

Absorption of Ultrashort Laser Pulses in Strongly Overdense Targets

M. Cerchez,* R. Jung, J. Osterholz, T. Toncian, and O. Willi

Heinrich-Heine Universität Düsseldorf, Universitätsstr.1, 40225 Düsseldorf, Germany

P. Mulser

Theoretical Quantum Electronics (TQE), Technische Universität Darmstadt, 64289 Darmstadt, Germany

H. Ruhl

Institute for Theoretical Physics I, Ruhr-Universität Bochum, 44797 Bochum, Germany

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Absorption measurements on solid conducting targets have been performed in s and p polarization with ultrashort, high-contrast Ti:sapphire laser pulses at intensities up to $5 \times 10^{16} \text{ W/cm}^2$ and pulse duration of 8 fs. The particular relevance of the reported absorption measurements lies in the fact that the extremely short laser pulse interacts with matter close to solid density during the entire pulse duration. A pronounced increase of absorption for p polarization at increasing angles is observed reaching 77% for an incidence angle of 80° . Simulations performed using a 2D particle in cell code show a very good agreement with the experimental data for a plasma profile of $L/\lambda \approx 0.01$.

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In the recent years, the availability of intense, ultrashort laser pulses has made the investigation of rapidly heated matter under extreme conditions possible [1–4]. These interaction processes are characterized by unique properties as the laser energy is absorbed on a short time scale, before significant hydrodynamic motion of the plasma occurs and the laser energy is transferred to high density matter. The experimental and theoretical studies of the interaction of femtoseconds laser pulses with solid targets have been motivated by many research fields and applications including ignition methods for ICF [5], generation of ultrafast x-rays [6] and high harmonics [2], highly energetic particles production [7], or isochoric heating [3]. Dense plasmas ($n_e > 10^{22} \text{ cm}^{-3}$) generated by ultrashort laser pulses represent an important interest for astrophysics (e.g. the study of the x-ray opacity of the matter in similar states as one finds in stars [8]), investigations in high-quality laser material processing [9], transport properties [10] or dense material equations of state.

A central issue of these applications is the question how and with what efficiency the laser energy is transferred to solid matter. Absorption of intense laser pulses in the ps [11] and subps regimes [4,12–14] has been measured in several experiments with solid targets in the past, in an intensity range which is of interest to the present letter. In all measurements, except [14] (no s polarization investigated), absorption has prevailed considerably under p polarization relative to s polarization. When the laser pulse is typically longer than 100 fs, and/or a prepulse is present, a preplasma is formed in front of the target and undergoes hydrodynamic expansion. In these situations, the absorption process has a characteristic dependence on the polarization and, for p polarization, is commonly attributed to

the mechanism of linear resonance absorption. Only the authors of [14] make an exception by claiming that vacuum heating [15] would dominate on resonant coupling. Under striking incidence and nonrelativistic laser intensities for p polarization absorption levels as high as 80% have been measured [12]. Particle-in-cell (PIC) [14–16] and Vlasov simulations [17] are in qualitative agreement with experiments and the characteristic angular distribution of linear resonance absorption with the increasing scale length is well reproduced.

In this Letter, we report on experimental investigations of laser absorption of high-contrast, sub-10 fs laser pulses by a conducting target over a large range of angular incidence and laser intensity ($5 \times 10^{12} \text{ W/cm}^2 - 5 \times 10^{16} \text{ W/cm}^2$). Our laser pulse parameters (duration and high-contrast) allowed, for the first time, to study the absorption under novel conditions where the pulse energy is basically directly transferred to the solid matter. The energy of these extremely short laser pulses can be efficiently absorbed up to $\approx 77\%$ by a plasma at density close to solid state, characterized by a very steep profile. The absorption of the p polarized laser pulses significantly exceeds the s polarization absorption. Computer simulations are consistent with the experimental results for a plasma profile of $L/\lambda \approx 0.01$.

The experiments have been carried out employing a Ti:sapphire laser system described in [18] operating in CPA mode. Under experimental conditions, the laser system delivers linearly polarized pulses of 100–120 μJ at 790 nm (central wavelength) and 8 fs duration on target. The pulse contrast was experimentally determined using a high dynamic range third-order autocorrelator (Sequoia). The diagnosis reveals a contrast ratio of 10^5 for times

larger than 1 ps before the main pulse and better than 10^8 for the amplified spontaneous emission prepulse. The laser pulse was focused in vacuum onto target by an $f/2.8$ off-axis parabola of 108 mm effective focal length to a spot diameter of $\approx 3.2 \mu\text{m}$ (FWHM), having at normal incidence, an average intensity of $(4 - 5) \times 10^{16} \text{ W/cm}^2$. The absorbed energy fraction was experimentally determined as a function of the incidence angle θ , laser pulse polarization and intensity. The targets consisted of mirror-flat aluminum layers with a thickness of $\approx 300 \text{ nm}$ and a roughness less than 5 nm, deposited on planar silica substrates. The target was placed at the center of an integrating sphere of 10 cm in diameter. The amount of laser light collected by the sphere was measured with a high-speed photodiode coupled to the sphere via an optical fiber bundle. For our energy range, we carefully checked the linearity of the photodetector and the optical bundle prior to the measurements.

The laser was operated in single shot mode and focused onto fresh target surface. The pulse energy fluctuated by less than 5% with respect to the average value over tens of shots. The intensity of the laser beam was varied by moving the target out of focus along the laser propagation direction. The signal at the photodetector was proportional to the fraction R of the laser energy reflected (specular and scattered) from the target. Previous experimental works (e.g., [19]) proved that the contribution of the backscattered laser energy represents less than 4% for incidence angles larger than 10° and thus, is negligible. The experimental investigations addressed here do not include the measurement of the backscattered light. The absorbed fraction A is given by $A = 1 - R$.

In Fig. 1, the experimental results of the angular dependence of the absorbed fraction for both s and p polarized

laser pulses incident on aluminum targets are presented. For s polarization, while the angle of incidence is increasing, the absorption drops from 19% at $\theta = 15^\circ$ to 6% at $\theta = 70^\circ$. Absorption of the p polarized laser light increases for larger angles and reaches its maximum value of 77% at 80° . Each data point represents an average value over 10–20 shots. The error bars shown on the graphs indicate the standard deviations and are in the range of 10%–40%. These experimental data points have been recorded in the best focal position of the target. Regarding the dependence of the absorbed fraction versus the laser intensity I_L , plotted in Fig. 2 for an incidence angle of $\theta = 45^\circ$ for both p and s polarization, the following observations are made: (i) In the case of s polarization, starting from the low intensity regime of $\approx 5 \times 10^{12} \text{ W/cm}^2$, the absorption is approximately constant (10%) over 2 orders of magnitude of the laser intensity. It starts to increase up to about 20% at the average intensity of $5 \times 10^{16} \text{ W/cm}^2$. (ii) P -absorption starts to increase significantly at 10^{14} W/cm^2 and is 5 times as strong when approaching $5 \times 10^{16} \text{ W/cm}^2$. (iii) In the intensity range between $5 \times 10^{14} \text{ W/cm}^2$ and $5 \times 10^{16} \text{ W/cm}^2$ the absorbed fraction of the p polarized beam A_p scales with intensity I_L and wavelength as $A_p \propto (I_L \times \lambda^2)^{0.12 \pm 0.02}$.

For investigating these experimental observations, we performed simulations using the 2D particle-in-cell (PIC) plasma simulation code (PSC) [20]. A temporally Gaussian shaped laser pulse with a duration of 10 fs (FWHM) was focused inside a simulation box of $20 \mu\text{m} \times 20 \mu\text{m}$. In the focus, the laser pulse achieved an intensity of $2 \times 10^{16} \text{ W/cm}^2$ (cycle averaged). A rectangular aluminum target of $15 \mu\text{m} \times 1 \mu\text{m}$ was placed at the best focal position in the center of the simulation box. The electron

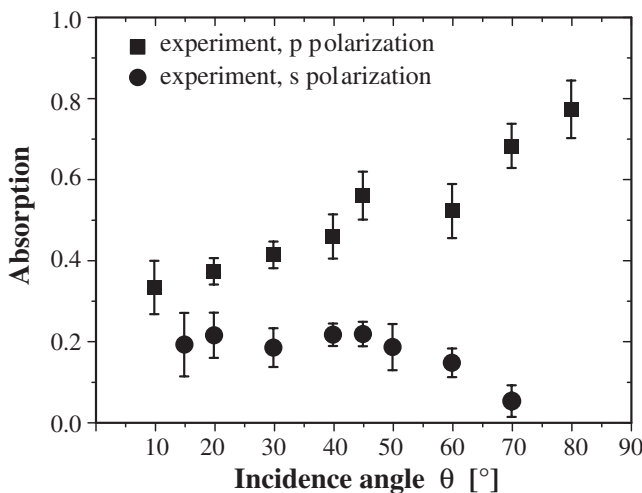


FIG. 1. Experimental angular dependence of the absorption of 8 fs, 790 nm laser pulses by an aluminum target, s (closed circle symbols) and p polarized (closed square symbols) at an average intensity of $5 \times 10^{16} \text{ W/cm}^2$.

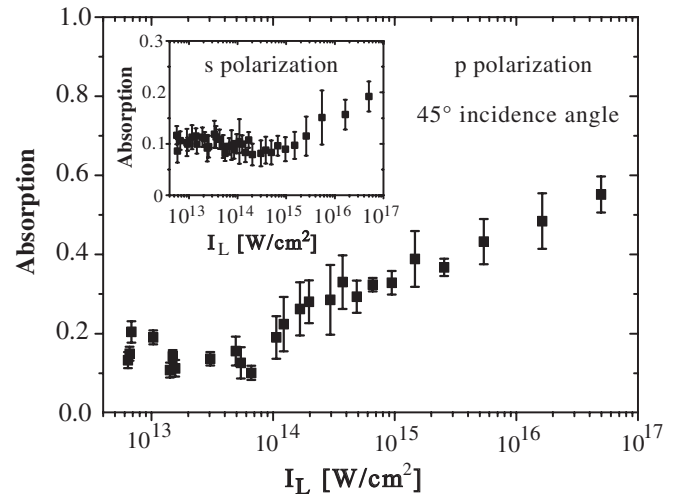


FIG. 2. Absorption of sub-10 fs, 790 nm laser pulse dependence on the laser intensity at the incidence angle $\theta = 45^\circ$, for an aluminum target. In the main frame, the absorbed fraction of the p polarized beam is shown and in the inset the dependence also on the laser intensity for an s polarized laser pulse.

density profile at the target boundary was given by $n_e(x)/n_{e0} = (1 + \exp(-2x/L))^{-1}$ with respect to the target normal, where $L = |\nabla n/n|^{-1}$ is the density scale length. For the simulations reported here a grid resolution of 40 cells per μm was chosen with 4 particles per cell and species. The target was rotated in steps of 10° around the position of the maximum density slope located at the best focal position (i.e. corresponding to $n_e/n_{e0} = 1/2$). Various density scale lengths L of 2, 10, 20, 200, and 500 nm were used. Additional simulations were performed for higher resolutions up to 120 cells per μm , but the results were not sensitive to the increased resolution. To account for the high-contrast ratio of the laser pulse, it was assumed that the target is primarily ionized by optical field ionization at the moment the 10-fs pulse interacts with the aluminum slab. Therefore, in the simulation, the aluminum was ionized from the ground state according to the ADK model [21] included in the code. The maximum field-induced ionization state observed in this scenario was about 3.5. The simulations were performed for p and s polarization of the incident laser pulse including the binary collisions in the code. Assuming collisional absorption for s polarization of the laser, we calculated the contribution of the collisionless absorption by subtracting the absorbed fraction A_s from the corresponding fraction A_p of the p polarized beam. These results have been compared with simulations in which the collisional module was switched off and similar results were obtained. This indicates that the fraction $A_p - A_s$ represents indeed a measure for the contribution of a collisionless absorption process. The computational and experimental results at an average focal

intensity of $2 \times 10^{16} \text{ W/cm}^2$ are shown in Fig. 3. The experimental data are well reproduced for profiles in the range of 10–20 nm. For longer profiles, $L = 200 \text{ nm}$ and $L = 500 \text{ nm}$, the well-known linear resonance absorption behavior is reproduced with an optimum absorption angle at intermediate values.

The simulations confirm the absorption of p polarization up to 80° and indicate that the interaction of the ultrashort laser pulses with the target takes place close to the solid density. There are more experimental indications, in addition to the above mentioned good contrast ratio that the laser is incident at steep plasma density: (i) in the structure of x-ray spectra as the higher order transitions are missing [22] and (ii) absence of a preplasma in the observations of the ionization front propagation in gaseous targets [23].

Previous experimental and theoretical works emphasize an increase and shift of maximum absorption towards larger angles in linear [24–27] and nonlinear [17] resonance absorption as L decreases. We shall emphasize that the classical model of linear resonance absorption [25] is not valid for these steep profiles. In such plasmas, the plasma frequency ω_p is everywhere much higher than the laser frequency ω . In [26,27] it was shown that in very steep plasma profiles, within a suitable range of parameters, the resonance absorption approaches the purely collisional model described by Fresnel equations. As mentioned above, the PIC simulations indicate that the preponderance of the p polarization absorption on s polarization found in our experiment is of collisionless nature. Moreover, the above mentioned threshold behavior is very unlikely to be produced in collisional processes.

In principle, other collisionless or collective absorption models exist showing a polarization dependence, like sheath layer inverse bremsstrahlung [28], anomalous skin layer absorption [29], vacuum heating (VH) [14,15], excitation of surface plasmons [30], and the Brunel effect [31]. Mechanisms such as described in Refs. [14,15,28,29] lead to the absorption of laser energy even in the absence of a low density plasma shelf and, in the non- or weakly relativistic regime, the contributions of these processes do not exceed 5%–10% [32]. For example, assuming a plasma profile of 10 nm then the electron quiver amplitude, $x_{\text{osc}} = eE/m\omega_L^2$, exceeds the plasma profile and consequently, we analyzed, in particular, the vacuum heating model. In [15] a detailed analysis of the VH mechanism and its dependence on the plasma profile, L was performed via PIC simulations. For a laser intensity of $1 \times 10^{16} \text{ W/cm}^2$ and a plasma profile of $L/\lambda = 0.01$, the contribution of the VH process to the laser absorption was found to be very small, with a maximum of $\approx 10\%$ at 45° incidence angle. This value is significantly smaller than the absorption measured in our experiment. Moreover, VH mechanism presents a couple of characteristics resulting in specific scaling laws which are not identified in our experiment. For example, in the context of the VH model, the collisionless absorption

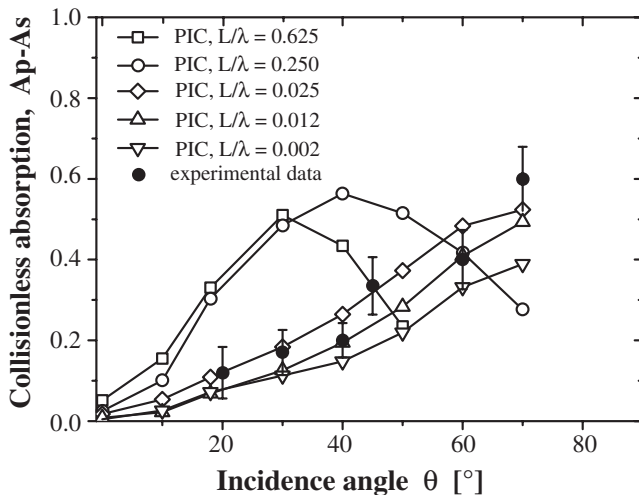


FIG. 3. Contribution of the collisionless absorption on p polarization expressed as difference between absorbed fraction on p and s polarization at an average laser intensity $I = 2 \times 10^{16} \text{ W/cm}^2$. The closed circle symbols represent the experimental data. PIC simulations for the same laser condition and different preplasma scale lengths L/λ are shown by open symbols.

fraction scales with the laser irradiance as $A_{\text{VH}} \propto (I_L \times \lambda^2)^{0.5}$ while from our experimental results $(A_p - A_s) \propto (I_L \times \lambda^2)^{0.10 \pm 0.05}$. This mismatch between the specific VH scaling laws and our experimental results, leads us to the conclusion that vacuum heating is not the dominant mechanism in the present experiment. Its presumable small contribution predicted by PIC simulations in [15] was not possible to be distinguished from our experimental results. Presently, new ideas [33] are under discussions which aim to understand the physical mechanisms responsible for the high collisionless absorption experimentally observed in overdense plasma regime at large incidence angle. These new models will be discussed in a separate publication.

In conclusion, we report on the first absorption experiments of sub-10 fs high-contrast Ti:sapphire laser pulses incident on solid targets. The very good contrast of the laser pulse assures the formation of a very small preplasma and the pulse interacts with the matter close to solid density. Experimental results indicate that p polarized laser pulses are absorbed up to 77% at an 80° incidence angle. The simulation results of the PSC code clearly confirm the observations and show that the collisionless absorption works efficiently in steep density profiles with a scale length of $L/\lambda \approx 0.01$.

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*mirela.cerchez@uni-duesseldorf.de

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