

# Transversely propagating light discharges and flares from moving laser beams—a new class of light and gas-dynamical effects

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(Submitted 10 April 1981)

*Pis'ma Zh. Esp. Teor. Fiz.* **33**, No 10, 528–533 (20 May 1981)

A new class of radiation and gas-dynamical effects — the transverse propagation of light discharges and flares produced by a moving laser beam—has been investigated. Oblique and curved plasma lines and surfaces have been obtained experimentally. The conditions for maintaining and terminating discharge propagation are given. It is shown to be possible to track the discharge behind a beam moving with a high velocity which is comparable to that of light detonation and to control the discharge propagation by moving the beam.

PACS numbers: 51.50. + v, 51.70. + f

Light discharges in gases<sup>1</sup> usually propagate opposite to the beam producing them. Evidence also exists<sup>2</sup> for the intrusion of a beam into a gaseous medium, heating and ejecting the medium from its path—a light discharge propagating along the beam. We have investigated a new class of radiation and gas-dynamical effects—the transverse propagation of light discharges due to the motion of the beam.

In order to transmit a beam at right angles to the axis, we used a laser that operated in the wave-generation regime<sup>2,3</sup>: A metallized Dacron film, which blocked the cavity mirror and spoiled the  $Q$ , was placed in the cavity at a small angle to the mirrors.

A localized clearing of the metallization by an auxiliary laser (or electrical initiator) at the instant of maximum inversion resulted in the generation of a giant pulse at the point of initiation. The evaporation of metal plating by the light, which expanded because of angular divergence, resulted in a lasing wave and the formation of a moving beam.

GLS-6 neodymium-glass rods with a diameter of 45 mm, a length of 640 mm, and ends cut at a 5° angle were used in the laser generator and amplifier. A diaphragm with a rectangular opening of length  $D = 4.5$  cm and width  $\Delta = 1$  cm was mounted in the generator cavity to produce rectilinear motion of the beam. The beam moved in one direction when the lasing wave was initiated at the edge of the opening; initiation at the center of the opening or with the diaphragm removed produced beams on the axis which moved in different directions. In the presence of the diaphragm the lasing energy  $\approx 40$  J ( $\approx 120$  J without the diaphragm). The light flux density  $I$  and the beam displacement velocity  $v_b$  could be varied by means of focusing as a function of the distance  $r$  to the beam focus  $v_b = v_0 r/F$ , where  $v_0$  is the velocity of the lasing wave and  $F$  is the focal length (a lens corrected for spherical aberration with  $F = 25$  cm was used). We note that beam motion appears only at distances

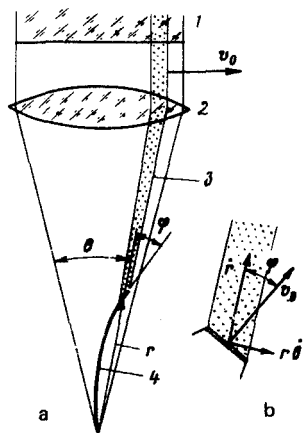


FIG. 1a—Schematic of the experiment: 1—Output end of laser; 2—lens; 3—beam from a lasing wave traveling with a velocity  $v_0$  at right angles; 4—light-breakdown plasma. b—Diagram of light-detonation wave propagating at an angle  $\phi$  to a beam moving with a velocity  $v_b$ .

up to the focus, which exceed the caustic length of the entire aperture  $l_c = F^2 \Phi / D \approx 2.5$  mm for a divergence angle  $\Phi = 2 \times 10^{-3}$  rad. The light flux densities can be varied within the limits  $I \approx 10^9 - 10^{11}$  W/cm<sup>2</sup>, depending on the distance to the focus:  $I = I_0 (l_1/r)^\alpha (l_2/r)^\beta$ , where  $l_1 = F^2 \Phi / d$  (the width of the lasing wave is  $d = \tau_s v_0 \approx 0.4 - 0.5$  cm for a local scintillation time  $\tau_s \approx 60 - 80$  nsec<sup>2</sup>) and  $l_2 = F^2 \Phi / \Delta$  are, respectively, the caustic lengths in the direction of beam motion and perpendicular to it. Since  $l_1 > l_2$ ,  $\alpha = 0$  and  $\beta = 0$  for  $r < l_2$ ;  $\alpha = 1$  and  $\beta = 0$  for  $l_2 \leq r \leq l_1$ ; and  $\alpha = 1$  and  $\beta = 1$  for  $r > l_1$ . Experiments were conducted at two lasing-wave velocities: 1)  $v_0 = 5 \times 10^6$  cm/sec, in this case the intensity at the focus was  $I_0 \approx 2.5 \times 10^{10}$  W/cm<sup>2</sup>,  $d \approx 0.4$  cm,  $l_1 = 1.2$  cm, and  $l_2 \approx 3$  cm; 2)  $v_0 = 8 \times 10^6$  cm/sec, in this case  $I_0 \approx 4 \times 10^{10}$  W/cm<sup>2</sup>,  $d \approx 0.5$  cm,  $l_1 \approx 1.2$  cm, and  $l_2 = 2.5$  cm. For  $r \leq 10$  cm the intensity  $I$  exceeded the threshold for maintaining light detonation<sup>1</sup> ( $I_{thr} \approx 10^8$  W/cm<sup>2</sup>).

Figure 1 shows the experimental setup. The beam 3 of the laser 1 produced a discharge in air, which was initiated either by a breakdown of the gas at the focus or at the metal surface.<sup>4</sup>

The surface was placed successively at different distances from the focus (Fig. 2) in order to observe the effect at different beam-displacement velocities ( $v_b = r\dot{\theta}$ , where  $\dot{\theta} = v_0/F$ ) and different intensities corresponding to different light-detonation velocities [ $v_D \approx (I/\rho_0)^{1/3}$ ].

A conical plasma surface was also obtained experimentally in the case of a lasing wave which was initiated on the axis and propagated radially in all directions: the thickness  $h \approx v_D \tau_s$  of such a plasma surface in our case ( $\tau_s \approx 70$  nsec) was quite small:  $h \leq 2$  mm for  $v_D \approx 2 \times 10^6$  cm/sec.

It can be seen in Fig. 2 that higher beam velocities correspond to larger inclination angles of the discharges to the beam, which ranged up to 60°. At  $v_b/v_D \approx 0.5 - 0.7$  the propagation ceased and a new discharge was formed on the surface. If, however, the surface was at a distance  $r$  such that  $v_b \geq v_D$  ( $r = 9$  cm in Fig. 2), then a discharge could be initiated at each point on the surface and no screening of the surface by the oblique discharge was observed. When the discharge was initiated on a small object, it ranged far laterally, if the conditions for maintaining the discharge  $v_b/v_D$

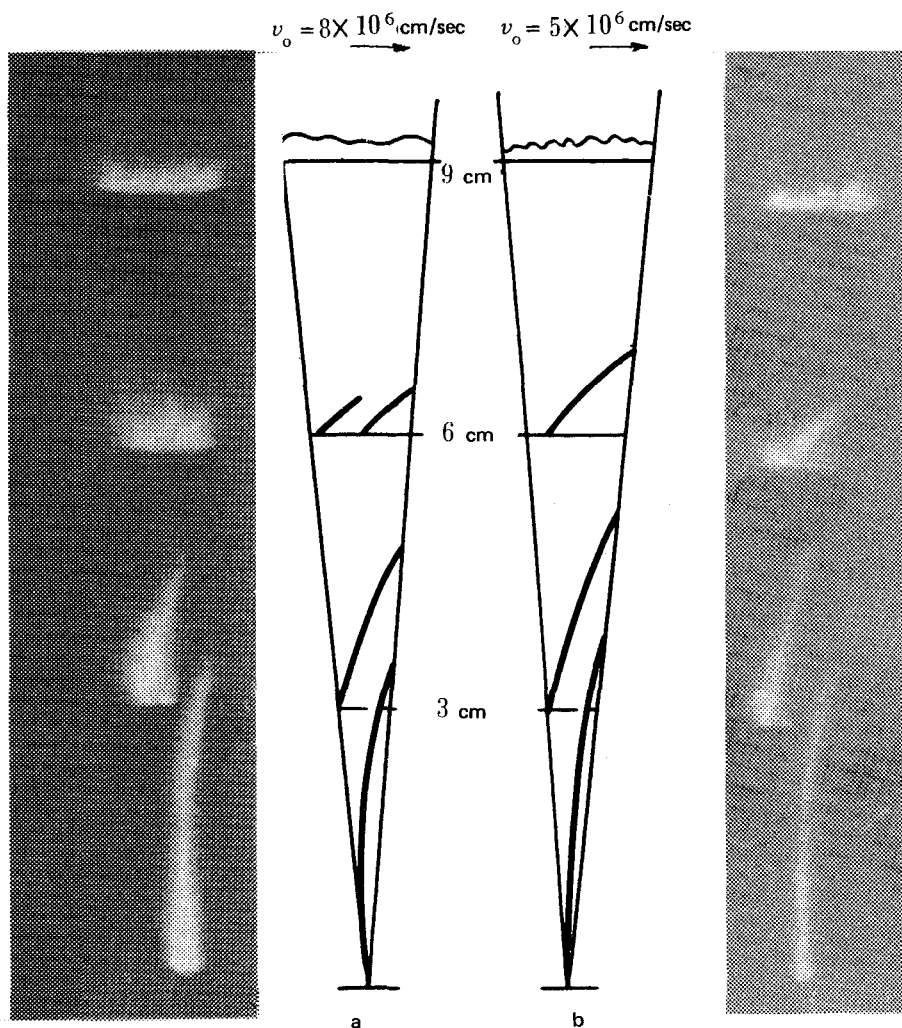


FIG. 2. Types of light breakdowns at different distances from focus for two wave velocities. (a)  $v_0 = 8 \times 10^6$  cm/sec and (b)  $v_0 = 5 \times 10^6$  cm/sec. Light breakdowns were initiated from a metal surface. The light breakdown becomes progressively more transverse with increasing beam velocity and decreasing flux density, i.e., with decreasing distance to the lens.

$\leq 0.7$  were satisfied.

It can be assumed that the observed transverse propagation of light discharges is attributable to the entry of the beam into the plasma or to a laterally scattered shock wave produced by light detonation and to the creation of new light-detonation waves. The observed effect can be described most simply by assuming that the propagation of the discharge is determined by the light detonation along the beam  $\dot{r} = v_D(r)$  and by the given variation of the beam angle  $\theta = \theta(t)$ . In this case the tangent of the discharge inclination angle is equal to  $v_D/v_b$ , where  $v_D \approx (I/\rho_0)^{1/3}$

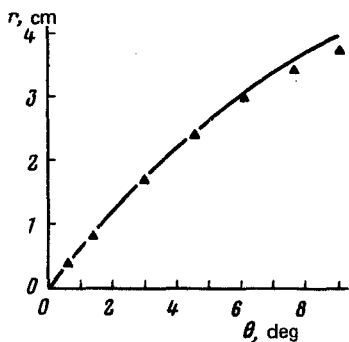


FIG. 3. Dependence of the radius of the discharge front on the beam rotation angle for a wave velocity  $v_0 = 5 \times 10^6$  cm/sec. The points represent the experimental data. The curve was plotted from the theory.

$\approx A/r^{(\alpha+\beta)/3}$ . Integration gives  $r^{(\alpha+\beta)/3+1} - r_0^{(\alpha+\beta)/3+1} = [(\alpha+\beta)/3+1] A t$ . For example, for  $\theta = \text{const}$ ,  $\theta - \theta_0 = \theta t$  and  $r^{(\alpha+\beta)/3+1} = r_0^{(\alpha+\beta)/3+1} + (\alpha+\beta/3+1) A/\theta (\theta - \theta_0)$ , i.e., for  $r > l_1$  the dependence is  $r \sim \theta^{3/5}$ .

Figure 3 gives the calculated  $r(\theta)$  dependence, and the experimental points are shown for a discharge propagating from the focus to  $r \leq 4$  cm for  $v_0 = 5 \times 10^6$  cm/sec. Quite good agreement is seen for  $v_D \gg v_b$ .

There is also a coordinated interaction of the moving beam with the created light-detonation front, which tilt the front in the direction of beam motion (Fig. 1b). In this case the angle  $\phi$  between the beam direction and that of light detonation is determined from the condition for motion synchronism:  $v_D \sin \phi = v_b$ , where  $v_D \approx (I \cos \phi / \rho_0)^{1/3} \approx v_{D_0} \cos^{1/3} \phi$ .

The maximum value  $v_b/v_{D_0} = \sin \phi \cos^{1/3} \phi$  is reached for  $\phi_m = 60^\circ$ ; in this case  $v_b/v_D = \sqrt{3}/2^{4/3} \approx 0.7$ . The angle  $\phi_m$  determines the cutoff of the beam from the discharge at high beam velocities, which is close to the cutoff angles  $\phi_m \approx 50-60^\circ$  obtained experimentally. The  $(v_b/v_{D_0})_m$  and  $r_m$  values given by this model are also close to the experimental values. For  $v_b/v_{D_0} \ll 1$  the  $r(\theta)$  dependence given by this model coincides with the  $r(\theta)$  dependence given by the simple description presented above.

The coordinated motion of light discharges at an angle to the moving beams represents a new class of light and gas-dynamical effects. The possibility of tracking a light discharge behind a beam moving with a high velocity, which is comparable to the light-detonation velocity, has been shown along with the possibility of controlling the light-discharge propagation by moving the beam.

The discussed transverse discharges are of more than phenomenological interest. They make it possible to analyze the conditions of lateral pickup or repeated initiation of light discharges in the plasma or laterally scattered shock wave, and they also show that the discharge in a gas initiated by the beam at a surface will not screen it from further action of the moving beam, if its velocity exceeds the detonation velocity.

The rapidly moving plasma front caused by a rapid movement of the beam over the surface can be used, by analogy with Ref. 5, for Doppler conversions of frequencies,<sup>6</sup> for acceleration of particles, etc.

The plasma layers and surfaces can be produced at a lower power and at a much lower energy consumption than that with use of short and high-power pulses which produce a breakdown over a large area; this is clearly not advantageous because of high breakdown thresholds. Such surfaces can be used, for example, as radio-wave reflectors.<sup>7</sup>

More complicated discharge trajectories (helical, spiral, letter-form, work-form, symbols, etc.) can be obtained by using an appropriate beam movement (in the case of out laser it is sufficient to place a special mask in the cavity in order to alter the path of the lasing wave.<sup>8</sup> The propagation and transfer of a discharge over long distances from the point of initiation and the transport of a discharge under transparent surfaces or in transparent tubes are also of interest.

There are other possible application of transverse, extended discharges. They can be used in conjunction with reduced-density channels<sup>9</sup> to transmit beams of charged and neutral particles and fast-moving macroparticles, to maintain light-reactive<sup>10</sup> and light-discharge<sup>11</sup> acceleration of macroparticles by a lateral beam, and to produce directed breakdowns and edge enhancements of a field of streamers upon application of an electric field.

1. Yu. P. Raizer, *Lazernaya iskra i rasprostranenie razryadov* (Laser Spark and the Propagation of Discharges), Nauka, Moscow, 1974; *Usp. Fiz. Nauk* 87, 29 (1965) [*Sov. Phys. Usp.* 8, 650 (1966)]; *Usp. Fiz. Nauk* 132, 549 (1980).
2. G. A. Askar'yan and B. M. Manzon, *Pis'ma Zh. Eksp. Teor. Fiz.* 27, 113 (1978) [*JETP Lett.* 27, 104 (1978)].
3. G. A. Askar'yan and B. M. Manzon, *Zh. Tekh. Fiz.* 49, 2202 (1979) [*Sov. Phys. Tech. Phys.* 24, 1214 (1979)].
4. N. N. Kozlova, I. E. Markovich, N. V. Nemchinov, A. I. Petrukhin, Yu. E. Pleshanov, V. A. Rybakov, and V. A. Sulyaev, *Kvantovaya Electron.* 2, 1930 (1975) [*Sov. J. Quantum Electron.* 5, 1048 (1975)].
5. G. A. Askar'yan and B. M. Manzon, *Pis'ma Zh. Eksp. Teor. Fiz.* 31, 283 (1980) [*JETP Lett.* 31, 259 (1980)].
6. V. I. Semenova, *Izv. Vyssh. Uchebn. Zaved. Radiofiz.* 10, 1077 (1967).
7. G. A. Askar'yan, B. M. Manzon, and I. M. Raevskii, *Pis'ma Zh. Tekh. Fiz.* 4, 1466 (1978) [*Sov. Tech. Phys. Lett.* 4, 593 (1978)].
8. G. A. Askar'yan and B. M. Manzon, *Pis'ma Zh. Tekh. Fiz.* 7, No. 11 (1981)
9. G. A. Askar'yan and N. M. Tarasova, *Pis'ma Zh. Eksp. Teor. Fiz.* 20, 277 (1974) [*JETP Lett.* 20, 123 (1974)].
10. G. A. Askar'yan and E. M. Moroz, *Zh. Eksp. Teor. Fiz.* 43, 2319 (1962) [*Sov. Phys. JETP* 16, 1638 (1963)].
11. F. V. Bunkin and A. M. Prokhorov, *Usp. Fiz. Nauk* 119, 425 (1976) [*Sov. Phys. Usp.* 19, 561 (1976)].

Translated by Eugene R. Heath

Edited by S. J. Amoretti