Ultra-fast melting of carbon induced by intense proton beams

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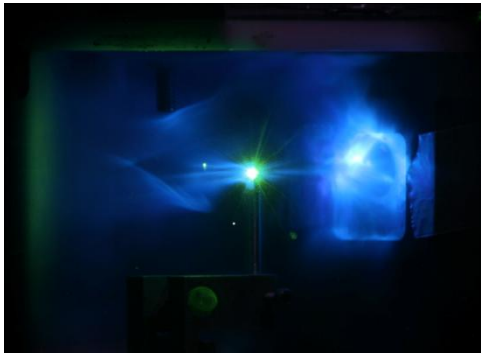
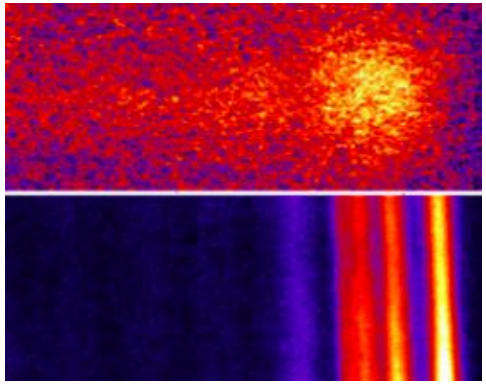
Laser teams: Vulcan Petawatt (RAL) &
Trident (LANL)

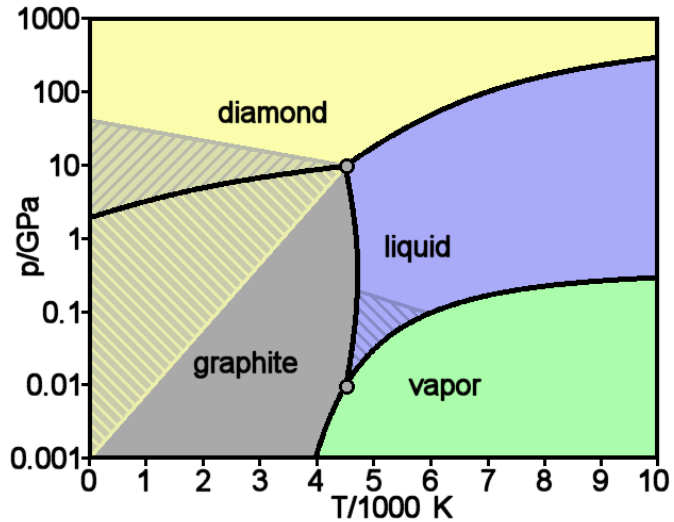




Motivation

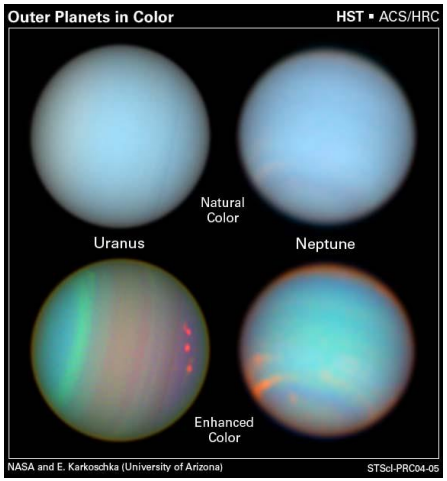
Carbon: common element on earth
Phase diagram including melt line is poorly understood

Pressure-Temperature Phase Diagram of Elemental Carbon,
F.P. Bundy, Physica A 156, 169 (1989).
A Model for Pulsed Laser Melting of Graphite,
J. Steinback et al., J. Appl. Phys. 58 (11), 4374 (1985)



Liquid state – pressure → directly sublimes into gas phase

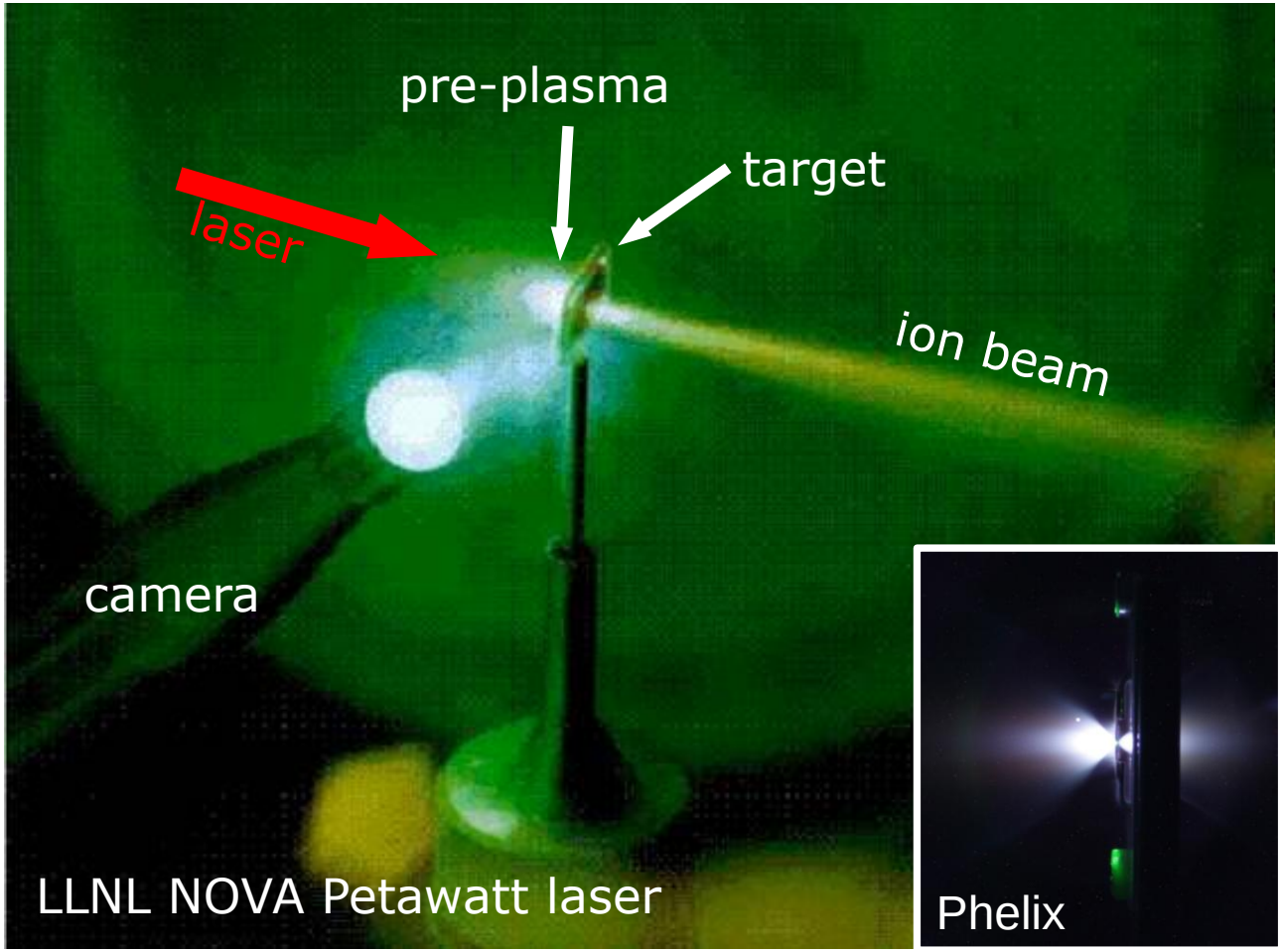
http://hubblesite.org



Develop realistic models for planetary formation
Describe the structure of giant planets (Uranus, Neptune)
→ accurate EOS data

Fluid carbon: rapid energy input, no expansion
High particles numbers in a short time (10^{11} in 10-100 ps)
→ **laser-accelerated protons**
Dense matter opaque to visible light → **x-ray scattering**

Laser ion acceleration - TNSA



$$I\lambda^2 > 10^{18}\,\frac{W}{cm^2}\,\mu m^2$$

$$\tau_{laser} < ps$$

$$\left|\vec{E}_{TNSA}\right| > 10^{12}\,\frac{V}{m}$$

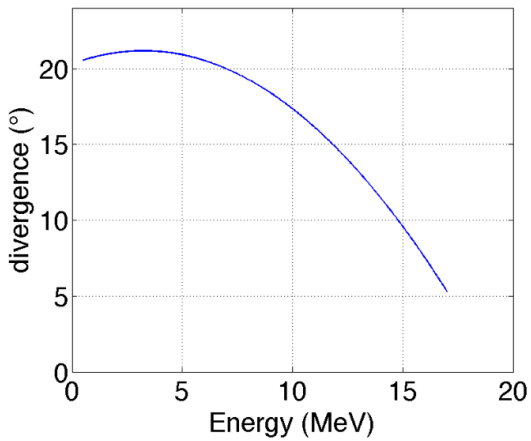
$$N_p \approx 10^{13}\,protons$$

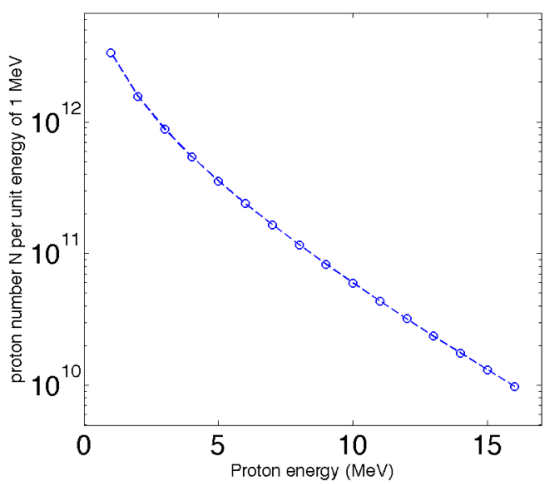
$$I_p \approx kA$$

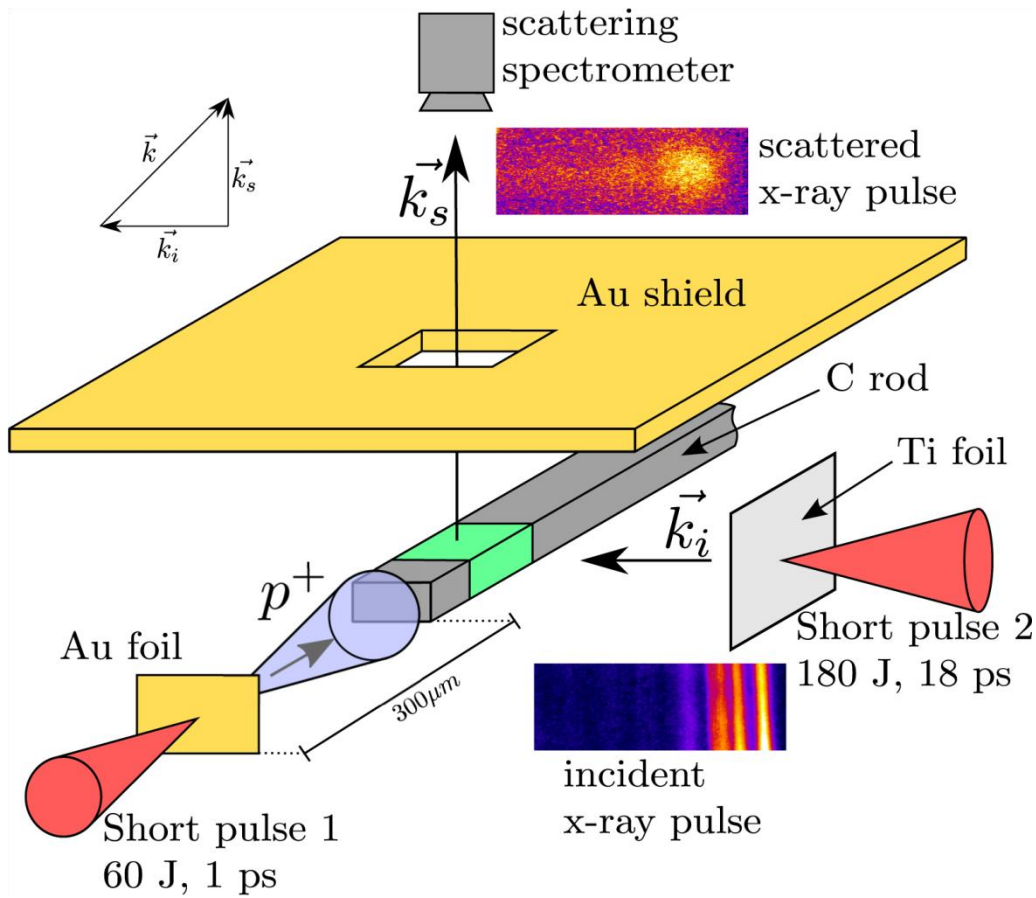
$$E_{p,\max} = 66\,MeV$$

Experiment I

Vulcan Laser Facility, Rutherford Appleton Laboratory, UK







Proton heating of matter

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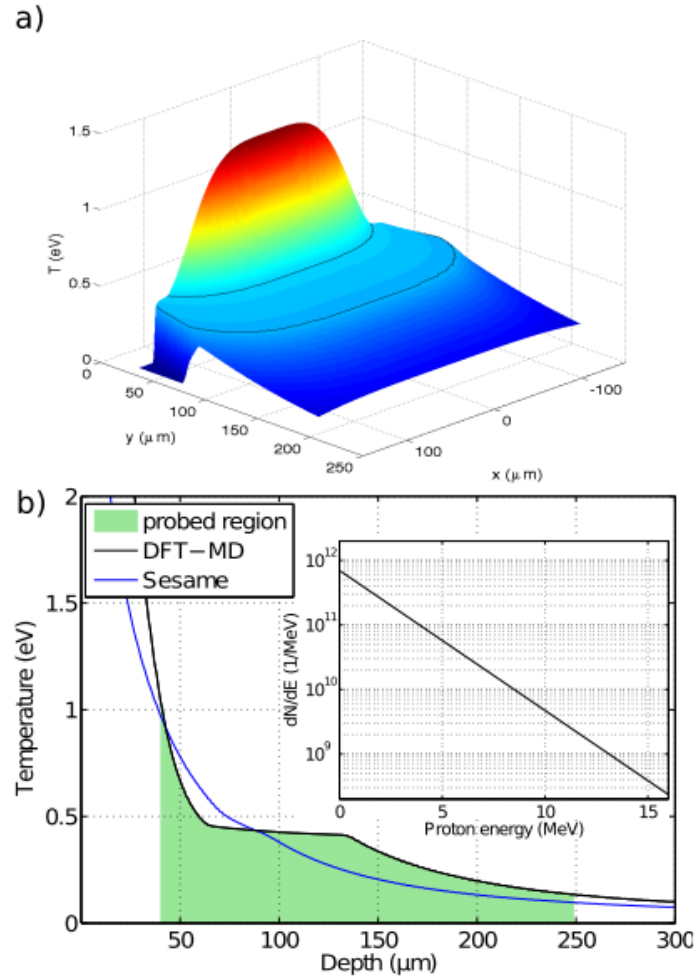
protons traveling through matter mainly ionize atoms, thus gradually loosing their energy in small steps

Temperature profile of Carbon, heated by laser generated protons

Multi2D (energy deposition) with
- **SESAME** library and
- EOS of density functional molecular dynamics (**DFT-MD**) simulation



X-Ray Thomson Scattering

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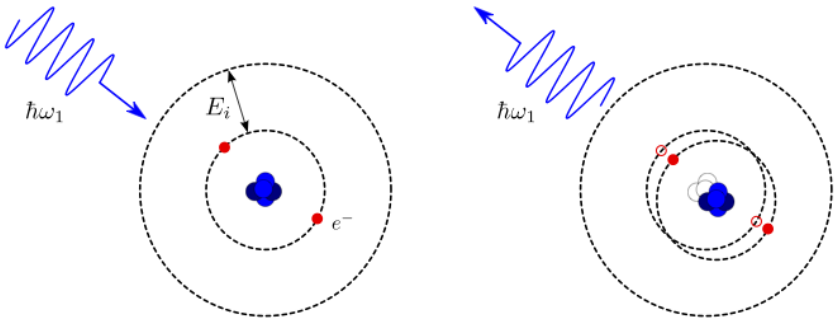
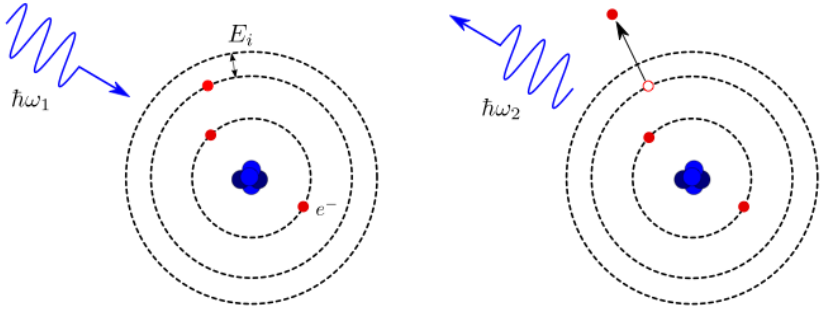
elastic scattering



inelastic scattering



total scattering cross section can be described by the total dynamic structure factor S(k,ω):

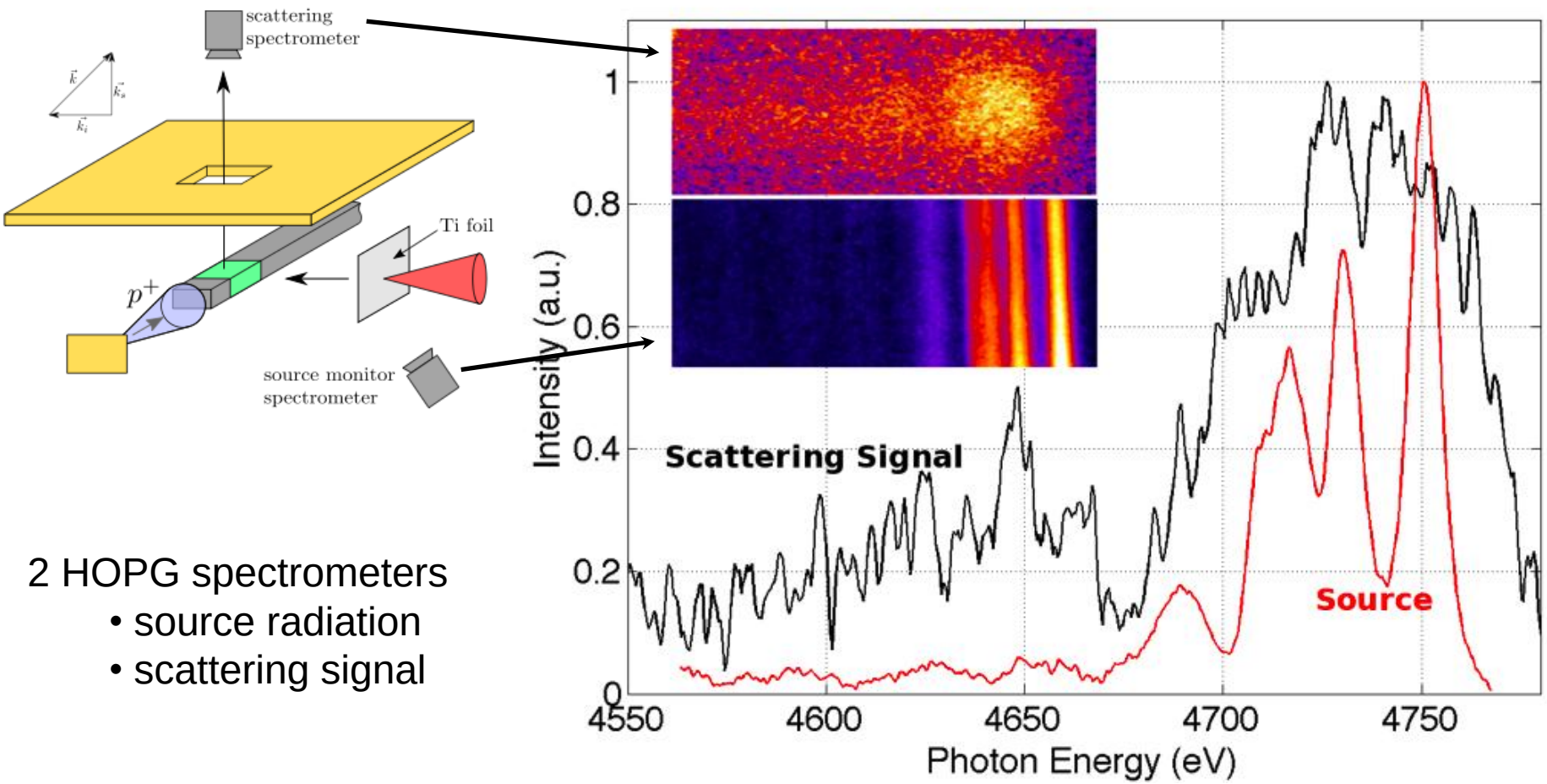
$$\frac{d^2\sigma}{d\Omega d\omega} = \sigma_T \frac{k_s}{k_i} S(k,\omega)$$

which can be written as a sum of the components related to the different scattering:

$$S(k,\omega) = |f+q|^2 S_{ii}(k,\omega) + Z S^0_{ee}(k,\omega) + S_{bf}(k,\omega)$$

elastic inelastic + bound-free

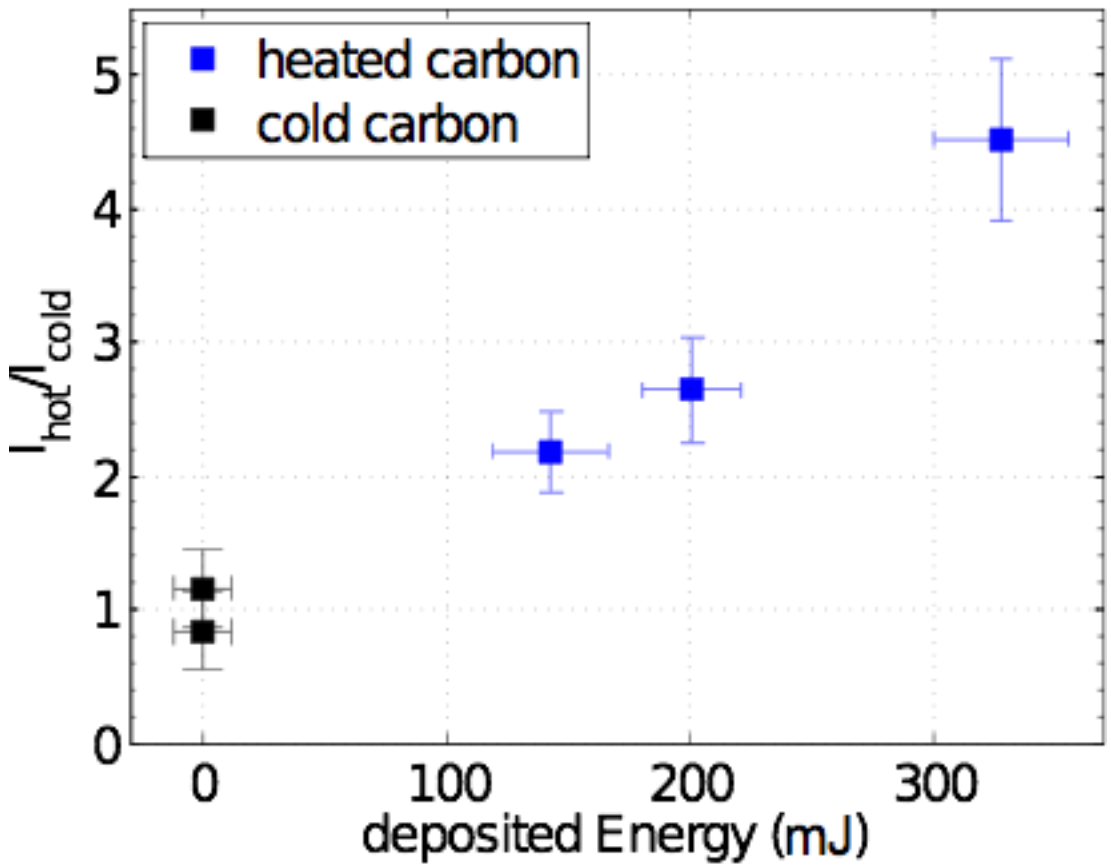
Results



2 HOPG spectrometers

- source radiation
- scattering signal

Results


heated carbon
cold carbon
I_{hot}/I_{cold}
0
1
2
3
4
5
0
100
200
300
deposited Energy (mJ)

Comparison between experimental data and theory

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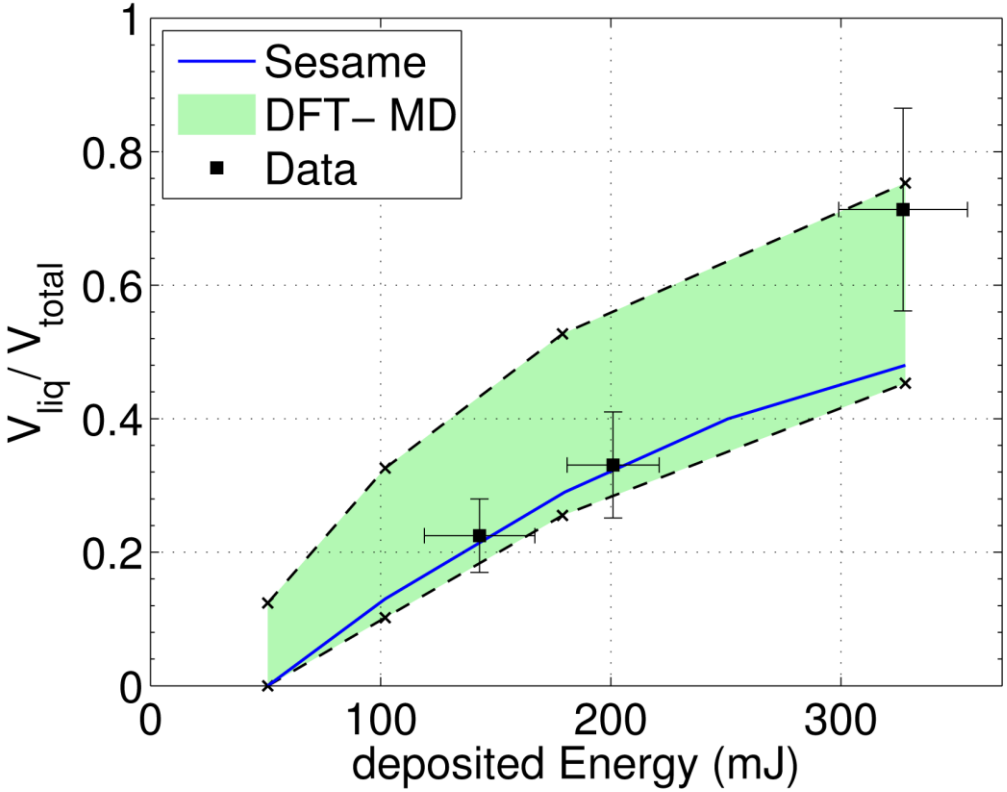
Liquid fraction of the sample, deducted from scattering data and calculated with Multi2D (SESAME)



from theory

from scattering data

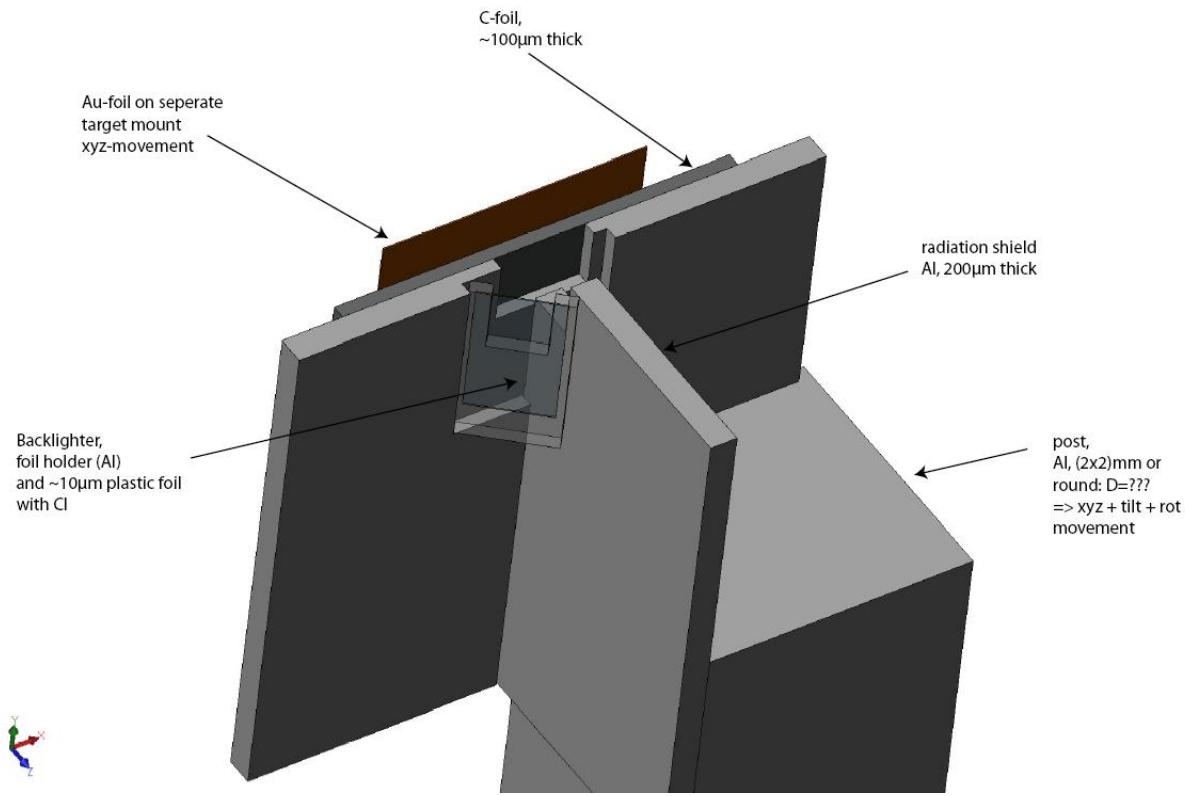
from absolute measurement of cold signal

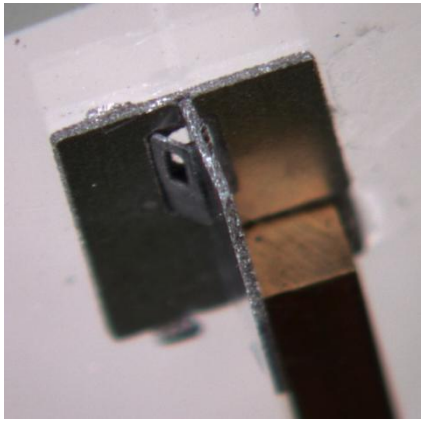
$$\frac{V_{liq}}{V_{tot}} = \left(\frac{I_{hot}}{I_{cold}} - 1\right)\left(\frac{f^2 S_{ii} + Z_C(1 - f^2/Z_C^2)}{S_s} - 1\right)^{-1}$$

Ultra-fast melting of carbon induced by intense proton beams
A. Pelka et al., submitted to Nature Physics

Experiment II

Trident laser facility, LANL, Los Alamos NM, USA





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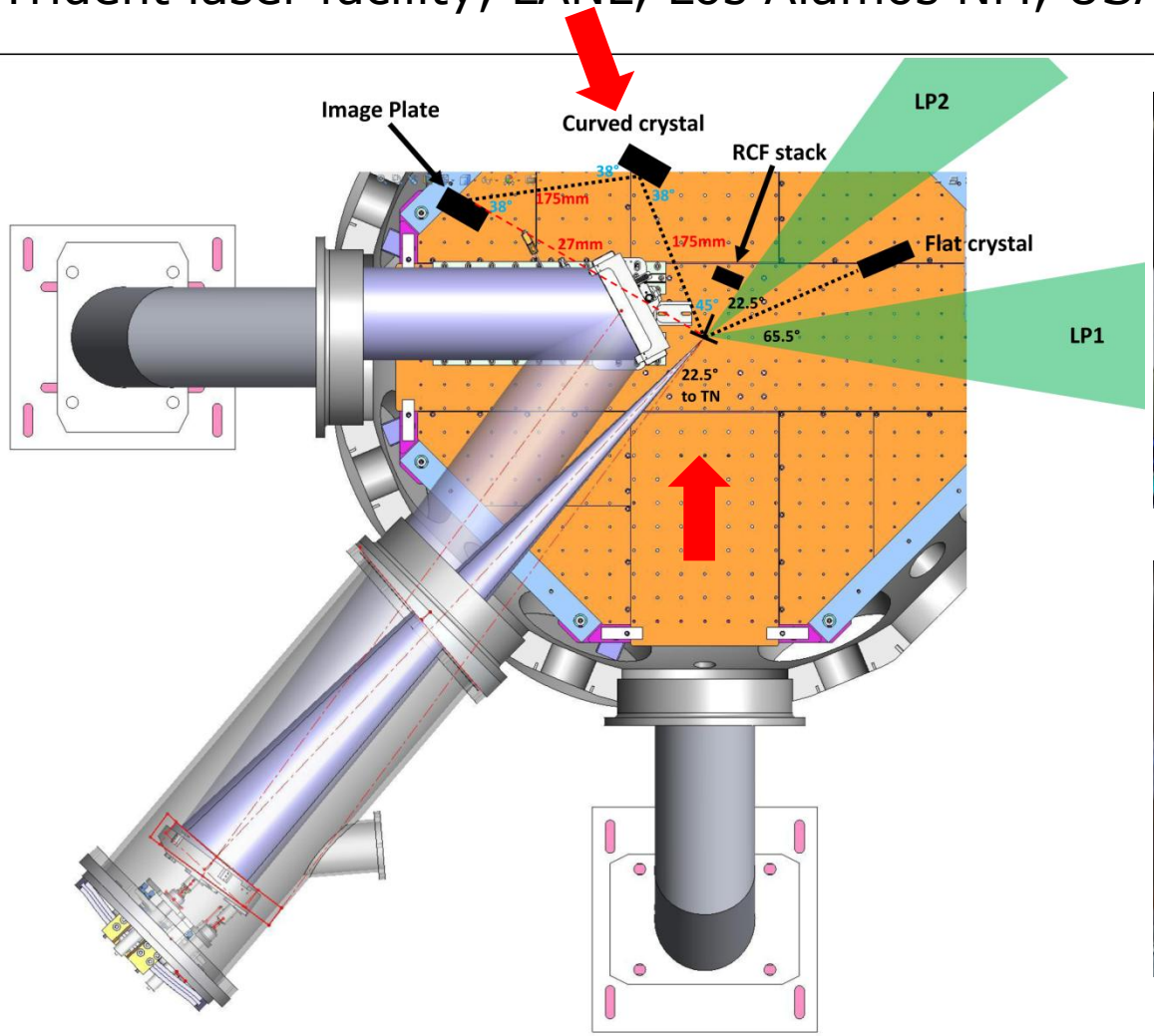
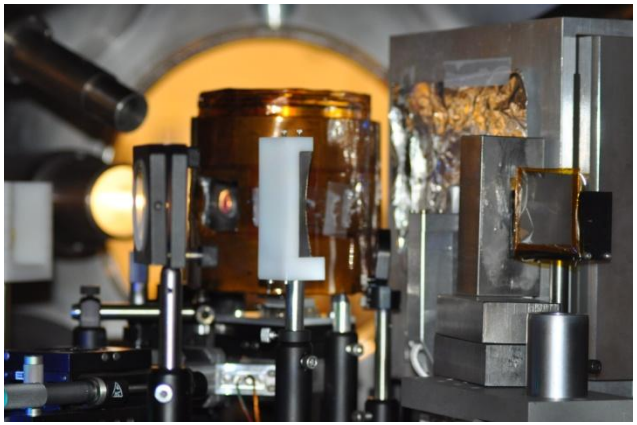
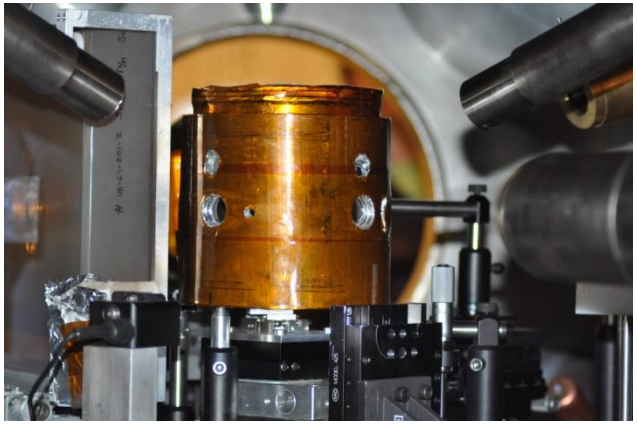
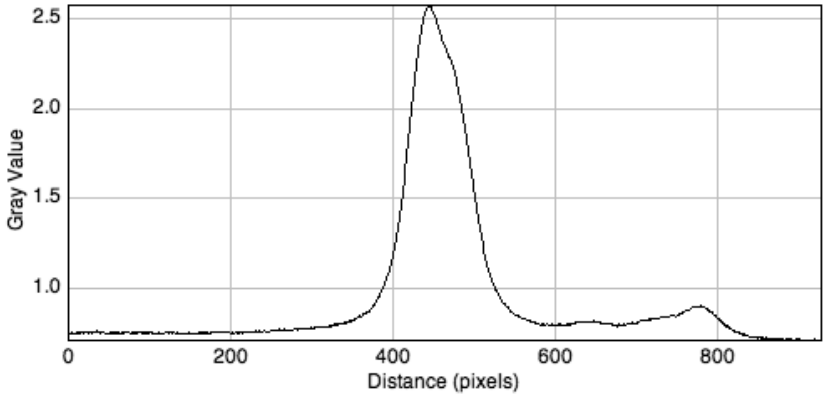


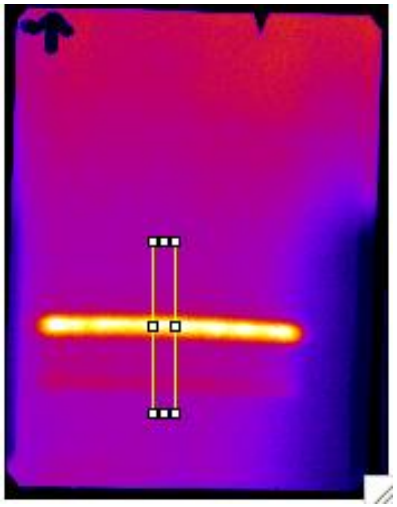


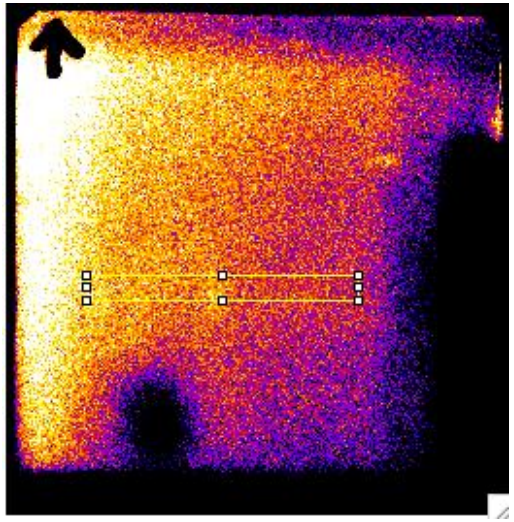


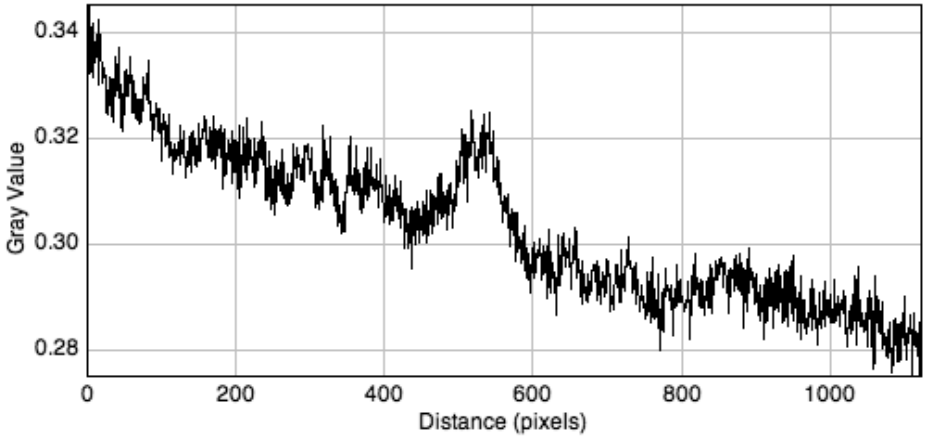
Results

- 75 µm C,
  4.7 µm CHCl,
  20 µm Al
  at 885 µm distance
- 73 J, 700 fs
- 365 J, 1ns 2ω
- 200 ps delay









Flat HOPG:
→ source

Curved HOPG:
→ scatter

Summary & outlook

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- Target and shielding studies
- A macroscopic carbon sample was heated using laser-generated proton beams
- A short pulse Ti He_a x-ray burst was scattered off a defined region of the heated sample
- The liquid fraction of the sample was deduced from the scattering data and compared to simulations
- Next step: Heat carbon with focussed proton beams (hemis, magnets), use stronger x-ray source to measure inelastic electron feature