An avalanche of runaway electrons formed in an air discharge

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Abstract. A numerical simulation of a beam of runaway electrons formed from an individual emission zone on a cathode has been performed for discharges in air of atmospheric pressure. The model is based on solving numerically two-dimensional equations of motion for the electrons and allows one to describe the dynamics of the fast electrons injected from the surface of the emission zone. In calculations it was supposed that the electric field at the surface of the emission zone is enhanced due to which conditions are realized for the electrons injected from the surface to switch into the mode of continuous acceleration.

1. Introduction

Runaway electrons (RE) were discovered in atmospheric pressure discharges in the late 1960th [1]. An RE beam passing through a gas initiates, due to avalanche multiplication of fast electrons, breakdown, which has been termed runaway electron breakdown (REB) [2, 3]. It is supposed that REBs take place in lightning discharges. The possibility of existence of REBs gave impetus to both theoretical [2-4] and experimental research [5,6] of RE avalanches. An RE avalanche was observed in an atmospheric pressure air discharge when the average electric field in the gap, \( E_{av} \), was much greater than the dc breakdown electric field, \( E_{br} \) [6]. These experiments have shown that the pulsed RE current in discharges with \( E_{av} >> E_{br} \) has the following structure. Its first portion of duration some tens of picoseconds, showing a strongly pronounced current peak, consists of high-energy runaway electrons. These are the electrons emitted from the cathode region where the field is enhanced due to the cathode geometry. Subsequently, with some delay, a second peak of RE current or a section of slowly decreasing current arises. This was accounted for by the formation of an avalanche of runaway electrons. The duration of the secondary electron beam was of the order of 100 ps and its current could be an order of magnitude greater than the current of the primary runaway electron beam. This took place if it was possible to avoid the decrease in electric field in the gap caused by the passage of the primary beam.

Laboratory investigations of REs in high pressure gas discharges are carried out both at microsecond rise times of the gap voltage [1,7,8] for \( E_{av} < E_{br} \) and at subnanosecond rise times (that is, in overvolted electrode gaps) [5,6,9] for \( E_{av} >> E_{br} \). In the latter case, the mechanism of formation of the runaway electron beam is the subject of discussion. The matter is that as the voltage across the gas
diode increases, conditions arise for the runaway of the electrons emitted from the cathode microprotrusions [10] that have formed as a result of the ionization of the gas by the voltage prepulse and also of the electrons emitted from the boundary of the plasma cloud formed around cathode microprotrusions. The well conducting plasma cloud, which is a source of REs, is formed due to impact ionization of the gas by priming electrons emitted from the cathode. The contribution of the electrons produced during the prepulse can be decreased by shortening it and by decreasing the voltage amplitude; the amount of field emission electrons is inappreciable in view of the small area of emission from cathode microirregularities. The emission current can increase abruptly only as a result of the transition of field emission to explosive emission. The electrons accelerated to high velocities in the high electric field region near microprotrusions [11] appear in a lower field region. If the density and energy of the electrons are high enough, this will lead to the formation of a virtual cathode [12] and, as a consequence, to disruption of the beam of the runaway electrons emitted by the cathode. In this work, we consider the emission zone formed by the plasma cloud surrounding an emitting microprotrusion to be a source of runaway electrons.

As mentioned above, in highly overvolted discharges, the source of electrons are individual emission zones (EZ) whose number in discharges with tubular cathodes can be more than ten [13]. Below we consider the formation of an RE beam for the case with a single emission zone. The size of the emission zone in atmospheric pressure air estimated by Babich et al. [1] and, in more detail, by Barengolts et al. [11] was obtained to be 50–150 µm.

2. Simulation of the evolution of a runaway electron beam in highly overvolted gas discharges

Suppose that an EZ is a plasma hemisphere of radius \( R_{ez} \). In this case, a negative superficial charge is concentrated at the hemisphere surface which screens the external electric field. The number of electrons at the hemisphere surface (in the Debye layer) is given [14] by

\[
N_d = \frac{E_{ez} R_{ez}^2}{2e},
\]

where \( E_{ez} \) is the electric field strength at the EZ surface. As conditions for runaway of electrons from the EZ surface are realized, electrons are injected with the current density [14]

\[
j_{em} \approx \frac{3}{2\pi} \sqrt{\frac{e}{m \tilde{l}}} E_{ez}^{3/2},
\]

where \( \tilde{l} \) is the mean free path of an electron (in elastic scattering by gas atoms). For \( E_{ez} \approx E_{cr} \) (\( E_{cr} \) is the critical electric field strength, when all electrons switch into the mode of continuous acceleration) the current density of electrons injected from the surface of an EZ in air at atmospheric pressure is \(~10^6\) A/cm\(^2\). The velocity of the injected electrons is determined by the drift velocity \( v_d \approx \sqrt{\frac{e}{m} \tilde{l} E_{ez}} \). The characteristic time of electron injection from an EZ surface, determined by the effluxion of electrons from the Debye layer, is estimated [14] as \( \tau_{em} \approx \frac{1}{6} \sqrt{\frac{m \tilde{l}}{e E_{ez}}} \).

We consider coarse particles each consisting of \( N \) electrons; the motion of a coarse particle is described a two-dimensional numerical model based on the Monte-Carlo method [5]. The basic equation of the model is an equation describing the variation of the momentum of an electron:

\[
\frac{dp}{dt} = eE - F - (\Delta p)_e,
\]

where \( p \) is the electron momentum, \( F \) is the braking force, and \( (\Delta p)_e \) is the variation of the electron momentum on elastic scattering. The elastic electron-atom collisions were taken into account using the
Monte-Carlo method [14]. Two components of the momentum were calculated: $p_x$, parallel to the vector $E$ and $p_y$, perpendicular to the vector $E$.

The electric field strength in Eq. (3) is the sum of two terms: $E = E_{av} + E_{ch}$, where $E_{av}$ is the average electric field depending on time and $E_{ch}$ is the electric field induced by the space charge. The space charge is generated by three species: the electrons injected from the EZ surface, the secondary electrons produced by fast particles, and ions. The equation of motion for ions is not solved. As their mobility is much less than that of electrons, they remain localized at the places of production of electron-ion pairs. The space charge field is assumed to be spherically symmetrical and it is found by solving numerically Maxwell’s equations

$$\text{div} E_{ch} = 4\pi\varepsilon(\varepsilon - n_i),$$

where $\varepsilon$ is the total density of the electrons injected from the EZ surface and of the secondary electrons and $n_i$ is the ion density. The boundary conditions to Eq. (4) specified at the EZ surface is

$$E_{ch}(R_{ez}) = \frac{2e(N_d - N_{ew})}{R^2_{ez}},$$

where $N_{ew}(t)$ is the number of electrons injected from the EZ surface within the time $t$; that is, after the injection, which lasts less than 1 ps, we have $E_{ch}(R_{ez}) = 0$.

3. Results of numerical simulations

The numerical simulation of the formation and acceleration of an RE beam was performed for air of atmospheric pressure and for conditions close to the conditions of the experiment [15]. The time dependence of the accelerating voltage amplitude was set by the relation

$$U(t) = U_0 \sin \frac{\pi t}{2 \tau_g},$$

where $U_0 = 160$ kV and $\tau_g = 100$ ps. In calculations, as well as in the experiment [15], the length of the electrode gap $L$ was varied. The radius of the runaway electron EZ was set the same for all calculation runs: $R_{ez} = 0.01$ cm [1, 11]. As mentioned above, in experiments with highly overvolted gas discharges, the time of RE injection is determined by some critical electric field at the cathode. In the experiments described elsewhere [10], this critical field was determined from the time-of-flight characteristics of an electron in vacuum, and it turned out to be ~1500 kV/cm. However, in gas, unlike in vacuum, an electron undergoes many collisions with gas atoms and thus loses its energy and diverges from a rectilinear path. Both of these the factor lead to an increased time of flight of an electron in the electrode space and, hence, to an overestimated field strength [10]. Therefore, in the calculations discussed below, the injection of electrons from the EZ surface was assumed to begin as the electric field at the cathode edge, $E_{ez}$, reached 1000 kV/cm, the same value for all calculation runs. Accordingly, the time of the beginning of injection was calculated by the formula $U(t) = \frac{E_{ez}L}{\beta}$, where $\beta = 10$ is the field enhancement factor.

As in all calculation runs the values of $E_{ez}$ and $R_{ez}$ were the same, the number of electrons injected from the EZ surface, equal to the number of electrons in the Debye sphere (1), was the same: $N_d = 5 \times 10^8$. The velocity vector of the injected particles was directed normal to the EZ surface. The energy of the injected particles, depending on the drift velocity of electrons in a field equal to $E_{ez}$, was determined as

$$E = \frac{mv^2}{2}(1 \pm 0.5) \approx 10 \pm 5 \text{ eV}.$$
The results of the calculations are presented in Figs. 1. Figure 1 gives the current of a runaway electron beam as a function of time for three runs with the electrode separation equal to 0.25, 1.0, and 1.25 cm. The vertical dashed lines mark the time of the beginning of injection of the electron beam from an EZ, lines 1 represent the voltage across the electrode gap as a function of time, lines 2 the total current of the RE beam, and lines 3 the current of the RE avalanche. It was assumed that the RE avalanche current was formed by electrons that had been produced more than 200 µm away from the EZ surface.

Figure 1. Waveforms of gap voltage (curve 1), total RE beam current (curve 2), and RE avalanche current (curve 3) calculated for an electrode separation of 0.5 (a), 1.0 (b), and 1.25 cm (c).
As can be seen from Fig. 1, in all calculation runs the RE current amplitude is close to 1 A with a current pulse FWHM of 12–25 ps and full duration of 50–100 ps. The peak in the beginning of the current pulse is caused by the electrons injected from the EZ surface and the extensive section by the avalanche electrons. Figure 1 clearly shows that avalanche processes play a great part in the formation of an RE beam at small lengths of the electrode gap, just as it was observed in the experiment [6]. Therefore, avalanche processes stronger affect the formation of an RE beam in shorter electrode gaps.

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