

Time-Resolved Imaging of “Plasma Bullets” in a Dielectric Capillary Atmospheric Pressure Discharge

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Abstract—Temporally resolved images acquired using a 5-ns gated intensified charge-coupled device camera show the dynamical behavior of a plasma jet emanating from the end of a dielectric capillary operating at atmospheric pressure. Broadband emission and filtered emission from excited Ar, He, N₂ and N₂⁺ species were acquired. The properties of the highly localized so-called “plasma bullets” that make up the plasma jet strongly resemble the properties of cathode-directed streamers in positive corona discharges.

Index Terms—Atmospheric pressure plasma jet (APPJ), dielectric capillary, streamers, time-resolved optical imaging.

SEVERAL atmospheric pressure plasma jet (APPJ) configurations are actively being studied for a variety of applications. These include single-cell configurations and multicell arrays. The single-cell dielectric capillary configuration presented here, with cylindrical, coaxial but nonconcentric electrodes, was introduced by Teschke *et al.* [1] and has been studied in various forms [2], [3]. This configuration is characterized by a capillary dielectric barrier discharge (CDBD) created within the gap between the electrodes and a plasma jet extending beyond the capillary tip into the open air.

We used a cylindrical glass capillary with a 2-mm inner diameter (ID) and a 3-mm outer diameter (OD). The copper ring electrodes surround the capillary OD and were spaced 1 cm apart. The anode was placed close to the edge of the capillary. The electrodes were energized with a unipolar voltage pulse with a rise time of 20 ns. A gated intensified charge-coupled device (ICCD) camera, with a 5-ns gate width, was synchronized to these voltage pulses to acquire the images in Fig. 1.

Fig. 1 shows a set of four emission sequences from the discharge, each showing eight consecutively acquired ICCD images at 10 ns intervals from the onset of emission. A magnified true-color photograph of the plasma jet and CDBD is shown in Fig. 1(a) for reference. The discharge was excited using an 11-kV voltage pulse at a 1 kHz repetition rate with a 5% Ar/He mixture flowing through the capillary at a rate of ~4.5 standard liters per minute. Fig. 1(b)–(e) respectively depict unfiltered broadband emission, 750 nm emission from the

Ar 3p⁵4p – 3p⁵4s transition, both 391 nm emission from N₂⁺B²Σ_u – X²Σ_g (0,0) and 389 nm emission from the He 3³P – 2³S₁ transition, and 337 nm emission from N₂C³Π_u – B³Π_g (0,0). An 8-bit false-color intensity map was applied to each of the sequence frames in Fig. 1(b)–(e). Normalized intensity scales are shown in the figure for reference and apply only to the specified subfigure. There is actually a large variation in intensity when comparing between the subfigures.

The most striking feature in Fig. 1 is that what appears to be a continuous jet to the eye [Fig. 1(a)] is actually a highly localized, propagating region of emission when viewed on a time-resolved scale. Each slice from the four image sequences shown was integrated over a period that ranged from 100 pulses for the unfiltered and 750 nm emission to 600 pulses for the weaker nitrogen emission bands to acquire sufficient signal to noise. This indicates a high degree of shot to shot repeatability as there is very little streaking apparent in the images. The time-resolved emission from this dielectric capillary configuration was first acquired by Teschke *et al.* [1] who termed the propagating ionization front as a “plasma bullet.” The “plasma bullet” was only visible following the rising edge of the voltage pulse. The choice of filters revealed the structure of the “plasma bullet.” Examination of Fig. 1(b) and (c) shows that the “plasma bullet” is not homogeneous, but is composed of a distinct region of emission from the Ar/He flow-gas plasma bounded by the capillary ID that is surrounded by nitrogen emission from an air plasma envelope. These are basic properties of the “plasma bullet” that have been observed previously [1]. The filtered emission covering the 389 nm He and 391 nm N₂⁺ transitions [Fig. 1(d)] tracks the ionization front and clearly outlines the “plasma bullet” while emission from excited N₂ at 337 nm [Fig. 1(e)] shows a weakly ionized plasma channel that persists behind the propagating front.

Noting the length scale indicated in the figure, the “plasma bullet” traverses about 3.5 cm in 70 ns. Such high propagation velocities on the order of 10⁷ cm/s have been consistently observed [1], [3]. A closer examination of the figure shows propagation with a constant velocity over much of the range with a visible deceleration noted in the final stages of the “plasma bullet.” Perhaps the most important feature to note in Fig. 1 is the relative timing of the plasma jet and inner CDBD. The plasma jet is initiated ~10 ns before the CDBD inside is initiated. This has not previously been observed and indicates that the plasma jet is a self-sustained discharge independent from the interior CDBD.

Using a different electrode arrangement, Lu and Laroussi [3] observed similarly high propagation velocities and suggested

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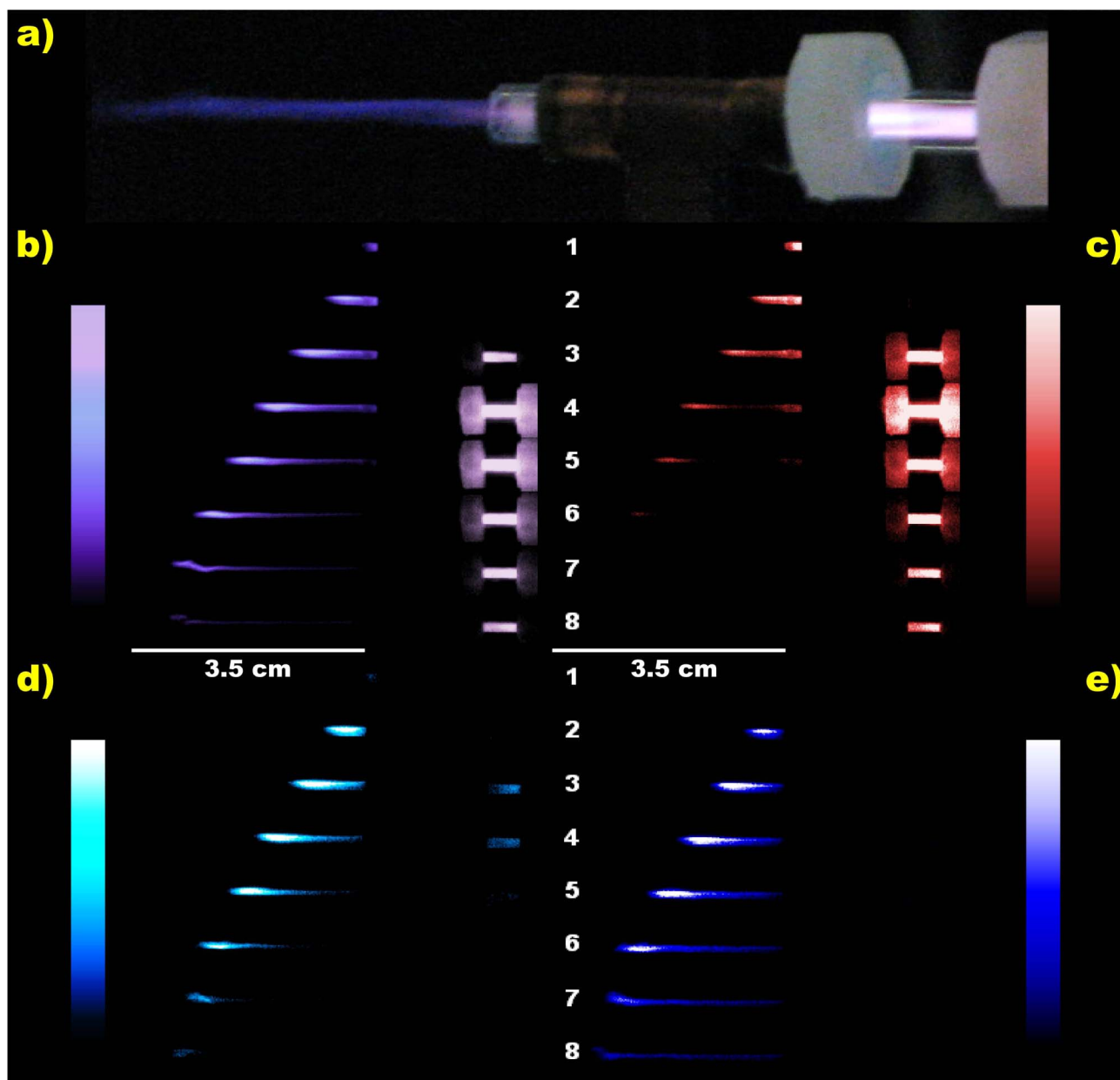


Fig. 1. (a) Magnified true-color photograph of the dielectric capillary APPJ. (b) False-color intensity maps representing time-resolved broadband emission, (c) excited Ar emission lines near 750 nm, (d) emission from N_2^+ at 391 and 389 nm emission from excited He, and (e) excited N_2 emission at 337 nm were acquired using an ICCD camera gated at 5 ns. Each frame represents an increment of 10 ns.

a streamer discharge mechanism similar to positive corona streamers. Our observations, gleaned from Fig. 1 and confirmed using more quantitative time-resolved spectroscopic measurements, strongly support this interpretation. Experimental observations and theoretical modeling of streamer discharge dynamics in point-plane positive corona setups show similar features to those observed in our configuration. There are some differences, however. Positive corona streamers can trace multiple paths with sometimes several bifurcations along the way and are not as repeatable in pulsed setups. The streamers associated with this dielectric capillary configuration are, in contrast, very repeatable and highly directed, tracing the same path consistently. We believe this can partly be attributed

to the accumulation of charge on the capillary tip and the focusing of the electric field along the flow axis.

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