NANOSECOND PULSED DISCHARGE DEVELOPMENT IN AIR AT DIFFERENT OVERVOLTAGE

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ABSTRACT

Detailed measurements of parameters of a streamer flash development in air for the pressure range 1300—90 torr have been carried out in the plane-toplane geometry for 20 - 42 kV positive and negative polarity nanosecond pulses. The discharge conditions under which branching form of streamer flash appears were investigated both for cathode and anode direct streamer. It was shown that branching process take place for cathode streamer. We have developed a numerical model, which successfully predicts the following streamer parameters: current, velocity of propagation, and diameter of streamer head in a wide range of pressures and voltages. We have numerically reconstructed the structure of streamer head and have shown that the result is in good agreement with that one obtained from experimental data.

INTRODUCTION

Plasma of pulsed gas discharges is widely used in different applications — from radiation sources to plasmachemical reactors — due to the main advantage in comparison with stationary and quasi-stationary discharges, namely — minimal rate of thermalisation. This leads to a high efficiency of the energy input to the channels with high energy thresholds. At this the gas state may be varied from low temperature plasma to high-temperature medium with the typical temperature values of a tens of thousands of K.

It is known that self-sustained discharge trends to contraction and transition to the arc. The arc discharge is characterized by low energies of charged particles and by high rate of energy transfer to gas heating, and this is not desirable for efficient plasmachemical applications. Due to this fact, one of the most promising ways to produce strongly nonequilibrium plasma is to organize pulsed discharge with capacitive coupling, for example, barrier discharge and its modifications, when one or both electrodes are covered with dielectric layer. The dielectric layer in this case restricts the discharge which can be transported through the layer.

As a rule, at moderate and high pressures, the barrier discharge develops in two stages: on the first stage the discharge gap bridges by a streamer flash, on the second one we observe non-zero electric current up to charging of the dielectric layer. The main energy input takes place on the second stage of the discharge development, whereas the first stage determines time of the gap closing and uniformity of filamentary structure in the gap. The last point is, undoubtedly, very important for design of the real devices [1]. More than that, streamer, like the electron avalanche, is a very important object in a physics of gas discharge, so, their study is promising from the fundamental point of view.

There are numerous papers reporting experimental and theoretical study of the streamer corona. Though the branching is a very significant process in streamer development and its action on the gas, it is possible to discuss quantitative agreements between theory and experiment for single filament streamers only [2].

The main processes, which define parameters and typical features of the discharges during their propagation, are quite similar. Among them are preionization of a gas ahead of the discharge front by fast electrons and by ionizing radiation, ionization by an electron impact in relatively strong electric field in the discharge front at relatively weak value of the electric field behind the front.

Difficulties in experimental techniques for the study of streamer discharges are evident: they are high rates of the processes, which need sub-nanosecond time resolution, small geometric size of the object and unpredictable development of a trajectory in a case of a streamer propagation, high electromagnetic noise and so on. At this, contact diagnostic techniques are practically useless because of strong distortion of the electromagnetic field by gauges inserted into discharge gap. Experimental study of streamer discharge is restricted by general electrodynamics and, less, by emission characteristics.

Up to now, numerical simulations of the streamer propagation and gas excitation in the plasma of the streamer channel have been practically the only method for studying the processes occurring in the streamer channel and its neighborhood. Numerical simulations are also necessary to more accurately interpret experimental data. From another point of view, while results for single streamer discharge simulation are in a good agreement with experimental measurements, simulations of streamer flash are highly limited due to absence of a clear physical model of streamer branching.

The proposed paper is directed to the development of a model of streamer flash which will combine electrodynamic description of the discharge with kinetic description of the processes in gas discharge plasma.

DESCRIPTION OF EXPERIMENT

A schematic of the experimental setup and diagnostic facility is shown in Fig.1. A thyristor generator PAKM with magnetic pulse compression was used as a pulsed voltage supply. The high-voltage pulses were fed through a 60-m-long RK-50-24-13 cable to the high-voltage connector of the discharge system. A calibrated back-current shunt placed in the break of the braiding of the feeding coaxial cable at a distance of 30 m from the discharge system was used to control the parameters of the pulses. The amplitude of the voltage pulse was 10 kV (positive polarity), the FWHM duration was 25 ns, the rise time was 9 ns, and the repetition rate was from 0.5 to 100 Hz.

The discharge section comprises a cube-shape vacuum chamber with 20 mm edge, made of stainless steel. The discharge emission was tested through the optical windows 100 mm in diameter, made of KY-1 quartz. The discharge was organized in a point-plane geometry with interelectrode distances from 20 to 60 mm. High-voltage electrode (cathode) was made of brass and had a disk shape with diameter of 80 mm. Grounded disk-shape anode was made from aluminium and was 100 mm in diameter. To initiate the cathode-directed streamer the needle 0.8 mm in diameter and 10 mm in height was placed in the center of grounded electrode.

Under the action of high voltage pulse of negative polarity the electric field near the needle tip exceeds significantly the value of uniform electric field between the electrodes. Thus, the streamer development from the grounded electrode is induced. Such geometry of electrodes allows to measure directly the current of a streamer flash. To do this, we shunt the needle to earth by 50 Ohm resistor.

The emission spectroscopy technique was used to analyze a cathode-directed streamer discharge. The active particles were detected with an absolute emission spectroscopy. The optical recording facility consisted of condensers, photomultipliers, monochromators, and a set of diaphragms. We used FEU-100 and SNFT-3 photomultipliers (with photocathode sensitivity ranges of 170-830 and 300-800 nm, respectively) and MDR-12-1 and MUM-2 monochromators (with operating ranges of 200-2000 and 200-800 nm, respectively).

To control spatial-temporal characteristics of the discharge we used ICCD camera PicoStar HR12 (LaVision) with a spectral sensitivity range of 300—700 nm and time gate of 200 ps. ICCD camera was focused on the needle of the grounded electrode in a such way that both electrodes were in the frame. Spatial resolution of the images was 1.0 mm. The detection of discharge current and voltage on the gap was made by Tektronix TDS 3054 oscilloscope simultaneously with camera synchropulse. In spite of the periodic regime of the work of generator, in experiments the ICCD camera image, voltage drop and current corresponded to the same streamer flash.

Measurements were performed in N_2-O_2 (4:1) mixture for two lengths of the discharge gap; 30 and 50 mm. At 30 mm gap the pressure in a chamber varied in the range of 740—320 torr, at 50 mm gap — in the range of 410-90 torr. Minimum of pressure for each length was limited by streamer transition to

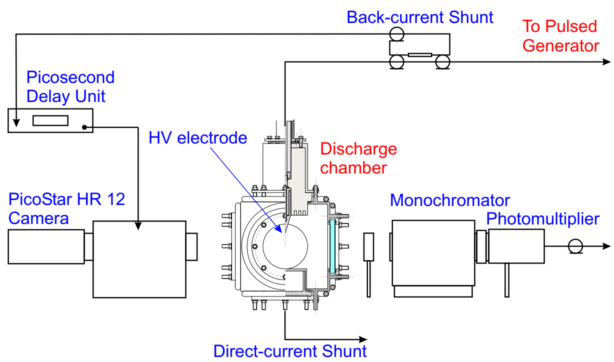

Figure 1: Experimental setup.

the spark form.

In the pressure range of 1300—680 torr we observe branched streamer flash only for all voltages applied (Fig. 2, 3, 4, 5). The flash had from 2 to 5 separate channels. At diminishing the pressure the number of branches decrease, for example, at a pressure range of 650—620 torr we observed three or less channels.

At pressures lower than 590 torr we could registered or branching structure or single streamer channel from experiment to experiment at the same experimental conditions. At pressures lower than 470 torr we observed a single streamer channel only.

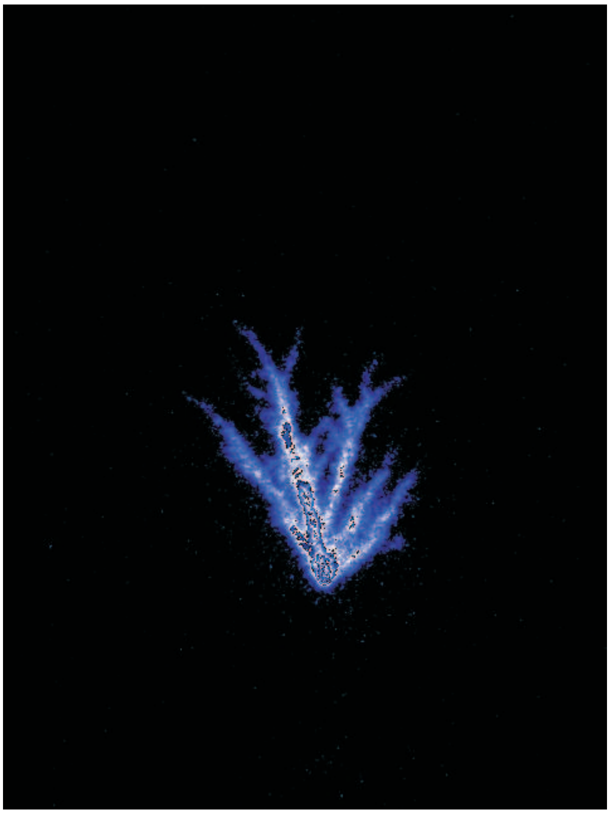

Figure 2: ICCD image of multi-channel flash. 1000 torr, 30 mm, 26 kV, 25 ns. Air.

For interelectrode gap of 30 mm in a pressure range of 380—350 torr the streamer channel bridges the discharge gap, and at further pressure decrease transforms to the spark.

Together with change of the discharge structure with pressure, we observed change in the streamer channel visible diameter. The measurements were carried out in the middle point of the channel. The results are represented as a dependence of diameter upon voltage for 30 mm gap in the Fig. 6. The values of the diameter were 0.3—4.0 mm in a pressure range 740—320 torr and 1.0—20 mm in a pressure range of 410—90 torr. Maximal values of streamer diameters are limited by streamer transition to the spark during the time of a high-voltage pulse.

Simultaneous synchronized measurements of electric parameters of the discharge demonstrate that at pressure decrease the current of a streamer, charge and energy input increase monotonically up to the transition to the spark.

STREAMER DEVELOPMENT AT DIFFERENT PRESSURES

Development of a streamer channel is defined by a density of seed electrons ahead of the streamer head. These electrons appear due to photoionization and ionization by an electron impact in the region of strong electric fields. Streamer head propagation in space takes place due to its excess electric potential relative to the ambient space. With the streamer motion from the high-voltage electrode to the low voltage one, the streamer channel length and, consequently, voltage drop on it increases. So, the potential of a streamer head decreases.

When the pressure diminishes at constant electric field configuration the reduced electric field in-

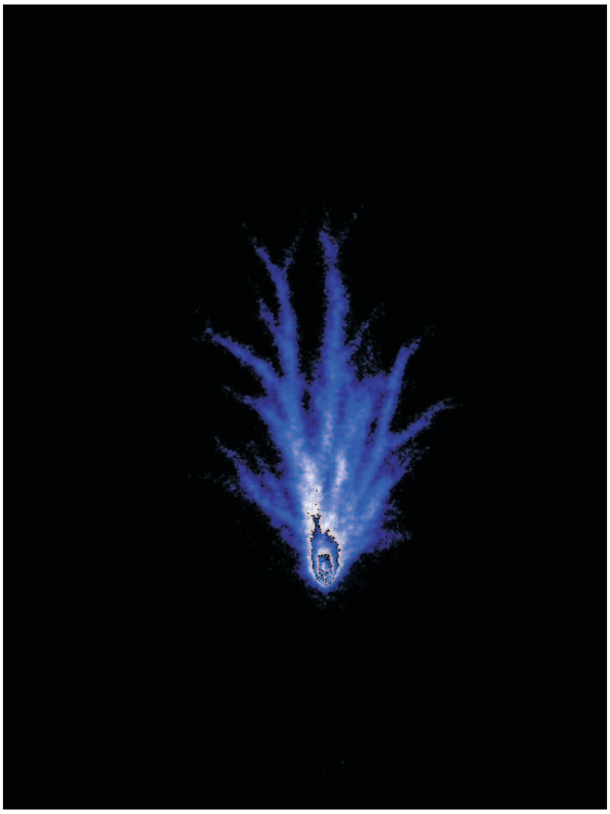

Figure 3: ICCD image of multi-channel flash. 1000 torr, 30 mm, 30 kV, 25 ns. Air.

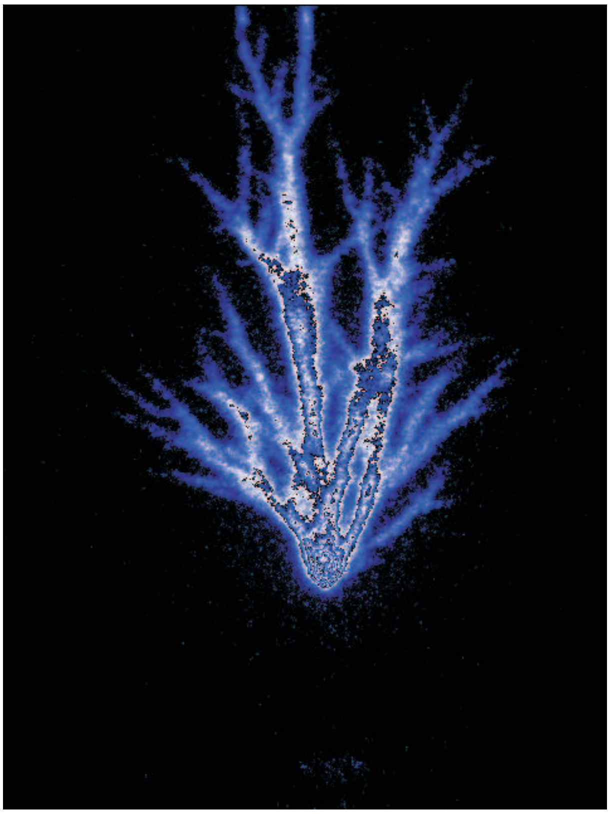

Figure 4: ICCD image of multi-channel flash. 1000 torr, 30 mm, 36 kV, 25 ns. Air.

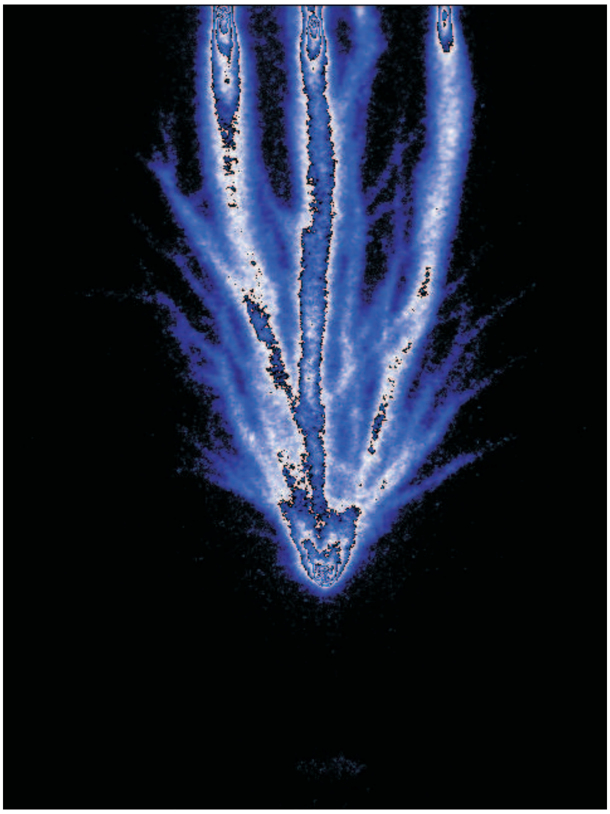

Figure 5: ICCD image of multi-channel flash. 1000 torr, 30 mm, 42 kV, 25 ns. Air.

creases. The rate of the ionization by an electron impact increase with the reduced electric field, at the same time the photoionization length increases due to decrease of gas density. As a consequence, the velocity of a streamer propagation and diameter of the streamer increase.

The anode current of a streamer increase with the lowering of gas pressure. Anode current profiles are represented in Fig. 7 for different pulse voltage in air at the discharge gap length of 30 mm. Velocity of streamer propagation dependence on the voltage applied to the gap is presented on the figure 8.

The streamer branching depends strongly on the gas pressure and voltage applied (Figure 9).

Dependencies of streamer velocity and current on the number of branches are presented at Fig.10, 11.

Streamer Head Fine Structure

For definition of spatial and temporal characteristics the camera PicoStar HR12 of company LaVision with a spectral range of sensitivity 200-800 nm and temporal exposure up to 200 ps was used. The camera ICCD was focused on the needle of the low-voltage electrode thus, so the upper and lower electrodes could hit in the picture. Photos of a streamer discharge were received in two modes of work of the high-speed camera: an integral and stroboscopic mode. By working in an integral mode the amplifier of the high-speed camera was switching on simultaneously with coming of a high-voltage pulse on an electrode. Time of exposure was 400 ns and included the duration of a high-voltage impulse. For working in a stroboscopic mode, on the amplifier of the camera is set a starting sine signal with frequency of 300 MHz, time of exposure of the camera's amplifier is set by the program and in our experiments it was 300 ps.

To restore a radiation pattern we used a photo of streamer head, which obtained with time gate about 300 ps. Using this picture we obtained profiles of radiation in different sections of the streamer head. This two-dimensional lateral profile is gained by summation of radiation of three-dimensional cylindrical rotationally symmetric object on (Fig. 12(1)). To restore the radiation profile we used the following procedure: the value of radiation vs. the head radius was represented by a set of basic functions:

$$G(n) = A(n) \times \exp(-(\frac{R - R(n)}{\sigma})^2),$$

were n — number of basic functions, $A(n)$ — variable amplitude of basic function, σ is a spatial resolution

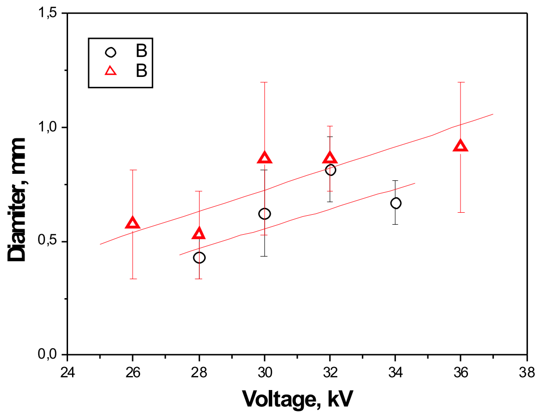

Figure 6: Measured Streamer Diameter at Different Voltage for Discharge Gap 30 mm. 25 ns. Air.

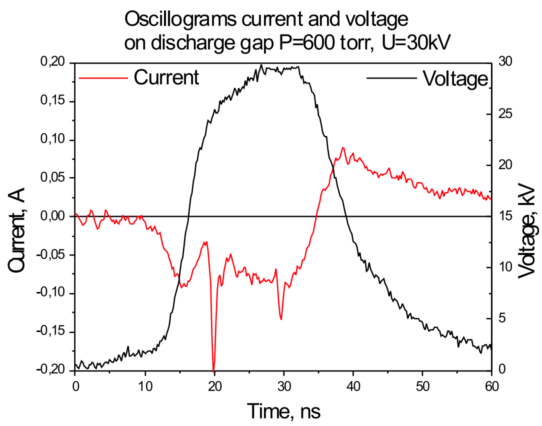

Figure 7: Voltage and anode current measurements. 30 mm. Air.

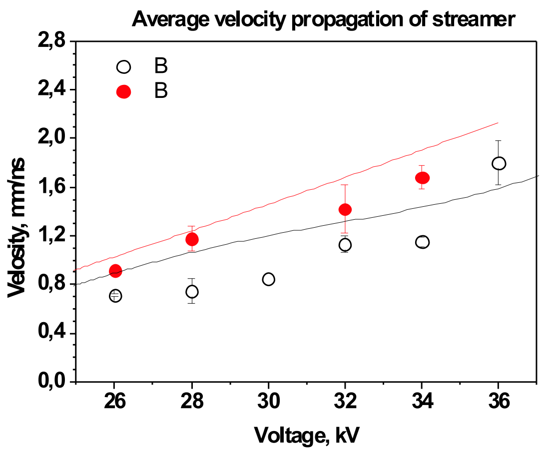

Figure 8: Velocity dependence on the voltage. 30 mm. Air.

of streamer head image, $R(n)$ — coordinate of basic function center. The sum of these basic functions equals of radiation from head radius (Fig. 12(2)). Then, the value of radiation vs. the head radius was

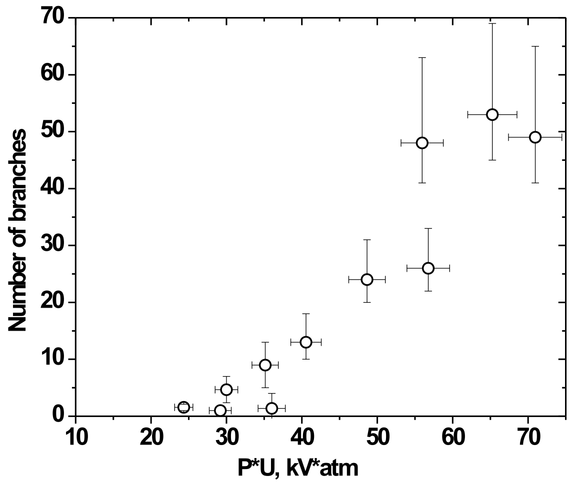

Figure 9: Dependence of number of branches from the pressure and voltage applied. 30 mm. Air.

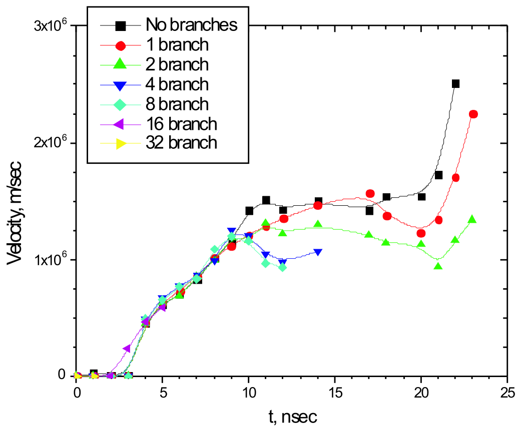

Figure 10: Dependence of the streamer velocity from number of branches. 30 mm. Air.

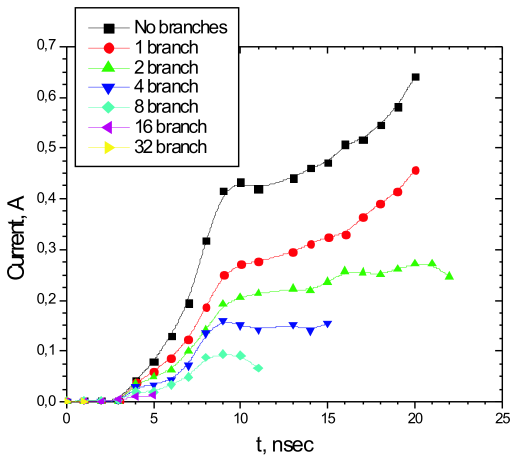

Figure 11: Dependence of the streamer current from number of branches. 30 mm. Air.

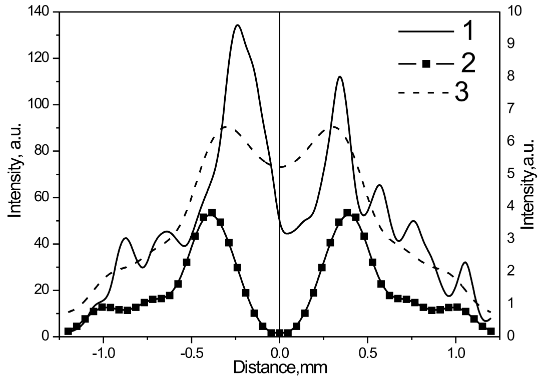

Figure 12: Dependence of the streamer velocity from number of branches. 30 mm. Air. 1) experimental profile; 2) value of radiation vs. the head radius; 3) restored value of radiation of 3D cylindrical rotationally symmetric object

summed up in two-dimensional profile of radiation of three-dimensional object (Fig. 12(3)). This profile was compared with the experimental profile, then, we varied coefficients $A(n)$ until best coincidence of experimental and restored profiles was occurred. Having a number of radiation profiles vs. radius in different sections of streamer head we restored a radiation pattern of streamer head (Fig. 13).

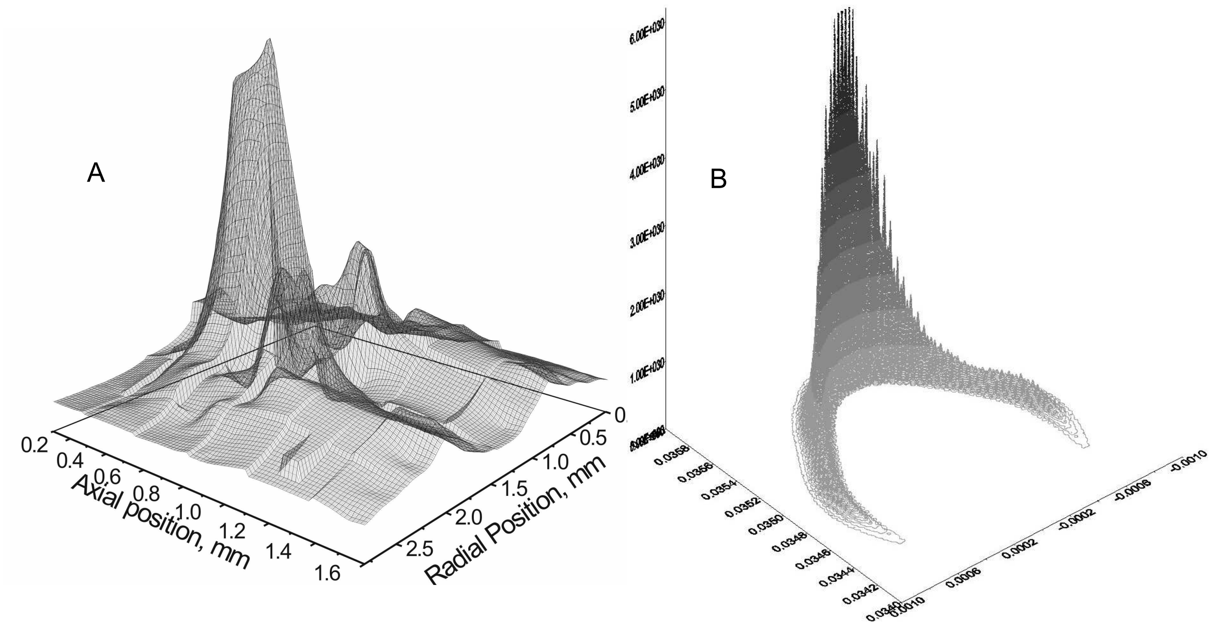

Figure 13: a) Picture of radiation of the streamer's head, restored on lateral views of radiation in different sections of the streamer's head. P=740 torr U=30 kV. b) The instantaneous image of concentration of excited states $N_2(C^3\Pi_u)$ for pressure $P = 740$ torr $U = 30$ kV, constructed by means of hudrodynamic 2D numerical model.

Thus, we restored the pattern of streamer had radiation. Profiles of emission of the streamer head, received with shot camera gate, prove the guess that in basic points the operating time of the active particles occurs on a surface of the streamer head.

CONCLUSIONS

Detailed measurements of parameters of a streamer discharge in synthetic air for the pressure range 1300—90 torr have been carried out in the plane-toplane geometry at interelectrode distance of 30 mm for the following high-voltage pulse parameters: the pulse amplitude is 20 - 42 kV (positive and negative polarity), the FWHM duration is 25 ns, the rise time is 8 ns, and the repetition rate is 0.5-100 Hz. It was demonstrated that there are different pressure ranges in which the propagation of the streamer differs qualitatively from the each other. Experimental measurements of streamer discharge dynamics in N_2/O_2 mixtures at different pressure have been compared with direct numerical simulation.

Streamer development was investigated by direct numerical simulation in 2D geometry using hydrodynamic approximation. Processes which determine the streamer propagation as well as processes that control streamer channel decay in long discharge gaps were analyzed.

We have shown that, the numerical results on the rate of development of the discharge and its geometric parameters agree well with those measured experimentally, while the calculated anode current is found to coincide with the experimental one only when kinetic processes of heavy particles in the streamer channel are taken into account.

ACKNOWLEDGMENTS

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