INITIAL STAGE OF SPARK GENERATION AND DEVELOPMENT IN A "DIFFRACTION-FREE" LASER BEAM

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The channel structure of a continuous long laser spark, generated along the axis of the atmospheric propagation path of a "diffraction-free" (Besselian) laser beam, formed by an axicone, is studied. Nanosecond imaging of its initial formation stage demonstrated this channel to consist of a regular sequence of plasma breakdown zones, which then diffuse into a funnel shape. An explanation for such a kind of structure is suggested: it is seen as self-modulation effect in a diffraction- free beam propagating through a non-linear medium.

When laser radiation is focused by a cone shaped lens (an axicone), a so-called "diffraction-free" laser beam is formed.[1,2] It can be characterized by its propagation path length $L \approx R/[(n-1)\alpha)$ (here R is the radius of the focused beam, n is the refractive index of the axicone, and α is its base angle), and by an axial caustic of a diameter $d_0 = 2.42\,\lambda\,[\pi\,\alpha\,(n-1)^{-1}$, constant along the path length L (Ref. 1). The laser is assumed to radiate at the wavelength λ. For a glass axicone of $\alpha = 15°$, $n = 1.5$, and radiation wavelength $\lambda = 1.06$ µm at $R = 2.5$ cm these parameters would be $L \approx 20$ cm and $d_0 \approx 6$ µm.

The term "diffraction-free" is not exact. Diffraction does take place in such beams; however, its effect is compensated by energy feed from the periphery (lateral feed). Therefore, the diameters of the axial and the lateral Intensity maxima are independent of distance along the beam path. . We shall use the above term, suggested in Ref. 2, for the sake of brevity, putting it in quotes every time, realizing however, that the expression "diffraction-compensated" or "Besselian" would be more appropriate.

Energy is independently fed into every spatial element of the axial zone, so that during optical breakdown in the atmosphere continuous elongated plasma discharge channels are formed. Their electro-physical properties testify to the lack of break-up in such discharge channels.[3] However, optical images of such sparks obtained by diffuse light from the heating radiation in the early stages of breakdown reveal a definite periodic structure in the plasma channel along the beam axis.[4] Such a periodicity can be related to either corrugation of the channel surface, resulting from the constant electron density along its axis, or to spatial modulation of the former along the same axis.

The initial stage of spark development is interesting both from the applications point of view (since the channel structure is then formed), and from a purely scientific point of view since we currently lack any common understanding of the physics of optical breakdown. The aim of the present work is a detailed study of the spark channel structure as generated in "diffraction-free" laser beams.

In our experiments the spark was generated by a single-mode Nd: glass laser with a pulse energy of 60 J and duration of 50 ns. The laser radiation was focused by an axicone with a refraction angle of either $\alpha = 10°$ or $\alpha = 15°$, thus producing beams converging into caustics of $\alpha = 5°$ or $\alpha = 7.5°$, respectively, with respect to their axes. Sparks generated in atmospheric air at pressures from $p = 0.5$ to 10 atm were studied. These were photographed in a plane normal to the discharge axis. Cameras with both open and electron-optical shutters, providing 5 ns exposure were used.[5] The pulses of the scattered radiation W_s and the spark natural emission W_n (Fig. 1) had maxima of 2–5 ns width and 100–200 ns, respectively. These intervals actually dictated exposure for the open-shutter cameras when photographing the process both by diffuse laser radiation and by plasma natural emission. To obtain sequential images from each single spark cycle three EOT's with cable delay were used (Fig. 2). Objective 4 and system of mirrors 5–8 projected the image of a fragment of the spark channel upon the EOT'S photo cathodes. Magnification produced by this system was 4. Energy was pulse-fed by a laser discharger 9 into the laser. The duration of the shutter-activating gate pulse was

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regulated by the length of the charging coaxial cable 10. Sequential shutter activation allowed images to be taken at different times depending on the length of coaxial cables 11–13. The shutter gate pulse was registered by a broad-band oscillograph 14 (C7-10B). The same oscillograph, coupled to the photo-elements 15, was used to register the scattered pulse of the heating radiation W_s. The latter temporally coincides with breakdown at the given point, as well as with the laser pulse W_L, and the plasma natural emission pulse W_n.

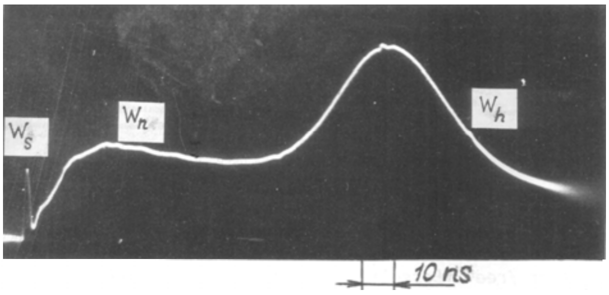

FIG. 1. Spark radiation oscillograms: W_s is the scattered, W_n is the natural radiation, W_h is the heating laser radiation

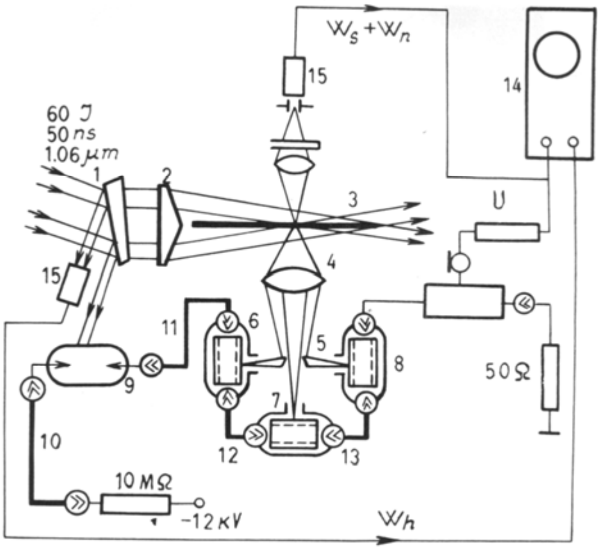

FIG. 2. Measurement scheme with electron-optical shutters: laser beam (1), axicone (2), laser spark in "diffraction-free" beam (3). For other legends see the text

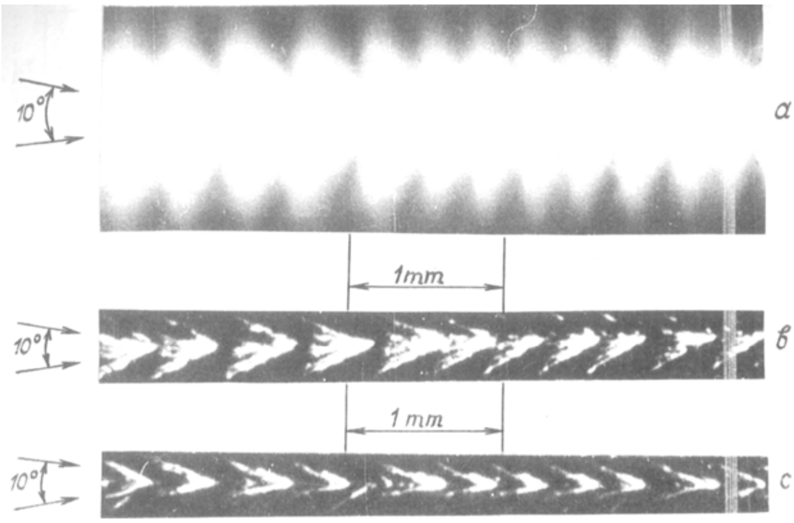

FIG. 3. Photographs of a segment of the spark channel in air: natural radiation (a) and scattered heating radiation *(b, c). (*$\alpha = 10°$, $p = 1$ atm*)*

Figure 3 displays large-scale images of the central part of channel in the atmospheric air, photographed in its natural emission (*a*), and in the scattered light from the heating radiation (*b* and *c*). The images were taken from two orthogonal directions and show one and the same spark. A "diffraction-free" beam was focused by an axicone of 10° base angle. Images 3*b* and 3*c* are qualitatively similar, which testifies to the axial symmetry of the channel. The emitting and scattering zones mutually correlate. Structures in the images coincide with each other; they are spatially periodic, with dimensions 0.4 ± 0.1 mm.

There are gaps in the axial zone of the channel images, immediately after breakdown. These are observed both in the natural emission (Fig. 3*a*) and the scattered radiation (Figs. 3*b*, 3*c*) images. The larger diameter and blurring of the image in Fig. 3*a* are the result of a longer exposure.

Figure 4 shows a sequence of three successive 5 ns-exposure images of a fragment from a spark in atmospheric air taken in visible light (Figs. 4*c*–*e*). Figure 4*b* is a time-integrated image of the same spark exposed for the entire time of its existence, taken in the scattered heating radiation. A "diffraction-free" beam was focused by a 15° base angle axicone.

The corresponding oscillogram (Fig. 4*a*) presents the scattered radiation pulse W_s, and the electron-optical shutter gate pulse U_g. It follows from the data obtained that during the early stage of the spark discharge (by the second nanosecond after breakdown) its channel consists of a string of periodically spaced plasma clots. Estimates of their electron density produced a figure of $N_e \sim 10^{20}$ cm^{-3} (Ref. 6). In between such clots this value must be considerably less (at least by an order of magnitude).

The sequence of Images in Fig. 4 confirms that initially breakdown centers appear in periodically spaced zones of the focal interval. It can be seen that breakdown centers quickly bloom into a continuous channel; however, traces of periodic structure remain. Breakdown first occurs on the beam axis. The image corresponding to this stage, obtained in diffuse radiation, looks like a string of axial points In the process of blooming shining zones on the surface of plasma clots follow fur-tree-like trajectories, which can be seen in the image taken in diffuse light.

Channel images obtained both at higher and lower air pressures were quite similar to those above.

The presumable cause of such observed periodicity in the spark channel structure is the self-modulation of the diffraction-free beam during its propagation through a non-linear medium.[7]

As noted in various studies[8–15] non-linearity during optical breakdown can occur as a result of the appearance of noticeable number of excited atoms and molecules or as a result of gas ionization, so that gas along the beam path is turned into weakly ionized plasma. If the latter is true, it must be assumed that emission from the column of such a weakly ionized and relatively cool plasma is not registered in the photographs because of the relatively low Intensity of such radiation. The periodic structure recorded is produced by intense plasma heating in the intensity maxima of the "diffraction-free" beam. Its scale coincides with that theoretically predicted, approximately reaching λ/γ^2, where λ is the heating laser radiation wavelength, and γ is the ray focusing angle with respect to the beam axis.

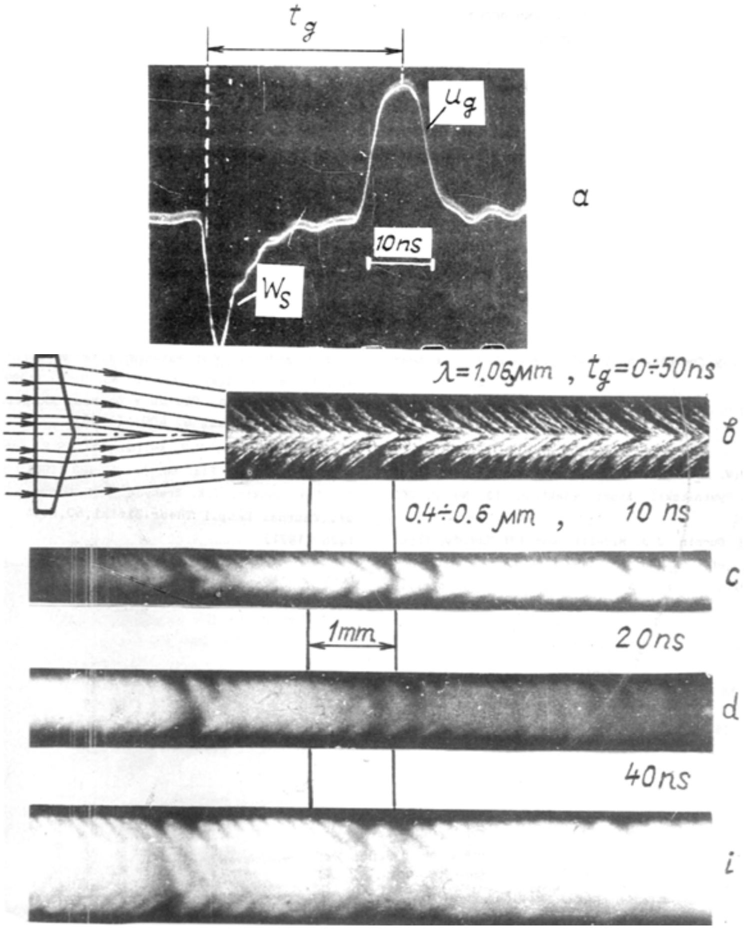

FIG. 4. Multi-frame images of the spark channel (α = 15°, *p* = *1 atm*)*: a) scattered signal* (W_s) *during breakdown and shutter pulse* (I_d)*; b) image of the channel segment in scattered light; c, e) images of the same channel segment in visible light; exposure is 5 ns, taken at different delays* (t_d) *after breakdown*

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