criticality is observed in the perturbations of the electron concentration at the edges of the solitons. Figure 4 shows a soliton in a plasma with $\omega_p^2/\omega^2=2,5$, in which perturbations of the ion concentration, reaching values of the order of 30%, are quite noticeable. There is a plasma transcriticality limit $(\omega_p^2/\omega^2)_{\mathrm{cr}}\sim 5$ above which no solitons solutions are observed. At postcriticality close to the limiting value, there exists only a soliton with one maximum of the potential and two maxima of the transverse field.

The numerical results given an idea of the qualitative picture of the distribution of the envelope solitons of circularly polarized radiation as a function of the velocity and of the ratio of the plasma frequency to the frequency of the RF carrier.[5]

Envelope solitons exist in the limit of strongly relativistic amplitudes, but their character differs significantly from the character of the soliton solutions with small amplitude. The question of the role of such solitons in the dynamics of nonstationary wave fields still remains open. For a nonstationary wave equation of the Klein–Gordon type it follows from numerical solutions obtained by N. Zabusky (private communication) that in the case of strong nonlinearity the envelop solitons play an equally fundamental role as at small amplitudes.

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[1] See also Refs. 2 and 3.

[2] Equation (7) describes all the solutions in which the envelope of the RF field, the particle masses, and their concentrations depend only on the self-similar variable. Relation (6) determines only the most successful choice of the coordinate system in which the equation for the envelope take the simplest form. The ratio of ω to k was not fixed in Ref. 5, but a phase shift that depends on the self-similar variable was introduced in the RF carrier. The integration of the equation for the phase shift leads to a result equivalent to (6).

[3] In this approximation, the equations are valid for envelopes of waves of arbitrary polarization, and the terms that describe the relativistic and striction nonlinearities are averaged over the period of the RF field. Therefore the coefficient of x^2 changes from $\frac{1}{2}$ for circular polarization of the radiation to $\frac{1}{4}$ for linear polarization.

[4] A similar expression for the soliton amplitude can be obtained from the results of Ref. 5 by assuming that the plasma concentration is close to critical and that the soliton velocities are much smaller than the velocity of light.

[5] However, the question of the number and shape of the discrete-spectrum soliton as a function of the parameter ω_p^2/ω^2 was investigated within the framework of numerical integration of the system of equations (14).

[1] A. I. Akhiezer and R. V. Polovin, Zh. Eksp. Teor. Fiz. **30**, 915 (1956) [Sov. Phys. JETP **3**, 696 (1956)].
[2] W. Lünov, Plasma Phys. **10**, 879 (1968).
[3] W. Lünov, Plasma Phys. **10**, 973 (1968).
[4] K. A. Gorshkov, V. A. Kozlov, and L. A. Ostrovskiĭ, Zh. Eksp. Teor. Fiz. **65**, 189 (1973) [Sov. Phys. JETP **38**, 93 (1974)].
[5] N. L. Tsintsadze and D. D. Tskhakaya, Zh. Eksp. Teor. Fiz. **72**, 480 (1977) [Sov. Phys. JETP **45**, 252 (1977)].
[6] V. I. Gurovich and V. I. Karpman, Zh. Eksp. Teor. Fiz. **56**, 1952 (1969) [Sov. Phys. JETP **29**, 1048 (1969)].
[7] A. V. Gaponov and M. A. Miller, Zh. Eksp. Teor. Fiz. **34**, 242 (1958) [Sov. Phys. JETP **7**, 168 (1958)].

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Electric field of a plasma produced by optical breakdown in air

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A probe method was used to study electric fields near a plasma resulting from the breakdown of air in the vicinity of a target subjected to CO_2 laser pulses. The probe signal amplitude was determined as a function of the radiation intensity (10^7-10^8 W/cm^2) and of the distance between the probe and plasma. The appearance of the electric field in the plasma was attributed to the separation of charges in the front of an optical detonation wave. The experimental values of the field potential near the plasma were in agreement with theoretical estimates. The results of the measurements were compared with the experiments in which a plasma was created by the more powerful neodymium laser radiation.

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Explosions of chemical materials are known to create electromagnetic perturbations in the surrounding air. For example, electric signals can be detected by placing a receiving antenna some distance from the center of an explosion.[1,2] However, the origin of such signals is far from clear.

Optical breakdown in air is in many respects similar to an explosion (see, for example, Ref. 3) but it can be investigated much more conveniently. The experiments described in Refs. 4 and 5 have shown that the breakdown plasma has electric and magnetic dipole moments. A study of the electric field in a plasma jet rising from a graphite target in vacuum has been investigated using a beam of helium ions passing near the plasma.[6] According to Ref. 6, the electric field in such a plasma can reach~ 10^3 V/cm. However, it is difficult to use this method in studies of air laser plasmas because low-energy ion beams are scattered in the gas and high-energy ions are hardly deflected in electric fields generated near plasmas.

A probe method was used by us earlier to detect and measure an electric field near an air breakdown plasma.[7] We recorded a double electric peak from a bare probe placed near an air plasma which was created by neodymium laser radiation on the surface of a conducting target. The existence of the first signal was attributed to the separation of charges in the front of an optical detonation wave traveling in air during a laser pulse. The supersonic plasma expansion into the surrounding gas generated a shock wave diverging from the plasma. The second signal appeared at the moment when the shock wave front, in which the charges became separated, closed the probe-target circuit.

The present paper reports a more detailed investigation of the first signal from a probe which appeared during a laser pulse. Our experiments were carried out using CO_2 laser pulses which created an air-breakdown plasma with parameters very different from those described in Ref. 7 and helped to understand better the mechanism responsible for the generation of electric fields in a laser plasma.

Radiation was directed to a metal chamber where recording apparatus was placed and air breakdown took place. This was done to suppress stray electric signals generated during an electric discharge inside the CO_2 laser system. The duration of the laser pulses was about 250 nsec at midamplitude and their energy was up to 3 J. The shape and energy of each laser pulse were monitored by a pyroelectric detector and a disk graphite calorimeter, to which part of the laser energy was deflected. The laser radiation was focused by a BaF_2 lens (with a focal length 5 cm) on the surface of a copper target in an area of about 2 mm². When the radiation intensity was $I \sim 10^7 - 10^8$ W/cm², low-threshold breakdown of air was initiated on the target surface.[8] Our probe was a section of the central core of a 75-Ω cable which had a load resistance $R_L \approx 75$ Ω. The signal from a probe passed through a wide-band amplifier to an inverting input of an S8-2 double-beam storage oscilloscope. The signal from the pyroelectric detector was applied to the second input.

Figure 1 shows an oscillogram of a laser pulse (upper trace) and a signal recorded by a probe located vertically $z = 4$ mm above the target surface at a distance $r = 4$ mm from the laser beam axis; the plasma front traveled toward the laser beam. The probe was ~ 1 cm long and was enclosed in a insulating sheath. A similar signal was observed also as a result of breakdown of air near an insulator target and in the absence of a target.

FIG. 1. Typical oscillograms of a laser pulse (upper trace) and probe signal (lower trace). The horizontal scale is 250 nsec/div.

If a probe is in an external alternating electric field, the signal from the probe can be described by

$$U \approx R_L C \, d\varphi/dt, \tag{1}$$

where C is the probe capacitance and φ is the field potential near the probe. This formula is valid if $R_L C \ll T$, which is the characteristic time of variation of the field. In our case the probe capacitance was ~ 1 pF and the characteristic time was $\tau = R_L C \approx 7.5 \times 10^{-11}$ sec, which was considerably less than the variation period of the resultant field. It is clear from Eq. (1) that on appearance of a video electric field pulse (and potential) the probe signal should be bipolar with the same areas under the negative and positive half-waves. This was indeed observed (Fig. 1).1) The maximum potential φ was found using Eq. (1) and analyzing the probe signal with the positive polarity on the oscilloscope screen (the value of φ could be estimated also from the negative half-wave). The amplitude U of this signal was related, in agreement with Eq. (1), to the field potential by the expression φ [V] = $0.66U$ [mV].

Figure 2 gives the dependence of the amplitude of the probe signal on the radiation intensity I for various distances r from the laser beam axis and $z = 4$ mm. The dependence of the signal amplitude on r for a fixed radiation intensity $I = 3 \times 10^8$ W/cm² is shown in Fig.

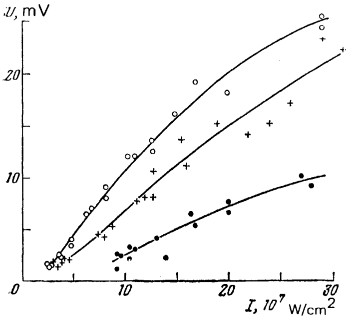

FIG. 2. Dependences of the probe signal amplitude U on the radiation intensity I for different distances from the laser beam axis r (mm): ○) 2; +) 4; ●) 6. The distance to the target was $z = 4$ mm.

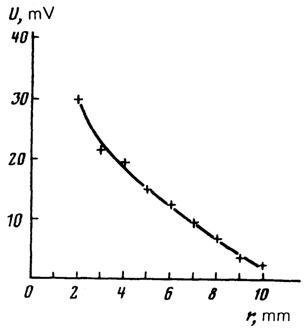

FIG. 3. Dependence of the probe signal amplitude on the distance r from the beam axis for radiation of $I = 3\times10^8$ W/cm^2 intensity.

3. We can see that for $I=$ const, the potential decreased away from the beam axis and the dependence $U(r)\propto 1/r$ for the CO$_2$ laser pulses was considerably weaker than that reported in Ref. 7. An increase in the radiation intensity from 4×10^7 to 3×10^8 W/cm^2 increased the maximum potential near the plasma from ≈ 1.5 to ≈ 20 V.

We shall now analyze the experimental results in detail. In the investigated range of radiation intensities the plasma front travels along the laser beam as an optical detonation wave. The front of this wave is characterized by considerable gradients of the electron temperature T_e and density N_e, i.e., of the electron pressure P_e. This results in a slight departure from the electrical neutrality of the plasma: if the characteristic length L in which there is a considerable rise of the electron density exceeds greatly the Debye radius of the plasma a $(L\gg a)$, the local deviation of the ion density N_i from the electron density is of the order of $\Delta(N_i - N_e)\approx (a/L)^2 N_e$. In our case we can assume that L is not less than the absorption length l_ω of the laser radiation because as long as the radiation energy is evolved in the plasma front, the electron density N_e rises. At a given radiation intensity I, the electron temperature T_e—assumed equal to the temperature of the plasma behind the front of the optical detonation wave—can be determined from the interpolation formula [9]$T_e\propto\varepsilon^{2/3}$, where ε is the specific internal energy of the plasma related to I by

$$\varepsilon=\frac{\gamma}{(\gamma+1)(\gamma^2-1)^{1/2}}\left(\frac{2I}{\rho_0}\right)^{2/3},$$

where γ is the adiabatic exponent and ρ_0 is the density of cold air. For $I=3\times10^8$ W/cm^2, we have $T_e\approx 3.7$ eV.

According to the results of Ref. 10 radiation of this intensity creates a plasma electron density $N_e\approx10^{18}$ cm^{-3}. Then, $a\approx10^{-6}$ cm, $l_\omega\approx10^{-4}$ cm, and we have $\Delta(N_i-N_e)\sim10^{-4}N_e$.

The departure from electrical neutrality in the plasma is due to the appearance, in the plasma front, of an electric field $\mathbf{E}_f$ equal to the effective hydrodynamic force acting on one electron $\mathbf{E}_f=-\nabla P_e/eN_e$, which prevents the diffusion of electrons out of the plasma. A double space-charge layer is formed in the plasma front in a distance L and then the potential discontinuity in the front or the emf of this double layer can be density of

$$\Delta\varphi\approx\frac{T_e}{e}\ln\frac{N_{e1}}{N_{e0}},\qquad(2)$$

where T_e is in electron volts; N_{e1} and N_{e0} are the electron densities in the plasma front and ahead of it. If we assume that the electron density rises by three or four orders of magnitude in the plasma front $[\ln(N_{e1}/N_{e0})\approx 7]$ for $I=3\times10^8$ W/cm^2 and $T_e\approx3.7$ eV, we find from Eq. (2) that $\Delta\varphi\approx30$ V.

If charge separation takes place in a distance L in the front of an optical detonation wave, so that a parallel-plate capacitor is formed, the dipole moment of this capacitor is $d\approx r_{pl}^2\Delta\varphi/4$, where r_{pl} is the plasma radius. The existence of this dipole moment gives rise to an electric field outside the plasma. The field potential in the region of a probe at a distance $r>r_{pl}$ is of the order of

$$\varphi\approx d/r^2.\qquad(3)$$

The measured values of the potential are in order-of-magnitude agreement with the values deduced from Eq. (3). The fact that our experiments have failed to reveal a quadratic dependence of the probe signal on the distance can be attributed to the inaccuracy of our measurements because the field varies strongly over the length of the probe itself. Moreover, the probe distorts the measured field so that measurements of this kind can only give approximate values of the field potential.

The electric field corresponding to the radiation intensity $I=3\times10^8$ W/cm^2 decreases away from the laser beam axis: $E\approx2\times10^2$ V/cm at a distance $r=2$ mm and $E\approx3$ V/cm at a distance $r=10$ mm.

The signal reported in our earlier investigation[7] is also of the same order of magnitude as the estimate given by Eq. (3).

Our experiments failed to reveal a time delay of the signal from the probe relative to the laser pulse. This shows that the electric field appears right from the beginning of evaporation of the surface layer of the target by the leading edge of the laser pulse, which precedes the low-threshold breakdown of air.[8] The electric field near the resultant plasma is recorded only during the laser pulse because the radiation heating of the plasma is asymmetric and this results in strong separation of charges, due to the electron pressure gradient, mainly in the front of an optical detonation wave. The asymmetry disappears after the end of the laser pulse and a practically homogeneous distribution of charges throughout the plasma boundary does not produce a field (and potential) outside the plasma, i.e., the electric field is localized in the plasma and the signal at the distant probe decreases rapidly. During the later stages the plasma is separated from the probe by the shock wave front whose polarization produces the second signal from a bare probe.[7]

The electric signal detected by the probe is essentially due to the mutual capacitance between the probe and a negatively charged "plate" formed in the plasma front of the capacitor. The polarity of the observed signal shows that electrons are the first to be released. A similar mechanism may also apply to the signals detected with a receiving antenna from explosions of chemical substances,[1,2] in which case there may be a capacitance between the antenna and one of the "plates" of the resultant double space-charge layer which appears in the explosion products.

The dependence of the observed electric field on the intensity and wavelength of the incident radiation is in conflict with the hypothesis that the field appears due to the asymmetry of an "ionization aureole" of the kind observed in nuclear explosions[11] or due to an electron density gradient in this aureole. Similar effects can be observed only in the case of high-temperature laser plasmas.

The emf of a double space-charge layer which appears in a plasma may give rise[12] to closed currents through the ionized gas surrounding the plasma and through the conducting target; the spatial distribution of these currents is in agreement with the measurements reported in Ref. 13 (in our experiments the target is used only to initiate breakdown of air). These currents may be responsible for the generation of magnetic fields near a laser plasma.

We shall conclude by noting that probe signals can be used also for diagnostics of breakdown plasma in pure gases and low-temperature breakdown plasmas near conducting or insulating targets, in contrast to the method proposed in Ref. 12, which can be used for diagnostics of plasmas formed by laser radiation near conducting targets in rarefied atmospheres.

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[1)] The photograph showing an oscillogram in Ref. 7 does not include the short but high negative half-wave from which the first signal begins.

[1] H. Kolsky, Nature (London) **173**, 77 (1954).
[2] L. M. Gorshunov, G. P. Kononenko, and E. I. Sirotinin, Zh. Eksp. Teor. Fiz. **53**, 818 (1967) [Sov. Phys. JETP **26**, 500 (1968)].
[3] G. V. Ostrovskaya and A. N. Zaĭdel', Usp. Fiz. Nauk **111**, 579 (1973) [Sov. Phys. Usp. **16**, 834 (1974)].
[4] G. A. Askar'yan, M. S. Rabinovich, A. D. Smirnova, and V. B. Studenov, Pis'ma Zh. Eksp. Teor. Fiz. **2**, 503 (1965) [JETP Lett. **2**, 314 (1965)].
[5] V. V. Korobkin and R. V. Serov, Pis'ma Zh. Eksp. Teor. Fiz. **4**, 103 (1966) [JETP Lett. **4**, 70 (1966)].
[6] C. W. Mendel, Jr. and J. N. Olsen, Phys. Rev. Lett. **34**, 859 (1975).
[7] I. N. Goncharov, V. I. Konov, T. M. Murina, P. I. Nikitin, A. M. Prokhorov, V. M. Sidorin, and V. A. Chudnenko, Pis'ma Zh. Eksp. Teor. Fiz. **26**, 551 (1977) [JETP Lett. **26**, 407 (1977)].
[8] V. P. Ageev, A. I. Barchukov, F. V. Bunkin, V. I. Konov, S. M. Metev, A. S. Silenok, and N. I. Chapliev, Izv. Vyssh. Uchebn. Zaved. Fiz. No. 11, 35 (1977).
[9] Ya. B. Zel'dovich and Yu. P. Raĭzer, Fizika udarnykh voln i vysokotemperaturnykh gidrodinamicheskikh yavleniĭ, Nauka, M., 1966 (Physics of Shock-Waves and High-Temperature Hydrodynamic Phenomena, Vols. 1–2, Academic Press, 1966, 1967).
[10] W. E. Maher and R. B. Hall, J. Appl. Phys. **46**, 761 (1975).
[11] A. S. Kompaneets, Zh. Eksp. Teor. Fiz. **35**, 1538 (1958) [Sov. Phys. JETP **8**, 1076 (1959)].
[12] S. L. Motylev and P. P. Pashinin, Zh. Tekh. Fiz. **48**, 742 (1978) [Sov. Phys. Tech. Phys. **23**, 436 (1978)].
[13] M. G. Drouet and R. Bolton, Phys. Rev. Lett. **36**, 591 (1976).

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