The dynamics of the formation of initial stages of a transverse nanosecond discharge with an extended slot cathode in argon

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Abstract. The dynamics of the main characteristics of a limited nanosecond discharge in an extended slot cathode in argon at the values of the applied voltage to the electrodes close to the values of the voltages of the formation of a volume discharge are studied by numerical simulation. It is shown that this type of discharge can be used to create an extended dense plasma column with a high density of charged and excited particles. The analysis of the spatio-temporal dynamics of development of the electron density and the electron energy distribution was carried out. It is shown that the high-energy electrons are formed at the front of the ionization wave due to the hollow-cathode effect.

1. Introduction

In recent decades, interest in the plasma of a high-voltage nanosecond gas-discharge has increased significantly. A pulsed volume nanosecond gas-discharge at high gas pressures is widely used, in particular, to create chemically active plasma. This type of gas-discharge plasma is widely used for cleaning and sterilizing surfaces, in additive technologies for precision modification of surfaces and near-surface layers of materials, decomposition of organic compounds and waste processing [1–4]. The optical properties of the plasma of the high-voltage nanosecond discharges at high gas pressures are also actively studied, primarily due to the possibility of using this type of discharges to create powerful sources of radiation of the optical and ultraviolet ranges [5–7].

Another technological application of high-voltage nanosecond discharge is the creation of sources of high-energy electrons and X-rays based on it [8, 9].

To optimize the plasma technologies, it is important to have a set of data on the parameters of a nanosecond pulsed gas-discharge plasma, for example, the distribution of the electric potential, electron density and energy, and the density of the excited particles.

The aim of the present work is to study the spatio-temporal dynamics of the charged particle density distributions, the density of excited atoms, and other parameters in the limited nanosecond gas-discharge plasma with an extended slot cathode in argon at the amplitude voltage value close to the values of the voltages of the formation of a volume discharge in the gap between the electrodes. The studies were performed at medium gas pressures using numerical modelling methods.

2. Model description
Numerical modelling was carried out using COMSOL Multiphysics software [10]. The solution of any problem in this software package is based on the numerical solution of partial differential equations by the finite element method. The geometry of the simulation area corresponded to the real geometry of the discharge tube, taking into account the features of the electrode system used in experimental work [11–14]. The hollow aluminium cathode is a round rod with a length of 5 cm with a rectangular cavity along with a depth of 0.6 cm and a height of 0.2 cm, and the anode is a flat aluminium plate with a width of 2 cm and a length of 5 cm. The distance between the electrodes is 0.6 cm. The geometry of the simulation area is shown in figure 1. The discharge region between the slot cathode and the flat anode is bounded on the sides by dielectric plates [12, 13], therefore, the modelling region is a rectangular parallelepiped 0.2 cm high and 1.2 cm long, filled with gas-discharge plasma (see figure 1). Since the conditions do not change along the entire length of the electrodes, therefore, a two-dimensional problem in 2D geometry was solved (see figure 1).

The task of numerical modelling is to study the dynamics of the formation and development of a limited nanosecond discharge with a complex cathode surface profile, and determination the spatio-temporal structure of the distribution of the main discharge parameters. The results provide an understanding of the kinetics of elementary processes involving electrons, atoms, ions, excited particles and photons involved in the formation of a high-voltage nanosecond discharge at various stages of its development and explain the experimental features of this discharge in argon.

In the modelling, a self-consistent system of equations consisting of the Poisson equation for calculating the potential, the drift-diffusion equation for the electron density, and the extended form of the Maxwell-Stefan equations for the transport of heavy particles is solved. The transport coefficients and rate constants are calculated using the electron energy distribution function (EEDF). To calculate the real EEDF in the current discharge configuration, it is necessary to solve the Boltzmann kinetic equation for the isotropic and anisotropic components of the EEDF, since the configuration of the hollow cathode creates conditions for the formation of accelerated electrons. Therefore, in this work, the Boltzmann kinetic equation for the isotropic and anisotropic components of the EEDF was solved using the program LoKI-B [15].

In order to numerically solve the system of equations, the initial conditions are used
\[ n_d(t = 0, x, y) = n_i(t = 0, x, y) = n_0, \] where \( n_0 \sim 10^{14} \text{m}^{-3} \) is the initial background plasma density corresponding to the residual electron density at the frequency-periodic discharge used by us in this cycle of experimental work [18].

The following boundary conditions are used:
1) \( V = 0 \) is the potential on the walls of the cathode;
2) \( V = U(t) \) is the potential on the anode wall, that sets from experimentally measured value of the voltage pulse at the anode;
3) Boundary conditions on the dielectric walls of the discharge chamber:
\[
-n \cdot D = \sigma_s + \varepsilon_r \varepsilon_s \frac{V_{ref} - V}{d_s},
\]
where \( \varepsilon_r \) is the relative permittivity, \( d_s \) is the thickness of the dielectric layer; \( V_{ref} \) is the reference potential determined by the charge trapped on the surface of the dielectric; \( \sigma_s \) is defined as follows:
\[ \sigma_n = n \cdot J_i + n \cdot J_e, \quad n \cdot J_e \] is the normal component of the total density for the wall electron current.

Elastic and inelastic collisions (direct and stepwise excitation of atoms, direct and stepwise ionization of atoms by electron impact, superelastic collisions, inelastic collisions of excited and ground state of argon atoms) are taken into account in the simulation. The loss of charged particles due to recombination in the volume and on the surface of the electrodes and dielectric walls is also taken into account. The secondary electron emission from the cathode surface was taken into account with a coefficient of 0.02.

3. Results and discussion

The numerical simulation of the discharge in argon was carried out at gas pressures of several Torr and the value of the applied voltage pulse to the electrodes of 1.2 kV, corresponding approximately to the value of the breakdown voltage for a given range of gas pressure. In the simulation, the pulse of the applied voltage and the discharge current corresponding to the real pulses from the experiment are used. Figure 2 shows the corresponding discharge current-voltage characteristics.

![Figure 2](image1.png)

**Figure 2.** Discharge voltage (black solid) and discharge current (red dashed) profile in argon at \( U_0 = 1.2 \) kV and gas pressure \( p = 5 \) Torr.

![Figure 3](image2.png)

**Figure 3.** Dynamics of electron density distribution in the gas-discharge gap with \( U_0 = 1.2 \) kV and gas pressure \( p = 5 \) Torr in the range of 90 to 110 ns from the moment a voltage pulse is applied to the electrodes.

Figures 3 and 4 present the results of numerical modelling of the dynamics of the spatio-temporal electron density distribution in the gas-discharge volume. These figures show the dynamics of the formation and propagation of the ionization wave front in the high-voltage nanosecond discharge.
volume with a slot cathode. It can be seen from figure 3 that at the initial stages of the formation of an electric breakdown of the gas, the background density of charged particles is redistributed due to the pulling of electrons onto the anode. By the time of about 90 ns, a plasma clot with a maximum density is formed at the surface of the anode in the center \(1.6\times10^{17}\ m^{-3}\). Further, there is an increasing of the electron density and its distribution in the discharge volume, which indicates the formation of an ionization wave directed towards the cathode. It is also seen that the maximum electron density is concentrated behind the front of the ionization wave. The speed of the ionization wave front propagation is of the order of magnitude \(4\times10^5\ m/s\) and reaches the boundary of the hollow cathode approximately 100 ns after the voltage is applied. At the time of 110 ns, the ionization wave front penetrates into the cavity of the hollow cathode. Further, as can be seen from figure 4, this front is divided into two fronts and, spreading along the cathode surface, they penetrate further into the cathode cavity. It should be noted here that the time in figures 3 and 4 is counted from the beginning of the application of the voltage pulse (see figure 2), and it includes the time of discharge formation.

![Electron density [1/m²]](image)

**Figure 4.** Dynamics of electron density distribution in the gas-discharge gap with \(U_0 = 1.2\) kV and gas pressure \(p = 5\) Torr in the range of 120 to 250 ns.

In the previous work, at \(U_0 = 1.2\) kV and \(p = 5\) Torr [15], it was shown that the ionization wave does not split after penetration into the cavity, penetrates further into the cathode cavity and then a volume plasma is formed in the cathode cavity. In this case, a peculiar discharge structure is formed with non-uniform plasma density distribution inside the cathode cavity and in the gap between the electrodes. At the initial moments after the plasma penetrates into the cathode cavity, the plasma is mainly localized along the internal surfaces of the cavity, which then eventually passes into the volume plasma. And in the gap between the electrodes, the plasma, unlike the previous results ([16], see figure 5 (a)), does not strongly contract to the center of the discharge gap (figure 4).

It was also shown in [16] that as the gas pressure increases, the speed of the ionization wave front also increases, the plasma front forms faster and covers the discharge gap earlier.

Figures 5 and 6 show the results of calculations of the EEDF under the studied conditions. Figure 5 shows the relaxation of the EEDF over time, measured at a point located inside the hollow cathode at a distance of 7 mm from the lower boundary of the hollow cathode in the center of the discharge tube.

It can be seen from this figure that at the initial moments, corresponding to the formation of an electric breakdown of the gas (50 ns), the EEDF is strongly decreasing, there are no high-energy electrons and there are a small number of low-energy electrons.

Further, we see that starting from 100 to 105 ns, the number of high-energy electrons grows up. This time corresponds to the moment when the ionization wave front reaches the point of 7 mm (see
Further, it can be seen from the figure that the EEDF begins to fall back, i.e. the number of fast electrons decreases after the ionization wave has passed.

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Figure 5. EEDF at a point located at a distance of 7 mm from the lower boundary of the hollow cathode in the center of the discharge tube.

Figure 6. EEDF at a point located at a distance of 1 mm from the lower boundary of the hollow cathode in the center of the discharge tube.

Figure 6 shows the relaxation of the EEDF over time, measured at a point located inside the hollow cathode at a distance of 1 mm from the lower boundary of the hollow cathode in the center of the discharge tube. From this figure, it can be seen that the EEDF at 50, 100, 105 and even 110 ns are basically zero, and only at time 114 ns at this point, electrons appear inside the cathode cavity. And starting from the time of 114 ns, the number of high-energy electrons increases rapidly. The time of 114 ns corresponds to the moment when the ionization wave penetrates into the cathode cavity and propagates further inside. Further, until 250 ns, the fast part of the EEDF increases, and after this moment it falls back.

These figures confirm the formation of high-energy electrons during the propagation of the ionization wave from the anode to the hollow cathode. This also shows that with the development of an electrical breakdown of a gas with an extended slot cathode, the number of accelerated electrons at the anode increases at the beginning of the electric breakdown. It is known that during the propagation of the ionization wave, almost all the electric field is concentrated on the front of the ionization wave. Free electrons accelerate and gain energy in this region of the enhanced electric field and lead to the excitation and ionization of gas atoms [17]. The characteristic size of the region of the amplified field (the length of the front ionization wave) has a value of the order \( l_1 = \pi \tau f \), where \( \tau \) is the duration of the leading edge of the ionization wave, \( \nu_1 \) is the speed of the ionization wave.

When the ionization wave reaches the base of the cathode slot, the formation of the cathode layer begins, where the potential of the applied field mainly decreases due to the ejection of the electric field by a dense plasma column. The electrons emitted from the cathode wall at the base of the slot pass through of the cathode potential drop without collisions and gain energy \( \sim eU_k \) [18, 19]. This is also confirmed by the results from the modelling (figure 6), where the maximum EEDF after the ionization wave reaches the slot base before the discharge is completed is localized at the base of the cathode slot.

4. Conclusion

Thus, the results of numerical simulation of a nanosecond discharge with a hollow cathode in argon limited by dielectric walls show that with such this discharge, at relatively low values of the applied voltage (about 1.2 kV), it is possible to create an extended dense plasma column with a high density of
charged and excited particles. The analysis of the obtained results shows that at the amplitudes of voltage corresponding to the value of the volume discharge formation (1.2–1.3 kV), the ionization wave, after reaching the cathode-dielectric boundary, splits into two fronts, after which the ionization front along the cathode walls penetrates into the depth of the cathode cavity.

The EEDF calculated at various points of the discharge gap shows the presence of high-energy electrons at the front of the ionization wave, and their number decreases after the ionization wave has passed. The analysis of the distribution areas of the volume charge, the electric field strength, the energy of free electrons and the density of excited particles shows that it is possible to optimize the operation of a pulsed plasma reactor based on a nanosecond discharge in order to obtain the characteristics of charged or excited particles required for technological application.

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