Fast electron energy deposition in aluminium foils: Resistive vs. drag heating

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Abstract. The high current electron beam losses have been studied experimentally with 0.7 J, 40 fs, 6 $10^{19}$ Wcm$^{-2}$ laser pulses interacting with Al foils of thicknesses 10-200 $\mu$m. The fast electron beam characteristics and the foil temperature were measured by recording the intensity of the electromagnetic emission from the foils rear side at two different wavelengths in the optical domain, $\approx 407$ nm (the second harmonic of the laser light) and $\approx 500$ nm. The experimentally observed fast electron distribution contains two components: one relativistic tail made of very energetic ($T_{\text{tail}} \approx 10$ MeV) and highly collimated ($7^\circ \pm 3^\circ$) electrons, carrying a small amount of energy (less than 1% of the laser energy), and another, the bulk of the accelerated electrons, containing lower-energy ($T_{\text{bulk}} = 500 \pm 100$ keV) more divergent electrons ($35^\circ \pm 5^\circ$), which transports about 35% of the laser energy. The relativistic component manifests itself by the coherent $2\omega_0$ emission due to the modulation of the electron density in the interaction zone. The bulk component induces a strong target heating producing measurable yields of thermal emission from the foils rear side. Our data and modeling demonstrate two mechanisms of fast electron energy deposition: resistive heating due to the neutralizing return current and collisions of fast electrons with plasma electrons. The resistive mechanism is more important at shallow target depths, representing an heating rate of 100 eV per Joule of laser energy at 15 $\mu$m. Beyond that depth, because of the beam divergence, the incident current goes under $10^{12}$ Acm$^{-2}$ and the collisional heating becomes more important than the resistive heating. The heating rate is of only 1.5 eV per Joule at 50 $\mu$m depth.

1 Introduction

A fast electron population ($\sim 100\text{keV–1\,MeV}$) can be efficiently generated (20–40% of the on-target laser energy) by the interaction of an intense laser pulse ($>10^{18}$ Wcm$^{-2}$) with matter [1]. The fast electrons are generated near the laser wavelength critical density and are injected to the over-dense target interior in a more or less collimated way. Their propagation, with current intensity $>10\text{MA}$ and current density $>10^{12}$ Acm$^{-2}$, would not be possible in free space (currents largely exceeding the Alfvén limit), but in dense matter they are very rapidly neutralized because of the setting of a return current of thermal electrons [2]. This way, the fast electrons can transport their energy over distances of a few 100 $\mu$m or more. This energy transport through dense matter can be of great advantage for the fast ignition of thermonuclear...
fusion targets, previously conditioned by laser compression [3] as well as for the improvement of ultra-short sources of energetic ion beams [4] or X-rays [5].

2 Synthesis of the experimental results

Fast electrons were generated on aluminium (Al) foil targets (10–200 μm thickness) by the LOA Salle Jaune laser at 6 × 10¹⁹ W cm⁻², with 40 fs, 0.7 J pulses, operating at λ₀ = 815 nm. Measurements of the laser-pulse contrast showed a 3 ns, 10¹³ W cm⁻² pedestal due to the Amplified Spontaneous Emission (ASE). According to hydrodynamic calculations with the 1D code CHIVAS [6], the intense pulse encounters a ≈20 μm scale-length under-dense pre-plasma.

The goals were to characterize, in our interaction conditions, the fast-electron energy distribution, the dynamics of their propagation and the level of the induced in-depth target heating. The chosen diagnostic was to measure the optical emission from the targets rear side, notably the dependence of the emitted signals spectrum and size on the target thickness. The detected signals were integrated over 5 ns, the minimum acquisition gate of the ICCDs used as detectors.

As we can see in Fig. 1-a), the spectra of the optical emission show clear spectral peaks at 2ω₀, twice the laser frequency, corresponding to Coherent Transition Radiation (CTR). This kind of emission is associated to a time modulation on the fast-electrons current crossing the target-vacuum boundary on the rear side. A broad spectrum is also seen for the thinner targets. It can correspond to either an incoherent emission (like thermal emission) or to the foot of the 2ω₀ coherent spike. We call this broad emission around 500 nm the visible light. The visible signals decrease faster with the target thickness than the 2ω₀ signals: For foils thinner than 50 μm, the two signals have the same order of magnitude, for foils thicker than 50 μm, the 2ω₀ signals are about 100 stronger than the visible signals (Fig. 1-b).

Fig. 1-c) shows the evolution of the radius of the emission zone for the different targets. The horizontal axis is the overdense thickness crossed by the fast electrons as computed by the 1D hydrodynamic code CHIVAS, accounting for the ASE-pedestal effects. This corresponds to a non-obvious longitudinal coordinate transformation, where for the thinner targets, decompressed by matter ablation (laser side) and shock breakout (rear side), the overdense thickness is risen with respect to the solid initial thickness; for foils ≥ 40 μm, no shock breakout is possible before the main pulse arrival, the total overdense thickness being quite the same of the unperturbed solid thickness. As for the spectral analysis, the spatial distribution of the emission on the targets rear side shows different behaviors for the visible and 2ω₀ spectral regions: The visible signals size grows steadily. They are practically only of thermal origin and associated to a divergent (35° ± 5°) bulk component of the fast electrons. The 2ω₀ data instead reveals a well