Generation and Transport of Fast Electrons in Laser Irradiated Targets at Relativistic Intensities

F. Amiranoff1, S.D. Baton1, L. Gremillet1, O. Guibaud1, M. Koenig1, E. Martinolli1, J.J. Santos1, M. Rabec Le Gloahec2, C. Rousseaux2, T. Hall3, D. Batani4, A. Bernardinello4, G. Greison4, E. Perelli4, F. Scianitti4, M.H. Key5, J.A. Koch5, A.J. Mackinnon5, R.R. Freeman6, R.A. Snavely6, C. Andersen6, T.E. Cowan7, R.B. Stephens7, Y. Aglistkiy8

Abstract. The transport of relativistic electrons in solid targets irradiated by a short laser pulse at relativistic intensities has been studied both experimentally and numerically. A Monte-Carlo collision code takes into account individual collisions with the ions and electrons in the target. A 3D-hybrid code takes into account these collisions as well as the generation of electric and magnetic fields and the self-consistent motion of the electrons in these fields. It predicts a magnetic guiding of a fraction of the fast electron current over long distances and a localized heating of the material along the propagation axis.

In experiments performed at LULI on the 100 TW laser facility, several diagnostics have been implemented to diagnose the geometry of the fast electron transport and the target heating. The typical conditions were: £/£<20 J, A=1 µm, r~300 fs, 7~10^{18}-5.10^{19} W/cm^{2}. The results indicate a modest heating of the target (typically 20-40 eV over 20 µm to 50 µm), consistent with an acceleration of the electrons inside a wide aperture cone along the laser axis.

INTRODUCTION

The fast-igniter scheme for the inertial laser fusion relies on the heating of a compressed DT core by a beam of high-energy electrons accelerated by an intense laser beam in the plasma surrounding the target [1-3]. The main physical issues are: (i) the transfer of the laser energy to fast electrons with a well adapted energy spectrum and angular distribution; (ii) the transport of these fast electrons from the acceleration region to the compressed core itself; (iii) the heating of the fuel by the fast electrons,
and; (iv) the resulting ignition of the fuel and neutron production. All of these aspects have already been addressed in theoretical, numerical and experimental studies [1-12].

The results obtained at the LULI laboratory on electron transport and solid target heating with a 100 TW laser beam are detailed in this paper.

**EXPERIMENTAL SET-UP AND RESULTS**

The experiments have been performed on the LULI 100 TW laser facility. The 350 fs, 1.057 μm laser pulse with an energy up to 10 J was focused by a f/3 off-axis parabola at normal incidence onto flat solid targets, either Al foils or sandwich targets. The laser focal spot was 15 μm to 20 μm in diameter corresponding to a maximum intensity of $5 \times 10^{19}$ W/cm$^2$. Several optical as well as x-ray diagnostics have been implemented to diagnose the geometry and the efficiency of the target heating.

**Visible Self Emission**

The target rear side was imaged with a f/2 optical system on both a CCD camera and a streak camera. The spectral sensitivity domain extends from 350 nm to 880 nm with a maximum at 600 nm, except for a 60 nm region around 530 nm, the second harmonic of the laser light. A typical time-integrated image consists of two features. A large and smooth halo, due to thermal emission of the cooling and expanding plasma lasts for nanoseconds. On the contrary, a smaller spot in the center is emitted in less than 10 ps. It is due either to the electrons crossing the back surface and emitting optical transition radiation (OTR) [13], or to the same electrons emitting bremsstrahlung radiation while reflecting in the Debye sheath [14]. The diameter of this prompt feature (shown in Fig.1) increases with Al target thickness (Fig.2), showing an electron spread in the target with a typical half angle of $\theta/2 \approx 17^\circ$. At the same time the corresponding integrated signal drops rapidly at small thicknesses before decreasing more smoothly.

![FIGURE 1. Time-resolved images for three Al thicknesses and $I = 10^{19} W/cm^2$.](image)

To estimate the light intensity we used the code PaRIS [12]. This code models both collision effects (multiple scattering and slowing down) and self-generated electric and magnetic fields. Simulation conditions for the initial electronic population were chosen in order to be as close as possible to experimental conditions. The initial hot
electron temperature is given by the scaling law [Beg] $T_h(r,t) = 100 \left(I_{17}(r,t)\right)^{1/3} \text{[keV]}$
where $I_{17}(r,t)$ is the laser intensity in units of $10^{17} \text{ W/cm}^2$. Injecting an electron population with a 1.6 J total energy, a pulse duration of 300 fs, over a 20 µm focal spot into a 75 µm thickness Al target, PâRIS gives $5.2 \times 10^{12}$ outgoing electrons with a total energy of 0.46 J. From this, the estimates of the OTR signal and the synchrotron radiation are both close to $4.10^{-13} \text{ J}$, in good agreement with the measured value.

![Graph](image1)

**FIGURE 2.** FWHM of the time-resolved images (left), integral of the signal (right)

**Reflectometry in the Visible Domain**

A probe beam at $\lambda = 0.53 \mu m$ was incident at 45° on the back side of the target. A second optical system measured the reflectivity of the target as function of space and time. Two modes of operation have been used. In the first mode, the probe beam was compressed to 300 fs and the image was measured on a CCD camera for different time delays between the interaction beam and the probe beam. In the second mode, the probe beam was frequency chirped to about 100 ps, and the image was sent through a spectrometer. The time-frequency relation then gives a time resolution of 2-3 ps over the whole duration of the probe beam [15].

![Graph](image2)

**FIGURE 3.** Rear side Reflectometry images; 17 µm Al target, $8.5 \times 10^{17} \text{ W/cm}^2$. 
The images presented in Fig.3 show a low reflectivity spot, which expands at an average radial speed of 2-3 $10^6$ m/s. The reflectivity in the center drops to values below 0.3. The chirped pulse data show that the change in reflectivity starts a few ps after the main pulse, expanding at a very high initial radial velocity of 5-7 $10^6$ m/s before dropping to $10^6$ m/s after 30 ps. For thin targets (35 µm), the initial diameter of the perturbation is only slightly larger that the focal spot while it increases for larger thicknesses.

The values of the reflectivity suggest that the back side temperature is between a few eV and 100 eV. Assuming that the radial expansion corresponds to the thermal electron velocity, we infer a temperature starting at $T \approx 120$ eV then decreasing to about 20 eV for the average expansion velocity.

**X-ray Kα Spectroscopy**

A conically bent KDP crystal x-ray spectrometer was used to measure the spectrum between 7 Å and 8.5 Å. This domain includes the cold Al Kα line as well as the shifted Kα line of heated and ionized Al. A typical spectrum is shown in Fig.4 for a 28 µm Al target and an incident laser energy of 10 joules. It shows a broad cold Kα emission spot (8.339 Å) and a shifted Kα line at 8.275 Å. This Kα line is relatively weak and is only visible up to 50 µm targets. The shift corresponds to an ionization stage (Z*) of 5. From the model of Lee and More [16], the estimated temperature is of the order of 40 eV. This result is preliminary and a more accurate model will be developed to calculate the ion populations.

**FIGURE 4.** Spectrum for a 28 µm Al target: cold Kα line (8.339 Å) and ionized Kα line (8.275 Å).

**Rear Side XUV Imaging**

The back side of the target was imaged in the XUV domain at 180 Å with a 5 µm spatial resolution using a multidielectric spherical mirror and an additional flat mirror with both a 50% reflectivity. Images obtained for 2.2 µm and 27 µm Al targets are shown in Fig.5. For the thinnest targets, the diameter at half-max intensity was 67 µm, much larger than the laser focal spot. For larger thicknesses, the increase in diameter suggests propagation in a $\approx 50°$-$60°$ cone angle.
The XUV signal is mainly due to thermal radiation of the cooling and expanding plasma at the back of the target. From the absolute intensity, and using 1D-LASNEX simulations for the evolution of the heated plasma, one can infer the initial temperature of the emitting region. At maximum laser energy, and for thicknesses up to 30 \( \mu m \), \( T \approx 20 \) eV. For larger thicknesses, the temperature decreases and the diameter increases so that the signal is too low to be detected.

**X-ray K\(_a\) Imaging of Fluor Layers**

In order to diagnose the propagation of the fast electrons in the bulk of the target, the Ti K\(_a\) line at 4.5 keV of embedded 20 \( \mu m \) thick Ti layers in Al/Ti/Al sandwich targets was imaged using a spherical Bragg crystal with a resolution of 10 \( \mu m \). Two examples are shown in Fig.6. In agreement with the XUV images, the data show a minimum radius of 34 \( \mu m \) and a cone angle of 54°.
PÂRIS SIMULATIONS

The experimental data indicate a temperature of the order of 20 eV up to Al thicknesses of 30 μm. Results obtained from PÂRIS simulations are shown in Fig. 7. When the electrons are injected at normal incidence, most of them are magnetically guided along the axis. The final temperature is of the order of a few hundred eV (and even a few keV near the front side of the target) over a radius of a few microns only, in disagreement with the experimental data. On the contrary, if the electrons are injected inside a wide aperture cone, only part of them are magnetically guided and the diameter of the heated region is much wider. The final temperature is of the order of a few 10 eV. These two features are in much better agreement with the measurements.

FIGURE 7. Temperature profiles in keV obtained from PÂRIS simulations. Electrons are injected from the bottom. Left: 1.6 J of electrons injected at normal incidence inside a 6 μm FWHM focal spot in 300 fs with $T_h = f(I)$ and $I_{\text{max}} = 3 \times 10^{19}$ W/cm$^2$. Right: same conditions except 1.2 J injected in a ±40° cone angle and $I_{\text{max}} = 2 \times 10^{19}$ W/cm$^2$.

CONCLUSION

Experiments on the generation and transport of fast electrons and on the resulting heating of the target have been conducted on the 100 TW LULI laser facility at a maximum intensity of $\approx 3 \times 10^{19}$ W/cm$^2$ and a maximum laser energy of 10 J. The results show a modest heating of the target, of the order of 20-40 eV up to 50 μm of Al. This is consistent with about 10% to 30% of the laser energy being transferred to fast electrons inside a large angle cone, typically ±20° to ±40°.

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