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Letter to the Editor

Direct comparison of reflectivity of picosecond and subnanosecond high-intensity light pulses from a metal target

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The specular reflectivities of picosecond and subnanosecond high-intensity light pulses from a gold target are investigated and compared. It is found that the reflectivity for a picosecond pulse is several times higher than for a subnanosecond one and that dependences of the reflectivity on light pulse energy or intensity are different for both kinds of pulses. A qualitative explanation of the observed features of reflectivity is provided.

1. Introduction

Reflectivity of light is one of the important characteristics of interaction of high -intensity laser pulse with condensed matter. Measurements of the reflectivity are particularly a source of information about mechanisms of energy transfer from light to a solid target and the energetic balance of the interaction. Therefore they have been carried on for many years for nano- and subnanosecond laser pulses (*e.g.*, [1], [2]) and recently also for pico- and femtosecond ones [3]–[9].

At high intensities of light incident on the target, when plasma is created on its surface, the process of light interaction with the target is very complex and reflectivity of light depends on numerous factors (duration and intensity of a pulse, angle of beam incidence, material of target, surface type and quality, *etc.*). For this reason, quantitative comparison of reflectivity measurements carried out in various experiments is difficult and sometimes impossible due to different experimental conditions of the measurements. Particularly, this concerns the reflectivity measurements for long (nano- and subnanosecond) and short (pico- and femtosecond) pulses, as they were performed during independent experiments in which, besides duration and intensities of the pulses, many other parameters determining the interaction process were essentially different.

In this paper, we present the results of measurements of specular reflectivity of picosecond and subnanosecond light pulses from a metal (Au) target for high intensities of light approaching $8\cdot 10^{16}$ W/cm^2 for picosecond pulses and 10^{14} W/cm^2 for subnanosecond ones. To our knowledge, they are the first direct quantitative comparison of the reflectivity of such pulses carried out in the same experimental conditions. It is shown that the reflectivity for a picosecond pulse is several times higher than for a subnanosecond one and that dependences of the reflectivity on light pulse energy or intensity are different for both kinds of pulses.

2. Experimental set-up

The investigations of reflection of picosecond and subnanosecond light pulses from a metal target have been performed in the arrangement similar to the one presented in [9], Fig. 1. In the experiment terawatt chirped-pulse-amplification Nd:glass laser, described in detail in [10], was used. With the large-aperture grating compressor the laser generates pulses of duration $\tau_L \approx 1.2$ 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 picosecond pulse was measured to be $\geqslant 5 \cdot 10^3$. 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. To investigate the target reflectivity with subnanosecond pulses ($\tau_L \approx 0.5$ ns) the pulse compressor containing the diffraction gratings (G1 and G2) was omitted by the laser beam by inserting totally reflected mirrors (M6 and M7) in the path of the beam propagation (see Fig. 1). Both in the case of picosecond and subnanosecond pulses a linearly polarized laser beam was transmitted towards the target along the same path and through the same optical components including focusing optics. Such geometry of the experiment ensured similar conditions of the measurements of the target reflectivity for both cases. The laser beam was focused onto a flat, polished, massive Au 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 axis. Both the traget 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

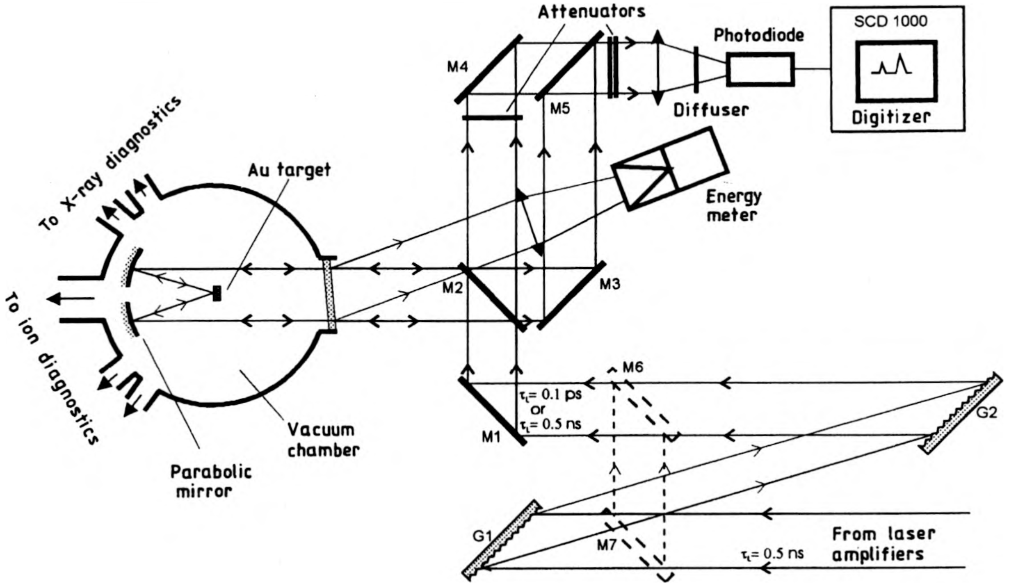

Fig. 1. Experimental arrangement for measurements of reflectivity of high-intensity picosecond and subnanosecond light pulses from a metal target. G1, G2 — diffraction gratings, M1—M7 — mirrors.

X-rays and ion streams produced as a result of the interaction of the laser pulse with the target [11]. The results of these measurements will be published in the other paper of ours.

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 target surface was maesured using the same methodology as in ref. [9]. For this purpose, the Si photodiode BPYP 35 (response time ~1 ns) and the oscilloscope Tektronix SCD 1000 (analogue bandwidth 1 GHz, sample rate 200 GS/s) were applied. The pulses incident and reflected from the target, delayed in relation each other by ~7 ns, were directed to a photodiode situated ~10 m from the target through the lens ($D = 10$ cm, $f = 18$ cm). With the use of attenuators and a diffuser, the level of intensity of light incident on the photodiodes was selected for the photodiode to work in a linear range. Specular reflectivity of the light from the target R was calculated on the basis of the measurement of the amplitudes of both incident and reflected pulses, registered on the oscilloscope. The calibration of absolute value of the reflectivity was made by comparing the amplitudes of the incident and reflected pulses with the amplitude of the pulse reflected from totally reflected mirror placed before the window of the vacuum chamber. In order to calculate the absolute value of light intensity on the target, the size of the high-energy beam focal spot was measured. This was done by registering of the image of the focal spot by CCD camera and, independently, by measuring the energy of the focused beam transmitted through diaphragms of various apertures [2].

3. Results and discussion

The comparison of specular reflectivity of picosecond and subnanosecond pulses from Au target was made for roughly the same, for both pulses, ranges of energies and sizes of the beam focal spot on the target. The influence of pulse energy as well as the beam focus position with respect to the target surface (FP) on the reflectivity was investigated. The focus position was checked with the use of an auxiliary red beam (from He-Ne laser) of angle divergence adjusted to the divergence of picosecond laser beam. Additionally, FP was checked by measuring the intensity of X-ray emission from a plasma produced by laser pulse on the target surface.

Figure 2 presents the dependence of the specular reflectivity on the focus position at fixed energy of light pulses. Each point in the figure is an average value of the reflectivities measured in several (2–6) laser shots. The focus position $\mathrm{FP} = 0$ is defined as a position where the focus of the auxiliary red beam is placed on the target surface. The X-ray measurements showed that in the case of a picosecond pulse the position $\mathrm{FP} = 0$ corresponds to the highest intensity of hard X-ray emission, so $\mathrm{FP} = 0$ can be identified with a position of the highest intensity of light on the target surface. For subnanosecond pulse the highest emission of hard X-rays was observed at $\mathrm{FP} = -0.3$ mm, thus, it is this a position that should be identified with a position of the best focusing (in the case of subnanosecond pulse the red beam was adjusted to the main beam only roughly). As can be seen from Fig. 2, the specular reflectivity for picosecond pulse is 2–4 times higher than the one for subnanosecond pulse. Moreover, the highest reflectivity takes place for the position of the best focusing ($\mathrm{FP} = 0$ for picosecond pulse and $\mathrm{FP} = -0.3$ mm for subnanosecond pulse).

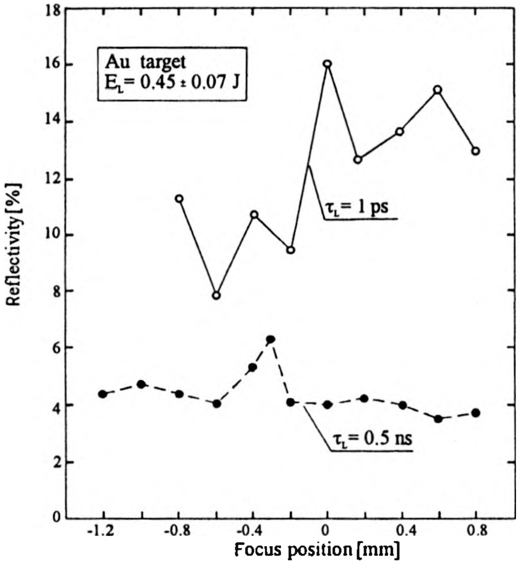

Fig. 2. Specular reflectivity as a function of laser beam focus position with respect to the target surface.

Figure 3 presents the dependences of specular reflectivity R on energy E_L of picosecond and subnanosecond pulses at $\mathrm{FP} = 0$. The corresponding ranges of variations of light intensities for both kinds of pulses are also shown. For subnanosecond pulses the reflectivity changes weakly with E_L and the tendency to rise in $R(E_L)$ may be noticed. For picosecond pulses the reflectivity decreases with E_L.

To understand the reflectivity behaviour presented in Figs. 2 and 3, it will be useful to realize that reflectivity of a plasma mirror produced on the target surface depends particularly on (*e.g.*, [4], [5]):

– density gradient scale length $L_n \approx [(1/n_e)\partial n_e/\partial x]^{-1}$, and more precisely the ratio L_n/λ (where n_e is the electron density and λ is a wavelength of light); most often the bigger the ratio L_n/λ, the bigger the light absorption and the smaller the reflectivity [4], [5];

– plasma electron temperature T_e; in the case where collisional absorption dominates (the case of our experiment) a growth of T_e leads to a decrease of light absorption (roughly as $T_e^{-3/2}$) and an increase of the reflectivity [5];

– a curvature of the surface of critical density $n_e = m_e\omega^2/(4\pi e^2)$, where m_e and e are the mass and the charge of electron, respectively, and ω is the light frequency;

– non-linear processes such as stimulated Brillouin scattering (SBS), stimulated Raman scattering (STS) and others.

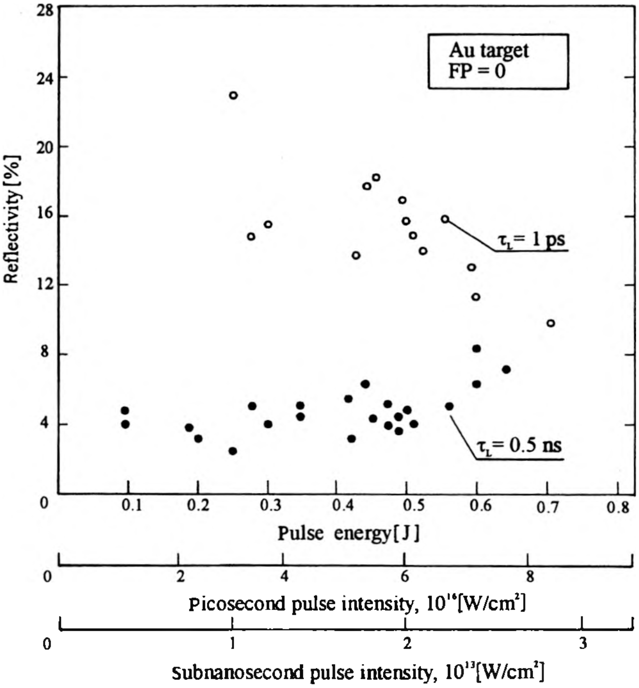

Fig. 3. Specular reflectivity as a function of light pulse energy.

For rough estimation of the density gradient scale length averaged during the interaction of a laser pulse with the target $\bar{L}_n$ is justified to assume that $\bar{L}_n \sim \bar{v}_{exp} \cdot \Delta t$ [5], where $\bar{v}_{exp}$ is an averaged velocity of plasma expansion and Δt is the effective time of interaction. As results from our measurements of plasma expansion velocity made with the use of ion diagnostics, for subnanosecond pulse $\bar{v}_{exp} \sim (2-6) \cdot 10^7$ cm/s. Taking $\Delta t \sim \tau_L \approx 0.5$ ns (τ_L is the laser pulse duration), we obtain $\bar{L}_n \sim (100-300)\lambda$. For picosecond pulses our measurements gave $\bar{v}_{exp} \sim (1.5-4) \cdot 10^7$ cm/s and at $\Delta t \sim \tau_L \approx 1$ ps we have $\bar{L} \sim (0.15-0.4)\lambda$. However, in the case of a picosecond pulse the prepulse on the target surface forms a cold preplasma and the main picosecond pulse can interact with the preplasma. Due to the low intensity of the prepulse ($I_{main} \geqslant 5 \cdot 10^3 I_{pre}$) expansion velocity of the preplasma is low and it is reasonable to assume that $\bar{v}_{exp} \leqslant (10^5-10^6)$ cm/s. Taking the time of preplasma expansion before arrival of the main pulse equal $\Delta t \sim 10^{-10}$ s, we obtain $\bar{L}_n \leqslant (0.1-1)\lambda$. Thus, for a picosecond pulse $\bar{L}_n \leqslant \lambda$ for both cases and $\bar{L}_n$ is by two orders of magnitude less than for a subnanosecond pulse. Since the average electron temperature of picosecond plasma is comparable or slightly lower than that of subnanosecond plasma (which results from comparison of the velocities of plasma expansion), the distinctly higher specular reflectivity for a picosecond pulse than for a subnanosecond one is most probably due to the considerably smaller density gradient scale length of picosecond plasma. Another reason can be smaller curvature of a critical density surface of the picosecond plasma (the surface where reflection actually takes place), whereas during picosecond pulse interaction the plasma expands only to the distance of $l_{exp} \leqslant 1$ μm, much less than the size of the focal spot $d_f > 10$ μm. Thus, the critical density surface for a picosecond pulse is almost flat. For a subnanosecond pulse $l_{exp} > d_f$ and the curvature of the critical density surface is considerable. As a result, a relatively big portion of light can be scattered into a large angle.

The highest specular reflectivity observed for FP corresponding to the best focusing, both for picosecond and subnanosecond pulses, can be explained by the fact that in such a focus position the electron temperature of plasma is the highest. A relatively weak dependence of specular reflectivity on focus position is probably related to the fact that the decrease of the electron temperature with increasing size of the focal spot on the target surface is compensated in part by decreasing both the density gradient scale length and the curvature of the critical density surface (especially in the subnanosecond pulse case).

We try to explain the different behaviour of the dependence $R(E_L)$ for picosecond and subnanosecod pulses (Fig. 3) taking again into account the difference in the density gradient scale length for both cases. Generally, growing E_L leads to an increase in L_n [4], so a decrease in R versus E_L can be expected. However, the growth of E_L also leads to an increasing in electron temperature which is a factor enhancing the reflectivity. In the case of a picosecond pulse $L_n \leqslant \lambda$. For such values of L_n variation of L_n in the vicinity of λ causes rapid changes of R [4]. These changes in R cannot be compensated by variations of T_e which are not very significant in the range of E_L under investigation. As a result, we observe a decrease of value R with growing E_L. In the case of subnanosecond pulse $L_n \gg \lambda$ and changes of L_n due to increasing of E_L do not cause any noticeable variation in the reflectivity. In this case, the influence of T_e on R can be more significant than L_n and it can lead to the growth of value R.

The effect of non-linear scattering phenomena on the reflectivity values measured in our experiment is not clear enough. Generally, an increase of the incident light intensity leads to the growth of the intensity of backscattered light due to SRS and SBS. For a subnanosecond pulse, because of its relatively low intensity (Fig. 3), the SRS is unlikely to occur and the influence of SBS is expected to be insignificant. For a picosecond pulse the influence of SBS on the reflectivity is more probable [8], [9], however not dominant, as it results from the fact that the observed dependence $R(E_L)$ is a decreasing function of E_L.

4. Conclusions

A quantitative comparison of specular reflectivities of picosecond and subnanosecond high-intensity light pulses from a metal target has been made in this paper. It has been found that:

a) the reflectivity for a picosecond pulse is several times higher than for a subnanosecond one,

b) the reflectivity is the highest at the best focusing of the laser beam on the target surface,

c) the dependences of the reflectivity on light pulse energy or intensity are different for both kinds of pulses.

It is believed that the differences in reflectivity for picosecond and subnanosecond pulses are mostly due to the different values of the density gradient scale length for picosecond and subnanosecond plasmas.

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