Experimental and theoretical study of Al plasma under femtosecond laser pulses

2009 J. Phys. A: Math. Theor. 42 214057

(http://iopscience.iop.org/1751-8121/42/21/214057)

IOP PUBLISHING JOURNAL OF PHYSICS A: MATHEMATICAL AND THEORETICAL

J. Phys. A: Math. Theor. **42** (2009) 214057 (4pp) doi:10.1088/1751-8113/42/21/214057

Experimental and theoretical study of Al plasma under femtosecond laser pulses

P S Komarov, S I Ashitkov, A V Ovchinnikov, D S Sitnikov, M E Veysman, P R Levashov, M E Povarnitsyn, M B Agranat, N E Andreev, K V Khishchenko and V E Fortov

Joint Institute for High Temperatures, Russian Academy of Sciences, Izhorskaya St. 13, Bd. 2, Moscow 125412, Russia

E-mail: bme@ihed.ras.ru

Received 17 October 2008, in final form 7 February 2009
Published 8 May 2009
Online at stacks.iop.org/JPhysA/42/214057

Abstract

The amplitude and phase of the complex reflection coefficient of a weak probe laser pulse from strongly coupled Al plasma created on the surface of a metallic target by pump femtosecond laser pulses with intensities $I \lesssim 10^{15}$ W cm^{-2} were measured using femtosecond interference microscopy. A theoretical model developed for the interaction of intense ultrashort laser pulses with solid targets on the basis of a two-temperature equation of state for an irradiated substance was used for numerical simulations of the dynamics of the formation and expansion of the plasma. A comparison of the experimental data with the simulated results shows that the model is suitable up to $I \sim 10^{14}$ W cm^{-2}. At higher intensities of the heating laser pulse, lower values of the reflection coefficient amplitude of Al plasma are observed in the experiment.

PACS numbers: 52.25.Os, 52.38.−r, 52.50.−b

(Some figures in this article are in colour only in the electronic version)

1. Introduction

The optical and transport properties of strongly coupled plasma formed on the surface of an aluminum target irradiated by femtosecond laser pulses with the intensity $I \lesssim 10^{15}$ W cm^{-2} have been studied both experimentally and theoretically. Such laser pulses produce a thin layer of the solid-density plasma with an electron temperature up to $T_e \simeq 60$ eV. We studied the initial stage ($t \leqslant 1$ ps) of the heating and expansion of the plasma under the conditions of the undeveloped hydrodynamic motion of ions. The present work continues our previous experimental and theoretical investigations of Al [1] and Ag [2] plasmas under the influence of femtosecond laser pulses on solid targets in the range of intensities up to $I \sim 10^{14}$ W cm^{-2}.

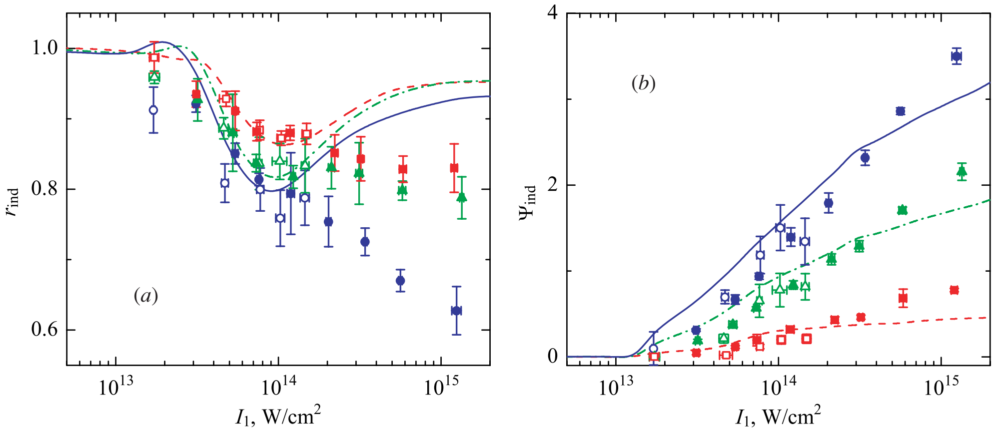

Figure 1. Experimental (markers) and calculated (lines) values of (*a*) r_{ind} and (*b*) Ψ_{ind} as functions of the peak intensity I_1 of the pump laser pulse for $\Delta t = 0.13$ (open squares), 0.2 (solid squares and dashed lines), 0.53 (open triangles), 0.6 (solid triangles and dash-dot lines), 0.93 (open circles) and 1 ps (solid circles and solid lines). Open markers are data from measurements in the air [1], solid markers are results of the present measurements in a vacuum.

2. Experiment

A source of radiation is a terawatt chromium-doped forsterite laser system that generates femtosecond pulses at the wavelength of 1.24 μm [3]. The full width at half-maximum pulse duration measured using the non-collinear second-harmonic autocorrelator was equal to $\tau_L = 100$ fs. The shape of the temporal pulse profile was approximated as squared hyperbolic secant. The pulse power contrast was no less than 10^4 at 1 ps before the pulse peak and more than 10^6 at 2 ps before the pulse peak [4].

The experiments were performed with Al films of 1 μm thickness on silica substrates. The *p*-polarized pump pulses at the fundamental wavelength $\lambda_1 = 1.24$ μm were focused on a target at the angle of incidence 45° in a vacuum. The energy of pump pulses was varied with the use of a half-wave plate in conjunction with an optical polarizer. The spatial distribution of the pump pulse fluence over the target had the Gaussian shape with the beam diameter $d_0 = 70$ μm at the level of $\exp(-2)$.

For the experimental study of optical properties of the excited area of a target the Michelson interferometer was used. The normally incident *s*-polarized probe pulse at the second harmonic wavelength $\lambda_2 = 0.62$ μm illuminated the heated area of the target with a varying time delay after the pump pulse. The spatial distribution of laser-induced changes of amplitude $r_{\text{ind}}(x, y) = r_t(x, y)/r_i(x, y)$ and phase $\Psi_{\text{ind}}(x, y) = \Psi_t(x, y) - \Psi_i(x, y)$ of the reflected probe wave from the excited area of the target were measured. Here $r_i(x, y)$ and $\Psi_i(x, y)$ are the amplitude and phase of the reflected probe wave from the target surface before the action of the pump pulse; $r_t(x, y)$ and $\Psi_t(x, y)$ are the amplitude and phase after the action of the pump pulse. The accuracy of measurements of the amplitude and phase variations was better than 1% and $\pi/200$, correspondingly.

The variations of r_{ind} and Ψ_{ind} as functions of the peak intensity I_1 of a heating laser pulse for various time delays between the pump and probe pulses ($\Delta t = 0.2$, 0.6 and 1 ps) are shown in figure 1. The presented values of r_{ind} and Ψ_{ind} were measured in the center of the spot. Each experimental point is a result of averaging over five laser shots. Data from previous measurements in the air [1] are also shown in figure 1; these data correspond to close values of the time delay ($\Delta t = 0.13$, 0.53 and 0.93 ps).

3. Theoretical model

The self-consistent theoretical model includes the system of electrodynamic equations for describing the absorption and reflection of the laser radiation in matter, ionization kinetic equations and one-fluid one-dimensional hydrodynamic equations containing electron–ion relaxation and electron heat conduction, as well as a two-temperature equation of state and semiempirical formulae for the effective collision frequency of electrons ν_{eff} for Al over a wide range of temperatures and pressures [1, 5]. Several improvements have been made to the model in comparison with the works [1, 5]. They cover the expression for the electron–phonon part of the effective collision frequency in the metal plasma [6] and the formulae for the electron optic mass both in solid and liquid phases according to [7]. These changes have not caused any significant influence on the calculation results discussed below.

4. Comparison of experimental and theoretical results and discussion

The measured and simulated, according to the model of section 3, relative module r_{ind} and phase Ψ_{ind} of the reflection coefficient of the probe laser pulse are shown in figure 1 as functions of peak intensity I_1 of the pump laser pulse for different time delays Δt between the pump and probe pulses.

As one can see in figure 1, our theoretical model is in reasonable agreement with experimental measurements of the phase Ψ_{ind}. This evidences the adequate description of the rate of expansion and ionization of the matter by the theoretical model, because these processes determine mainly the rate of change of Ψ_{ind}.

The calculated module r_{ind} is in reasonable agreement with the measurements at intensities $I_1 \lesssim 10^{14}$ W cm^{-2}, while at higher fluxes the calculated r_{ind} increases with I_1 at $I_1 > 10^{14}$ W cm^{-2}, whereas the experimental data show further decreasing of $r_{\mathrm{ind}}(I_1)$. The existence of the maximum of absorption (and minimum of reflectivity) at $I_1 \simeq 10^{14}$ W cm^{-2} is connected with the existence of the maximum ($\nu_{\mathrm{eff}} \sim \omega_{\mathrm{p}e}$, where $\omega_{\mathrm{p}e}$ is the electron plasma frequency) of electron collisions frequency at electron temperatures above the Fermi temperature [1, 2].

The maximum of the absorption at intensities of laser radiation of several units of 10^{14} W cm^{-2} was earlier detected in experiments [8] with the second harmonic of laser radiation ($\lambda_1 = 0.4$ μm). The second harmonic was used in order to decrease the effect of plasma formation due to pre-pulse [8].

In the present experiment, with the first harmonic, the possible plasma formation due to pre-pulse could change the density profile near the critical density and thus could change the absorption of a *p*-polarized heating pulse. This can be one of the reasons why the maximum of absorption was not detected up to $I_1 \simeq 1.3 \times 10^{15}$ W cm^{-2}.

It should be noted that in the experiments with $\lambda_1 = 0.62$ μm [9] such a maximum of absorption also was not revealed, while in the experiments with $\lambda_1 = 0.308$ μm [10] the maximum was observed. These cases make challenge for further experimental and theoretical studies of the laser–plasma interaction at moderate intensities.

5. Conclusion

New data for the amplitude and phase of the complex reflection coefficient of strongly coupled Al plasma created on the surface of a solid target by femtosecond laser pulses with intensities $I \lesssim 10^{15}$ W cm^{-2} were obtained. The theoretical model used for simulations of the interaction of intense ultrashort laser pulses with metals is in good agreement with the data up to

$I \sim 10^{14}$ W cm^{-2}. At higher intensities of the heating laser pulse, however, lower values of reflection coefficient amplitude of Al plasma are observed in the experiment and this fact stimulates our further investigations.

Acknowledgments

The work was partially supported by the Russian Foundation for Basic Research, grants no. 07-02-92160 and 08-08-01055.

References

[1] Agranat M B, Andreev N E, Ashitkov S I, Veisman M E, Levashov P R, Ovchinnikov A V, Sitnikov D S, Fortov V E and Khishchenko K V 2007 *JETP Lett.* **85** 271–6
[2] Veysman M E, Agranat M B, Andreev N E, Ashitkov S I, Fortov V E, Khishchenko K V, Kostenko O F, Levashov P R, Ovchinnikov A V and Sitnikov D S 2008 *J. Phys. B: At. Mol. Opt. Phys.* **41** 125704
[3] Agranat M B, Ashitkov S I, Ivanov A A, Konyashchenko A V, Ovchinnikov A V and Fortov V E 2004 *Quantum Electron.* **34** 506–8
[4] Agranat M B, Andreev N E, Ashitkov S I, Ovchinnikov A V, Sitnikov D S, Fortov V E and Shevel'ko A P 2006 *JETP Lett.* **83** 72–4
[5] Khishchenko K V, Veysman M E, Andreev N E, Fortov V E, Levashov P R and Povarnitsyn M E 2008 *Proc. SPIE* **7005** 70051S
[6] Fisher D, Fraenkel M, Henis Z, Moshe E and Eliezer S 2001 *Phys. Rev.* E **65** 016409
[7] Huttner B 1994 *J. Phys.: Condens. Matter* **6** 2459–74
[8] Price D F, More R M, Walling R S, Guethlein G, Shepherd R L, Stewart R E and White W E 1995 *Phys. Rev. Lett.* **75** 252–5
[9] Grimes M K, Rundquist A R, Lee Y S and Downer M C 1999 *Phys. Rev. Lett.* **82** 4010–3
[10] Milchberg H M, Freeman R R, Davey S C and More R M 1988 *Phys. Rev. Lett.* **61** 2364–7