“STUDY OF THE DYNAMICS OF SUBNANOSECOND DISCHARGE DEVELOPING IN NITROGEN AT A PRESSURE OF 6 ATMOSPHERES WITH THE PARTICIPATION OF RUNAWAY ELECTRONS”

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The dynamics of the development of a subnanosecond discharge in nitrogen at a pressure of 6 atm was studied experimentally and numerically. In this experiment, the anode had a hemispherical shape with a radius of 1 cm. The cathode consisted of a hemispherical base with a radius of 1 cm into which the cylinder with a length of 3 mm and a radius of tip curvature of 1 mm was screwed. The length of the cathode-anode gap was 5 mm. The breakdown occurred at the end of front of voltage pulse with amplitude of 140 kV, which was applied to the discharge gap. The average value of the reduced electric field at the beginning of the breakdown (the upper limit) was 43 V/(cm Torr). In the cathode region, it was 206 V/(cm Torr). That is, the magnitude of the electric field substantially lower than that required by the electron runaway criterion [1-3]. Integral and streak photos of the discharge glow were obtained. It is seen that at the beginning, the gap was bridged by plasma column, which turned into a spark later. The diameter of the spark is approximately 2 mm, which is slightly wider than a typical channel diameter in the streamer breakdown (0.1-1 mm) [4]. The development of the plasma column at the initial stage of discharge formation could be initiated by runaway electrons, which, as shown in [5], can be generated in areas of electric field amplification at pressures up to 40 atm, when the middle electric field in the gap is significantly lower than the required by the runaway criterion [1-3]. As shown in [6], the runaway criterion can realize in area near of micro-tip on a cathode surface at a pressure up to 10 atm. At the same time, the drop in the potential in the region of the amplified field near micro-tip allows the electron to gain energy sufficient to continue of runaway mode in a weak average field, from the point of view of the runaway criterion. Using a 3D model, we performed a numerical simulation of transition into runaway mode of an electron emitted from the top of the micro-tip at the cathode at the initial stage of the discharge development. The Monte Carlo method was used for modeling. As a result, the spatial distribution of the concentration of slow (plasma) electrons in the discharge gap, which occur when the gas is ionized by runaway electrons, was calculated. These electrons are the initiation points for the development of a multi-avalanche discharge. Multiplication of these electrons via ionization leads to the formation of a plasma column at the initial stage of the discharge development. Further development of the spark channel occurs.

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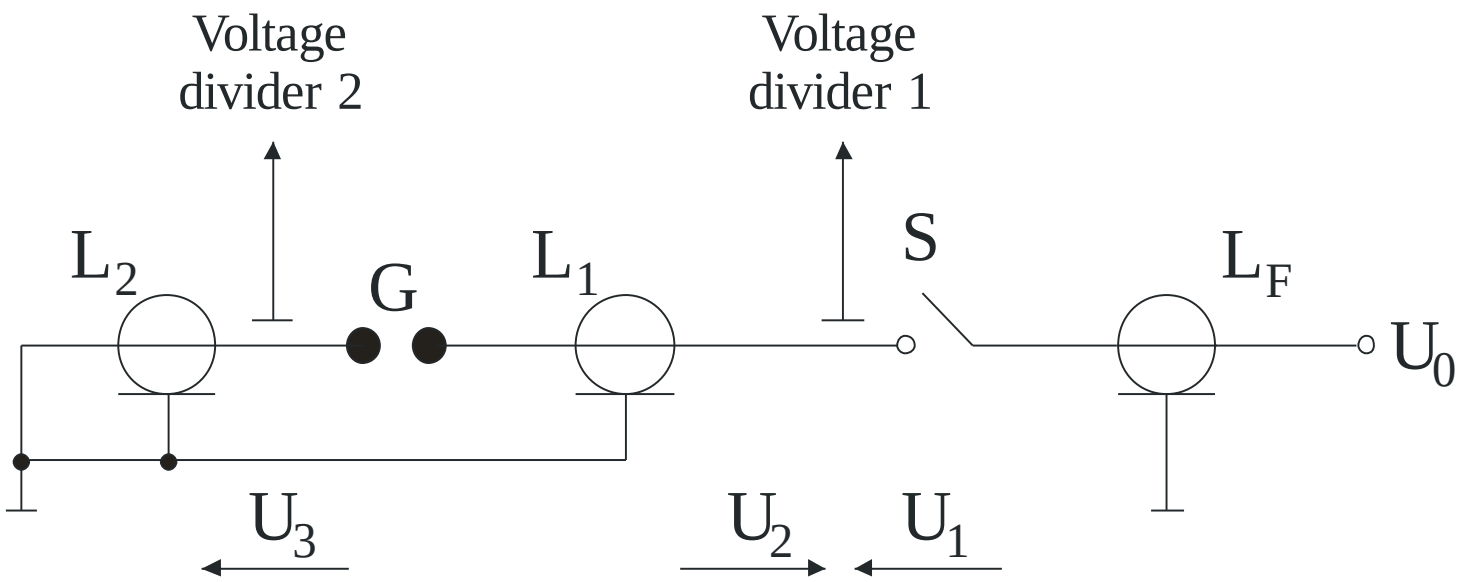
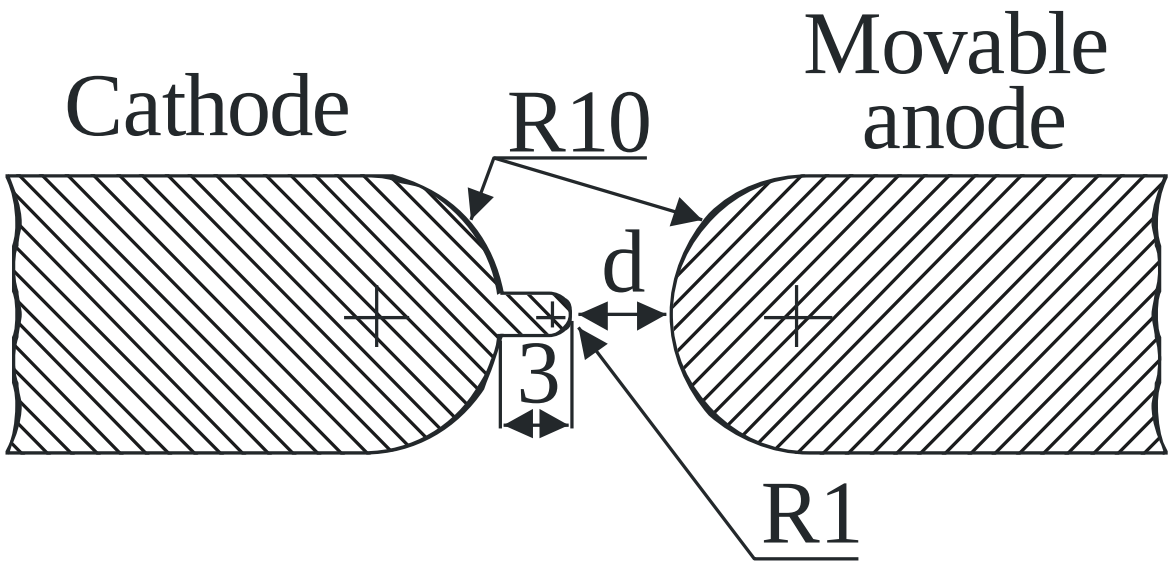


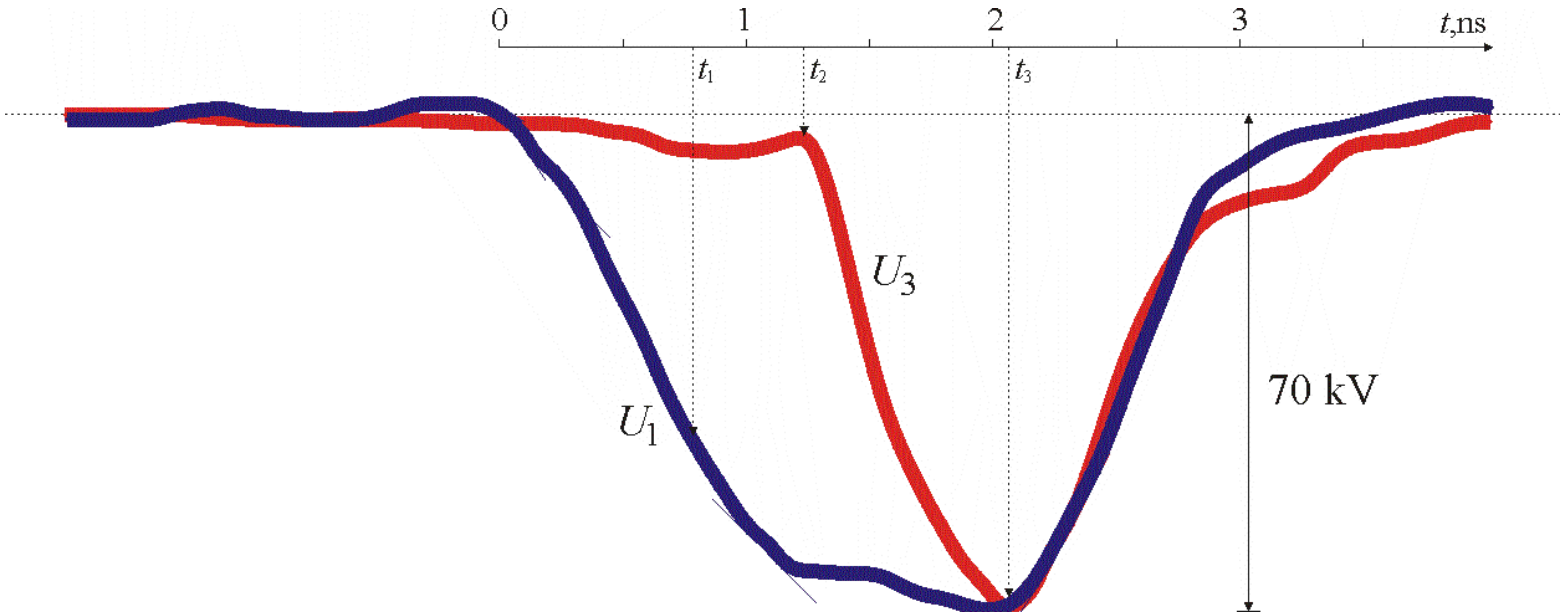
Эквивалентная схема разрядного контура. L_F – формирующая линия ГИ; S – ключ; L_1– передающая 50-Омная коаксиальная линия; L_2 – нагрузочная 50-Омная коаксиальная линия; G – разрядный газовый промежуток, выполненный в виде разрыва центрального электрода коаксиальной линии; U_0 – напряжение зарядки ГИ; U_1 – падающая волна напряжения; U_2 – напряжение на разрядном промежутке на стадии запаздывания пробоя; U_3 – волна напряжения в нагрузочной линии L_2.

The equivalent circuit of discharge circuit. L_F – pulse generator (PG) forming line; S – key; L_1– 50-Ω coaxial transmission line; L_2 – 50-Ω load coaxial transmission line with grounded end; G – a gas discharge gap formed as a break in the central electrode of a coaxial line; U_0 – the charging voltage of the PG; U_1 – the incident voltage wave ; U_2 – voltage across the discharge gap at the breakdown delay and the breakdown stages; U_3 – voltage wave in the load line L_2.



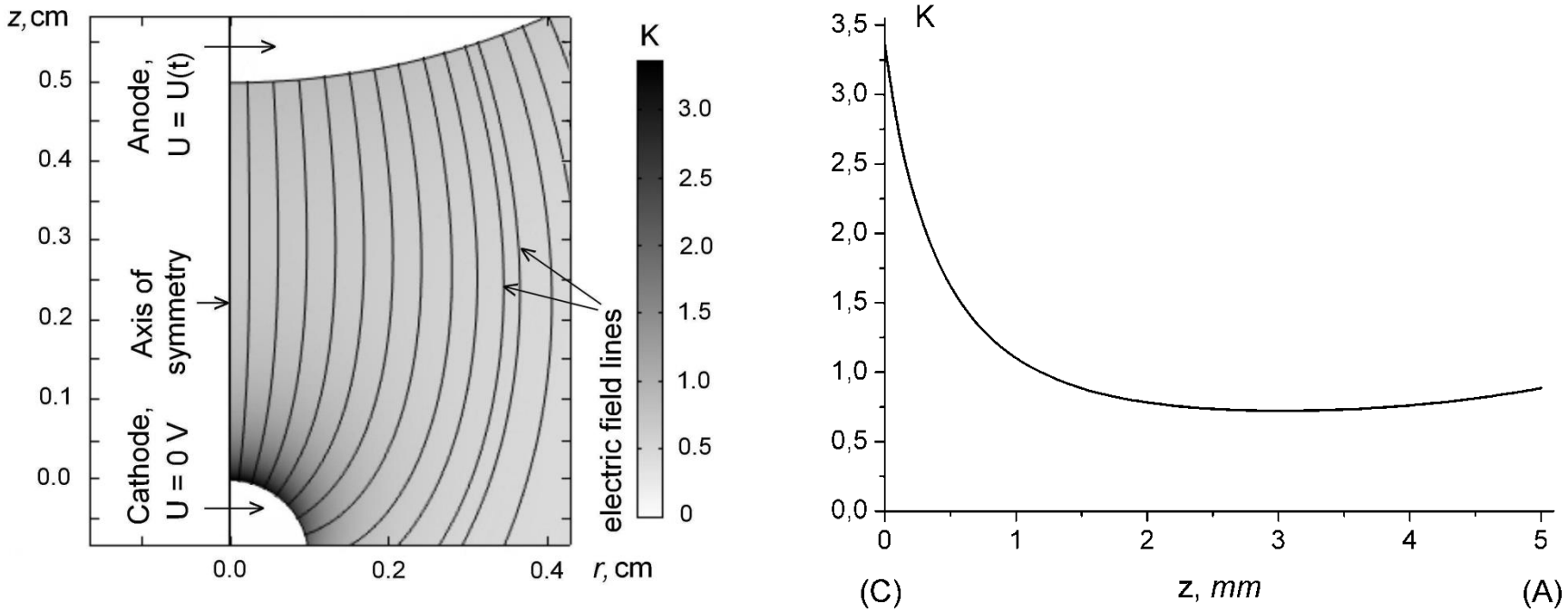
Конфигурация электродов разрядного промежутка.

The configuration of the electrodes of the discharge gap.



U_1 – падающая волна напряжения; U_3 – волна напряжения в нагрузочной линии L_2. Фактически волна напряжения U_3 соответствует току разряда, амплитуда которого $I = U_3/\rho$=1.4 кА.

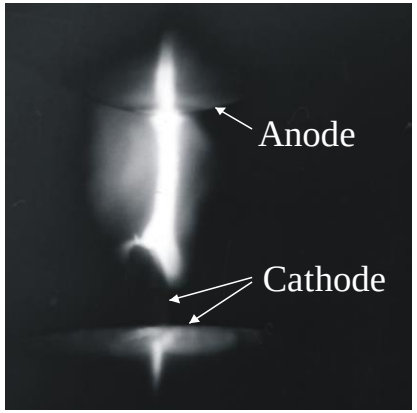
U_1 – is the incident voltage wave; U_3 – is the voltage wave in the load line L_2. In fact, the voltage wave U_3 corresponds to the discharge current, whose amplitude $I = U_3/\rho$=1.4 кА.

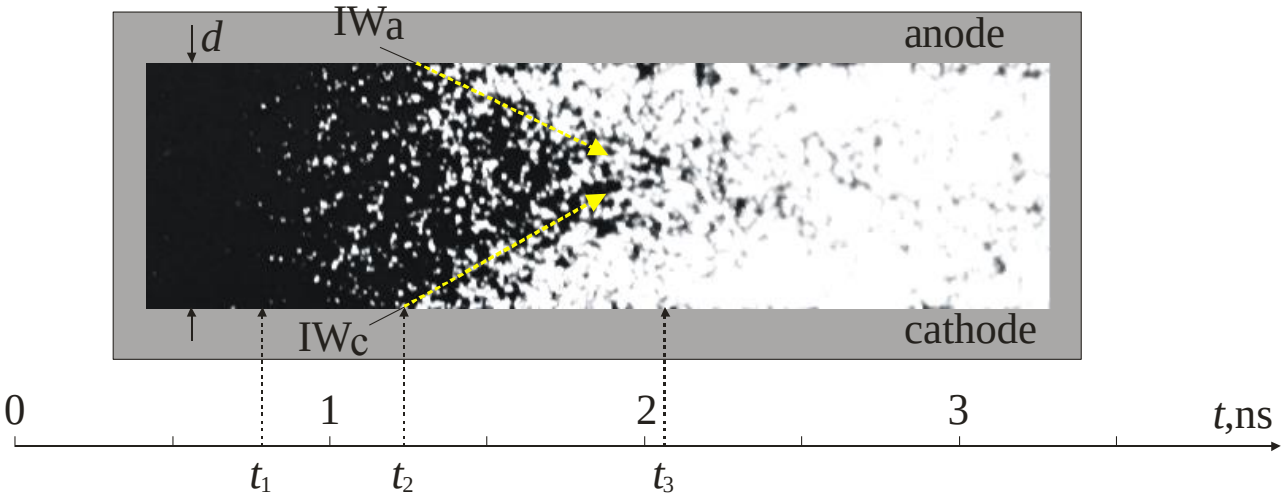


(a) (b)

Стационарное распределение коэффициента усиления K_1 электрического поля в объеме разрядного промежутка (а) и вдоль оси симметрии катод-анод (б) определяемое геометрией электродов разрядного промежутка. $K_1 = E/E_m$, где: E – локальное значение электрического поля, E_m – среднее значение поля в промежутке, равное $E_m = U/d$, где: U – напряжение на межэлектродном промежутке, d - расстояние катод - анод.

Stationary distribution of the gain coefficient K_1 of the electric field in the volume of the discharge gap (a) and along the cathode-anode symmetry axis (b) determined by the geometry of the discharge gap electrodes. $K_1 = E/E_m$, where: E is the local value of the electric field, E_m is the average value of the field in the interval equal to $E_m = U/d$, where: U is the voltage at the interelectrode gap, d is the cathode-anode distance.



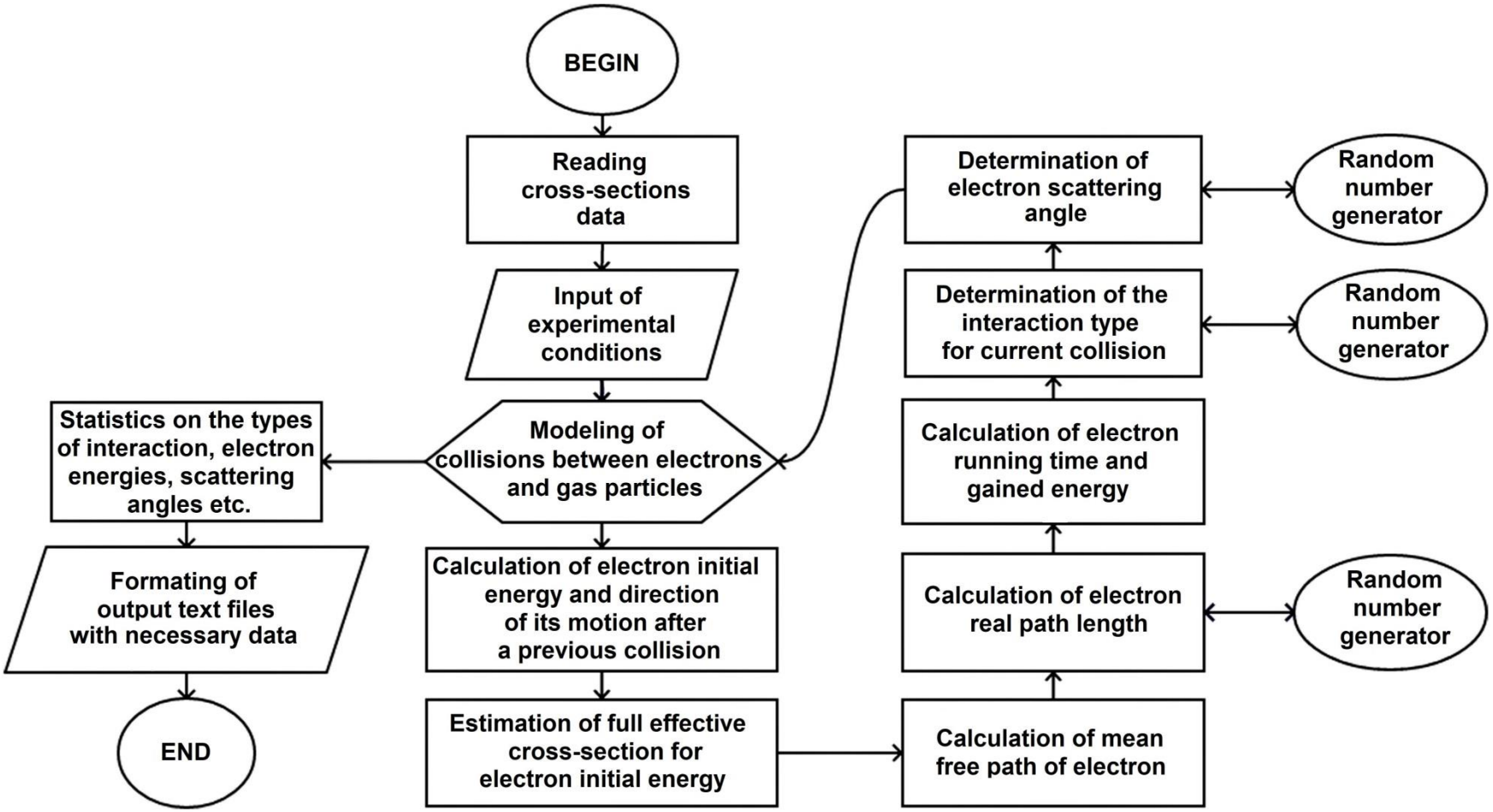


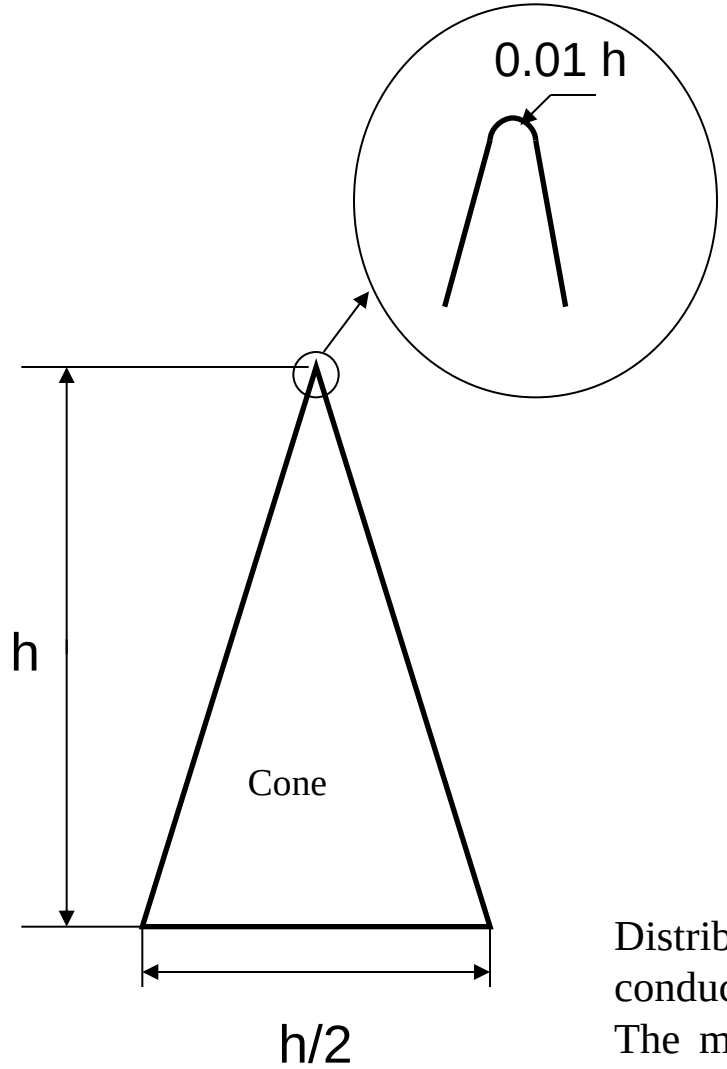
(a) (b)

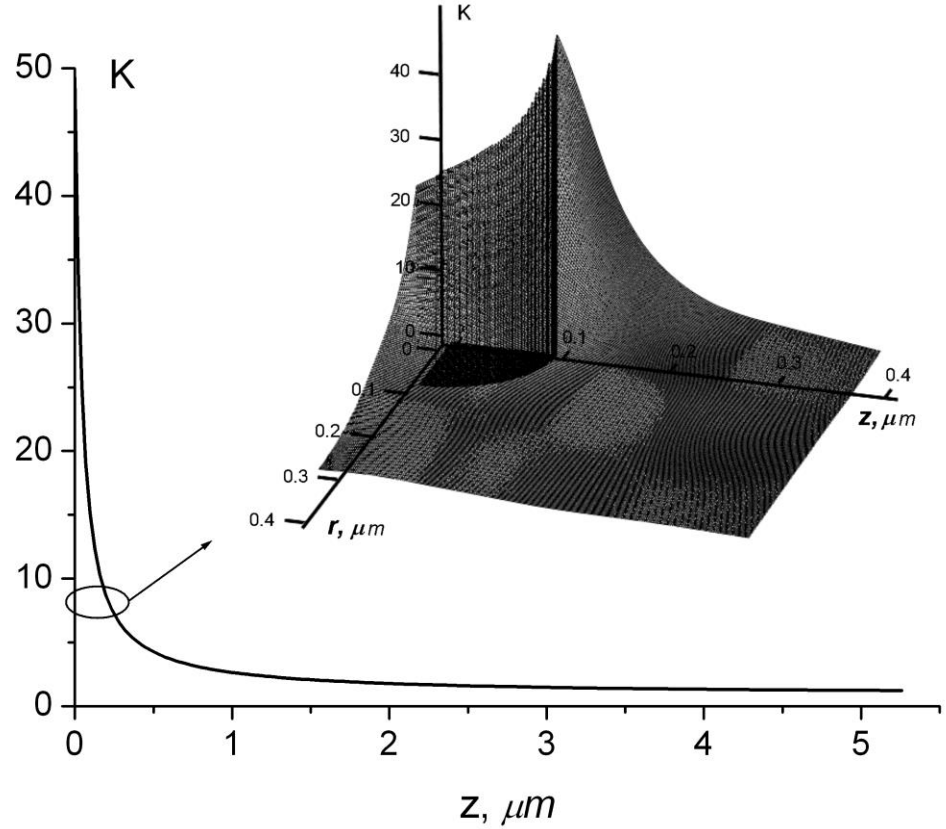
Интегральная (a) и развернутая во времени (b) фотографии свечения разряда (азот, *p*=6 атм, *d*=5 мм). Шкала времени привязана к шкале времени на осциллограммах напряжения (см. слайд 4). За нуль шкалы принят момент начала нарастания напряжения на разрядном промежутке. IWa и IWc - волны ионизации сопровождающие развитие искрового канала.

Integral (a) and streak (b) photos of the discharge glow (nitrogen, *p*=6 atm, *d*=5 mm). The time scale is linked to the time scale on the voltage waveforms (see slide 5). The zero of the scale is taken as the moment when the voltage begins to rise at the discharge gap. IWa and IWc are the ionization waves accompanying the development of the spark channel.

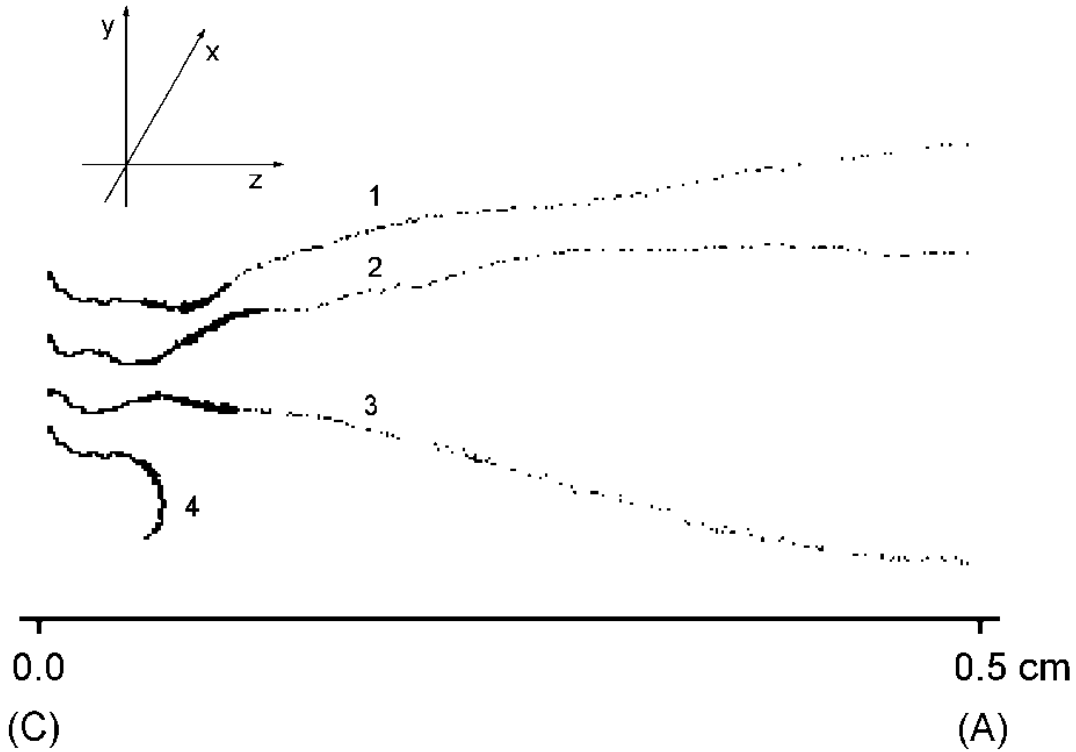
Block diagram of Monte-Carlo module



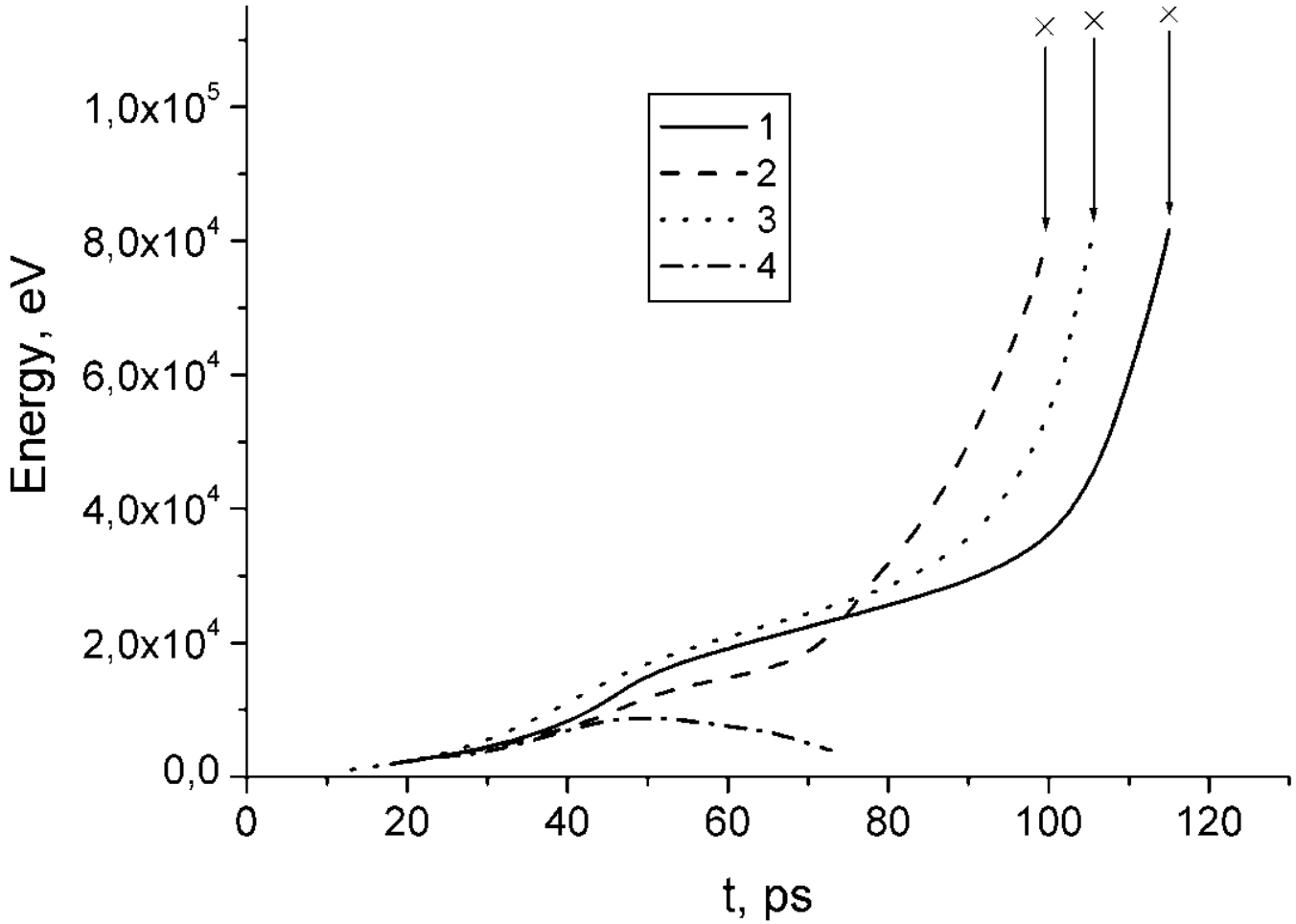




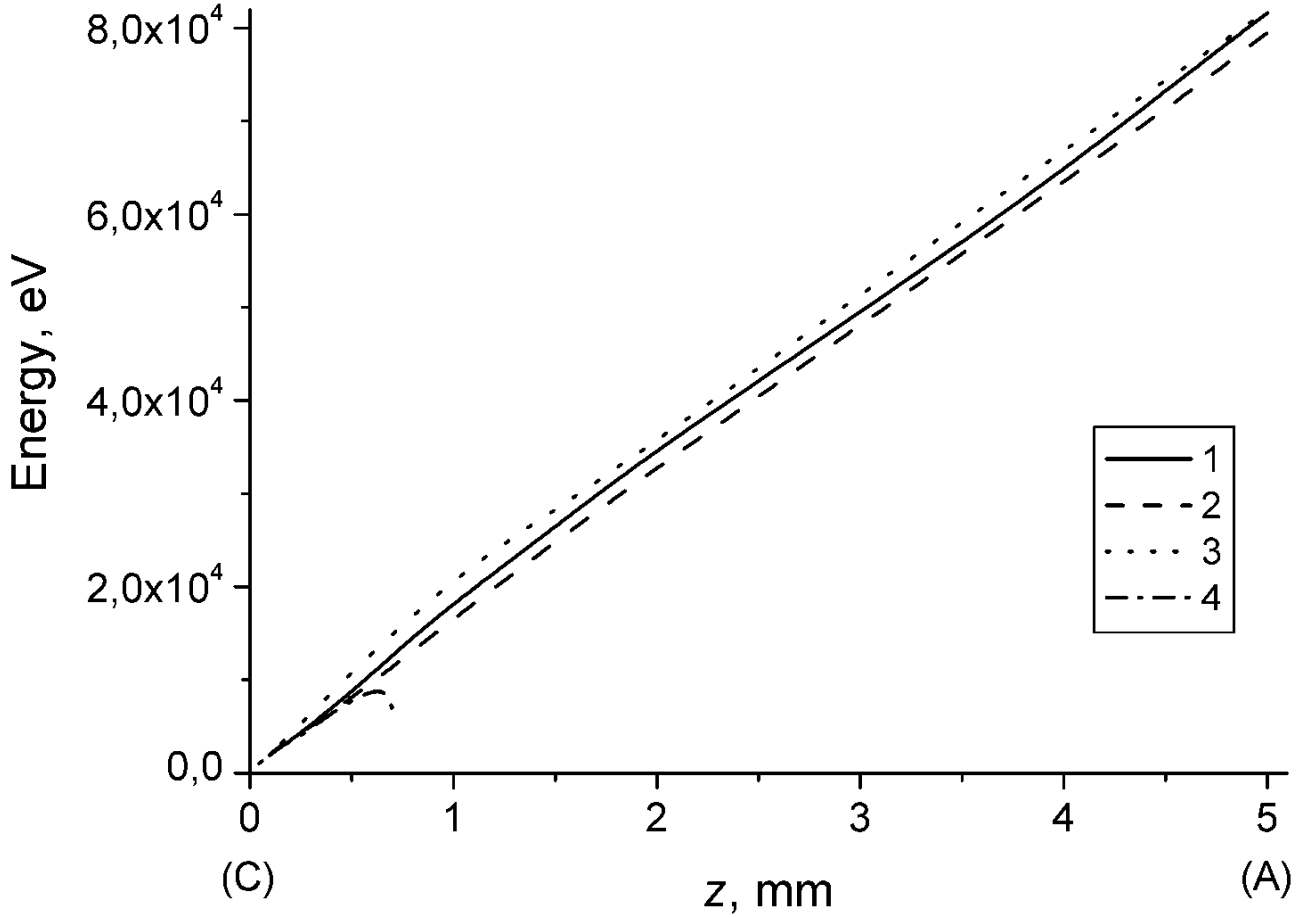
Distribution of the electric field gain K_2 in the vicinity of an ideally conducting metal micro-tip at a cathode with a height of h = 10 μm. The main graph shows the distribution of K along the axis of the cone (z). The vertex of the cone is taken as the origin. The insert shows the spatial distribution of K in the area of sharp decline near the rounded tip of the micro-protrusion. This vertex is shown as a dark area with zero K at the origin. From the top of this micro-tip, a field emission electron starts, which initiates an electron avalanche.



Spatial distributions of slow electrons that occurred during gas ionization by runaway electrons, and showing different versions of the trajectories (tracks) of the movement of runaway electrons. Runaway electrons started under the same conditions in the zone of an amplified electric field near micro-tip at the cathode. The total gain of the electric field K=K1xK2. The electron moving along the trajectory 4 experienced a "catastrophic collision”, as a result of which it abruptly changed the direction of movement, began to lose energy and left the runaway mode.



Dynamics of acceleration of runaway electrons for the trajectories shown on slide 10. Crosses indicate the maximum possible energy values for the trajectories (indicated by arrows) corresponding to the voltage between the electrodes at the time of arrival of the corresponding runaway electron at the anode.



Dependences of the energy of the runaway electrons on the z coordinate for the trajectories shown on slide 10.

CONCLUSIONS

It is shown that at the initial stage of development, the discharge has a volume form, which later turns into a spark. The contraction of the discharge starts from the cathode and anode almost simultaneously. The rate of development of ionization waves accompanying the development of the spark channel is 4.2×10^8 cm/s. The diameter of the spark channel is slightly larger than the typical diameter of channels formed during streamer discharge. The volume form at the initial stage of development of discharge is provided by the pre-ionization of the gas by runaway electrons. The generation of runaway electrons occurs in the zone of an amplified electric field formed near the micro-tip at the cathode. In this case, the macro geometry of the discharge gap does not provide the electric field amplification to the value necessary for the implementation of the electron runaway criterion.