Space- and time-resolved dynamics of a solid target rear surface expansion induced by fast electrons and of the energy partition into bulk cold electrons

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Abstract. Fast electrons accelerated by lasers into solids expand into vacuum from the target rear surface. They also transfer their energy to target bulk electrons, inducing target expansion into vacuum. Both the low-density cloud of fast electrons, as well as the expansion gradient of the high-density, cold target have been measured via optical probe reflectometry. This allows accessing the time- and space-resolved dynamics of the fast electron density and temperature and of the bulk (cold) electrons temperature. In particular, indicates that the mean fast electron energy, as seen at the target rear side, is a decreasing function of the target thickness.

1. Introduction
A detailed understanding of the generation of high-energy electrons by ultra-intense lasers [1] from solid-density materials and of their transport through it [2] is crucial for a number of applications. These include the fast ignition of fusion targets [3] by having large currents of electrons depositing locally their energy in precompressed fuels, and the development of bright sources of radiation (x-rays, γ-rays, neutrons) [4] or of sources of high-energy ions [5]. Indeed, all these sources result from energy transfer from fast electrons through scattering, nuclear reactions or charge-separation fields.

At laser-intensities \(>10^{18}\) W/cm², electrons are generated at the laser-solid interface with mean energies in the MeV range by a variety of mechanisms (ponderomotive acceleration [6], resonant
absorption [7], vacuum heating [8]) either in the laser direction, the target normal direction [9] or along the target [10], all depending on the laser incidence angle on the solid and on the gradient scale-length at the target front [11].

We have performed an experiment to measure the longitudinal and radial variation of the fast electron energy distribution.

2. Experiment
The experiments were performed using the LULI 100 TW laser facility working in the chirped pulse amplification (CPA) mode at a wavelength $\lambda_0 = 1.057 \text{ mm}$. The experimental set-up is shown in Figure 1a. Targets, Al foils of different thicknesses with optical quality surface and positioned at focus, were irradiated by the main laser at normal incidence. The main diagnostic was time and space-resolved interferometry (TASRI) of a probe beam reflecting off the rear (non-irradiated) surface of the solid targets. The probe beam, a pick-off from the main beam that was independently recompressed, had the same wavelength, 100 mJ energy and was chirped linearly to about 30 ps (FWHM). It was incident on the target at 45°. The delay between the main beam and the probe beam was set with a time-slide with <1 ps precision. As we want to analyze in time and space the phase of the probe beam reflecting from the target, the rear surface of the target was image- relayed on a Mach-Zender interferometer to create a spatial interference pattern (due to the angular difference of the two beams in the output) from which the spatial phase of the beam can be measured. Further image-relay brought the image of the target surface on a slit of a high-dispersion spectrometer and then onto a CCD in the dispersion plane. Since the slit selects only a part of this image, i.e. a 1D line going through the axis of the laser irradiation, on the CCD we have one dimension which corresponds to the radius on the target surface (see Figure 1b).

![Figure 1: (a) set-up of the experiment. (b) Interferogram obtained by the TASRI diagnostic.](image-url)

The other dimension is the spectrally dispersed dimension, i.e. the temporal dimension since the probe beam is linearly chirped. The spatial resolution is given by the optics and is ~5 µm; the temporal resolution is given by the spectral width of our pulse and is in our case ~4 ps. We can compare the recorded phase maps (and the dephasing velocity) to the dephasing (and dephasing velocity) obtained by simulations of the plasma expansion into vacuum, i.e. by the electron density profiles. For this we used the relativistic hybrid code described in [12]. In this way we can estimate the cold (bulk) electron temperature ($T_c$) and hot electron density ($n_h$) and temperature ($T_h$), the bulk density is known as it given by the density in the solid.

3. Results
Figure 2a shows the experimental phase map recorded at the rear target surface of a 9 µm thick aluminium target irradiated by a $\sim 5.10^{19}$ W/cm² intense laser. Time goes from left to right (time 0 corresponds to ~1.6±1 ps after the arrival of the peak of the main laser beam on target) and the ordinate corresponds to the radial dimension. The leftmost region shows no dephasing, as expected since the laser beam has not reached the target and the rear surface expansion process induced by the fast electrons has not started. After the laser irradiation, the phase of the probe beam increases, to reach several radians in a few tens of picoseconds. The dephasing is stronger in the centre of the phase map – corresponding to the centre of the laser-matter interaction point (r=0) - and decreases with
increasing radial dimension. Figure 2b shows the dephasing velocity at three radii, \( r = 0, 45 \) and \( 75 \) \( \mu m \).

We observe that the dephasing velocity reduces with the distance from the centre of the heated zone, corresponding to lower \( T_c \) with increasing radius. The dephasing velocity saturates at late times because the probe beam reflects off a constant-velocity critical surface, as is expected during the isothermal expansion of the bulk plasma heated by the fast electrons. Before this saturation takes place, i.e. at the early stage, we however observe a fast increase of the dephasing velocity, which overshoots the final constant value and then decreases progressively towards it. This transient overshoot of the dephasing velocity is due to the low-density cloud of hot electrons that can this be measured independently of the target heating.

Fitting the experimental phase maps with those obtained analytically, we find that the dephasing velocity shown in Figure 2 correspond to \( n_h \) ranging from \( 4 \times 10^{19} \text{ cm}^{-3} \) for the lineout with maximum dephasing to \( 2 \times 10^{19} \text{ cm}^{-3} \) for the lineout displaced \( 75 \mu m \) and to cold electron temperature ranging from \( 40 - 3 \text{ eV} \). The best fit has been obtained with an initial hot electron temperature of \( 0.85 \text{ MeV} \).

All fits are very sensitive to those parameters, since one can easily detect substantial differences of the dephasing velocity when increasing or decreasing the hot electron density by \( 5 \times 10^{18} \text{ cm}^{-3} \) and the hot electron temperature by \( 0.2 \text{ MeV} \). Also the cold electron temperature is univocally detected with a precision of \( \pm 10 \% \). We can therefore retrieve unambiguously \( n_h, T_h, T_c \) from the experimental phase maps. Note that for hot electron densities \( < 5 \times 10^{18} \text{ cm}^{-3} \) the hot electron contribution in the dephasing velocity becomes not anymore appreciable compared to the contribution and fluctuation of the cold electron dephasing velocity.

Figure 2: a) phase map of a \( 9 \mu m \) aluminium target, b) dephasing velocity of three lineouts taken from the phase map shown in a).

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