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A hypersonic plasma bullet train traveling in an atmospheric
dielectric-barrier discharge jet

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An experimental observation of fast-moving plasma bullets produced in an atmospheric
dielectric-barrier discharge jet is reported in this paper. Nanosecond imaging suggests that the
atmospheric discharge jet consists of a plasma bullet train traveling at a hypersonic speed from
7.0 km/s to 43.1 km/s. Yet on a millisecond scale, the bullet train appears as a plasma jet of several
centimeters long. The plasma bullets are produced through several possible mechanisms, the most
likely of which is related to the ionization wave. Time and space resolved optical emission
spectroscopy show that reactive plasma species can be delivered to different spatial sites with

I. INTRODUCTION

Nonthermal atmospheric plasma jets have recently attracted growing interest, motivated by their considerable application potentials for material modification and biomedical applications. These plasma sources can be generated with sinusoidal excitation at 60 Hz, kHz, MHz, and with repetitive nanosecond pulses at kilohertz. For many of their applications, nonthermal plasma jets offer a useful practicality of separating the plasma generation region from the application region thus facilitating access to an extensive range of reaction chemistry. However, possible mechanisms responsible for the production of atmospheric plasma jets remain largely unknown. Several recent reports suggest that atmospheric plasma jets could be formed through fast-moving plasma bullets. Further investigations are needed to progress to these preliminary studies and to advance the current understanding of atmospheric plasma jets. In this article, we present an experimental investigation of fast-moving plasma bullets formed in an atmospheric dielectric-barrier discharge jet.

II. EXPERIMENTAL SETUP

The atmospheric plasma jet used in this study was produced in a dielectric tube wrapped with a metal strip of 10 mm wide as the power electrode and a metal plate as the ground electrode placed a distance of 27 mm away from the nozzle of the dielectric tube, as shown in Fig. 1(a). The inner and outer diameters of the dielectric tube were 1.58 and 2.44 mm, respectively. The electrodes were connected to a 20 kHz sinusoidal voltage with an amplitude of 4 kV. A helium gas flow of 5 standard liters per minute (SLM) was fed through the dielectric tube and the resulting discharge was ejected out of the outlet of the dielectric tube, in the form of a plasma jet, into the surrounding ambient air. Therefore, it was essentially an atmospheric dielectric-barrier discharge jet, details of which have been reported elsewhere. Current and voltage were measured by a current probe (Tektronix P6021) and a voltage probe (Tektronix P6015A), and recorded on a digital oscilloscope (Tektronix TDS 3000B). To image the plasma jet on a nanosecond scale, an intensified charge coupled device (iCCD) camera (Andor i-Star DH720) was used with its triggering achieved using a pulse generator. Optical emission spectrum was measured with a spectrometer system (Andor Shamrock) with a focal length of 0.3 m and a grating of 600 grooves/mm.

III. RESULTS AND DISCUSSIONS

With the exposure time of the iCCD camera set at 1 ms, the plume of the atmospheric dielectric-barrier discharge was imaged and it appeared as a plasma jet as shown in Fig. 1(a). Typical waveforms of discharge current and applied voltage are shown in Fig. 1(b). The applied voltage is predominately sinusoidal but with a small positive dc offset, and its positive and negative amplitudes are 3.94 kV and 3.57 kV, respectively. The total current measured from the ground electrode is made of a displacement current and a discharge current, with the former being largely sinusoidal and the latter being essentially conductive current. The discharge current appears in Fig. 1(b) as a large spike superimposed onto a small sinusoidal displacement current. As the applied voltage has a positive dc offset, the current has a distinct peak of 1.28 mA in each positive half-cycle of the applied voltage, whereas its peak is barely visible in the negative half-cycles. Further increase of the applied voltage will lead to a significant current peak in both the positive and the negative half-cycles of the applied voltage, exhibiting the typical current-voltage characteristics of atmospheric dielectric-barrier discharges. The gate signal for triggering the iCCD camera is also shown in Fig. 1(b) and its time delay was used to correlate the bullet...
images directly to a specific time instant on the discharge current waveform. As indicated in Fig. 1(b), the plasma jet at the positive and negative half cycle of the applied voltage are referred to as Jet-1 and Jet-2, respectively. It is worth mentioning that the plasma plume can also be produced in the absence of the ground electrode.

Figure 2 shows a sequence of 20 images of the plasma jet, each with an exposure time of 1 ns, during a positive half-cycle of the applied voltage (Jet-1) when the ground electrode was the instantaneous cathode. The time interval between any two successive images was fixed at 100 ns. These nanosecond images suggest that the plasma jet shown in Fig. 1(a) with 1 ms exposure time was actually formed by a fast moving plasma bullet. In each pulse of the discharge current, one plasma bullet is produced and so over a sufficiently long period of time the atmospheric dielectric-barrier discharge jet is essentially a fast-moving train of plasma bullets. As a plasma bullet traveled from the outlet of the dielectric tube to the ground electrode, its optical signature changed its intensity and size. The time delay marked in Fig. 2 corresponds to the time difference between the gate signal and a point on the discharge current waveform in Fig. 1(b), and so at a time delay of 38.7 μs, when the discharge current start to go up, marks the emergence of a plasma bullet from the dielectric tube. At a time delay of 39.3 μs, the discharge current reached its peak value, and the intensity of the plasma bullet also became strongest. This suggests that during the rising phase of the discharge current, the plasma bullet grew and became stronger, as shown in Fig. 2(a). After that, the plasma bullet started to die off as the discharge current started to decline. During this current-falling phase, there were fewer and fewer sufficient energetic electrons to produce relevant excited plasma species resulting in a diminishing optical emission. Figure 2(b) shows the plasma bullet reaching the ground electrode and extinguished there. The time between the first and the last images in Fig. 2 is 2.0 ms, close to the current pulse width of 2.3 μs. Therefore the discharge current peak may be attributed to the moving of the plasma bullet across the discharge gap.

Although there is no large discharge current peak in the negative applied voltage phase, a weak plasma bullet (Jet-2) was observed during this voltage-falling phase. It is shown in Fig. 3 that a sequence of 18 images of Jet-2. As Jet-2 was much weaker and traveling at a slower speed than Jet-1, which will be shown later, the time interval between any two successive images was fixed at 500 ns and the image intensity was enhanced. Compared to the plasma bullet in Jet-1, the plasma bullet in Jet-2 was longer and started to die off in between any two successive images was fixed at 100 ns.
The intensity of the plasma bullet reaches its maximum of 31.5. These results suggest that the plasma jet was dominated by Jet-1 although it was sustained over a longer period in Jet-2. As the plasma jet is dominated by Jet-1, the characteristics of Jet-1 are explained in the following. The speed of the plasma bullet in Jet-1 is at the very high end of the hypersonic range. The gas flow rate of helium in the dielectric tube is estimated to be 10.6 m/s, some three orders of magnitude lower than the bullet speed. Further experiments (not shown here) suggest that the speed of the plasma bullet is independent of flow rate of fed helium gas. Therefore, it is unlikely that the plasma bullets are propelled by the gas flow. By assuming that the electric field was uniform and set up by the applied voltage, the drift velocity of helium atom ions and molecular ions are estimated to be 133.4 m/s and 319.6 m/s thus suggesting their minor roles, if any, in the production of the plasma bullets. Again assuming a uniform electric field, the electron drift velocity is found to be 15.0 km/s, similar to the bullet velocity of 7.0–48.7 km/s. However, it does not explain why plasma bullets, if composed of negatively charged electrons, move towards the instantaneous cathode.

It is possible that the plasma bullet is produced by the ionization wave front. There are three mechanisms through which to contribute to the ionization front velocity, namely the electron diffusion, the ponderomotive force and the breakdown wave. The ionization wave front velocity due to electron diffusion can be expressed as \( v = \frac{1}{2} \frac{D_e}{D_p} \), where \( D_e \) is the electron diffusion coefficient with \( D_p \) being the gas pressure in Torr. As the cross-sectional area of the plasma jet is about 0.02 cm², the maximum current density is 64.0 mA/cm² at the peak current of 1.28 mA. Given that the discharge event lasts for 2.3 \( \mu \)s during which the applied voltage changes very little, this transient discharge may be approximated as a dc discharge occurring at the discharge current peak. According to a simple model for dc atmospheric pressure glow discharges in helium, the maximum electron energy is 32.2 eV at a current density of 64.0 mA/cm². In turn, this leads to an estimate of the frequency of direct helium ionization by electrons at \( 1.45 \times 10^{11} \) s⁻¹. With these parameters, the velocity of the ionization wave is estimated to be 27.7 km/s. This is close to the maximum plasma bullet velocity of 43.1 km/s in Fig. 5. Given that only the electron diffusion mechanism is...
It suggests that more must be done in order to understand the relative contributions of different mechanisms to the ionization wave. These authors proposed a model based on the ponderomotive force and the breakdown wave, depend on the gradient of the electric field. Although the current lack of established experimental techniques for measuring the electric field has prevented a reliable estimate of their contributions to the ionization wave in this study, it is conceivable that they are likely to add to the ionization front velocity. Therefore, the maximum plasma bullet speed of 43.1 km/s estimated from electron diffusion only and thus bring the overall speed of the ionization wave front closer to the maximum plasma bullet speed of 43.1 km/s. In short, it is likely that plasma bullets are produced through the ionization wave front. An atmospheric pressure plasma plume generated by submicrosecond voltage pulses was studied by others. These authors proposed a model based on photoionization to explain the dynamics of the plasma plume.\(^{15}\) It suggests that more must be done in order to understand the relative contributions of different mechanisms being put forward.

FIG. 6. (a) The optical emission spectrum from the plasma jet taken at 10 mm away from the exit of the dielectric tube and with 1 ms exposure time; (b) the time-resolved 391 nm line measured with 5 ns exposure time and at 0, 10, and 20 mm away from the exit of the dielectric tube.

In summary, the atmospheric dielectric barrier discharge jet has been shown to be formed by a hypersonic plasma bullet train. It has been established that their production is likely to be through the ionization wave and that they can be used to deliver reactive plasma species to different processing locations.

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