Fast electron propagation in high-density plasmas created by shock wave compression

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Abstract. Until now almost all the experimental results on fast electron generation and transport have been obtained in solid targets. It is clear instead that the fast ignitor approach to inertial fusion concerns the propagation of a fast electron beam in dense hot plasma in the pellet surrounding the nuclear fuel.
We present preliminary results from a recent experiment on fast electrons propagation and energy deposition in high density plasmas created by shock wave compression. The results were obtained at the PICO 2000 laser system at LULI, coupling a 400 J, 1.5 ns, 2ω compression beam with a counter-propagating 50 J, 1 ps high-intensity beam. Focused intensities larger than 10^{18} W/cm^2 generated intense currents of fast electrons through the in-depth regions of the target, which are shock-compressed at 3-4 times the initial solid density.
We used multi-layered targets with thin copper and aluminium X-ray fluorescent layers and either aluminium or plastic (CH) propagation layers of variable length. The geometry (divergence) and the range of the fast electrons propagation were diagnosed by Cu X-Kα signal imaging and by X-ray spectroscopy, covering both Al (1st diffraction order) and Cu (5th order) Kα emissions. Target heating was measured from ionisation-shifted Al Kα emission. For each kind of target, the results are compared to the cold case (no compression beam).
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1. Introduction

Practically, until today, all the experimental studies on fast electron propagation have been conducted with targets, which, at least initially, are in solid state. However it is clear how the fast ignitor scheme [1] concerns the propagation of fast electron beam in the dense and hot plasma in the pellet, which surrounds the thermonuclear fuel.
There are only two exceptions, which have tried to address the last phase of the fast ignitor approach to ICF, i.e. the hot electron propagation and energy deposition in strongly compressed materials. The first one has been an experiment performed at the Rutherford Appleton laboratory 10 years ago, by an Italian-French-English scientific team. The experimental results were presented in [2] and analysed in details in [3]. The second experiment is much more recent and studied fast electron transport study in beyond solid density targets produced by cylindrical implosions [4].
In this experiment however we follow the approach of [2,3] because ewe think that the simpler (1D) geometry offers more accessibility to diagnostics and also intrinsically allows for the production of more uniform compressed matter, which in turns may provide a simpler interpretation of obtained experimental data. The experimental data of [2,3] showed a much larger fast electron penetration in the shocked material (about a 100% increase), which was due to the phase change produced in the target material by the shock wave. While the initially cold solid target was an insulator (plastic), the shocked target was ionized and changed to a

conductor state by shock compression and heating. Indeed the theoretical/numerical analysis showed how the effects of self-generated strong electric fields were essential for the interpretation of results.
With respect to this, we want to stress how shock compression does not change stopping power of matter significantly: the parameters of the target material appear inside a logarithmic term and therefore do not produce large variations. The stopping power is instead inversely proportional to target density (which appears outside of the logarithmic term) and which is directly and strongly affected by shock compression (up to a maximum factor of 4 for strong single shocks). However, since compression up to a certain factor reduces the target thickness of the same factor, the total areal density remains the same. Therefore no large variations of the collisional stopping power are expected in this kind of experiments.
Instead, collective effects (due to self generated magnetic and electric fields) will be dramatically affected both because of the change in the material properties, and because, for instance, the deceleration of hot electrons in the electric field is proportional to $\int E \cdot dl$. and therefore to the total target thickness, which is reduced in the experiments.

With respect to the old experiment at RAL, we have implemented several changes, which completely change the character of the experiment:

1) we have used metal targets in addition to plastic ones. This has several implications:
   a] no energy from the fast electron beam is spent for the ionization of the target material (it is well known that in insulators, ionization of the background material must take place in order to create free electrons available for the return current)
   b] the behaviour of electrical conductivity vs. target temperature and density is much better known for conductors than for insulators. This knowledge is both experimental (see e.g. the well known measurements by Milchberg et al. for Al [5]) and theoretical (using semi-quantum models like those of More [6] or of Eidmann and Huller [7]). Moreover the both the cold and shocked targets have a significant conductivity (again with respect to insulators) being at the same time closer between them and closer to the regime of ICF plasmas.
2) the CPA beam intensity was much higher than in the RAL experiment. There the intensities of 10^{17} W/cm^2 were used, really far from the range of interest for fast ignition. Indeed the energy of the hot electrons produced was quite low ($\approx$ 50 keV). Although this did not jeopardise the physical interest of results reported in [2,3], in the present experiment we produced truly relativistic electrons ($\approx$ 1 – 2 MeV), which will allow an easier extrapolation of our results to the fast ignitor regime.
3) The energy of the ns laser beam was larger and its pulse duration longer, thus allowing to create a larger shock pressure, implying a larger compression factor (which will approach the factor 4 limit), a larger material temperature, and a larger shock velocity. The larger velocity, coupled to the longer pulse length, allowed for the uniform compression of longer targets. To this aim, we used Phase Zone Plates (PZP) [8] to produce a flat shock and thus more homogeneous plasmas.

2. Experimental set-up

Here we present preliminary results from a recent experiment on fast electrons propagation and energy deposition in high density plasmas created by shock wave compression. The results were obtained at the PICO 2000 laser system at LULI, coupling a 400 J, 1.5 ns, 2 omega compression beam with a counter-propagating 50 J, 1 ps high-intensity beam. Focused intensities larger than 1e18 W/cm2 generated intense currents of fast electrons through the in-depth regions of the target, shock-compressed at 3-4 times the initial solid density. In reality, due to technical constraints in the interaction chamber, the two beams were not exactly counter-propagating, the ns laser beam being focused at 45 degrees on the target "front" side, while the ps beam was focused at 22.5 degrees on the target "rear" side. This does not imply any change in the basic scheme because both the generated shock and the fast electron beam are travelling normally to the target. The scheme of the experiment is shown in Fig. 1.

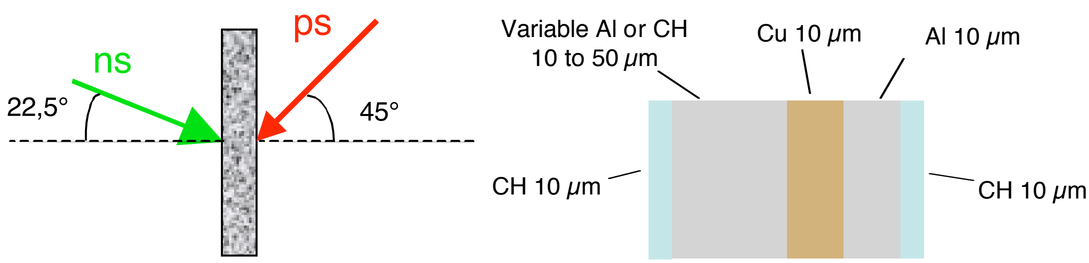

FIG. 1. In-principle scheme of the experimental set-up and of the used targets.

The diagnostic system was based on the use of a fluorescent bi-layer made in all cases of 10 micron Al and 10 micron Cu. The Kα signal from the Cu layer was recorded through a spherical Bragg crystal imaging the X-ray source on a CCD or onto image plates [9]. This imaging diagnostics allowed to get 2D images of the spatial distribution of fast electrons as they cross the Cu tracer (producing ionization followed by Kα emission), therefore allowing reconstructing the beam geometry and divergence.

The Kα emission from the Al layer was recorded in the 1st diffraction order by a conical crystal X-ray spectrometer [10]. Its spectral resolution allowed measuring both the Kα from cold Al atoms and the shifted Kα emission from Al ions. Since the degree of ionisation in the Al layer is a function of temperature, in principle such a diagnostics allows to infer the background temperature in the tracer by measuring the ratio between cold and "hot" Kα lines [11]. The spectrometer also measured the Cu Kα emission in the 5th diffraction order. Both diagnostics allowed measuring the propagation range of fast electrons in the material by plotting the Kα signal vs. target thickness obtained on different shots.

The thickness to be changed was the "propagation layer" (as shown in Fig. 1). We used both "conducting" targets (Al propagation layer) and "insulating" target (plastic layer) in order to compare different materials, which have shown different propagation characteristics in previous works [12, 13], and to see if they behave in a similarly under shock compression. For each kind of target, the results are compared to the cold case (no compression beam).

In the case of Al layer, the Cu layer also filtered the X-ray emission from the propagation layer, so that only the Al X-rays emitted from the Al tracer layer could reach the spectrometer. Two additional plastic layers, each 10 microns, were added on both sides. On the ns side this served to reduce preheating which could arise from the direct interaction of the ns beam with Al. The presence of plastic on the ps beam was due to the fact that in all cases we wanted the same fast electron source; therefore we chose to have the laser always interacting with a plastic layer. At the same time, plastic reduced any X-ray preheating, which could arise due to the laser prepulse. For the same reason (i.e. maintaining the same fast electron source in all cases), when the ns beam was fired, the ps beam was timed so to be fired before shock breakout (actually leaving the last 10 microns of plastic uncompressed). Finally a very thin Al layer was added onto plastics in order to avoid laser shine-through.

3. Experimental results

Fig. 2 shows the results from the shock breakout diagnostics (time resolved visible imaging using a streak camera), which allowed the timing of the ps beam. In order to produce a flat-top laser intensity profile, and therefore an uniform compression of the material, the ns beam was smoothed by using Phase Zone Plates [8].

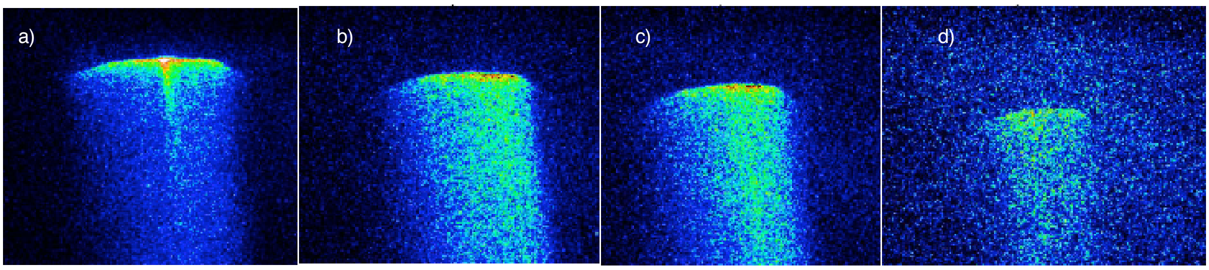

FIG. 2: Images of shock breakout from rear side of multilayer targets: a) 10 CH / 10 Cu / 10 Al / 10 CH, Breakout time = 1.79 ns , Laser energy before conversion = 777 J; b) 50 CH / 10 Cu / 10 Al / 10 CH, Breakout = 4.72 ns, Energy = 853 J; c) 10 CH / 29 Al / 10 Cu / 10 Al / 10 CH, Breakout = 3.32 ns, Energy = 849 J; d) 10 CH / 10.7 Al / 12.4 Cu / 13.2 Al / 10 CH, Breakout = 2.71 ns, Energy = 833 J. Target thickness are given in microns.

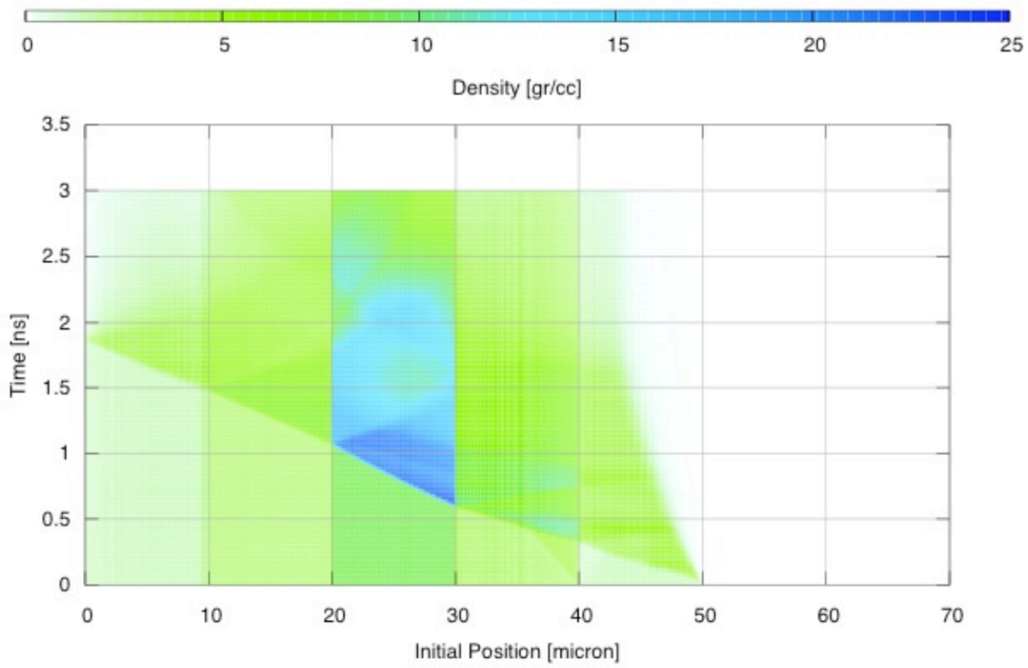

FIG. 3: Results of shock propagation in a multilayer target (10 μm CH / 10 μm Al / 10 μm Cu / 10 μm Al / 10 μm CH) obtained by using the 1D hydro code MULTI.

Such experimental images, together with numerical hydro simulations, allowed for the timing of the ns laser beam. For instance, Fig. 3 shows the results of shock propagation in a multilayer target (10 µm CH / 10 µm Al / 10 µm Cu / 10 µm Al / 10 µm CH) obtained by using the 1D hydro code MULTI [14]. The shock breaks out of the rear plastic target at about 1.9 ns after the ns the laser pulse arrival on target front side. Moreover we see that by firing the ps laser beam at about 1.5 ns, we leave the last 10 µm plastic uncompressed. This assures that in both case (with or without the ns beam fired) the short-pulse high-intensity beam interacts with *the same* material and therefore the fast electron source is the same.

Fig.4 shows some experimental results (Kα images obtained with the spherical crystal) for various conditions, while Fig. 5 gives a summary of our experimental results obtained by Kα imaging (the Kα spectrometer gave qualitatively the same kind of results). Here the total Ka signal (obtained by integration of the images, like those in Fig. 4, over the spot size) is shown vs. the thickness of the propagation layer.

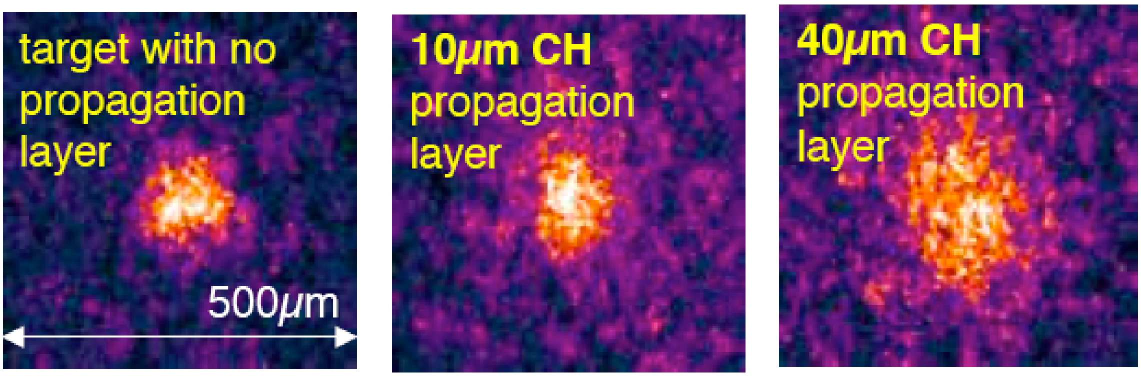

FIG. 4: Typical results from the Kα imaging spectrometer (Kα emission from the Cu layer)

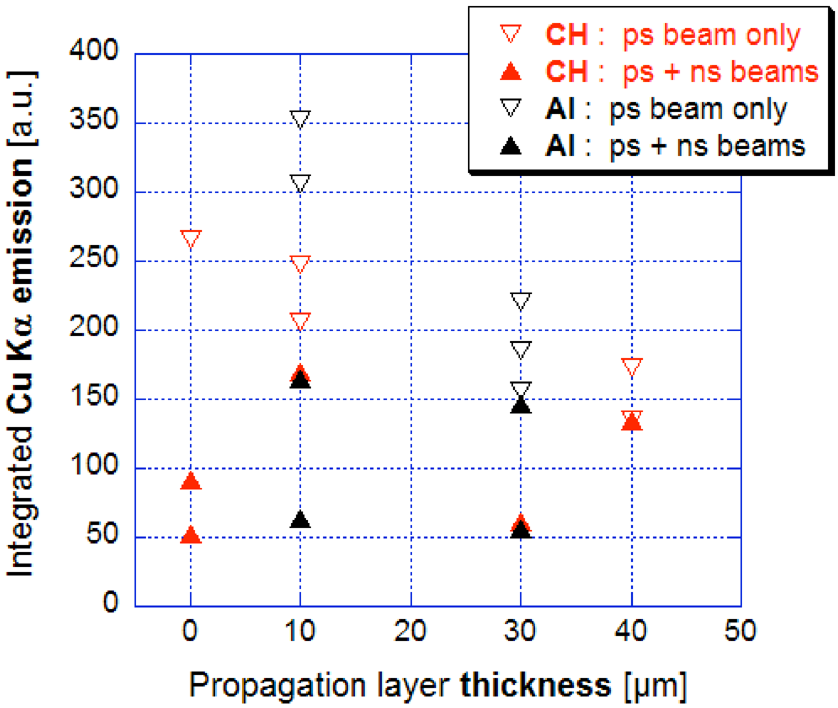

FIG. 5: Kα yield (integrated over the Kα spot) from Kα Cu imager vs. the thickness of the propagation layer.

4. Conclusions

We have presented preliminary results from an experiment, conducted at the LULI laboratory in the first months of 2008, concerning fast electron transport in shock compressed targets at laser intensities relevant for fast ignition (I > 10^{19} W/cm^2).

The complete analysis of our results is still under way and only preliminary conclusions are available [15]. Our results still need to be checked by careful modelling and simulations accounting for both hydrodynamics and fast electron induced heating. For each target layer, we must consider density and temperature-depending properties: the collisional stopping power (bound and free electrons, and excitation of plasma wave), the Cu K-shell ionization cross section, the electrical conductivity, the electric field transport inhibition and the role of magnetic fields.

The analysis of only the fluorescence yields of a target-embedded copper layer, we can nevertheless point out a few preliminary conclusions. As already observed in previous works [12], in solid matter the fast electron transport is more inhibited in CH targets (insulator) as compared to Al targets (metallic conductor). This is clearly due to the effects of self-induced electric fields.

In the case of shock compressed materials, the fast electron penetration range is roughly equivalent for compressed CH and Al, as both targets are ionised by shock propagation and behave like a conducting plasma independently of their initial nature. Therefore, the collisional stopping power should not be a determinant parameter in determining propagation dynamics.

What remains to be understood is the (at least apparent) decrease in yield in the case of shock compressed targets, a somewhat unexpected result, especially in comparison with results shown in [2.3].

Acknowledgments

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