Dependence of threshold for air breakdown by a focused laser beam on the geometry of the focal region

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The effect of the parameters of the laser beam and of the focusing system on the threshold of breakdown of laboratory air by laser radiation of 1.06 μ wavelength is investigated. The electron diffusion losses in the focal-volume range investigated are negligible over the duration of the pulse. It is proved experimentally that in this case the breakdown threshold is determined by the length of the caustic and is independent of size of the focal volume. The decrease of the breakdown threshold of air with increasing caustic length is attributed to self-focusing of the laser radiation in the air, which is weakly ionized by the action of the laser radiation on the aerosols that are always present in laboratory air.

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INTRODUCTION

Earlier investigations of the breakdown of laboratory1) air and other gases by laser radiation of various wavelengths have shown that the cascade theory is incapable of fully explaining the available experimental data. In particular, it does not explain the dependence of the breakdown threshold on the laser pulse duration and on the dimensions of the focal region, when the diffusion losses of the electrons are insignificant.[1,2] In the opinion of the authors of [1,2], a possible cause of this disparity may be the self-focusing of the laser radiation. A proof of the existence of self-fucusing in the breakdown of gases under the influence of neodymium and ruby lasers is provided by the experimentally observed plasma filaments, [2,3] and also by the unique angular and spectral distributions of the scattered light.[4,5] The plasma filaments were noted during the initial breakdown stage at an electron density lower than 10^{18} cm^{-3}.[3] Intense light scattering without the appearance of a visible arc was observed in [1] at a laser-pulse power somewhat lower than threshold.

In addition to self-focusing, the breakdown threshold of air can be influenced by suspended particles (aerosols) present in the focal region.[6-8] In [7], where breakdown of air by radiation of wavelength 10.6 and 1.06 μ was investigated as a function of the focal-spot dimension and of the suspended particles, it was concluded that the breakdown threshold depends on the amount of aerosol in the focal volume and their dimensions. A theoretical analysis has shown that the threshold of breakdown by radiation of 10.6 μ wavelength is determined by "thermal explosion"2) of the suspended particle, caused by the laser radiation. It was shown there that "thermal explosion" of particles cannot play an important role in the breakdown of air at near-infrared and visible wavelengths.

We have investigated experimentally the dependence of the threshold intensity of the breakdown of air at 1.06 μ on the parameters of the beam and of the focusing system. We show that as the length of the caustic increases from 5×10^{-2} to 6×10^{2} cm the air breakdown threshold decreases from 1×10^{11} to 4×10^{8} W/cm^2. At the same time, an increase of the focal volume from 1×10^{-2} to 6×10^{-1} cm^3 at a constant caustic length 2 cm does not change the breakdown threshold. In purified air, the decrease of the breakdown threshold with increasing caustic length is relatively small. We discuss a physical model that explains the observed phenomena.

EXPERIMENTAL RESULTS

The experimental setup is shown in Fig. 1. By using a neodymium-glass multimode Q-switched driving laser and two neodymium-glass amplifiers we were able to obtain a light beam with peak power up to 1.5 GW at a pulse duration 35–40 nsec. The beam divergence at half-intensity level was $(1-2) \times 10^{-3}$ rad for various pulses. To determine the time characteristics of the radiation we used FÉK-14 coaxial photocells jointly with an S1-26 two-beam oscilloscope. The radiation energy was measured with an IKT-1M calorimeter and the peak power with an FOG photometer. The beam divergence was measured in each pulse with a mirror wedge and with an objective of focal length 1 m corrected for spherical aberration. The laser parameters were measured ahead of the lens L_1 at the focus of which the breakdown was observed, and past the breakdown region. The air breakdown was identified with the spark visually observed in the focal region of the lens. The breakdown threshold was taken to be the minimum radiation intensity at which breakdown still took place.

When a laser beam is focused with a spherical lens, the focal volume is customarily taken to be a cylinder of diameter $d = f\theta$ and length $L = (\sqrt{2} - 1)f^2\theta/(D - f\theta)$, where f is the focal length of the lens, θ is the radiation divergence, and D is the diameter of the entering beam. The caustic length L is defined as the distance between the planes where the average radiation intensity is half the maximum value. The focal volume is therefore

$$V = \frac{\pi}{4}(\sqrt{2}-1)f^4\theta^3/(D-f\theta).$$

The diffusion losses considered in cascade theory are characterized by an effective diffusion length Λ, given in the case of a cylindrical volume by

$$\left(\frac{1}{\Lambda}\right)^2 = \left(\frac{\pi}{L}\right)^2 + \left(\frac{4.8}{d}\right)^2.$$

The average time required for the particle to leave the

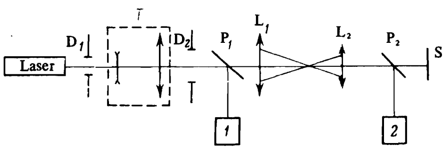

FIG. 1. Experimental setup: D_1, D_2—diaphragms; L_1, L_2—focusing and reprojecting lenses; P_1, P_2—semitransparent plates; T—telescope; S—screen; 1, 2—aparatus for varying the laser-beam parameters.

focal volume is Λ^2/D_0, where D_0 is the diffusion coefficient. In the present study, the measurements were made with focal volumes for which the diffusion losses during the pulse duration were negligibly small ($\Lambda^2/D_0 > \tau_p$). In this case, according to cascade theory, the breakdown threshold should be constant when the size and configuration of the focal volume are varied.

1. In the first run of experiments performed under the described conditions, we investigated the dependence of the breakdown threshold intensity on the size of the focal volume, when both the length of the caustic and the diameter of the focal spot were varied. We used the setup illustrated in Fig. 1, without the telescope T and the diaphragm D_2. The dimension of the entrance beam was limited by the diaphragm D_1. The caustic length was varied by using lenses L_1 with different focal lengths (from 20 cm to 15 m). The length of the caustic ranged from 0.05 to 680 cm, and the diameter of the focal volume changed in this case by approximately 100 times. The obtained relation is shown in Fig. 2 (curve 1). It is well described by the formula $I \sim L^{-0.6}$ and cannot be attributed to diffusion loss of electrons from the focal region.

In accordance with [6,7], we can propose that the decrease of the breakdown threshold of air with increasing focal volume (caustic length) is due to the influence of the suspended particles that are always present in the laboratory air. With increasing focal volume, the number of particles suspended in the air increases, as does the probability that some of the particles are of large dimension. If the decisive role in the spark formation is played by the suspended particles, then the breakdown threshold must be connected with the change of the focal volume. To check on the influence of the suspended particles, we measured under the same conditions the breakdown threshold of purified air. It remained practically constant in the caustic range from 3×10^{-2} to 2 cm (Fig. 2, curve 2), in agreement with the cascade theory of breakdown. The air was purified with a nickel filter that prevented passage of particles measuring more than 0.1 μ.

2. In the second run of experiments the focal-spot diameter was kept practically constant, and only the length of the caustic was varied. We used the setup illustrated in Fig. 1. The dimension of the laser beam was bounded by a 30-mm diaphragm D_1 and was enlarged to 90 mm with telescope T having a magnification 3×. The caustic length was varied by using diaphragms D_2 of different diameters, keeping constant the focal length of lens L_1 (80 cm) and the divergence of the laser radiation. The length of the caustic could be varied by approximately one order of magnitude (from 0.2 to 2 cm), and the focal volume could be varied at the same time by the same factor (from 1×10^{-3} to 1×10^{-2} cm^3). The breakdown threshold was decreased by a factor more than 3 (Fig. 3, points 1 and 2). When the caustic length was increased in the same range (from 1.6×10^{-1} cm to ~ 2 cm), the breakdown threshold in the first run of measurement decreased by approximately the same factor (Fig. 2), although the focal volume was increased then by approximately 250 times. It follows from the described experimental runs that the breakdown threshold varies in the same way following an equal change of the length of the caustic but under appreciable variation of the size of the focal volume.

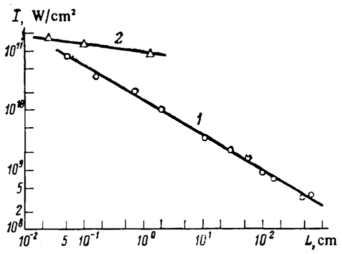

FIG. 2

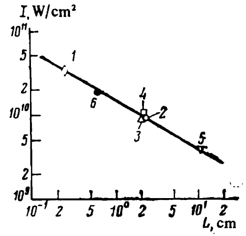

FIG. 3

FIG. 2. Dependence of the threshold intensity of air breakdown on the length of the caustic: 1—for laboratory air, 2—for purified air. The length of the caustic and the focal volume vary with the focal length of lens L_1. The focal volume ranged from 1×10^{-5} to 2×10^{-3} cm^3.

FIG. 3. Dependence of the threshold breakdown intensity of laboratory air on the length of the caustic under various configurations of the focal region. The focal volumes are: 1) 1×10^{-3}, 2) 1×10^{-2}, 3) 1×10^{-1}, 4) 6×10^{-1}, 5) 1, and 6) 3×10^{-3} cm^3. The diameter of the focal spot remains practically constant in section 1–2 at $d \approx 7 \times 10^{-2}$ cm.

It must be noted that in the same series of measurements the breakdown had a statistical character, apparently brought about by the partial influence of electron diffusion from the focal region, owing to the smallness of the focal-spot diameter. The scatter of the values of the radiation intensity at which breakdown of the air was observed decreased with increasing focal volume. As already mentioned, the breakdown threshold was taken to be the minimal radiation intensity at which the breakdown occurred.

3. In the third and final run of experiments we investigated the dependence of the breakdown threshold on the focal volume under conditions when the length of the caustic remained practically constant and the focal-spot diameter changed.

To this end, the divergence of the laser radiation and the dimension of the diaphragm D_2 were varied in such a way that their ratio remained constant. This was done by removing the telescope T (the beam divergence was increased threefold), and by inserting 30-mm diaphragm D_2. This changed the focal volume tenfold (from 1×10^{-2} to 1×10^{-1} cm^3) without changing the length of the caustic (2 cm). The breakdown threshold did not change (Fig. 3, points 2 and 3). Further increase of the focal volume by another six times (to 6×10^{-1} cm^3) at the same caustic length was effected by using the prismatic raster system described in detail in [9], with the telescope T and a 90-mm diaphragm D_2. In this case the length of the caustic was measured experimentally by a photoelectric method. The breakdown threshold remained likewise constant (Fig. 3, point 4).

As a control, in the same experimental run, a spherical lens of focal length 1.9 m was used to increase the length of the caustic to 10 cm at a focal volume approximately equal to that of the raster system (~ 1 cm^3). The breakdown threshold was lowered in accordance with the relation $I \sim L^{-0.6}$ (Fig. 3, point 5).

Thus, in the caustic length region 0.2–10 cm and at focal volumes from 1×10^{-3} to 1 cm^3 the breakdown threshold of laboratory air is independent of the size of the focal volume and is determined by the interaction length of the intense laser radiation with the medium. It is seen that for larger focal volumes the breakdown threshold is also determined by the length of the caustic.

DISCUSSION OF RESULTS

The mechanism whereby air breaks down by "thermal explosion" of the particles does not operate under the conditions of the described experiments. This follows from a comparison, carried out in accord with [8] for the corresponding values of the focal volume, of the experimentally observed dependence of the air breakdown threshold on the shape of the focal volume and from the estimate of the threshold for air breakdown by 1.06-μ radiation, due to "thermal explosion" of particles.

The experimental data allow us to propose the following breakdown mechanism: When high-power laser radiation acts on the suspended particles, initial ionization is produced in the focal region. The produced electrons do not have enough energy to ionize directly the molecules of the gases making up the air. As they are accelerated in the field of the light wave, they excite and ionize these molecules. The presence of excited molecules increases the refractive index of the medium, and this causes self-focusing of the laser radiation and leads to breakdown of the air.

It follows from the proposed mechanism that in order for breakdown to develop it is necessary to satisfy at least two conditions: the average radiation intensity must exceed the threshold intensity for the evaporation of the suspended particles, and the beam must attain a definite power required for self-focusing to develop. Since the first requirement is usually the stronger, one should expect the air-breakdown threshold intensity to approach, with increasing length of the caustic, the particle-evaporation threshold intensity $I_0 \approx (1-3) \times 10^8$ W/cm^2.

With the aid of our results, using [10], we can estimate the critical self-focusing power. Pasmanik[10] investigated the self-focusing of a spatially-incoherent beam, such as the beam of a multimode neodymium laser.

The estimates were made under the following assumptions:

1) The neodymium laser emits individual "spots" of size ρ, within which the radiation is coherent.

2) The beam divergence θ is equal to the diffraction divergence of the individual "spot"

$$\theta = 1.22\lambda/\rho.$$

According to [10], the self-focusing length z_f is given by

$$z_f = z_d/(P_0/P_{cr} - 1)^{1/2},$$

where $z_d = kRr$ is the length of the diffraction broadening of the beam; $k = 2\pi/2$ is the wave vector; R is the radius of the beam; r is the radius of the coherence region of the radiation; P_0 is the power contained in the region of the radius r; P_{cr} is the critical self-focusing power.

Self-focusing is observed if the length l of the nonlinear medium exceeds the self-focusing length z_f. In accord with the proposed mechanism, we define the length of the nonlinear medium as the dimension of the region where the average radiation intensity I exceeds the intensity I_0 needed for the evaporation of the suspended particles:

$$l = \frac{L}{\sqrt{2}-1}\left(\left(\frac{I}{I_0}\right)^{1/2} - 1\right);$$

here L is the length of the caustic.

In the focal region, where self-focusing takes place, the radii of the beam and of the radiation-coherence region should be taken to be the quantities

$$R = {}^1/_2 f\theta, \quad r = {}^1/_2 \rho f\theta/D,$$

where f is the focal length of the lens and D is the diameter of the entering beam.

The self-focusing condition can then be written in the form

$$\frac{L}{\sqrt{2}-1}\left(\sqrt{\frac{I}{I_0}} - 1\right) \geqslant \frac{1.22\pi f^2\theta}{2D}\left\{\left(\frac{1.22\lambda}{D\theta}\right)^2 \frac{P}{P_{cr}} - 1\right\}^{-1/2},$$

where P is the total beam power. An estimate of the critical self-focusing power P_{cr} for $I_0 = 1 \times 10^8$ W/cm^2 then shows that within the limits of experimental error P_{cr} remains constant at $(1-3) \times 10^5$ W, even though the experimental conditions vary in a wide range (see the table).

We present some estimates that confirm the validity of the proposed breakdown mechanism. Air presently contains particles less than 1 μ in dimension. According to [11], the concentrations of particles measuring ~1 and ~0.5 μ, which are optically active, are respectively 2.5×10^3 and 2×10^4 cm^{-3}. In the case of total evaporation and single ionization, they yield an initial electron density ~10^{14} cm^{-3}. Solving the kinetic equation for the density of the vibrationally excited nitrogen molecules we find that during a laser-pulse duration 40 nsec, at an initial electron density ~10^{14} cm^{-3} the density of the excited nitrogen molecule is ~10^{18} cm^{-3}. The excitation of the oxygen molecules can be disregarded, since they have a small excitation cross section. According to the data of [12], the polarizability of the vibrationally-excited nitrogen molecules increases 1.5% in comparison with the polarizability of the molecules in the ground state. This leads to an increase of the refractive index n by $\Delta n = 3.3 \times 10^{-7}$. The negative refractive-index decrement due to the free electrons amounts in this case to 5×10^{-8}. Thus, only the increase of the linear polarizability of the vibrationally-excited molecules of the nitrogen in the focal region gives rise to an increase of the refractive index, and this contributes to the self-focusing of the laser radiation.

The refractive index can also be increased by the nonlinear polarizability of the excited atoms and molecules. As shown in [13], the cubic nonlinear polarizability of the excited atoms can exceed by 10^9 the polarizability of unexcited atoms. So large an increase of the polarizability can lead to sufficiently low values of the critical self-focusing power.

It is difficult at present to make detailed estimates, owing to the lack of published data on the nonlinear polarizabilities of the nitrogen and oxygen molecules.

In our investigation, the breakdown of the air was observed at relatively low average laser-radiation intensities, when according to estimates of the cascade theory impact ionization by electrons is impossible. Therefore the number of electrons in the focal region should have remained constant and equal to the number of electrons

f, cm	θ, 10^{-3} rad	D, cm	P, MW	P_{cr}, 10^5 W	f, cm	θ, 10^{-3} rad	D, cm	P, MW	P_{cr}, 10^5 W
1500	1.4	4	1200	3.0	450	2.1	4	1050	2.0
1000	2.1	4	1180	1.3	340	1.8	4	765	2.0
800	1.6	4	859	2.2	190	1.9	3	407	1.9
520	2.5	4	1130	1.3	80	0.81	3	63	1.8

obtained as a result of evaporation of the suspended particles ($\sim 10^{14}$ cm^{-3}). At this low electron density, self-focusing due to the change of the spatial distribution of the electron density is impossible.[14]

Thus, the obtained experimental results indicate that when laser radiation acts on laboratory air the self-focusing takes place prior to the formation of the visually observable spark, owing to the increased polarizabilities of the excited molecules of the gases making up the air.

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[1] By laboratory air is meant air not subjected to special purification.

[2] "Thermal explosion" of a particle occurs when the energy absorbed by the particle during its inertial stay in the vapor state exceeds the particle evaporation energy. [8]

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