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SHORT COMMUNICATIONS

On the Question of the Source of the Apokamp

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Abstract—The object of this work is the apokamp—a new type of plasma jet, which is formed from a bright offshoot emerging at the bending point of a channel of a high-voltage pulse-periodic discharge under conditions where the electrodes have a capacitive decoupling with the ground. The aim of this work is the identification of distinctive properties of the offshoot in comparison with the apokamp. The differences in the spectra of the offshoot and plasma jet (apokamp) were detected experimentally in air under normal conditions. The results of the previous studies, according to which the apokamp is a wave of ionization, were confirmed. The launch of a helium plasma jet from the offshoot of the pulse-periodic discharge in a mode of the apokamp forming was demonstrated experimentally. It was shown that the offshoot of high-voltage pulsed discharge in the mode with the apokamp is a medium that is strongly heated and conducting electric current.

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INTRODUCTION

In 2016, a new type of plasma jet—apokamp (from the Greek από—from and καμπη—bending, turning), was discovered in the air of atmospheric pressure, and then in mixtures of inert gases with additions of electronegative gases at pressures of up to one atmosphere [1–3]. As it is shown in Fig. 1a, the apokamp is a plasma jet *9* (or several jets), which is produced by a bright offshoot *8*, which is formed at the bend of the channel of high-voltage pulsed periodic discharge *7* between the two electrodes. At least one of the electrodes *2* is a high voltage one and is made in the form of a point, and the other *3* is under floating potential.

The apokamp differs from the known sources of plasma jets of atmospheric pressure [4–8] by a simplified design, comparative ease of formation in the air at atmospheric pressure and in mixtures with electronegative gases (at pressures less than the atmosphere), and by the fact that its formation does not require forced gas pumping through the discharge zone.

High-speed recording of the apokamp *9* under normal conditions (pressure and temperature) revealed [2, 9] that it is a set of so-called "plasma bullets" moving at a speed from 100 to 220 km/s, on the distribution of which convection does not exert a significant influence. They are visually observed as one or more plasma jets due to the high speed of motion and high repetition rate of pulses, although they are inherently discrete. Each "bullet" represents a footprint from the motion of the ionization wave.

There are still many questions about the mechanism of formation of the phenomenon. In particular, the nature of the offshoot *8* (Fig. 1a) serving as a source of the apokamp remains unclear. It is in this

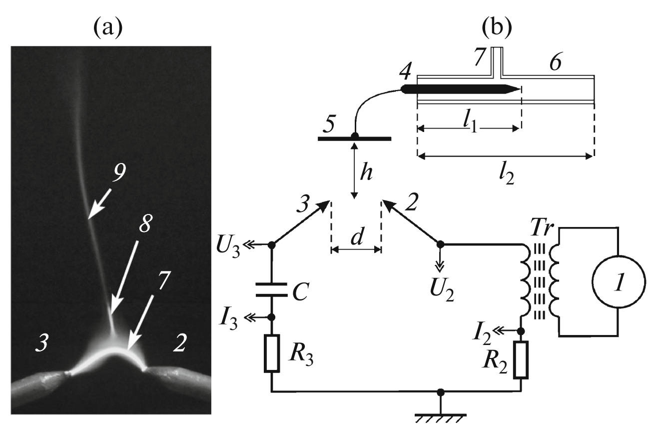

Fig. 1. The external form of the discharge initiating the formation of the apokamp (a) and the experimental setup (b): *1*—the source of impulse voltage of positive polarity; *2*—electrode; *3*—electrode which is grounded through the capacitance $C = 11.65$ pF; *4*—rod electrode; *5*—round current collector; *6*—quartz tube with gas inlet; *7*—pulse-periodic discharge channel; *8*—bright offshoot; *9*—apokamp; and $R_2 = 3.6\ \Omega$; $R_3 = 1\ \Omega$; $l_1 = 75$ mm; $l_2 = 100$ mm.

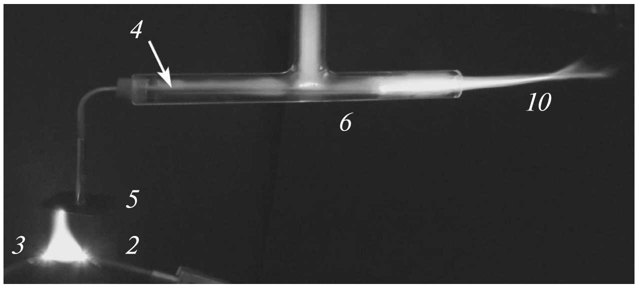

Fig. 2. The experimental setup during the tests: *2–4*—electrodes; *5*—current collector; *6*—quartz tube which is filled with helium; and *10*—helium plasma jet.

zone where the phenomenon is formed. The assessment of the temperature of the offshoot, according to [10], gave a value between 1300 and 1000°C.

In this paper, the data on the spectral composition of the radiation in the offshoot have been clarified, the fact that the apokamp is an ionization wave has been confirmed, and the presence of an electric current transfer in the region of the offshoot of the pulse-periodic discharge channel, in contrast to the plasma jet that this channel generates, is proved experimentally.

1. EXPERIMENTAL SETUP AND METHODS OF MEASUREMENTS

The experiments were carried out on the installation, the schematic diagram of which is presented in Fig. 1b. The source of the high-voltage pulses *1* and step-up transformer *2* provided at the output at idle, the voltage pulses of positive polarity with an f frequency from 16 to 50 kHz, the pulse duration τ =1.5–2.5 μs, and the voltage amplitude of up to 13 kV. The pulses were applied to the discharge interval of length d, which was formed by two point-shaped electrodes *2* and *3* made of stainless steel. d = 9.2 mm in most experiments. The electrode *3* was connected to the high-voltage output of the pulse transformer, and the electrode *4* had a capacitive decoupling with grounding through the capacitor C. Figure 1b also shows the places of the recording of the voltage and current at the electrodes depending on time (U_2, U_3, I_2, I_3).

A round collector *5* for current collecting was placed over the discharge interval at the height of h to study the offshoot. There was a leakage current on the collector (depending on the value of h) that managed to lead to the ignition of the plasma jet of the atmospheric pressure in the classical installation for obtaining plasma jets in inert gases, which was located above the collector. The installation included a quartz tube with an inner diameter of 7 mm, in one end of which the sharp electrode *4* (length l_1 = 75 mm) was hermetically placed, and the other one was open and served as a nozzle for the forming plasma jet. The inert gas He was fed into the tube through the nozzle *7* at a speed of 2–3 L/min. Thus, the described installation allowed the changing of the leak current to the collector and visual monitoring of the intensity of this leak by the length of a plasma jet by varying the height of the collector above the area in which the apokamp is formed.

The PowerShot SX60 HS camera in the serial shooting mode with a frequency of ~6.4 fr/s was used to shoot the appearance of the discharge and helium plasma jet for each h value. Then, their statistical processing was carried out.

In addition, the registration of spectra was carried out. The HR2000+ES (Ocean Optics, Inc.) spectrometer based on the Sony ILX511B multichannel CCD ruler (operating range 200–1100 nm, spectral half-width of the hardware function of ~1.33 nm) was used for this purpose. The signal was fed to it from an optical fiber with a known transmission spectrum and a collimating lens placed on it with a focal length of 30 mm. Lens was located at different heights h.

2. RESULTS AND DISCUSSION

Figure 2 shows the experimental setup in operation. A direct closure to the discharge current collector, which initiates the apokamp, leads to the ignition of a helium plasma jet *10*, which has the $L = 5.4 \pm 0.7$ mm maximum length. The length of the helium jet decreases with the increasing in the h height, as shown in Fig. 3. The confidence intervals are constructed for the probability of 90%. It can be seen that the length of the helium plasma jet changes statistically insignificant at heights of up to 2 cm, but the subsequent increase in $h > 2$ cm leads to a sharp reduction in the length of the plasma jet in helium. Here, the last point (h = 3.7 cm) corresponds to a corona glow from the tip of the electrode *6* (a dim point of glow which is tied to the end of the electrode *6*).

Thus, it was shown experimentally that the offshoot of the high-voltage pulse discharge channel (*8* in Fig. 1a) has the properties of the current conductor, and the apokamp itself does it no longer. The latter corresponds to the earlier established fact [2, 7] that the apokamp is a wave of ionization, but not an avalanche of charge carriers.

Figure 4 shows the radiation spectra of the pulse discharge (*7* in Fig. 1a), offshoot (*8* in Fig. 1a), and helium plasma jet (*10* in Fig. 2). It is seen that the spectrum of the discharge, which initiates the apokamp, contains the bands $N_2(C^3\Pi_u - B^3\Pi_g)$, $N_2^+(B^2\Sigma_u^+ - X^2\Sigma_g^+)$, $N_2(B^3\Pi_g - A^3\Pi_u)$, and is richer than the offshoot spectrum. This spectrum corresponds to the low-current stage of discharges in air and nitrogen [11]. It is known that intense nitrogen molecular bands indicate that excited nitrogen molecules and ions $N_2(A)$, $N_2(B)$, $N_2(C)$, $N_2(a)$, and $N_2^+(B)$ are formed in plasma in excess [12]. The population of the $N_2(A)$ state occurs due to the relatively low value of the excitation

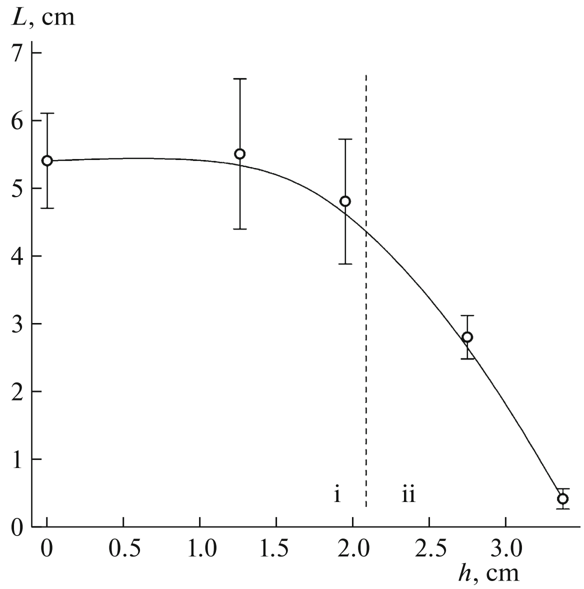

Fig. 3. Dependence of the length of the helium plasma jet L on the distance h at $d = 9$ mm, $f = 49$ kHz: (i) the zone in which the length of the helium jet varies slightly; (ii) the zone in which the length of the jet is significantly reduced.

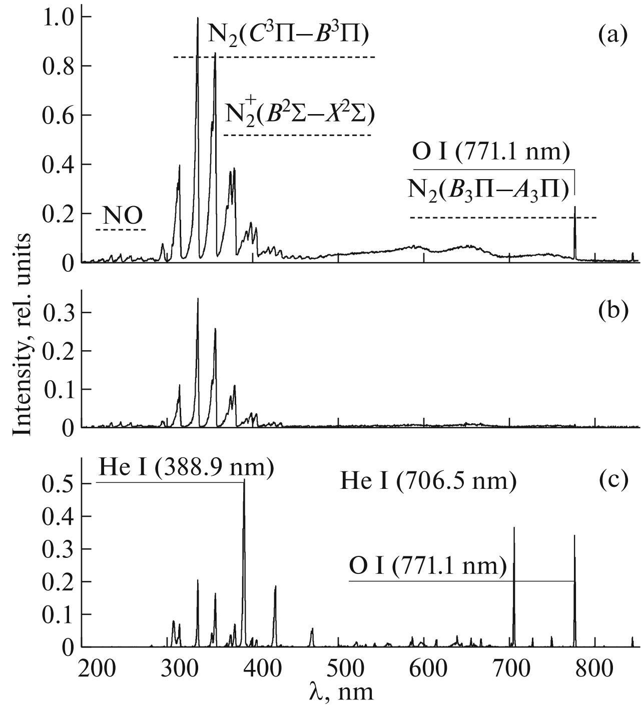

Fig. 4. The radiation spectra of the pulse discharge channel at h = 0 mm (a), offshoot h ~ 20 mm (b) and helium plasma jet (c) at $d = 9.2$ mm, $h = 20$ mm, $f = 49$ kHz.

energy (6.17 eV) for the reaction $e + N_2(X^1\Sigma_g^+) \rightarrow N_2(A^3\Sigma_u^+) + e'$ and collisions of the vibrationally excited nitrogen molecules $N_2(v_1) + N_2(v_2) \rightarrow N_2(A^3\Sigma_u^+) + N_2(X^1\Sigma_g^+)$. In addition, there is a partial population of the $N_2(B)$ state. The fact that the radiation of the second positive nitrogen system $N_2(C^3\Pi_u - B^3\Pi_g)$ is the most intense in the spectrum means that the temperature of the electrons in these conditions is close to the optimum for the population of the $N_2(C)$ state.

The spectrum of the helium plasma jet near the nozzle contains resonant bands of the He atom (the $3d$–$2p$ and $3s$–$2p$ transitions), Ne atom (the $3p$–$2s$ transitions), as well as the oxygen bands on the transitions $3p^5P$–$3s^5S°$ and $3p^3P$–$3s^3S°$. Its composition did not change at different values of h.

The calculations of the power which is released in the discharge circuit were made from the oscilloscopes which had been obtained at $h = 20$ and 40 mm, i.e., in cases when the collector collects the current from the offshoot and does not overlap with it. It turned out that in the case when the offshoot touches the current collector approximately 15% more energy is released in an electrical circuit than in the case when the collector touches only the apokamp.

In both cases the currents almost do not change at different heights (Fig. 5). So in one case, the energy is spent on the creation of the apokamp and in the other—to the ignition of the helium plasma jet.

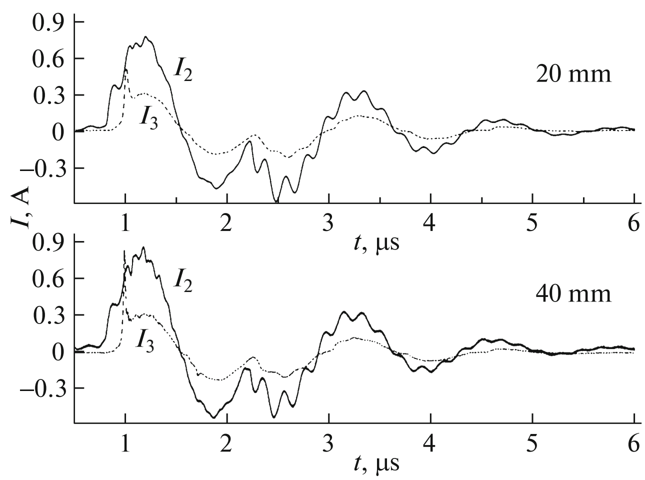

Fig. 5. The dependance of the current value on time at $d = 9.2$ mm, $h = 10$ mm, and $f = 53$ kHz.

CONCLUSIONS

1. The launch of a helium plasma jet from the offshoot of the pulse-periodic discharge in the mode of the apokamp forming was experimentally demonstrated.

2. The differences in the spectra of the offshoot and plasma jet (the apokamp) were marked in air under normal conditions.

3. It was experimentally proved that electric current is transferred only in the offshoot area of a pulse-periodic discharge channel, and the apokamp is a wave of ionization. It is shown that there is an offshoot critical h_s height, above which the transferred current is negligibly small. This value statistically corresponds to the length of the offshoot of the pulse-periodic discharge channel. When the collector was moved away from the offshoot the energy that had been contributed to the discharge was spent on the formation of the apokamp.

Thus, the offshoot of the high-voltage pulsed discharge in the mode with the apokamp is the medium conducting electric current and strongly heated (~1000–1300°C). On this basis, it is possible to hypothesize that the offshoot is an analogue of the corona discharge, which develops not from the tip of the metal electrode, but at the point of increasing of the field strength of the discharge channel. In the future, it is planned to test this assumption.

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