Propagation of Microwave Subcritical Streamer Discharge Against Radiation by Brunching and Looping

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The intriguing property of subcritical discharge to propagate against microwave radiation forming thin curved channels with branches and loops is investigated theoretically. Using various approaches of electromagnetic field calculations for typical streamer system configurations and numerical modeling, author become to conclusion about main physical mechanisms, determining the discharge propagation against radiation. By direct modeling, which uses electron impact ionization, free electron diffusion, Ohm heating and electric field increase at tops of the streamer, is confirmed the resonant streamer nature of the freely propagating subcritical MW discharge, its ability to use branching for saving of resonant state continuously during development, and its property to propagate against radiation by means of looping. Significant role can play the appearance of mini-streamer hedgehogs at streamer head. These hedgehogs preserve appear of areas with strongly overcritical field near streamer head and create conditions for brunching. Radiation shielding by front streamer channels is not determinative. The understanding of so important properties of microwave streamer discharges is necessary for define of their application domains

Nomenclature

E_0	=	effective amplitude of electric field of original microwave radiation
E_{cr}	=	critical value of electric field
E	=	effective amplitude of electric field
c	=	light velocity
ω, λ	=	microwave radiation circular frequency and wave length
k	=	$2\pi/\lambda$ - wave number
Λ	=	character sizes of high amplitude area
a	=	streamer radius
l	=	distance along streamer
J	=	streamer current
σ	=	plasma electrical conductivity
τ_{exp}	=	exposition time
τ_{pause}	=	pause time
R_{sph}	=	radius of metal sphere
t	=	time

I. Introduction

ELECTRICAL gas discharges in a strong microwave (MW) radiation are subject of experimental and theoretical investigations during almost half century. However, what do we know now about them? We know the breakdown threshold in dependence on gas pressure and character sizes of high amplitude area Λ for various gases. In earlier works Λ is determined by sizes of MW waveguide or MW resonator[1]. In more late investigations of breakdown threshold created in a focus of MW beam radiation parameter Λ was determined by sizes of focus area[2].

It is known that at low pressure discharges represent the smooth diffusion clouds. The diffusion type of discharges is the most investigated. Many kinds of instabilities were studied[3]. There are well-known field–ionization instability, overheating instability and many others[4]. All these instabilities are developing in a ground of almost homogeneously ionized gas, and can be described in frame of linear theory. The diffusion MW discharges are match for standard diagnostic method such as nterferometry, spectroscopy and similar to.

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Rather different situation takes place for MW discharges at high gas pressure. In this case, diffusion factor is suppressed. Discharge as rule starts from single free electron. The linear stage of avalanche is very short and all farther development of discharge is strongly nonlinear and cannot be described by linear theory. Moreover, discharge represents a net of branching and looping thin channels with very high gas temperature and electrical conductivity. Traditional plasma diagnostics is inapplicable for such strongly inhomogeneous object. In spite of a lot of experimental and theory investigations, the physics of high-pressure MW discharges is unclear in many aspects. We know that filaments of MW discharge are cardinally increase electrical field at their tops thus so named streamer effect allows the discharge propagation in radiation with level less than critical (breakdown) value. Elementary theory, based on simplest observations by open length camera and measurement of integral characteristics such as absorbed and reflected power, gas dynamical perturbations, caused by filament heating, densitometry of integral and short-exposition photos, and numerical modeling with rather various approaches, allows estimating the radius of filament, its gas and electron temperature, absorbed energy, velocity of the streamer growth. We can estimate the domain of existing of subcritical MW discharges bounding with overcritical and deeply subcritical discharges (last cannot propagate far from initiator being attached to it). Designed numerical models quite satisfactory describe the initial stage of streamer growth up to length about half-length of MW radiation. The some summary of the streamer development scenario and main estimations are presented in Ref.5. In a difference to DC streamer, the MW streamer, being a single, cannot use the streamer effect at its length more resonant value, which is approximately half-wavelength. Experimental observations executed by V.Brovkin and Yu. Kolesnichenko[6] show very clearly the important role of branching in process of the streamers propagation. Recently it was demonstrated by numerical modeling that farther, than $\lambda/2$, grows is performing only by branching of the streamer channels[7]. Later it was confirmed by numerous modeling used rather different approach[8].

Other unclear property of MW subcritical discharge is its invariable propagation from initiator against MW radiation. It was seemed, that this effect could be explained by elementary shielding of back part of discharge by its front part (something like skinning of field). The field before discharge front is more than field behind it so streamer, of course, has possibility to rise in direction of higher field, it is against MW radiation. Nevertheless, experiments show that in cases, when effect of shielding is excluded in principle (discharge in axicone caustic or longitudinal surface discharge) the noted property of propagation against MW radiation is observed too, so the role of shielding is insignificant. This paper is devoted to clarification of this peculiarity of subcritical MW discharge.

II. Formulation of task

Figure 1 demonstrates the typical photo of subcritical streamer MW discharge by open length. Gas is air at atmospheric pressure and room temperature, λ = 8.9 cm, τ_{pulse} = 43 μs. Initiator is at right part of the image, bright spots at its ends are result of metal evaporation, caused by high temperature of streamers started from them. Radiation goes from left to right. One can see that, as usual, discharge propagates from initiator against radiation.

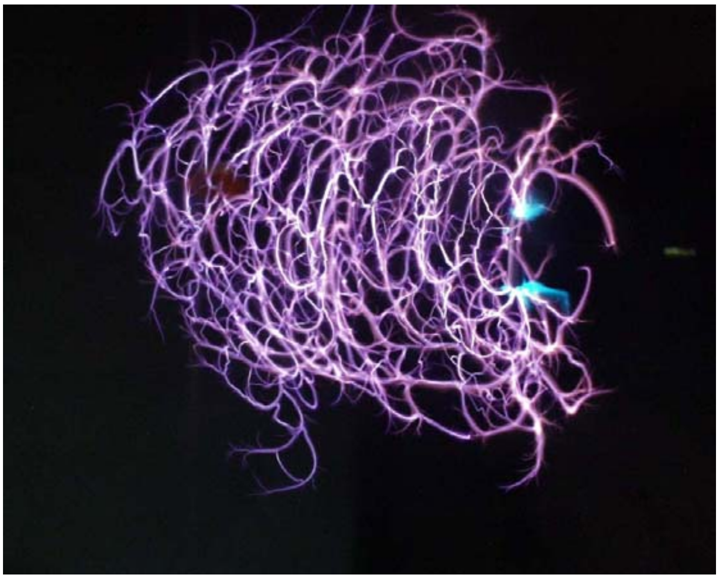

Figure 1. The typical view of subcritical streamer MW discharge.

It is confirmed by speed-camera framing represented in Fig.2, which shows the time evolution of surface subcritical discharge at the almost same conditions[9].

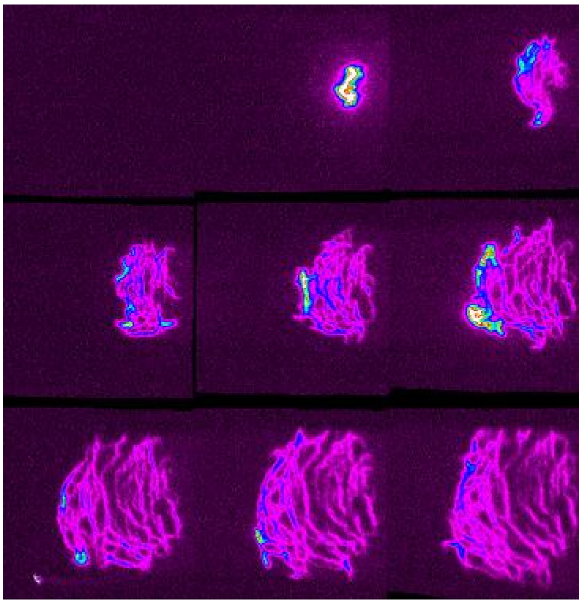

Figure 2. Frame-by-frame photography of the longitudinal surface streamer MW discharge (τ_{exp}=0.1 μs; τ_{pause}=2 μs)

The insignificant influence of radiation shielding on discharge property to propagate against radiation is especially clearly seen in Fig.3, which demonstrate the initial stage of the streamer discharge development. The metal ball plays role of initiator. One can see that from the very beginning main streamer goes against radiation[10]. At that it is absolutely clear, that this phenomenon cannot be explained by radiation shielding.

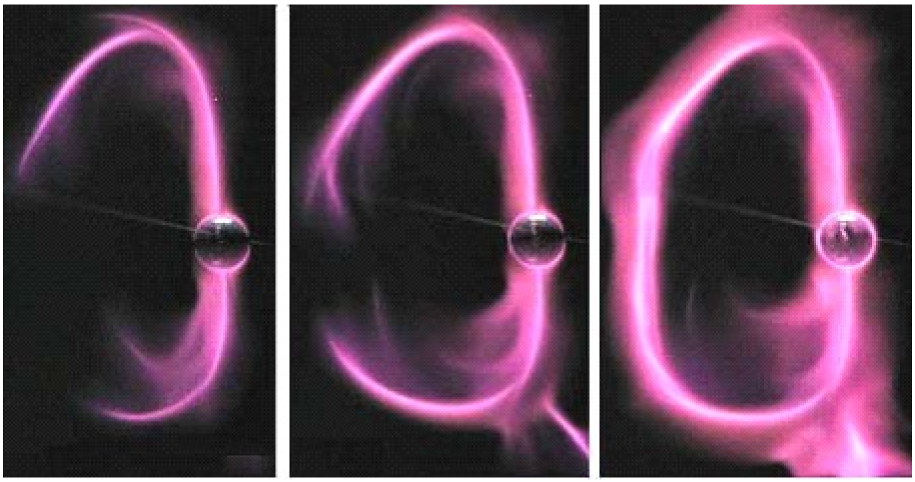

Figure 3. Time-lapse filming of subcritical MW discharge, initiated by metal sphere (τ_{exp}=τ_{pause}=1μs). Radiation is directed from left to right. R_{sph} = 0.05·λ

It is naturally to suppose that the streamer must have tendency to rise in direction, where electric field amplitude in the nearest vicinity of its head is maximal. All used early numerical models are based on this supposition. For checking of this supposition the row of model calculations of MW field distribution around spherical initiator with short thin streamer channels of conductivity $\sigma \approx \omega/4\pi$ and various lengths was performed. Figure 4 shows the electric field distribution around metal sphere, the same as in Fig.3, without streamers ($R_{sph} = 0.05\cdot\lambda$). One can see that maximum field is located on poles of sphere. It means that streamers must develop along axis coincident with original MW electric field direction. Indeed, initially, as it is seen in Fig.3, the streamer goes in direction of maximal electric field amplitude, almost in direction of maximal total field generated by spherical initiator in flat wave radiation.

Calculated field distribution with started streamer showed that maximum field lies not at the streamer axis near its heads but at of side of axis (see Fig.5 and Fig.6). This shift rises with short (comparatively with resonant value) streamer length increasing. Consequently the streamers must curve itself if its length more some value. Indeed streamers in Fig.3 are being curved if their length achieves a couple of centimeters.

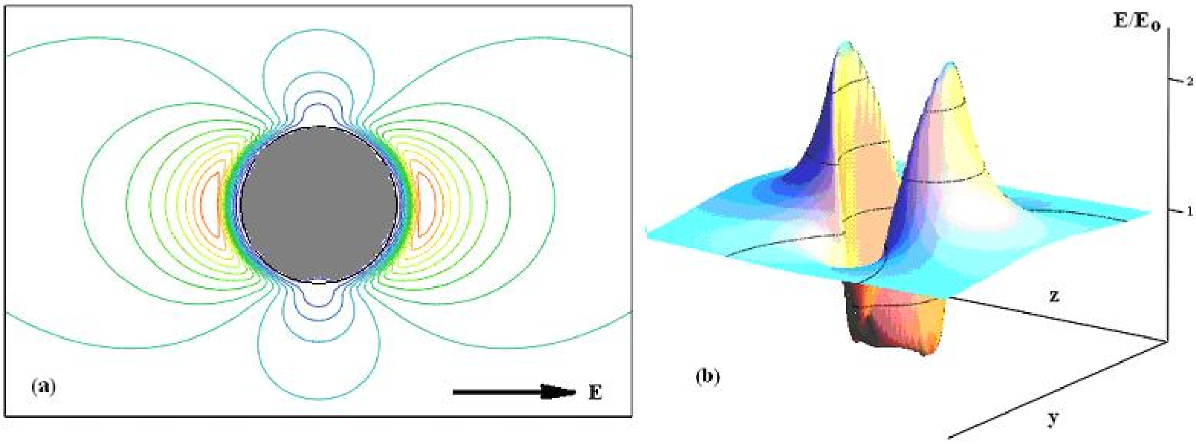

Figure 4. Electric field amplitude distribution around spherical initiator. (a) – lines of equal magnitudes, red are zones of high amplitude. (b) – surface E(y,z). $R_{sphere} = 0.05 \cdot \lambda$

However, the problem is arising. The streamers accordingly with Fig.4 must be curved in direction of MW radiation propagation (in direction of wave vector ***k***), while in reality they are being curved against radiation, in opposite direction. The question is: whether the streamer is finding the way where the field on its head is maximal? It does the used model of streamer theory, based on this supposition, doubtful. For answer on this question the detail investigation by numerical modeling was undertaken. The modeling, used model with allowed branching, showed that streamers create loops after branching8. The rise of situation, when top field has two maximum, creates the possibilities for the streamer brunching, which of course is able cardinally change the field distribution and general picture of propagation process. But in the case of Fig.3 the brunching is absent! What factor forces the streamers without branches to be curved towards radiation source?

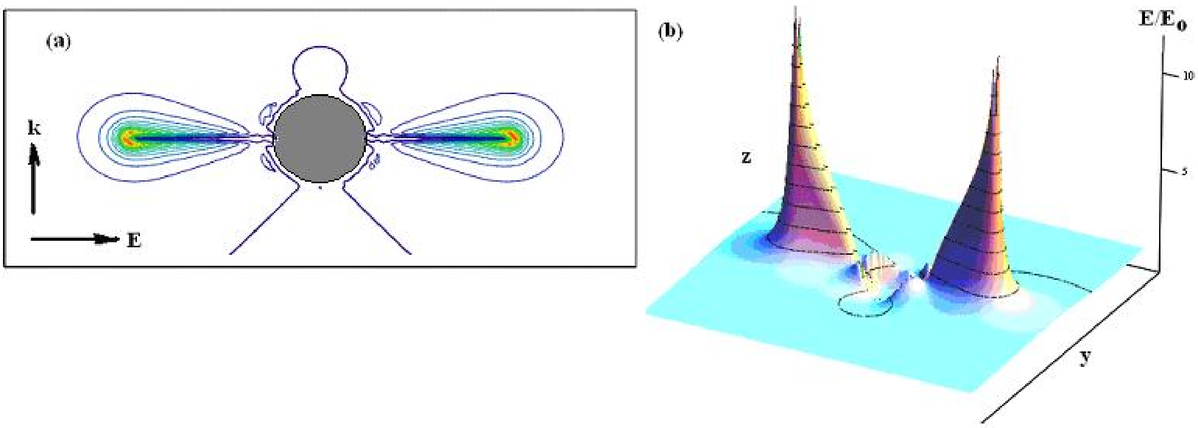

Figure 5. Electric field amplitude distribution around spherical initiator with started streamer in MW radiation with flat phase front: (a) – lines of equal magnitudes, red are zones of high amplitude. (b) – surface E(y,z). $R_{sph} = 0.05 \cdot \lambda$

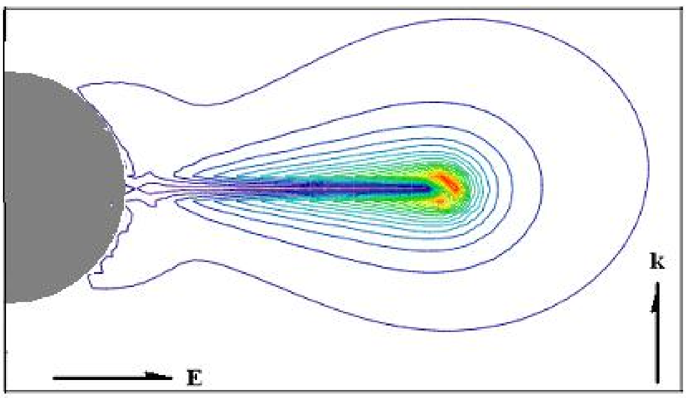

Figure 6. Electric field distribution around started streamer in MW radiation with flat phase front . $R_{sph} = 0.05 \cdot \lambda$

For investigation of this problem I have performed the numerical modeling on specially designed model.

III. Numerical model

The fully adequate model, able to describe the process of MW discharge development in subcritical field, demands use of the system of Helmholtz equations for electromagnetic field plus gas-dynamic system for multi-component plasma mix taking into account needed physical-chemical processes in 3-D frame. Experience of designing of such model[11,12], have shown that difficulties of technology of calculation by such model do not allow investigating the process saving main its properties.

For design of the simplified model, I use the circumstance that the streamer channels are thin comparatively with wavelength and its length electrically conducting objects. It give the possibility using for calculation of MW current inducted in channels at given distribution of electrical conductivity along streamers and known space distribution of channels. The inducted currents is being calculated by integral equation Eq.(1)

$$J(l)=\vartheta(l)\left(\vec{E}_0(\vec{r}(l))\cdot\frac{d\vec{l}}{dl}\right)+i\frac{k}{c}\vartheta(l)\int J(l')\left[G(\vec{r}(l),\vec{r}(l'))\left(\frac{d\vec{l}\,'}{dl'}\cdot\frac{d\vec{l}}{dl}\right)+\frac{1}{k^2}\left(\frac{d\vec{l}}{dl}\cdot\nabla_r\left(\frac{d\vec{l}\,'}{dl'}\cdot\nabla_r(G(r,r(l')))\right)\right)\right]dl', \qquad (1)$$

where

$$R(\vec{r},\vec{r}\,')=\sqrt{a^2+|\vec{r}-\vec{r}\,'|^2}$$

$$G(\vec{r},\vec{r}\,')=\frac{exp(ikR(\vec{r},\vec{r}\,'))}{R(\vec{r},\vec{r}\,')},$$

$$\vartheta(\mathbf{l})=\pi\cdot\mathbf{a}^2\cdot\sigma(\mathbf{l})$$

$$\vec{r}=\vec{r}(l)$$

Equation (1) is exact consequence of Maxwell equations for monochromatic electromagnetic radiation for canonical radial distribution of electrical conductivity with character radius a. It is similar to well known Pocklington equation[13], but modified for arbitrary distributed conductivity along channels and for arbitrary distribution of channels in 3D space.

Electric and magnetic (if needed) fields inside channels and at vicinity of channels are being calculated by Eq.(2).

$$\vec{E}(\vec{r})=\vec{E}_0(\vec{r})+i\cdot\frac{k}{c}\cdot\int J(l')\cdot\left[G(\vec{r},\vec{r}(l'))\cdot\frac{d\vec{l}\,'}{dl'}+\frac{1}{k^2}\cdot\nabla_r\left(\frac{d\vec{l}\,'}{dl'}\cdot\nabla_r(G(r,r(l')))\right)\right]dl'\,. \qquad (2)$$

Those equations (Eq.(1) and Eq.(2)) were used for calculation of field distributions represented on Fig.4, Fig5 and Fig.6.

From earlier investigations, described in Ref.14 and more detail in Ref.15, the typical values of streamer parameters, particularly, the channel conductivity. are well known. Usually, the electric conductivity of main body of streamer behind its head has a value optimal for maximum absorption of MW energy. This value was accepted in designed model as given. The main attention was concentrated on imitation of streamer ability to self defining of its way in the complicated field distribution, changing commonly with the streamer development.

The model use the real mechanism of streamer propagation, observed in experiment. In Fig.7a the photo of area around streamer head is shown. Many test-streamers started from main streamer head in all directions have small conductivity, short length (about several diameters of streamer) and short life-time. The concurrence between test-streamers results to win of one of them, which is developing in direction with maximum MW field amplitude (at low pressure when diffusion smoothes process it corresponds to known mechanism of the overheating instability). At every step of time the program generates many test streamers (blue in Fig.7b) and defines the direction with maximum field amplitude. Main streamer (red in Fig.7b) does a step in defined direction. Thus step by step the streamers are forming their trajectories. Of course designed model is very simplified. In particular, it does not able to describe the streamer brunching, but can imitate the free self evolution of streamer at initial stage at self consistent approach.

IV. Result of modeling

Calculation was performed for MW origin field $E_o = 0.4\ E_{cr}$ at $\lambda = 8.9$cm. Length of the initiator is much less than resonant value $\sim\lambda/2$. Its radius 0.15cm is enough for initiating of discharge at given origin field.

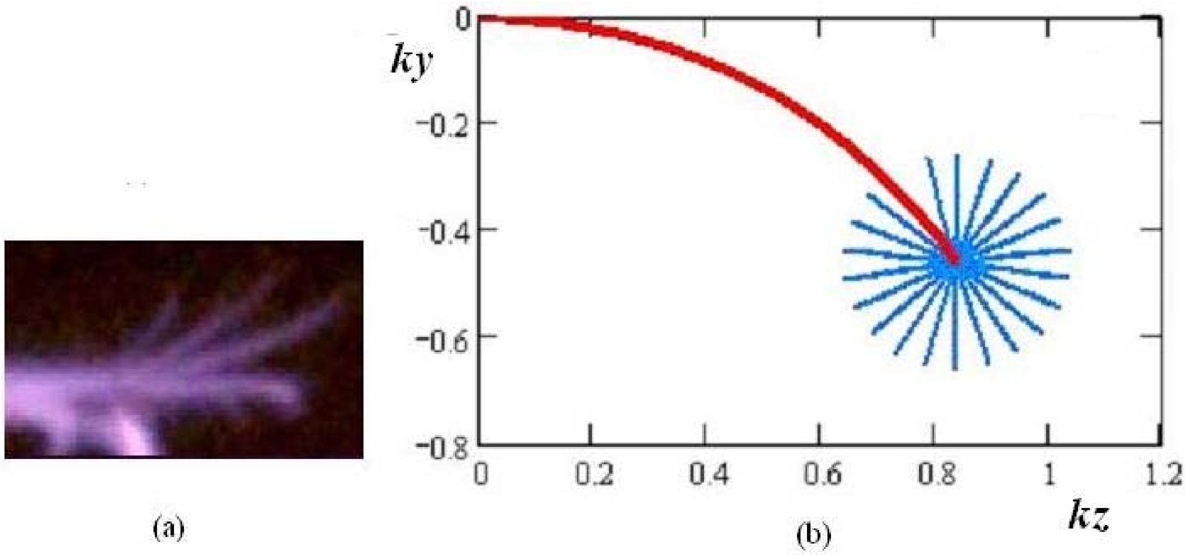

Figure 7. Photo of many test-streamers at head of main streamer – (a). Scheme of selfcontrolled streamer propagation. Red – main streamer, blue – test-streamers.

Flat MW radiation

Firstly numerical experiment was performed at MW radiation with flat phase front because it is the most general situation. Modeling gives the same result as in paragraph II: the streamer curves in direction of MW radiation propagation as it is predicted in paragraph II. It is demonstrated in Fig.8.

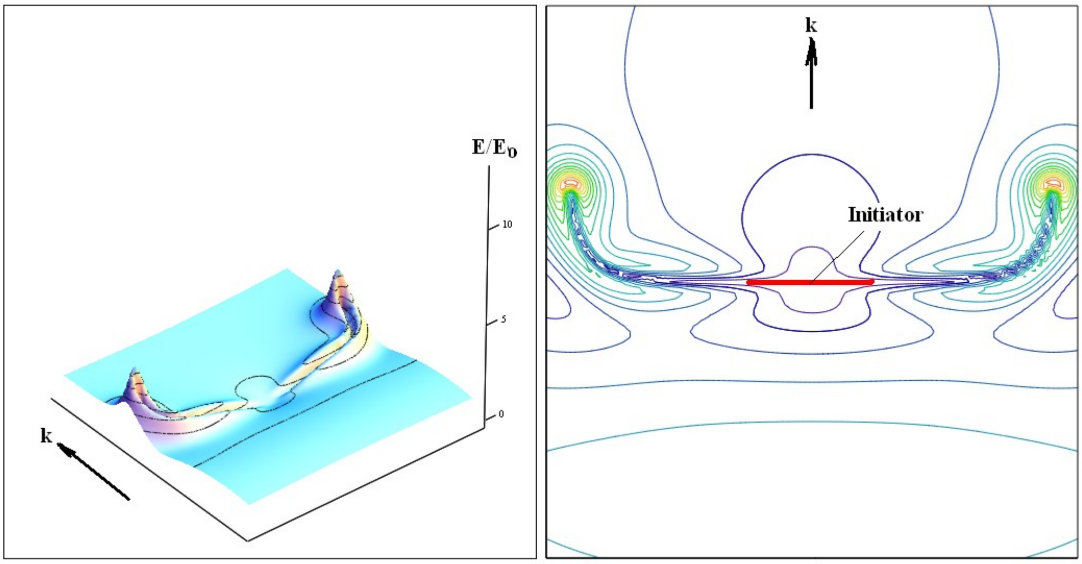

Figure 8. Streamer configaration in MW radiation with flat phase front, t = 10μs

Focused MW radiation

But MW radiation with flat phase front (flat MW) is some ideal situation. All investigations of subcritical MW discharges were performed in focused radiation for achieving of maximum electric field at limited generator power. Typical scheme of these experiments[16] is represented in Fig.9.

Field distribution in focus is different from case of flat MW. Distribution calculated for real setup with wavelength 8.9 cm where main part of subcritical streamer discharge observation was performed (including photo in Fig.3) is presented in Fig.10. In center of focus amplitude is maximal. Phase front of focused MW radiation (focused MW) is spherical. Curvature radius changes a sign at passing of focus point. The periodical structure is a standing wave resulted by interference of direct and reflected waves.

Modeling of the subcritical streamer discharge development in focused MW shows that direction of streamer curving depends on place of initiator location. If the initiator is located behind the focus streamers develop the same way as in the flat MW. But if initiator is located in focus point or a little before focus as it was in experiment Fig.3 the streamers develop against focused radiation creating closed loop by the same way as in experiment.

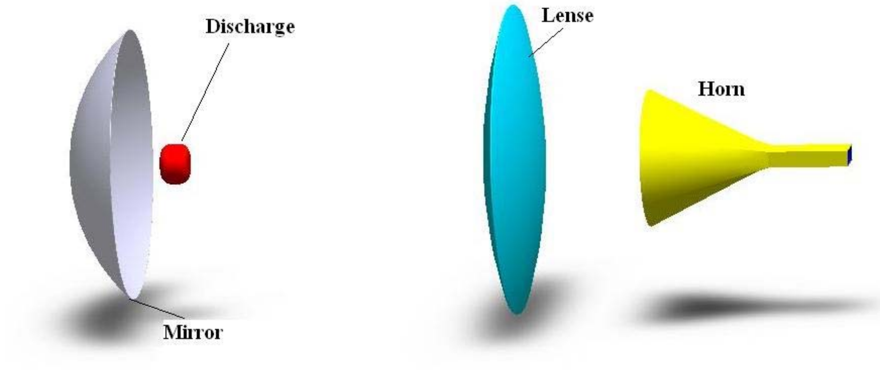

Figure 9. Scheme of subcritical streamer discharge investigation in focus of MW radiation.

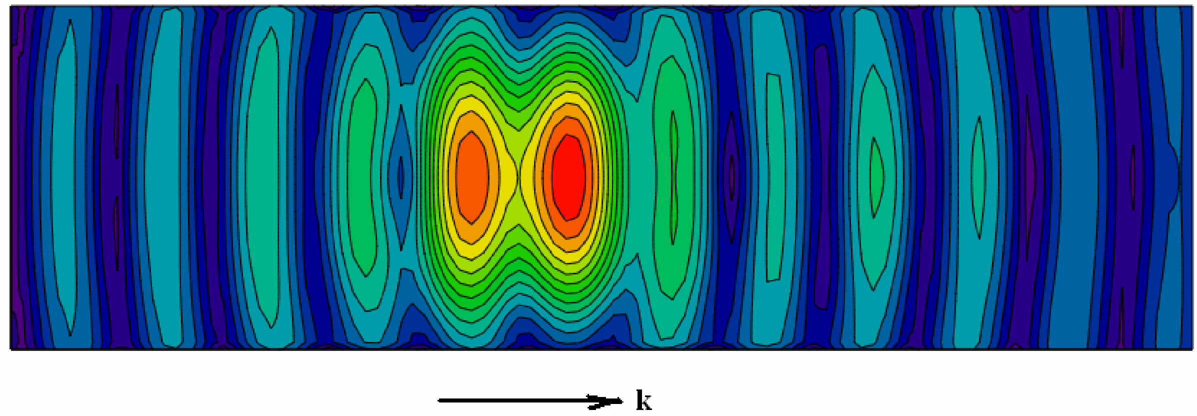

Figure 10. Calculated distribution of electric field amplitude in installation shown in Fig.9.

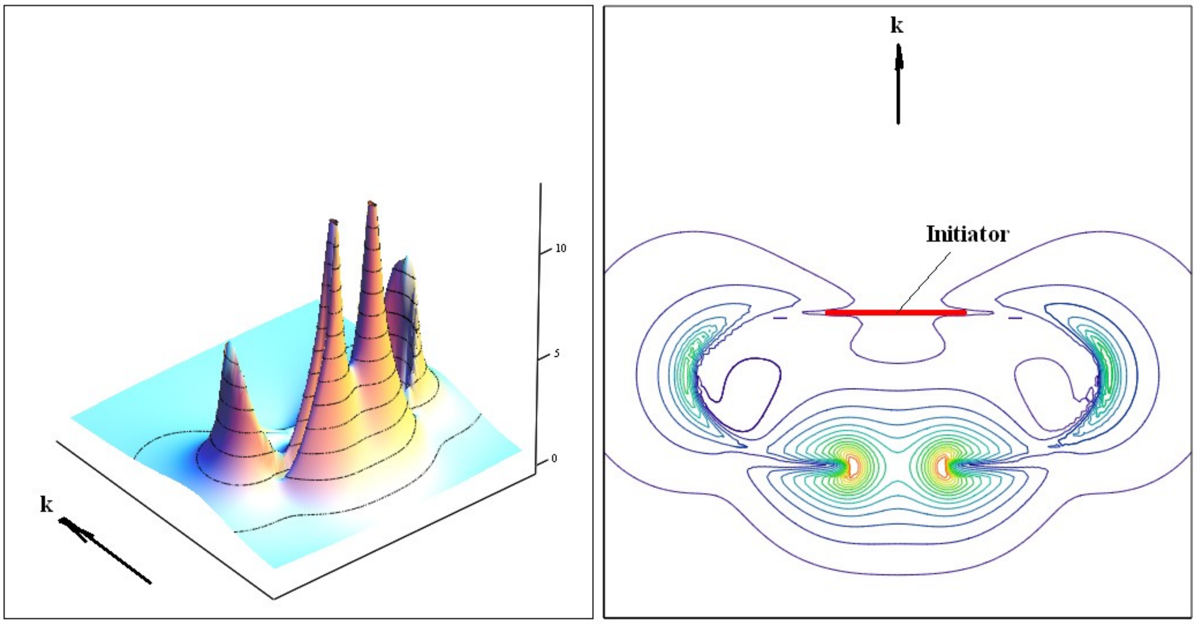

Figure 11. Field distribution around streamers developing in focused MW. Initiator is located in focus point. Streamers curve against radiation. Left – surface E/Ecr(y,z), right – lines of equal level of E/Ecr(y,z), t = 10μs

The character curvature of forming loop depends on initiator location relatively focus point. At some locations streamers developing along snake-shaped trail as it is observed in experiment. It is clearly seen in Fig.12 where configuration of electric field distribution at t= 10 μs is compared with photo of real streamer.

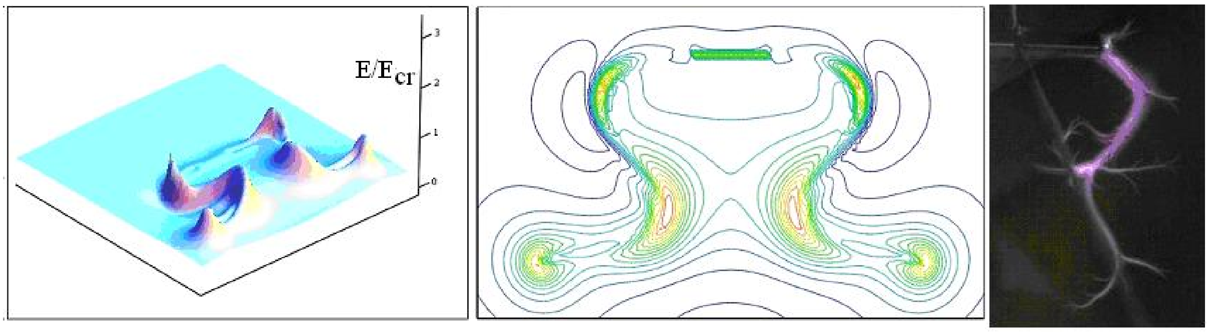

Figure 12. Field distribution around streamers developing in focused MW. Initiator is located before focus point. Streamers rise against radiation as a snakes. Left – surface E/Ecr(y,z), center– lines of equal level of E/Ecr(y,z), t = 10μs, right – photo of real streamer rising from initiator end.

Modeling shows that in dependence on concrete distribution of MW field the streamers are able to form freely loops and snakes.

Role of the brunching

The situation is very being complicated at streamer brunching. The taking into account the streamer brunching can influence on condition of streamer curving against radiation from the very beginning. As have shown earlier numerical investigations, undertaken for flat MW, at some conditions (for example, at initiator length near to resonant value) the branching can appear at early stage. In Fig.13 are shown the results of subcritical streamer development modeling by model allowing branching but ordering possible ways of streamer development, borrowed from 8. The streamers can propagate along orthogonal rare net of initially not ionized channels. At this case the branching forces streamers to curve and to form loop against radiation.

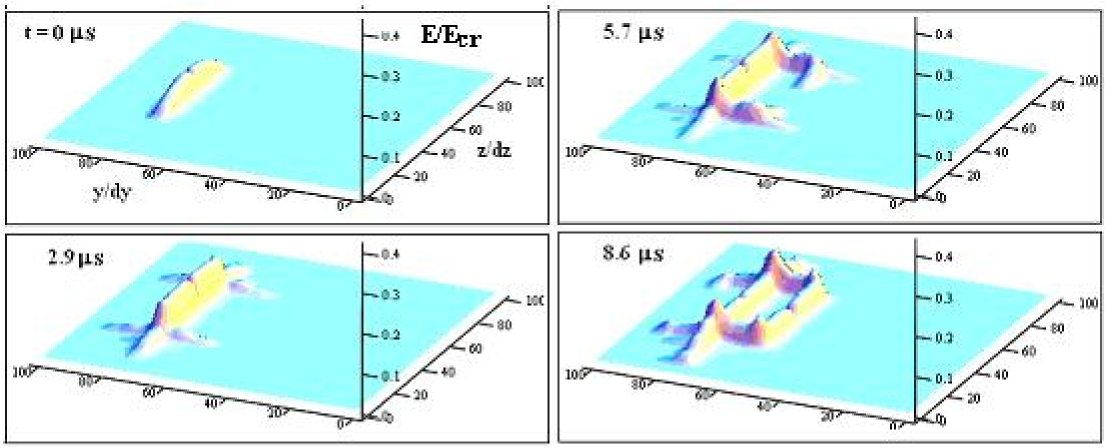

Figure 13. Inducted current space distribution in dependence on time.

The secondary branching of additional streamers developing against radiation results forming of closed loop together with initiator. Such picture is typical for subcritical discharges initiated by electromagnetic straight vibrator. Farther development goes from front part of appeared loop against radiation.

The average velocity of discharge front is ~1 km/s and streamer velocity along the trail is ~2 km/s. It well coincides with both observations and estimations in 5], based on taking into account of main factors: ionization frequency, electron free diffusion, Ohm heating and top field increasing.

V. Discussion

By direct modeling on various numerical models, is confirmed the resonant nature of the streamer subcritical MW discharge, its ability to use branching for saving of resonant state continuously during development, and its property to propagate against radiation by means of looping in flat MW and at initial stage without branching in focused MW.

The appearance of test-streamer crown at streamer head plays significant role. These crown preserve appear of areas with strongly overcritical field near streamer head, creates conditions for brunching and continuously defines direction of streamer propagation every time moment.

The designed physical model of subcritical streamer MW discharge development, based on self consistent nonlinear electrodynamics and plasma dynamics taking into account ionization by electron impact and dissociate attachment, free electron diffusion and Ohm heating, can be used as the quite adequate.

VI. Acknowledgments

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