Absorption of ultrashort laser pulses in strongly overdense targets

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Absorption measurements on solid conducting targets have been performed in s and p polarization with ultrashort, high-contrast Ti:Sa laser pulses at intensities up to $5 \times 10^{16}$ 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 2-D 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, 2, 3, 4]. These interaction processes are characterized by unique proprieties 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 ($n_c > 10^{22}$ 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 sub-ps regimes [4, 12, 13, 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 [12] (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 pre-plasma 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 would dominate on resonant coupling. Under striking incidence and non-relativistic laser intensities for p polarization absorption levels as high as 80% have been measured [12]. Particle-In-Cell (PIC) [14, 15, 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 ($5 \times 10^{12}$ W/cm$^2 - 5 \times 10^{16}$ 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:Sa 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 auto-correlator (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 $\approx 3.2 \mu m$ (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 $\theta$, laser pulse polarization and intensity. The targets consisted of mirror-flat aluminium 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 backscattered light. The absorbed fraction $A$ of the backscattered fraction to increase up to about 20% at the average intensity of $5 \cdot 10^{16} \text{W/cm}^2$. (2) P-absorption starts to increase significantly at $10^{14} \text{W/cm}^2$ and is 5 times as strong when approaching $5 \cdot 10^{16} \text{W/cm}^2$. (3) In the intensity range between $5 \cdot 10^{14} \text{W/cm}^2$ and $5 \cdot 10^{16} \text{W/cm}^2$ the absorbed fraction of the p polarized beam $A_p$ scales with intensity $I_L$ and wavelength as $A_p \propto (I_L \cdot \lambda^2)^{0.12\pm0.02}$.

For investigating these experimental observations, we performed simulations using the 2-dimensional 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 $\mu m \times 20 \mu m$. In the focus, the laser pulse achieved an intensity of $2 \times 10^{16} \text{W/cm}^2$ (cycle averaged). A rectangular aluminium target of 15 $\mu m \times 1 \mu m$ was placed at the best focal position in the center of the simulation box. The electron density profile at the target boundary was experimentally determined as a function of the incidence angle $\theta$, laser pulse polarization and intensity. The targets consisted of mirror-flat aluminium layers having at normal incidence, an average intensity of $10^{16} \text{W/cm}^2$. Absorption of the p polarized beam is shown and in the inset the dependence also on the laser intensity for a s polarized laser pulse.

In Fig. 1 the experimental results of the angular dependence of the absorbed fraction for both s and p polarized laser pulses incident on aluminium 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 light increases for larger angles and reaches its maximum value of 77% at $80^\circ$. 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: (1) In the case of s polarization, starting from the low intensity regime of $\approx 5 \cdot 10^{12} \text{W/cm}^2$, 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 $5 \cdot 10^{16} \text{W/cm}^2$. (2) P-absorption starts to increase significantly at $10^{14} \text{W/cm}^2$ and is 5 times as strong when approaching $5 \cdot 10^{16} \text{W/cm}^2$. (3) In the intensity range between $5 \cdot 10^{14} \text{W/cm}^2$ and $5 \cdot 10^{16} \text{W/cm}^2$ the absorbed fraction of the p polarized beam $A_p$ scales with intensity $I_L$ and wavelength as $A_p \propto (I_L \cdot \lambda^2)^{0.12\pm0.02}$.

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The experimental data are well reproduced for profiles in the range of 10-20 nm. For longer profiles, \( L=200 \) nm and \( L=500 \) 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 and (ii) absence of a preplasma in the observations of the ionization front propagation in gaseous targets.

Previous experimental and theoretical works emphasize an increase and shift of maximum absorption towards larger angles in linear and nonlinear resonance absorption as \( L \) decreases. We shall emphasize that the classical model of linear resonance absorption is not valid for these steep profiles. In such plasmas, the laser frequency \( \omega_p \) is everywhere much higher than the laser frequency \( \omega \). In [20, 24] 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 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 unlike to be produced in collisional processes.

In principle, other collisionless or collective absorption models exist showing a polarization dependence, like sheath layer inverse bremsstrahlung, anomalous skin layer absorption, vacuum heating \((VH)\), vacuum heating \((VH)\) and nonlinear resonance absorption as \( L \) decreases. We shall emphasize that the classical model of linear resonance absorption is not valid for these steep profiles. In such plasmas, the laser frequency \( \omega_p \) exceeds the laser frequency \( \omega \). In [20, 24] 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 unlike to be produced in collisional processes.

In principle, other collisionless or collective absorption models exist showing a polarization dependence, like sheath layer inverse bremsstrahlung, anomalous skin layer absorption, vacuum heating \((VH)\), vacuum heating \((VH)\), excitation of surface plasmons, and the Brunnell effect. Mechanisms such as described in references 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%.

For example, assuming a plasma profile of 10 nm then the electron quiver amplitude, \( x_{osc} = eE/m\omega_p^2 \), 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 \( 1 \times 10^{16} \) 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 fraction scales with \( L/\lambda \), but in the collisional model, the scale length is always included in the same equation.
the laser irradiance as $A_{VH} \propto (I_L \cdot \lambda^2)^{0.5}$ while from our experimental results ($A_p - A_s \propto (I_L \cdot \lambda^2)^{0.10 \pm 0.05}$. 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:Sa laser pulses incident on solid targets. The very good contrast of the laser pulse assures the formation of a very small pre-plasma 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 80° incidence angle. The simulation results of 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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