FACTORS DEFINING PROPAGATION OF MICROWAVE SUBCRITICAL STREAMER DISCHARGE AGAINST RADIATION

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This paper is devoted to theoretical study of the intriguing property of subcritical microwave discharge to propagate against microwave radiation forming thin curved channels with branches and loops. Using approach of excluding, author has come to the conclusion about important role of ionized halo generated by UV of the discharge hot channel.

Nomenclature

E = effective amplitude of electric field of microwave radiation
E_{cr} = critical value of electric field
I = streamer current
c = light velocity
ω, λ= microwave radiation frequency and wave length
σ = plasma electrical conductivity
T = gas temperature
N = gas number density
C_p = gas thermal capacity at a constant volume
D = free electron diffusion coefficient
K_i, K_a= reaction rate of ionization and electron attachment
a = streamer radius
V = streamer radial velocity
f = ionization coefficient
β = recombination coefficient
p = gas pressure
ρ = gas density
t = time
l = distance along streamer
k = $2\pi/\lambda$ - wave number
Λ = character sizes of high amplitude area
τ_{exp} = exposition time
τ_{pause} = pause time

Introduction

Electrical gas discharges in 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[1,2]. In more late investigations of breakdown threshold created in a focus of MW beam radiation parameter Λ was determined by sizes of focus area. It is known that at low pressure discharges represent the smooth diffusion clouds[3]. The diffusion type of discharges is the most investigated. Many kinds of instabilities were studied. 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.

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 faith 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 attaché 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 λ/2, grows is performing only by branching of the streamer channels[7].

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 explanation of this peculiarity of subcritical MW discharge.

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.

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

It is confirmed by time-lapse filming represented in Fig.2, which shows the time evolution of surface subcritical discharge at the same conditions[8].

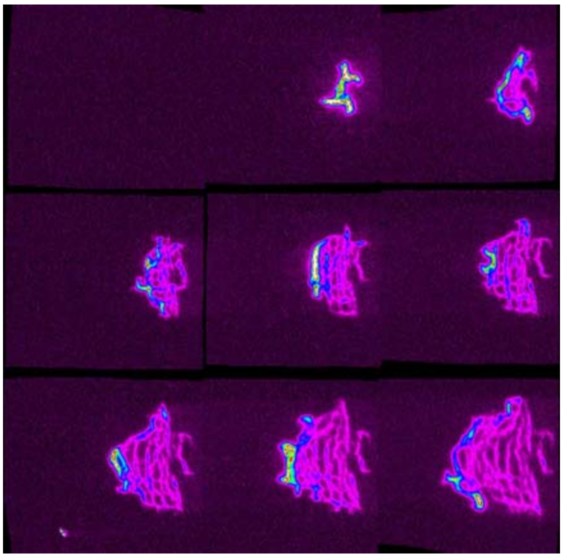

Fig.2. Frame-by-frame photography of the longitudinal surface streamer MW discharge (τ_{exp}=0.1 μs; τ_{pause}=2 μs)

The insignificant influence of radiation shielding on discharge property to propagate against radiation is especially clearly seen in Fig.3, which demonstrate the very 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 at that it is absolutely clear, that this phenomenon cannot be explained by radiation shielding[9].

It is naturally to suppose that the streamer head must have tendency to rise in direction in nearest vicinity, where electric field amplitude is maximal. Indeed, initially the streamer goes in direction of maximal electric field amplitude, almost along vector of electric component of original field. Figure 4 shows the electric field distribution around metal sphere, presented in Fig.3, without streamer ($R_{sphere} = 0.05\cdot\lambda$). One can see that maximum field is located on poles of sphere. The initiator radius is small comparatively with wavelength, so distribution differs from distribution in DC field insignificantly.

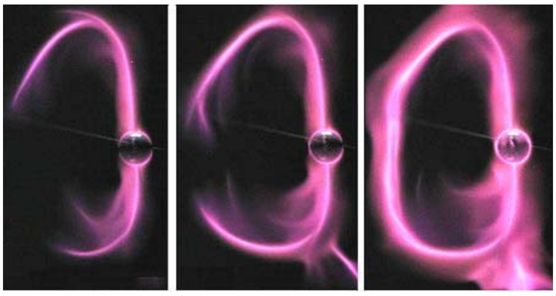

Fig.3. Time-lapse filming of subcritical MW discharge, initiated by metal sphere ($\tau_{exp} = \tau_{pause} = 1$ μs). Radiation is directed from left to right.

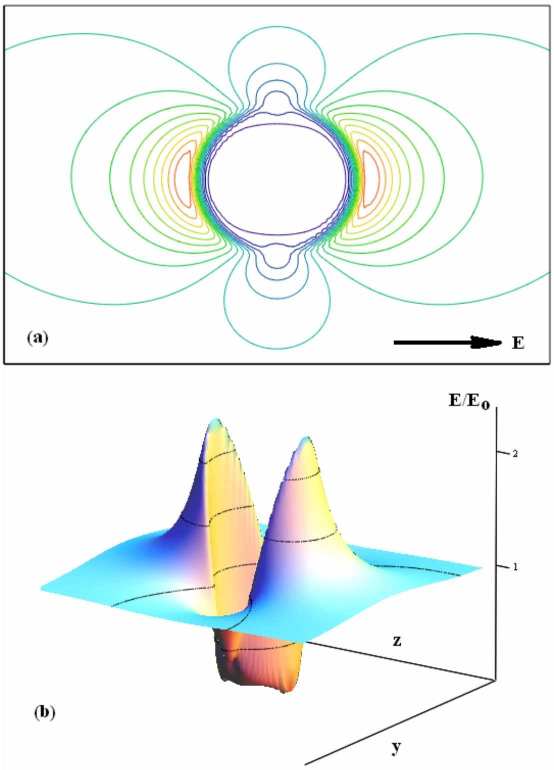

Fig.4. Electric field amplitude distribution around spherical initiator. (a) – lines of equal magnitudes, red are zones of high amplitude. (b) – surface E(y,z). $R_{sphere} = 0.05\cdot\lambda$

However, field distribution with started streamer has maximum field not at the streamer axis near its heads but at side opposite the side of radiation source location.

The field amplitude near streamer top in several times higher than maximum field at poluses of spherical initiator.unperturbed (see Fig.5). The more length of the streamer, the more top field increase (while the length is less than resonant value).

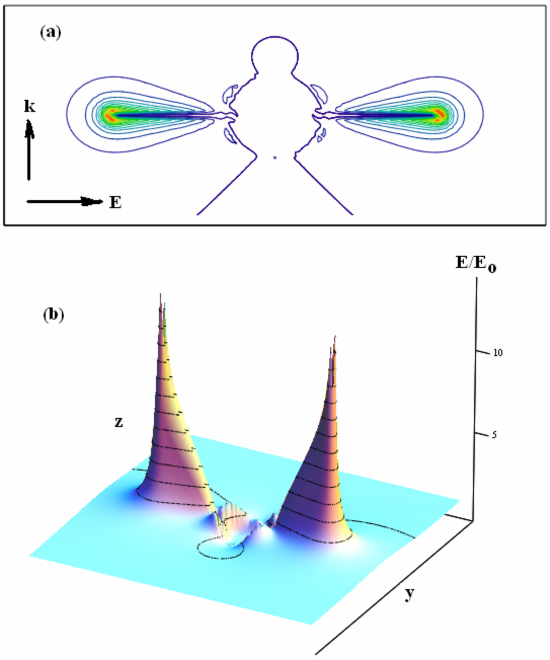

Fig.5. Electric field Amplitude distribution around spherical initiator with started streamer. (a) – lines of equal magnitudes, red are zones of high amplitude. (b) – surface E(y,z). $R_{sphere} = 0.05\cdot\lambda$

Fragments of field distributions in Fig.6 for different length of straght streamer channels demonstrates that near top of the streamer field has one maximum at small length (Fig.6a) and two maximum at incresed its length (Fig.6b). This effect is strongly increased by observed hedgehog of mini-streamers at the streamer head (see photo in Fig.7a). These mini-streamers are short-living creatures. They are arising when area of overcritical electric field around main streamer head is quite enough. Executed calculation of field distribution around streamer with hedgehog taking into account, presented in Fig.7, show the deformation the field distribution. As result, the field amplitude inside area of hedgehog has value that is more critical a little only. The presence of two maximums becomes obvious. The electrical conductivity of mini-streamers is very small, about $\omega/4\pi$. There lifetime are about several nanoseconds.

The main maximum laies behind the streamer axis relatively to radiation source. It means that one can wait, that the streamer will develop in direction of the wave propagation (in direction of wave vector k). Nevertheless, experiment shows that streamer develops against radiation, in opposite direction.

The rise of situation, when top field has two maximum, create the possibilities for the streamer brunching, which of course is able cardinally change the field distribution and general picture of propagation process. For test of this supposition, I have performed the numerical modeling.

Model of initiator streamer system

The fully adequate model, able to describe the process of MW discharge development in undercritical field, demand use of the system of Helmholtz 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[10,11] have shown that difficulties of technology of calculation by such model do not allow investigating the process saving main its properties.

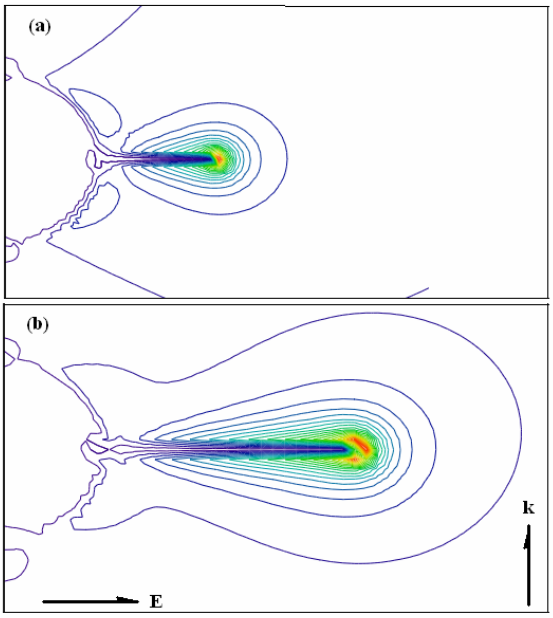

Fig.6. Electric field distribution around started streamer. $R_{sphere} = 0.05\cdot\lambda$

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

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

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[12], 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.

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

Those equations (Eq.1 and Eq.2) can be used for calculation of diffraction of MW radiation on volumetric metal bodies too, as one can see on Fig.4, Fig5 and Fig.6.

For research of formulated task, the simplified model of plasma thin channel dynamics was used. First it was described in Ref.[13] and more detail in Ref.[14]. Equation (3) describes processes of ionization by electron impact, electron diffusion, attachment and recombination in air

$$\frac{\partial f}{\partial t} = N\cdot\left(K_i(E)-K_a\right)\cdot f + \\ + \frac{\partial}{\partial l}\left(D(N)\cdot\frac{\partial f}{\partial l}\right) - \beta\cdot\left(f\cdot N\right)^2 \qquad (3)$$

Equation (4) takes into account the gas Ohm heating by inducted MW current

$$C_v\left(T_g, N\right)\frac{dT_g}{dt} = \frac{\sigma(f)\cdot|E|^2\cdot\Phi(\sigma,a)}{N} - T_g\cdot\frac{2V}{a} \qquad (4)$$

Equations (5) – (6) correspond to so-called envelop model, often used for approximate simulation.

$$\frac{\partial N}{\partial t} = -2\frac{V}{a} \qquad (5)$$

$$\frac{dV}{dt} = 2\cdot\frac{P_0 - P}{\rho_0\cdot a} \qquad (6)$$

$$\frac{da}{dt} = V \qquad (7)$$

The system Eq.(3)-Eq.(7) is closed by Eq.1-Eq.2 for electric field inside of arbitrary oriented thin channels with given (calculated on each time step) distribution of conductivity. Comparatively to Ref.[13] the used integral equation was modified for any complicated form of conducting thin channels. The integral equation defines the MW current distribution along channels with known distribution of conductivity. Calculated current defines the field distribution by means of integral operators.

The designed model is based on main physical factors controlling the process of streamer development in undercritical field: ionization and electron diffusion, field increasing on the streamer tops and gas heating.

Calculation was performed for air at initial pressure 200 Torr and gas temperature 300K and MW origin field $E_o = 0.4\ E_{cr}$ at $\lambda = 8.9$cm. Length of the initiator equals to $\lambda/4$. Its radius 0.15cm is enough for initiating of discharge at given origin field.

The ways of possible streamer development are chosen in form of rectangular net with quite small cells. The way net and initiator is presented in Fig.8.

Results of modeling

Modeling confirms the ability of the streamer discharge to propagate infinitely in undercritical field against MW radiation far away from initiator by means of branching with loops creation.

The discharge development is demonstrated in Fig.9, showing the inducted current space distribution in time. Initially the current exists in the initiator only. Initiator length is less than resonant value, and current amplitude is less than resonant one.

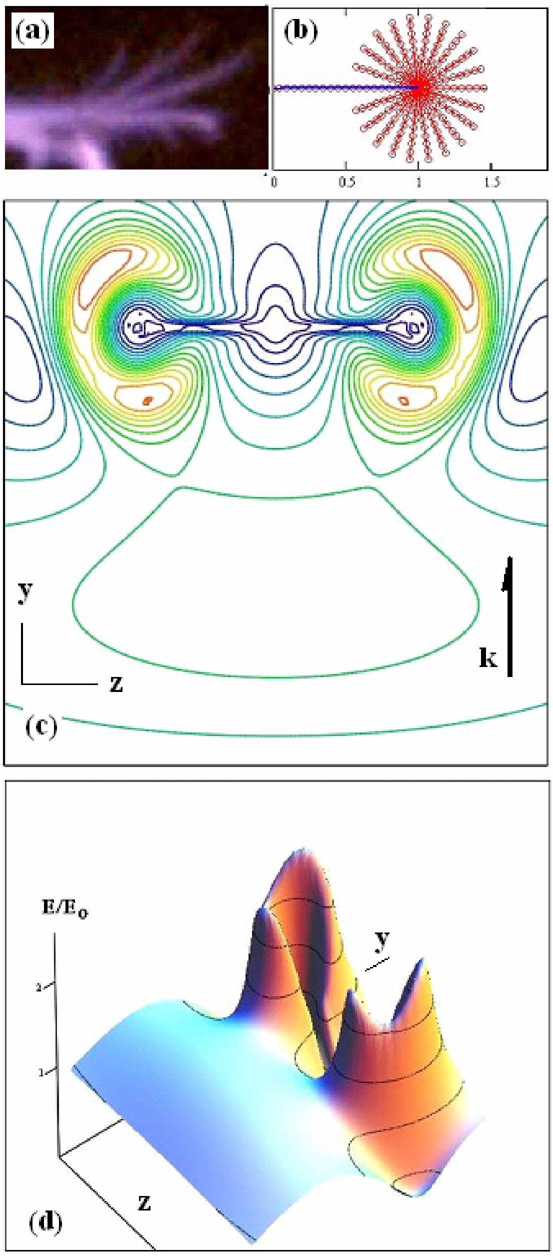

Fig.7. The mini-streamer hedgehog influence on electric field amplitude distribution at the streamer head vicinity. (a) – photo the mini-streamer hedgehog, (b) – artificial hedgehog in modeling, (c) and (d) – electric field distribution around main streamer with hedgehog.

Then the streamers starts to rise from top of initiator along initiator axis (oriented along electric field of MW radiation with linear polarization). Total electrical length of initiator with streamer achieves resonant value and current amplitude has increased up to resonant value. Simultaneously additional branches grow, as it has been predicted earlier.

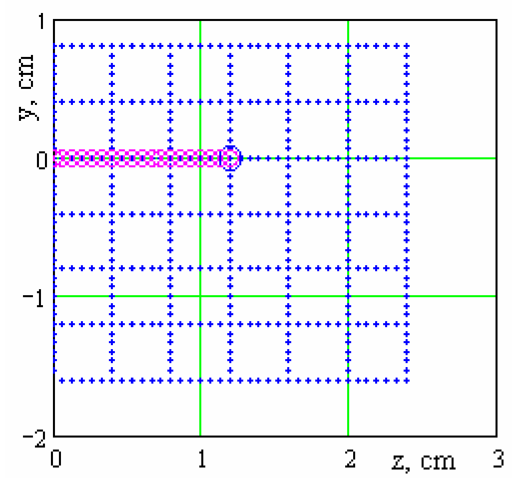

Fig.8. Way-net of streamer possible development and initiator location (right half of simmetrical system)

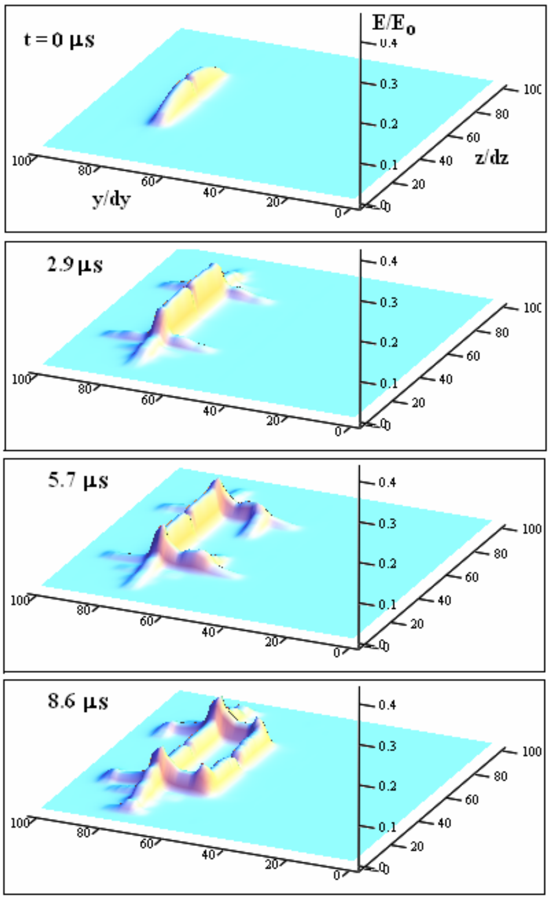

Fig.9. Inducted current space distribution in dependence on time.

The secondary branching of additional streamers developing against radiation results forming of closed loop together with initiator. Such picture is typical for undercritical 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 Ref.[5], based on taking into account of main factors: ionization frequency, electron free diffusion, Ohm heating and top field increasing.

Summary

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.

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