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Features of pulsed discharge formation in pre-ionized helium

V. S. Kurbanismailov¹, G. B. Ragimkhanov^{1,*}, D. V. Tereshonok², Z. R. Khalikova¹,
S. A. Maiorov² and Kh. M. Abakarova¹

¹ Dagestan State University, Republic of Dagestan, Makhachkala, 367025 Russia

² Joint Institute for High Temperatures of Russian Academy of Sciences, Moscow, 125412 Russia

* E-mail: gb-r@mail.ru

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The results of an experimental study of pulsed gas discharge in helium at atmospheric pressure with ultraviolet pre-ionization of the gas in a "mesh cathode – flat anode" system are presented. The voltage on the discharge capacitor was varied in the range of 3–14 kV. It was found that the peak current value increases monotonically from several tens to ~1000 A with increasing applied voltage, demonstrating an almost linear dependence of the peak current value (I_{max}) on the applied voltage.

Keywords: pulsed gas discharge; helium; pre-ionization; aperiodic regime.

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Introduction

The study of physical processes in pulsed gas discharges at atmospheric and higher pressures is of significant interest from both fundamental and applied perspectives, particularly for the development of efficient radiation sources in the VUV, UV, and visible ranges, as well as for pumping gas lasers. Substantial roles in the formation of such discharges are played by gas pre-ionization mechanisms, electrode system geometry, high-voltage pulse parameters, and working gas medium properties.

The review by Osipov V. V. [1] outlines the current state of research in the field of physics of high-power electrical discharges capable of exciting large gas volumes. The properties and characteristics of self-sustained high-pressure discharges are described. Experimental results and physical models of their formation and contraction are examined. The lower ignition limit of a volume discharge is shown to be associated with cathode instability. The challenges in deriving a complete theory of

volume discharge are noted. One of the main reasons for discharge contraction is the development of explosive processes on the electrode surfaces, ectons, a topic addressed in the review paper by G. A. Mesyats.

The review paper by V. F. Tarasenko et al. [3] summarizes data on diffuse and volume high-pressure discharges with transverse pumping. It emphasizes that the major difference between them is due to the ignition mechanism: a volume discharge requires pre-ionization and a uniform field, while a diffuse discharge is enabled through streamer-type breakdown and runaway electrons, especially with a small electrode radius of curvature.

The series of modern studies using high-voltage pulses [3–7] have shown that the structure and dynamics of the discharge channel depend on the ionization history, field distribution, and gas pressure. It has been established that, an oscillatory current regime can develop due to parasitic circuit inductance under certain circuit and gas parameters [8–10], while the spatial structure of the discharge can change from diffuse to spark pattern.

The previous studies [11–13] provide the detailed analysis of electrical, optical, and spectral characteristics of a pulsed discharge in helium subjected to UV pre-ionization (solid cathode, mesh anode). The paper [11] analyzes the process of contraction of a volume discharge in helium at the atmospheric pressure while the initial experimental conditions are being changed. The paper [12] reveals the features of the emission spectrum of the gas under study and electrode material's spectrum under various initial conditions: specifically, in the mode of homogeneous burning of the volume discharge, in the mode of transition from the volume discharge to the spark channel, and in the mode of transition from the volume discharge to the high-current diffuse mode in the helium pulsed discharge of high pressure. The paper [13] outlines the experimental results of studying the emission spectrum of the pulsed discharge in helium vapor-gas mixtures of high pressure, where easily ionizable impurities of electrode material vapours (Fe, Al) appear due to sputtering of electrodes subjected to ion bombardment. The electrode material vapours were shown to have significant influence on the discharge and largely determine its spectral characteristics.

This paper presents the results of the experimental study of a pulsed gas discharge in helium at the atmospheric pressure subjected to ultraviolet pre-ionization of gas in a “mesh cathode – flat anode” system, and compares experimental data to the calculations of the equivalent circuit parameters.

Experimental Setup and Measurements

Figure 1 shows the schematic diagram of the setup for studying the pulsed discharge in helium. After capacitor C_0 was charged to 3–14 kV, the voltage therefrom was applied to two electrodes: a flat anode with radii $r_0 = 2$ cm and a mesh cathode, with a distance $d = 1$ cm between

them. Pre-ionization was performed with a spark discharge.

A photo of discharge glow was taken using mirrorless digital camera Sony Alpha A7 III (ILCE-7M3B). The discharge voltage and current were recorded using Tektronix TDS 2024B digital oscilloscope with 200 MHz bandwidth, low-resistance shunt R_b and ohmic voltage divider R_1, R_2 .

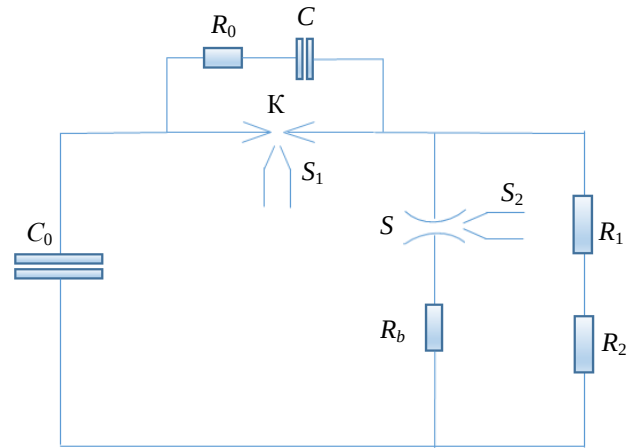


Fig. 1. Schematic diagram of the setup. C_0 – discharge capacitor, R_b – ballast resistor, K – switch, S_1 – pre-ionization source for the switch's gas medium, S – main discharge gap, S_2 – pre-ionization source for the main discharge gap ($R_0 = 300 \Omega$, $R_1 = 21.3 \text{ k}\Omega$, $R_2 = 50 \Omega$, $C = 4 \text{ nF}$, $C_0 = 15 \text{ nF}$)

Results of Studying the Aperiodic Discharge Characteristics

Figure 2 shows the oscillograms of the current discharge in the aperiodic current conduction mode for two values of the voltage applied. In the aperiodic mode, the current pulse shape changes depending on the voltage applied, which indicates a complex dynamics of processes in the discharge gap. At low voltage values U_0 , the current pulse is bell-shaped, while at high values of the field applied, oscillations can be seen.

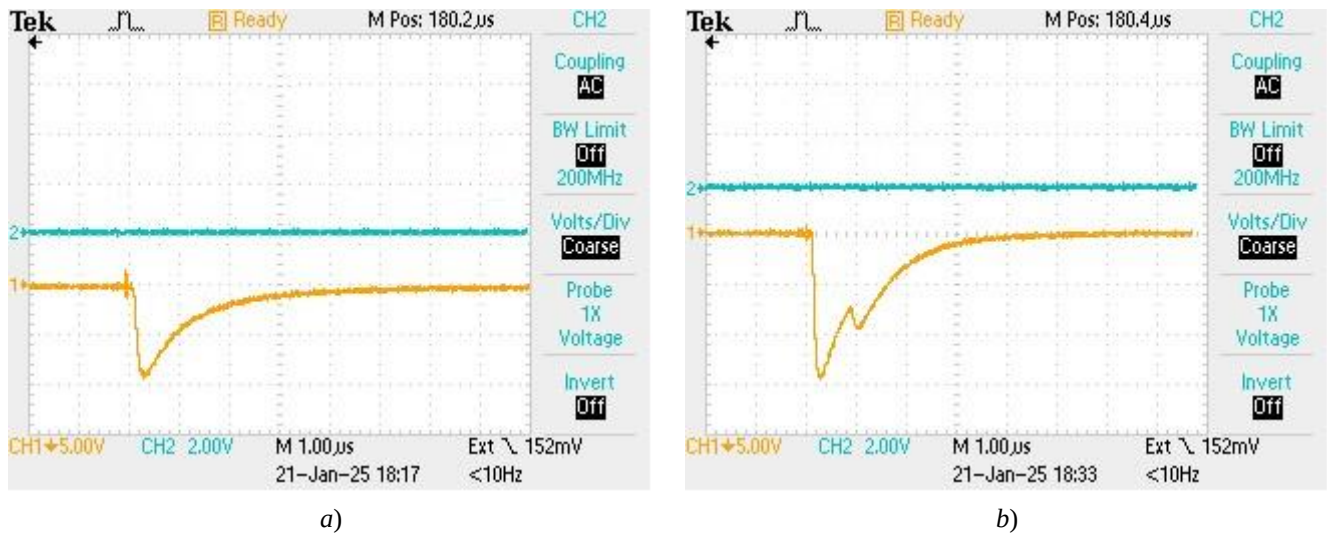


Fig. 2. Characteristic oscillograms of the discharge current in the aperiodic current conduction mode at pressure $p = 3$ atm and $R_b = 2 \Omega$: a) – $U_0 = 8$ kV, b) – $U_0 = 11$ kV

As the gas pressure increases, the current amplitude decreases (see Fig. 3b) along with concurrent increase in the duration of the discharge current flow. Where a spark channel develops against the background of a volume discharge, two characteristic maxima appear on the current oscillogram (Fig. 2b). The first corresponds to the formation of the volume

discharge, and the second – to the transition into a spark channel.

As the voltage amplitude grows from 3 to 14 kV, a linear growth in the peak current value from tens to hundreds of amperes can be seen (Fig. 3a, b). Moreover, the peak current value increases as the ballast resistance decreases.

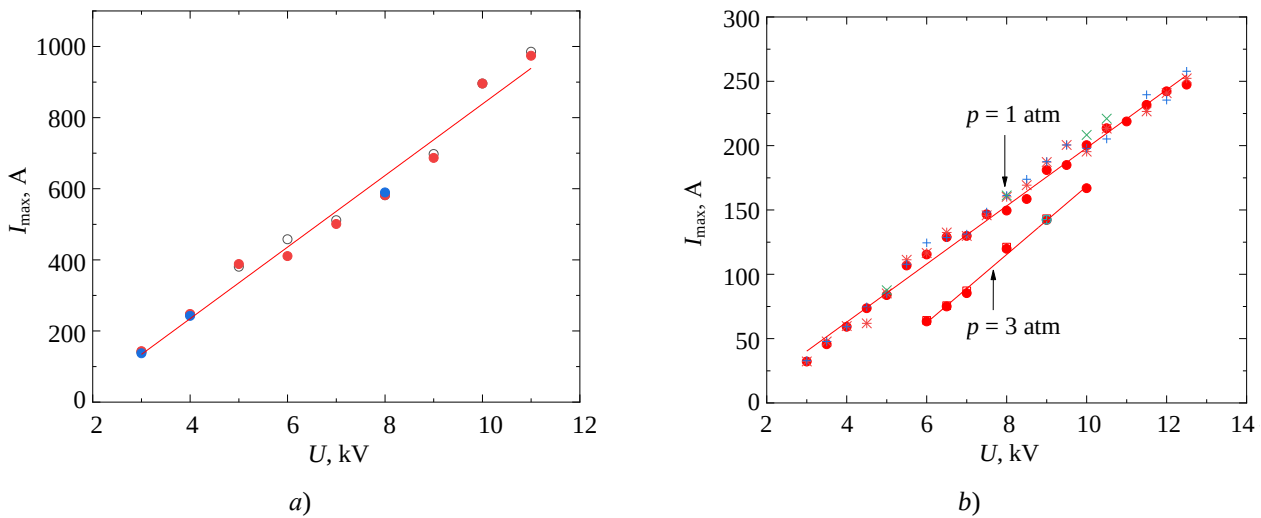


Fig. 3. Amplitude values of the discharge current in the aperiodic mode in various experiment conditions: a) $R_b = 2 \Omega$, $p = 1$ atm, b) $R_b = 52 \Omega$, $p = 1$ atm and 3 atm.

Figure 4 shows integral images of discharge glow in the aperiodic mode at $R_b = 2 \Omega$. The lower electrode is mesh (cathode), the upper one is solid (anode). As can be seen, a volume discharge, which is a collection of diffuse channels attached to the cathode, is formed at the

voltage of 3 kV under conditions of gas pre-ionization. As the gas pressure increases and at higher voltages, diffuse channels, that is localizations of current in the form of bright narrow channels, primarily near the mesh cathode, may appear. Starting from 7 kV, at the

atmospheric pressure, bright luminous spots develop on the anode. As voltage $U_0 \geq 8$ kV increases, the spark channels can be seen to develop, both from the cathode and anode; the channels can overlap each other, while the number of anode spots increases. The characteristic diameter of the channels, when estimated by the glow, is about 0.6–0.7 mm.

When the pressure is increased to 2 atmospheres, a significant number of current

channels are observed, which are mainly concentrated in the central part of the discharge gap. At high voltages, one pronounced spark channel with a diameter of about 2 mm forms against a background of numerous diffuse channels. The spark channel is smaller in diameter at the pressure of 2 atm than at the atmospheric pressure. This effect is apparently related to the enhancement of self-contraction under conditions of increased gas density.

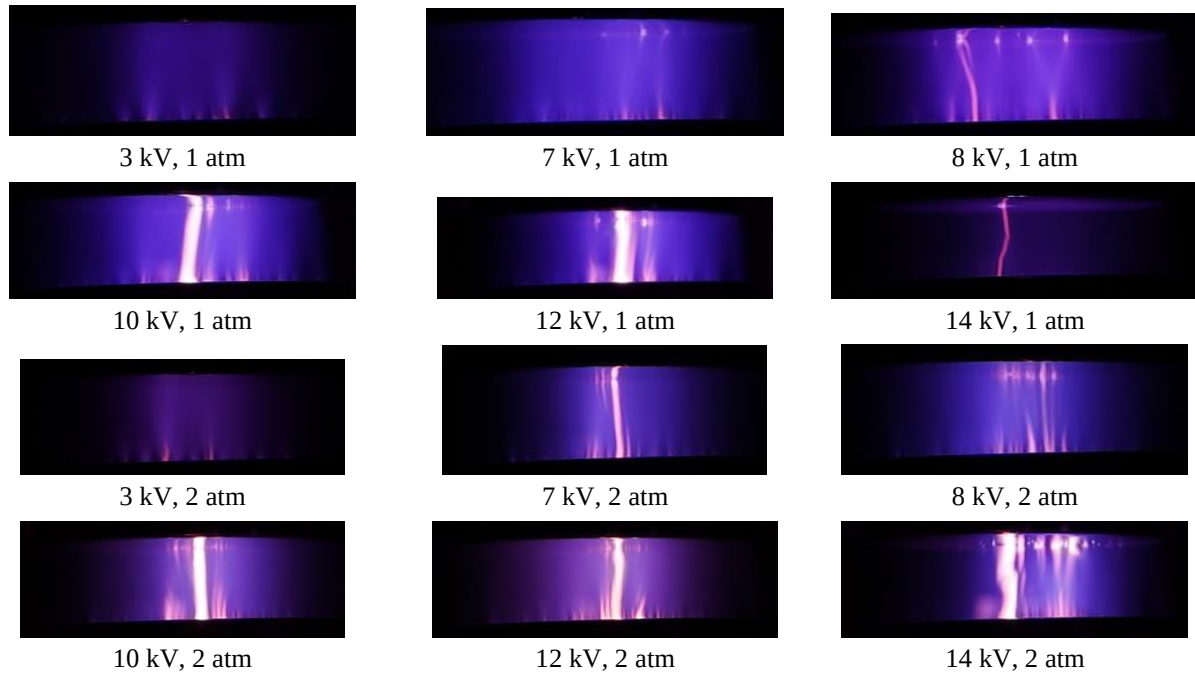


Fig. 4. Integral images of discharge glow (aperiodic mode) at $R_b = 2 \Omega$

As it was mentioned above, minor oscillations could be observed on the oscillogram as the applied voltage increased (Fig. 5).

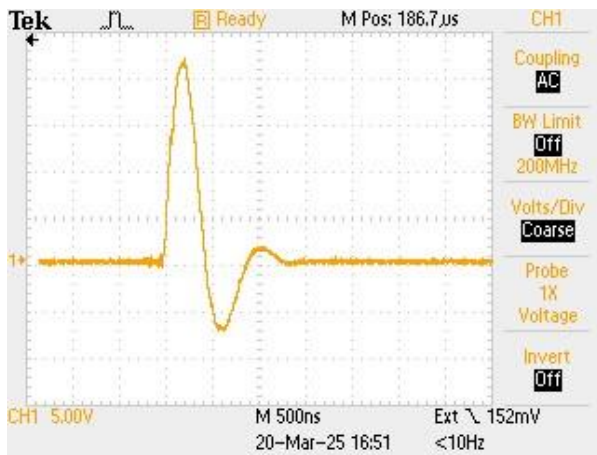


Fig. 5. Characteristic oscillograms of the discharge current: $p = 1$ atm, $U_0 = 8$ kV, $R_b = 2 \Omega$

The presence of the oscillatory mode allows for the discharge gap to use a closed RLC circuit with resistance R_d , inductance L_d , and capacitance C_d , where current oscillations I are described by the expression: $I(t) = I_0 e^{-\delta t} \cos(\omega t)$, where t is time, $\omega = \sqrt{\omega_0^2 - \delta^2} = \frac{2\pi}{T}$, T is oscillation period,

$$I(t=0) = I_0 \text{ is current amplitude, } \delta = \frac{R_d}{2L_d},$$

$$\omega_0 = \frac{1}{\sqrt{L_d C_d}}.$$

Conditions of oscillatory mode presence are determined by inequation:

$$L_d > \frac{R_d^2 C_d}{4}.$$

If oscillations begin after a certain distance in the switch is reached, it can be assumed that effective inductance L_d of the circuit under study

increases with the growth of the switch's interelectrode gap. This is qualitatively consistent with experimental observations. All other conditions being equal (values of R_b and U_0), the aperiodic mode transitions to the oscillatory one when the switch's interelectrode gap increases.

It should be noted that damping coefficient δ is determined by the ratio of current amplitudes with an interval equaling to one period, i.e. $\delta = \frac{\ln(I_0 / I(T))}{T}$. The results in $\delta \approx \frac{\ln(11)}{T}$.

Therefore, we get $\omega \approx \omega_0$ from definition $\omega = \sqrt{\omega_0^2 - \delta^2} = \frac{2\pi}{T}$.

In accordance with the previously calculations [11], the electron concentration in the discharge gap in the diffuse mode at the atmospheric pressure is at a level of $n_0 \sim 10^{20} \text{ m}^{-3}$, which gives the discharge gap resistance $R_d \approx (\pi r_0^2 n_e \mu_e)^{-1} d \approx 5 \Omega$, where e is electron charge, n_e , μ_e are concentration and mobility, $\mu_e \approx 0,1 \text{ m}^2/(\text{s} \cdot \text{V})$ at the normal gas density [14, 15].

As the effective capacitance value, we take the capacitance of the discharge capacitor $C_d = C_0 = 1.5 \times 10^{-8} \text{ F}$. This assumption is justified by the fact that discharge gap capacitance $C_g \sim \epsilon_0 \pi r_0^2 / d \sim 1 \text{ pF}$ and plasma capacitance $C_p \sim 2\pi \epsilon_0 d \sim 0,6 \text{ pF}$ are much smaller than C_0 . Then, in accordance with the definition of δ , we find the inductance: $L_d = \frac{R_d T}{2 \ln(11)} \approx 0.84 \mu\text{H}$.

From graph 2b, we see that the oscillation period is $0.8 \mu\text{s}$, then for the inductance we obtain

$L_d = \left(\frac{T}{2\pi} \right)^2 / C_d \approx 1.1 \mu\text{H}$. The value of L_d in the equivalent circuit proved to be quite large, which is apparently due to the parasitic inductance of the setup. The plasma inductance is quite small: $L_p \sim \frac{\mu_0 d}{2\pi} = 2 \text{ nH}$ (μ_0 is the magnetic constant)

compared to L_d . Meanwhile, a connecting wire with length $l = 1 \text{ m}$ and radius $r = 1 \text{ mm}$ has an inductance of $L_w \sim \frac{\mu_0 l}{2\pi} \ln\left(\frac{l}{r}\right) \approx 1.4 \mu\text{H}$, which is comparable to the estimates of L_d .

Thus, while the presence of parasitic inductance leads to current oscillations, it also allows obtaining a diffuse discharge in helium at the atmospheric and higher pressures with the time over $1 \mu\text{s}$, which can be used in gas-discharge applications.

Conclusion

Thus, under conditions of gas pre-ionization in the range of 3–14 kV and ballast resistance of 2Ω in helium at the atmospheric pressure, two discharge burning modes have been identified: oscillatory and aperiodic. It has also been found that the interelectrode distance in the switch determines the transition from the aperiodic to the oscillatory discharge burning mode. The aperiodic current conduction mode is characterized by almost linear dependence of discharge peak current $I_{\max}$ on the voltage applied, with typical current values ranging from tens to approximately $\sim 1000 \text{ A}$. Increase in gas pressure from 1 to 3 atm leads to decrease in the peak current value. Optical diagnostics show that a diffuse volume discharge forms at 3 kV, while starting from 7–8 kV, localized current filaments with a diameter of 0.6–0.7 mm appear, their number increasing with voltage. However, a single bright spark channel can be observed at 14 kV.

Based on this experimental fact and analysis of the conditions for discharge current oscillations to exist, the interelectrode distance in the switch has been proposed to determine the inductance value in the equivalent RLC circuit. The effective inductance of the setup under consideration was determined based on current oscillograms.

The established patterns allow for the targeted selection of circuit parameters (capacitance, ballast resistance, length of connecting buses) to suppress oscillations in the single-pulse current mode, which is critical for pumping VUV/UV lasers and other plasma applications requiring high peak energies without subsequent dampening.

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About authors

Kurbanysmailov Vali Suleimanovich, Professor, Doctor of Physical and Mathematical Sciences Dagestan State University, (367025, Russia, Republic of Dagestan, Makhachkala, M. Gadzhiev st., 43a) E-mail: vali_60@mail.ru SPIN code: 3774-5509, AuthorID: 124135

Ragimkhanov Gadzhimirza Balaglanovich, Candidate of Physical and Mathematical Sciences, Associate Professor Dagestan State University, (367025, Russia, Republic of Dagestan, Makhachkala, M. Gadzhiev st., 43a) E-mail: gb-r@mail.ru SPIN code: 8156-8736, AuthorID: 417790

Tereshonok Dmitry Viktorovich, Candidate of Physical and Mathematical Sciences, Leading Research Scientist Joint Institute for High Temperatures of Russian Academy of Sciences (125412, Russia, Moscow, Izhorskaya st., 13, bldg. 2) SPIN code: 3790-9092, AuthorID: 601492

Khalikova Zaira Rasulovna, Dagestan State University, (367025, Russia, Republic of Dagestan, Makhachkala, M. Gadzhiev st., 43a). SPIN code: 3112-0424, AuthorID: 1031654

Maiorov Sergey Alekseevich, Doctor of Physical and Mathematical Sciences, Leading Research Scientist, Joint Institute for High Temperatures of Russian Academy of Sciences (Russia, 125412, Moscow, Izhorskaya st., 13, bldg. 2) E-mail: mayorov_sa@mail.ru SPIN code: 9331-1751, AuthorID: 24761

Abakarova Khalimat Magomelovna, Head of Office, Dagestan State University, τ (367025, Russia, Republic of Dagestan, Makhachkala, M. Gadzhiev st., 43a) E-mail: abakarova2412@mail.ru