# Recent and proposed opacity experiments at the AWE HELEN laser.

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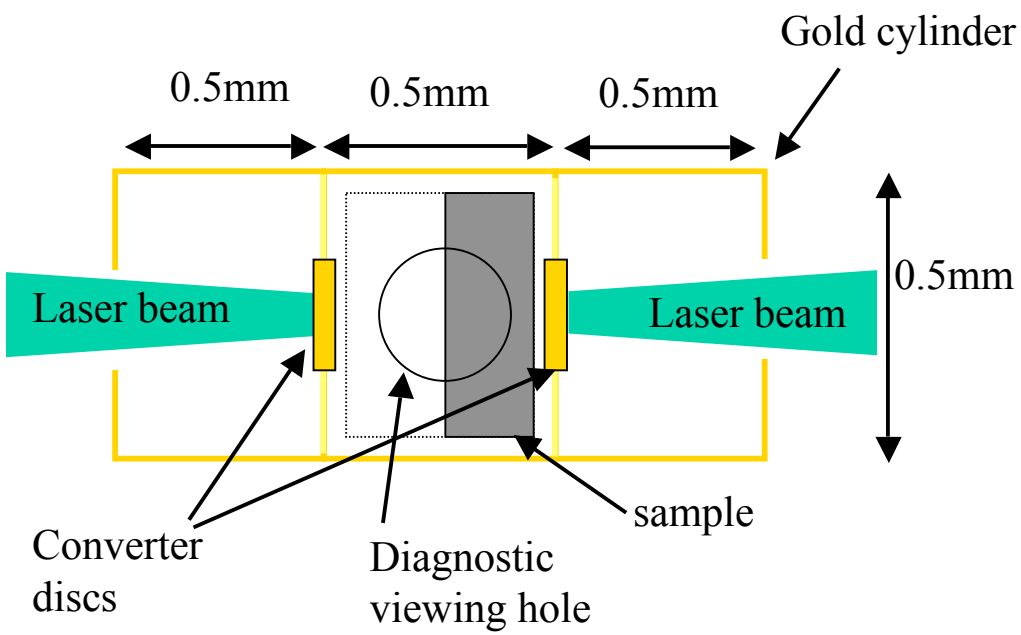
J W O Harris, L Upcraft, P Graham, S F James, S G Gales,
C D Bentley, C C Smith.

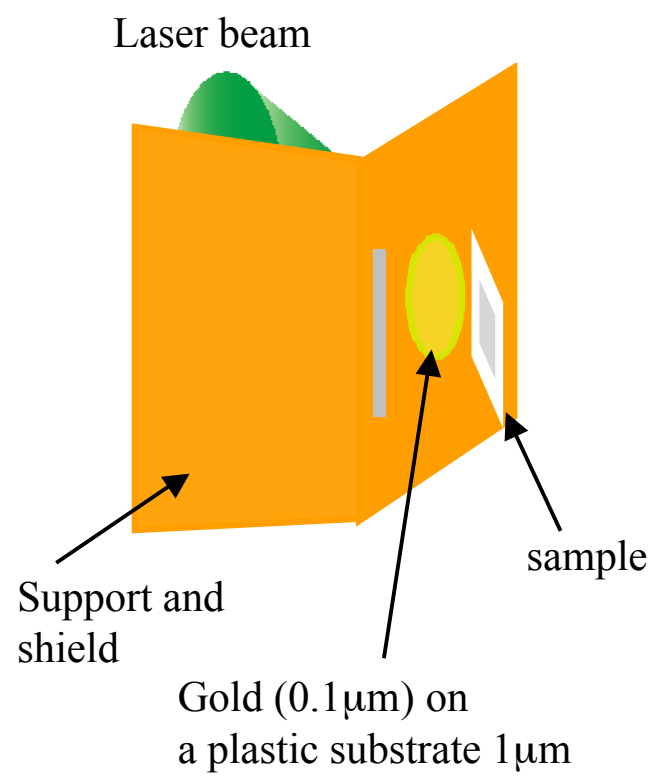
# HELEN experiments-creating the opacity sample by X-ray heating of thin foils

Two methods :

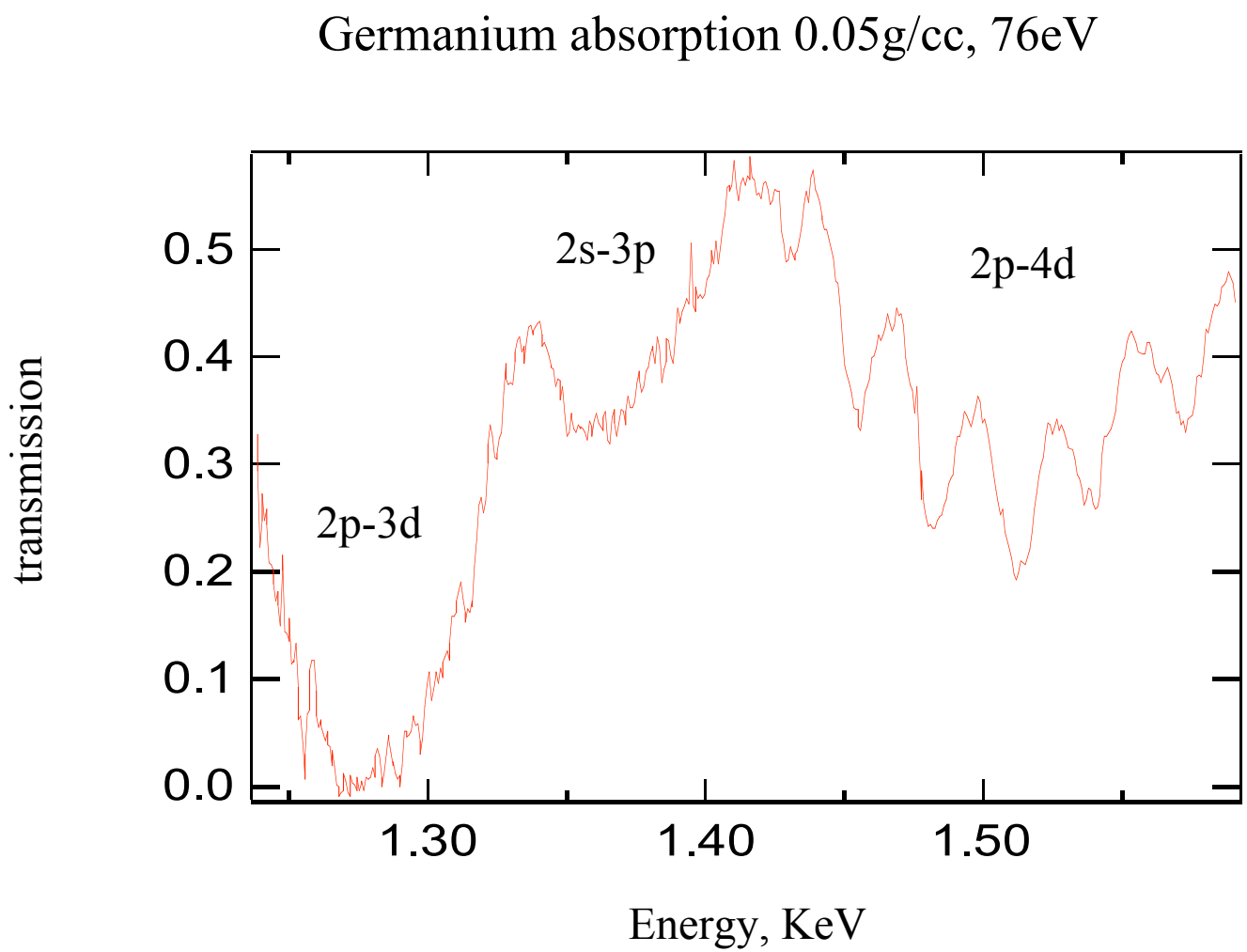
1. Hohlraum



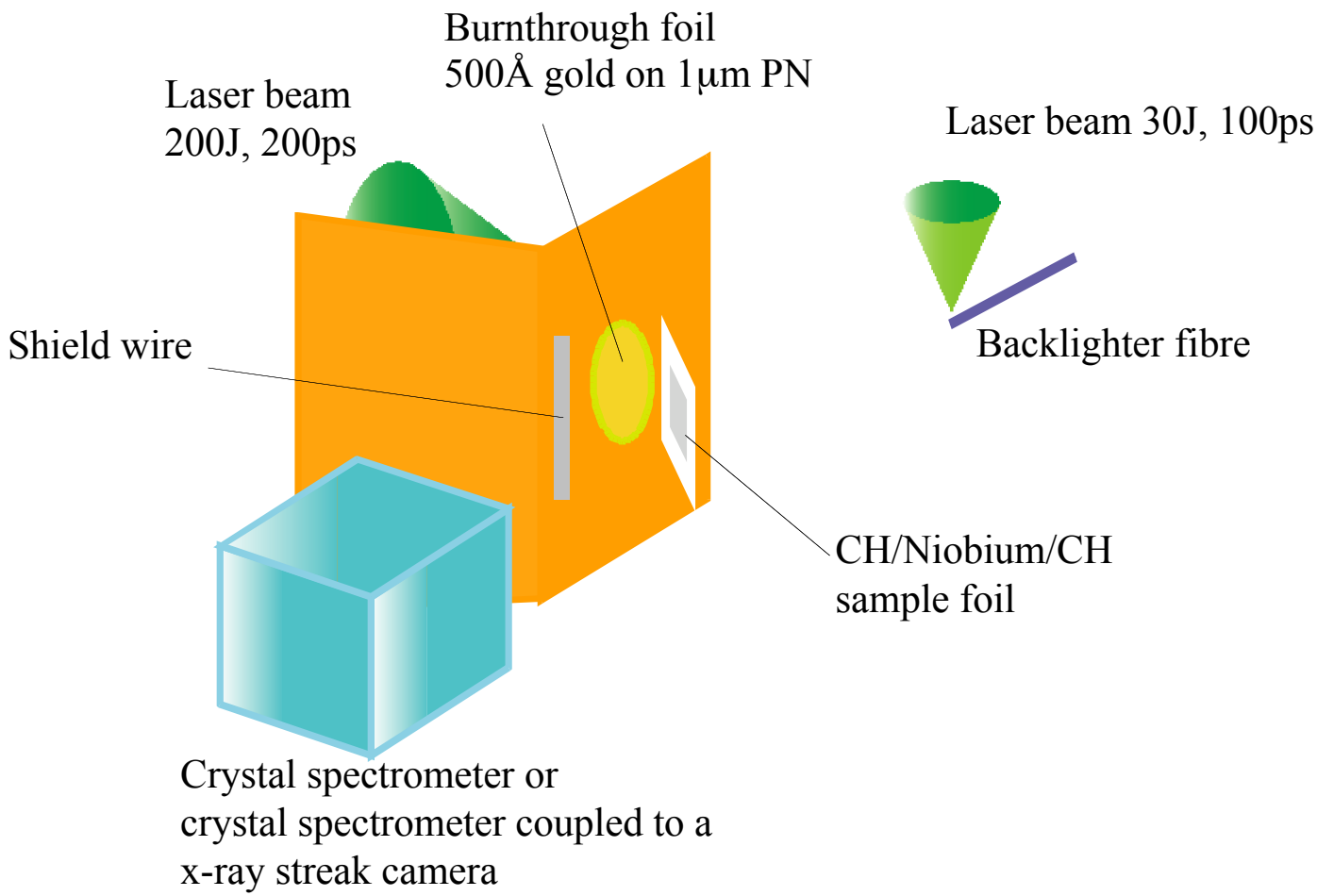

2. Burnthrough foil



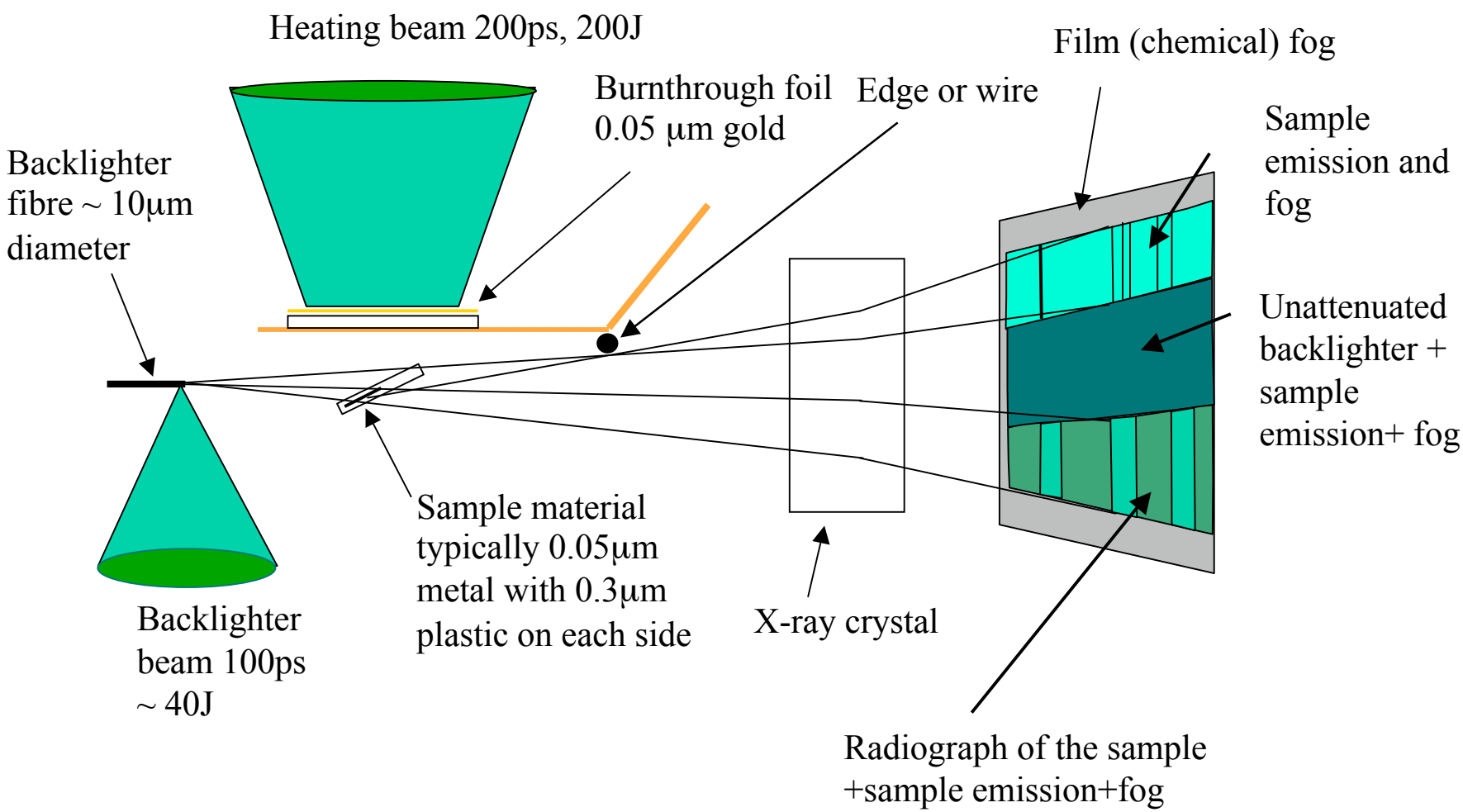
Past HELEN experiments have measured absorption in open M-shell configurations using germanium samples heated in hohlraums.



# Niobium experiments used point projection spectroscopy and samples heated by burnthrough foils.



# Diagnosing the sample with point projection spectroscopy



# Absorption spectra are rich in detailed information to compare to calculation predictions.

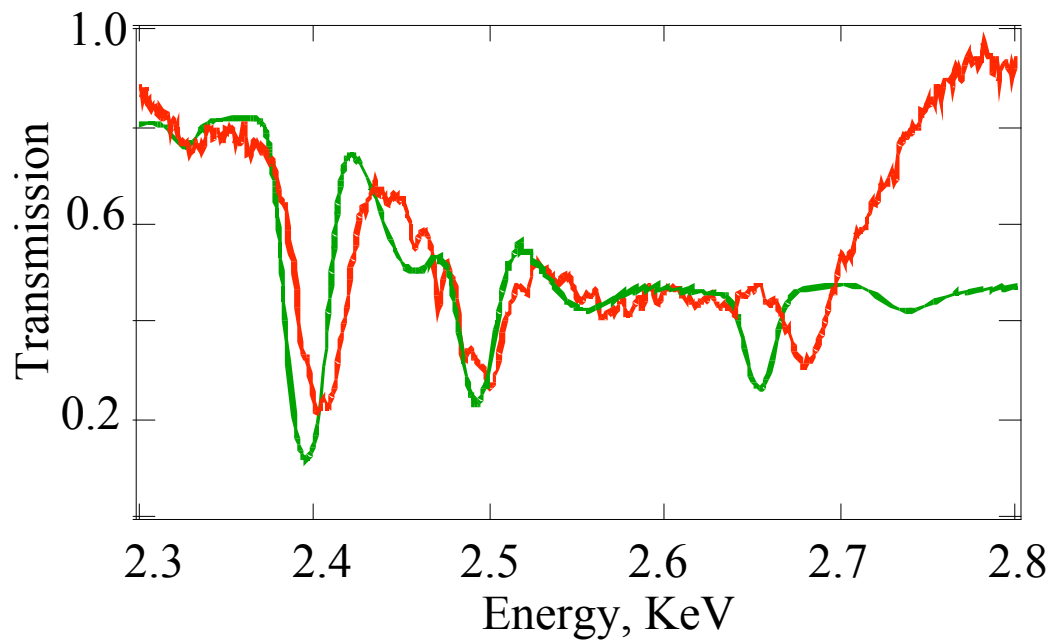
- Data give information on: -

-the position and width of transition arrays.

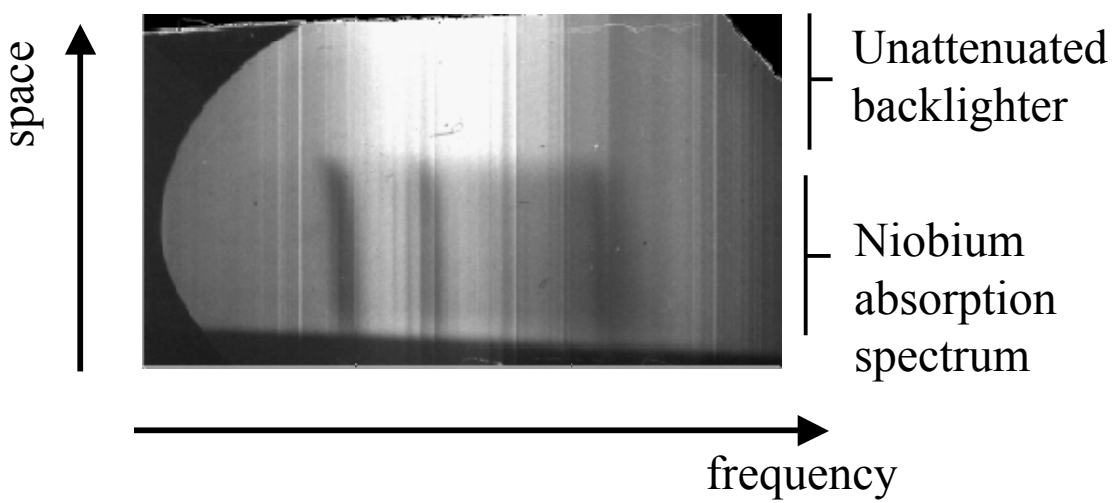
- the positions of absorption edges

- the transmission of arrays

- the transmission between arrays

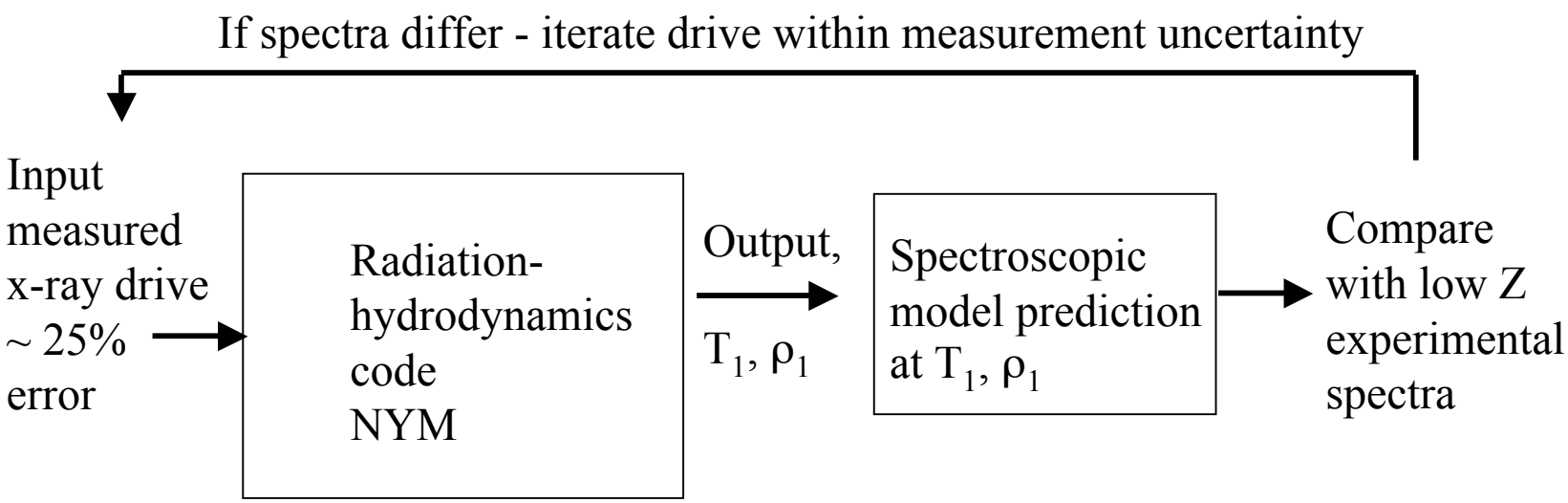



Dispersed radiograph



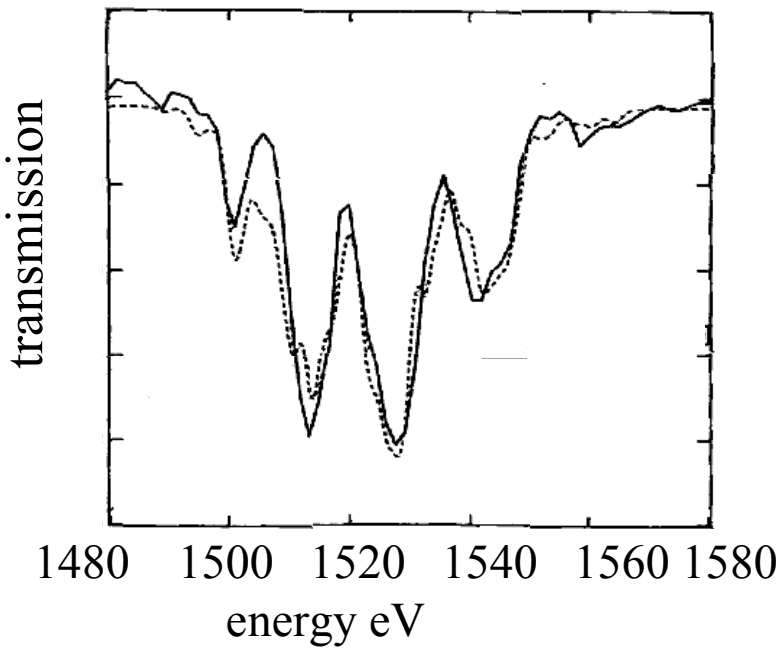
# Diagnosing the sample conditions.

- Not enough to measure an absorption spectrum, the sample conditions must be known.
- The conditions are constrained by a combination of measurements and two-dimensional radiation hydrodynamics modelling.
- Measurements include x-ray flux measurements of the hohlraum x-rays using flat response x-ray diodes and x-ray spectroscopy of low Z materials (Al or Mg).
- Recent experiments have used mixtures of low and high Z materials.

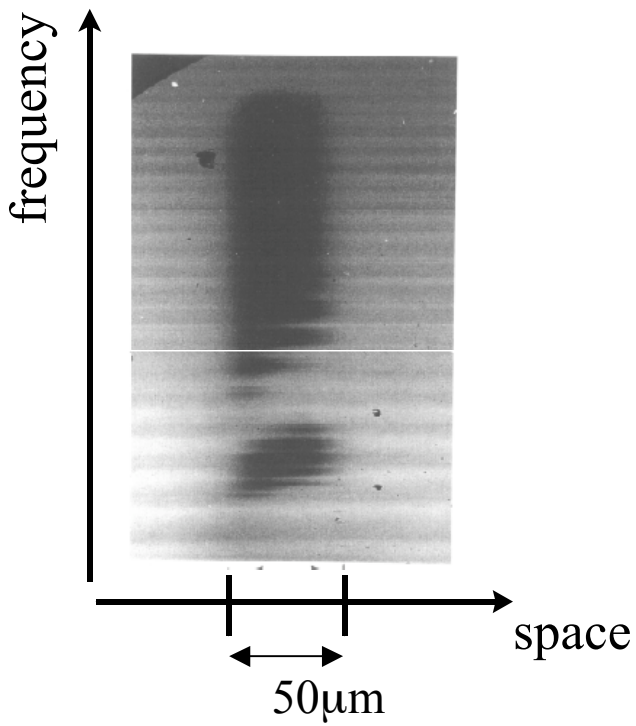


# Drive and sample characterisation - expansion and ionisation measurements.

Modelling of the 1s-2p transitions in LTE ionised aluminium samples to infer the heating effect of the burnthrough foils

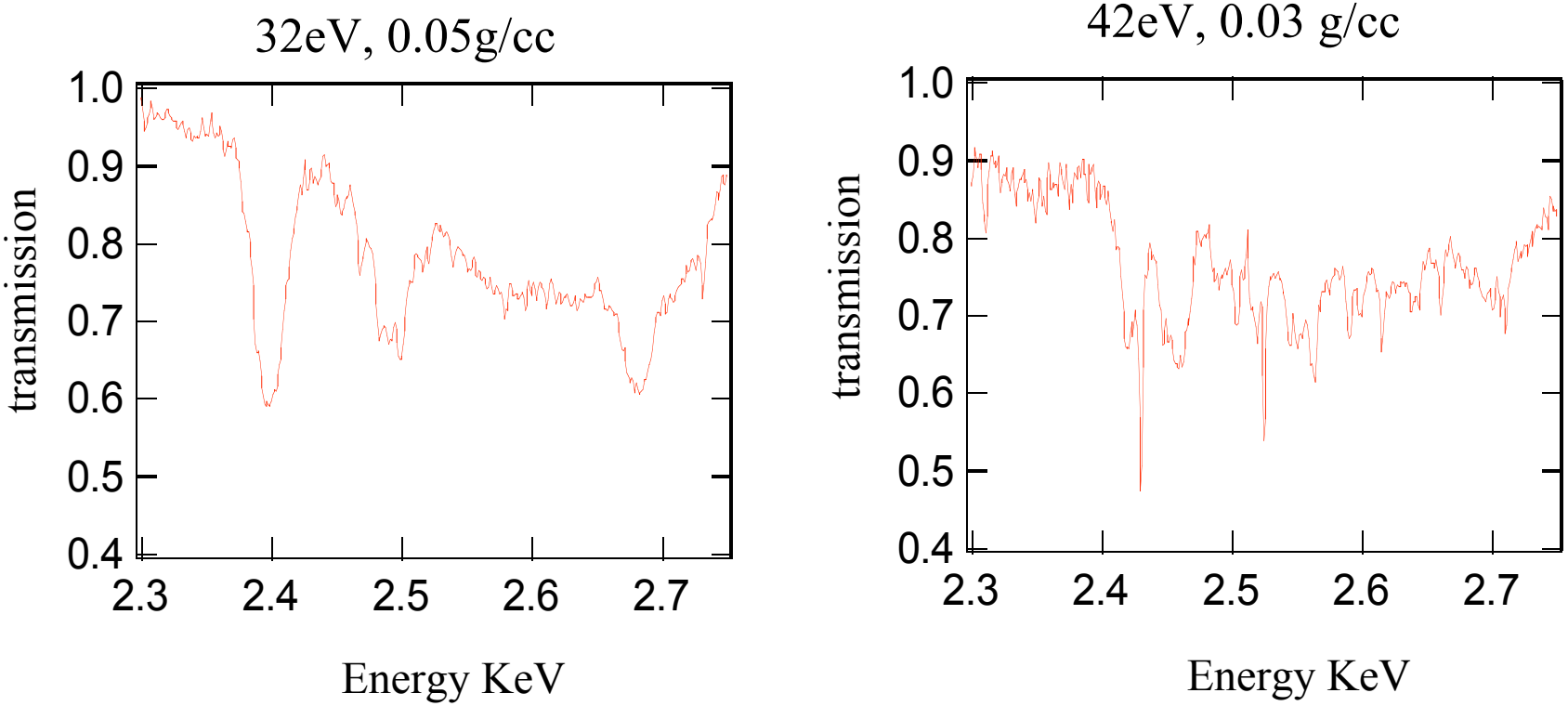



Side-on radiographs of expanded Al samples

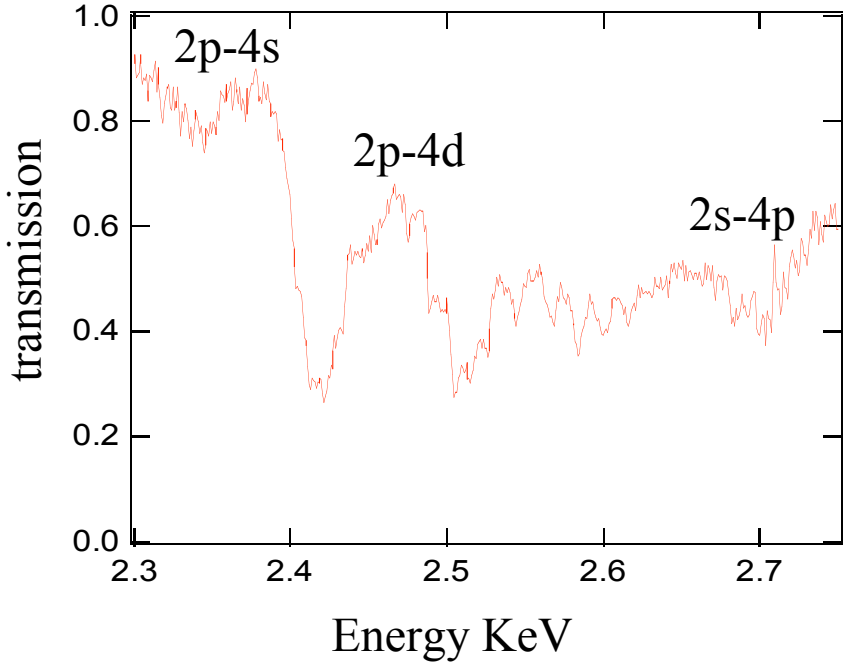


# The L-shell absorption spectrum in plasmas with a near full M-shell changes dramatically over a small temperature range.

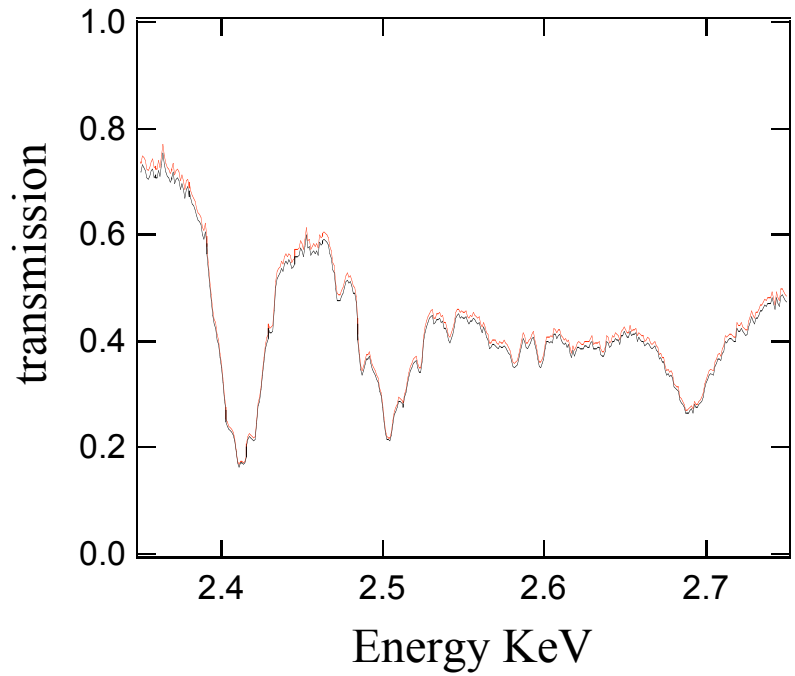
Niobium absorption spectra in the region of 2p-4d transitions



The experimental data were obtained at slightly different conditions by varying the backlighter delay with respect to the heating beam.

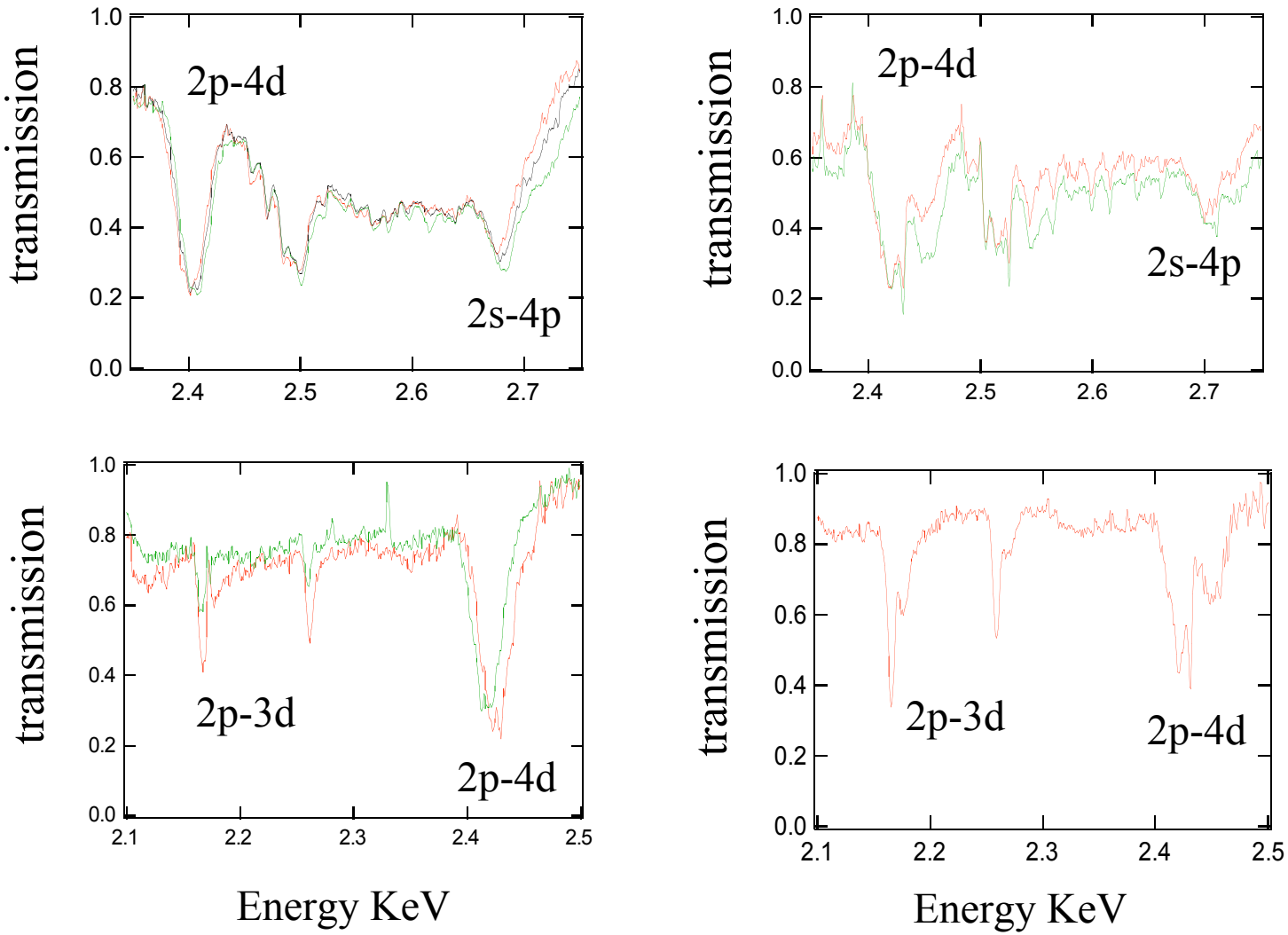



~Te 38eV, density 0.05g/cc

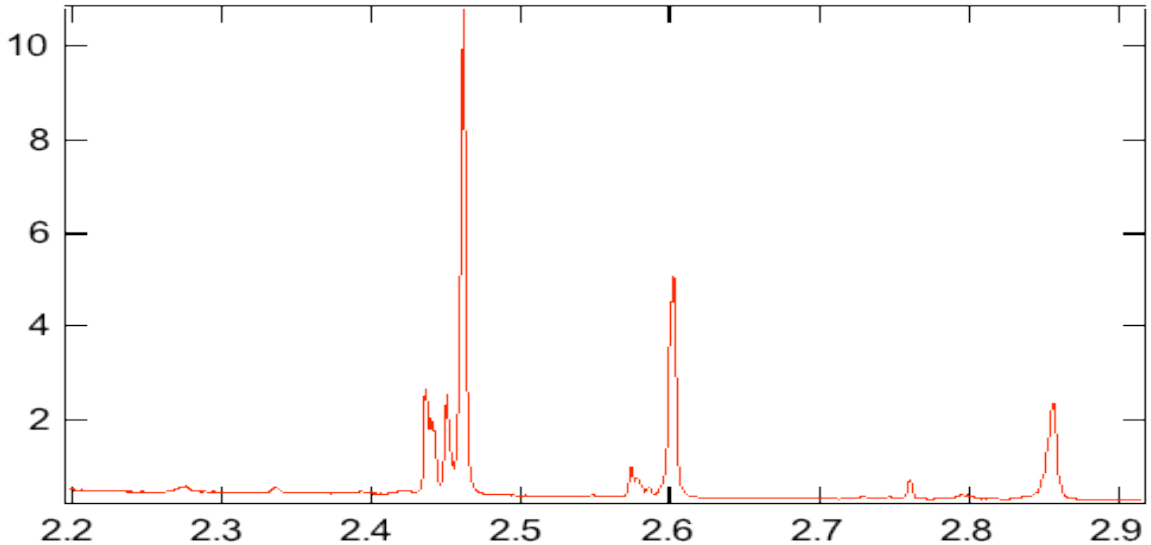


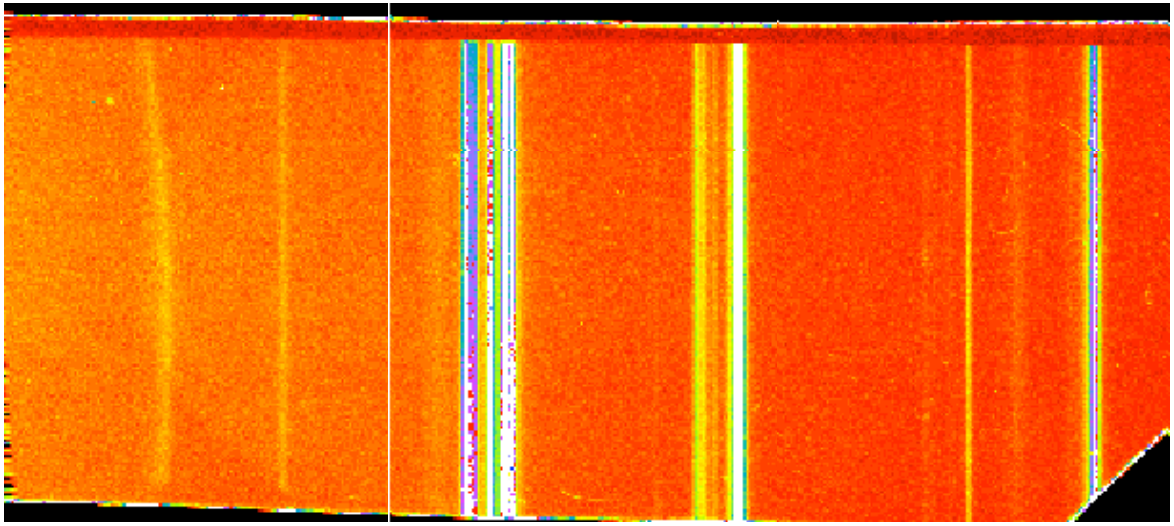

~ Te 34eV, density 0.06g/cc

Measurements of niobium L-shell transitions were made at conditions where the M-shell average occupancy changes from zero to one.



# Spectrometer spectral calibration using low Z (Sulphur) K-shell line emission

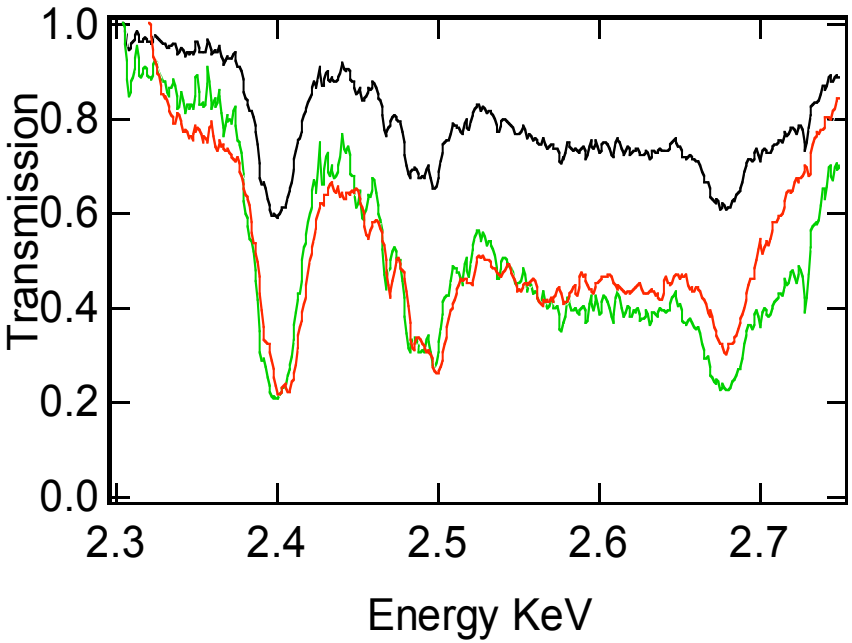


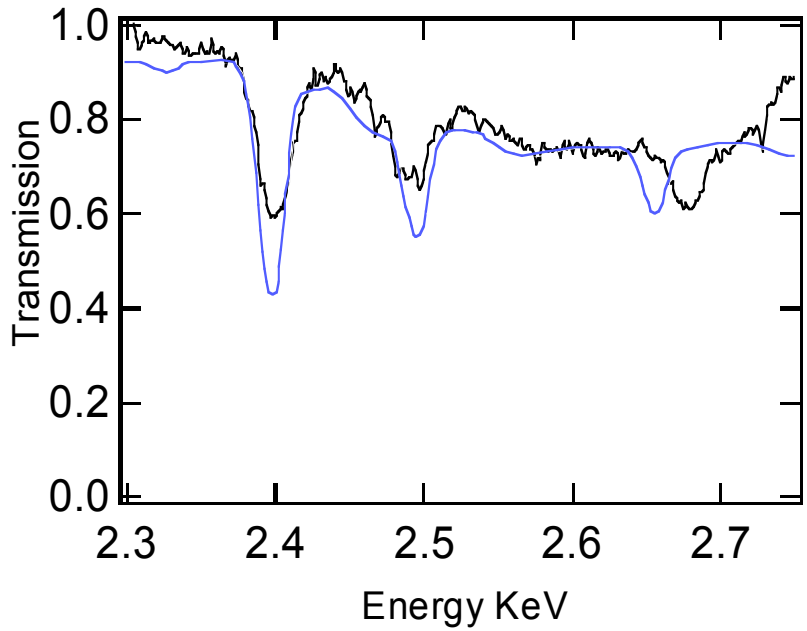



# Helen experiments on different thickness samples suggest arrays are not porous. However a discrepancy with the calculations remains.

Experiments on thick and thin samples suggest there is no significant unresolved structure.

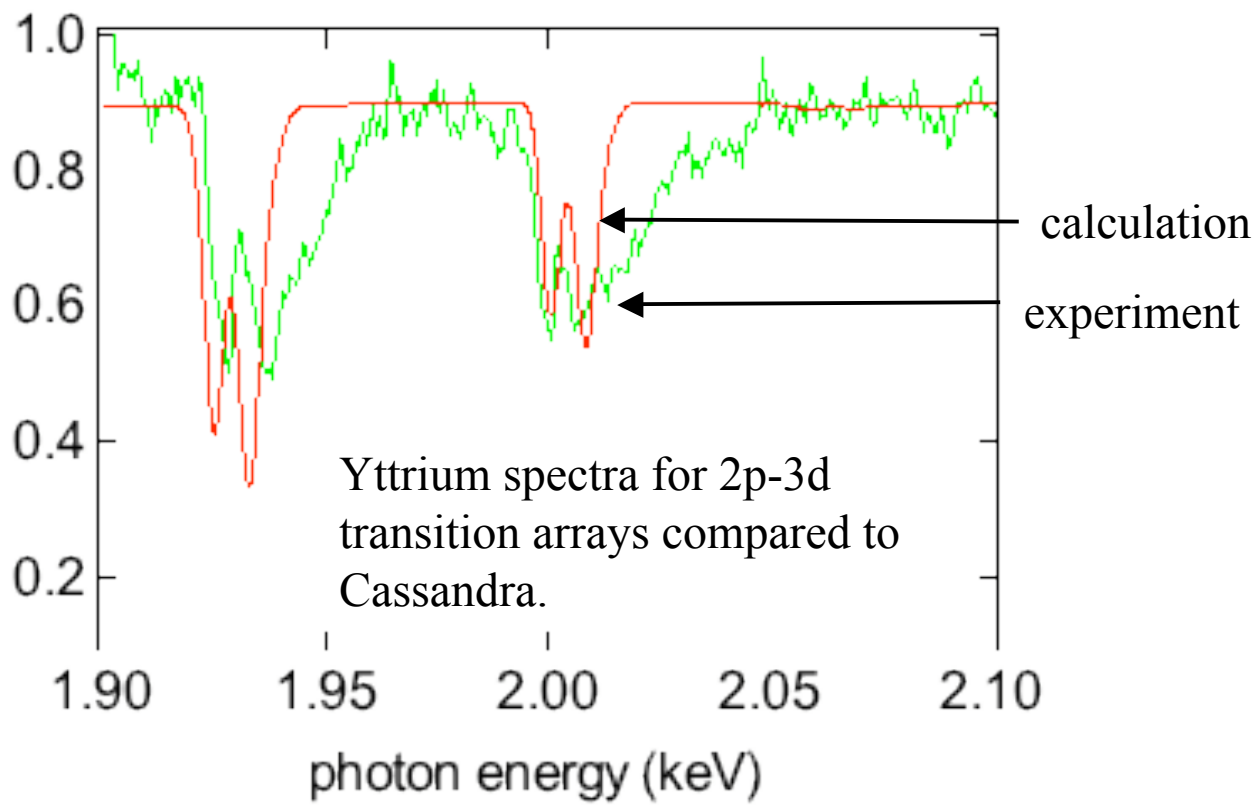
However calculation and experiments disagree on the transmission in the centre of transition arrays.



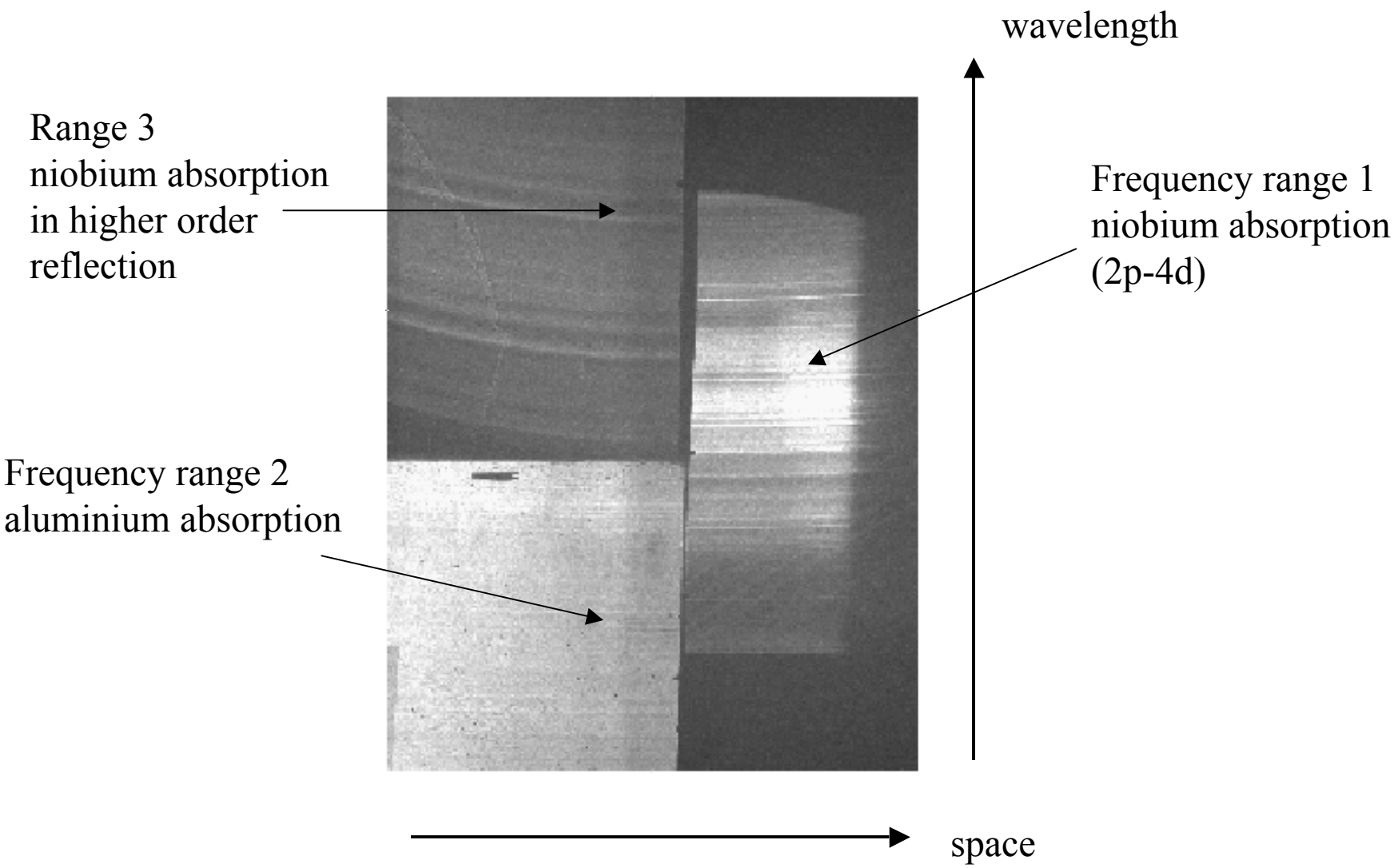



# Some experimental findings still remain unexplained - transition array porosity in mid-Z elements and transition array wings.

- HELEN experiments showed blue wings on transition arrays for near full M-shell configurations. These were not predicted by Cassandra.

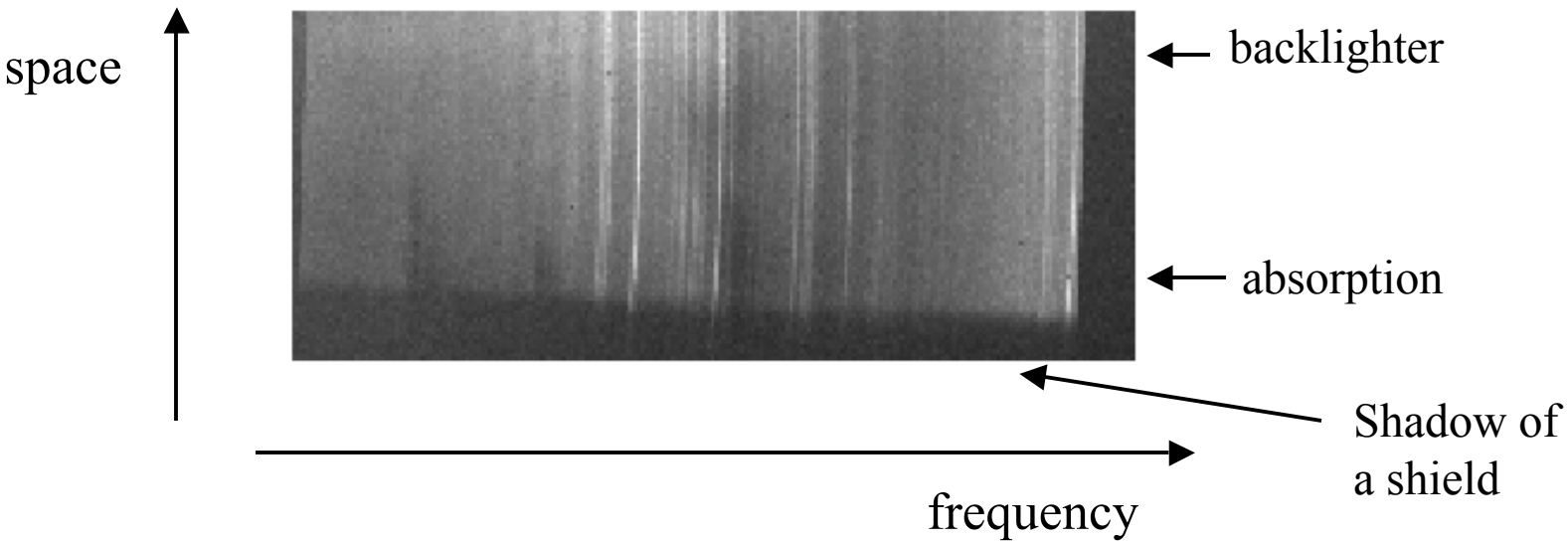


Spectra from mixtures of niobium and aluminium have been measured to help fix the conditions in the earlier experiments.



# Yttrium measurements have been repeated with different backlighter spectra to try to resolve the blue wing discrepancy

Yttrium spectra in the region of the 2p-3d transitions backlit by a gold spectrum



# Summary

- Absorption data has been taken in the spectral range of 2.1-2.8KeV, covering 2p-4d and 2p-3d transitions arrays in niobium, under conditions were the niobium ions have full or almost full M-shell occupancy and the spectra change very rapidly as a function of temperature.

- The data show transition array positions, structure, widths, bound-free absorption, high-lying lines and transmission both in transition arrays and between arrays.

- Additional data was taken on Yttrium samples with slightly higher M-shell vacancies than the niobium.

- Some more shots are planned in 2005 using hohlraum heating and short pulse (CPA) back lighting.

# High density opacity experiments

D.J. Hoarty, J. W. O. Harris, B.J. B. Crowley, S. James, S. Gales, C. Bentley,
C. C. Smith, S. J. Davidson P. Graham, S. J. Rose, M. Stevenson,
E. L. Clark, L. Upcraft.

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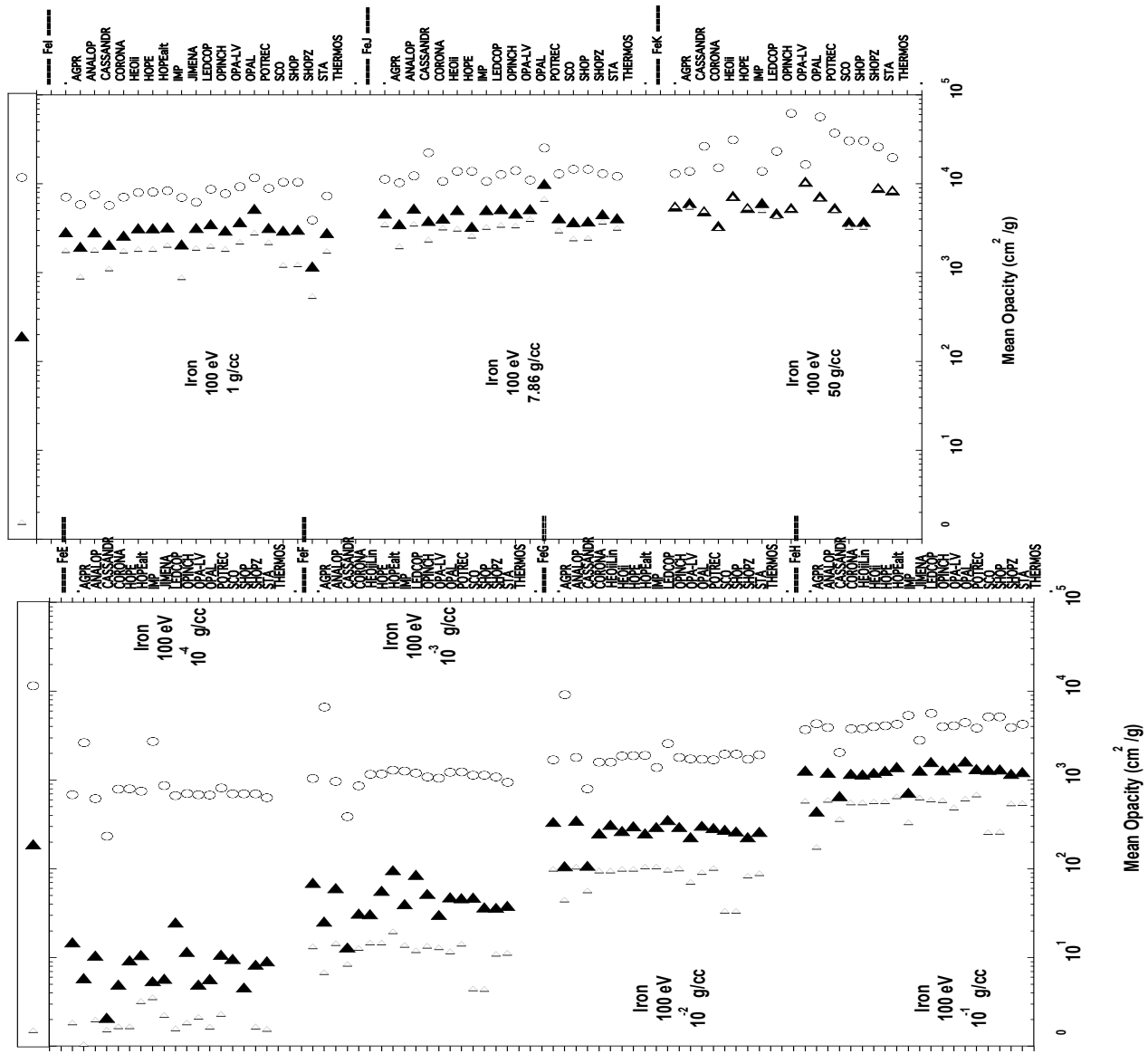
# Code comparisons reveal disagreements between models

Open circles
Planck mean

Black triangles
Rosseland mean

Open triangles
Rosseland mean
continuous opacity




**Iron 100eV, 10e-05 - 50g/cc**

# Extension of opacity measurements to high density strongly coupled plasma

- At high density ion-ion interactions are strong.

A **strongly coupled plasma** is defined by the plasma coupling constant: -

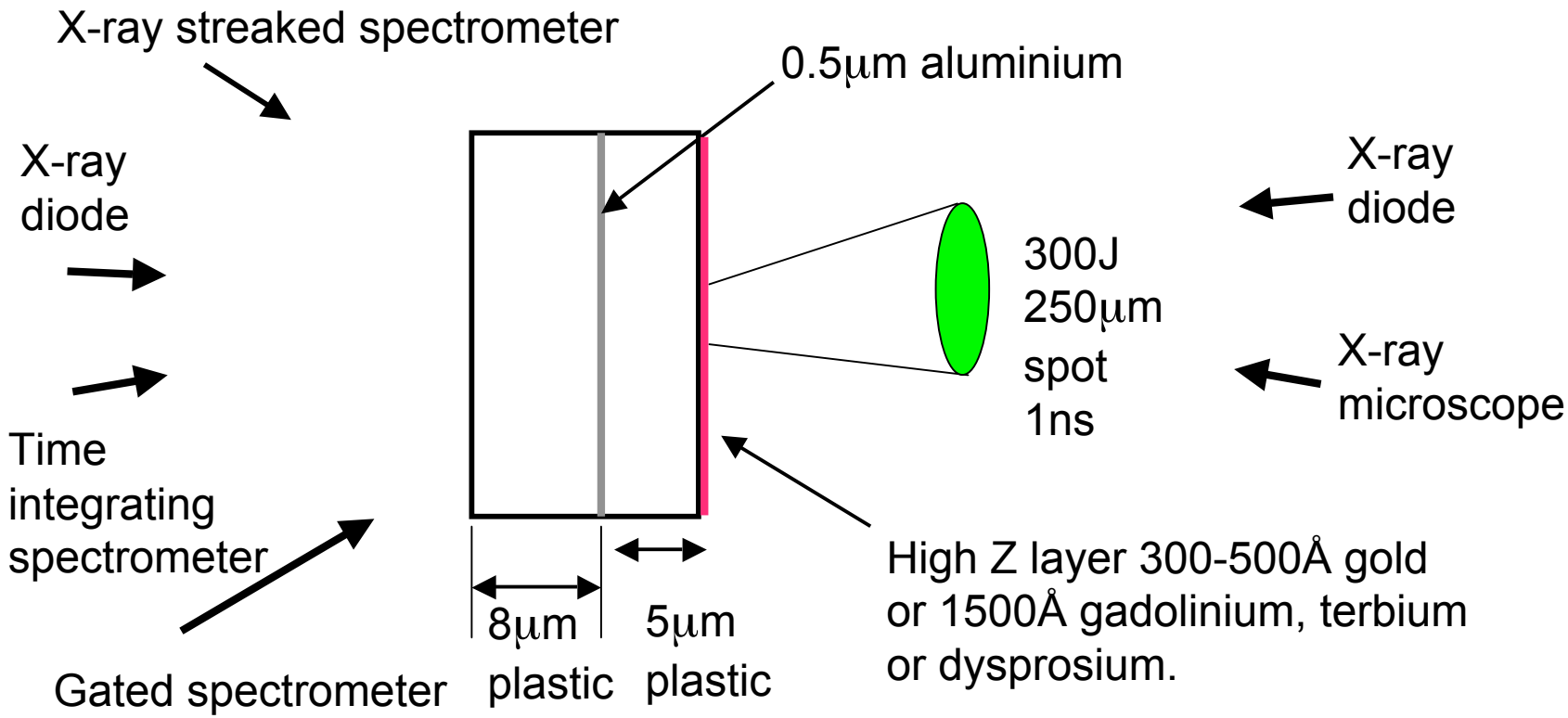
$$\Gamma = \frac{Z^2 e^2}{R_i T}$$

**The plasma is strongly coupled when Γ >1**

- High density effects include :-

- lowering of the ionisation energy (ionisation potential depression)
- merging of high series lines
- Stark broadening (quasi-static, electron impact broadening)

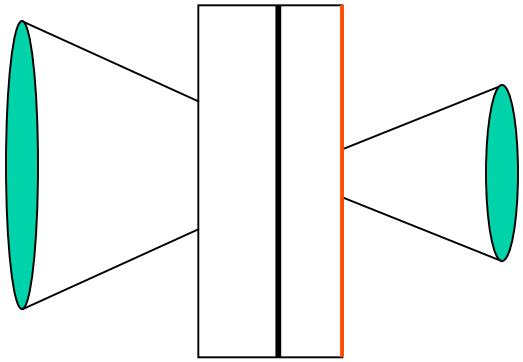
# Experimental Setup



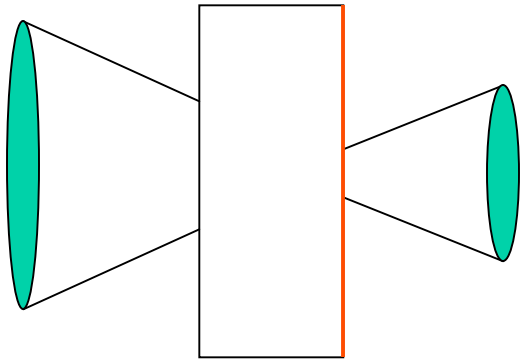

The buried layer is heated and shocked to create a high density open L-shell aluminium plasma.

**There was a range of different irradiance conditions in the study. Targets with no buried layer gave the high Z emission spectrum.**

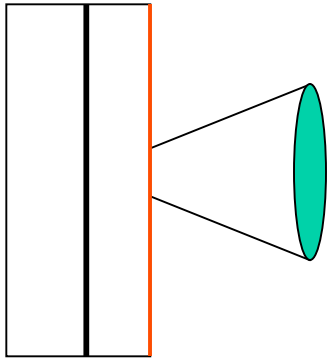
Double sided unequal irradiance.

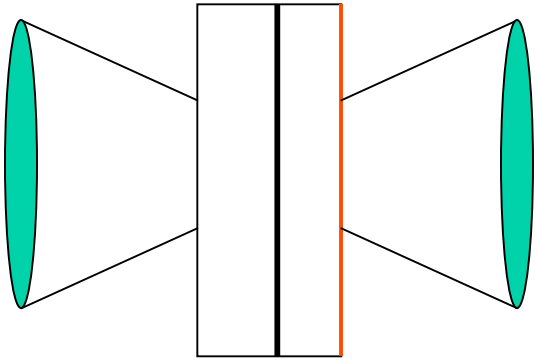


Targets without the buried layer



Single sided





Double sided equal irradiance.

## Absorption spectra were measured time resolved and time integrated on the same shot

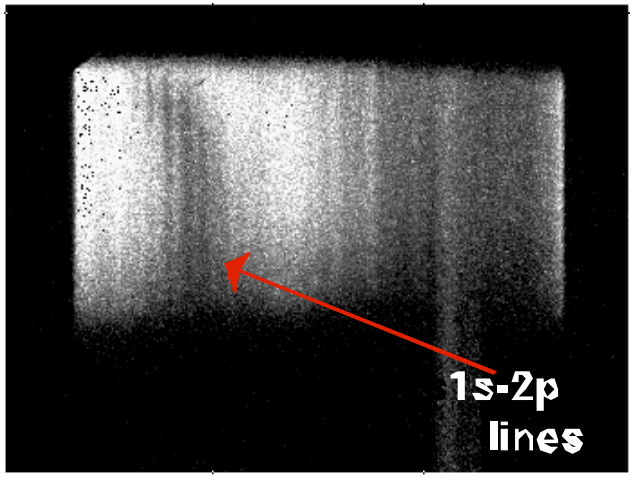
**streaked spectra**

increasing frequency

0

1ns

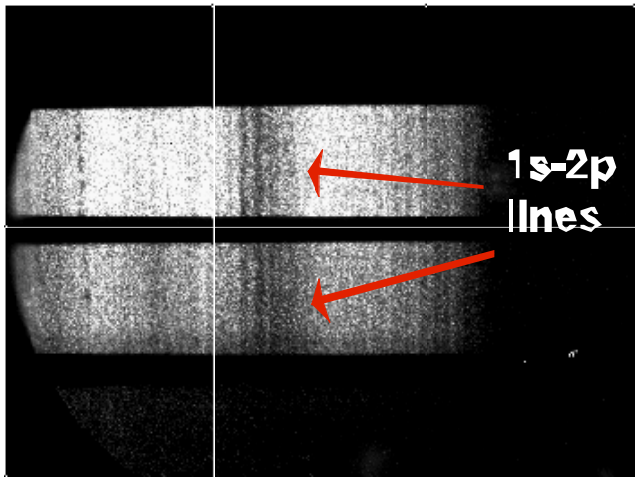
time

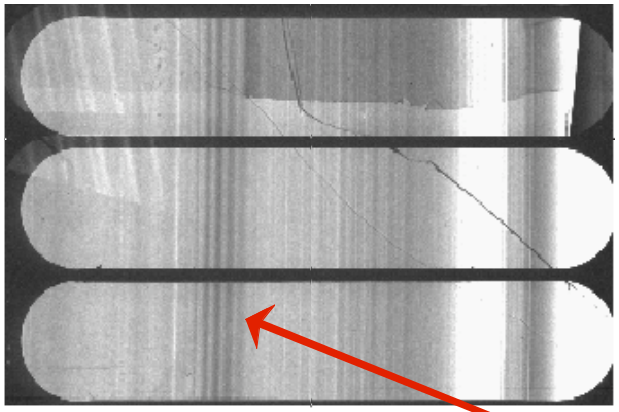



**gated spectrometer**

increasing frequency

time



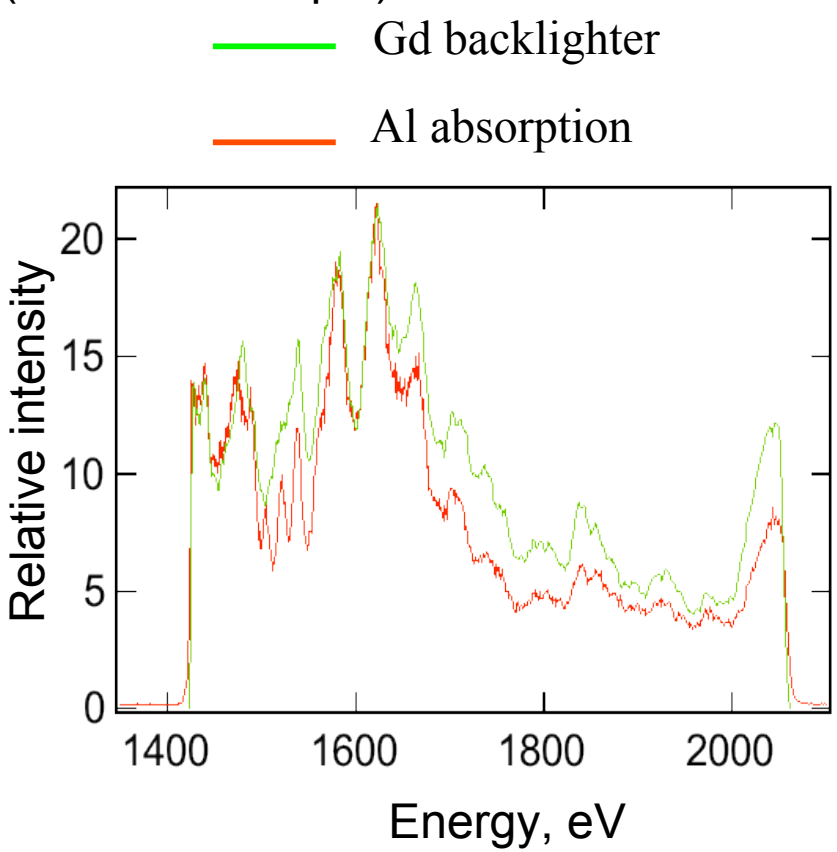



**time integrating spectrometer**

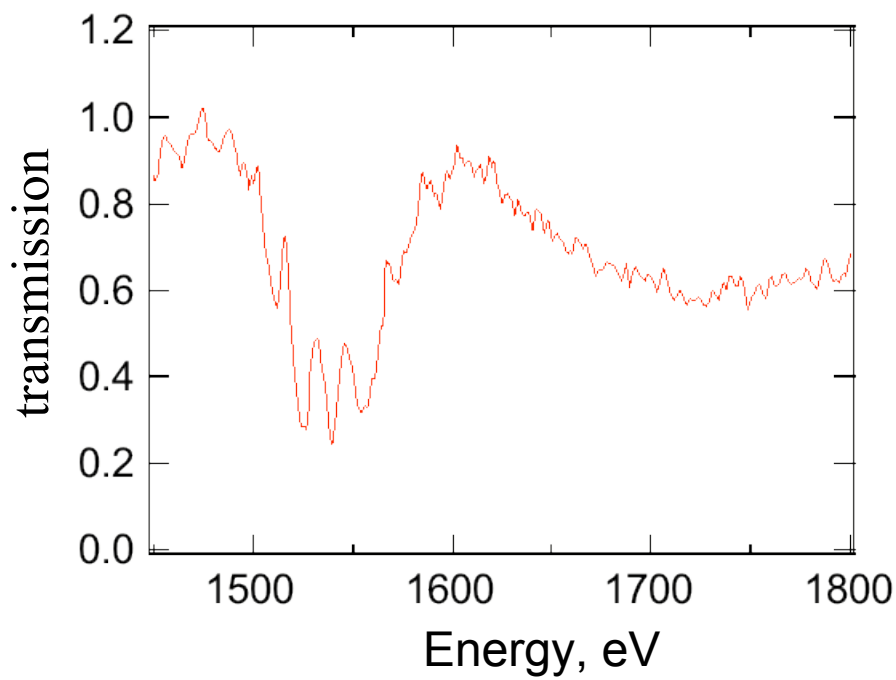
1s-2p lines

# High Density transmission spectra

Line-outs through the backlighter (no Al sample) and absorption spectra (0.5um Al sample)



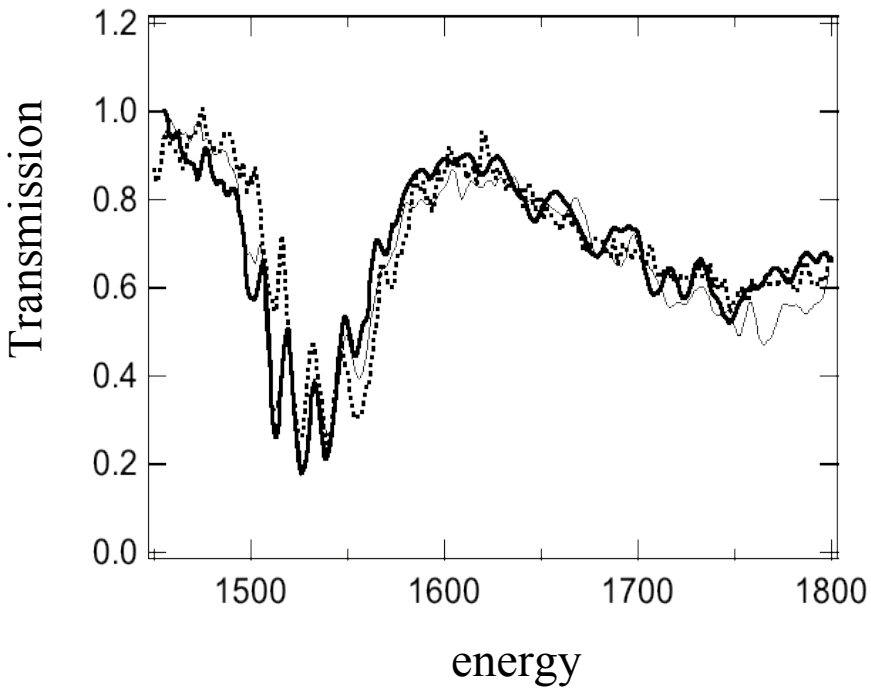

Al Transmission spectra backlit by Gadolinium.



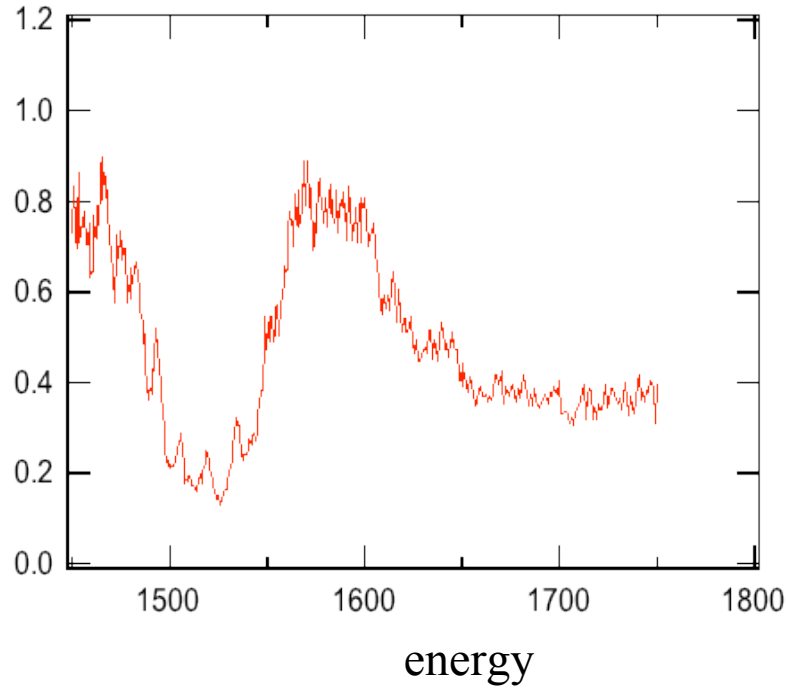
# High density Al transmission spectra were reproducible

Spectra were checked for reproducibility using different back-lighters, crystals and photo-cathodes.

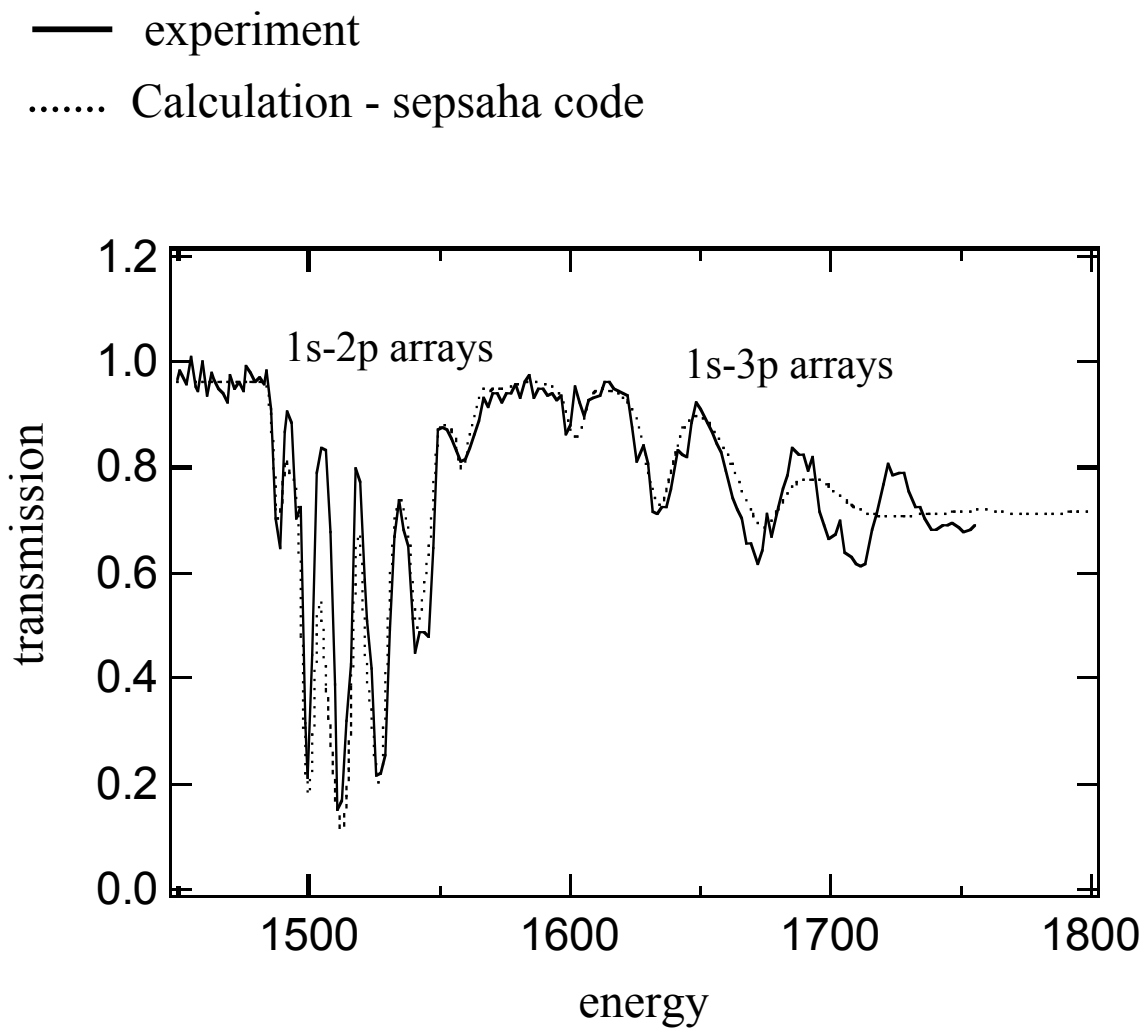
- ····· Gadolinium backlighter
- — Gadolinium backlighter
- — Gold backlighter



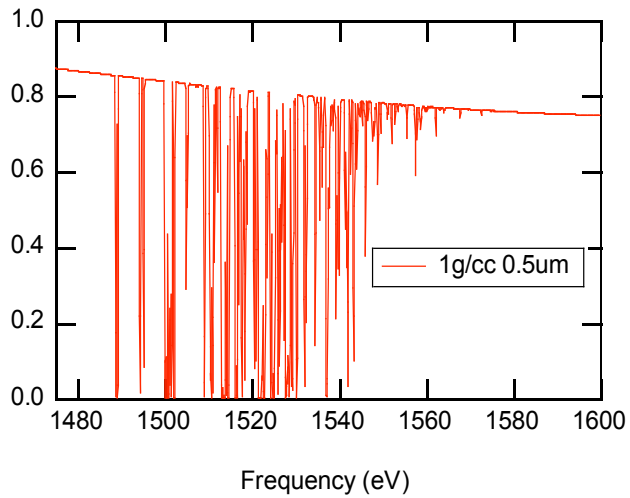

1 micron thick aluminium sample (backlit by terbium).

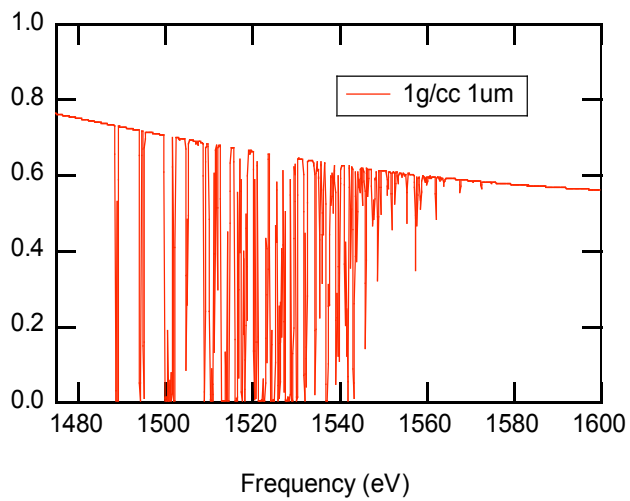


Low density 0.5μm aluminium foil transmission spectra exhibit clear 1s-3p array absorption.

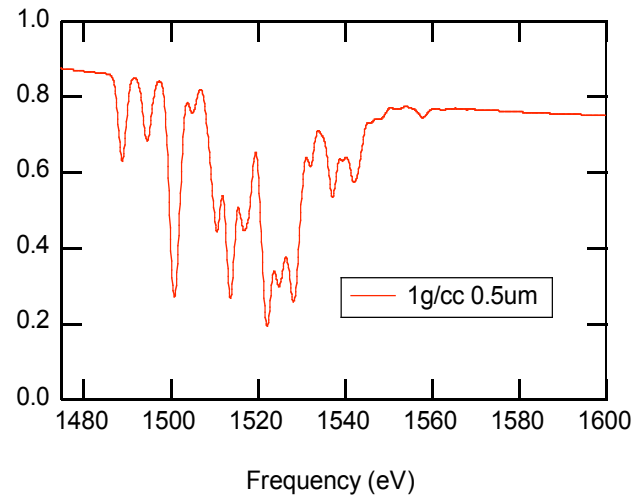


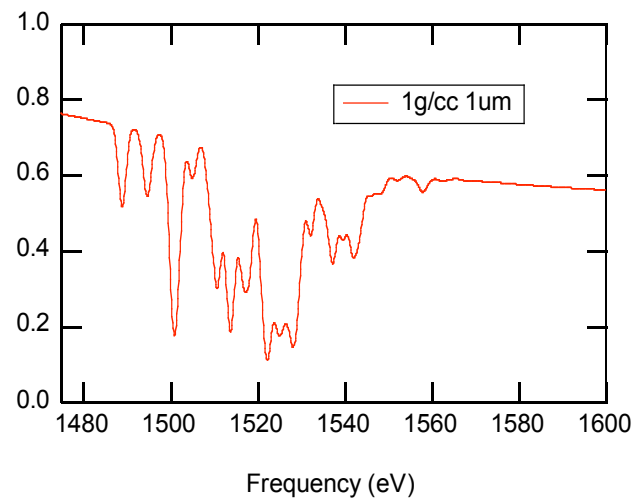
# Effect of instrumental broadening




Absorption spectrum Doppler broadened




With instrumental broadening

# Effect of instrumental broadening

- Instrumental broadening puts a limit on the optical depth of material that can be measured. Beyond this limit (typically $\tau$ ~3-4) further increases in optical depth cannot be measured in the transmission spectrum. The absorption is said to be **saturated**.

- Transmission in a spectrum with large unresolved transition arrays (UTA's), in which lines wholly or partially overlap, may be poorly approximated by modelling with statistical methods using continuous envelopes. If there are gaps between lines in these arrays they may be more transmitting than calculation predicts. Such arrays are said to be **porous**.

- UTA's may be more transmitting than calculated due to spectral structure below resolution limit of the spectrometer leading to **array porosity**. This is so-called **unresolved structure.**

# Tests for saturation and unresolved structure

- If the absorption spectrum is saturated (or has unresolved structure) then the spectrum will no longer scale with thickness according to Beer's law.

- Test by taking measurements at different thicknesses.

$$T_1 = \exp(-\rho\kappa x_1)$$

$$T_2 = \exp(-\rho\kappa x_2) \qquad \text{Let} \quad x_2 = 3x_1$$

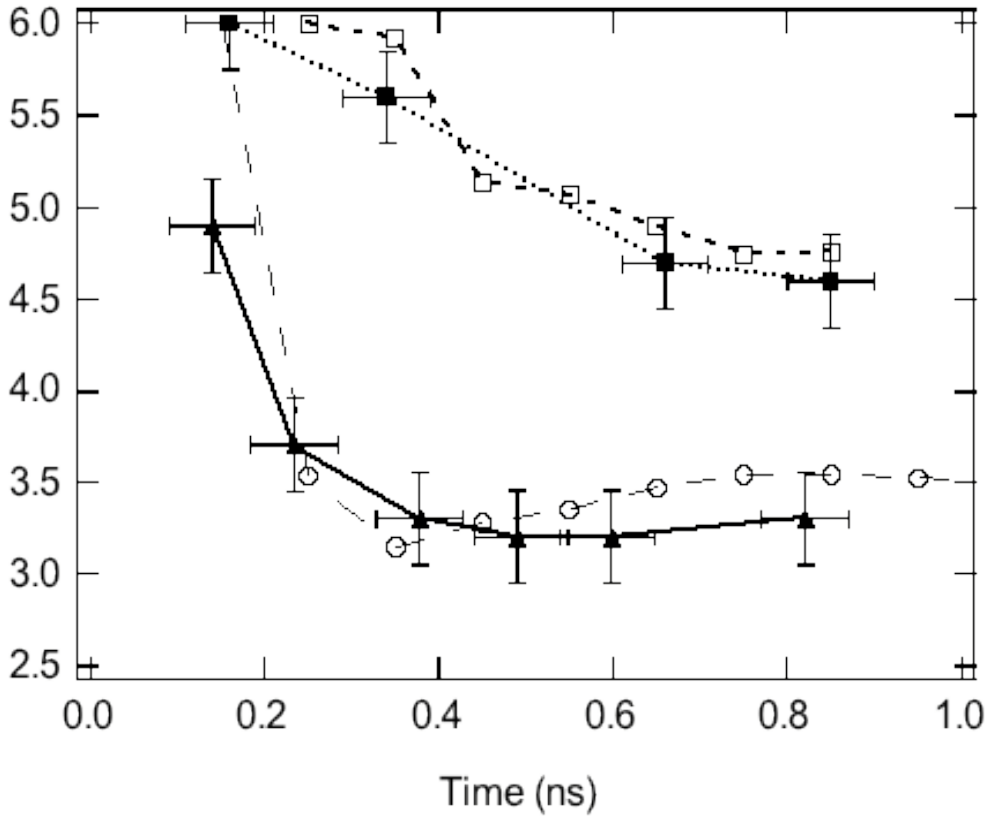
Then in the absence of unresolved structure $T_2 = T_1^3$

## The experimental conditions were obtained from radiation hydrodynamics simulations. The simulations were constrained by experimental measurements.

To infer the experimental conditions simulations were compared to measurements of :-

- The ionisation history of the buried layer.
- The target mass ablation rate
- The X-ray flux emitted from the target.

# Time dependent plasma conditions - 2p occupancy



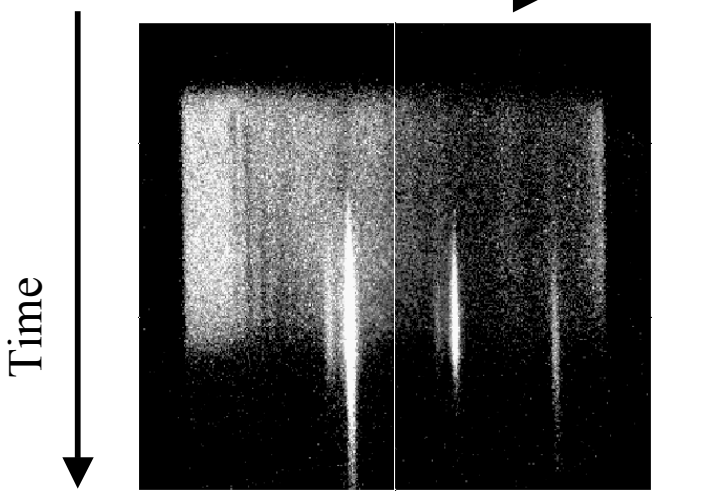

—— Solid lines are ionisation inferred from the experiment

..... Dashed lines are ionisation inferred from predicted conditions

# Plasma conditions - mass ablation rate

- Pressure and density were constrained by target mass ablation rate. This was measured by the onset of bright He and H-like emission from the buried layer, and compared to hydro simulations
- The mass ablation rate is directly related to the ablation pressure and hence the sample pressure

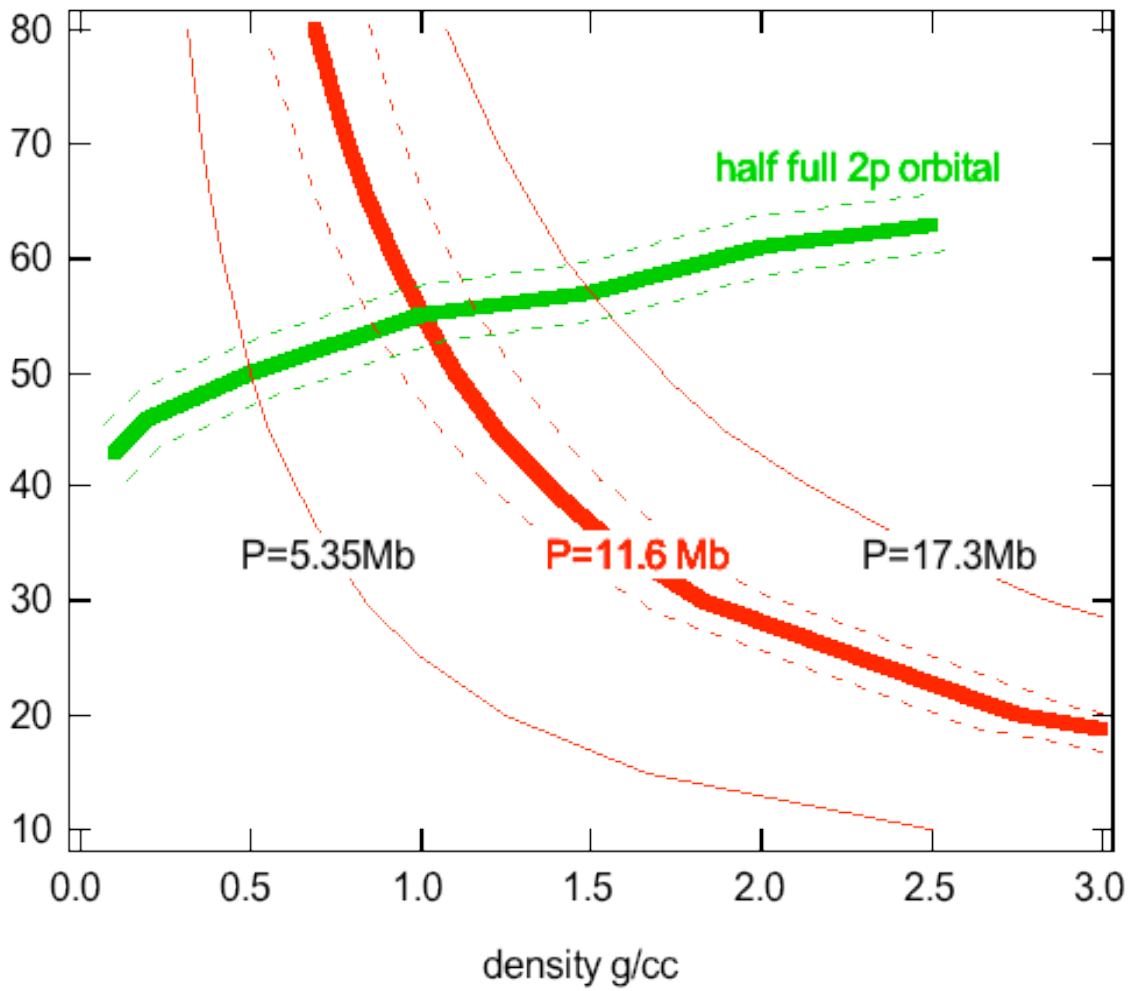
$$P_a \propto \left(\frac{dm}{dt}\right)^{1/2}$$




Pressure variations for aluminium with a half full 2p orbital

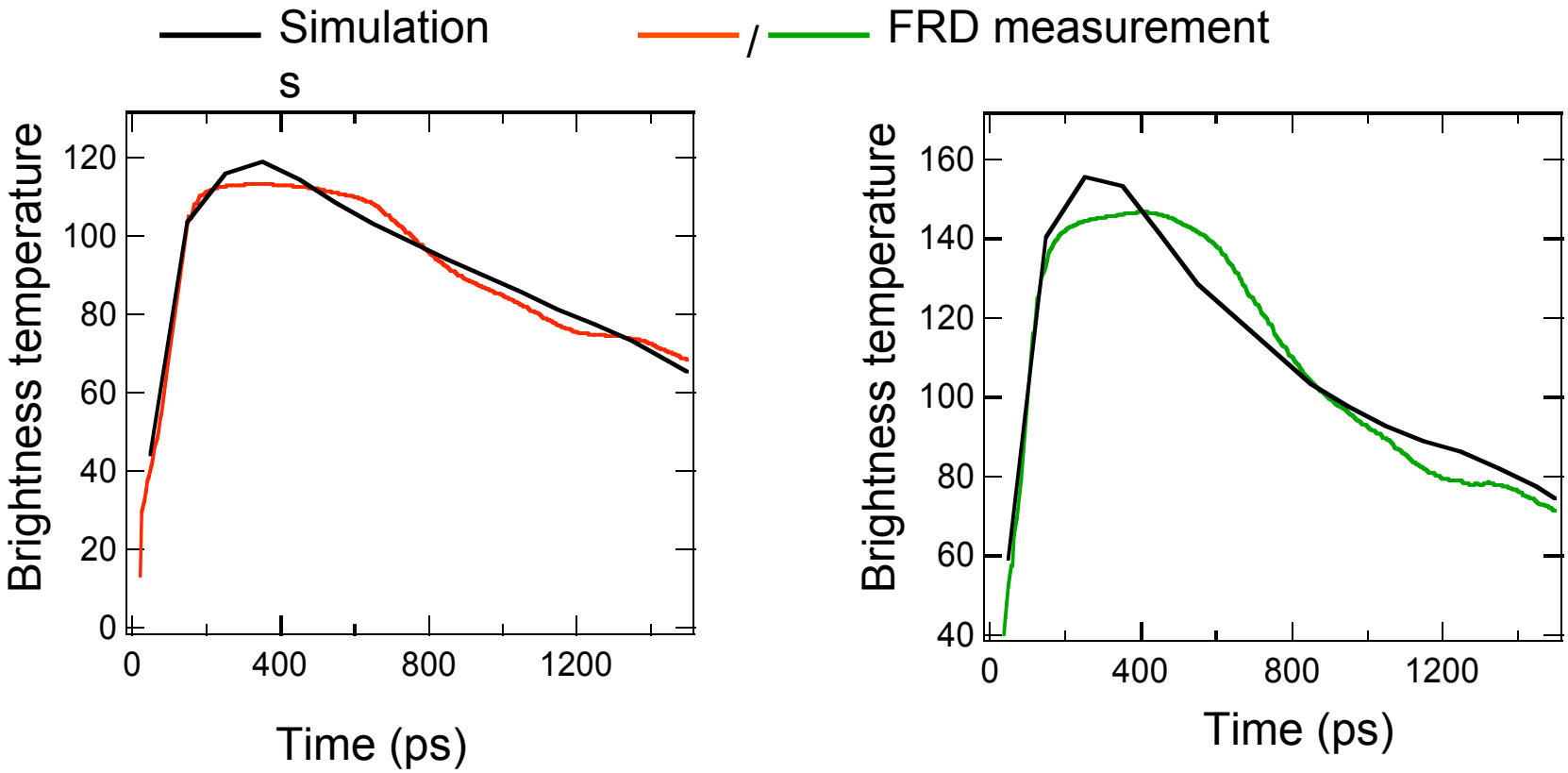
| $\rho$ g/cc | Te eV | p Mbar |
|---|---|---|
| 0.1 | 43 | 0.98 |
| 0.2 | 46 | 2.03 |
| 0.5 | 50 | 5.35 |
| 1.0 | 55 | 11.6 |
| 1.5 | 57 | 17.3 |
| 2.0 | 61 | 34.3 |
| 2.5 | 63 | 42.5 |

The range of ablation pressure and 2p occupancy, taken together, constrain the plasma conditions.

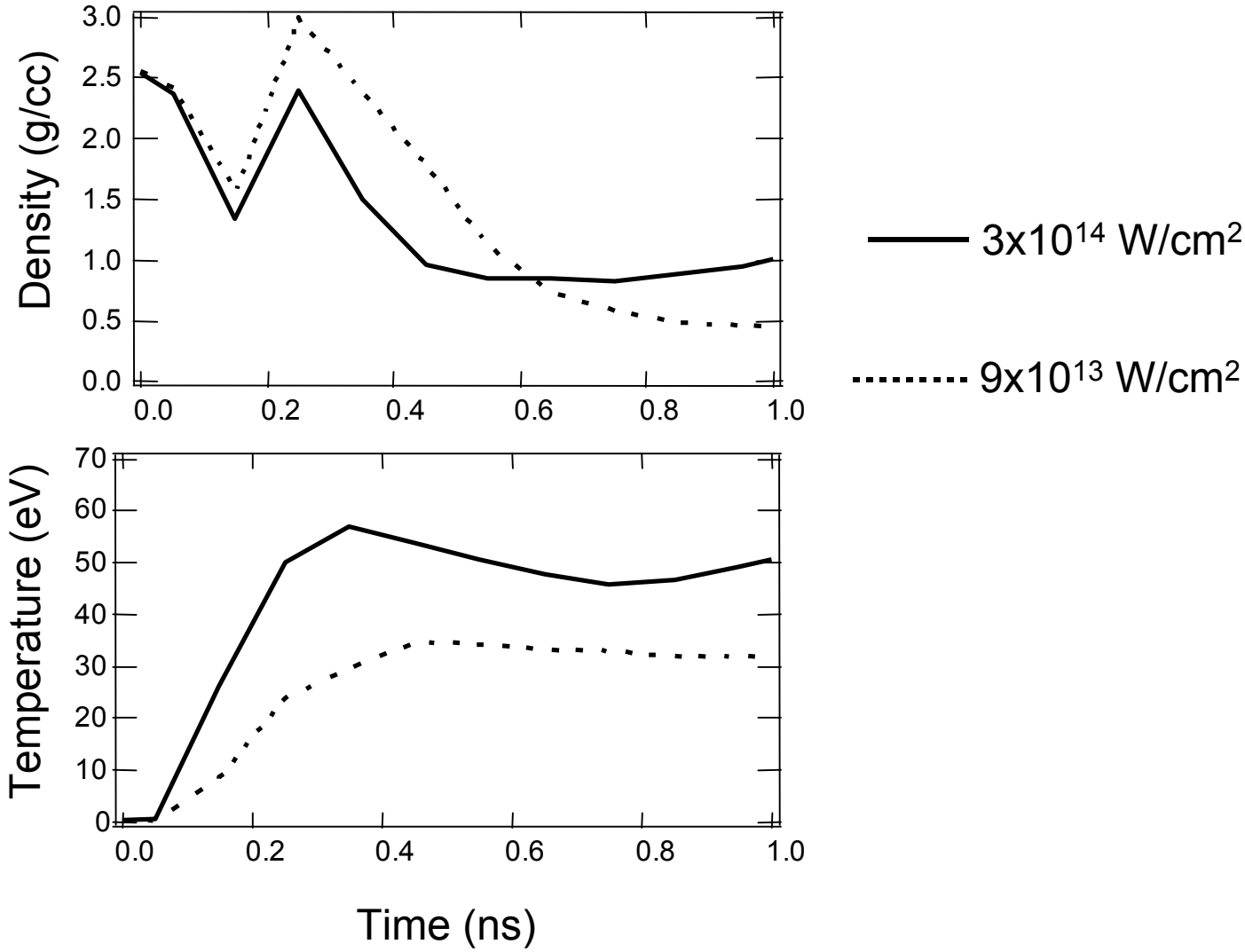


# X-ray flux measurements

Flat response x-ray diode measurements of the flux from the high Z (back lighter) layer were compared to the flux from radiation-hydrodynamics predictions.

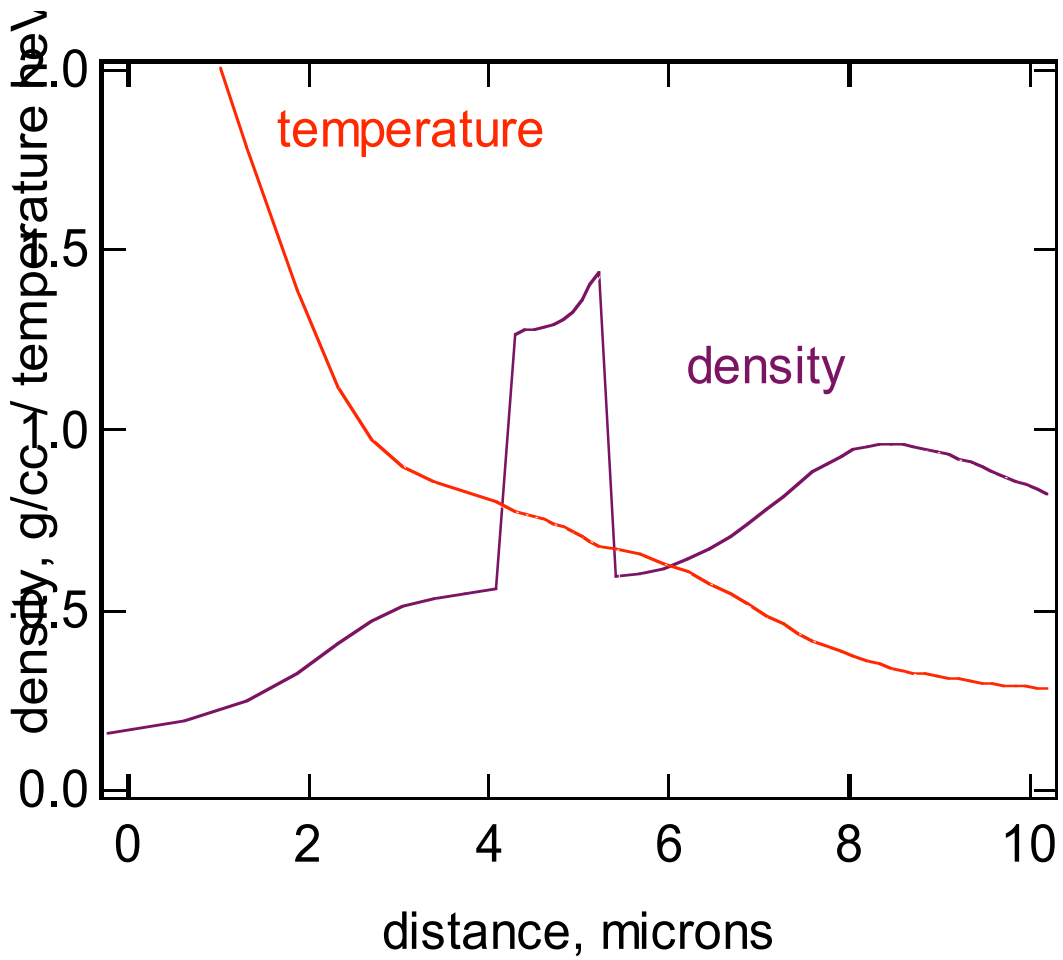


# Time dependent density and temperatures in the sample

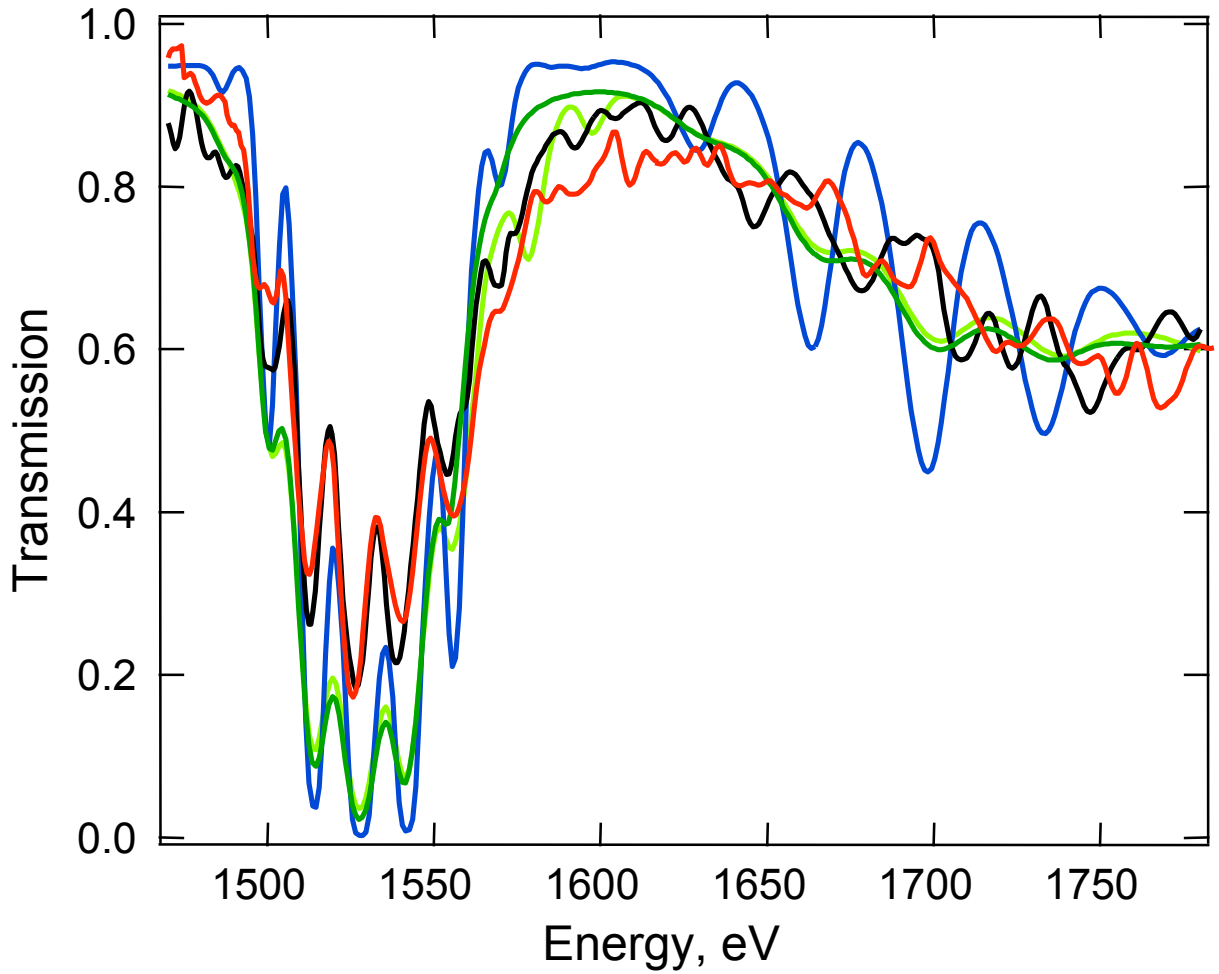


# Spatial gradients

The buried layer is predicted to have reasonably small temperature and density gradients after the initial shock reverberation.



Comparisons with simulations show the effect of broadening on the absorption spectrum. In these experiments electron impact broadening is the dominant effect. 1s2p transmission differs from calculation due to porosity and saturation.




Black - experiment
Red - experiment

# Summary/conclusions

• HELEN experiments have started to measure X-ray absorption at high material density (~1g/cc) and electron densities ~$10^{23}$/cc.

• Comparisons with opacity simulations suggest it is important to include line broadening due to electron impact at high densities.

• The 1s-2p transition arrays are more transmitting (porous) than predicted if term structure is treated as a UTA.

• Note the electron impact width $w \propto \frac{n_e}{\sqrt{T_e}}$

In a high temperature, high Z plasma the electron density, at a similar material density, may be much higher than in this experiment and the electron impact width could be similar to that used here.
This effect is currently being investigated with CASSANDRA.

# Future high density opacity experiments

• Long pulse direct drive opacity experiments are difficult!

• Experiments using short pulses represent a still more difficult challenge.

- Short pulse lasers have a different interaction with matter compared to long pulse systems.

- LTE is more difficult to establish.

- fast particle heating poorly understood.

- Diagnosis of rapidly changing plasma conditions much more difficult.

• Further diagnostic development is needed.

• Initial experiments will be carried out between $10^{17}$ - $10^{18}$W/cm$^2$ where fast particle production is low.

# HELEN CPA high density opacity experiments

- Foils irradiated with short pulse lasers to give high temperature and high density data . (Emission and possibly absorption experiments.)

- Fe near solid, ~500eV - expect $Z^*$~23, Li-like ions predominate

- We can measure line widths in emission to further investigate electron impact broadening in a relatively simple plasma.

- Investigate higher Z more complex spectra at high electron densities and high ion densities to compare to CASSANDRA.

- Studies of very strongly coupled plasmas (warm dense matter).

# Aims of the proposed HELEN experiments

- To measure emission spectra at near LTE conditions from high density and high temperature buried layers in plastic foils irradiated with the CPA, to compare to predictions of the CASSANDRA code and other state of the art opacity codes.

- To establish the uniformity of the buried layer heating as a function of time.

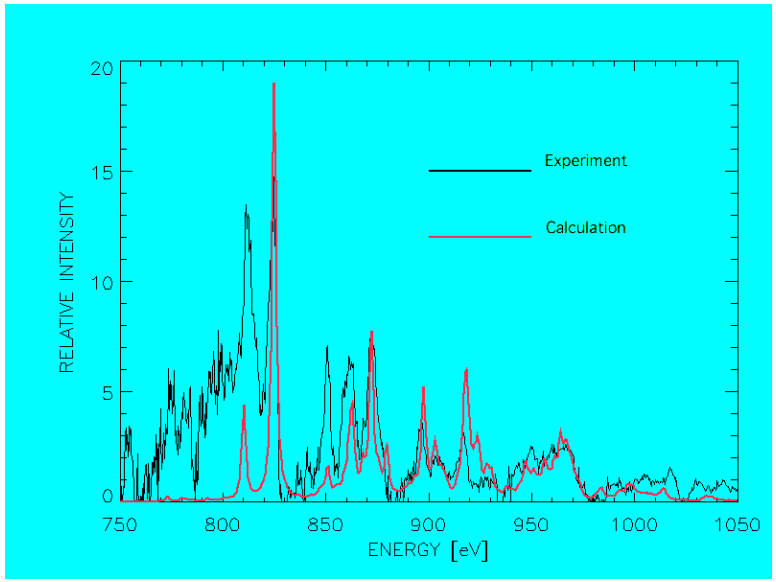
- To better understand the mechanisms of production and heating of buried layers at $10^{18}$-$10^{19}$W/cm$^2$.

- To assess the feasibility of performing such experiments using the ORION laser.

# Thermal conduction heating experiment is based on the work of K. Nazir et al.

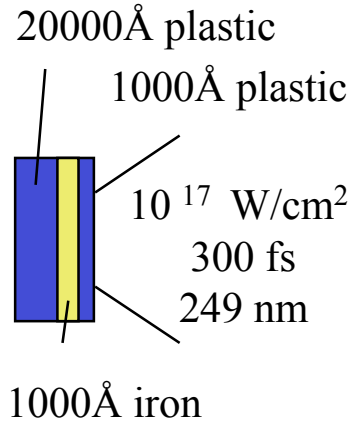
Conditions - Solid density, 700eV with gradients

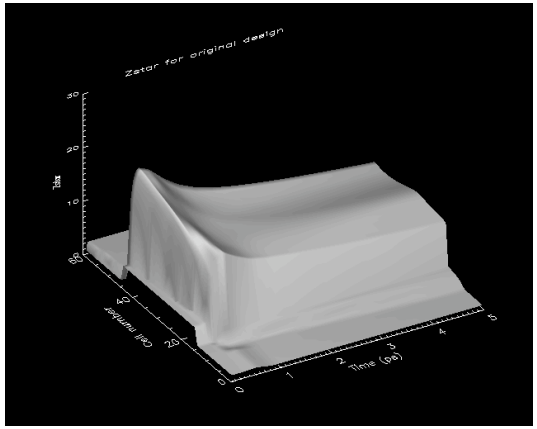
Nazir et al, Appl Phys Letts 69 (24) 1996




Ion stages from time when buried layer is cooler, before and mainly after peak emission

Ion stages from near the peak of the emission




Z* as a function of time and space

# Two buried layer experiments combined

- Thermal conduction heating of a layer near the surface of a plastic foil irradiated at $10^{17}$W/cm$^2$ - emission measurements time resolved and time integrated. Imaging measurements.

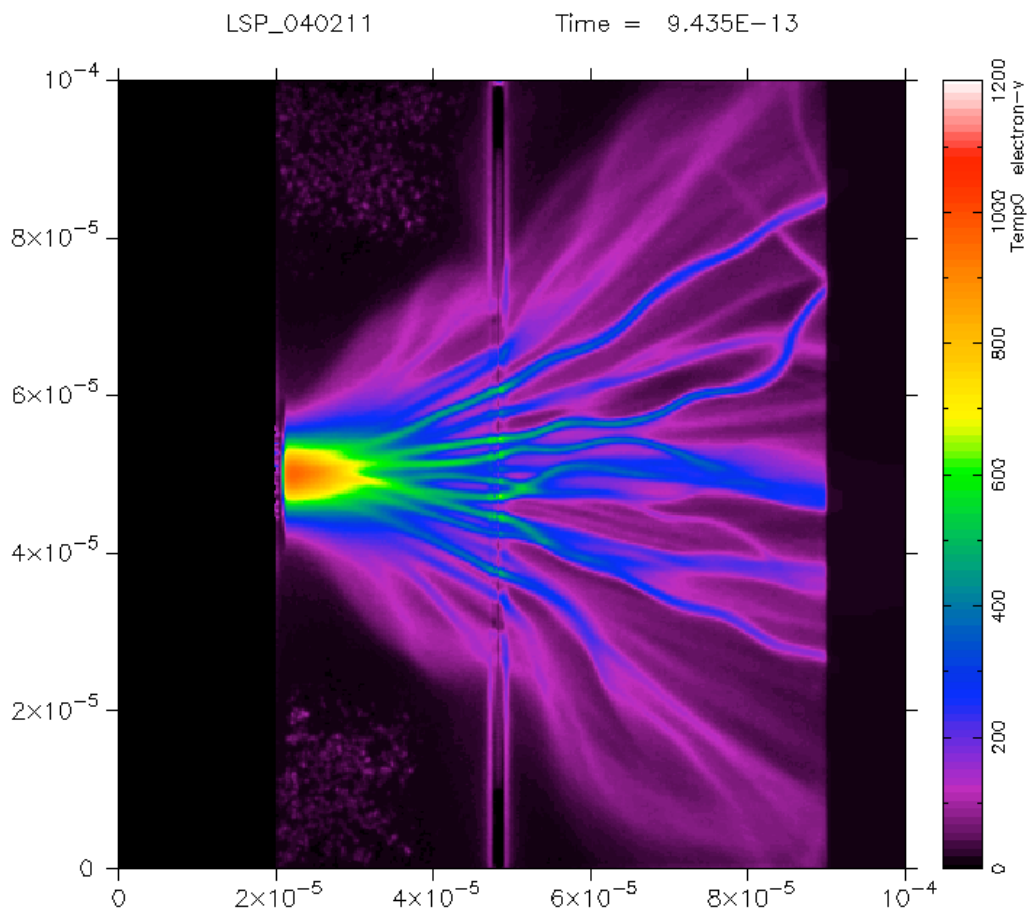
- Fast electron and return current heating of more deeply buried layers - up to 25μm into the foil. Emission measurements and imaging measurements at 1 and 2ω.

- Measurements will be split in two:-

1. Spectral measurements for both types of foil using streak cameras and time integrating spectrometers.

2. Imaging measurements for both types of foil using the spherical multilayer and spherical crystal imaging system

X-ray imaging using spherical multilayer and crystal mirrors will study the temperature uniformity of the buried layers




Filamentary structures in the electron temperature for a fast electron heated buried layer

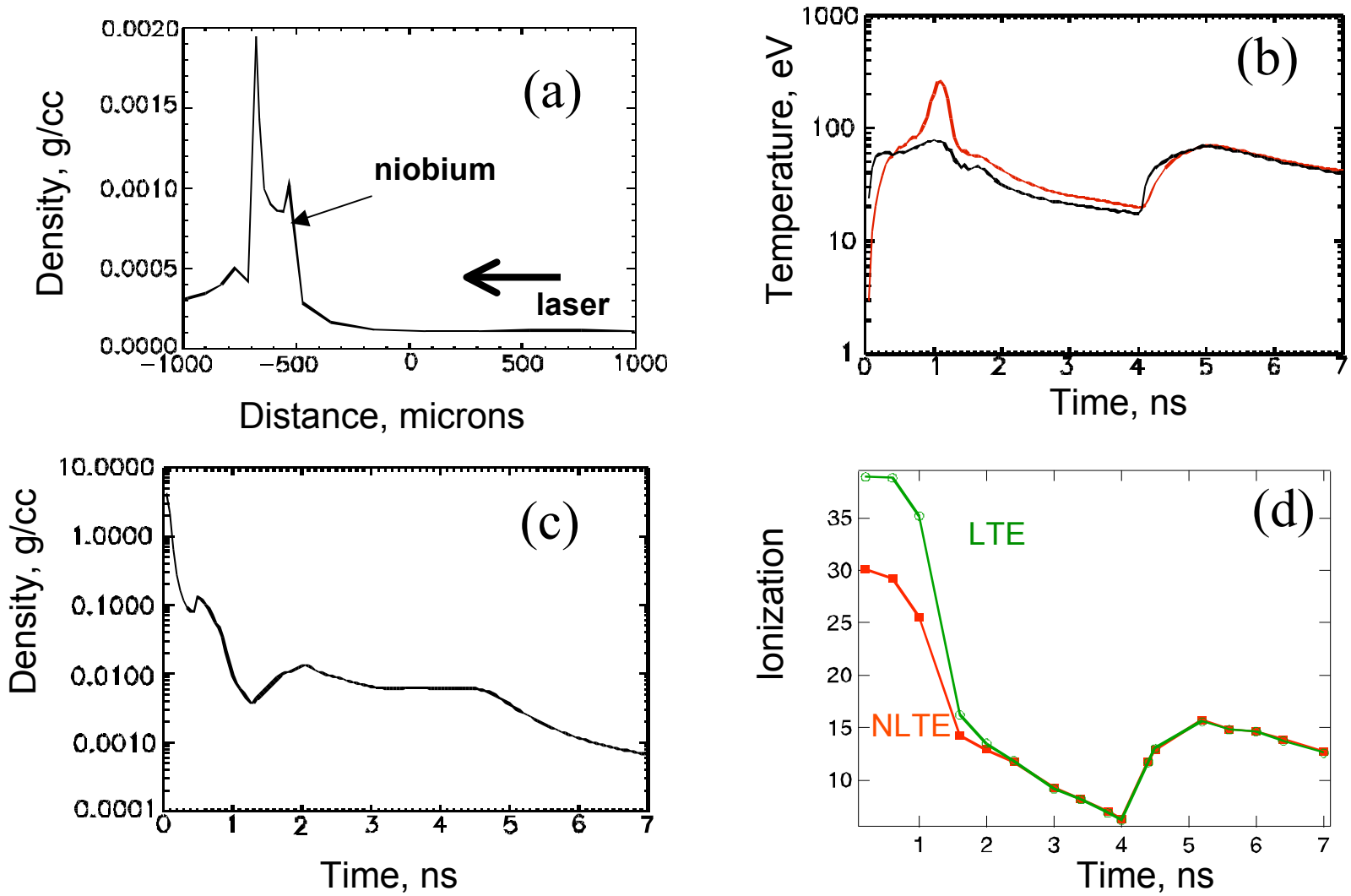
The simulation box is 100 micron square

# Low density experiments to measure UTA break-up.

- Low density opacity samples created by exploding thin foils with direct laser irradiation and after a delay reheating them inside a hohlraum.

- Absorption spectra to be diagnosed with high resolution spectrometers.

Exploding foils reheated by a X-ray drive are predicted to give LTE low-density samples.



# Summary

- Opacity experiments on HELEN will attempt to measure spectra in temperature/density regimes in which there is presently little or no data.

- High density - Stark effect, continuum lowering
- buried layer targets irradiated with CPA pulses.

- Low density - UTA break- up
- exploding foil targets
- combination of direct and indirect laser heating
- higher resolution spectral measurements.