Opacity of Dense Plasmas: Challenges for XFEL

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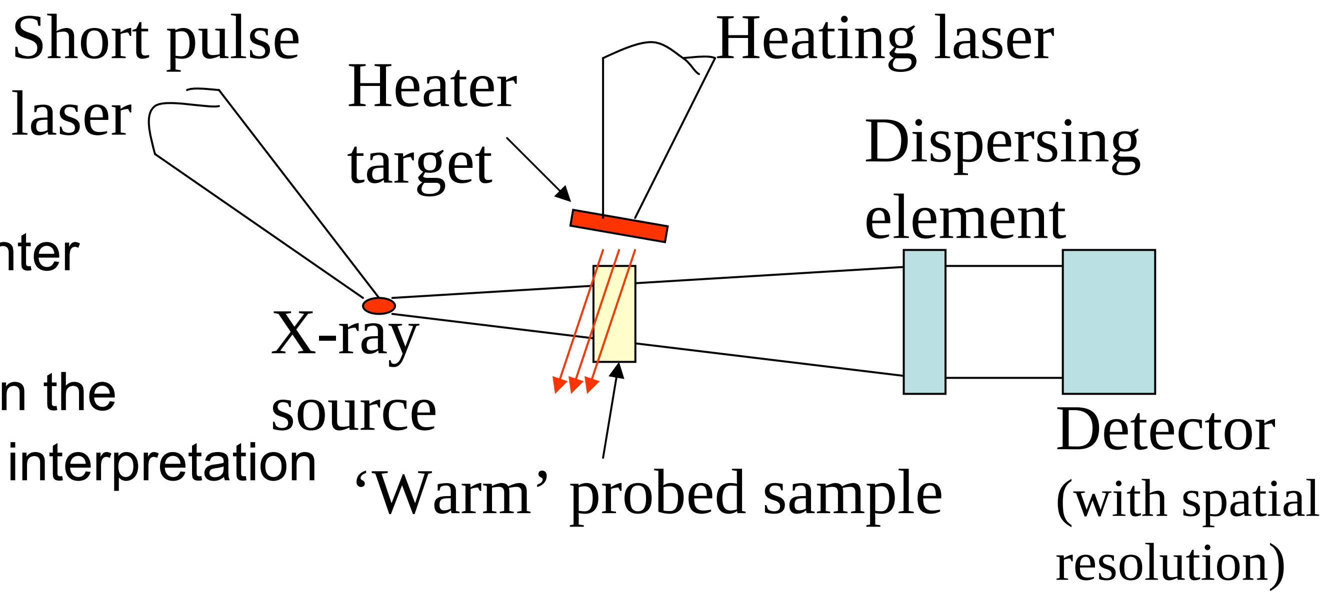
Summary

- Review previous opacity measurement techniques
  - Review EUV experiments (with plasma EUV laser).
- Application of EUV experiments to XFEL.
- Novel experiments?

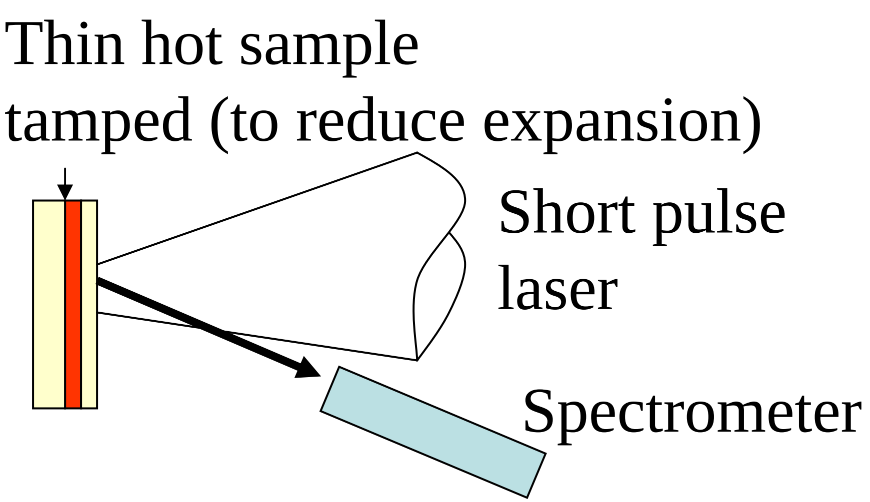
Relevant XFEL performance

- 100 fs pulses
- 10^{12} photons
- 0.2 – 12.4 keV photons
- Beam size 100 μm
- Bandwidth 0.1%.
- → 10^{14} Wcm^{-2} in the unfocussed beam.
- → 10^{18} Wcm^{-2} in beam focused to 1 μm.
- → 1 mJ of energy in the beam.

Previous methods of measuring plasma opacity



- Shine a bright backlighter through an x-ray heated plasma – line radiation in the backlighter complicates interpretation



- Emission spectroscopy can be used:
  assume plasma is in LTE
  calculate opacity from emissivity of a thin sample – not useful for 'warm dense plasma' as emission is weak.

Emission spectra can give opacity*

X-ray spectroscopic studies of hot, dense iron plasma formed by subpicosecond high intensity KrF laser irradiation

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The time-integrated x-ray emission from a hot, dense iron plasma has been recorded. The iron plasma was created when a target with a 1000-Å-thick iron layer buried beneath 1000 Å of plastic was irradiated by a 300 fs pulse of 249 nm laser light at an intensity of approximately 10^{17} W cm^{-2}. Two models have been used to construct a synthetic x-ray spectrum. The first employs detailed, spectroscopically accurate atomic data and the second uses a local thermodynamic equilibrium opacity model. The detailed model shows fairly good agreement with experiment whereas the opacity model only shows agreement in the gross features. © *1996 American Institute of Physics.* [S0003-6951(96)04350-1]

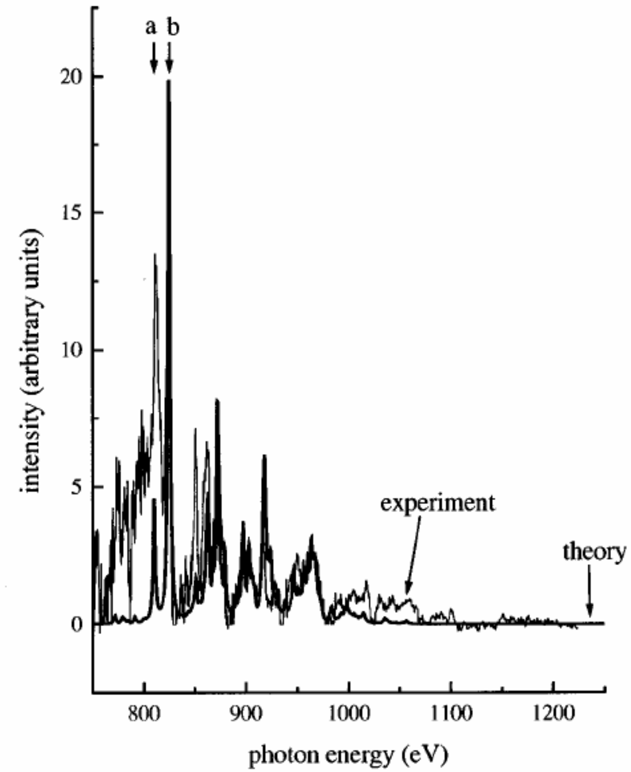
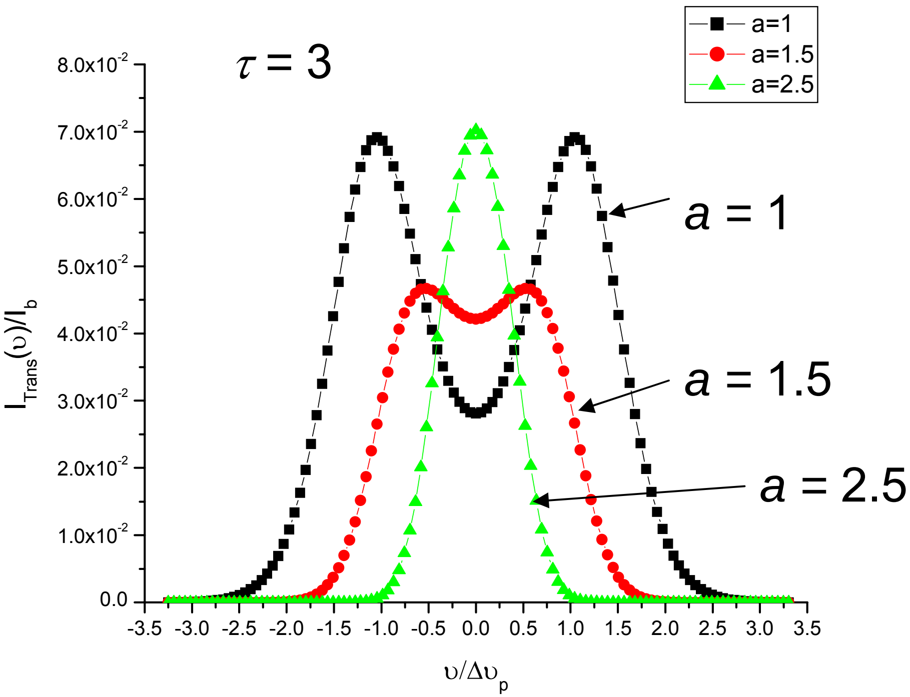
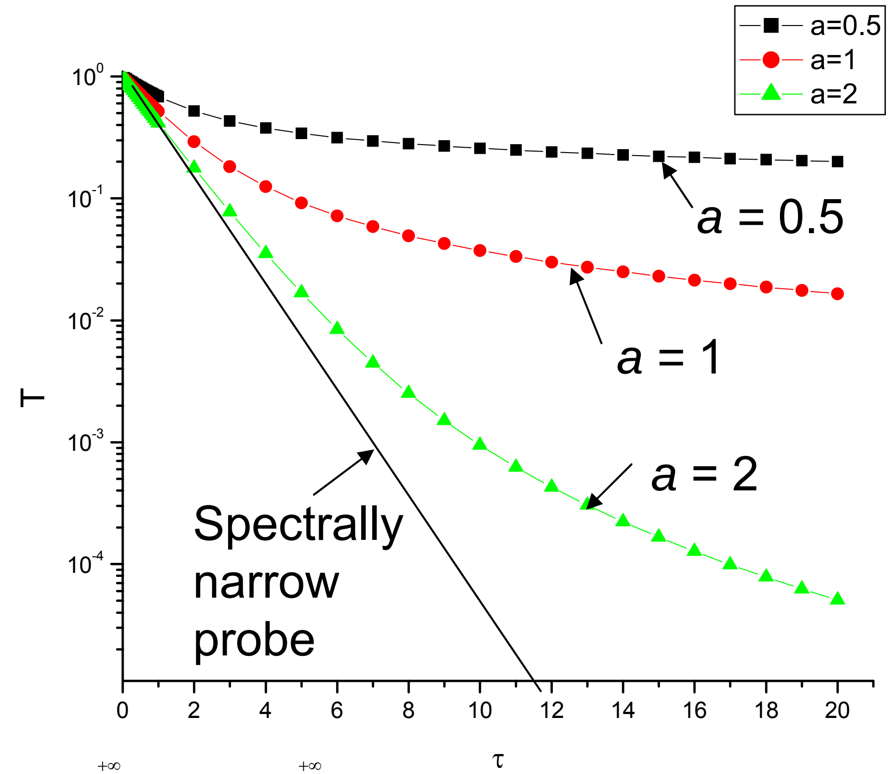


FIG. 2. Comparison between measured x-ray intensity (with background subtracted) and theoretical intensity calculated from Eq. (1). Line *a* is the Ne-like iron transition: $1s\,^22s\,^22p_{1/2}\,2p_{3/2}\,^43d_{3/2} \rightarrow 1s\,^22s\,^22p_{1/2}\,^42p^4_{3/2}$. Line *b* is the Ne-like iron transition: $1s\,^22s\,^22p_{1/2}\,^22p_{3/2}\,^33d_{5/2} \rightarrow 1s\,^22s\,^22p_{1/2}\,^42p^4_{3/2}$.

* Provided the plasma is optically thin and in LTE.

X-ray laser output is narrow-band – better for probing





$$T = \frac{\int_{-\infty}^{+\infty} I_{Trans}\, d\upsilon}{\int_{-\infty}^{+\infty} I_b(0) f_b(\upsilon) d\upsilon} = \frac{\int_{-\infty}^{+\infty} I_{Trans}\, d\upsilon}{I_b(0)} = \int_{-\infty}^{+\infty} f_b(\upsilon) \exp[-\tau \frac{f_p(\upsilon - \Delta\upsilon_{shift})}{f_p(0)}] d\upsilon$$

Transmission (spectrally resolved) and (spectrally integrated) is shown for different values '*a*' of probed plasma linewidth/backlighter linewidth assuming Gaussian line profiles.

'Saturation' behaviour limits usefulness of probing with broad linewidths at high optical depth >> narrow XRL spectral width is better

Demonstration experiment that could be carried over onto FELs

PRL **97,** 035001 (2006) PHYSICAL REVIEW LETTERS week ending 21 JULY 2006

Opacity Measurements of a Hot Iron Plasma Using an X-Ray Laser

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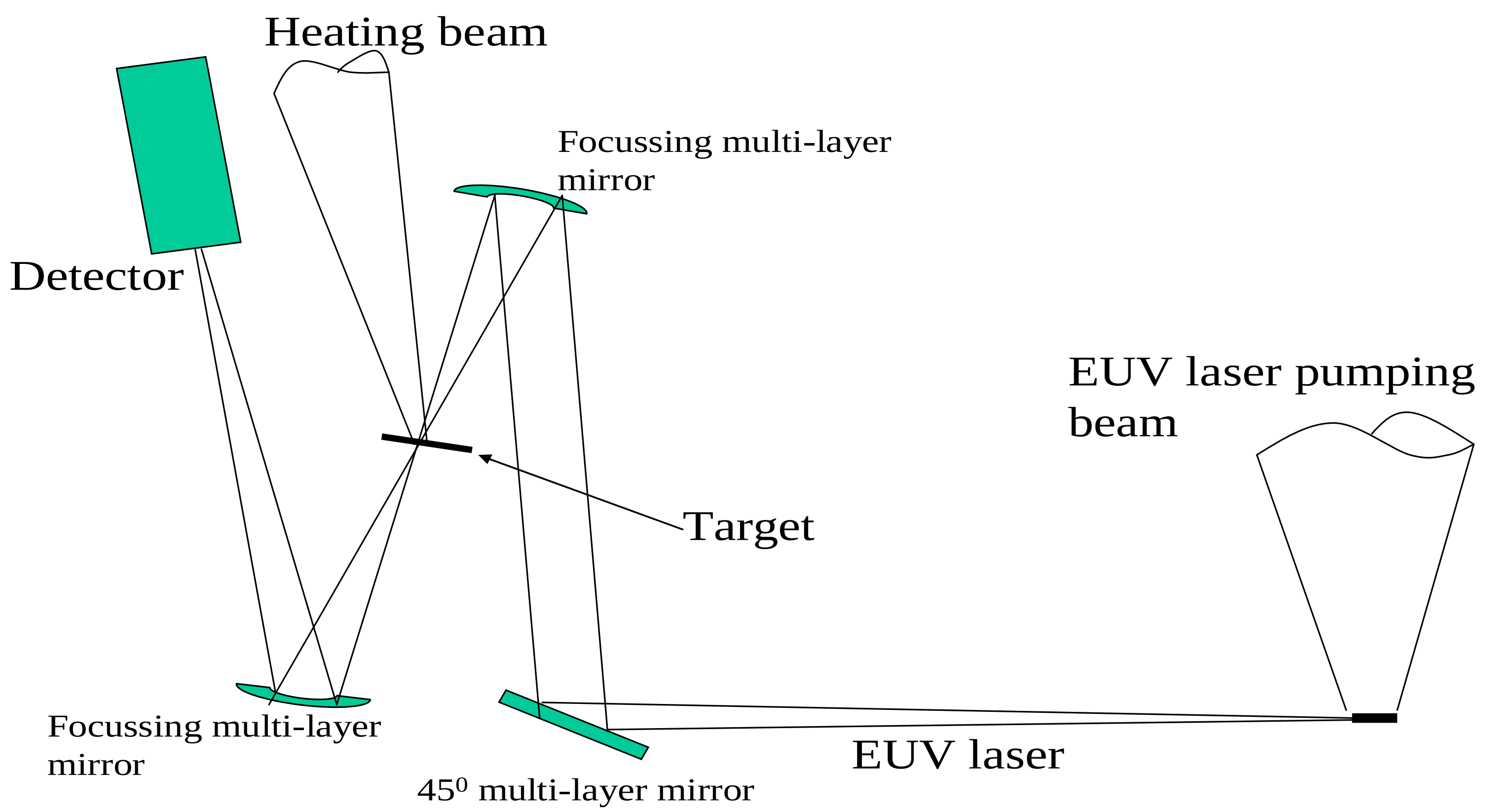
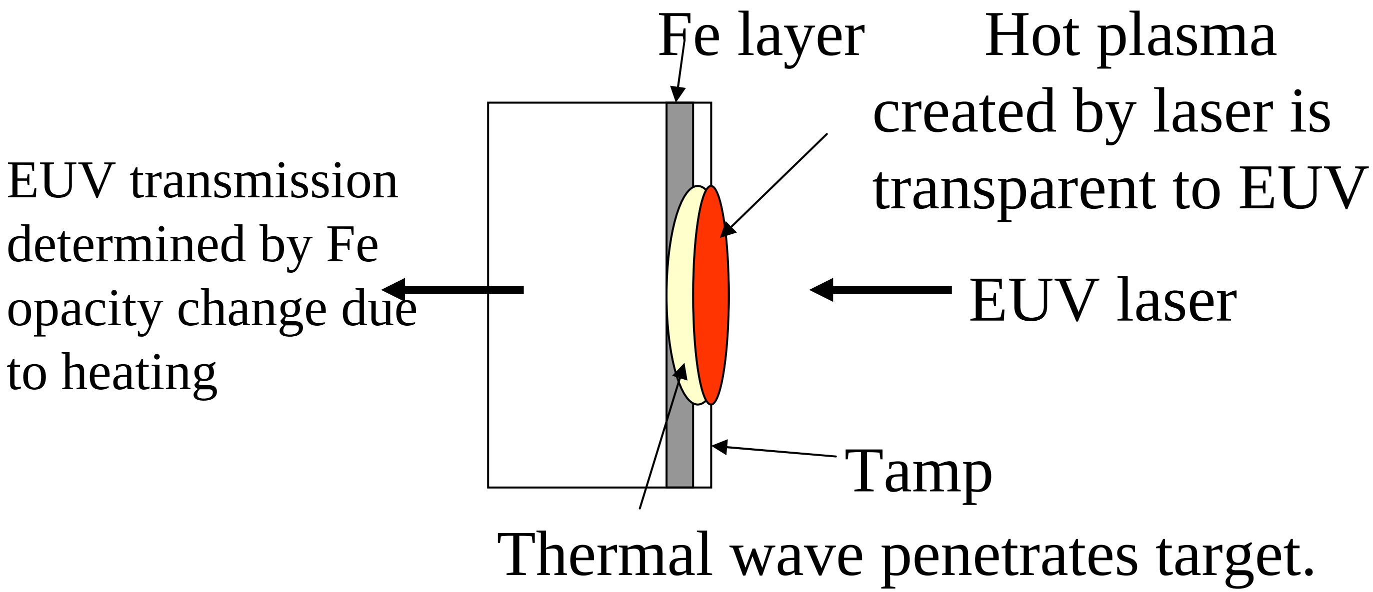
(Received 9 January 2006; revised manuscript received 27 March 2006; published 18 July 2006)

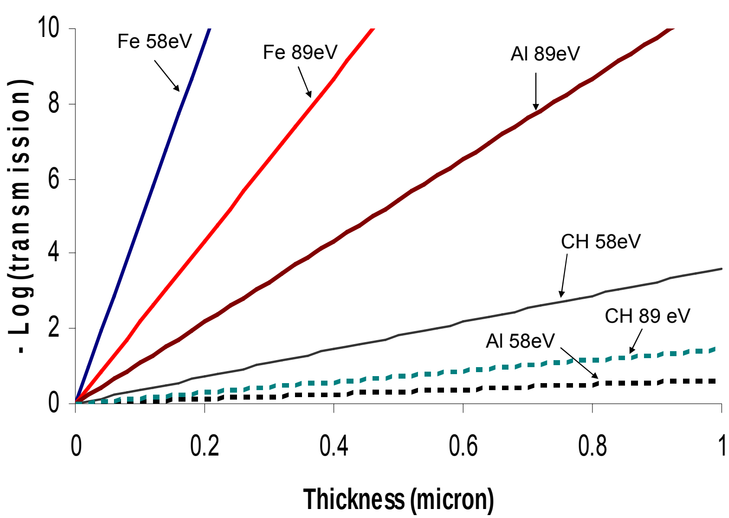
The temporal evolution of the opacity of an iron plasma at high temperature (30–350 eV) and high density (0.001–0.2 g cm^{-3}) has been measured using a nickel-like silver x-ray laser at 13.9 nm. The hot dense iron plasma was created in a thin (50 nm) iron layer buried 80 nm below the surface in a plastic target that was heated using a separate 80 ps pulse of 6–9 J, focused to a 100 μm diameter spot. The experimental opacities are compared with opacities evaluated from plasma conditions predicted using a fluid and atomic physics code.

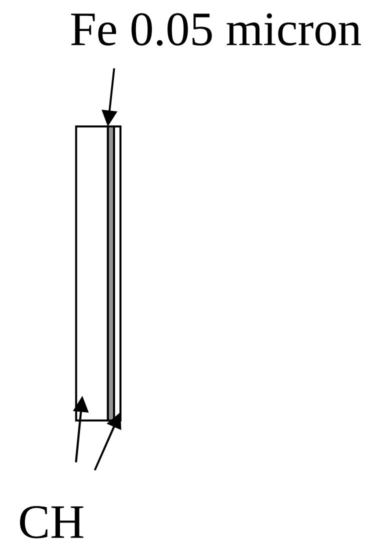
An experiment to use EUV laser output as a backlighter to measure plasma opacity



The opacity targets



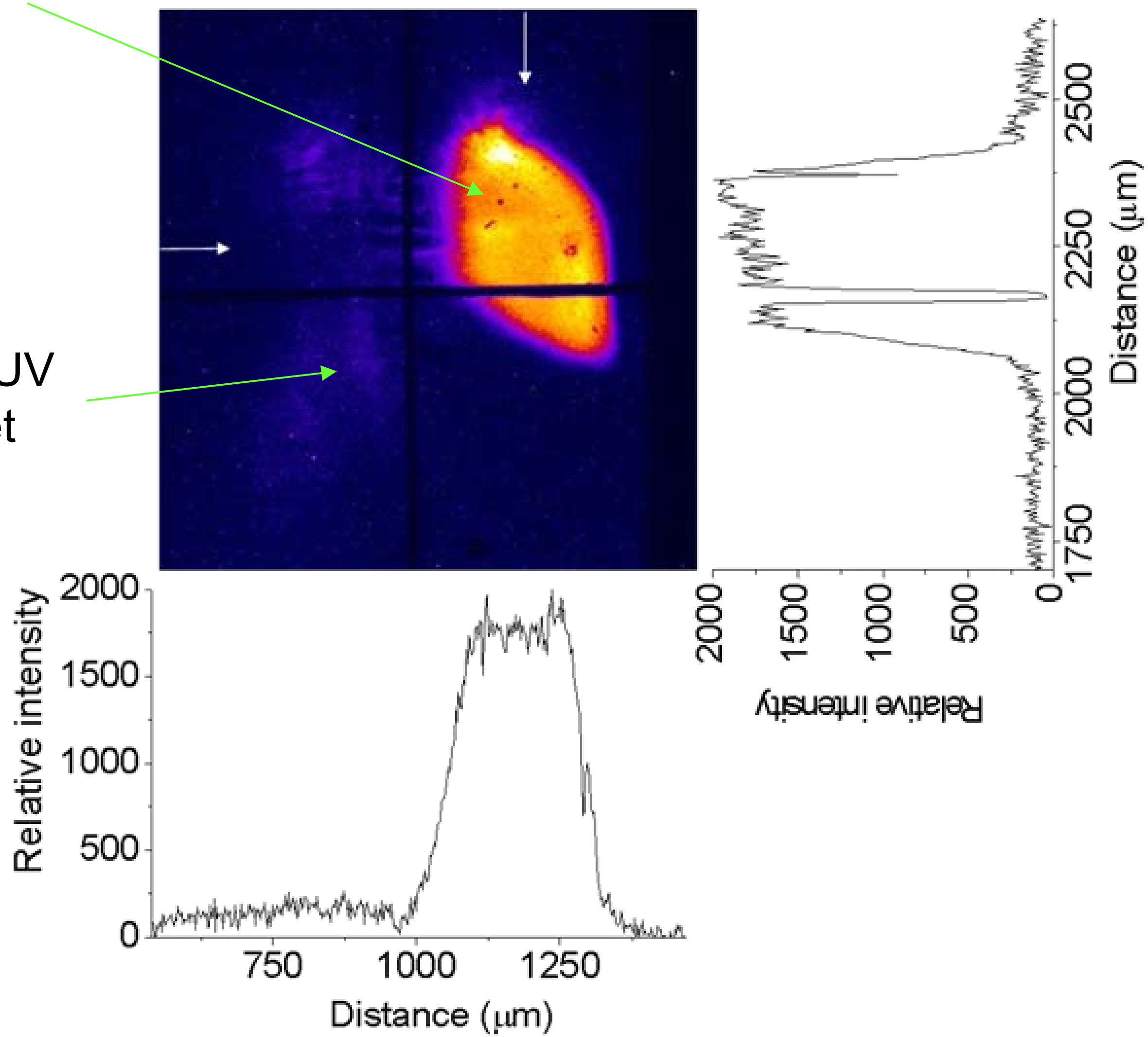




EUV laser footprint at opacity target

Region of target heated by a visible laser

Transmission of EUV through solid target



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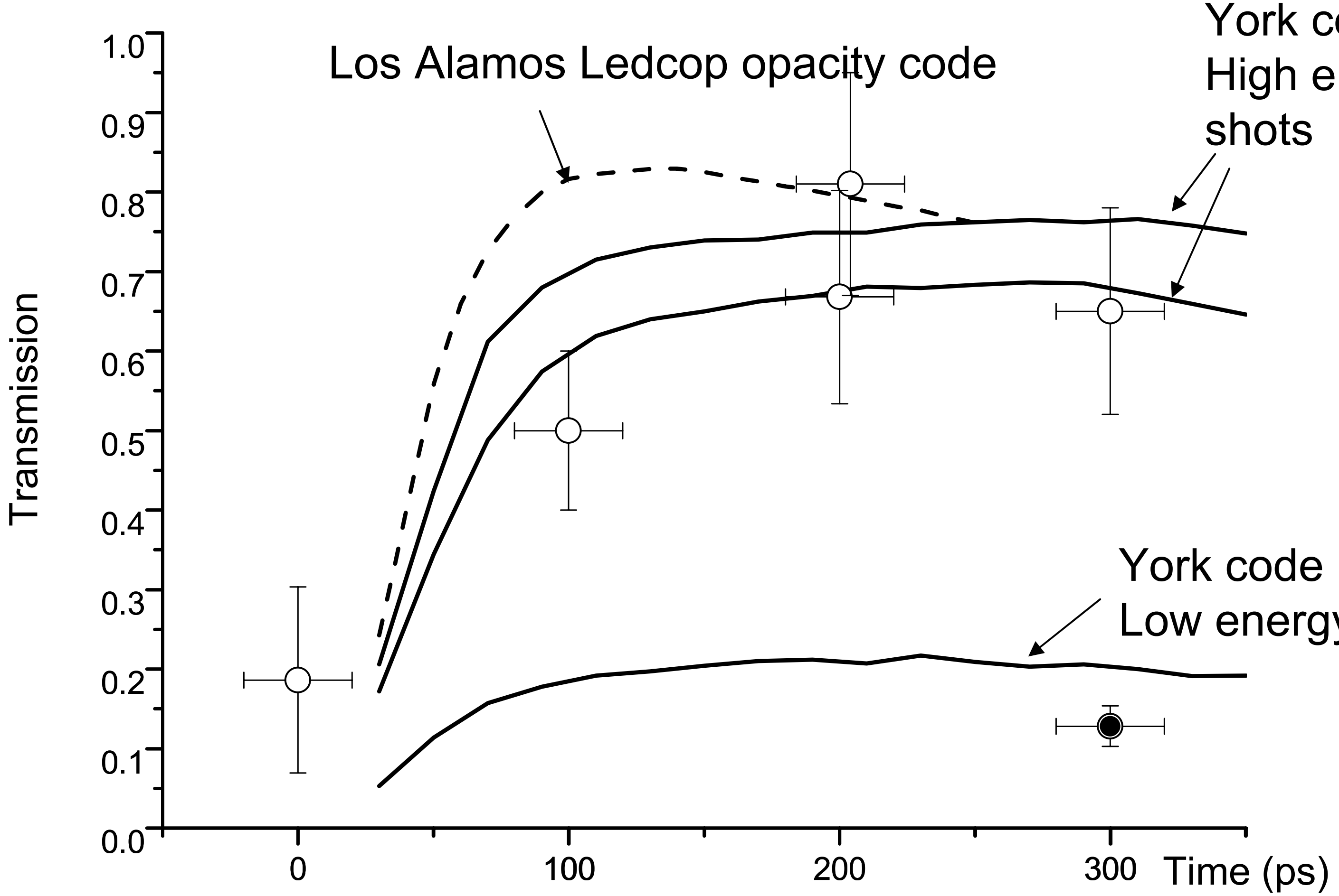
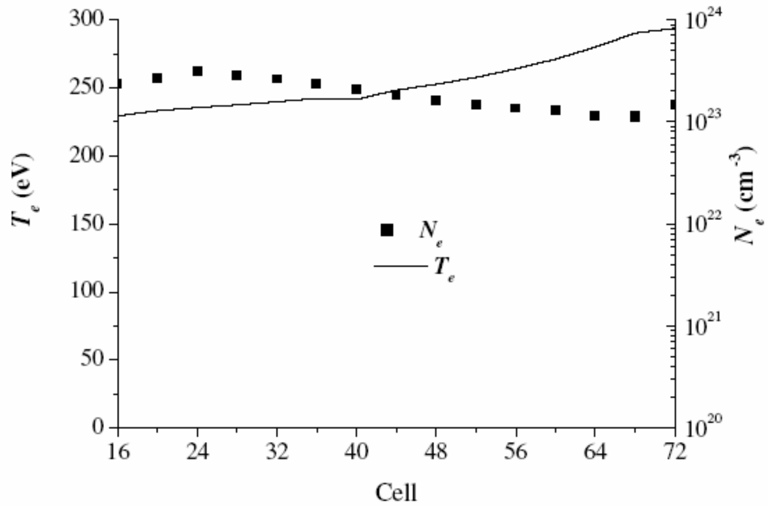
Transmission at 89 eV through iron irradiated by a laser pulse

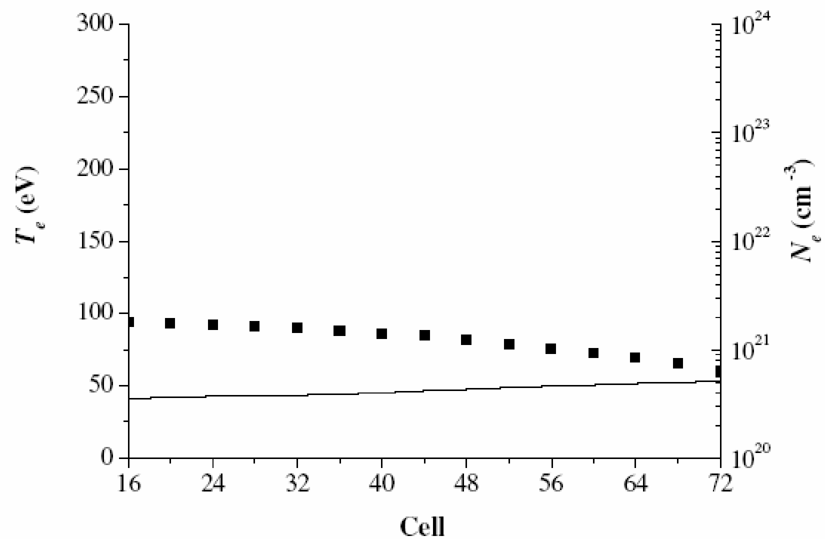


50 ps temporal resolution

Short pulses produce uniform plasmas in buried layer targets



Time 4 ps



Time 100 ps

Variation of electron temperature and density in an initially 50 nm thick Fe layer tamped by 20 nm CH irradiated by 4 x 10^{17} Wcm^{-2}, 3 ps pulse as simulated by the Ehybrid code at times shown.

Demonstration experiment that could be carried over to FELs

Measurements of opacity and temperature of warm dense matter heated by focused soft x-ray laser irradiation

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In press:
High Energy Density Physics

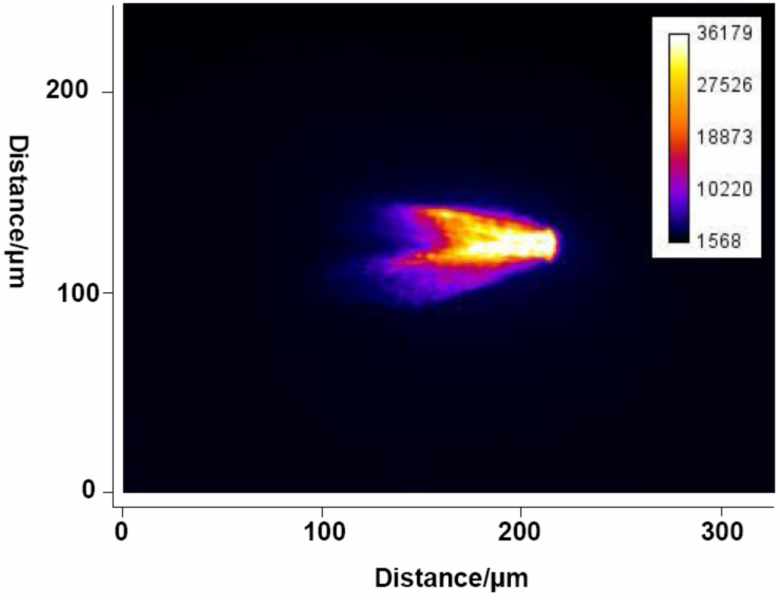
Abstract

The transmission of plasma-based soft x-ray lasers through thin targets can be used to measure the target opacity. Measurements of warm dense matter transmission obtained using a focused 59 eV photon energy laser irradiation on thin targets of polyimide ($C_{22}H_{10}N_2O_5$) and aluminum are shown to produce simultaneous heating and probing enabling opacity and temperature measurements of warm dense matter. It is shown that the opacity of the warm dense matter considered in the experiments follows closely tabulated cold 'room temperature' opacities at temperatures below ~ 10 eV. Transmission measurements of thin iron targets which are highly opaque to the x-ray laser radiation are also presented.

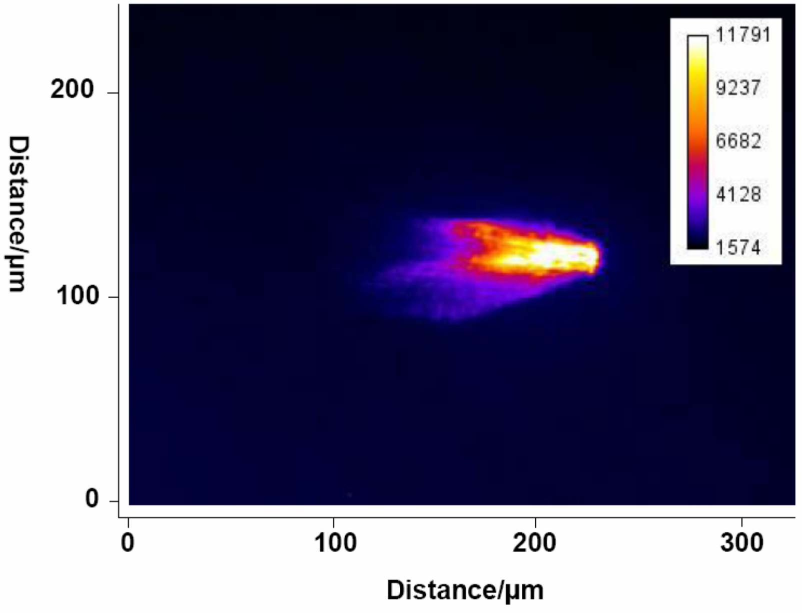
***Keywords*:** plasma, opacity, x-ray laser
***PACS*:** 52.25.Os, 52.70.Kz,78.20.-e

Transmission of **focussed** moderate irradiance EUV laser thru Al target – simultaneous heating and diagnosis

90 ps pulses, 59 eV photon energy



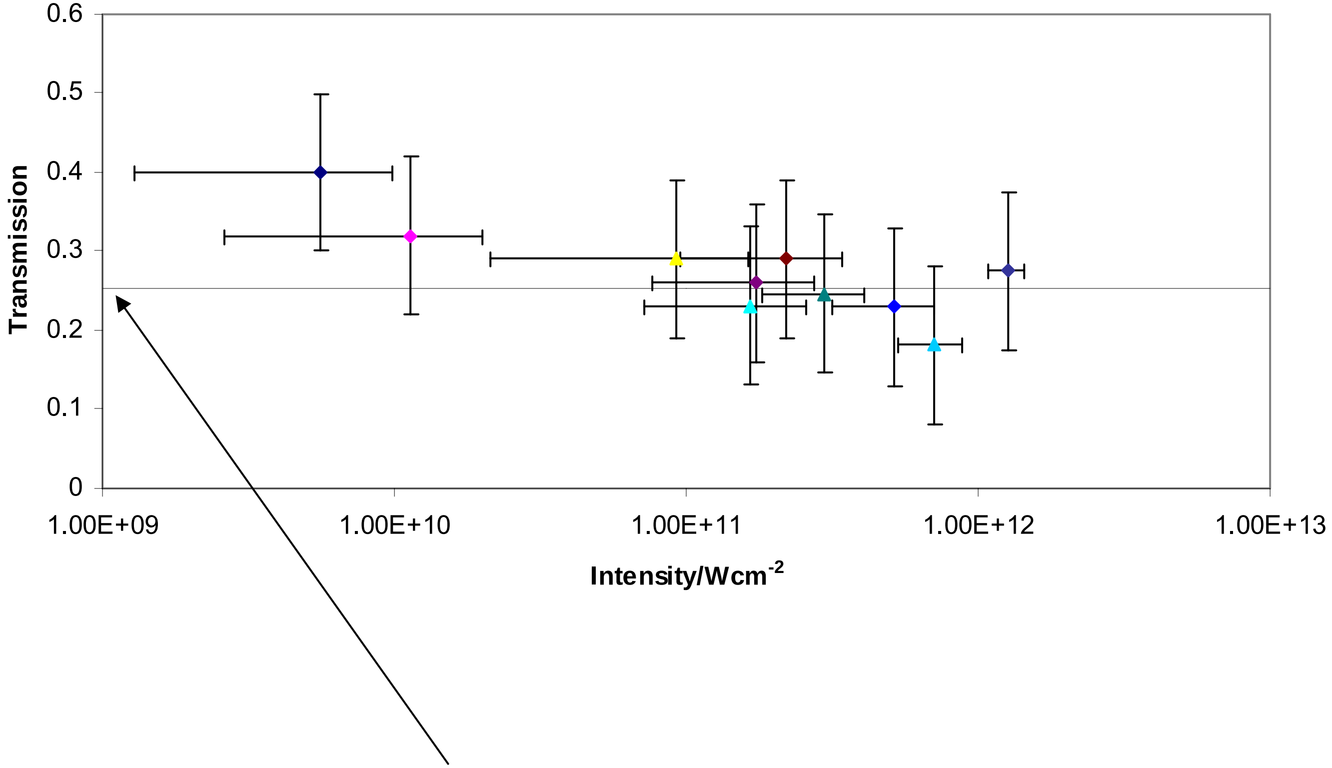
Footprint of x-ray laser
at focus position (no target).



Footprint of x-ray laser
transmission through
500 nm Al target.

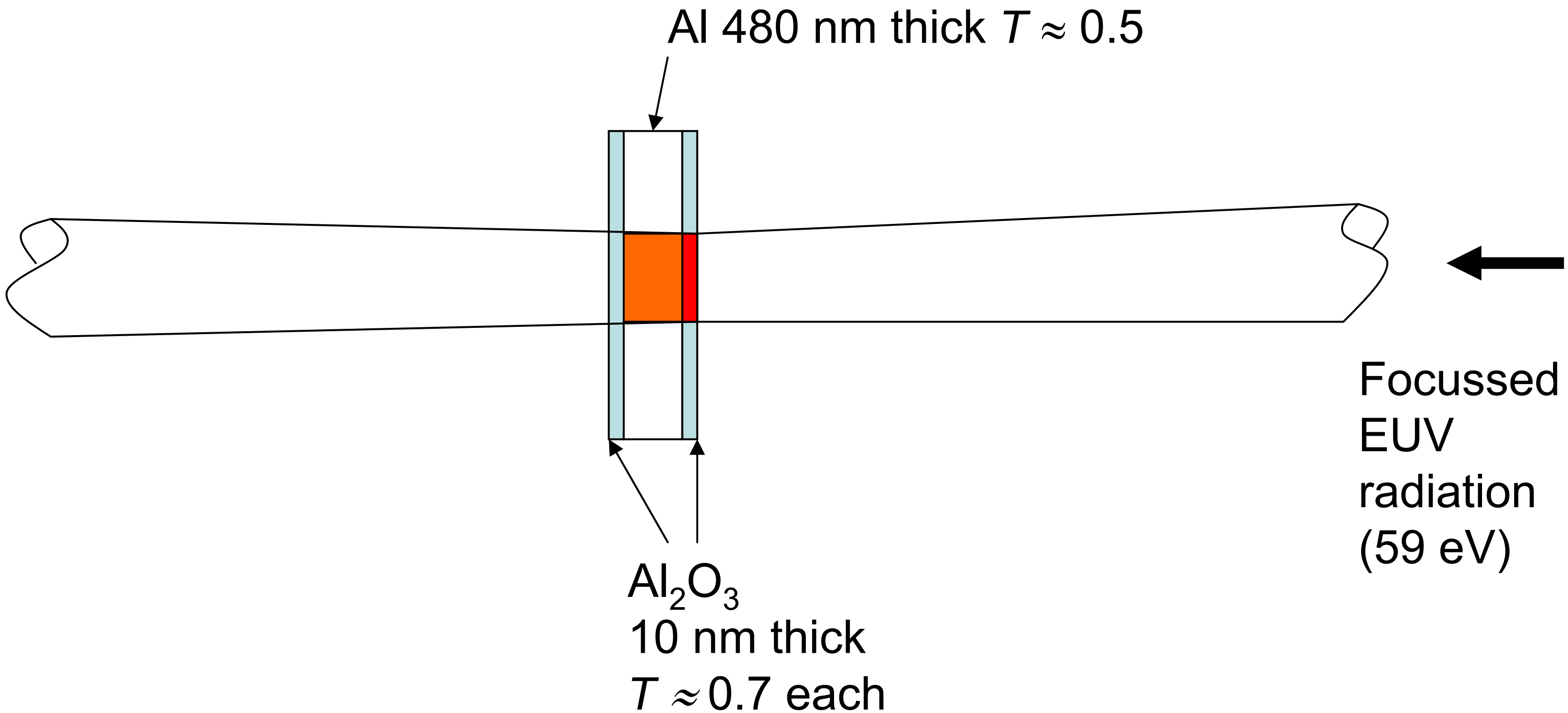
No additional optical laser heating

Transmission of 23.1 nm focussed EUV radiation through Al as a function of EUV irradiance



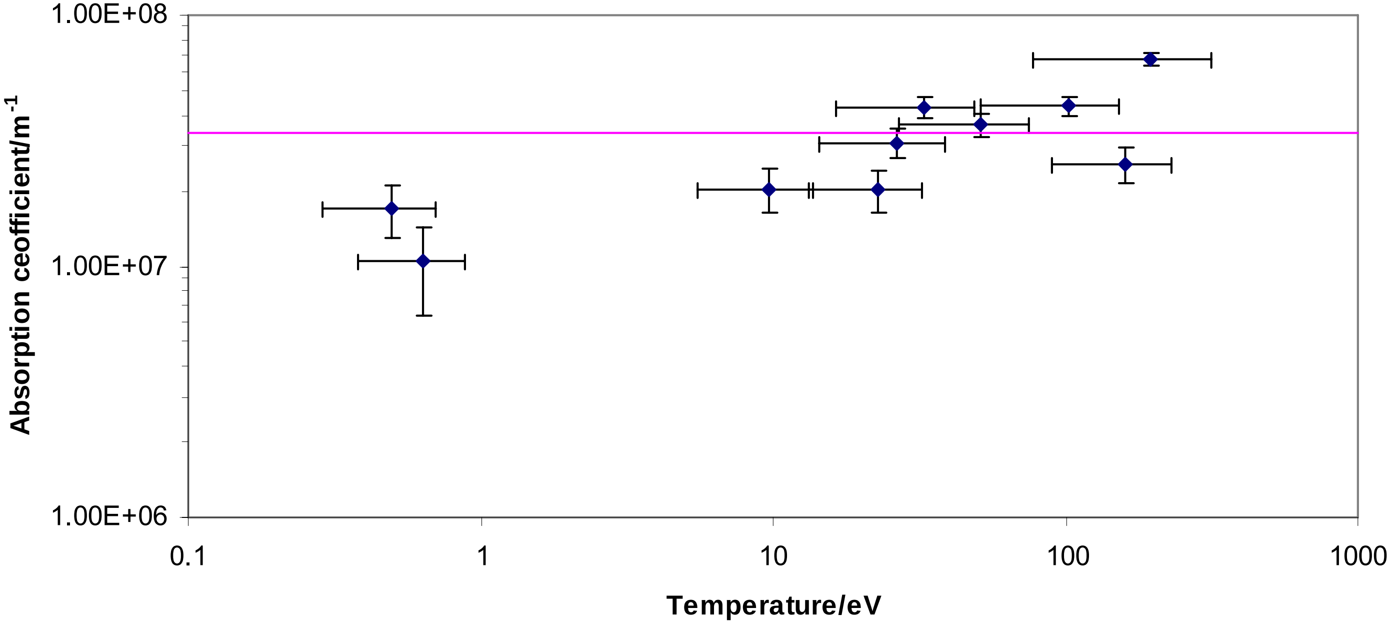
Transmission solid 480nm Al + 20nm Al_2O_3 T=0.25344

Al targets have 3 layers – complicates transmission probing

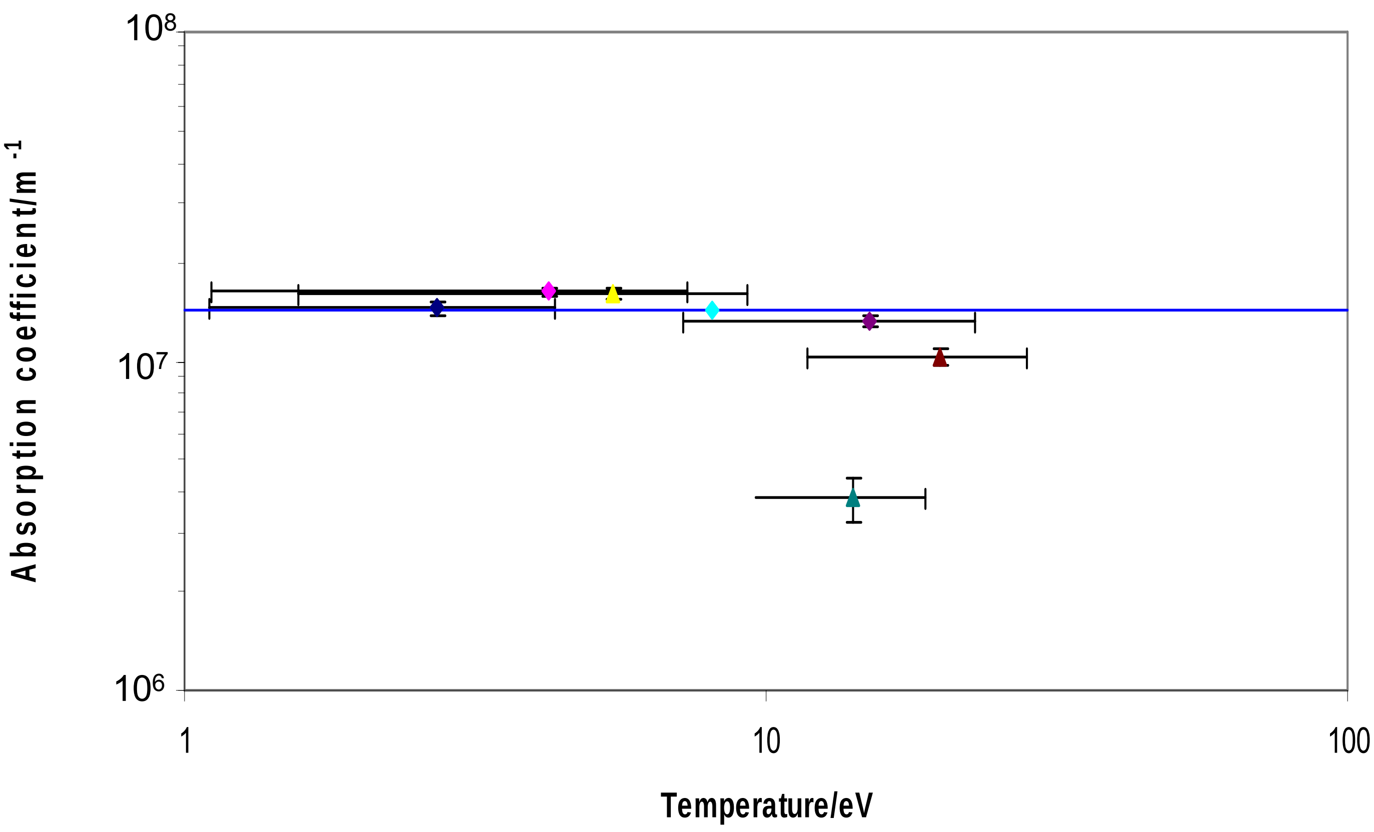


Front Al_2O_3 layer heats to the highest temperature

Absorption coefficient of Al_2O_3 as a function of temperature



Absorption coefficient of polyimide as a function of temperature as heated by EUV laser



To interprete opacity experiments, simulation capability is required

Submitted to MNRAS.

Iron Opacity Predictions under Solar Interior Conditions:

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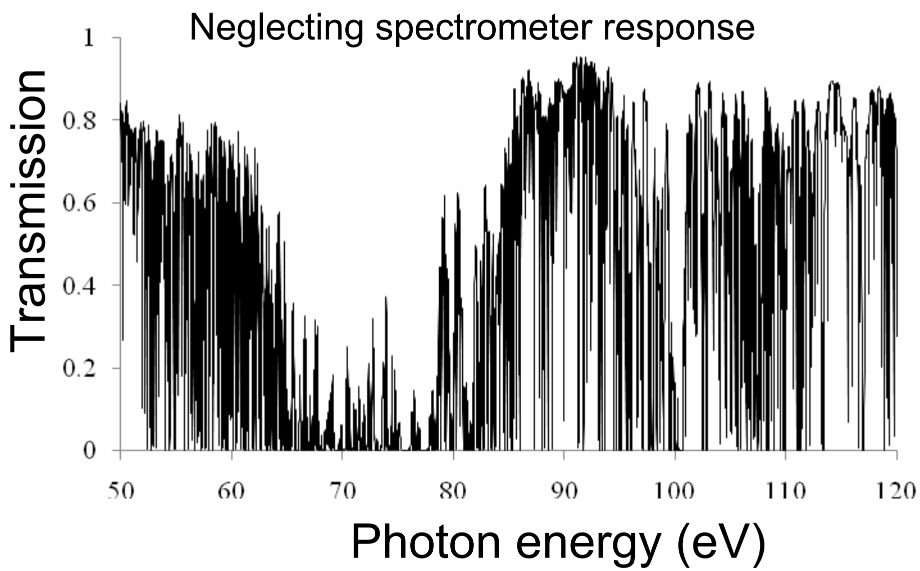
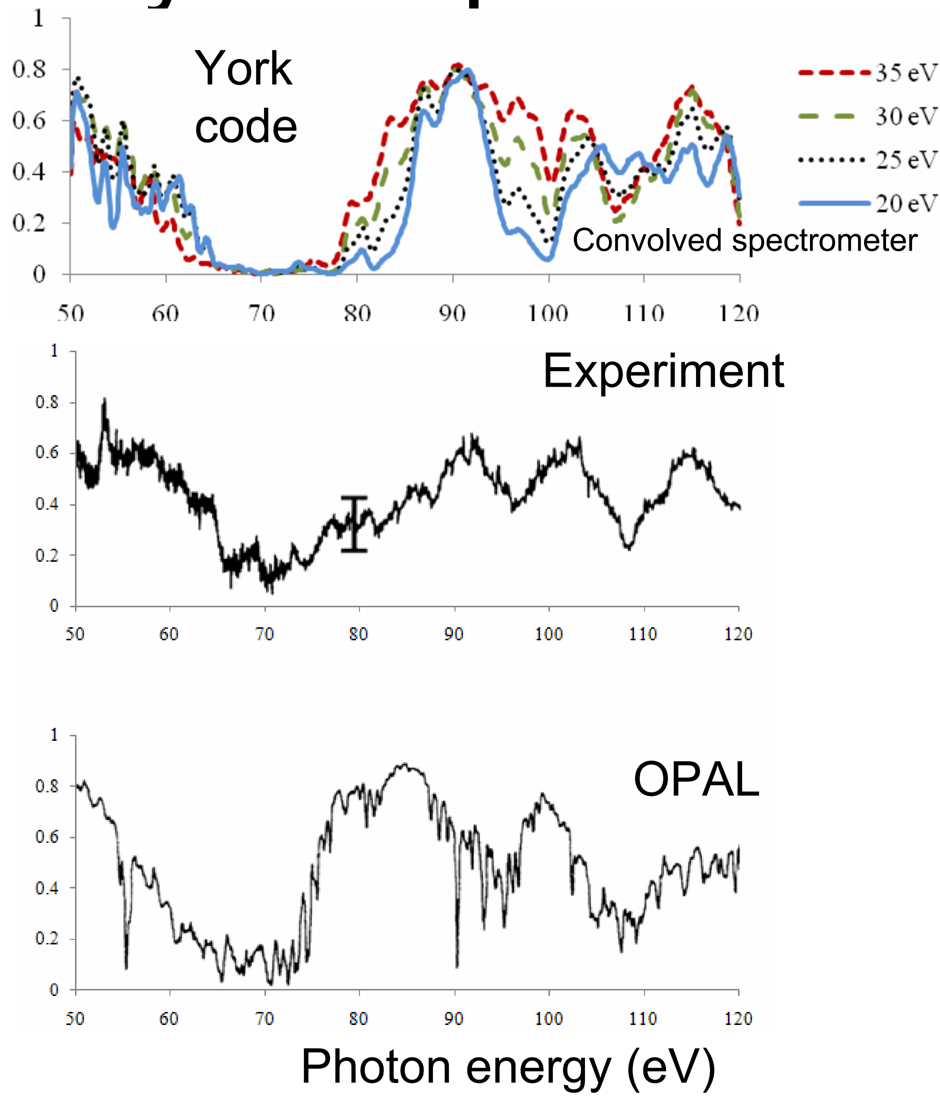
ABSTRACT

Iron opacity predictions over an extended spectral range are obtained with a model using Opacity Project atomic data for conditions within the solar convective zone. These predictions are compared with the published results of a laboratory experiment using a laser-plasma backlighter. The effect of differing line broadening treatments on monochromatic and the Rosseland mean opacity is also investigated.

Key words: atomic processes – radiative transfer – stars: interiors.

To interprete opacity experiments, simulation capability is required



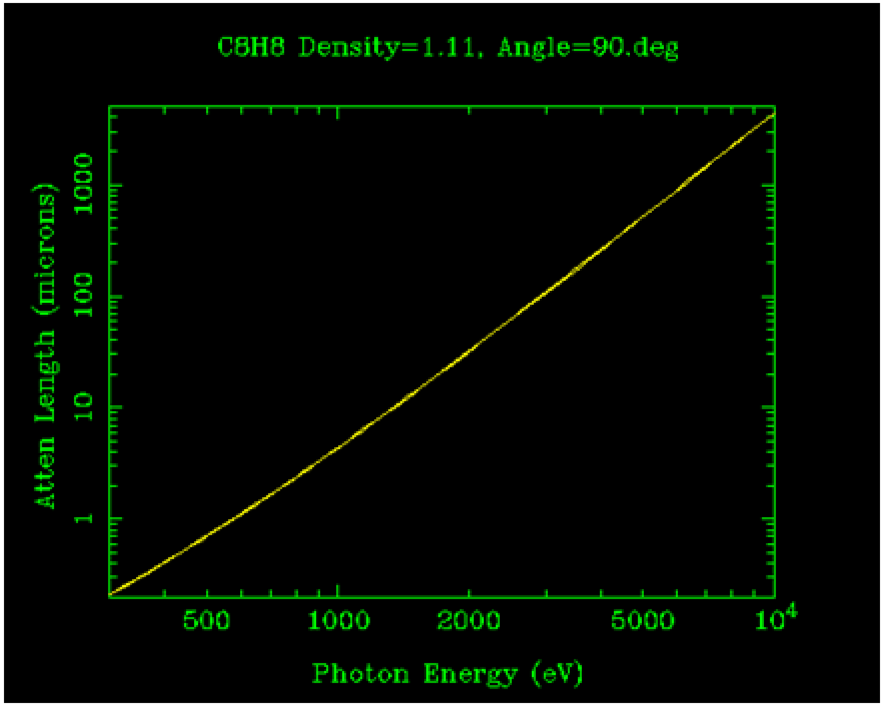


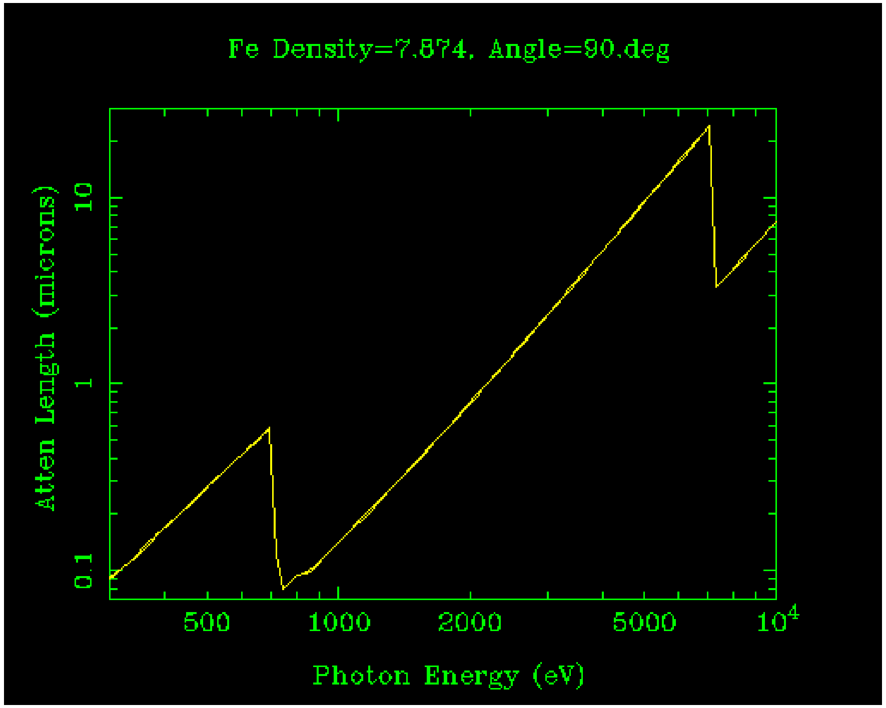
The York opacity code (using Opacity Project data) is used to simulate the experimental results of Da Silva et al (PRL **69**, 438, 1992)

Probing a plasma with XFEL

- Harmonics could be used to probe plasma opacity at several frequencies.
  - WDM experiments without separate optical laser heating
  - Hot plasma measurements with separate optical heating.
- XFEL could be used to launch a Marshak wave? Propagation gives opacity and heat capacity.

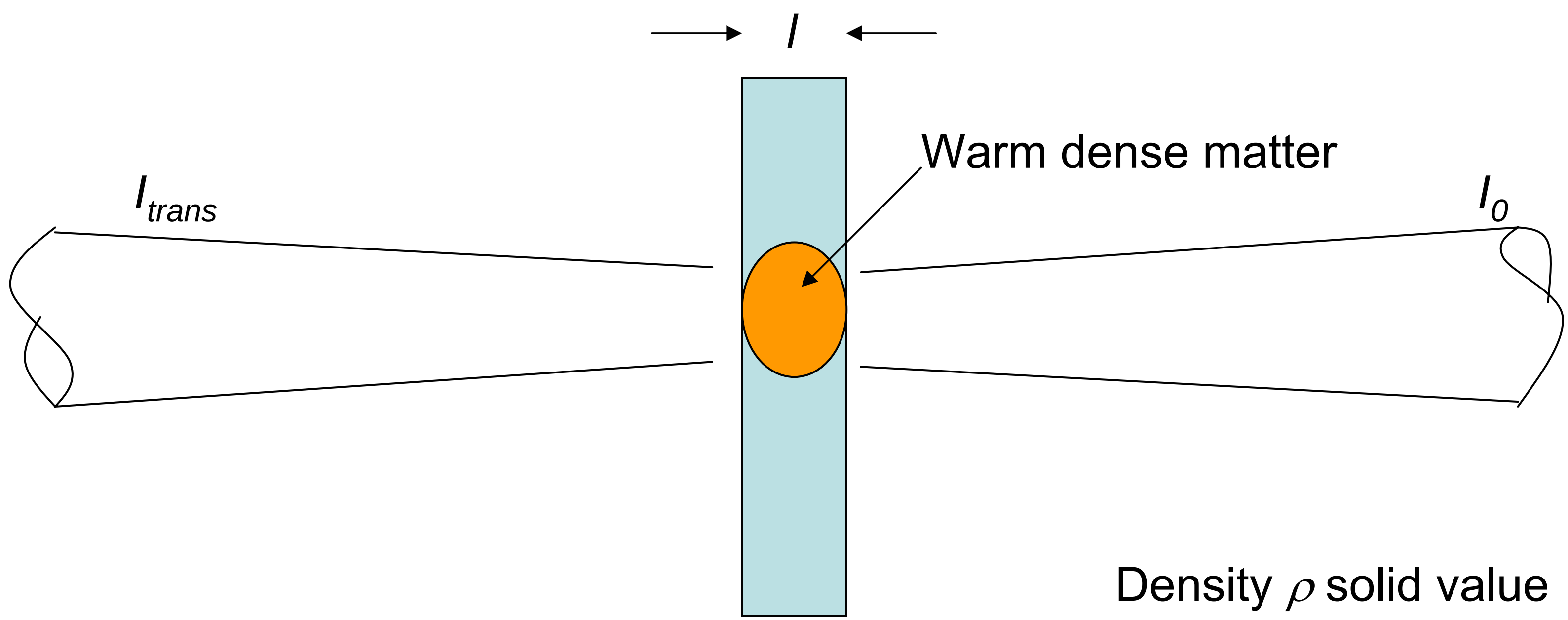
FEL radiation will be highly penetrative





High penetration depth and moderate energy → warm dense matter is produced by x-ray laser heating. To produce high temperature matter, an optical heating (short pulse) laser will be required.

A simple FEL transmission measurement gives the material opacity at solid density (with a good estimate of temperature)



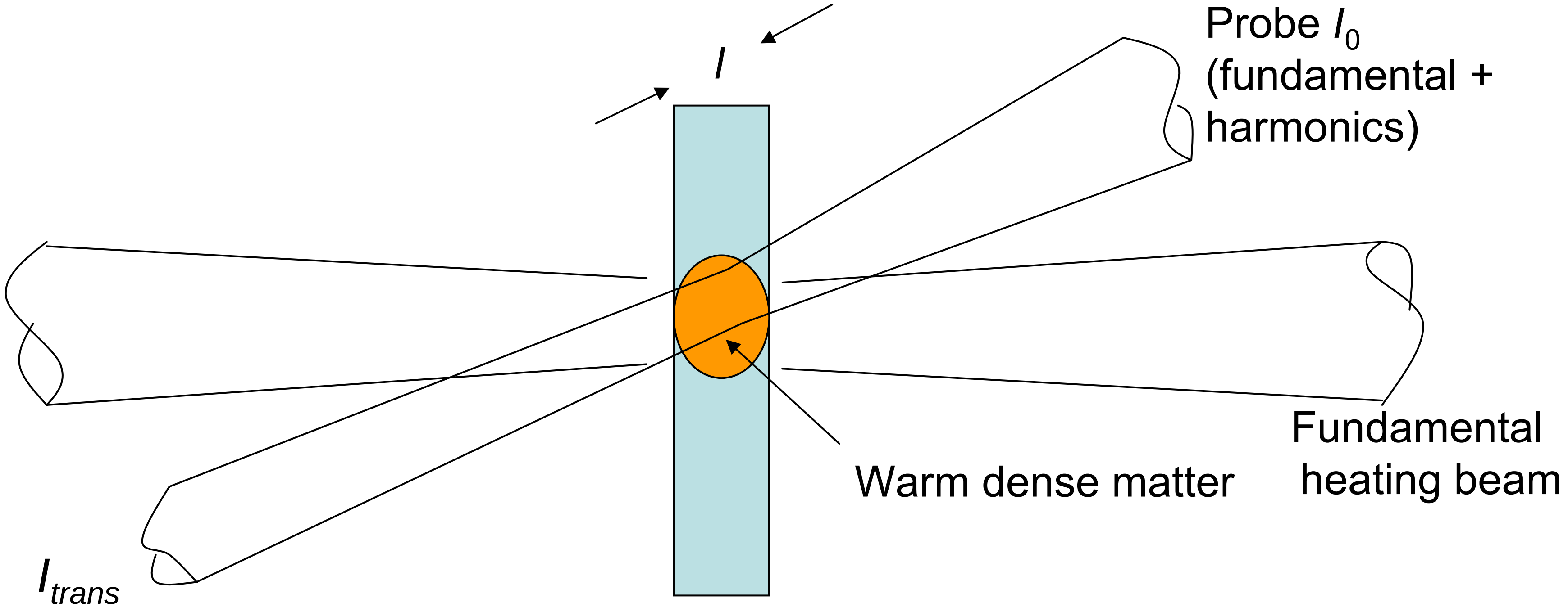
Density ρ solid value
Opacity σ measured

$T = I_{trans}/I_0 = \exp(-\sigma\rho l)$

Temperature of the solid material can be calculated from the transmission T (assuming a knowledge of the material heat capacity).

Can produce the beam with FEL and probe with FEL

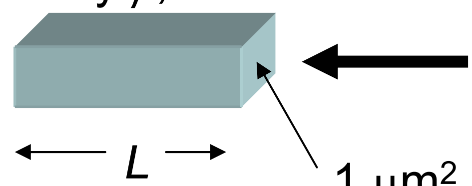
The effect of the heating variation during the pulse is removed by sampling with a FEL probe



$T = I_{trans}/I_0 = \exp(-\sigma\rho l)$

Density ρ solid value
Opacity σ measured

Estimation of XFEL direct heating



Number of heated particles = $10^{16} L\rho/(1.67M)$

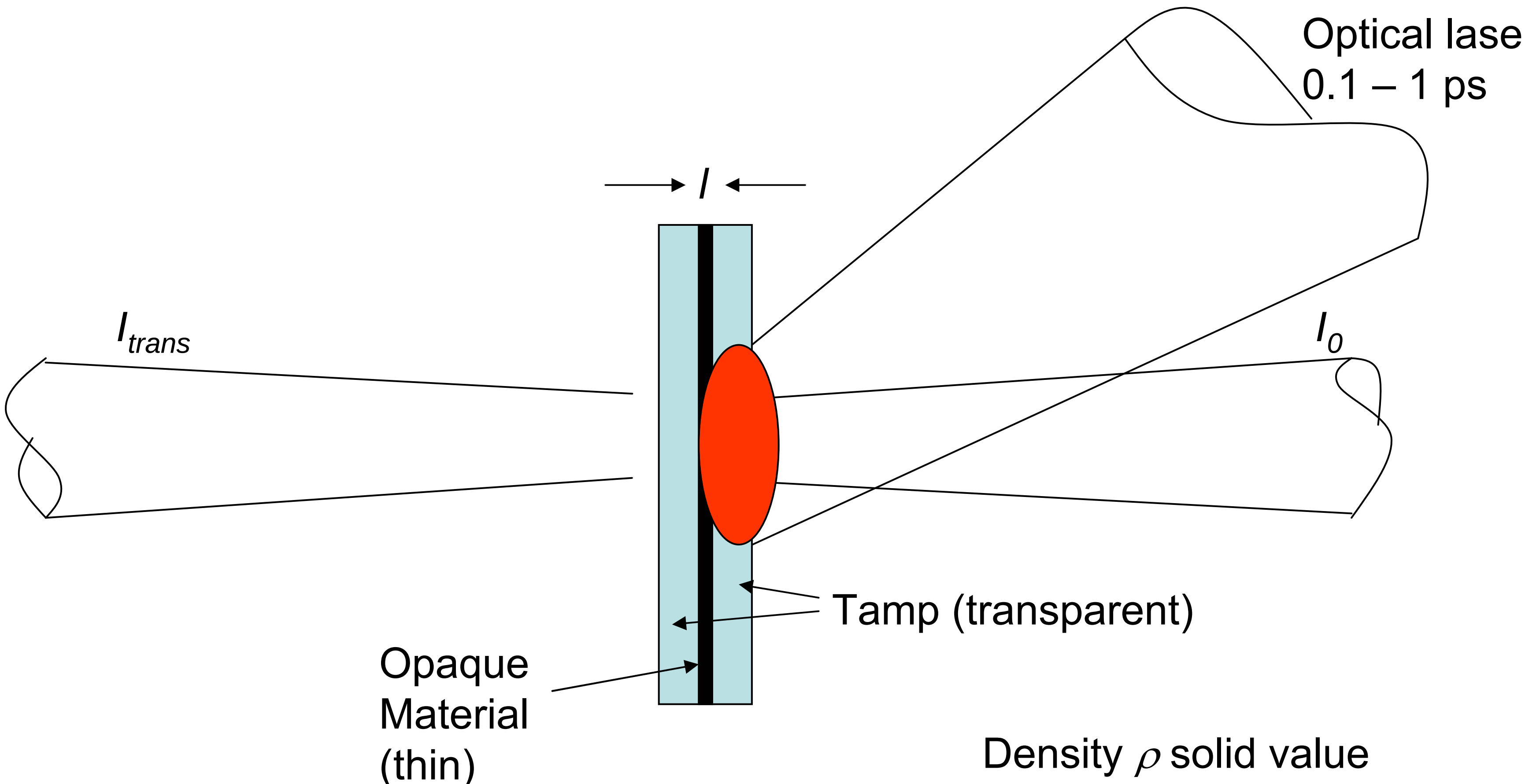
Heat capacity/particle $\approx 3kT$ (neglecting phase changes and ionization)

$$\Rightarrow \quad T \text{ (in eV)} = \frac{E_{FEL} \text{ (in mJ)} \times M}{3L\rho}$$

Fe T = 2 keV (L = 1 μm) CH T = 20 eV (L = 100 μm)

$\Rightarrow$ Short pulse optical laser is needed to heat low Z material to high temperature

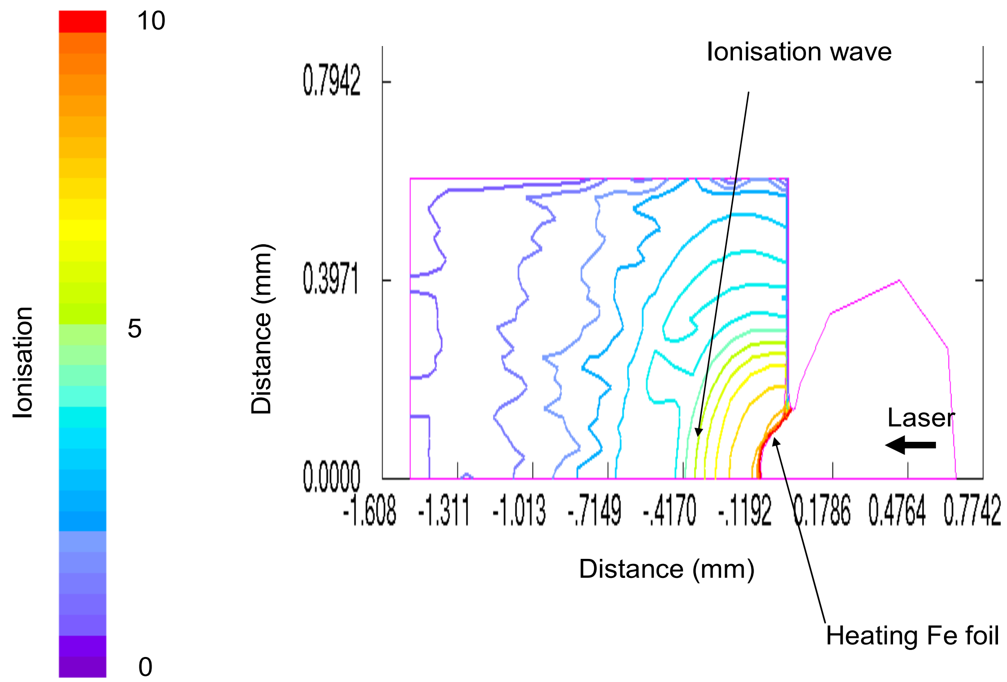
Can probe plasma produced by an optical laser



Density ρ solid value
Opacity σ measured

$T = I_{trans}/I_0 = \exp(-\sigma\rho l)$

Propagation velocity of an ionisation wave can give the Rosseland mean opacity



Could launch a Marshak wave

Ionisation wave in Ne
- Simulated by h2D (John Pasley).

Conclusions

- Warm dense matter opacity can be measured from FEL transmission.
- Hot plasma opacity will require a short pulse heating laser. Targets need to be thin (and tamped) for uniformity.
- May be possible to launch Marshak waves for a measurement of the Rosseland mean opacity.