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PLASMA

Numerical Study of the Feasibility of Runaway Electron Generation in an Emerging Cathode Layer of a Self-Sustained High-Pressure Space Discharge

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Abstract—The formation of the cathode layer of a self-sustained high-pressure space discharge with preliminary ionization of a gas medium, excited by nano- and subnanosecond voltage pulses, is calculated. It is shown that, at pressures of ~1 atm, at the final stage of cathode layer formation, conditions for runaway electron generation are created. Runaway electrons from the electric field amplification region in front of the leading edge of a plasma (streamer) channel, originating from the top of the cathode micronib, is considered. It is shown that, at pressures of ~10 atm, conditions are created for the runaway of electrons immediately after their emission from the top of the micronib in its amplification zone; the runaway electrons thus obtained, in turn, can create preliminary ionization of the gas medium and ensure the formation of the initial phase of space discharge in systems without illumination.

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INTRODUCTION

The study of runaway electron generation in high-pressure gases, in particular, in air, is one of the most interesting problems in gas discharge physics. Interest in this phenomenon is due to its various practical applications. First, it is the development of electron accelerators without a foil separating vacuum and gas volumes, which is a trouble spot of accelerators. Second, it is the generation of electron beams of picosecond duration.

In general, the state of affairs in this area is described in sufficient detail in the reviews [1–3]. More recent results are presented in [4–7]. It is known that an electron goes into the runaway mode when the average increase in the electron energy in the electric field exceeds the energy loss as a result of inelastic collisions with the molecules of a gas medium. There is also a widely known analytical criterion for runaway electrons (see [2] and the references therein). According to this criterion, electron runaway is realized at sufficiently high electric field strengths, several times higher than breakdown values. Therefore, runaway electron generation is realized in high-pressure discharges, as a rule, in separate local regions of the discharge, where, for a short time, necessary conditions are created. This is why runaway electron beams are usually obtained using electrode systems with a cathode of a special shape providing a significant amplification of the electric field in the cathode region (see, e.g., [4, 8]). It is also generally known that runaway electrons can appear in the amplified-field region in front of the leading edge of the streamer channel. This possibility was analyzed, in particular, in review [1] and book [9]; however, the correct numerical simulation by the Monte Carlo method was carried out much later [2, 3, 10, 11]; most of these works are concerned with the study of runaway electron generation during the formation of lightning [2, 10, 11].

It is also known that, in the cathode layer of both a low-pressure glow discharge and a high-pressure space discharge, the electric field can exceed the mean value by many times in the discharge gap even with flat electrodes. In many cases, the electric field strength is formally sufficient for the electron to go into the runaway mode, but this possibility is not necessarily realized due to a small cathode voltage drop (hundreds of volts). In the case of low pressure, even such a small energy may be sufficient for the electrons to pass from the high-energy part of the energy distribution function to the runaway mode. This phenomenon is also widely known and has been repeatedly mentioned in the literature (see, e.g., [12, 13]). With increasing pressure, the possibility of runaway electron generation in the cathode layer becomes less likely. For medium pressures, the runaway electron generation is still mentioned in [14], whereas, for high pressures, such generation becomes impossible at the quasi-steady stage. However, theoretical studies of the formation of a cathode layer [15–17] showed that there is a stage in which the electric field becomes high enough (~10^5 V/(cm atm)) and the cathode drop has not decreased to quasi-steady values and remains at the kilovolt level. Under such conditions, electrons can go into the runaway mode, which was shown in [17] by Monte Carlo modeling. However, the one-dimensional model used in the above-cited studies cannot take into account all features of this process. In particular, within the one-dimensional model, it is impossible to calculate electron runaway in front of the leading edge of the plasma (streamer) channel, which can be initiated by emission inhomogeneity on a cathode surface, e.g., by a micronib. The amplification of the electric field in front of the leading edge of such a channel in combination with the amplification in the emerging cathode layer can lead to earlier runaway electron generation in comparison with the values obtained within the one-dimensional model.

A similar situation was not theoretically investigated earlier, despite the fact that the development of the streamer channel from the cathode was modeled in a number of studies. A possible reason is that earlier researchers were interested in discharge contraction, i.e., the transformation of a space charge into a spark charge at the final stage. This phenomenon is described in detail in [9] and the literature cited therein. In addition, it is worth referring to [18], which is not cited in [9].

As applied to the initial stage, the first attempts of 2D modeling were undertaken in [19, 20]. In [21], more detailed 2D modeling of the development of the streamer channel from the cathode in the emerging cathode layer was carried out. It was shown that increasing the emission of a small section of the cathode (the nature of which is not specified) accelerates the approach of the ionization wave front to the cathode in this section in comparison with neighboring regions. However, further development of the inhomogeneity caused by this breakdown is not considered in [21]. In some sense, a logical continuation of this study is [22]. In this study, also using the 2D model, the evolution of the inhomogeneity that initially arose from a small plasma region with a higher conductivity near the cathode surface is studied. The contraction of the current to this section is considered in dynamics, and the possibility of further formation of a highly conductive spark channel is investigated. However, in the above-cited studies, the generation of runaway electrons and their effect on the formation of a self-sustained space discharge are not considered.

The aim of this study is numerical analysis of the feasibility and conditions for the initiation of runaway electrons at the stage of formation of the cathode layer of a self-sustained space discharge with uniform preliminary ionization of a gas medium.

MODEL AND CALCULATION RESULTS

For calculations, we used a numerical model based on a system of equations for electrons, ions, and excited atoms and Poisson's equation. Kinetic coefficients, which depend on the electric field, including the probability for an electron to go into the runaway mode, were obtained by simulating electron motion by the Monte Carlo method. A detailed description of this model is given in [17, 23]. 1D calculations of the formation of a space discharge with preliminary ionization of the gas medium were performed earlier in [15] for a CO_2 : N_2 : He mixture with a pressure of 1 atm under the experimental conditions of [24, 25] and, in [17], for N_2 with a pressure of 4 atm under the experimental conditions of [26–29]. In this study, analysis is carried out using nitrogen at a pressure of 1 atm. As initial conditions, a previously uniformly ionized discharge gap with a length of 0.5 cm was taken. It was fed with a voltage pulse with an amplitude of 50 kV and a linear leading edge with a duration of 50 ns.

The results are presented in Fig. 1, which shows the spatial distributions of electron density (Fig. 1a) and electric field strength (Fig. 1b) at different time points. They qualitatively illustrate the formation of the cathode layer of a self-sustained space discharge. It can be seen that, at the initial stage, when the electron density in the gap is relatively small, the plasma column moves away from the cathode by 0.36 cm. In this case, the electron density rapidly increases. Between the plasma column and cathode, a charge-depleted zone is formed in which the ion density is higher than the electron density. Ions partially shield the external field, weakening it in the plasma column and amplifying it in the cathode region. As a result, an increase in the electron density in the column slows down and the current density increases. As a result of the increase in the ionization rate in the cathode region, the ionization wave (plasma column) quickly (for 31–32 ns) approaches the cathode, forming a cathode voltage drop.

The characteristics of the emerging cathode layer are presented in Fig. 2. Figure 2a shows the time dependence of the cathode voltage drop (U_c) and electric field strength (E_c) near the cathode surface. Figure 2b shows, respectively, the dynamics of the changes in the length of the cathode layer (d_c) and increase in current density (j) in the discharge gap. It is seen that, as the ionization wave approaches the cathode (d_c decreases), the electric field in the cathode layer increases and the cathode voltage drop decreases. The latter creates the prerequisites for the development of instabilities in the

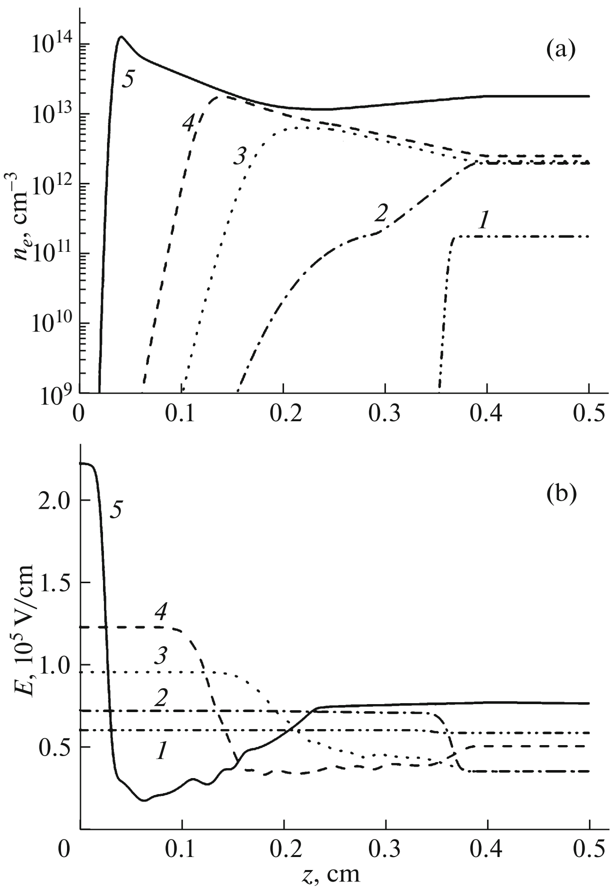

Fig. 1. Distributions of (a) electron density and (b) electric field strength in the interelectrode gap (z is the distance from the cathode) at different moments of time: (*1*) 30, (*2*) 31, (*3*) 31.5, (*4*) 31.7, and (*5*) 31.95 ns.

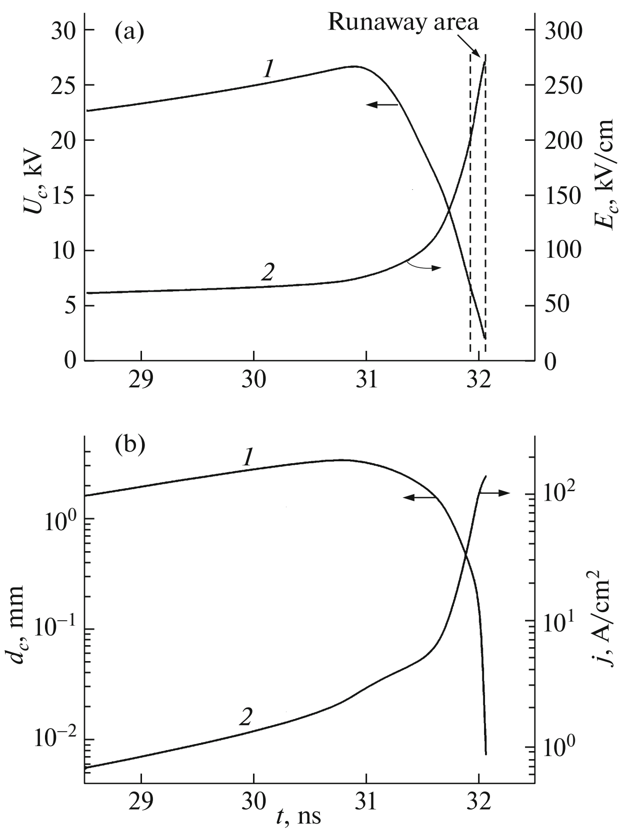

Fig. 2. Time dependence of the integral parameters of the emerging cathode layer: (a) cathode voltage drop (U_c) and maximum field strength (E_c); (b) the length of the cathode layer (d_c) and the current density in the discharge gap (j).

cathode layer. All this occurs with an increase in the conductivity of the plasma column and an increase in the current density in the discharge gap.

Monte Carlo simulation of electron motion has shown that, in the time interval 31.95–32.04 ns, under the conditions calculated above, electrons can go into the runaway mode with their further acceleration in the discharge gap; i.e., the electric field is high enough to go into the runaway mode and the cathode drop is also still enough for an electron to gain the energy necessary to continue the runaway mode in a smaller electric field of the discharge plasma column.

However, there is a possibility for the runaway electrons to enter the emerging cathode layer earlier. For example, an electron emitted from the top of the micronib can initiate an electron avalanche, which, having reached a nearly critical size, can amplify the electric field in front of its leading edge and enable the electrons to go into the runaway mode more than in other areas of the emerging cathode layer. An analytical model describing such a mechanism is described in [7, 30], but its direct application in our calculations is impossible, since it uses approximations that are not satisfied under the conditions of this study and, as a result, do not allow an accurate calculation. Therefore, in this study, we used a hybrid model presented in [31]. In this model, electron multiplication in the region of amplified electric field near the micronib was calculated by simulating their motion and collisions using the Monte Carlo method. After the number of electrons in the avalanche exceeds ~10^6, the hydrodynamic model used in 1D calculations presented above is replaced with 2D model. The calculations showed that the electron avalanche starting from the micronib has initially more compact dimensions and a high charge density in comparison with an avalanche starting from a flat cathode surface. While developing, such an avalanche can cause distortion of the electric field inside the emerging cathode layer of the self-sustained discharge. As a result, runaway electron generation can begin in the amplified field in front of the leading edge of this avalanche even before such conditions are created in the entire volume. The calculation geometry is shown in Fig. 3.

The results of calculating the motion of the wave front of the streamer channel from the cathode toward the plasma column and the dynamics of changes in the electron density and electric field are presented in Fig. 4. It is seen that, in the amplified-field region in front of the leading edge of the plasma channel, by the time of

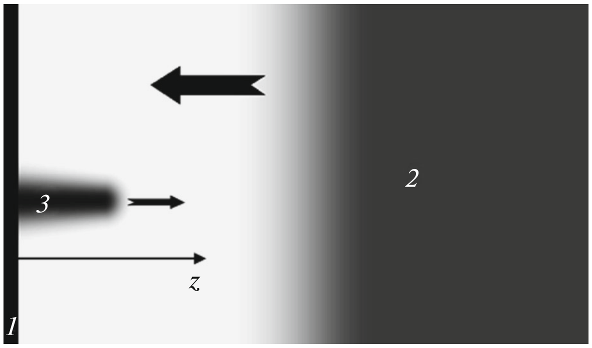

Fig. 3. Illustration of the calculation geometry inside the cathode layer: (*1*) cathode, (*2*) plasma column, and (*3*) plasma (streamer) channel starting from the top of the micronib at the cathode. Shades of gray represent the degree of ionization of sections of the interelectrode gap. The arrows indicate the direction of movement of the plasma column toward the cathode during the emergence of the cathode layer and the direction of movement of the channel toward the plasma column. The direction of the *z* axis for Fig. 4 is also shown.

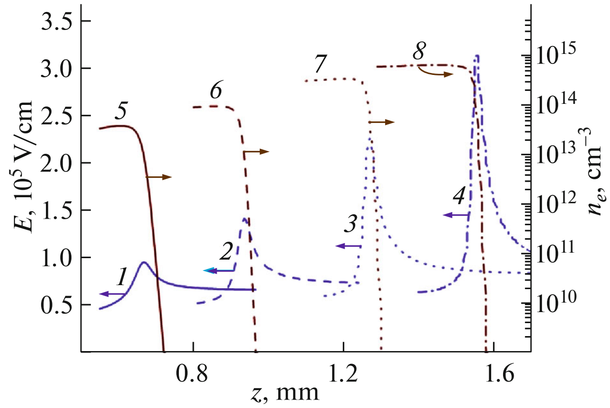

Fig. 4. Dynamics of the measurement of the leading edge of the plasma channel initiated by an avalanche starting with a micronib with a height of 10 μm at an instant of time of 28 ns in the emerging cathode layer in nitrogen for conditions corresponding to Figs. 1 and 2; (*1–4*) electron density and (*5–8*) electric field strength at an instant of time of (*1* and *5*) 30.1, (*2* and *6*) 30.4, (*3* and *7*) 30.6, and (*4* and *8*) 30.7 ns.

30.7 ns, conditions for runaway electron generation are created, while, in the main volume of the cathode layer emerging in the space discharge in nitrogen at $p = 1$ atm (Figs. 1 and 2), such conditions have not yet been reached. In this case, the avalanche that initiated the plasma channel started with a micronib of height $h = 10$ μm in the emerging cathode layer in a space discharge in nitrogen at $p = 1$ atm at a time of 28 ns (the situation corresponds to Figs. 1 and 2). Calculations showed that runaway electron generation under these conditions is possible only from plasma channels that started in the time interval 25–31 ns. In the channels that started earlier, the amplification of the electric field at the leading edge will not be enough to generate runaway electrons and, in the channels that started later, the electrons going into the runaway mode will not have time to gain enough energy to continue runaway in the plasma column. In this case, the time interval in which the initiation of the runaway mode is possible is rather narrow: only 1.5 ns (Fig. 5a). If we simulate a geometrically similar situation at a pressure of 10 atm, i.e., if we take height of the micronib $h = 1$ μm, then we have a completely similar situation, with the only difference being processes shift to the subnanosecond range (Fig. 5b). However, the situation changes for a micronib with a height of 10 μm. In [32], it was shown that, at pressures above 10 atm, the electrons can go into the runaway mode directly from the top of the micronib at an electric field strength in the interelectrode gap of 820 kV/cm. In [31], it was shown that such a field strength can be realized in the very beginning of the emergence of the cathode layer, which can give rise to a streamer channel directed to the anode, which leads to contraction of the space discharge. On the other hand, in the absence of preliminary ionization, it can be provided by runaway electrons (albeit nonuniformly) and lead to ignition of a space discharge for a short time before its contraction. A photo of such a discharge stage is given in [28].

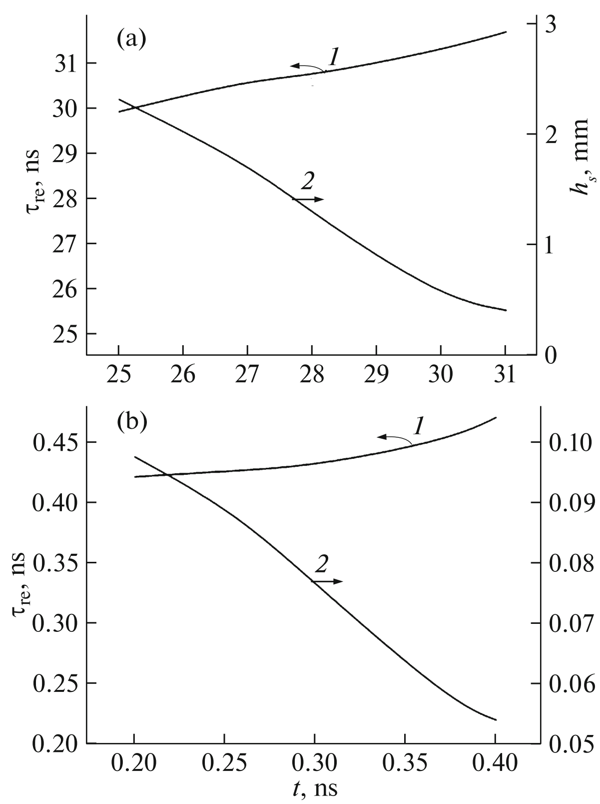

Fig. 5. (*1*) Time (τ_{re}) and (*2*) plasma channel height (h_s) corresponding to the beginning of the runaway mode in the amplified field region in front of the leading edge of the channel since the start of the channel from the micronib when the cathode layer emerges in a space discharge in nitrogen at pressures of (a) 1 and (b) 10 atm.

CONCLUSIONS

Our calculations have shown the feasibility of runaway electron generation during the emergence of the cathode layer of a self-sustained high-pressure space discharge. Within the one-dimensional model, it has been shown that electrons can go into the runaway mode at the final stage of cathode layer formation at pressures of ~1 atm. The use of the two-dimensional hybrid model made it possible to improve the model significantly and show that the electrons can go into the runaway mode from the region of amplification of the electric field in front of the leading edge of the plasma channel originating from the top of the micronib at the cathode. In this case, runaway electron generation is also possible at an earlier stage of cathode layer formation.

In the present and earlier studies, it has been shown that, at pressures of ~10 atm, there is another possible mechanism for the initiation of runaway electrons. At such pressures and, correspondingly, higher electric field strength, conditions are created for the escape of electrons immediately after their emission from the top of the micronib in its amplification region. The runaway electrons thus obtained can themselves create preliminary ionization of the gas medium.

CONFLICT OF INTEREST

The author declares that he has no conflicts of interest.

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