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ACOUSTICAL MONITORING AND MATHEMATICAL MODELING OF LASER ABLATION PROCESS

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Summary. A review of experimental and theoretical results on laser – condensed matter interaction is presented with special accent on pressure signals generated in the irradiated media. The pressure signals give information about various nonequilibrium processes in the media. In the case of nanosecond laser pulses with periodically modulated intensity this information can be used to determine a movement of irradiated surface during laser pulse action.

1 INTRODUCTION

The impact of laser pulses on absorbing condensed medium leads to pressure change in the irradiated zone, which in the form of acoustic disturbances propagates into the depth of the target and into the surrounding atmosphere and can be registered with broadband piezoelectric sensors or by other means. The generation of such signals can be considered as a generalized (nonlinear) case of the photoacoustic effect, which was first observed in the nineteenth century as a generation of acoustic waves in gas due to absorption of light with variable intensity[1-3].

Acoustic diagnostics has been used for almost half a century for the study of laser action on absorbing condensed media and using it (as well as some other techniques) many interesting results were obtained, in particular concerning the non-equilibrium behavior of matter and phase transitions in the irradiated zone (see e.g. [4-49] and references therein).

Review of some experimental results on laser ablation and corresponding theoretical models is presented in the second part of this work. The third part is devoted to the effects that occur when the absorbing medium is exposed to laser pulses with a periodical modulation of intensity. Some of the (quasi-resonant) features of the evaporative pressure response to the modulation of the laser intensity have been considered theoretically in [8-9] and recently in [10-13] new possibilities for investigating laser ablation have been experimentally demonstrated with the help of periodically modulated laser intensity.

The last part offers concluding remarks.

2. BEHAVIOR OF MATTER DURING IRRADIATION BY LASER PULSES WITH SMOOTH ENVELOPE OF THE INTENSITY

In most cases, irradiation of absorbing condensed media is realized by laser pulses with a smooth envelope of the intensity. Such a regime is considered in this section, although a number of theoretical formulas containing time-dependent intensity, applies, of course, not only to smooth pulse shapes.

2.1 Photoacoustical effect

Generation of pressure is associated with a change of state of matter under the action of laser radiation. This change may be quasi-equilibrium, i.e. be in accordance with the equation of state of the substance, or non-equilibrium, even for a nanosecond laser pulse of not too great intensity. An example of such non-equilibrium changes caused by non-thermal excitation of electron subsystem is the case of exposure of silicon to laser pulses with nanosecond duration and wavelength of 1.06 microns[4]. In this case the photoacoustic pressure signal is inverted in sign compared to that realized by conventional thermal mechanism of photoacoustic signal generation in absorbing media[7,9,14].

In the quasi-equilibrium case the mechanism of the pressure generation is described by a complete system of hydrodynamic equations, which for this problem in the linear approximation is reduced to the wave equation with a source, caused by absorption of radiation, see e.g.[19].

$$\frac{1}{v_s^2}\frac{\partial^2 P}{\partial t^2}-\frac{\partial^2 P}{\partial z^2}-\frac{\beta}{c_p}\left\{\frac{\partial}{\partial z}\left[\kappa\frac{\partial}{\partial z}\left(\frac{\partial T}{\partial t}\right)\right]+\alpha\frac{\partial I}{\partial t}\right\}=0\,, \tag{1}$$

where v_s - sound velocity, β - thermal expansion coefficient, c_p - heat capacity, χ_t - thermal conductivity coefficient, α - coefficient of absorption, $I(t)$ - the intensity of absorbed laser radiation.

For the free irradiated surface and for not too rapid heating (characteristic time of heating corresponding to the laser duration τ is greater than the travel time of sound in the warm-up area: $\tau\alpha v_s > 1$), one obtains for the pressure in the area, whose dimension z^* exceeds the warm-up depth, but still is small compared to the characteristic acoustic wavelength:

$$P(z^*,t)=P(0,t)+\int_0^{z^*}dz'\int_{z'}^{z^*}\left(\frac{\partial^2 P}{\partial z^2}\right)dz=P(0,t)+\frac{\beta}{c_p}\left\{\kappa\left(\frac{\partial T}{\partial t}\right)_{z=0}+\frac{1}{\alpha}\frac{\partial I_0}{\partial t}\right\}, \tag{2}$$

where the temporal dependence of the surface temperature and its time derivatives is determined by the heat conduction equation:

$$\rho_0 c_p\frac{\partial T}{\partial t}=\frac{\partial}{\partial z}\left(\kappa\frac{\partial T}{\partial z}\right)+\alpha I\ . \tag{3}$$

In the one-dimensional approximation, this pressure pulse will propagate into the target depth and it will be registered by a pressure sensor with the appropriate time delay due finite value of sound velocity. The relative magnitude of the second and third terms in (2) depends on the absorption coefficient α: for large absorption coefficient the last term can be neglected (the case of surface absorption). In the opposite limiting case the volume character of absorption is crucial and the pressure signal becomes independent on the thermal diffusivity due to the relative smallness of the second term in (2).

The pressure at the surface of the irradiated medium $P(0,t)$ is determined by the boundary conditions, which depend on the particular physical problem. In the case of free surface without evaporation and the possibility of appearance of a plasma plume, $P(0,t)=0$, so that the pressure signal with a relatively long laser pulse is completely determined by the last two terms in (2), each of which has both positive and negative phases.

Bipolarity of the pressure signal persists also for shorter laser pulses when $\tau\alpha v_s <1$. In this case, the temporal dependence of the positive phase of the pressure signal in the linear approximation corresponds to the spatial distribution of the absorbed intensity in the irradiated material. This fact can be used to determine the absorption coefficient along the profile of the acoustic signal[14].

For the surface evaporation with a constant Mach number $M=1$ at the outside border of the Knudsen layer the value of $P(0,t)$ is approximately half that of the saturated vapor pressure $P_s(T_0)$ for the given surface temperature T_0, and the temperature in the vapor flow T is about $0.67T_0$. The value of $P(0,t)$ is determined by non-equilibrium gas-kinetic processes on the surface of evaporation and in the adjacent Knudsen layer. In contrast to the usual shock wave, the determination of the macroscopic relations at the evaporation jump can not be obtained only on the basis of conservation laws with no consideration of its non-equilibrium structure. Investigations of such boundary conditions, that use some model assumptions on the explicit form of the non-equilibrium distribution function in the Knudsen layer, or a variety of numerical methods for solving the corresponding kinetic problem, continue for many decades[53-56].

Pressure at the surface can also be determined by external reaction in the case of the loaded surface. If the irradiated surface is not free due to contact with another (transparent) medium, then the value of $P(0,t)$ is determined by solving the dual problem for the two half-spaces (or layers) with a common boundary, where appropriate boundary conditions of continuum mechanics are formulated[14,19]. In this case the temperature of the two media in the contact area may not coincide with each other due to the Kapitza jump (see e.g. [37]).

In the simplest case, when one can neglect the heat flow into the loading medium, one can obtain the following expression for the pressure at the surface of the irradiated metal. Instead of (2) the following expression for the pressure[22,23]:

$$P(t,z=0)=\frac{I(t)\beta^* c_s}{(N+1)c_P}, \tag{4}$$

where $\beta^* = \beta\left(1-4c_t^2/c_s^2\right)$, c_t - transverse speed of sound, N - the ratio of acoustic impedances of loading and absorbing media: $N=\rho c_s/\rho_g c_g$, ρ - density of absorbing medium, ρ_g - density in transparent medium, c_g - longitudinal speed of sound in transparent medium.

Pressure signals according to formula (4) at sufficiently low absorbed intensities of irradiation, were experimentally observed, for example in [21-24].

2.2 Photoacoustic signals in the case of melting of irradiated target

A special case of non-linearity is realized during the melting of material in the irradiated zone, which is accompanied by a density jump, as well as other changes in thermal and optical parameters of the substance. In the general case this problem can be solved only by numerical methods.

For the free surface the irradiated photoacoustic signal in the presence of melting was investigated theoretically as a generalized Stefan problem taking into account changes in density and other parameters of the material[9,18]. To our knowledge, experimental data that could be compared with these theoretical results are not yet available.

In the papers[22-23] photoacoustic response in the case of laser-induced melting of indium and lead at a confined surface was experimentally studied. The surface of the metal was covered with a layer of optical glass. In these experiments, there was a significant broadening of the pressure pulse (compared to the laser pulse duration), which may be associated with the formation of a layer of molten metal. However, the sharp features due to melting (kinks in the photoacoustic signals) were not detected.

The broadening of the pressure pulse was observed in[21,24] during irradiation of the mercury layer, sandwiched between the plates of optical glass, witch can be attributed to the process of explosive boiling (see section 2.4). The sharp rise in pressure also was not detected (as well as in the case of melting of lead).

2.3 Modification of pressure signals due to surface evaporation

As noted above, in the case of the free irradiated surface the value of $P(0,t)$ can be determined by the process of surface evaporation, the intensity of which very strongly depends on the surface temperature T_0 and increases rapidly with T_0 increasing. Evaporation pressure signals at the thermal photoacoustic background were observed in [7,9,49] and many other papers.

Fig. 1 shows evolution of the evaporation peak on the photoacoustic signal background with about two-fold increase of laser intensity as it was observed in[11] where absorbing liquid (water) was irradiated with erbium laser pulses (duration of 200 ns, the wavelength of 2.94 microns). It is seen that evaporation peak grows much stronger than photoacoustic signal amplitude which is approximately proportional to laser pulse intensity (note the voltage scale difference in Fig. 1 a, b.).

Evaporative peak first appears on the falling part of the photoacoustic pressure pulse near its zero value, when the surface temperature reaches its maximum during laser heating, and the process of thermal expansion gives way to contraction due to cooling. Such a difference in the behavior of the photoacoustic and evaporative pressure leads to the characteristic features of the acoustic signal behavior in the case of periodic modulation of the laser pulse intensity which is discussed in Section 3.1.

In a quasi-stationary evaporation into a vacuum or gaseous medium with low pressure at the outer boundary of the Knudsen layer the Mach number $M=1$ in vapor flow remains constant and pressure $P=P[T_0(t)]$ depends only on surface temperature T_0. The more general case with non-negligible back pressure when the value of M is less than unity and does not remain constant, requires the solution of the dual hydro-gas-dynamic problem for the condensed target material and the outer gaseous medium with the evaporation boundary conditions already mentioned above. Restriction of the free evaporation may be associated with the occurrence of plasma plume in the vapor flow. This can result in such a regime where under certain conditions[9] the evaporation process is replaced by condensation[38-41].

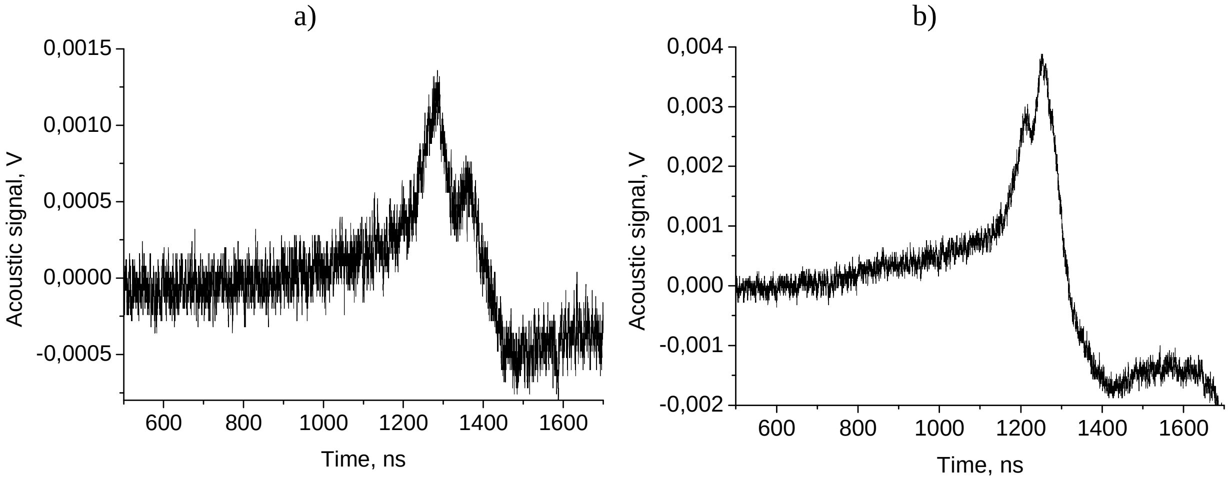

Figure 1: Photoacoustic and surface evaporation pressure signals at different laser intensities $I_b \sim 2I_a$

2.4 Explosive boiling

Since evaporation is a very energy consuming process, the evaporative cooling in the case of bulk absorption of radiation results in diminishing of surface temperature with respect to temperature maximum in the heated surface layer and formation of “cold” film at the irradiated surface (see, for example, [9] and references therein). The temperature profile in the stationary regime of evaporation is shown in Figure 2 a) as it depends on dimensionless quantity αz.

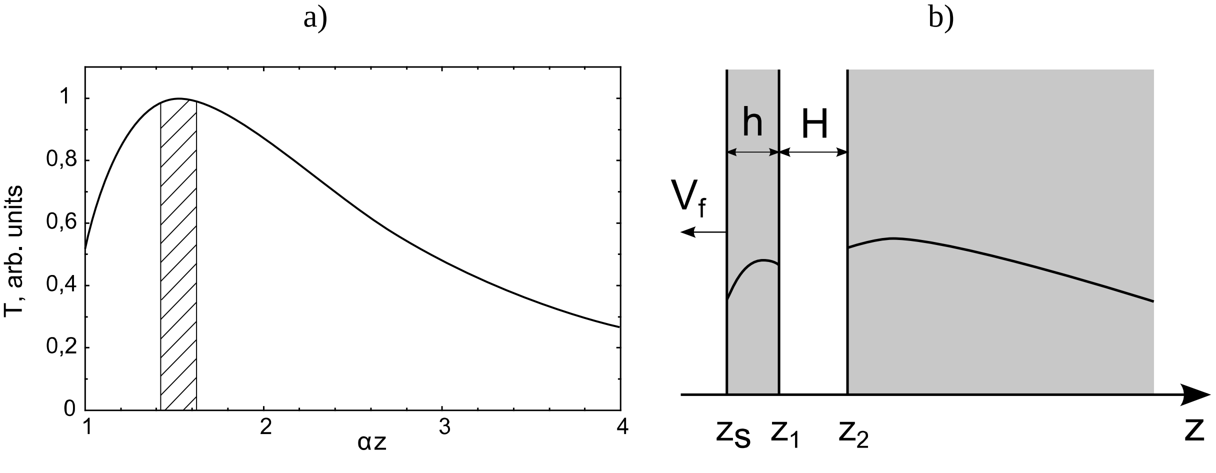

Figure 2: Spatial profile of temperature in the condensed matter for bulk absorption: a) before explosive boiling, b) during the formation of vapor cavity *H* due to explosive boiling and “cold” film *h* lift-off

Superheating in the region of the temperature maximum gives rise to the process of explosive boiling in the heated layer, which is known under different terms as phase explosion, bulk evaporation, etc. and was considered in many theoretical and experimental works[25-31]. For sufficiently long (nanosecond or longer) laser pulses the explosive boiling process can be repetitive[5, 9]. Duration of a single peak pressure in such a repetitive process may be less than a nanosecond[19]. This duration is determined by the dynamics of expanding vapor cavity H due to movement of liquid layer h with velocity V_f and temperature variation of cavity walls z_1 and z_2.

Despite decades of the explosive boiling study [25-31], repeated short pressure peaks have been observed only recently under the action of the erbium laser pulse (duration of 200 ns, the wavelength of 2.94 microns) on the water surface[11, 42]. Fig. 3 - shows pressure signals near the threshold of the short peak appearance when only two of them are observed while on Fig. 4 at somewhat greater laser intensity multiple peak structure is visible.

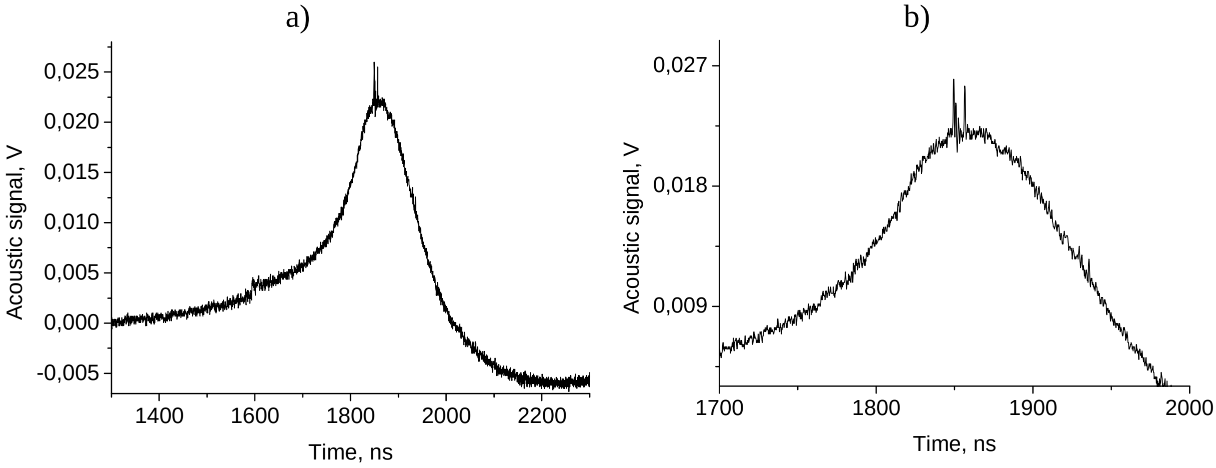
a) b)

Figure 3: Pressure signals near the threshold of the short peak appearance with two short peaks (b) is the same signal as in a) except for change in the time scale)

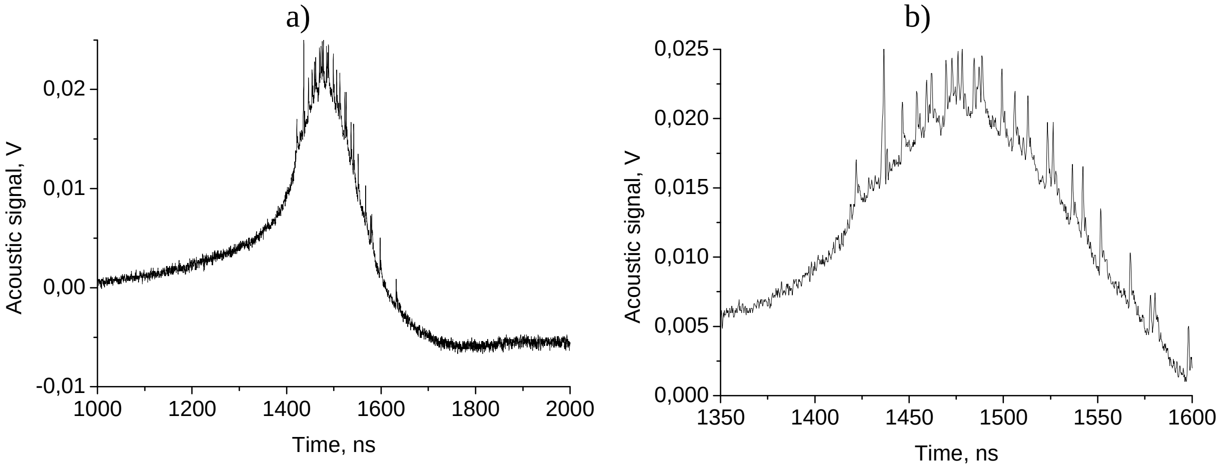
a) b)

Figure 4: Pressure signals above the threshold of the short peak appearance (b) is the same signal as in a) except for change in the time scale)

In earlier works such peaks were not observed, probably because of insufficient time resolution. It should be also minded that in the cases where the distribution of the laser radiation intensity over the spot is not constant, the individual pressure peaks can be observed only in a narrow range of the laser fluence near the threshold for this process while above this threshold the peaks registration will be difficult because of their temporal overlap.

The process of periodic explosive boiling was recorded with a microphone in air when absorbing liquid was exposed to millisecond pulses from a CO_2 laser[9]. It should be noted that an unambiguous interpretation of this experiment is complicated by the possibility of significant effect of convection in the liquid during irradiation, and insufficient time resolution of the microphone.

Short pressure peaks must also be observed during explosive boiling and subsequent lift-off of a transparent liquid film adjacent to the absorbing wafer heated by nanosecond laser pulses[37, 43]. However in these experiments pressure behavior in wafers were not measured. A theoretical analysis of similar process was carried out by molecular dynamics method[45] and using the gas-kinetic approach, taking into account the temperature dependence of the evaporation process[19-20].

Explosive boiling also should give rise to sharp pressure peaks in absorbing target immersed in transparent liquid in the case of one-dimensional regime of laser action, i.e., constant distribution of laser intensity through the laser spot.

However, in experiments of this kind[15] such pressure behavior was not observed. As mentioned above, this may be due to the limitations of temporal resolution and the variability of the intensity at the irradiation spot.

For the same reasons, probably, such a behavior was not observed also in work[24] where the laser-induced boiling of mercury confined by transparent dielectric was studied.

In work[30] the results of time-resolved dynamics of 5-nanosecond laser-induced phase explosion in aluminum are presented. The influence of vaporization and phase explosion on shock wave velocity was directly measured. A significant increase in the shock wave velocity was observed at the onset of phase explosion. However in this condition it is difficult to detect pressure variations with sub-nanosecond resolution.

2.5 Ablation (spallation) with sub-picosecond laser pulses

Creation of femtosecond lasers has allowed to realize such a mode of action, in which the energy is delivered into the substance so quickly that hydrodynamic processes in the target and a plasma plume on the irradiated surface have no time to develop. In other words, the laser pulses actually prepare the initial state of matter which subsequently undergoes expansion after the energy from the excited electronic subsystem is transferred to the lattice.

Because of the very short duration and high intensity of laser action, the amplitude of negative pressure, pertinent to bipolar photoacoustic pulses in the case of free surface, can lead to spallation of the surface layer of the target. This "cold boiling" in the unloading wave at negative pressures differs from described above usual boiling of superheated metastable liquid because in the former case spallation is mainly due to inertia of the expanding layer and not due to vapor pressure rise in the cavity.

Such spallation processes have been observed in several experiments[32-34] using optical methods of registration of irradiated surface behavior, which takes place after the laser pulse at such a time, when it is possible to use acoustic diagnostics. To our knowledge, however, such measurements have not been conducted yet.

At the same time, theoretical calculations of matter evolution after the irradiation by intense short laser pulses, including calculations of the pressure evolution, were performed using different approaches such as continuum mechanics, molecular dynamics, and its various combination[35-36,44-45].

It should be noted that the consideration of nonequilibrium phase transitions (explosive boiling, etc.), generally speaking, is beyond the scope of continuum mechanics where the continuous equation of state is used, in particular, because of the need to consider kinetic processes in the appeareang new interfaces. However, the usage of this approach[47-48] to analyze the initial stage of the evolution of matter near the thermodynamic stability limit is of some interest, particularly from the standpoint of the possible application of various computational schemes for the cases where physical system and mathematical scheme loose their stability.

3. PRESSURE SIGNALS IN ABSORBING CONDENSED MATTER IRRADIATED BY NANOSECOND LASER PULSES WITH PERIODICALLY MODULATED INTENSITY

Variation of light intensity is a necessary condition to produce photoacoustic pressure signals in absorbing media[1-3]. This fact is also clearly evident from eq. (2) which contains time derivatives of light intensity and surface temperature of irradiated media. It is evident also that laser pulse intensity can have smooth envelope or can be periodically modulated (see, e.g., [7]). In this section two effects are discussed which were observed recently in [10,12-13,42] in the case of modulated laser intensity.

3.1 Amplitude variation of pressure response due to interference of photoacoustic and surface evaporation effects

Fig. 5 shows the total modulated photoacoustic signal (a) and its decomposition to smooth (slow) and modulated (high-frequency) parts. According to (2), the envelope of the high-frequency signal component in Fig. 5 (b) approximately reproduces the shape of the smooth component of the laser pulse, and the modulation depth of the acoustic signal increases in comparison with laser intensity modulation depths in proportion to the ratio of the laser pulse duration τ_p to the modulation period τ_m. It should be noted here that the observed difference between amplitudes of slow and fast signals depends also on different acoustic extinction of these signals in water.

A remarkable feature of the curves in Fig. 5 (b) is a noticeable asymmetry between positive and negative parts of the smooth bipolar signal unlike the symmetric pattern for the high-frequency component. Such a difference can be caused by the fact that acoustic diffraction distortions of the signals depend on its characteristic frequency.

Indeed, the characteristic diffraction length of the acoustic signal $l = d^2/\lambda_s$, where $\lambda_s \sim v_s \tau_p$ and v_s are the characteristic sound wavelength and the speed of sound, respectively. Under given conditions, at squared diameter d^2 ~ 0.01 cm^2, v_s = 1.4 km/s and τ_p = 200 ns, the value l < 0.1 cm is smaller than the acoustic sensor thickness which gives main contribution to the diffraction distortions, but significantly exceeds it at τ_m = 5 ns that is shorter than τ_p. In other words, the effect of acoustic diffraction distortions should be weak for a high-frequency signal component. Exactly this is observed in Fig. 5 where diffraction distortions of the bipolar signal are noticeable only for the smooth (long-wavelength) signal component.

An increase in the laser fluence significantly changes the high-frequency component of the measured signal, as is seen in Fig. 6, 7. It is believed that such a signal behavior is caused by the manifestation of the pressure generation mechanism due to surface evaporation which leads, in particular, to mutual suppression of high-frequency components of photoacoustic and evaporation pressures.

To realize the effect of mutual compensation of the high-frequency photoacoustic and evaporation signals, these signals should be out-of-phase, i.e., the mutual compensation depth depends on the proximity of the phase shift to π. Such a phase shift can result from the following reasons. Formula (2) shows that the photoacoustic signal, which is proportional to the time derivative of the laser intensity, is phase-shifted by $\pi/2$ with respect to the modulated intensity part. If it is further assumed that the evaporation signal is proportional to the temperature change whose derivative (according to Eq. (3)) depends on the laser intensity, the phase shift for this signal will also be equal to $\pi/2$ in magnitude, but with an opposite sign with respect to the photoacoustic signal.

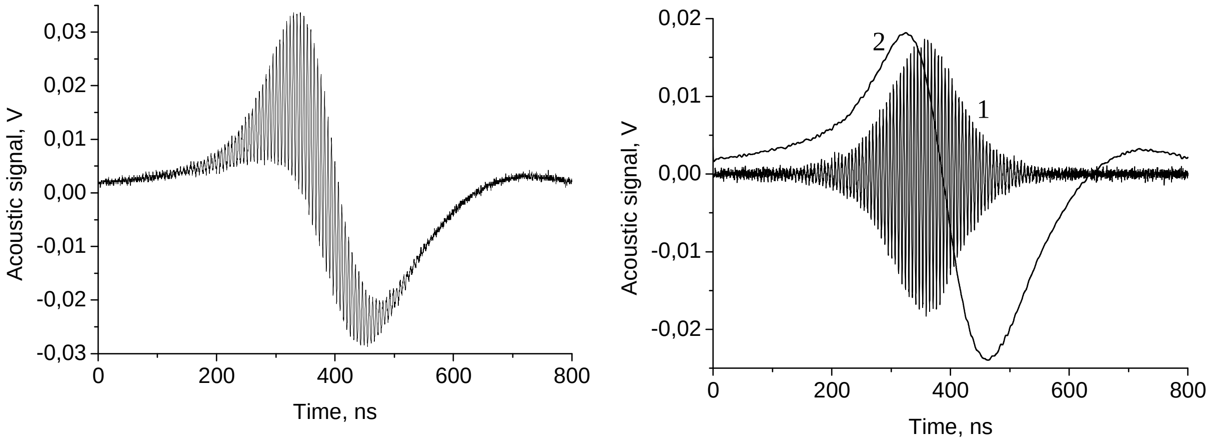
a) b)

Figure 5: Pressure response to modulated laser pulse: a – total pressure signal, b – modulated pressure component (curve 1) and slow pressure component (curve 2)

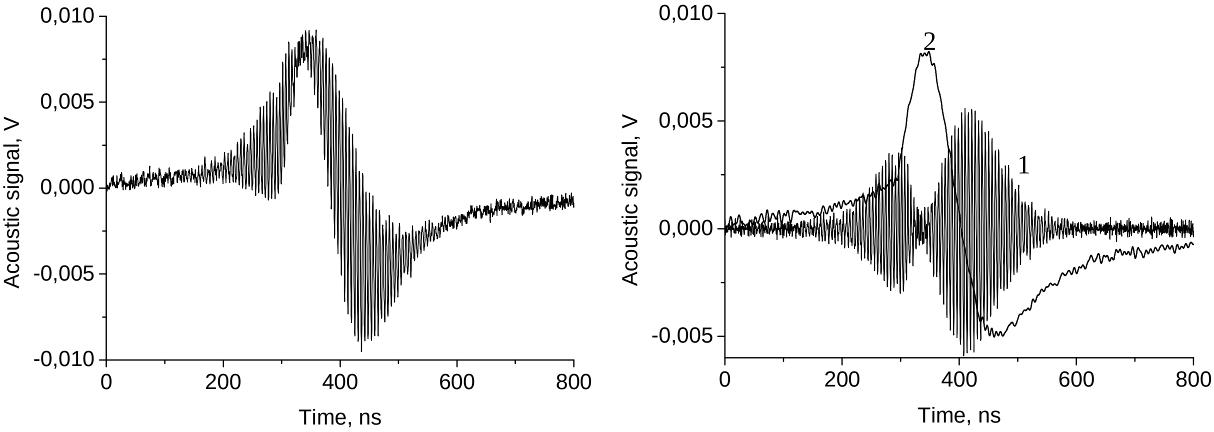
a) b)

Figure 6: Pressure response to modulated laser pulse: a – total pressure signal, b – modulated pressure component (curve 1) and slow pressure component (curve 2)

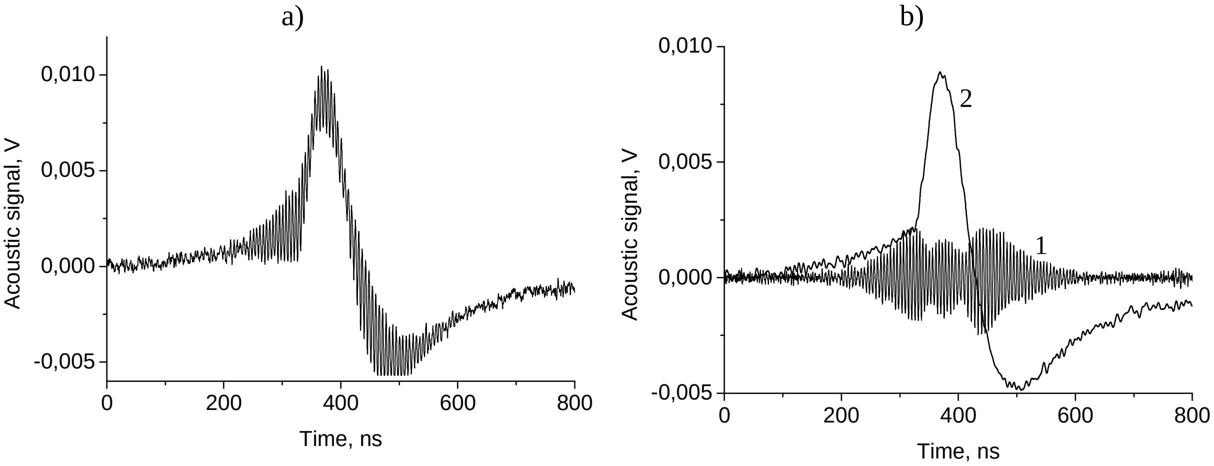

Figure 7: Pressure response to modulated laser pulse: a – total pressure signal, b – modulated pressure component (curve 1) and slow pressure component (curve 2)

As a result, the total relative phase shift is π, which just allows mutual compensation of the photoacoustic and evaporative signals, when their amplitudes become equal during an increase in laser fluence. In Fig. 6, such compensation occurs exactly near the maximum of the smooth evaporation signal. As the laser pulse intensity and corresponding evaporation signal further increase, two minima can be observed in the behavior of the high-frequency component of the sum signal, which is shown in Fig. 7. The central maximum of the envelope of the modulated component in Fig. 7 is probably mainly due to surface evaporation mechanism while the other two maximum are mainly determined by photoacoustic response with no evaporation effect.

It should be mentioned that laser intensity increases from Fig. 5 to Fig. 7 while the amplitudes of signals in Fig. 5-7 do not reflect their real relative pressure values because the radiation spot in this case was not the same in these three cases.

We recall that the evaporation signal increases much more rapidly with the intensity than the photoacoustic signal due to the strong temperature dependence of the saturated vapor pressure, which is most pronounced under non-stationary evaporation conditions.

The evaporation signal is controlled by nonequilibrium gas-kinetic processes near the surface and surface evaporation kinetics which depends strongly, in particular, on the mass accommodation coefficient γ of vapor molecules to the liquid surface and other kinetic parameters. Experimental value of γ is not well determined[50-52] and more detailed quantitative experimental and theoretical investigation of, in particular, modulated photoacoustic response can help to solve this problem.

3.2 Acoustic monitoring of irradiated surface movement

Important information about processes in the irradiation zone can be inferred also from the behavior of the acoustic signal modulation period. This period, in contrast to the laser intensity modulation period, varies during laser pulse action. It means that the zone of acoustic signal generation changes its position with respect to the transducer surface (Doppler effect). First observation of this effect in the case of periodically modulated nanosecond laser pulses was reported recently in a letter[12]. Behavior of modulated components of laser and acoustic pulses are shown in Fig. 8 which demonstrate clearly the difference between laser and acoustic modulation periods that increases to the end of the pulses.

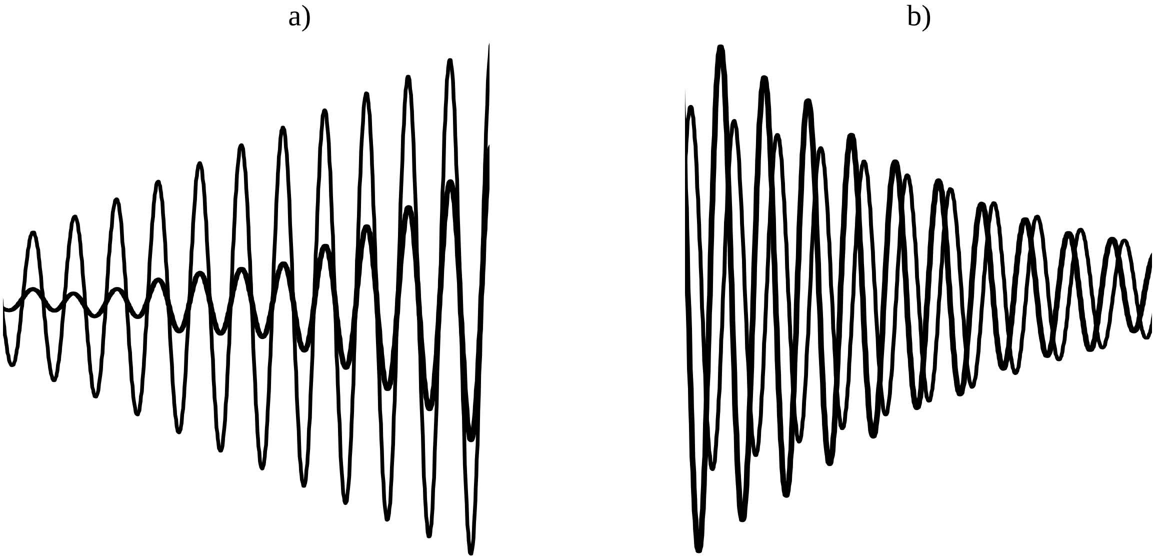

Figure 8: Laser and acoustical modulation signals at the beginning (a) and at the end (b) of the pulse

To calculate variation of the acoustic signal modulation period, the authors[12] used the expression for the time delay $t_f = t_n - n\Delta t$, which is the difference between the real-time position t_n of the nth zero point of the signal modulation component and its extrapolated value $n\Delta t$ with some fixed half period Δt determined, e.g., in the acoustic pulse beginning where the laser heating effect is small. Instead of $n\Delta t$, one can use the real positions of zero values in the laser pulse modulation component.

Evolution of discrete values of t_f during laser action on ethanol is described in Fig. 9a by continuous curve 1 A positive value of the time delay means that the liquid effective surface where the pressure signal is generated moves away from the transducer. It is believed that this movement is due to heat expansion of the irradiated liquid. The effective surface displacement $h = v_s t_f$ with ethanol sound velocity v_s = 1.2 km/s and t_f = 1,5 ns amounts to a rather large value of h ~1,8 μm. From Fig. 9b it can be also seen that modulated part of acoustic signal is practically unaffected by vaporization pressure represented by slow part of acoustic signal (curve 2). Difference in modulation amplitude behavior of laser and acoustic pulses is probably due to nonlinearity of the acoustic response

Behavior of the time delay for irradiated water in Fig. 10a is different (curve 1). The time delay t_f (and corresponding displacement $h = v_s t_f$, v_s = 1.4 km/s) changes its sign from positive to negative at the moment when the vaporization pressure (curve 2) begins to rise. For this reason, one can suggest that the effective surface displacement towards the transducer is due to a vaporization process. However, at this intensity the vaporization process does not affect the behavior of the modulated part of the acoustic signal, as is seen from Fig. 4b.

At higher laser intensities the vaporization process diminishes the modulation amplitude of the acoustic signal in water (Fig. 10 b) In accordance with Fig. 5a, the effective surface displacement $h = v_s t_f$ is about 3 μm.

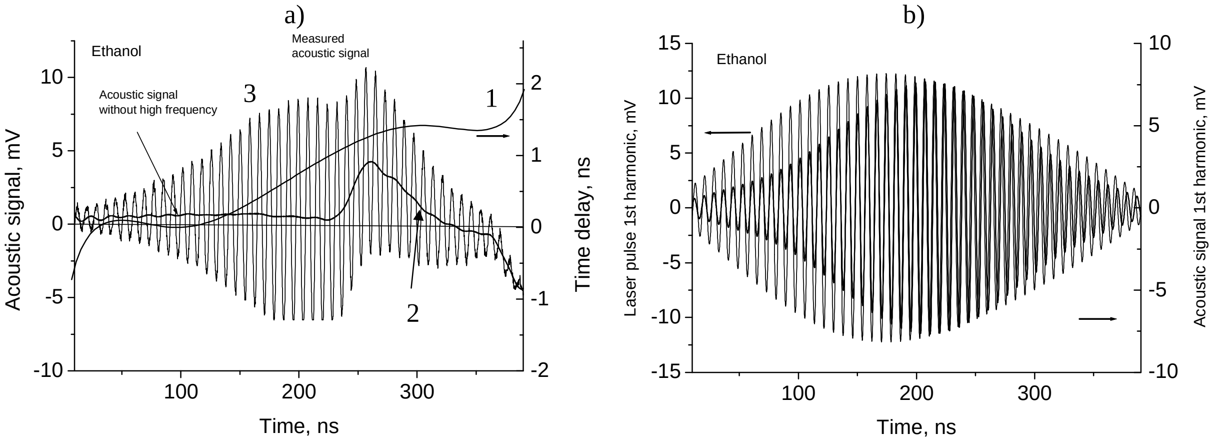

Figure 9: Pressure response to modulated laser pulse and delay time behavior (ethanol) a: curve 1 – time delay, 2 - slow pressure component, 3 – total pressure signal; b: modulated component of laser and acoustic pulses

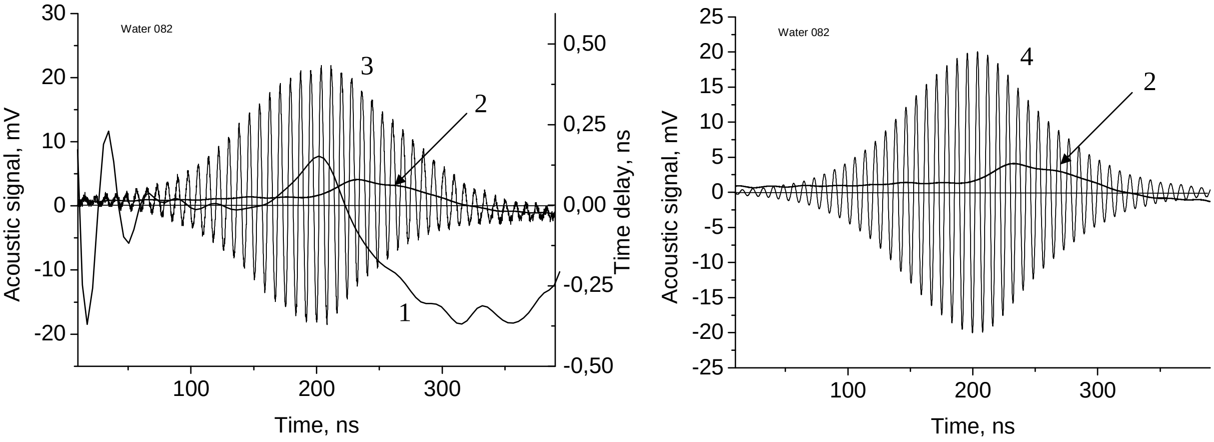

Figure 10: Pressure response to modulated laser pulse and delay time behavior (water) (curve 1 – time delay, 2 - slow pressure component, 3 – total pressure signal, 4 – modulated pressure component)

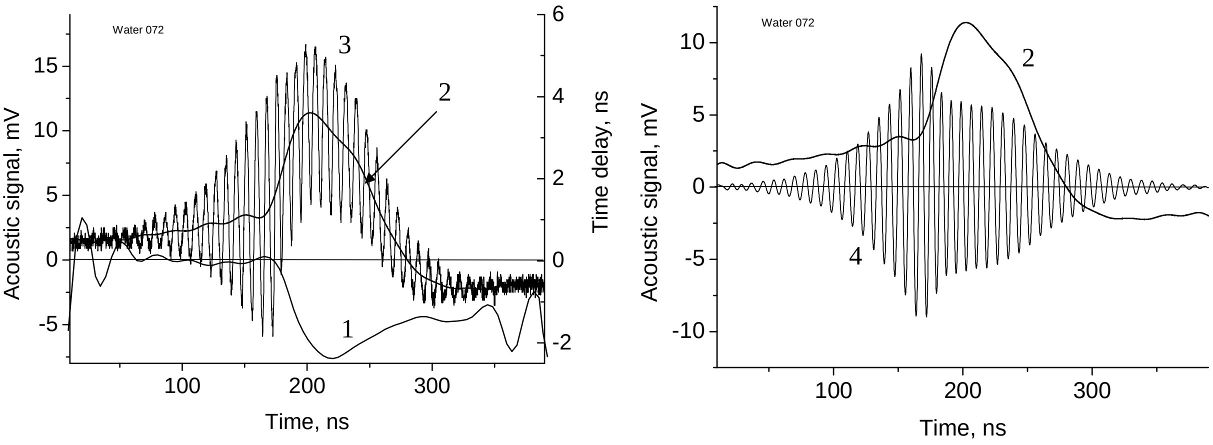

Figure 11: Pressure response to modulated laser pulse and delay time behavior (water) (curve 1 – time delay, 2 - slow pressure component, 3 – total pressure signal, 4 – modulated pressure component)

4.CONCLUDING REMARKS

After the construction of lasers with ultrashort pulses and its application to the study of laser ablation processes several new experimental results were obtained particularly concerning non-equilibrium behavior of matter at high pressure with both positive and negative values. These experiments stimulated intense theoretical research of such processes using different modes of theoretical methods and mathematical modeling.

At the same time for the nanosecond laser pulses there is a definite lack of experimental data on the dynamics of non-equilibrium melting and evaporation of matter. This fact makes it difficult to choose the adequate model for description of laser ablation in this range.

Usage of laser pulses with periodically modulated intensity opens new possibilities for experimental investigations of laser ablation in nanosecond regime. The modulation period variations in the acoustic signal give information about the irradiated surface movement which is registered simultaneously with recoil pressure behaviour.

Acoustical transducers with sub-nanosecond temporal resolution also allow to study the processes of explosive boiling which can manifest itself with (multiple) appearance of short pressure peaks at the smooth pressure envelope due to surface evaporation. Investigation of this effect can give information about critical pressure value because such peaks are observable only in subcritical evaporation regime.

Some of the results discussed in the paper were presented at the previous International seminar on Mathematical models and modeling in laser-plasma and advanced science technologies[58-62].

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