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Peculiarities of pulsed plasma jet initiation

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The generation of a cold plasma jet of atmospheric pressure in helium by unipolar positive pulses excitation at a voltage of 2–6 kV and the impact on a dielectric target made of aluminum oxide has been studied. It is shown that the main parameter influencing the regular nature of the streamer breakdown is the pulse duration, and the achievable parameters of cold plasma impact on the target identical to those for sinusoidal excitation.

Keywords: plasma jet of atmospheric pressure, pulse excitation.

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The field of medicine focused on research into the influence of plasma formations on biological objects is currently advancing rapidly (see, e.g., [1–3] and references therein). Strong electric fields and chemical reactions at the surface of live tissue in interaction with a cold plasma jet (CPJ) of atmospheric pressure induce changes in the composition of active radicals and ions in cells, thus allowing one to control biological processes in various cell culture types. The capacity of a CPJ to suppress cancer cell viability attracts special attention.

The application of sinusoidal or unipolar pulsed voltage to electrodes is one of the methods of generation of a plasma jet. Cathode streamers are formed by positive voltage and propagate along the flow of an inert gas pumped through the device toward the external environment, generating a plasma jet. The irregular nature of a streamer breakdown (self-organization effect, which is not observed in free jet propagation) was noted in [4] in the interaction between a CPJ and a target. Depending on amplitude U, frequency of the applied sinusoidal voltage f_U, distance from a nozzle to a target z, and the target type, frequency of current pulses f_I detected near the target deviates from f_U. The nature of irregularity is governed by the relation between the plasma density in a streamer head and the residual plasma density above the target surface. Only a fraction of streamers reach the target surface; the other ones decay in interaction with a cloud of quasi-neutral plasma generated by the previous streamers. It has been demonstrated in comparative studies of CPJ initiation by sinusoidal and pulsed voltage in [5] that touching-target current frequency f_I in the former case is equal to the frequency of the applied voltage or is a unit fraction of it: $f_I \approx f_U$, $f_U/2$, $f_U/3$, or $f_U/4$ ($f_U \approx 52$ kHz). Note that the propagation of streamers at moderate U and f_U values is regular in nature, but the plasma–target interaction intensity in this case is too low to suppress cancer cell viability efficiently. With pulsed initiation at pulse repetition frequency f_0, the regular nature of streamer propagation ($f_I = f_0$) was maintained under all excitation conditions studied in [5]. It was found in subsequent biophysical experiments that, under certain conditions, $f_I \neq f_0$ even in this case.

The uncertainty of operating parameters of electrophysical devices (plasma sources) and the corresponding uncertainty of parameters of irradiation of biological objects preclude one from introducing the plasma treatment technique into biophysical experiments and clinical practice. Therefore, the aim of the present study is to examine the specific features of streamer breakdown dynamics and the plasma jet parameters in the case of initiation by unipolar positive pulses.

A pulse generator with variable repetition frequency $f_0 = 5–40$ kHz was used to generate a CPJ. A rectangular pulse was formed by a push-pull transistor converter with a pulse step-up transformer. The first transistor shaped the leading edge and the top of a pulse, while the second one shaped the falling edge. Ballast resistance at the transformer output was used to limit the transient processes at the leading and falling edges of a pulse. Voltage amplitude $U = 2–6$ kV was limited to ensure safe CPJ treatment conditions for future experiments with animal models. The pulse duration (measured at the base) varied within the $\tau = 6–20\,\mu$s range.

Just as in [5], the CPJ source was a coaxial dielectric channel 100 mm in length with an inner diameter of 8 mm and a nozzle (in the form of a capillary 2.3 mm in diameter) at its end. The discharge region was formed by two electrodes. Voltage was applied to an inner rod electrode 50 mm in length and 2 mm in diameter, which was positioned at the center of the dielectric channel. A grounded annular electrode was positioned at the end of the dielectric channel on its outer surface. Voltage U was measured with a high-resistance divider. A dielectric

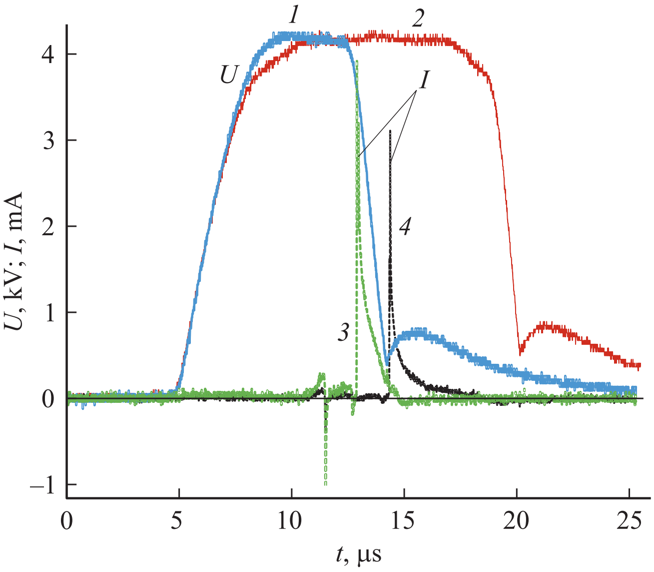

Figure 1. Oscillogram records of U (*1*, *2*) and I (*3*, *4*) at excitation pulse duration $\tau = 8$ (*1*, *3*) and $15\,\mu s$ (*2*, *4*). $\nu = 9$ l/min, $f_0 = 30.6$ kHz.

Al_2O_3 plate with a thickness of 1 mm was used as the target. Current measurements were performed at the target surface that was positioned at distance $z = 25$ mm from the nozzle transversely to the CPJ propagation axis. The value of z was chosen so as to match the standard conditions of experiments on CPJ treatment of culture media and test animals. The current sensor was constructed from 16 symmetrically positioned and parallel SMD resistors. Resistors were arranged in a circle between two concentric rings of copper foil of different diameters on an aluminum oxide plate, which was positioned so that a plasma jet (the jet diameter at the point of contact with the target was ~ 2 mm) hit the center of the smaller ring [4]. This sensor geometry allowed us to measure the current spreading over the target.

With the working gas (grade A helium, 99.995% pure) pumped through the channel with flow velocity $v > 1$ l/min and unipolar positive pulses applied to electrodes, a discharge was initiated in the discharge gap, and a plasma jet extending beyond the channel formed when a certain U threshold was crossed. The voltage pulse amplitude at which a CPJ reached the target was $U > 3$ kV and depended only weakly on the pulse duration. The spatial localization of a plasma jet was governed by the channel geometry, the capillary size, the gas flow rate, and the voltage amplitude. The jet length reached ~ 50 mm under the optimum conditions at $U \approx 3{-}4$ kV and $v = 5{-}10$ l/min.

Figure 1 presents the oscilloscope records of voltage U and current I at $\tau = 8$ and $15\,\mu s$. Under equal voltages, current delay time τ_d increases with τ; the value of τ_d for pulses of the same duration τ decreases with increasing U. Figure 2 presents dependences $I(U)$ of the current amplitude at the target surface on the voltage amplitude for excitation pulse duration $\tau = 6$, 7, 10, 12, and $15\,\mu s$ at $v = 9$ l/min. These dependences are sublinear curves that are similar in nature to those reported in [5]. It can be seen from Fig. 2 that, under otherwise equal conditions, greater current amplitudes are achieved at $U > 4.2$ kV for pulses with smaller τ values; at $U < 4.2$ kV, longer pulses allows one to reach greater current amplitudes. The current amplitude increases with the working gas flow rate. For example, the current strength increases by a factor of ~ 2 at $U \approx 4.2$ kV and $\tau = 12\,\mu s$ when v increases from 3 to 9 l/min. The maximum amplitude of the CPJ current reaching the target is ~ 10 mA. Under otherwise equal conditions, this corresponds to the parameters determined with sinusoidal initiation [5]. The examination of spectroscopic parameters of the region of interaction between a CPJ and the culture medium revealed that the OH hydroxide line intensity ($\lambda \approx 309$ nm, transition $A^2\Sigma{-}X^2\Pi$) increases when shorter excitation pulses are used.

The frequency characteristics of a CPJ (dependences $I(f)$) were examined at a constant voltage amplitude $U = 4.2$ kV and excitation pulse duration $\tau = 8$ and $16\,\mu s$ within the $f_0 = 7{-}36$ kHz range (Fig. 3, *a*). It was found that the $I(f)$ dependence corresponding to CPJ initiation by a „short“ voltage pulse with $\tau < 12\,\mu s$ descends monotonically at $f_0 > 15$ kHz, and f_I (the frequency of current pulses reaching the substrate) matches repetition frequency f_0 of voltage pulses within the entire studied range. If a CPJ is initiated by „long“ voltage pulses with $\tau > 12\,\mu s$, the current pulse frequency becomes lower than the repetition frequency of voltage pulses. At $f_0 \approx 5{-}25$ kHz, $f_I \approx f_0$; an unstable mode with $f_I \approx f_0$ or $f_0/2$ is established at $f_0 \approx 25{-}30$ kHz; at $f_0 > 30$ kHz, $f_I \approx f_0/2$. If $z \leqslant 10$ mm, $f_I \approx f_0/2$ for any pulse duration.

It was found by varying the experimental parameters within a wide range that pulse duration τ is the parameter that affects the regularity of the CPJ–target interaction ($I(f_0)$). The leading-edge and falling-edge times, the pulse-

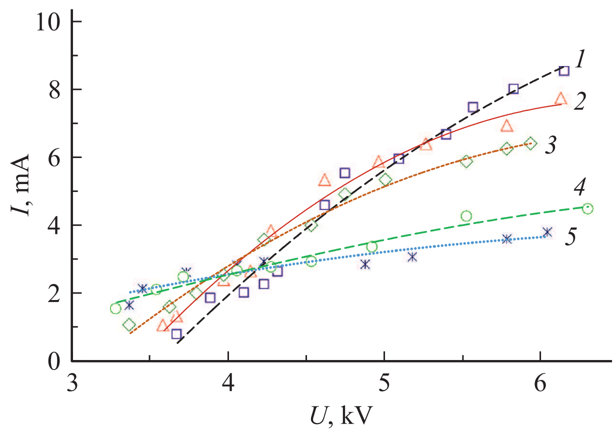

Figure 2. Dependences $I(U)$ at excitation pulse duration $\tau = 6$ (*1*), 7 (*2*), 10 (*3*), 12 (*4*), and $15\,\mu s$ (*5*) at $v = 9$ l/min, $f_0 = 30.6$ kHz.

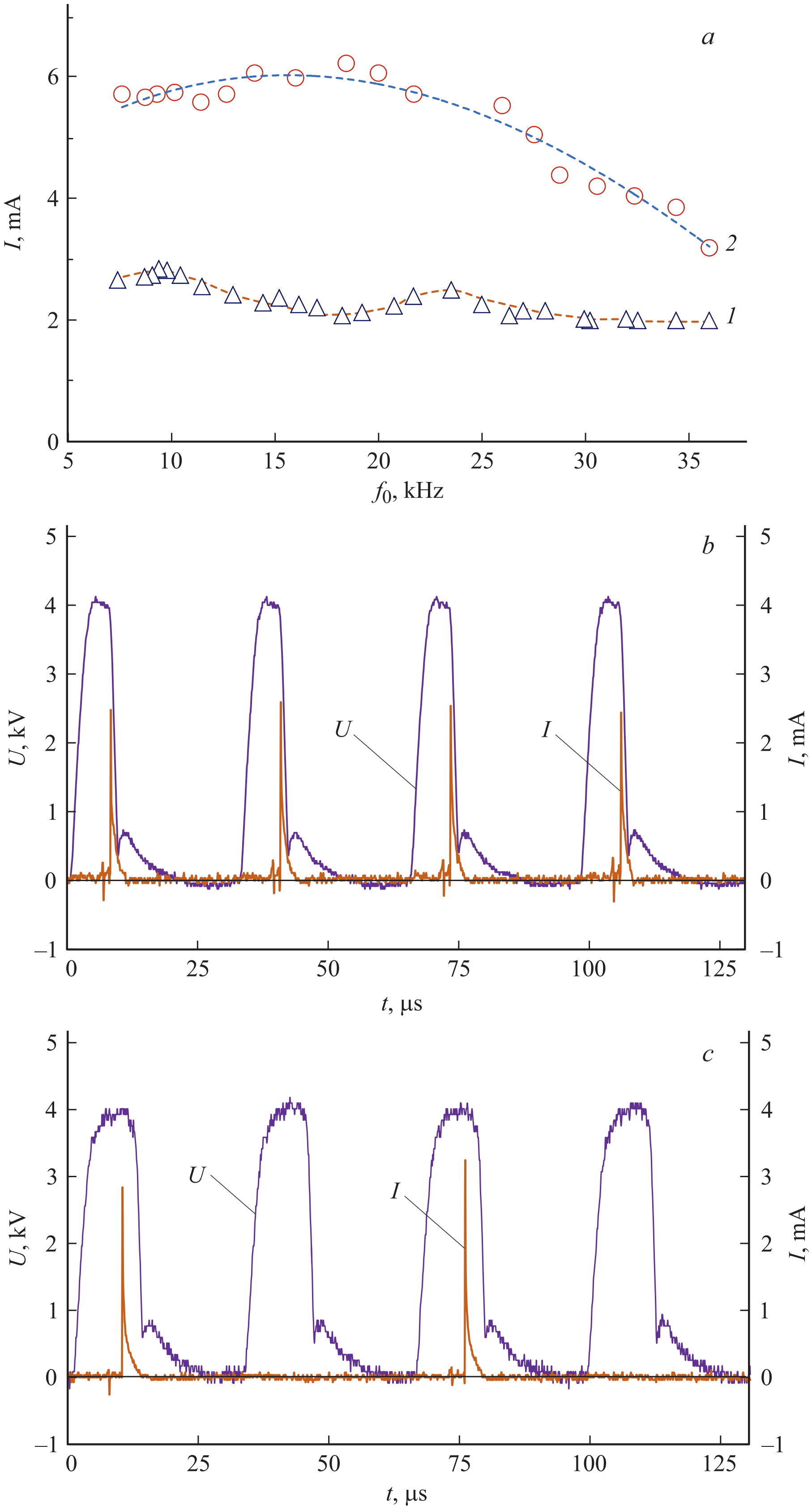

Figure 3. *a* — Dependences $I(f_0)$ for pulses with $\tau = 8$ (*1*) and $16\,\mu s$ (*2*). $U = 4.2\,kV$, $\upsilon = 9\,l/min$. *b*, *c* — Oscillogram records of pulses with duration $\tau = 8$ (*b*) and $16\,\mu s$ (*c*).

top ripple, and the negative bias magnitude did not affect touching-target current frequency f_I.

Figures 3, *b* and *c* show the oscilloscope records illustrating the process of frequency division for pulses with duration $\tau = 8$ and $16\,\mu$s at $U = 4$ kV and fixed $f_0 = 30$ kHz. Under the conditions typical of biophysical experiments ($U \approx 4.2$ kV), frequency $f_I = f_0$ at flow velocity $\upsilon = 9$ l/min, $z = 25$ mm, and $\tau = 8\,\mu$s (Fig. 3, *b*). At $\tau = 16\,\mu$s, frequency $f_I = f_0/2$ (Fig. 3, *c*). With the voltage pulse parameters kept unchanged, f_I becomes equal to f_0 as the flow velocity decreases to $\upsilon < 6$ l/min. This agrees with the results reported in [5], where $f_I = f_0$ within the entire studied range at $\tau = 20\,\mu$s and $\upsilon \approx 4.5$ l/min.

Thus, it was demonstrated that the attainable parameters of the CPJ–target interaction under pulsed excitation are the same as those corresponding to sinusoidal excitation. The key parameter affecting the nature of the CPJ–target interaction ($I(f)$) is pulse duration τ. Adjusting the pulse parameters, one may thus maintain a regular and predictable regime of plasma treatment of targets within a wide range of pulse repetition frequencies.

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Compliance with ethical standards

This article does not contain any studies involving animals performed by any of the authors.

Conflict of interest

The authors declare that they have no conflict of interest.

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