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HCM Large Facilities Access Programme Energy Deposition by Hot Electrons - Studies Related to the Fast Ignitor Concept

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Energy Deposition by Hot Electrons - Studies Related to the Fast Igniter Concept

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SUMMARY

This report describes the experiment entitled 'Energy Deposition By Hot Electrons - Studies Related to the Fast Igniter Concept' carried out at the Central Laser Facility (CLF) from February 20th to March 31st 1995. The experiment, funded by the Framework III Large Facilities Access Scheme, was proposed by Professors Roland Sauerbrey and Eckhart Förster of the Friedrich Schiller University in Jena, Germany, and carried out by a visiting team of researchers from two separate groups within the University. They were supported by Professor Michael Key of the University of Oxford, UK, and by staff of the CLF, co-ordinated by Dr Graeme Hirst.

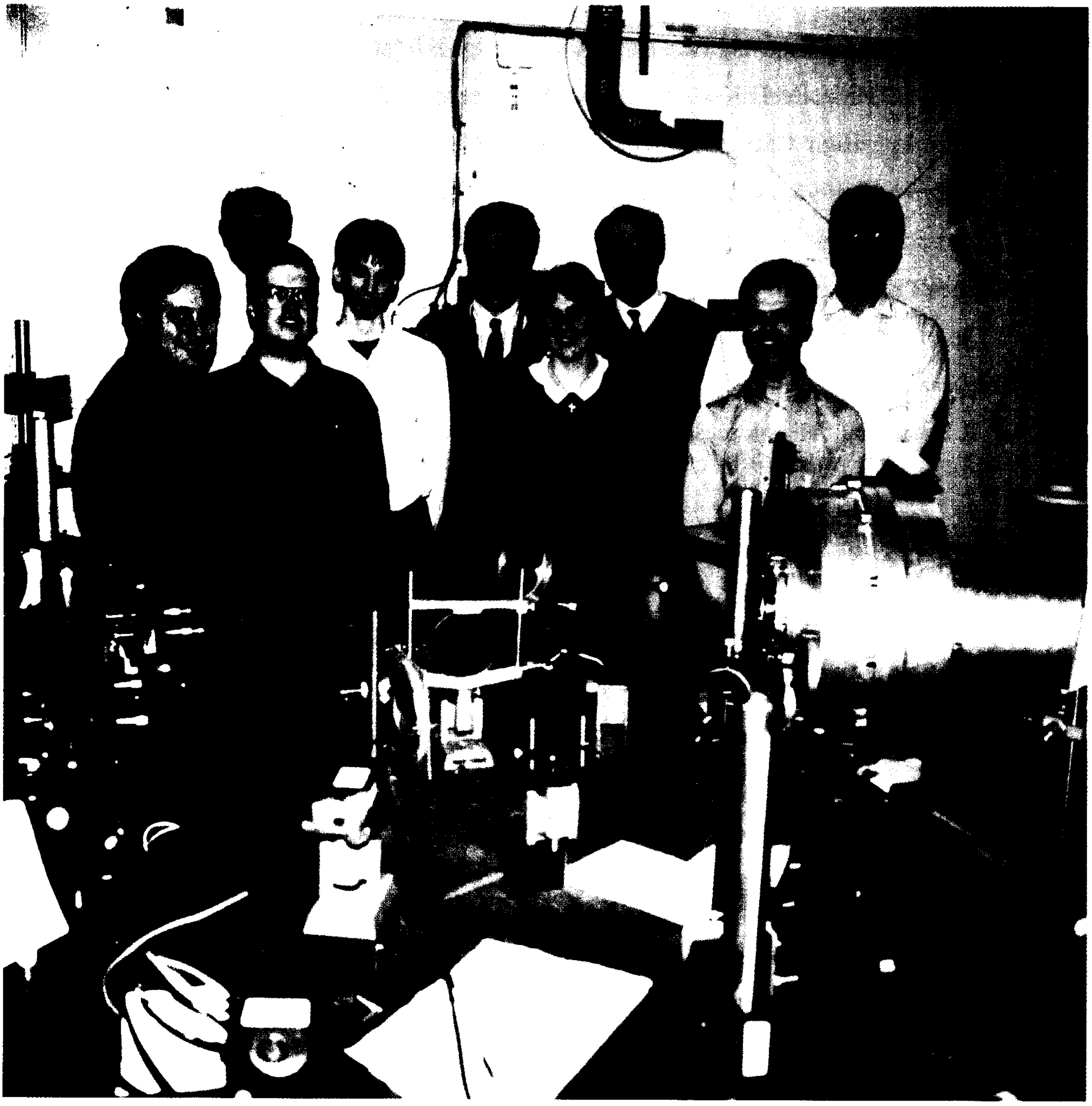
Experimental Results

- Absorption is shown to be >50% efficient, even at intensities $>10^{18}$ W/cm^2
- The angular dependence of the absorption is consistent with the dominant absorption mechanism being anomalous skin depth effects
- The temperature of the "hot" electrons, even at the highest intensities, is only ~10 keV
- The production efficiency of hot electrons seems to be relatively low

Arising Publications

This work has already been the subject of a major publication in an international journal. It has also led to a number of conference presentations, including three papers at the 2nd European Workshop on the Generation and Application of Ultra-Short X-ray Pulses (Pisa, Italy 20-23 September 1995) and an invited paper at the 8th Conference on Laser Optics, (St. Petersburg, Russia 27 June - 3 July 1995).

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



Part of the experimental team in the Sprite laser target interaction area.
From left to right: Dr. W Theobald (FSU Jena), Dr. G J Hirst (Sprite Group Leader), Dr. D Neely (CLF Target Area Co-ordinator), R Parker (Student, RAL), Prof. E Förster (Experimental Proposer), D Altenbernd (Student, FSU Jena), Prof. R Sauerbrey (Experimental Proposer), J Lister (CLF Sprite Operations Group), Dr. I Uschmann (FSU Jena).

Refereed Publication

U Teubner, I Uschmann, P Gibbon, D Altenbernd, E Förster, T Feurer, W Theobald, R Sauerbrey, G Hirst, M H Key, J Lister and D Neely, "Absorption and Hot Electron Production by High Intensity Femtosecond UV-Laser Pulses in Solid Targets", Phys Rev E, 54 (4) 1996.

Conference Presentations

8th Conference on Laser Optics, St Petersburg, Russia, 27th June - 3rd July 1995.

R Sauerbrey, "High Intensity Laser Plasma Interaction" (invited paper).

2nd European Workshop on the Generation and Application of Ultra-Short X-ray Pulses, Pisa, Italy, 20-23 September 1995.

R Sauerbrey, T Feurer, W Theobald, I Uschmann, P Gibbon, U Teubner, D Altenbernd, G Hirst, D Neely, M H Key and E Förster, "Energy Deposition by Hot Electrons: Studies Related to the Fast Igniter Concept"

T Feurer, W Theobald, U Teubner, I Uschmann, D Altenbernd, P Gibbon, J Lister, G Hirst, D Neely, M H Key, E Förster and R Sauerbrey, "Absorption of Intense Femtosecond UV-Laser Radiation in Solid Targets"

I Uschmann, U Teubner, D Altenbernd, P Gibbon, T Feurer, W Theobald, J Lister, G Hirst, D Neely, M H Key, R Sauerbrey and E Förster, "Investigation of Electron Energy Distribution in Plasmas Created by the CPA-Sprite Laser System by X-ray Spectroscopy of Al-Si Layered Targets"

CECAM workshop "The Interaction of Short Ultra-Intense Laser Pulses with Plasmas", Lyon, France, 25th-29th September 1995.

D Altenbernd et al, "Interaction of High Intensity UV Laser Radiation with Solid Targets"

INTRODUCTION

One of the most exciting ideas that has been proposed in connection with the interaction of high intensity ultrashort laser pulses with matter is the *fast igniter* concept [1, 2] that may lower the ignition requirements for inertial confinement fusion dramatically. The basic idea is to separate the fuel compression (by implosion) from the ignition of the compressed core. The ignition could be performed by a burst of "hot" electrons (about 1 MeV energy) with a duration comparable to the inertial confinement (of the order of 10 ps) that will heat the target to the necessary temperature. The requirements for ignition under the isochoric conditions of this scheme have recently been calculated in more detail and indicate a temperature of 12 keV at a density-radius product of $\rho r = 0.5$ g cm^{-2} [3].

The fast igniter concept depends on the efficient generation of electrons with the optimum energy. In principle this can be performed by collisionless absorption of an intense ultrashort laser pulse and associated collective electron acceleration in the driving laser field.

In this context it may be interesting to use laser radiation with a short wavelength (for instance UV light) because in this case the laser pulse could propagate to higher electron density, i.e. closer to the compressed core. In addition scaling analysis suggests that the rate of heating at a hot electron range matched to the minimum ignition volume scales as λ^{-2}, giving better prospects for achieving the required ignition temperature. Two fundamental questions need to be answered: first, how and, in particular, how efficiently is an intense ultrashort laser pulse absorbed in a solid target and second, what is the depth, energy, flux and production-efficiency of the hot electrons generated by the laser plasma interaction.

The absorption of intense femtosecond laser radiation in solid targets or plasmas of solid density has recently been of great interest [4-12] but there are still a number of unresolved questions. Early theories predicted that collisional heating should be the only important absorption process and therefore the absorption should decrease with increasing laser intensity. For obliquely incident light, however, resonance absorption and other collisionless absorption mechanisms, active for *p*-polarised light, should enhance the absorption [5-8, 13-17]. This experiment addresses both the question of absorption at high intensity and the investigation of energy deposition by hot electrons.

EXPERIMENTAL ARRANGEMENT

The experiments were carried out using the Sprite laser [23] operating in CPA mode at 249 nm. The pulse duration (assuming a Gaussian profile) was 380 fs FWHM with an uncertainty of 20 %.

The focusing optic was an f/3.2 off-axis parabola. The diameter of the central part of the focal spot was 3 μm FWHM with an uncertainty of 20 % and a shot-to-shot variation of 30 %. The central spot contained 30 % of the energy, E_0, reaching the target surface. E_0 was limited to ~250 mJ by the damage threshold of the compressor gratings.

The focal spot profile was characterised in two ways. Firstly the profile of a low energy beam (obtained by not firing the final two amplifiers) was measured at the target position using a UV-microscope objective and a CCD camera. Secondly the full energy beam was measured in an equivalent plane after the last amplifier. Both measurements yielded a maximum intensity (for normal incidence) $I_{0_\perp}$ of $5 \cdot 10^{18}$ W/cm^2 with an overall accuracy (systematic error) of 40 %. For the angle dependent measurements the intensity on the target, I_0, has been corrected for the angle of incidence, α, using the relation $I_0 = I_{0_\perp} \times \cos\alpha$.

The ASE intensity contrast ratio for most of the experiment was measured to be ~10^7. Some of the X-ray measurements were performed with a contrast ratio approaching 10^8.

Targets for the absorption measurements were plane highly polished slabs of carbon, aluminium, silicon, copper and platinum. Layered targets (vapour deposited aluminium on a thin silicon substrate, or foils) were used for the X-ray measurements . The targets were mounted on an *xyz*-translation and rotation unit in order vary α and to adjust the polarisation of the pumping pulse. Using a high magnification alignment system the targets were positioned with an accuracy of 10 μm. They were moved perpendicular to the laser beam between consecutive shots so that each pulse struck a fresh spot on the target surface.

The absorption measurements were carried out at three different intensities. The laser beam energy (rather than the focusing) was altered either by using a 10 % mirror to reduce E_0 to ~25 mJ or by switching off the final amplifier, Sprite, to give an E_0 of ~1 mJ.

The absorption was determined by measuring the reflected UV-laser light. The apparatus consisted of a calibrated energy meter and a calibrated Ulbricht sphere, which collected all of the reflected light except the backreflected fraction. This fraction however, is less than a few percent and thus negligible [10].

The time-integrated X-ray emission of the plasma was measured at various laser intensities, mainly at $\alpha = 45°$ and with *p*-polarised light. The measurements were carried out with an X-ray photodiode (IRD, AXUV 100) and an X-ray pinhole camera (5 μm pinhole, filtered by a 25 μm Be-foil). The soft X-ray region (i.e. between 50 and 400 Å) was dispersed by a flatfield spectrometer (spectral resolution $\Delta\lambda \approx 0.8$ Å) onto X-ray film (Ilford Q-plates).

A "von Hamos" spectrometer [24] using X-ray film (Kodak DEF) was used to measure the K-α emission and the X-ray spectra over a wavelength range from 5 Å to 9 Å. For some spectra it was necessary to accumulate as many as 5 shots on the film, depending on the laser intensity and the polarisation. The spectral resolution $\lambda/\Delta\lambda$ was approximately 1800. Observations were made from both the front and the back of the layered targets. Due to the aperture of the crystal the observation angle depends on the X-ray wavelength (35.2° for the Si I K-α line and 42.4° for the Al I K-α line).

The electron temperature of the plasma has been estimated from a measurement of the X-ray continuum emission filtered by various combinations of transmission foils as described in Ref. [25]. The X-ray detector used was again Kodak DEF film.

In addition to the X-ray measurements the ion current emitted from the plasma was detected by Faraday cups.

ABSORPTION EXPERIMENTS

Fig. 1 shows the measured total reflectivity as a function of the laser intensity on the target surface, I_0. The target was aluminium, α was 67° and the light was either *p* or *s*-polarised. The diagram also includes data from our previous work [7]. The systematic error of each point is ~± 10 % in both cases. The statistical error of the individual points may be seen from their fluctuation in the diagram. As mentioned above, the accuracy of I_0 is about 40 %.

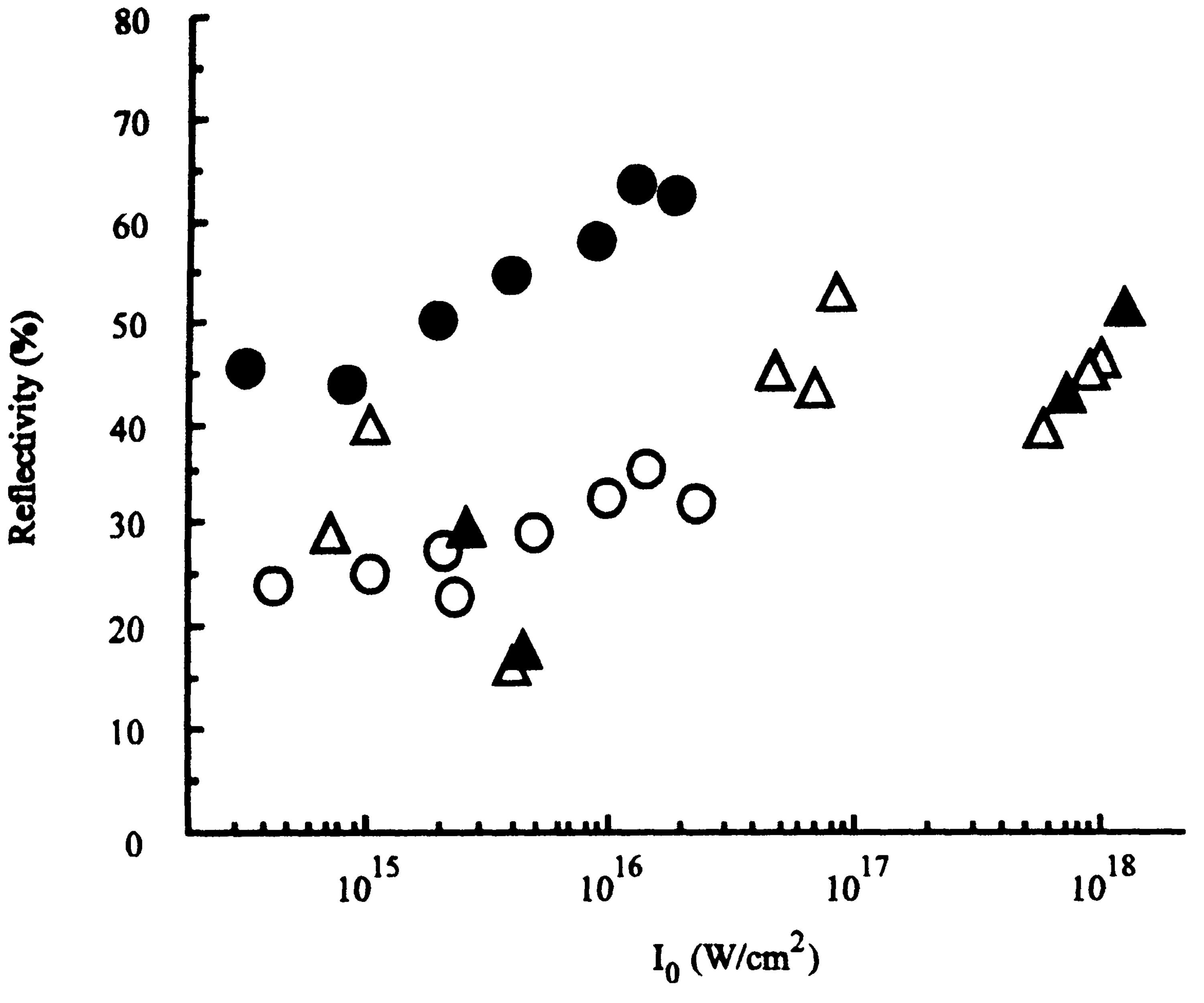


Figure 1 Intensity dependence of the reflectivity for both *p*-polarised pulses (open symbols) and *s*-polarised ones (solid symbols). Triangles represent data from this experiment, circles data from Ref. [7]

From Fig. 1 it may be seen that the reflectivity for *p*-polarised laser light, R_p, increases only weakly with the laser intensity from ~25% at $I_0 \approx 10^{14}$ W/cm^2 to ~45% at $I_0 \approx 10^{18}$ W/cm^2. The R_p values from this work for intensities up to ~10^{17} W/cm^2 agree with the previous results. In addition the measurements at lower laser intensities show that nearly all of the light is reflected specularly, with a solid angle not much larger than that of the input beam. The angular dependence of the reflectivity ($R_p(\alpha)$, not shown here) has a distinct minimum near $\alpha = 45°$ at intensities of ~10^{16} W/cm^2. It also agrees, within experimental errors, with the earlier data.

In contrast to the lower-intensity results the nonspecular component increases substantially at intensities exceeding several times 10^{17} W/cm^2, although the light is still mostly reflected in the specular direction. The solid angle at 10^{18} W/cm^2 is roughly a factor of 3 larger than at 10^{16} W/cm^2 (measured at $\alpha = 45°$). Furthermore, for higher intensities a shift of the minimum

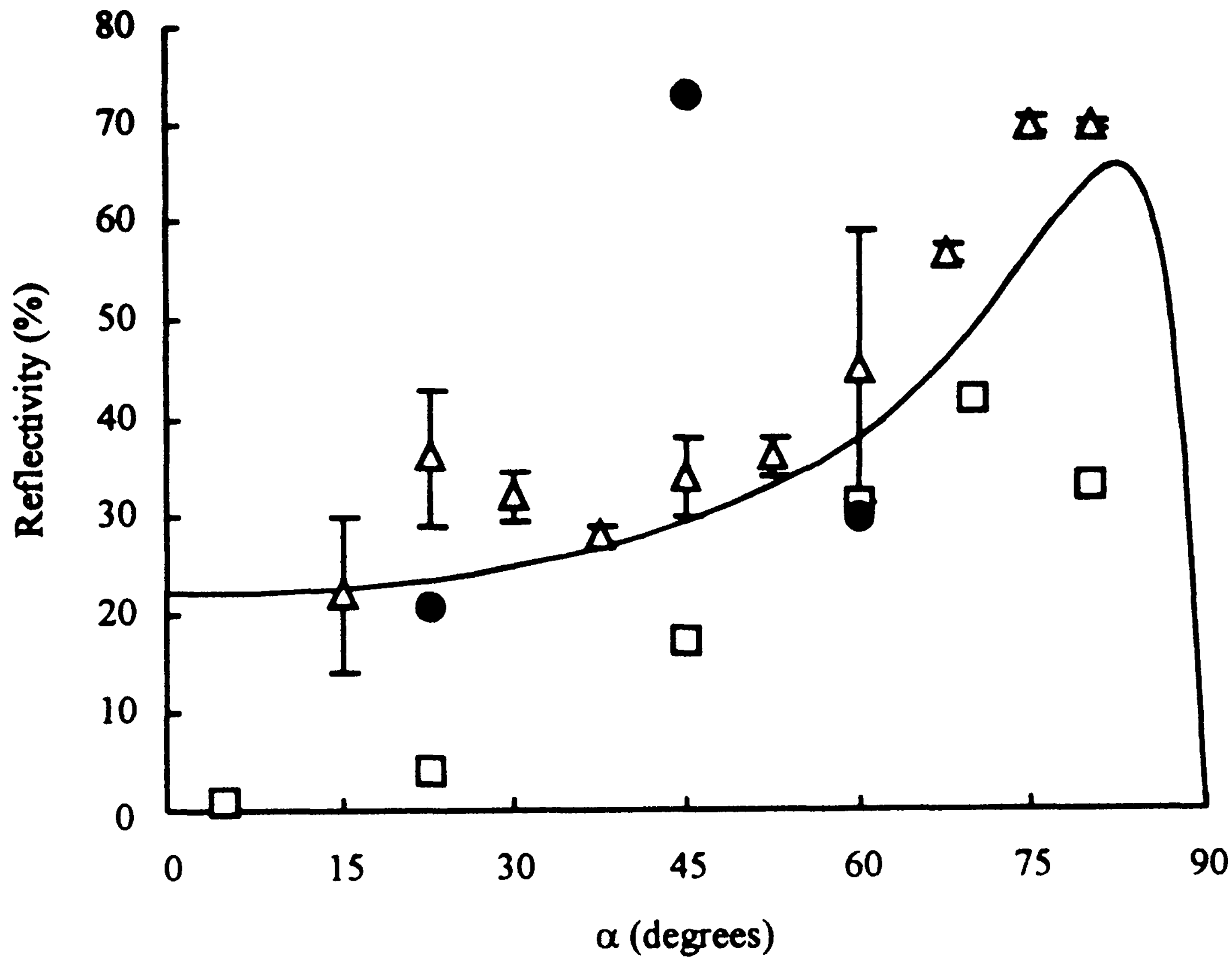


Figure 2 Angular dependence of target reflectivity. Experimental results (triangles) are compared with an analytical curve for the anomalous skin effect (solid line) and PIC simulations for fixed ions (squares) and mobile ions (circles).

of the $R_p(\alpha)$ curve to larger angles of incidence has been found as may be seen from Fig. 2 ($I_{0\perp} \approx 2.5 \cdot 10^{18}$ W/cm^2).

The reflectivity of *s*-polarised light, R_s, is lower than measured previously and is similar to R_p at the highest laser intensity. Further reflectivity measurements were performed at $I_{0\perp} \approx 1.5 \cdot 10^{18}$ W/cm^2 and $\alpha = 80°$ ($I_0 \approx 3 \cdot 10^{17}$ W/cm^2) with *p*-polarised laser light using various target materials (carbon, aluminium, copper and platinum and slab, foil and evaporated targets). It was found that the reflectivity scales only weakly with the atomic number, Z, increasing from approximately 30 % for light elements (Z = 6) to nearly 45 % for Z = 78. No significant difference in the reflectivity was observed between the highly polished slabs, the foils and the evaporated targets.

The data of Fig. 1 imply that the absorption for the higher intensities (10^{18} W/cm^2) exhibits a Fresnel-type angular dependence with a maximum at α = 70 - 80°. Such behaviour is predicted for collisional absorption (inverse bremsstrahlung) in a highly overdense step profile [6], but for temperatures of the order of 1 keV this contribution is almost negligible [26]. Collisionless absorption via the anomalous skin effect also shows a maximum at large angles [15, 17]. This has been calculated (after Ref. [15]) and the resulting curve is displayed in Fig.2 for parameters relevant to the experiment ($n_e/n_c = 10$, $T_e = 1.5$ keV).

For the step-profile, in which $L/\lambda = 0$, there is qualitative agreement between the reflectivity measurements, theory and PIC simulations. However, further simulations including ion motion and realistic pulse shapes indicate that the absorption maximum should shift back to 40 - 50° due to the formation of an underdense plasma shelf in front of the target. Relaxation of the density scale-length by the prepulse would also shift the absorption maximum towards smaller angles. This would imply that the density gradient remains very steep throughout the interaction with the main pulse, and that ion motion is somehow inhibited.

We conclude that although the theoretical analysis is preliminary, the reflectivity results represent the first experimental evidence for the anomalous skin effect.

X-RAY MEASUREMENTS

Fig. 3a shows a spectrum observed with the von Hamos spectrograph from the front side of a 1000 nm Al layer on a Si substrate. The spectrum was measured with *p*-polarised light at $I_0 = 3 \cdot 10^{18}$ W/cm^2 and $\alpha = 45°$. The spectrum consists of the Al K-shell lines, i.e. the H-like and He-like resonance lines together with their satellites which are labelled according to the notation of Gabriel [27]. Little self-absorption (due to opacity) in the peaks of the He-α and He-β resonance lines has been observed. The doublet in the Ly-α resonance is resolved and the intercombination line is clearly visible. Weak continuum emission is present as the background. The "cold" K-α line from the solid Al (i.e. Al I) is also present but there is almost no Si K-α emission.

Figs. 3b and 3c show, respectively, spectra from targets consisting of a 600 nm and a 100 nm Al layer on a Si substrate. It may be seen that with decreasing layer thickness d the Al I K-α emission decreases and at the same time the Si I K-α line is enhanced. In addition emission from a Si plasma is visible, i.e. the Si He-α line together with satellites. For $d = 100$ nm no

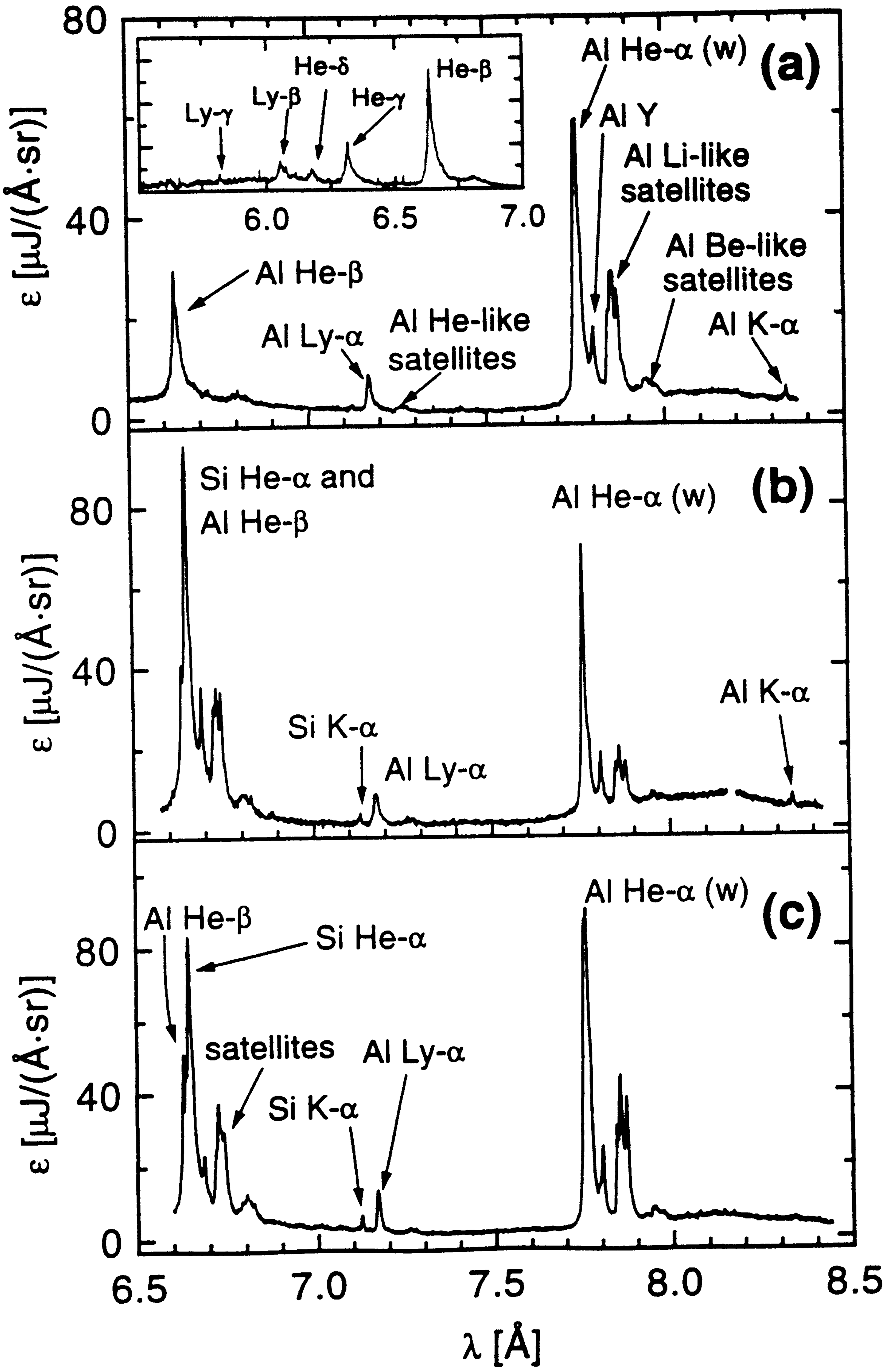


Figure 3 Von Hamos spectra from Al layered targets on a Si substrate with Al thicknesses of (a) 1000 nm, (b) 600 nm and (c) 100 nm (backgrounds have been subtracted)

cold Al K-α emission has been observed. This indicates that all the Al has been ionised.

In contrast with similar experiments performed at longer laser wavelengths [19-21] the K-α emission from Al and Si is relatively weak when compared with the hot plasma emission (e.g. the He-α line). Furthermore no K-α emission from multiply ionised atoms (i.e. Al I, Al II etc.) was seen in the present experiments.

The electron density of the hot Al plasma has been estimated using the diagnostics described in [28], i.e. the intensity ratio of different X-ray lines, the width of the resonance lines and also the intensity ratio of the lines in the Ly-α resonance doublet. These yield an electron density, n_e, of 1 to 2 times the critical density, n_c, (i.e. $1.8 \cdot 10^{22}$ cm^{-3} for KrF* laser radiation) for the emission volume of the resonance lines. The emission from the satellites originates from higher densities.

It has been found that the influence of the Al layer thickness (0.1-6 μm) on the spectral shape and hence on the plasma conditions is small. This indicates that the hot plasma is produced mainly in a depth not much larger than 100 nm behind the original surface and that the electron density scale length L is very small.

It has been shown previously [28] that the plasma electron density is expected to increase with the laser intensity. However, the electron density in the present experiment is a little lower than that of plasmas produced with similar conditions but an order of magnitude less intensity [28]. This may be explained by the presence of an underdense preplasma created by an ASE prepulse. The influence of the ASE prepulse was checked by blocking the fs seed pulse. By observing the ion signals from the Faraday cups an onset of plasma production was found at both the usual ASE intensity (i.e. about 10^{11} W/cm^2, at $I_{0_\perp} > 10^{18}$ W/cm^2) and at the reduced (by 1 order of magnitude) value.

Although n_e is lower than expected, the X-ray emission and the energy deposition still occur at the overdense region in the present conditions. This can be explained by the large ponderomotive force which strongly pushes the underdense plasma [26, 28].

The time averaged electron temperature of the hot plasma $\overline{T}_e$ has been estimated from the foil transmission measurements. For the aluminium plasmas produced at an intensity of

$I_0 = 10^{18}$ W/cm^2 using *p*-polarised light at $\alpha = 45°$ $\bar{T}_e$ is approximately 1500 eV (± 300 eV). This value agrees with the $\bar{T}_e(I_0)$ dependence deduced previously for Al subpicosecond UV-laser produced plasmas [26, 28]. $\bar{T}_e$ is much lower than the "initial temperature" $T_{e,o}$, i.e. the temperature at the peak of the laser pulse, which can be estimated [26] for the present experimental conditions to exceed $T_{e,o} \approx 3$ keV (in the vicinity of the critical density).

Furthermore, it was found that the electron temperatures $\bar{T}_e$ of the Si-plasmas and the plasmas from the slab and layered Al targets produced under nearly the same experimental conditions were approximately the same, indicating similar plasma conditions. The value for the Cu plasma produced at normal incidence was lower ($\bar{T}_e \approx 1$ keV) as would be expected given the lower absorption.

The measurement of the K-α emission in multilayered targets is a convenient way [18-22, 29] to study the energy of the hot electrons (usually characterised by a "hot electron temperature", T_h). The technique relies on the fact that the electrons lose some of their kinetic energy in the Al layer before penetrating into the Si substrate. In each material electrons which have enough energy can ionise the K-states, leading to Al and Si K-α emission. Varying the thickness of the Al layer affects both the absolute value and the ratio of the Al and Si K-α line intensities. Hence intensity measurements as a function of layer thickness (Figs 3 and 4) provide a method for deducing T_h.

In the present experiment the measurement was carried out with the von Hamos spectrograph. To allow for the reabsorption of the Si K-α emission in the Al layer, which depends on the layer thickness, both front observation (preferable for layers less than 1 μm thick) and back observation (preferable for thicker layers) was performed. The Si substrate thickness was 10 μm.

In order to extract T_h from the dependence of the K-α signals on layer thickness a simple model has been developed. It is 1-dimensional, based on a Bethe-Bloch energy loss function and it neglects electron scattering. The electron energy distribution (which cannot be determined from the experiment) is assumed to be Maxwellian. With these assumptions the electron energy E_e can be calculated as a function of depth. The energy fraction $F(E_e)$ converted into K-α radiation is

$$F(E_e) = \frac{n_A \cdot \sigma_K(E_e) \cdot E_K}{\frac{dE_e}{dX}} \qquad (1)$$

where n_A is the number of atoms per unit volume, σ_K the cross section for K-shell impact ionisation (from [30]) and E_K the energy needed to ionise the K-shell.

The K-α yield per electron into unit solid angle is given by

$$\zeta(E_e) \cdot dE_e = \frac{1}{4\pi} \cdot \frac{E_{K\alpha}}{E_K} \cdot \eta_K \cdot F(E_e) \cdot dE_e \qquad (2)$$

where E_{K_α} is the energy of one K-α photon and η_K is the fluorescence efficiency. The total yield may then be obtained by integrating over the whole energy range

$$\zeta = \int_0^\infty \zeta(E_e) \cdot f(E_e) \cdot dE_e \qquad (3)$$

where $f(E_e)$ is the Maxwell-Boltzmann distribution function.

The experimental result of the simulation is shown in Fig. 4 where the Si K-α yield ζ observed from both the front and the back of the target is plotted as a function of layer thickness. All the data have been corrected for reabsorption in the Al and Si layers respectively using the absorption coefficients from Ref. [31]. In addition, due to the shot-to-shot fluctuation of the laser energy and the accumulation of several shots for some of the spectra the data have been normalised to the accumulated incident laser energy.

The hot electron temperature has been fitted for both front and back observation and it was found that detection from the back is more sensitive. The best fit to the experimental data was obtained with T_h = 8 keV (Fig. 4). This may be regarded as an upper limit because the model neglects both additional electron scattering, which reduces the penetration depth, and also K-α production by plasma fluorescence.

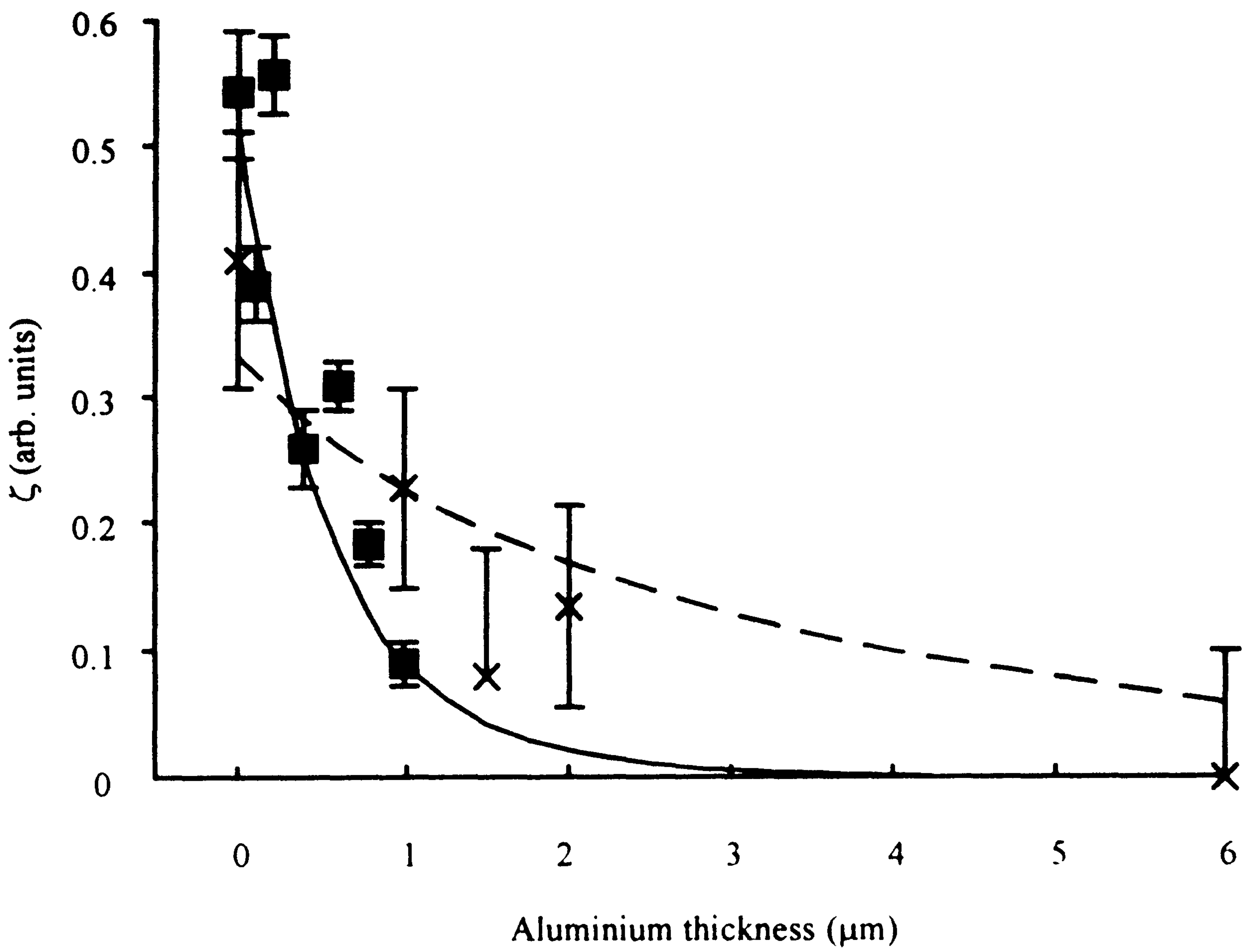


Figure 4 Si K-α line intensity ζ emitted from Al layered targets on a Si substrate. Experimental results viewed from the front (squares) and rear (crosses) of the target are compared with simulations (solid and dashed lines respectively)

The hot electron temperature deduced from the high energy electrons ($T_h \approx 8$ keV) is much larger than the plasma electron temperature estimated from the X-radiation ($\overline{T}_e \approx 1.5$ keV and $T_{e,o} \approx 3$ keV, see above). The high energy electrons are mainly present during a short time interval at the peak of the laser pulse, i.e. at the time when the electron temperature in the hot plasma also has its maximum value, $T_{e,o}$ [26]. Thus, like $T_{e,o}$, T_h corresponds much more to a temporal snapshot (and a space average of the region where most of the K-α line radiation occurs) than to a time averaged value like $\overline{T}_e$. In addition it should be noted that the spatial regions for T_h (the cold bulk material), and $\overline{T}_e$ and $T_{e,o}$ (the critical density region), are different.

Calculations of the hot electron distribution from PIC simulations give hot electron temperatures $T_h = 50 - 60$ keV for the experimental parameters (n_e / n_c = 10 - 20, T_e = 1 keV,

$I = 2 \cdot 10^{18}$ W/cm^2), i.e. a factor of 5 - 6 times the value estimated from the K-α measurements. One possible explanation for this discrepancy is the irregular beam shape, which had only 30% of the energy in the central (3 μm) spot, the remaining 70% being spread over a much broader (15 μm) spot with an intensity of the order of 10^{17} W/cm^2. Simulations at this intensity indeed predict temperatures of the order of 10 keV.

To make an accurate comparison with the experiment it would be necessary to use weighted electron distributions corresponding to the intensity variations. The result could then be carried over to the Bethe stopping calculation. On the other hand, the contribution from the "high intensity" electrons (> 50 keV) is arguably negligible in our case, because their stopping range is of the order of 15 μm, i.e.: much longer than the maximum Al target thickness used (3 μm).

CONCLUSIONS

The present experiments address both the coupling of UV radiation at intensities in the range 10^{15} W/cm^2 to 10^{18} W/cm^2 to solid targets and the production of fast electrons from the laser-target interaction.

The absorption measurements reveal substantial absorption (about 50%) of the *p*-polarised laser radiation in the solid even at intensities in excess of 10^{18} W/cm^2. The peaking of the absorption for large angles of incidence (about 70° to 80°) is in agreement with theoretical calculations that assume anomalous skin effect as the dominant absorption mechanism.

For UV wavelengths the production of fast electrons is surprisingly inefficient when compared to visible and infrared laser radiation. Also the hot electron temperature of ~ 8 keV at $I_{0\perp} \approx 10^{18}$ W/cm^2 is considerably lower than the fast electron energies in the 100 keV range deduced from experiments using lasers of longer wavelength and comparable intensity.

These result show that the laser wavelength has a substantial effect on the absorption mechanism of intense light in solid targets.

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