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Microwave Discharge in Quasi-optical Wave Beam*

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A review of experimental results on microwave (MW) electric discharges in air at moderate and high pressure is presented. These discharges were created using in the beam of quasi-optical microwave electromagnetic radiation. Discharges were investigated both in a pulse mode at pulse duration up to tens of microseconds and in quasi-continuous mode with duration on the order of 0.3 s. In these investigations the wavelength and electromagnetic radiation pulse duration, electromagnetic field level, air pressure and its humidity were varied. MW discharges were created in ambient air, in air containing a water aerosol, in flammable propane-air mixtures and in high-speed flows of these mixtures. These experiments have investigated the different forms of MW discharge, the range of conditions over which they can be formed, and the spatial and temporary characteristics of the streamer discharge type. We have experimentally estimated the temperature in the discharge plasma. The experimental results obtained thus far have allowed the construction of a theoretical model for the undercritical microwave discharge generated using a quasi-optical electromagnetic beam.

I. Introduction

In the present report, a review is presented of experimental results on one type of electric discharge in air. These investigations were carried during the time period from 2003 to 2006 [1, 2, 3]. In this investigations, the characteristics of an electrical discharge generated using a quasi-optical beam of microwave (MW) electromagnetic (EM) radiation with linearly polarized TEM field structure were investigated. During these experiments the discharge area was essentially far away from all surrounding constructive elements, which results in the near-absence of a "backward" influence of the discharge plasma EM field on the EM radiation source. In these results the electric field in the discharge region represents a superposition of the invariable ambient field (with amplitude E_0 of electric component) and the induced field E_{pl} of the discharge plasma. In the experiments we realized both freely localized MW discharge in fields E_0 greater than the critical breakdown field E_{cr}, which ensures a self-maintained electrodeless air breakdown, and discharges in fields with $E_0 < E_{cr}$ (i.e. under-critical) and $E_0 \ll E_{cr}$ (i.e. deeply under-critical). We initiated air breakdown in these undercritical and deeply undercritical fields with the help of a metallic EM vibrator placed in the EM beam parallel to the vector E_0.

The basic experimental schemes used to generate the electric discharges are shown in Fig. 1. EM radiation generated by a MW source is formed into a quasi-optical beam using a radiating waveguide horn, a dielectric quasi-optical lens, and a metallic mirror reflecting the EM radiation. Depending on the particular experiment, different elements are used in different combinations as shown in Fig.1. The formed EM beam is irradiated into a hermetically-sealed "EM echoless" chamber and is usually focused in the central area of the chamber where the MW discharge is realized.

The following results were obtained in the undertaken investigations:

- requirements necessary for electric air breakdown in different conditions were defined more accurately;
- typical MW discharge forms and the range of conditions for their realization were determined;
- spatial and temporary characteristics of most promising MW discharge types were obtained;
- efficiencies of the interaction of different MW discharge types with the exciting EM fields were estimated; and
- parameters of the discharge plasma, such as temperature, were estimated .

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II. Ranges of varied parameters

An investigation of the features of this form of electric gas discharge is practically impossible using local sensors placed directly into the discharge area due to the interaction of the discharge with the sensor. Also, investigation of the discharge plasma properties using spectral methods is difficult due to the significant spatial and temporal variability of the discharge. With these considerations, the principal technique for investigating the features of the discharge involves generating the discharge over widely varying experimental conditions. In the framework of the executed works, EM beams were generated at different wavelengths, λ, and initial air pressures. Discharges were also generated in air with differing relative humidity, in the presence of a water aerosol, and in propane C_3H_8-air mixtures. Finally, the discharges were investigated in both stationary mixtures and in high-speed flows.

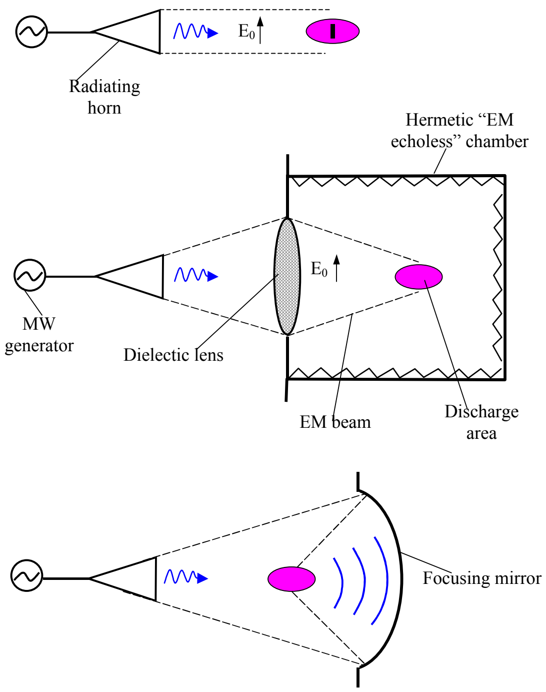

Figure 1. MW discharge in quasi-optical EM beam realization scheme

Experiments were conducted with wavelengths $\lambda = 2.5$ cm, 8.9 cm and 12.3 cm. In these experiments, the EM beam in the discharge area has relatively uniform conditions over a volume with transversal and longitudinal dimensions comparable to the wavelength $D \approx \lambda$. The ambient field level in the discharge area was varied from $E_0 \approx 10^2$ V/cm to $E_0 = 6.5 \cdot 10^3$ V/cm, using both a pulsed mode of the MW generator with a single pulse duration τ_{pul} between 4 μs and 40 μs, and a quasi-continuous mode with microwave duration τ_{MW} on the order of 0.3 s. The initial pressure in test chambers was set in a range from $p \approx 10$ Torr to $p = 760$ Torr. Hence, the discharge plasma is essentially a "collisional" plasma at the indicated λ. The humidity of the air composition was varied from %RH ≈ 0 to %RH = 100%. The aerosol concentration was up to $n_{aer} \approx 10^3$ 1/cm^3 with aerosol droplet diameters up to d_{aer} = (50-80) microns. Experiments were also conducted using lean, stoichiometric, and rich mixtures of propane and air. Finally, experiments were conducted in static conditions and in submerged isobaric streams of air, air-propane mixtures, and air-water aerosol mixtures with maximum velocity up to v_{fl} = 500 m/s at Mach $M = 2$ and local gas temperature $T = 150$ °K.

For convenience in Fig. 2 we have listed the range of conditions investigated.

λ = 2.5 cm; 8.9 cm; 12.3 cm;

$E_0 = (10^2 \div 6.5\cdot10^3)$ V/cm;

$\tau_{pul} = (4 \div 40)$ μs; $\tau_{MW} < 1$ s;

p = (10 ÷ 760) Torr; air

%RH = (~0 ÷ 100) %;

n_{aer} – up to 10^3 1/cm^3;
d_{aer} – up to 120 μ;

air + C_3H_8 ;

v_{flow} = 500 m/s (M = 2)

Figure 2. MW discharge experimental investigation ranges

III. MW discharge forms in E_0 - p parameters range

The form of a microwave discharge in air varies with ambient electric field, E_0, wavelength, λ, initial pressure, p, and pulse duration, τ_{pul}. Typical MW discharge forms in different E_0 - p ranges are shown in Fig.3. The boundaries between the different forms correspond to discharges with λ = 8.9 cm and τ_{pul} = 40 μs.

One can see in Fig. 3 that MW discharges investigated in overcritical fields at $E_0 > E_{cr}$ can be diffuse at low pressure and filamentary at high pressure. Experiments have shown that the field induced at the ends of the plasma filament channels $E_{pl} >> E_0$, and this high local field significantly influences the spatial development of the filaments. In this connection we can call the filaments MW streamer discharges by analogy with discharges in the constant electric field.

Filamentary discharges are realized also in undercritical fields if they are initiated. In a so-called under-critical field with $E_0 < E_{cr}$, the initiated streamer MW discharge has a volumetrically developed form. In the so-called deeply under-critical field with $E_0 << E_{cr}$, the streamer channels remain "attached" to the initiator. Diffuse discharge plasma at $E_0 < E_{cr}$ also remain attached to the initiator.

In Fig. 3 one can see the boundaries between the different forms of MW discharge, which were determined experimentally.

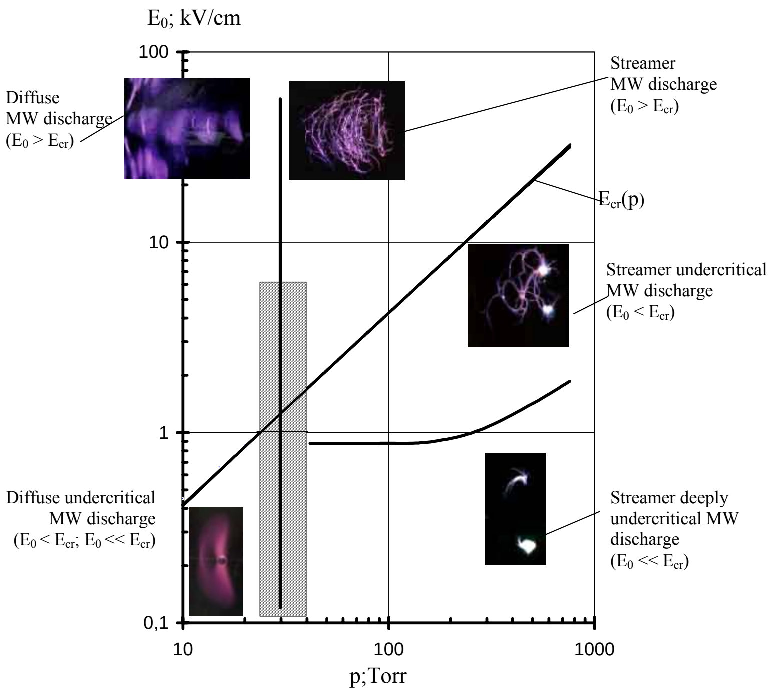

Figure 3. MW discharge forms in quasi-optical EM beam (λ = 8.9 cm; τ_{pul} = 40 μs)

The different forms of the MW discharges are present for the entire range of λ investigated, although the boundary separating the diffuse and streamer discharge forms is shifted to higher p with decreasing λ. In addition, the boundary separating the streamer undercritical and streamer deeply undercritical discharges is shifted to larger E_0 with decreasing λ. In Fig.4 one can see E_0 - p diagrams illustrating this fact for $\lambda = 8.9$ cm and $\lambda = 2.5$ cm[4].

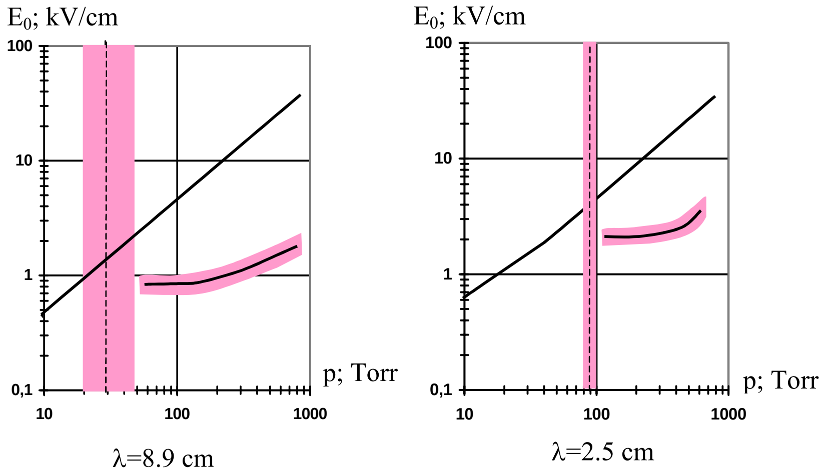

Figure 4. Existence areas of different MW discharge forms in quasi-optical EM beam

Experiments have shown that the diffuse type of discharge interacts inefficiently with the exciting EM field, but the efficiency of the MW streamer discharge interaction with the incident EM field is relatively high. This last feature stimulates a search of their practical application[5,6,7].

The results presented in Figs. 3 and 4 show that a high level of E_0 is required for realization of overcritical and undercritical discharge types with a volumetrically developed streamer structure. The EM beam power P_{MW} corresponding to these fields is from hundreds of kilowatts to megawatts in the investigated range of λ. Generation of these levels of MW radiation can only be realized in a pulse mode with τ_{pul} on the order of microseconds (up to 10s of μs). Such parameters were used in the present investigations in setups with $\lambda = 8.9$ cm and $\lambda = 2.5$ cm. In contrast, the deeply undercritical streamer discharges can be realized in fields with E_0 on the order of 10 V/cm. In this case the discharges can be realized in a continuous mode at P_{MW} of kilowatt scale. Such parameters characterize the setup with $\lambda = 12.3$ cm in the undertaken investigations. The EM radiation has a duration of $\tau_{MW} = 0.3$ s in these experiments.

IV. Spatial and temporary characteristics of streamer undercritical and deeply undercritical MW discharges

Investigations undertaken have shown that the spatial and temporal structure of the streamer undercritical MW discharges is formed by branching plasma channels, which start from the poles of the EM initiator, and grow mainly towards the source of the EM radiation. The channels of the deeply undercritical streamer discharge starts from the poles of the EM vibrator that initiates the discharge, but the discharge is not “capable” of separating from the poles.

Investigations were conducted to determine: the streamer channel growth velocity v_{str}; the velocity v_{fr} of the front of the spatially-developed streamer undercritical MW discharge as it propagates towards the EM radiation; and determination of geometry of the separate plasma elements. These characteristics were determined using photographic detection of the discharge area at different values of E_0, p and τ_{pul} or measurement of the parameters needed to generate the discharge in a high-speed air flow.

In Fig. 5 one can see a photograph of typical plasma element, which builds to form the spatially developed structure of a MW undercritical discharge. This element is like a snake – a sinusoid with sprouts of new plasma channels at the top of the sinusoid. Separate elements of this “snake” have a length comparable with $\lambda/2$.

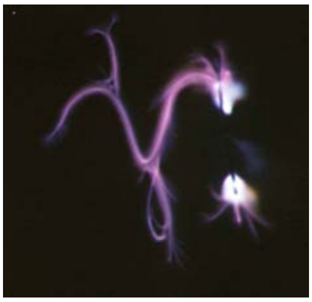

Figure 5. Typical plasma element of undercritical MW discharge (λ = 8.9 cm; E0 = 0.2·Ecr; p=150 Torr; EM initiator's length– 2 cm)

These plasma elements possess resonance properties with the incident EM field, which ensures a high energy interaction efficiency. In the case of deeply undercritical discharge, the system that possesses these resonance features consists of the EM vibrator-initiator and plasma formations attached to its poles. A typical photograph is shown in Fig. 6.

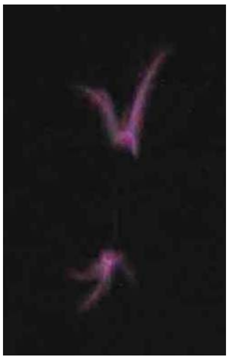

Figure.6. Deeply undercritical MW discharge initiated by EM vibrator with a diameter of 1 mm and length *7 mm (λ = 2.5 cm; τ_{pul} = 5 μs; E_0 = 0.1·E_{cr}; p = 760 Torr)*

In Fig. 7 a series of streamer undercritical MW discharge photographs are shown for different τ_{pul}. Analysis of these photographs allows one to estimate the average velocity v_{str} and typical velocity v_{fr}. In Fig. 8 one can see an analogous set of photographs for a deeply undercritical streamer MW discharge. Experiments have shown that the velocity v_{str} for the undercritical MW discharge with a volumetrically developed streamer structure is about (10^5 - 10^6) cm/s and the velocity v_{fr} lies in the range (10^4 - 10^5) cm/s independent of the EM radiation λ. The deeply undercritical MW discharge has the same scale of average velocity v_{str} , but the discharge channels continuously appear and then become dim.

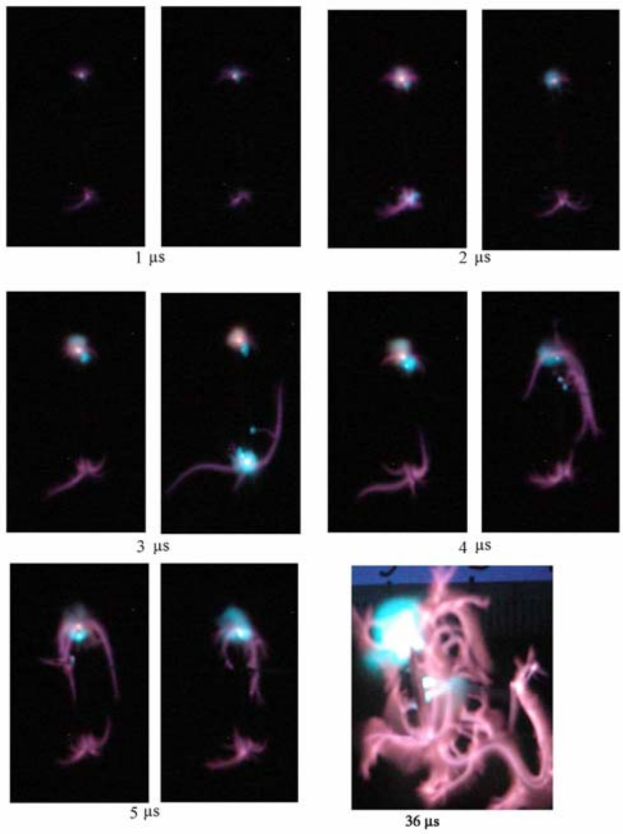

Figure 7. Streamer undercritical MW discharge at different τ_{pul} (λ = 2.5 cm; $E_0 = 0.37 \cdot E_{cr}$; p=240 Torr; EM vibrator's length is 12 mm)

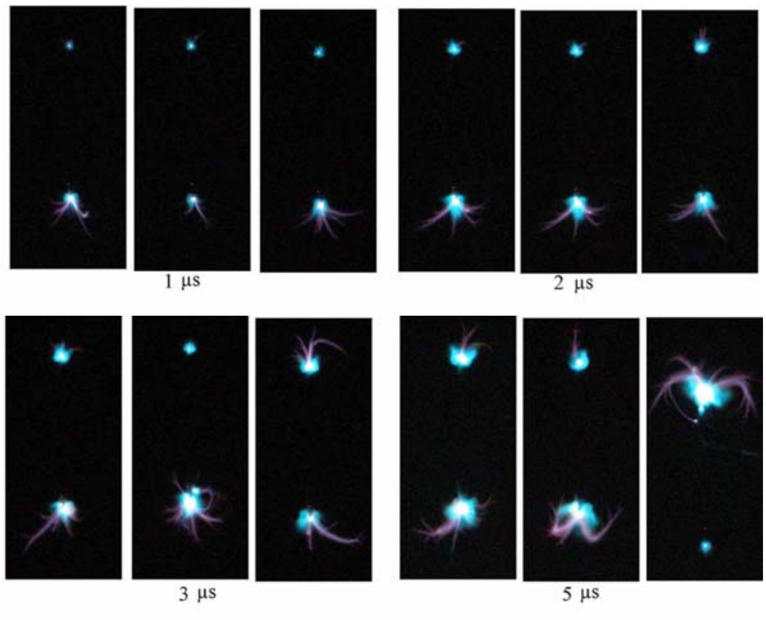

Figure.8. Streamer deeply undercritical MW discharge at different τ_{pul} (λ = 2.5 cm; $E_0 = 0.12 \cdot E_{cr}$; p=760 Torr; EM vibrator's length is 12 mm)

Streamer MW discharges were realized in a high-speed air flow at $v_{fl} = 5 \cdot 10^4$ cm/s as an independent check on the estimated velocity v_{str}. Typical photographs of the discharges in a flow and without it are provided in Fig. 9. It follows from these photographs that the appearance of undercritical MW discharge did not practically change in the flow with $v_{fl} << v_{str}$, as was expected. In contrast, the appearance of the deeply undercritical MW discharge changed when generated in the high-speed flow. It is believed that this changed appearance is connected with the average air heating in the local discharge area near the pole of the EM vibrator-initiator.

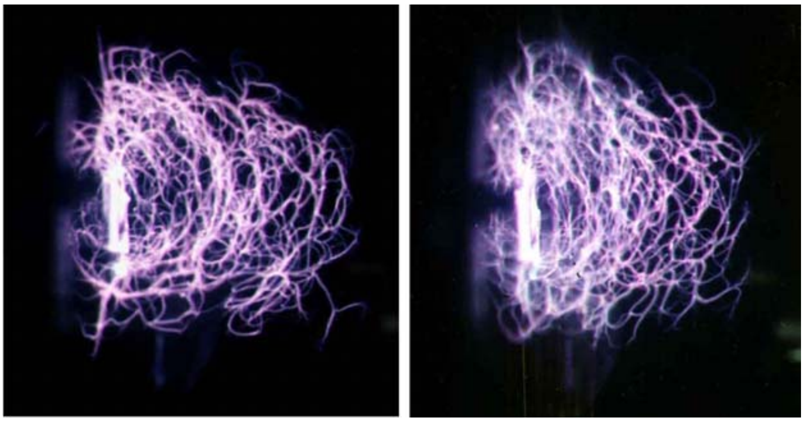

Figure 9. Streamer undercritical MW discharge in dead air (left photo) and in its supersonic flow (right photo) (λ = 8.9 cm; p=200 Torr; $E_0 = 0.77 \cdot E_{cr}$)

V. Gas temperature in streamer channels

Streamer MW discharges have a complicated non-uniform spatial structure consisting of thin plasma channels, see Fig.3[8]. In addition, experiments show that the position of the streamer channels is not the same in different EM pulses. This characteristic of the discharge makes spectral analysis of the features of the streamer MW discharge very difficult since one cannot predict from where the radiation that arrives at an analyzer came.

The minimum air temperature T in discharge plasma of streamer channels was estimated by creating the discharge in a flammable propane-air mixture, which has an ignition temperature about T_{ig} = (1000-1200) °K. In Fig. 10 one can see the corresponding photographs[9,10]. In these experiments, the flammable mixture was delivered to the discharge area with a comparably low velocity v_{fl} about of 1 m/s.

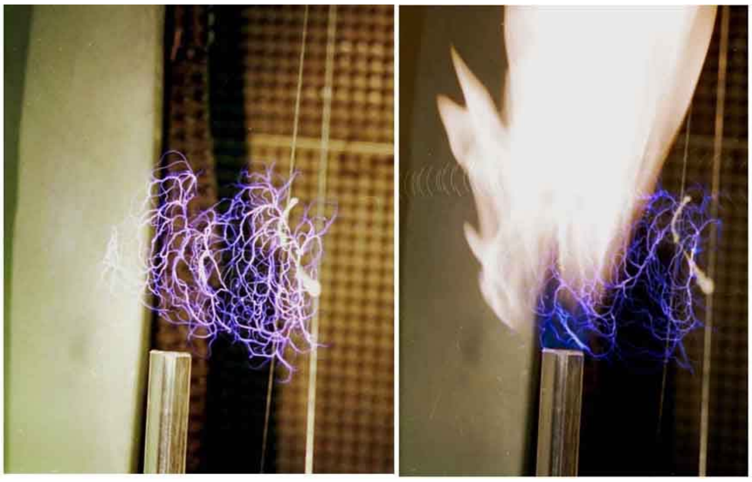

Figure 10. Undercritical streamer MW discharge in dead air (left photo) and at presence of propane-air flammable mixture stream (right photo) (λ = 8.9 cm; $E_0 = 0.2 \cdot E_{cr}$)

In Fig.11 one can see a series of photographs of MW undercritical discharges generated in high-speed propane-air mixtures at different equivalence ratios. The average photograph corresponds approximately to a stoichiometric mixture, with lean and rich mixture shown to the left and right, respectively. It can be seen that MW undercritical streamer discharge ignites the mixture in all cases. The combustion of the mixture in this experimental formulation has an essential peculiarity. For example in Fig.12 a fragment of the combustion area of the stoichiometric mixture is shown, where the flow comes to MW discharge area from below. Measurement of the half-angle of the "combustion cone" allows one to estimate the flame front velocity v_{flame}, which has a value approximately 150 m/s.

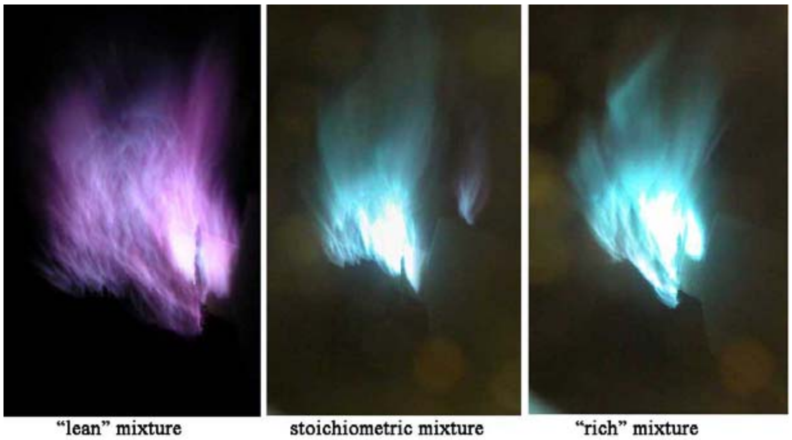

Figure 11. Undercritical MW discharge in supersonic flow of propane-air flammable mixture (λ = 2.5 cm; τ_{pul} = 34 μs; $v_{fl} = 5{\cdot}10^2$ m/s)

One can presume that this high flame velocity v_{flame} is connected with "hard" ultra-violet (UV) radiation generated in the central regions of streamer channels. In turn, this UV radiation carries information about elementary processes in the plasma of these channels.

Figure 12. MW undercritical discharge fragment in supersonic flow of stoichiometric propane-air mixture (λ = 2.5 cm; τ_{pul} = 34 μs; $v_{fl} = 5{\cdot}10^2$ m/s)

VI. MW discharge in humid air

It is well known that electron attachment to oxygen molecules plays an important role in discharge development in air. To a greater extent, attachment processes in humid air can also influence the development of a MW discharge. In the executed works, the influence of air humidity on MW discharge was investigated in a special series of experiments.

In Fig. 13 one can see the experimental dependence of electrodeless breakdown field E_{br} in air on the volumetric weight content η of moisture at p = 100 Torr. Note that 100%RH (i.e. the dew-point) in air corresponds to $\eta = 1.4{\cdot}10^{-2}$ at T = 20 °C. It follows from the figure that E_{br} increases with increasing air humidity. These results can be used to develop a humid air MW breakdown model for the real atmosphere.

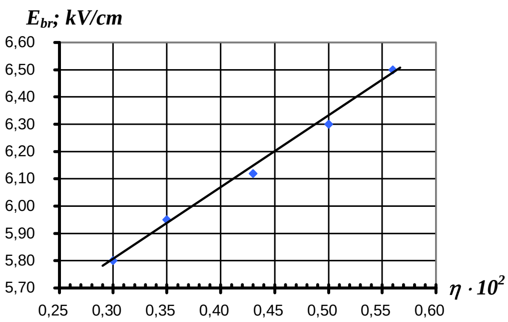

Fig.13. Experimental dependence of electrodeless breakdown field E_{br} in air via volumetric weight content η of moisture in it (λ = 8.9 cm; τ_{pul} = 40 μs; p = 50 Torr)

In Figs. 14 and 15 one can see typical photographs of undercritical and deeply undercritical MW discharges at different η values. It follows from these results that the appearances of these discharges are, in principle, independent of η**.** The discharges continue to have a streamer characteristic. The velocity v_{fr} insignificantly drops with increasing η in the case of undercritical discharge and the “thickness” of plasma channels decreases.

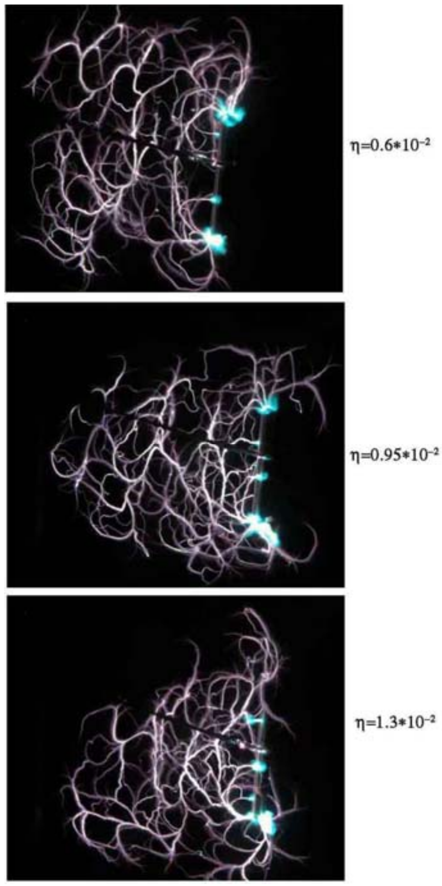

Figure 14. Undercritical MW discharge in humid air (λ = 8.9 cm; τ_{pul} = 40 μs;E_0 = 0.2·E_{cr}; p=760 Torr)

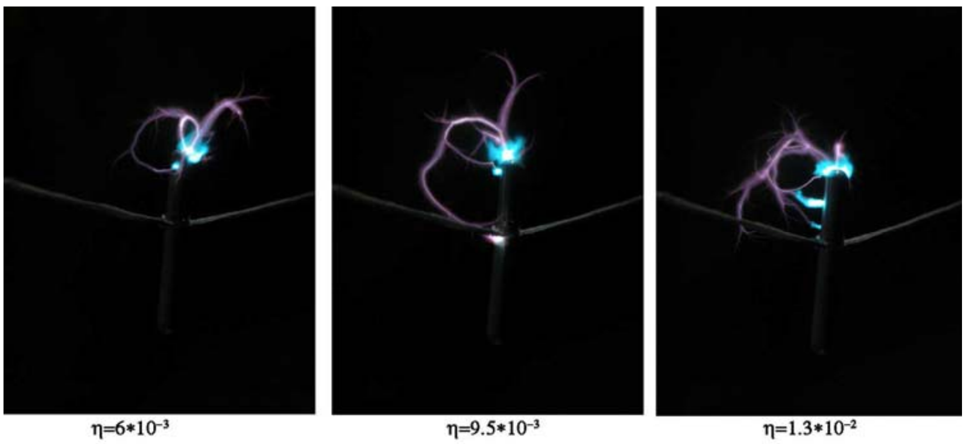

Figure 15. Deeply undercritical MW discharge in humid air (λ = 8.9 cm; τ_{pul} = 40 μs; $E_0 = 9{\cdot}10^{-2}{\cdot}E_{cr}$; p=760 Torr)

VII. MW discharge in air with water aerosol

Experiments with MW discharge in air with a water aerosol were carried out at p = 760 Torr using only the initiated MW streamer type of discharge. In Fig. 16 one can see a typical photograph of the EM vibrator initiating the discharge with a spherically-rounded pole of diameter $2a$ = 5 mm placed in aerosol-air mixture. These photographs were used to determine the concentration of aerosol particles, n_{aer}, and their diameter d_{aer}.

Figure 16. EM vibrator initiating a discharge placed in aerosol-air mixture

Experiments have shown that $\boldsymbol{E_{br}}$ practically does not depend on the aerosol presence if the EM vibrator pole surface is illuminated by sufficiently hard UV radiation. Photo electrons starting from the initiator's surface in local places without aerosol drops do not attach and serve as the source for the discharge avalanches.

In Fig. 17 a comparison is shown of photographs of typical MW undercritical discharges in air with and without aerosol for two τ_{pul} values. It follows from these photographs that the presence of the aerosol in air does not influence the discharge appearance in principle, which retains a streamer characteristic with a volumetrically developed structure. At the same time, the velocity v_{fr} decreases about of 25% in the air-water aerosol mixture, and the color of the plasma channels is changed. For example and comparison one can see fragments of these discharges in Fig. 18.

Experiments have shown that the presence of a water droplet on the EM vibrator-initiator does not influence the beginning development of the MW streamer discharge. This water droplet has a high dielectric permeability ε, which is similar to metal in an electrodynamic sense. For example in Fig.19 one can see fragments of plasma channels starting from the water droplet in cases with undercritical and deeply undercritical MW discharges.

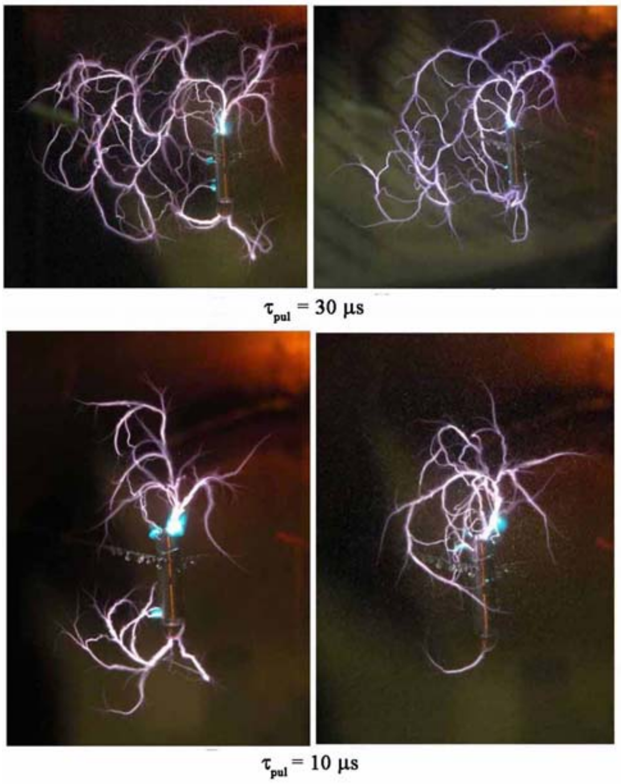

Figure 17. Undercritical MW discharge in air (left photos) and in air-water aerosol mixture (right photos) (λ = 8.9 cm; $E_0 = 0.15 \cdot E_{cr}$)

In addition, experiments were conducted to investigate the influence of water aerosol in air on the spatial and temporary characteristics of undercritical and deeply undercritical streamer discharges by creating these discharges in a high-speed flow of a water-aerosol mixture.

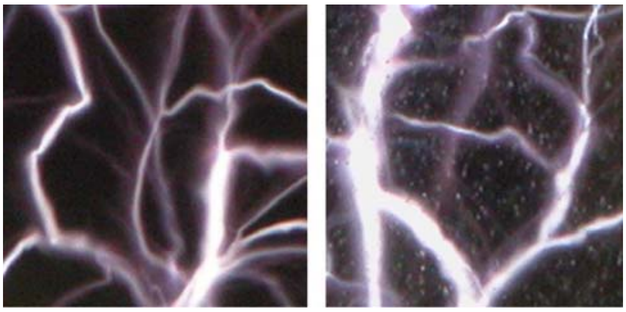

Figure 18. Fragments of undercritical discharge in air (left photo) and in air-water aerosol mixture (right photo) (λ = 8.9 cm)

Figure 19. Fragments of undercritical MW discharge (left photo) and deeply undercritical MW discharge (right photo) starting from water drops (λ = 8.9 cm)

In Fig. 20 one can compare photographs of an undercritical MW discharge in high-speed air flows with and without the aerosol. It can be seen that presence of the aerosol does not essentially decrease the velocity v_{str}, which continues to be substantially higher than the flow velocity. Hence, the discharge structure does not change with the addition of the aerosol to the flow.

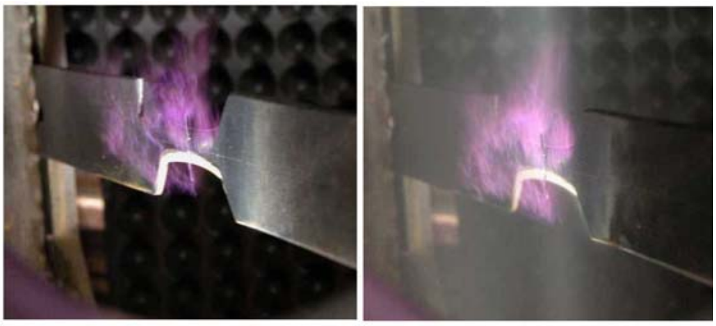

Figure 20. Initiated undercritical MW discharge in a supersonic air flow (left photo) and in a supersonic air with water aerosol flow (right photo) (λ = 2.5 cm; $E_0 \approx 0.4 \cdot E_{cr}$; $v_{fl} = 5 \cdot 10^2$ m/s)

Finally, in left portion of Fig. 21 one can see a photograph of a deeply undercritical MW discharge in a high-speed air flow. This discharge is realized in the base area of a pipe-type EM vibrator-initiator.

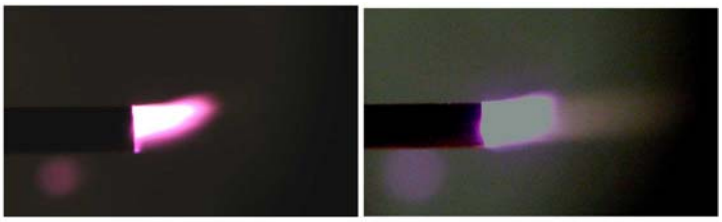

Figure 21. Deeply undercritical MW discharge initiated by a pipe-type EM vibrator in a supersonic air flow (left photo) and in a supersonic air with water aerosol flow (right photo) (λ = 12.3 cm; $E_0 \approx 10^2$ V/cm $\approx 10^{-2} \cdot E_{cr}$)

The right photograph was obtained when a water aerosol was injected into the supersonic (SS) air flow in the presence of the pipe-type EM vibrator-initiator. The discharge continues to exist in the base area of the initiator, but its geometry changes significantly.

VIII. Model Development

Discussions of experimental formulations, theoretical assistance of experiments and analysis of the obtained data have allowed for the determination of the main physical factors impacting the development of a MW streamer type discharge created in a quasi-optical wave EM beam. As a result, a series of numerical models were developed describing the main parameters of this phenomenon [11,12,13,14]. These models produce and explain many peculiarities of MW streamer discharges. For example, one model successfully simulates the streamer ability to propagate continuously in undercritical MW field by periodical branching [ ]. In this model a typical configuration was selected for the trajectory of the channel trajectory of the initiated streamer undercritical MW discharge presented in Fig. 22 close to the experimental one (see Fig. 5). In Fig. 23 one can see a picture of the computed development of the current distribution in time obtain using this model.

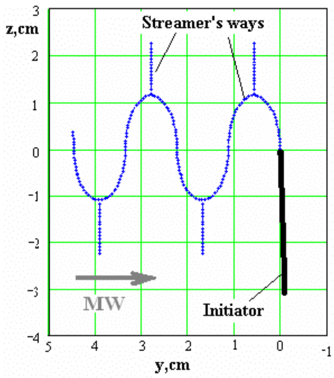

Fig.22. Development trajectory configuration of undercritical MW discharge streamer channel (λ = 8.9 cm; $E_0 \approx 0.3 \cdot E_{cr}$)

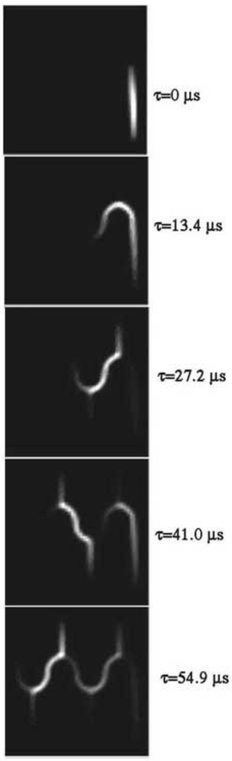

Fig.23. Temporary development of the current distribution in undercritical MW discharge channels. Computations.

The developed model

- confirms the streamer character of high pressure undercritical MW discharge propagation in space;
- confirms a resonance character of the discharge channel energy interaction with the EM field;
- gives values of discharge front propagation average velocity and average velocity of streamer growth;
- explains the high values of the gas temperature in the plasma discharge channels, etc.

At the same time such a large amount of experimental date is available that wide open possibilities for further theoretical constructions are available. For example, the influences of high humidity and aerosols on the development of the MW streamer discharge needs to be better understood. Models must also be developed to consider the influence of discharge plasma processes and its radiation on the combustion characteristics of air mixtures with different fuels.

IX. Summary

Experimental results on microwave (MW) electric discharges in air at moderate and high pressure were reviewed. These discharges were created using a quasi-optical beam of microwave electromagnetic radiation. The impacts of electric field strength, pressure, pulse duration, air humidity, and flow velocity on the characteristics of the discharges were investigated. The impact of the presence of a water aerosol was also investigated. Results of these investigations have led to the development of a series of numerical models that are used to explain many of the characteristics of an undercritical MW discharge. The unique characteristics of this class of electrical discharge, including its high efficiency, provide encouragement for further development of fundamental understanding and practical applications.

X. Acknowledgments

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