Diagnostics of the breakdown sources in the atmosphere with acoustics

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Analysis is presented of an acoustic response from a CO_2-laser pulse radiation propagation channel along an atmospheric path. It is shown that the acoustic technique makes it possible to perform a prompt diagnostics of the plasma formation efficiency in the atmosphere depending on its optical and meteorological state and on the laser pulse power.

The problem of plasma generation in the atmosphere under the action of intense laser radiation has been very urgent over a long time. It is important for studying the problem of laser radiation propagation at large distances.[1] In recent years the problem has been discussed of laser transmission of a lightning discharge along a given path.[2,3] Several physical problems were formulated,[2,3] which were important in creating the setups capable of operating in the atmosphere. Among which are the problems on laser radiation propagation through the atmosphere and the efficiency of generating highly ionized channels in the atmosphere.

To solve these problems, we need to have a method of diagnostics of the optical state of the atmosphere operating in real time and the methods for predicting the efficiency of making use of the geometric and power properties of laser radiation under specific optical and meteorological conditions in the atmosphere. The acoustic technique can be used as a diagnostic instrument of the ionization channel of a long laser spark type,[1] when the efficiency of the channel formation can be judged from a detected acoustic signal generated by plasma sources occurring at interaction of a CO_2-laser pulse with the solid aerosol particles. The formation efficiency of highly ionized channels lies in the creation of high concentration of plasma cells and their homogeneous distribution along the channel. Physical grounds for the acoustic method as an indicator of the process of interacting intense laser radiation with the aerosol particles are given in Ref. 1. To make use of this physical basis under atmospheric conditions, it is necessary to develop methods of reception, recording, and interpretation of the "sound tracks" formed by plasma cells initiated by laser beams propagated along extended atmospheric paths.

The paper describes the data on acoustic diagnostics of an extended laser spark in the atmosphere. Analyzed are the measurement results on a series of parameters of an acoustic response from the propagation path of the μs-duration CO_2 laser radiation along the near-ground atmospheric path at 4 m height above the ground. Figure 1 shows the block-diagram of the experiment. A microphone with the frequency transmission band of 20 kHz and the dynamic range ~54 dB was set at a distance about 1 m from the beam axis perpendicular to it. In acquiring the "sound track" archives the twelve-bit analog-to-digital converter at the digitization frequency of 36 kHz was used.

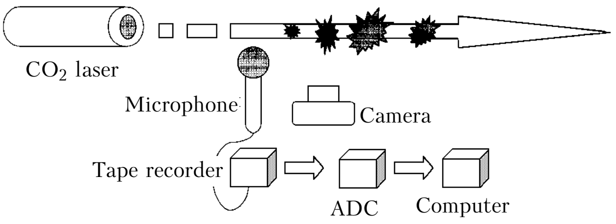

Fig. 1. Block-diagram of the experiment on acoustic diagnostics of the laser propagation along the atmospheric paths.

Figure 2 shows the time scan of acoustic response of the atmospheric channel of laser pulse propagation under different optical and meteorological conditions (OMC) in the atmosphere. The OMC with close values of the gas absorption coefficient a_g are presented to demonstrate the influence of the atmospheric aerosol component (the aerosol extinction coefficient a_a) on the occurrence of the primary breakdown sources (BS) responsible for the formation of a highly ionized channel. The quantities a_g and a_a were calculated based on the meteorological data according to Ref. 4. The dependences of optical characteristics of the atmosphere on its meteorological condition were first proposed as separate types (haze, foggy haze, etc.) in Ref. 5 and developed by other researchers.

Figure 2*a* shows the time scan of the acoustic response from the propagation path of a laser pulse with the power density at focus $E = 17.5$ J/cm^2. The reference point of time scale corresponds to "turning on" a laser pulse. The first peak corresponds to the so-called thermal signal generated due to gas heating and broadening of the propagation channel. The low-frequency component of an acoustic signal connected with the natural noises (wind, rain) was filtered out. It should be noted that further increase of the radiation power can result in

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generation of the optical breakdown cells prior to the caustic and blocking of the major part of beam power. As a result, in the focal range the development of plasma cells can be found to be less effective.

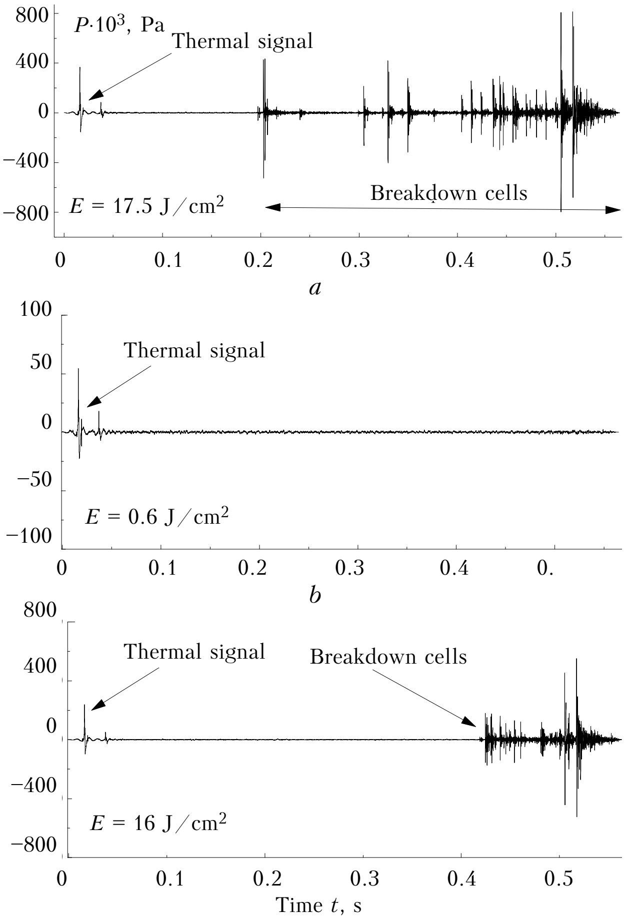

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Fig. 2. Time scan of acoustic signal from the laser pulse propagation channel under different atmospheric optical and meteorological conditions: stable summer haze: $a_g = 0.23$ km^{-1}; $a_a = 0.271$ km^{-1} (*a*); light rain, $a_g = 0.228$ km^{-1}, $a_a = 0.042$ km^{-1} (*b*), mist; $a_g = 0.216$ km^{-1}, $a_a = 0.333$ km^{-1} (*c*).

Figure 2*b* shows a “sound track” excited by a laser pulse with the energy density in the focus of 0.6 J/cm^2. From this figure we notice that no plasma cells, namely, their acoustic response, are detected. However, the problem of generation of an extended laser spark does not reduce to the increase of the laser radiation source power to obtain a stable source situation on the propagation path. Figure 2*c* shows the situation at $E = 16$ J/cm^2 that does not differ from Fig. 2*a* by the radiation power density. The distribution of the beam energy over its cross section for these starting values according to the recorded thermal acoustic signal does not differ essentially. However, one can see from the figure, that the length of the path segment filled with the breakdown cells, reduced by a factor of three and was about 30 m.

An essential difference in the acoustic responses indicates that in addition to the energy factor an important contribution to the generation of breakdown cells comes from the optical and meteorological conditions in the atmosphere. The generation of the breakdown cells primarily occurs at low humidity of the air (Fig. 2*a*). The increased moisture content in the atmosphere results in the water coating of solid phase aerosol. The water shell of such aerosols increases the time delay of the breakdown cell generation with respect to the start of a laser pulse. For values of $E \le 30$ J/cm^2 and the relative humidity $f > 85\%$ this time can increase by up to 1.5 times.[1] This results in a decrease of concentration of the breakdown cells and, hence, the efficiency of the generation of a highly ionized channel.

With the increase of radiation power and the increase of slope of the forepart, the effect of humidity on the time of the breakdown cell generation weakens or does not manifests itself at all.

The time of existence of liquid-drop aerosol on the laser radiation propagation path affects essentially on the probability of the breakdown source generation. The presence of precipitation favors the removal of the coarse aerosol fraction. In this case the particle concentration of radius ≥ 1 μm decreases significantly. The long rains are most unfavorable for the generation of the breakdown cells.

Figure 3 shows a detailed image of a thermal acoustic pulse. The duration of a positive pulse phase corresponds to the sound track time in the laser beam cross section; a heterogeneous structure of the positive phase (compression phase) is determined by the energy distribution in the laser beam cross section. It is known that the dependence of the thermal signal amplitude (as opposed to the evaporation, explosive, breakdown signals) on the incident radiation power is linear.[1] Figure 4 shows the dependence of the peak pressure of compression phase on the laser pulse power density denoted by filled circles. It can be seen from the figure that the point location on the plot does not allow definite conclusion about any, including linear, dependence. The uncertainty in the dependence is due to the inhomogeneity of the power distribution of the laser radiation in a beam, which differs essentially for different starts of the laser pulses. However, if we have a numbered acoustic analog of the light field intensity distribution over a beam (the compression phase of the acoustic pulse is 200 points), for each start the variance characterizing the beam power inhomogeneity can be calculated. The dependence of $P(E)$ with the account for a given factor is shown in Fig. 4 by open circles. It is clear that the dependence of the pressure in an acoustic pulse on the laser radiation power density obtained with the account for the inhomogeneity, determined from the thermal signal, can reliably be approximated by a straight line. Thus the acoustic measurements enable us to correct the interpretation of the results taking into account the laser beam power structure.

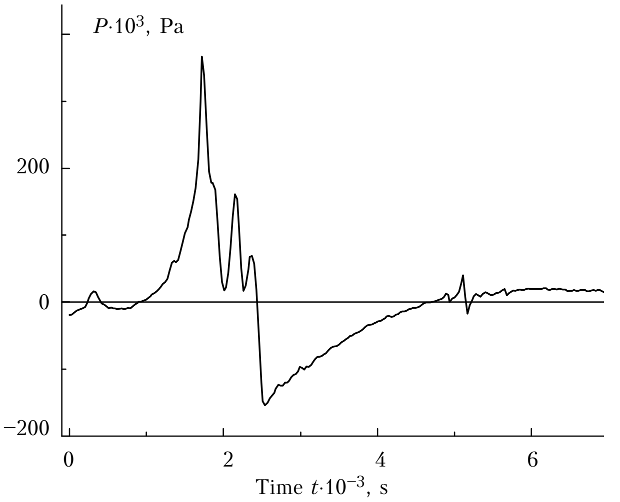

Fig. 3. Time scan of a thermal acoustic signal from the laser pulse propagation channel at E = 17.5 J/cm^2.

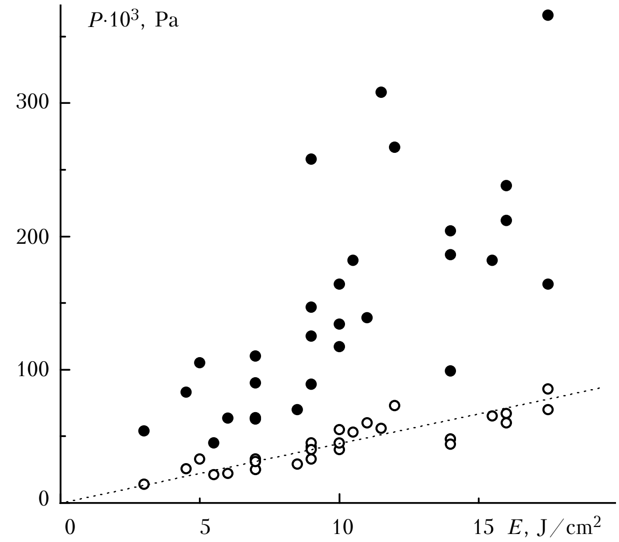

Fig. 4. Dependence of the acoustic pressure of thermal signal compression phase on the laser radiation power density.

The recorded acoustic pulses from the breakdown sources are N-wave and are accompanied by a satellite, i.e., a response reflected from the underlying surface. The distance between a signal and a satellite decreases with the increase of the distance of a plasma cell from a microphone. In the thermal regime of generation of an acoustic signal, its duration corresponds to the size of the increased pressure area, however, in case of a signal from plasma formation the direct connection is not observed. To determine the size of a plasma source, we photographed the area filled with the breakdown cells, as well as combine visual and sound series of measurements, and construct an empirical relationship between the cell size, determined using photographing, and the measured acoustic signal amplitude. This relationship serves as a nomogram for reconstructing the plasma cell size.[1] In Ref. 6 a model of a pulsating sphere was used to determine the size of the area of acoustic signal generation at explosive boiling up of an aerosol particle. Use of this technique for interpretation of a signal from optical breakdown makes it possible to estimate the size of a plasma cell based on the amplitude-time characteristics of the measured acoustic signal without recording optical signals. Figures 5 and 6 show the results obtained by the processing of acoustic response from separate plasma cells generated by CO_2-laser radiation propagated along a near-ground atmospheric path.

The data obtained were processed using specially created software package, which makes it possible to assign numerical values to a recorded sound signal and to make a necessary preparation, for example, to filter out the low-frequency atmospheric noise. The sound tracks of laser start were processed at the pulse energy density varied within E = 7–17.5 J/cm^2 under different optical and meteorological conditions in the atmosphere. The dependence of peak pressure on the duration of a positive phase of acoustic pulse of a separate breakdown source obtained earlier is presented in Fig. 5. It is apparent that the acoustic signal duration tends to the growth with the increasing peak pressure with the subsequent saturation at $P > 50 \cdot 10^{-3}$ Pa; however, a great spread of points (> 200%) does not allow one to describe quantitatively this tendency. It is assumed that such a great spread of points is a consequence of “atmospheric factor” since under laboratory conditions this spread of points was less than 15%. One of such atmospheric factors can be the frequency dependence of the sound power extinction when propagating through the atmospheric layer of different length. As the generated acoustic pulse is short, its energy spectrum is broad.

Figure 5 shows the dependence $P \sim \Delta\tau^2 \sim \lambda_s^2 \sim a^2$ where $\Delta\tau$ is the acoustic pulse duration, λ_s is the acoustic wavelength, a is the breakdown cell radius. To determine possible effect of the path length of acoustic signal propagation on the extinction of different spectral components in the signal, the path was divided into three parts (see Fig. 6). It is clear that under the action of this factor even such a minor fragmentation of the channel must result in a decrease of the data array scatter on a separate segment.

It is evident that with the increase of the signal range the duration of an acoustic pulse increases, i.e., the pulse is “broadened.” This is connected with the sound absorption in the air; high-frequency components of the signal spectrum are absorbed more heavily and for this reason the pulse “spreads.” At the same time, from a comparison of versions a, b, and c the conclusion can be drawn that the segment length of acoustic signal propagation does not affect essentially the variations of its variance that, in its turn, allows, in further processing of the results of field experiments, not to introduce the appropriate coefficients that take into account the remoteness of a breakdown cell from the acoustic signal receiver. In this case, the problem of a large variance remains a subject for a separate study.

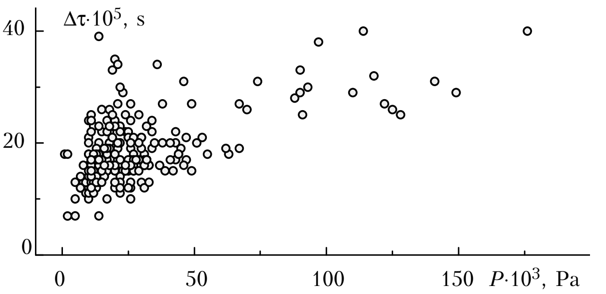

Fig. 5. Dependence of the peak pressure P of the acoustic pulse compression phase on its duration $\Delta\tau$.

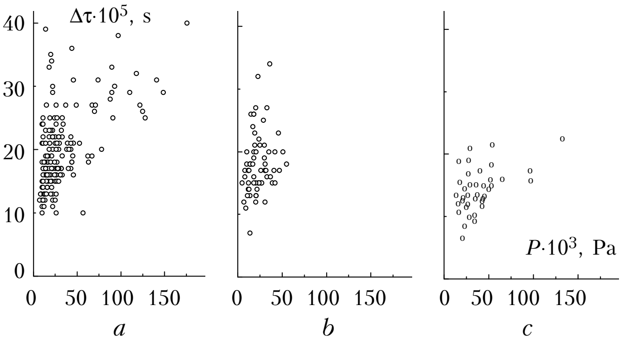

Fig. 6. Dependence of the acoustic pulse duration on peak pressure for different distances of the signal reception: 60 m $< L_3 \le 100$ m (a); 30 m $< L_2 \le 60$ m (b); $L_1 \le 30$ m (c).

The acoustic technique makes it possible to perform the detection of the plasma cells, their distribution along the laser radiation propagation path and diagnostics of the size of a separate cell. The accompanying meteorological and aerosol measurements enable us to determine the relationship between a stable development of a long laser spark and the optical-meteorological condition of the atmosphere and to formulate corresponding recommendations for the radiation power characteristics to increase the efficiency of plasma formation in the atmosphere.

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