How ionization waves (plasma bullets) in helium plasma jet interact with a dielectric and metallic substrate

Yu S Akishev\textsuperscript{1,2}, V B Karalnik\textsuperscript{1}, M A Medvedev\textsuperscript{1}, A V Petryakov\textsuperscript{1}, N I Trushkin\textsuperscript{1} and A G Shafikov\textsuperscript{1}

\textsuperscript{1} SRC RF TRINITI, 108840, Moscow, Troitsk, Pushkovykh street, 12, Russia
\textsuperscript{2} NRNU MEPhI, 115409, Moscow, Kashirskoe shosse, 31, Russia

Abstract. Plasma jets generated by DBD are not uniform along their length because of existence of so called "plasma bullets" (ionization waves) travelling each half-cycle in the jets. The bullet velocity and the visual shape of plasma jet will change, if plasma jet meets the substrate. This work is devoted to the detail experimental study on influence of the substrate material (dielectric or metal) on the bullet propagation velocity in plasma jet formed by the cylindrical DBD in He flow. It was found out that the conductivity of the substrate has a great impact on the plasma bullets parameters.

1. Introduction
Plasma jet generated by dielectric barrier discharge (DBD) in He flow blown through a narrow dielectric tube is the object of many studies [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. A visual length of plasma jet in a free space is determined therefore by a maximum distance traveled by a bullet from the DBD exit. In fact, plasma bullet is the ionization wave, the propagation mechanism of which is similar to the propagation mechanism of the head of normal streamer. One of the important parameters influences the streamer propagation is the displacement current collected by streamer head from the space in front of the streamer. For the case of a sinusoidal DBD in He, it means that the bullet propagation velocity depends not only on parameters of the applied voltage (amplitude and frequency of sinusoidal voltage) but on the configuration of the variable electric field formed around plasma jet in the course of the bullet propagation. If the plasma jet treats the dielectric or metallic substrate placed on different distance from the DBD outlet (in other words, the space in front of the jet is not free), the configuration and amplitude of the variable electric field in front of the moving bullet will change appreciably compared to that for plasma jet in free space. One can possible expect therefore that both the bullet velocity and the visual shape of plasma jet interacting with the substrate will change as well. This work is devoted to the detailed experimental study on influence of the substrate material (dielectric or metal) on both the bullet propagation velocity in plasma jet and shape of the plasma jet contacting the substrate.
2. Experimental setup
In order to generate a long non-thermal plasma jet we used a sinusoidal DBD in He flow. Frequency of the applied voltage is equal to 100 kHz; amplitude of the applied voltage was varied up to 4 kV; gas flow velocity at the DBD exit is equal to 25-30 m/s. Plasma jet enters the ambient air at atmospheric pressure and strikes the substrate. Dielectric substrate were quartz (\(\varepsilon \approx 4\)) and ceramic (\(\varepsilon \approx 8.5\)) plates with thickness \(d = 12\) and 1.65 mm respectively. Sketch of the experimental setup is shown in figure 1. The treated substrates were placed on the metallic plate which can be grounded, if it was necessary.

3. Experimental results and discussions
The images of plasma jet either entering free space or striking the dielectric and metallic substrate are shown in figure 2. One can see that plasma jet spreads over a dielectric substrate (the higher applied voltage and ratio \(\varepsilon/d\), the stronger spreading) but does not do that on the metallic substrate. A reason is that the plasma spreading over a dielectric substrate is a normal surface dielectric barrier discharge (SDBD) [5]. Indeed, plasma jet plays a role of the conductor transferring the high-voltage potential to the substrate. Due to existence of the stray capacitance between a dielectric substrate and ground, the SDBD over substrate happens. One of the needed conditions for appearance of SDBD is a formation of the tangential electric field on the surface. This condition is not fulfilled for metallic substrate, i.e. SDBD plasma cannot happen on metallic surface. Equivalent electric schemes of DBD corresponding to the images in figure 2 are presented in figure 3. These schemes take into account an existence of stray capacitance of the "plasma jet - substrate" system for different ambient conditions.

Figure 1. Sketch of the experimental setup used for generation of a plasma jet by DBD in He flow and investigation of the plasma bullets colliding with a dielectric and metallic substrate.

Figure 2. The images of plasma jet under different conditions. Exposure time of each shot is 0.5 ms. a) free plasma jet, some expansion of the jet at its end happens due to transition of gas jet at this place into a turbulent regime; b), e) quartz substrate placed on non-grounded and grounded metallic plate; c), f) ceramic substrate placed on non-grounded and grounded metallic plate; d), g) non-grounded and grounded metallic plate.
Figure 3. Equivalent electric schemes of DBD with plasma jet. Left and right sides of each picture depict the scheme of DBD and plasma jet. a) jet enters a free space; b) jet impacts a dielectric substrate placed on the grounded metallic plate; c) jet impacts a metallic plate at the floating potential; d) jet impacts a grounded metallic plate. $R_1$ and $R_2$ notate the effective resistances of DBD plasma and plasma jet; $C_1$ and $C_2$ notate the capacitance of DBD and plasma jet for every configuration a)-d).

The current-voltage waveforms of DBD correlated with the images of plasma jet taken by a fast frame camera at different time moments are presented in figure 4 and figure 5. The enumerated quadrates in the legends of figure 4 show the time position of the corresponding shots presented in figure 5.

Figure 4. The current-voltage waveforms of DBD in He corresponding to the cases: a) free jet; b) jet impacts the grounded ceramic substrate; c) jet impacts the metallic plate at floating potential.
In contrast to figure 2, one can see in figure 4 that the existence of the substrate practically does not influence the current-voltage waveforms of DBD. However, a spatial-temporal behavior of plasma jet and plasma "bullets" strongly depends not only on the existence of substrate but on the material of substrate and its proximity to the ground as well.

In the case of a free jet (figure 5a), the stray capacitance of plasma jet regarding the ground is not so large. In a free jet, the negative "bullets" are practically invisible. A positive plasma "bullet" appears at the exit of the discharge tube not immediately at the moment of the DBD breakdown (shot #5, figure 5a) but about 1 µs later. In general, slow bullet propagation inside the tube correlates with the growth of current but fast bullet propagation in plasma jet correlates with diminishing the current. Fast decay of brightness of the plasma jet (#15, 16, figure 5a) is followed by shortening of his visible length.

In the case of a plasma jet striking a thin grounded ceramic substrate (figure 5b), the stray capacitance of the "plasma jet - substrate" system is large. It leads to that the electric current flowing through plasma jet increases appreciably compared to the case of a free jet. In this case the amount of the electric charge deposited on the substrate in the course of every half-cycle is large and the behavior of "plasma jet - substrate" system is similar to normal DBD. In other words, plasma jet spreading over dielectric substrate can be considered as a single large microdischarge of DBD. The mentioned above results in the following features. The plasma "bullets" are absent in negative half-cycles: the brightness of plasma jet increases simultaneously over the whole length between the substrate and the tube exit (#2-5, figure 5b). The growth of brightness correlates with the current diminishing. Fast decay of the plasma jet brightness (#6, 7, figure 5b) happens also practically simultaneously over the whole length of plasma jet. In a positive half-cycle, the luminosity of plasma jet is forming due to simultaneous movement of two ionization waves quickly propagating from a discharge zone and substrate (#9-11, figure 5b). Maximum luminosity of plasma jet (#13, figure 5b) happens approximately at the moment when the applied voltage is maximum but the discharge current is close to zero. Note that the current flowing to the ground through plasma jet may not be zero at this moment. Decay of the brightness (#14, 15, figure 5b) happens again practically simultaneously over the whole length of plasma jet.

As it is shown in figure 2.g, b, plasma jet does not spread over the metallic substrate and this property does not depend on that there is or not a connection of the substrate with the ground - the connection with the ground leads only to strong increase in both the current flowing through plasma jet and brightness of its luminosity but does not lead to spreading the plasma over the substrate. Figure 5c presents the set of the instant shots of plasma jet interacting with a metallic plate at the floating potential. Interesting that in the negative half-cycle the ionization wave propagates from the substrate towards the discharge tube (#5-8, figure 5c). Possible reason of that is associated with the large
charge deposited on the metallic surface at the preceding half-cycle. However, the positive "bullets" propagate in "right" direction from the discharge exit towards the substrate (#11-16, figure 5c).

Close examination of the data similar to those presented in figure 5 allowed us to determine the velocity of the positive plasma bullets vs their distance from the discharge zone. The type of the substrate (dielectric or metal) and its connection with the ground (grounding or floating potential) were the variable parameters of the experiment. The appropriate results are shown in figure 6.

One can see in figure 6 that there is a small influence of any substrate on the velocity of positive bullets if the substrate is placed closer than 20 mm from the discharge zone. However, after this distance the existence of the substrate leads to diminishing the bullet velocity propagation in the plasma jet striking the substrate.

4. Conclusion
It was shown that interaction of He plasma jet with the substrate depends on its conductivity – plasma jet striking the dielectric spreads over a substrate (the higher applied voltage and ratio \( \varepsilon /d \), the stronger spreading) but plasma jet does not do that on the metallic substrate. It was found out also that there is a small influence of any substrate on the velocity of positive bullets in plasma jet, if the substrate is placed closer than 20 mm from the discharge zone. The existence of any substrate placed at longer distance leads to diminishing the bullet velocity propagation compared to that for free plasma jet.

5. References
[1] Akishev Yu, Balakirev A, Grushin M, Karalnik V, Kochetov I, Napartovich A, Petryakov A and Trushkin N 2015 Trans. Plasma Sci. 43 745
[2] Korolev Yu 2015 Russian Journal of General Chemistry 85 1311
[3] Lu X, Naidis G, Laroussi M and Ostrikov K 2014 Phys. Rep. 540 123
[4] Teschke M, Kedzierski J, Finantu-Dinu E, Korzec D and Engemann J 2005 IEEE Trans. Plasma Sci. 33 310
[5] Akishev Yu, Aponin G, Balakirev A, Grushin M, Karalnik V, Petryakov A and Trushkin N 2013 J. Phys. D: Appl. Phys. 46 464014

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