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Transport in Ultra-Dense Plasmas Produced by a Picosecond Laser Pulse

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13. ABSTRACT *(Maximum 200 words)*

This report presents recent experimental results obtained with the Table Top Terawatt laser at the Ultrafast Science Laboratory (University of Michigan). Interaction of the picosecond laser pulse with an overdense plasma was investigated with spectroscopic observations in the XUV range using a compact 1 m grazing incidence spectrograph.

The emission from laser-irradiated targets made of silicon wafers coated with aluminum layers of variable thicknesses (from 100 to 5000 Å) was recorded to allow spectral line intensity measurements from silicon and aluminum L-shell ions. The experiment was conducted using laser irradiation at both wavelengths $\lambda_L = 1.06$ or $0.53\ \mu$m.

The laser energy penetration depths were derived from the variation of the XUV spectral intensities with the different layer thicknesses. The values obtained cover the range 300-700 Å at $\lambda_L = 1.06\ \mu$m and 250-400 Å at $\lambda_L = 0.53\ \mu$m. The smaller penetration depth determined at the laser doubled frequency corroborates earlier x-ray results in the keV range at the same laboratory. The penetration depths derived provide a better understanding of the electron heat transport phenomena, supporting in particular the assumption of thermal condition in an overdense plasma.

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TRANSPORT IN ULTRA-DENSE PLASMAS PRODUCED BY A PICOSECOND LASER PULSE

1. INTRODUCTION

XUV radiation from plasmas generated by laser-irradiated solid targets represent an important diagnostic tool to characterize the compressed matter in a hot, dense plasma state. Of particular interest is the light-matter interaction with very short laser pulses -in the picosecond or subpicosecond range- to study the electron heat transport before any plasma expansion occurs i.e. at or above solid density.

Spectroscopic experiments were carried out at the Ultrafast Science Laboratory (University of Michigan) using the Table Top Terawatt (T^3) laser. A detailed description of this system is given elsewhere.[1] The T^3 laser delivers up to 300 mJ in a 1 ps pulse at a wavelength $\lambda_L = 1.06$ μm. The frequency can be doubled using a KDP crystal for irradiation at 0.53 μm at about one quarter of the energy. In this experiment the available laser intensity of irradiance (on target) was estimated to be 1.2×10^{15} W cm^{-2} at $\lambda_L = 1.06$ μm and 3×10^{14} W cm^{-2} at $\lambda_L = 0.53$ μm. The focal spot diameter was about 200 μm. The laser intensity of the prepulse had a contrast ratio to that of the main pulse better than 10^{-3}:1 at 1.06 μm and at most 10^{-4}:1 at 0.53 μm.

Previous experimental studies with x-ray spectroscopy in the keV range at the Ultrafast Science Laboratory facility[2] have characterized the absorption of the laser radiation in the target and the high density plasmas generated by the T^3 laser. More detailed laser absorption measurements by the same group[3] established the existence of a steep density gradient in the plasma. In these previous studies, spectroscopic measurements at both laser wavelengths (using a

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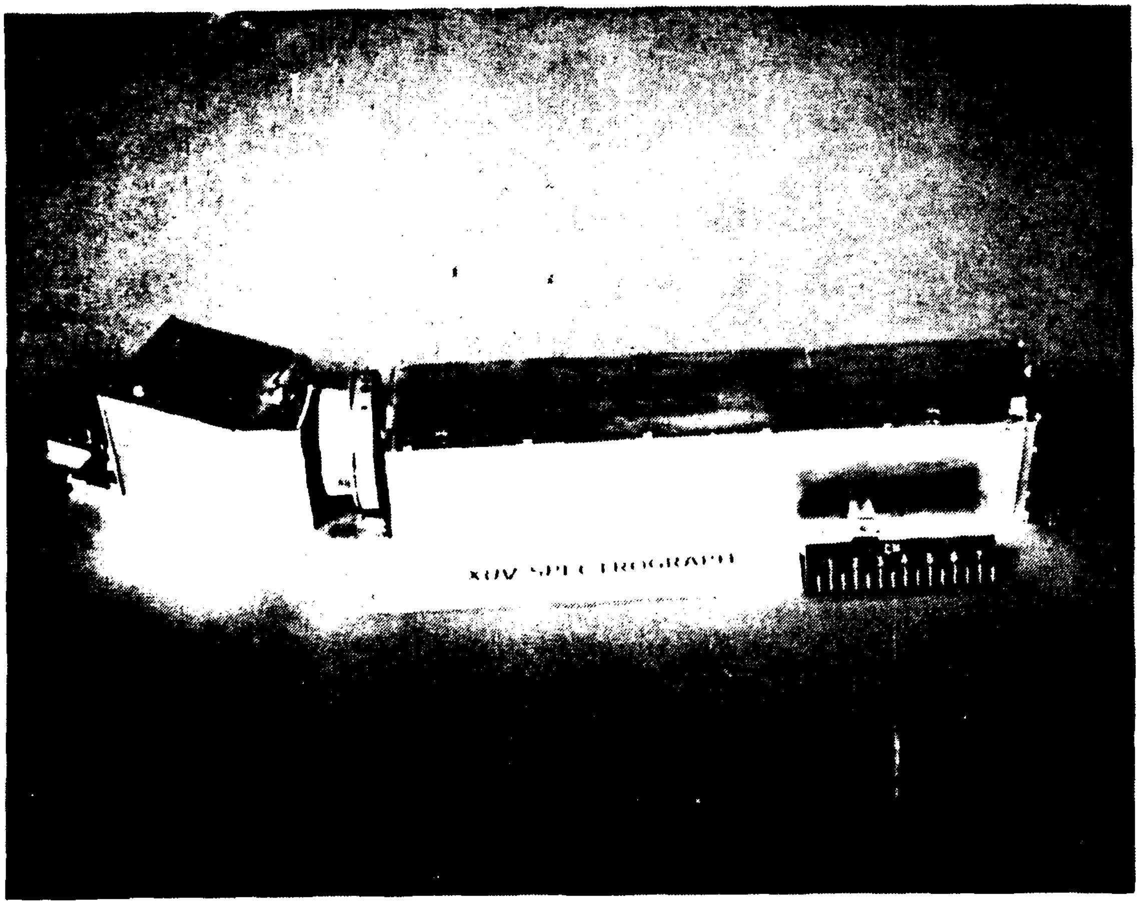
Figure 1. XUV Grazing incidence grating spectrograph.



Von Hamos PET crystal spectrograph to collect spectra from layered aluminum targets on silicon wafers) provided the intensity variations of the helium-like Al XII and SI XIII lines (K-shell) as a function of the aluminum coating thickness. The laser energy penetration depth was determined with this method.

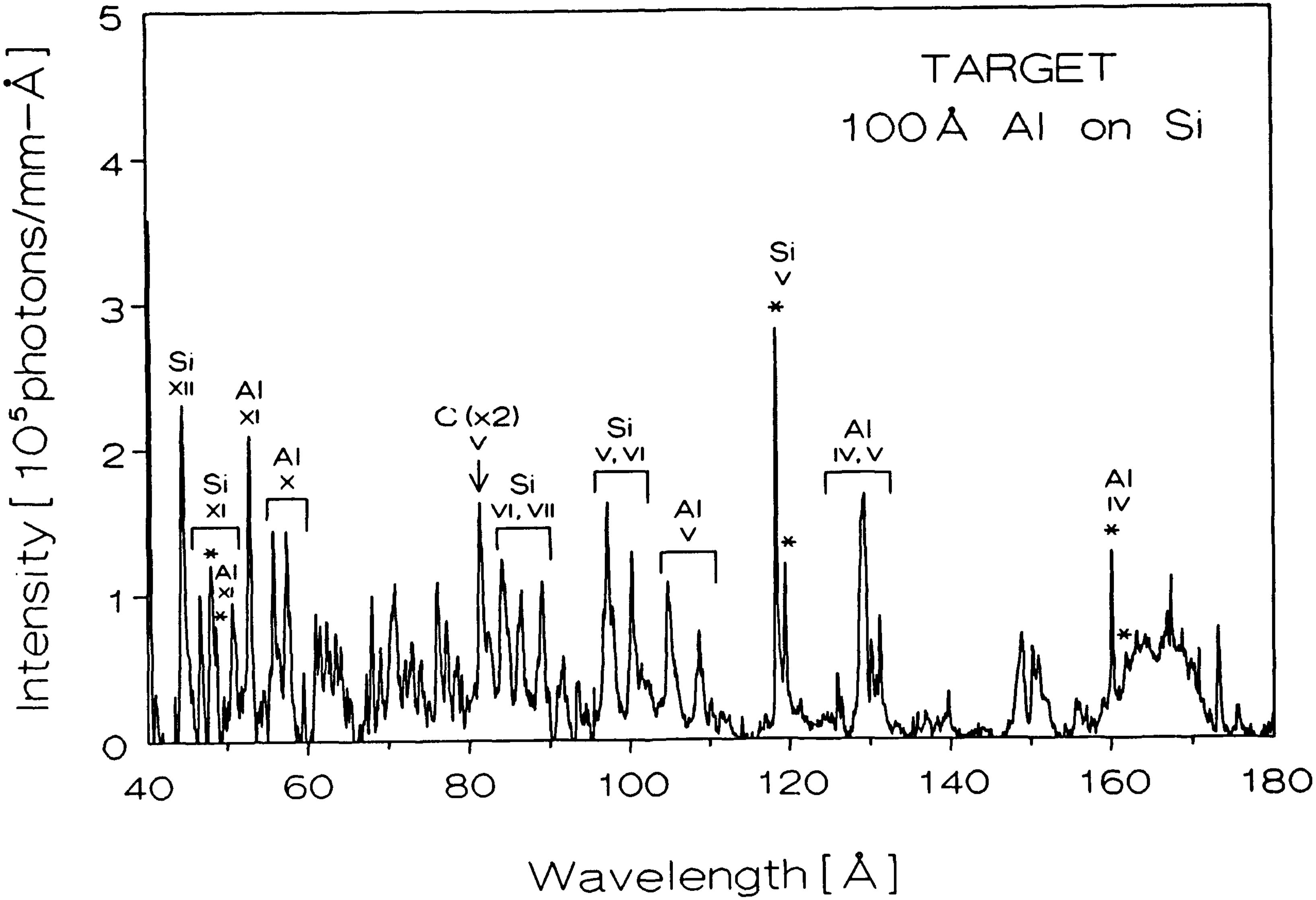
In the current work we sought to perform spectroscopic observations in the subkeV energy range to record the emission from less highly ionized ions (L-shell). The targets were constructed of vacuum-deposited layers of aluminum with thicknesses 0, 100, 300, 500, 1000, 3000 and 5000 Å on flat silicon wafers; they were irradiated in vacuum by the focused linearly polarized laser pulse at both available wavelengths. The targets were mounted at 45° with respect to the beam and the time-resolved K-shell x-ray yield from the plasma was monitored by x-ray diodes. The laser energy penetration depths were derived from the intensity variations of some silicon lines (L-shell radiation).

2. EXPERIMENTAL

XUV spectra of aluminum and silicon were recorded in the range 25-250 Å with a grazing incidence grating spectrograph[4] shown in Fig. 1. The grating with 1 m radius of curvature, 1200 lines/mm was illuminated through a 25 μm-wide slit at an angle of incidence of 88°. The spectrograph axis was at 45° from the target normal and the entrance slit was located about 5 cm from the target.

Spectral data were recorded on Kodak 101 emulsion. Measurable film densities required 87 shots at $\lambda_L = 1.06\ \mu m$ and 150 shots at $\lambda_L = 0.53\ \mu m$. During the exposure the targets were translated in the vacuum chamber in order to irradiate a new area for each shot. The films were densitometered with a PDS scanning densitometer and computer-processed for conversion to XUV spectral

Figure 2. Spectral trace in the 40-180 Å range showing the various ion line intensities (on film).
*measured lines



intensities on the film (photons/cm^2) using published film calibration data.[5] The wavelength calibration was obtained using the grating equation together with published wavelengths for the intense transitions observed from carbon and oxygen impurity ions in first and second order throughout the XUV spectra.

3. SPECTROSCOPIC RESULTS

The picosecond, focused laser beam generated plasmas in the layered-aluminum, silicon targets radiating essentially a line spectrum from all L-shell ions from neon-like Aℓ IV (and Si V) to lithium-like Aℓ XI (and Si XII) in the 25-250 Å region. Fig. 2 shows the spectral region 40-180 Å with intensity units obtained on the photographic emulsion. The trace corresponds to irradiation of the type of target indicated with the 0.53 μm laser wavelength . Some of the major ion lines are identified and the asterisks indicate the transitions for which the integrated line intensities were measured. The trace shown represents the radiated intensity above background, the continuous radiation having been subtracted for a better display of the relative contribution from the various ions. Table I gives the list of the transitions from the silicon and aluminum ions selected for intensity measurements.

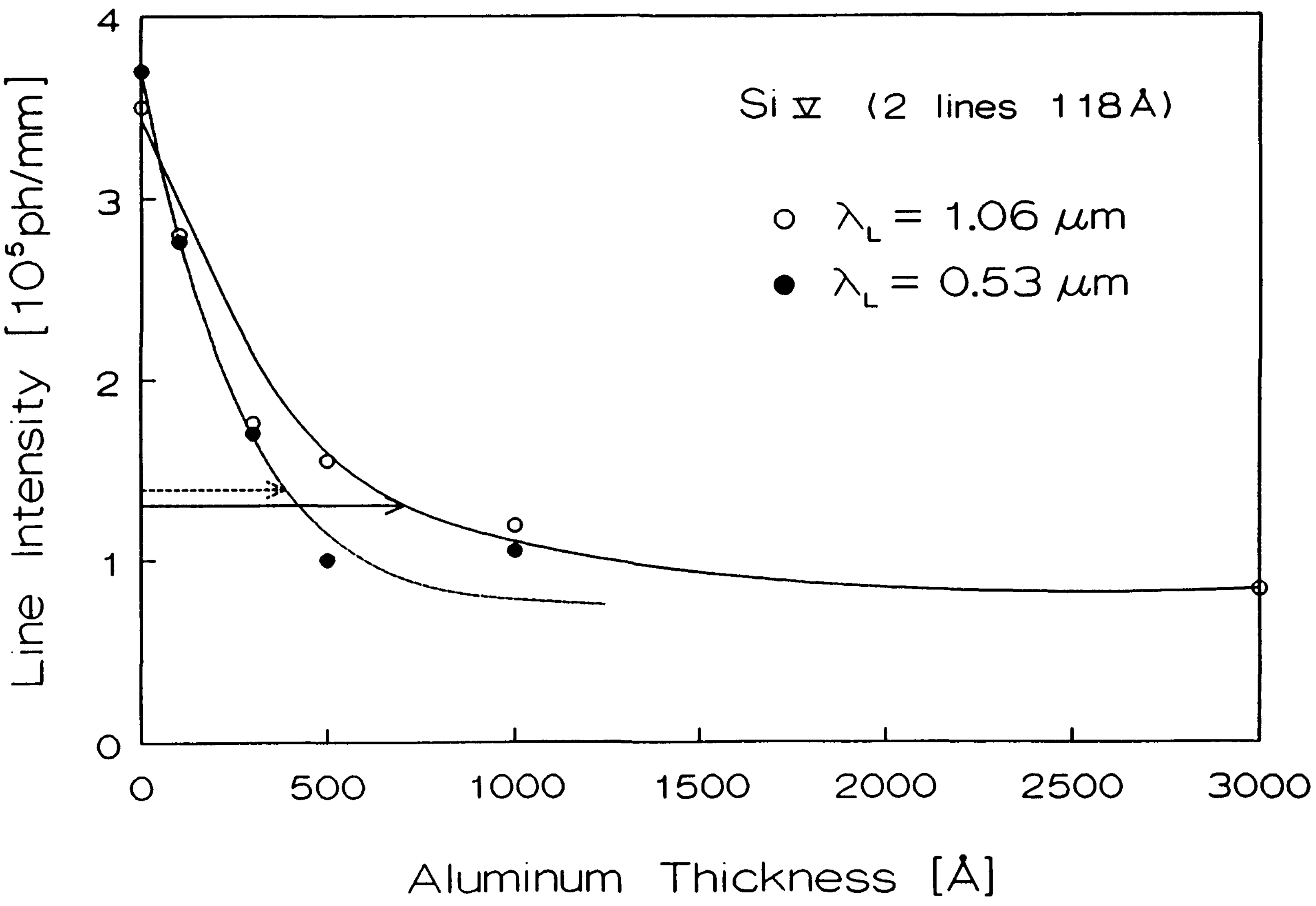
For some of the lines emitted by silicon and aluminum ions we measured the integrated intensity (in photons per mm) and plotted the values as a function of the aluminum thickness for targets of pure silicon to 3000 Å aluminum coating. The laser light conversion efficiency derived from x-ray diode signals that record the plasma K-shell radiation has been observed to vary from shot-to-shot by as much as 60 %. The measured neon-like Al IV and Si V line pairs correspond to the same transitions for these isoelectronic ions with a difference of 1 in atomic number. Considering that the excitation energy is not too different for

Table I

Selected spectral lines for measurement

Ion	λ [Å]	Transition
Si XIII	6.650	$1s^2\ {}^1S_0 - 1s2p\ {}^1P^0_1$
Al XII	6.635	$1s^2\ {}^1S_0 - 1s3p\ {}^1P^0_1$
Si XI	47.607 47.653	$2p^2\ {}^3P - 2p3d\ {}^3D^0$
Al XI	48.297 48.338	$2s\ {}^2S_{1/2} - 3p\ {}^2P^0_{3/2,1/2}$
Si V	117.86	$2p^6 - 2p^5 3s$ [1/2],1
	118.968	[3/2],1
Al IV	160.073	$2p^6 - 2p^5 3s$ [1/2],1
	161.686	[3/2],1

Figure 3. Variation of the Si V line intensity with the aluminum layer thickness under irradiance of: 1.2×10^{15} W cm^{-2} at 1.06 μm and 3×10^{14} W cm^{-2} at 0.53 μm.



both ions, it seems reasonable to expect that the sum of both ion line pair intensities (from these resonance transitions) should not vary much with the aluminum layer thickness if the laser intensity and target irradiation conditions were identical. In this experiment the peak radiated value corresponds to the pure silicon target and was used as the reference. Using this and the above assumption we corrected the measured intensities on the multiple shot exposures. The correction factor which is the ratio of the pure silicon target radiated energy (Si V line pair) to the radiated energy from both Si V and Al IV line pairs is meant to compensate for the laser energy conversion efficiency fluctuations . On the other hand, the thick aluminum targets (5000 Å or pure aluminum foils) appear to radiate much less possibly because of much decreased laser light conversion efficiency. Due to the lack of experimental data on the laser light absorption as a function of the aluminum target thickness with these particular experimental conditions, we did not retain the measurements of the aluminum ion line intensities for large aluminum thicknesses when the spectra had noticeably decreased overall intensity. This was the case for measurements with aluminum foil targets irradiated at $\lambda_L = 1.06\ \mu m$ and with 5000 Å Al on Si or Al foil targets at $\lambda_L = 0.53\ \mu m$. At this wavelength we did not collect spectra from targets with a 3000 Å Al coating.

Figure 3 is a plot of the intensity variations with the aluminum- layer thickness of the Si V lines, the intensity values (y-axis) corresponding to the sum of the two silicon line intensities. These intensities were corrected in the fashion outlined above for the laser conversion efficiency variations. The Si V line intensities were plotted for both wavelengths in Fig. 3.

For the lithium or beryllium-like ion line intensities we did not attempt to correct the measured intensity values of Si XI or Al XI ions because the

Figure 4. Variation of the Al XI and Si XI line intensity with the aluminum layer thickness.

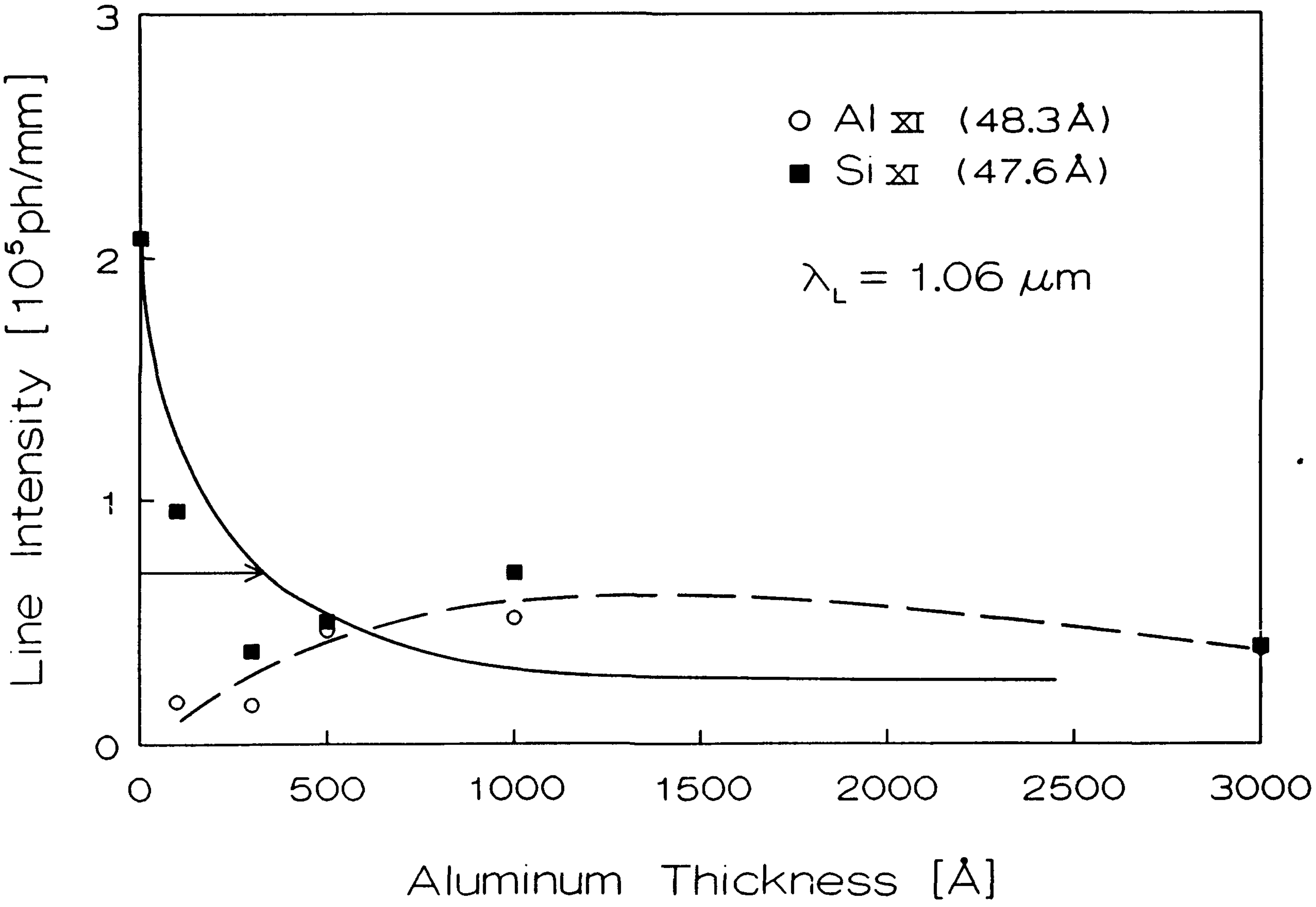
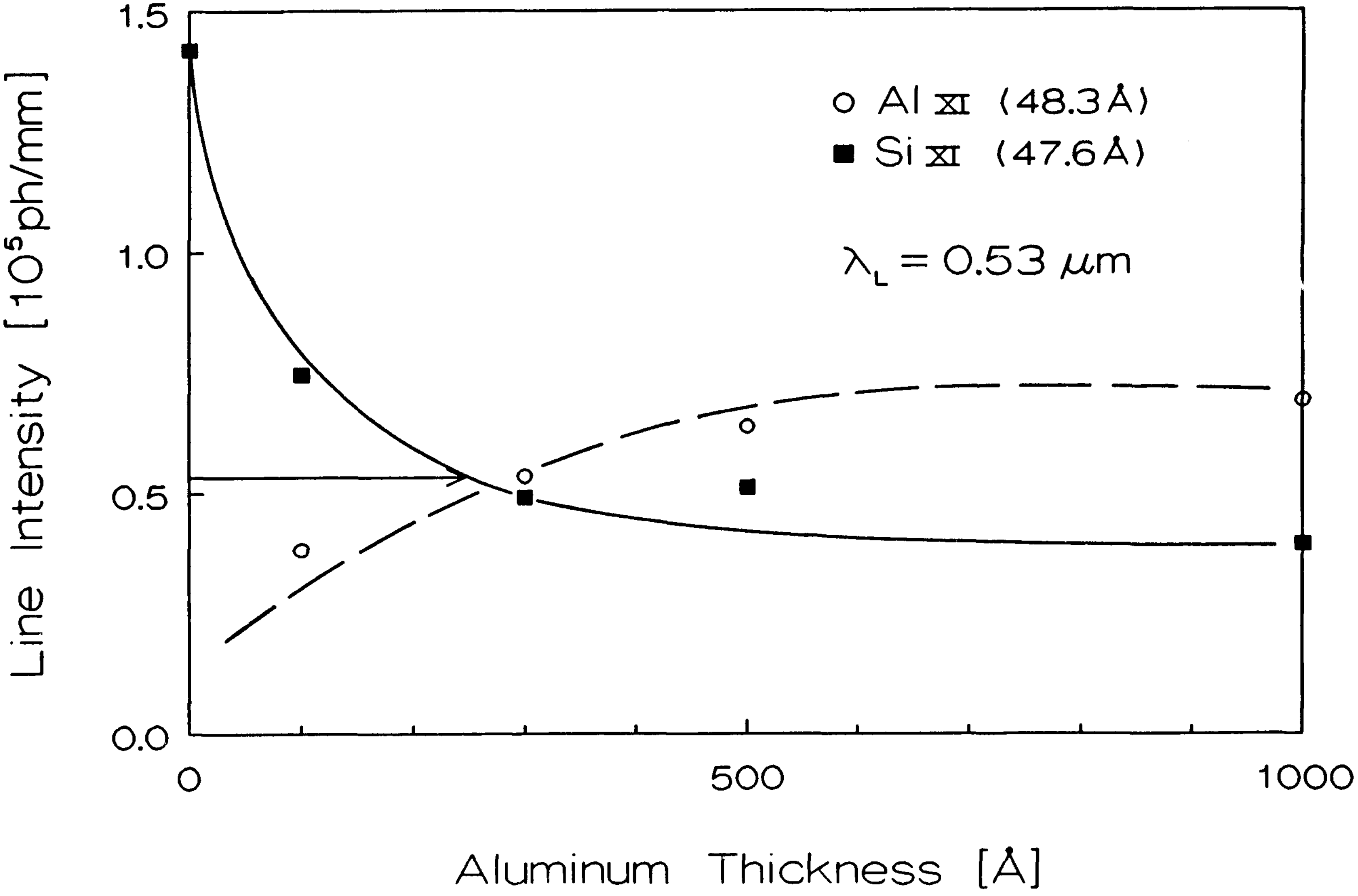


Figure 5. Variation of the Al XI and Si XI line intensity with the aluminum layer thickness.



plasma radiation balance cannot be overly simplified as for the Si V and Al IV ions. In figures 4 and 5 are shown the line intensity variations as a function of the aluminum thickness for the Al XI and Si XI ion transitions. Figure 4 corresponds to the plasma emission from targets irradiated with the $\lambda_L = 1.06\ \mu m$ laser wavelength and Figure 5 with the $\lambda_L = 0.53\ \mu m$ laser light. From the Al XI line intensity variations (see plot in Fig. 4 for example) we observe that for thicknesses above 1000 Å the aluminum emission shows saturation. The same effect was observed from the measurements of the other aluminum ion radiated intensities (especially Al IV).

4. DISCUSSION

Defining the energy penetration depth, Δ, as the aluminum thickness for which the measured Si line intensity has decreased by a factor of e from its peak (with a solid silicon target), we may obtain the value of Δ on any silicon line intensity plot versus aluminum thickness. In Figures 3, 4, and 5, the thickness read at the ordinate marked at I_{max}/e is the penetration depth Δ.

The values of Δ determined in these figures from the fall off of the silicon line intensity (with increasing aluminum layer thickness) are given in Table II. The experimental uncertainty from this graph determination is about ± 100 Å caused mainly by shot-to-shot variations in the laser x-ray conversion efficiency. The derived values indicate a slightly larger penetration depth at the longer laser wavelength, visible in Fig. 3.

For the picosecond-pulse, 0.53 μm-wavelength laser irradiation we established that the penetration depths are only of the order of 300-400 Å at a laser intensity of 3×10^{14} W cm^{-2}. The less steep density gradients characteristic of the laser interaction at its Nd wavelength of $\lambda_L = 1.06\ \mu m$ [2] are confirmed by the new spectral observations which yield penetration depths of the order of 300-700 Å. These observations are in agreement with the earlier x-ray experimental results [2] obtained from the Si XIII line (at 6.65 Å). The previous laser penetration depth values were 200 to 300 Å at λ_L = 0.53 μm and 300 to 700 Å at λ_L = 1.06 μm.

Table II

Penetration Depths, Δ, Derived from Silicon Line Intensity Variations

Laser	λ_L = 1.06 μm Δ [Å]	λ_L = 0.53 μm Δ [Å]
Si XI	300	250
Si V	700	400

Zigler et al [6] determined the penetration depth of a 0.6 picosecond KrF* laser pulse of wavelength 0.248 μm at an intensity about two orders of magnitude higher than that available with the T^3 laser used in this experiment at 0.53 μm. This difference in the target irradiation conditions make the comparison of the results from both experiments difficult but it seems reasonable to expect much larger penetration depths[2] with increased laser intensity. The derived penetration depths with the KrF* laser system used by Zigler et al are about an order of magnitude larger than the ones found in the present work at the frequency-doubled irradiation.

With the 1.06 μm-wavelength laser, silicon ion emission (Si V to Si XI) is observable even with aluminum coatings 3000 Å thick; in fact the silicon radiation appears to be of comparable intensity for 3000 and 1000 Å aluminum layers (Figs 3 and 4). Time-resolved spectroscopic observations are needed to correlate the silicon emission time-history with the laser energy deposition time scale. It appears, however, that the short penetration depths derived in this experiment from recording the plasma radiation by lower ionization degree species support the assumption of electron heating in the solid target. The high thermal gradients produced in the solid, which are associated with rapid conduction of electron energy into the bulk of the target, allow radiation by L-shell ions well beyond the penetration depth.

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