Optical discharge accompanying a restriction imposed on lateral expansion of gas and a reduction in the threshold of light-induced detonation

I. A. Bufetov, A. M. Prokhorov, V. B. Fedorov and V. K. Fomin
Institute of General Physics, Academy of Sciences of the USSR

(Submitted 12 January 1983)
Pis'ma Zh. Eksp. Teor. Fiz. **39**, No. 5, 216–219 (10 March 1984)

Subsonic propagation of an optical discharge in atmospheric air along a quartz tube is transformed into a light-induced detonation regime for neodymium laser radiation intensities in the range (1–5) MW/cm^2.

In our experiments (Fig. 1), the discharge propagated along the beam of a millisecond neodymium laser (L1).[1] The pulse had a duration of up to 5 ms, the power $W \leqslant 2$ MW, and the pulse shape was nearly square. The radiation was focused in laboratory air with a lens with $f = 1$ m. The diameter of the spot at the constriction neck of the caustic was 5.3 mm, and the caustic was 21.7 cm long at the one-half intensity level. The radial motion of the gas in the region of the discharge was restricted by a quartz tube, whose axis coincided with the axis of the beam L1 and whose length l greatly exceeded the diameter of the beam. Since the intensity of the beam L1 is not high enough to create a plasma, the discharge was initiated by breakdown of air at the center of the tube by radiation from an auxilliary Q-switched (40 ns, 1 J) laser (L2). In the experiments, we recorded the transmission of the L1 radiation discharge plasma and the spectrum of the characteristic plasma radiation. The propagation of the discharge was observed with the help of high-speed photography.

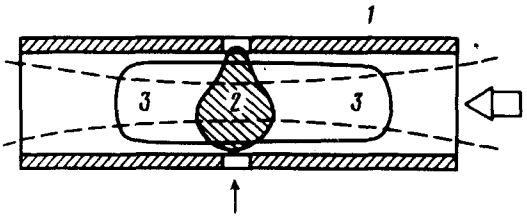

FIG. 1. Experimental arrangement. 1) Quartz tube; 2) plasma initiating breakdown; 3) optical discharge; ⇐ L1 beam (its boundaries are shown by the dashed curves); ↑ L2 beam.

Immediately after initiation, the discharge propagated symmetrically on both sides relative to the beam L1 with increasing velocity (Fig. 2a). As the plasma volume was increased, the discharge became optically dense. The transmission of the plasma decreased to less than 5%. The luminescing region of the discharge at this stage moved collectively toward the beam L1; the velocity of the leading edge of the plasma (LP), V, prior to exiting from the tube remained approximately constant, indicating that the propagation process was stationary. The diameter of the luminescing region was (0.8–0.9)d (d is the inner diameter of the tube). The plasma temperature, estimated from the transmission spectrum, was $\sim 2\times 10^4$ K. No changes were observed on the inner surface or the quartz tubes after the experiments.

The values of V exceeded the speed of sound in the air. The motion of shock waves (SW) in this case was observed by means of Toepler photography. Two qualitatively different patterns of propagation of the discharge were observed. One of them (Fig. 2d) is characterized by the fact that the LP moves at the same velocity as the SW

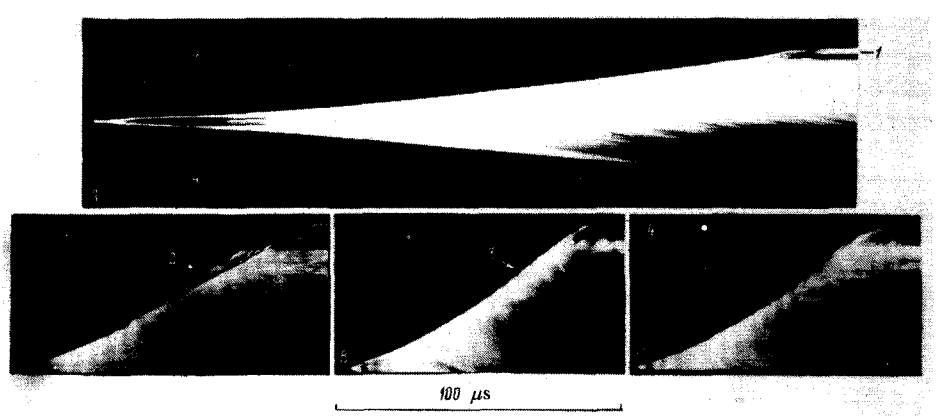

FIG. 2. Sequence of photographs showing the propagation of an optical discharge along a tube. The L1 laser radiation in the photographs is directed from top to bottom: a—d = 11.3 mm, l = 24 cm, W = 1.4 MW; b—d = 7.3 mm, l = 20 cm, W = 1.6 MW; c— and d—d = 7.3 mm, l = 20 cm, W = 1.8 MW; a and b show the characteristic emission of the discharge; b and d show the Toepler unfolding. The motion of the front LP only is shown in b, c, and d. 1) Stationary SW at the outlet from the tube; 2) SW moving in front of LP; 3) sinusoidal section of the scan of the motion of LP; 4) position of the edge of the tube.

moving in front of it. The distance between them is constant ($\sim$2 mm). This indicates that the detonation mechanism of discharge propagation in this case is in effect. The intensity of the laser radiation on the front of the detonation wave varied (due to the divergence of the beam) in the range $I = (6.4–4.5)$ MW/cm^2, which is much less than the minimum intensity for maintaining detonation in free space.[2] A decrease in the threshold for maintaining the detonation is attributed to the decrease in the gas-dynamic energy losses from the discharge. We also note that here a distinct sine-shaped sweep of the luminescence of LP is observed (Fig. 2c). This could be a result of the small spiking modulation of the L1 pulse (its amplitude did not exceed 20% of the constant component). However, taking into account the similarity between the pattern in Fig. 2c and the motion of the front of a spin chemical detonation (see, for example, Ref. 3), it can also be interpreted as being a result of the complicated structure of the light-induced detonation wave.

When the intensity of the radiation L1 is decreased and d is increased, a different picture of propagation of the discharge is observed; the SW moves with a higher velocity than LP (Figs. 2a and 2b). Since the LP moves along the SW-compressed gas with subsonic velocity, the discharge in this case can be viewed as a type of optical discharge in the slow combustion regime. In contrast to a discharge at a pressure equal to the surrounding gas pressure,[1] where $V \ll c$ (c is the velocity of sound in the gas in front of the LP), this situation, characterized by the relation $V \leqslant c$, is a transitional step that leads to a light-induced detonation. The same circumstance is also indicated by the fact that the interval between LP and SW (Fig. 2b) is not uniform: it is filled by waves of excitations moving from LP to SW.

The velocity V of steady propagation of LP along the tube depended both on W and on d. As the experimental data show (Fig. 3), the dependence $V(W,d)$ can be viewed to some extent as $V(I_{av})$ (where $I_{av} = 4\,W/\pi d^2$), which is characteristic for a one-dimensional (flat) process. The one-dimensional model of subsonic propagation of a discharge from a barrier in a gas, in which a strong SW precedes the plasma front, was examined in Ref. 4. Taking into account the expansion of the gas on both sides of

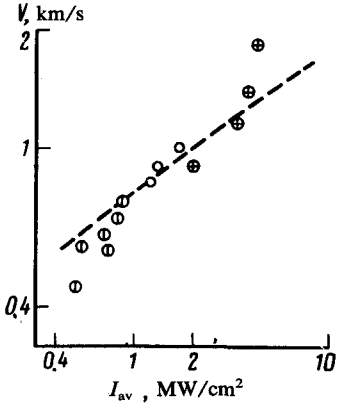

FIG. 3. Velocity of steady propagation of LP in the tube: ⦶—$d = 16.6$ mm; ●—$d = 11.3$ mm; ⊕—$d = 7.3$ mm. The dashed line denotes the computed dependence $V(I)$.

the beam, we obtained on the basis of this model a working dependence $V(I)$ (it was assumed that all of the absorbed energy goes into increasing the enthalpy of the discharge plasma). Comparison of experimental data with $V(I)$ shows satisfactory agreement. The disagreement at high intensities (~ 4 MW/cm^2) is due to the transition to the light-induced detonation regime. A disagreement is also observed at low (~ 0.5 MW/cm^2) intensities.

Thus a restriction of the radial motion of the gas increases the energy input into the plasma and increases by approximately a factor of 100 the observed rates of development of the discharge: from ~ 10 m/s[1] to ~ 1 km/s. Under conditions of nearly one-dimensional gas flow, the regime of light-induced detonation can be observed at $I_{av} \approx 4.3$ MW/cm^2, which is much less than the threshold values for maintaining detonation by a laser beam with the same diameter in an unbounded gaseous medium. In particular, the threshold for maintaining waves of light-induced detonation must drop in the region of one-dimensional gas flow under the action of laser radiation on a flat target.

[1]I. A. Bufetov, A. M. Prokhorov, V. B. Fedorov, and V. K. Fomin, Kvant. Electron. **10**, 1817 (1983) [Sov. J. Quantum Electron., to be published].
[2]I. Z. Nemtsev, B. F. Mul'chenko, and Yu. P. Raizer, Pis'ma Zh. Tekh. Fiz. **2**, 13 (1976) [Sov. Tech. Phys. Lett. **2**, 5 (1976)].
[3]A. Ferri [Ed.], Osnovnye rezul'taty éksperimentov na udarnykh trubakh (Basic results of shock-tube experiments), Moscow, 1963.
[4]I. V. Nemchinov, Izv. Akad. Nauk SSSR, Ser. Fiz. **46**, 1026 (1982).

Translated by M. E. Alferieff
Edited by S. J. Amoretty