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ABOUT THE UNIFORMITY AND THE STABILITY OF A VOLUME DISCHARGE IN HELIUM IN NEAR-ATMOSPHERIC PRESSURE

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Abstract. We present experimental electric and time-spatial characteristics of a volume discharge and of the transition from a volume burning stage into a channel mode nearing atmospheric pressure. We show that the discharge uniformity rises with the increase of cathode spots density and gas pressure.

Keywords: discharge formation; volume discharge; streamer; discharge plasma.

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1. Introduction

One of the applications of volume discharges in inert gases is gas laser pumping. In this case, in order to increase the power characteristics of gas lasers, we need (i) to improve the pumping methods and (ii) to optimize the excitation conditions [1,2,3,4,5,6,7]. A problem of pumping optimization consists in the reception of certain electric characteristics of discharge plasma with a constant spatial uniformity during the pumping. The discharge instability results in the transition from volume burning into a channel stage (contracted discharge). There can be various physical mechanisms responsible for discharge instabilities. They depend on the gas (or the gas mixture) [8,9,10,11,12]. Therefore the study of volume discharge properties in pure gases has both basic and practical interest.

Toward this general aim we have experimentally investigated under a wide range of initial conditions, the plasma characteristics of volume and contracted discharges, as well as the processes of discharge counteraction and plasma torch creation in helium at atmospheric pressure.

2. Experimental installation and research methods

The experimental setup and research methods are similar to those described in our previous papers [13,14,15]. The gap under study (about 1 cm in length) irradiates either by spark discharge through the grid anode or by UV source placed in the same gas at a distance of 5–7 cm from the main gap axis. The diameter of the electrodes is 4 cm. We have used electrodes with various shapes (plane and hemispherical, $R = 30\,\mathrm{cm}$) made of different materials: aluminium, stainless steel and copper.

The pulsed voltage source generates voltage pulses with a variable amplitude of up to 30 kV and a front duration of $\sim 10\,\mathrm{ns}$. The discharge voltage and current are measured with the application of digital oscilloscopes. Frame photographs of the discharge glow (showing the distribution of radiation intensity both along, and across electrodes) are obtained using a FER-2 streak camera with the UMI-92 image tube. When photographing a discharge in the frame mode, the scanning voltage of the FER-2 is switched off. Frame photographs are synchronized with electrical characteristics of the discharge by simultaneously supplying the triggering voltage pulse to the FER-2 and the signal of the discharge current (or voltage) pulse to double-beam storage oscilloscopes. Streak images of the discharge glow (discussed in [15]) are also obtained and synchronized with the discharge current (or voltage) pulse by applying the signal of the current (or voltage) pulse to the deflecting plates of the UMI-92 image tube, simultaneously with the discharge scanning. Time-integrated photographs of the discharge glow with a high spatial resolution are taken using a digital camera.

3. Results and discussion

We have investigated a discharge transition from a volume burning into a channel stage in helium with a discharge area $S = 12\,\mathrm{cm}^2$, a distance between electrodes $d = 1\,\mathrm{cm}$, a gas pressure $P = 1$–$5\,\mathrm{atm}$, a discharge voltage U from static discharge up to hundreds of percent of overvoltage.

As we can see from Fig. 1 photos 1–4, a homogeneous volume discharge burns at small external fields ($E_0 < E_{\mathrm{critical}} = 6\,\mathrm{kV/cm}$). The growth of uncompleted anode channels (which are adhered to cathode spots with high conductivity) starts from a current density of about $40\,\mathrm{A/cm}^2$ (see Fig. 1 photos 5–6). An increase in current density up to $60\,\mathrm{A/cm}^2$ (see Fig. 1 photos 7–11) leads to further promotion of uncompleted anode channels, anode spotting, and also to the appearance of uncompleted cathode channels. When the current density surpasses $100\,\mathrm{A/cm}^2$, the anode and cathode channels merge (Fig. 1 phot 12).

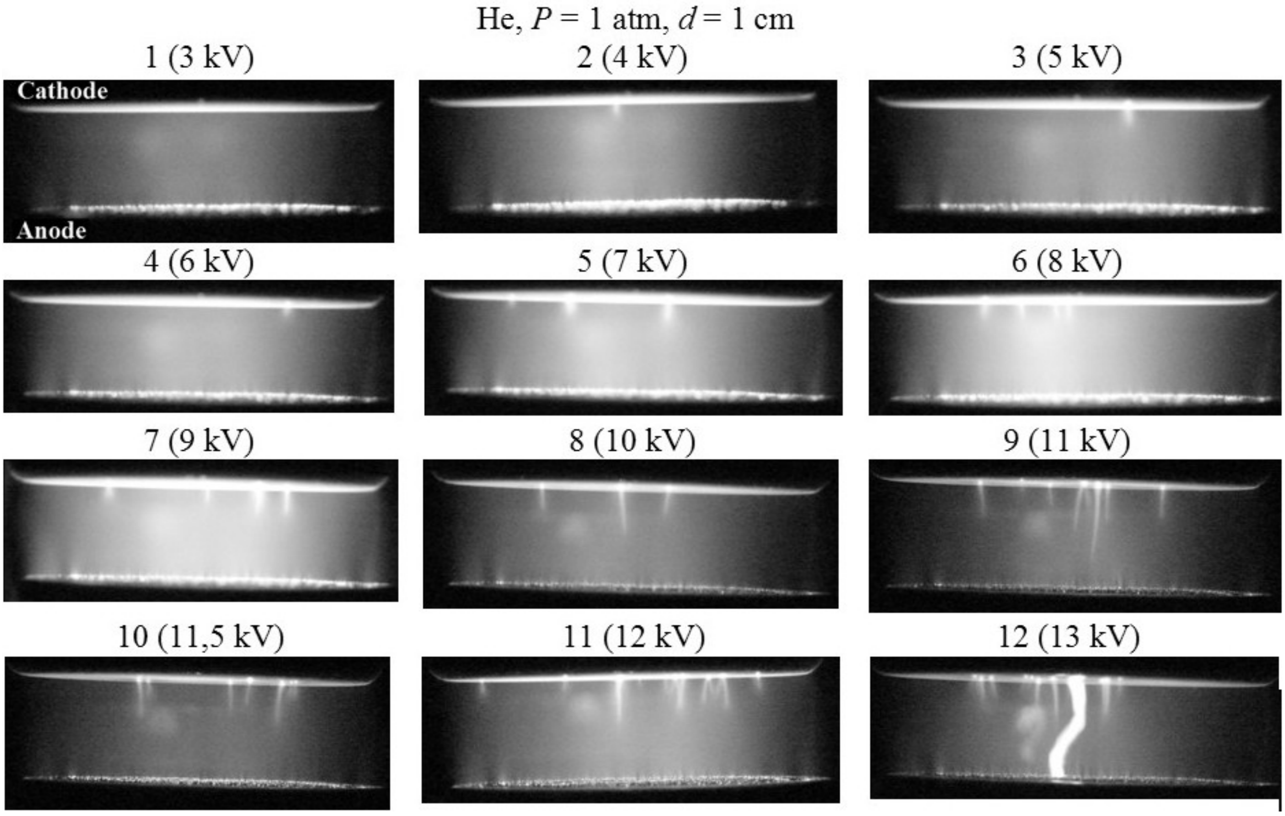
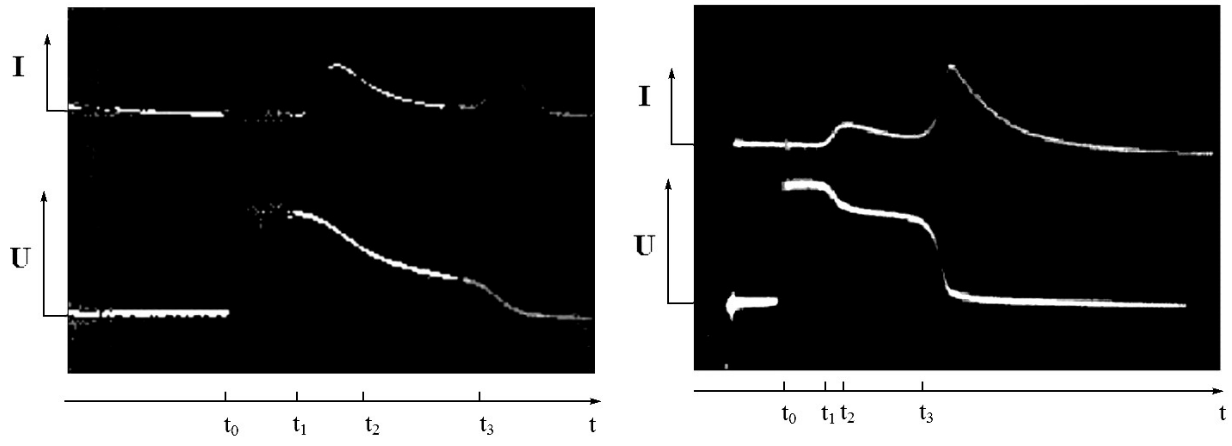


Figure 1. Time-integrated photos of the discharge glow at atmospheric pressure.



(a) (b)

Figure 2. Typical oscillograms of current and voltage: (a) $U_0 = 8\,\mathrm{kV}$, $P = 1\,\mathrm{atm}$, $d = 1\,\mathrm{cm}$; (b) $U_0 = 9\,\mathrm{kV}$, $P = 3\,\mathrm{atm}$, $d = 1\,\mathrm{cm}$). Here, t_0 is the beginning of the applied voltage growth; t_1 is the beginning of the first voltage drop; t_3 is the beginning of counteraction of a volume discharge in a spark channel; $t_3 - t_2$ is the volume phase duration.

The instant of a discharge interval overlapping with a plasma channel (Fig. 1 photo 12) is clearly visible, when the growth of channel conductivity causes a second sharp voltage drop (see Fig. 2).

In the coordinated pump mode, a specific heat input of $\sim 0.1\,\mathrm{J/cm^3}$ is provided, which is the maximum for helium in a homogeneous burning stage. The duration of discharge uniformity is adjusted by the reduction of the current density or by the increase of gas pressure. At a pressure of 5 atm, the step on a pulse voltage is practically not visible. In this case the volume discharge duration is defined by the time of switching of the discharge current. The voltage pulse on the discharge interval thus smoothly falls down up to arc value.

Oscillograms (Fig. 2) and discharge glow pictures, with fixed spatial (Fig. 1) and temporal (see [15,16]) resolutions, show on the one hand the dynamics of discharge development, and on the other hand allow us to define the duration of breakdown stages.

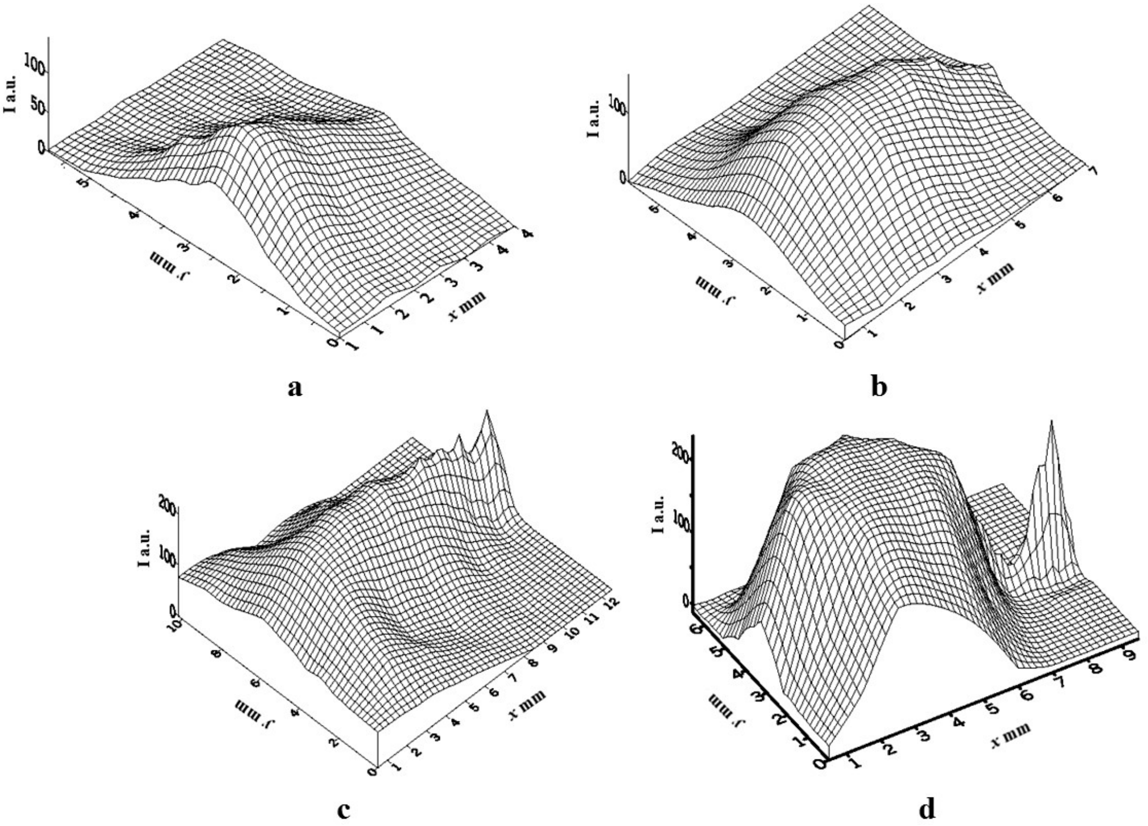


Figure 4. Distributions of radiation intensity (in a.u.) both along and across electrodes ($d = 1\,\mathrm{cm}$, $P = 1\,\mathrm{atm}$): (a) $t = 105\,\mathrm{ns}$; (b) $t = 130\,\mathrm{ns}$; (c) $t = 155\,\mathrm{ns}$; (d) $t = 210\,\mathrm{ns}$. Here x is the coordinate along a field, and y is the coordinate across a field.

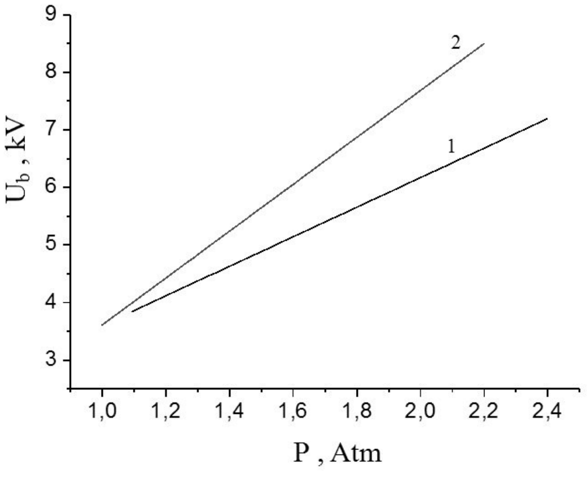


Figure 3. Dependences of the burning voltage of volume discharge on pressure: (1) $E/P = 3\,\mathrm{kV/cm\,atm}$; (2) $E/P = 3.5\,\mathrm{kV/cm\,atm}$.

The reduction of the duration of the volume discharge burning stage due to the pressure growth, is the result of non-compensated growth of the number of ionization processes relatively to the recombination ones. The increase in gas pressure results in an increase of the voltage at the discharge column. This results in the growth of ionization processes due to the shock ionization that is caused by the strong dependence of the factor α on E_0, as well as to the step ionization. The rough uncompensated growth of electron concentration then results in growth of conductivity and in the recession of voltage up to the arc value. Afterwards, the discharge moves to a recombination mode and dies. The increase of the overvoltage up to 300 % causes the appearance of a large number of plasma channels having a rather large diameter. The time-differentiation of volume and high-current stages is well visible on oscillograms of the discharge current or of the voltage on the plasma channel.

At volume stage of discharge burning the voltage U_b =const., and this constant value depends on pressure (see Fig. 3), corresponding to the minimal voltage of the breakdown with the fixed value of Pd, where P is gas pressure and d is interval length.

To obtain a sparkless mode we need to obtain a full dispersion of storage element energy ($C = 1.5 \cdot 10^{-8}\,\mathrm{F}$) for burning time τ_b [1]. For volume discharges in He this requirement is reached at $U_0 = 2U_b$, where $U_b \approx 3000\,\mathrm{V}$ is the volume discharge burning voltage at $P = 1\,\mathrm{atm}$, $d = 1\,\mathrm{cm}$). The analysis of such measurements shows that the spark channel in this case is initiated by instabilities in near-electrode areas [15,18]. These instabilities define the binding of narrow diffusive channels and cause the transition from a volume discharge mode into a spark mode. Figure 4 shows the distributions of radiation intensities both along the field and across electrodes. From this figure follows that the counteraction process is defined by near-electrodes phenomena.

On the other hand, the basic energy is entered in the discharge in quasi-stationary stages. Then, fot the energy density, it is possibleto write:

$$W = \frac{P\tau_b}{V} = \frac{IU\tau_b}{Sd} = \frac{jU\tau_b}{d}, \qquad (1)$$

where τ_b is the volume stage duration, j is the current density.

The energy, given to the gas before the formation of the spark channel, increases the power, although the burning duration τ_b exponentially decreases with field growth [16]. Finally, the volume discharge emits a spark in the channel at the critical current density $j \geq j_{\mathrm{critical}} \approx 40\,\mathrm{A/cm^2}$ and the extreme specific inputs ≈ 0.1–$0.2\,\mathrm{J/cm^3}$ [13].

In a voltage drop stage (when we have a quasi-neutral plasma column with the cross-section area S and electron density n_e in the discharge interval) the resistance of this column defined by

$$R = \frac{U}{I} = \frac{Pd}{Sen_e k}, \qquad (2)$$

where μ and $\nu_{dr} = \frac{kE}{P} = \mu E$ are the mobility and the drift speed of electrons. Accordingly, $k = \mu P = 6.72 \cdot 10^5\,\mathrm{cm^2\,torr/V\,sec}$ [1].

For our experiment $S = 12\,\mathrm{cm^2}$; $P = 760\,\mathrm{torr}$; $d = 1\,\mathrm{cm}$; $n_e \approx 10^{13}$–$10^{14}\,\mathrm{cm^3}$. The resistance ranges from 10 to 100 Ω.

4. Conclusions

To sum up, we can observe a clear sequence of events:

(1.) the occurrence of cathode spots in an initial stage of discharge;

(2.) the development of uncompleted anode channels;

(3.) the formation of uncompleted cathode channels; and finally

(4.) the merging of counter channels and the growth of their conductivity.

In conditions of strong preliminary ionization and with a wide range of initial voltage values the discharge has a volume structure, and the duration decreases with the growth of the initial voltage and gas pressure. In the case of an extreme specific heat input $\approx 0.1\,\mathrm{J/cm^3}$ and a critical current density $j_{\mathrm{critical}} \geq 40\,\mathrm{A/cm^2}$, the discharge contracts to a spark channel.

The burning voltage U_b at various values of E/P tends to reach such value at which U_b/Pd is constant. At the same time the ionization ability of electrons $\eta = \alpha/E_0$ is maximal and optimal for electron multiplication. The relation E/P in the volume discharge plasma does not depend on an initial voltage (for $P = 1\,\mathrm{atm}$, $E/P \approx 3 \cdot 10^3\,\mathrm{V/cm\,atm}$). A volume discharge voltage determined basically by gas pressure, has a linear dependence in quite wide ranges.

Acknowledgements

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