Self-Igniting Pulsed Optical Discharge in an Erosion Laser Plasma

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We have obtained, for the first time, a pulsed optical discharge at atmospheric pressure in the focus of a lens at a radiation flux density 10^7–10^8 W/cm^2. The discharge was ignited by an erosion plasma produced by the plasma radiation proper acting on the absorbing materials. The combustion features of a self-ignited pulsed optical discharge are investigated. Spectroscopic investigations of the plasma in the discharge yield an electron concentration $\sim 2 \times 10^{17}$ cm^{-3} and an excitation temperature $\sim 22\,000$°K.

REALIZATION of pulsed and continuous optical discharges ignited in the focus of a lens at subthreshold radiation intensity with the aid of a gas-discharge plasma prepared beforehand by auxiliary sources was reported in[1-3]. In the present study, we obtained for the first time a pulsed optical discharge at atmospheric pressure, ignited by an erosion plasma produced by the intrinsic radiation of a laser acting on absorbing materials; we have investigated the combustion features of such a discharge.

We used in the experiments a neodymium-glass laser operating in the free-running spike-generation regime with energy 1–1.5 kJ and with pulse duration $\sim$1.5 msec. The experimental setup used to obtain self-ignited optical discharges at atmospheric pressure is shown in Fig. 1a. The radiation of the laser was focused by lens 1 on plasma-producing material 2 in such a way that its focus 3 was located at a certain distance from the surface of the material. This distance ranged from 10 to 20 mm. The average laser-radiation flux density on the surface of the material was $(1-4) \times 10^6$ W/cm^2, and of the order of 5×10^7 W/cm^2 at the focus of the lens. The plasma-producing materials were different metals and opaque dielectrics (ebonite, bakelite).

On the basis of high-speed photography investigations, the formation of the optical discharge can be represented in the following manner. When the defocused laser radiation acts of the surface of the plasma-producing material, an erosion plasma cloud is produced, the velocity of which is $\sim$100 m/sec. After the plasma cloud reaches the focus (after 100 μsec), the discharge is ignited and continues to burn during the entire lasing time in the produced erosion laser plasma (Figs. 2a–c). A peculiar slow-burning laser spark is produced in the erosion laser plasma, in which practically the entire laser radiation is absorbed. The fraction of the radiation reaching the surface produces during the optical discharge a vapor that maintains the discharge at the focus of the lens (Fig. 2a). The optical discharge can exist in the focus of the lens also in the absence of the maintaining vapor. This is done by acting on a thin foil. Unlike the usual laser spark, the energy released during the entire generation is produced in the focus of the lens, as the result of which the plasma formation "hangs" over the surface at the height of the focus (Figs. 2, b).

In general, the optical discharge is a conical plasma formation that flows out, as it were, from the focal region towards the lens (Figs. 1d and 2b). Its propagation speed, determined by measuring the leading front of the glow, is $\sim$100 m/sec. The transverse dimensions of the plasma formation at the start of the development of the discharge are determined by the geometry of the focused laser beam, and subsequently there occurs a radial compression of the plasma formation, i.e., a cumulation of some kind in the light cone (Fig. 2b).

Continuous photography of the plasma formation shows that it is intermittent, owing to the spiked character of the laser radiation (Figs. 2a, c). The "ignition" occurs in individual radiation pulses (spikes). As a result, flashes are produced at the focus of the lens, from which microplasma formations propagate in a direction opposite to that of the laser beam with velocity $\sim$600 m/sec in the medium produced by the preceding pulses. The plasma formation is heated during each succeeding passage of the radiation pulses. This is evidenced by the vertical beams of increased intensity, which terminate at the focus of the lens (Figs. 2a, c). The increased-intensity bands are observed also in plasma flares produced when laser radiation is focused on certain absorbing materials[4-6].

In some cases, individual laser-radiation pulses "break through" to the surface of the material and form clearly pronounced plasmoids (Fig. 2c), which escape at a velocity of 1800 m/sec. An interesting feature of these plasmoids is that their transverse dimensions ($\sim$1 mm) are much smaller than the dimensions of the focusing spot ($\sim$6 mm), which should have determined the true dimensions of the plasmoid (Fig. 2d). This is probably connected with the self-focusing of the radiation in the discharge plasma.

We investigated the character of the combustion of the optical discharge in an erosion laser plasma as a function of the flux density of the radiation producing

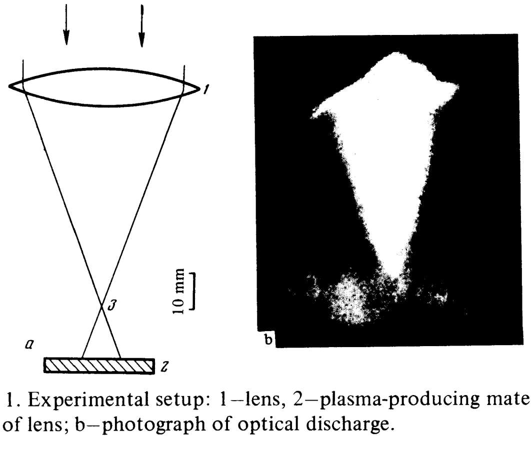

FIG. 1. Experimental setup: 1–lens, 2–plasma-producing material, 3–focus of lens; b–photograph of optical discharge.

the igniting plasma, and as a function of the composition of the plasma-producing material. The stability of the combustion is determined by the full pattern in the igniting laser plasma flare (formation of stationary shock wave, periodic structure), which depends on the dimensions of the crater (focusing spot) in the plasma-producing material, and also by the component composition of the disintegration products (plasma, finely-dispersed particles, liquid drops, etc.). As is well known, in a plasma flare, depending on the ratio of the pressure in the crater and in the surrounding medium, there is produced either a stationary shock wave[4-9] or a periodic structure[6]. Naturally, the occurrence of the discharge and the stability of its combustion depend on the location of the focus of the lens relative to the produced wave structure. A stable optical discharge was observed at the focus of a lens located 10 mm from the surface (crater diameter 9 mm, radiation flux density ~2 × 10^6 W/cm^2) when laser radiation was applied to brass. In this case, an igniting plasma cloud is produced and there is no shock wave. When the focus is closer to the surface, when a flare is produced and a stationary shock wave is formed in it (the focus is in front of the shock wave), no discharge is ignited, and the usual heating of the flare by absorption of laser radiation takes place. A stable optical discharge is produced also when the focus is behind the shock wave. If the focus is on the surface, then a shock wave is formed in the produced plasma flare and exists during the entire time that the plasma flows out of the crater. The stationary shock wave exerts its influence on the attenuation of the laser radiation and probably shuts off the radiation under definite conditions and detaches the flare as a result of radiation absorption, as indicated in[9]. It should be noted that the flare detachment due to absorption of laser radiation in the flare-proceeds gradually as the plasma accumulates and is most probable for plasma-producing substances with large absorption coefficients[6]. The radiation heats the moving disintegration products along its path, but does not lead to combustion and formation of plasmoids, as is the case when an optical discharge is produced in the focus of a lens.

A number of distinguishing features is possessed by the optical discharge in a plasma produced from the alloy POS-40. The combustion pulsates relative to the focus of the lens, owing to the change in the plasma density as a result of the presence of a clearly pronounced liquid phase. In the case of action on a thin brass foil, when the optical discharge is maintained in the plasma cloud produced at the start of the pulse, discontinuities of the discharge are observed, probably connected with the homogeneity of the spike structure of the laser radiation. For such metals and absorbing dielectrics as tungsten, lithium, ebonite, or bakelite, in the disintegration products of which the laser radiation is strongly attenuated, no optical discharge is produced at initial radiation fluxes 10^7–10^8 W/cm^2.

As already indicated, a feature of the obtained optical discharge is that it is produced in the vapor produced by the action of the intrinsic laser radiation. This is evidenced also by a spectroscopic investigation of the discharge plasma. Figure 2e shows a typical spectrum of a self-igniting pulsed optical discharge when brass is used. The qualitative analysis of the plasma spectrum shows that it contains the spectral

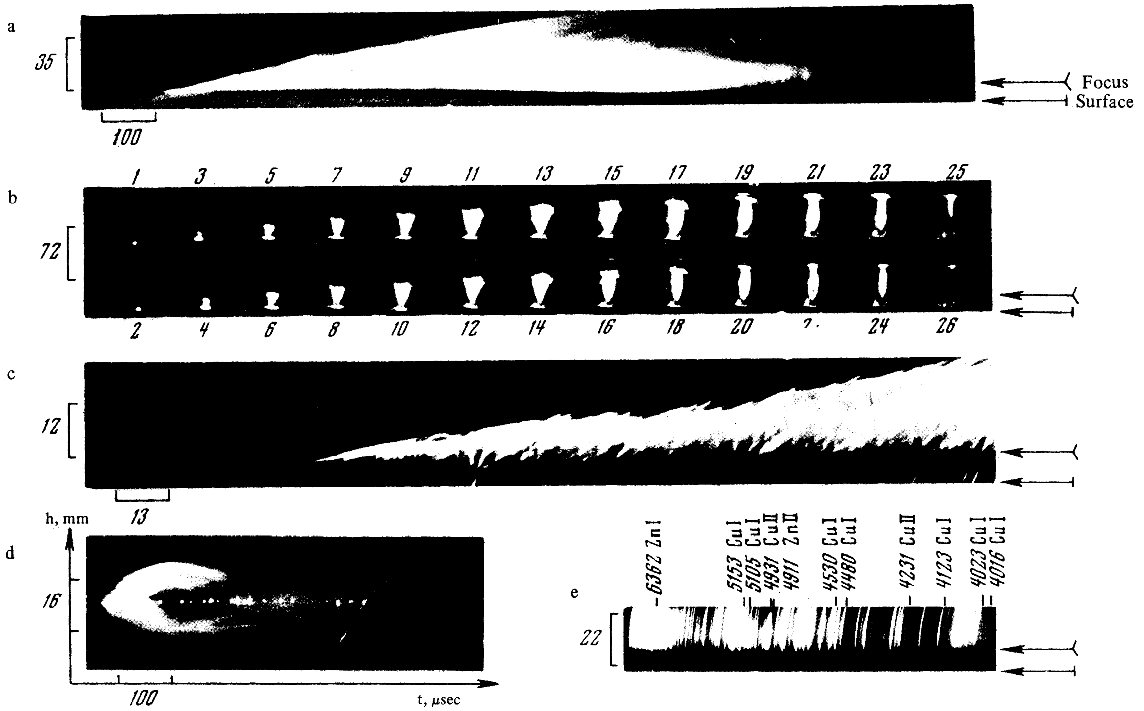

FIG. 2. High-speed photographs and spectrum of self-igniting pulsed optical discharge: a, c—longitudinal streak photographs (the plasma-producing material is brass); b—frame-by-frame scanning (brass; photography rate 31 × 10^3 frames/sec; 1, 2, 3, . . .—sequence of frames); d—transverse streak photograph at the surface of the plasma-producing material, corresponding to the streak c; d—spectrum of discharge plasma (brass).

lines of the atoms and ions of elements contained in brass only. Their emission has a unique character. In the region of the lens focus, an intense spectrum of atomic and ionic lines is observed, as well as continuous radiation. Most lines are broadened. Spectral motion-picture photography shows that no significant changes occur in the discharge spectrum in the course of time. The spectral lines of the ions appear simultaneously with the occurrence of the discharge and exist until the lasing terminates.

Estimates were made of the discharge plasma parameters. The electron density was determined from the broadening of the Cu I 4480 Å line[5], due to the quadratic Stark effect, and amounts to 2×10^{17} cm^{-3}. An estimate of the temperature, obtained on the basis of a calculation of the temperature maxima of the intensities of single ions of copper, yields 22 000°K.

Thus, our investigations have demonstrated the feasibility, in principle, of obtaining a pulsed optical discharge at atmospheric pressure in an erosion plasma produced by laser radiation proper and serving as an igniting plasma, at relatively low radiation flux density 10^7–10^8 W/cm^2. The use of a cw CO_2 laser for this purpose makes it possible, at the appropriate flux densities, to produce a continuous optical discharge in an intrinsic erosion laser plasma at atmospheric pressure. The self-igniting optical discharge is of interest both from the point of view of its use to generate directional erosion plasma fluxes, and for further study of the physics of the interaction of laser radiation with matter at moderate radiation flux densities.

Such a phenomenon can take place in investigations of the interaction between a laser radiation focused on different materials and can occur in the crater formed during the course of the action. This changes significantly the entire picture of the disintegration. Deliberate production of a self-igniting optical discharge in an erosion laser plasma makes it possible to study this phenomenon in pure form, so as to be able to take it into account in investigations of the physics of disintegration of different materials by laser radiation and to use it for different plasma dynamics researches. Detailed investigations of the obtained optical discharge are being presently continued.

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