The space charge formed by the runaway electron beam

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Abstract. For discharges in atmospheric pressure air, a numerical simulation of the process of formation of a runaway electron beam from the emission zone at the cathode was performed. The model is based on the numerical solution of the equations of motion of electrons injected from the surface of the emission zone and secondary electrons that appeared during gas ionization. It is shown that when a beam of runaway electrons passes through, a space charge is formed, which determines the electric field in the interelectrode gap.

1. Introduction

Laboratory studies of runaway electrons (REs) are carried out in high-pressure gas discharges at microsecond [1–3] and subnanosecond rise times of a voltage pulse [1, 4–7]. In case of microsecond rise times, discharge gaps are used in which the average electric field strength is comparable to the electric field strength during static breakdown (approximately 30 kV cm⁻¹ [4]). The mechanisms of runaway electron formation in discharges with high overvoltage were considered in [1, 8–11]. An analysis of the experimental results carried out in [10] showed: a) the emission of electrons does not occur uniformly from the entire edge of the cathode, but there are separate emission zones (EZs) of runaway electrons; b) the emission boundary of the EZ is formed not by the edge of the cathode, but by an ionized gas layer; c) the moment of injection of the RE beam from the emission zone is determined by a certain critical field at the cathode. According to estimates, the size of the emission zone is 50–100 µm [1, 9–11]. Emission from the EZ begins after an electric field is reached on its surface, at which all electrons are able to go into continuous acceleration. In the case when the electric field is independent of spatial coordinates, all electrons begin to continuously accelerate when the field strength is equal to the critical value \( E_{cr} \) [1, 4]. In air at atmospheric pressure \( E_{cr} \approx 500 \text{ kV cm}^{-1} \). When the electric field is on the surface of the emission zone \( E_{ez} \approx E_{cr} \), the current density of the electrons injected from the surface of the EZ is about \( 10^6 \, \text{A cm}^{-2} \) [12]. If the field strength decreases with distance from the surface of the EZ, as is the case, for example, on the streamer head [4], then the transition of electrons to the continuous acceleration mode requires field intensities significantly exceeding \( E_{cr} \) [1–3, 11].

After the start of electron injection, the field on the surface of the emission zone decreases due to the formation of a negative space charge around it; therefore, the intensity \( E_{ez} \) is a function of time:

\[
E_{ez}(t) = E_{out}(t) - E_{em}(t),
\]

where \( E_{out}(t) \) is the electric field created by the voltage source on the surface of the emission zone, \( E_{em}(t) \) is the electric field created by the space charge of the injected electrons. The space charge consisted of large particles of three types: “electrons” injected from the surface of the emission zone; secondary
"electrons" born by fast particles; "ions". The equations of motion were solved only for "electrons", "ions" were considered immobile.

2. Numerical modeling

Numerical modeling of the process of formation of the RE beam was carried out for conditions close to the experimental ones [5, 10, 13]. In the simulation, a kinetic model was used, in which the equations of motion of individual "electrons" (large particles) were solved and which were described in detail in [14, 15]. The production of secondary electrons, which leads to the appearance of an RE avalanche, was taken into account using the technique described in [15, 16]. In this technique, the braking force was divided into two terms: the first term describes the braking with the transfer of low energy, which does not lead to the appearance of REs. The second term describes the braking with the transfer of energy sufficient for the appearance of RE.

In the calculations, it was assumed that the air with which the discharge gap is filled consists of nitrogen (78% by weight), oxygen (21%) and argon (1%). The air pressure was 1 atm. The following time dependence of the amplitude of the accelerating voltage was used:

\[ U(t) = U_0 \sin \frac{\pi t}{2 \tau_g} \]  \hspace{1cm} (2)

The calculation was carried out for air pressure of 1 atm, at \( \tau_g = 100 \text{ ps} \) and \( U_0 = 200 \text{ kV} \). The interelectrode gap length was \( L = 1 \text{ cm} \), and the radius of the runaway electron emission zone was taken equal to \( R_{ez} = 50 \mu \text{m} \). Injection of electrons from the surface of the EZ began at time \( \tau_{inj} \), at which the field strength on the surface of the EZ reached \( E_{out}(\tau_{inj}) = E_{ez}(\tau_{inj}) \approx 2 E_{cr} \), which approximately corresponds to the field strength at which the electron runaway conditions are achieved on the surface of the emission zone with a radius of 50 \( \mu \text{m} \). The moment of the beginning of the injection was calculated in accordance with the expression:

\[ E_{out}(t) = \frac{U(t)}{L} \beta, \]  \hspace{1cm} (3)

where \( \beta = 10 \) is the field amplification factor. The electron injection rate had a pronounced maximum at \( t \approx \tau_{inj} \), then it dropped sharply and was maintained in such a way that, with an increase in the voltage across the gap \( U(t) \), the field strength \( E_{ez} \) on the surface of the EZ would be close to zero.

3. Numerical calculation results

The calculation results are presented in figures 1–3. Figure 1 shows the time dependences of the runaway electron beam current for air with a pressure of 1 atm. The vertical dotted line in figure 1 shows the moment of the beginning of injection of the electron beam from the EZ. Line 1 shows the time dependence of the voltage across the interelectrode gap, line 2 shows the total current of the RE beam, and line 3 shows the current of the RE avalanche [13, 17, 18]. It was believed that the current of the RE avalanche is formed by electrons that were born at a distance of more than 200 \( \mu \text{m} \) from the surface of the EZ. As can be seen from figure 1, the amplitude of the RE current is close to one ampere, at a half-maximum duration of about 20–25 ps, and at a total duration of about 100 ps. The peak at the beginning of the current pulse is due to electrons injected from the surface of the emission zone, and the extended section is due to avalanche electrons.

Figure 2 shows the distributions of the axial component of the electric field in the interelectrode space at different points in time. The dependencies shown in figure 2 are plotted along the \( z \) axis at \( x = 0 \) and \( y = 0 \). As can be seen from this figure near the cathode, the electric field strength is mainly determined by the space charge of electrons, while the field strength at the anode differs little from the average.
**Figure 1.** Calculated time dependences: voltage on the interelectrode gap (curve 1); total current of the RE beam (curve 2); runaway avalanche current (curve 3).

**Figure 2.** The calculated spatial dependences of the electric field in the interelectrode gap at various points in time.
Figure 3. Spatial distribution of space charge at $t = 133$ ps.

The spatial distribution of the space charge is shown in figure 3, which shows the concentration of particles creating the charge $n_p = n_i - n_e$, where $n_i$ is the concentration of ions, $n_e$ is the concentration of electrons. The spatial distribution is shown in the $(r, z)$ geometry; during its construction, the coordinate $r = (x^2 + y^2)^{1/2}$ was calculated for each particle. It can be seen from figure 3 that a cloud of negative space charge is formed around the emission zone, the dimensions of which subsequently change little. The sizes of this electron cloud are 150–200 µm. A space charge cloud shields the emission zone; therefore, after the passage of the runaway electron beam on the surface of the emission zone, the field strength remains close to zero (see figure 2). This leads to the fact that during further evolution of the discharge near the surface of the emission zone, conditions are not formed under which the electrons can go into continuous acceleration mode, that is, the RE beam does not renew.

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