Technical Report
RAL-TR-98-015

Fast electron heating of shock compressed solids at high intensities relevant to fast ignition

TMR Large-Scale Facilities Access Programme

D Batani et al

February 1998

COUNCIL FOR THE CENTRAL LABORATORY OF THE RESEARCH COUNCILS

Fast electron heating of shock compressed solids at high intensities relevant to fast ignition

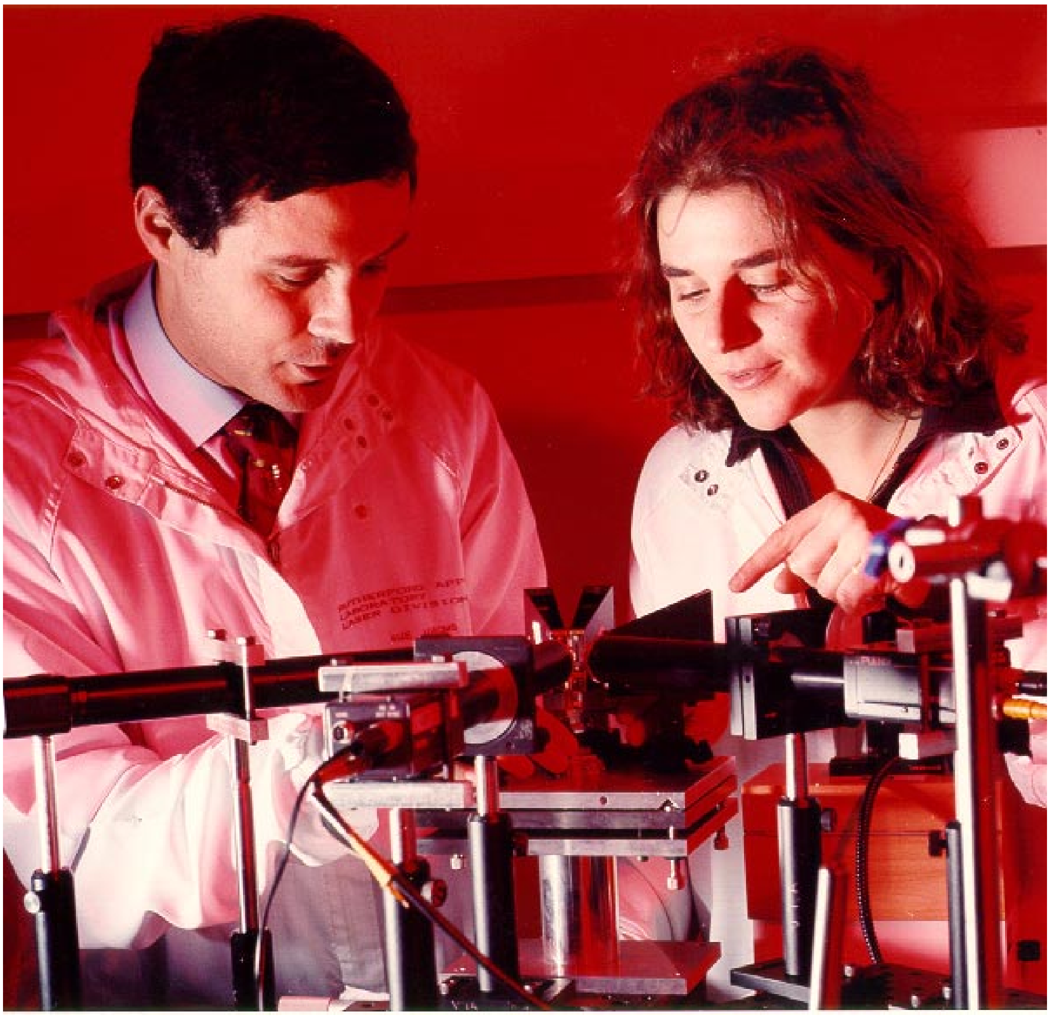
D Batani et al

University of Milan, Italy

An experiment performed with funding from the

TMR Large-Scale Facilities Access Programme

Contract No. ERBFMGECT950053



Fast electron heating of shock compressed solids at high intensities relevant to fast ignition

An experiment performed with funding from the
TMR Large-Scale Facilities Access Programme

Access to Lasers at the Central Laser Facility
Rutherford Appleton Laboratory
Contract No. ERBFMGECT950053

D Batani, A Bernardinello and V Masella
Dipartimento di Fisica, Universita degli Studi di Milano and INFM, Italy

M Koenig, A Benuzzi, J Krishnan and F Pisani
LULI, CNRS, Ecole Polytechnique, Palaiseau, France

S Ellwi and T A Hall
University of Essex, Colchester, UK

A Djaoui, P Norreys, D Neely, S Rose, and M H Key*
(Report prepared by C Danson and G Booth)
Rutherford Appleton Laboratory, Chilton, Didcot, UK

P Fews
Department of Physics, University of Bristol, Bristol, UK

*present address: LLNL, Livermore, Ca, USA

SUMMARY

This report describes the experiment entitled ‘Fast electron heating of shock compressed solids at high intensities relevant to fast ignition’; carried out at the Central Laser Facility (CLF) from the 5th January to the 15th February 1997. The experiment, funded by the Framework IV Large-Scale Facilities Access Scheme, was proposed by Dr D Batani, University of Milan, Italy and carried out by visiting researchers from the University and Ecole Polytechnique, Palaiseau, France. They were supported by UK researchers from the University of Essex, the University of Bristol and the Central Laser Facility, Rutherford Appleton Laboratory.

Experimental Results

- The experiment demonstrated the first results for fast electron deposition in compressed matter. The irradiances used in these experiments are lower than would be used in the fast ignitor scheme but the significance of the results is, nevertheless very relevant to this scheme.
- It is shown that in the experiments presented here that ionised, compressed plastic is less effective at stopping the fast electrons than uncompressed, unionised plastic. The stopping power of the compressed material is reduced by a factor of two (in areal density units) over the uncompressed materials.
- These experiments are the first measurements of electron stopping power in compressed plasmas but further experiments with more highly compressed plasmas are necessary before the results may be safely extrapolated to fast ignitor conditions.

The CLF makes beam time at its facilities available to European Researchers with funding from DG-XII, CEC under the Large Facilities Access Scheme. For further information contact Dr. Chris Edwards at the CLF. Tel: (0)1235 445582, e-mail: c.b.edwards@rl.ac.uk

The experimental team and support staff from RAL

From left to right:

Top row: D Hitchcock, D Neely, V Masella, J Krishnan, C Danson, D Batani, M Koenig, A Bernardinello, P Grifiths, I Gray

Bottom row: M Stainsby, C McCoard, J Ellwood, S Ellwi, F Pisani

Fast electron heating of shock compressed solids at high intensities relevant to fast ignition

Abstract. We present the first results of fast electron propagation and deposition in a laser compressed plasma. The interaction of a 4 ps, 15 J laser pulse with solid polyethylene targets is used to produce fast electrons on one side of foil targets and a 2 ns duration laser pulse is used to drive a shock wave into the target from the opposite side. K-alpha emission from Chlorine fluor buried layers is used to measure the electron transport and deposition. The hot electron range in the compressed plastic is found to be approximately twice as large as the range in the uncompressed plastic.

INTRODUCTION

The fast ignitor scheme[1] gives a possible route to reducing the energy required to achieve break-even and gain in laser driven Inertial Confinement Fusion (ICF). This scheme requires that an intense, short (~ 10^{19} W cm^{-2}, 10 ps) laser pulse produces fast electrons which are then absorbed in a small region of dense compressed plasma in order to produce local heating and ignition[2]. Previous experiments have been conducted to measure the fast electron production and the deposition of their energy in solid density targets and reasonable agreement has been obtained with models[3-5].

The goal of this experiment was to begin to address the problems connected with the last phase of the fast ignitor approach, namely the interaction, propagation and energy deposition of hot electrons in compressed matter. We report here experiments using the VULCAN laser to extend these measurements to the study of fast electron production and deposition in shock compressed plasmas using k-alpha emission spectroscopy. The use of k-alpha emission from buried layer fluors is now an established technique and has been widely used in the study of fast electrons from femtosecond laser plasma interactions[6].

To obtain this goal we used two ns laser beams to shock compress a plastic target and a Chirped Pulse Amplified (CPA)[7] beam to generate hot electrons and study their propagation in the compressed material. A large focal spot[8] of ~100 µm was used for the CPA laser beam to reduced the CPA intensity to a relatively low value ~10^{16} W cm^{-2}. This was a necessary requirement in our experiment since a larger CPA intensity would have meant a higher hot electron temperature T_{hot} and an increased hot electron penetration depth. This would have required thicker targets which would have a lower compression uniformity and therefore produce less clear results.

EXPERIMENTAL SET-UP

Fast electrons were produced on the "rear side" of plastic foil targets by focusing the VULCAN CPA beam to a focal spot of 100 µm diameter using an f/10 off axis parabola (OAP) as shown in figure 1. The energies of the CPA beam used in these experiments was in the range 4 to 15 J and the pulse length was 4 ps. Maximum irradiances on target were approximately 5×10^{16} W cm^{-2}. The foil targets were compressed using two, 108 mm diameter frequency doubled long pulse beams (**2** ns) of the VULCAN laser with a total energy of up to 160 J focused onto a spot of diameter 200 µm using random phase plates (RPP)[9]. The shock compression laser pulses were incident on the targets from the "front side" i.e. from the opposite side from the CPA beam. The chlorine k-alpha spectra were used as diagnostics for hot electron penetration by putting a chloride plastic layer (13.5 µm thick) in the target. The intensity of the K-α line of Cl, at ~ 2.6 KeV, was recorded on DEF film using three PET flat crystal spectrometers. Two spectrometers were placed on the front side, one at near normal incidence and the other at approximately 60° incidence and one spectrometer was placed on the rear side at about 30° incidence. These positions and angles were mainly determined by beam constraints. The layout of the experiment is shown in figure 1.

Additional diagnostics were used on each laser shots including:

- Far field imaging and autocorrelator to measure the CPA focal spot and pulse duration.
- Calorimeters to measure the CPA and the ns beams pulse energies.
- CR39 foils to measure the hot electron temperature with ion impact technique[2].
- X-ray active pin-hole cameras on both sides of the target to measure respectively the size of the plasmas created by the CPA and the ns laser beams.

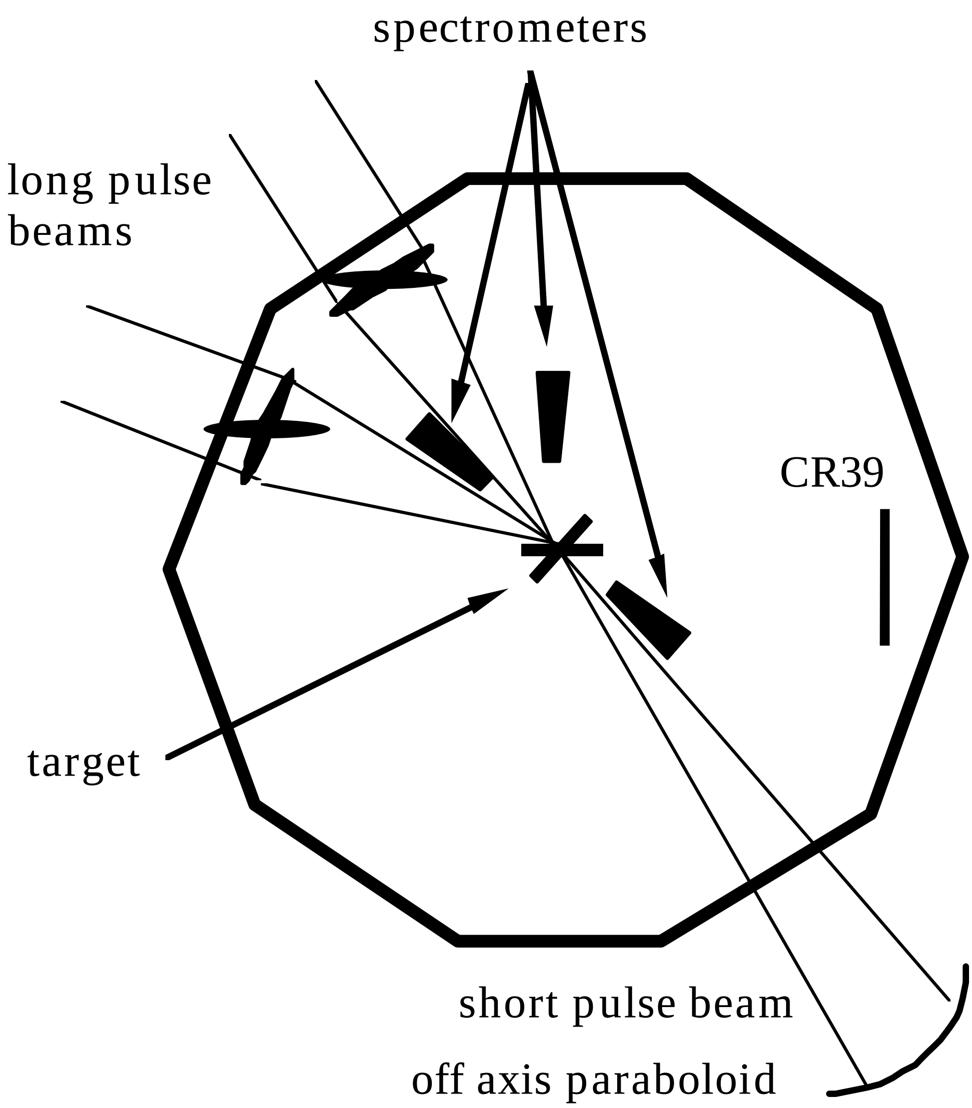


Figure 1. Experimental set-up

The targets in these experiments consisted of a PVC plastic fluor layer (mostly of 13.5 µm thickness) sandwiched between two thicknesses of polyethylene, see figure 2. The thickness of the polyethylene layer on the rear side of the target was varied from 10 µm to 150 µm. The front side polyethylene overlayer was 26 µm. This front side overlayer prevented any excitation of the plastic fluor layer by the long pulse beams and also prevented any fast electrons from the CPA interaction zone from travelling around the target and hitting the fluor layer from the front side. Such fast electron excitation was observed to take place if this overlayer was omitted.

SHOCK COMPRESSION

The determination of the shock velocity was very important in our experiment for two reasons:

- It permitted exact timing of the CPA beam. The delay between the time at which the CPA beam was fired and the time of the shock breakout was chosen so that at least a few µm of plastic were still uncompressed. Indeed, we wanted to avoid the opposite case because if the CPA arrives after the shock breakout it would find a plasma expanding from the rear side and the interaction and the generation of hot electrons would be completely different.
- From the shock velocity, by using the Hugoniot of polyethylene (given by the Sesame tables) we could determine the other parameters of the compressed material, such as pressure, temperature, and density.

Initial experiments were carried out using the long pulse beams alone to time the breakout of the shock by imaging the shock breakout region on the rear of the target onto the slit of a visible streak camera[10] as shown in figure 3.

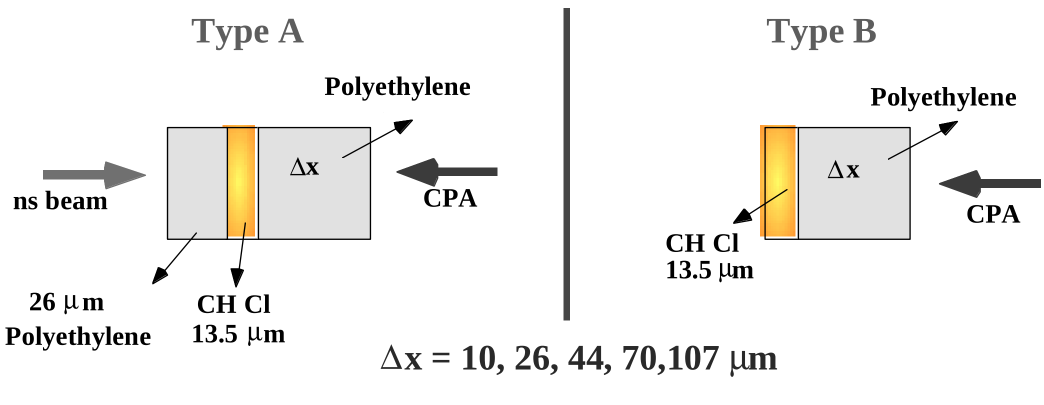


FIGURE 2. type of targets used in the experiment.

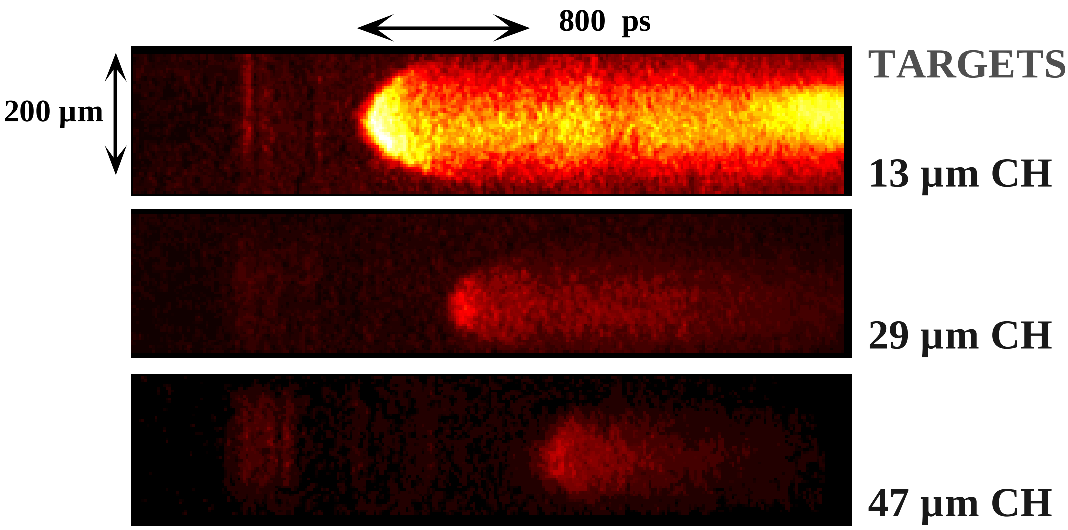


Figure 3. Streak camera images of shock breakouts with targets of different thickness.

The breakout was timed for various thicknesses of target and for a range of laser energies. Figure 4 summarises the results of the shock breakout showing breakout time for various thicknesses of plastic target for two different laser energies. The continuous line in the figure are the predictions of the one dimensional MULTI code[11] using SESAME equation of state[12]. The code predicts under these conditions a compression of x3.2 at an irradiance of 1.5×10^{14} W cm^{-2} and a compression of x3.0 at an irradiance of 1.0×10^{14} W cm^{-2}. Temperatures are in the range 7 to 8 eV.

The result show that the shock wave is slowing down slightly towards the rear of the thicker targets. This arises for two reasons, firstly the laser pulse does not sustain the drive pressure throughout the shock transit and the rarefaction wave follows. Secondly, two dimensional effects become important for the thicker targets where the thickness is of the same order as the focal spot diameter. Nevertheless, reasonably accurate measurements can be made of the shock breakout time for all thicknesses of target. Using these values of shock breakout time, the short pulse beam was timed to be incident on the rear side ~ 100 ps before shock breakout. This ensured that no expansion occurs from the rear side ahead of the arrival of the CPA pulse and all but a few microns of plastic is compressed (see later). For the thickest targets, no optical emission at breakout was observed due to the weakening of the shock and in these cases timing

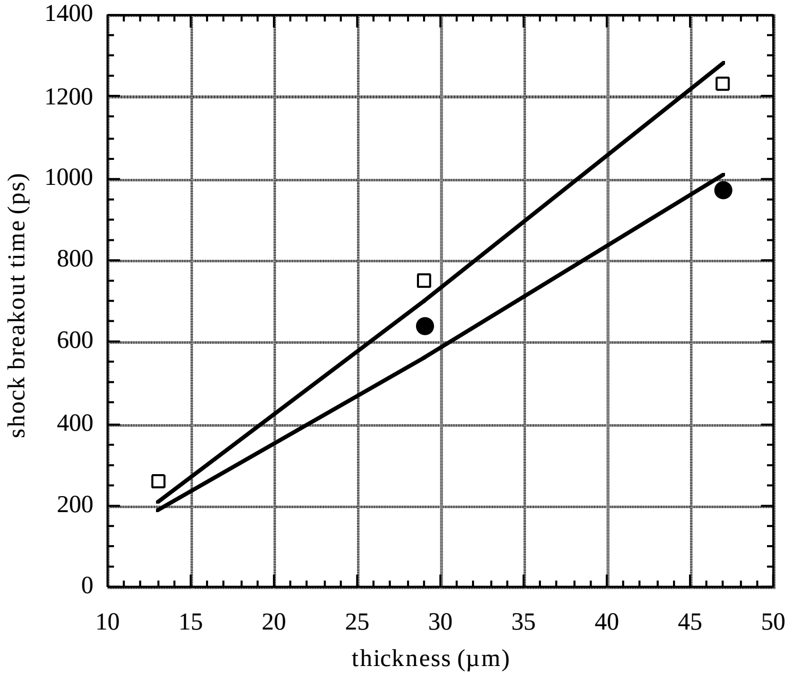


Figure 4. Shock breakout time for three different thicknesses of plastic target. The open squares are the experimental values for an irradiance of $1x10^{15}$ Wcm^{-2} and the filled squares are for an irradiance of $1.5x10^{15}$ Wcm^{-2}. The continuous lines are the predictions from the MULTI code for the respective irradiances.

was achieved by extrapolation of the graphs shown in figure 4. This could be done with reasonable confidence because the results for the thinner targets are in good agreement with MULTI code.

CHARACTERISATION OF HOT ELECTRONS

K-alpha spectra were obtained for a range of CPA laser pulse energies corresponding to irradiances up to $5x10^{16}$ W cm^{-2} on target. This range of irradiance was chosen so as to match the expected fast electron range to the target thickness. The spectra were obtained for targets with and without shock compression. On some laser shots, CR39 filtered track detector plastic[16] was used in the chamber in order to measure the proton energy spectrum.

The k-alpha x-ray intensity was measured as a function of laser energy for one depth of buried fluor layer (10 µm plastic overlayer). The results show a linear dependence on laser energy and as a result of this, for the remainder of this paper we use specific yields (yield per Joule incident laser energy). The use of specific yields is justified because the range of laser energies used is relatively small and any effect on the electron energy range is of secondary importance to the number of electrons produced. The specific k-alpha yield is plotted in figure 5 as a function of depth of fluor layer for the uncompressed plastic. All points on the graph are averages over a number of experimental values and each experimental value is the mean of the results from the three spectrometers. The error bar represents the standard deviation of these values.

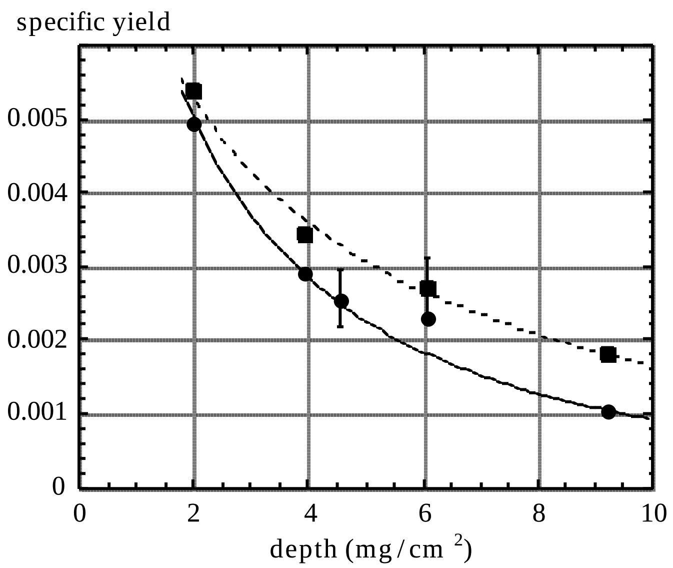


Figure 5. Specific k-alpha yields from uncompressed (●) and compressed (■) as a function of depth of the buried fluor layer. The continuous line is due to the model of Harrach and Kidder for a curvilinear range of 2.7 mg cm^{-2} and the broken curve for a range of 5.8 mg cm^{-2}.

Figure 6 shows instead the results of K-α emission as a function of target thickness for type B targets (uncompressed). Their behaviour is as expected, i.e. K-α emission increases when CPA energy is increased or the target thickness is decreased.

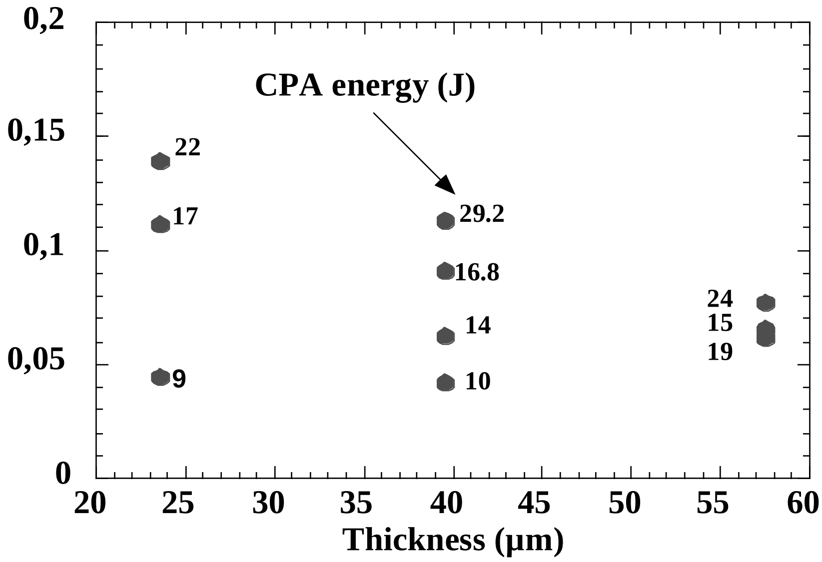


Figure 6. K-α yields for different CPA laser energies as a function of target thickness.

The continuous curve shown on figure 5 is derived from the work of Harrach and Kidder[17] where the deposition, ε (z), is of the form:

$$\varepsilon(z) \propto \exp(-\beta\sqrt{\frac{z}{R_0}}$$

with the value of β taken for carbon as 1.85. These values give the curvilinear range, R_O, as 30±5µm ≡ 2.7 ± 0.5 mg cm^{-2}.

The hot electron temperature can be inferred from the model of Harrach and Kidder, we find:

$$kT_{hot} = 6.3\ \{R_O(kT_{hot})\}^{0.56}$$

where kT_{hot} is in KeV and R_O is in µm. This gives a hot electron temperature of ~ 42 KeV. This value is not too different from the value obtained from the CR39 measurements which gives the value of kT_{hot} in the range 25 - 50 KeV. These values are also consistent with the hot electron temperature scaling given by Beg et al.[3] :

$$kT_{hot} \sim 100\ (I_{17})^{1/3}\ \text{KeV}$$

where I_{17} is the absorbed irradiance in units of 10^{17} W cm^{-2}. A hot electron temperature of 42 keV corresponds to an absorbed irradiance of $7x10^{15}$ W cm^{-2}. The incident irradiances in these experiments were in the range 10^{16} W cm^{-2} to $6x10^{16}$ W cm^{-2}.

The yields for the shock compressed plastic are also shown in figure 5. The values of yields for the shock compressed plastic lie above those for the solid density plastic in all cases. In these experiments, the areal density, ρz, is constant. The broken line in figure 5 represents the yields in the shock compressed plastic fitted to the model of Harrach and Kidder. The range of the electrons in the shock compressed plastic is found to be 7.2 ± 2.0 mgcm^{-2} compared to 3.7 ± 1.0 mgcm^{-2} in the solid density plastic.

Not all the plastic between the fluor layer and the rear side is compressed. Careful measurements of the shock drive parameters, *a posteriori* , show that the thickness of the solid density plastic layer was on average ~ 8 µm. The yield results suggest that the number of electrons emerging from this 8 µm boundary is identical in the two cases, within experimental error, and that the difference between the two sets of results is due to a difference in the ranges of the electrons. The difference in the ranges of the electrons may be due either to different energy spectra or as a result different stopping powers.

The production of fast electrons could be affected by the shock compression if shock preheat were to cause some of the rear side to spall or evaporated material in advance of the CPA pulse arrival. Such an evaporation would provide a low density gas in front of the target prior to the arrival of the CPA pulse and thereby influence the absorption mechanism and hence fast electron production. Previous experiments[15] with plastic targets under similar conditions have shown no pre-heat at these shock drive irradiances. This is confirmed by the form of the optical emission at shock breakout[16] but we did not take any particular efforts to measure pre-heat in these experiments. A low density gas is produced by the laser pedestal due to finite contrast ratio of the CPA pulse[8] (10^{-6}) which would mask any long pulse shock preheat spall (if there were any). Recent papers[17, 18] have shown that the electrical conductivity plays critical role in fast electron penetration. Bell et al.[18] describe the conditions when flux inhibition can restrict the penetration of fast electrons and change their energy spectrum. The penetration depth, z_o, given by Bell can be written in the form:

$$z_o = 3x10^{-3}\,(kT_{hot})^2\;\;\sigma_6\;\;I_{17}^{-1}\quad \mu m$$

where σ_6 is the conductivity of the material in units of $10^6\ \Omega^{-1}m^{-1}$. The interaction of the CPA beam with the target rear side will create a hot, very dense plasma layer and the conductivity of the material inside the rear surface of the target is likely to change very dramatically in space and time and to be determined by the position of the heat front from the CPA pulse. Simulations using the hydro code MEDUSA[19] with multi group non-local electron transport have been carried out to model the CPA pulse driven heat front. The results show that the position of the heat front 2 ps after the peak of the CPA pulse is 2.5 µm from the original target surface with a shock wave preceding the heat front to a further 1 µm. The temperature behind the heat front lies in the range 0.4 to 0.5 keV. Using these values of the electron temperature, we can estimate the electrical conductivity: from Spitzer, we find that $\sigma_6 \approx$ Å5. Using this value in Bell's formula for z_o we find that $z_o \approx$ Å 375 µm, i.e. much larger than the penetration depth of the heat front. At the heat front itself the temperature drops rapidly and the conductivity and z_o fall even more steeply to the values in the shock front driven by the CPA pulse, so that, at the temperature in the shock region the value of z_o has fallen to ~ 0.4 µm. Thus, according to Bell's model, flux inhibition will be important in the surface layers determined by the plasma layer produced by the CPA pulse but cannot explain the differences observed in our experiments. Also, due to the rather low CPA laser intensity we used, magnetic fields effects will also not play any significant role[20].

The further possibility for the reason for the difference is due to dense plasmas effects on the stopping power of fast electrons. In particular in the case of compressed materials this is given by

$$\frac{dE}{dz} = -\frac{2\ ^1\ e^4}{E}\,(n_f\,L_f + n_b\,L_b)$$

where E is the electron energy, n_f and n_b are the densities of free and bound electrons, and L_f and L_b are the respective stopping numbers. In the cold material, there is only the contribution from bound electrons, plastic being an insulator. The effect on range can thus be explained by a reduction of the stopping number of bound electrons due to the increase in their effective ionisation/excitation potential as a consequence of ionisation. This can be described with the work of More[21] using the value of ionisation (≈ Å1.7) obtained from the SESAME tables. The effect has been described in theoretical papers such as[2,22] considering both the cases of fast electrons and fast ions moving in a dense plasma. However care should be taken in extrapolating these results to our case which is characterised by a lower temperature and hence higher degrees of degeneracy and correlation. A calculation of stopping power performed for the case of plastic, following Val'chuk et al.[2] yields a 30 % reduction of the stopping power in the compressed material consistent with our results.

CONCLUSION

In conclusion, we have presented the first results for fast electron deposition in compressed matter. The irradiances used in these experiments are lower than would be used in the fast ignitor scheme but the significance of the results is, nevertheless very relevant to this scheme. It is shown that in the experiments presented here that ionised, compressed plastic is less effective at stopping the fast electrons than uncompressed, unionised plastic. The stopping power of the compressed material is reduced by a factor of two (in areal density units) over the uncompressed materials.

These experiments are the first measurements of electron stopping power in compressed plasmas but further experiments with more highly compressed plasmas are necessary before the results may be safely extrapolated to fast ignitor conditions.

ACKNOWLDGEMENTS

This work has been supported by the E.U. Programme: TMR Laser Facility Access (contract ERBFMGEC950053) and by the LEA "High Power Laser Science". The participation of V.M has been possible also thanks to an ERASMUS grant obtained in the framework of the PIC co-ordinated by Prof. L.Lanz of the University

REFERENCES

1. M. Tabak, J. Hammer, M. E. Glinsky, *et al*., Phys. Plasmas **1**, 1626-1634 (1994).
2. C.Deutch, H. Furukawa, K. Mima, *et al*., Phys. Rev. Lett. **77**, 2483-2486 (1996).
3. F.N. Beg, A. R. Bell, A. E. Dangor, *et al*., **4**, 447-457 (1997).
4. G. Malka and J. L. Miquel, Phys. Rev. Lett. **77**, 75-78 (1996).
5. S.C. Wilks, W. L. Kruer, M. Tabak, *et al*., Phys. Rev. Lett. **69**, 1383-1386 (1992).
6. R.C. Mancini, toto, toto, *et al*., J. Phys. B **27**, 1671 (1994).
7. D. Strickland and G. Mourou, Optics Comm. **56**, 219-221, (1985)
8. C. Danson et al, J. of Mod. Opt. in press 1998
9. Y. Kato, K. Mima, N. Miyanaga, S. Arinaga, Y. Kitagawa, M. Nakatsuka and C. Yamanaka, Phys. Rev. Lett. **53**, 1057-1060 (1984)
10. M. Koenig, B. Faral, A. Benuzzi, *et al*., Phys. Rev. E **50**, R3314 (1994).
11. R. Ramis, R. Schmalz, and J. Meyer-ter-Vehn, Comp. Phys. Comm. **49**, 475 (1988).
12. Sesame, The LALL equation of stste database, LA-UR-923407 (1992)
13. P. Fews, P. A. Norreys, F. N. Beg, *et al*., Phys. Rev. Lett. **73**, 1801-1804 (1994).
14. R.J. Harrach and R. E. Kidder, Phys. Rev. A **23**, 887-896 (1981).
15. Benuzzi, M. Koenig, and B. Faral, Phys. Plasmas (1997).
16. A. Benuzzi, T. Löwer, M. Koenig, *et al*., Phys. Rev. E **54**, 2162 (1996).
17. E. Glinsky, Phys. Plasmas **2**, 2796-2806 (1995).
18. R. Bell, J. R. Davis, S. Guerin, *et al*., Plasma Phys. Control. Fusion **39**, 653-659 (1997).
19. Djaoui and A. Offenberger, Phys. Rev. E. **50**, 4961 (1994).
20. J. R. Davis, A. R. Bell, M. G. Haines & S. M. Guérin, to be published in Phys. Rev. E., (1997).
21. R.M. More, in *Scottish Universities Summer School in Physics*, St. Andrews, 1985, **29**, 157-214.
22. V.V. Val'chuk, N. B. Volkov, and A. P. Yalovets, Plasma Physics Reports **21**, 159-164 (1995).