Influence of DC and AC external electric field on the propagation of "plasma bullets" along DBD helium plasma jet

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Abstract. Plasma jet generated by sinusoidal DBD in a tube blown with He is not uniform along its length because of existence of so called "plasma bullets" (ionization waves) travelling in jet each half-cycle. The bullet velocity and the visual shape of plasma jet will change, if to vary the ambient conditions for plasma jet. This work is devoted to the detailed experimental study on influence of the external DC and AC electric field with different amplitude and polarity on the bullet propagation in plasma jet. It has been established that one can change appreciably the plasma bullet velocity and even wholly suppress the bullets in the plasma jet.

1. Introduction
Non-thermal plasma jet can be generated by different discharges in narrow tube blown with various gas mixtures. The most popular source of non-thermal plasma jet is a sinusoidal dielectric barrier discharge (DBD) in He flow [1,2]. The detailed review of experimental and theoretical investigations devoted to different properties of such plasma jet was done in paper [3]. One of the interesting phenomena observed in DBD plasma jet is so called "plasma bullets" travelling along plasma jet. These "bullets" have been for the first time revealed by M. Teschke et al [4]. The bullets are characterized by higher electric field and higher light emission. In other words, the bullets flash the trajectory of plasma jet. This is a reason why the visual length of plasma jet is determined by a maximum distance that can be passed by a bullet after its run-out from the DBD zone. Note plasma bullet, in fact, is the ionization wave, the propagation mechanism of which is similar to the propagation mechanism of the head of normal streamer. According to this mechanism, the electric field strength in/around streamer head plays a crucial role in the propagation of the streamer. Based on this similarity, one may state that the bullet propagation velocity will depend not only on the parameters of the applied voltage (amplitude and frequency of sinusoidal voltage) influencing the electric field in the bullet but the polarity and amplitude of DC and AC external electric field formed artificially around the plasma jet as well. Moreover, in principle it is possible to arrange the configuration of the electric field around plasma jet which suppresses wholly the bullets. This work is devoted to the detailed experimental study of influence of the DC and AC external electric field formed artificially around the plasma jet on both the bullet propagation velocity in He plasma jet and possibility for existence of the bullets in plasma jet.

2. Experimental setup
Non-thermal plasma jet in helium flow was generated by sinusoidal dielectric barrier discharge (DBD) operating at atmospheric pressure. Gas discharge was excited in the quartz tube with inner and outer
diameters of 2.5mm and 4mm, respectively. The high-voltage electrode was a stainless steel wire with a diameter of 1 mm. The frequency of the applied voltage is equal to 100 kHz; the amplitude of the applied voltage was varied up to 4 kV; gas flow velocity at the DBD exit is equal to 40 m/s. Plasma jet enters the ambient air at room temperature and is directed towards thin metallic disc of 120 mm in diameter located at a distance of 36 mm from the tip of HV-electrode (or 28 mm from the discharge tube exit). In some experiments, we used the disc with a circular hole of 4 mm in diameter at his center. Metallic disc can be supported either at floating potential or stressed by DC or AC voltage. Sketch of the experimental setup is shown in figure 1.

Figure 1. Sketch of the experimental setup used for generation of a plasma jet by DBD in He flow

3. Experimental results and discussions

The images of plasma jet striking the metallic disc stressed by different DC potentials are shown in figure 2. All photos were taken at the same exposure time equal to 250 µs that is much longer compared to the period T of sinusoidal voltage (T = 10 µs).

Figure 2. The images of plasma jet colliding with metallic disc. The top of each jet corresponds to the exit from a discharge tube. The disc is stressed by different DC potentials (a)-(e); the enlarged negative image of plasma jet with visual length less of 2 mm, the disc is connected to the HV electrode (f). Amplitude of sinusoidal voltage powering the DBD is 3 kV. Exposure time for shots (a)-(e) is equal to 250 µs and 0.5 s for shot (f).

Note that in contrast to the dielectric substrate, plasma jet practically does not spread over the metallic disc. A reason is an absence on the metallic surface of the tangential component of electric field which is necessary for plasma spreading [5]. However, the diameter of area activated by plasma jet on the metallic disc is much larger compared to the size of visual plasma spot on the surface. This statement was proved by measurement of a radial distribution of contact angle of the water droplets deposited on the metallic surface treated by plasma jet with the small visual spot. It means that plasma jet contains a lot of reactive species which do not emit the light but they are transported by gaseous jet and spread (together with the spreading jet) over the metallic surface in the radial direction.

Another feature of the experimental results presented in figure 2 is the strong dependence of the brightness of plasma jet on DC potential applied to the metallic disc - the higher DC potential, the
stronger brightness of the jet. Such dependence is more pronounced for the positive polarity. It is clear that an existence of DC potential on the disc influences the voltage drop along plasma jet owing to changing the potential difference between HV electrode and disc in every half-cycle. For instance, DC positive potential increases the voltage drop along plasma jet in the negative half-cycle and diminishes it in the positive half-cycle. For DC negative potential, everything will be on the contrary.

Figure 3. The set of plasma jet images taken by fast frame camera at different DC potentials $U_p$ on the disc. The shots are distributed over a single cycle of the current and voltage of DBD. Each isolated shot correlates with the image of the discharge tube shown in the top of every shot. The exposure time of every shot is 200 ns. a) Free jet; $U_p = +2$ kV (b); +1 kV (c); 0 kV (d); -1 kV (e); -2 kV (f).
In the case of the disc connected to the HV electrode (figure 2.f), the electric field strength in the space between HV electrode and disc is equal to zero at any moment. It leads to that the luminosity of plasma jet disappears in this space - only the dim light has been emitted from very short area located in vicinity of the discharge tube exit. This is a reason why we used a very long exposure time of 0.5 s in order to get the image of the dim plasma jet. Based on this experiment we can conclude that plasma bullets cannot develop in plasma jet with zero electric field. However, the absence of plasma bullets in plasma jet does not mean that dark plasma jet is not enriched with the reactive species. This statement was proved again by the measurement of a radial distribution of contact angle of the water droplets deposited on the metallic surface treated by dark plasma jet. As it turned out, the dark plasma jet treats the substrate with the efficiency close to that for bright plasma jet with bullets.

The images presented in figure 2 give only general impression about influence on plasma jet of DC potential applied to the disc. To clarify in more detail what happens in plasma jet during each half-cycle of sinusoidal voltage, we have taken the shots of jet with short exposure time and synchronized with the voltage and current of DBD. The obtained results for different DC potentials on the disc are presented in figure 3. For the reference, the set of images of free jet is presented in figure 3a. In free plasma jet, the bullets can be seen clearly only in positive half-cycle.

The disk under floating potential $U_p = 0$ kV leads in itself to change of behavior of plasma bullets (see figure 3d). A reason of that is an existence of the stray capacitance of the disc regarding the ground. This capacitance increases the current flowing through plasma jet to the ground. In this case plasma bullet appears a bit later and propagates more slowly compared to that in free jet. In the negative half-cycle, plasma bullet again does not happen but the brightness of plasma jet increases for short time simultaneously throughout its length. Positive potential $U_p = +1$ kV on the disc leads to still more lag in arising of plasma bullet and its deceleration (see figure 3c). As for negative half-cycle, the increase of brightness of plasma jet along its full length lasts a bit longer. Further growth of positive potential ($U_p = +2$ kV) results in a full cessation of the bullet appearance in positive half-cycle (see figure 3b) but in negative half-cycle both the brightness of full plasma jet and the duration of stage with bright plasma grow up still more appreciably.

The applying of DC negative potential to the disc leads to the acceleration of plasma bullet movement in positive half-cycle - the higher negative potential, the faster movement – (see figures 3e and 3f). The arrival of the bullet to the disc is followed by formation of plasma filament when plasma jet increases appreciably its brightness simultaneously throughout its full length. The duration of this bright stage increases with the increase of negative potential. In negative half-cycle, the length of bright plasma filament formed in previous positive half-cycle diminishes due to its reducing towards a disk.

Close examination of the images presented in figure 3 allowed us to determine the distribution of plasma bullet velocity along the jet for different experimental conditions. The summary of the obtained results is shown in figure 4.

![Figure 4](image-url)  
**Figure 4.** The distribution of plasma bullet velocity along He plasma jet. a) free plasma jet (1); plasma jet colliding with the disc under floating potential (2). b) plasma jet colliding with the disc: $U_p = 0$ kV
(1), Up = +1 kV (2), Up = -1 kV (3). x is the coordinate along the plasma jet; x = 0 corresponds to the exit of the discharge tube.

Figure 5. The images of the plasma jets for different conditions of their propagation.
a) plasma jet in free space; total plasma jet length is 43 mm; DBD power is 2.9 W.
b) plasma jet meets the metallic disc with a hole of 4 mm in diameter and passes through this hole; the disc is non-grounded (floating potential); total plasma jet length is 41 mm; DBD power is 3.0 W.
c) plasma jet meets the metallic disc with a hole of 4 mm in diameter and passes through this hole; the disc is grounded; total plasma jet length is 39 mm; DBD power is 4.1 W.
d) the current and voltage waveforms of DBD which practically the same for a), b) and c) cases.

We studied the possibility of plasma jet to pass through the metallic substrate (disc) having a hole. The obtained results are presented in figure 5. As it turned out, plasma jet can pass through the hole if its diameter exceeds 3 mm whether the disk is grounded or not. Besides, the disc increases the brightness of the jet between the discharge exit and disc. This effect is more pronounced for the case of the grounded disc. We attribute this effect to an increase the stray capacitance provided by the disc that leads to increasing of both the displacement current between the lateral area of plasma jet and disc and conductivity current flowing through plasma jet to HV electrode.

4. Conclusion
It was shown that interaction of He plasma jet with the metallic substrate placed transverse to the jet depends on the polarity and amplitude of potential applied to the substrate. It has been established that one can change appreciably the plasma bullet velocity and even wholly suppress the bullets in the plasma jet by changing the potential on the substrate. It is found out that the conductivity current flowing through plasma jet depends on the stray capacitance formed around the jet - the higher stray capacitance, the higher conductivity current flowing through plasma jet and higher its brightness.

5. References
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Acknowledgments
This work was supported by Russian Foundation for Basic Research (grant № 17-02-00234).