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FORMATION OF A LONG SPARK IN AIR UNDER THE ACTION OF WEAKLY FOCUSED LASER RADIATION

1. In the currently known works on the laser spark (see, for example, the review by Yu. P. Raizer (^{1})), gas breakdown is studied when the radiation of optical quantum generators is focused by short-focus lenses with modulated quality factor. The use of short-focus lenses is due to the use of ruby lasers, whose divergence reaches rather large values ($\sim 10^{-2}$ rad). In a number of experiments it was found that the breakdown front moves toward the lens (^{2}). The formation and motion of the breakdown front resembles the propagation of a detonation wave, in which the release of energy is realized through the absorption, in the hot plasma, of the radiation energy. With an increase in the focus, the breakdown mechanism becomes more probable. In this case the velocity of breakdown motion can reach extremely large values, while nevertheless retaining its direction toward the lens. The initial shape of the region of heated plasma, as a rule, reproduces the caustic of the lens, i.e., it has the form of a cone expanding toward the lens.

The development of laser technology and the appearance of generators based on neodymium glass, making it possible to obtain powers on the order of a gigawatt at a divergence close to the diffraction divergence, have led to the possibility of studying breakdown over a wide range of parameters of focused radiation. In the present work the dynamics of spark formation is investigated as a function of the space-time structure of the laser radiation.

2. Figure 1 shows a photograph of a "spark" obtained with the aid of a lens with focal length $f = 2.5$ m. The power of the neodymium laser with two amplification stages was about 1 GW (energy 15 J, duration at half-height 18 nsec). The number of individual sparks in such a spark reaches one hundred. With increasing energy the number of sparks grows; some of them merge with one another. The greatest concentration of sparks is always observed near the focus. The length of the spark was more than 2 m*.

Fig. 1

Figure 1: Fig. 1

Fig. 3

Figure 2: Fig. 3

The development of breakdown in the initial stage was investigated with the aid of a linear time sweep with a resolution of 1.5 nsec. An analogous method was used in work ([3]). However, when photographing the spark in the longitudinal direction in the case of long-focus lenses, the described method encounters difficulties associated with adjustment of the system and with the necessity of accurately aiming a greatly reduced image of the spark at the slit. Therefore we used a slitless time-sweep method, which consisted of the following. The slit of the photographic recorder was removed entirely. The spark, with large reduction, was projected onto the plane where the slit had previously been located. Since the longitudinal dimension of the spark in the case of lenses with $f = 2.5$ m exceeds its transverse dimensions by 1000 times or more, the need for a slit disappears, because in this case the transverse size of the spark on the photographic film is smaller than the diffraction limit of the recording system.

* The breakdown in air considered for the first time in the present work was observed by N. G. Basov, V. S. Zuev, and Yu. Yu. Senatskii in 1965.

Fig. 1. "Spark" obtained with the aid of a lens with focal length $f = 2.5$ m

Fig. 3. a –time sweep of the radiation field in the near zone; b, c, d –time sweep of the radiation field in the far zone (the exposures are in the ratio $13 : 3 : 1$)

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Figure 2 shows the dependence of the coordinates of the sparks on the moment of their appearance. It is seen that, after breakdown in the focus, the breakdown front moves both toward the lens and away from it. Here we use the concept of the breakdown front in the sense of the appearance of successive discrete sparks. Its propagation velocity toward the lens is $1.2 \cdot 10^9$ cm/sec; in the opposite direction it is $3.8 \cdot 10^9$ cm/sec. It is characteristic that the breakdown develops along a straight line. The deviation of individual sparks from the axis of the entire spark does not exceed 2 mm (Fig. 1). These results correspond to a fivefold margin for breakdown, by which we mean the excess of the laser power over the minimum power necessary for breakdown to occur.

Fig. 2. Dependence of the coordinates of sparks on the moment of their appearance (the laser radiation is incident from right to left; point F is the focal point of the lens)

3. For interpreting the breakdown results, we investigated the spatiotemporal structure of the radiation of the laser, which consisted of a neodymium

Fig. 2. Dependence of the coordinates of sparks on the moment of their appearance (the laser radiation is incident from right to left; point F is the focal point of the lens)

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rod 240 mm long and 15 mm in diameter. Q-switching was performed with a Kerr cell with two polarizers. The opaque mirror had a reflection coefficient of 99%; a plane-parallel plate was used as the output mirror.

The structure of the radiation in the near and far zones was investigated by means of a linear sweep. Figure 3a gives the time sweep of the radiation in the near zone. The velocity of propagation of the radiation over the end face is $\dot{a} \approx 2.2 \cdot 10^7$ cm/sec. Figures 3b, c, d give the time sweep of the field structure in the far zone. The radiation was photographed with the same setup, but in different pulses and with different exposures, which were selected by means of calibrated neutral filters. It is seen from Fig. 3 that the divergence in the mode is diffraction-limited and equal to $\sim 2.5 \cdot 10^{-4}$ rad. Toward the end of the pulse the divergence increases by an order of magnitude. The average, over the pulse, rate of change of the divergence for various flashes is $\bar{\dot{\vartheta}} = (0.75—2) \cdot 10^5$ rad/sec. Similar measurements for ruby with a passive shutter were carried out by V. A. Korobkin et al. (^{4}), and a theoretical calculation of the field structure was performed by V. S. Letokhov and A. F. Suchkov (^{5}). Taking into account the complex structure of the breakdown region, consisting of many sparks, there is reason to suppose that each mode is modulated in time. However, such modulation was not found in the photographs because of insufficient time resolution. For ruby, modulations of the order of several nanoseconds were observed in work (^{6}).

4. Before proceeding to the interpretation of the results, let us briefly consider the features of focused monochromatic laser radiation. In our case, blurring of the focal "point" due to aberrations of the focusing system is small in comparison with blurring due to divergence. Therefore, the size of the focal "point" and the possible geometrical figure of its degeneration are determined by the degree of parallelism of the rays in the beam (i.e., the deviation of the front of the incident wave from a purely plane one). Thus, for example, even with a focus $f = 2.5$ m, blurring of the beam in the focus due to aberrations is no more than 0.5 mm, whereas blurring due to divergence is ~ 5 mm.

We approximate the laser radiation by a spherical wave with a low index in the angle ϑ, whose radius R depends on the radiation parameters (divergence ϑ and size of the generation region $2a$, Fig. 4). The distance x to the focusing point of the spherical wave is equal to

$$x = -Rf/(R-f), \tag{1}$$

where f is the focal length of the lens. From Fig. 4 we determine the radius as

$$R = l + a/\vartheta, \tag{2}$$

where l is the distance from the end face of the crystal to the lens. From (1) and (2) it follows that

$$x = -f(\vartheta l/a + 1)\left[1 + \vartheta(l-f)/a\right]^{-1}.$$

Hence the velocity of displacement of the focusing point of the spherical wave is

$$\dot{x} = \frac{f^2\vartheta}{a}\left(\frac{\dot{a}}{a} - \frac{\dot{\vartheta}}{\vartheta}\right)\left(1 + \vartheta\frac{l-f}{a}\right)^{-2}. \tag{3}$$

From expression (3) it is seen that, when

$$\dot{a}\vartheta < a\dot{\vartheta} \tag{4}$$

the velocity of motion of the focusing point may be negative, i.e., it will move away from the lens. Obviously, a decrease in the divergence of the radiation promotes fulfillment of condition (4). Thus a breakdown that has arisen at some instant in the focus of the lens may propagate not only toward the lens, but also in the opposite direction, following the focusing point of the spherical wave. This is possible under the following conditions, in addition to inequality (4): first, there must be a large margin for breakdown; second, the laser radiation must not be completely absorbed in the spark propagating from the focus toward the lens, so that the fraction of the radiation that has passed through the focus still appreciably exceeds the threshold value. The latter condition is possible only for long-focus lenses and an inhomogeneous beam structure, since in the case of a short focus and large ϑ condition (4) will not be fulfilled.

Substituting into formula (3) the experimentally measured values of the velocities $\dot{a}$ and $\dot{\vartheta}$, given in the preceding section, we obtain for the average velocity of propagation of the spark beyond the focus

$$\dot{x} \simeq (2 \div 8) \cdot 10^9 \text{ cm/sec}$$

for $l = 3 \cdot 10^2$ cm; $f = 2.5 \cdot 10^2$ cm; $a = 0.5$ cm; $\vartheta = 10^{-3}$ rad; $\dot{a} = 2.2 \cdot 10^7$ cm/sec; $\dot{\vartheta} = (0.75 \div 2) \cdot 10^5$ rad/sec.

Fig. 4. Diagram explaining the mechanism of motion of the focusing point of laser radiation beyond the focus of the lens

Figure 4: Fig. 4. Diagram explaining the mechanism of motion of the focusing point of laser radiation beyond the focus of the lens

The accuracy of the velocity measurement is not great; therefore, from the estimates given, despite their apparent agreement with experiment, one should not infer the reliability of the assumptions underlying expression (3). In reality the distribution of the field with respect to the angle ϑ may be more complex and may correspond to higher values of the angular index, as is confirmed by Fig. 3b, c. However, this does not change the essence of the matter, and it is evident that the approximation of the complex space-time structure of the laser radiation by a spherical wave with variable radius qualitatively explains the propagation of breakdown beyond the focus. It is also quite possible that the radiation intensity is modulated in time with frequency $\dot{x}/\sigma$, where σ is the distance between individual sparks. For $\sigma \sim 0.27 \div 1.8$ cm and $\dot{x} \sim 5 \cdot 10^9$, the modulation period is $\tau_0 \sim 0.05 \div 0.4$ nsec. It follows from this that, in the individual peaks, the duration of the radiation is less than the time of one passage of light through the resonator. Such a beam structure can be only the result of complex interference of nonstationary radiation, the structure of which is still subject to further refinement.

Fig. 4. Diagram explaining the mechanism of motion of the focusing point of laser radiation beyond the focus of the lens.

On the other hand, it is also possible to attempt to explain the formation of a long spark from the standpoint of self-focusing ([7]). However, such an interpretation requires a separate theoretical analysis.

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