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Electrodynamics of many vibrators system for fuel ignition[*]

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The microwave discharge technology provides the unique possibility of the wireless feeding of system of initiators arbitrary located in space. The work is devoted to the design of computation method and the study of electrodynamics of complicated system of thin electromagnetic vibrators. The main problem is the defining of conditions which creates ability to sustain the stable burning of attached microwave discharge at all initiators simultaneously. Parameters for optimization are vibrators length, distances and angles in 3-D space between them, direction of microwave radiation, its polarization and level.

Nomenclature

E = effective amplitude of electric field of microwave radiation
E_{cr} = critical value of electric field
I = inducted current
c = light velocity
ω, λ= microwave radiation frequency and wave length
σ = plasma electrical conductivity
T = gas temperature
N = gas number density
C_v = gas thermal capacity at a constant volume
D = free electron diffusion coefficient
K_i,, K_a= reaction rate of ionization and electron attachment
a = conducting channel radius
V = streamer radial velocity
f = degree of ionization
β = recombination coefficient
p = gas pressure
ρ = gas density
V_{flow} = velocity of gas flow
t = time
l = distance along conducting channels
k = $2\pi/\lambda$ - wave number
i = $(-1)^{1/2}$
L_v = length of vibrator
Δ = distance between neighborhood vibrators in a flat system
R_s = radius of cylindrical system
α = azimuthal coordinate of vibrators in cylindrical system

I. Introduction

Between many types of microwave (MW) discharges[1,2,3] the attached MW discharges represents the most interest. It is caused by three important circumstances. It can be executed in very slight MW radiation, can exist in supersonic gas flow and is able to ignite a combustible mix just in a high-speed flow[4,2,5]. The attached MW

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discharge (named also deeply undercritical discharge) can be created by means of special igniters. The most frequently for the attached discharge creation electromagnetic vibrator is used. Electromagnetic vibrator represents a metal cylinder oriented along electric field of linear polarized MW radiation. Its length is compare with half wavelength of radiation. It can play role of initiator because is able to increase origin field near its tops in many times. Cylinder can be sharpened for more increase field amplitude near tops. Without an initiation undercritical discharge can't start. But if the initiator creates the overcritical field at its top the streamer is starting from point of maximum field on the top of initiator. If the streamer radius is more than curvature radius of vibrator's top needed for required field increase the streamer cant rise to length exceeded the small part of wavelength so the streamer past be attached to point of initiator[6,7]. In Fig.1 this type of discharge corresponds to area III[2].

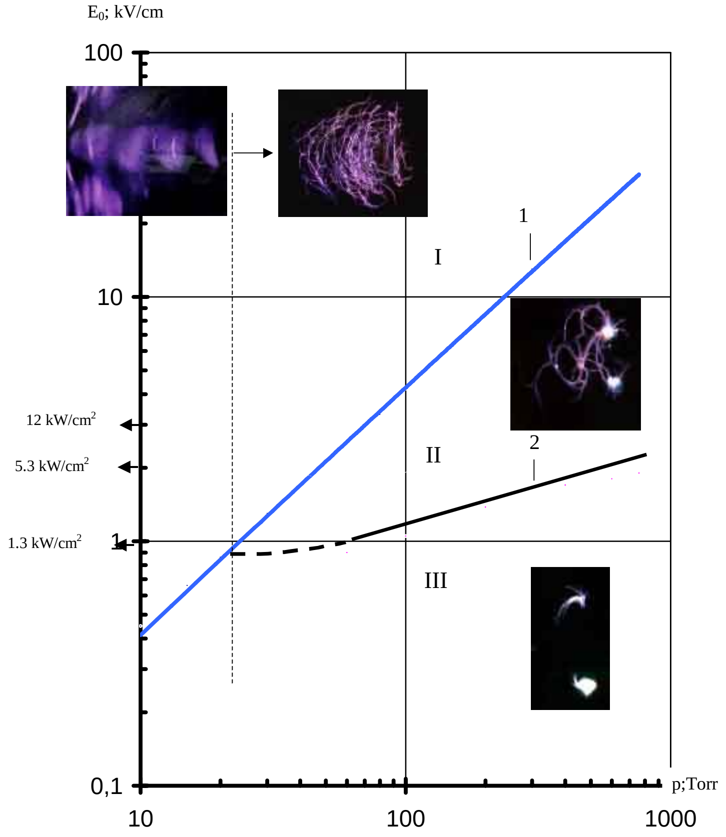

Figure 1. Various type discharge dominions in a motionless air in pulse MW beam, λ=8.9 cm, τ=40μs. 1 – Ecr(p), 2 – bound between undercritical and deeply undercritical discharges. Area I – overcritical discharges. Area II – undercritical volumetric discharges. Area III –undercritical attached discharges

If vibrator is flowed by high-speed stream (including supersonic one) the attached streamer creates very hot tail in the flow. Temperature in the streamer and tail achieves some thousands Kelvin, which is more than enough for fuel mix ignition. Direct experiments confirm this ability[4]. So this type of MW discharge successfully can be used in devices with internal and external combustion for fuel ignition. Important advantage of this method of fuel ignition is possibility of remote feeding of igniter without wires.

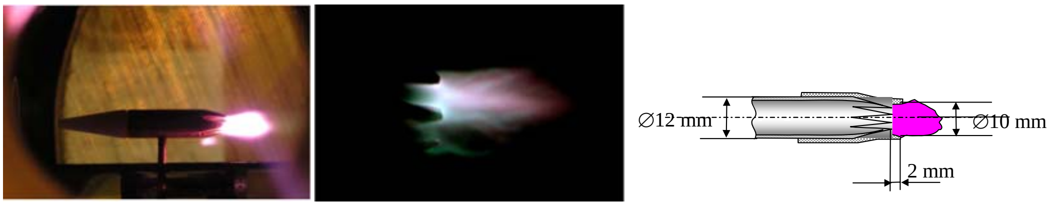

Figure 2. MW discharge initiated by passive vibrator with many sharpened tips in SS flow: general view, open lens – left, aft area, short exposition – middle, vibrator aft scheme – right.

This circumstance allows the location of the igniter arbitrary far from other elements of construction and, if needed, using system of igniters simultaneously in common volume. In experiment on combustion ignition by attached MW discharge in supersonic cold airflow the vibrator with many points in its aft is used for increase the combustion efficiency[8]. In Fig.2 the photos of attached discharge in supersonic airflow, ignited by such complicated vibrator, and vibrator scheme are shown.

This complicated vibrator can be approximated by cylindrical system of separate thin vibrators for calculation of electrical field distribution at the aft of vibrator. It is easy to imagine situations, when initiating vibrators are located separately for creation many points of ignition simultaneously. In all cases the vibrators are coupled electromagnetically one with another, so the distribution of field amplitude at tips of vibrators between them can be significantly inhomogeneous. Knowledge of inducted current distribution in system of vibrators both in free running and at discharge presence is needed for prognosis and explanation of experimental data.

II. Numerical model

The fully adequate model, which is able to describe the process of MW discharge development in undercritical field, demands use of the system of Helmholtz for electromagnetic field plus gas-dynamic system for multi-component plasma mix taking into account the needed physical-chemical processes in 3-D frame. Experience of designing of such model[9,10] have shown that difficulties of technology of calculation by such model do not allow investigating the process saving its main properties.

Thus for realization of formulated task the simplified model of vibrators with plasma thin channel dynamics was used. First it was described in Ref.[11] and more detail in Ref.[12].

For calculation of current inducted in system of vibrators loaded by discharges (arbitrary oriented thin channels with given calculated on each time step distribution of conductivity) the 1-st kind integral equation Eq.(1) is used

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

where

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

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

$$\vartheta(l)=\pi\cdot a^2\cdot\sigma(l).$$

Calculated current defines the field space distribution by known operators:

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

The conductivity of vibrators is being elected quite large. Length of vibrators is a little less than resonant value. Its radius is small enough for initiating of discharge at specified external field amplitude.

Conductivity of discharge channels is defined by equation system of simplified plasma dynamics. Equation (3) describes processes of ionization by electron impact, electron diffusion, attachment and recombination in air

$$\frac{df}{dt}=N\cdot\left(K_i(T_e)-K_a\right)\cdot f+\frac{\partial}{\partial l}\left(D(N,T_e)\cdot\frac{\partial f}{\partial l}\right)-\beta\cdot(f\cdot N)^2. \tag{3}$$

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

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

Equations (5) – (9) correspond to so-called envelop model, often used for approximate simulation:

$$\frac{dN}{dt} = -2\frac{V}{a}\,, \tag{5}$$

$$\frac{dV}{dt} = \frac{2}{a}\cdot\left(\frac{P_0 - P}{\rho_0} - V^2\right), \tag{6}$$

$$\frac{da}{dt} = V\,, \tag{7}$$

$$p = N\cdot\left(T_g + f\cdot T_e\right), \tag{8}$$

$$T_e = F\left(\frac{E}{N}\right), \tag{9}$$

$$\frac{d}{dt} = \frac{\partial}{\partial t} + V_{flow}\frac{\partial}{\partial l}\,.$$

Coordinates of the conducting channels (including vibrators and discharge) are defined parametrically. Area of integration L includes all conducting channels: vibrators and discharges. Location of vibrators with discharges in space is given. All channels oriented along electric field of linear polarized external radiation and along gas flow. The longitudinal velocity of gas flow V_{flow} is given.

Comparatively to Ref.[12] 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.

The designed model takes into account main physical factors controlling the process of streamer development in undercritical field: ionization by electron impact, electron attachment and recombination, electron diffusion, field increasing on the streamer tops, gas heating and caused gas dynamics.

The trails of developing streamers follow the gas flow.

III. Results of modeling

A. Cylindrical system of vibrators

Figure 2 shows the example of complicated vibrator with many tips use. It is the case when many separate vibrators system is modeling the real device.

Such method is suitable if the tips are quite long comparatively with vibrator length. But cylindrical system of vibrators can be used with arbitrary distance between them if on needs have many separated points of ignition in a flow. The scheme of vibrators location in general case of cylindrical system is shown on Fig.3. Electric field of external MW radiation is oriented along axis z (ψ_w=0). Wave length is accepted equaled to λ=12.5 cm. It is the same value as in experiment Ref.[8].

In experiment Ref.[8] many-tips vibrator is located in maximum of standing wave created by direct wave of radiation and back wave reflected by metal shield. The calculated field distribution in cross-section corresponding to ends of vibrator with eight tips and radius R_s=0.5 cm, which is the same as in experiment[8], is demonstrated in Fig.4. The calculation is performed for free running, other words, the discharges is absent. One can see that maximal field values at each tip are almost the same.

It means that one may suppose the homogeneous ignition of discharges at each tip. The real experiment confirms this hope. The discharge in left photo in Fig.2 is almost homogeneous in transverse cross-section. All discharges create united torch indeed.

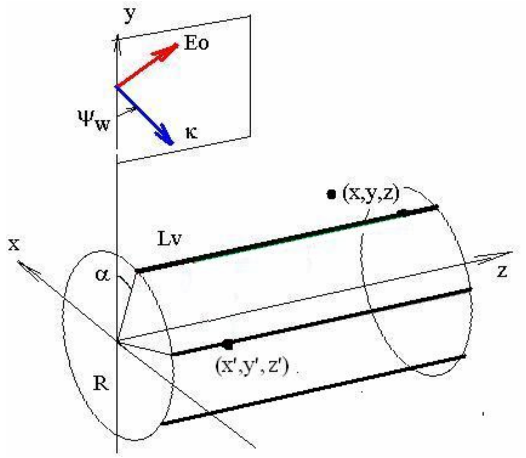

Figure 3. Cylindrical system of parallel passive vibrators. Parameters b and d corresponds to Eq.(5) and Eq.(6)

The different situation arises when the same system is placed into radiation wave in traveling mode (back wave is absent). Than each vibrator is excited with its own magnitude of field phase shift and in result of vibrators electromagnetic interaction the maximal field distribution between vibrators can be significantly inhomogeneous.

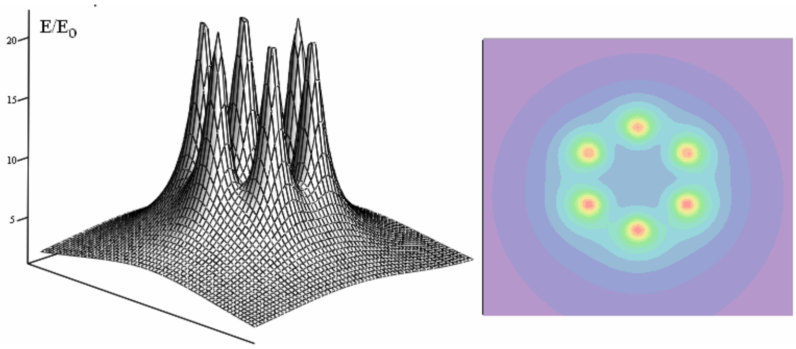

Figure 4. MW field distribution near vibrator's sharpenings, system is located in maximum of a standing wave of MW radiation

This effect is seen clearly in Fig.5, which demonstrates electric field distribution for system with the same geometry parameters as in previous case.

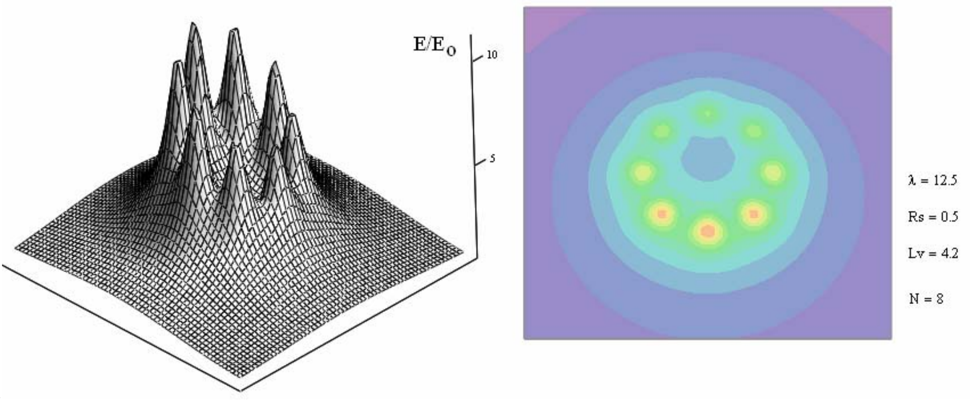

Figure 5. MW field distribution near vibrator's sharpenings, traveling wave mode

It is easy to see that in traveling wave the same system of vibrators create inhomogeneous distribution. Interesting, that minimal field is creating from side looking to sours of radiation. This inhomogeneity and form of distribution depends on the system radius. In fig .6 the distribution of maximum values of current inducted in vibrators is shown for systems with varied radius. Note, that maximum field at tip of vibrator is proportional to current in vibrator. Figure 7 and Fig.8 demonstrate electric field distributions corresponding to Fig.6, R_s=2 cm (middle) and R_s=6 cm (right).

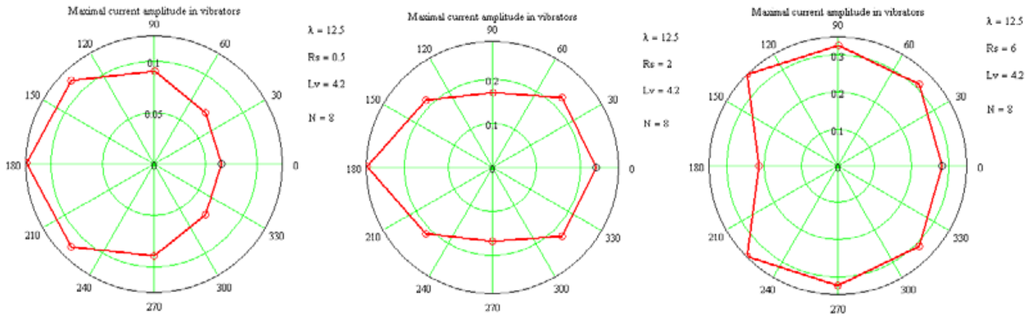

Figure 6. Amplitude of MW current inducted in vibrators, traveling wave mode. MW radiation is directed from right to left. Rs= 0.5 cm (left), 2 cm (middle), 6 cm (right)

At system radius R_s=6 cm the diameter of system almost equals to wavelength. In Fig.8 the wave diffraction on vibrators system is seen clearly. The reradiating by vibrators creates the interference picture with cone of causality because vibrators represent delay structure scattering initial radiation.

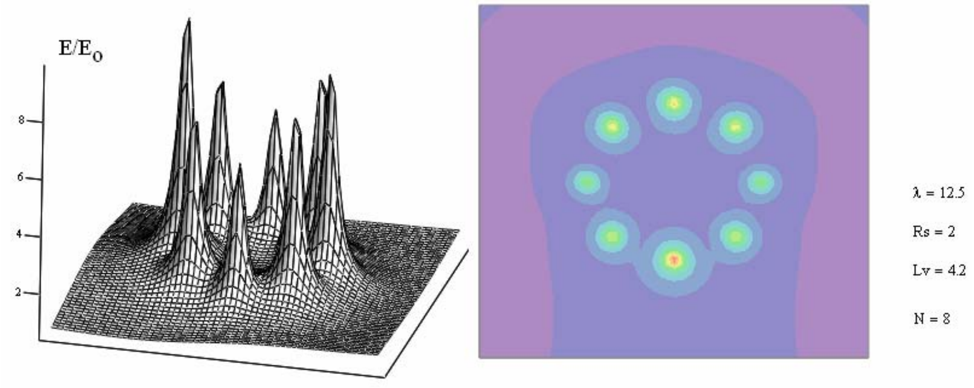

Figure 7. The MW field distribution near vibrator's sharpenings, traveling wave mode

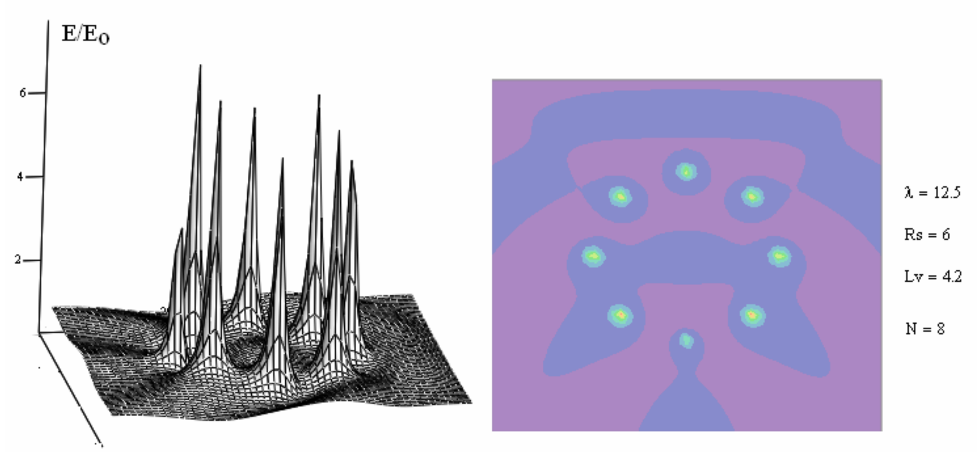

Figure 8. MW field distribution near vibrator's sharpenings, traveling wave mode

B. Flat system of vibrators

In many practically cases the flat system of igniting vibrators can be interesting. Precedent of experimental use of vibrators flat system for MW attached discharge ignition is described in Ref.[13] The example of such flat system and scheme of MW power feeding is represented in Fig.9 (left). The MW wave with flat phase front is radiated normally to plane of vibrators system or along the plane. Scheme of geometrical configuration of the system accepted for modeling is shown on Fig.9 on the right.

The consequence of passive vibrators laying in common plane represents the delay line with its own phase speed of electromagnetic waves. Passive vibrator is a vibrator without any feeding by external electrical circuit. The delay line of finite length has a spectrum of eigenmodes. Even at discharge absence this open system is dissipative because losses on radiation in consequence of reemission of external wave. The losses limit the quality factor of each eigenmodes so frequency diagram remains band-pass filter. Created distribution of induced current between vibrators depends on proximity of external field frequency to neighborhood eigenfrequency of system and direction of wave vector of external wave. If external wave propagates along axis y (see Fig.9 (right)) the losses of reemission cause the decrease of induced currents along system.

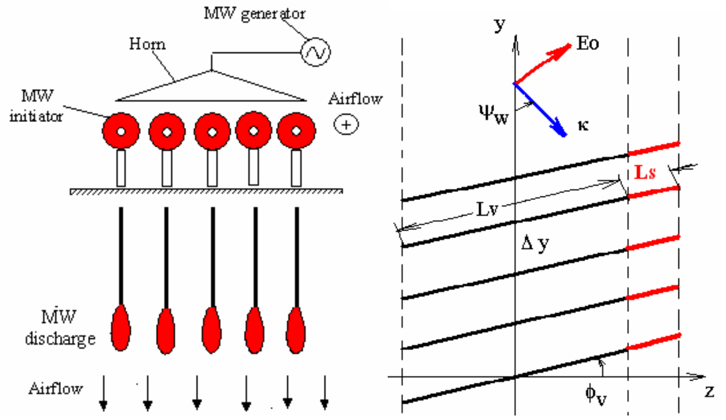

Figure 9. The possible scheme of flat system of passive vibrators (left). The geometry of system used in modeling (right).

Example of such decay is shown on Fig.10, which demonstrates the calculated electric field spatial distribution at plane of system, consisting from 8 vibrators (Fig.10-a and Fig.10-c) and current maximal amplitude distribution on vibrator's number **n** (Fig.10-b)). Effect of spatial decay can be interpreted as result of shielding of next vibrator by previous one. The shadow created by vibrator was investigated in Ref.[14].

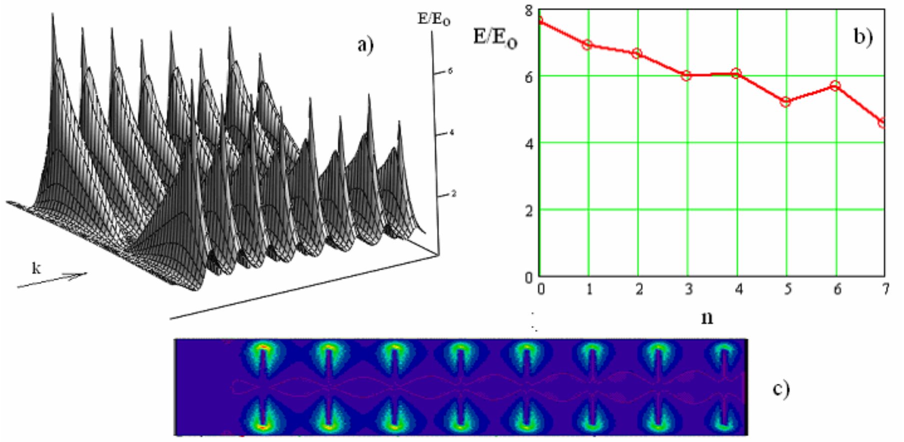

Figure10. MW field distribution in vibrator's plane, traveling wave mode, Δ=3.2 cm, Lv=4.2 cm, N=8, λ=12.5 cm

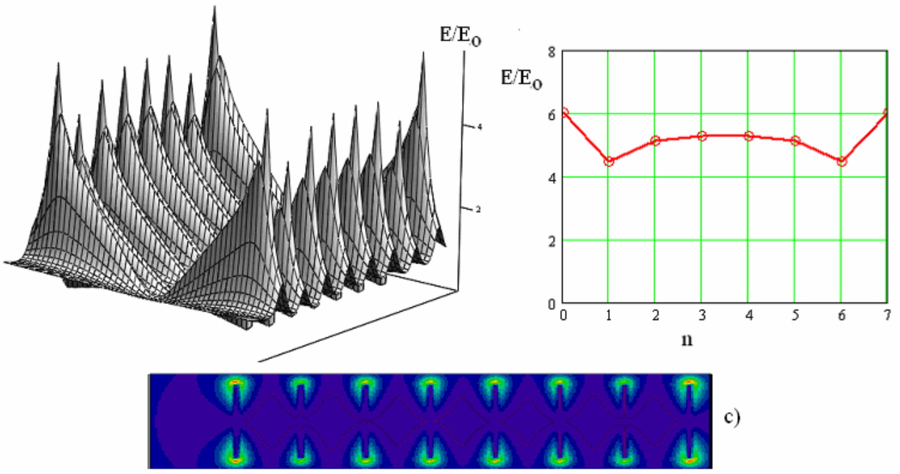

Figure 11. MW field distribution in vibrator's plane, Δ = λ/4, Lv = λ/3, N = 8, λ = 12.5 cm

Other distribution appears if wave vector of external wave is normal to vibrator system plane. All vibrators are being excited in one phase (synchronously), so distributions of electric field (Fig.11-a and Fig.11-c) and induced current (Fig.11-b) are symmetric.

In all cases of synchronous excitation the induced current distribution is symmetrical concerning median line of system. Profile of distribution depends on electrical length of vibrators and distance between them. As rule, the field increase created by system of vibrators is less than increase by a single vibrator.

C. Flat system of vibrators loaded by discharges

No doubt that homogeneous distribution of inducted current in system of vibrators at normal to system plane falling of external wave can be achieved by accordance election of individual parameters of vibrators (its length, radius and distance between them). But significantly more complicated problem is a question how will work the system with discharges of attached mode in a high speed flow. How to achieve the homogeneous burning of discharges? Will be the burning stationary? We know from experiment[15] that single attached discharge in supersonic flow is approximately stable. Its typical photo is presented in Fig.12.

From other side it is known that the discharges in many electrode gaps system feeding from a common direct current (DC) source cant burn together. Only one gap can burn at given time moment. In difference from DC systems the investigated flat system of passive vibrators excited by external MW radiation is able to sustain simultaneous burning of discharges attached to every vibrator.

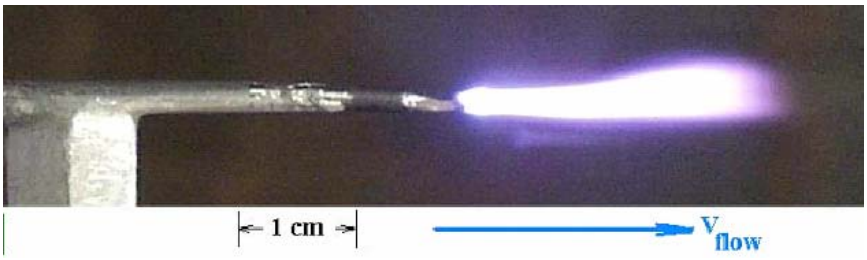

Figure 12. Attached MW discharge in supersonic airflow

Carried out preliminary numerical investigation have confirmed this ability. For nonstationary describing of attached discharge in supersonic airflow the system Eq.(5) – Eq.(9) is used together with system Eq.(1) – Eq.(2) for electromagnetic field. The field is being calculated at each time step of solving of equations system for discharge.

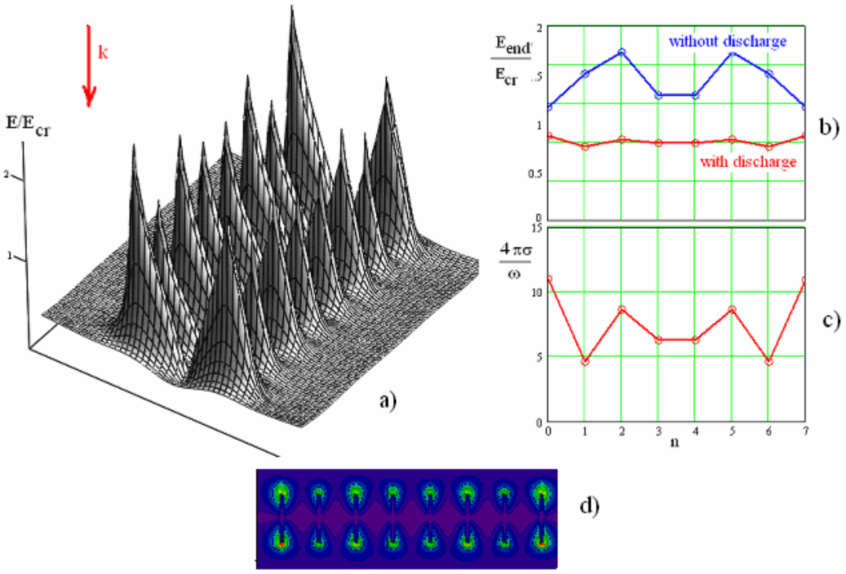

Figure 13. MW field distribution in vibrator's plane for discharges in SS flow, $\Delta=\lambda/4$, $Lv=\lambda/2.6$, $N=8$, $\lambda=12.5$ cm, $Eo/Ecr=0.3$, air pressure equals to 0.3 atm

Figure 13 demonstrates example of stable simultaneous burning of discharges attached to all eight vibrators. Starting from small ionization at aft of each vibrator, the attached discharges are developing and are being saturated on levels, which are sustained almost stationary. Figure 13-a and Fig.13-d show the spatial distribution of field amplitude. Figure 13-b and Fig.13-c demonstrate distribution of top electric field and maximal discharge electric conductivity in dependence on vibrator's number accordingly. On Fig.13-b one can see the difference between mode of free running and regime of discharge loading at saturated state. Although the top field distribution at load regime is more homogeneous than without discharge, parameters of discharge are highly different.

IV. Summary

Carried out investigations, which used designed numerical code, have preliminary character. They confirm the work ability of designed model of vibrators system loaded by attached discharges in a gas speedy flow. Modeling of concrete examples of vibrators system serving for discharge ignition allows doing some resumes.

In free running mode the distribution of inducted currents in vibrators can be very inhomogeneous in dependence on geometrical parameters of system, direction of wave vector of external wave concerning orientation of system, standing wave coefficient of external field and others. The problem of homogeneity of inducted current distribution can be solved by selection of individual length of vibrators and distances between them and of propagation direction of external wave.

The attached discharge loads each vibrator and changes its electric length influencing on its eigenfrequency. Parameters of discharge depend on inducted current in each vibrator. Behavior of such nonlinear dissipative system can be predicted only by modeling. Preliminary experience of modeling of a flat vibrators system loaded by discharge showed that in concrete variant of system the process is saturated by almost stationary state. But it is not mean that the steady-state solution can be achieved in any cases. The photo of attached discharge in figure 2 (middle) can be interpreted (if one wishes) as display of the discharge instability. Possibly, the streamer loads only one tip of initiator and travels from one to other successively. This problem must be studied by separate research.

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References

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[1] *High frequency discharge in wave field.* Scientific works collection IPM AN SSSR, Gorkii, 1988.

[2] I. Esakov, L. Grachev, and K. Khodataev and D. Van Wie. *Investigation of the Undercritical Microwave Streamer Gas Discharge for Jet Engine Fuel Ignition*. AIAA Plasmadynamics and Laser Conference, 32nd, and Weakly Ionized Gases Workshop, 4th, Anaheim, CA. Jun 11-14, 2001. AIAA Paper 2001-2939.

[3] Igor Esakov, Lev Grachev and Vladimir Bychkov. *Experimental determination of microwave undercritical discharge transition to deeply undercritical at different wavelengths.* 43nd AIAA Aerospace Sciences Meeting 10-13 January 2005, Reno, NV. Paper AIAA 2005-597.

[4] K. V. Khodataev, A. Ershov. *Experimental investigation of a possibility of a MW streamer gas discharge application for fuel ignition in jet engine.* Proc. supplement of 2-nd Weakly Ionized Gases Workshop. Waterside Marriott Hotel, Norfolk, Virginia, USA, 24-25 April, 1998, pp. 339-350.

[5] Igor Esakov, Lev Grachev, Kirill Khodataev and David Van Wie. *Experiments on propane ignition in a high-speed airflow with a help of deeply undercritical microwave discharge.* 42nd AIAA Aerospace Sciences Meeting 5-8 January 2004, Reno, NV. Paper AIAA-2004-0840.

[6] Kirill V. Khodataev. *Development scenario and main parameters of different types of the microwave streamer discharges.* Proc. of the 15-th Intern. Conf. on MHD Energy Conversion and Sixth International Workshop on Magnetoplasma Aerodynamics (May 24-27, 2005, Moscow, Russia), pp.556-564

[7] Kirill V. Khodataev. *The initial phase of initiated undercritical microwave discharge.* Proc. of 43-rd AIAA Aerospace Sciences Meeting and Exhibit, 10-13 January 2005, Reno, NV, USA. Paper AIAA-2005-0598

[8] Igor I. Esakov, Lev P. Grachev, Kirill V. Khodataev, Viacheslav A. Vinogradov and David M. Van Wie. *Efficiency of Propane-Air Mixture Combustion Assisted by Deeply Undercritical MW Discharge in Cold High-Speed Airflow.* Proc. of 44-rd AIAA Aerospace Sciences Meeting and Exhibit, 9-12 January 2006, Reno, NV, USA. Paper AIAA-2006-1212.

[9] O. I. Voskoboynikova, S. L. Ginzburg, V. F. D’achenko, K. V. Khodataev. *Numerical investigation of subcritical microwave discharge in high-pressure gas*. Tech. Phys. Vol.47, No. 8, pp. 955-960.

[10] S. L. Ginzburg, V. F. D’achenko, V. V. Paleychik, K. V. Khodataev. *3-D model of microwave gas discharge*. Preprint M.V.Keldysh Applied Math. Inst. RAS. 2005.

[11] K. V. Khodataev. *Physics of super undercritical streamer discharge in UHF electromagnetic wave*. Proc. XXIII ICPIG, 17-22 July 1997, Toulouse-France, Contributed papers, IV-24.

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[12] K. V. Khodataev. *Theory of the microwave high-pressure discharge*. Proc. of IV International workshop “Microwave discharges: fundamentals and applications”, September 18-22, 2000. Zvenigorod, Russia, pp. 35-44. (Yanus-K, Moscow 2001)

[13] S. Popovich, R. J. Exton, G. C. Herrig. *Transition from diffuse to filamentary domain in a 9.5 GHz microwave-induced surface discharge*. Appl. Phys. Let. 87, 061502(2005)

[14] Kirill V. Khodataev. *The physical basis of the high ability of the streamer MW discharge to a resonant absorption of MW radiation.* 42nd AIAA Aerospace Sciences Meeting 5-8 January 2004, Reno, NV. Paper AIAA-2004-0180.

[15] Igor Esakov, Lev Grachev and Kirill Khodataev. *Investigation of an undercritical Microwave discharge in air flow near body and its influence on the aerodynamics of the body*. 41st AIAA Aerospace Sciences Meeting 6-9 January 2003, Reno, NV. Paper AIAA-2003-0529.