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LASER SPARK IN THE "SLOW COMBUSTION" REGIME

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In our experiments, by focusing the radiation of a neodymium-glass laser operating in the millisecond-pulse regime in a discharge gap, we observed "combustion" of a laser spark at an intensity I below the optical breakdown threshold. The process started with electric breakdown in a discharge gap placed in the focal plane of a lens with f = 50 cm. In the breakdown region, the ionized gas absorbed the laser radiation. As a result, a spark was produced along the laser-beam axis; the spark was symmetrical with respect to the breakdown region and its longitudinal dimensions greatly exceeded those of the initial ionization region. The spark combustion time exceeded by many times the duration of the electric discharge and was determined by the duration of the generation pulse. The radiation-intensity threshold of the described effect was $I \sim 10^7$ W/cm^2. We note that at millisecond durations the threshold of optical breakdown in air at atmospheric pressure amounts to 10^9 W/cm^2 (see [1]).

The electric discharge was induced by the laser radiation pulse in a discharge gap consisting of two metallic needles by evaporation of the metal from the needle surface. The discharge gap length was ~ 5 mm. The discharge was connected to a 6.5-μF capacitor charged to 6 kV. When the capacitor was not charged, there was no effect, and only a small flare of metal evaporated from the needle surfaces was observed.

A photograph of the spark is shown in Fig. 1. The spark dimensions (length $\ell = 7.5$ cm and glow-region width $d \approx 3.5$ mm) correspond approximately to the dimensions of the central

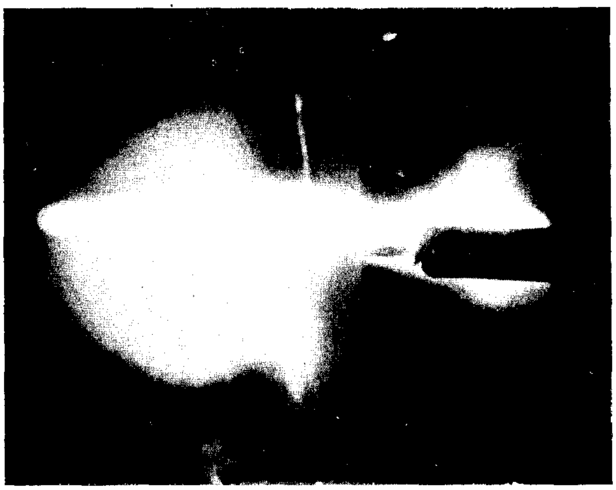

Fig. 1. Photograph of spark in the "slow combustion" mode in the case when the threshold of the effect is exceeded 2.4 times. Linear scale 1:1. Part of the spark image on the right of the photograph is covered. The laser beam moves from left to right.

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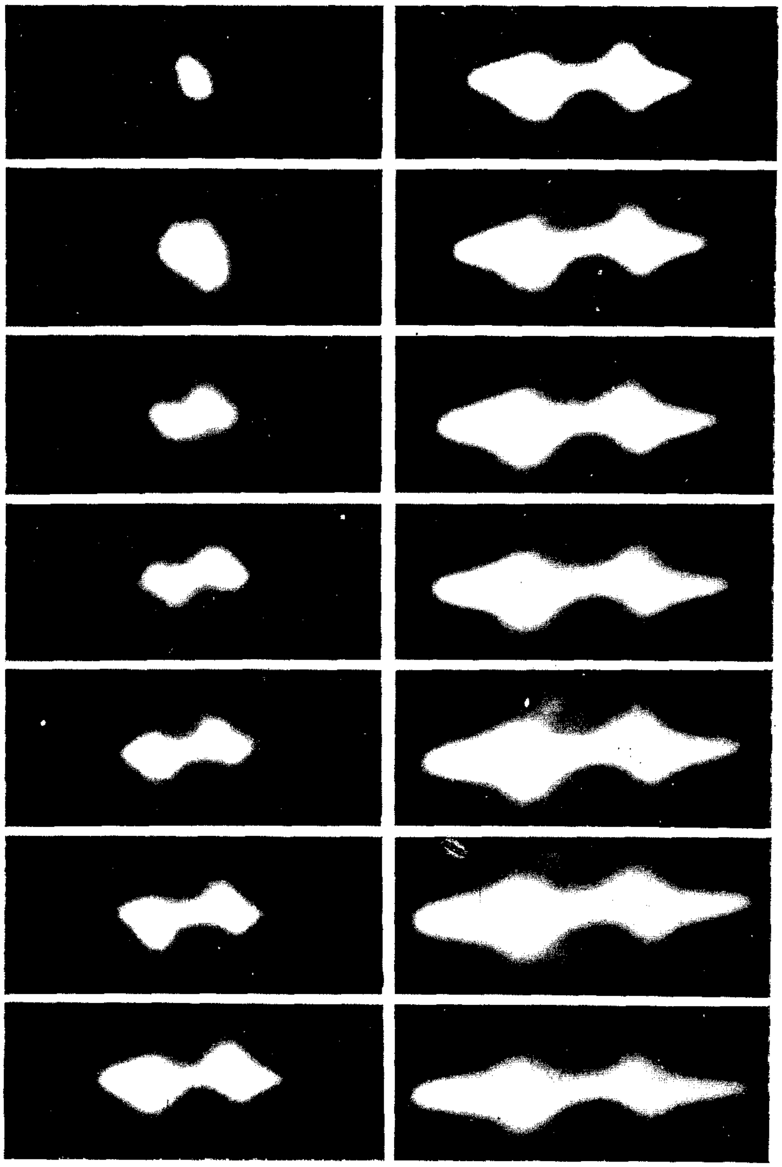

Fig. 2. Time sweep of laser spark in the "slow combustion" mode. Laser energy E = 1150 J. Time interval between frames is 32 μsec from the first to the sixth and 96 μsec from the sixth on. Linear scale 1:1. Laser beam moves from left to right.

part of the lens caustic, $2\theta f^2/a \approx 6$ cm and $2\theta f \approx 2.5$ mm (2a - aperture of beam incident on the lens, $2\theta \approx 5 \times 10^{-3}$ rad - divergence of laser beam). The symmetry of the spark shows that the absorption of the incident light in the spark is small. Measurements of the plasma-spark absorption coefficient $\alpha = \Delta E/E\ell$ (ΔE - absorbed energy) at $E \approx 1000$ J yielded $\alpha \lesssim 7 \times 10^{-3}$ cm^{-1}. The threshold of the effect was determined by an experiment in which the spark was barely distinguishable against the background glow of the electric-breakdown region. This corresponded to an energy E = 730 J. Since the spot diameter in the focus of the lens was $d \approx 2.5 - 3.5$ mm, the threshold radiation intensity was $I_{thr} \approx (0.8 - 1.5) \times 10^7$ W/cm^2. All our experiments were performed at a slight excess over threshold; this explains, in particular, why the spark filled only the central part of the lens caustic.

High-speed photography was used to investigate the time evolution of the process (Figs. 2 and 3). It is seen from Fig. 2 that the electric breakdown producing the triggering ionization zone lasts about 0.1 msec (first three frames). This is followed by the laser spark. The shape of the spark is determined by the filling of the lens caustic. It is seen that the caustic varies somewhat with time. This is apparently connected with the change of the laser beam divergence during the lasing pulse. The time dependence of the spark length is plotted in Fig. 3. The time variation of the spark length agrees qualitatively with the time dependence of the radiation intensity I(t), namely,the length of the spark reaches a maximum, varies slowly, then decreases until the spark is extinguished. This agreement apparently signifies that the spark combustion process is stationary. From Fig. 2 we can estimate that the average speed of spark development is D ≈ 40 m/sec.

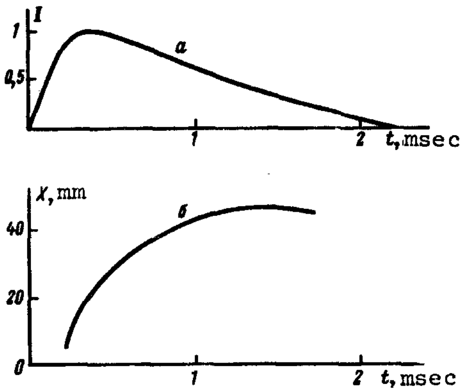

Fig. 3. a) Oscillogram of radiation pulse of laser with energy E = 1100 J. b) Time dependence of length of spark, obtained by high-speed photography

No spectroscopic measurements of the spark plasma temperature were made. The spark temperature can be estimated from the obtained experimental value of the absorption coefficient α by means of the Kramers-Unsold formula [2, 3]:

$$a(T) = 6{,}2\cdot10^{-20}\, n\, T_{\mathrm{deg}}\, (h\nu_{\mathrm{eV}})^{-3} e^{-\frac{\Delta - h\nu}{kT}} \left(1 - e^{-\frac{h\nu}{kT}}\right), \qquad (1)$$

where n is the density of the atoms per cm^3, hν is the photon energy, and Δ is the atom ionization potential. Substituting $\alpha \approx 7 \times 10^{-3}\ \mathrm{cm}^{-1}$ and Δ = 14.2 eV we obtain T ≈ 1 eV.

In our opinion, the described effect is analogous to the process of slow combustion of a gas. The rate of heat release of the "exothermal reaction" is determined here by the intensity of the laser radiation I and by the absorption coefficient α(T) of the heated gas (spark). The gas front, just as in ordinary combustion, moves as a result of heat transfer from the "combustion" zone (spark) to the cold gas, the heat-transfer mechanism being the usual thermal conductivity of the gas. It should be noted that the effect under consideration differs strongly from the effects described in the literature [2, 3], dealing with the displacement of the zone of beam absorption in the case of optical breakdown by a "giant" laser pulse (detonation mechanism, radiation mechanism, breakdown wave), when the absorption takes place in a thin layer of strongly ionized gas moving with a velocity ∿ 100 km/sec.

Starting from the concepts of the slow-combustion mechanism, we can determine the dependence of the rate of spark development on the radiation intensity I and on the spark temperature T. Since the spark expands symmetrically along the beam, the rate of displacement of its fronts (relative to the stationary initial breakdown zone) should be determined in the same manner as the velocity of a combustion front propagating from the open end of a tube. We then have [4]:

$$D = u_H \frac{\gamma_0(\gamma - 1)}{\gamma(\gamma_0 - 1)} \frac{c_p T}{c_{p_0} T_0}, \tag{2}$$

where the subscript "o" pertains to the cold gas, γ is the adiabatic exponent, c_p is the specific heat at constant pressure, and u_H is the so-called ignition velocity, which is determined by the rate of release of the heat of the combustion reaction and by the thermal-conductivity coefficient κ of the gas. In our case the heat-release rate equals $\alpha(T)I$, and therefore (cf., e.g., [5])

$$u_H = \frac{1}{\rho_0 q} \sqrt{2\kappa I \int_{T_0}^{T} \alpha(T) dT}, \tag{3}$$

where $q = c_p T - c_{p_0} T_0$ and ρ_0 is the density of the cold gas.

On the basis of formulas (1 - 3), introducing the temperature-conductivity coefficient $\chi = \kappa/c_p\rho$ and taking into account the connection between ρ and ρ_0 for the combustion process [4], we obtain a final formula for the speed D (we take account of the fact that $c_p T \gg c_{p_0} T_0$):

$$D = \sqrt{2 \frac{\gamma_0(\gamma - 1)}{\gamma(\gamma_0 - 1)} \frac{\chi I \alpha(T)}{\rho_0 c_{p_0} T_0} \frac{kT}{\Delta - h\nu}}, \tag{4}$$

A numerical estimate based on this formula yields $D \simeq 50$ m/sec for air under normal conditions and for $I = 10^7$ W/cm^2, $T = 1$ eV, $\Delta = 14.2$ eV, $h\nu = 1.17$ eV, and $\chi = 40$ cm^2/sec. This is in good agreement with the foregoing experimental estimate.

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