

## **Rapid Heating of Solid Density Material by the VULCAN Petawatt Laser**

R G Evans<sup>1</sup>, E L Clark<sup>1</sup>, R T Eagleton<sup>1</sup>, A M Dunne<sup>1</sup>, R D Edwards<sup>1</sup>, W J Garbett<sup>1</sup>, T J Goldsack<sup>1</sup>, S James<sup>1</sup>, C C Smith<sup>1</sup>, B R Thomas<sup>1</sup>, R Clarke<sup>2</sup>, D J Neely<sup>2</sup> and S J Rose<sup>3</sup>

*AWE plc, Aldermaston, Reading, RG7 4PR*

*Central Laser Facility, CCLRC Rutherford Appleton Laboratory*

*Clarendon Laboratory, University of Oxford, UK*

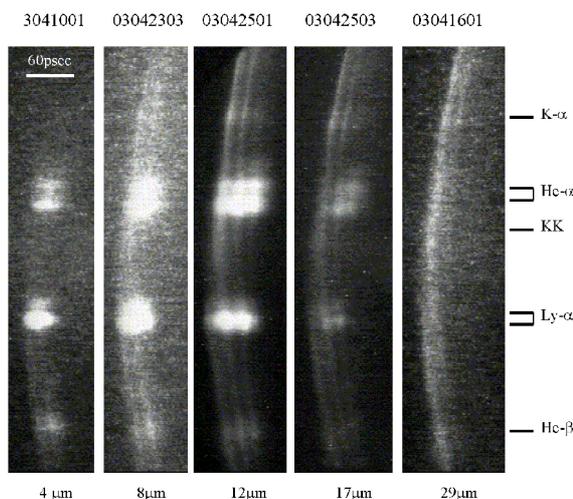
When Petawatt class lasers are focussed to intensities of around  $10^{20} \text{Wcm}^{-2}$  on solid targets they generate intense beams of relativistic electrons, much greater than the Alfvén current. These intense electron beams find important applications in the 'fast ignition' of IFE fusion pellets<sup>1</sup>, and as sources of protons and X-rays for medical and materials applications<sup>2</sup>. There is also the opportunity to create extremely high pressure material by heating solid density material to temperatures of order 1keV and to measure equation of state and opacity under conditions relevant to astrophysics<sup>3</sup>.

Previous experiments have measured the K- $\alpha$  emission induced by the energetic electron beam in passing through relatively cold material and used this to infer the electron beam dynamics. Koch and others<sup>7</sup> have measured thermal X-ray spectra from buried aluminum tracer layers and deduced temperatures in solid density material of 200eV to 350eV at an irradiance of  $3 \times 10^{19} \text{Wcm}^{-2}$  and a pulse length of 5 psec.

Our targets are a planar sandwich consisting of a front layer of CH, a thin aluminum tracer layer 0.2  $\mu\text{m}$  thick and a rear surface layer of CH 4 $\mu\text{m}$  thick which is sufficient to tamp the hydrodynamic expansion for the duration of the X-ray emission. The Vulcan Petawatt laser is focussed at 35 degrees, the highest irradiance of more than  $10^{20} \text{Wcm}^{-2}$  was achieved with 300J of laser energy focussed into a spot size of 10 $\mu\text{m}$  in less than 1ps. Time resolved X-ray spectra from the rear of the target had a time resolution of 14psec and spectral resolution of 0.02 $\text{\AA}$ .

Aluminum spectra were recorded with front CH layer thicknesses from 4 $\mu\text{m}$  to 29 $\mu\text{m}$ . Figure 1 shows a sequence of spectra at varying depths of the tracer layer together with identification of the spectral features. The He-like and H-like n=2 to n=1 transitions each have dielectronic satellite lines which are an aid to diagnosing the density and temperature of the emitting region. There is an emission feature to the high energy side of He- $\alpha$  labeled KK which is clearest at depths of 12  $\mu\text{m}$  and 17  $\mu\text{m}$  which we identify, using Dirac Fock

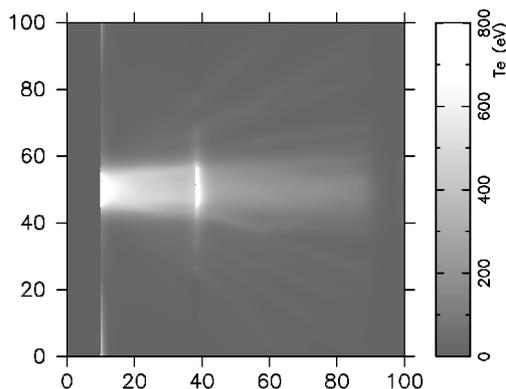
calculations of energy levels, as a 'hollow atom' transition in an aluminum ion with a double K-shell vacancy<sup>4)</sup>.



**Figure 1** Time resolved X-ray spectra for different buried layer depths

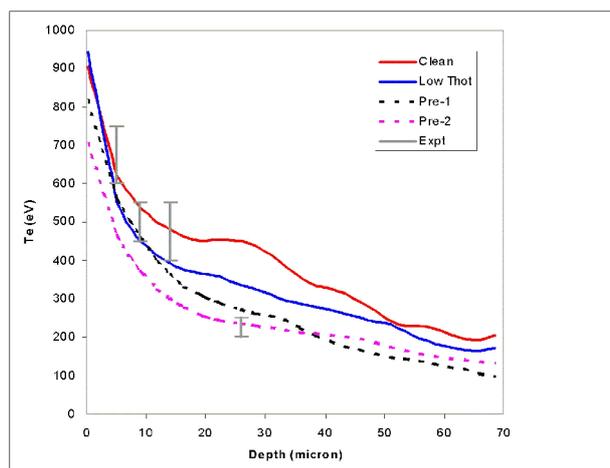
During the 1 psec laser pulse the electron distribution in the solid material is strongly non-Maxwellian due to the large number of electrons accelerated by the laser. However electrons below 5keV energy (ie those responsible for exciting the line radiation) and at solid density have collision times of less than  $10^{-13}$ sec and the time dependent atomic physics code FLY<sup>5)</sup> shows that at solid density the transient populations persist for at most 1 - 2 psec so we are able to infer temperatures and densities on the basis of steady state atomic rate equations provided there is evidence that the density remains high. Synthetic spectra from FLY are fitted to the observations. At depths greater than 4  $\mu\text{m}$  the density is in the range 1.0 - 3.0  $\text{g cm}^{-3}$  and the temperature falls from 650 - 750eV at 8  $\mu\text{m}$  to 450eV - 550eV at 17  $\mu\text{m}$ . At 29  $\mu\text{m}$  the upper limit on temperature is estimated to be 250eV

We have used the LSP code<sup>6)</sup> to model the heating of the target by a laser generated electron beam with appropriate energy and angular distributions. We use LSP in its direct implicit mode with particle beam electrons and fluid target electrons to model the propagation of the relativistic electron beam together with its self-consistent electric and magnetic fields and collisional effects in the beam and return currents. The resistive return current preferentially heats the higher Z layer resulting in the aluminum becoming substantially hotter than the CH substrate as shown in Figure 3 within the diffusion approximation for heat flow. However the aluminium layer is only 2 - 3 mean free paths thick for the 1.5 - 2.0 keV electrons exciting the X-ray emission spectrum so that the measured 'aluminium' temperature more closely approximates the bulk temperature in the CH. The temperature in the CH is insensitive to the size of the computational mesh.



**Figure 2.** Temperature distribution from LSP simulation at  $t = 1\text{psec}$

In Figure 4 we show a comparison of our measurements with LSP. There is good agreement at depths to 15  $\mu\text{m}$  but the baseline LSP simulations show that aluminum layers buried at depths to at least 35 $\mu\text{m}$  should achieve a temperature of 300eV and generate observable aluminum X-ray emission. Reducing the electron beam energy does not resolve this.



**Figure 3** Axial temperature profile from the LSP simulations

The pre-pulse from the VULCAN Petawatt laser is believed to be at a level of  $10^7$  of the main pulse for up to 2nsec, 2D fluid simulations show that near the focal spot a steady state is reached where the critical density layer sits about 5  $\mu\text{m}$  from the ablation surface. Injecting the electrons a little way from the solid surface strongly affects the electric fields in the target. Since the Spitzer resistivity is largely independent of density, the same electric field is generated as in the solid target but over a larger distance so that the 'potential drop' is larger. Electrons with energies below this 'skin potential' are unable to reach the solid and there is reduced heating in the solid. This is similar to electron preheat inhibition at much lower irradiances described by Bond, Hares and Kilkenny<sup>7</sup>. Figure 4 also shows two LSP

calculations including a density tail as might be produced by the laser pre-pulse and showing the reduced heat front penetration in substantially better agreement with the observations.

In conclusion we have significantly extended the experimental measurements of the deep heating of solid targets by Petawatt lasers and through the novel application of the LSP computer model we have demonstrated the reduced penetration of the heat front resulting from the effects of laser pre-pulse. The observation of the double K-shell vacancy 'hollow atom' transition gives rise to the possibility of a new diagnostic technique to measure the fast electron flux inside solid targets in future experiments.

We acknowledge funding for this experiment from the UK MoD and acknowledge the support of the operational staff at the Central Laser Facility.

### References

1. M Tabak, et al  
Physics of Plasmas 1, 1626 (1994)
2. E L Clark, et al  
Phys. Rev. Lett. 85, 1654 (2000)
3. S J Rose  
Journal of Quantitative Spectroscopy and Radiative Transfer 71, 635 (2001).
4. A Y Faenov, et al  
Physica Scripta T80B, 536 (1999)
5. R W Lee and J T Larsen  
Journal Quant Spectroscopy and Radiative transfer 56, 535 (1996)
6. D R Welch, D V Rose, B V Oliver, and R E Clark  
Nucl. Instrum. Methods Phys. Res. A 464, 134 (2001)
7. D J Bond, J D Hares, and J D Kilkenny  
Plasma Physics and Controlled Fusion 24, 91 (1982)