Research of the streamer microwave discharge in a quasi-optical beam of electromagnetic wave with application of the K011 image converter camera

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ABSTRACT

Nowadays of microwave (MW) gas discharge applications are actively investigated in different areas of science and technology. Greatest optimism in applications is connected with streamer discharge forms.

A possibility of streamer form discharge applications is determined by their specific features. An efficiency of energy absorption is close to 100% in this discharge. The discharge develops in a form of a spatial structure consisting of streamer element interconnected. They explode at reaching of electrodynamic resonance. The discharge structure represents a net of thin plasma channels. Gas temperature reaches several thousands of Kelvin degrees inside them. A typical time of energy absorption by separate plasma channels is several units of microseconds. A velocity of a streamer growth is about of - 10^6 cm/s.

Main physical mechanisms determining features of MW discharges have been qualitatively clarified nowadays. But quantitative investigations of discharge creation processes are required for effective applications of these discharges. For this purpose equipment, which has characteristics allowing detecting processes with resolution time in microsecond and submicrosecond range, is necessary. In this work we represent investigation results of streamer MW discharge in air: initial development stage, developed stage of a volumetric discharge and development of the discharge on a surface of radiotransparent dielectric material. Investigations have been realized with a help of K011 image converter camera.

Keywords: streamer microwave discharge, surface streamer microwave discharge, electromagnetic wave, image converter camera.

1. INTRODUCTION

During last decade there is a growing interest to an investigation of microwave (MW) gas discharge application in different areas of science and technology. A spectrum of MW discharge plasma possible applications is wide. These problems are under active discussions at, for example, specialized international [1-10] and Russian conferences [11-12]. They are, in particular, devoted to ignition of flammable mixtures, optimization of combustion in high-speed flows and a modification of a flow field around flying vehicles (FV) for decrease of a drag force and flight control. Greatest optimism in these areas is connected with application of volumetric and surface types of MW streamer discharges.

MW discharge investigations showed that the discharge is realized in two main forms. At low pressure **p** it is realized in a diffuse form and at high pressure – in a streamer form. Physical mechanisms responsible for creation of discharges in these forms are principally different. Their features are also different. A diffuse discharge practically does not absorb MW field energy (that excites it) as a rule. To the contrary a discharge in the streamer form is characterized by a high energy efficiency of interaction with electromagnetic (EM) wave exciting it.

MW streamer discharge develops in a form of interconnected streamer element chains. These elements explode at reaching of electrodynamic resonance. The discharge structure represents a net of thin plasma channels. Gas temperature reaches several thousands of Kelvin degrees inside them. A typical time of EM energy absorption by separate plasma channels of a resonance length is several units of microseconds. A typical velocity of a streamer growth is about of - 10^6

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cm/s. A typical velocity of discharge front propagation towards EM radiation is 10^5–10^6 cm/s [13]. A time integral photo of such a discharge with a volumetrically developed structure is represented in Fig.1.

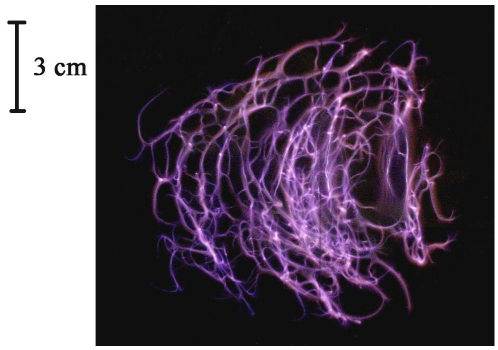

Fig. 1. Typical appearance of MW streamer discharge with volumetric structure in air

An analogous photo of MW discharge created on a surface of radiotransparent dielectric material is represented in Fig.2. It is important that streamer discharge nature allows it to not only in a focus where a field is maximal, but also in a converging EM beam. In this case electric field level in the volume of the beam is smaller than those of a critical (breakdown) level. This undercritical discharge can be initiated by creation of breakdown conditions locally with a help of an initiator. In practice at pressure of hundreds of Torr one create only undercritical initiated MW discharges with application of traditional microwave devices like klystron and magnetron.

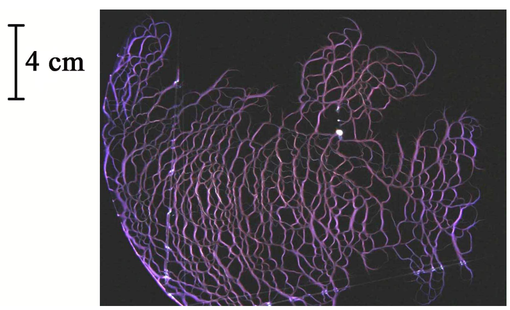

Fig. 2. Typical appearance of streamer microwave discharge on a surface of a dielectric material in air

One can use a vibrator [14], a plasma channel created by a radiation of low powerful laser and etc. as an initiator. Streamer channels stay to be "attached" to an initiator during a pulse duration $\boldsymbol{\tau_{pul}}$ at very low, so called, deeply undercritical values of electric field ($E_0 << E_{cr}$). This discharge still conserves a property to effectively absorb microwave energy. Enumerated features of the undercritical and deeply undercritical discharges determine active interest to them from application point of view.

MW discharge is realized in definite range of ($\mathbf{E_0}$, **p**) in each of described forms. Their fields of existence are illustrated in Fig.3. In this picture we also represent typical discharge photos in each of its forms. Line **II** in the figure represents $\mathbf{E_{cr}(p)}$ dependence. It can be conditionally called "Paschen curve" in MW wave range. Realization of non initiated discharges is possible above this line, and a discharge has to be obligatory initiated below it. Line **I** is a line of a boundary pressure $\mathbf{p_{th}}$, it separates diffuse discharges of «low» pressure p from streamer discharges of «high» pressure **p**. Line **III** separates undercritical and deeply undercritical discharge forms of MW initiated discharges with respect to– $\mathbf{E_{th}(p)}$.

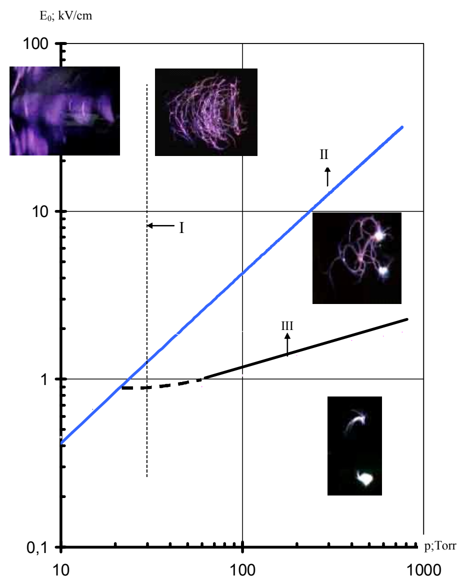

Fig. 3. Existence areas of different MW discharge types

At the same time in spite of high pressure MW discharge in wave beams physical mechanism determining feature qualitative knowledge one has to undertake thorough quantitative investigations of discharge creation process for effective discharge applications. Besides, our experiments showed that it is usually impossible to investigate MW discharges in EM beam features by “contact” methods. For undertaking of these investigations one requires equipment, which has characteristics allowing detecting processes with time resolution in microsecond and submicrosecond ranges. Application of K011 image converter camera proved to be one of most convenient and informative “non contact” means of these discharges investigation.

2. EXPERIMENTAL SET UP FOR MW DISCHARGE INVESTIGATION

MW discharge investigations have been undertaken with a help of experimental set up, in which a microwave generator with a wavelength of λ = 8.9 cm was applied. Its pulse power was up to P_{pul}=2 MW, it insured a radiation pulse with rectangular envelop duration up to 40 μs. A lens system forms an electromagnetic beam with required amplitude and phase transversal distribution. It comes to a vacuum system through a dielectric lens. EM radiation coming to the chamber is collected in a mirror focus. An initiating element is located in the focus. Air pressure in the chamber can be regulated. One can see a scheme of main elements of experimental design displacement in Fig.4, it is aimed for investigations of MW streamer discharge with a volumetric structure.

Application mainly of initiated streamer MW discharge forms is realistic in applications as it was mentioned above. So an initiator is located in the focus of a metallic mirror. Electromagnetic vibrators or a metallic ball can be used as an initiator during experiments. An area near an initiator where a field exceeds a critical value is very small. A probability of a free

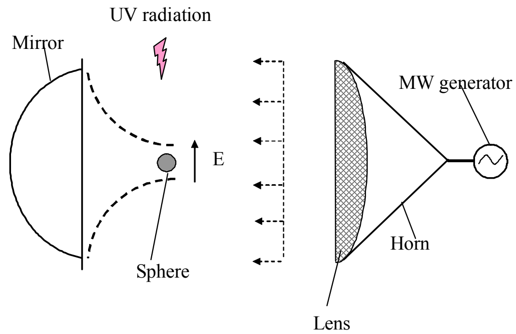

Fig. 4. Investigation experimental scheme of MW streamer discharge in a volumetric form

electron appearance in it at limited duration of MW pulse is also very small. So in order to stabilize a discharge in time and in space we usually illuminated one of initiator poles by a pulsed source of ultra violet (UV) radiation of low intensity. A flash duration is about of 3 μs. UV radiation leads to creation of photo electrons on a surface of the initiator.

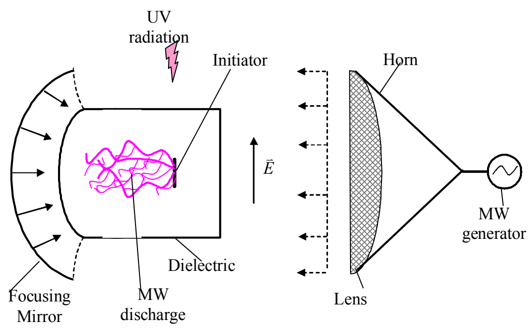

Fig. 5. Streamer discharge on a surface of radiotransparent dielectric material realization scheme

Initiated electric air breakdown and MW discharge development take place at presence of photo electrons on the initiator at definite power level of MW beam $\mathbf{P_{pul}}$ in the mirror focus and at set air pressure **p**. Luminescent discharge structure formingin a course of its development is an important source of information about physical processes taking place in it. It is an object of our investigation.

In Fig.5 one can see a scheme of a surface MW streamer discharge experimental realization. A sheet of radiotransparent dielectric material (glass-cloth laminate), which form is clear from the figure, is located over EM beam axis in the focus area in a plane **k** x **E** of running wave. Its thickness is 1 mm, and typical sizes are 300 x 300 mm. A copper initiating vibrator is fixed to the dielectric surface on a side of observation in the focus area. Its diameter is 1 mm and length is 10 mm. The vibrator is illuminated by the pulsed UV source as in all previous investigations for creation of initial electrons and controlling of a moment of discharge origination.

3. K011 IMAGE CONVERTER CAMERA

We applied K011 miniature programmable 9-frame image converter camera for detection of MW streamer discharge luminescent structure development in spectral range 400–800 nm. This camera was developed and created by Russian BIFO Company [15]. The camera provided independence duration of each frame and each interframe pause in range from 0.1 up to 102.4 μs with 0.1 μs step.

Range of the K011 camera characteristics allows to observe and detect a development of investigated processes in time and in space with required temporary and spatial resolution with respect to experimental conditions.

The K011 image converter camera was placed on three-coordinate optic table in front of an illuminator of the vacuum chamber. The illuminator was equipped with water protection from MW radiation. It was oriented and focused at a space area where MW discharge was realized. We applied objective lenses with a focus distance of 50 mm, 200 mm and 300 mm with different combination of elongation rings for realization of required scale of an image. A moment of the image converter camera switching on was synchronized with moments of MW and UV pulses switching on.

General appearance of the image converter camera in a composition of the set up in working position is represented in Fig. 6.

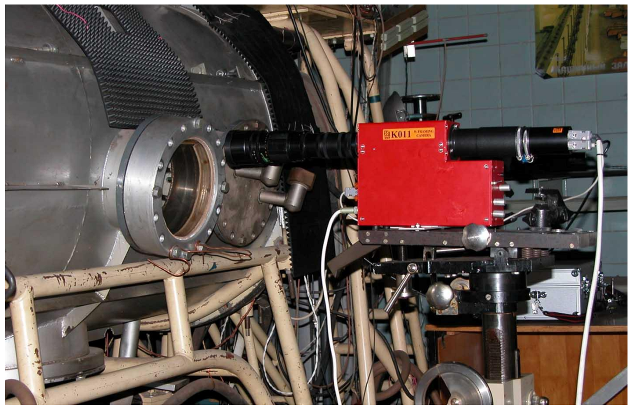

Fig. 6. General appearance of the K011 image converter camera in working position

4. EXPERIMENTAL INVESTIGATIONS OF STREAM MW VOLUMETRIC DISCHARGE INITIAL DEVELOPMENT STAGE IN AIR

Investigations of the streamer MW discharge in air at initial stage of its development have principle character both for understanding of physical processes in the discharge and for solution of applied problems. So energy requirements to MW generator finally depend on correct understanding of discharge development features at this stage and knowledge of different processes main temporary scales with respect to gas pressure and MW field amplitude.

The experiment was carried out with an application of different initiators in wide pressure range at different levels of MW field.

Measurement undertaking method was the following. Required initiator type was placed in a focus area. A given pressure level in the vacuum chamber was set. A field level equal to a critical value $\mathbf{E_{cr}}$ at the given pressure was experimentally selected. Fore and back fronts of the MW pulse have temporary scale of about 2 µs. Besides, MW radiation amplitude has some small vibrations near a stationary level in vicinity of the fronts. So it is desirable the discharge to be started, for example, 5 µs later than the fore envelope front for improvement of experimental conditions with respect to the field level.

At limited duration of MW pulse forced creation of free electrons with a help of UV radiation is necessary for breakdown origination as it was mentioned above. This phenomenon can be used for controlling of the breakdown starting moment with respect to MW pulse start. For this purpose UV pulse was given 5µs later than the start of MW pulse. The start of the image converter camera was synchronized with a moment of UV pulse giving. (Accounting passport value of synchronizing delay).

During this experiment we used an aluminum ball as initiator, its diameter was 11 mm. In Fig.7 one can photos of streamer pulsed MW discharge initial development stage in air. Air pressure was p = 60 Torr, MW wave electric field component strength was E_0 = 800 V/cm. This corresponds to a breakdown level of electric field strength $\mathbf{E_{br}}$ near a pole of a ball with this diameter at the given pressure [16]. Exposure time was t_{exp} = 0.1 µs, a pause duration between frames was t_p = 0.2 µs. Frames are placed consecutively from left to the right and up - down. Photos are painted by conditional colors, to which definite brightness levels are attached in a «Klen 4» program of image treatment [15].

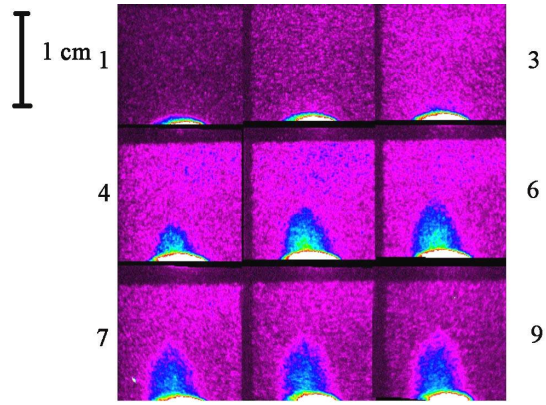

Fig. 7. Initial stage of the streamer MW discharge development: p = 60 Torr, E_0 = 800 V/cm, t_{exp} = 0.2 µs, t_p = 0.1 µs

One can see a polar part of initiating ball in lower parts of all frames. A white spot on a pole, which can be seen already in the first frame, is a reflex of a UV radiation flash visible spectrum part on a surface. It can be seen that sizes of this sport enlarge starting from the first frame. It is a consequence of a discharge illumination brightness variation inside UV lamp during the discharge formation. In the third frame one can see that a luminescent layer has appeared over the polar ball surface. Its formation means that multiplication of initial photo electrons in an area of a near polar field and elongation of a plasma region along an own ball field direction took place. In frames 4-6 one can observe this plasma region growth along the field with a simultaneous creation of bright core in its central part. In final three frames one can see that growth of the plasma region practically stops. A degradation of the bright core takes place. It is accompanied by sufficiently smooth variation of its longitudinal and transversal sizes. Whole observed process takes place during 2.6 µs.

The pause duration was increased to 0.3 µs in the next series of measurements. More than that, a moment of the image converter camera switching on was consciously shifted in direction of MW pulse fore front for a value of about 1.5 µs in this experiment.

Typical appearance of a process at this temporary scale is represented in Fig.8.

In the first frame one can observe only a reflex of UV flash on the ball surface. In frames 2, 3, 4 there are also no any peculiarities in comparison with observations in Fig.7. But in the fifth frame one can see that the plasma region is visibly modulated with respect to brightness along a direction parallel to the ball surface at its far end with respect to the ball surface. In other words bright channels begin to appear in uniformly shining plasma region. In accordance with [17] one can suppose that ionization-overheating instability is reason for these channels formation. In next frames one can see a following development of the discharge. A development of one channel was suppressed already at initial stage, after birth of two channels. Brightness of left plasma channel begins to increase, and there is only one channel in the eighth frame.

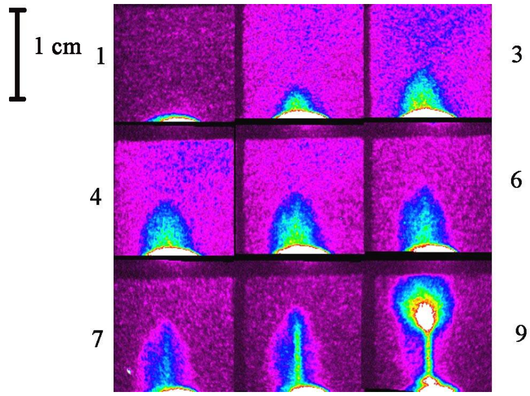

Fig. 8. Initial stage of the streamer MW discharge development: p = 60 Torr, E_0 = 800 V/cm, t_{exp} = 0.2 μs, t_p = 0.3 μs

Plasma luminescence brightness is usually bounded up with electron concentration value $\mathbf{n_e}$**.** So we can speak about increase of $\mathbf{n_e}$ in the channel and its electric conductivity as well with high level of reliability. This supposition is confirmed by the plasma channel evolution, which is observed in frames 8 and 9. One can see that the plasma channel begins to grow out of initial plasma region. This is possible only at high level of its own field at its tip and sufficiently high electric conductivity in the channel. In fact here we observe an origination of MW streamer.

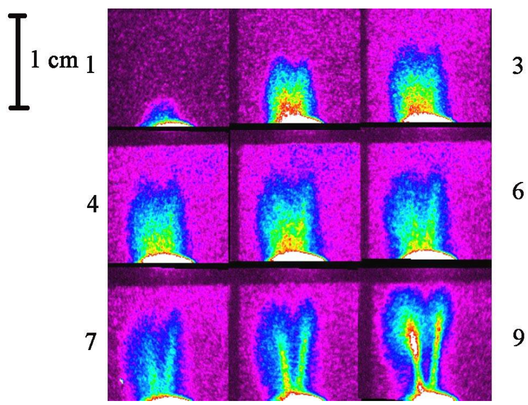

Fig. 9. Initial stage of the streamer MW discharge development: p = 60 Torr, E_0 = 1100 V/cm, t_{exp} = 0.2 μs, t_p = 0.1 μs

Finally in the ninth frame one can observe a spherical luminescent area formed at the end of the channel. This reflects sharp increase of the field at its end.

The field exceeded its critical value in a large area (so that is why we observe a spherical luminescent area). Observed phenomena are evidences of a resonance phenomenon. The object created by the initiating ball and the streamer channel reaches such length and electric conductivity value that reactive resistance compensation takes place in its structure. It is accompanied by current growth and voltage rise on a tip of the streamer near the initiating ball.

All considered photos were obtained near the ball surface at the field level approximately equal to the breakdown value. Below one can see two realizations of discharge initiation processes at the field level equal to $1,3 \cdot E_{br}$. It is naturally to expect that processes already observed at the field level $\mathbf{E_{br}}$ will take place at a new field level, but characteristic time constants of their development will decrease.

In Fig.9 is represented initial discharge stage one of possible realizations at p = 60 Torr, $E_0 \approx 1100$ V/cm, t_{exp} = 0.2 μs, t_p = 0.1 μs. It confirms our supposition.

One can see that two but not one full streamer channels have been formed here. It is connected with the fact that all processes develop with higher velocities at higher field values. As a result plasma streamer channel formation takes place during a very small time, and initial modulation parameters of the plasma area do not time to visibly change. One can see that in accordance with photos they were formed during a time smaller than 0.3 μs.

Besides, the photos give grounds to an idea that instability of ionization front during developing of initial plasma region plays substantial role in formation of conditions for creation of plasma channels. Such instability can quite take place at experimental conditions [18]. Indeed, in first three frames one can see non-uniformity of a front is observed surface practically immediately (see second frame) at plasma boundary motion from the ball. As it can be seen from the next frames it is spatially attached to places of streamer localizations.

All the processes observed at initial stage of the discharge development accelerate with rise of pressure. It is quite understandable: the discharge is developing at higher strength of the electromagnetic field, so the energy flux, which plasma structures absorb, considerably rises.

5. EXPERIMENTAL INVESTIGATIONS DEVELOPED STAGE OF VOLUMETRIC STREAMER MW DISCHARGE IN AIR

Examples of MW discharge initial stage development in different conditions are represented above. Temporary and spatial investigation scales in these experiments were selected so that it was in essence possible to investigate processes preceding to a streamer channel formation in the initiated discharge and first streamer channel forming and developing process. Everything in the streamer MW discharge development after this moment left of the frame.

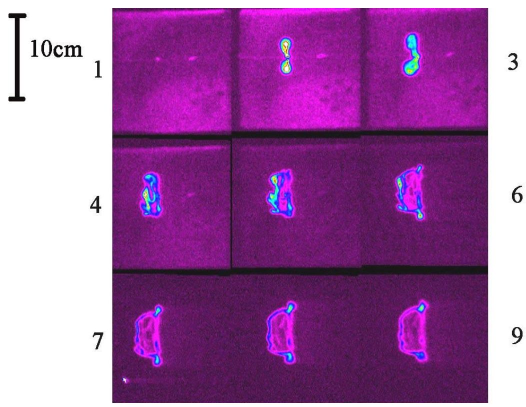

Fig. 10. Developed streamer MW discharge: p = 60 Torr, E_0 = 1100 V/cm, t_{exp} = 0.5 μs, t_p = 3 μs

Below we represent investigation results of MW streamer discharge developed stage. The spatial scale is selected so that the whole process of the discharge developing in space is within a frame of the image converter camera.

Photo detection method was analogous to tat of previous experiments. In Fig.10 one can see photos of MW discharge obtained at pressure of p = 60 Torr, E_0 = 1100 V/cm, t_{exp} = 0.5 μs, t_p = 3 μs.

In frames from first to third one can see initial discharge development stage, which was in details investigated, see above. But already in the fourth frame one can observe the following events development in the discharge. It can be seen than new streamer channels start from a spherical area in the end of the streamer channel, which correlates with level of the field. After some time they create an arc-type channel, with convex side facing the focusing mirror. The discharge gradually moves towards the radiation as it can be traced in frames 6-9.

In Fig.11 one can see discharge photos at higher pressure p = 150 Torr and E_0 = 1700 V/cm, t_{exp} = 0.5 μs, t_p = 2 μs. It can be seen that streamer channels begin to form more complicated structure with rise of pressure and of electric field strength, at which the discharge was realized. Two types of channels can be confidently singled out in it by their appearance. The first is: brighter channels with blue and green conditional colors; the second is: less bright channels with pink conditional color.

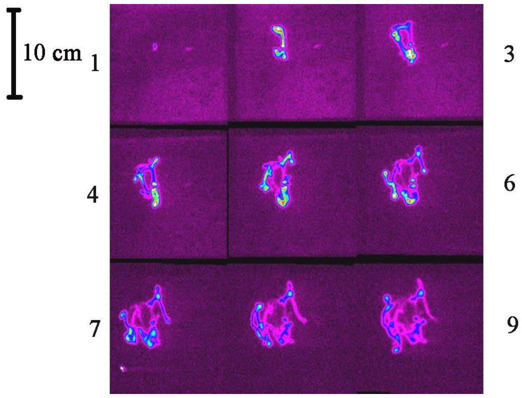

Fig. 11. Developed streamer MW discharge: p = 150 Torr, E_0 = 2800 V/cm, t_{exp} = 0.5 μs, t_p = 2 μs

The first ones apparently correspond to the channels that are intensively absorbing electric field energy at the present moment. The second ones are the channels that practically are not absorbing energy during the present moment, and are in a decay stage. One can conclude from this set of photos that plasma channel structure development takes place explicitly in a direction of the falling field. Discharge front propagation velocity towards the focusing mirror can be estimated with a help of these photos. It is about $4 \cdot 10^5$ cm/s.

6. EXPERIMENTAL INVESTIGATIONS OF THE STREAMER MW DISCHARGE ON A SURFACE OF A DIELECTRIC MATERIAL IN AIR

Investigation method was in general analogous to that applied at investigations of MW discharges with volumetric structure. Experimental scheme is represented in Fig.2. As earlier UV pulse was given at the time moment, which was 5 μs later than the fore front of MW pulse. The discharge development starts from a pole of the initiating vibrator. The discharge propagates to the side of the focusing antenna over a surface of a dielectric sheet in a form of a complicated flat channel system.

For example, in Fig.12 we represent a set of photos where a surface streamer MW discharge initial stage of a development is represented, the scale is large, it is comparable with a size of the vibrator pole. Photos were obtained at p = 760 Torr, E_0 =2 kV/cm. Frame exposure time is t_{exp} = 0.1 μs, interframe pause was t_p =0.2 μs. Initial stage development pictures of the surface and volumetric discharges are close. But there are some essential differences in them.

One observes more intensive branching of the streamer channel along its length in case of the surface discharge, it was not observed in case of the volumetric discharge. Apparently it is connected with the streamer channel development near the dielectric surface.

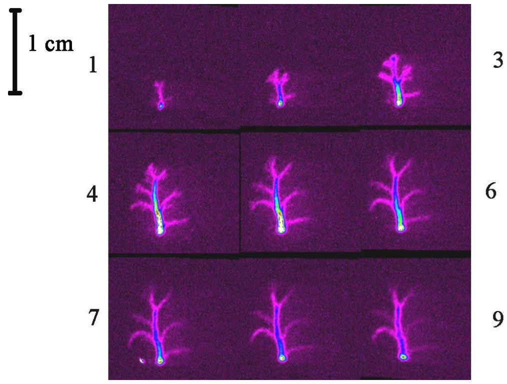

Fig. 12. Surface streamer MW discharge initial stage of a development: p = 760 Torr, E_0 = 2000 V/cm, t_{exp} = 0.1 μs, t_p = 0.2 μs

In Fig.13 and 14 photos of the surface streamer MW development is represented in a smaller spatial scale, which allows to trace a development of a whole discharge structure. Photos have different temporary scale of the interframe pause from 0.2 to 3 μs .

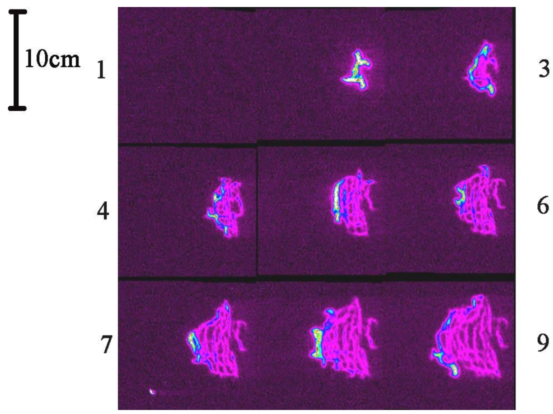

Fig. 13. Surface streamer MW discharge: p = 760 Torr, E_0 = 6500 V/cm, t_{exp} = 0.1 μs, t_p = 1 μs

These photos allow to conditionally single out three main stages of the discharge development. The first stage- initial stage of the discharge development: a first streamer formation takes place during it.

The second stage: a developed streamer structure is formed during it. Its front propagates in a direction of a radiator. At that one can see that bright hot channels are localized mainly in a thin front of the discharge structure facing the radiator.

Only their "dim" traces can be seen behind the front. The front propagation velocity determined with a help of photos is of about $5 \cdot 10^5$ cm/s.

The third stage: here the front motion to the radiator is held up. At that bright channels begin to appear over a whole thickness of already "extinguished" by this moment structure.

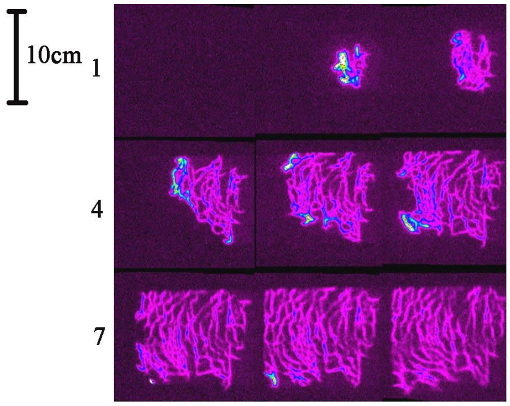

Fig. 14. Surface streamer MW discharge: p = 760 Torr, E_0 = 6500 V/cm, t_{exp} = 0.1 μs, t_p = 3μs

7. CONCLUSIONS

Experimental investigations of MW streamer discharge with a help of the K011 image converter camera have been carried out in air, in wide range of pressure, at different levels of MW field.

Results of streamer MW discharge initial development stage investigation have allowed to single out main stages of initial streamer channel formation, and to reveal main stages time constants dependences with respect to external experimental parameters. It was, in particular, validated that increase of the initial field leads to sharp decrease of the streamer channel development time. Simultaneous increase of air pressure and MW field level can lead to mutual creation of two or more initial streamers.

Experimental results of streamer MW discharge with developed volumetric structure investigation in air have allowed to detect that the streamer channel structure formed after the initial stage of the discharge development propagate towards EM energy radiator. At that the plasma channels located at the front of the structure have greater brightness of luminosity with respect to the channels in the depth. The discharge structure front propagation velocity is about $4{\cdot}10^5$ cm/s at pressure of p = 150 Torr.

Experimental investigations of the streamer MW discharge on a surface of a radiotransparent material have revealed that this discharge has qualitatively the same development stages as MW volumetric discharge, including its propagation to the radiation source at some stage of its development, and the discharge structure front velocity is about $5{\cdot}10^5$cm/s. However there are some differences, in particular, in the streamer formation during initial stage of development.

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