Investigation of electron transition into runaway mode in inhomogeneous electric field in various gas media

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Abstract. Transition of field-emitted electrons into the runaway mode is investigated in the region of enhanced electric field determined by the configuration of a microtip on a cathode for various gas media composition and pressure. The research is done using simulation of electron motion in the inhomogeneous electric field with a help of the Monte-Carlo procedure in the 3D configuration. Calculations were carried out for Nitrogen, Hydrogen and CO\textsubscript{2}:N\textsubscript{2}:He mixture (1:1:3). It’s shown that passage through a relatively small region of the enhanced field in the vicinity of the micro-spike may substantially facilitate electron transition to the runaway mode. This effect enhances at pressures of greater than 10 atm. In our opinion, the resulting runaway electrons may provide pre-ionization of gas medium and formation of the initial stage of a volume discharge. The results obtained are of interest for studies of the switching properties of ultrahigh pressure gaps and the use of a volume discharge for lasers pumping.

1. Introduction
Nowadays, phenomenon of runaway electrons (RE) is one of the most intensively investigated areas in the field of gas discharge physics. The term “running away of electrons” (in other words, continuous acceleration of electrons) means that electrons gain more energy from an electric field than they spend in collisions with gas particles. This phenomenon may be observed in electric fields of high intensity, if a value of reduced electric field strength E/N (here E is electric field strength, N is gas particles concentration) is high enough for electrons transition into runaway mode. High strength of electric field may be reached by using of cathodes of small curvature radius (e.g. tips or thin foil). Also it’s necessary to use subnanosecond pulse generators, which can provide a short front of voltage rise.

Earlier [1], generation of RE was registered in Nitrogen at the pressures up to 40 atm. In our opinion, at such high pressures generation of RE may be provided by accelerating of field emitted electrons. The acceleration may occur in an enhanced electric field near micro-spikes (or other microgeometry structures) on a cathode surface at the stage of cathode layer formation. In this case, RE may influence on commutation of a discharge gap. In particular, a beam of fast electrons may provide pre-ionization of a gas medium. It may cause decrease of commutation time and initial ignition of a discharge in a volume form in absence of an outer pre-ionization source.

In this paper, the Monte Carlo procedure in the 3D configuration for simulation of electron motion was applied for investigation of generation of RE. The electrons were considered to be emitted from the top point of a micro-spike or from the flat surface of the cathode. Calculations were done for various gas media at different pressures from 0.5 up to 40 atm. Nitrogen (N\textsubscript{2}), a laser mixture
CO$_2$:N$_2$:He (1:1:3) and Hydrogen (H$_2$) were considered. Also the simulation of electron avalanche formation process was carried out. Two cases of the avalanche formation were compared: the homogeneous electric field and the inhomogeneous enhanced field near a micro-spike on the cathode surface.

2. Monte-Carlo algorithm description (a model of individual collisions)
The block diagram of the Monte-Carlo software module is shown in figure 1. The program was written by us in C++. The program took into account the gain of energy of an electron, when it moved between collisions, and losses as a result of inelastic collisions. The nature of the each collision (elastic, excitation of the vibration or electronic levels, ionization) was played out with a help of a random number generator. The necessary data on cross sections were taken from [2–8]. The program was tested for different values of a uniform electric field. The obtained constants of ionization and drift velocity of the electron were well coincided with the data [9, 10].

![Figure 1. Block diagram of the Monte-Carlo module.](image)

3. Conditions under modelling
The possibility of electron motion transition into a runaway mode was investigated for electrons emitted from a micro-spike on the cathode (case of an inhomogeneous field) and from the flat surface of the cathode (case of a homogeneous field). The micro-spike was taken as a cone with height $h$ and base $h/2$. To avoid singularities, the top of the cone was rounded with a hemisphere of radius $0.01h$. The presence of such a micro-spike on the flat surface of the cathode causes distortion of the electric field. The field near the top is significantly amplified in comparison with the average field value in the gap. In such cases, the field amplification coefficient $K = E/E_h$ is usually used, where: $E$ is the local value of the electric field, $E_h$ is the average value of the field in the gap equal to $E_h = U/d$, where: $U$ is the voltage on the gap, $d$ is the cathode – anode distance (length of the gap).

To calculate the spatial distribution of $K$, the Laplace equation was solved with ANSYS software package [11]. Figure 2 shows the characteristic distribution of the electric field gain ($K$) of the micro-spike with $h = 10$ µm. The main graph shows the distribution of $K$ along the axis of the cone (z). The top of the cone is taken as point of origin. The insertion shows the spatial distribution of $K$ in the area of a sharp decline of $E$ near the rounded top of the micro-spike. This top is shown as a dark area with $K = 0$ in the main graph.
In this paper, modeling of electron kinetics was carried out at different gas pressures from 0.5 up to 40 atm for various gas media: N₂, CO₂:N₂:He (1:1:3), H₂. In the case of the inhomogeneous electric field, the height $h$ of the micro-spike was varied from 5 µm (a trained cathode) up to 50 µm (a not-trained cathode with high surface roughness). Also the electron avalanche formation process was investigated for both field cases. For this investigation, the inhomogeneous field was considered to be near the micro-spike of 10 µm high. The average electric field strength was set at $E = 5 \text{ MV cm}^{-1}$ in both cases.

4. Results and discussion

As a result of simulation, the dependences of the average critical electric field strength $E_m$ (at which generation of RE becomes possible) from the gas medium pressure were received. Since the transition of electron motion into runaway mode is a probabilistic process, a criterion of this transition was set as at least 1% of the possibility. Also the dependence of $E_m/E_{mh}$ ratio (where $E_{mh}$ is critical electric field strength in the homogeneous field) from the gas medium pressure was calculated. The dependences obtained are presented in figure 3 for N₂, for CO₂:N₂:He (1:1:3) on figure 4 and for H₂ in figure 5.
Figure 4. (a) – The dependences of the average critical electric field strength $E_m$, which corresponds to the running-away threshold, from the CO$_2$:N$_2$:He – mixture (1:1:3) pressure $p$; (b) – The dependences of $E_m/E_{mh}$ ratio ($E_{mh}$ – the critical electric field strength in the homogeneous field) from the CO$_2$:N$_2$:He – mixture (1:1:3) pressure $p$. All calculations were done for micro-spikes of 5 µm (curves 1), 10 µm (curves 2), 20 µm (curves 3) and 50 µm (curves 4) high.

Figure 5. (a) – The dependences of the average critical electric field strength $E_m$, which corresponds to the running-away threshold, from H$_2$ pressure $p$; (b) – The dependences of $E_m/E_{mh}$ ratio ($E_{mh}$ – the critical electric field strength in the homogeneous field) from H$_2$ pressure $p$. All calculations were done for micro-spikes 10 µm (curves 1) and 20 µm (curves 2) high.

Presented graphs show micro-spike facilitates sufficiently to generation of RE. This effect is observed in all gas media investigated and enhances with increase of gas pressure $p$ above 10 atm [12]. For example, in Nitrogen N$_2$ at pressure $p = 5$ atm critical electric field strength $E_m$ decreases approximately on 40% with presence of micro-spike of 10 µm high in comparison with homogeneous field case. If pressure increases up to 40 atm, $E_m$ decreases down to 20% of $E_{mh}$. For the other gas media the dependencies have a qualitatively analogous view. For both CO$_2$:N$_2$:He (1:1:3) and H$_2$, at 40 atm pressure, $E_m$ decreases 4 times relative to $E_{mh}$ for a micro-spike of 10 µm. For all gas media investigated, if micro-spike height $h$ increases the described effect of $E_m$ decrease enhances because of field gain increase and amplification space area extension.

In our opinion, the effect observed occurs, because, in the inhomogeneous field, not only reduced, but also the absolute value of the electric field strength affects the probability of transition into runaway mode. An electron emitted from the top of the micro-spike appears in the area of the
amplified field. This inhomogeneous field decreases rapidly with the distance from the cathode. The electron passes through this short area practically without collisions and gains some energy from the electric field. Further, the electron gets to the extended area with a relatively small field gain. The electron may accelerate passing through the second area, but also it spends some energy for ionization. Finally, after passing through the whole field amplification area, the electron energy must be greater than the energy of the ionization cross-section curve maximum (since ionization losses are the main losses for generation of RE). This energy value is of the order about 100 eV. It’s obviously that the more energy gained is, the more probability of the transition into runaway mode is. This is illustrated by a comparison of the dependences of ionization cross-section $\sigma_{\text{ionization}}$ from energy of an incident electron and the critical reduced electric field strength $E_{\text{mh}}$ from the contingent initial electron energy, what electrons gain in the enhanced field area near the micro-spike. These dependences are given in the figures 6a and 6b.

![Figure 6.](image)

*Figure 6. The dependences of the ionization cross-section from the energy of an incident electron (a) and the critical reduced electric field strength $E_{\text{mh}}$ from the contingent initial electron energy (b) for all gas media investigated: curves 1 – N$_2$, curves 2 – CO$_2$:N$_2$:He (1:1:3), curves 3 – H$_2$.*

The results of simulation show that, for example, for N$_2$, if the contingent initial electron energy is 1000 eV, the critical electric field strength $E_{\text{mh}}$ is about 40 kV-cm$^{-1}$-atm$^{-1}$. If the energy decreases down to 300 eV and lower, $E_{\text{mh}}$ increases up to 220 kV-cm$^{-1}$ atm$^{-1}$ (the runaway threshold for slow plasma electrons). The same dependences for the other gas media (CO$_2$:N$_2$:He (1:1:3) and H$_2$) have a qualitatively analogous view. If the value of the average absolute electric field strength $E$ or extent of the amplified field area (or micro-spike high) increases, electrons gain more energy after passing through the amplified field area. This facilitates the transition of electrons into runaway mode in the homogeneous field of a discharge gap.

Described kinetic of electrons affects the dynamic of electron avalanches formation process in the discharge gap. This process was also modelled with a help of our algorithm for simulation of electron motion in the 3D-space. The simulation was carried out for N$_2$ of 20 atm pressure. The cases of homogeneous and inhomogeneous field were investigated. In the second case, the inhomogeneous field was considered to be created near a cone micro-spike of 10 µm high on the flat surface of the cathode. The average electric field strength was 5 MV-cm$^{-1}$ in both cases ($E = 5$ MV-cm$^{-1}$ equals approximately to the critical electric field strength for N$_2$ of 20 atm pressure, so possibility of the electron transition into runaway mode is about 1% in the homogeneous field). The initial electrons were considered to be emitted from the flat surface of the cathode (the case of the homogeneous field) or from the hemispherical top of the micro-spike (the case of the inhomogeneous field). During the simulation the spatial distribution function along z-axis was calculating. The average electric field
strength was considered to have the same direction. The results obtained are given in figure 7 (the first case) and figure 8 (the second case).

**Figure 7.** The electron avalanche formation process in the homogeneous electric field in N\textsubscript{2} of 20 atm pressure. The electric field strength is 5 MV-cm\textsuperscript{-1}.

**Figure 8.** The electron avalanche formation process in the inhomogeneous electric field in N\textsubscript{2} of 20 atm pressure. The average electric field strength is 5 MV-cm\textsuperscript{-1}. The high of the cone micro-spike is 10 µm.
In the inhomogeneous field (figure 8), the additional maximum of linear electron density appears on the graph of the electron space distribution function. While the main bulk of electrons propagates in the space with the drift velocity (as well as the avalanche on the figure 7), the additional bulk propagates much faster. Propagation of the second avalanche is provided by REs of high energy. These electrons move in the runaway mode and preionize gas medium in front of the main bulk of electrons. At the moment 2.2 ps on the figure 8, the second avalanche is in advance of the first one on about 30 µm. Linear electron densities in both avalanches become approximately equal at this moment.

So, the simulation of the electron avalanche formation shows that, for the inhomogeneous field (figure 8), the velocity of electron avalanche propagation is much more than for the homogeneous field (figure 7), which the diffuse-drift approximation is applicable in. Besides, in the inhomogeneous field (figure 8), rate of the electron reproduction is much higher in comparison with the homogeneous field case (figure 7). Hence, if some part of field-emitted electrons transits into runaway mode in the area of enhanced electric field near cathode surface, high rate of discharge gap commutation has to be observed (in comparison with the case of absence of fast electrons). Also RE may provide pre-ionization of gas medium in front of the main bulk of electrons and facilitate to initial discharge ignition in the volume form without an outer pre-ionization source.

5. Conclusion
The results of simulation show an important role of the cathode microgeometry and related heterogeneities of the electric field for the kinetic of electrons in discharge gaps of high pressure. In particular, in this paper, it was shown that presence of the enhanced field area facilitates to electrons transition into continuous accelerating regime at the pressures up to 40 atm. This is because not only the reduced, but also the absolute value of the electric field strength affects the probability of transition into runaway mode. Acceleration of some part of electrons may provide higher rate of the discharge gap commutation in comparison with the case of absence of fast electrons. Also RE may provide pre-ionization of gas medium and facilitate to initial discharge ignition in the volume form without outer source of pre-ionization.

The results obtained are of importance for investigation of commutation features of high pressure discharge gaps, for development of super fast gas dischargers of high pressure and also for research in the field of subnanosecond volume discharges initialization for laser technique.

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