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Experimental investigation of a surface discharge in focused beam of microwave radiation at wavelength of 2.5cm and 8.9cm

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Microwave generator feeds trough waveguide horn-shaped antenna, forming by dielectric radio transparent lens and spherical metal mirror the focused beam of radiation. Radiation is vertical linearly polarized. The dielectric plane layers of varied thickness and substance are being located in the focus of radiation. The surface of layer is parallel to electric field vector. If needed, half-wavelength metal thin initiator is located in surface of layer. Influence of dielectric layer on breakdown and discharge processes is investigated. The properties of surface discharge are studied.

Nomenclature

E_0	=	amplitude of electric field of original microwave radiation
E_{cr}	=	critical value of electric field
E	=	amplitude of electric field
c	=	light velocity
λ	=	microwave radiation wavelength
k	=	$2\pi/\lambda$ - wave number
p	=	air pressure, Torr
h	=	dielectric layer thickness
ε	=	dielectric permittivity
τ_{exp}	=	exposition time
τ_{pause}	=	pause time
τ_{pul}	=	MW pulse duration
MW	=	microwave
EM	=	electromagnetic

I. Introduction

ONE of the interest forms of microwave (MW) discharges is a surface subcritical streamer discharge[1]. The subcritical MW discharges has a streamer structure and can be created at

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gases of median and high pressures by means of initiation with help of for example metal electrodynamic vibrator. This type of discharges is propagating against radiation far from place of initiation unlimitedly. But if the dielectric radio transparent plate is located on its way of propagation the discharge starts develop its net exclusively on the surface of plate. The situation is the same if the initiator is located just on the surface of plate. It is clear that this type of discharges can be used in many important applications can born new technologies. [2,3,4]

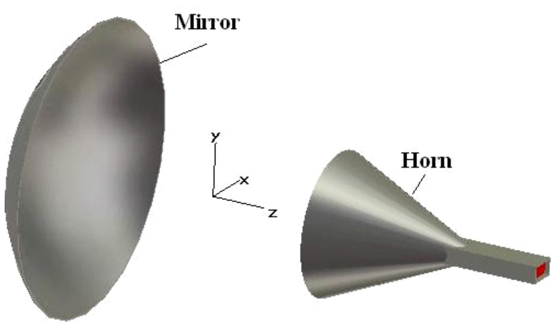
This paper is devoted to experimental study of basic problems regarding to surface subcritical streamer discharges in various conditions: the problem of breakdown threshold at dielectric plate presence, problem of dielectric plate influence on initiation of discharge, and to study of the surface discharge properties. The different orientations of dielectric plate relative to Umov-Pointing vector (transverse or along) in dependence of pressure at two values of wavelength (8.9cm and 2.5cm) are investigated.

II. Experimental facility

Installation with λ = 8.9 cm

Experiments with λ = 8.9 cm have been carried out in the installation with the following parameters: generator power in the pulse $P_{gen} \leq 1$ MW, pulse duration τ = 43 μs, operation mode – single pulses. General appearance of the installation is represented in **Fig.1a**. A scheme of the radiation focus formation in the installation with λ = 8.9 cm is represented in **Fig.1b**.

(a)



(b)

Fig.1. General appearance of the installation – (a), scheme of the radiation focus formation –(b). λ = 8.9 cm

The microwave generator feeds the antenna horn through the waveguide. A radio transparent lens forms the radiation with flat phase front. A spherical metallic mirror creates the focus of MW beam. The calculated distribution of electric field amplitude is represented in **Fig.2**. A level of the field in the radiation focus depends on the location of an attenuator included in the feeding waveguide. With a help of the installation with the wavelength λ = 8.9 cm we have made a calibration of the electric field amplitude values in the radiation focus with respect to the attenuator position in the waveguide tract.

The calibration was made by means of designed earlier method of measuring of local absolute value of electric field amplitude[5]. Essence of method is the following. A small (comparatively to wavelength) metal ball is being located in a given place. Maximum value of perturbed electric field on ball surface is 3 times exactly excides the origin value of field. Determination of breakdown threshold of gas pressure at ball presence dives information about origin field if at known dependence of breakdown field on gas pressure (see, for example, Ref.[6].

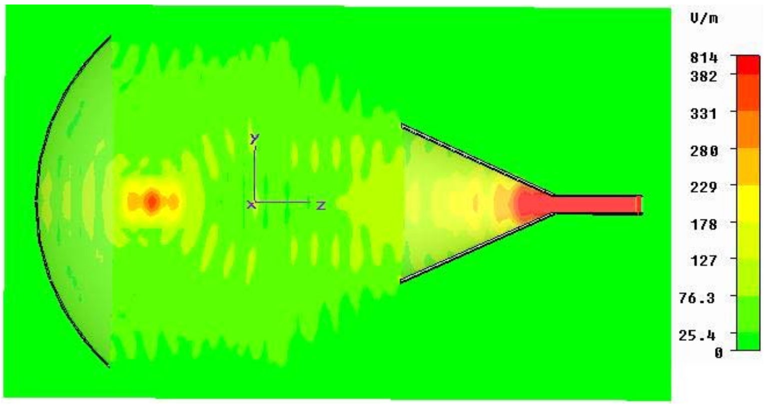


Fig.2. Calculated distribution of electric field amplitude in the installation with λ=8.9см in absence of the dielectric plate

Installation with λ = 2.5 cm

Experiments with λ = 2.5 cm have been carried out with a help of the installation, which principal scheme is the same as scheme of installation with λ=8.9cm and its appearance photo is represented in **Fig.3**. In the photo one can see a vacuum chamber, the generator with a modulator and control panel.

Fig.3. General appearance of the installation with λ = 2.5 cm

Parameters of MW generator are the following: pulse power P_{pul} = 100 kW; pulse duration τ_{pul} = 30 μs, operational mode – single pulses.

A rectangular waveguide with a cross section of 8mm×17 mm is connected with the generator outlet. A conjugation section with the round waveguide of 20 mm diameter and the conical horn with the opening angle 32° and the outlet diameter of 86 mm are located at its end. EM wave is irradiated from the horn outlet to free space in a form of linearly vertically polarized TEM wave. The horn is hermetically fixed over a center of immovable vertical flange. The outlet opening of the horn is sealed by a flat radio transparent plate. The waveguide system is filled by the sulfur hexafluoride for prevention of undesirable breakdowns in it.

A cylindrical vacuum chamber of 375 mm diameter and 475 mm length can be hermetically connected with the immovable flange with the radiating horn fixed to it. The chamber with a help of the corresponding motion device can be moved aside the flange making free access to elements of the installation fixed to it. The internal surface of the chamber is covered by the radio absorbing material that insures its "echoless" in used MW range... For visual detection of the discharge processes, the chamber has a horizontal illuminator on the side surface at the level of the axis at a distance of 215 mm from the flange. The illuminator is made in a form of a tube with an internal diameter of 60 mm. Two optically transparent quartz glasses are hermetically fixed in its free face; the cavity between them is filled by distilled water.

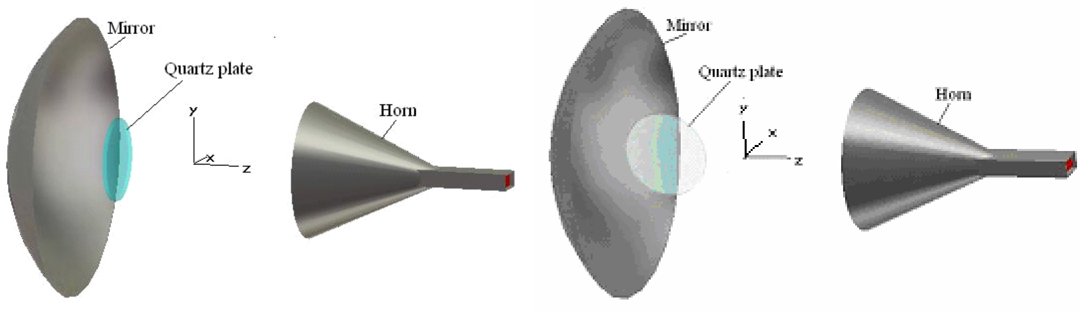
The temperature of cathode of MW generator outlet clystron was varied for change of the field amplitude. The electric field value in focus of radiation was being determined with a help of described above method[5].

III. Electric field breakdown threshold at presence of a dielectric layer in MW radiation

The essential question arises: can a dielectric presence in a MW radiation influence on breakdown threshold? For answering on this question the experimental study have been performed in following formulation.

Experiments at λ = 8.9 cm

Dielectric plates were located in the radiation focus where the field was maximal. For dielectric plates we used ordinary foil of polyethylene and a quartz plate with a diameter of 20 cm and thickness 1 cm. A scheme of the radiation focus formation and variants of dielectric sample location is represented in **Fig. 4**.



(a) (b)

Fig.4. A scheme of the radiation focus formation in the installation with λ = 8.9 cm and versions of dielectric layer positioning: (a) – transversal positioning, (b) – longitudinal positioning

We have made measurements of the breakdown pressure values at presence of the quartz disk with thickness of 10 mm and 20 mm or thin dielectric film, located in the radiation focus in the transversal or longitudinal plane. In **Fig.5** is represented the calculated electric field amplitude distribution at presence of the quartz plate at its transversal (**a**) and longitudinal (**b**) positioning.

Measurements have shown that the dielectric plate without an initiator influences the breakdown threshold since its presence changes a value of the electric field amplitude in the region of the beam propagation. The plate with the finite thickness **h** and dielectric permittivity **ε** reflects a part of radiation, and the electric field amplitude on the surface decreases, becoming equal to

$$|\mathbf{E}_{\mathbf{surf}}| = |\mathbf{E}_0| - |\mathbf{E}_1|,$$

And the field at the distance λ/4 from the plate rises

$$|\mathbf{E}_{max}| = |\mathbf{E}_0| + |\mathbf{E}_1|,$$

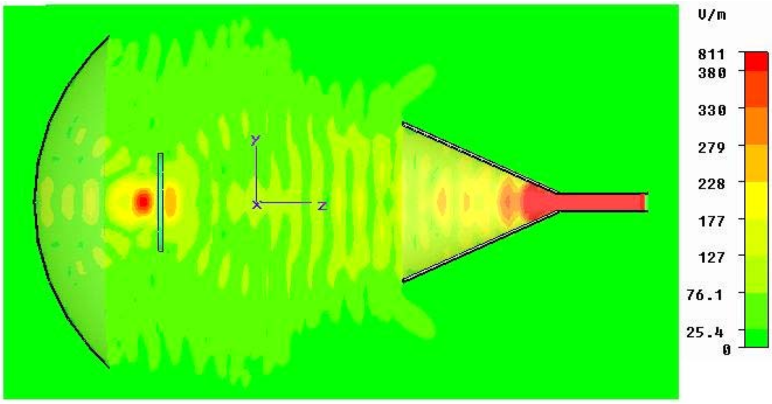


Fig.5a. Electric field amplitude distribution in the installation with λ =8.9 cm at presence of the quartz plate at its transversal positioning

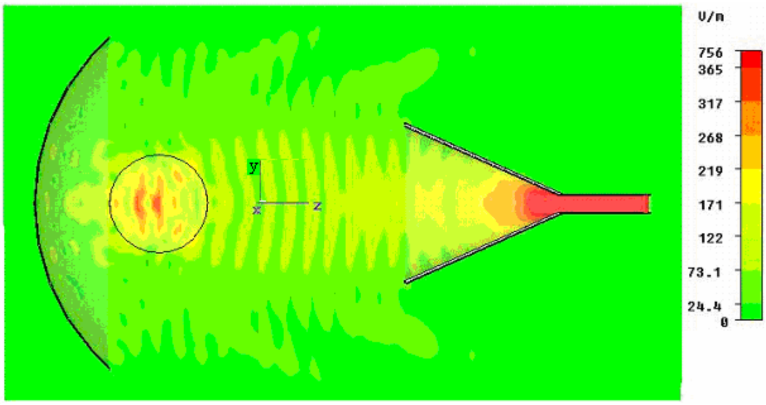


Fig.5b. Electric field amplitude distribution in the installation with λ =8.9 cm at presence of the quartz plate at its longitudinal positioning

Where the second term in equations depends on the thickness of the plate

$$E_1(h) = E_0 \frac{\frac{1-\sqrt{\varepsilon}}{1+\sqrt{\varepsilon}} + \frac{\sqrt{\varepsilon}-1}{\sqrt{\varepsilon}+1}\exp\left(-i2\sqrt{\varepsilon}kh\right)}{1+\frac{1-\sqrt{\varepsilon}}{1+\sqrt{\varepsilon}}\frac{\sqrt{\varepsilon}-1}{\sqrt{\varepsilon}+1}\exp\left(-i2\sqrt{\varepsilon}kh\right)}, \quad \mathbf{k} = \frac{2\pi}{\lambda}.$$

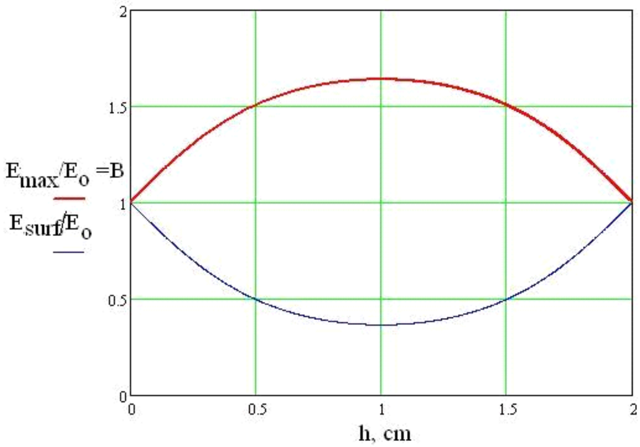


Fig.6. Relative amplitude on the plate surface (ε=4) and the maximal in the volume one with respect to the plate thickness h

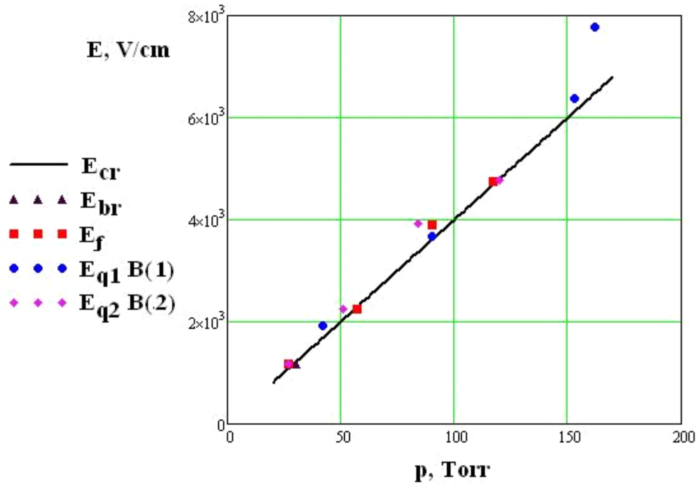


Fig.7. Electric field amplitude at breakdown with respect to air pressure

A dependence of the relative amplitude on the plate surface with **ε** = 4 with respect to the plate thickness **h** at normal fall of the wave λ=8.9cm, $\eta(h) \equiv \frac{E_{surf}}{E_0}$, is represented in **Fig.6**. Respectively, the threshold breakdown field rises by **η** times.

Measurement results of the field breakdown amplitude are represented in **Fig. 7**. Measurements surely show that the surface itself does not influence the breakdown processes. Measured values of the electric field breakdown amplitude coincide with critical values for free space.

So we have cleared that the dielectric field influence the breakdown threshold so far as its presence changes the maximal value of the electric field amplitude in the area of MW radiation beam propagation. The field amplitude change is determined by the reflection coefficient from the plate. The discharge has a volumetric character in general case.

Experiments have shown that the plate presence at the longitudinal positioning (also as in the case of the transversal positioning) influences the value of the breakdown field so far as the presence of the dielectric changes the electric field distribution with respect to the case of its absence. Respectively, a thin dielectric film does not influence the breakdown electric field strength at all.

Experiments at λ = 2.5 cm

Minimal air breakdown electric field $\mathbf{E_{cr}}$ at presence of the dielectric plate in EM quasioptical beam was experimentally determined at the wavelength λ=2.5 cm at different values of air pressure. The plate had different thickness; it was parallel to the vector **E** and perpendicular or parallel to the wave vector **κ** (as it is shown in **Fig.1**).

Experiments at the wavelength λ=2.5 cm completely confirmed the conclusion that the presence of the dielectric body influences the breakdown threshold only due to redistribution of the electric field at its presence. The presence of the surface itself does not influence a value of a breakdown threshold. This fact is most evidently revealed in the case of negligibly thin dielectric plate (the film in particular), which influence on the field distribution is small and the surface effects can be revealed in full measure.

The repeated measurements of threshold pressure in the case of dielectric film absence in the radiation focus; have shown that the gas pressure value, at which the discharge extinction takes place at the film presence and without it, has a difference in the range of 1%. It is substantially smaller then the accuracy of measurements.

IV. Dielectric surface influence on initiated subcritical MW discharges

The MW subcritical discharge, initiated by metal vibrator, is studied quite well[7,8,9,10,11]. The discharge forms complicated net of resonant streamers, freely propagating against radiation. Preliminary experiments[1] had shown that at a dielectric layer presence the discharge develops plane net of streamers at dielectric surface only. Influence of dielectric layer on MW subcritical discharge has been studied in detail. In all experiments the initiator was located on surface of dielectric layer.

Experiments at λ = 8.9 cm

For the initiation we have used a piece of copper wire of 1.2 cm length and 0.031 cm diameter (in the photos one can see bright points at its ends.

At transversal positioning of the dielectric layer the streamer discharge initiated by the vibrator placed on the surface from the horn side develops exclusively over the layer surface. At the vibrator's location on the mirror side the streamer discharge can be developed either exclusively over the dielectric layer surface or over the surface and in the volume in respect to air pressure at fixed radiation level. In **Fig.8** one can see photos of initiated "transversal" discharge at the electric field strength 3.7 kV/cm and air pressure 200 Torr (a) and 150 Torr (b).

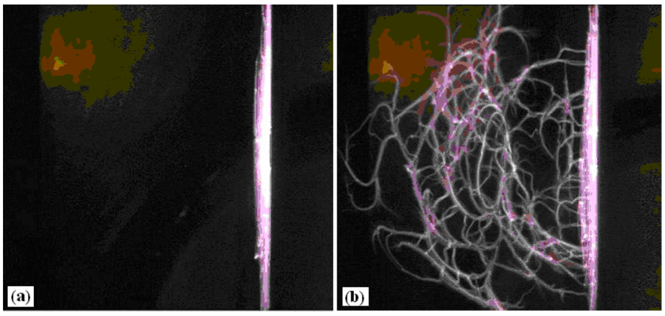


Fig.8. Photos of initiated "transversal" discharge on the polythene film at the electric field strength 3.7 kV/cm and air pressure 200 Torr (a) and 150 Torr (b). View along layer.

In **Fig. 9** one can see photos of mixed type of the discharge made at different values of electric field strength for the dielectric film - (a) and quartz disc of 1 cm thickness -(b).

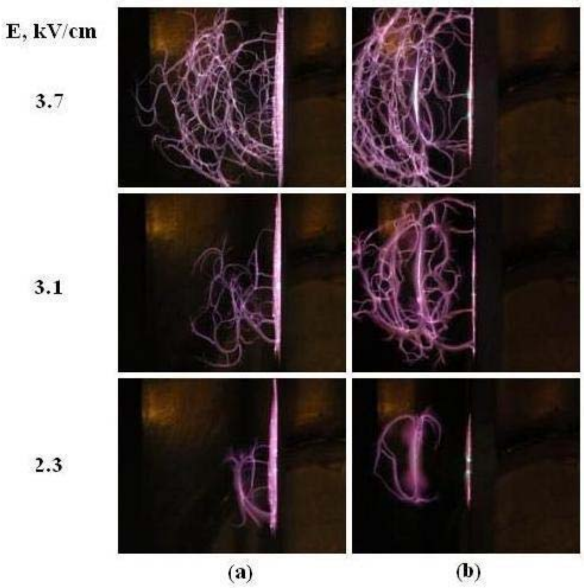


Fig.9. Surface-volumetric discharge at different values of the electric field amplitude: (a) – a film , (b) – a quartz disc of 1 cm thickness

The boundary (in coordinates - electric field – pressure) between the surface and surface-volumetric discharges (**E_i** is the red line in **Fig.10**) lies between the line of the critical field (**E_{cr}** and **E_{br}** – the black line in **Fig.10**) and the boundary of the attached discharge (**E_s** – the blue line in **Fig.10**). Purely surface discharge exists in the area between the lines **E_s** and **E_i**.

Photos in **Fig.9** have been made at air pressure little higher then the E_i boundary in **Fig.10**

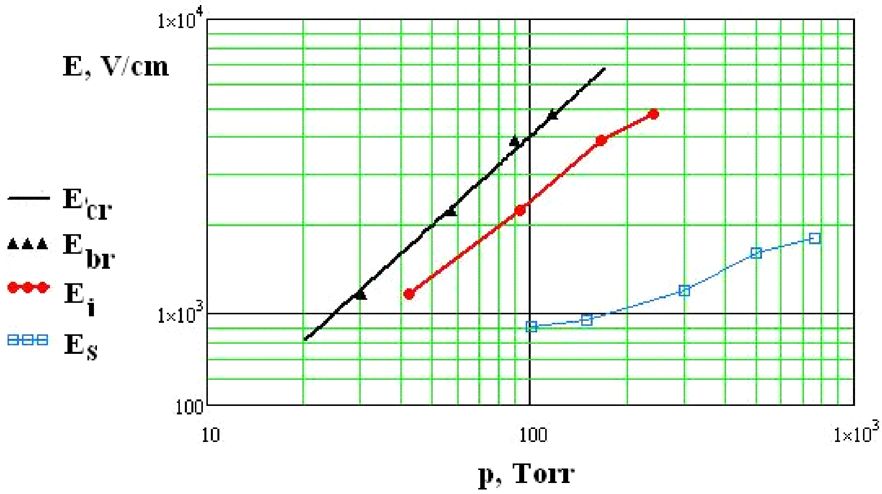
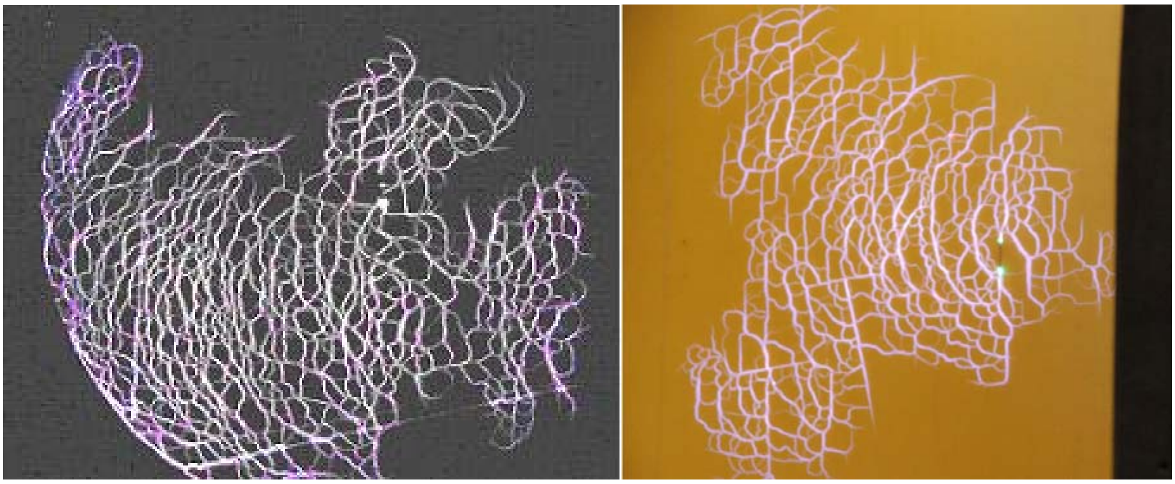


Fig.10. The boundary dividing the surface and the surface-volumetric discharges, the red line, λ=8.9 cm. The initiator is placed on the dielectric film on the side of the mirror

A phenomenon of discharge separation from the surface of transversally positioned layer and placing of the initiator on the side of the focusing device is necessary to take into account at discussion of possible versions of surface discharges application.



(a) (b)

Fig.11. Surface initiated discharge at the longitudinal positioning of the dielectric layer (a) -quartz disc of 1 cm thickness and 20 cm diameter, (b) - textolite plate 0.1 cm thickness. Focusing mirror is located to the left

The discharge always develops over the surface at initiation of the streamer discharge by the initiator on the surface of the dielectric layer at its longitudinal positioning. A photo of initiated “longitudinal” surface discharge on the quartz disc of 20 cm diameter and thickness 2 cm is represented in **Fig.11a**. The "longitudinal" discharge on a surface of a textolite plate with thickness 0.1см in the same conditions is shown on **Fig.11b**. The type of a dielectric material does not influence in the appreciable image the size of cells of the discharge and diameter of channels. However the sizes of area of the discharge propagation are a little bit wider

The area of surface streamer discharge propagation is substantially wider than the area of the focus. The discharge propagation is limited by the sizes of the dielectric layer.

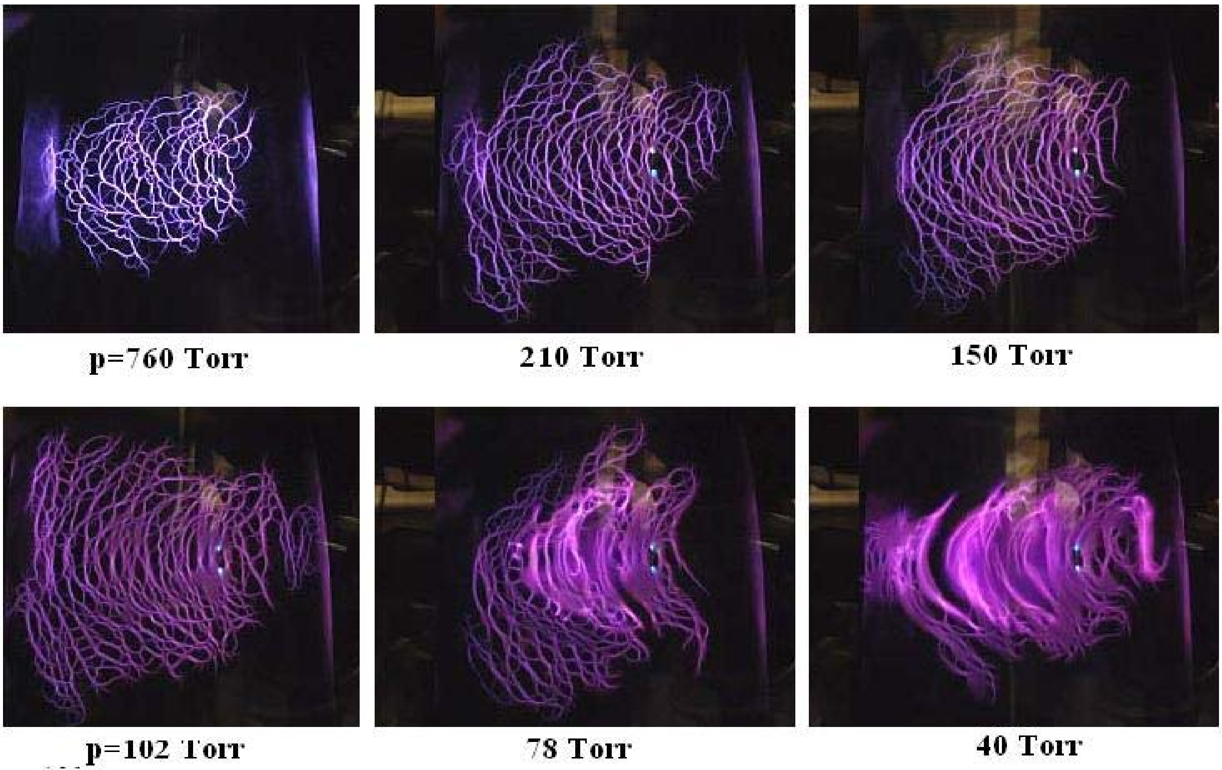


Fig.12. Photos of the "longitudinal" surface discharge. Eo=4 kV/cm, λ = 8.9 cm

Detailed investigations of initiated "longitudinal" discharge have been undertaken on a thin polyethylene film of 40 μm thick, since the thin film does not disturb the radiation field distribution. Investigations have shown that the discharge stays purely the surface one in the whole area of the subcritical streamer discharge (the area between the lines $\mathbf{E_{cr}}$ and $\mathbf{E_s}$ in **Fig.10**).

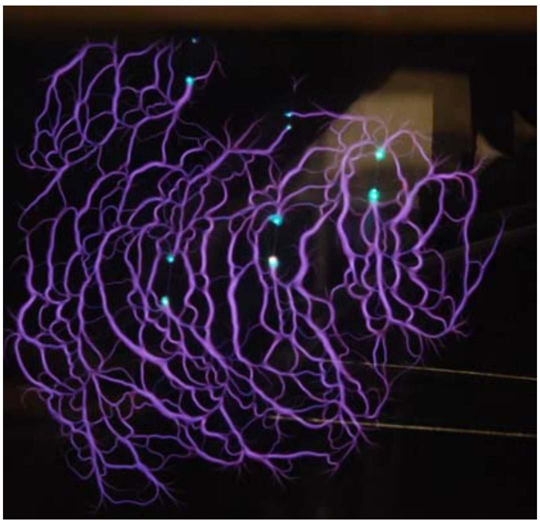


Fig.13. Typical kind of the surface discharge at "longitudinal" accommodation of a dielectric layer (system of 5 initiators); λ=8.9.см, p=150 Torr

The discharge develops in the volume only in the area of overcritical discharges (over the line $\mathbf{E_{cr}}$ in **Fig.10**). In **Fig.12** one can see photos of “longitudinal” surface discharge at electric field amplitude 4kV/cm in the radiation focus at different air pressure values in the chamber. At the given value of electric field amplitude the pressure 100 Torr is the critical value. Accordingly the discharge from the surface comes out to the volume if pressure below this value, having the diffuse character.

Experiments on initiation of the surface discharge by the vibrators system in the installation with the wavelength $\lambda = 8.9$ cm did not reveal new features of the surface discharge in respect to the initiation with a help of the single vibrator. Typical appearance of the surface discharge at “longitudinal” positioning of the layer is represented in **Fig.13** (the system consisting of 5 initiators). Positions of initiators can be determined by bright points on their ends. Firstly the “transversal” multi initiation surface discharge was observed in Ref.[12]. In that experiment MW discharge was initiated by system of 9 resonant vibrators embedded on surface of Teflon cap located at exit plane of the antenna horn, radiating MW field with wavelength 3cm at pressure 45÷760Torr.

Research of evolution of the "longitudinal" surface discharge initiated by system of 5 vibrators depending on pressure of air (see **Fig.14**) has shown that the border of propagation of the discharge is determined by area of existence of subcritical surface discharge. The streamer form of the surface discharge is replaced by diffuse form at pressure of air smaller 45 Torr.

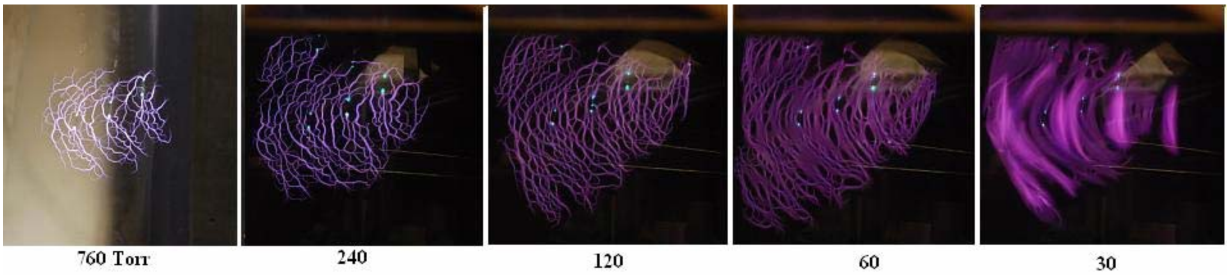


Fig.14. Evolution of the "longitudinal" surface discharge initiated by system from 5 vibrators depending on pressure of air; E=3.7кВ/см

At close positioning of the vibrators one has to take into account their electromagnetic connection influence on the currents distribution induced in the vibrators. We have developed a calculation method of strongly connected vibratos system which can be applied at creation of definite initiating devices[13].

Experiments at λ = 2.5 cm

Polyethylene films were applied as the dielectric layers of 1 and 2 cm thickness (they were the same as in the experiments with λ=8.9 cm) and the ceramic disc of 12 cm diameter at 0.4 cm thickness. The experiments have been carried out at the field strength 1.7÷3.2 kV/cm in the focal area of the system.

We have applied two initiator versions. The first (thick) vibrator was the aluminum wire 0.965 cм long and with 0.15 cm diameter, its ends were sharpened, the next one (thin) – was the copper wire 0.95 cm and with 0.02 cm diameter.

The initiators were glued to the dielectric in the area of the maximal field. The vibrator axis was parallel to the field vector E.

In experiments with “transversal” surface discharge we have obtained data on boundary pressure value at which the streamer discharge separation takes place and its volumetric development in case of the initiator positioning on the side of the mirror. Typical photos of purely surface discharge (a) and surface discharge with developed volumetric structure (b) are represented in Fig.**15**.

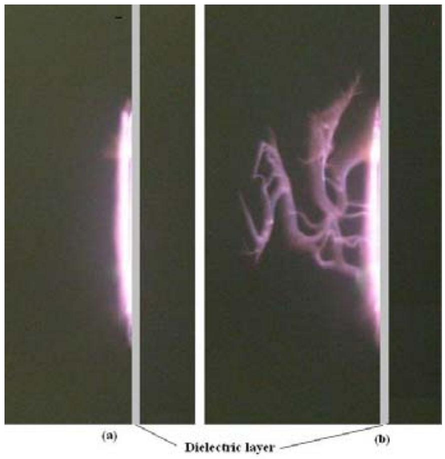


Fig.15. The initiated discharge at transversal positioning of the dielectric layer: (a) – p=700 Torr, (b) – p=480 Torr

For determination of the transition boundary of the initiated volumetric-surface discharge to the purely surface one we made photographing of them at different pressure and electric field strength values in the chamber. With a help of the photos we have determined the sought for boundary. The electric field strength on the surface of the dielectric layer was changed by its motion along the axis of the system. At that we used known field distribution along the system axis. The polyethylene film with the initiator on the side of the mirror was placed perpendicular to the axis of the system at required distances from the mirror. Obtained photos are represented in **Fig.16** and the result of our analysis – in **Fig.17**.

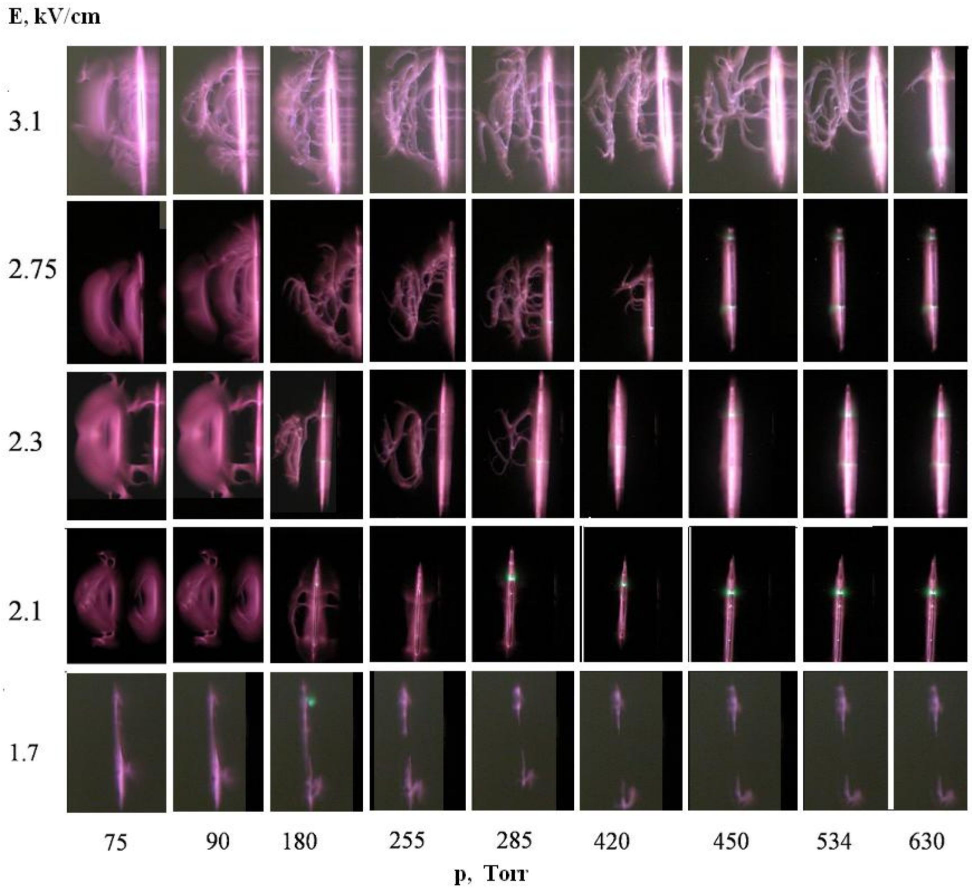


Fig.16. "Transversal" initiated discharge at different values of electric field strength and air pressure, λ=2.5 cm

The streamer discharge does not create the spatial structure in case of the initiator location in the focus of the system on the side of the horn. The polyethylene film prevents its development to the side of higher field and it stays to be purely the surface one up to atmospheric pressure.

The analogous process takes place in the case of quartz glass with the initiator in the focus area of the system.

Streamers separation to the volume does not take place at longitudinal positioning of the dielectric layer.

The diffuse discharge at E=3.2 kV/cm also transits to the streamer one at pressure 30-40 Torr. However, the transition process of the diffuse discharge to the streamer one is not sharp as at E=1.0 kV/cm, but smoothly changes in the pressure range approximately from 70 to 150 Torr. The streamer discharge in difference with the case with E=1.0 kV/cm has clearly expressed spatial form. The spatial structure becomes simpler with rise of pressure but, though, exists at the atmospheric pressure as well.

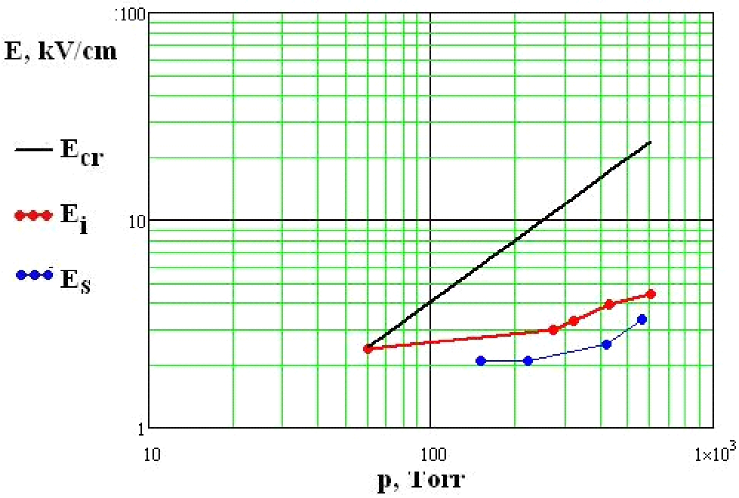


Fig.17. The boundary dividing the surface and the surface-volumetric discharges – the red line, λ=2.5 cm. The initiator is located on the dielectric film on the side of the mirror

The analogous process takes place on the quartz glass with the initiator in the focus area. A comparison of initiated discharge photos on the dielectric layer with and without the initiated discharge speaks about the absence of the film influence on a development of the streamer volumetric discharge.

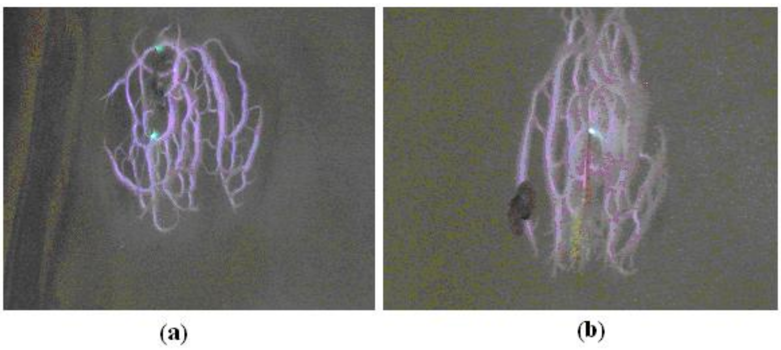
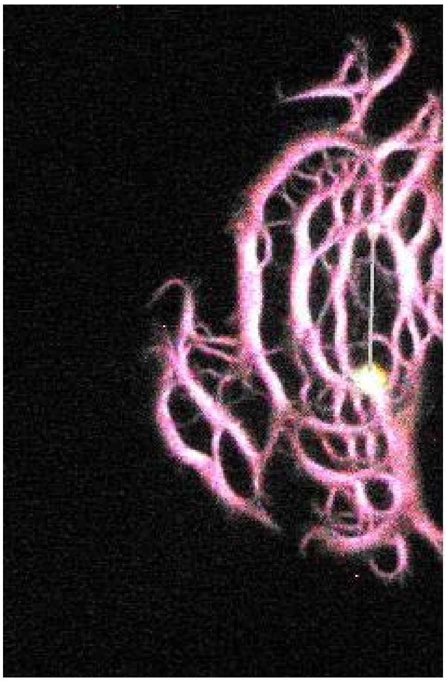


Fig.18. Photos of the "transversal" discharge at atmospheric pressure made at the angle of 45^o to the surface of the polyethylene film (a) and of the quartz disc (b) which were made at moved aside case of the vacuum chamber.

The principle difference consists in the fact that the surface streamer discharge with the complicated structure exists on the dielectric surface namely up to atmosphere. In **Fig.18** one can see photos of the "transversal" discharge at atmospheric pressure at the angle of 45^o to the surface of the polyethylene film (a) and of the quartz disc (b) which were made at moved aside case of the vacuum chamber.

The spatial streamer discharge does not originate in the case of the "longitudinal" positioning of the dielectric film (along the axis of the system parallel to **k** and **E** vectors**,** the initiator is located on the dielectric in the focus of the system). The appearance of longitudinal surface discharge on the polyethylene film is represented in Fig.**19**. Its structure and development dynamics with respect to pressure are analogous to those of the transversal surface discharge.



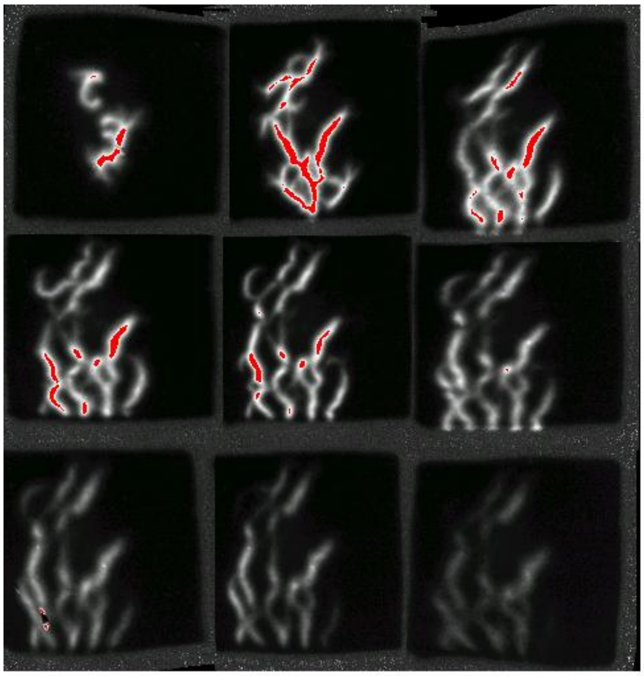


Fig.19 (left). A photo of "longitudinal" surface initiated discharge. The initiator-is the straight line. The mirror is to the left, p=370 Torr

Fig.20 (right). Frame by frame scanning of the "longitudinal" initiated discharge at atmospheric pressure and Eo=3.1 kV/cm by the high-speed camera. Exposure time τ_{exp} = 0.5 μs, τ_{pause} = 3 μs

A temporary development of the surface discharge has been investigated with the high-speed framing camera Klen-4 (maid in Russia). Frame by frame scanning of the "longitudinal" discharge on the film at atmospheric pressure and field amplitude of 3.1kV/cm is represented in **Fig.20**. The period of frames change is 3.5 μs at exposure time 0.5 μs. Most bright parts of the image are separated by red color. Decrease of radiation level for 40 % during the pulse influences the spatial discharge development.

Visual analysis of the film after experiments has revealed a trace on the film surface made by the surface discharge. This confirms obtained results on change of the surface properties by MW surface discharges[4].

V. Summary

A dielectric layer itself influence on breakdown appearance only far from layer, not nearer than λ/4, by means of reflection creation, depending on layer dielectric permittivity. Thus a dielectric layer can not use as some kind of initiator. But if subcritical discharge is initiated on the layer surface it prefers to propagate exclusively along the surface (always, if initiator is located at back side of layer, and defined domain of electric field amplitude and air pressure, if initiator is located at front side of layer). Out of this domain the streamer discharge goes out of surface to free space (at higher field amplitude) or changes into attached type discharge (at lower field amplitude). The causes of this preference lay out of electrodynamic reasons and related to exclusively physics of surface phenomena.

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