S6-P-020004
S6 - Discharges with runaway electrons
Poster session (September 21-25, 2020)

Atmospheric Pressure Corona Discharge in the Needle-Plane Electrode System: Influence of Field Peaking on Electrophysical Parameters

Vladimir Kuznetsov*, Victor Tarasenko*, Alexander Kokovin**, Andrey Kozyrev**

* Optical Radiation Laboratory, Institute of High Current Electronics SB RAS, Tomsk, Russian Federation
**Laboratory of Theoretical Physics, Institute of High Current Electronics SB RAS, Tomsk, Russian Federation

Aim

The purpose of the present work is s to study the features of the initiation of a corona discharge in air at atmospheric pressure under conditions of a sharply inhomogeneous electric field experimentally and as a result of modeling. In particular, to determine the initial conditions for the formation of a corona discharge at various radii of curvature of the plane electrode in the point-plane configuration.

EFRE 2020

Experimental Setup

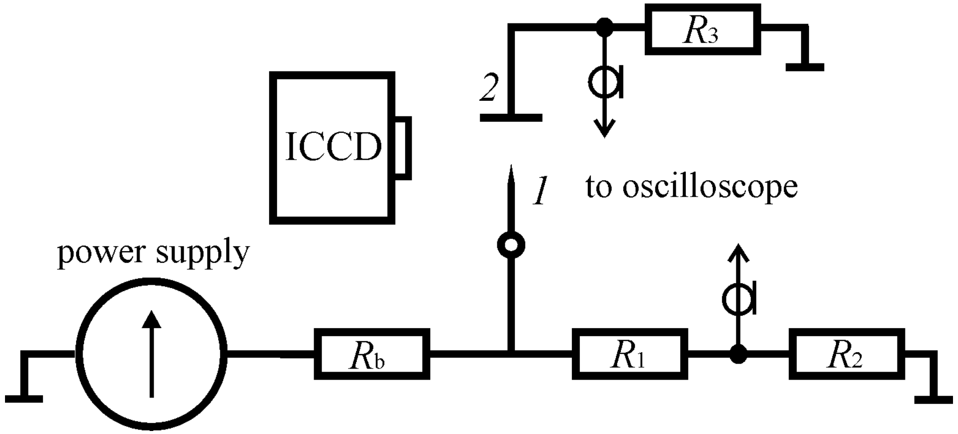

Fig. 1. Experimental setup Rb = 18 MΩ, R1 = 2.5 MΩ, R2 = 2.5 kΩ, R3 = 1 kΩ.

To study the corona discharge, the setup shown in the Fig. 1 was used. This scheme was traditional for studies of a corona discharge with a point-plane gap. A “bead” needle with a diameter of 0.32 mm with a radius of curvature of the tip of 11 μm (No. 1) or a needle with a diameter of 0.64 with a radius of curvature of 30 μm (No. 2) was used as a high-voltage electrode. The discharge was ignited between the point and the plane electrode at a voltage of negative polarity. The discharge gap was 5–30 mm. We used a pulsed constant voltage source, which slowly increased in the gap.

A photograph of the integral corona glow was obtained using a Canon PowerShot SX 60 HS digital camera in single-shot shooting with an exposure time of 15 s. Using a TDS 3034 digital oscilloscope (Tektronics, Inc.) and a high voltage probe, the time course of the voltage was determined. The pulses of the discharge current from a high-resistance current shunt (R3 = 1 kΩ) were also recorded by an oscilloscope at a time resolution of about 5 ns. This made it possible to measure both the pulsed and components of the direct current through the gap. The experiments were carried out in atmospheric air at a temperature of 20°C and a humidity of not more than 60%.

Results (1)

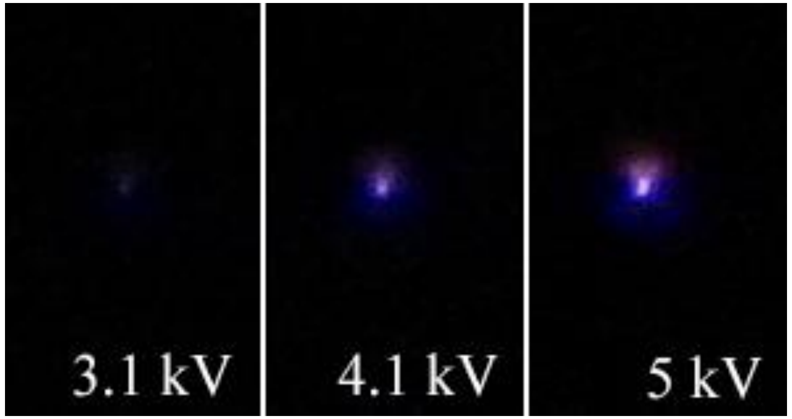

Fig. 2. Photographs of the integral plasma glow at tip needle of 11 μm and gap of d = 2 cm for the negative polarity of the tip. Exposure time 15 sec., frame height 2.2 mm.

When dc voltage was applied to the electrode at its tip appeared plasma structure of ball shape (Fig. 2).

The plasma glow at the tip at minimum voltage was very difficult to detect due to its low radiation intensity. With increasing voltage, the intensity of the plasma glow increased and was sufficient for recording.

Results (2)

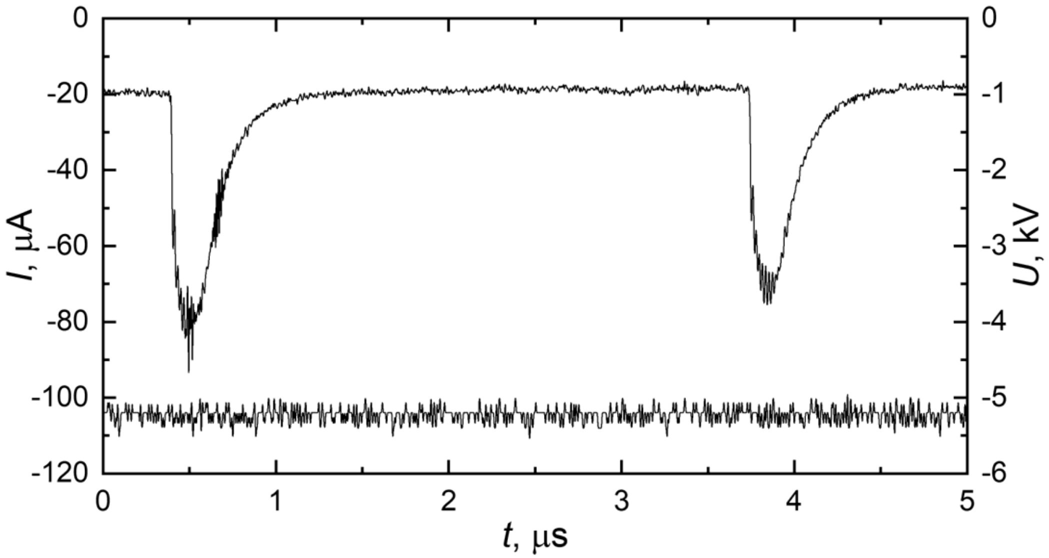

Fig. 3. Voltage time dependence (bottom line in the picture) at a negative polarity of the tip, as well as current pulses (top line in the picture) from the shunt. The gap of d = 15 mm, a tip needle of 30 μm.

To determine the point in time corresponding to the initiation of a corona discharge, a signal from a shunt was used, the value of which (1 kΩ) was chosen sufficiently large. Trichel pulses recorded upon initiation of a corona discharge of negative polarity are shown in Fig. 3.

The current pulses had a half-maximum duration of about 200 ns. A decrease in the radius of curvature of the tip, the diameter of the needle, and the interelectrode gap led to a decrease in the voltage of initiation of the corona discharge. Depending on the radius of curvature of the point electrode at which the corona discharge was ignited, the voltage could vary by more than 1 kV. So, when applying voltage of negative polarity, the starting voltage of the corona discharge in the case of a needle electrode with a radius of curvature of 11 μm with an interelectrode gap of 1 cm was ≅ 2.2 kV and the starting voltage when using a needle with a radius of curvature of 30 μm and an interelectrode gap of 3 cm was ≅ 3.6 kV.

EFRE 2020

Results (4)

Table I. The system of plasma-chemical reactions

No.	Reaction	No.	Reaction
R1	$e+N_2 \rightarrow e+e+N_2^+$	R11	$O_2+O_2^- \rightarrow e+O_2+O_2$
R2	$e+O_2 \rightarrow e+e+O_2^+$	R12	$e+O_2+N_2 \rightarrow N_2+O_2^-$
R3	$e+e+M^+ \rightarrow e+M$	R13	$O_2+O_2^- \rightarrow e+O_2+O_2$
R4	$O_2+N_2^+ \rightarrow N_2+O_2^+$	R14	$e+O+O_2 \rightarrow O+O_2^-$
R5	$e+N_2^++M \rightarrow N_2+M$	R15	$O_2+M+O_2^+ \rightarrow M+O_4^+$
R6	$e+O_2^++M \rightarrow O_2+M$	R16	$O_2+O_4^+ \rightarrow 2O_2 +O_2^+$
R7	$e+O_4^+ \rightarrow O_2+O_2$	R17	$e+N_2 \rightarrow e+N+N$
R8	$e+O_2^+ \rightarrow O+O$	R18	$e+O_2 \rightarrow e+O+O$
R9	$e+N_2^+ \rightarrow N+N$	R19	$O_2^-+O_4^+ \rightarrow 3O_2$
R10	$e+O_2+O_2 \rightarrow O_2+O_2^-$		

For theoretical modeling of a pulsed discharge, experimentally implemented in the setup shown on slide 3, the one-dimensional (coaxial) problem was first formulated, and after optimization the plasma-chemical scheme, a two-dimensional axisymmetric problem with the "point-plane" geometry was created, which was solved in the COMSOL Multiphysics v5.5 computing environment with the Plasma module.

The system of plasma-chemical reactions shown in the table I below was based on [S. Pancheshnyi, M. Nudnova, and A. Starikovskii, "Development of a cathode-directed streamer discharge in air at different pressures: Experiment and comparison with direct numerical simulation," Physical Review E, vol. 71, p. 016407, February 2005.].

The model used artificial air (N_2:O_2 in a 3:1 ratio), taking into account the following types of particles: molecular nitrogen N_2 and oxygen O_2, atomic nitrogen N and oxygen O, free electrons e and four types of ions O_2^-, N_2^+, O_2^+ и O_4^+.

The discharge model also took into account field and secondary electron emission at the cathode for each type of ion with a coefficient of $\gamma = 0.01$ and an average secondary electron energy of $\varepsilon = 0.026$ eV.

During the simulation, homogeneous initial conditions were chosen: the initial concentrations of electrons and O_2^- negative ions were $1.5 \cdot 10^3$ cm^{-3} each, and N_2^+, O_2^+, O_4^+ positive ions were 10^3 cm^{-3} each component to satisfy the condition of the medium electro-neutrality. All calculations were performed for a fixed gas temperature of 300 K.

Results (5)

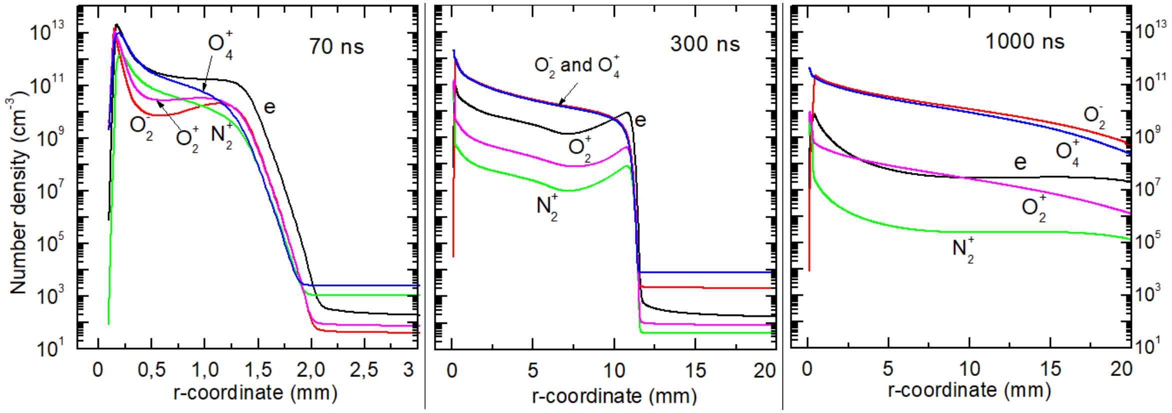

Fig. 4. Radial distributions of the charged components of the air plasma at various points in time of the development of the corona discharge in a coaxial diode.

Discharge in one-dimensional (coaxial) geometry, radius of the internal electrode 100 μm, external 20 mm, constant voltage of the source U_0 = 10 kV, capacitance parallel to the gap C_b = 100 pF, ballast resistance of the circuit R_b = 1 kΩ, linear length of the coaxial 1 cm. Discharge in this geometry was used to optimize the calculation algorithms and the scheme of plasma-chemical reactions in artificial air at atmospheric pressure. (N_2:O_2 in a 3:1 ratio).

The progress of the discharge in this geometry proceeded stably without any current fluctuations. Fig. 4 shows the spatial distributions of the charged components along the radius of the coaxial discharge at different times. These graphs show that at the initial stage of the discharge development (70 ns), the plasma conductivity near the tip is electronic and all ions have comparable concentrations. At the middle stage (300 ns), an extended ion-ion plasma is formed, at the anode boundary of which the predominance of electron concentration is maintained. At the late stage (1000 ns), almost the entire volume of the gap is filled with ion-ion oxygen plasma (O_2^- and O_4^+) which monotonically decreases from 10^{11} to 10^9 cm^{-3} from the inner core to the anode.

After testing the plasma-chemical scheme, it was used to simulate a two-dimensional discharge in geometry with a negative polarity of the point electrode.

Results (6)

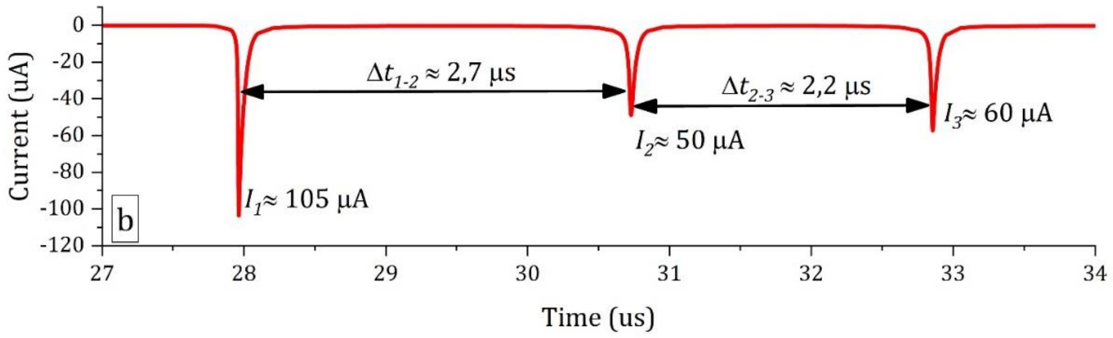

Fig. 5. The calculated discharge current at the negative polarity of 30 μm tip.

The main parameters of the two-dimensional model: air pressure p = 1 atm, interelectrode distance d = 1 cm, similarity parameter pd = 1 atm·cm. A constant voltage U_0 = 3.9 kV, a ballast resistance of the circuit R_b = 1 MΩ and a capacitance parallel to the gap C_b = 100 pF were applied to the gap. In our calculation, the parameters of the needle-shaped cathode were varied, but the simulation results are given below only for the needle diameter of 0.6 mm, the radius of curvature of the vertex of 30 μm and the angle at the tip of 21° .

Fig. 5 shows the time dependence of the calculated discharge current, which is a quasiperiodic sequence of short pulses. The amplitude of the current in the pulse and the pulse repetition rate strongly depend on the radius of curvature of the tip: the sharper the needle, the earlier the first current pulse is formed, the lower its amplitude and the higher the pulse repetition rate. However, a pulse-periodic discharge mode was observed in a wide range of discharge conditions.

Results (7)

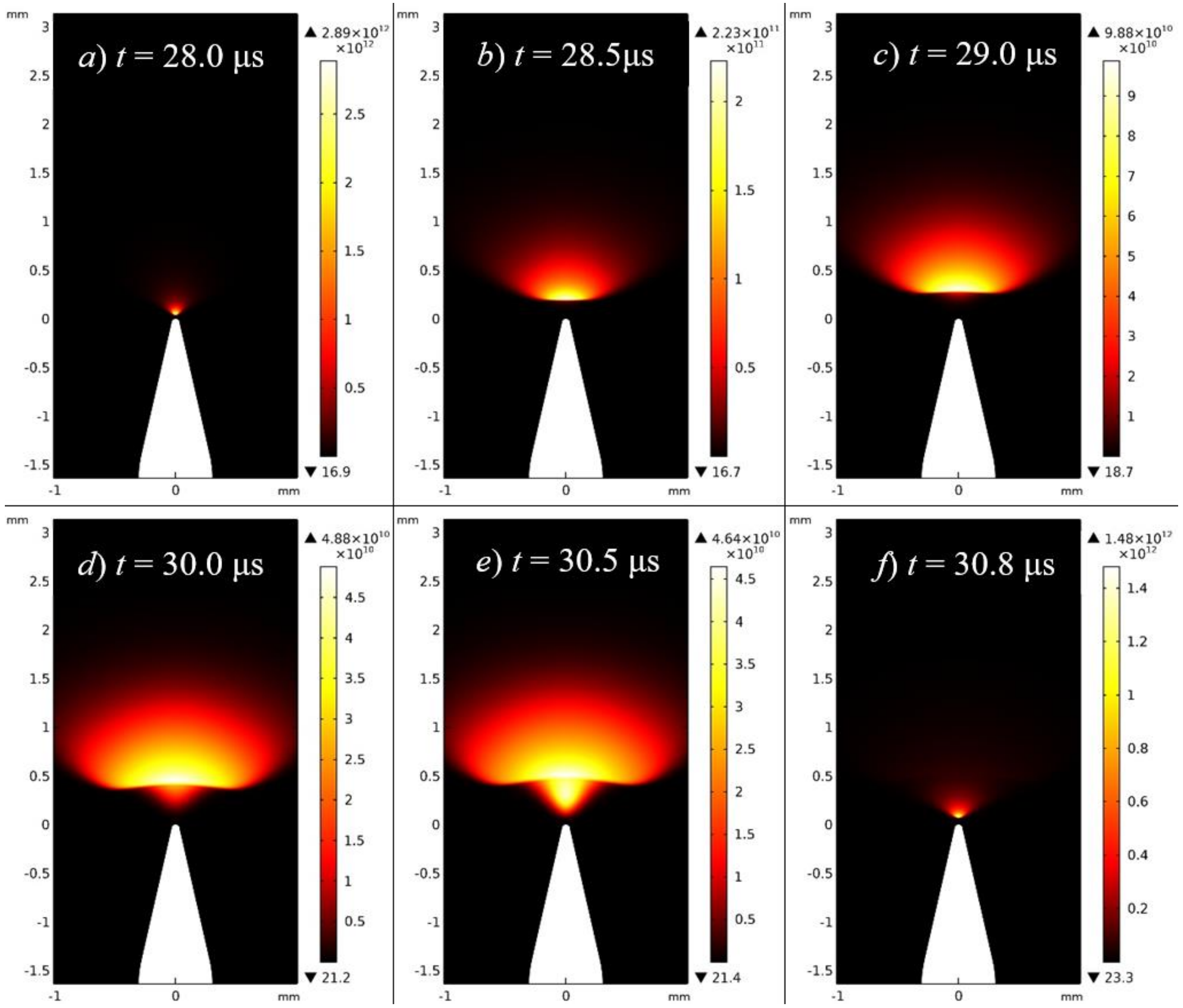

Fig. 6. Plasma dynamics in the gap between current pulses shown in Fig. 5.

To illustrate the plasma dynamics in the interval from pulse to pulse, Fig. 6 shows the instantaneous distribution of O2− ions in the interval from the beginning of the first current pulse to the beginning of the second pulse. An analysis of the dynamics of the electric field showed that the current pulse under these conditions is generated by a rapid increase in the plasma concentration near the tip. But almost immediately, the field under the plasma is partially screened, the current drops sharply, and the plasma moves away from the tip and expands relatively slowly into the gap. Then the field at the top of the tip increases again, and the process begins again, generating a second current pulse.

Modeling showed that the periodicity of the discharge current in our model is observed only in the case of adding electron detachment reactions to the plasma-chemical scheme (reactions R11 and R13 in the table). The reason for the pulse-periodic mode of current flow is the presence of negative O2− ions. As the avalanche grows, a positive volumetric charge forms near the cathode, which amplifies the field, and a little further from the cathode, a negative space charge that almost does not shield the field near the tip. Electrons moving away from the cathode bind to molecules almost immediately, which lead to an increase in the space charge and screening of the cathode with a negative space charge. Because of this, the propagation of avalanches ceases and the current decays. As negative ions are drawn toward the anode, and positive ions are drawn toward the cathode, the field is restored and conditions are created for a new pulse.

Conclusion

From the experiment and from the simulation results it follows that when a corona discharge is ignited from a negative tip with a small radius of curvature, individual pulses (Trichel pulses) are formed even at a gap voltage of several kilovolts. Both in the calculation and in the experiment, pulses of the discharge current with shorter rise time and longer fall time were obtained, which go into the quasi-stationary stage of the discharge (Figs. 3 and 5). The reason for the pulse-periodic mode of current flow, as shown by the simulation, is the presence of negative ions O_2^-.

The work was supported by the state assignment of IHCE SB RAS on project No. 13.1.4 and grant RFBR No. 19-32-90023.

EFRE 2020