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Experimental Characterization of Electron Heat Transport on the LIL Facility

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1 – Motivations

The amount of energy available to drive the ablative implosion of an ICF capsule as well as the stability and symmetry of the ablation front mostly depend on the electron thermal conduction. A basic model for heat conduction in local thermal equilibrium (LTE) plasmas is the Spitzer Harm (SH) heat flux. This theory has been modified to model the experimental observations limiting artificially the SH flux to some fraction f of the free-streaming flux. A few years ago, a more sophisticated non-local heat conduction model has been introduced in 1D hydrodynamic simulations [1] . Recently, a non-local model [2,3] was introduced in the new two-dimensional hydro code CHIC [4] developed at CELIA.

We present here an experiment designed to test this numerical tool in conditions relevant to direct-drive ICF. A preliminary campaign was achieved in December 2005 at the “Ligne d’Integration Laser” facility, the prototype of the Laser Megajoule (LMJ). The LIL facility routinely delivers 10 kJ, 2.7ns laser pulses, in quasi-gaussian smooth focal spots. Maximum intensities (up to 2 10^{15} W/cm^2) and large focal spots (320 μm FWHM) create plasma parameters similar to future LMJ implosion experiments. LIL was thus appropriate to study the propagation of an electron heat wave in ICF relevant conditions.

2 – Principle of the experiment

The purpose of the experiment is to measure the velocity of the heat wave for different laser intensities. At low intensities, we expect SH to be correct. At high intensities, we expect the appearance of long-range electrons, responsible for non-local heating. In any case, two dimensional effects, among them self-generated B-fields, are likely to occur.

The time dependent He-like lines emission of two thin metallic markers embedded in a thick plastic disc **(figure 1)** was measured in order to obtain the heat wave velocity. The disc was thick enough (300μm) so that the rarefaction wave originating from the rear side of the target did not interact with the ablation front: the target is not accelerated and is therefore Rayleigh-Taylor stable.

The markers are Vanadium and Titanium layers (helium-like resonance lines at 5.2 keV and 4.7 keV respectively). The layer geometry naturally generates 2D effects related to the finite size of the focal spot, which make the interpretation more difficult. Nevertheless, we have chosen this shape in order to maximize the X ray emission. The markers thickness is constrained by two opposite trends: the markers should be thick enough to radiate a measurable signal and as thin as possible in order not to perturb the heat flow. For this experiment, we used 0.05 and 0.2 micron thick layers. The laser energy was varied from 4 kJ to 10 kJ, corresponding to intensities of 8 10^{14} - 2 10^{15} W/cm^2.

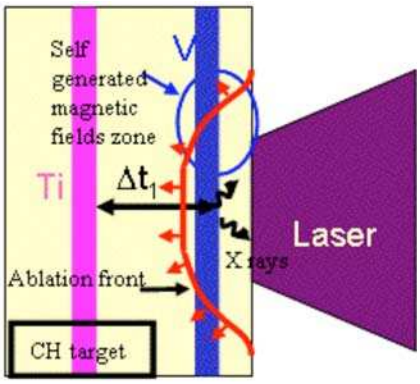

***Figure 1** : principle of the experiment. The heat flow velocity is measured by time-resolving the X-ray emission of two markers.*

3 – Plasma diagnostics

The main diagnostic was a time-resolved, crystal spectrometer [5]. It measured the emission of the metallic layers in the 4.5 – 5.5 keV spectral range at an angle of 50° with respect to the laser beam direction. It was equipped with a graphite HOPG cylindrical Johan crystal (inter-reticular distance 2d = 0.6708 nm) to provide a very high efficiency (about 20 %) in the spectral region of interest, with a low spectral resolution. The spectrum was recorded with a streak camera. The time resolution was better than 100 ps.

A 250 mm radius cylindrical Johan crystal of germanium (111) (inter-reticular distance 2d = 0.6532 nm) was used to record the time-integrated spectrum in the range of 5 to 5.5 keV, at an angle of 10° with respect to the laser beam direction. The spectrum was filtered with a 10 μm thick Al foil and 5 μm thick Cu foil.

A broadband, time-resolved X ray spectrometer [6] complementary to the crystal time-resolved spectrometer measured the K-shell lines emitted by the markers, and was also recording the L-shell emission (at about 800 eV).

Two 2D imagers observed the X ray emission (typically at energy higher than 4 keV) of the plasma in a front view. One of them (pinhole imager) is time integrated and the recorded images show a circular X ray emission zone of about 600 μm diameter.

The other one is a gated Kirkpatrick – Baez 2D multi-imager [7]. It was time-resolved and recorded images at four different times. For each time, two different filters allowed to image the plasma in two spectral ranges. The exposure time was 400 ps, and the delay between each image was set to 0.5 ns. The results of this diagnostic, not fully analyzed yet, should give valuable information regarding the lateral heat flow.

Finally, a Kirkpatrick – Baez imager coupled to a X-ray streak camera recorded time resolved 1D image of the target at 90°. This diagnostic gives an insight into the hydrodynamic expansion of the plasma.

4 – Experimental results and discussion

The vanadium spectrum has been measured with the time integrated crystal spectrometer, for 10 kJ incident on a target with 0.2 μm thick layers of V buried at 10 μm from the target surface and Ti buried at 30 μm. Ti lines were too weak to be observed. V lines were recorded, covering the He α line at 5204.6 eV, the H-like Ly α at 5443.4 eV and the He β line at 6118.3 eV. The spectrum is in quite good agreement with the emission spectrum calculated by the TRANSPEC code [8] for a V plasma with fixed electronic density (5 10^{21} cm^{-3}) and temperature (2 keV).

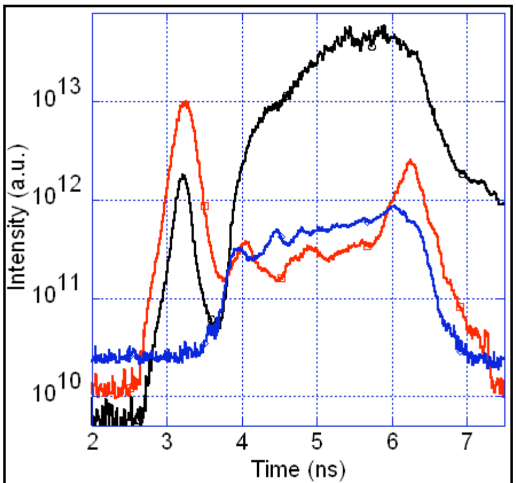

***Figure 2** : Vanadium(black), titanium (red) and continuum (blue) X-ray emission as a function of time, of a target embedded with 0.05 μm layers of V and Ti buried at 5 and 15 μm respectively (E_{laser}=3.7 kJ).*

Figure 2 shows a typical time evolution of the X-ray emission of the target recorded by the time resolved crystal spectrometer. This spectrometer was able to record the signals on every shot, including when the markers thickness was 0.05 μm. The duration of the continuum emission is consistent with the laser duration. The two peaks around 3.2-ns are spurious direct X-rays.

The time delay between the onsets of the K-shell lines of the markers, as measured by both independent spectrometers (crystal and broadband), are in good agreement **(figure 3)**. The time delay varies with the inverse one-third power of laser energy, that is the same scaling law as the inverse of the ablated mass yield. For a 0.05 μm thick layer, the delay is noticeably shorter than the scaling law plotted for the 0.2 μm thick markers, due to the transit time through the first probe layer.

2D simulations with the CHIC code with the non-local model without magnetic fields do not reproduce the measurements. Additional simulations with the flux limit model reproduce the measured delays, but using several flux limit values, from f = 20% for 4 kJ laser shot, to 5% for 10 kJ. However, an ideal MHD module in the hydrocode shows very intense magnetic fields (a few MGauss) that could inhibit the heat transport. Simulations with magnetized transport are under investigation.

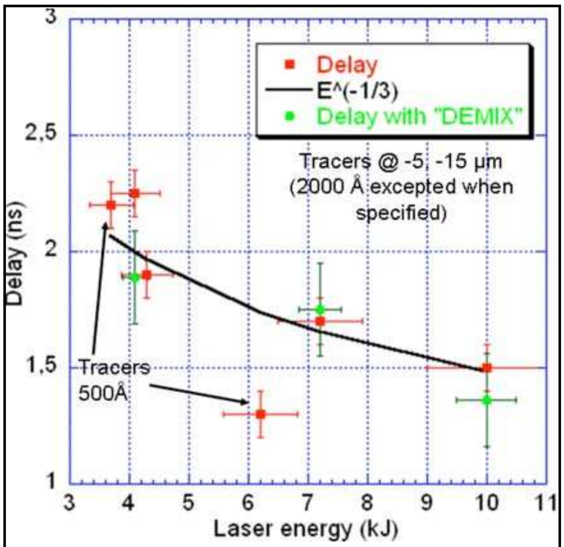

Figure 3 : Time delay between the onsets of the K-shell lines of the markers as a function of the laser energy

Conclusion

This first campaign performed on the LIL facility to study the electron heat transport in the conditions relevant to direct-drive ICF brings preliminary conclusions. The main experimental result is the evolution of the time delay between the emissions of He alpha lines of two markers embedded in the target, as a function of the laser energy. Comparison with the CHIC 2D hydrocode results shows a general agreement which should be improved taking into account the self-generated magnetic fields. However, 2D effects in the probe layers induce substantial uncertainties (see error bars in figure 3), and a second campaign with dot markers instead of layers is scheduled later in 2006.

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