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# Formation of an argon plasma jet fed by bunches of bipolar high-voltage pulses

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An argon plasma jet, which is formed in an ambient air at the output of a quartz tube by a dielectric-barrier discharge with an electrode system consisting of central rod and outer ring electrodes and fed by an applied voltage generated as bipolar pulses bunches of variable duration, has been studied. The reproducible from bunch to bunch dynamics of propagation of guided streamers forming a plasma jet was observed. An increase in the distance traveled by each subsequent streamer compared to the previous one in each subsequent positive pulse in the bunch has been recorded. The streamer imaging was carried out in the presence of a dielectric target; the jet approaching to the target surface up to its contact has been registered. The nature of the jet propagation to the target has been shown to be controlled by changing the duration of the bunches and the time between them.

**Keywords:** argon atmospheric pressure plasma jet, guided streamer, control of streamer propagation dynamics, dielectric barrier discharge.

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Nowadays the development of sources of low temperature weakly ionized highly non-equilibrium atmospheric plasma is a sphere of active studies, and has prospects of immediate implementation in some practical applications [1,2]. For local treatment of the thermosensitive surfaces the cold plasma jets based on a dielectric barier discharge in helium or argon flow are most suitable [3]. The visible continuous plasma jet is a string of series of streamers or ionizing waves passing through the work gas flow from the discharge tube, they occur in each period of the applied voltage [4–6]. Under certain conditions each new streamer strictly follows the previous streamer path thus determining the name „guided streamer“.

Currently the concept of adaptive plasma jets appears [7]. It means the direct operative monitoring of the jet effect on the object upon its characteristics change in real time [2], this especially important for live targets. Different strategies of making the controllable plasma jet and setting of the control parameters of the jet source according to the target response are suggested (see, for example, [7,8]). The dynamics of streamers propagation in the plasma jet is interrelated to the electric field distribution in the system, accumulation of active chemical components, charge transfer to the target. Control of streamers propagation mode makes it possible to provide the controllable effect on the target [8].

Use of the applied voltage of specific waveform affects the dynamics of the guided streamers in the plasma jet and determines the mode of target approaching by jet, as it was shown by us for the jet in helium [9,10]. A stepwise mode of the streamer propagation near the target is registered, and possibility of the streamer stopping near its surface with fine and smooth adjustment of the approaching mode is shown [10,11].

The present paper presents data on the guided streamer propagation in argon plasma jet to the surface of dielectric target upon supply with voltage in form of bipolar pulse bunches. Change in duration $\tau_{bunch}$ of voltage bunches and pause $\tau_{pause}$ between them ensures smooth control of the jet approaching the target.

Th plasma jet was generated by a dielectric barier discharge in a quartz tube with inner and outer diameters 2 and 4 mm respectively. The electrode system comprises HV central rod rounded at end with diameter of 0.9 mm, and earthed outer ring 4 mm wide. Edge of rod and ring electrodes was at tube end at distance 4 mm. Disk of polished quartz glass 4 mm thick, and 22 mm in diameter was installed at distance of 15 mm from the discharge tube end. A copper washer connected to earth via the measuring capacitor (200 pF) was under the disk. High pure argon 99.998% was delivered via the discharge tube with volume flow rate of 1 l/min. The plasma jet was directed downwards (Fig. 1, $a$). The electric discharge in the tube was generated when powered with bunches of changed duration of bipolar pulses of voltage with oscillations at plateau (Fig. 1, $b$). The voltage pulse bunches are reproduced from bunch to bunch. The reproducibility was checked by record of four strings of 50 voltage bunches each. The change of pulse period duration did not exceed 6 ns. Amplitude change was 20 V maximum. All measurements were made with time delay at least 5 min after high voltage switching onto exclude effect of different transient processes. Procedure for conducting experiments, measurements and registration described in [10] was used.

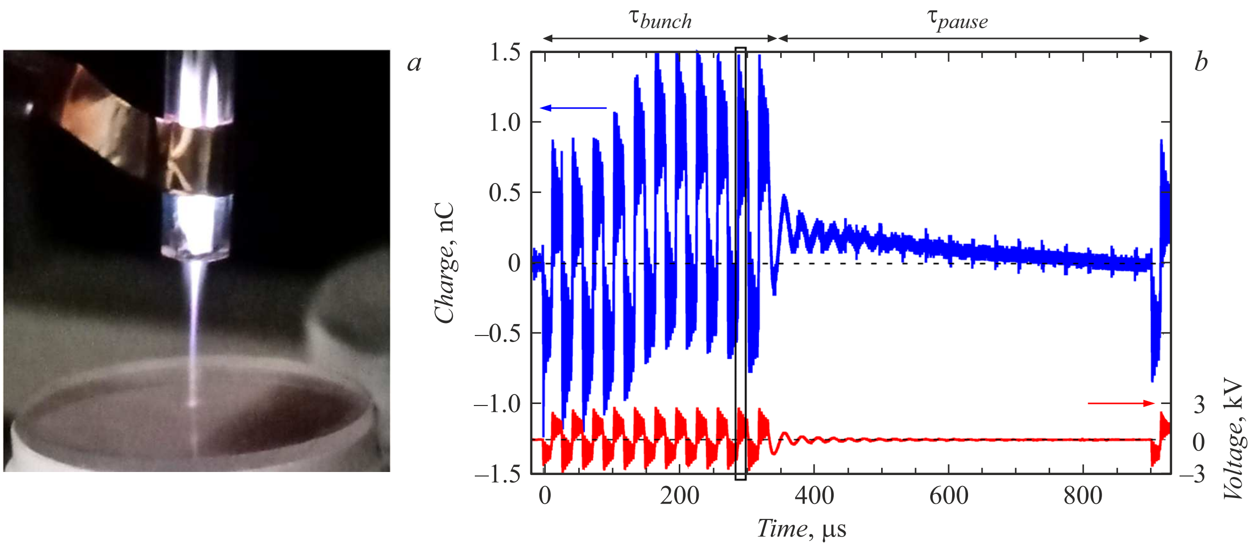


**Figure 1.** View of argon plasma jet ($a$) and applied voltage signal and charge on measuring capacitor in target circuit ($b$).

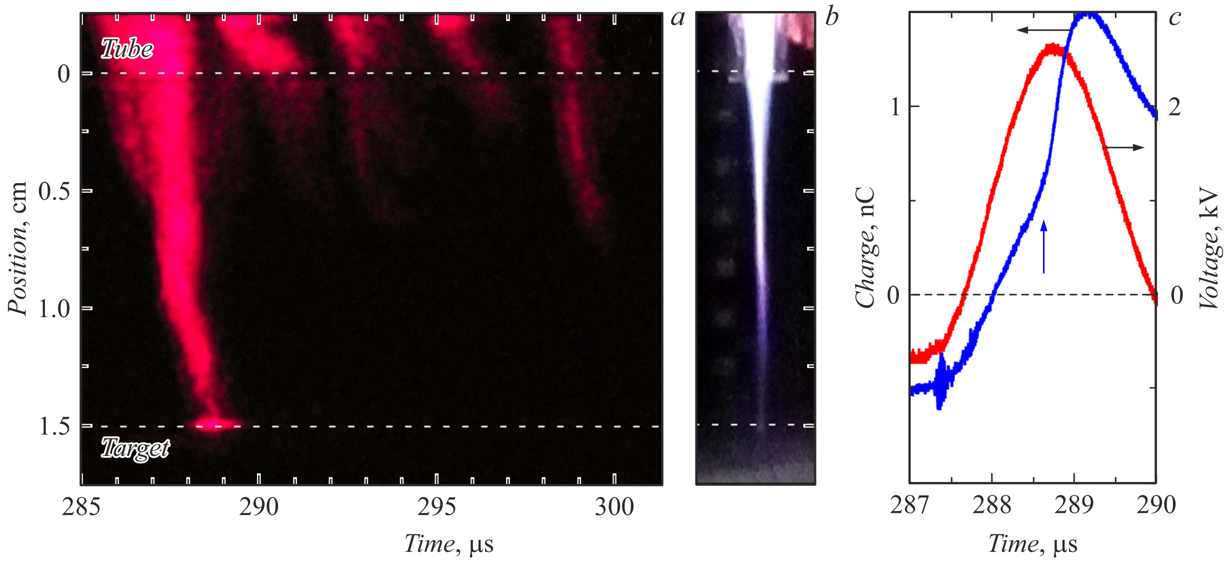


**Figure 2.** High-speed photostreak of guided streamer to target surface at positive pulse in bunch ($a$) (for pulse in rectangular frame in Fig. 1, $b$), photo of jet combined with photostreak ($b$) and voltage signals on HV electrode with charge on measuring capacitor in target circuit ($c$). Vertical arrow on the fragment $c$ shows the knee in the charge curve when streamer approaching to the target. High-speed image was obtained with accumulation of 100 shots.

Fig. 2, $a$ shows high-speed photostreak of the guided streamer achieving the target, and corresponding to jet photo (Fig. 2, $b$). The characteristic knee on the charge curve in the target circuit (Fig. 2, $c$) corresponds to the moment when the streamer approaches the surface. The shooting was performed at positive pulse of voltage shown with frame in Fig. 1, $b$. For the plasma jet generation with guided streamers formation in the gas flow with temperature in channel close to the room temperature, the optimal experiment parameters were selected based on our previous studies [9,10,12–14] and data [15,16]. Formation of the streamer guided along the flow without branches and without formation of a narrow hot channel is determined by front duration of the applied voltage and voltage amplitude at set geometric characteristics of the gas flow [13,15,16]. In very wide gas flow at high voltage the streamer will branch out. At high voltage a hot discharge channel to target will be formed. At the same time for extra narrow flow at low voltage the plasma jet will not be formed. Maximum length of the plasma jet is formed at gas flow near the transfer from laminar flow to turbulent one [12,14].

The regular formation of guided streamers in the argon plasma jet occurs for the selected experimental conditions. The guided streamer consistently and monotonically in-

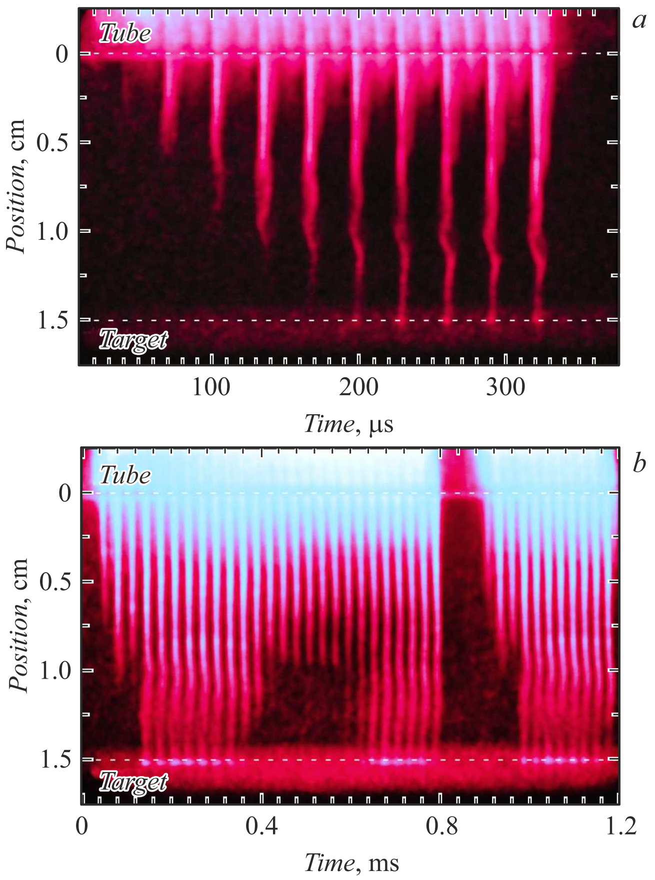


**Figure 3.** High-speed photostreak of guided streamers propagation at duration of voltage bunch 340 $\mu$s (*a*) (for voltage signal in Fig. 1, *b*) and 800 $\mu$s (*b*). High-speed image was obtained with accumulation of 100 shots.

creases the distances passed at each next positive voltage pulse in the bunch until the target is approached. This process is shown in Fig. 3, *a* for applied voltage shown in Fig. 1, *b*. This process is due to residual ionization after previous streamer passage (in memory effect), and is described for plasma jets in helium [5,9,17,18].

When duration of pulse bunch $\tau_{bunch}$ increases after definite pulse the streamers in the bunch stop to achieve the targets, as it is shown in Fig. 3, *b*. Presumably this is due to accumulation of uncompensated charge in space and on target, this screens the streamer field [19,20]. Gradual charge accumulation can be observed in the signal curve of the measuring capacitor in the target circuit (Fig. 1, *b*). The positive streamer approaching to the surface is always accompanied by the knee in charge curve on target (Fig. 2, *c*). At negative voltage pulses the knees in the charge curve are not observed. The time periods, when the streamer touches the surface, correspond to larger average positive offset of charge signal in the target circuit. At negative pulses and upon decrease in average offset in the charge curve the streamers do not approach the target surface. The negative streamers are formed, but, apparently do not approach the target. Fig. 3, *a* well shows short „teeth" of negative streamers between long „crests" of positive one. The charge is transferred to the target mainly by positive streamers at positive voltage pulses. On the target and in space the uncompensated positive charge is formed, which starting from some time do not permit the streamers approach to the target. Rather high conductivity of the environment ensures discharge of the charged surfaces and volume. Apparently, after the charge relaxation from the target region the streamers again approach to the target. The effect of frequency self-organization described in [21,22] for the helium jet begins to appear.

At that the pause between the bunches sufficient for relaxation of accumulated charges system results in repetition in evolution of the streamers dynamics (Fig. 3, *b*). At pause $\tau_{pause}$ between the bunches $\sim 100\,\mu$s the observed effect of the passed pulse bunch on the streamers formation in jet in present bunch disappears, as during time period $\sim 100\,\mu$s the charges relaxation occurs in the surrounding space and on the surfaces [9]. The argon plasma is deionized in jet for the time period $\sim 1\,\mu$s [23]. Selection of optimal pause between the bunches ensures the reproducible dynamics of streamers in each bunch. Presence of gradual accumulation of positive charge by the positive streamers without discharging by negative streamers results in possibility of smooth adjustment of the target touching mode by change in duration of the voltage bunches and pause between them.

So, the regulations of voltage bunches regime provides the possibility to control the propagation of argon plasma jet in the surrounding air towards the target. Change in duration of bunches and pause between them provided monitoring of the mode of guided streamers approaching to the target.

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## Conflict of interest

The authors declare that they have no conflict of interest.

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