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Fast electron transport and heating in solid-density matter

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Abstract

Two experiments have been performed to investigate heating by high-intensity laser-generated electrons, in the context of studies of the fast ignitor approach to inertial confinement fusion (ICF). A new spectrometer and layered targets have been used to detect K_α emission from aluminum heated by a fast electron beam. Results show that a temperature of about 40 eV is reached in solid density aluminum up to a depth of about 100 μm.

Keywords: Fast electron beam; Fast ignitor; K_α spectroscopy; X-ray spectrometer

1. INTRODUCTION

In the fast ignitor scheme for inertial confinement fusion (ICF), the phase of compression of the nuclear fuel is separated from the phase of ignition. Heating and ignition are caused by a fast (relativistic) electron beam travelling in the fuel, generated by a short-pulse, high-energy laser beam focused on the target at high irradiance.

Various experiments have been done to investigate the propagation of the fast electron beam into solid density materials. These demonstrated good conversion efficiency from laser energy to electrons, and high electron temperatures in agreement with the scaling law

$$T\,(\text{keV}) = 100(I\lambda^2)^{1/3}$$

(Beg *et al.*, 1997), where I is in units of 10^{17} W/cm^2 and λ in microns. As an example, at a laser irradiance of about 10^{19} W/cm^2 at LULI, Pisani *et al.* (2000) obtained a conversion efficiency of about 25% with an average fast electron energy of about 500 keV and a penetration depth $l_0 \approx$ 230 μm in solid aluminum targets ($\rho = 2.7$ g/cm^3). Such penetration was in good agreement with *collisional* models, aluminum being a good conductor, which implies negligible electric field inhibition, as predicted by Bell *et al.* (1997).

Until now, no experiment really investigated the heating effect of fast electron beams, a crucial point in fast ignition. With this goal, we carried out two experiments with the LULI and VULCAN lasers, with an energy on target of about 20–25 J and 100–120 J, respectively, and intensity on target of the order of 10^{19} W/cm^2. In particular, we wanted to have as accurate as possible an indication of the temperature reached in the metal, at solid density and at different depths, due to heating by the electrons.

As a diagnostic for the temperature, we used K_α emission from aluminum. In many recent experiments K_α emission from cold atoms has been used as a diagnostic for fast electron penetration (see, e.g., Beg *et al.*, 1997; Pisani *et al.*, 2000). Here we have exploited the fact that ionized atoms emit shifted K_α lines (the wavelengths depend on the ionization stage of the emitting atom; House, 1968). This effect is due to the reduced screening in the ionized atom, due to the lower number of electrons. In our case, ionization arises because of strong heating of the material (to temperatures of several electron volts) induced by the passage of the fast electron beam. Then, using appropriate models, the shifted

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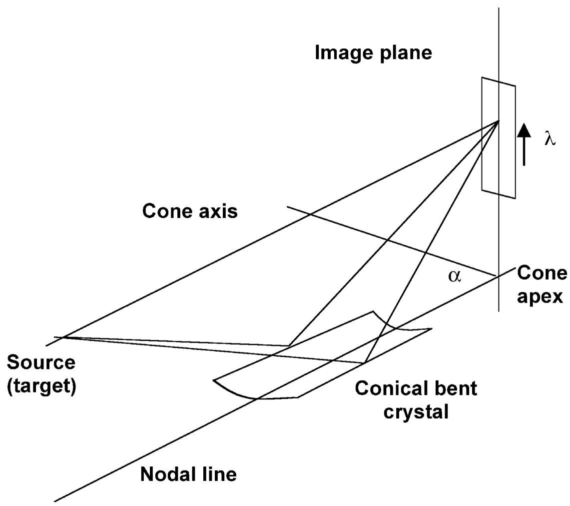

Fig. 1. Spectrometer schema.

K_α emission can be related to the ionic population and to the temperature of the emitting material.

One of the goals of the experiments was to separate the fast electron contribution to the heating from other effects. To do this, we used multilayered targets, as discussed in the following section.

2. EXPERIMENTAL SETUP

We performed experiments using the LULI terawatt laser chain and the VULCAN laser chain. The LULI CPA laser chain (a Ti:sapphire laser pulse amplified by four Nd:glass stages) allowed us to reach a pulse duration of about 300 fs, with an energy (measured at the output of the compressor) of 20–25 J at $\lambda = 1057$ nm. About half of this energy was contained inside the focal spot. The laser pulse was focused on a focal spot with a typical diameter of about 10 μm (as verified with a pinhole camera). The irradiance on the target was about 10^{19} W/cm^2.

The VULCAN laser chain (with five amplification stages) allowed us to focus an energy up to 120 J on a focal spot of about 6 μm radius; the duration of the pulse was of 1 ps, and the irradiance was a few times 10^{19} W/cm^2.

To detect the X-ray lines, a new spectrometer has been developed, based on a conically bent KAP Bragg crystal, a scheme first proposed by Hall (1994). Such a device, shown in Figure 1, presents some advantages with respect to the traditional Von Hamos spectrometer: a great compactness, a high brightness (the conical bent crystal concentrates photons on the detector), and a large spectral window (7–8.5 Å).

Targets used during the experiments were of two types: Some were of pure aluminum, others were "sandwich" targets composed of two aluminum foils, with variable thickness, and a central copper foil (see Fig. 2). We used pure aluminum target from 2.2 μm to 450 μm (at LULI) and from 6 to 1000 μm (at VULCAN); the Al-Cu-Al targets had a central copper layer of 20 μm and a final layer of 20 μm, while the first aluminum (propagation) layer ranged from 20 to 500 μm. A few targets had instead a 25-μm copper layer and a 16-μm third aluminum layer: This does not change the general meaning of the results.

When a high intensity, short-pulse laser is focused on the front face of the first aluminum layer, a fast electron beam is produced. On the other hand, the interaction also produces high intensity X-ray bremsstrahlung inside the material. This continuum radiation could mask the K_α lines from deeper material. Also, the front layers are directly heated to high temperatures by the direct action of the high intensity laser beam. This could result in unwanted shifted K_α emission. To avoid this problem, a central copper layer was used: This absorbs a large part of the bremsstrahlung while the electrons easily pass through it and reach the third layer of the target, also made of aluminum, used as a fluorescer.

As a detector, we used X-ray Kodak DEF film.

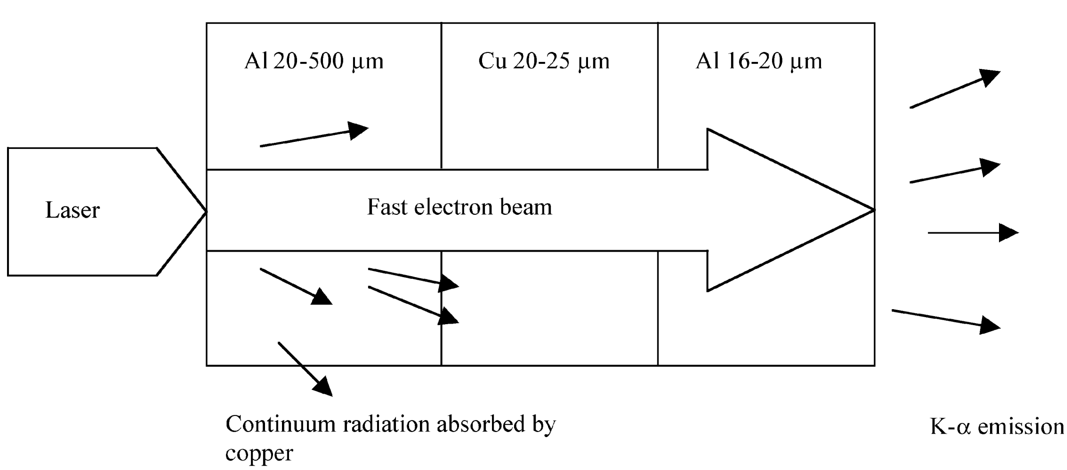

Fig. 2. Structure of the "sandwich" targets.

3. TYPICAL RESULTS AND DISCUSSION

In this preliminary presentation, we consider only the results obtained at LULI with simple targets.

In many cases, the films show the presence of a blue-shifted line near the “main” K_α line at 1486.7 eV photon energy (see Fig. 3). The films also presented the He-like lines from aluminum (see the whole film in Fig. 4) at 1588.3 eV photon energy. We used these lines for wavelength calibration. It is known that ionized atoms give K_α lines of shorter wavelength than neutral ones. This blue shift is due to the reduced shielding by electrons of the nuclear coulomb

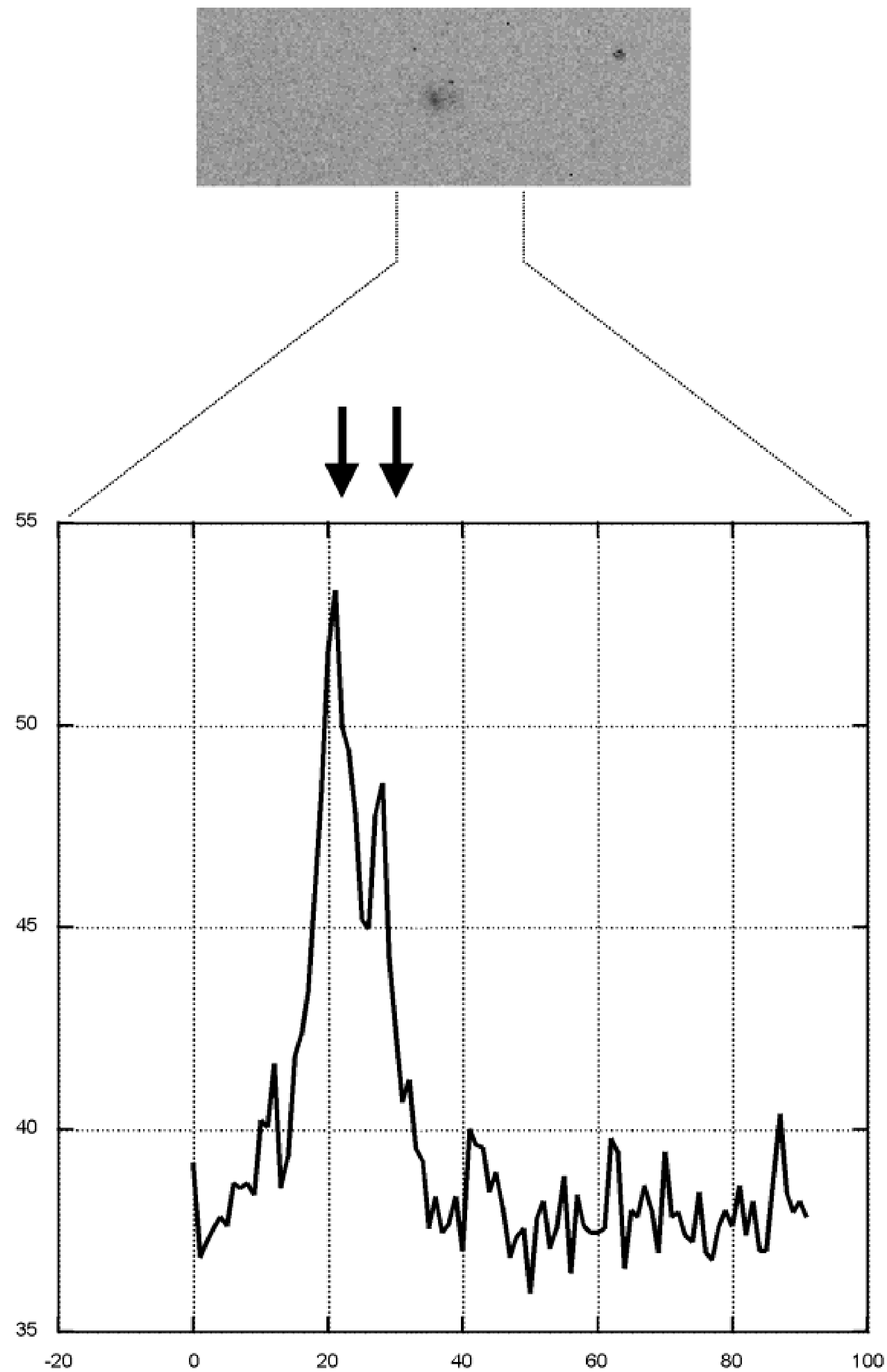

Fig. 3. Image of a film recorded at LULI and corresponding densitometry showing the cold and hot K_α lines indicated by the two arrows respectively at 8.34 and 8.27 Å (intensity in arbitrary units vs. photon energy also in arbitrary units). The shot energy was 24 J and the target was 40 μm Al foil.

Fig. 4. This film shows the cold K_α lines and the He_α line; these two lines have been used to get a calibration of the wavelength scale. The shot energy was 4.22 J and the target was 2.2 μm Al foil.

potential. Aluminum atoms which are ionized once, twice, three, or four times emit K_α lines of about the same wavelength of neutral atoms, while the blue-shift effect becomes more important for more highly ionized atoms (see Fig. 5). By detecting K_α emission we can get an idea of the ionic population distribution inside the emitting material; this can then be related to the temperature with appropriate models. We chose the model by Lee and More (1984) that considers average ionization stages, as shown in Figure 6. The blue-shifted ("hot") line present on the films at 8.27 Å corresponds to a significant presence of 5+ ions. At the same time, in almost none of the films we detected the presence of the hot line corresponding to 6+ ions; thus we can deduce a temperature of about 40 eV, for simple targets up to about 40 μm.

Results obtained at VULCAN were very similar, with, in general, less noise (thanks to the use of compound targets), which allowed us to observe K_α lines up to more than 100 μm thickness of the propagation Al layer. In a very few cases, all with less than 50 μm thickness, the presence of the 6+ "hot" line was detected, suggesting a slightly higher temperature. Indeed, for a more precise determination of the material temperature, we need to evaluate the relative amount of different ionization states and relative emission. This work is now in progress.

Such results can be compared with the order of magnitude expected for the temperature induced in the background material by the passage of the fast electrons. In a very simple way, the average temperature can be written, by neglecting ionization losses and using energy equipartition, as

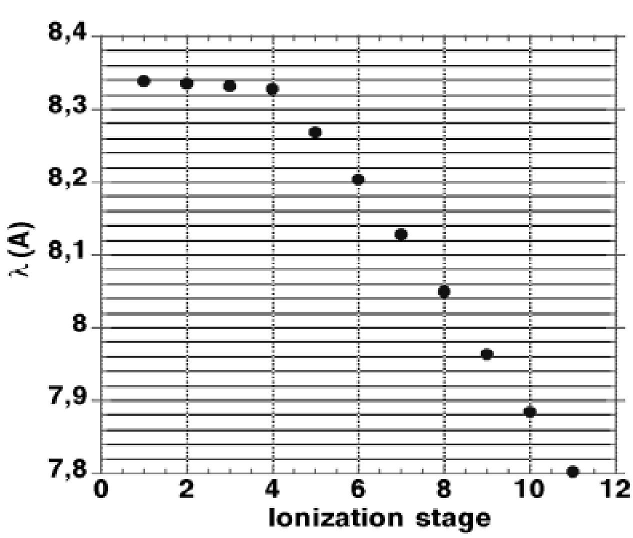

Fig. 5. Wavelengths of Al K_α emission as a function of the ionization stage of the emitting atoms.

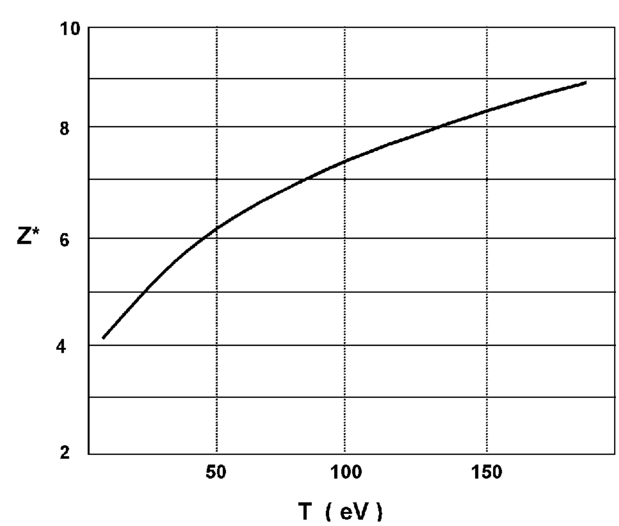

Fig. 6. Dependence of the average ionization from the temperature, according to the model of Lee and More (1984).

$$T = \frac{\alpha \eta E_L}{n_e V},$$

where ηE_L is the energy in hot electrons, α is the fraction of such energy deposited in the volume V, and n_e is the background electron density. This simple equation shows how T depends on the propagation details trough the volume V. We can consider the limiting cases of collimated propagation (due to self-pinching of the beam induced by magnetic fields), where $V \approx \pi R^2 l$, and of "free" collisional propagation, where $V \approx 2/3\pi l^3$. Here R is the dimension of the hot electron source and l the considered penetration depth. R is a quantity of the same order, but bigger, than the laser focal spot radius, as already shown in shadography images by Gremillet *et al*. (1999). The fraction α can be estimated, by assuming an exponential profile for energy deposition as $1 - \exp[l/l_0]$, where l_0 is the typical penetration of fast electrons in Al (see, e.g., Pisani *et al*., 2000). Finally, we take $n_e = N_A \rho Z^*/A$, with $Z^* = 5$, as shown by our experimental results. This gives $T \approx 440$ eV for cylindrical propagation and $T \approx 60$ eV for semispherical propagation.

A big source of uncertainty in these estimates is the problem of refluxing of hot electrons. Once they reach the target rear side, they cannot escape from the targets due to the huge electric fields which are created and pull the fast electrons back. This means that most of the fast electron energy is finally transferred inside the target. However little can be said at the moment about the geometry of such reflection, and then about the fraction of the refluxed energy which is deposited in the volume V. Since, however, some additional energy will be deposited inside V, we can conclude that the previous estimates are probably a lower limit. We must also notice that this simple model does not consider that the energy deposition inside the material is radially not uniform. Even if the comparison between these simple models and experimental results seems to suggest a lower-than-expected temperature, clearly detailed computer simulations are needed in order to drive any conclusion.

Nevertheless, the two experiments have shown the possibility of measuring the temperature of a solid as a result of the passage of the fast electron beam, using X-ray spectroscopy. Also the use of a Al-Cu-Al sandwich has allowed a lower noise and a better definition of the signal. This allowed the fast electron contribution to be clearly distinguished from other possible sources of heating of the background matter.

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