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# Peculiarities of the ionized fronts formation and development in pre-ionized gas

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**Abstract** We present the results of the investigation of the initial stage of volume discharge formation in helium of atmospheric pressure. The investigation of the non-locality of energy distribution influence on the ionization wave parameters in the front area is carried out on the basis of a two-dimensional axial-symmetry drift-diffusion model. The results of numerical calculations are in a satisfactory agreement with the experimental data.

## 1. Introduction

The impulse volume discharge can be used for a wide range of technological applications as the power laser, plasma shields and screens, plasma-chemical reactors due to the unique proceeding processes. Physics of these processes is quite complicated and now is under consideration [1-5]. Crucial improvement of performance data of plasma devices demands reliable quantitative data about the processes of discharge formation. One of the main characteristics of the discharge are the electric field dynamics, the distribution of the charged particles concentration in a discharge gap, the elementary processes frequency, the discharge current, and the gap-drop voltage.

This paper studies the detailed analysis of the impulse volume discharge formation process in the high pressure helium [6, 7] on the basis of numerical simulation.

Now, there are three approaches for the numerical simulation of plasma: the kinetic, in which Boltzmann equations are numerically solved either directly, or using the microparticle method with regard to collisions, according to Monte Carlo method [8, 9], the hydrodynamical one, in which the equations are solved numerically for several first moments of Boltzmann equation [9, 10], and the hybrid method [11]. The choice of the model is defined by a free path length for every sort of the particles. For discharge under the atmospheric-pressure, the hydrodynamical and the hybrid methods are usually used for numerical simulation.

In recent works [1-2], we have presented the experimental results of electric, spectral, and optical properties of initial formation stages of the impulse volume discharge in the atmospheric pressure helium. In particular, the research results with the use of high-speed photoelectronic subnanosecond time-resolved register (PER2-1) have allowed us to establish the successive steps of the formation and development of the impulse volume discharge in the atmospheric pressure helium.

This research work is the continuation of the cycle of the works performed earlier.



## 2. Physical Model and Numerical Approach

For discharge description, we use a drift-diffusion model, which includes equations for electron and ions, Poisson equation for the electric field [12]. The energy equation for the neutral gas taken into account does not change dramatically the results. That is why in our present numerical simulation we do not consider the energy equation for the neutral gas.

$$\begin{aligned}\frac{\partial n_e}{\partial t} + \nabla \cdot \vec{\Gamma}_e &= \alpha_{nl} |\vec{\Gamma}_e| - \beta n_e n_i, \\ \frac{\partial n_i}{\partial t} + \nabla \cdot \vec{\Gamma}_i &= \alpha_{nl} |\vec{\Gamma}_e| - \beta n_e n_i, \\ \nabla \cdot \vec{E} &= \frac{e}{\varepsilon_0} (n_+ - n_e)\end{aligned}\quad (1)$$

Here, the electron and ion fluxes, which can be expressed like that  $\vec{\Gamma}_e = -n_e \mu_e \vec{E} - D_e \nabla n_e$ ,  $\vec{\Gamma}_+ = n_+ \mu_+ \vec{E} - D_+ \nabla n_+$ , is the current density,  $n_e$  and  $n_+$  are the density of electrons and ions,  $\alpha_{nl}$  is a nonlocal first Townsend coefficient, and  $\beta$  recombination coefficient,  $\mu_e(E/N)$  и  $\mu_+(E/N)$  electron and ion mobility,  $D_e = \frac{kT_e \mu_e}{e}$  and  $D_+ = \frac{kT_+ \mu_+}{e}$  electron and ion diffusion coefficients,  $\varepsilon_0$  is the dielectric constant;  $\vec{E}$  is the electric field strength,  $\varphi$  is the electric potential,  $N$  - concentration of neutral particles,  $T_e(E/N)$  - electron temperature,  $T_+ = T_0$  - ion temperature,  $k$  - Boltzmann constant,  $e$  - elementary charge.

The geometry of calculated domain is a gap between two plate electrodes with radius  $r = 2$  cm. The distance between these electrodes is 1 cm. This gap is connected to the charged capacitor  $C = 15$  nF with voltage  $U_0 = 7$  kV through the ballast resistance  $R_b = 2$  Ohm.

Transport coefficients, ionization, and deionization parameters are given by dependences from [13, 14].

At the initial time moment, the everywhere temperature is  $T_0 = 293$  K, the initial pressure is  $p = 760$  Torr. Initial distribution of the electric field is found in the solution to Poisson equation. The electron and ion density at the initial time inside the computational domain is:  $n_e(x, y, 0) = n_+(x, y, 0) = n_0$ . ( $x$  - a dimension in radial direction).

Boundary conditions for the cathode are  $y = 1$  cm,  $\vec{\Gamma}_e = \gamma \vec{\Gamma}_+$ ,  $\partial n_+ / \partial y = 0$ ,  $\varphi_k = 0$ , where  $\gamma = 0,1$  is a secondary emission ratio, for the anode they are  $y = 0$  cm,

$$\partial n_e / \partial y = 0, n_+ = 0, \varphi_k = U(t) - I(t)R_b, I(t) = 2\pi \int_0^r j_a(x, t) x dx, \partial \varphi / \partial y = 0.$$

$I(t)$  is a total current in electrical circuit,  $j_a(x, t)$  is a distribution of the current density on the anode. Calculations were performed on a nonuniform grid with an increased mesh resolution near the cathode and the anode. The number of the cells between the electrodes is 300, and a radially uniform grid has 200 cells.

The calculation method is explicit with the first-order accuracy in space and time. Poisson equation for an electric field was solved by the iterative method. The calculation was made in a two-dimensional axisymmetric position.

A non-local ionization coefficient was taken from [15]:

$$k_{i\_nl}Nn_e = k_i \left( 1 + \frac{\vec{E}D_e \nabla n_e}{\mu_e n_e E^2} \right) Nn_e = \alpha |\vec{\Gamma}_e| \left( 1 + \frac{\vec{E}D_e \nabla n_e}{\mu_e n_e E^2} \right) = \alpha_{nl} |\vec{\Gamma}_e|, \quad (2)$$

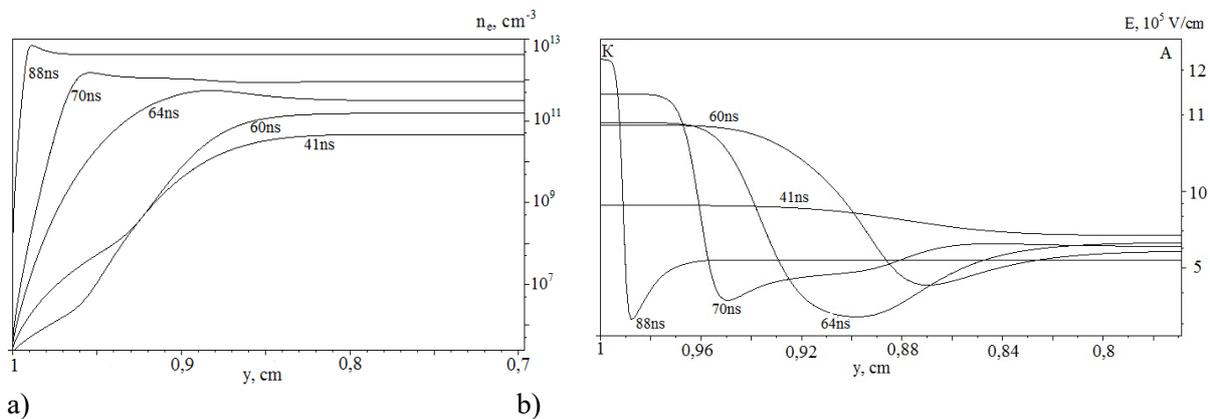
Here  $\alpha$  is a local first Townsend coefficient.

The non-locality for electron mobility is calculated in the same way:

$$\mu_{e\_nl} = \frac{1}{n_e m_e \nu_m E_x} (n_e e E_x + \nabla(n_e k T_e)_x) = \mu_e \left( 1 + \frac{\nabla(n_e k T_e)}{e n_e E_x} \right). \quad (3)$$

Here  $m_e$  is an electron mass,  $p_e = n_e k T_e$  - the electron gas pressure,  $\nu_m$  - the frequency of the electron collisions with neutral gas particles,  $k_{i\_nl}$  is the non-local ionization rate constant,  $\mu_{e\_nl}$  is the non-local electron mobility coefficient.

Let's examine the results of discharge numerical study.



**Figure 1.** Electron concentration distribution (a) and electric field strength (b) in discharge gap:  $U_0=7$  kV,  $p=760$  torr,  $d=1$  cm.

### 3. Result and Discussion

The electron concentration distribution in a discharge gap at various time moments is presented in figure 1a. According to the figure 1a, from the beginning plasma polarization occurs near cathode. Since the drift electrons leave the cathode, a region and the area with a small electron density appears and electric field strength increases (fig.1b), which leads to the high direct ionization. The electron density increases in a polarized layer with increasing the distance from the cathode due to a decrease of their drift speed in a non-uniform field. The positive charge accumulation in the cathode region leads to the field enhancement and to the most intensive collision ionization. This means a transfer of the electron and ion maximum density to the cathode. Because of opposite drift directions of the charged particles maximum values, the density of electrons and ions is displaced relative to each other, and the electric field profile has an inflection and is minimum. It should be mentioned that the main process in the cathode layer is a collision ionization. When the ionization wave approaches the cathode, the plasma parameters and electric field strength become established in the cathode layer. A settling time is defined by the ion drift velocity in a strong electric field.

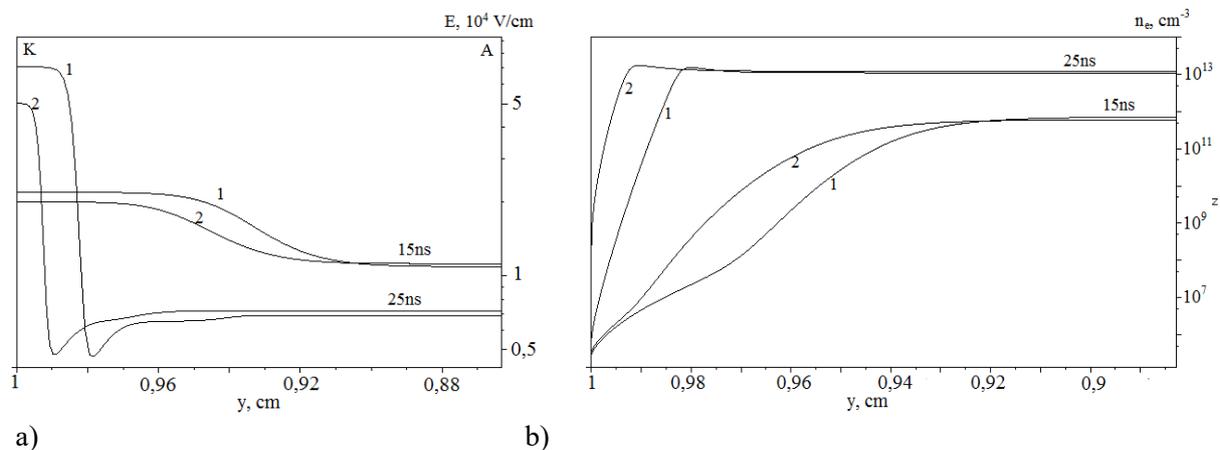
The results of calculations show that electric field strength in the cathode layer is up to  $\sim 10^4$ - $10^5$  V/cm at the stage of volume discharge. This is especially important at the initial stage of discharge formation, when the development of the cathode directed ionization wave occurs.

Figure 2a, b shows the electron concentration distribution and the electric field strength without (1) and with taken into account (2) non-local effect. We can see, that taking into account the non-local effect leads to an increase of the wave-ionization velocity.

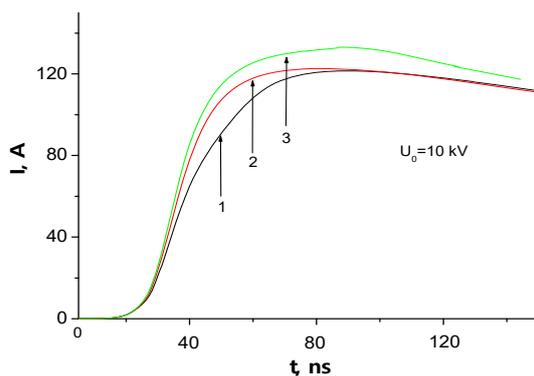
Figure 3 presents temporal variation of the discharge current. The given dependences show the importance of the taken into the account non-local effect on the stage of the current growth.

Figure 4 presents maximum amplitude values of the discharge current for the different applied voltage. Taking into account the non-local effect for the ionization constant rate and for the electron mobility doesn't change dramatically the result. The discharge current under  $U_0=10$  kV approaches to its maximum at 90 ns, and experimentally measured time [1, 2] is  $\approx 95$  ns.

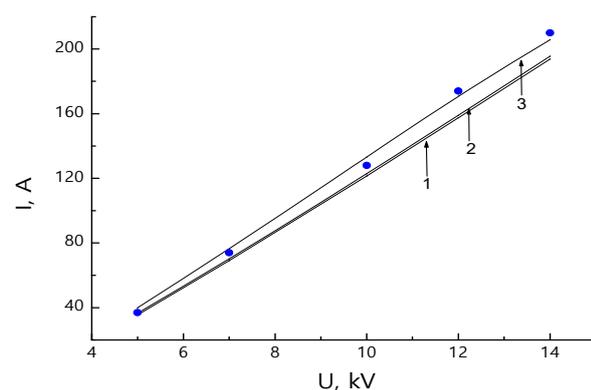
This means that, the results of the numerical simulation are in a good agreement with the results of the experiment. The characteristics of time dependency for the voltage after the swift drop show a step, which conforms to the stage of the overall combustion. At this stage, the basic discharge parameters remain guise-steady.



**Figure 2.** Distribution of the electric field (a) and electron concentration (b): curve 1- without taking into the account the non-locality; curve 2- taking into the account the non-locality ( $U_0=12$  kV).



**Figure 3.** Temporal variation of discharge current: 1- without taking into the account the non-locality; 2- taking into the account the non-locality of ionization constant rate; 3- taking into the account the non-locality effect for the ionization constant rate and electron mobility.



**Figure 4.** Maximum amplitude values of discharge current for different applied voltage: 1- without taking into the account the non-locality; 2- taking into the account the non-locality of ionization constant rate; 3- taking into the account the non-locality effect for the ionization constant rate and electron mobility.

#### 4. Conclusion

So, the use of non-local corrections leads to an increase of the ionization wave velocity, but the main discharge characteristics do not change dramatically and may be calculated in the assumption of the local approximation.

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