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WORKSHOP ON PLASMA PHYSICS

7 - 11 March 2005

Measurements of Plasma Opacity using X-Ray Lasers

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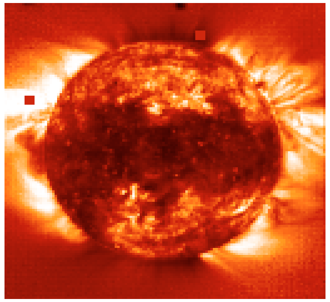

FeX11/FeX1 ratio

Using lasers to measure the solar opacity

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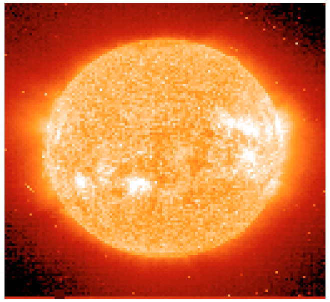


He II emission

Acknowledgements

- I would like to acknowledge members of my research group: Matthew Edwards, Pritesh Mistry, David Whittaker and the team at the Prague Asterix Laser headed by Bedrich Rus.
- Funding from EU Access to Large Scale Facilities and EPSRC.

Outline

- Explanation of opacity in plasmas.
- Previous laboratory methods to measure opacity.
- Why opacity measurements are needed- relevant to solar plasmas?
- Opacity measurements using x-ray lasers.
- Conclusions.

The equation of radiative transfer

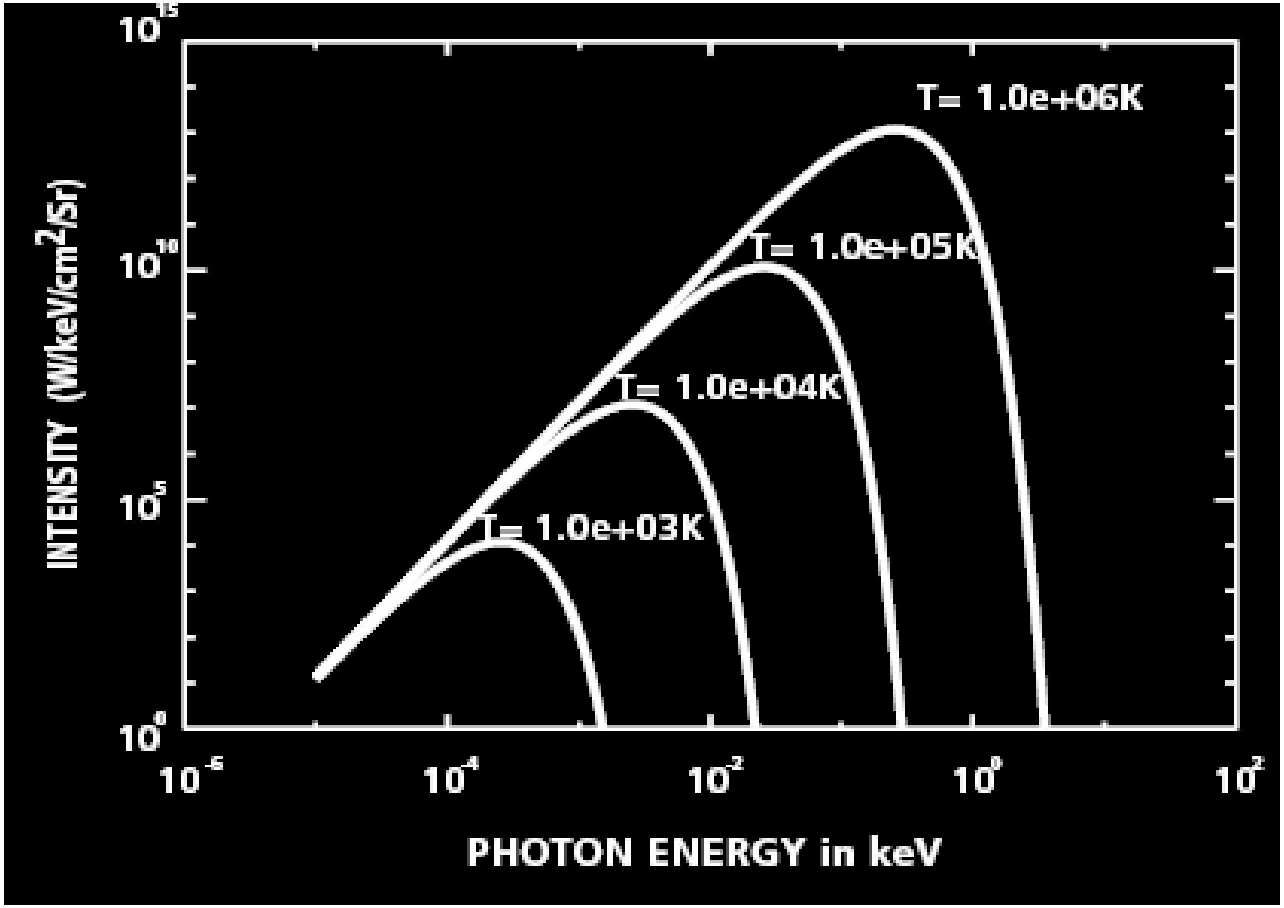
- For a beam of light of single frequency, the change in light intensity dI_ν in passing through a slab of matter of thickness *ds* is
  - $$\frac{dI_\upsilon}{ds} = -k_\upsilon I_\upsilon + j_\upsilon$$
  - where j_ν is the emissivity (and scatter into the beam) and k_ν is the total opacity at the particular frequency.
- In modelling solar and stellar energy flow (and other thermal plasmas), a frequency averaged measure of opacity *k* is used known as the Rosseland mean opacity so that radiation outflow can be modelled as a diffusion process

$$\frac{1}{\bar{k}} = \frac{\int_0^\infty \frac{1}{k_\upsilon}\frac{dB_\upsilon}{dT}d\upsilon}{\int_0^\infty \frac{dB_\upsilon}{dT}d\upsilon} = \int_0^\infty \frac{1}{k_\upsilon} f(u)du$$

  - where B_ν is the black-body radiation distribution, *f(u)* is a weighting function and $u = h\nu/kT$.

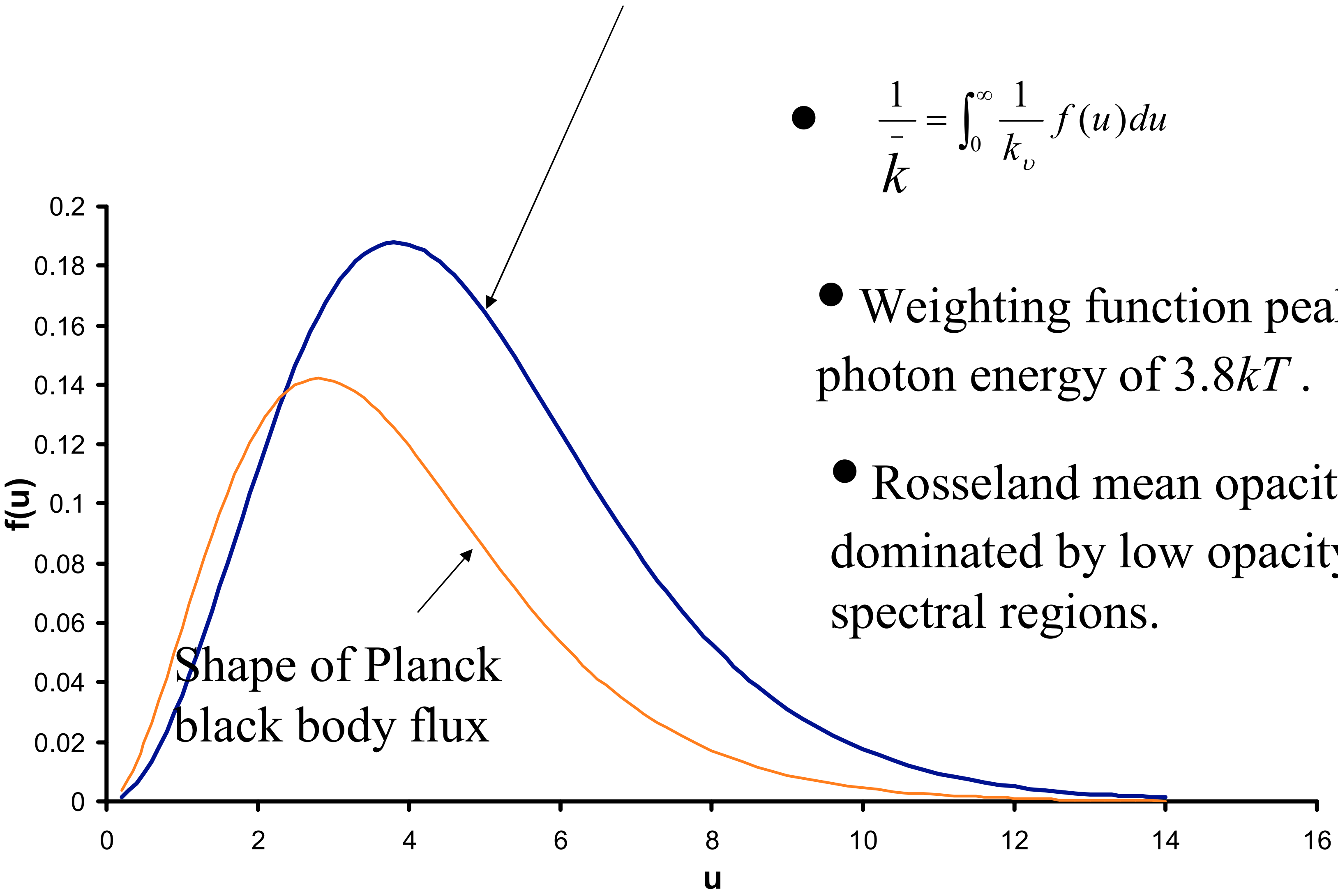
Black body radiation

- The radiation field when radiation is in equilibrium with matter.
- The peak of intensity is at photon energy 2.8 *kT*
- 11605 degrees Kelvin = 1 eV.



Taken from AWE website

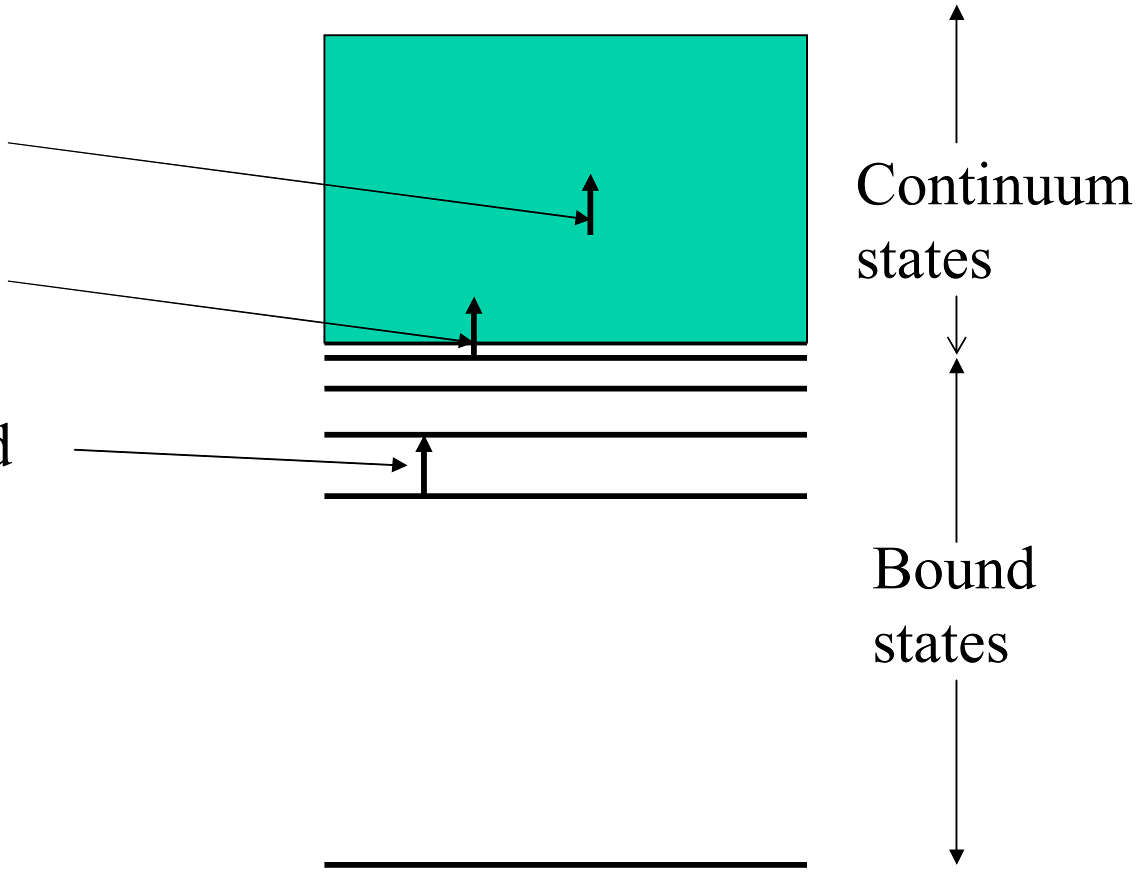
The Rosseland mean opacity weighting



Shape of Planck black body flux

- $$\frac{1}{\bar{k}} = \int_0^\infty \frac{1}{k_\upsilon} f(u)\,du$$
- Weighting function peaks at photon energy of $3.8kT$.
- Rosseland mean opacity is dominated by low opacity k_ν spectral regions.

Important photon absorption processes



Free-free absorption

Bound-free absorption

Bound-bound absorption

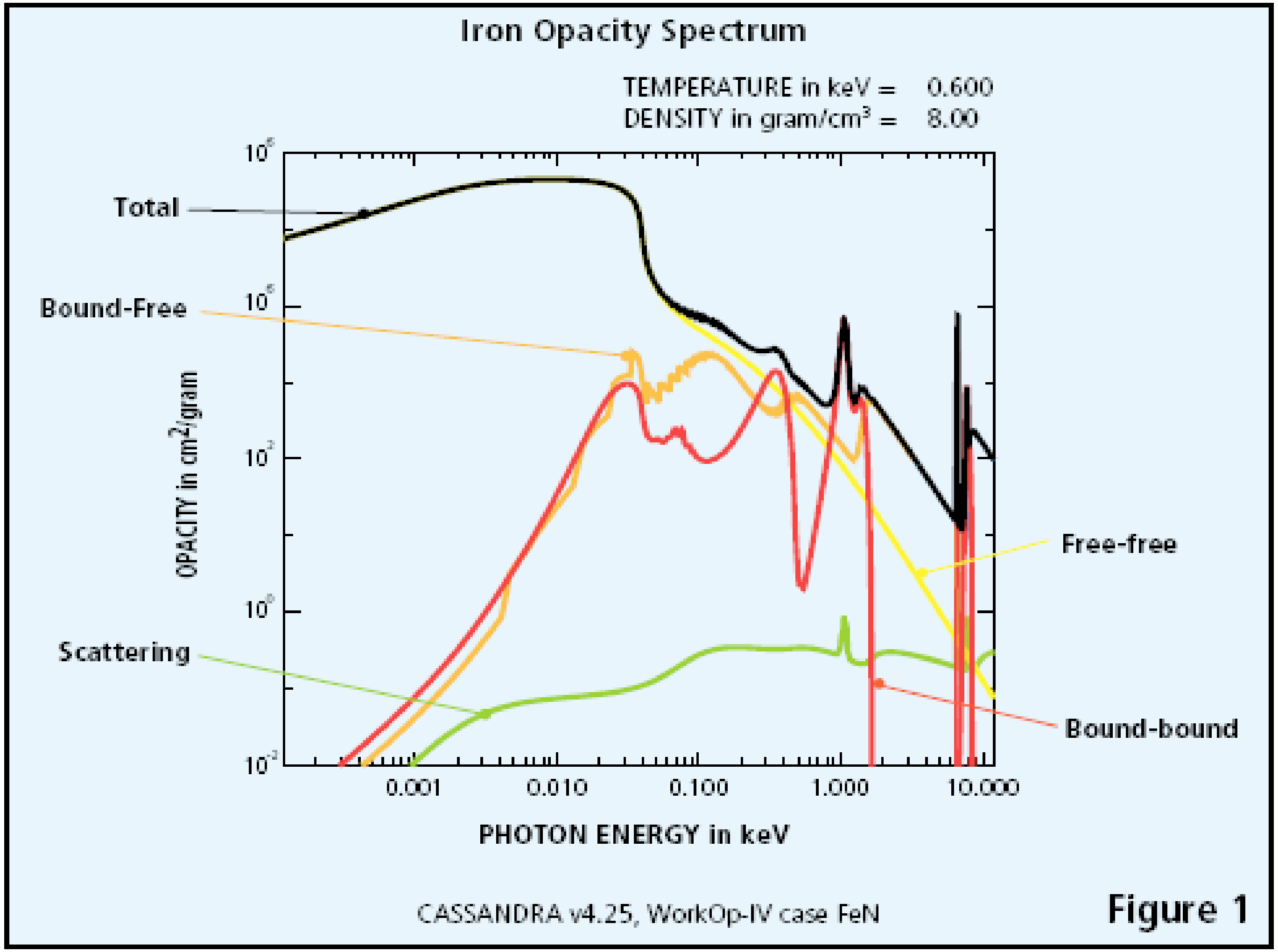
Continuum states

Bound states

+scattering processes
e.g. Compton scatter

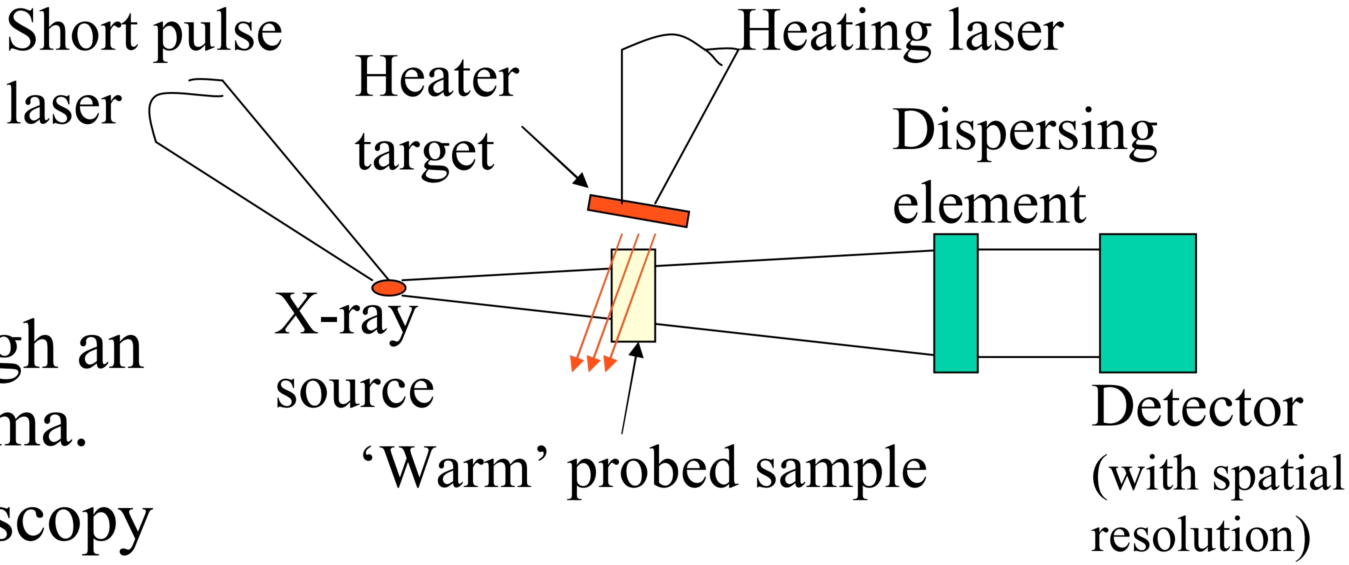
Energy levels of an ion

Processes contributing to opacity



Taken from AWE website

Previous measurements of plasma opacity in the laboratory



Short pulse laser

Heater target

Heating laser

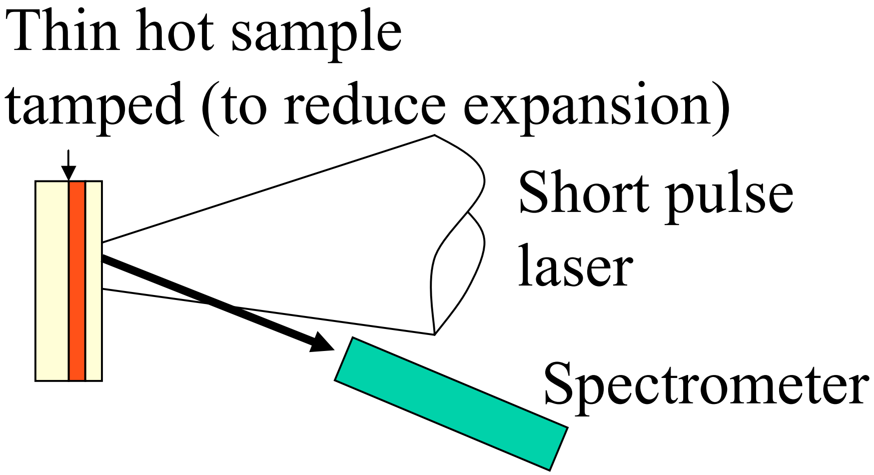
Dispersing element

X-ray source

'Warm' probed sample

Detector (with spatial resolution)

- Shine a bright backlighter through an x-ray heated plasma.
- Emission spectroscopy can be used:
  - Assume plasma is in LTE
  - Calculate opacity from emissivity of a thin sample.

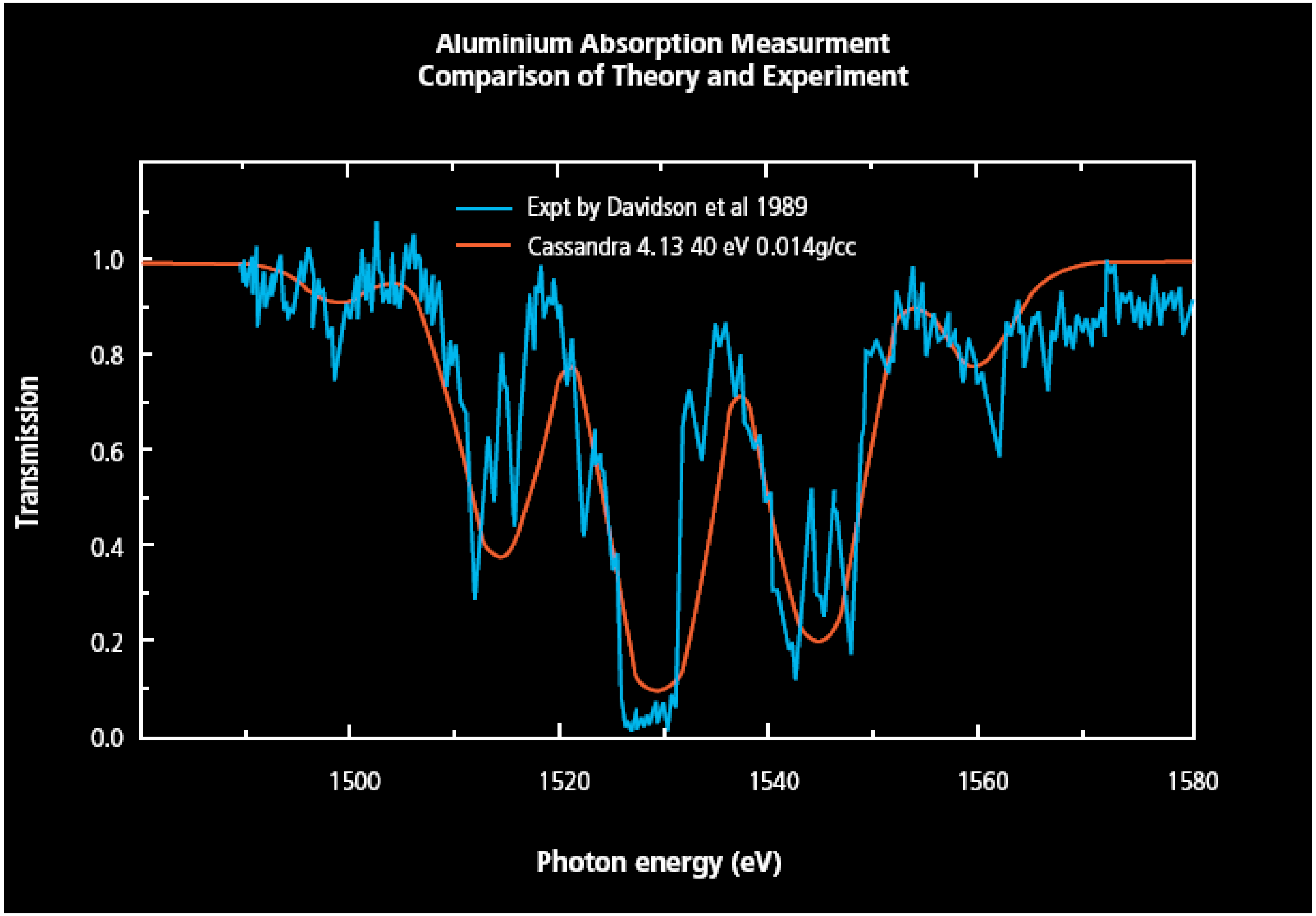


Thin hot sample tamped (to reduce expansion)

Short pulse laser

Spectrometer

Sample x-ray backlighter measurement of opacity

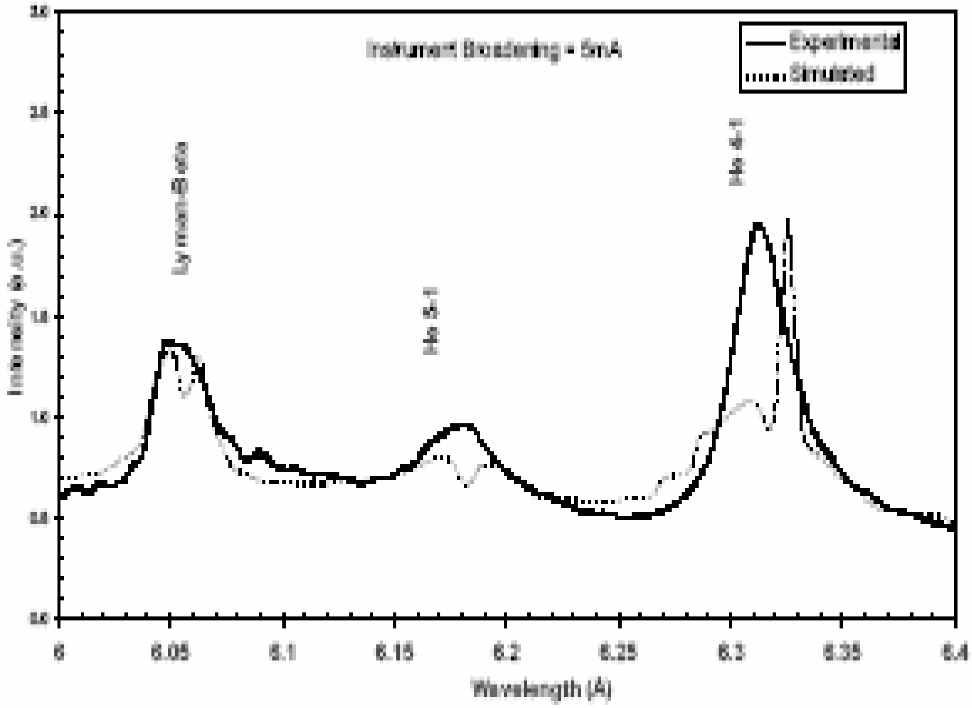


Taken from AWE website

Plasma Conditions: 4.13 eV and 0.014 g cm^{-3}.

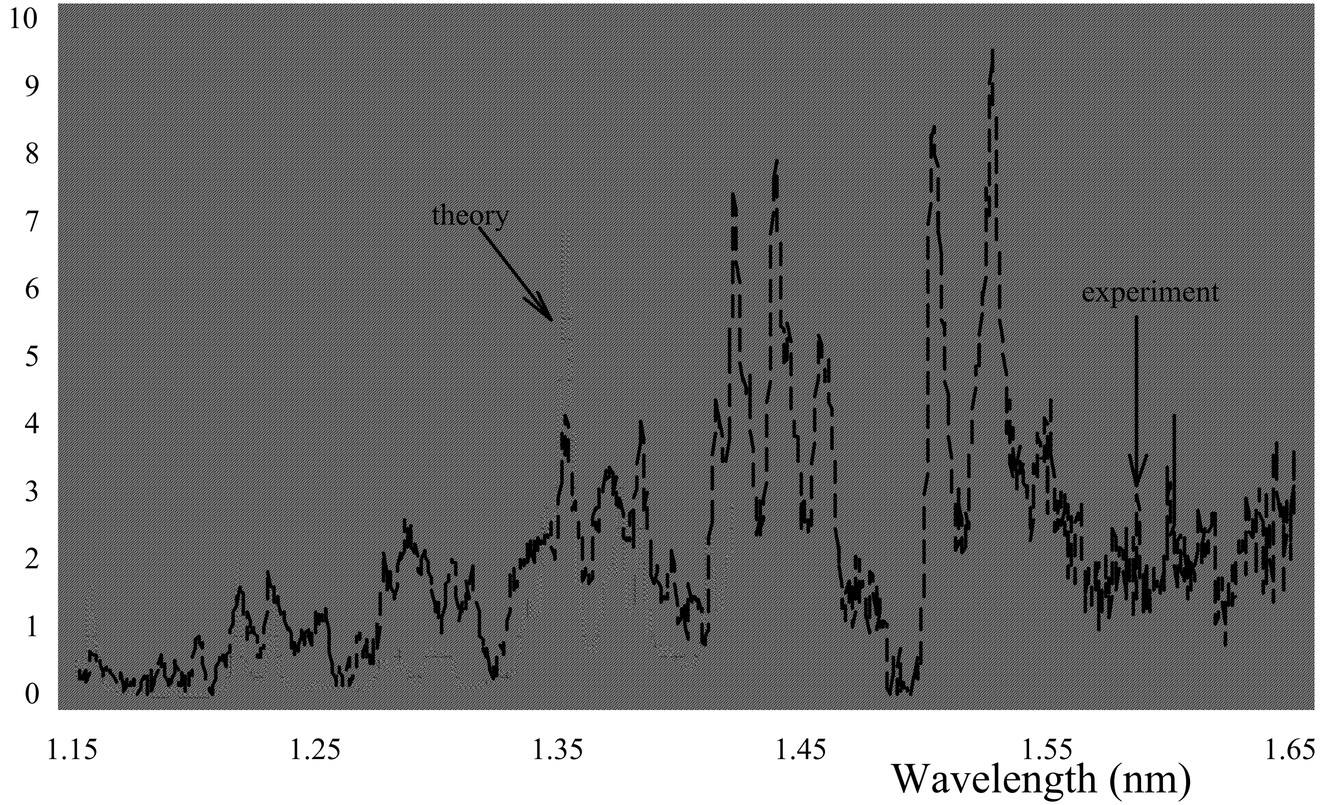
Opacity from thin heated targets

Plasma conditions deduced by
fitting simulation of emission
for a buried Al layer
in CH directly heated
by a laser: electron
density 6.9x $10^{22}/cm^3$ (~0.3 gcm^{-3})
electron temperature 400 eV.



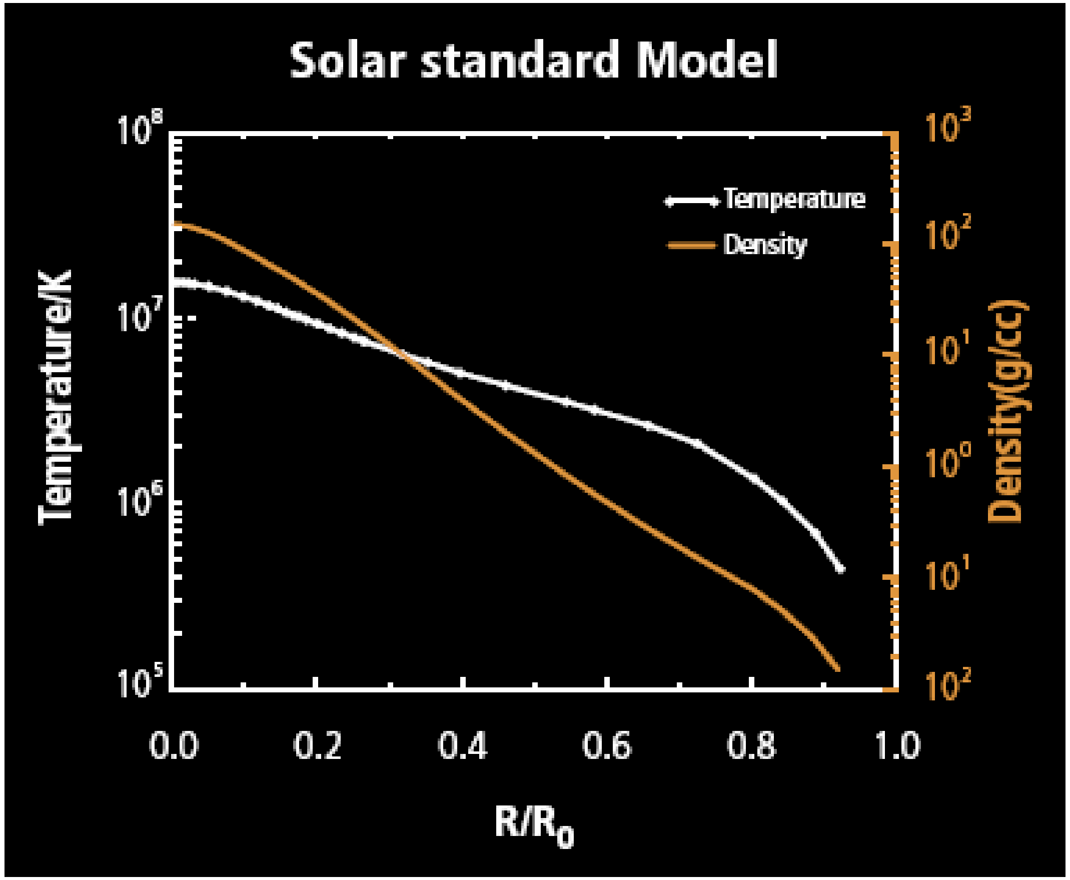
Opacity deduction from thin heated targets

Plasma conditions deduced by fitting simulation to experimental Fe spectrum for Fe layer buried in CH: electron density 10^{24} cm^{-3} (~ 3 gcm^{-3}), temperature 150 eV.



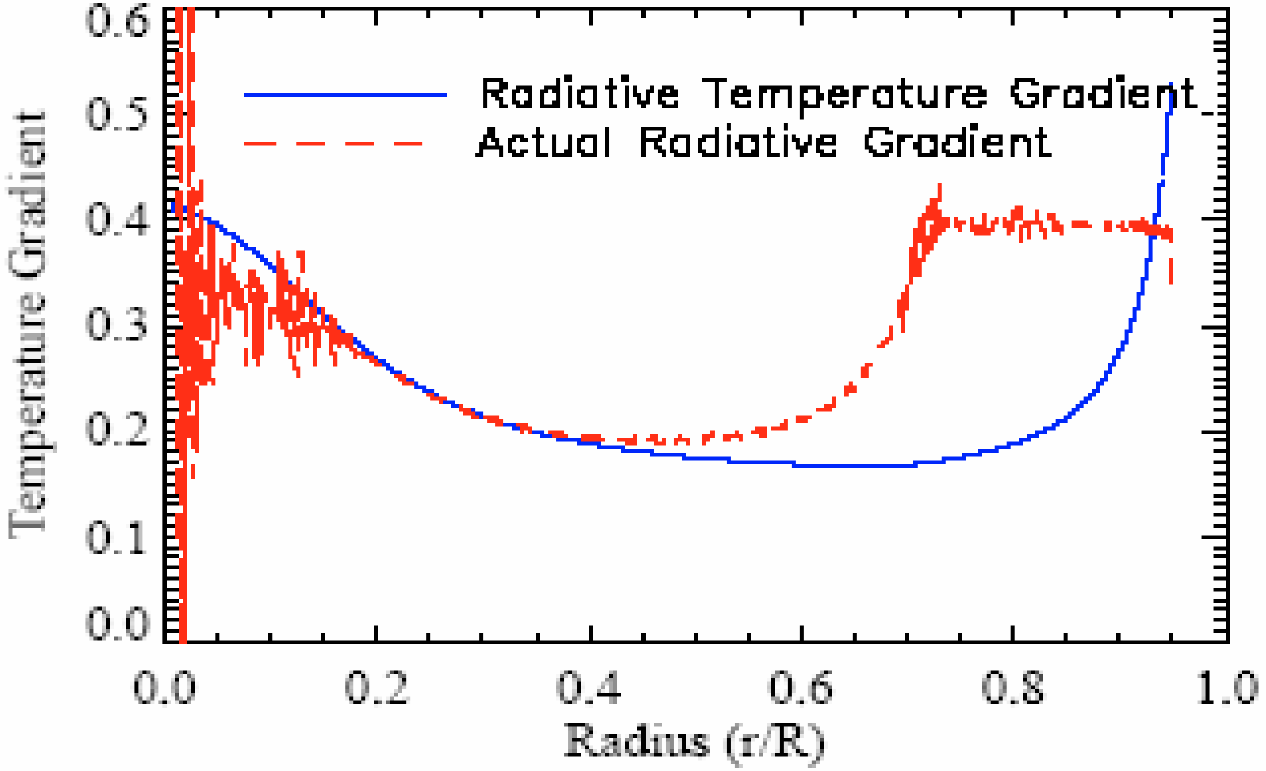
Are laboratory opacity measurement relevant to the sun?

- Backlighter measurements with x-ray heating of targets have measured the opacity of plasmas around 10^{-2} gcm^{-3} and up to 40 eV: corresponding to the outer regions of the sun.
- Direct heating of thin layers and deduction from emissivity (assuming LTE) has measured opacities up to 500 eV and density close to solid (0.1 - 10 gcm^{-3}): $\Rightarrow R/R_0 \sim 0.5$



Taken from AWE website

Opacity dominates solar energy outflow at the solar centre and is important in the outer solar region



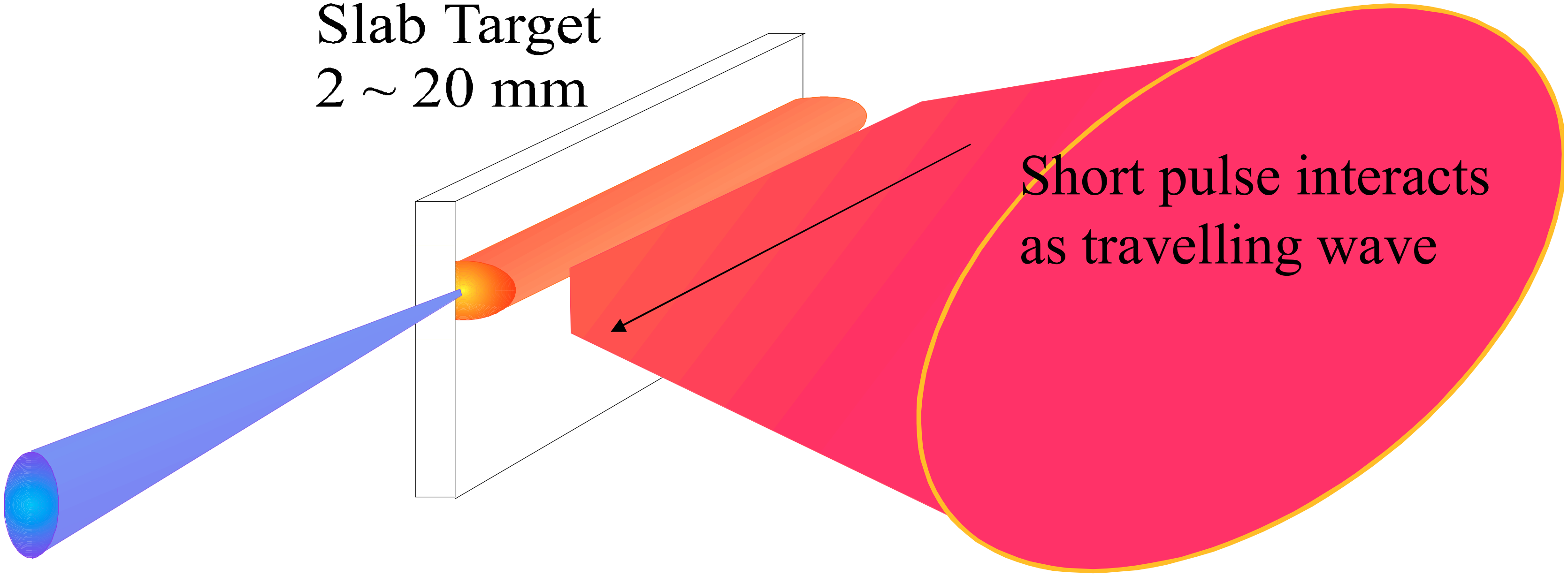
- Takes ~ million years for light to travel from the Solar centre to the photosphere.
- Mean free path for light absorption at the Solar centre is 1 mm.

X-ray lasers are much brighter than conventional backlighters

- X-ray lasers produce pulses of 60 – 200 eV photon energy over durations of 3-100 ps.
- Saturated irradiances are ~ 3×10^{10} Wcm^{-2}.
- Photons are produced in a beam with divergence 5 – 20 mrad.
- Spectral bandwidth is very narrow ($v/\Delta\nu > 10^4$).

$\Rightarrow$ Beam-like nature and narrow spectral bandwidth should enable x-ray lasers to 'out-shine' emission from solar condition plasmas (solar surface flux is ~ 6×10^{17} Wcm^{-2}).

X-ray lasers


Slab Target
2 ~ 20 mm

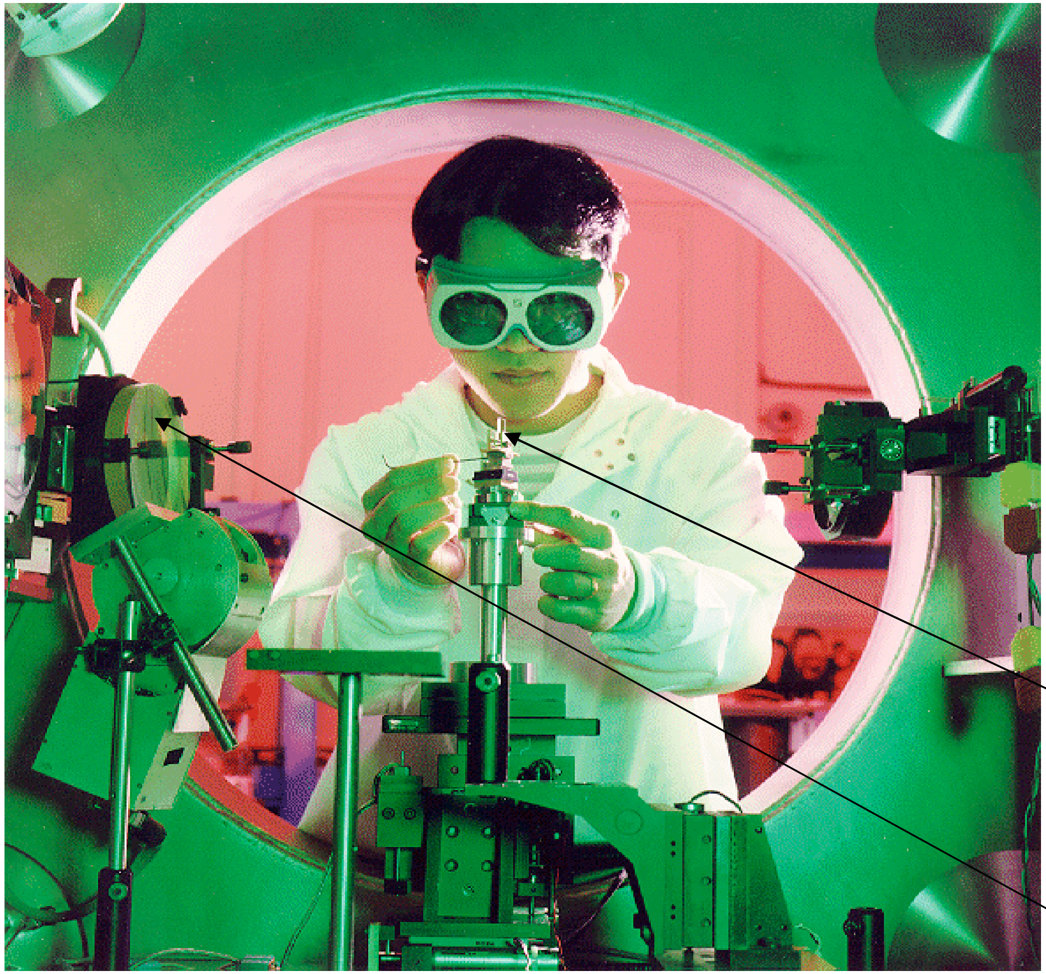
Short pulse interacts
as travelling wave

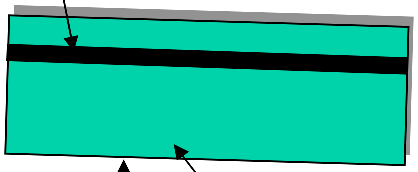
X-ray Laser
5.9 – 30 nm

Infrared Drive Laser Pulse

Two pulses - typically of 75 ps separated by 2 ns or 1-2 ps superimposed on a 300 ps background pulse.

Adjusting an x-ray laser target





Stripe coated on slide

Glass slide

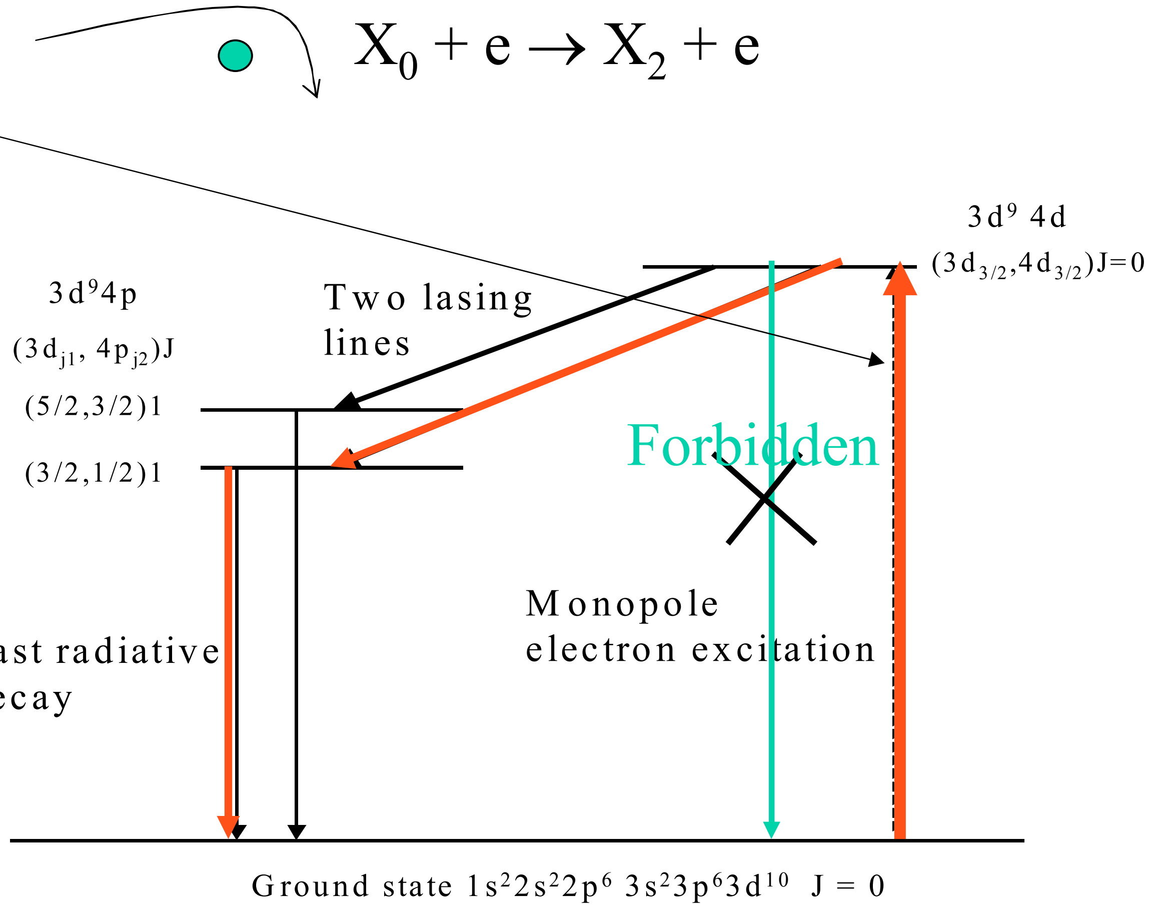
Target

Mirror to focus pump laser

Electron collisional pumping in laser-produced plasma creates x-ray lasing

Monopole excitation

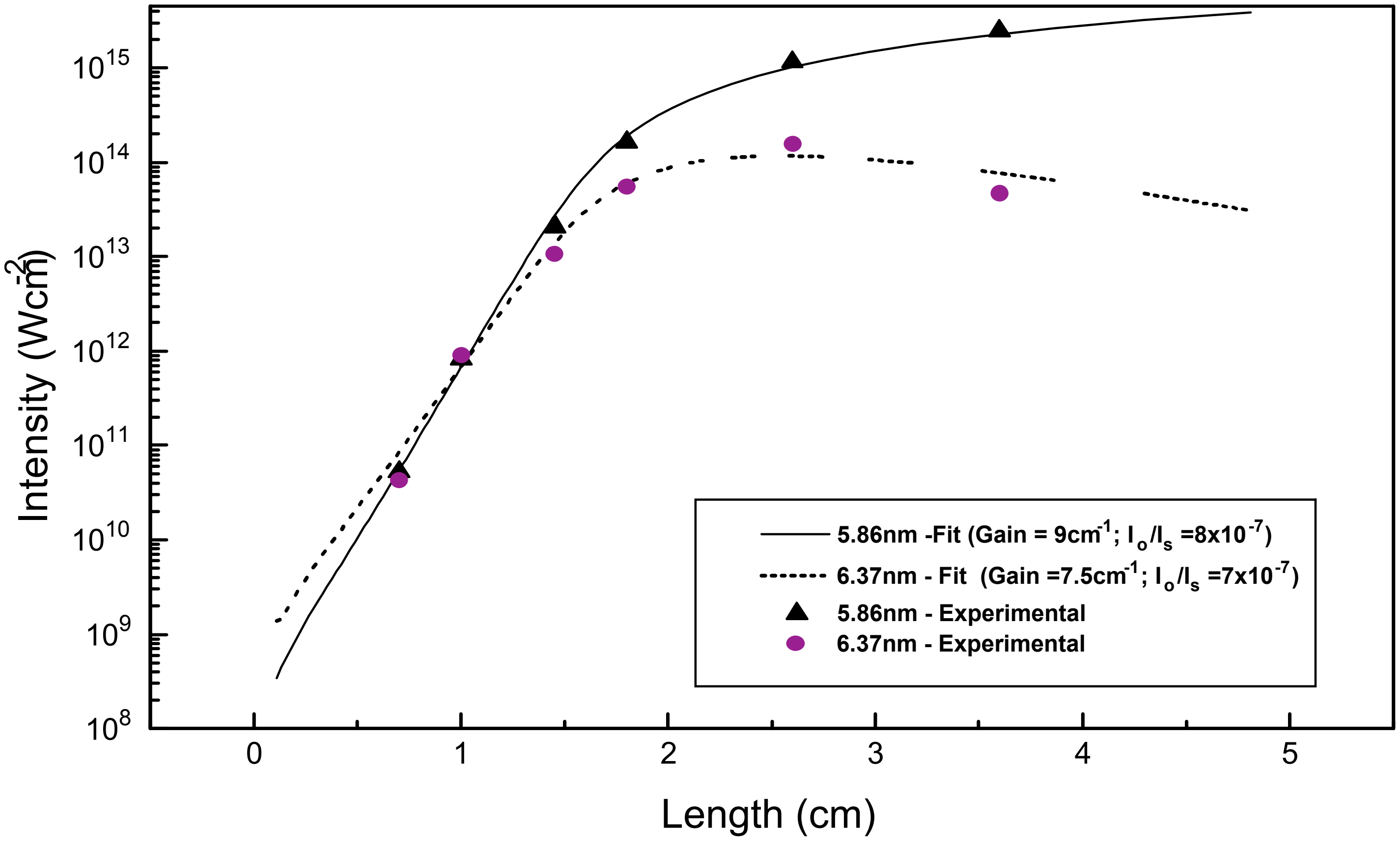
$X_0 + e \rightarrow X_2 + e$



Energy levels important for lasing in Ni-like ions

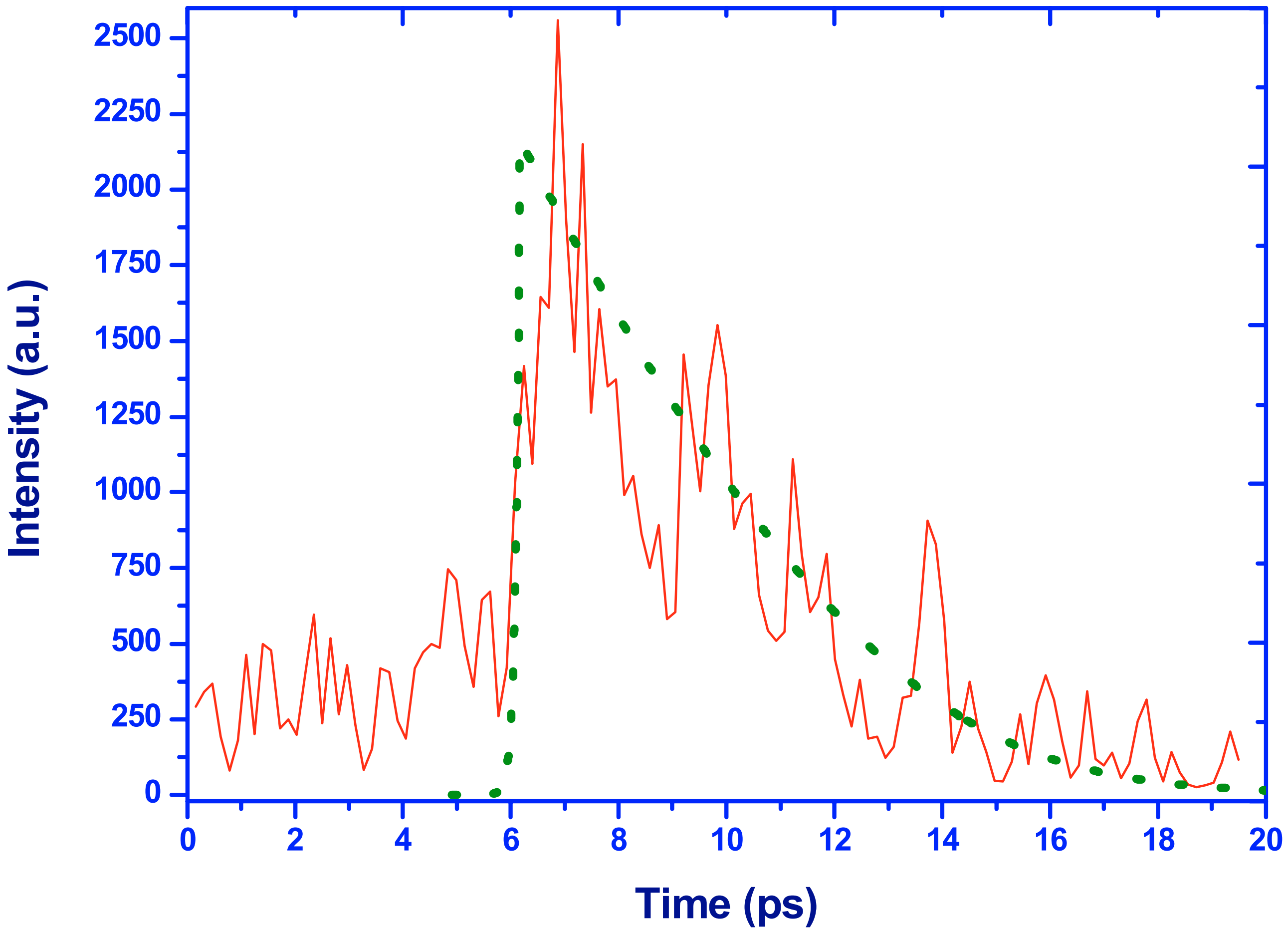
Shortest wavelength saturated laser is at 5.9 nm (210 eV)

X-ray laser
output of
Ni-like Dy

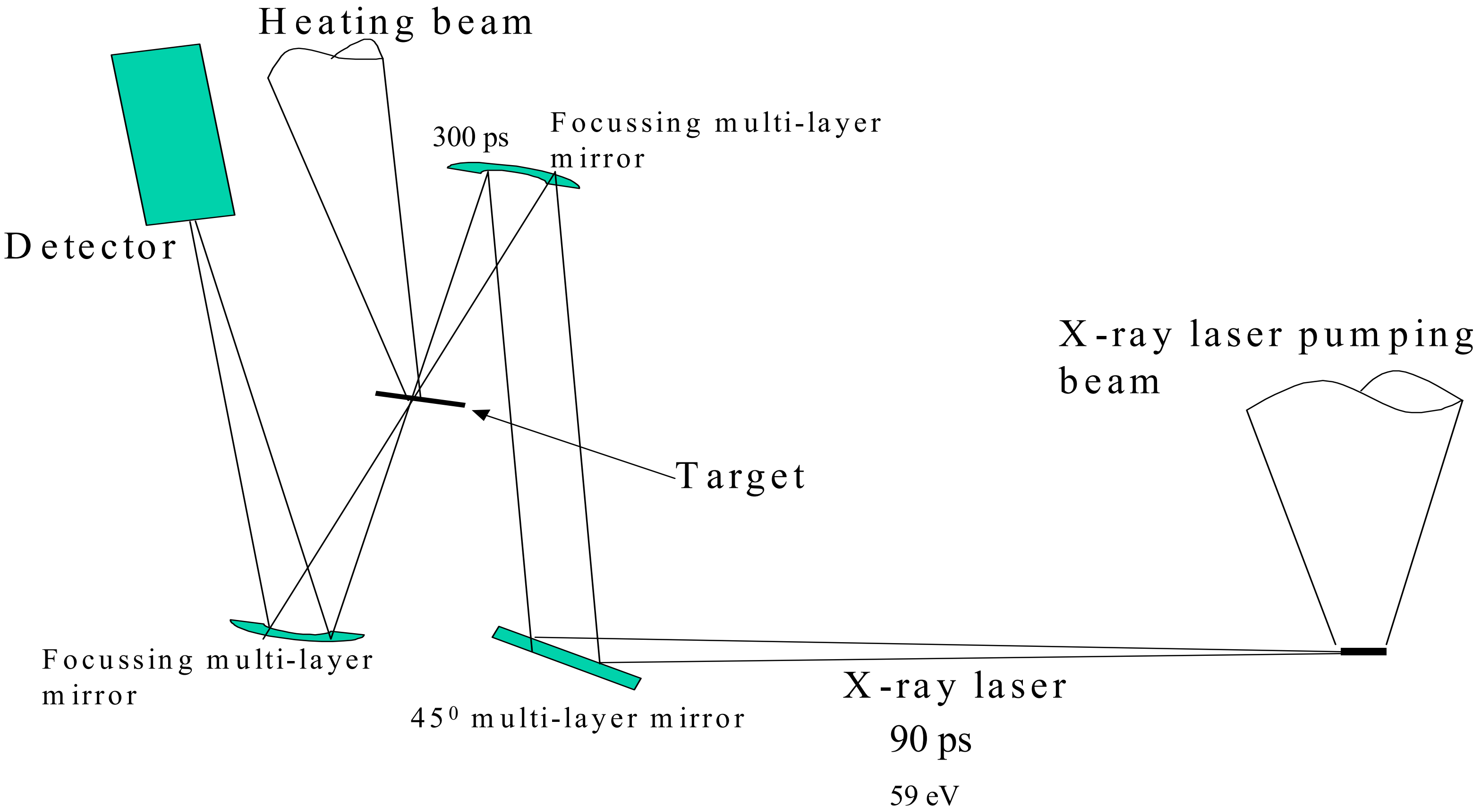


X-ray laser pulse duration as short as 3 ps have been measured

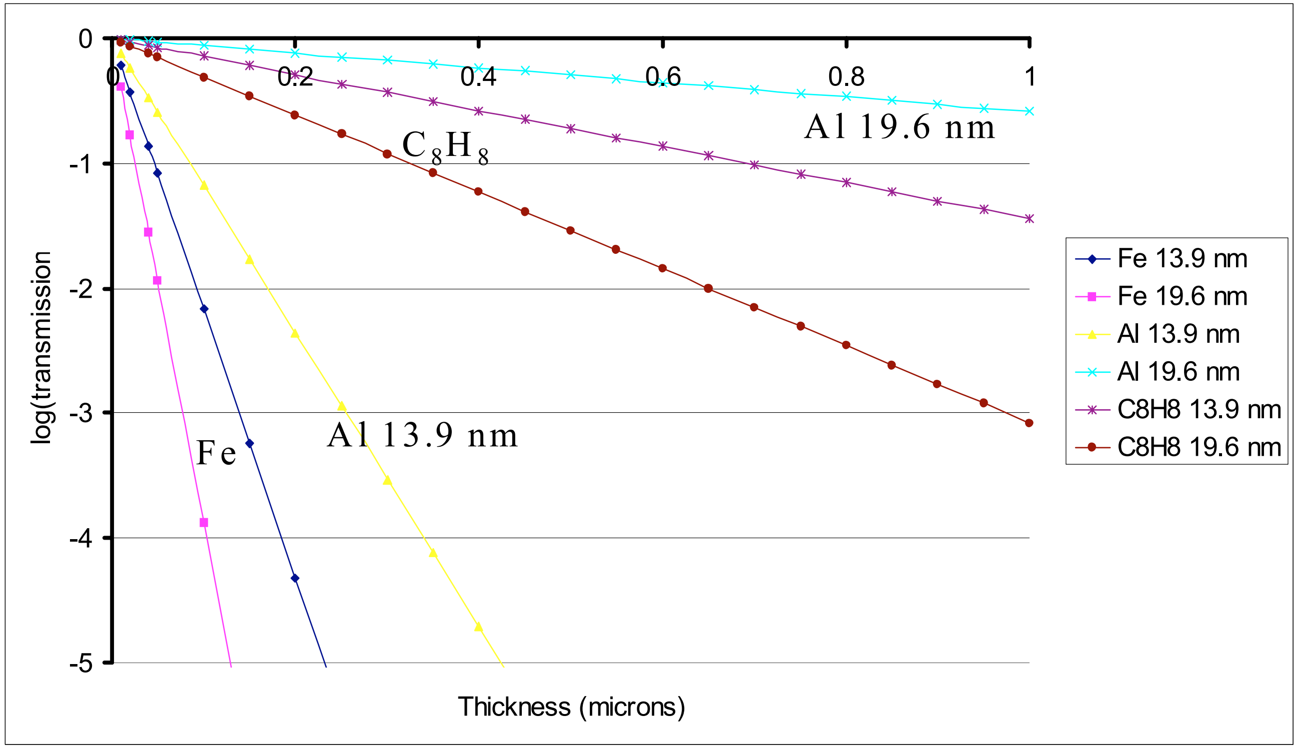
Ni-like Ag
output at
13.9 nm.



An experiment to use x-ray laser output as a backlighter to measure plasma opacity



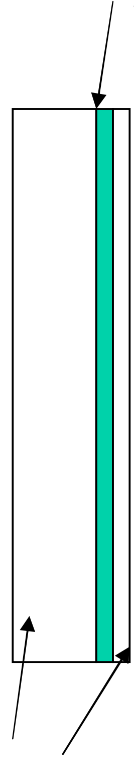
Targets



Transmission of solid,
room temperature material

>>

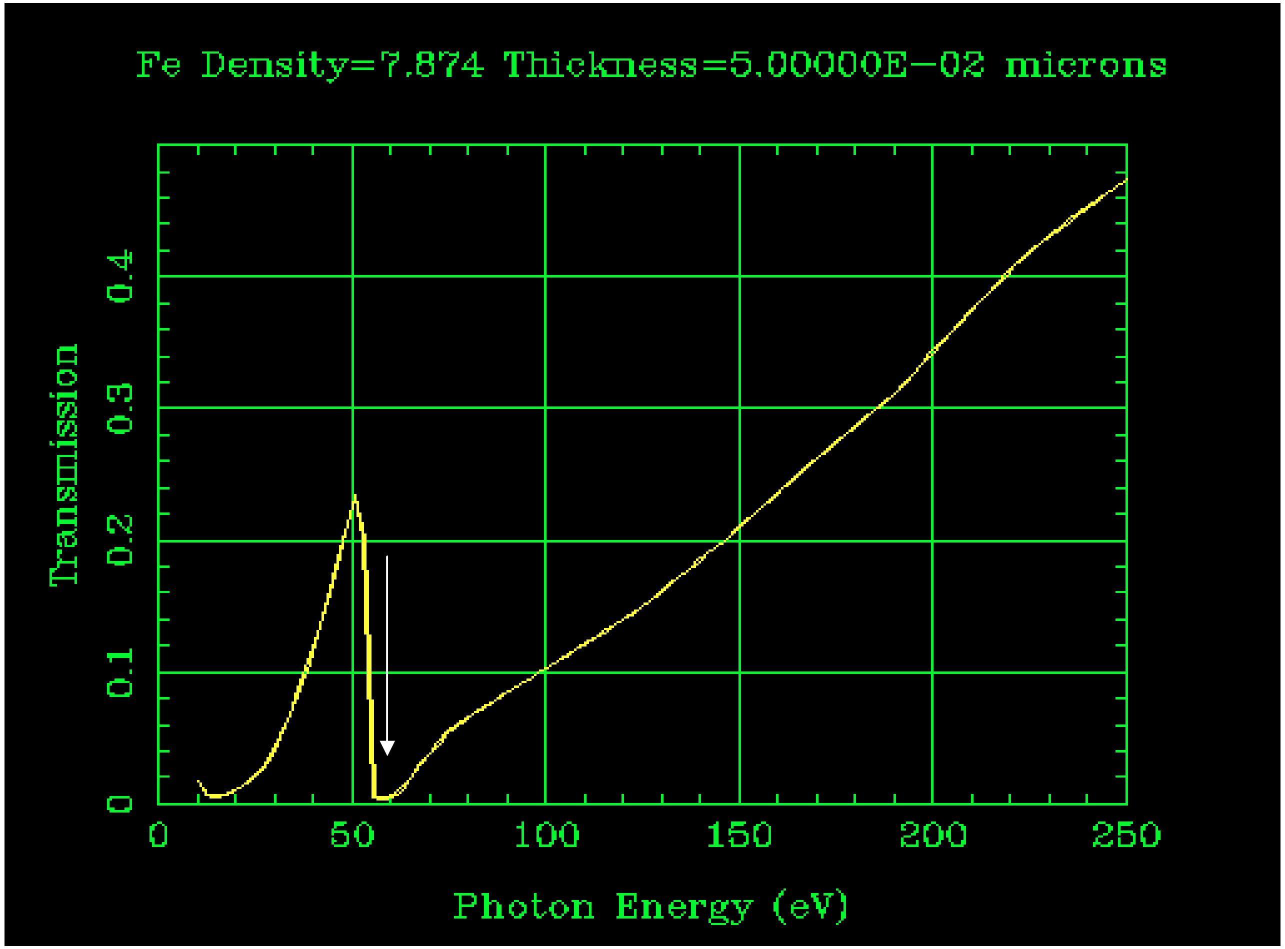
Fe
0.05 micron
with some Mg
as a signature



Al or CH

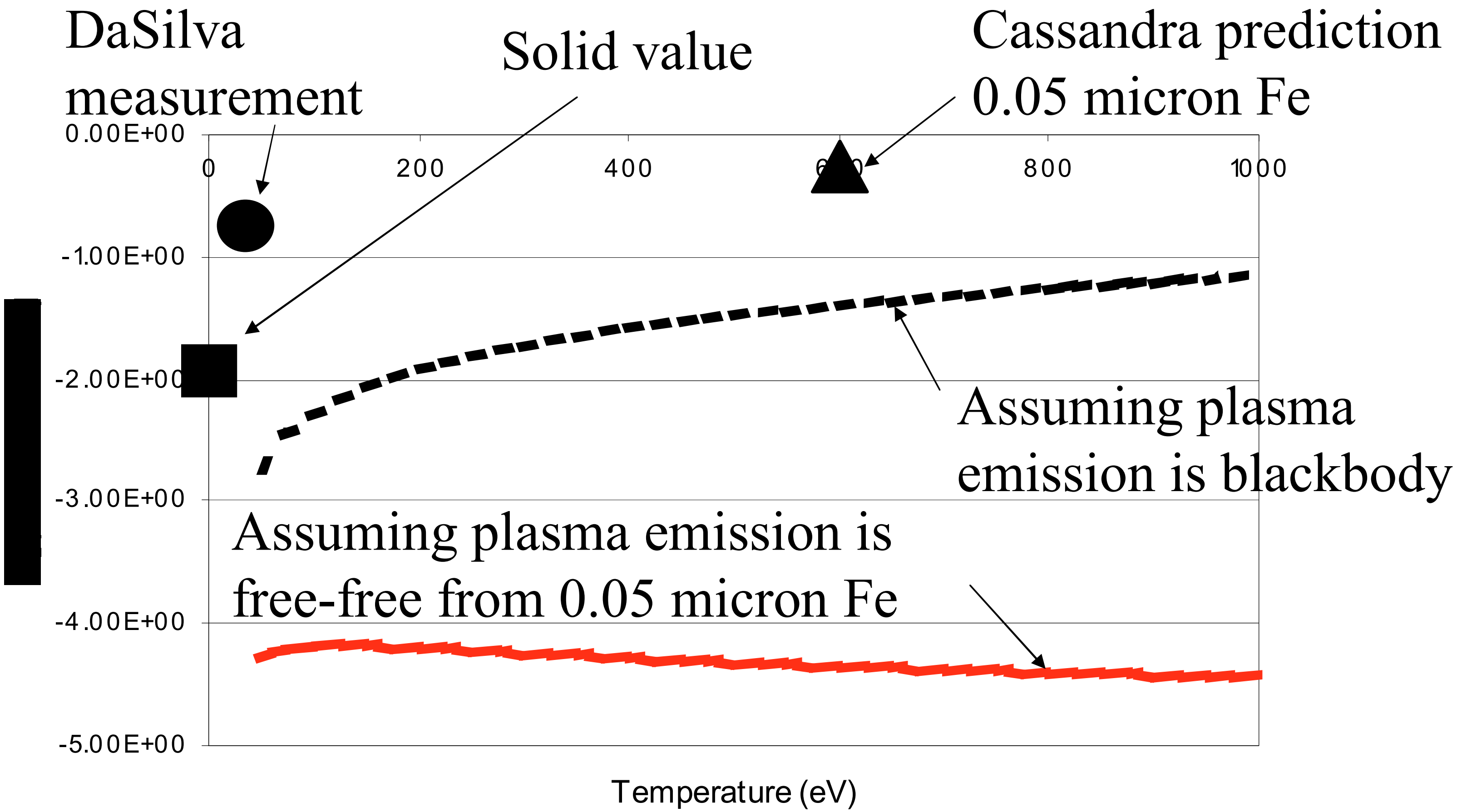
The opacity of solid iron at EUV photon energies

Experiment at 21.2nm has a high opacity in cold Fe. Opacity rapidly decreases with ionisation.



Arrow shows photon energy for 21.2 nm.

Signal to noise for Fe target transmission measurement



DaSilva measurement

Solid value

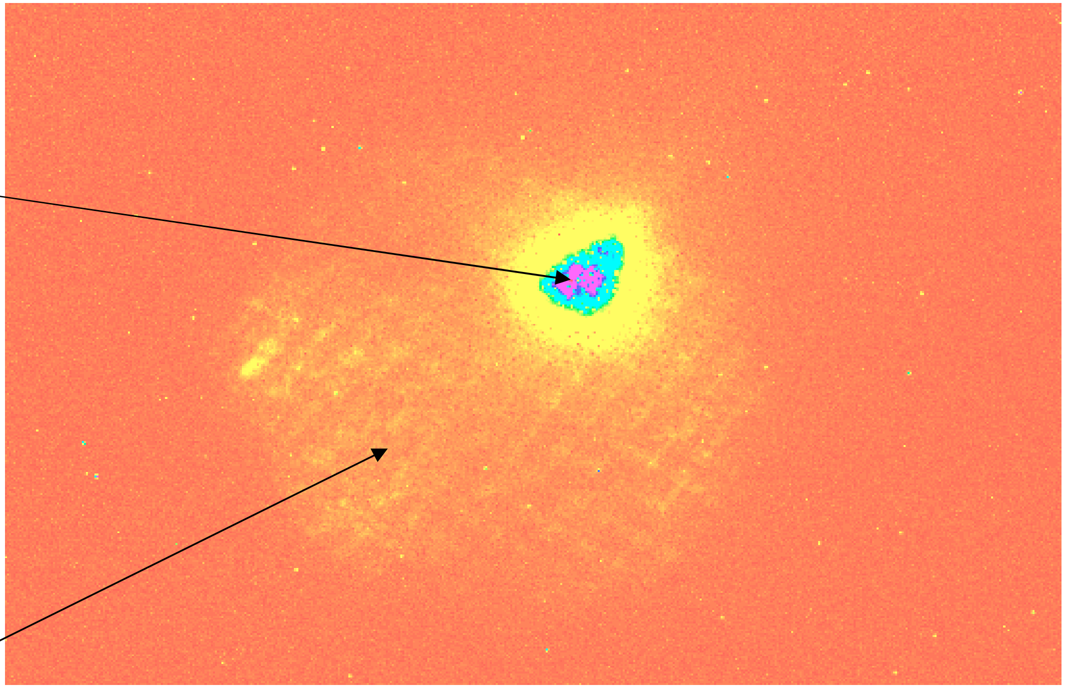
Cassandra prediction 0.05 micron Fe

Assuming plasma emission is blackbody

Assuming plasma emission is free-free from 0.05 micron Fe

Transmission minimum producing 10X x-ray laser flux compared to plasma background (as labelled).

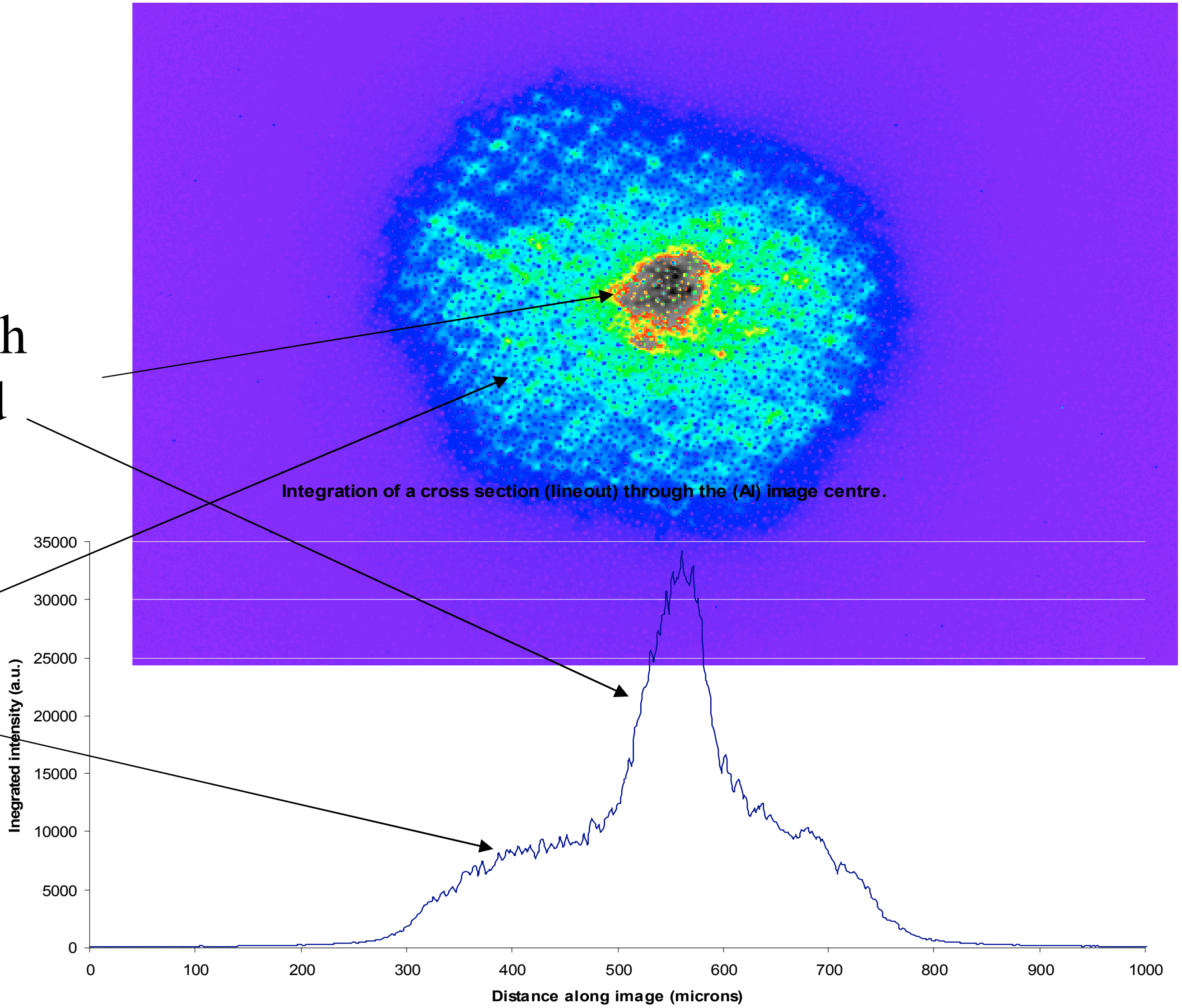
Transmission of 21.2 nm x-ray laser through 0.8 μm Al heated by laser



Transmission of X-ray laser through heated and ionised material

X-ray laser shining through unheated Al

Another probed Al plasma

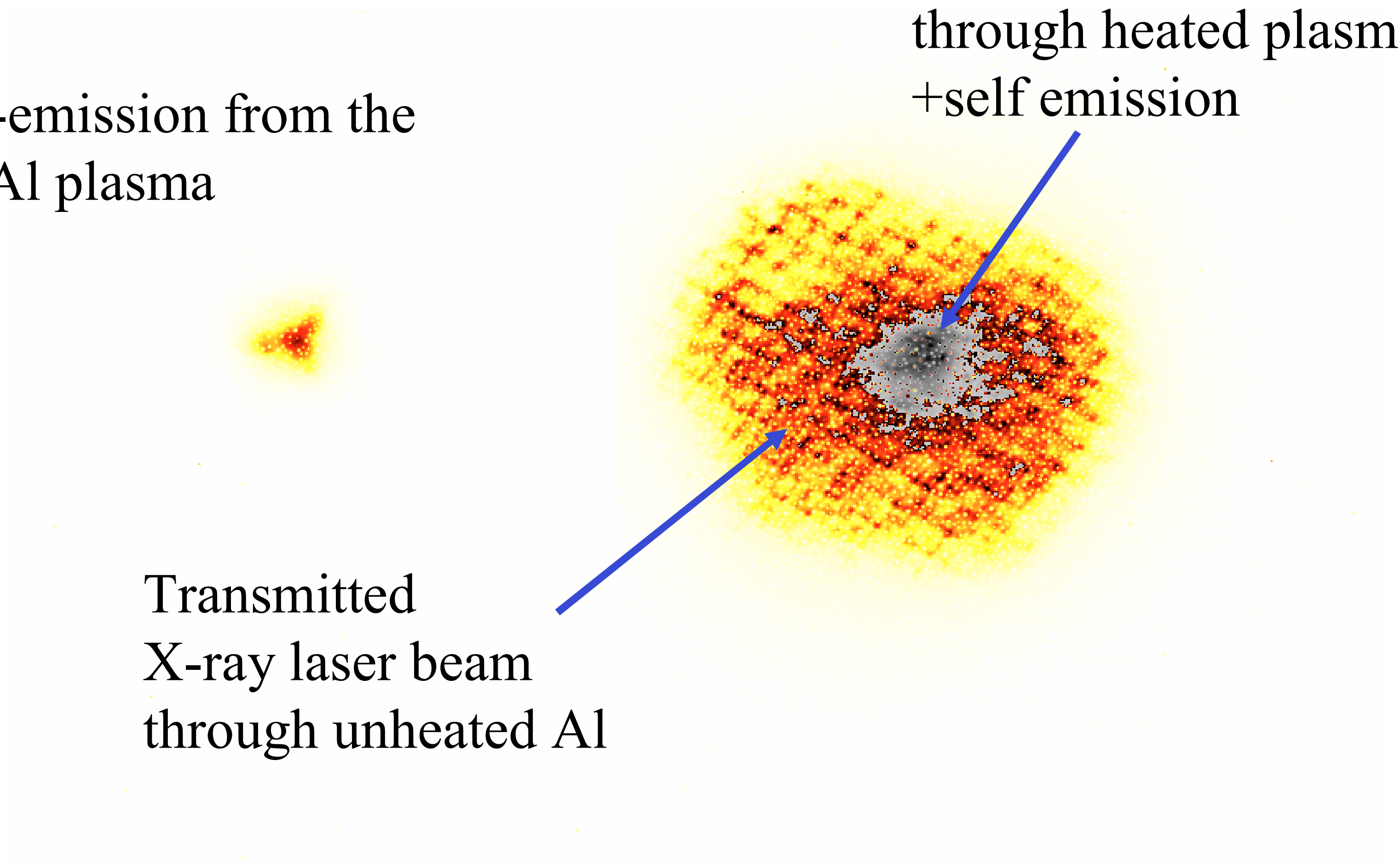


Transmission of
X-ray laser through
heated and ionised
material

X-ray laser shining
through unheated Al

⇒44% transmission
through ionised Al
while unheated Al
transmits 12%

Probed Al with a measure of self-emission

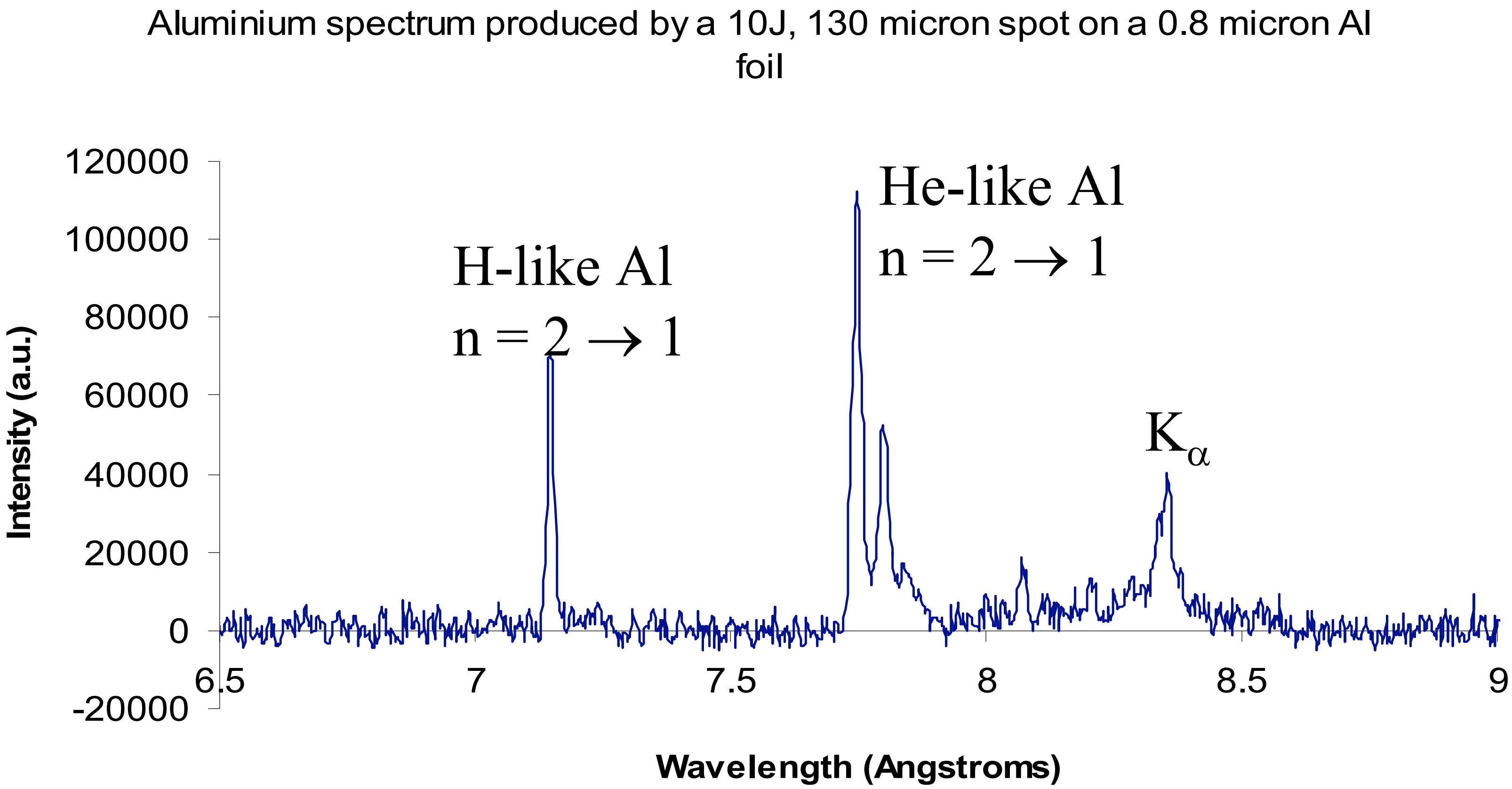


Transmitted
X-ray laser beam
through heated plasma
+self emission

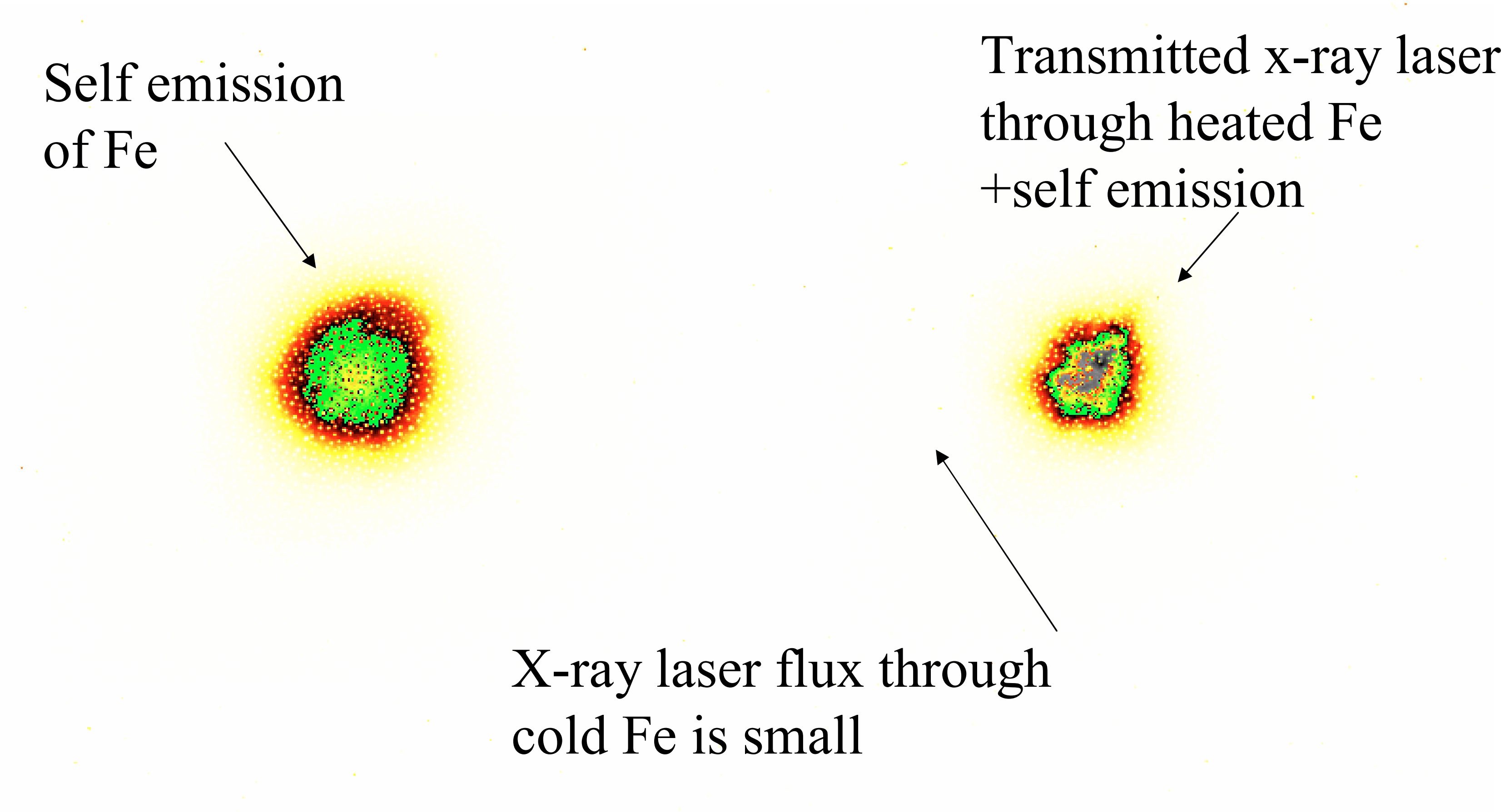
Self-emission from the
hot Al plasma

Transmitted
X-ray laser beam
through unheated Al

Aluminium is well ionised



Opacity of thin targets of Fe

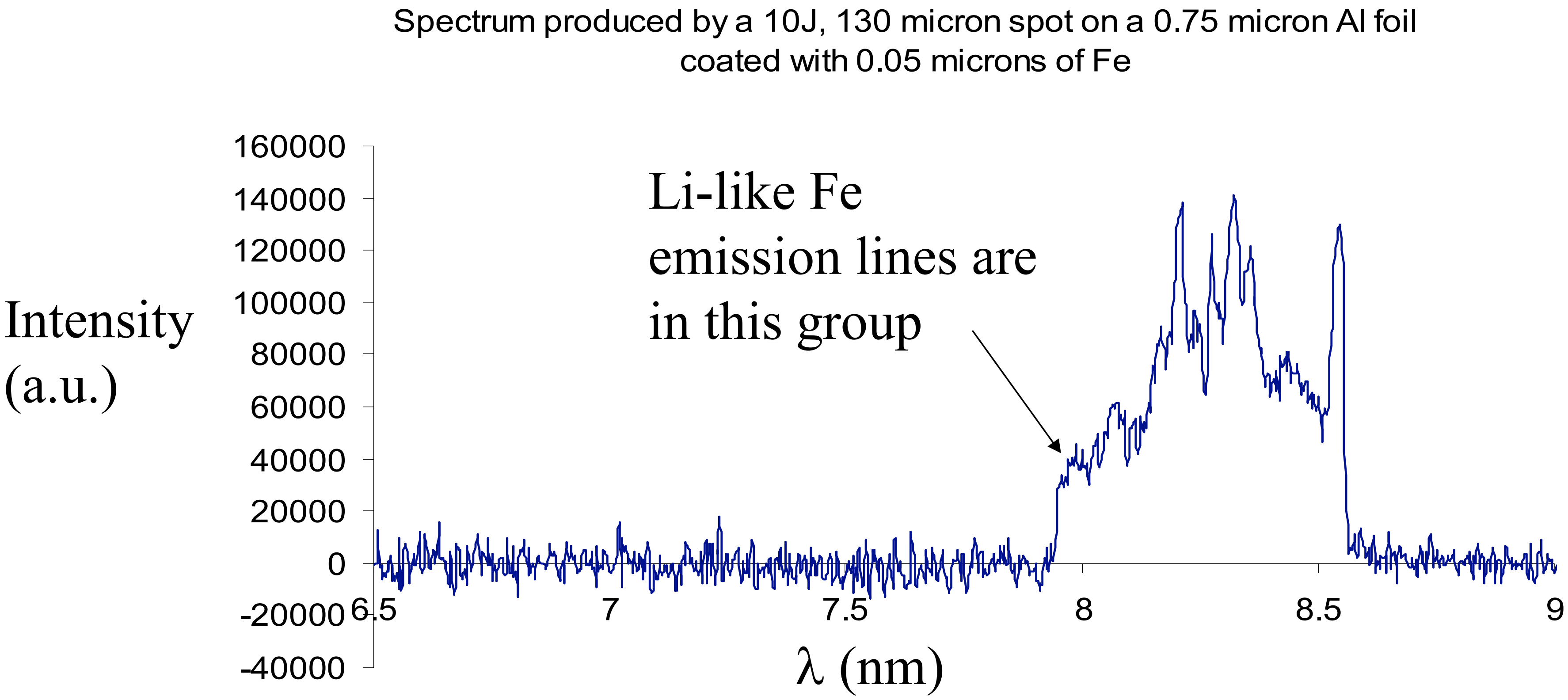


Self emission of Fe

Transmitted x-ray laser through heated Fe +self emission

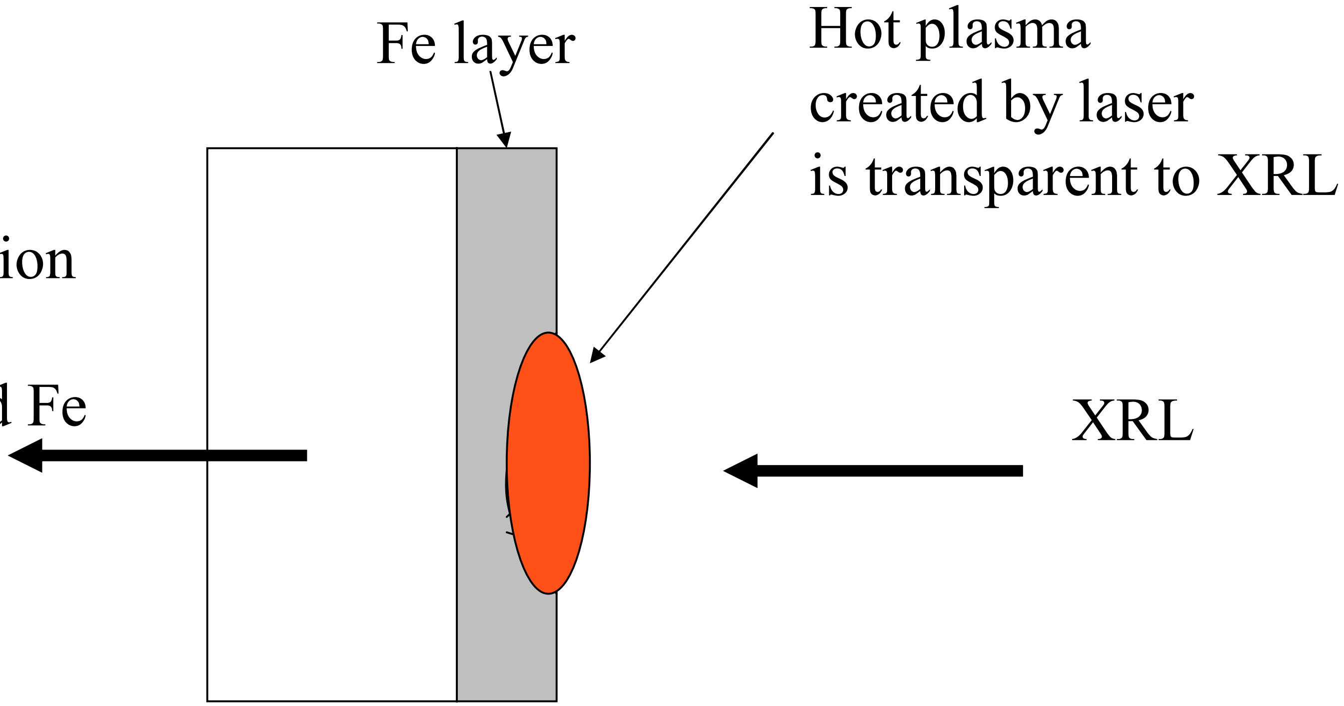
X-ray laser flux through cold Fe is small

Thin iron targets are also well ionised



Li-like Fe emission lines are in this group

Schematic of physics of transmission with thin non-tamped foils.



Fe layer

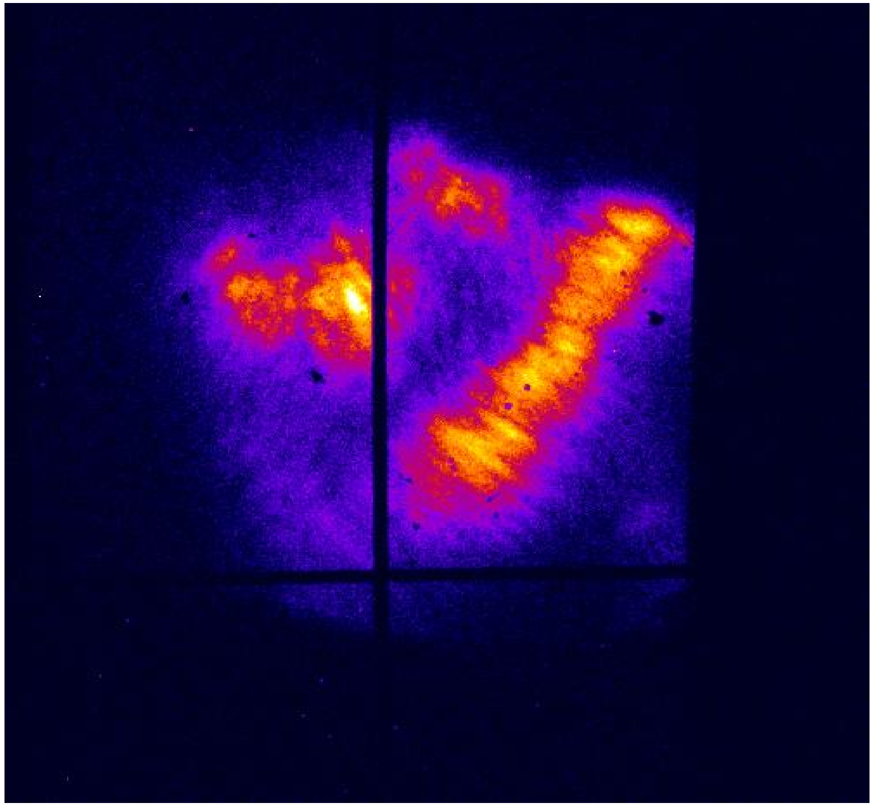
Hot plasma
created by laser
is transparent to XRL

XRL transmission
determined by
remaining solid Fe

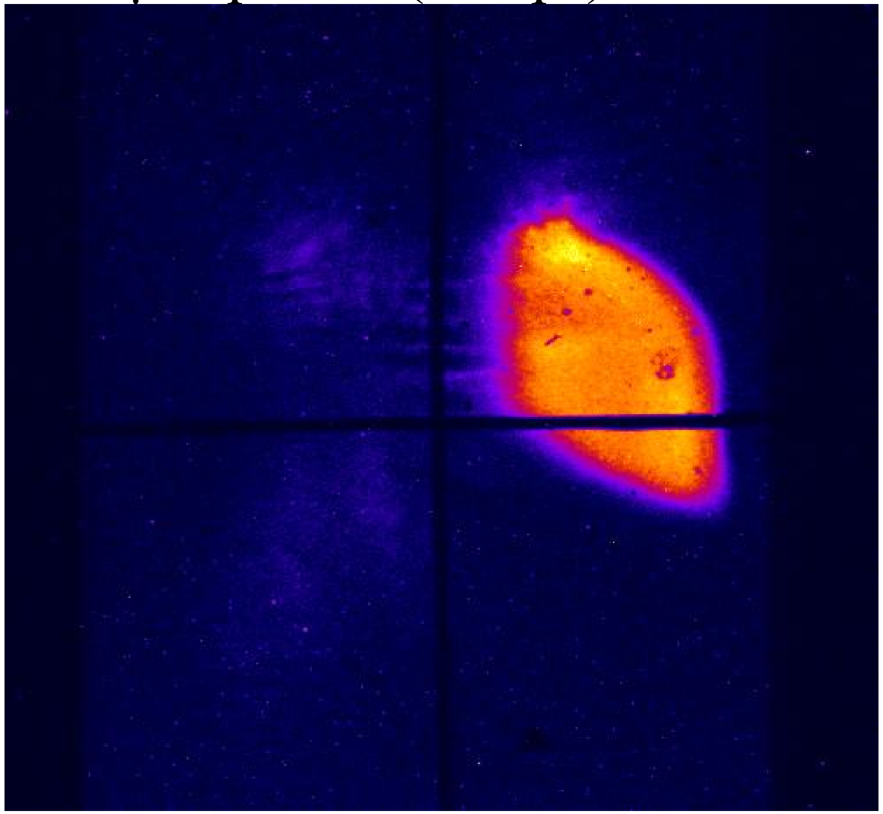
XRL

Iron transmission over the laser heated area

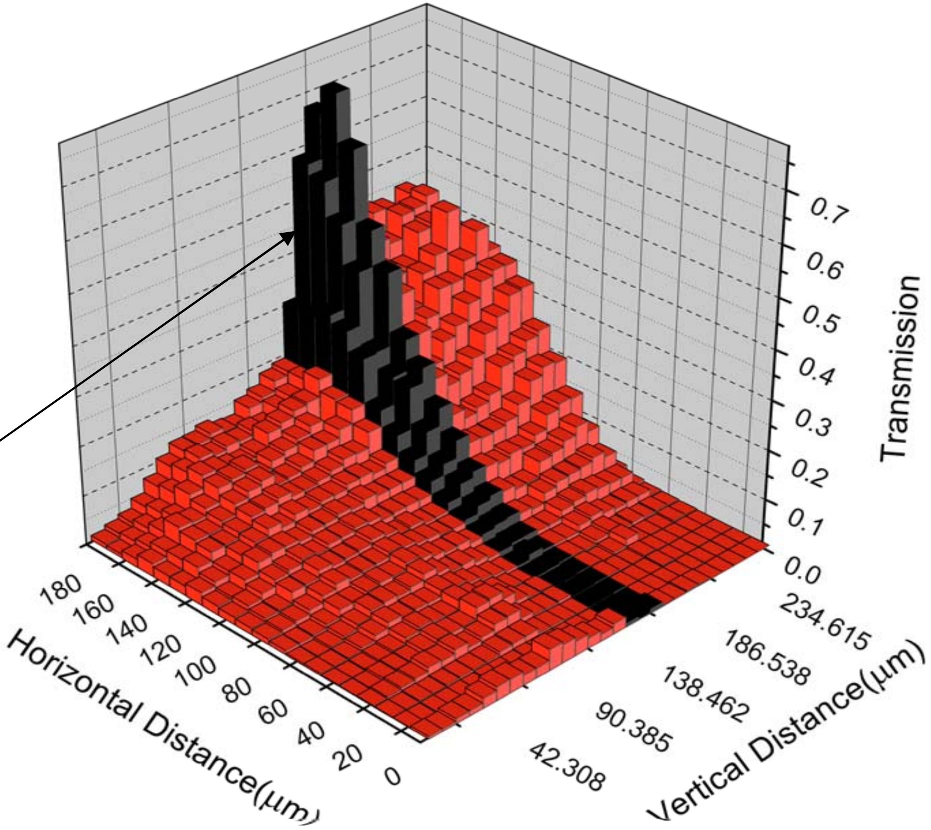
XRL beam profile



Transmission of XRL thru heated 0.05 μm Fe under 0.05 μm plastic (100 ps)

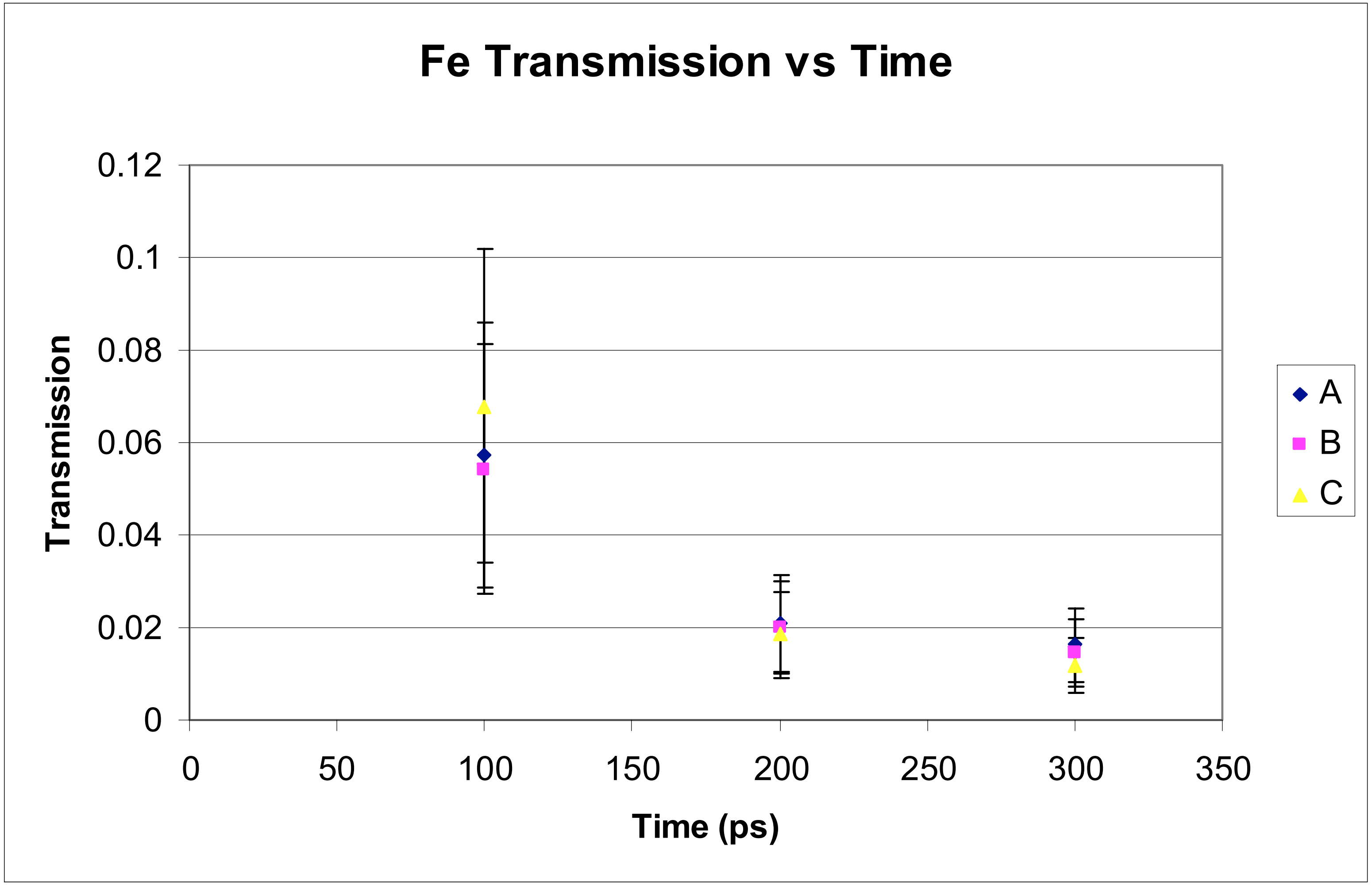


Transmission can be deduced taking account of XRL variation

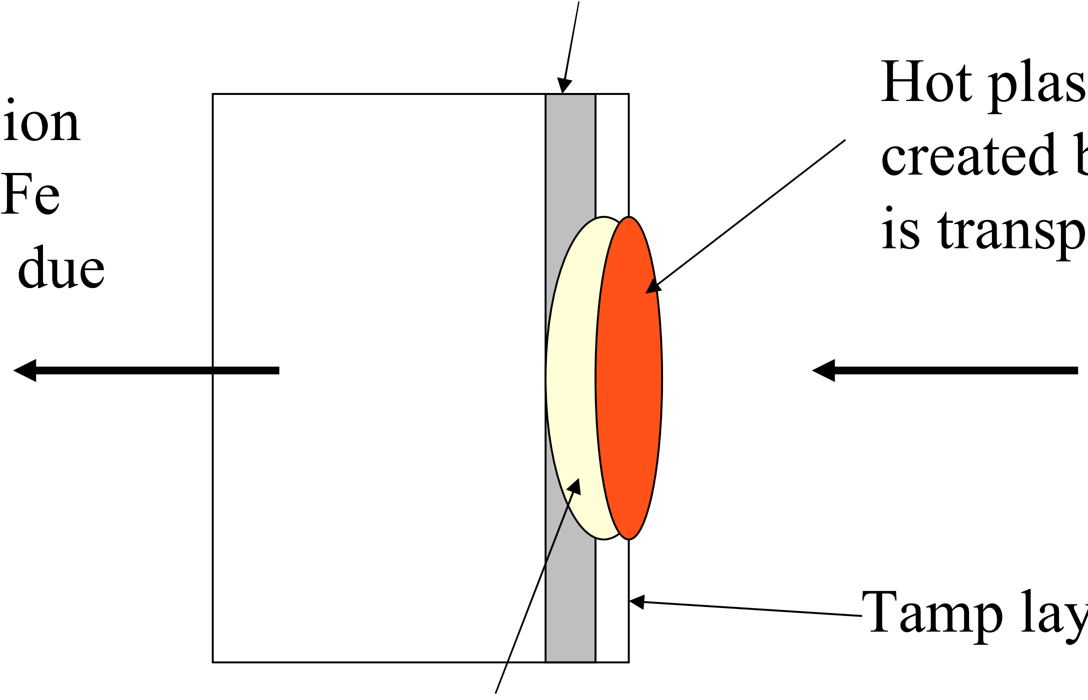


Fiducial
wire effect
(in black)

Iron transmission when buried under plastic



Schematic of physics with tamped Fe targets



Fe layer

Hot plasma
created by laser
is transparent to XRL

XRL transmission
determined by Fe
opacity change due
to heating

XRL

Tamp layer

Thermal wave penetrates target.

Conclusions

- Plasma opacity is important in astrophysical plasmas and can be measured in the laboratory using lasers to heat the plasma samples and to produce ‘backlighters’: opacities for temperatures up to 40 eV for densities ~ 10^{-2} gcm^{-3} have been previously measured.
- An ‘X-ray laser’ backlighter at 60 eV photon energy has been demonstrated to be able to measure opacity in plasmas heated to 100’s eV at near solid density (1 – 8 gcm^{-3}).