the vertical plasma plume velocity at the same instant.

## 4. Discussion

Based on Fig. 3, there are interesting points worth emphasizing. Firstly, Fig. 3(h) shows that the horizontal/secondary plasma is induced by the vertical/primary plasma. Since the primary plasma plume can be touch by a human hand without any feeling of electrical shock, the secondary plasma cannot be produced by the external electric field from the applied voltage. It is probably created by the charge from the primary plasma plume. More experiment and simulation work are needed to understand this phenomenon. In addition, studies are also needed to understand how the energy of the primary plasma is divided between the horizontal and vertical parts of the plasma cross when the primary plasma is passing through the intersection of the cross.

Secondly, as can be seen from Fig. 3(d) and (e), the shape of the plasma plume is similar with that of the well-known electron avalanche. However, for the electron avalanche, it propagates from the cathode to the anode. This is opposite to our case, which propagates from the anode to the cathode (ambient air), like a cathode-directed streamer. For a cathode-directed streamer, high-energy photons emitted from the primary avalanche provide photo-ionization in the vicinity, which initiates secondary avalanches. Electrons of the secondary avalanches are pulled into the streamer head and create a quasi-neutral plasma. They also excite atoms, so that new photons are emitted. Subsequently, the process repeats, providing growth of the streamer [20]. However, there is at least one difference between this bullet-like plasma plume and the widely studied streamer [21–24]. For the widely studied streamer, the applied external electric field is at least several kV/cm ranges. This is not the case for our plasma device. Since a human finger can contact with any part of the plasma plume without any harm, the electric field along the plasma plume should be very low. Nevertheless, in order to propagate, the plasma plume has to be under high electric field. So the electric field has to be created by the space charge in the plume head for our plasma. In the next, the electric field created by the space charge is estimated. Assuming the plasma plume head is a charge ball with a radius $R$ same as that of the nozzle. The charge density $n$ of the plasma plume is estimated according to $n=\frac{j}{e\cdot v_d}$, where $j$ is the current density and $v_d$ is the drift velocity. The current is on the order of 100 mA [16]. Assuming the current density is uniform along the cross-section, then the current density can be estimated to be about 10 A/cm$^2$. The drift velocity is assumed to have the same order as the plasma bullet velocity, which is about $10^5$ m/s. So we can obtain the charge density, which is on the order of $10^{12}$ cm$^{-3}$. So the upper limit of the electric field $E$ next to the charge ball, i.e. at distance $r=R$, can be calculated according to

$$E=\frac{enV}{4\pi\varepsilon_0 r^2}\ \underset{=\!=\!=}{\overset{r=R}{=}}\ \frac{enR}{3\varepsilon_0} \qquad (1)$$

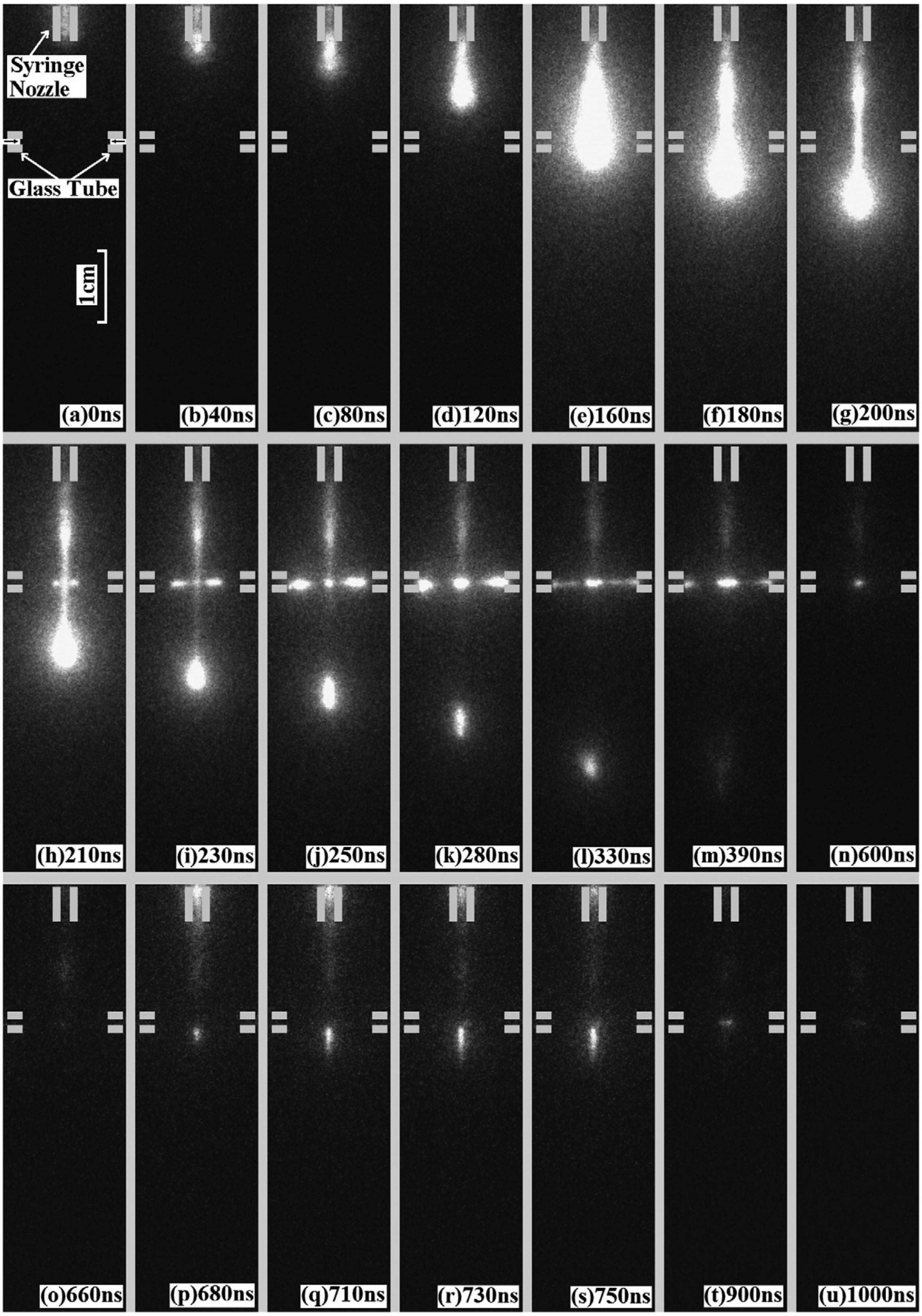

**Fig. 3.** High-speed photographs of the plasma cross. The exposure time is 2 ns. The time labeled in each photo is corresponding to the time in Fig. 2.

Where $V$ is the volume of the charge ball, $e$ is the charge of an electron, and $\varepsilon_0$ is the vacuum dielectric constant. The upper limit electric field created by the space charge according to Eq. (1) is about 36 kV/cm at $r=R$. The actual electric field at $r=R$ could be significantly lower than this upper limit because there are some electrons inside the plume head too. The ignition of the horizontal/secondary plasma can now be explained as following. Since the plasma plume head (charge ball) moves regardless of the external field, when it reaches the intersection of the cross, it should propagate along the horizontally flowing helium gas too because the magnitudes

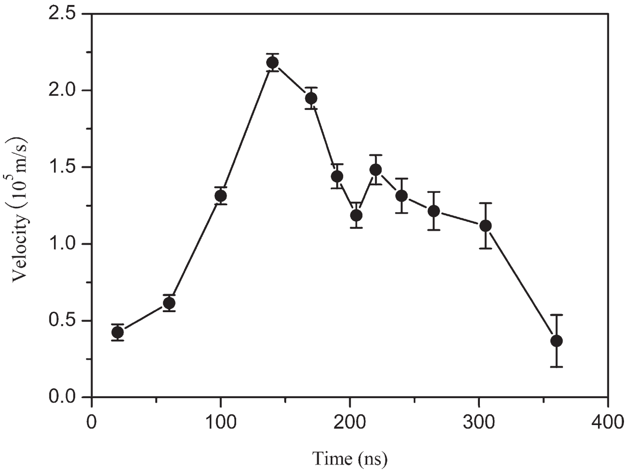

**Fig. 4.** Vertical plasma plume propagation velocities vs time.

of the electric field created by the charge ball are same for both vertical and horizontal directions at the same distance from the ball center. Besides, according to Eq. (1), if the discharge current is mainly concentrated along the axis center, which is probably closer to the reality, the effective radius $R_{\mathrm{eff}}$ is smaller than $R$. Then the charge density $n$ within $R_{\mathrm{eff}}$ need to be increased to keep the same induced electric field at $R_{\mathrm{eff}}$. But the required discharge current $I$ is lower since $I \propto nR_{eff}^2$. For example, for $R_{\mathrm{eff}} = 10\,\mu\mathrm{m}$, to have the induced electric field of tens kV/cm, the charge density of the order of $10^{14}\,\mathrm{cm}^{-3}$ and the discharge current of the order of tens mA are needed.

Thirdly, Fig. 3(p) to (t) show that the plasma jet nozzle and the intersection of the three gas flow become bright again. They are corresponding to time of the falling edge of the applied voltage as can be seen from Fig. 2. This second discharge ignites because of the voltage induced by the charges, which have accumulated on the surface of the quartz tube during the first discharge. This is similar with that was reported before on pulsed dielectric barrier discharge [17]. However, it is still not well understood why the intersection of the three gas flow also becomes bright at the moment.

Fourthly, it is noticed that the length of the plasma plume is affected by the pulse duration. The plume reaches its maximum length when the pulse duration is about 1 µs. Therefore it is suspected that, although the applied external electric field along the plasma plume is low (Any part of the plasma plume can be touched by bare hand without any feeling of electrical shock), it still plays some role in the propagation of the plume. In other words, the conductivity of the tail of the plume is low, but it is not negligible. It affects the propagation of the plume [25].

Finally, it should be pointed out that, according to Fig. 3(e)–(h), the secondary plasma is not ignited at 160 ns (Fig. 3(e)) when the primary reaches the intersection of the cross. It is ignited about 50 ns later (Fig. 3(h)) instead. This is still not clearly understood.

## 5. Conclusion

A vertical bullet-like plasma plume is generated by a plasma jet device. The vertical bullet-like plasma plume can further trigger a horizontal plasma along the horizontal helium gas flow path. The propagation of the original bullet-like plasma plume looks like the streamer propagation, but the electric field of the plume head is not so high as in the streamer head. Therefore, the propagation of the plasma is probably due to the electric field induced by the charge particles within the streamer head. In addition, after the first bullet-like plasma plume passed the intersection of the two helium gas flow, the second plasma is observed in the area where the two helium gas flows intersect. This phenomenon is not understood yet. Further studies, especially computer simulation are needed to understand this observation.

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