Forming of a Beam of Runaway Electrons in a Gas in Outer Heterogeneous Electric Field.

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Abstract – In this assignment it was searched the formation of a beam of runaway electrons in nitrogen under the atmospheric pressure by Particle-in-Cell method. It was showed the possibility of continuous acceleration of electrons that were emitted from edge cathode in gas-filled diode in heterogeneous electric field and formation out of them of the beam of runaway electrons.

1. Introduction

In the last period of time a lot of attention is paid for the research of formation of electron beams of sub nanosecond duration under atmospheric pressure in different gases [1-4]. There are two basic models explaining processes that take place the in such a situation.

In the first model it is assumed that the runaway electron beam forms in highly heterogenic electric field nearby head of streamer [2] or nearby cathode edge [1].

At that the electric field tensity nearby heterogeneity such as that must satisfy the criteria of runaway electrons $E > E_{cr}$. According to this criteria electron gets more energy than it loses by inelastic (impacts) at the unit of path length. E_{cr} is a critical electric field tensity.

Authors of the second model [3,4] believe that in conditions of experiments [1] an area with a high electric field intensity appear as a result of movement of conductive plasma channel which, extending from cathode to anode, «squeeze out» electric field into a gap d_{ef} between the plasma frontier and anode. To cause electron runaway the «non-local criteria of runaway electrons» $\alpha_i(E_{cr}, p)d \le 1$ in a gap is necessary. Here α_i is an inverse *Townsend coefficient*, p – gas pressure. Actually such a situation means that in runaway regime get only those electrons that do not have more than one ionizing collision in plasma-diode gap. This condition is not full filled for the cathode-anode gap in experiments [1] according to the second model that is why electrons, injecting from cathode with thermal velocities, can not get into the regime of continuous acceleration. In particular, in the work [4] it is considered that in the conditions of the experiments "remarkable portion of particles injecting from cathode riches the anode only if the particles injected with a rather big energy (ε_0 ~ 6 keV)". But while in this work the movement of electrons in the plane gap is reviewed, the heterogeneous of distribution of electrical field for the real diode geometry [1] does not taken into the account.

To research the possibility of continuous acceleration of electrons injected from cathode with thermal initial energy in gas under atmospheric pressure in conditions of experiments [1] there were made numerical modeling of processes happening during the movement electrons in gas in heterogeneous outer electrical by Particle-in-Cell and Monte-Carlo methods.

2. Model

The model of electron trajectory construction used in the program is analogical to [4]. In the process of modeling electrons were injected from cathode during the entire pulse of voltage with an initial velocities corresponding to the hydrodynamic velocity of explosive-emission plasma flying away. During the each time step they were solved the equation of movement of electrons where were taking into the account inelastic interactions with molecules of nitrogen under the atmospheric pressure and elastic dispersion on atomic nucleuses of gas. The calculation of inelastic losses of electrons was made by method of continuous losses with the usage of date published in [6,7]. Elastic dispersion of electrons was simulated by Monte-Carlo method in the model of individual collisions corresponding with differential section [8].

Outer electric field was calculated by the salvation of Poisson equation in cylindrical geometry for the diode which was used in experiments [1]. $d = 1$ cm.

In the process of calculations the voltage between cathode and anode varied as a function of time $U(t)$. Oscillogram of voltage pulse having amplitude U_{max} = 140 kV is given on Fig.1. The calculation was always provided when the voltage on the diode was equal to $U_{t=0}$ = 20 kV as far as in experiments [1] the basic voltage pulse was preceded by forerunner pulse with a duration t = 3 ns and amplitude of voltage U ~ 20 kV. In this assignment the influence of forerunner pulse on the processes happening in cathode-anode gap was not considered.

Accept for that space charge of electrons and movements of secondary electrons were not considered in the model either.

In the process of calculation during the quantity of electrons injected from cathode and reached the anode was watched in different period of time.

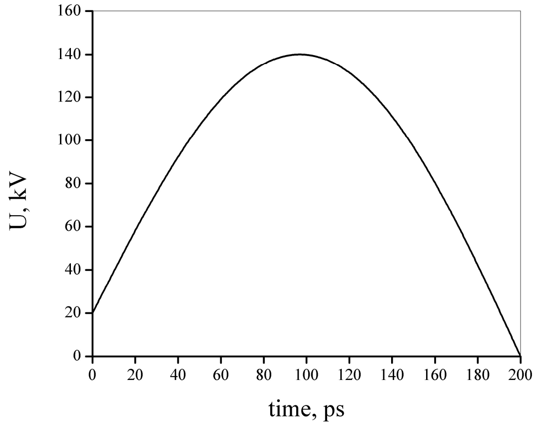

Fig. 1. *Oscillogram of voltage pulse at maximum voltage in pulse* 140 kV

3. Results

In order to test in model there were made calculations in which the outer electric field was specified homogeneous. There was defined the minimal intensity of electric field which is necessary for the continuous acceleration of electron having initial energy ε_0. The results of calculations obtained by PIC/MC-method are showed on the Fig.2. and correspond with previous results of analytical salvation of energy balance equation very well [2].

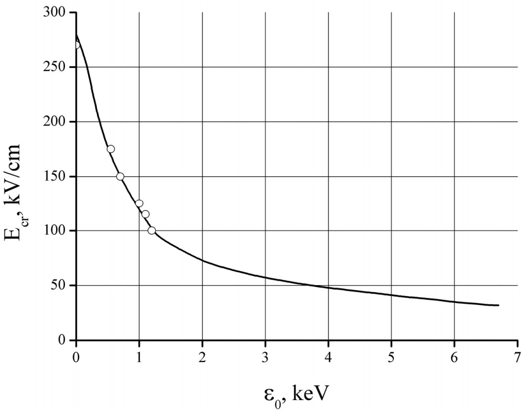

Рис. 2. Minimal intensity of the electric field E_{cr} providing continuous acceleration of the electron with the energy ε_0 in nitrogen under atmospheric pressure. Points are equal to the date in [2]

It is obvious that electric field intensity necessary for the continuous acceleration of electrons from the energy $\varepsilon_0 \approx 0$ is approximately $E_{cr} \approx 270$ kV/cm.

The distribution of potential of intensity of electric field typical for the diode [1] is showed on Fig.3. It is seen that intensity of the electric field near by cathode edge is approximately 5 times exceeds the intensity of electric field in plane diode. Therefore the minimal voltage between cathode and anode necessary for runaway electron criteria $E > E_{cr}$ near by the cathode edge is $U \sim 50$ kV as far as for the nitrogen $E_{cr}(\varepsilon_0 = 0) \approx 270$ kV/cm [2]. Accept for that on the Fig.3. there is dotted line which shows minimal energy necessary for the continuous acceleration of electron in the electric field defined in a given point, obtained by the modeling at the constant voltage on diode $U = 50$ kV.

Conditionally the entire gap can be splitted on the two areas: the area of highly heterogeneous electric field near by cathode ($x = 0 \div 0.1$ cm) and area of approximately homogeneous electric field ($x = 0.1 \div 1$ cm). It is also seen that if the electron is injected into the second area with the energy $\varepsilon > 0.04U$ it will accelerate persistently. For the constant voltage on the diode U = 50 kV this energy is $\varepsilon = 2$ keV. But this energy is not "the energy of electron injected from plasmas bulge" [4]. It is collected by the electron during the passage of area of highly heterogeneous electric field near by cathode.

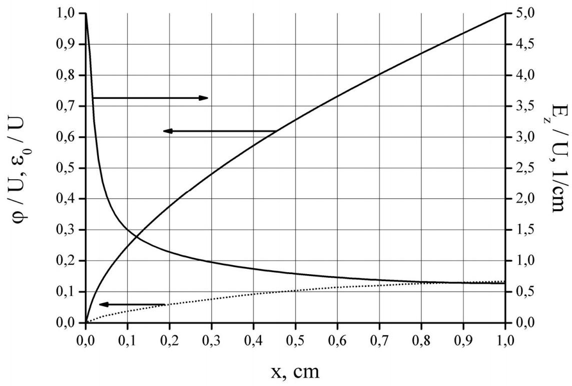

Fig. 3. Distribution of electric field intensity and potential (typical for device [1]) in gap divided by voltage. Dotted line is a minimal energy necessary for acceleration of electron in defined point, $U = const$ = 50 kV

In the real experiment [1] the voltage on the diode vary as a function of time $U(t)$. The modeling at the changing voltage on the diode demonstrated that in the gap there are runaway electrons able to reach the anode by the time of voltage pulse finish (T = 200 ps) at voltage pulse amplitude $U_{\max} \geq 50\text{kV}$. On the Fig.4. are shown dependences of portion of electrons reached the anode at the time of peak voltage in the gap (T = 100 ps) and at the time of voltage pulse ending (T = 200 ps) on the maximum pulse voltage U_{max}.

In calculations [4] there was used the model according to which all the electrons were injected only in initial period if time t = 0, although on the diode particles are emitted during the entire voltage pulse. Graphical chart of dependence of portion of electrons reached the anode in this model [4] is showed on Fig.4. with a doted line. It is clear that runaway electrons can not be registry on the anode at the voltage pulse with amplitude U_{max} < 80 kV. It is obvious that the intensity of electric field near by the cathode is not enough to form the beam of runaway electrons at the moment of time t = 0.

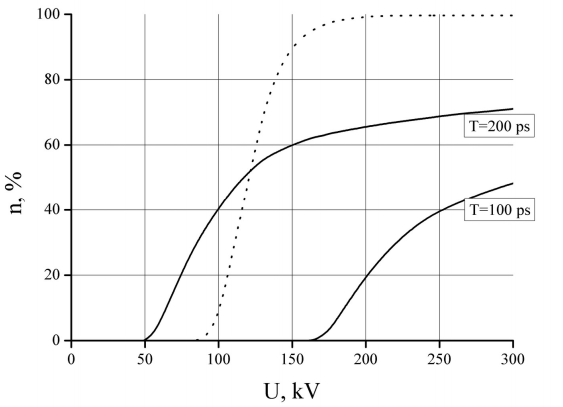

Fig. 4. Dependences of portion of electrons reached the anode till the time of peak voltage in the gap (T = 100 ps) and till the time of voltage pulse ending (T = 200 ps) on the maximum pulse voltage. Dotted line – dependence of portion of electron injected from cathode in the moment t = 0 and reached the anode at the time of voltage pulse ending

To research the influence the model of injection of electrons on the conditions of the transportation and formation of the beam it was provided the modeling were electrons were injected only in moment of time t = t_0. Calculations showed that runaway electrons able to reach the anode till the moment of voltage pulse ending (T = 200 ps) appear in the gap already at the pulse of voltage with amplitude U_{max} = 50 kV. In this case runaway electrons appear just at the moment when the voltage reaches its maximal value on the diode.

On the Fig.5. are shown the dependences of portion of electrons started from cathode in the moment t_0 and reached the anode till the moment of voltage pulse ending on t_0. The abrupt drop of quantity of electrons started in the periods of time $t_0 \approx 100 \div 140$ ps and reached the anode is conditioned by the fact that even quick electrons can not have time to reach the anode till the time of voltage pulse ending.

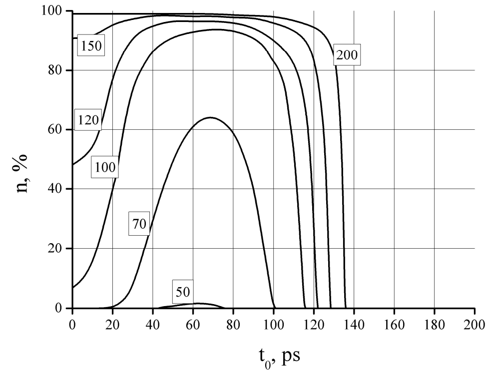

Fig. 5. Portion of electron injected from cathode in moment t_0 and reached the anode till the time of voltage pulse ending. Numbers on the plots indicate the maximal voltage in pulse (kV)

It is obvious that the moment of injecting of electron in the highly heterogeneous electric field area near by cathode influences the conditions of transportation of electron dramatically.

4. Conclusion

Thus, a modeling of the movement of electrons in nitrogen under atmospheric pressure in heterogeneous outer electric field was provided by PIC/MC-method. It is showed that continuous acceleration of electrons from cathode edge and formation of beam of runaway electrons is possible in the diode [1].

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