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Letters to the Editor

Reflection of ultra-intense picosecond light pulse from metal target

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The dependence of specular reflectivity of a picosecond ligh pulse from a metal (Cu) target — placed perpendicularly to direction of incident light — on the light intensity in the intensity range $3\cdot10^{14}-3\cdot10^{16}$ W/cm^2 is investigated experimentally. It has been found that, contrary to the experiments with high-contrast femtosecond pulses, the reflectivity decreases as light intensity increases to the value $\sim 7\cdot10^{15}$ W/cm^2, and above this intensity the value of the reflectivity is approximately constant. A qualitative explanation of observed changes of reflectivity is provided, assuming that the interaction of the main picosecond pulse with the target is modified by a short-lasting (<1 ns) prepulse producing an expanding preplasma on the target surface.

1. Introduction

The development of ultrashort-pulse high-power lasers has made the study of laser-matter interaction on a pico- and subpicosecond time scale at very high intensities of light possible [1], [2]. In the study of this interaction, the investigations of reflection and absorption of laser light by the target are quite essential as they are an important source of information about the energetic balance and the physical features of the interaction as well. In the 1970s and 1980s the research of reflection and absorption of high-intensity laser light by solid targets was carried out with the use of nano- and subnanosecond pulses (*e.g.*, [3]). Recently, ultrashort pulses such as picosecond ones (1–2 ps, [4]–[8]) and femtosecond ones (100–400 fs, [9]–[13]) have also been used in this research. Due to generally considerably higher intensities of such pulses and a very short time of their interaction with the target, the processes of reflection and absorption of the pulse by the target are different from those with long pulses. These processes are strongly non-linear and nonsteady-state, and their dynamics depends on numerous factors, including: intensity and duration of a pulse, angle of incidence of a beam, material of a target, *etc.* Therefore, in spite of the recent intensive study of these processes, they are still relatively poorly known.

The purpose of the experiment presented in the paper was the investigation of the dependence of specular reflectivity of a high-intensity picosecond light pulse from a metal target on the light intensity. The measurements were made in $3\cdot10^{14}-3\cdot10^{16}$ W/cm^2 intensity range for the case of the Cu target placed perpendicularly to the direction of incident light. The study of reflectivity in similar geometric circumstances and intensity range was carried out for femtosecond pulses [11]–[13], whereas experiments where measurements could have been done for picosecond pulses in similar conditions are not known to us.

2. Experimental set-up

The investigations of reflection of a high-intensity picosecond light pulse from a metal target have been performed in the arrangement presented in Fig. 1. In the experiment terawatt chirped-pulse-amplification Nd:glass laser, described in detail in [14] was used. The laser generates pulses of duration $\tau \approx 1.2$ ps and intensity contrast ratio in the long-time scale ($\geqslant 1$ ns) of $\geqslant 10^8$. The short-time scale (< 1 ns) contrast ratio of the pulse is estimated to be $\geqslant 10^3$. Short-lasting (< 1 ns) background of the pulse contains a sequence of picosecond pulses whose period amounts to several tens of picoseconds and the amplitude gets smaller with the growth of time distance from the main pulse. The 85×60 mm^2 cross-section linearly polarized laser beam was focused onto a flat, polished, massive Cu target with the use of a parabolic mirror of the focal length $f = 27$ cm. The surface of the target was put up perpendicularly to the laser beam's axis. Both the target and the parabolic mirror were placed in a vacuum chamber evacuated to the pressure $\sim 5 \cdot 10^{-6}$ Torr. Besides, the chamber contained devices meant for measuring characteristics of X-rays and ion streams produced as a result of the interaction of the laser pulse with the target. The results of the measurement have been presented in the other papers of ours [15], [16].

Absolute values of the energy of light incident on the target were measured with the use of energy meter Scientech AD 30. The ratio of the energy of light incident on the target to the energy of light reflected from the target perpendicularly to the

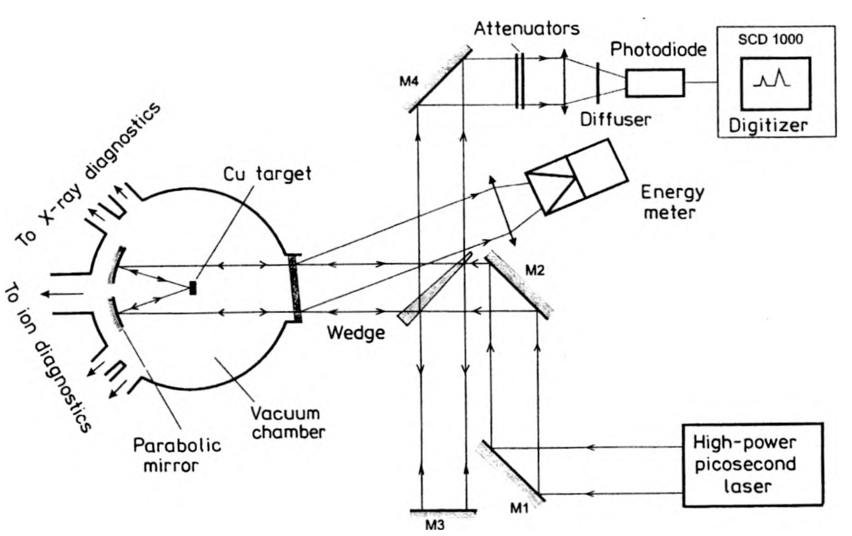

Fig. 1. Experimental arrangement for measurements of reflectivity of a high-intensity picosecond light pulse from a metal target.

target surface was measured with the use of the fast photodiode TF 1850 (response time ~100 ps) and the oscilloscope Tektronix SCD 1000 (analogue bandwidth 1 GHz, sample rate 200 GS/s). The pulses incident and reflected from the target, delayed with respect to each other by ~7 ns, were directed to a photodiode situated ~7 m from the target through the lens ($D = 10$ cm, $f = 18$ cm). Owing to this both the incident and reflected beams were fully placed in the active area of the photodiode. With the use of attenuators and a diffuser, the level of intensity of light incident on the photodiode was selected for the photodiode to work in a linear range. Specular reflectivity of the light from the target was calculated on the basis of the measurement of the amplitudes of both incident and reflected pulses, registered on the oscilloscope (with relative losses of light energy in the optical elements taken into account).

In order to investigate the dependence of specular reflectivity of the light on the incident light intensity, this intensity was changed by means of changing the energy of the pulse incident on the target (with the position of the target along the laser beam axis being set). In order to calculate the absolute value of light intensity on the target, a measurement of the size of the beam focal spot d_f^0 was performed on the photosensitive material placed in the position of the target surface. The measurement was done with small energy of the pulse, which did not make any plasma generate on the surface of the material. For calculating the focal spot size d_f with higher energy values, advantage was taken of the dependence of laser beam divergence $\Theta(E_L)$ on the pulse energy E_L measured experimentally in [14], as well as the fact that $d_f(E_L) \propto \Theta(E_L)$. It allowed us to determine the dependence of light intensity on the target on the picosecond pulse energy. The relative systematic error of the intensity calculated in this way is estimated to be $\pm 40\%$.

3. Results and discussion

Figure 2 shows some exemplary oscillograms of the incident and reflected pulses, obtained with two different intensities of light on the target. On the basis of a series of such oscillograms the dependence of specular reflectivity of the picosecond pulse

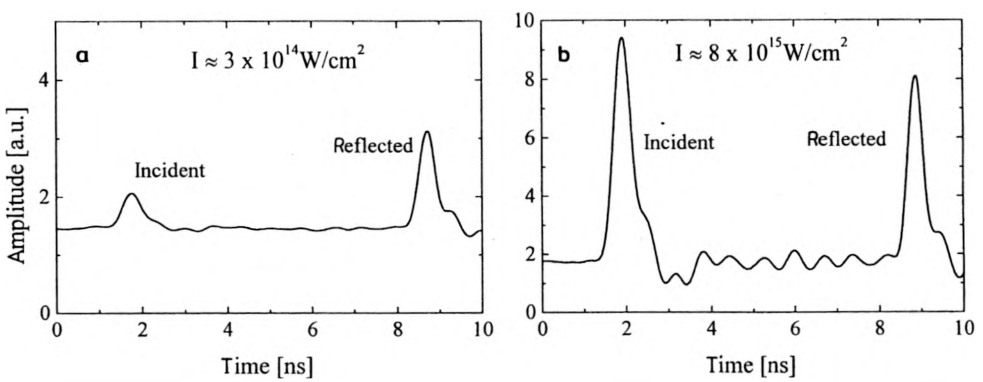

Fig. 2. Oscillograms of incident and reflected pulses at two different intensities of light on the target.

from the target on its intensity $R(I)$ was obtained. It is presented in Fig. 3. Each point in this drawing stands for a result of measurement in one laser shot. The relative systematic error for some points is indicated.

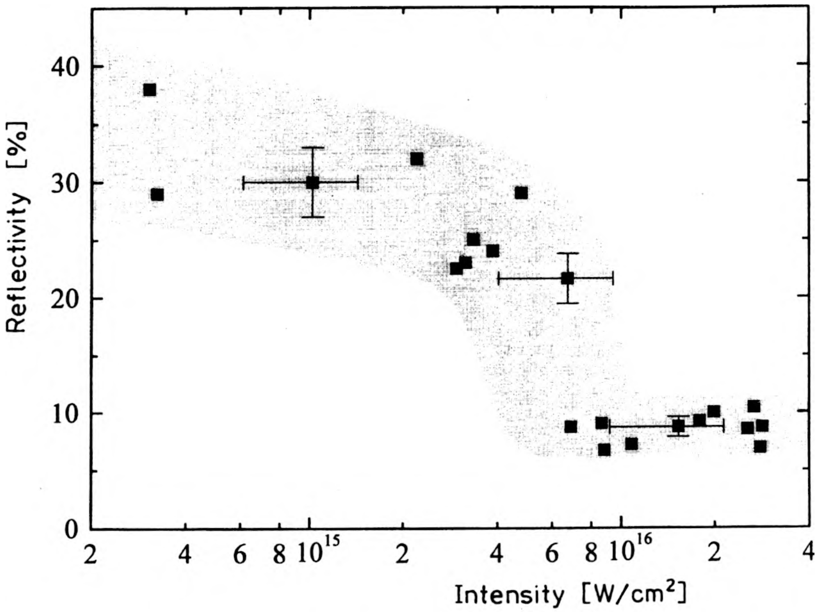

Fig. 3. Specular reflectivity as a function of light intensity on the target.

The dependence $R(I)$ presented in Fig. 3 is basically different from the dependences $R(I)$ obtained for high-intensity high-contrast femtosecond pulses [10]–[13]. In the case of femtosecond pulses, in the range $I > 10^{14}$ W/cm^2, the growth of specular reflectivity together with the growth of intensity are being observed, both for the target placed perpendicularly [11], [13] and at some angle [10], [12] to direction of the incident light. In the experiments with the picosecond pulse in [7] the fall of specular reflectivity with the growth of intensity I from 10^{16} to 10^{18} W/cm^2 for the CH target placed at the angle of 22.5° to the direction of the incident light was observed. So, the tendency was similar to that in our experiment. However, in the picosecond experiment performed with the Cu target placed perpendicularly to the laser beam [4], [5], a decrease of absorption together with increasing intensity of the picosecond pulse in the range $10^{15}-10^{16}$ W/cm^2 was observed. This suggests the possible growth of reflectivity with an increase of intensity I, thus showing an opposite tendency.

In the dependence $R(I)$ presented in Fig. 3, the following areas can be conventionally distinguished:

i) the area of relatively low intensities ($I \leqslant 10^{15}$ W/cm^2), characterized by high reflectivity (30–40%),

ii) the area of 10^{15} W/cm$^2 < I < 7 \cdot 10^{15}$ W/cm^2, where a relatively fast decrease of reflectivity with the growth of I is observed,

iii) the area of high intensities ($I \geqslant 7\cdot10^{15}$ W/cm^2), where reflectivity is roughly kept steady (8 – 10%).

Such a course of the dependence $R(I)$ can be explained on an assumption that the interaction of the main picosecond pulse with the target is modified by a short-lasting (< 1 ns) prepulse which produces expanding preplasma on the target surface. In such a case the absorption of light takes place in the plasma area of $n_e \leqslant n_c$ [5], [11], where n_e – electron density, $n_c = m_e\omega^2/(4\pi e^2)$ – critical density, m_e and e are the mass and the charge of electron, respectively, ω is the light frequency. The value of absorption and reflectivity is then determined by density gradient scale length $L_n \simeq [(1/n_e)\partial n_e/\partial x]^{-1}$, and more precisely the ratio L_n/λ, where λ is a wavelength of light [5], [11]. Most often the bigger the ratio L_n/λ, the bigger the absorption and smaller the reflectivity [5], [11].

In our experiment in the area of the intensity of the picosecond pulse $I \leqslant 10^{15}$ W/cm^2 the intensity of the prepulse is on level $I_{pre} \leqslant 10^{12}$ W/cm^2. Such a prepulse produces relatively cold plasma, thus having small speed of expansion. However, considering relatively long effective duration of the prepulse ($\sim 10^{-10}$, or slightly longer), the ratio L_n/λ is not very small (~ 1, see further), though $L_n \ll d_f$, where $d_f \sim 30$ μm is an effective size of the beam focal spot on the target. Thus the main picosecond pulse interacts with plasma with the finite but relatively sharp gradient of density and with practically flat critical density surface. This means that the contribution of radiation scattered into a large solid angle in the energetic balance is insignificant, whereas the reflection in the direction perpendicular to the target may be considerable. From comparison of the values $R \sim 30-40\%$ measured in our experiment with the dependences of absorption and reflectivity on L_n/λ calculated in [5] it is evident that in the range of intensity considered ($\leqslant 10^{15}$ W/cm^2) of the picosecond pulse $L_n \sim \lambda \approx 1$ μm. This particularly explains the fact why the reflectivity in our experiment is twice as small as that in the experiment with high-contrast 120-fs pulse [13], ($R \sim 70-80\%$ at 10^{14} W/cm^2 $< I < 10^{15}$ W/cm^2). It is so, because in the latter case the femtosecond pulse interacts with plasma of practically step-density profile ($L_n/\lambda \ll 1$), which can be treated as an ideal metallic mirror and can be described by Drude model [11], [13], [17].

The decrease of reflectivity in the intensity range 10^{15} W/cm$^2 < I < 7\cdot10^{15}$ W/cm^2 can be explained based on two reasons: the increase of density gradient scale length L_n of the preplasma and increase of the curvature of critical density surface with the increase of the prepulse intensity. The growth of L_n makes the absorption increase, whereas the curve of critical density surface leads to the scattering of a part of the radiation into a large solid angle [5], [11]. Moreover, the curve of the critical density surface may lead to the appearance of an additional mechanism of absorption, namely resonance absorption [7], [18] (due to the possibility of distinction of p-polarization in the incident beam). The increase of absorption and the contribution of scattered radiation into a wide angle automatically leads to a decrease of the contribution of specular reflection in the energetic balance.

The above mentioned mechanisms which bring about a decrease of specular reflectivity may also occur in the area of high intensities ($\geqslant 7\cdot10^{15}$ W/cm^2). In this area, however, reflectivity roughly remains at a constant level. One should expect that in this area an additional mechanism occurs which compensates for the decrease of specular reflectivity caused by the growth of L_n and the curve of the critical density surface. This mechanism is probably stimulated Brillouin scattering (SBS) producing backscattered radiation. It results from the measurements described in [7], [8] that the effectiveness of backscattered SBS grows together with the increase of intensity of a picosecond pulse and at $I > 10^{16}$ W/cm^2 backscattered energy may reach the value $\sim 5-15\%$ of incident energy. This result well corresponds with the reflectivity value obtained in our experiment. One may believe that backscattered SBS is the main reason of the observed dependence $R(I)$ in the area of high intensities.

4. Conclusions

The dependence of specular reflectivity of a picosecond light pulse from a metal (Cu) target, placed perpendicularly to direction of incident light, on the light intensity in the intensity range $3\cdot10^{14}-3\cdot10^{16}$ W/cm^2 has been investigated experimentally in this paper. It has been found that, contrary to the experiments with high-contrast femtosecond pulses, the reflectivity decreases as light intensity increases to the value $\sim 7\cdot10^{15}$ W/cm^2 and above this intensity the value of the reflectivity is approximately constant. A qualitative explanation of observed changes of reflectivity has been provided, assuming that the interaction of the main picosecond pulse with the target is modified by a short-lasting (<1 ns) prepulse producing an expanding preplasma on the target surface. A possible contribution of a backscattered SBS to the reflectivity in the high-intensity range is underlined.

The dependence of the reflectivity on the light intensity observed in our paper can be recognized as typical of the interaction, with a solid target, of pico- and subpicosecond pulses of moderate and low intensity contrast ratio. Such light pulses are particularly interesting for an efficient generation of short, intense pulses of X-ray radiation from a laser-produced plasma [19]–[21].

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