Acoustical monitoring of laser-matter interaction using nanosecond radiation pulses with periodically modulated intensity

A E Zubko[1], A A Samokhin[1], E V Shashkov[1] and N S Vorob'ev [1]

[1] Prokhorov General Physics Institute of the Russian Academy of Sciences, ul. Vavilova 38, Moscow, 119991 Russia

Abstract. Nanosecond laser ablation of metal target under the action of radiation pulses with periodically modulated intensity is investigated. Generated pressure pulses are detected by piezo-transducer (lithium niobate) on the back target side. Such approach permits to measure simultaneously recoil pressure behavior and calculate the irradiated surface displacement during laser action by comparison modulated parts of laser and acoustic signals. Nanosecond laser pulses contain 10–15 short peaks of 60 ps duration (1.08 μm wavelength) which provide fluence values up to 30 J cm^{-2} in the pulse. Plasma light emission is also registered with the help of photodiode. At the considered fluences surface displacement during the pulse turns out to be considerably smaller than theoretical estimation for free vacuum vaporization and measured experimental displacement which follows from the arrival time delay of another pressure signals generated with subsequent laser pulse directed to the same spot. Such behavior can be evidence that crater formation in the considered irradiation regime occurs after the pulse end.

1. Introduction

In ref. [1] behavior of absorbing dielectric liquids under the action of nanosecond Er-laser pulses (λ = 2.94 μm) with harmonically modulated intensity was investigated using piezo-transducer to measure recoil pressure response. It was shown that from the difference between modulated parts of laser and acoustic signal one can obtain information about irradiated surface displacement. However for metals such intensity modulation due to mode-beating is less appropriate because of interference between thermoacoustic and vaporization mechanisms of recoil pressure generation [2] than pulsed modulation obtained in mode-locking regime [3].

Experimental investigation of pressure recoil behavior in metal irradiated with such intensity modulated nanosecond laser pulses is presented in ref. [4, 5] at relatively small pulse fluences $E \lessapprox 2$ J/cm^2 when ablation effect during the pulse is also small compared with heat expansion of irradiated matter. In the present paper higher laser pulse fluences are used which permit to observe the ablation effect from the pulses.

2. Experimental setup

In the considered experiment the same laser as in [4, 5] is used which gives radiation pulses with λ = 1.08 μm and maximum duration $\Delta t \lessapprox 100$ ns consisting of short peaks (60 ps duration) divided with 8 ns intervals. Maximum pulse energy amounts to 10 mJ. To obtain higher than in [4, 5] fluences smaller spot sizes (d = 0.7 and 0.1 mm) are used. At such small spots pressure signals measured with the piezo-transducer [4, 5] are diffraction distorted so that its straightforward absolute value determination is not possible. For this reason the acoustic signal value is given only in millivolts. It should be mentioned here that absolute piezo-transducer calibration which depends also on spot size value is not necessary for surface displacement calculation. The laser pulse and plasma light are monitored with corresponding photodiodes (Avalanche photodiode and Hamamatsu C1083 PIN diode) the last of which is protected from laser light with the help of blue-green light filter strongly absorbing and relatively transparent at the wavelength λ = 0.7-1.5 μm and 0.35-0.55 μm respectively. Plasma light was directed to the photodiode (at 37 cm from the irradiation spot and angle 35°) with the help of glass lens (diameter 5 cm, F = 7 cm) which is placed at 17 cm nearer than the photodiode.

Irradiated target has the same parameters as in [4, 5] and is located on upper transducer surface with very thin water layer between the target and transducer surfaces. Two types of laser pulses striking the target at normal incidence are used with different number of peaks: 15 (spot 0.7 mm) and 10 (spot 0.1 mm). One of the series formed from the pulses striking successively the same irradiation spot (0.7 mm) consist of 38 pulses and other series (5 pulses) strike the same spot with smaller diameter 0.1 mm and different location on the surface target compared with the spot 0.7 mm.

3. Results and discussion

Fig. 1 shows behaviour of laser pulse intensity (red), acoustic response (black) and plasma light emission (blue) together with calculated as in [4, 5] displacement τ (green curve in the inserts) during laser pulse action at fluences $E \gtrapprox 3$ J/cm^2. Total number of pulses striking the same spot size with d = 0.7 mm amounts to N = 38 while in fig. 1a,b,c the numbers N = 3, 6, 30 are presented. Acoustic peaks are considerably (more than order of magnitude) wider than laser peaks due to some manufacturing shortcoming as well as principal limitation of the registration system. At the principal limitation level the difference between laser and acoustic peaks can be probably significantly lower.

Behaviour of τ is approximately the same as in ref. [4, 5] with no explicit demonstration of ablation when τ diminishes during the pulse. There is no also detectible shift between arrival times of acoustical response which correspond to different pulses as it seen from fig. 1b′,c′ on extended time scale. The arrival times (averaged) are shown in fig. 2a for all pulses N = 1–38 using integral fluence scale, where the difference $\Delta E_N = E_N - E_{N-1}$ means fluence of the pulse with number $N \gtrapprox 1$ and $E_0 = 0$. The points in fig. 2a are obtained as a result of averaging procedure over 5 neighbor initial experimental points to diminish noise scatter effect.

At $E \gtrapprox 2$ J/cm^2 laser plasma appearance is detected with photodiode as it is seen clearly from fig. 1b,c while in fig. 1a the plasma light signal is very small. From fig. 1b,c it follows also that plasma effect on fast and slow parts of acoustical response is not pronounced.

In the following experiment the spot size diameter is diminished d = 0.1 mm to obtain higher fluences E and corresponding results are shown in fig. 3a–c which is arranged in the same way as fig. 1a–c. Total pulse number in the series is N = 5 (the same as maximum number) while cases in fig. 3a–c correspond to N = 1–3 respectively. As in fig. 1a′–c′ (inserts) there is no apparent signs of ablation in fig. 3a′–c′ despite the fluences in the latter case are an order of magnitude greater than in fig. 1. However the arrival times demonstrate the decreasing delay for subsequent pulses (fig. 2b) which can be explained as crater formation in the irradiation spot. The shift in fig. 3c′ is about $\tau \approx 3$ ns compared with fig. 3a′ and it corresponds “crater depth” $h \sim c\tau \approx 6$ μm at sound velocity $c \approx 2$ km/s [4, 5] for the considered target. At N = 5 the shift $\tau \approx 5$ ns (fig. 2b) and $h \approx 10$ μm for total series fluence $E \approx 100$ J cm^{-2} (without the last pulse fluence).

From simple energy balance estimate it follows that the absorbed fluence value ε needed to ablate (vaporize) the target at the depth $h \approx 10$ μm can be found from the relation

$$\varepsilon = (C\Delta T + L)\, h \tag{1}$$

For heat capacity C = 1.6 kJ K^{-1} cm^{-3}, average temperature rise ΔT = 3000 K and latent vaporization heat L = 13 kJ cm^{-3} this estimation gives ε = 18 J cm^{-2}. This ε value can be in agreement with incident fluence E = 100 J cm^{-2} at absorption coefficient $A \approx 0.2$ though the estimation is too crude because the real (intensity modulated) pulse form is not taken into account.

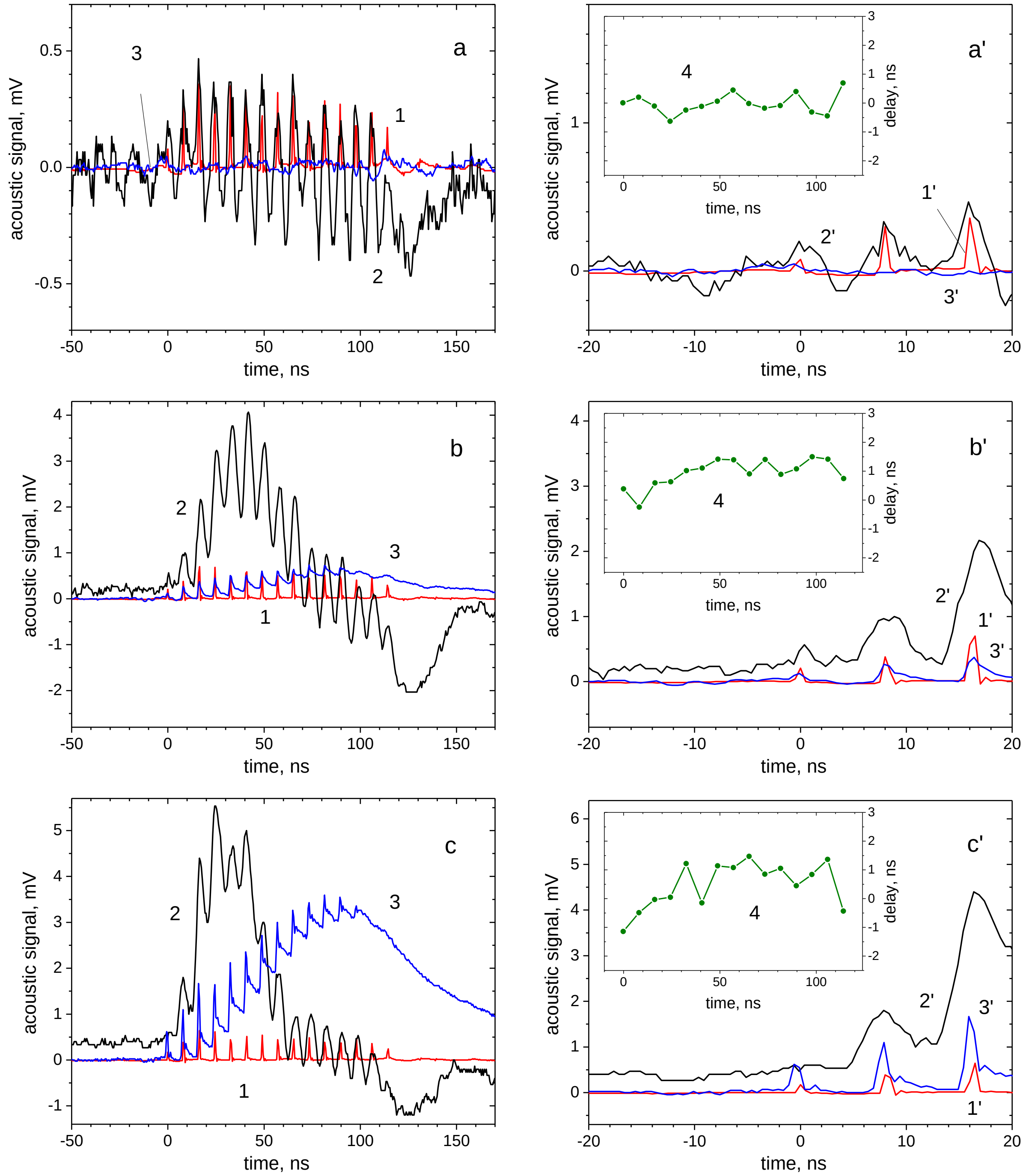

Figure. 1. Laser pulse intensity (red curves 1, 1′), acoustic pressure response (black curves 2, 2′) and plasma light emission (blue curves 3, 3′) together with calculated time delay between acoustic and laser pulse maxima (green curves 4 in the inserts) at laser pulse fluences E = 1.5 (a), 2.0 (b), 1.9 (c) J cm^{-2} with laser spot 0.7 mm.

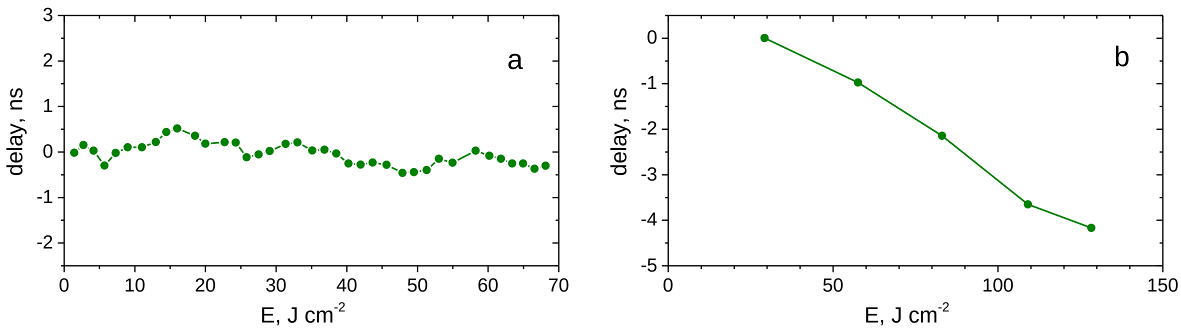

Figure. 2. Dependence of the acoustic signal time delay with respect to the initial pulse on the integral incident laser fluence *E* in a series of successive irradiations of the same area on the target surface different for the cases of laser spot 0.7 mm (a) and 0.1 mm (b).

The processes in the considered ablation regime are rather complicated. Absence of detectible displacement during irradiation pulses can be probably explained with plasma effect due to laser light absorption and inhibition of free vapour expansion. For small spot size the melt expulsion effect after the pulse end can also be significant.

It is useful to note that in ref. [6] it was concluded using experimental results [7] that the observed vaporization process during nanosecond laser ablation with irradiation spot d = 5 mm is there less intensive than it should be in the case of vaporization into vacuum because of plasma pressure effect. The same effect probably prevents intensive ablation during the laser pulse used in the present paper. Different target behavior after the pulse here and in ref. [7] is due to significant difference in irradiated spot diameters.

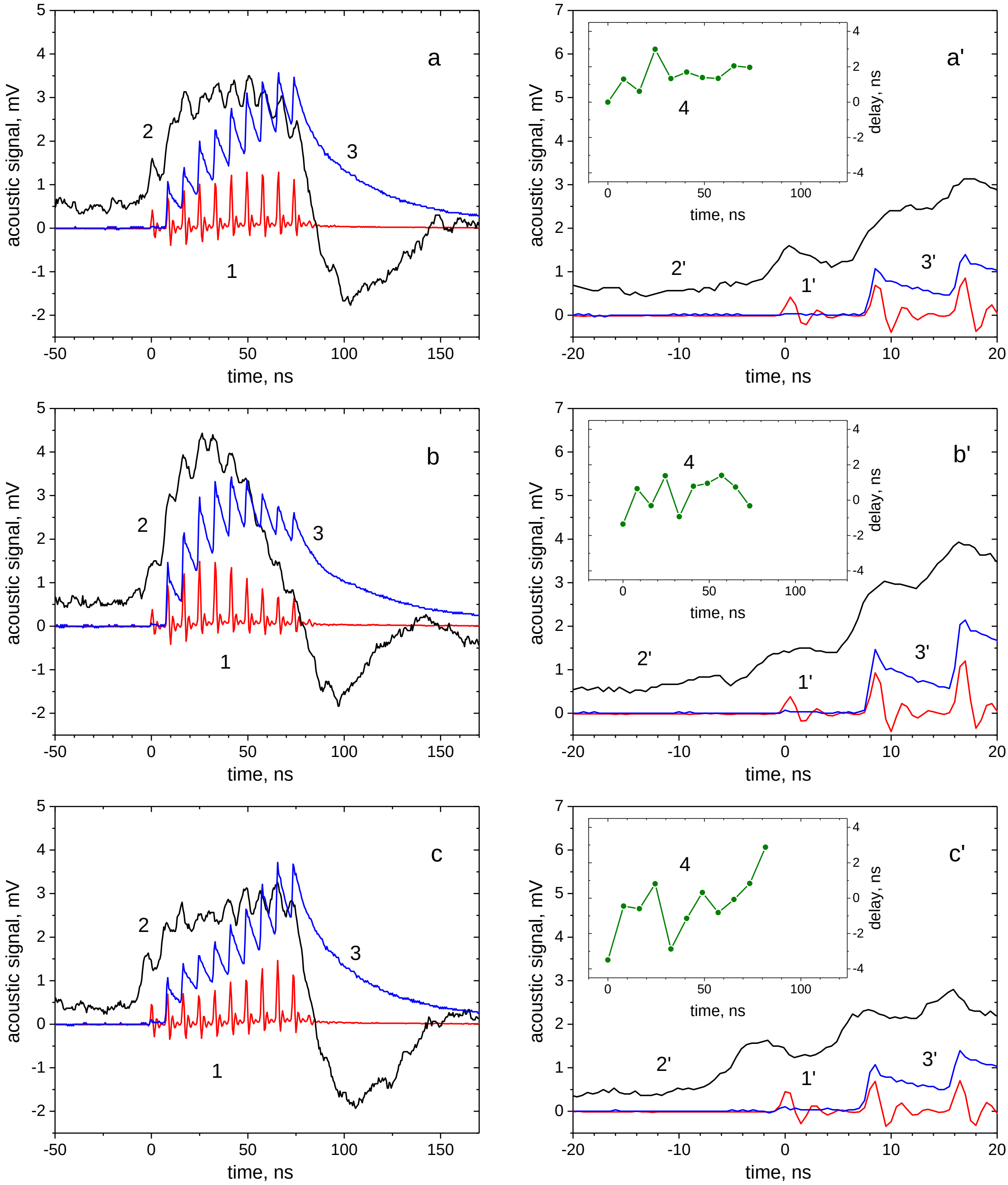

Figure 3. Laser pulse intensity (red curves 1, 1′), acoustic pressure response (black curves 2, 2′) and plasma light emission (blue curves 3, 3′) together with calculated time delay between acoustic and laser pulse maxima (green curves 4 in the inserts) at laser pulse fluences E = 29 (a, a′), 28 (b, b′), 25 (c, c′) J cm^{-2} with laser spot 0.1 mm.

4. Conclusion

The results presented in this paper demonstrate how periodically modulated laser intensity and acoustic diagnostic can be applied to obtain (together with other diagnostics) new information about nanosecond laser ablation of metals. To develop the acoustical monitoring method it is necessary to use bigger irradiation spot with flat (constant) intensity distribution over it which should provide higher time resolution and diminish acoustic diffraction effects. Such resolution should give the possibility to observe more detailed matter behaviour in its strongly non-equilibrium liquid phase state in near-critical metastable region and possible critical parameter manifestations in this conditions.

5. References

[1] Samokhin A A and Il'ichev N N 2001, *Quantum Electron.* **40**(8) 659
[2] Samokhin A A, Kudryashov S I, Zubko A E, Sidorin A V 2016 *Mathematica Montisnigri* **37** 76
[3] Zubko A E and Samokhin A A 2017 *Engineering Physics* **3** 47
[4] Samokhin A A, Shashkov E V, Vorob’ev N S, Zubko A E 2018 *JETP Letters* **108**(6) 364
[5] Samokhin A A, Shashkov E V, Vorob’ev N S, Zubko A E 2019 *Phys. Wave Phen.* **27**(1) 42
[6] Samokhin A A 1990 First-order phase transitions induced by laser radiation in absorbing condensed matter, In *Effect of laser radiation on absorbing condensed matter* (Nova Science Publishers, ed. by Fedorov V B), p 203
[7] Krehl P, Schwirzke F and Cooper A W 1975 *Journal of Applied Physics* **46**(10) 4400