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SIMULATION ON HIGH-PRESSURE NANOSECOND GAS DISCHARGE IN COAXIAL GAP[1]

The paper presents the results of numerical simulation of a nanosecond high-pressure gas breakdown in a coaxial geometry. This geometry was chosen to simulate the simplest quasi-one-dimension geometry, which can be implemented in a spatially nonuniform electric field. The simulation shows that the ionization wave with a fairly sharp leading edge moves in strongly overvoltage gap. Plasma concentration jump on the wave front of the order of 10^{14} cm^{-3}, and the propagation velocity of the ionization region reaches $2\cdot10^{9}$ cm/s. By the end of the anode voltage pulse uncompensated charge of positive ions remains in the discharge gap, it creates a sufficiently strong electric field of the bipolar orientation.

Keywords: *nanosecond gas discharge, runaway electrons, breakdown of high-pressure gas.*

Introduction

In recent years, there has been an increased interest in nanosecond discharges in an inhomogeneous electric fields under high pressures [1–3]. The nanosecond discharges in inhomogeneous electric fields can be attributed to the practical application of spark discharges.

Prerequisite of runaway electrons is the presence in the discharge gap is quite large region of very strong electric field. Typically, this situation occurs when applying for a gas-filled gap electric pulse with a short front of the growing voltage. This work was stimulated by experiments with fast electrons in a pulsed corona discharge, in particular [4].

Theoretical model of nanosecond discharge

The coaxial geometry of the discharge gap was selected as the simplest example of a one-dimensional and non-uniform problem at the same case as well.

To simulate the corona "minimal" theoretical model was exploited, which consists of two equations of continuity for the concentrations of ions (n_i) and electrons (n_e), including the function of the impact ionization source ($\alpha w_e n_e$), as well as the Poisson equation for the calculation of the electric field E. In the model singly charged ions and electrons fluxes are described in drift-diffusion approximation. So we research only short time discharges (2 ns and shorter) it was supposed ions were motionless during all stages.

Basic equations of the model were as follows:

$$\frac{\partial n_e}{\partial t}+\frac{1}{r}\frac{\partial}{\partial r}\left(r\Gamma_e\right)=\alpha w_e n_e, \qquad \Gamma_e=-\mu_e E n_e - D_e\frac{\partial n_e}{\partial r},$$
$$\frac{\partial n_\text{i}}{\partial t}=\alpha w_e n_e, \qquad \frac{\alpha}{p}=A\exp\left(-\frac{B}{E/p}\right), \tag{1}$$
$$\varepsilon_0\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial\varphi}{\partial r}\right)=-e\left(n_\text{i}-n_e\right), \qquad E=-\frac{\partial\varphi}{\partial r}.$$

Where μ_e, D_e are mobility and diffusion coefficient of electrons; $w_e=\mu_e E$ is a drift electron velocity; A and B are constant parameters of empirical expression for the first ionization Townsend function α; ε_0 is the electrical constant, and φ is an electric potential.

As for initial distribution of the electric field and charged particles densities we take simple conditions:

$$n_e(r,t=0)=n_0, \quad n_\text{i}(r,t=0)=0, \quad \varphi(r_1,t)=\varphi(r,t=0)=0, \quad \varphi(r_2,t)=U(t).$$

At the initial time the electron density does not exceeds 10^{3} cm^{-3}. Electron equation of continuity requires of boundary conditions, such as conditions zero diffusion fluxes at anode and cathode walls.

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Electrical voltage pulse $U(t) = U_0 \sin^2(\pi t / T)$ is applied to the coaxial gas-filled gap (inner electrode-cathode of radius r_1 = 0.1–0.5 mm, outer electrode-anode of radius r_2 = 4 cm >> r_1), gas (air, argon, nitrogen) at a pressure of p = 100–760 Torr, T = 1–2 ns.

The simulation results and discussion

For the Poisson's equation solution can be formally written in the symbol form expressions:

$$\varphi(r,t) = \frac{U(t)}{\ln(r_2/r_1)}\ln(r/r_1) - \frac{q}{\varepsilon_0}\left\{\int_{r_1}^{r}\frac{1}{r''}\int_{r_1}^{r''} r'\Delta n(r',t)dr'dr'' - \frac{\ln(r/r_1)}{\ln(r_2/r_1)}\int_{r_1}^{r_2}\frac{1}{r''}\int_{r_1}^{r''} r'\Delta n(r',t)dr'dr''\right\},$$

$$E(r,t) = -\frac{U(t)/r}{\ln(r_2/r_1)} - \frac{q}{\varepsilon_0 r}\left\{\frac{1}{\ln(r_2/r_1)}\int_{r_1}^{r_2}\frac{1}{r''}\int_{r_1}^{r''} r'\Delta n(r',t)dr'dr'' - \int_{r_1}^{r} r'\Delta n(r',t)dr'\right\}.$$

For the ions density we can write the symbol expression too:

$$n_i(r,t) = \mu_e \int_0^t \alpha(E(r,t)) n_e(r,t) E(r,t) dt .$$

Solutions for these equations in quadratures simplify calculations greatly, since the integration is a stable numerical operation with respect to the grid methods.

Thus the final design solutions of the system is reduced to the numerical solution of the sole remaining continuity equation for the electron density, taking into account the distribution of the electric field strength. For the numerical solution of partial differential equations Method-Of-Lines was used. In coaxial geometry, the electric field near the cathode is essentially uniform, so non-uniform computational grid was chosen, and cell sizes decreased exponentially from the anode to the cathode.

Fig. 1 shows the calculated electric field distribution in the coaxial argon-filled gap at atmospheric pressure is applied to the anode of the voltage pulse amplitudes 250 kV. The radius of the cathode wire is 0.2 mm, the radius of the anode tube is 4 cm.

We emphasize that the accumulation of the positive charge of the ions leads to an inversion of the field strength, when the anode voltage is greatly reduced. By the end of the pulse field maximum has the opposite direction. At this time-point in Fig. 1 correspond to the dotted lines *6*.

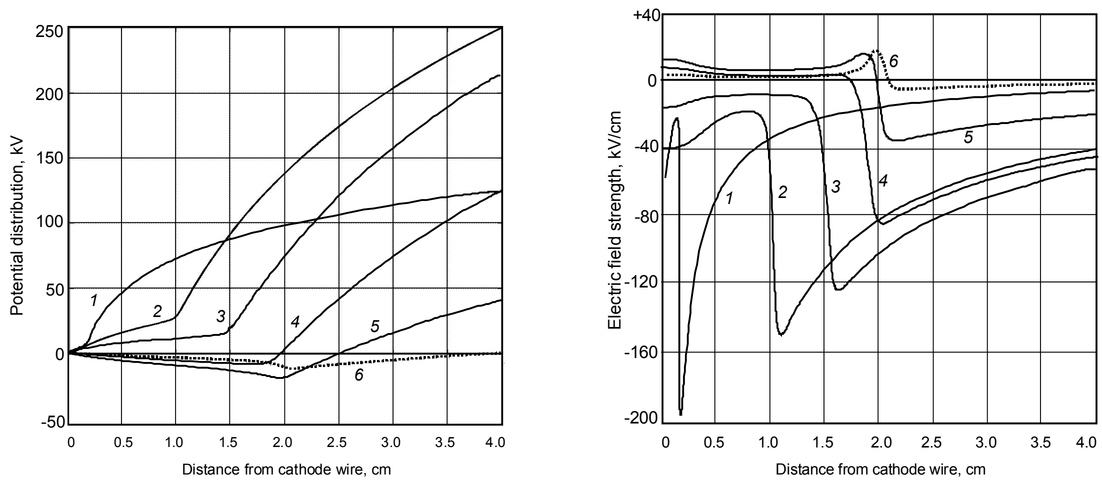

Fig. 1. Spatial distributions of the potential (left picture) and electric field strength (right picture) at different times: curves *1* – 0.50, *2* – 1.00, *3* – 1.25, *4* – 1.50, *5* – 1.75, *6* – 2.00 ns.

Plots clearly show the location of the ionization wave front, where the maximum electric field energy is concentrated. The ionization wave (sharp gradient of plasma concentration) expands from the cathode to the anode. This wave front has a velocity of about ~ $2 \cdot 10^9$ cm/s. Behind the front of the ionization wave field strength is high enough to continued gas ionization. Therefore, the concentration of plasma near the cathode continues to grow after the front moves forward.

On the wave front is an abrupt increase in the plasma concentration. The magnitude of this concentration jump can be accurately estimated from energy considerations. Concentration jump, Δn, is roughly equals to the ratio of the field energy density to the total ionization energy of atom:

$$\Delta n \sim \frac{E_{\mathrm{m}}^2/2}{eE_{\mathrm{m}}/\alpha(E/p)} = \frac{\varepsilon_0}{2e} ApE_{\mathrm{m}} \exp\left(-\frac{B}{E_{\mathrm{m}}/p}\right).$$

Here, E_{m} is local maximum electric field strength at ionization wave front. For example, the calculation of concentration jump, Δn (with respect to the curve 2 in Fig. 2 value E_{m} = 200 kV/cm) gives an estimate ($1.5\cdot10^{14}$ cm^{-3}) of almost coinciding with the simulation results ($1.2\cdot10^{14}$ cm^{-3}).

If the 1D-planar geometry discharge the main source of fast electrons is located at the cathode region of enhanced field where located ion space charge, the coaxial geometry likely place the appearance of fast electrons may be moving front of the ionization wave, where a strong electric field is concentrated. It is noteworthy that to the end of the anode voltage pulse remaining space positive charge forms a bipolar field. And the maximum intensity corresponds to the “reverse field” accelerating electrons in the cathode side. Inversion of the field direction is probably the cause of the observed in the experiments of fast electrons not only for the anode, but the cathode and discharge gap [5].

Analysis of simulation results shows that pulse current of fast electrons is determined by the ionization wave velocity and the conditions considered being less than a nanosecond. This agrees well with the experimental data, when applied to the gas diode voltage pulse 100 kV level formed runaway electron beams duration of ~ 100 ps or less [6].

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