# Absorption of variable contrast femtosecond laser pulses by overdense plasmas in the relativistic regime

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The efficiency of the laser energy transfer to the matter plays a central role in different physical processes and phenomena specific to laser produced plasmas. It has been shown that the energy absorption has an impact on various physical processes, including energetic particle acceleration, high harmonics generation and hard X-ray production. Absorption depends on large number of physical conditions which can control and optimize the coupling of the laser energy [1]. In particular, recent studies concentrated on the dependence of laser polarization and preplasma density profiles on these processes at ultrahigh laser intensities [2, 3].

We report here on the recent experimental investigations on the absorbed energy fraction of the 100 TW laser energy pulse by close to solid density plasma in the relativistic regime. Extensive experimental studies have been performed measuring the dependence of the absorbed energy fraction on different interaction geometry (incidence angle, laser polarization and intensity) and different sorts of targets (thin foils, flat and rough bulk targets) have been investigated. The role of the laser contrast on the plasma formation and expansion was tested by irradiating ultra-thin DCL foils with a laser pulses with different temporal profiles.

The experiments have been carried out employing the new commissioned 100 TW Ti:Sa Arcturus laser system (at the Institute of Laser- and Plasma Physics of the University of Düsseldorf) [4] which delivers laser pulses of 790 nm wavelength with pulse duration of 25 fs (FWHM). After being compressed, the laser pulse propagates through a single pass plasma mirror system. In this way, the nanosecond pre-pulse and the picosecond ASE pedestal were reduced corresponding to the reflectivity of the substrates. By employing BK-7 uncoated or monolayer and multilayer AR coated plasma mirror substrates the laser contrast was varied by three orders of magnitude. For the best laser contrast, the laser contrast was improved typically up to $10^{11}$ on a *ns* time scale and up to $10^9$ at 10 ps before the main pulse. The improvement of the contrast achieved in the present experiments reduces significantly the preformed plasma compared with experimental studies previously reported [2]. After the plasma mirror, pulses with energy up to 1 J were focused by means of an off-axis parabola down a focal spot of about $\approx 5\,\mu$m (containing

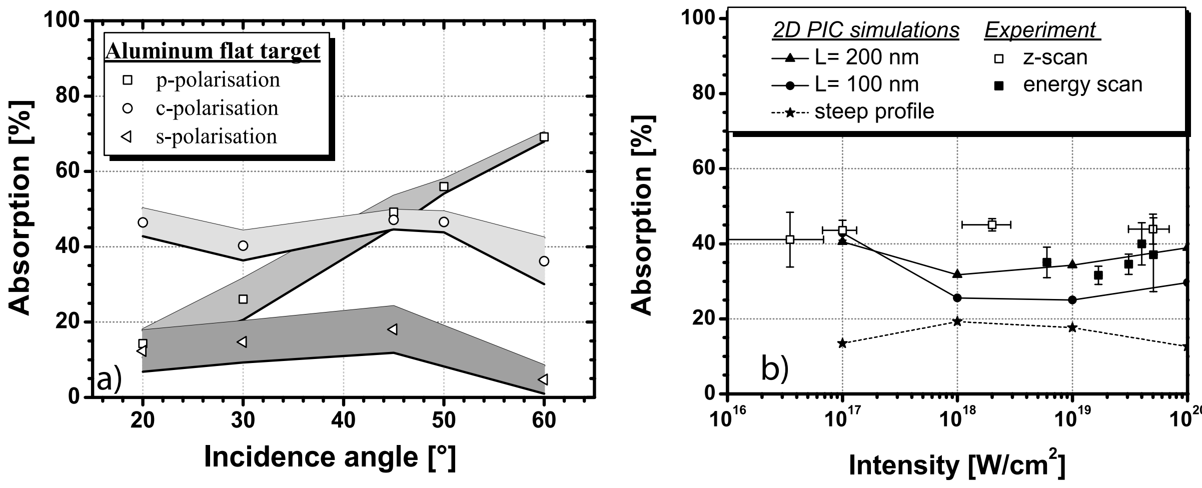


Figure 1: (a) Angular dependence of the absorbed energy fraction of p-, s- and circular polarized laser pulses by flat surface target (25 fs, $5 \times 10^{19}\,\mathrm{W/cm^2}$); (b) The experimental results of absorption energy fraction at 45° incidence angle as function on the laser intensity compared with 2D PIC simulation for different plasma profile.

50% of the laser energy). Thus, laser pulses are incident onto the targets at an average intensity of $I \approx 5 \times 10^{19}\,\mathrm{W/cm^2}$. An integrating Ulbricht sphere 20 cm in diameter was employed for measuring the absorption energy fraction.

On the first set of the experimental investigations, laser pulses were focused under different incidence angles onto an Aluminium layer with a thickness of about $1\,\mu$m deposited on glass substrate. Different polarization configurations of the pulse (p-, s- and circular) have been considered. The experimental results which show the dependence of the absorption fraction on the incidence angle are presented in Figure 1 a). It was found that the absorption fraction presents a strong dependence on the incidence angle for the p-polarization geometry and a maximum absorption fraction of about 70% was measured at an angle of incidence of 60° for targets with a surface roughness of a few nm ($<<$ laser wavelength). The data have been recorded at high laser contrast using AR multilayer coated substrates on the plasma mirror system. The absorption levels for s-polarized laser pulses are about 10% at 20° and drop off to a few percents at larger angles. In the case of circular polarized laser pulses, the absorption fraction was found to be almost constant (50% – 60%) across the investigated angular range (20° – 60°). Combined simulations using hydrodynamic and Particle-in Cell codes were performed in order to investigate the dependence of the plasma scale length and the absorption mechanisms involved. The dependence on the absorbed energy on the laser intensity was investigated over 3 orders of magnitude of the intensity range ($5 \times 10^{16}\,\mathrm{W/cm^2} - 5 \times 10^{19}\,\mathrm{W/cm^2}$) (Figure 1 b)). The incidence angle was 45° and the laser intensity was modified by moving the target along the laser axis (z-scan) and by varying the energy of the incident pulse. 2D PIC collisionless simulation have been performed for different plasma profiles. The results indicate that in the high intensity regime ($5 \times 10^{19}\,\mathrm{W/cm^2}$) the contribution of the collisionless absorption is about $25\% - 30\%$ for a plasma profile of 100 nm. This agrees with collisionless absorption estimated from the experimental measurements as $A_p - A_s$ at same incidence angle (where $A_p$ and $A_s$ is the absorption in p- and s- polarization geometry, respectively).

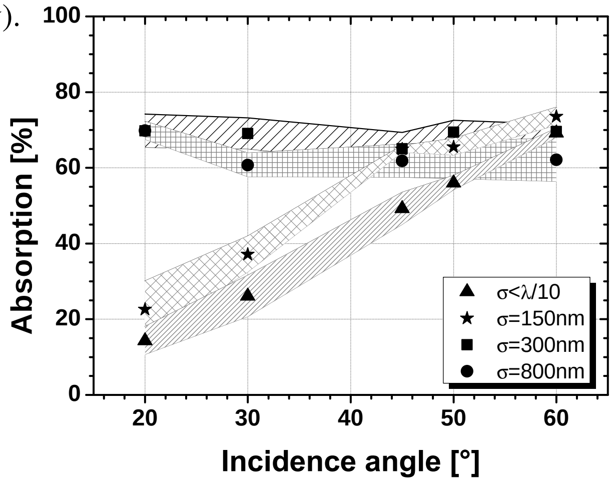

Figure 2: Experimental results representing the angular dependence of the absorption of 25 fs laser energy pulses by flat and rough targets at an average intensity of $I \approx 5 \times 10^{19}\,\mathrm{W/cm^2}$.

The effect of the surface quality on the absorption was measured by using targets with a randomly rough surface. The laser pulses have been focused in p-polarization geometry onto solid Aluminium foils commercially polished to different roughnesses. The surface structure was investigated using the atomic force microscopy method and the roughness $\sigma$ was estimated by averaging the peak-valley target nonuniformities over samples of surface $5 \times 5\,\mu\mathrm{m}^2$. The measurements have been performed in the best laser contrast conditions. In Figure 2 the absorbed fraction of the laser energy as a function of the incident angle is shown for comparison for flat targets and for targets with different roughnesses (150 nm, 300 nm and 800 nm, respectively). As can be seen, the absorption fraction for targets with a surface roughness of a few hundreds of nm was almost constant ($50\% - 60\%$) across the investigated angular range (20°-60°) whereas a clear angular dependence has been observed for targets with a modulation depth of $\leq 150$ nm.

The enhancement of the absorption in case of rough targets can be explained accounting on a couple of geometrical effects of the incident laser beam onto the target surface nonuniformities. A rough surface leads to an increased averaged incidence angle due to multiple possible incidence angles compared to an flat target in the same geometry. In addition, in case of targets with high roughness, multiple scattering of the pulse are possible which determine an enhancement of the absorption. For interpreting the experimental measurements, 2D PIC simulation were carried out and a very good agreement with the experiment was found. Moreover, the combined effect of the expanded preplasma and the target surface modulations on the absorption process was investigated. The results confirm a preplasma profile L of about 100 nm in agreement with the investigation on the flat target surface.

The irradiation of DCL foils with high intensity laser pulses has recently gained on popularity due to the prospect of high quality proton acceleration specially accessing the radiation pressure acceleration regime. In the present experiments the laser contrast enhancement was tested by irradiating ultra-thin DCL foils with a laser pulse with and without the plasma mirror arrangement. The laser energy reflected from the target and transmitted through the foil was measured. The target thicknesses varied from 10 to 100 nm. In Figure 3, there are presented the experimental results of energy transmission fraction for three different qualities of the laser contrast. With an uncoated glass plate in the mirror set-up (reflectivity is 4% before the main pulse) about 80% of the laser energy was transmitted for all the foil thicknesses used. In contrast, the transmitted fraction was only a few percents for an AR (reflectivity is 0.2%) coated plasma mirror substrate which corresponds to an improvement of the laser contrast up to a maximum value of $10^{11}$ in *ns* time scale. This indicates that the foil target was still overdense during the interaction with the high intensity laser pulse. In fact, by detecting Coherent Wake Emission harmonics in transmission the electron density was diagnosed to be greater than $300 n_c$ during the laser pulse. Together with hydro simulations the effect of the picosecond rising edge of the laser pulse on the decompression of the DLC foil targets was analyzed.

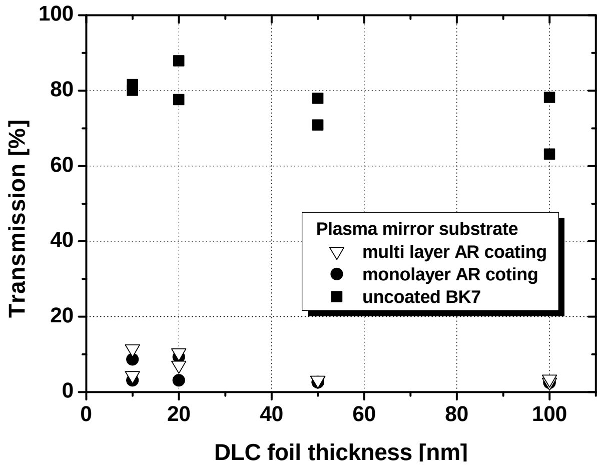


Figure 3: Transmission energy fraction through DLC foils irradiated with 25 fs laser pulses with different laser pulse contrasts.

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