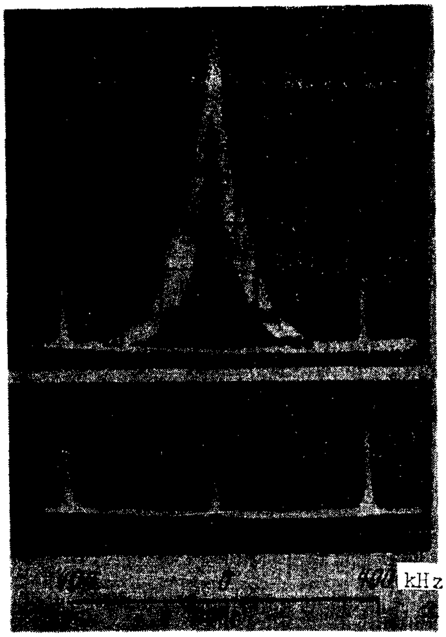

Fig. 3. Oscillation spectra: a - zero electrode potential, b - potential 40 V.

In the presence of radiation, the energy loss by the beam electrons increases, and the low-frequency occillations (drift and drift-dissapative) disappear (Fig. 3). The accelerated ions also disappear in this case. The change of the radial distribution of the plasma density leads to a transition from regime (b) to regime (c) and to stabilization of the low-frequency instabilities. Our investigations show that the same results on the quenching of low-frequency instability can be obtained also by specifying density gradients analogous to Fig. 1, by choosing the pressure in the interaction region, or by magnetic-field gradients.

In conclusion, we are grateful to Ya.B. Fainberg for valuable advice and to A.S. Bakai for a discussion of the results.

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LOW-THRESHOLD BREAKDOWN OF AIR NEAR A TARGET BY CO_2 RADIATION, AND THE ASSOCIATED LARGE RECOIL MOMENTUM

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A sharp drop (by more than two orders of magnitude) was observed in the threshold intensity for the breakdown of air near a target by CO_2-laser radiation. The target recoil momenta due to the optical breakdown of the air are measured. The experimental data are interpreted on the basis of the theory of a point-source explosion.

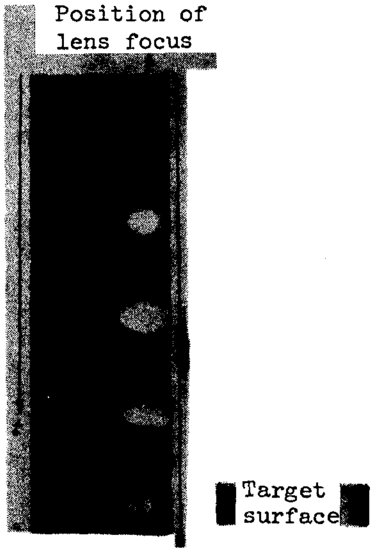
It was reported in [1] that plasma is produced near a target when laser radiation with $\lambda = 2.36\ \mu$ is focused on its surface and the light intensity is less than the threshold value for the breakdown of the air. It was shown recently [2] that the threshold for breakdown of air by CO$_2$ laser radiation depends strongly on the purity of the gas, and the threshold can be lowered to 10^8 W/cm^2 if impurity microparticles are introduced.

In the present study we have observed that optical breakdown of air by radiation from a pulsed CO$_2$ laser is produced at much lower light intensities, $S \approx (5 - 10) \times 10^6$ W/cm^2, near the surfaces of various solid targets (Al, Cu, Mg, NaCl and others). Breakdown near optical surfaces occurs at approximately the same values of the intensity. The breakdown plasma absorbs practically all the laser radiation and screens the surface of the target. The shock wave produced in the breakdown imparts a recoil momentum I to the target; in our experiments, the relative recoil momentum $P = I/E$ (E is the energy of the laser pulse) reached high values on the order of 45 dyn-sec/J for specially shaped targets.

In the experiments we used a multimode CO$_2$ laser with transverse discharge, capable of producing single pulses with duration $\tau \approx 15$ μsec at the base and with energy E up to 4 J; the latter was monitored with a graphite disk calorimeter. The laser radiation had a divergence $2\theta = 10^{-2}$ rad at the half-power level and was focused near the target surface by a lens of focal length f = 10 cm. Optical breakdown of the air was produced inside the caustic of the lens; its occurrence was accompanied by a light spark with a characteristic "click." Without the target, the single pulses did not produce breakdown in the air.

Fast frame-by-frame photography with a high-speed motion-picture camera (SFR) shows (see the figure) that the air breakdown is initiated in a focal volume located ∿0.5 cm away from the target surface. During the laser pulse, the plasma fills the caustic of the lens (approximately symmetrically about the focus), and then dies out. The character of the breakdown does not change if the radiation is incident at a certain angle to the target. No craters are produced on the target surface. It was noted that the breakdown threshold depends little on the target material and is determined principally by the purity of the surface and by the pressure of the surrounding gas. Thus, whereas for an unpolished copper plate the threshold intensity was $S_{\text{thr}} \approx (5 - 10) \times 10^6$ W/cm^2 and the breakdown was produced by practically every generation pulse, in the case of a copper mirror with absorption ∿1% the threshold was increased by a factor of 4 and in the case of repeated radiation it was not produced at all - the first pulse, so to speak, cleaned out all the absorption centers from the surface. A microscopic investigation of the irradiation spots on the mirror has shown that local damage spots, with diameter on the order of 10 - 50 μ, are produced on its surface. The optical breakdown is apparently initiated by strongly absorbing macroscopic particles from the target surface.

Calorimetric measurements of the absorption in the breakdown plasma have shown that 10 - 20% of the laser-pulse energy reaches the target surface.



Fast scan of air breakdown near a magnesium target. Time interval between frames ∿6 μsec. Scale 1:1. Energy in pulse E ≈ 1.5 J.

The relative recoil momentum P was determined from the horizontal deflection of a pendulum. For a flat target of copper, at a pulse energy E ≈ 1 J, the maximum value was P ≈ 10 dyn-sec/J and depended on the mutual location of the target end of the lens. No strong dependence of the recoil momentum on the transverse dimensions of the flat target was observed (in a range of target diameters from 1 to 4 cm), but when the radiation was focused inside a hollow magnesium cylinder of ~ 1 cm diameter, closed on one end, the relative recoil momentum reached 45 dyn-sec/J at the same energy $E \simeq 1$ J. We have also performed an experiment with a pendulum placed near a stationary target; the plane of the pendulum swing was perpendicular to the light beam. When breakdown was produced near the target surface, a lateral recoil momentum was registered, of approximately the same value as in the forward direction.

Our experimental data for the recoil momentum agree with the results of [3], where the interaction of a $(10^7 - 4) \times 10^8$ W/cm^2 near-collimated CO_2 laser beam was interacted with opaque flat targets. The authors of [3] attributed the pressure on the target to the production of an optical-detonation wave propagating from the target in a direction opposite to the light beam. The decrease of the relative recoil momentum with increasing energy flux density E_1 was attributed to the increase in the propagation velocity of the front of the optical-detonation wave, $D \sim E_1^{1/3}$, and the ensuing more effective screening of the surface against the incident radiation.

Our results on the recoil momentum for flat and cylindrical targets can be interpreted quite satisfactorily by assuming that the recoil momentum is due entirely to a shock wave produced in air as a result of a point-source explosion releasing an energy E in the focal volume, when $I \sim \sqrt{E}$ and $P \sim 1/\sqrt{E}$ (see [4]). For a flat target we have in this case [4]

$$P_{\mathrm{fl}} \simeq 0.5\sqrt{\ell\rho/E_1} \qquad (1)$$

where ρ is the density of the air, ℓ is the distance from the focus of the lens ("explosion point") to the target. At $\ell = 0.5$ cm and $E_1 = 50$ J/cm^2, formula (1) yields $P \simeq 6$ dyn-sec/J. In the case of a cylindrical target, we can approximately use the expression for the relative momentum P_{sph} produced in a spherical shock wave [4]

$$P_{\mathrm{sph}} \simeq \sqrt{\rho R_0^3/E}, \qquad (2)$$

where R_0 is the radius of the hemisphere that takes up the recoil momentum. At $R_0 = 0.5$ cm and $E = 1$ J formula (2) yields $P_{\mathrm{sph}} \simeq 41$ dyn-sec/J.

On the basis of our experiments we can state that when CO_2 laser radiation of intensity $S \geq (5 - 10) \times 10^6$ W/cm^2 interacts with targets, optical breakdown of the air occurs near the target surface. The question of the mechanism that produces this breakdown still remains open. The laser pulse energy is released in the focal volume, and the recoil momentum should be symmetrical, as is well illustrated by experiments with a lateral pendulum and a cylindrical target.

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