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Domains of Existence of Various Types of Microwave Discharge in Quasi-Optical Electromagnetic Beams

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Abstract—High- and medium-pressure discharges excited by quasi-optical microwave beams in air are classified using experimental data. Diffuse, streamer, overcritical, undercritical, and deeply undercritical discharges are distinguished. The domains of existence of each type of discharge are determined as functions of the air pressure and field strength for two particular electromagnetic wavelengths.

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INTRODUCTION

In this paper, we will consider pulsed discharges excited by linearly polarized quasi-optical microwave beams in air [1–7]. The discharge is assumed to operate under the following conditions:

(i) the microwave wavelength λ is in the range 1–10 cm;

(ii) the initial pressure p of the atmospheric-composition air is from several torrs to 760 Torr;

(iii) the initial free-electron density is determined solely by natural factors;

(iv) the duration of rectangular microwave pulses, τ_{pul}, is a few tens of microseconds;

(v) the discharges are excited by individual microwave pulses or a series of pulses, the pauses between the pulses being long enough for the subsequent discharges not to influence one another;

(vi) the discharge region is remote from the beam-forming devices and neighboring constructional elements by at least several wavelengths λ; and

(vii) the initial electric field E_0 of the microwave beam in the discharge region slightly exceeds the minimal (critical) breakdown field E_{cr} required for a self-sustained breakdown in air at (or below) a given pressure p.

Such discharges differ from one another in both the methods for their excitation and the main physical factors responsible for their properties and the formation of their spatial structure. For instance, at $E_0 > E_{st}$, microwave breakdown in air can occur spontaneously, whereas at $E_0 < E_{st}$, it should be initiated [3, 6]. The structure and properties of a low-pressure discharge in air are primarily determined by the field-ionization processes [5]. At a relatively high pressure, the properties of the discharge and the formation of its structure are also affected by thermal processes in the gas [5].

At the given pulse duration τ_{pul}, such discharges are inherently dynamic objects. In the course of their evolution, they expand preferentially toward the exciting microwave radiation. In the inner regions of such a discharge, its parameters are essentially unsteady.

Experiments show that, within a certain range of air pressures p and at the corresponding initial field strength E_0 of the microwave radiation, such discharges are capable of efficiently interacting with the exciting electromagnetic (EM) field. This provides a wide variety of their practical applications [8].

Attempts to classify such discharges were made in [1–3]. In the present paper, we propose a more detailed classification and experimentally determine the domains of existence of each type of discharge in the (E_0, p) plane for two particular microwave wavelengths, λ = 8.9 and 2.5 cm.

DISCHARGE IN A MICROWAVE BEAM WITH λ = 8.9 cm

Experiments with quasi-optical microwave beams with λ = 8.9 cm were performed on the facility that was described in detail in [9].

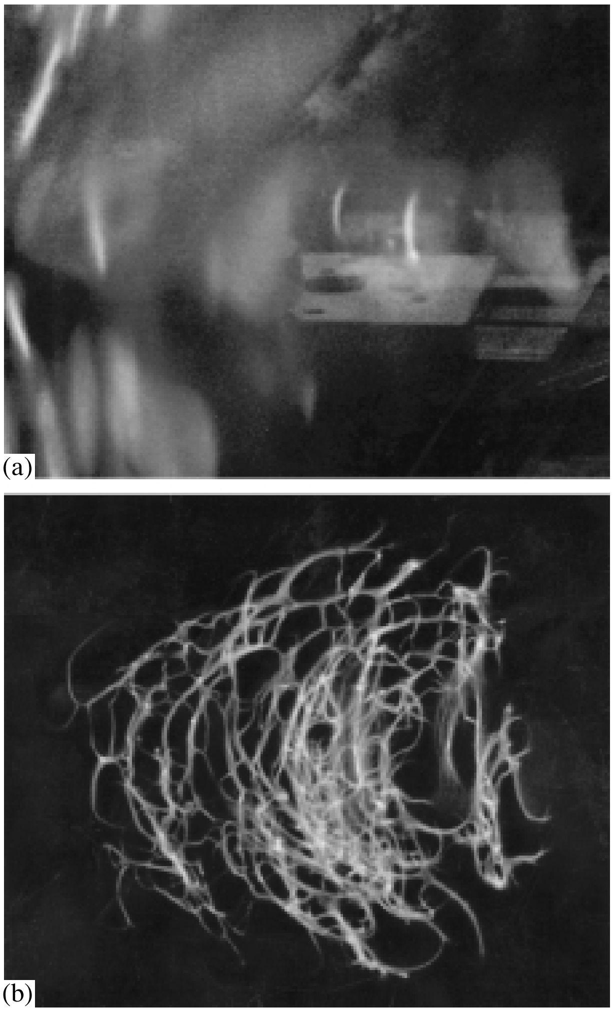
A linearly polarized microwave beam with a duration of τ_{pul} = 40 μs was focused into the central region of a nonreflecting airtight working chamber with a size of about 10λ. The characteristic focal spot size Δ was a few centimeters, and the longitudinal size of the focal region was $\Lambda \approx$ 10 cm. In different pulses, the maximum electric field E_0 in the focal region varied from 6.5 to 100 V/cm. The air pressure p in the working chamber was in the range 3–760 Torr.

Under our experimental conditions, self-sustained breakdown could occur only at air pressures lower than $p \approx 100$ Torr. At pressures below several tens of torrs, the discharge operated in the diffuse mode. At pressures exceeding a certain threshold value p_{thres}, a diffuse discharge transformed into a streamer one. Typical time-integrated (i.e., obtained with an exposure time of $\tau_{exp} \gg \tau_{pul}$) photographs of such discharges are shown in Fig. 1. In these and the subsequent photographs, microwave radiation is incident from the left and the vector $\mathbf{E}_0$ is directed vertically.

Figure 1a corresponds to one of the possible forms of an overcritical ($E_0 > E_{cr}$) diffuse discharge operating at an air pressure of $p < p_{thres}$. The spatial structure and properties of such a discharge are primarily determined by the field-ionization processes; i.e., gas ionization in the discharge region is governed by the mutual dynamic influence of the initial field and the field generated in the plasma produced [5]. The discharge structure depends on the air pressure. At low pressures (typically, at $p < 10$ Torr), the discharge region with $E_0 \geq E_{st}$ was nearly uniformly filled with a plasma. As the pressure increased, the plasma broke into separate diffuse plasmoids, which could be stretched either along the vector $\mathbf{E}_0$ [1, 4, 5] or across it [4, 5]. An overcritical diffuse microwave discharge consumed almost no microwave field energy, and the air in the discharge region was heated by no more than several tens of degrees [10].

Figure 1b shows a photograph of a typical overcritical ($E_0 > E_{st}$) streamer discharge operating at a pressure of $p > p_{thres}$. The discharge presents a rather complicated system of thin plasma channels. It originates against the free-electron background and then develops as a system of growing and branching streamer channels. The ionization of air in the channels is substantially affected by the ionization–heating process [5], whereas their growth and branching are determined by the magnitude and distribution of the field at the channel heads. Individual parts of the plasma channels with lengths close to $\lambda/2$ interact resonantly with the exciting EM field. As a result, the overcritical streamer discharge almost completely absorbs microwave energy and the gas temperature T in the resonant plasma channels increases to 1000 K and more. It is due to this property that this type of discharge have found various practical applications.

On the other hand, at relatively high air pressures p, a self-sustained discharge is rather difficult to excite by using microwave radiation in the centimeter wavelength range. Thus, even in the case of a tightly focused microwave beam, the focal spot size is no less than $\Delta \approx \lambda$]. Therefore, because of the limited peak power of the conventional pulsed microwave generators ($P_{gen} \geq 10^5$–10^6 W), the field strength E_0 in the focal region of such a beam usually does not exceed several kV/cm, whereas a few tens of kV/cm are required to excite a self-sustained discharge in air at a pressure of $p >$ 200 Torr [11]. Experiments show, however, that a discharge in a quasi-optical microwave beam can be excited even in an undercritical field ($E_0 < E_{cr}$). In order to achieve gas breakdown under these conditions, special measures should be undertaken, i.e., breakdown should be initiated.



(a)

(b)

Fig. 1. Overcritical ($E_0 > E_{cr}$) discharges in a quasi-optical microwave beam with $\lambda = 8.9$ cm at $\tau_{pul} = 40$ μs: (a) diffuse discharge ($p = 15$ Torr, $E_0 = 6.5$ kV/cm) and (b) streamer discharge ($p = 130$ Torr, $E_0 = 6.5$ kV/cm).

One possible method for initiating microwave breakdown is to place a metal sphere [12] or an EM vibrator parallel to the vector $\mathbf{E}_0$ [13] in the microwave beam. At a sphere diameter of $2a \ll \lambda/2$, the field strength triples at the poles of the sphere, where the vector $\mathbf{E}_0$ is perpendicular to the sphere surface. Similarly, at a vibrator length of $2L \approx \lambda/2$ length and diameter of $2a \ll \lambda/2$, the field strength at the vibrator poles increases multifold.

Experiments show that, similarly to discharges in an overcritical field, undercritical initiated microwave discharges can operate in either the diffuse or the streamer mode, depending on the air pressure. When the air pres-

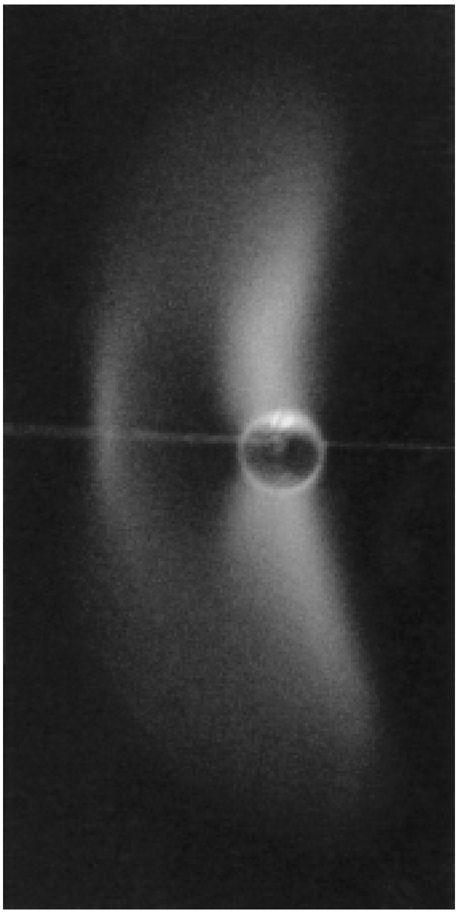


Fig. 2. Undercritical ($E_0 < E_{cr}$) diffuse discharge in a quasi-optical microwave beam with λ = 8.9 cm at τ_{pul} = 40 μs, p = 20 Torr, and $E_0 = 7 \times 10^2$ V/cm. The discharge is initiated by a sphere of diameter $2a$ = 2.5 mm.

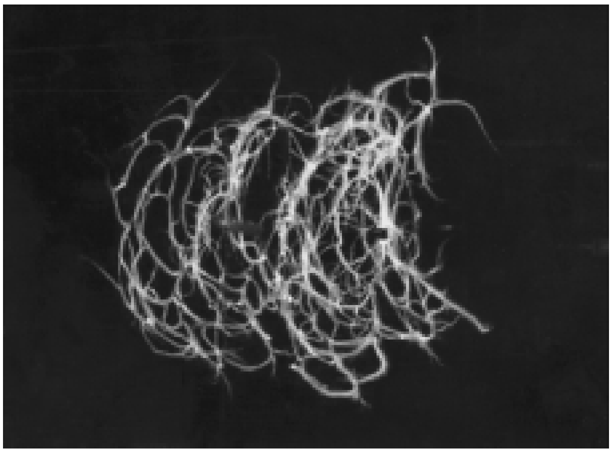


Fig. 3. Undercritical ($E_0 < E_{cr}$) streamer discharge in a quasi-optical microwave beam with λ = 8.9 cm at τ_{pul} = 40 μs, p = 360 Torr, and E_0 = 6.5 kV/cm). The discharge is initiated by a sphere of diameter $2a$ = 5 mm.

sure p exceeds the threshold value p_{thres}, a diffuse initiated discharge also transforms into a streamer one.

A typical photograph of an undercritical diffuse discharge initiated by a sphere at a filed strength of $E_0 < E_{cr}$ and an air pressure of $p < p_{thres}$ is shown in Fig. 2. In this type of discharge, the plasma is localized near the initiator. Depending on the field strength, either the initiator poles are connected by a discharge plasma arc (Fig. 2) or diffuse plasma clouds are localized only near the poles. Similarly to overcritical diffuse discharges, air in undercritical diffuse discharges is heated only by a few tens of degrees.

As was mentioned above, in experiments with an undercritical field strength ($E_0 < E_{cr}$) at an air pressure of $p > p_{thres}$, an initiated discharge operates in the streamer mode. However, unlike undercritical diffuse discharges, there are two types of undercritical streamer discharge [14].

Within a certain range of undercritical field strengths ($E_{cr} > E_0 > E_{thres}$, where E_{thres} is a certain threshold field strength), a streamer discharge originating at the initiator poles can detach from them. In this case, as in an overcritical discharge, the growing and branching streamer channels form the discharge structure. A typical photograph of this type of discharge is shown in Fig. 3.

A representative structural element, the set of which form an undercritical ($E_0 < E_{cr}$) streamer discharge, is shown in Fig. 4. The segments of this wavy branching structural element that are parallel to the initial field vector $\mathbf{E_0}$ are in resonance with the field of the microwave beam. It is the presence of such segments that ensures the high efficiency of the interaction between the spatially developed structure of an undercritical streamer discharge and the exciting microwave field. The air temperature T in the resonant plasma regions of such a discharge increases to a few thousand degrees. As a result, the surface of an initiator made of copper or aluminum is evaporated in the regions where the plasma channels contact this surface.

As the initial field strength E_0 decreases below the threshold level E_{thres}, a deeply undercritical ($E_0 \ll E_{cr}$) streamer discharge fails to detach from the initiator. In experiments with such a weak field, an air discharge was usually initiated by an EM vibrator. The streamer channels of such a deeply undercritical discharge either connect the ends of the vibrator to one another or to its side surface or are localized only at the vibrator ends. Such an electrodynamic system, which is composed of an EM vibrator and plasma channels, also possesses resonant properties. As a result, the gas temperature T in the plasma channels reaches a few thousand degrees, which leads to the evaporation of the vibrator surface in the regions where the plasma channels contact this surface.

Thus, the experiments show that the following types of discharge can occur in a quasi-optical microwave beam with $\lambda = 8.9$ cm: an overcritical diffuse discharge, an overcritical streamer discharge, an undercritical diffuse discharge, an undercritical streamer discharge, and a deeply undercritical streamer discharge. The domains of existence of these types of discharge in the (E_0, p) plane [15] are shown in Fig. 5 and are designated by Roman numerals *I–V*, respectively. These domains were determined by analyzing a series of time-integrated photographs of discharges operating at different initial field strengths E_0 and different air pressures p.

Line *1* in Fig. 5 corresponds to $E_0 = E_{cr}(p)$. Above this line, self-sustained air breakdown can occur, whereas below it, air breakdown has to be initiated. In analyzing the experimental results, it is convenient to introduce the effective critical breakdown field, $E_{cr} = 42p\sqrt{1 + (\omega/\nu_c)^2}$ V/cm [11], where ω is the circular frequency of the microwave field, $\nu_c = 4 \times 10^9 p$ is the collision frequency of the plasma electrons with air molecules, and the air pressure is in Torr. Line *2*, which corresponds to the experimentally determined threshold pressure p_{thres}, separates the domains of existence of diffuse and streamer discharges, which occur to the left and to the right of this line, respectively. Finally, curve *3* corresponds to the experimentally determined field $E_{thres}(p)$ [14]. In the pressure range $p > p_{thres}$, it separates undercritical ($E_0 < E_{cr}$) streamer discharges with a developed spatial structure that are capable of detaching from the initiator and deeply undercritical ($E_0 \lll E_{cr}$) streamer discharges, whose plasma channels are attached to the initiator.

Line *2*, which corresponds to p_{thres}, is, to a certain extent, conventional. In experiments, there is an air pressure range (the hatched region in Fig. 5) in which it is difficult to distinguish between diffuse and streamer discharges.

Over the entire range of air pressures, there is a narrow transition region below line *1* ($E_0 < E_{cr}$) in which weak reflection of microwave radiation from an initiated undercritical discharge can lead to self-sustained air breakdown in the microwave beam in front of this discharge [3].

DISCHARGE IN A MICROWAVE BEAM WITH $\lambda = 2.5$ cm

Experiments with quasi-optical microwave beams with $\lambda = 2.5$ cm were performed on the facility that was described in detail in [16].

In these experiments, a linearly polarized microwave beam with a duration of $\tau_{pul} = 35$ μs was focused into the central region of a nonreflecting airtight working chamber with a size of 16λ. The characteristic focal spot size was $\Delta \approx \lambda$. In the longitudinal direction, the amplitude of the microwave field was substantially modulated, the modulation period in the focal region being $\Lambda \approx 1.5$ cm. The experiments were performed at

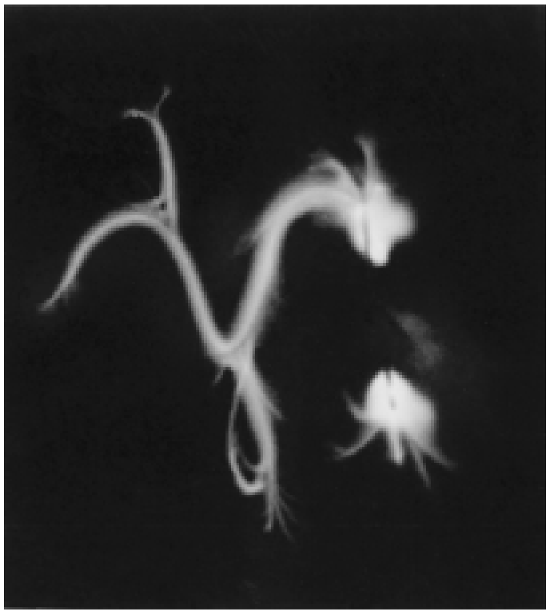


Fig. 4. Characteristic structural element of an undercritical ($E_0 < E_{cr}$) streamer discharge in a quasi-optical microwave beam with $\lambda = 8.9$ cm at $\tau_{pul} = 40$ μs, $p = 150$ Torr, and $E_0 = 1.2$ V/cm. The discharge is initiated by an EM vibrator with $2L = 20$ mm and $2a = 0.8$ mm.

a fixed microwave generator power, $P_{gen} \approx 100$ kW, which remained unchanged in the consecutive pulses. The maximum field amplitude in the focal region was $E_0 = 3.7$ kV/cm, whereas in the neighboring minimum, it was $E_0 = 1.8$ kV/cm. On the beam axis, the average value of the field strength E_0 rapidly decreased with distance from the focal plane. The air pressure p in the chamber was in the range 3–760 Torr.

In this facility, self-sustained air breakdown in a microwave field with $E_0 > E_{cr}$ can occur only at pressures of up to $p \approx 80$ Torr. As in the case of a microwave beam with $\lambda = 8.9$ cm, a low-pressure overcritical diffuse discharge in air operated in the diffuse mode. The experiments showed that, under the given experimental conditions, a self-sustained overcritical discharge remained to be diffuse over the entire pressure range under study, up to the maximum possible value of p.

In experiments on undercritical discharges, air breakdown was initiated by an EM vibrator. In order to investigate the discharge over a wide range of the initial filed strengths E_0, the vibrator was placed at different points along the axis of the microwave beam. The experiments show that, at $\lambda = 2.5$ cm, similarly to the case of a microwave beam with $\lambda = 8.9$ cm, undercritical initiated discharge can operate in the diffuse or streamer mode. In the latter case, the spatial structure of the discharge can be well developed or the plasma channels can be attached to the initiator.

Photographing discharges at different values of E_0 and p allowed us to determine the domains of existence

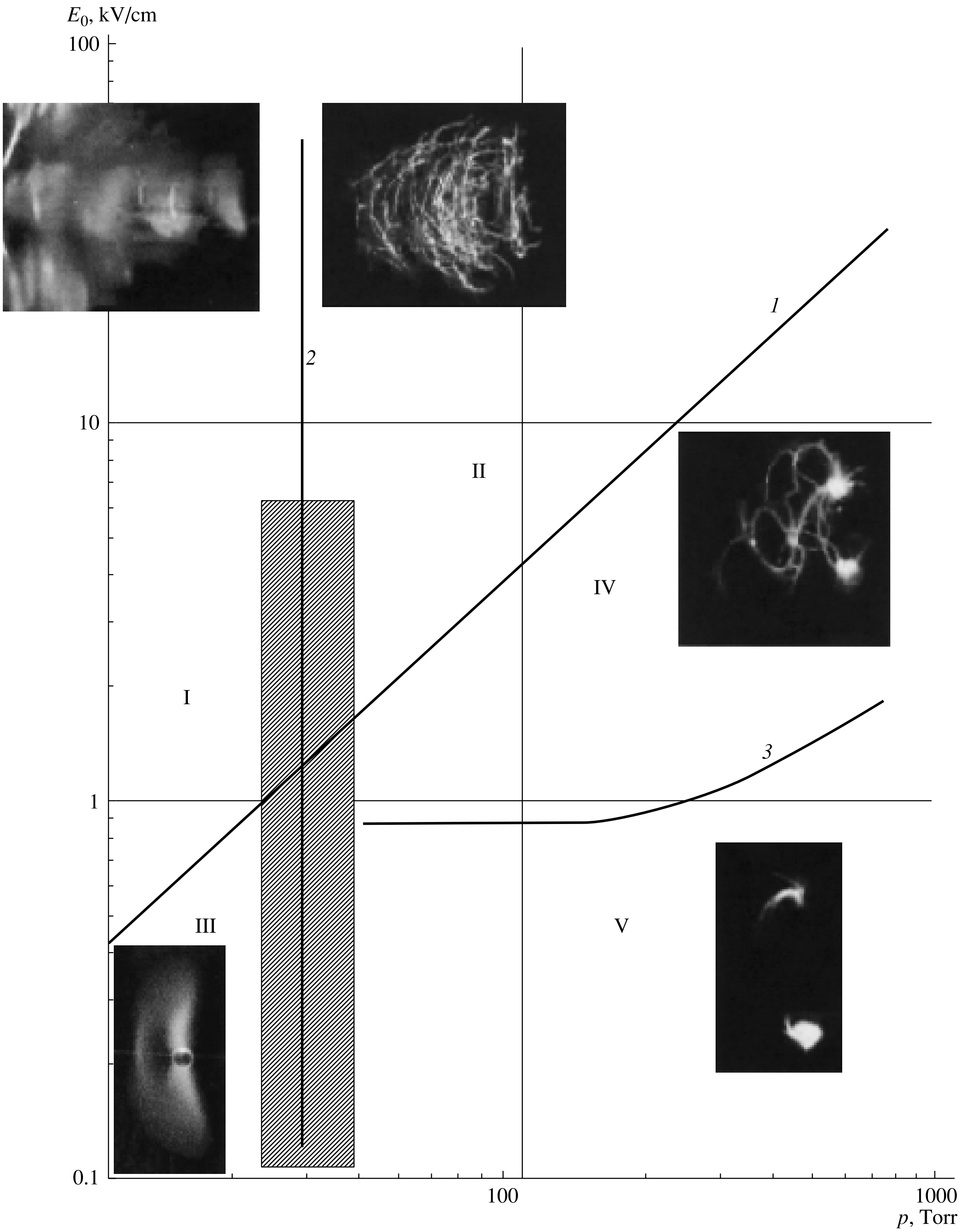


Fig. 5. Domains of existence of different types of discharge excited by a quasi-optical microwave beam with λ = 8.9 cm in air.

of various types of discharge in the (E_0, p) plane at this wavelength [16]. These domains are shown in Fig. 6 and are designated by Roman numerals *I–V*, according to the type of discharge. The physical meaning of lines *1–3* is the same as in Fig. 5. Figure 6 also shows the characteristic spatial structure of different types of microwave discharge excited by a microwave beam with λ = 2.5 cm in air.

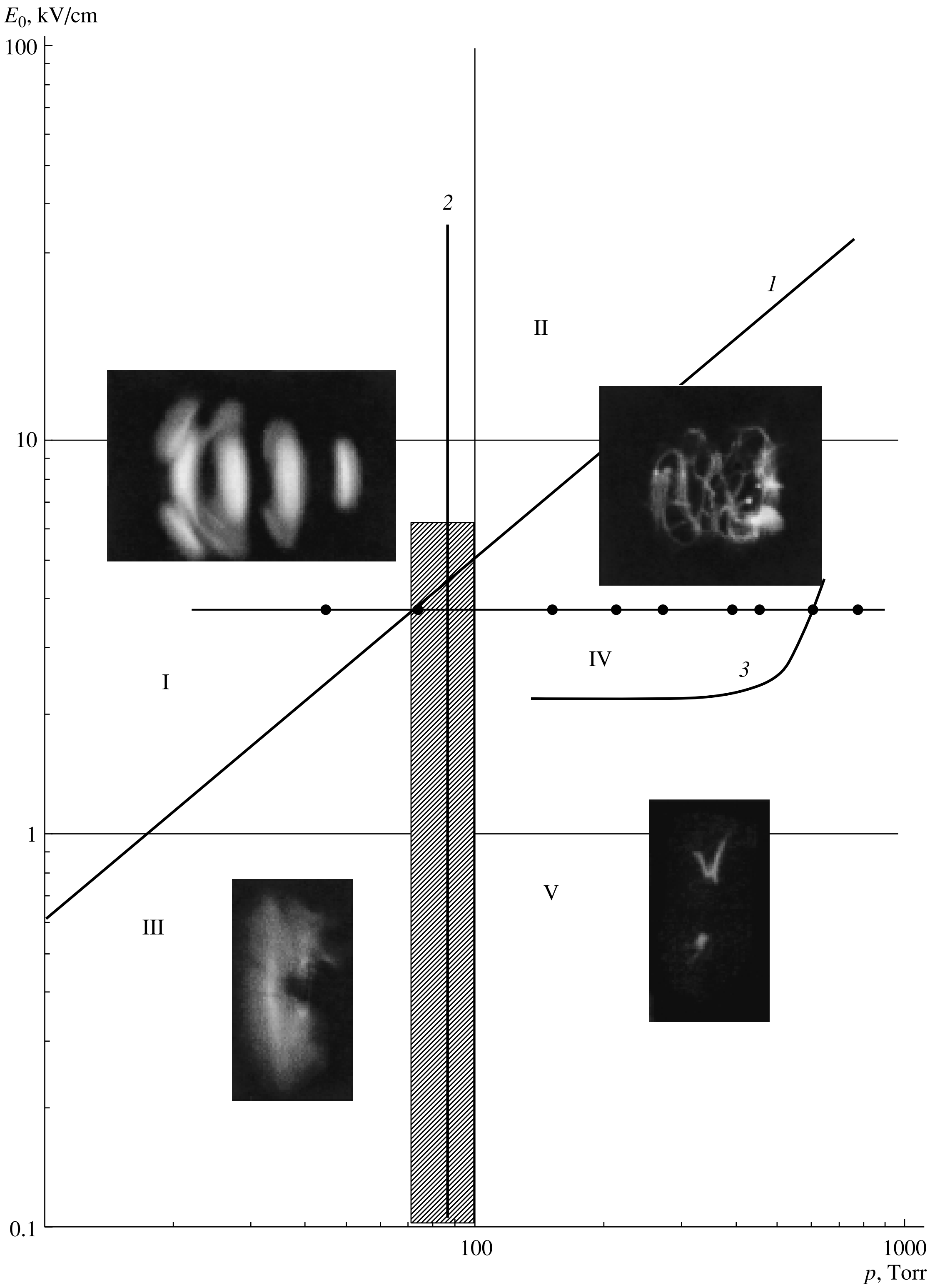
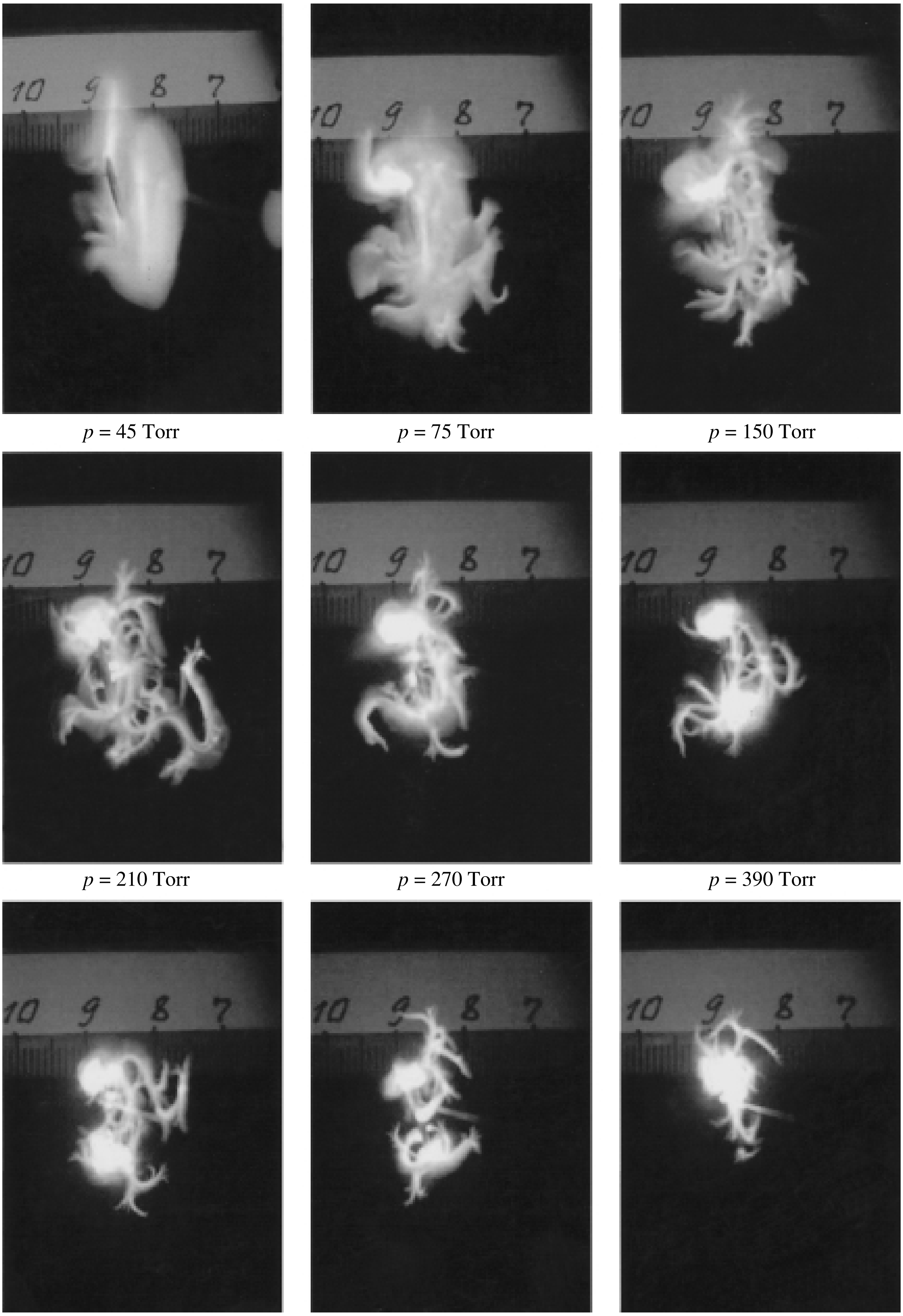


Fig. 6. Domains of existence of different types of discharge excited by a quasi-optical microwave beam with $\lambda = 2.5$ cm in air.

A comparison of Figs. 5 and 6 shows that the domains of existence of different types of microwave discharge are different for these two wavelengths. Both the threshold air pressure p_{thres} and the threshold field strength E_{thres} are higher for the shorter wavelength λ.

As an example, Fig. 7 shows photographs of different types of discharge for $\lambda = 2.5$ cm (microwave radiation is incident from the right). All of the discharges presented in these photographs were produced with the help of an initiating EM vibrator ($2L = 12$ mm and $2a =$



p = 45 Torr | p = 75 Torr | p = 150 Torr

p = 210 Torr | p = 270 Torr | p = 390 Torr

p = 450 Torr | p = 600 Torr | p = 760 Torr

Fig. 7. Different types of microwave discharge in a quasi-optical wave beam with λ = 2.5 cm at E_0 = 3.7 kV/cm.

1.2 mm) placed in the focus of the microwave beam, where the field strength of the incident radiation was maximum, E_0 = 3.7 kV/cm. The photographs corresponds to different air pressures p in the working chamber. The numerals in each photograph show the spatial scale in centimeters.

Let us comment on the photographs presented in Fig. 7. For illustrative purposes, a horizontal line corresponding to the field strength E_0 = 3.7 kV/cm is drawn in Fig. 6. The markers on this line show the air pressures p corresponding to particular photographs in Fig. 7.

The photograph taken at p = 45 Torr presents a typical discharge operating in domain I in Fig. 6. It can be seen that this discharge is overcritical and diffuse. The discharge plasma is seen to be fairly uniform and localized in the focal region of the microwave beam, where the EM vibrator is placed, and in the close vicinity of it.

At p = 75 Torr, the discharge is seen to change in structure. According to Fig. 6, it corresponds to the transition region between a diffuse and a streamer discharge. It can be seen that the discharge has a significant diffuse component and that the surface of the upper end of the initiator is being evaporated, which is typical of a streamer discharge.

The photographs taken at pressures of p = 150–450 Torr correspond to undercritical ($E_0 < E_{cr}$) streamer discharges with a developed spatial structure, i.e., to domain IV in Fig. 6. In the photographs corresponding to p = 210 Torr and 450 Torr, characteristic branching plasma sinusoids forming the spatial structure of this type of discharge are clearly seen. All of these discharges are characterized by the evaporation of the surface of the initializing EM vibrator, thereby indicating the high interaction efficiency of the discharge with the microwave field.

At p = 600 Torr, the discharge operates at the boundary between the domains corresponding to an undercritical ($E_0 < E_{thres}$) and a deeply undercritical ($E_0 \ll E_{cr}$) streamer discharge (see Fig. 6). At p = 760 Torr, the discharge operates in the deeply undercritical mode: the point corresponding to the given values of the field strength E_0 and air pressure p lies to the right of line *3* in Fig. 6, i.e., in domain V.

CONCLUSIONS

Thus, we may conclude that the proposed classification of discharges excited by quasi-optical microwave beams in air is universal in the wavelength range under study. It is unclear, however, whether it is valid for significantly longer and shorter wavelengths. For example, the formation of a developed spatial structure of an undercritical streamer discharge capable of detaching from the initiator is significantly affected by the resonant EM properties of individual regions of the plasma channels with lengths comparable to $\lambda/2$. These properties may be violated at radiation wavelengths lying beyond the wavelength range under study. As the wavelength decreases, the domain of existence of an undercritical streamer discharge with a developed spatial structure shifts toward higher pressures p and higher field strengths E_0. It is quite possible that, at significantly shorter wavelengths, this domain in the (E_0, p) plane will lie beyond the atmospheric pressure range. Outside the wavelength range under study, other physical factors that are not accounted for by this classification may also come into play.

In [3], results were presented from experimental studies of discharges excited by quasi-optical microwave beams with λ = 4.3 cm in air at $p \le 250$ Torr. It was shown that, under these conditions, the filed strength corresponding to the boundary between an undercritical and a deeply undercritical streamer discharge is E_{thres} = 1.8 kV/cm. Experiments also showed that a streamer discharge operated at pressures higher than p_{thres} = 70 Torr. As was expected, these values of E_{thres} and p_{thres} at λ = 4.3 cm lie between the corresponding values shown in Figs. 5 and 6 of the present paper for λ = 8.9 and 2.5 cm.

Results of experimental studies [3, 17] of microwave discharges in various gases allow us to suppose that the classification of microwave discharges in quasi-optical microwave beams that was proposed in this paper also applies to other gases.

The results obtained in this study allow one to specify the operating conditions that are necessary for the excitation of a particular type of discharge in air and thus can be used in designing devices based on such discharges. In this context, the problem arises of determining the domains of existence of these types of discharge in other gases. The results obtained can also be used in developing physical models of these types of microwave discharge.

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