Quantum Electronics **30** (1) 51 – 54 (2000)

PACS numbers: 78.20.Ci; 42.62.Eh

Investigation of the energy balance components for a plane target irradiated with a picosecond laser pulse

V G Borodin, V V Il'in, V M Komarov, V A Malinov, V M Migel', N V Nikitin, A V Charukhchev, V N Chernov

DOI: 10.1070/QE2000v030n01ABEH001657

Abstract. The scattering and absorption of a high-power picosecond laser pulse by a solid target were investigated experimentally making use of the 'Progress-P' Nd : glass laser facility ($\lambda = 1053$ nm, $\tau = 1.4$ ps) at radiation intensities $I = 10^{16} - 10^{19}$ W cm^{-2} on the target surface. It was found that, for $I \leqslant 10^{17}$ W cm^{-2}, more than 30% of the intensity of the scattered light was contained in the specularly reflected component. The absorption coefficient of the laser radiation with intensities ranging from 10^{18} to 10^{19} W cm^{-2} was higher for targets made of materials with higher atomic numbers.

1. Introduction

A laser-produced plasma excited by a picosecond laser pulse with the intensity $I \leqslant 10^{16} - 10^{19}$ W cm^{-2} is a unique source of x rays and charged particles, whose parameters depend directly on the absorption of laser pulses in a target. The absorption of picosecond pulses is the central issue in the theory of interaction of ultrashort light pulses with solid targets [1 – 9]. The experimentally determined absorption (reflection) coefficients [10 – 14] are usually interpreted either in terms of a resonant mechanism, implying linear transformation of a pump light wave polarised in the plane of incidence (p-polarisation) into plasma waves [3] (this mechanism is well known from experiments on nano- and subnanosecond pulses), or in terms of new absorption mechanisms, such as the vacuum heating (Brunel absorption) [4], anomalous skin effect [5], and $j - B$ heating [6]. These new mechanisms are used in theoretical models because, at the laser radiation intensities on a target surface $I \geqslant 10^{17}$ W cm^{-2}, a strong optical pressure of the laser pulses gives rise to major changes in the plasma density profile. Under these conditions the resonant absorption becomes ineffective.

An analysis of the data [10 – 14] obtained for different laser systems in experiments that were mainly performed within comparatively narrow intensity ranges (see also the review in Ref. [15]) shows that, even for similar values of the parameter $I\lambda^2$ (λ is the wavelength of a laser pulse), the absorption coefficients measured in experiments carried out on different lasers differ considerably (by a factor of 2 – 3) from each other. In such situations a determination of the energy balance components within a broad range of the laser radiation intensities with fixed parameters of the laser pulses (including the laser wavelength, polarisation, power and energy contrast, and pulse duration) reaching a target would provide a more correct description of the absorption energy laser mechanisms.

V G Borodin, V V Il'in, V M Komarov, V A Malinov, V M Migel', N V Nikitin, A V Charukhchev, V N Chernov Research Institute for Complex Testing of Optoelectronic Devices, 188537 Sosnovyĭ Bor, Leningrad Province, Russia

Received 23 July 1999
Kvantovaya Elektronika **30** (1) 51 – 54 (2000)
Translated by A M Zheltikov, edited by A Tybulewicz

2. Experimental setup and procedures

Our experiments were performed making use of the 'Progress-P' Nd:glass picosecond laser ($\lambda = 1053$ nm) [16, 17]. The laser radiation energy in the interaction chamber was as high as 16 J and the pulse duration was ~ 1.4 ps. An axial parabolic mirror with an aperture ratio of 1 : 1.1 focused the laser beam (with a diameter of 190 mm), forming a focal spot (containing 50% of the laser energy) on the surface of a target with a diameter no larger than 7 μm. Laser beams with energies up to 1 J and a beam diameter of 35 mm were focused by a lens with an aperture ratio of 1 : 4 and with a dispersion circle (containing at least 50% of the pulse energy) no more than 15 μm in diameter. An amplified luminescence prepulse, which preceded the main pulse, had a duration of ~ 5 ns and an intensity no higher than $10^{-8}I$. The intensity of the prepulse during 10 – 100 ps before the appearance of the main pulse did not exceed $10^{-3}I$, which was the upper limit of our experimental technique. We performed experiments (Fig. 1) on both p- and s-polarised radiation and on targets made of different materials. The incident laser beam made an angle of 33° or 45° with the normal to the surface of the target.

The energy balance in the interaction accompanying the irradiation of plane targets by laser pulses is governed by the relation

$$E = E_s + E_d + E_{ap} + E_{ab} ,$$

where E, E_s, E_d and E_{ap} are the energies incident on the target, specularly and diffusely reflected from the target, and reflected within the aperture of the focusing system; E_{ab} is the energy absorbed by the target.

At radiation intensities up to 10^{17} W cm^{-2} on the target, we measured the absorption coefficient in an Ulbricht sphere which collected the radiation scattered by the target and we determined the energy of this radiation. We separately collected and detected the specularly scattered light and the radiation backscattered within the aperture of the

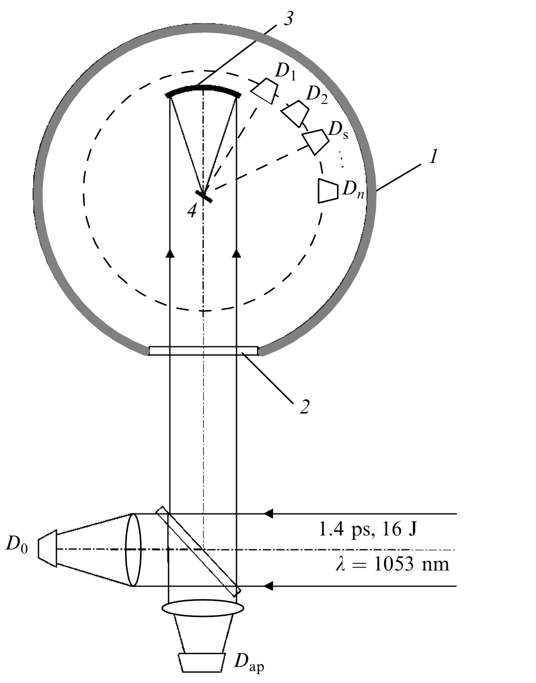

Figure 1. Set used in determination of the energy balance components: (*1*) vacuum chamber; (*2*) input window; (*3*) focusing mirror. Calorimeters were used in measuring the energy incident on the target (D_0), the energy of diffuse-scattered radiation ($D_1, \ldots, D_n$), the energy of the specularly reflected radiation component (D_s), and the radiation backreflected within the aperture of the focusing mirror (D_{ap}).

focusing lens. The incident and backreflected components of the laser radiation were determined behind a rotating mirror. The focusing lens was also used as the input window of the vacuum chamber.

The specularly reflected radiation component was coupled out of the sphere through a hole with an aperture ratio (1 : 4) equal to the aperture ratio of the input hole intended for the incident focused laser beam. To prevent the appearance of nonlinear distortions with increase in the laser beam power, we employed the axial parabolic mirror with an aperture of 1 : 1.1 instead of the focusing lens. In the investigation of the energy balance, we used a set of calorimetric sensors. One of these sensors recorded the entire radiation flux reflected specularly from the target, while the other sensors were placed around the target both in the plane of incidence and in a plane perpendicular to the incidence plane (Fig. 1). We measured separately the energy of the radiation backscattered within the aperture of the focusing mirror (lens). All the components of the scattered and incident radiation were recorded by a multichannel measuring system based on an analogue-to-digital converter built into a computer [18].

3. Experimental results and discussion

Fig. 2 presents the measured reflection coefficients for the specularly reflected component (R_s) and for the radiation component scattered within the aperture of the focusing system (R_{ap}), as well as the total reflection coefficient R for targets made of different materials (Al, Sn, and Au) exposed to laser radiation of the intensity $I \approx 10^{16} - 10^{19}$ W cm^{-2}.

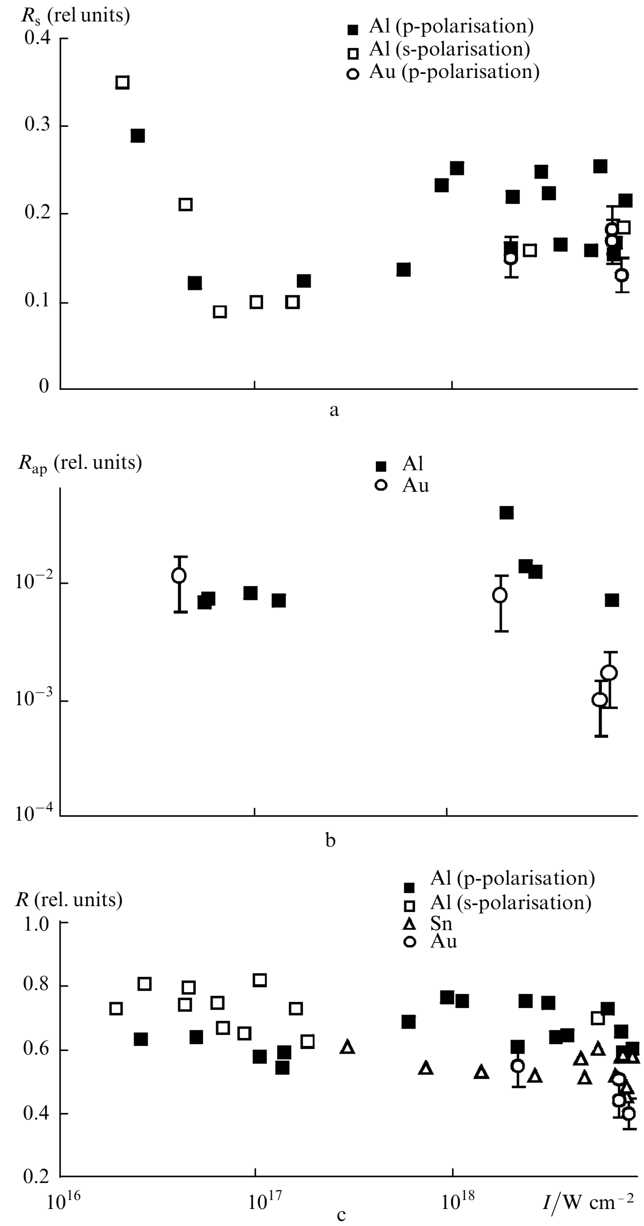

Figure 2. Reflection coefficients of laser pulses measured for the specular reflection direction (R_s) (a) and for the direction of backward reflection within the aperture of the focusing system (R_{ap}) (b), and the total reflection coefficient R (c), all plotted as functions of the radiation intensity on the target surface.

The absorbed energy was determined from the difference between the radiation energy reaching a target and the total energy of all the radiation components scattered by the target. The dependence of the resulting absorption coefficient $A = 1 - R$ on the radiation intensity on the target is shown in Fig. 3.

It can be seen from Fig. 2b that the energy of the radiation backreflected within the aperture of the focusing optical element does not exceed 1% of the total energy. Thus, this radiation component does not play a significant role in the energy balance. However, R_s (Fig. 2a) decreases rapidly from 30%–35% at $I \approx 2 \times 10^{16}$ W cm^{-2} down to 10%–12% at $I \approx 10^{17}$ W cm^{-2}, and then remains virtually unchanged up to $I \approx 10^{18}$ W cm^{-2}. The coefficient R_s for the p-polarised light is somewhat lower than that for the

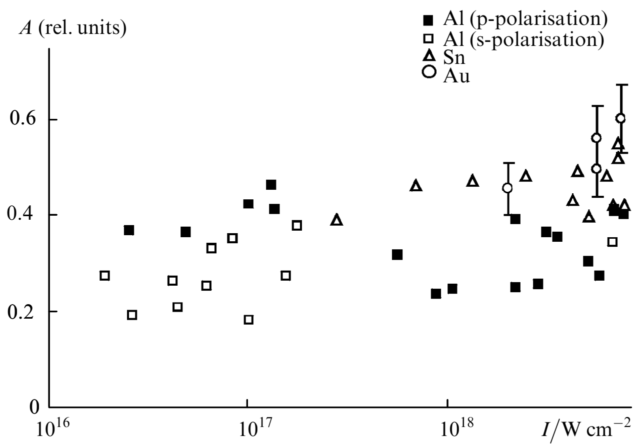

Figure 3. Dependences of the absorption coefficients of the laser radiation on the radiation intensity on the surfaces of plane targets made of different materials.

s-polarised light. An increase in the radiation intensity to $\sim 10^{18}$ W cm^{-2} increases R_s, which reaches the level of 18%–25% and then remains virtually constant on further increase in I.

A quantitative explanation of the nature of the dependences presented in Figs. 2 and 3 requires a detailed numerical simulation including all the energy absorption mechanisms and taking into account the spatial and temporal parameters of the laser radiation on the target, which is a quite difficult task. However, the observed dependences can be understood qualitatively in terms of the following simple considerations. As shown in Refs [1, 2], an increase in the electron temperature in the absorption area at the intensities $10^{15} < I \leqslant 10^{17}$W cm^{-2} lowers the efficiency of the collisional absorption. The resonant mechanism then becomes the main mechanism responsible for the absorption of light in a plasma [3].

Although the difference between the reflection coefficients of the s- and p-polarised light for $I \leqslant 10^{17}$ W cm^{-2} is noticeable (Figs. 2a and 2c), it is not as high as that predicted by calculations [1, 2]. Keeping in mind the results of [12], obtained under similar experimental conditions ($I \leqslant 10^{17}$ W cm^{-2}, $\tau = 1.5$ ps, and $\lambda = 1053$ nm), we may infer that this discrepancy between the theoretical predictions and the experimental data may be attributed to a nonuniform spatial distribution of the laser energy within the focal spot, which distorts the target surface ('riffling') [9] near the absorption area because of the exerted optical pressure. This effect reveals a significant s-component in an initially p-polarised laser beam (and, vice versa, a p-component can be detected in an initially s-polarised laser beam). Depending on the initial polarisation of the laser radiation, this phenomenon either increases or reduces the absorption of light. Such an approach allowed Andreev et al. [12] to achieve a reasonable agreement between the results of calculations and the experimental data.

At the laser intensities $I \geqslant 10^{17}$ W cm^{-2} the nonuniformity of the target irradiation clearly has an even stronger influence on the distribution of the optical pressure over the plasma surface, reducing the difference between the reflection coefficients for light beams with different polarisations. Furthermore, strong distortions of the reflecting surface may also account for the drastic reduction in R_s with virtually constant R.

In contrast to Klem et al. [19], we detected a fairly larger (at least 30%) specularly reflected component in the reflected radiation for $I \leqslant 10^{17}$ W cm^{-2}. In the experiments reported in Ref. [19], the contribution of this component did not exceed 10% (for $I \approx 10^{16} - 10^{18}$ W cm^{-2}) and varied only slightly, possibly due to the initial nonuniformity (roughness) of the target surface (this was pointed out in Ref. [19]).

An analysis of the dependences $A(I)$ presented in Fig. 3 shows that, while the difference between the absorption coefficients for the s- and p-polarised light is still noticeable for $I \leqslant 10^{18}$ W cm^{-2}, this difference vanishes on further increase in the radiation intensity, and the value of A becomes less sensitive to I. Similar results for $I \leqslant 10^{18}$ W cm^{-2} were also obtained earlier [14] ($\lambda = 1053$ nm): the absorption coefficient was about 40% for both polarisations.

Targets with higher atomic numbers (Sn, Au) had higher absorption coefficients than Al. Qualitatively, this can be interpreted in the following way. At the intensities $I \geqslant 10^{18}$ W cm^{-2}, we can assume that nonlinear collisionless mechanisms allow the energy of a laser pump wave to be transferred directly to plasma electrons [15, 20]. Therefore, under these conditions the electron flux accelerated by the light wave should be proportional to the electron density in the absorption area, which in its turn is determined, by the degree of ionisation z of the target material. According to the estimates presented in Ref. [21]. The temperature T_e of the plasma electrons in the target may reach 1 keV for $I \approx 5 \times 10^{18}$ W cm^{-2}. Taking into account the relationships $z \approx (2/3)(AT_e)^{1/3}$, derived in [22]. We find that this temperature is sufficient for the complete ionisation of an Al atom and ensures an effective ionisation degree $z \approx 25-35$ for Sn and Au. In our experiments (Fig. 3), the absorption coefficients of Sn and Au were 1.5–2 times higher than the absorption coefficient of Al, which agrees well with the ionisation degrees of Al, Sn and Au.

4. Conclusions

We investigated the energy balance components in the interaction of picosecond laser pulses with solid targets made of materials with different atomic numbers. This was done at radiation intensities $I \approx 10^{16}-10^{18}$ W cm^{-2} on the surface of a target. It was found that, for $I \leqslant 10^{17}$ W cm^{-2}, about 30% of the incident radiation energy reaching the target was contained in the specularly reflected component. In the range $I \approx 10^{18} - 10^{19}$ W cm^{-2} the absorption coefficients of targets made of heavy elements (Sn, Au) were 1.5–2 times higher than the absorption coefficient of an Al target.

Acknowledgements. We are grateful to A A Andreev for valuable discussions. This work was partially supported by the International Science and Technology Centre.

References

1. Rozmus W, Tikhonchuk V T *Phys. Rev. A* **42** 7401 (1990)
2. Pert G *Phys. Rev. E* **51** 4778 (1995)
3. Forslund D W, Kindel J M, Lee K, et al. *Phys. Rev. A* **11** 670 (1975)
4. Brunel F *Phys. Rev. Lett.* **59** 52 (1987)
5. Andreev A A, Gamalii E G, Novikov V N, Semakhin A N, et al. *Zh. Eksp. Teor. Fiz.* **101** 1808 (1992) [*Sov. Phys. JETP* **74** 963 (1992)]
6. Kruer W L, Estabrook K *Phys. Fluids* **28** 430 (1985)

7. Andreev A A, Platonov K Yu *Technical Digest of the Joint Symposium at the Fifteenth International Conference on Coherent and Nonlinear Optics (ICONO) and the Laser Optics Conference, St Petersburg, 1995*, p. 14
8. Wilks S C, Kruer W L, Tabak M, Langdon A B *Phys. Rev. Lett.* **69** 1383 (1992)
9. Estabrook K *Phys. Rev. Lett.* **50** 2082 (1983)
10. Meyerhofer D D, Chen H, Delettrez J A, Soom B, et al. *Phys. Fluids B* **5** 2584 (1993)
11. Bastiani S, Rousse A, Geindre J P, Audebert P, et al. *Phys. Rev. E* **56** 7179 (1997)
12. Andreev A A, Bayanov V I, Van'kov A B, Kozlov A A, et al. *Kvantovaya Elektron. (Moscow)* **23** 907 (1996) [*Quantum Electron.* **26** 884 (1996)]
13. Komarov V M et al. *AIP Conference Proceedings of the Thirteenth International 'Laser Interaction and Related Plasma Phenomena Conference, Monterey, CA, 1997* (Vol. 406) (Woodbury, NY: American Institute of Physics, 1997), p. 443
14. Tabak M, Hammer J, Glinsky M E, Kruer W L, et al. *Phys. Plasmas* **1** 1626 (1994)
15. Andreev A A, Mak A A, Yashin V E *Kvantovaya Elektron. (Moscow)* **24** 99 (1997) [*Quantum Electron.* **27** 95 (1997)]
16. Borodin V G, Komarov V M, Krasov S V, Malinov V A, Migel V M, Nikitin N V, Popov V S, Potapov S L, Charukhchev A V, Chernov V N *Kvantovaya Elektron. (Moscow)* **25** 115 (1998) [*Quantum Electron*. **28** 108 (1998)]
17. Borodin V G, Charukchev A V, Chernov V N, Komarov V M, Krasov S V, Malinov V A, Migel V M, Nikitin N V, Popov V S, Potapov S L AIP *AIP Conference Proceedings of the Thirteenth International 'Laser Interaction and Related Plasma Phenomena Conference, Monterey, CA, 1997* (Vol. 406) (Woodbury, NY: American Institute of Physics, 1997), p. 389
18. Il'in V V, Komarov V M, Charukhchev A V, Vel'gorskaya N S, et al. *Prib. Tekh. Eksp*. **40** (4) 113 (1997)
19. Klem D E, Darrow C, Lane S, Perry M D*Proc. SPIE Int. Soc. Opt. Eng.* **1860** 98 (1993)
20. Ruhl H, Sentoku Y, Mima K, Tanaka K A, et al. P*hys. Rev. Lett.* **82** 743 (1999)
21. Andreev A A et al. *Izv. Akad. Nauk, Ser. Fiz*. **63**, 1239 (1999)
22. Murnane M M, Kapteyn H C, Rosen M D, Falcone R W *Science* **251** 531 (1991)