21. STRUCTURES OF EXTENDED LASER SPARK

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Abstract. There are presented typical structures of laser spark formed by wave beams with Rayleigh divergence compensated. The structures differ from those in gaussian beams. The phenomenon explanation and mechanism are discussed. Variety of the structures is associated with the beam features which imply the field radial distribution being of besselian kind, and the axial distribution modulation caused by the wave nonlinear interaction with gas target.

Introduction

The extended spark is created by wave beam with compensation of Rayleigh divergence. The compensation can be realized with concave conical wave front. The angle at the wave cone generatrix corresponds to the Rayleigh divergence angle, \( \gamma = \lambda/d \), where \( \lambda \) and \( d \) are wavelength and diffractive diameter of the compensated beam. In this case the beam length \( L \), in contrast to Gaussian beam, does depend not on wavelength \( \lambda \), but on the cone diameter \( D \), \( L=\pi D/2\gamma \). Accordingly, the length of such a beam does not seem to be restricted, and may exceed its diameter many orders of times, \( L/d=2\lambda \).

The extended spark is formed by wave beams with Rayleigh divergence. Uniform axially symmetric radiation energy feed to the focal setting region permitted to count on ideal homogeneity of the spark. However, structures of rather complex configurations used to appear in the sparks. Therein some sequence of disturbances (reminding the beads) located at the axis were found at the beginning of studying the structures [2,3]. First they were supposed to occur because of complicated mode composition of that laser radiation. Later on the experiments with single frequency laser [4] gave precisely the same result. After that the beadlike structures of the optical discharge have been accounted for by specific features of the wave beam itself, which origin from non-linear processes of the wave propagation [5,6].

The beam structure

Within the beams under consideration the wave non-linear propagation through some medium depends, just as in Gaussian beams [7], on dielectric permeability \( \varepsilon = \varepsilon_0 + \varepsilon' + \varepsilon_{NL} \left| E \right|^2 \), where \( \varepsilon' \) determines the wave damping, and \( \varepsilon_{NL} \) is non-linear functional term responsible for interaction with medium. Description of the field complex amplitude \( E(r,z) = \Re \{ e^{i(\varepsilon_0 r - kr \sin \gamma}) \} \) in the beam with compensated divergence is based on the parabolic equation \( (k^2 = (\omega/c)^2 \varepsilon_0) \)

\[ 2ik \frac{\partial E}{\partial z} + \frac{1}{r} \left( \frac{\partial E}{\partial r} \right) + \left( \frac{\omega}{c} \right)^2 \left( i\gamma + \varepsilon_{NL} \left| E \right|^2 \right) E = 0 \]

(1)

and boundary condition for radiation focusing by the axicon with aperture of \( R \)

\[ E(r, z =0) = E_\in(r) \exp(-i \ k \ r \ \sin \gamma) \]

(2)

This condition provides \( E_\in(r>R)=0 \), 

\( E_\in(r\leq R) = I_{L0}^{-2}(r) \) where \( I_{L0}(r) \) is intensity of the beam to be focused.

Equation (1) with condition (2) has solution \( E^{(0)}(r,z) \) in the axis vicinity \( r < z \sin \gamma \), \( k r^2 < z \) along the length \( \lambda \sin^2 \gamma << z < L \) can be expressed in terms of Bessel function \( J_n(\kappa r \sin \gamma) \) with amplitude \( E_0(z) \):

\[ |E^{(0)}(r,z)|^2 = |E_0(z)|^2 J_0^2(\kappa r \sin \gamma), \]

\[ I \sim E_0^2(z) J_0^2(\kappa r \sin \gamma) \]

(3)

As analysis [6] shows, in linear case, \( \varepsilon' = \varepsilon_{NL} = 0 \), amplitude \( E_0(z) \) can only change slowly and fluently, whereas when \( \varepsilon_{NL} \neq 0 \) (for different kinds of non-linearity), the amplitude longitudinal distribution \( E(z) \) can be modulated, the scale being of typical value

\[ l = 2\lambda / \sin^2 \gamma \].

(4)

In Fig.1a the intensity radial distribution measured in experiment for \( \gamma = 5^\circ \) is given. Values of radii \( r_n \) of Bessel function zeroes are plotted on the dial to the right of the photo. The graphs in Fig.1b depict the longitudinal field modulation \( \left| E \right| / E_0 \) \( (E_0 \) represents linear solution) along z axis as function of relative length \( z/l \) for four parameter \( E_0/E_\in \) values. The graphs are built according to results [5] of numerical solution of system (1)-(2)
for cubic non-linearity, $\varepsilon_{NLE} = (n/n_{cr})(|E|/E_*)^{2}$, where $n$, $n_{cr}$ are current electron density and its critical value for frequency $\omega$, and symbol $E_*$ stands for the amplitude critical value for self-focusing field with given kind of non-linearity. The combination of radial and longitudinal distributions of the beam field forms structure implying some system of intensity peaks. A fragment of the structure is shown in Fig.1c [8].

In Fig.1c the intensity at an axial horizontal plane is presented as its variable part related to the linear solution (3) in order to underline the effect. The arguments are $x = kr\sin \gamma$ (Bessel function argument) and the length $z$ expressed in the longitudinal structure scale $l$ values, $z/l$. The value of $x = 0$ corresponds to symmetry axis of the beam. The separations between adjacent radial and longitudinal maximums are $\delta r = \lambda/2\sin \gamma$ and $l = 2\lambda/\sin^2 \gamma$, $\delta r < < l$.

The modulation (4) appears, when the field amplitude $E$ over central (or some of annular) zone of radial distribution (3) comes nearer to critical value $2E_*$. What is ‘nearer’ does depend on the kind of self-focusing. E.g., in case of Fig.1b, this value must satisfy following condition:

$$0.2 \leq \frac{n}{n_{cr} - n \cdot \sin^2 \gamma} \left| \frac{E^{(0)}}{E_*} \right| ^2 \leq 1$$

When the field weakens, its longitudinal modulation diminishes, and for the field under lower limit of condition (5) it does not appear. In opposite case some large scale structure with period $l_1 \sim 10l$ may appear along with the basic one (4). When intensity reaches the level of $5 \times 10^{13}$ W/cm$^2$, non-linear absorption of beam field can influence processes of longitudinal modulation as well. This absorption process develops as a result.

Fig.1. Field in the beam with diffraction divergence compensated: radial for $\gamma=5^\circ$ (a) and longitudinal (b) distributions, chart of beam structure (c)
of the field interaction with resonant modes of plasma broadening channel. It modulates the plasma heating and brings into existence channel structure depending on medium and its initial pressure [9].

Note, that the longitudinal modulation does not affects the field radial distribution which, as before, is described by Bessel function. Hence, the term of “Bessel beam”, or “Besselian beam” will be used to name the beams with compensation of diffraction divergence.

The brief review of Bessel beam features makes it possible to estimate processes, happening in formation of structures of optical discharges. First, however, let us consider the configurations of these structures, detected in experiments.

**Spark structures observed**

In the work heating radiation was created by the laser at the wavelength $\lambda=1.06\,\mu m$, and concentrated by conical lens, axicon. Generation conditions of the sparks varied over wide ranges.

The angle $\gamma$ varied from 1 up to 18°, that foreordained the beam diameter $d$, from 50 to 3μm, and the beam length $L$, from 130 to 1.5cm. The sparks were created in gases of ten different compositions at pressures 0.05–10 at. While experiments executing the heating pulse duration was decreasing step by step from 50ns down to 100ps, and, accordingly, the energy dropping from 70 to 0.6J.

Some techniques of laser diagnostics [10] were attracted for the spark structure investigations. The spark structures within the channel were determined with plasma emission and scattered light, optical path disturbances, including waves propagating in plasma channel of optical discharge, were visualized by shadow and schlieren methods (see [1]). In experiments with short (100ps) laser pulse duration Mach-Zender interferometer was used for the purpose [11]. The structure images were registered with IC and CCD cameras. Systematization of data has let distinguish five typical structures shown in Fig.2 in accordance with chronology of their generation. The light propagates from the left to the right in these frames.

Fig.2a represents structure of optical discharge in air at atmospheric pressure, formed by the beam with parameters: $\tau=40ns$, $E=70J$ and $\gamma=7.5^\circ$ ($L=17cm$). The structure specific feature is presence of branches coming from the symmetry axis at an angle $\beta$ to axis, that reminds the fir-tree. Emphasize, that inclination angle of these branches far exceeds the angle $\gamma$, $\beta \gg \gamma$. Therefore, their origin can not be explained merely by the discharge running against propagation of the heating radiation, as it is with optical discharges in focus of spherical lens [12]. Also note that the branches are located along the axis at a distance $l=0.12mm$ from each other, and each of them consists of discrete breakdown series.

In Fig.2b structure of the discharge in argon of atmospheric pressure for beam with same

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**Fig.2.** The spark structures:: (a, b) – air and argon at 1at, $\tau=40ns$, $E=70J$, $\gamma=7.5^\circ$; (c) – air 1at, 20ns, 20J, 5°; (d) – air 1at, 0.8ns, 173, 2.5°; (e) – fragment of frame (d); (f) – Ar 0.2at, 0.8ns, 10J, 1°.
parameters as in Fig.2a ($t=40$ns, $E=70$J and $\gamma=7.5^\circ$) is shown. Here one can see large scale structures of funnel-like shape, separated by the intervals about 1mm. It is known [12, 13] that the threshold intensity level in argon is 5.3 times lower ($I_{th}=1.5\times10^{10}$W/cm$^2$), than in air ($I_{th}=8\times10^{10}$W/cm$^2$). So, the excess of threshold intensity in argon seems to be more considerable in the case of the same beam parameters. Evidently, this is the reason why there is such a noticeable difference between structures in air (Fig.2a) and in argon (Fig.2b). Attentive seeing will mark beadlike structures in air (Fig.2a) and in argon (Fig.2b). There is such a noticeable difference between the neighbors being separated by the distance $l=0.12$mm which coincides with structure period of Fig.2a.

In Fig.2c–2f the results for shorter heating radiation pulses are given. The structure in Fig.2c is created in atmospheric air by the beam with parameters: $t=20$ns, $E=20$J and $\gamma=5^\circ$ ($L=26$cm). Here the intensity is six times as small in relation to experiment in Fig.2b, and the specific energy is reduced by twelve times. The structure periodicity of breakdowns along the axis comes to light in this case as well, though the period has enlarged up to $l=0.28$mm. At the same time, the structural bubbles, or spots, remaining in the axial zone, turned into continuous plasma units, let its name be “cell”.

In Fig.2d optical discharge developed in air at atmospheric pressure with the beam parameters: $t=0.8$ns, $E=17$J and $\gamma=2.5^\circ$ ($L=52$cm). The intensity was almost three times as much in compare with experiment shown in Fig.2c, but at the specific energy level of one tenth of the previous one. As Fig.2d frame can be understood, the specific energy reduction corrupts the uniformity of plasma structural cells. Moreover, each cell is getting appreciable to consist of smaller cells of 0.02–0.05mm size, which group around branches, coming from the discharge centermost line. For all this the separation of the sells remains constant, and the longitudinal structure period equals $l=1.1$mm. A fragment of the picture is presented in Fig.2e in enlarged scale. Therein the cells and how they group around individual branch lines are distinctly seen. Again, inclination angle $\beta$ of these lines far exceeds angle $\gamma$.

In Fig.2f the breakdown structure was obtained in argon at a pressure 0.2at in the beam with parameters: $t=0.8$ns, $E=101$J, $\gamma=1^\circ$, the intensity being two orders below compared with preceding experiment. With whole beam length $L=130$cm the frame of Fig.2f covers only its part, 50cm. The beam intensity near the axicon (in figure on the left) only just exceeds the breakdown threshold level, and makes approximately $1/4$ part of the mean value along the whole length. It is clearly seen, that the microbreakdowns rest on the beam axis as a periodical sequence of spots with spatial period increased up to $l=7$mm. Away from the axicon, when intensity in the beam grows, the individual spots begin to merge, showing the trend toward formation of continuous channel.

As it follows from above shown data, the scale value $l$ of the beadlike structure observed does not depend on gas sort, pressure, energy and duration of heating radiation, and is only associated with angle $\gamma$ of the conical wave front inclination. At the same time, there can exist other types of structure of larger and small scales. Evidently, configurations of larger scale depend not only on the beam parameters, but on other conditions of the experiment as well. Intensity excess above threshold value and heating pulse duration should be mentioned among them. On the other hand, dependence of small scale structures on experimental conditions is not so evident, though to some extent they present in all structures of the sparks, produced by conical wave front.

In described experiments the arrangement of prime sites of breakdowns could be registered in the light of scattered heating radiation. However, measurement of the breakdown dimensions did not succeed in with this technique. One of the reasons consists in long duration of heating radiation pulse. Indeed, even for the most short pulse (duration about 1ns) the breakdown spot boundary runs ~40µm, that can appreciably exceed its original radius. Therefore in the following experiments the pulse duration was reduced tenfold.

Experiments mentioned in [11] were fulfilled with the set-up equipment [14], where the wave beam ($\lambda=1.06$µm) was created by the heating pulse with parameters: $t=100$ps, $E=0.6$J. The energy level provided the medium choice (nitrous oxide) and relatively large angle $\gamma=18^\circ$ with diameter of central part of the beam $2a=2.6$µm at the length $L=1.5$cm to match. The density perturbations in the discharge channel were observed by Mach-Zehnder interferometer with laser (0.53µm, 70ps) as illumination source. The magnified image of interferograms was registered by CCD camera, the matrix length being 512µm (320 pixels).

In these measurements the intensity in the beam has reached the level of $5\times10^{13}$W/cm$^2$, so the longitudinal field structure could be influenced by modulation of heating radiation absorption [9]. To avoid error in interpretation of observed effects, the optical discharge was examined in the development, and at different pressures.

There are presented in Fig.3 interferograms $a$, $b$ and $c$ registered with various exposure delays relatively to the heating pulse start, accordingly by 0, 100 and 250ps. Indices 1 and 2 at
the interferograms correspond to nitrous oxide pressures of 200 and 500Torr (0.27 and 0.67at). Numerals mark numbers of the matrix pixels of dimension 1.6 \mu m each.

The spark channel contours are seen in Fig.3 on the background of interference fringes of equal inclination, and the fringe displacement expresses the medium density changes along the illumination ray direction. Interferograms \(a_1, b_1\) and \(c_1\) (Fig.3) show, that at pressure 0.27at the channel of optical discharge remains uniform throughout observation time. On the contrary, as it follows from the frames \(a_2, b_2\) and \(c_2\) for pressure 0.67at, the interferometer records density perturbations from the very beginning of the discharge. At least disturbances are seen on the interferogram made with zero delay shot, i.e. during the period of the heating pulse action. The problem, however, consists in low temporal and spatial resolution of interferometry technique, and the interferograms let not visualize initial breakdown spots.

At the same time, the pictures of fringe shift in interferograms \(a_2, b_2\) and \(c_2\) testify discrete nature of the discharges. This means that the entire structure is formed as a result of density waves propagating throughout the channel. The source of these waves can not help being microdischarges located at the symmetry axis. This understanding lets reconstruct all the history of optical discharge development by computational way. Frame \(c_2\) (Fig.3) is especially useful for that, because the interferogram has been obtained at the later stage of the process, and the disturbance distribution can be resolved to satisfy precision necessary for quantitative estimation the channel state.

**Computation of breakdown structure for short heating pulse**

Matrix of CCD camera covers \(N=56\) interference fringes along axis \(z\). Displacement \(\delta\) of the fringes can be considered as function \(\delta(N)\), or \(\delta(z)\), where \(z=Nh\), \(h\) is the average distance between the fringe lines. In fact the function represents the density total perturbation along the chord sited at some distance \(r\) away from \(z\)-axis.

Such dependences, \(\delta(N)\), have been built in Fig.4 for various radius \(r\) of the channel \(c_2\) (Fig.3). In Fig.4 values of the radius are presented as ratio \(r/R\), where \(2R=41.0\mu m\) is the diameter of real channel \(c_2\). The upper graph in Fig.4 refers to displacement of the fringe lines far away from the channel axis, \(r/R=5\), and actually demonstrates the line arrangement periodicity and accuracy of the measurements. The next graphs show the displacement dependence \(\delta(N)\) for sequence of the ratio values \(r/R=0, 0.25, 0.50\) and 0.75. The last graph, \(r/R=1\), describes the radial displacement of upper and lower boundaries of the channel.

The distribution patterns of the density disturbance confirm the discrete nature of breakdown. Also, it is evident how distributions shown in Fig.4 arise. Indeed, each microbreakdown
creates some volume with elevated temperature and pressure, which then propagates as the spherical wave. Let the microbreakdown zone look like a small ball of radius \( a \), centered at origin of coordinates at the moment \( t=0 \). Also, let excess density be some arbitrary function \( f(r) \) within the ball, \( r\leq a \), and \( f(r)=0 \) outside, \( r > a \), surrounding density being \( \rho_0=1 \). Then the wave propagates as follows \([15]\):

\[
\rho = \frac{f(r - ct)}{r} \quad (6)
\]

when \( |r-ct| \leq a \), and \( \rho = 0 \), when \( |r-ct| > a \).

At some distance \( r>>a \) the disturbance, independent of its original form, turns into the spherical pack which represents in reality a spherical layer of the thickness \( 2a \). Within the layer hydrodynamic parameters pulsate as specified by the function \( f(r) \). In this manner, the wave disperseds the pulsations over the channel. Temporal-spatial field of the pulsations throughout all the channel is determined by superposition of individual waves (6). This superposition forms the observable density fluctuations.

It is naturally to suppose that the microbreakdowns appear at a maximums of the beam intensity distribution. If solution (3) is true, and the beam structure corresponds to scheme of Fig.1c, then the maximum sequence forms the periodical series of the microbreakdowns along the axis, separated by the distance \( l=2\lambda/\sin^2\gamma \) which equals \( l=21\mu m \) in our case. The beam radial structure is set by Bessel function rings. Relative radii of the rings (scaled by Fig.2c channel half diameter, \( 20.5\mu m \)) are \( a=0.063, 0.145, 0.227 \) etc. There arises a question, however, which namely of the maximums the breakdowns take place in. This problem can be solved by means of modeling \([16]\).

Consider the case, when the breakdown zone is limited by Bessel function central part, or one of the rings, the diameter being \( 2a \). If the discharge is dispersed among the longitudinal maximums, then their number (along the length \( 512\mu m \)) equals 24. According to symmetry of the problem the propagation process can be described by means of two coordinates: longitudinal, \( z \), and radial, \( r \). The values of \( z \) and of the fringe

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**Fig.4.** Density pulsations within the channel (frame c2 in Fig.3) for various \( r/R \)
displacement are convenient to scale by $h$ (the step of interference fringes along the axis $z$), and investigate the structure along the same line (and length), as it is observed, i.e. $\{z_1, z_2\} = \{0, 55\}$. One more circumstance should be taken into account. The fringe displacement observed corresponds to total phase change of the wave running over the path $y$ along the chord of the channel cylinder with impact parameter $r_0$.

Place the chord in position with coordinates $r_0 = R/2$ and $z_0 = (z_2 - z_1)/2$. Its length equals $2r_0\tan\varphi$, where $\varphi$ is azimuth angle, and $y$ runs along the chord half, from 0 to $r_0\tan\varphi$. Total phase change means including all the waves that arises at points $pz(z)$ of the axis $z$ within the interval $\{z_1, z_2\}$. The following parameters can be introduced for outlining possible (without any suggestions) allocation of the points: shift $Q$ of the sequence $pz(z)$ as a whole, $Q < 1$; interval $q$ of chance deviations of points $pz(z)$ from their uniform distribution, $q < 0.5$; part $t_0$ of heating pulse duration $\tau$, while breakdowns occur; interval $pt$ of disorder in the breakdown arising, $pt \leq t_0$; quantity $k$ of the wave sources arising along the length $z_2 - z_1$; function $f(r)$ of density distribution in prime microbreakdowns; quantity $m$ of the chord $r$ elements intended for the phase calculation. The magnitudes $pt$, $t_0$ и $\tau$ are expressed in scale of channel $c2$ (Fig.3) lifetime, 250ps. With this scale the heating pulse duration, for example, makes up $\tau = 0.4$. Some variant of full set of initial conditions for the problem can now be summarized as:

$$ a = \{0.063, 0.145, 0.227\}; \\
 k = 25; \tau = 0.4; t_0 = 0.4; \{z_1, z_2\} = \{-1, 56\}; \\
 \{y_1, y_2\} = \{0, r_0\tan(\pi/3)\}; \\
 f(r) = 1; m = 11; Q = 1; q = 0. \quad (7) $$

The results of calculation for the initial sizes of the disturbances $a = 0.063, 0.145, 0.227$ (the central part, first and second rings of Bessel function) are given in Fig.5 as graphs 1, 2, 3 accordingly. In the same Fig.5 graphs E reproduces the experimental density distribution for parameter $r_0/R = 0.5$, shown in Fig.4, and its spectrum. The density distributions along the line $r_0/R = 0.5$ are on the left of Fig.5, their spectra are collected on the right.

Comparing of the graphs shows, that it is parameter $a = 0.145$ for which features of the experimental curves are the most close to the computation results. Really, in the case of $a = 0.063$ the structure is too small, whereas when $a = 0.227$ it is too large. Hence, further elaboration of the structure other parameters was executed for $a = 0.145$. There were varied: disturbances number $k$, distribution of $pz$, displacement $Q$ of all the sequence, dispersion band $q$, interval $t_0$, and kind of function $f(r)$.

![Fig.5. Density longitudinal structure ($r/R = 0.5$) of optical discharge channel: experiment, E, and computations, $a = 0.063$ (1), 0.145 (2), 0.227 (3)](image-url)
It was found, that most exactly the observed structure of disturbances is described for the following values of the parameters: $k=25$; $t_0=0.2$; $Q=0.17$; $q=0$; $f(r)=1$. According to this result, microdischarges appear in the beam during interval $t_0=0.2$ (~50ps), in each axial maximum (4), and the deviation from period $l=21\mu m$ does not exceed several percents. Dimensions of the prime discharge are restricted by second zero of Bessel function, and corresponds to radius $2.9 \mu m$. It worth to note, the equality $t_0=0.2$ means, that the discharge occurs at the radiation intensity level 0.8 of maximum value, and the beam intensity becomes insufficient for breakdown in the outer rings of Bessel function.

Therefore, with heating pulse $\tau=100$ps and energy of $E=0.6J$ the structure origin of optical discharge is connected with non-linear interaction, which corresponds to the scheme of Fig.1c. The longitudinal structure of the spark is realized at maximums of those rings of the beam radial structure, where the intensity satisfies condition (5).

**Formation of intricated spark structures**

The microdischarge boundary runs the path which does not exceed $1\mu m$ during the interval, $t_0=50$ps. And the microdischarge itself reminds explosion of small (point) diameter, which is followed by free propagating explosive wave. When however the heating pulse is prolonged, the radiation begins interact with the discharge plasma, and influence the process. A lot of information on optical discharge propagation was accumulated while studying laser spark created in focus of spherical lens (see, e.g., [11,12]). There was established, that the breakdown threshold is proportional to ionization potential, it decreases with increasing of pressure, of focal volume diameter and laser pulse duration. The breakdown propagates backward the heating radiation rays with velocity $10^7-10^8$cm/s according to one of three mechanisms: the ionization wave, breakdown wave or so called light detonation. The optical discharge configuration does not look as symmetrical body, since the velocity of its side extension is close to sound speed in arising plasma, that is well below above mentioned magnitudes.

Similar phenomena should have place in the beam with compensated divergence, as well. However in this case it is necessary to take into account running focus regime, and field structure of Bessel beam (Fig.1c). Diagram of longitudinal propagation of non-linear interaction front is shown in Fig.6, where the intensity is presented as function of distance and time, $I(z,t)$. The shaded surface in the figure denotes lower level of the intensity, $I_1$, at which, according to (5), the non-linear processes start. In the range $0<i\ll I_1$, the intensity increases along the axis monotonously, as it is illustrated by heavy line drawn in vertical plane $z-I$. When $I > I_1$, the intensity modulation develops, maximums being at points $z_2$ and $z_3$. The diagram explains observed in Fig.2 microdischarge enlargement with $z$, and the trend to merging of the discharge spots.
The intensity dependences on time at points z₁, z₂ and z₃ are shown in the diagram as well. The heating pulse reach its maximum values at those points at the moments t₁, t₂, t₃. Though, as it is clear from the diagram, the non-linear processes begin developing only at points z₂ and z₃, and at the moments t₂ and t₃, some time before the maximums arrival. Hence, the discharge jumps from some point zₙ₋₁ to the next zₙ consecutively only under condition that the heating pulse grows (from I₁ to the maximum) faster, than it sweeps the distance between the two points, i.e., δτₙ₋₁<(|zₙ−zₙ₋₁|/v)ν, where v=c/cosγ [17]. This restriction is possible to be approximated as δτ<c·cosγ/c. The sequence can be violated for longer rise of the heating pulse, when the discharge sequence can run forwards as well as backwards.

The breakdown propagation in radial direction has its own peculiarities. When the intensity is just beginning to exceed threshold value, the breakdown takes place only in the caustic of Bessel function central part, value, the breakdown takes place only in the intensity is just beginning to exceed threshold direction has its own peculiarities. When the discharge sequence can run forwards as well as backwards.

Analysis of the structures available for the heating pulses of nanosecond range (Fig.2) is convenient to start from the experiments with short pulses. In the experiment presented in Fig.2f (argon, 0.2at, pulse duration τ=0.8ns) there are distinguished the microdischarges themselves as the nearest radial maximums, and on the limits of condition (5). Accordingly, the breakdown propagates jumping from one radial intensity maximum to another.

Relative conditions of formation the structures in Fig.2 can be estimated by using values of laser radiation specific power and specific energy over the channels, w ≈ E/τ and v·E/τ. For the discharge shown in Fig.2f the parameters magnitudes wₓ=Eₓ=1 can be accepted. Then the parameters for other frames of Fig.2f will be (wₓ=wₓ, eₓ=eₓ, rₓ=rₓ):

\[ wₓ = 50.7, \quad eₓ = 40.6, \quad rₓ = 0.1 \text{ mm}; \]
\[ wₓ = 91.2, \quad eₓ = 4.56·10^2, \quad rₓ = 0.31 \text{ mm}; \]
\[ wₓ = 15.4, \quad eₓ = 384, \quad rₓ = 0.08 \text{ mm}; \]
\[ wₓ = 1250, \quad eₓ = 6.3·10^4, \quad rₓ = 1.1 \text{ mm}. \]  

Here are presented radii rₓ of the channels, measured on their images in the frames of Fig.2.

Relative values of specific power make it possible to find out the number n of the Bessel ring (and argument k·rsin γ) for which the breakdown threshold is reached. On the other hand, the ring number, denoted through m in this case, can be calculated using the channel radii measured with Fig.2 frames. Both ways give following magnitudes for parameter n and m:

\[ nₓ/mₓ = 8/8; \quad nₓ/mₓ = 3/16; \]
\[ nₓ/mₓ = 251/266; \quad nₓ/mₓ = 19/74. \]  

For channel in Fig.2d (and 2c) the specific power grows almost by 40 times compared with the channel of Fig.2f. This growing leads, in spite of the same pulse duration, to much more complicated structure. It implies a lot of discharge centers combined in cells, instead of separate microdischarges. Nevertheless, distance between the cell centers equals to period of longitudinal structure l=1.1mm (for angle γ=2.5°), and both techniques of the ring number determination give one the same value, namely nₓ=mₓ=8.

As it is seen from Fig.2e (fragment of Fig.2d), internal structure of the cells reminds the field distribution shown in Fig.1c. Therefore, the breakdowns, most likely, localize at the points where longitudinal structure of the beam is intersected by that outer ring of radial structure, in which the intensity reaches threshold values.

The longitudinal structure in Fig.2c has the period l=0.28mm, which corresponds exactly to its value for γ=5°. At the same time, the number of Bessel function ring, calculated by two above mentioned techniques, gives absolutely different results: nₓ=3 and mₓ=16. Such a difference, obviously, is associated with pulse duration, which can be treated equal E*≈6.5J, while microbreakdowns are located within the central caustic of Bessel function, and at the longitudinal maximums separated by l.
makes up $\tau = 20\text{ns}$ for this frame, and more than by 20 times exceeds the pulse duration of previous test. So, specific energy rises by $w_c/w_d = 384/40.6$ times at relatively small specific power, $w_c/w_d = 15.4/50.7$. With such a level of the power the prime sites of breakdown appear in the region of the first three rings of the beam structure ($n = 3$). And after the first breakdowns has happened, the pulse heating action induces the discharge propagation to the ring number 8.

At similar conditions the discharge plasma used to expend in all the directions with the velocity $u \sim 10^6 \pm 5 \times 10^5\text{cm/s}$. The discharge is preceded by the ionization wave, forerunner. And the breakdown front in spherical lens focus moves to meet light rays with the speed of $v \sim 10^7\text{cm/s}$. All the same, the breakdown in a probe maximum of Bessel beam could run backwards the light rays. However, in contrast to the case of spherical lenses, there can exist other maximums in the vicinity of the probe discharge in Bessel beam. If the ionization wave comes to one of them sooner than it can rich such a maximum in the ray direction, the breakdown jumps to the nearest maximum, a peculiar combination of mechanisms.

In this case it is important to know the propagation direction. Let $X$ and $u$ be the above mentioned velocities, $\delta r_1$ be separation of adjacent rings of the beam radial structure, and $\delta r_2$, correspond to the distance between the nearest maximums, but in the angle $\gamma$ direction, $\delta r_2 = \delta r_1 / \sin\gamma$. Since angle $\gamma$ is small, $\delta r_1 \ll \delta r_2$, the direction of breakdown front propagation has to deviate from angle $\gamma$, and move at angle $\beta > \gamma$. The velocity components in the direction of $z$ axis and along the radius $r$ can be presented as $v_\gamma = u \cos\gamma$ and $v_r = u \sin\gamma + u$. Hence, the angle $\beta$ is defined by the relation:

$$tg\beta = \frac{3 \sin \gamma + u}{3 \cos \gamma} \quad \text{(10)}$$

For example, with usual for ionization mechanism values $v = 10^7\text{cm/s}$ and $u = 2 \times 10^6\text{cm/s}$ the angle makes up $\beta = 16^\circ$. It coincides with inclination $\beta = 13 \pm 17^\circ$, received from the image of the channel shown in Fig.2d, 2e.

For longer heating pulses the aggregation of closely spaced microdischarges turns into nearly continuous plasma body due to the breakdown threshold reduction and discharge spot growth. The microdischarge merging can be seen in Fig.2c. In the example the discharge radius grows during the time $t \sim 0.5\pi$ ($t = 20\mu\text{c}$) by $\delta r \geq 0.2\text{mm}$, that much exceeds the ring separation, $\delta r = 0.006\text{mm}$, and promotes the merging.

The spark structure in Fig.2a differs from the previous example (Fig.2c) in quantitative sense, rather than qualitatively. Indeed, the ring number $n$ found by the first way provides the breakdown threshold being at $n = 19$ ($x_a = 59.0$), whereas the discharge radius measurement corresponds to the ring number $n = 74$ ($x_a = 238$). It is understandable, that the same mechanisms participate in formation of the structure, and great number of the rings involved in the process of breakdown is associated with increase of the radiation specific power and energy.

Therefore the structure side branches are found to be longer, than in case of Fig.2c. At the same time, the change of angle $\gamma$ (from $5^\circ$ up to $7.5^\circ$) prevents from merging process, so that complete merging is observable only in $z$ axis vicinity. Also, the specific power increase (by nearly two orders of magnitude) and angle $\gamma$ change lead to inclination growth of the branch lines (angle $\beta$). Expression (10) lets get rare opportunity to estimate ratio of the velocities, $u/v$, which depends directly on the discharge propagation mechanism. For the structure of Fig.2a angle $\beta$ makes up $\beta = 36^\circ$, from which $(u/v) = 0.56$.

In experiment of Fig.2b the prime breakdown has shape of large bright spot. Such spots are situated at peripheral rings of the radial structure. The big dimensions of the breakdowns and, evidently, high concentration of plasma electrons screen the central part of the beam within those rings from radiation influence, to a great extent. Intensity screened is only able to produce microbreakdowns in central caustic of the channel, even in some parts of the caustic length. Therefore separate fragments of the branch lines can be seen in the structure of Fig.2b. The screening explains the rare arrangement of breakdown groups observed in the frame, as well. The overall picture of the discharge explicitly indicates the appreciable change in breakdown propagation mechanism.

Great specific power, $w_c = 1250$ (and specific energy, $w_a = 6.3 \times 10^4$) provides significant excess of intensity above the threshold value, and the discharge spreads over large number of radial structure rings, $n = 251$ ($x_a = 803$). On the other hand, the radius measurements lead to magnitude $m = 266$ ($x_a = 851$). Generally speaking, the numbers $n_a$ and $m_a$ are intuitively expected to be much more different. This disparity of real and expected data points out once again to the change of structure formation mechanism.

For clearing the structure formation process let us turn to expression (10), and estimate the ratio of $(u/v)$ from discharge pattern of Fig.2b. Structural blocks of the pattern have inclination angle $\beta = 48^\circ$ which means $(u/v) = 1$ and confirms the detonation mechanism of discharge propagation. Thus, when the intensity exceeds strongly the
threshold level, and heating pulse lasts for a long time, the optical discharge structure degenerates into a set of groups, in which the breakdown propagates in accordance with detonation mechanism.

Conclusion

Analysis of processes of spark structure formation in Bessel beams shows, that principal cause of laser spark uniformity destruction is the non-linear interaction of heating radiation with medium of the wave propagation. In linear case the radial distribution of the beam field is described by Bessel function with annular maximums, whereas lengthwise the field remains monotonously, slowly changing. Non-linear interaction induces modulation of the field longitudinal distribution with spatial frequency $\lambda / 2\gamma^2$, where $\lambda$ is wavelength of radiation, and $\gamma$ is inclination angle of the light rays. These two distributions form space structure of Bessel beam with its maximums, in which prime breakdowns arise. Their localization and the structure of spark depend on combination of many factors, including duration and energy of heating pulses. Short pulses create microbreakdowns like the point explosions, that cover some rings of Bessel function, depending on the intensity. The larger pulses interact with plasma of prime breakdowns, forming structures which configurations are defined by the process of the discharge propagation. The processes are similar to the ones that develop at spherical lens focus, however they should be corrected for specific character of Bessel beam. For example, the breakdown propagates not backwards the heating radiation ray, but under large angle to it, depending on propagation mechanism. General property of observable structures is their discrete nature. The structure formation understanding enables us to operate the process, suppressing or increasing the beam structure in response to demand of available application.

References