The increase ΔT_m of the gas temperature depends on the degree of ionization $N_{e\max}/N_m$ of the average energy of the electrons T_e and on the time γ^{-} of the passage of the active zone through the given point. The quantities T_e and γ, in turn, are determined by the ratio of the energy w of the oscillatory motion of the electrons in the wave field to the potential I of the ionization of the atoms. At the usual radiation intensities for pulsed laser breakdown, w lies in the range $\delta I < w < I$, where δ is the fraction of the energy lost by the electrons in the collisions. Under these conditions, at incomplete ionization of the gas $T_e \approx I \approx 10$ eV, $\tau = \gamma^{-1} \approx \nu^{-1} I/w$ and ΔT_m is quite small even if one includes in it the entire energy given up to the electrons in the elastic and inelastic collisions:

$$\Delta T_M \approx T_e \delta \nu \tau \frac{N_{e\max}}{N_m} \approx I \frac{\delta I}{w} \frac{N_{e\max}}{N_m}. \tag{15}$$

Behind the breakdown-wave front the heating of the gas by the electrons continues, but it now occurs actually in the absence of a field and can be of importance only during the succeeding stages of the discharge.

We present in conclusion some quantitative estimates, assuming $\ln(N_{e\max}/N_{e0}) = 30$, $I\delta/w = 10^{-1}$. For a neodymium laser ($N_c \approx 10^{21}$ cm^{-3}), at pressures $p \approx 1$ atm, even in the case of very small angles $\theta \approx 3\times10^{-2}$, the considered breakdown-wave regime does not occur in a cold gas ($N_{e\max} \approx N_m$; T_e, $T_m > I$). For a CO_2 laser ($N_c \approx 10^{19}$ cm^{-3}) at $p = 1$ atm and $\theta = 3\times10^{-2}$ we have $N_{e\max} \approx 3\cdot10^{17}$ cm^{-3} and $\Delta T_m \approx 100$ K. In the region of longer wavelengths and at not too low pressures, there is practically no heating of the gas: at $\lambda = 3\cdot10^{-2}$ cm ($N_e \approx 10^{16}$ cm^{-3}), $p = 0.1$ atm, and $\theta = 10^{-1}$ we have $N_{e\max} \approx 3\cdot10^{15}$ cm^{-3} and $\Delta T_m \approx 10$ K.

The author is grateful to A. G. Litvak, Yu. P. Raĭzer and V. E. Semenov for discussions and remarks.

[1)] The kinematics of the breakdown wave in a given field (without allowance for the screening action of the produced plasma) was investigated in Refs. 4 and 5.

[2)] A similar result was obtained in an investigation of the stationary regime of a nonequilibrium discharge in the field of two waves that converge at a small angle,[7] as well as in a numerical simulation of the dynamics of a discharge in a wave beam.[8]

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Probe investigations of electric fields produced in air near a laser spark

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We registered two components of the electric field produced near the plasma due to breakdown of air by CO_2 laser radiation. The appearance of a rapidly alternating component with duration of the order of the duration of the laser pulse is connected with the separation of charges on the plasma front that propagates in a direction opposite to that of the laser beam. It is shown that the cause of the slowly varying component of the field is the photoeffect, induced by the plasma radiation, in the gas on the surfaces of the bodies surrounding the probe.

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In our preceding studies[1,2] we investigated signals from a differentiating electric probe located near air-breakdown plasma initiated on the surface of a conducting target. It was shown that registered signals were due not to radiation from the plasma, but to separation of the charges in the moving plasma front. The duration of these signals did not exceed the duration of the laser pulse. In the present paper we report probe measurements of the potentials φ of the electric fields near the plasma of air breakdown by radiation of a pulsed CO_2 laser on a dielectric target and in the absence of a target.

It is shown that if a "transmitting" rather than a differentiating electric probe is used (producing a signal $\propto\varphi$) there can be registered near the plasma potentials due not only to the proper electric field of the plasma produced by the optical breakdown of the air, but also

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to the electric field of the space-charge double layer produced on the surfaces of objects subjected to the action of the plasma radiation (the target, the lens, the probe, etc.). The measured values of φ can reach 10–100 V, and the growth time of the potential exceeds substantially the total duration of the laser pulse. We therefore call this electric-field component near the plasma "slowly varying" to distinguish it from the rapidly varying registered in Refs. 1 and 2.

The results permit not only a better understanding of the physics of the electric phenomena that accompany the breakdown of air by laser radiation, but also an interpretation of some results obtained when chemical explosives are used.

EXPERIMENTAL SETUP

We used in the experiment a pulsed CO_2 laser with transverse discharge and an ultraviolet pre-ionization gas mixture. The laser operated in a multimode regime with a pulse energy E up to 30 J. The total duration of the laser pulse, shown in Fig. 1, was ~2 μsec. The waveform of the laser pulse was monitored by a pyroreceiver, and the energy by a graphite disk calorimeter. The pulse has 3 clearly pronounced maxima, with ~40% of the energy concentrated in the first spike of 300 nsec duration. This pulse waveform was due to the construction of the laser, which consisted of three cells, the discharge in each of which was triggered by a separate discharger.

The radiation was guided to a metallic screened chamber, inside of which were placed an optical bench and recording apparatus. The radiation was focused with a NaCl lens of focal length 10 cm. The intensity of the laser radiation in the focal spot was 10^7-10^9 W/cm^2.

To investigate the potentials of the electric field near the air-breakdown plasma we used a probe method. The rapidly alternating component of the field was registered with a differentiating probe. It consisted of a segment of the central conductor of a 75 Ω cable, 1 cm long, placed in a dielectric jacket. A resistor $R_L = 75$ Ω was soldered between the conductor and the cable braid. The cable was connected through a broadband amplifier (U3-7A) to the input of an S8-2 oscilloscope.

In the measurement of the slowly varying component of the field we used a transmitting probe. It is constituted a segment of wire 1–2 cm long (whisker) soldered to the input of an emitter follower having a voltage trantransfer coefficient $K = 0.4$, an input resistance $R_{in} \approx 220$ MΩ, an input capacitance $C_{in} \approx 10$ pF, an output resistance $R_{out} \lesssim 200$ Ω. The output capacitance was determined by the capacitance of the cable leading to the oscilloscope, and amounted to $C_{out} \approx 100$ pF.

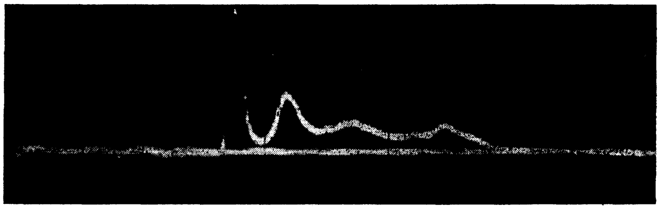

FIG. 1. Oscillogram of CO_2 laser emission pulse.

The signals from probes of this type are equal to

$$U = \begin{cases} R_{in} C \, d\varphi/dt & \text{at} \quad R_{in}(C+C_{in}) \ll T \\ C\varphi/(C+C_{in}) & \text{at} \quad R_{in}(C+C_{in}) \gg T' \end{cases} \tag{1}$$

where C is the capacitance of the probe proper, ~1 pF, φ is the potential of the field produced at the location of the probe, and T is the characteristic time of field variation.

In the case of the differentiating probe $R_{in}(C + C_{in}) \approx 10^{-8}$ sec. It was this value which determined the time resolution of the measurements, $d\varphi/dt$. For the transmitting probe we had $\tau_{in} = R_{in}(C + C_{in}) \approx 2$ msec, so that we could observe signals $U \propto \varphi$ during a time $\lesssim \tau_{in}$. The time resolution of this probe was $\tau_{out} = R_{out} C_{out} \lesssim 2 \times 10^{-8}$ sec.

Simultaneously with the probe measurements of the electric fields, we recorded the radiation pulse of the laser plasma in the band from 4000 to 4500 Å with an FÉU-29 photo-multiplier. The time resolution of these measurements was determined by the characteristics of the S8-2 oscilloscope.

RESULTS AND THEIR DISCUSSION

Figure 2 shows the signals from the photomultiplier and from a transmitting probe located at a distance $r = 4$ mm from the axis from the air-breakdown plasma initiated on the surface of a grounded aluminum target, and at a distance $z = 5$ mm from the plane of the target. The energy in the pulse was $E \approx 3$ J, the diameter of the irradiation spot on the target was $d \approx 1$ mm.

We examine now the characteristic features of these signals.

A. First, the registered field potential starts out with a negative pulse in synchronism with the laser spike, and with intense glow of the plasma. At the same time, an optical detonation wave moves opposite to the laser beam and the largest values of the plasma temperature are reached. On the front of the plasma there are appreciable gradients of the electron density and of the

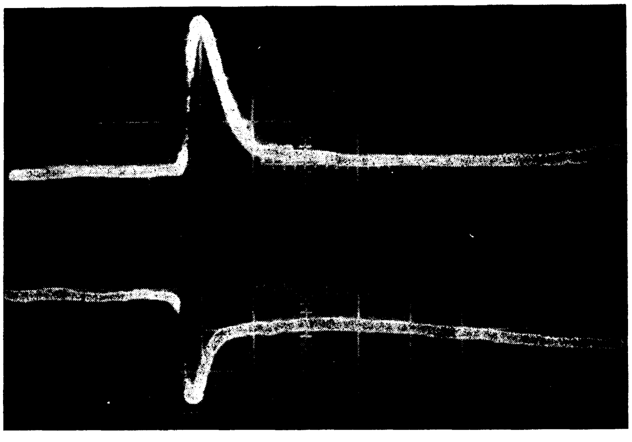

FIG. 2. Oscillograms of signlas from transmitting pulse located at a conducting target (lower trace) and of the signal from a photomultiplier (upper trace). Sweep 250 nsec/division.

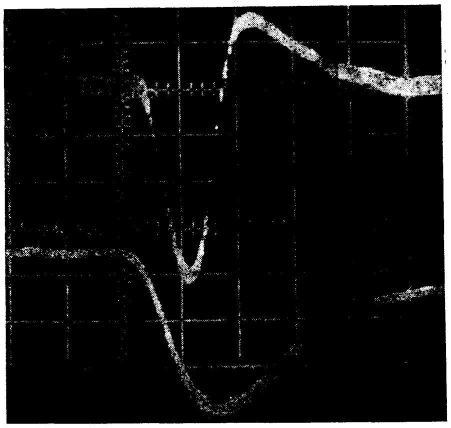

FIG. 3. Oscillograms of signal from a differentiating probe (upper trace) and of a photomultiplier signal (lower trace). Sweep 100 nsec/division.

temperature T_e. As predicted in Ref. 2, when the charges are separated on the front of the moving plasma the potential of the field at a distance $r > r_{pl}$ is given by

$$\varphi(r) \approx \frac{1}{4}\left(\frac{r_{pl}}{r}\right)^2 \frac{T_e}{e} \ln \frac{N_{e1}}{N_{e0}}, \qquad (2)$$

where r_{pl} is the radius of the plasma, e is the electron charge, and N_{e1} and N_{e0} are the concentrations of the electrons in the plasma front and ahead of the front.

The value of the field potential φ measured by the transmitting probe is in satisfactory agreement with the potential calculated from formula (2). These measurements agree also, accurate to a factor of 2, with the values of φ registered under the same experimental conditions by the differentiating probe (Fig. 3).

It also follows from (2) that $\varphi \sim T_e$, i. e., the maximum value of the field potential near the plasma should be reached at the peak laser intensity. To the same instant of time there should correspond also the maximum of the intensity of the light reradiated by the plasma, as is in fact confirmed by our measurements (Fig. 2 and 3). After the termination of the principal laser spike, the signal from the photomultipleir decreases by approximately one order of magnitude, although as its emitting surface is increased as a result of the expansion of the plasma. However, at the same time the plasma temperature T_e and its pressure decrease drastically. We note that when the sensitivity of the measuring apparatus on the $\varphi(t)$ curves were increased, we were able to observe not one but several spikes corresponding to the emission pulse shape, and the amplitude of the first spike φ was much larger.

It must be emphasized that the total duration of the plasma emission registered by the photomultiplier was in our experiments 15–20 μsec, in satisfactory agreement with the time of stopping of the "fireball" produced in the breakdown of the gas—the hot core from which the shock wave is detached.

To determine the influence of the target and of its presence in general on the signal produced during the laser pulse, we used the differentiating probe to investigate the electric fields near the air-breakdown plasma on a dielectric target and in the absence of the target. However, an analysis of the equivalent circuit in Fig. 4 shows that the probe measurements of φ have in this case peculiarities of their own. The positively charged electrode of the capacitor produced in the plasma probe is connected in this case to a zero-potential point ("ground") not directly, as in the breakdown of air on a grounded conducting target, but through a mutual capacitance C_0. Under the condition

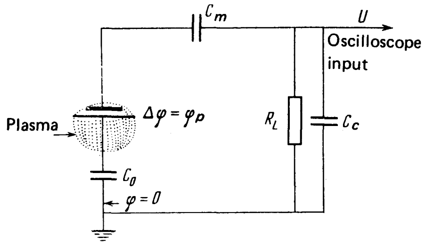

FIG. 4. Equivalent circuit of probe registration of the electric field near a laser spark in a gas.

$$R_L\left(C_c + \frac{C_m C_0}{C_m + C_c}\right) \ll T$$

the signal from the probe is

$$U = \frac{d\varphi_p}{dt} R_L C_m \quad \text{at} \quad C_0 \gg C_m \qquad (3a)$$

$$U = \frac{d\varphi_p}{dt} R_L C_0 \quad \text{at} \quad C_0 \ll C_m \qquad (3b)$$

(where C_m is the mutual capacitance between the probe and the negatively charged electrode of the plasma capacitor, φ_p is the jump of the potential on the plasma front, C_c is the capacitance of the cable leading to the oscilloscope). The case (3a) corresponds to a plasma on a conducting target, and (3b) to the breakdown plasma of pure air. The value of the observed signal U is in this case C_0/C_m times smaller than in the case (3a).

To observe near the breakdown plasma of pure air field potentials at the same sensitivity of the apparatus (it was impossible to increase it substantially because of the level of induced static), in our experiments the value of C_0 was increased by placing alongside the plasma a segment of a thin (0.2 mm diameter) grounded wire. If the wire was placed at a distance 3 mm from the axis of the laser beam and was certainly not subjected to its direct action, then the signals from the probe upon breakdown of the air near the dielectric target and in its absence were close in amplitude to the signals observed under analogous conditions near a plasma on a conducting target, and to observe the signal from the probe an important role was played not by the presence of the wire itself, but by its grounding.

B. A second feature of this signal from the transmitting probe (Fig. 2) is the presence of a slowly growing component of the field potential. The growth time of this potential correlates with the time of the total emission of the plasma, and in many cases even exceeds it by one order of magnitude, reaching 500 μsec.

We note that within the limits of the sensitivity of the measurements, the slowly varying component of the field was not registered by the differentiating probe.

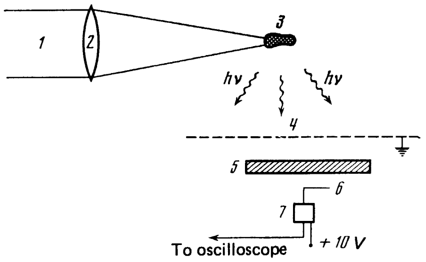

FIG. 5. Experimental setup used in the investigation of the slowly varying component of the electric field: 1—laser beam, 2—lens with $F = 10$ cm, 3—plasma, 4—screening grid, 5—charged screen, 6—transmitting probe (whisker), 7—emitter follower.

When a grounded metallic grid was placed between the transmitting probe and the target with the plasma, the rapidly varying signal vanished and the slowly varying signal in a series of control pulses remained unchanged. This grid transmitted almost completely the plasma radiation, but screened well the probe from the electric fields produced in the region between the plasma and the target.

The polarity in the amplitude of the observed signal change strongly when various objects are placed near the whisker. To eliminate these effects and for an unambiguous interpretation of the results, the probe measurements were made under conditions illustrated in Fig. 5. We used screens of different dielectrics and ungrounded metallic plates with dimensions 8×8 cm and thickness 2–10 mm, which were located at a distance 4 cm from the plasma. The distance between the whisker and the screen ranged from 2 to 30 mm. Figure 6 shows a characteristic oscillogram of the signal from the whisker located behind an ebonite screen. The intensity of the laser emission was $I \approx 10^9$ W/cm^2. The amplitude of the potential of the field observed behind the screen was $\varphi \approx 2.5$ V.

In our opinion, the cause of the slowly varying field component is the charge of the bodies surrounding the probe (in our case of the screen) due to the photoeffect induced on the surface by the plasma radiation.

Let us make a few estimates. Assume that photons with energy in the region $\hbar\omega = 6.7$ eV are incident on the screen surface; this corresponds approximately to the transparency region of air for ultraviolet photons.[3] Then electrons of energy 2–3 eV are emitted from the surface of the screen (we assume that the work function is ~4 eV). The velocity of electrons corresponding to this energy is $v_e \approx 10^8$ cm/sec. The mean free path of the electron in air is $\lambda_0 \approx 10^{-4}$ cm.[4] The average distance between the air molecules, on the other hand, is $r_0 \approx 3 \times 10^{-7}$ cm, i. e., a considerable layer of air is located between the emitted electron and the screen, and the electron begins to diffuse in this layer, while the influence of the Coulomb interaction of the electron at distances $\sim\lambda_0$ from the positive ion can be neglected. It is known[4] that, on the average, after 2×10^5 collisions the electron sticks to an air molecule. The time between the collisions and the electron with the air molecules is $\sim 10^{-12}$ sec, therefore the electron sticks to the molecules after a time $t_{st} = 10^{-7}$ sec. The most probable is the formation of O_2^- ions. There are electrons which diffuse during this time to a distance $r_{st} \approx (6Dt_{st})^{1/2} \simeq 4 \times 10^{-2}$ cm from the surface of the screen, where D is the coefficient of diffusion of the electrons in air, $D = \langle v_e \rangle \lambda_0 / 3$. The knocked-out electrons move away from the screen during the time t_{st} to a distance 4×10^{-2} cm and stick to the molecules. The produced O_2^- ions, whose diffusion is extremely small, reach the surface of the screen after a time considerably exceeding the time of observation of the signals from the probe.

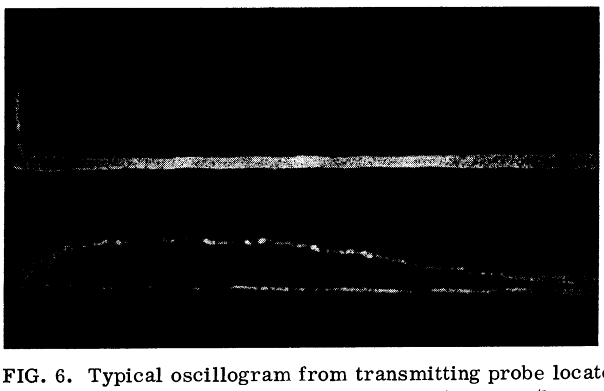

FIG. 6. Typical oscillogram from transmitting probe located behind an ebonite screen. Sweep 0.5 msec/division (lower trace). Signal from photomulitplier—upper trace.

Thus, during the entire time of observation a space-charge double layer is produced and exists near the surface of the screen. Let us estimate how many electrons must be knocked out to produce the observed signals from the probe.

Consider the field outside of the parallel-plate capacitor with a distance $r_{st}/2$ between the plates. If we assume that the whisker registered the potential of the field of the effective dipole, then, in order to have a potential $\varphi \approx 1$ V at a distance $x \approx 1$ cm behind the screen, the dipole moment must be $d = \varphi x^2 \approx 3 \times 10^{-2}$ cgs esu. This means that the charges of the dipole must have a value $Q = 2d/r_{st} = 1$ cgs esu, which is equal to 10^9 electrons. The double-layer surface itself is equal to the surface of the screen, 8×10 cm. It can be shown that the charge of the effective dipole in this case can be taken to be the charge on an area of the order of 1 cm^2. Thus, in order to cause the observed signal from the probe, 10^9 electrons/cm^2 should be knocked out from the surface of the screen. In fact, this number should be several times larger, since the negative ions are distributed over a distance $0 < r < r_{st}$ from the screen.

Let us obtain the lower bound of the number of plasma emission photons capable of producing a photoeffect from a screen located 4 cm away from the plasma. Our measurements have shown that at $I \approx 10^8$ W/cm^2 not less than 10% of the energy of the laser pulse E goes over into the plasma radiation, and in the photon energy range of interest to us (4–6.7 eV) there is contained not less than $0.01E$. In our experiments at $E \gtrsim 1$ J this produces a photon flux on the screen surface $\gtrsim 10^{14}$ photons/cm^2. This photon flux is perfectly sufficient to cause the effect observed by us, inasmuch as for most materials the quantum yield at a photon energy larger than the work function is $10^{-1}-10^{-3}$ electron/photon. It is also easy to show that the influence of the thermionic emission and field emission of the electrons can be neglected in our case.

A natural upper bound on the charge Q is the following: the resultant field between the electrodes of the double layer of the charge near the screen should not reach the breakdown value for air, $E_{br} \approx 3 \times 10^4$ V/cm. When E_{br} is approached, the blocking action of the negatively charged ion cloud on the emission of the electrons from the screen also comes into play. Estimates show that the maximum value of the charge per unit surface of the screen is $\sim 10^{10}$ electrons/cm^2. It is possible that in our experiments the surface charge was close to the limiting value.

The presence of a charge on the screen prior to the shot greatly changed the amplitude of the observed signals from the transmitting probe. As should indeed be the case in the photoeffect, in the case of dielectrics negatively charged by surface friction (for example, when an ebonite plate is rubbed with rubber on the side facing the plasma), the signal from the probe increased by one or two orders of magnitude. It appears that in this case the limiting value of the charge at which electron emission from the screen saturates has also increased, since the knocked-out photoelectron is repelled not only by the negatively charged ion cloud, but also by the charged screen. In addition, drift in the field of the screen charge is superimposed on the diffusion of the electron from the screen.

We note in conclusion that thermionic emission and photoemission from the surface of a solid target exposed to laser radiation and to the plasma of optical breakdown of a gas can lead to a separation of the charges near the surface. In turn, the field of such a parallel-plate capacitor can in many cases distort significantly the laser-spark electric field connected with the separation of the charges on the spark front.

CONCLUSIONS

The considered mechanisms for the onset of electric fields near a laser spark can be used also to explain certain characteristic features of electric signals from antennas located near centers of chemical explosions. This means that, by performing, under relatively simple conditions, experiments with plasma of optical breakdown of gases we can simulate the electric phenomena that accompany the detonations of explosives. This simulation is based on the deep analogy between a laser spark and an explosion (see, e. g., Ref. 5).

Thus, in the study of Gorshunov *et al.*[6], where a spherical charge of mass 1 kg, suspended 6 m above the earth's surface, was exploded, no signal came from an antenna located at a certain distance from the center of the explosion in the case of symmetrical initiation with fire. However, when any grouded conductor was placed near the charge, and when an electric detonator was used, antenna signals with amplitude up to 5 V were received at the same sensitivity of the apparatus. Gorshunov *et al.*[6] believe that the possible cause of the signal is the electrification of the asymmetrically dispersing explosion products. In the case of electric detonation this asymmetry is produced by the conducting leads, which influence the distribution of the charges in the explosion products. From our point of view, grounded conductors placed in the explosion zone not only change the symmetry of the problem, but also increases the capacitance C_0 in the equivalent circuit of the measurement setup (Fig. 4), and this can lead to a considerable growth of the amplitude of the recorded signal.

In addition, in blasts of explosives, just as in optical breakdown of gases, antenna signals can be produced by the photo-effect from the surrounding objects, especially during the initial stages of the explosive, when the temperature of its products is high enough and the produced plasma radiates intensively in the ultraviolet region of the spectrum.

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