Optical breakdown of air under exposure to a broadband radiation

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In this paper we describe the effect of optical breakdown of air under exposure to a high-power broadband incoherent radiation pulse. This effect was observed experimentally for the first time.

Before 1963 any assumption that optical breakdown can be achieved with the use of focusing tools, even the most powerful ones, seemed completely fantastic.[1] The breakdown of gas under exposure to a focused laser radiation was observed for the first time (in 1963) upon the advent of ruby and neodymium lasers with modulated Q-factor. These lasers give a short (about $3\cdot10^{-8}$ s) pulse with the peak power of tens of megawatts. This phenomenon has been called a laser spark. In a short period the optical breakdown in gases was thoroughly studied both theoretically and experimentally, as well as the related processes of the development of shock and detonation waves.[1–3] According to Refs. 1 and 3, the optical breakdown in air is characterized by a visible flash at the focus of a lens or mirror, appearance of conductivity of the metal type, and characteristic sound associated with the spark discharge and development of shock and detonation waves. Although all experimental data on optical breakdown were obtained with laser sources, from the physical viewpoint there are no restrictions on the use of a broadband (non-monochromatic) pulsed radiation.

The use of high-power broadband radiation sources with stable spectral characteristics (for example, xenon arc lamps) is attractive in view of their lower cost. It is also interesting because it extends our knowledge about the interaction of high-power radiation with the matter. We have conducted some experiments with the setup employing high-pressure xenon arc lamps as a source of pulsed radiation. The lamps were the following: the standard DKSSh-3000 lamp and a pilot sample of DKSSh-4000-based pulsed lamp (manufactured at Tomsk Plant of Electric Lamps). It should be noted that the DKSSh-3000 lamp was not designed to operate in the pulsed mode. This circumstance was taken into account in the experiments.

The radiation from DKSSh lamps has a continuous spectrum in the UV, visible, and near infrared spectral regions. In the near infrared region there are also intense spectral lines in the wavelength range from 800 to 1000 nm. The lower boundary in the UV region is 210 ... 220 nm for the DKSSh-3000 lamps and 300 ... 310 nm for the DKSSh-4000 lamps.

The optical scheme includes two parabolic mirrors arranged on the optical axis. One mirror serves as a transmitter, while the other one serves as a receiver of radiation from the xenon arc lamp. The radiation source was at the focus of the first mirror (46 cm diameter, 12 cm focal length). The parabolic mirror 64 cm in diameter and 27 cm in the focal length (the receiver) was separated by 2 to 7.5 m from the transmitter. The area of the focal spot depended on the shape and size of an arc in the lamp, as well as on the parameters of optical elements and the accuracy of system alignment. In the experiment, the results of which are given in this paper as an example of breakdown in air, this area did not exceed 1 cm^2 and the minimum ever observed focal spot area was 0.03 cm^2 in such an optical arrangement.

Specially developed power supply was used to generate pulses of the discharge current. The capacitance of the discharge battery ranged from hundreds to units of microfarads; the voltage ranged from hundreds volts to 30 kV. The discharge was of oscillatory character. Up to ten oscillations were recorded with the maximum amplitude and energy release during the first half-cycle. The radiation pulses generated by the setup lasted from tens microseconds to milliseconds. According to our estimates, the efficiency of the system (allowing for the electric-to-radiative energy conversion coefficient for xenon arc lamps,[4] the coefficient of radiation “interceptionB by the mirrors, and the coefficients of reflection from the mirror surfaces) was no less than 0.1 and no more than 0.2.

In the experiments we have observed the following phenomena: flash, appearance of conductivity, and characteristic sound. These phenomena accompanied the discharge at the focus of the parabolic mirror with the radiation pulse having the duration of 10^{-5} s and the

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radiant flux density of 10^8–10^9 W·cm^{-2}. To detect the flash at the focal spot, we used the photometric setup based on the FEU-79 photomultiplier tube (the passband of the current amplifier up to 20 MHz) and integrated with the oscilloscope, as well as a video camera connected to a computer. The breakdown was detected both in air and on different targets. The appearance of conductivity in air during breakdown was detected by the change in the capacitor charge (100–200 V) (Ref. 1). Toward this end, the capacitor was connected to two electrodes separated by no more than 0.5 cm in the focal space of the second mirror. The characteristic sound accompanying the discharge in air was recorded with a set of measuring acoustic and vibration devices (VEB RFT Messelelectronic “OttoSchonB, Dresden) integrated with a computer. This set includes the MK–301 capacitor measuring microphone (20 Hz ... 100 KHz), MV–201 pre-amplifier, and the MKD 00011 microphone amplifier. The breakdown phonogram at irradiation of a target gives the value of the sonic wave amplitude many times exceeding the amplitude at the breakdown in air. This fact was taken into account when checking the linearity of the operation mode of the recording setup.

Upon the exposure of plane targets made of different materials (metals and non-metals) to radiation, the effect of “near-wallB development of the plasma cloud was observed. As a target we used the flat surfaces: white dense paper, black paper, emulsion layer of photographic paper, aluminum capacitor foil, and fluoroplastic film of different thickness. At the pulse duration about tens microseconds, the area of the focal spot was estimated by the size of the opening broken down in the foil. In this case, the breakdown zone was a “burned outB surface with multiple microscopic through holes. It was noticed in the experiments that with a pulse several milliseconds long and the discharge voltage about 10 kV, an opening with the diameter exceeding the size of the focusing zone was broken down in the foil, while all other targets simply inflamed.

Figures 1 and 2 show the video frames of the optical breakdown of air at the mirror focus (Fig. 1) and the target's surface located in the near-focal space (Fig. 2). The scale in Figs. 1 and 2 is the same. The first frames (Figs. 1*a* and 2*a*) show the background; the arrows indicate the direction of radiation incidence and the radiation focusing angle (roughly). The frame presented in Figs. 1*b* and *c* demonstrates one of the stages of the spark evolution. The frame shown in Fig. 1*c* is the frame shown in Fig. 1*b* minus the background. Figure 2 demonstrates three successive frames of the video record of irradiation of the sheet photographic film surface. The frame in Fig. 2*b* shows the flash and the bright cloud of plasma resulting from irradiation of the evaporated substance of the target. The frame in Fig. 2*c* shows the emission of the cooling cloud of the target substance toward the mirror.

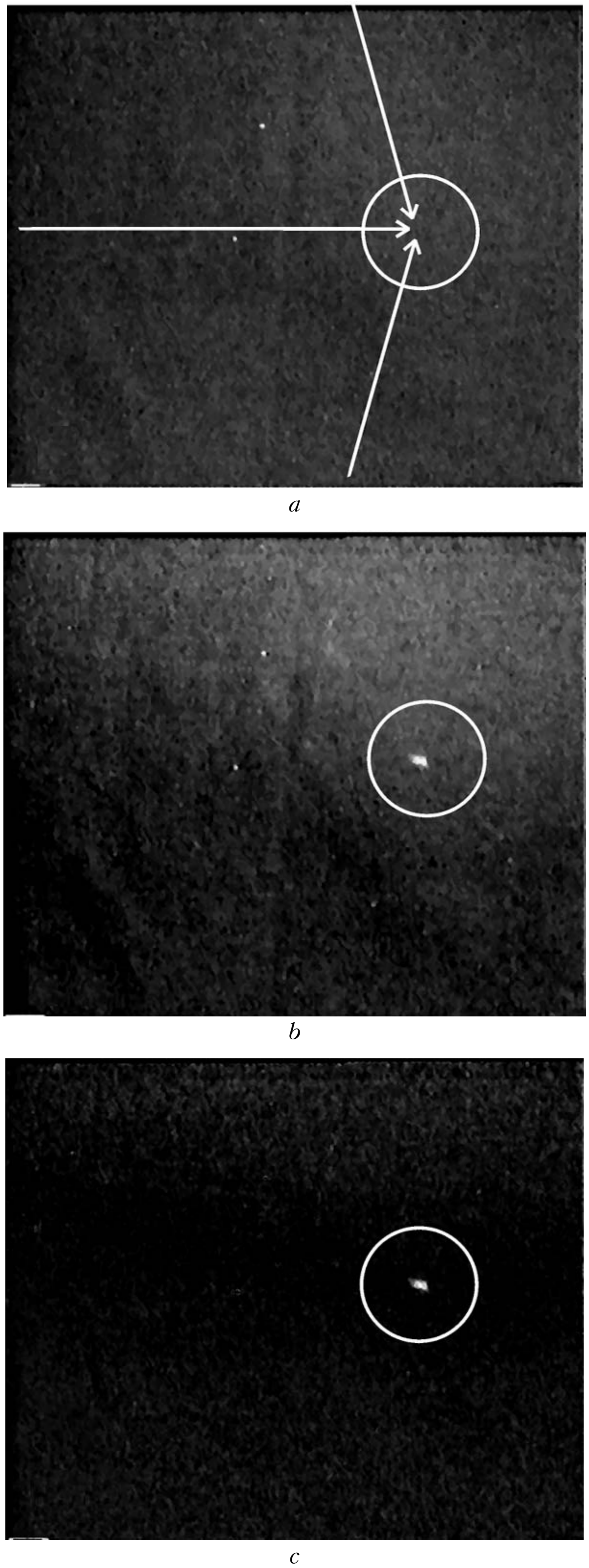

Fig. 1. Video frames of the breakdown in air at the mirror focus: the background and the geometry of irradiation (*a*), the spark (*b*), the frame *b* minus the background (*c*) (the scale is the same as in Fig. 2).

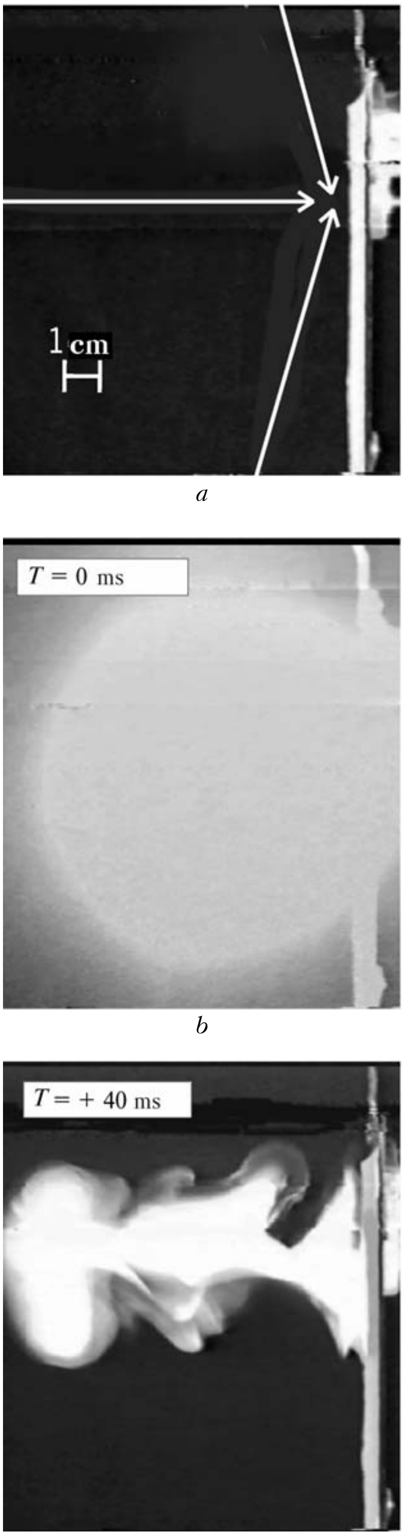

Fig. 2. The video frames of the breakdown at radiation focusing onto the surface of the target (photographic emulsion): the background, geometry of irradiation, and scale (*a*); the flash and evolution of the plasma cloud (*b*); emission of the evaporation products of the target substance (*c*).

Figure 3 presents phonograms of the optical breakdown. The relative amplitude is plotted as an ordinate, and the time, in ms, is plotted as an abscissa. Since the mirrors were separated by about 7.5 m, the sound accompanying the pulsed discharge in the lamp came with some delay needed for the sound wave to travel along the way from the lamp to the receiving mirror (shown with the dashed line). In the phonograms the sonic wave was recorded in this time interval. This wave accompanied the optical breakdown due to focusing of an optical pulse in the atmosphere or on the surface of a target set at the focal zone of the parabolic mirror. In the case of radiation focusing in air, the microphone was set at a distance of ~1.5 cm from the mirror focus, while in the case of a target it was set 5 cm far from the focus. In the lower phonogram (breakdown in air), the step along the scale of relative amplitude is one tenth of the step in the upper plot (breakdown on a target). In both of these cases, the time of recording of the sonic wave exceeds the duration of the discharge in air, what also corresponds to the description of development of the shock and detonation waves at the optical breakdown.[1]

From the indications detected in the experiment, we concluded that as the radiation pulse from a high-power xenon arc lamp is focused (in this case by the parabolic mirror) at the mirror focus, the optical breakdown of air occurs. The estimates of the main parameters are the following: the lamp electric energy of the breakdown is about 10^4 J (at the capacity about hundreds microfarads and voltage about 10^4 V), the pulse power is about 10^8–10^9 W (at the pulse duration of 10^{-5} s), the electric-to-radiative energy conversion coefficient is about 10^{-1} allowing for the losses at optical elements, the focal spot area is about $10^0 \ldots 10^{-2}$ cm^2.

Thus, in the zone of focusing of the radiation pulse the irradiance can reach hundreds megawatts and even higher, what is sufficient for the breakdown in air at the atmospheric pressure.[1–3] In our opinion, both of the known mechanisms of ionization in the zone of concentration of a high-power radiation pulse are involved in this experiment: development of the avalanche in the light wave field and the multiquantum photoeffect. The duration of the radiation pulse allows the criteria of the BstationaryB breakdown to be applied.[1] The allowance for the volume of ionization (no less than 1 cm^3) gives the value of the time of electron diffusion, which coincides with the duration of the pulse by an order of magnitude. The allowance for condition of spectral distribution of light pulse energy (9% in the UV, 35% in the visible region, and 56% in the near IR region[4]) makes the multiquantum photoeffect a preferable explanation for the appearance of the effect of ionization observed in the experiment and the optical breakdown at the mirror focus. The oscillatory character of the discharge creates conditions favorable for successive

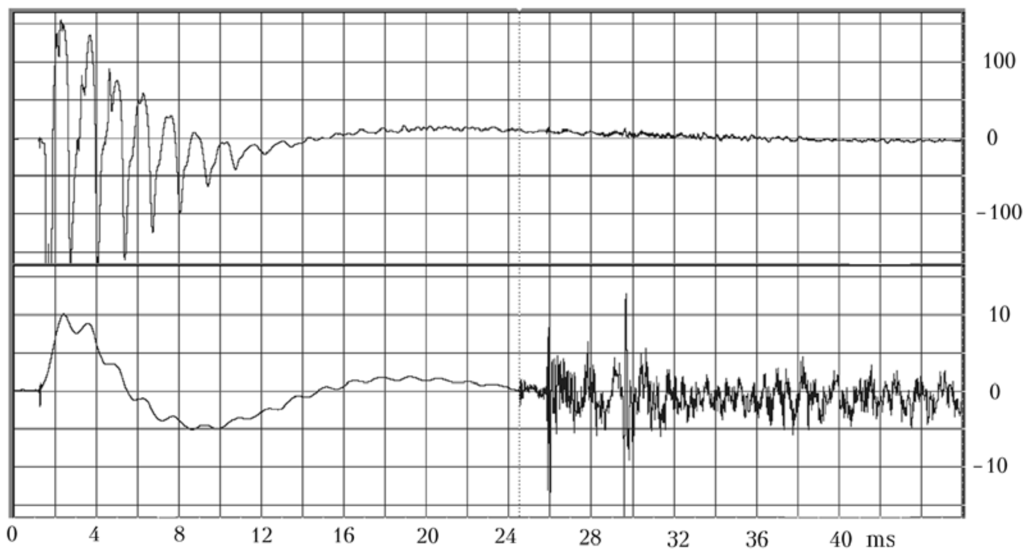

Fig. 3. Phonograms recorded at the optical breakdown. The upper plot shows the phonogram corresponding to the optical breakdown at the target set in the focal zone (U = 3000 V, C = 1000 μF, τ = 150 μs); the lower plot shows the phonogram of the optical breakdown in air at the mirror focus (U = 7000 V, C = 100 μF, τ = 50 μs).

action upon electrons and excitation of atoms of the atmospheric gas in the field of a light wave with their following ionization in the process of avalanche development and, probably, appearance of a series of optical breakdowns during a single radiation pulse.

In our opinion, the effect obtained does not contradict the physical grounds of the phenomenon of the optical breakdown and requires further investigation for future practical implementation.

References

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