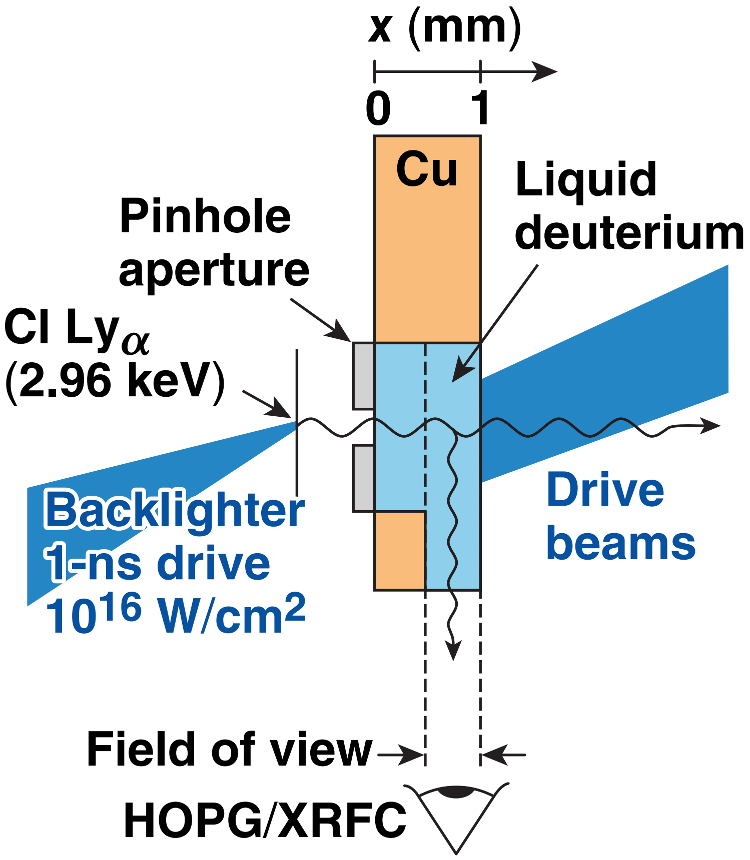
X-Ray Thomson-Scattering: Incisive Probe for Warm, Dense Matter



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Laboratory for Laser Energetics

Omega Laser Facility
Users' Group Workshop
Rochester, NY
25–27 April 2012

Summary

X-ray Thomson scattering* (XRTS) is a primary diagnostic for high-energy-density-physics (HEDP) experiments

- The conditions of dense plasmas are probed with XRTS, especially warm, dense matter with $T_e \sim T_F$ and the ratio of potential energy to kinetic energy of the ions greater than unity
- The elastic and inelastic x-ray scattering features are spectrally resolved
  - scattering from electrons (noncollective) → T_e, Z
  - scattering from plasmons (collective) → n_e
  - elastic scattering → structure of matter
- A review of XRTS experiments is presented
  - inertial confinement fusion (ICF)
  - radiation heated
  - shock heated and compressed
  - proton heated
  - laboratory astrophysics (radiative shocks and planetary interiors)

Many XRTS experiments need spatially resolved spectral measurements.

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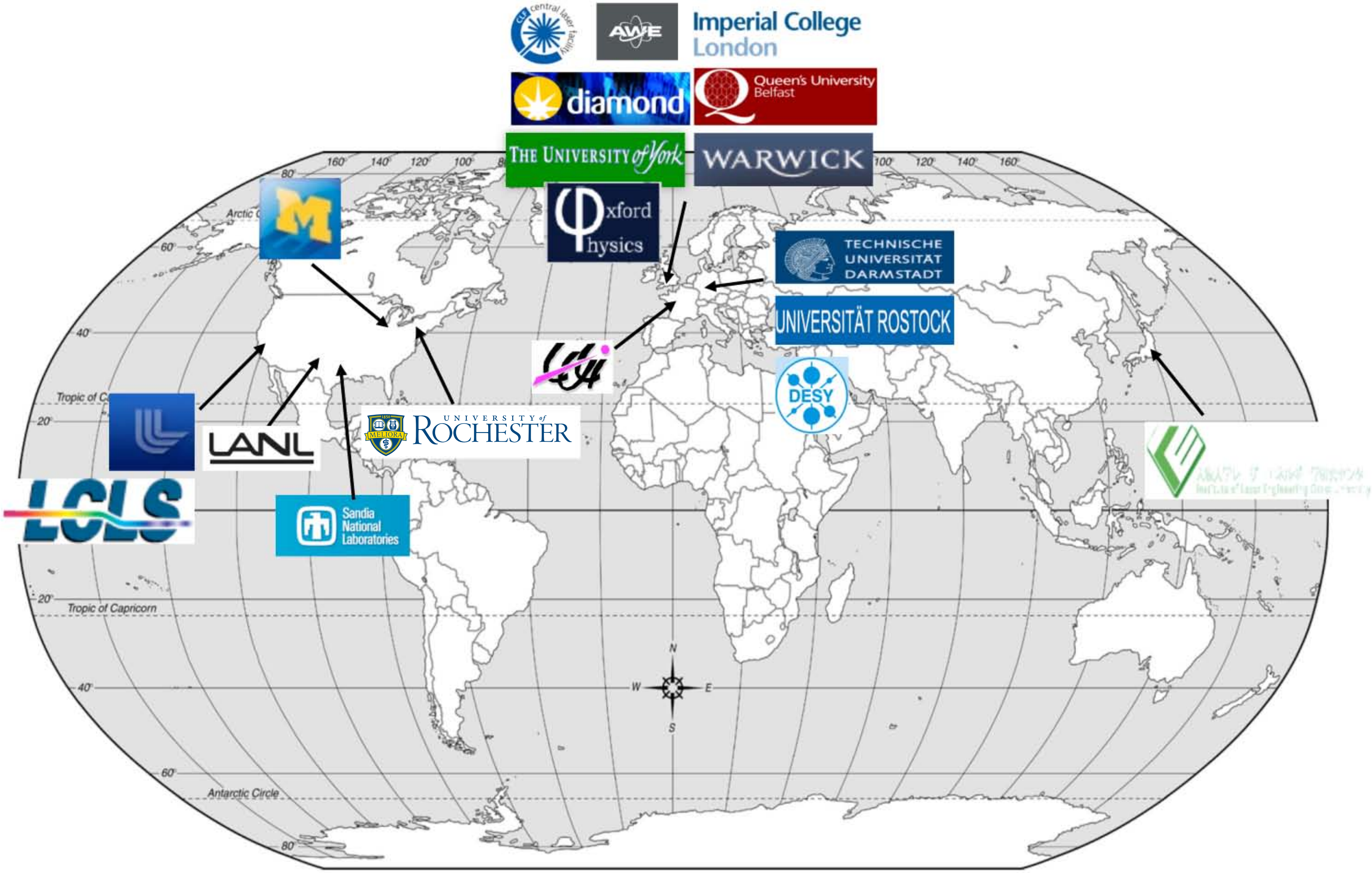
*S. H. Glenzer and R. Redmer, Rev. Mod. Phys. 81, 1625 (2008).
O. L. Landen *et al*., J. Quant. Spectrosc. Radiat. Transf. 71, 465 (2001).
G. Gregori *et al*., Phys. Rev. E 67, 026412(2003).

XRTS research involves many international collaborations



Collaborators for XRTS experiment of shocked liquid deuterium

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B. Crowley,[2,3] S. H. Glenzer,[4] O. L. Landen,[4] D. O. Gericke,[5]
T. Doeppner,[4] D. D. Meyerhofer,[1*] C. D. Murphy,[2] T. C. Sangster,[1]
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[3]Atomic Weapons Establishment, Reading, UK
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Warwick University, Coventry, UK
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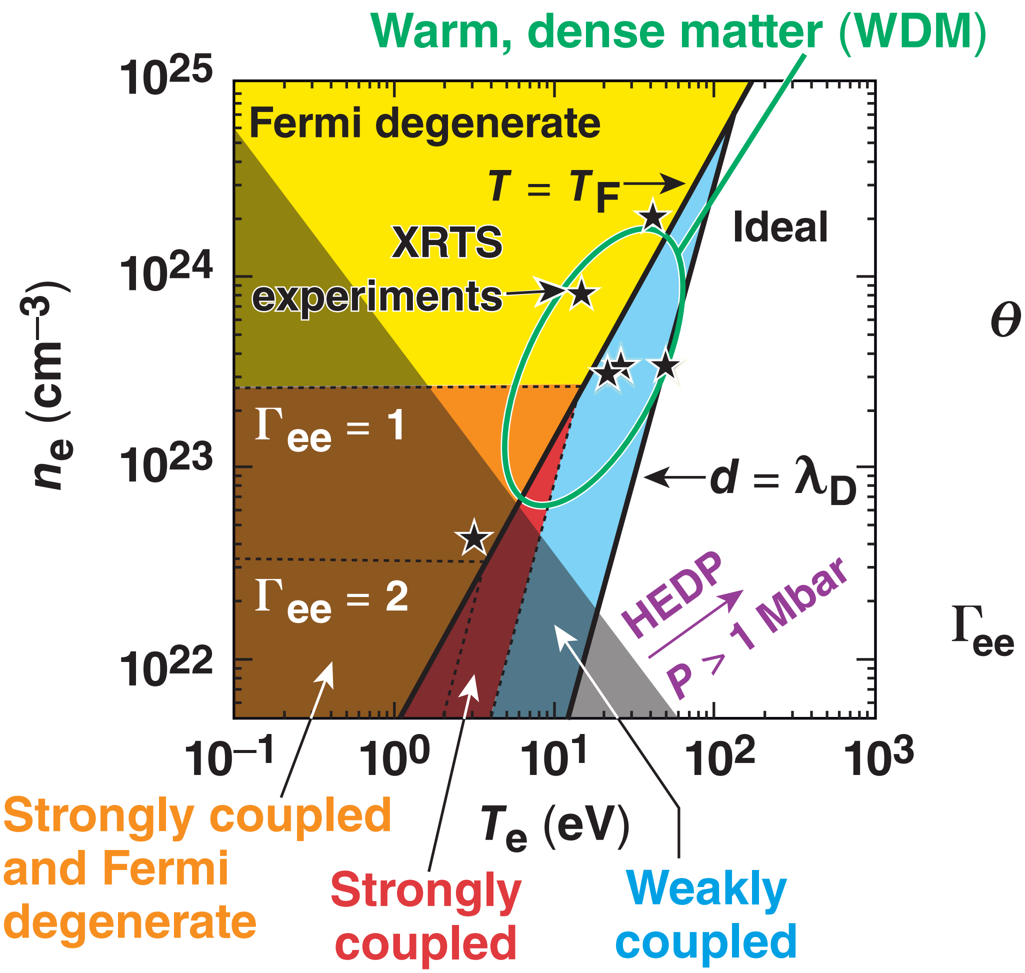
University of Rochester

Outline

- **Motivation**
- XRTS
- Experiments
- Future

X-ray Thomson scattering* (XRTS) is a primary diagnostic for HEDP experiments



Degeneracy parameter

$$\theta = \frac{k_B T_e}{E_F}, \quad E_F = \frac{\hbar^2}{2m_e}\left(3\pi^2 n_e\right)^{2/3}$$

Coupling parameter

$$\Gamma_{ee} = \frac{e^2}{4\pi\varepsilon_0 \bar{d} k_B T_e}, \quad \bar{d} = \left(\frac{4\pi n_e}{3}\right)^{-1/3}$$

Penetrating x rays are needed to probe dense plasmas.

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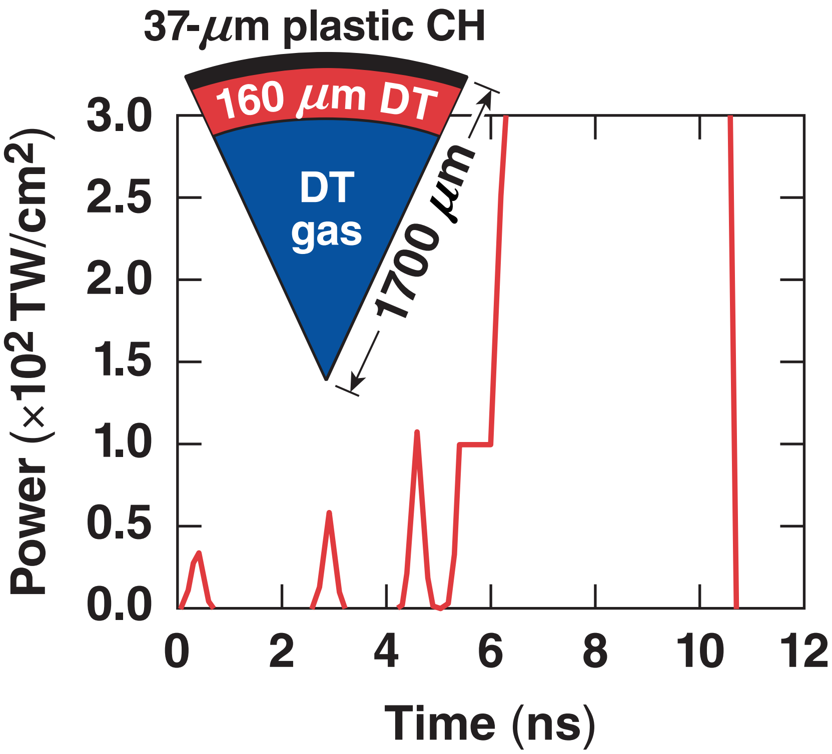
*S. H. Glenzer and R. Redmer, Rev. Mod. Phys. 81, 1625 (2008).
O. L. Landen *et al.*, J. Quant. Spectrosc. Radiat. Transf. 71, 465 (2001).
G. Gregori *et al.*, Phys. Rev. E 67, 026412(2003).

Diagnosing the shock heated and compressed-shell conditions in an ICF target is an ideal XRTS application

Triple-picket, direct-drive design for the NIF[1]



$$E_{\text{min}} \sim \frac{\alpha^{1.8}}{V_{\text{imp}}^{5.8}}$$

(minimum laser energy for ignition)[2,3]

$$\text{Minimize} \rightarrow \alpha = \frac{P_{\text{fuel}}}{P_{\text{Fermi}}}$$

The minimum energy needed for ignition depends on the plasma conditions in the fuel layer (P_{fuel}), which can be diagnosed with XRTS.

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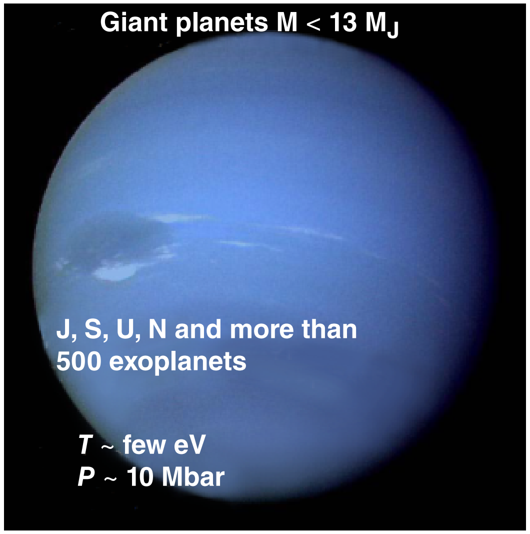
[1] V. N. Goncharov *et al.*, Phys. Rev. Lett. 104, 165001 (2010).
[2] M. C. Hermann, M. Tabak, and J. Lindl, Nuc. Fusion 41, 99 (2001).
[3] R. Betti *et al.*, Phys. Plasmas 9, 2277 (2002).

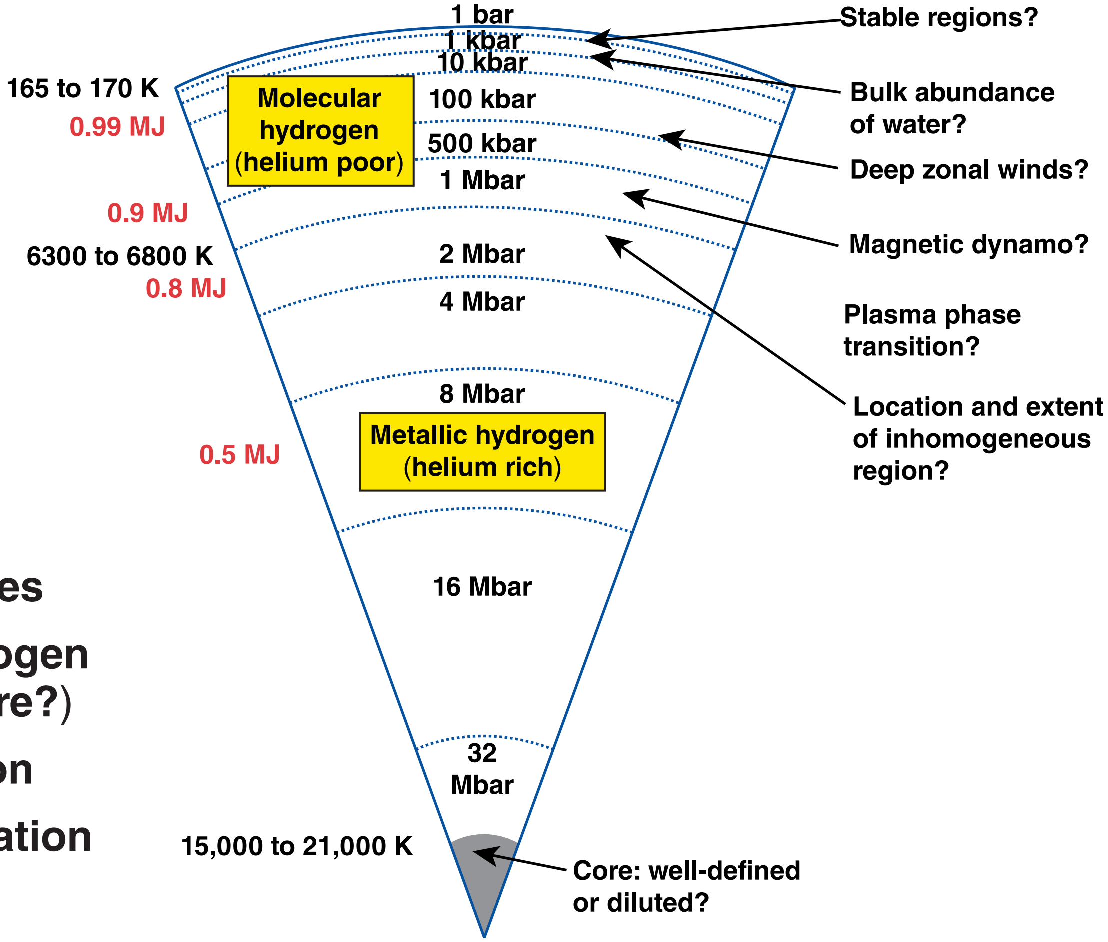
XRTS can provide accurate measurements of conditions in HEDP plasmas designed for planetary science



Giant planets M < 13 M_J

J, S, U, N and more than 500 exoplanets

T ~ few eV
P ~ 10 Mbar



1 bar
1 kbar
10 kbar
100 kbar
500 kbar
1 Mbar
2 Mbar
4 Mbar
8 Mbar
16 Mbar
32 Mbar

165 to 170 K
0.99 MJ
0.9 MJ
6300 to 6800 K
0.8 MJ
0.5 MJ
15,000 to 21,000 K

Molecular hydrogen (helium poor)

Metallic hydrogen (helium rich)

Stable regions?

Bulk abundance of water?

Deep zonal winds?

Magnetic dynamo?

Plasma phase transition?

Location and extent of inhomogeneous region?

Core: well-defined or diluted?

- Outstanding physics issues
  - metallization of hydrogen (pressure, temperature?)
  - H/He phase separation
  - magnetic-field generation

Outline

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- **XRTS**
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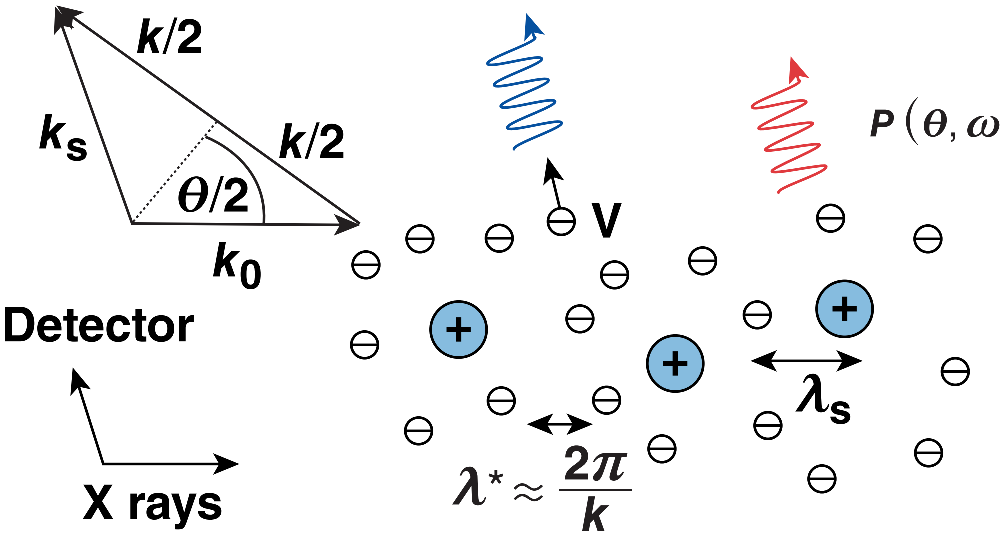
The properties of dense plasmas can be diagnosed with XRTS



$$P(\theta,\omega) \sim \underbrace{|f(k)+q(k)|^2 S_{ii}(k,\omega)}_{① \text{ Elastic}} + \underbrace{ZS_{ee}(k,\omega)}_{② \text{ Inelastic (free-free, free-bound)}}$$

① **Ion–ion correlations**

- scattering as a function of the scattering angle exhibit peaks that are representative of the structure (diffraction)

② **Electron–electron correlations**

- scattering as a function of energy describes either single-particle dynamics or correlated plasmons

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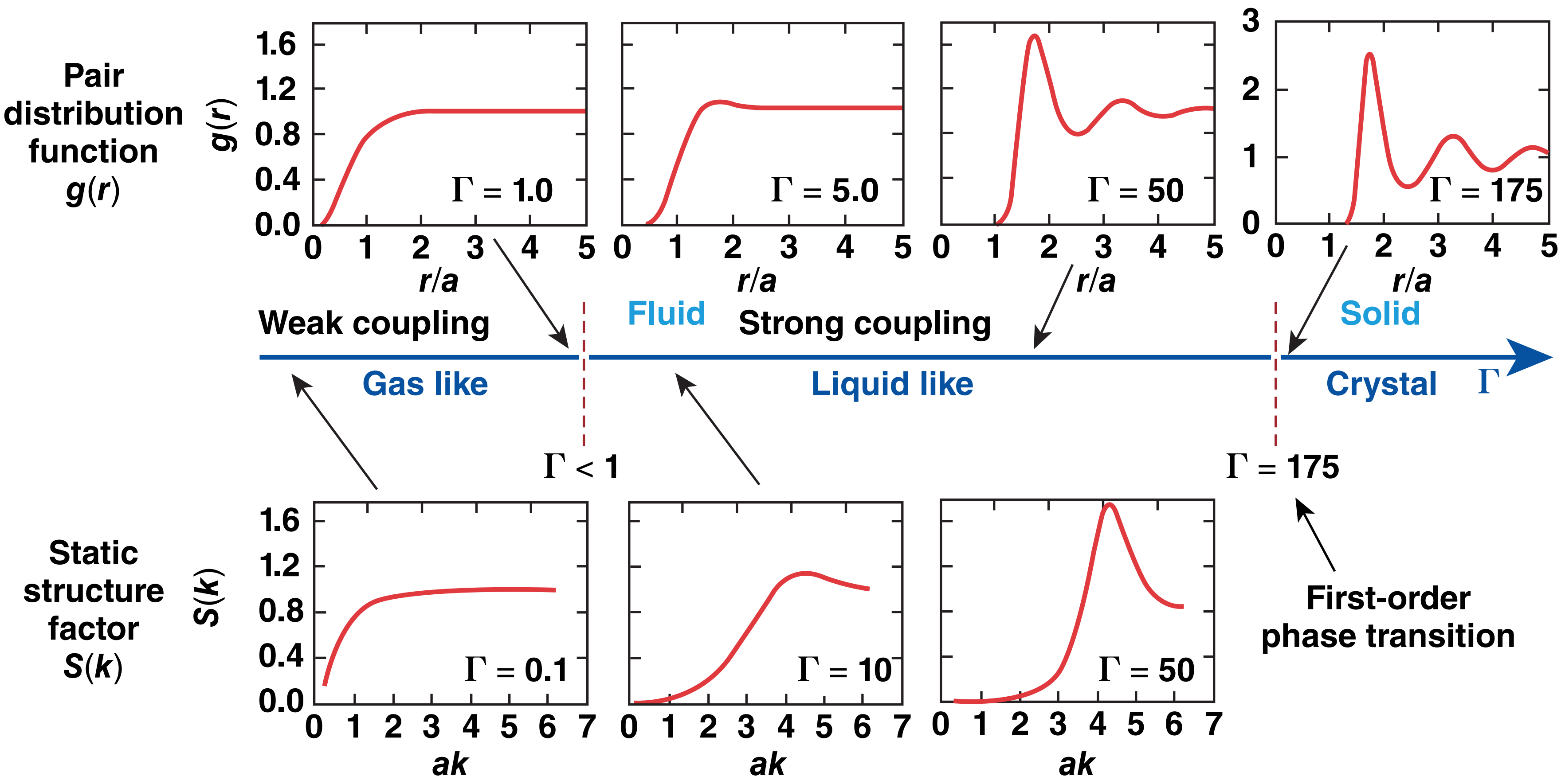
S. H. Glenzer and R. Redmer, Rev. Mod. Phys. 81, 1625 (2008).
G. Gregori *et al*., Phys. Rev. E 67, 26412 (2003).

Elastic scattering (diffraction) is used to test the degree of correlation between ions



Pair distribution function $g(r)$

Static structure factor $S(k)$

Weak coupling

Strong coupling

Fluid

Solid

Gas like

Liquid like

Crystal

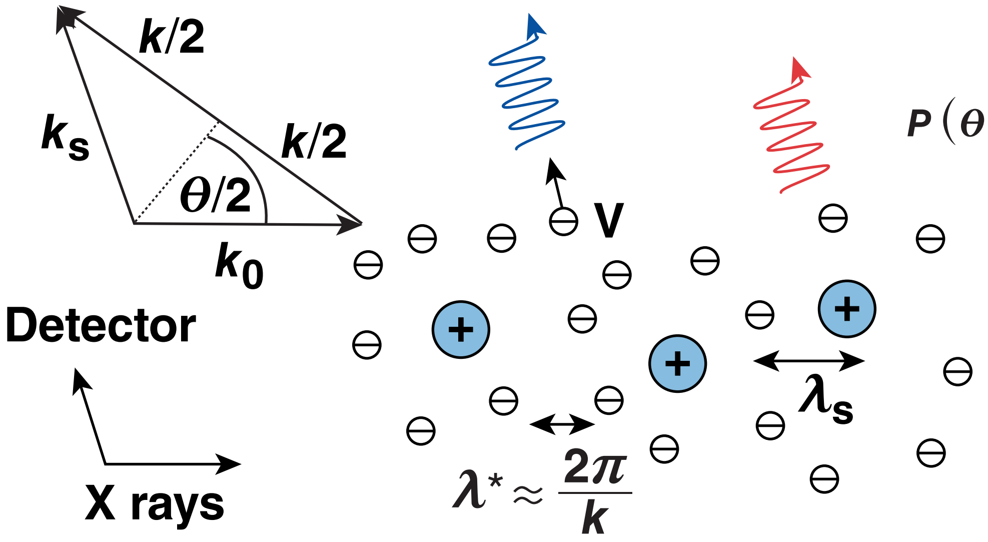
$\Gamma < 1$

$\Gamma = 175$

First-order phase transition

- As the plasma gets denser (or cooler) correlations among ions emerge with the formation of crystalline structure

The microscopic characterization of warm, dense matter is inferred from inelastic scattering



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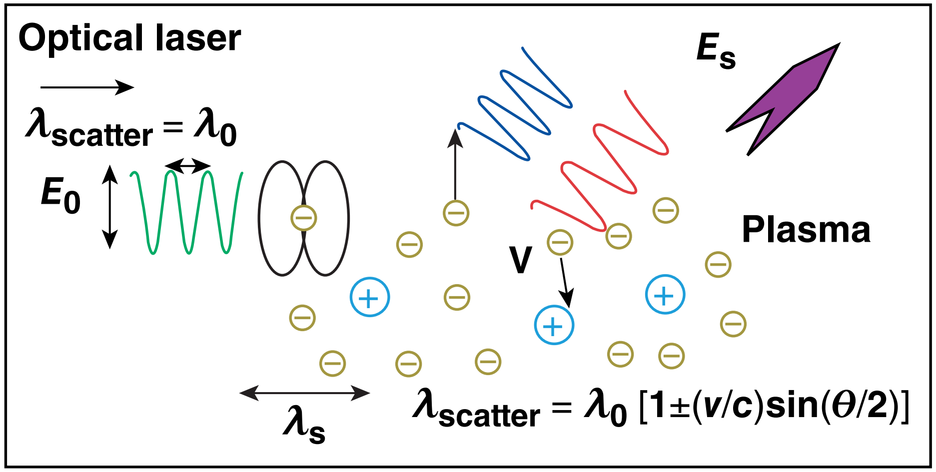
S. H. Glenzer and R. Redmer, Rev. Mod. Phys. 81, 1625 (2008).
G. Gregori *et al*., Phys. Rev. E 67, 26412 (2003).

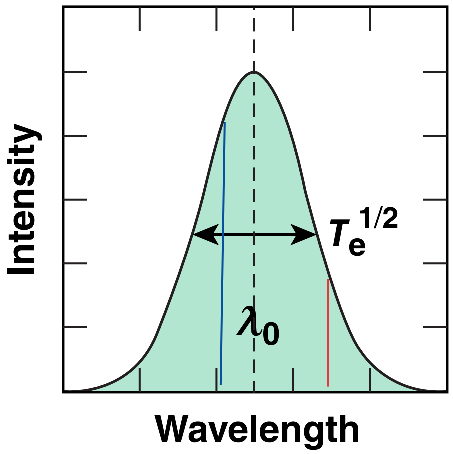
Inelastic x-ray scattering probes the electron-velocity distribution function

Noncollective Thomson scattering ($\lambda_{\text{scatter}} < \lambda_s$)

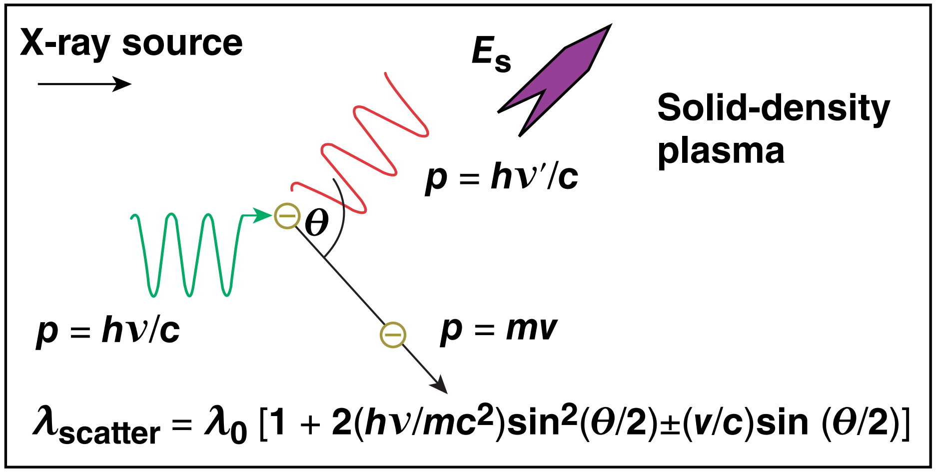


Scattering on free electrons

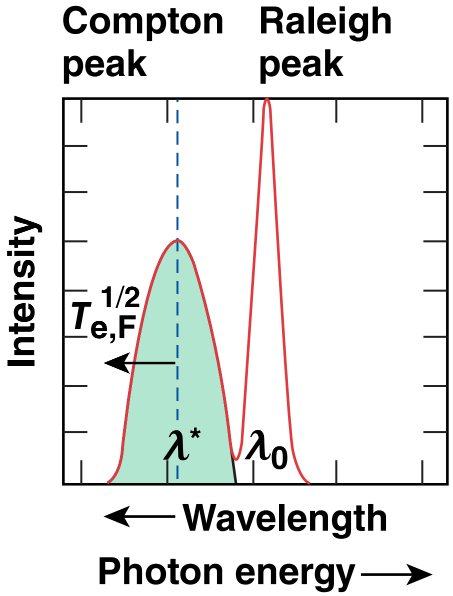
Boltzman distribution



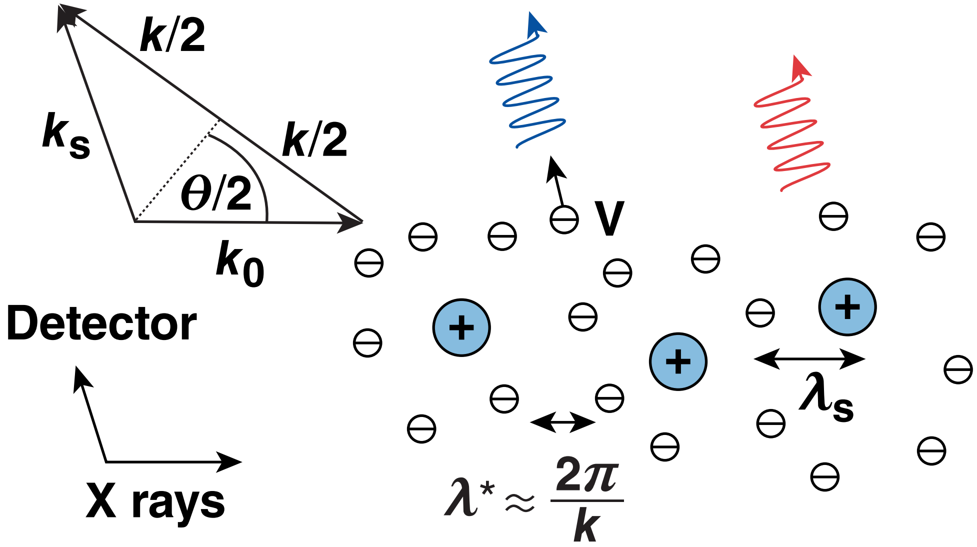
X-ray Compton scattering



Scattering on free and weakly bound electrons



Collective inelastic x-ray scattering is used to diagnose the electron density



Scattering parameter

$$\alpha = \frac{\lambda^*}{2\pi\,\lambda_s} = \frac{1}{k\lambda_s}$$

$$k = |\mathbf{k}| = 4\pi \frac{E_0}{hc} \sin(\theta/2)$$

- $\alpha < 1$: scattering from electrons (noncollective) → T_e, Z
- $\alpha > 1$: scattering from plasmons (collective) → n_e

$$\omega_{\text{plasmon}} \sim \omega_{\text{plasma}} = \sqrt{n_e e^2/\varepsilon_0 m_e}$$

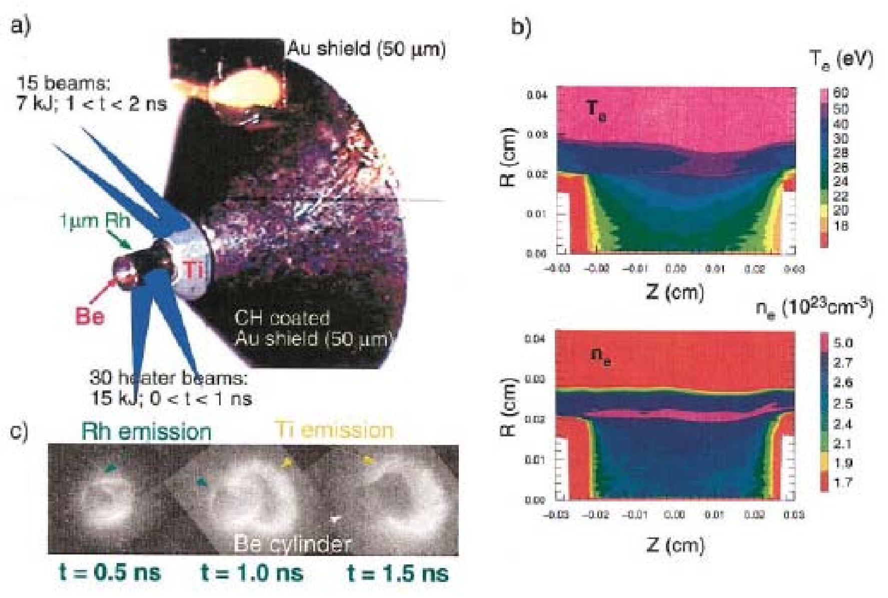
S. H. Glenzer and R. Redmer, Rev. Mod. Phys. 81, 1625 (2008).
G. Gregori *et al.*, Phys. Rev. E 67, 26412 (2003).

Outline

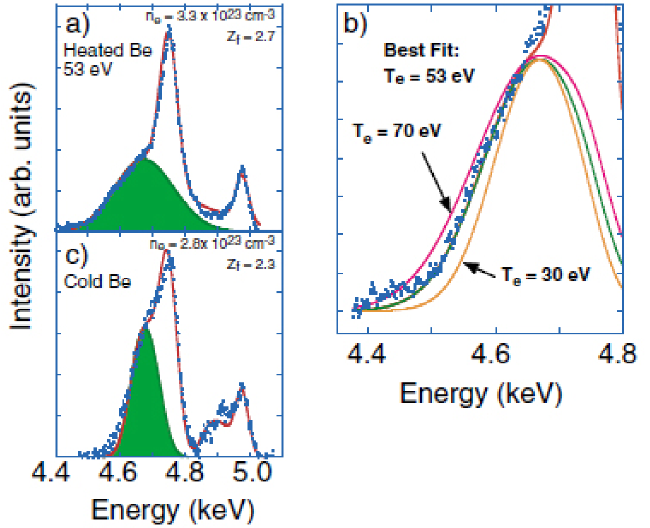
- Motivation
- XRTS
- **Experiments**
- Future

The first noncollective XRTS experiment diagnosed isochorically heated Be on OMEGA

Noncollective scattering from radiatively heated Be



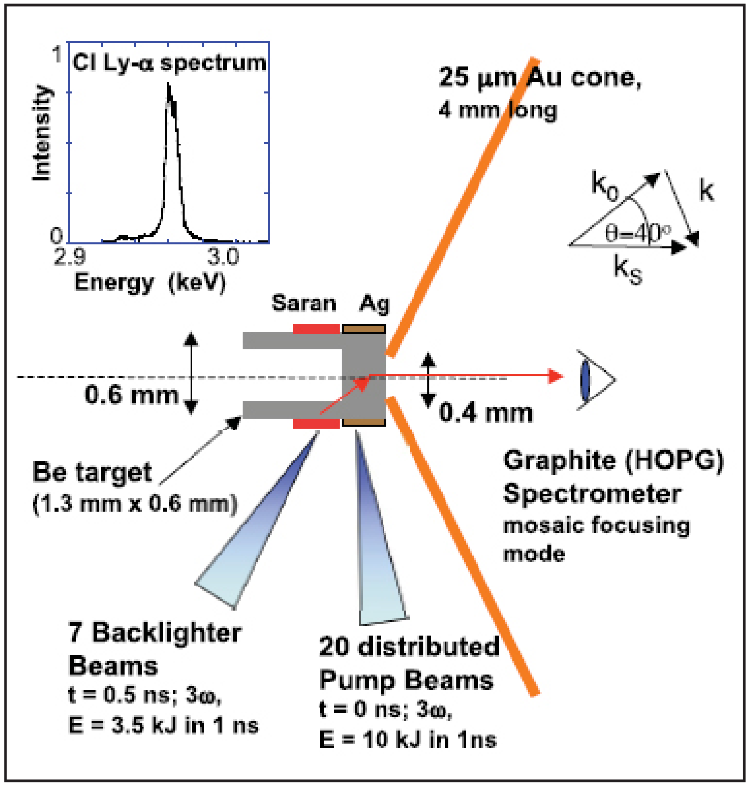
Noncollective XRTS



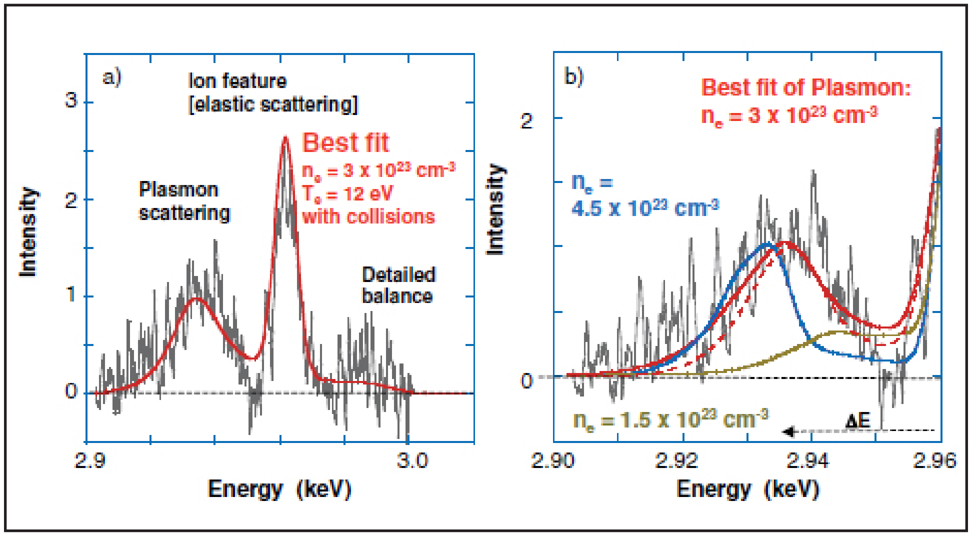
S. H. Glenzer *et al*., Phys. Rev. Lett. 90, 175002 (2003).

Collective XRTS was first demonstrated using isochorically heated Be on OMEGA

Collective scattering from radiatively heated Be



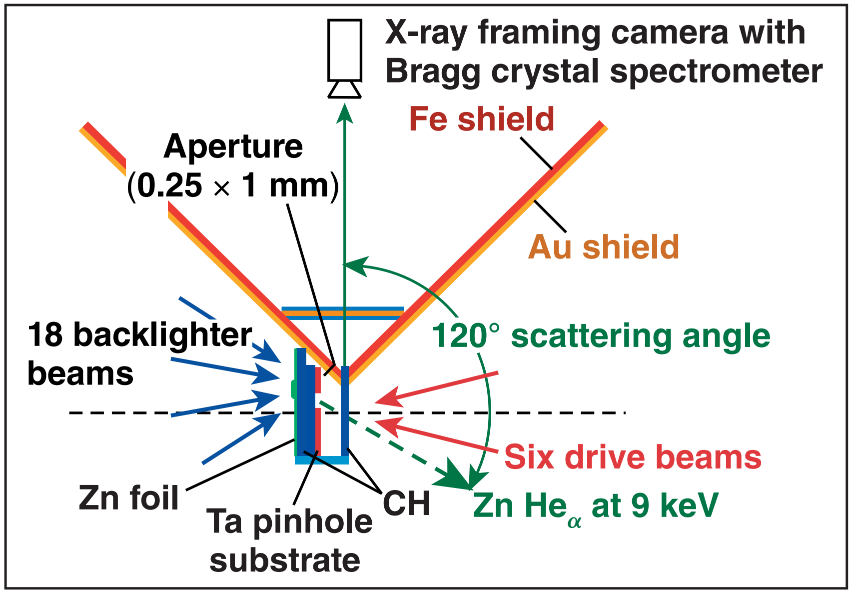
Collective XRTS



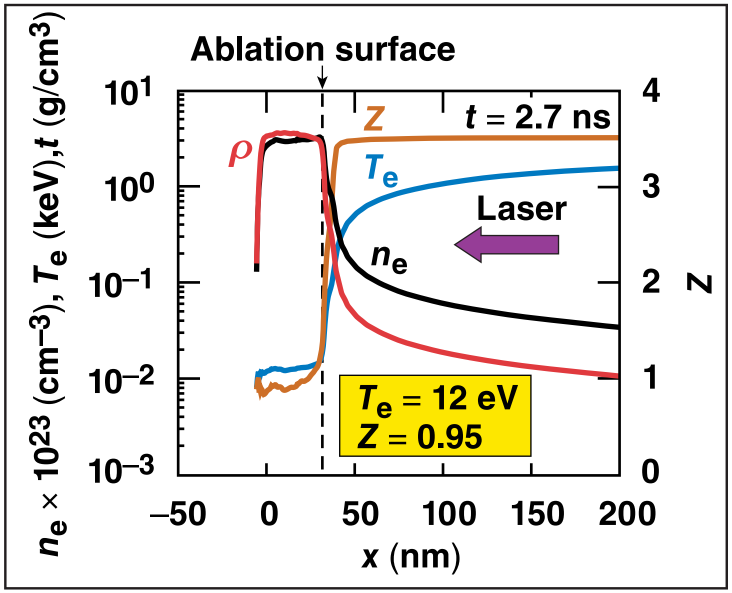
S. H. Glenzer *et al*., Phys. Rev. Lett. 98, 065002 (2007).

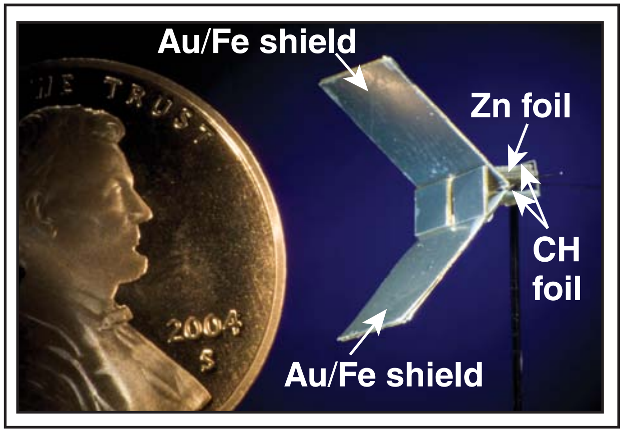
XRTS was applied to a laser-driven, shock-heated, and compressed CH foil on OMEGA

Shock heated and compressed CH foil



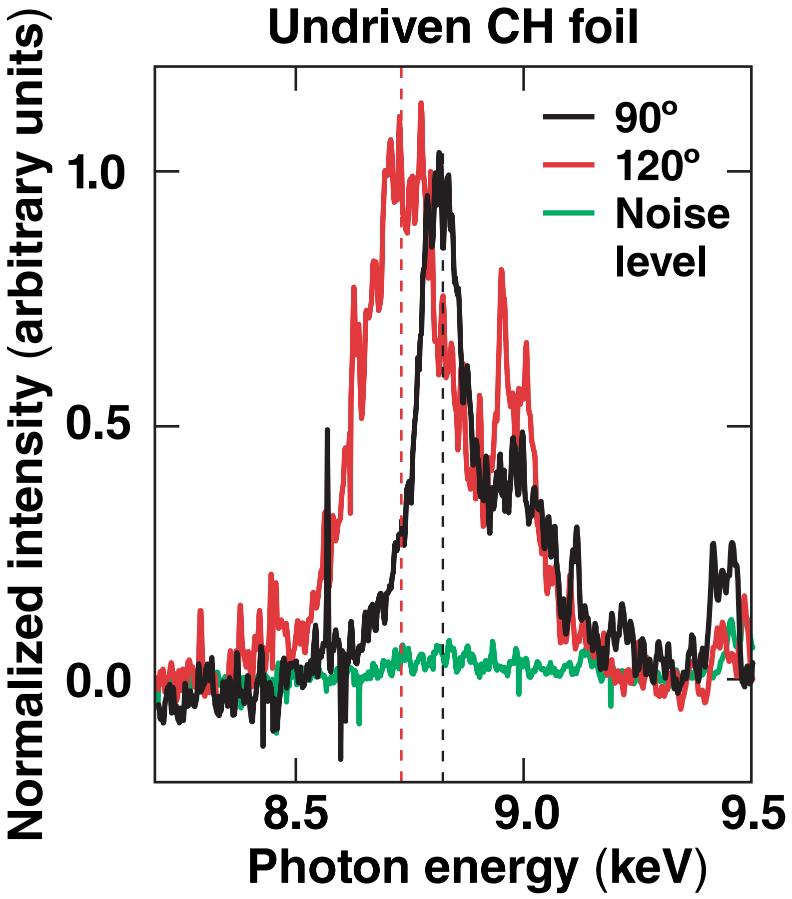
1-D simulation





H. Sawada, S. P Regan *et al.*, Phys. Plasmas 14, 122703 (2007).

The Compton energy downshift is observed to be greater for the larger scattering angle



Compton downshifted energy (eV)

$$\Delta E_c = \frac{\hbar^2 k^2}{2m_e} \quad k = \frac{4\pi}{\lambda_0} \sin\left(\frac{\theta}{2}\right)$$

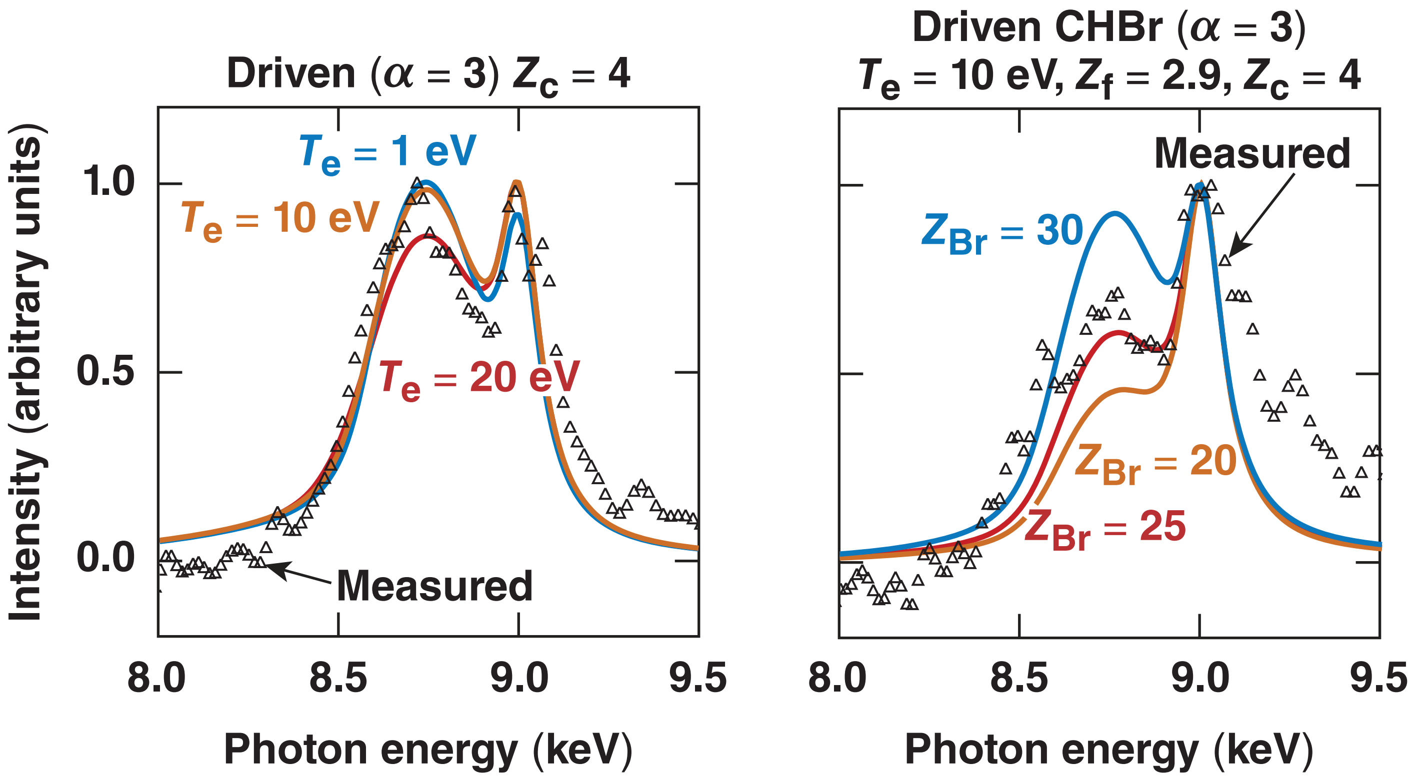
θ: scattering angle
λ_0: wavelength of probe

(Zn He$_\alpha$ ~ 1.3 Å ~ 9.0 keV)

$$\Delta E_C = 178 \text{ eV (for } 90^\circ) = 267 \text{ eV (for } 120^\circ)$$

H. Sawada, S. P. Regan *et al.*, Phys. Plasmas 14, 122703 (2007).

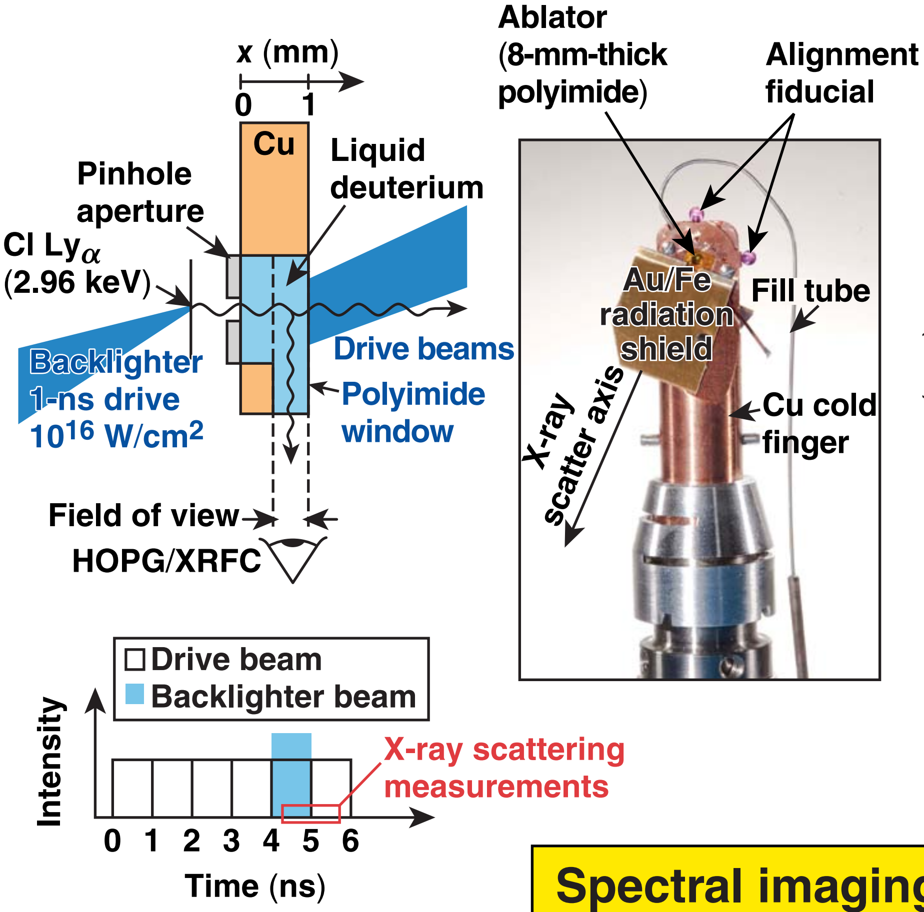
An electron temperature of 10 to 20 eV was inferred from noncollective XRTS

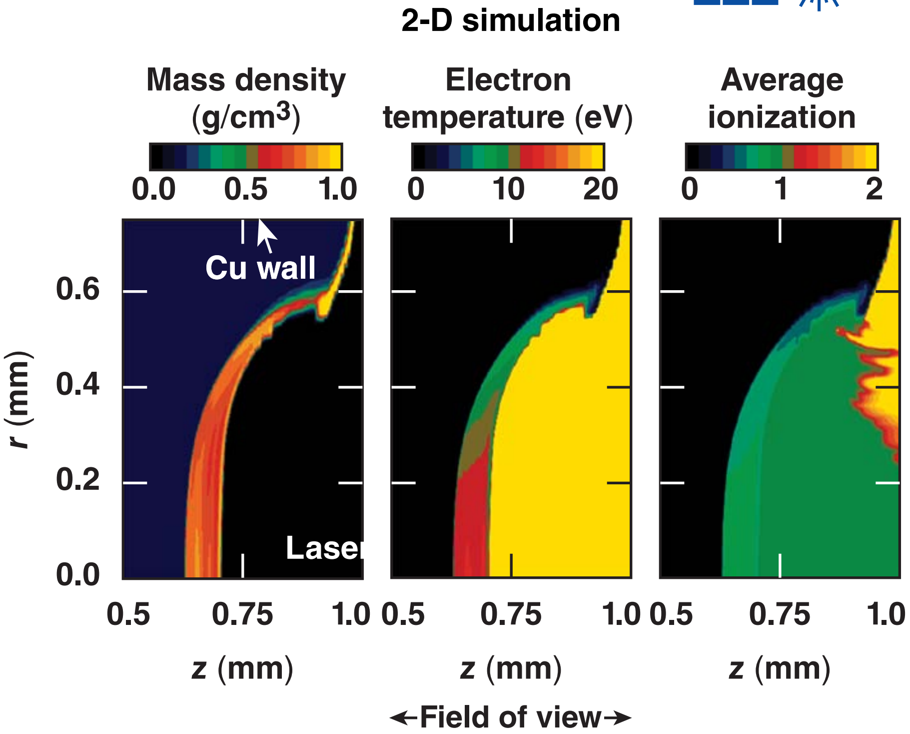


Br dopant in plastic increased the elastic scattering component.

H. Sawada, S. P. Regan *et al.*, Phys. Plasmas 14, 122703 (2007).

Shocked liquid deuterium is being studied with noncollective XRTS to infer the electron temperature

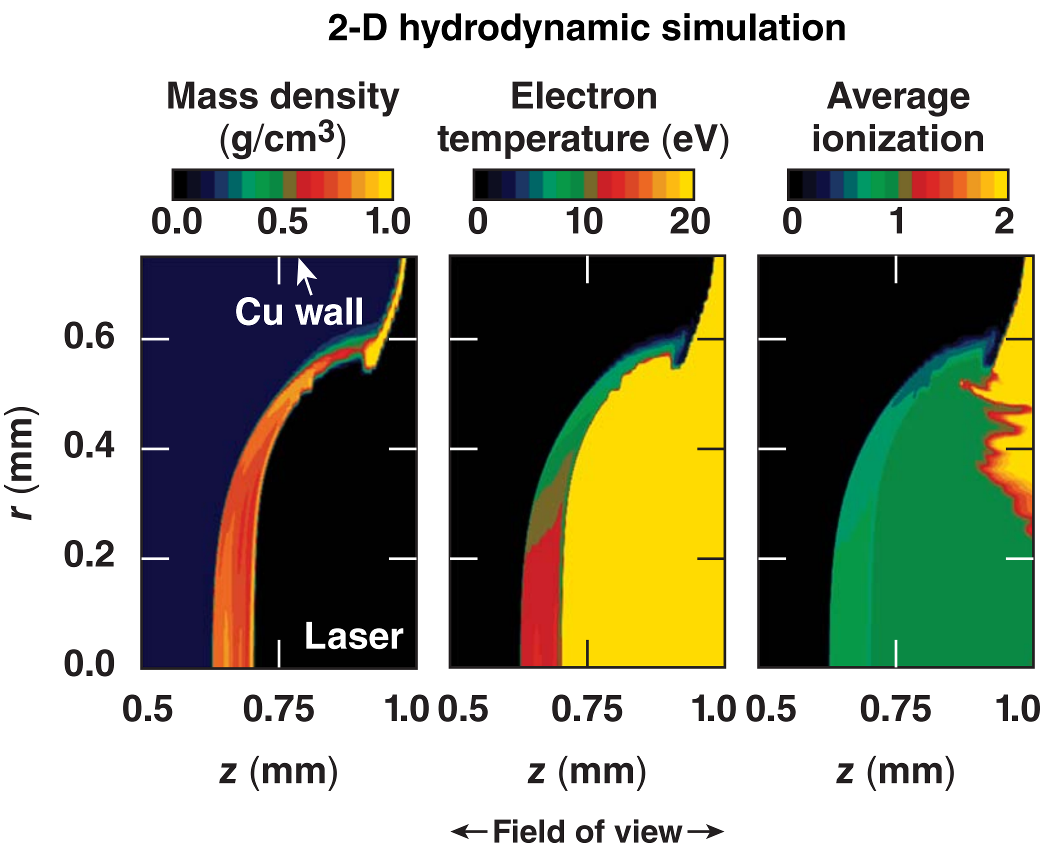


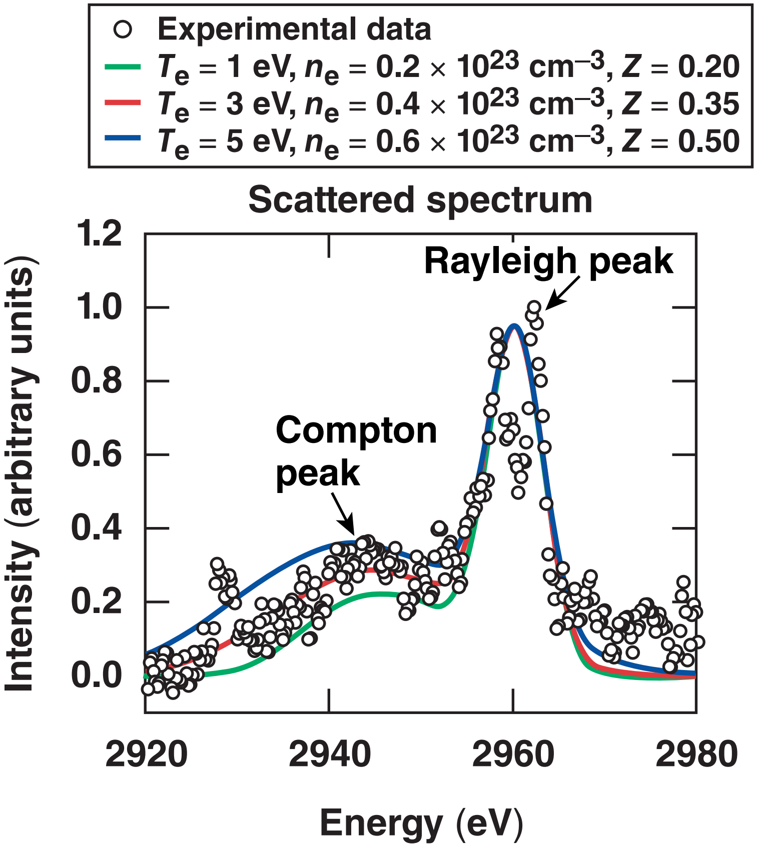


Spectral imaging is needed to discriminate different scattering regions within the field of view.

S. P. Regan *et al.*, submitted for publication.

Shocked liquid deuterium is being studied with noncollective XRTS to infer the electron temperature



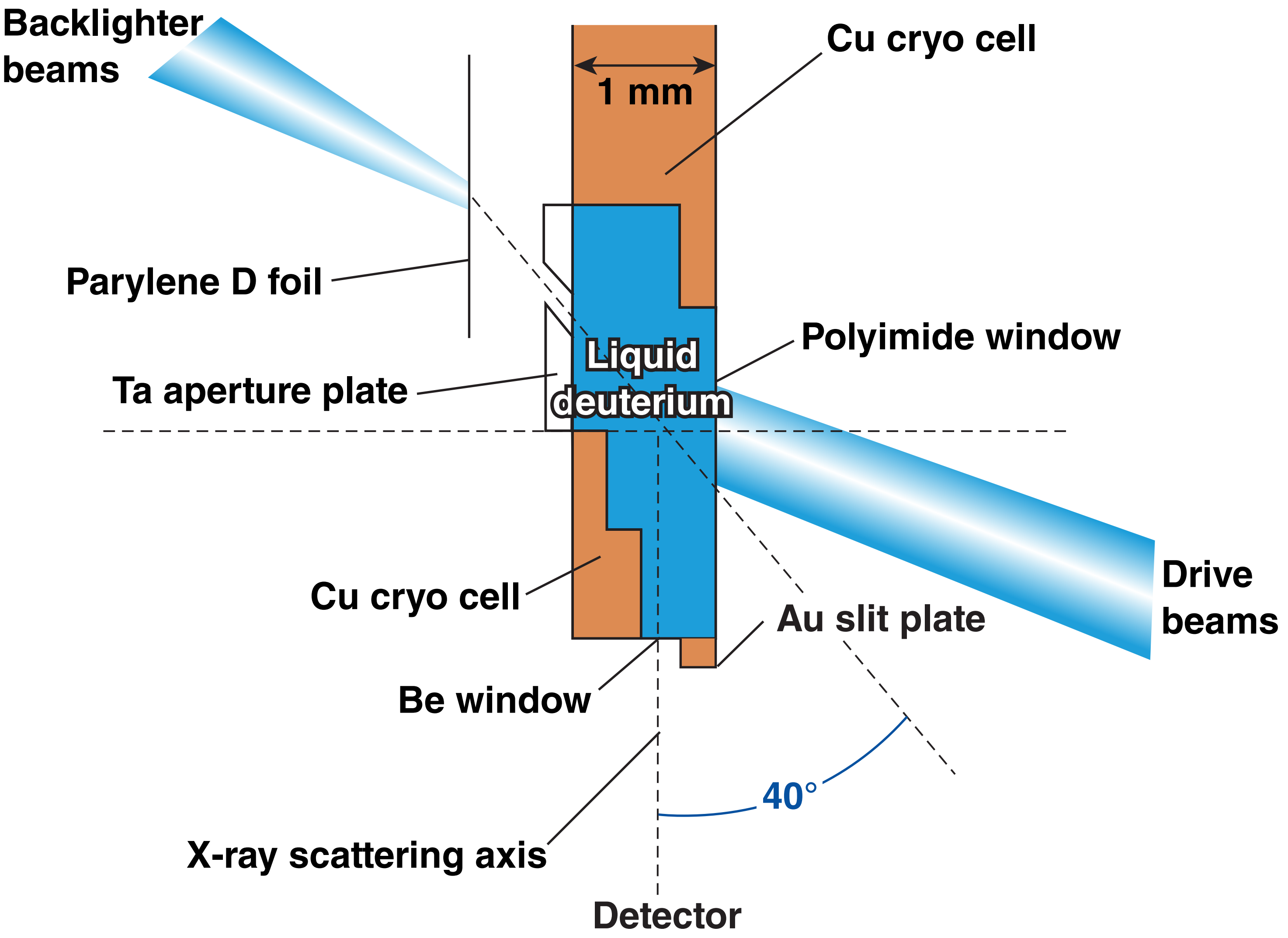


Spectral imaging is needed to discriminate scattering from shocked and unshocked matter.

S. P. Regan *et al.*, submitted for publication.

Scattering angle will be decreased from 90° to 40° to measure collective XRTS and infer electron density

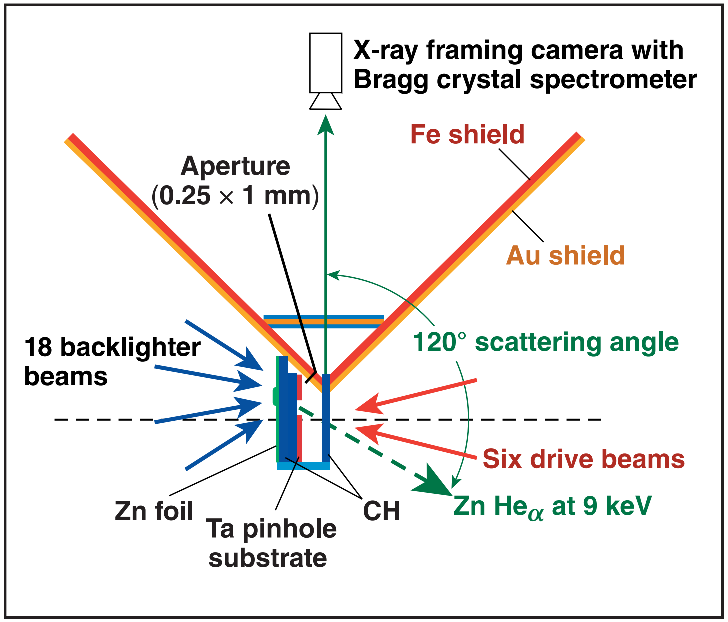
Shocked liquid deuterium experiment with 40° scattering geometry



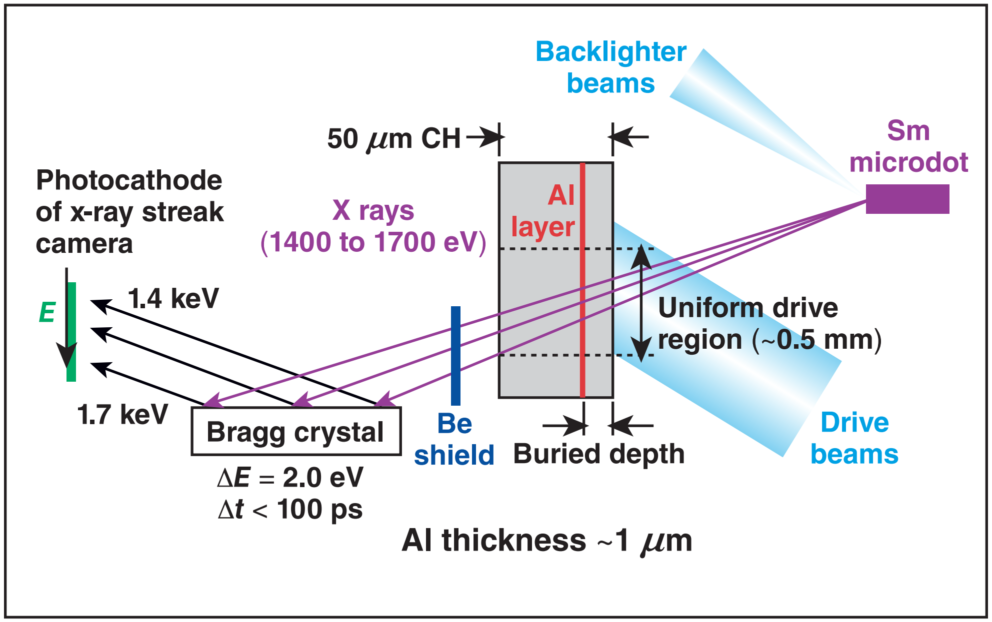
E21078

XRTS is a noninvasive probe

XRTS experiment[1]



X-ray absorption spectroscopy[2]



Compared to absorption spectroscopy, no tracer layers are required for XRTS.

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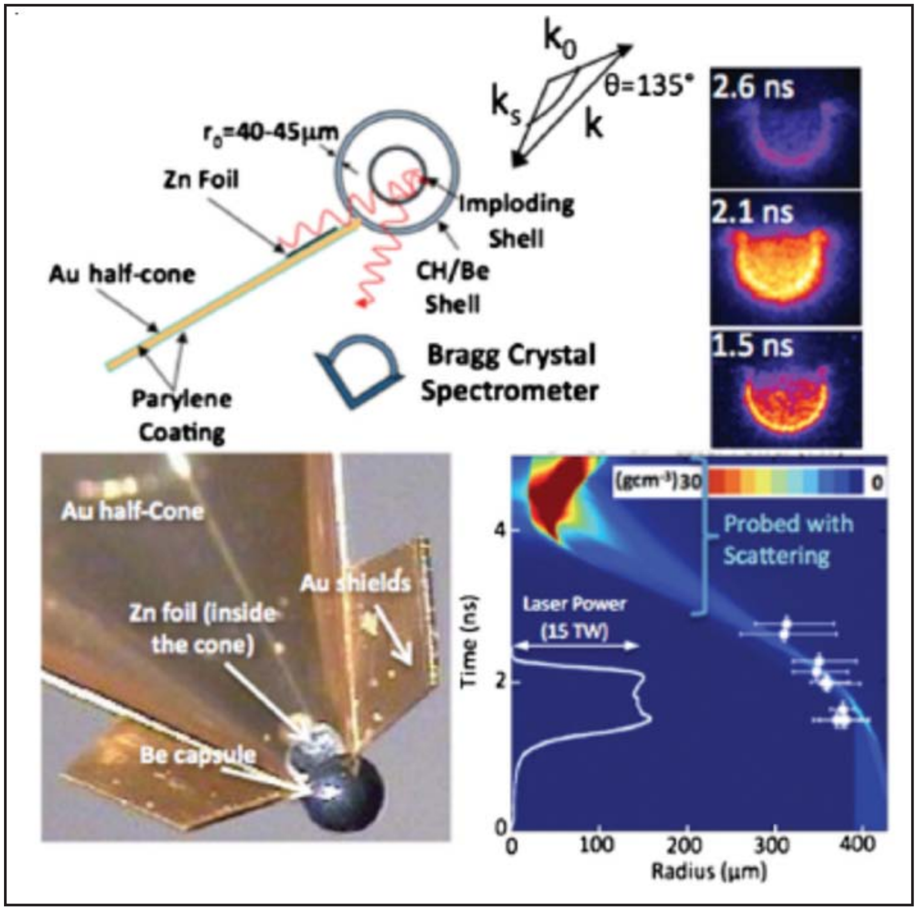
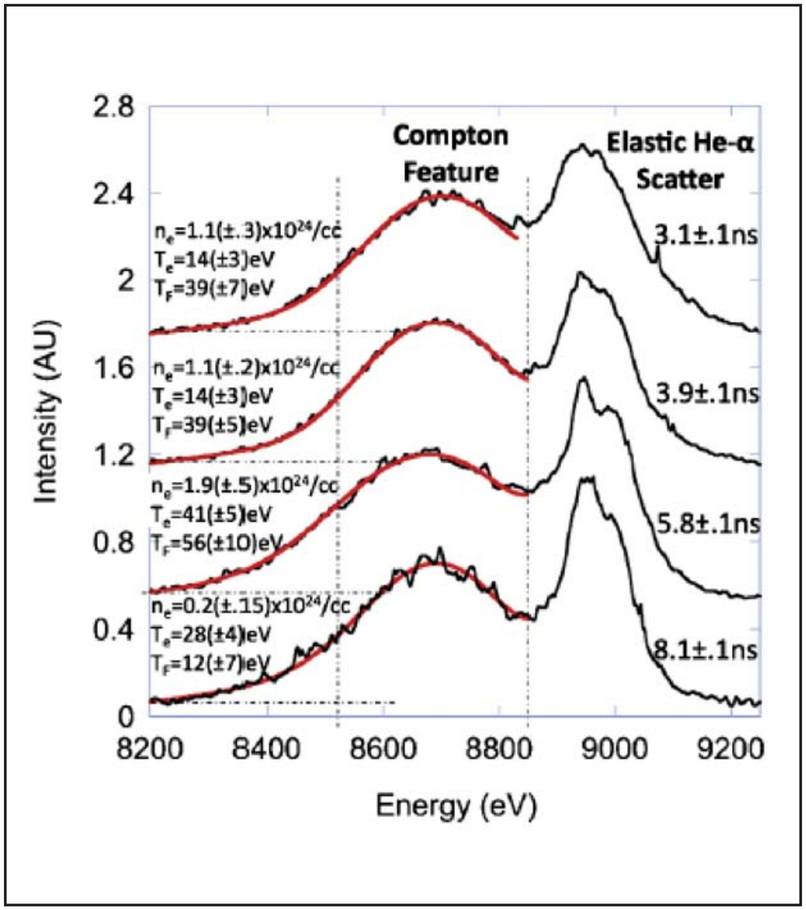
[1] H. Sawada, S. P. Regan *et al.*, Phys. Plasmas 14, 122703 (2007).
[2] H. Sawada, S. P. Regan *et al.*, Phys. Plasmas 16, 052702 (2009).

Compressed CH and Be shells were imploded on OMEGA and diagnosed with XRTS

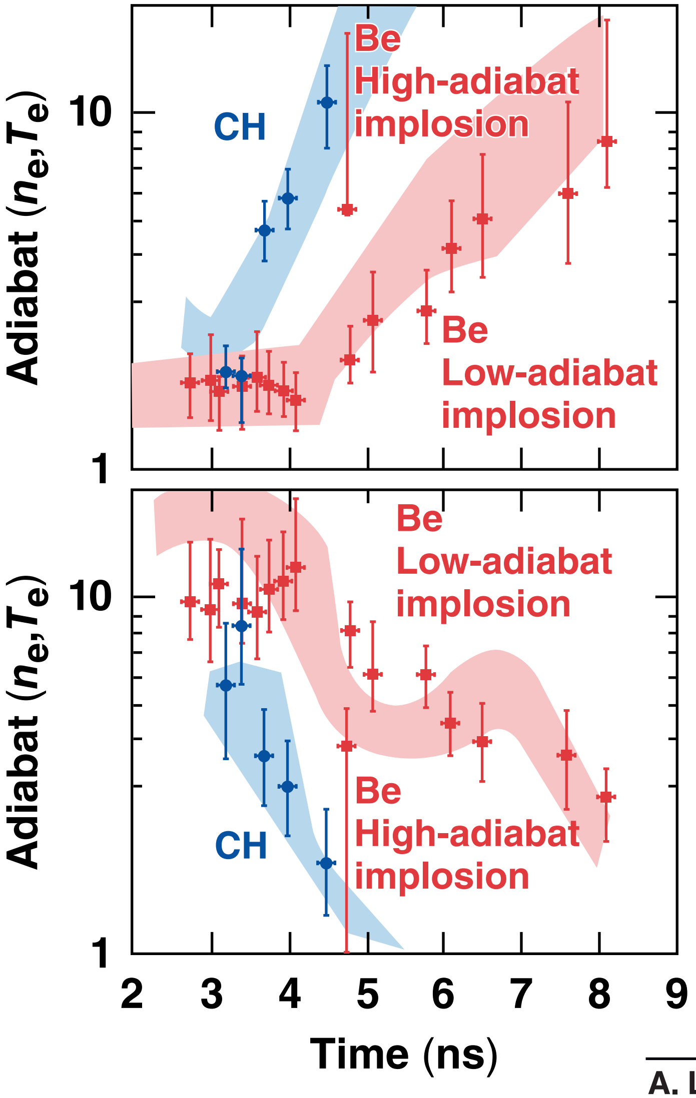
Spherical direct-drive implosion





A. L. Kritcher *et al*., Phys. Rev. Lett. 107, 015002 (2011).

The adiabat and the ion–ion coupling parameter were inferred from the XRTS measurements



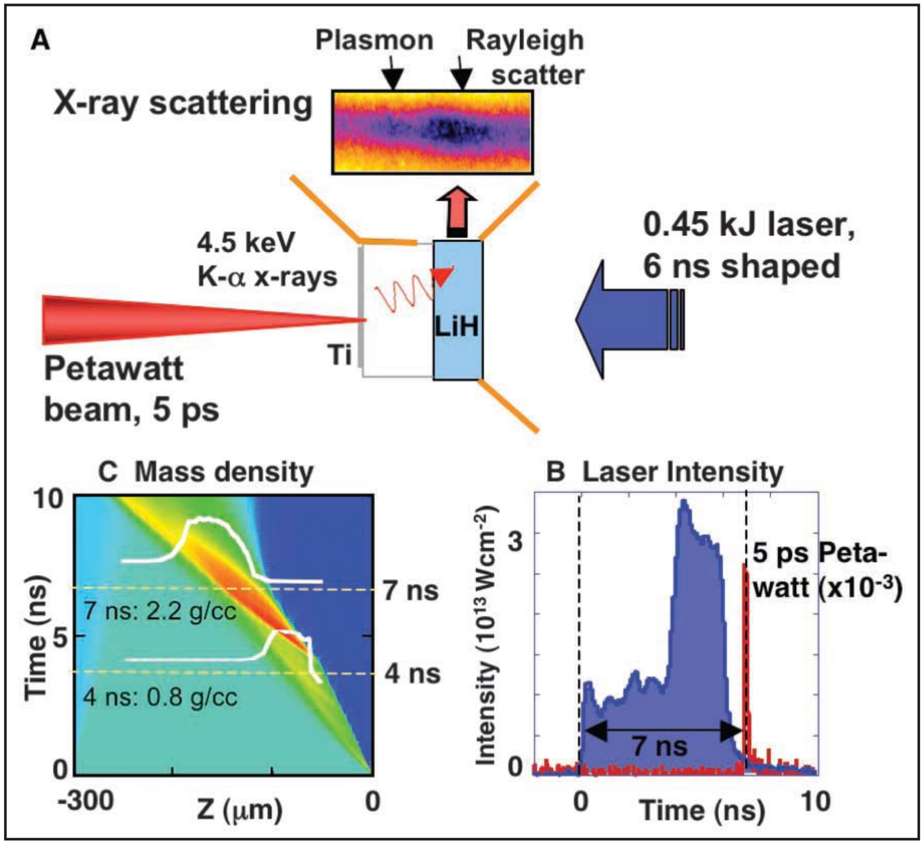
$$\alpha = \frac{P_{\text{final}}}{P_{\text{Fermi}}}$$

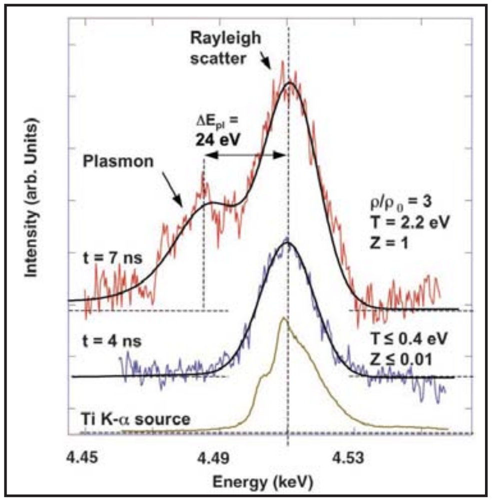
$$\Gamma_{ii} = (Ze)^2 / (4\pi\varepsilon_0 a\, k_B T_i)$$

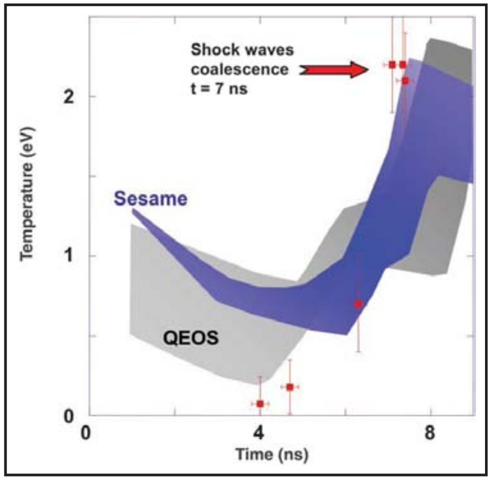
$$a = (4/3\pi n_i)^{-1/3}$$

A. L. Kritcher *et al.*, Phys. Rev. Lett. 107, 015002 (2011).

Ultrafast XRTS was used to probe shock-compressed matter





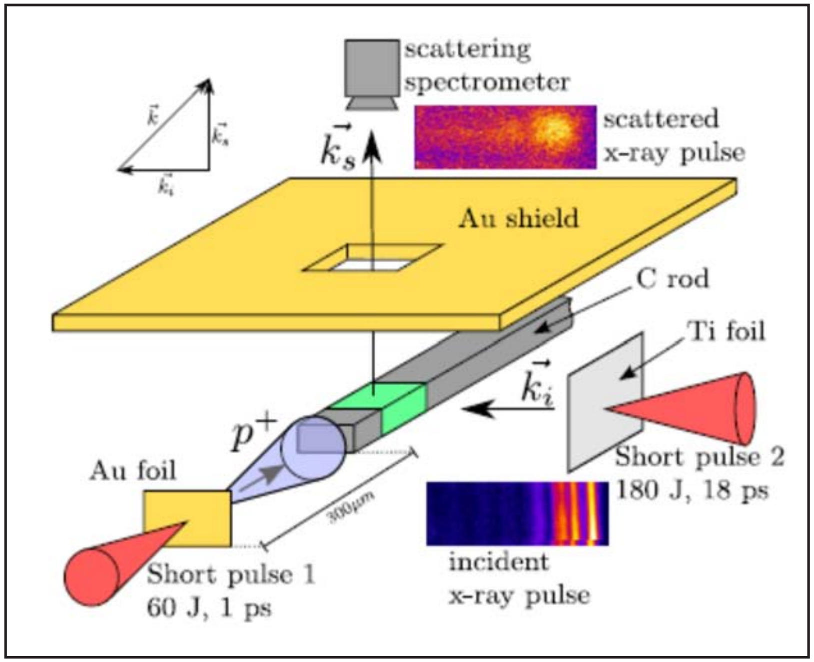


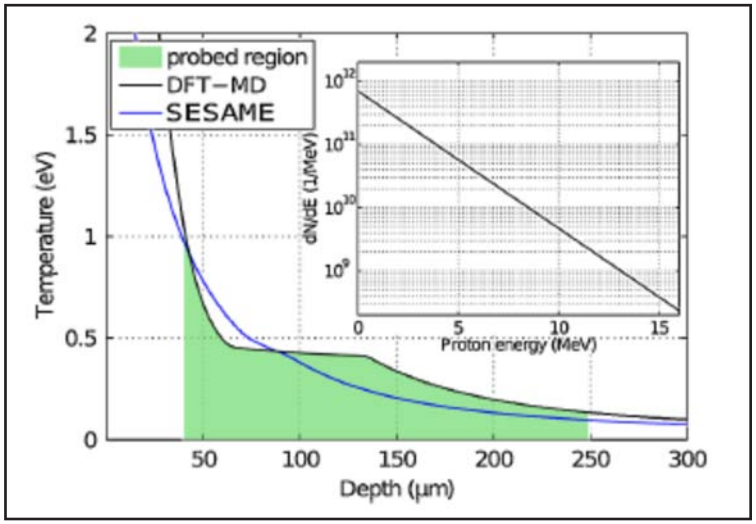
XRTS with 10-ps temporal resolution was achieved.

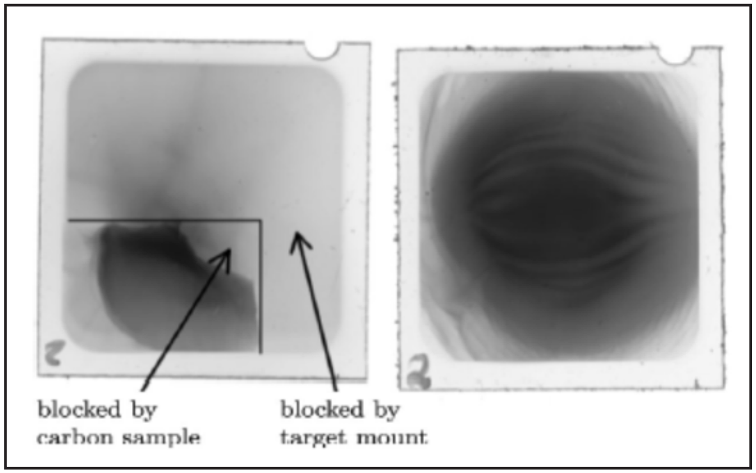
A. L. Kritcher *et al*., Science 322, 69 (2008).

The amount of liquid carbon was diagnosed with elastic x-ray scattering from a proton-heated target

Ultrafast proton-heating experiment



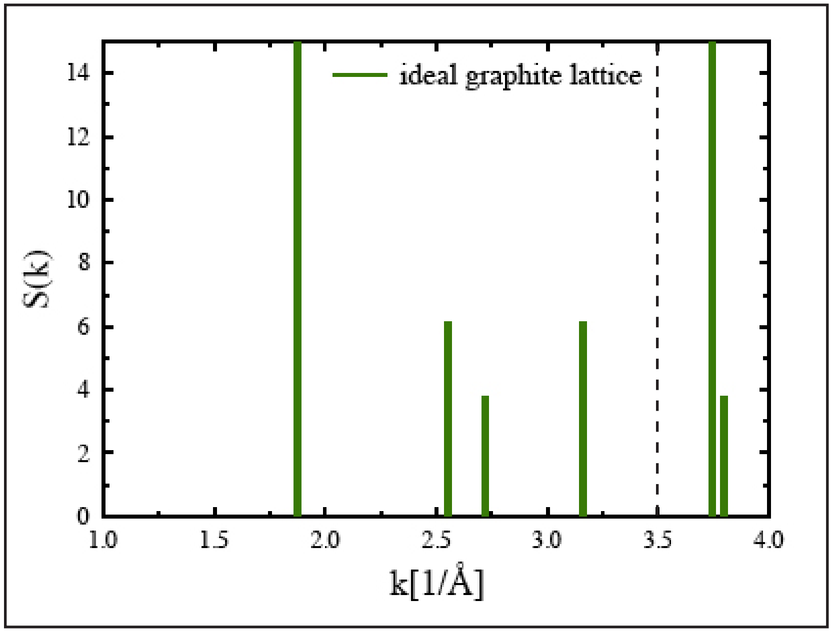


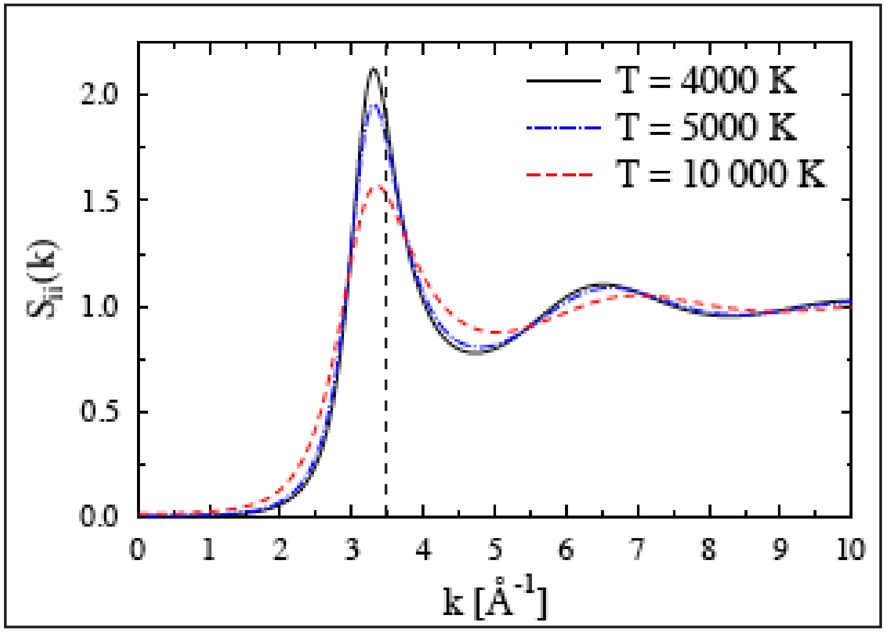


A. Pelka *et al.*, Phys. Rev. Lett. 105, 265701 (2010).

DFT-MD simulations of heated carbon show that scattering comes only from liquid phase

Density functional theory molecular dynamics (DFT-MD)

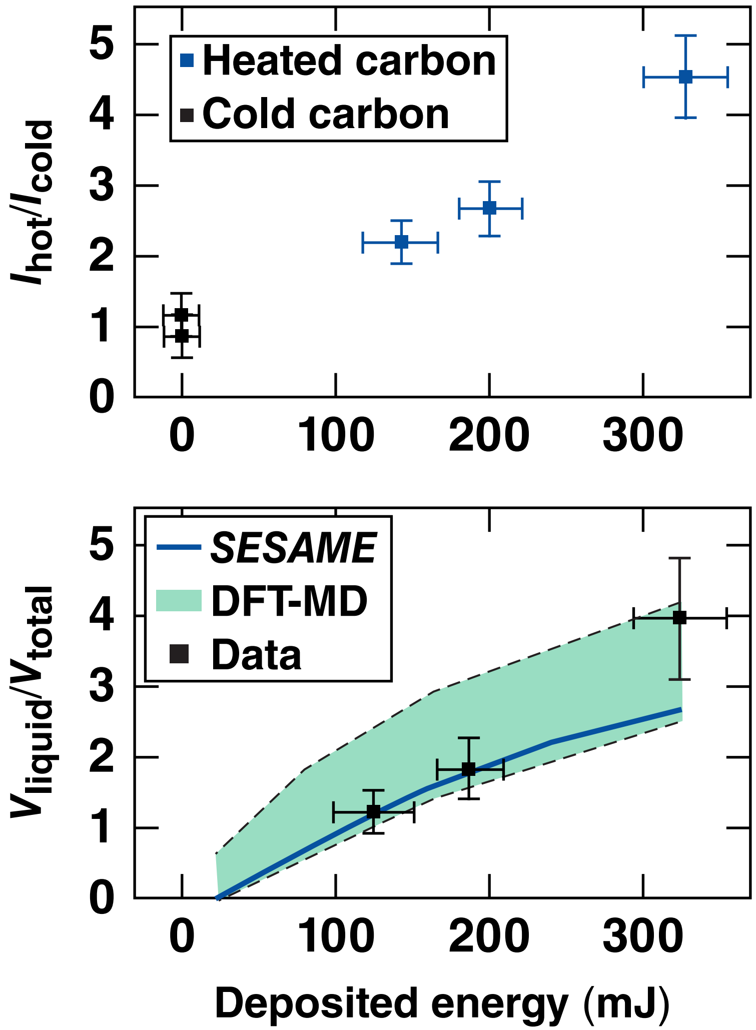




- Experiment probes k = 3.5 Å^{-1}

A. Pelka *et al.*, Phys. Rev. Lett. 105, 265701 (2010).

Experimental data on liquid fraction is used to validate equation-of-state models



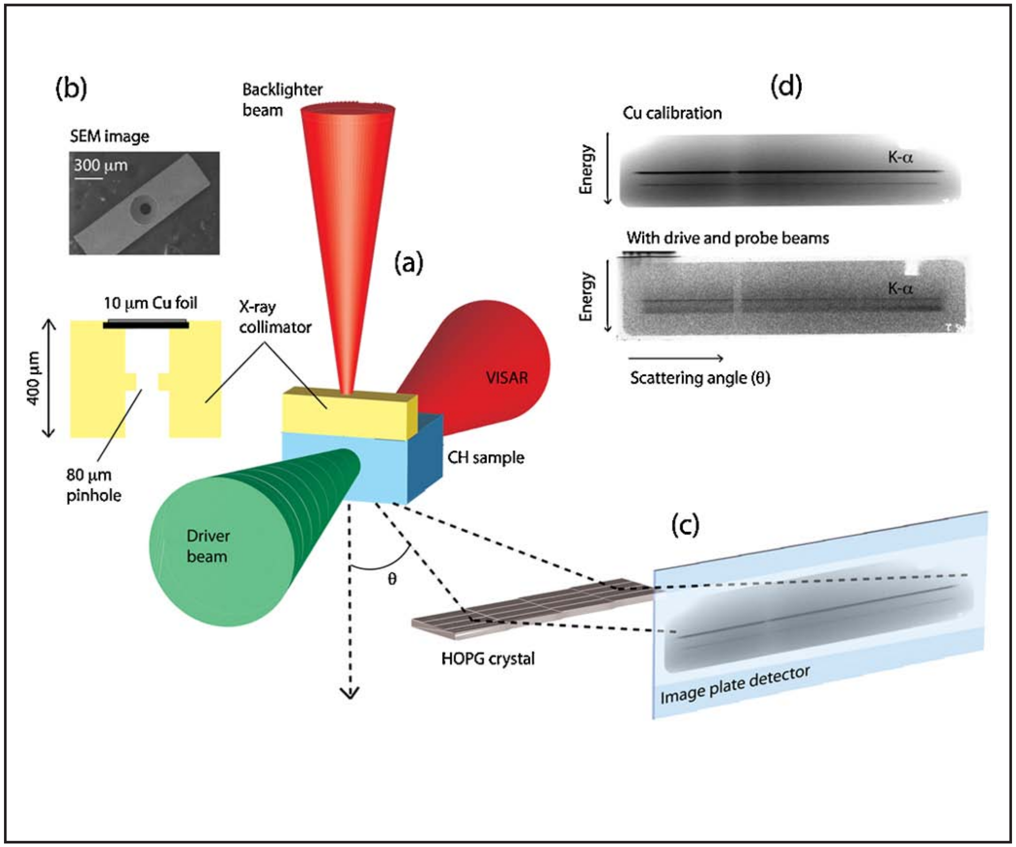
$$I_{sc} = CI_0\left[V_s S_s^{tot}(k) + V_l S_l^{tot}(k)\right]$$

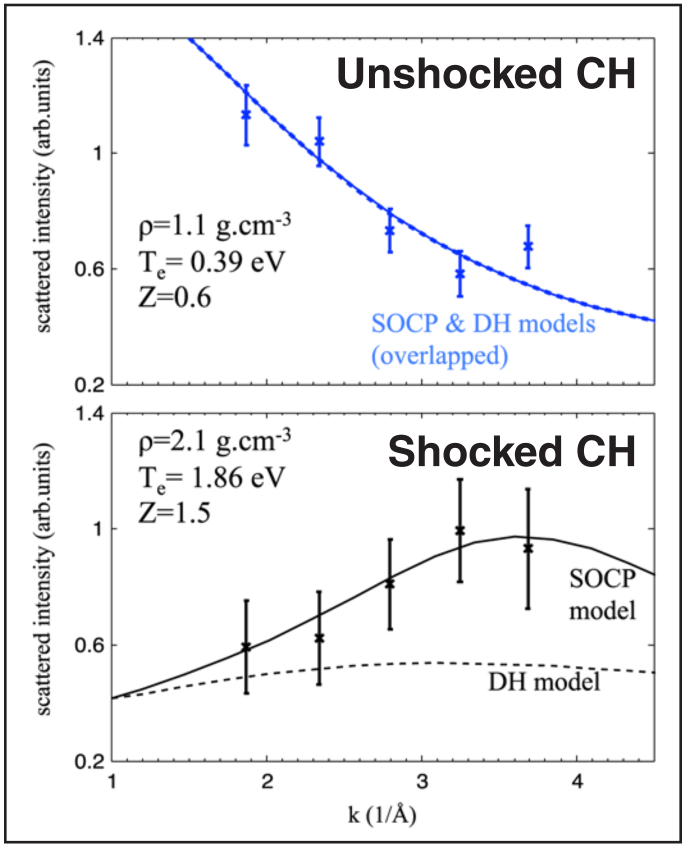
$$\frac{V_l}{V_{tot}} = \left(\frac{I_{hot}}{I_{cold}} - 1\right)\left(\frac{S_l^{tot}}{S_s^{tot}} - 1\right)$$

The correct modeling of the liquid content at high pressures in carbon-rich planets has implications on the predicted magnetic fields.

A. Pelka *et al*., Phys. Rev. Lett. 105, 265701 (2010).

Time-resolved XRTS shows change in CH structure as shock wave enters the line of sight



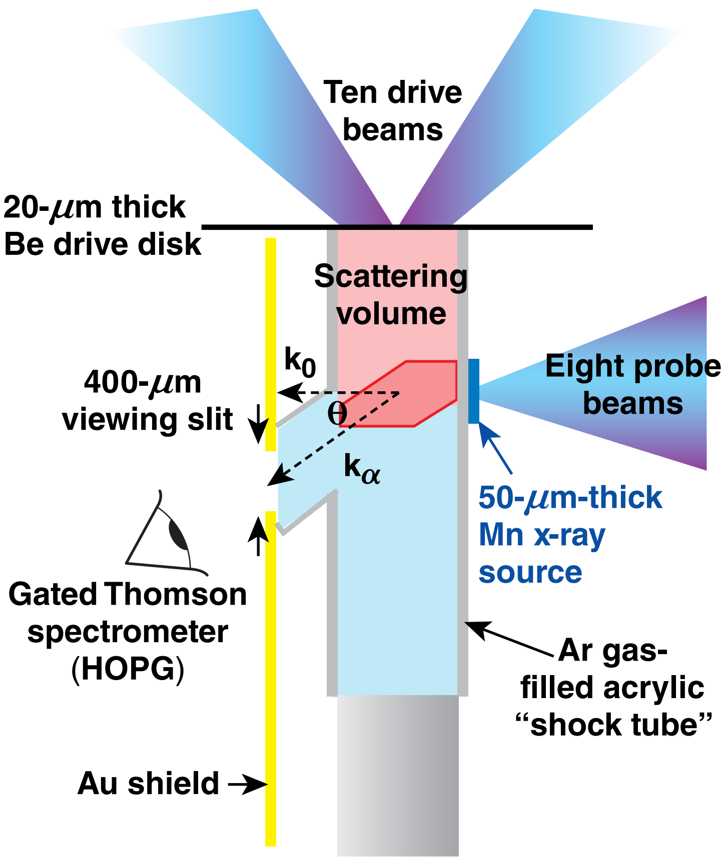


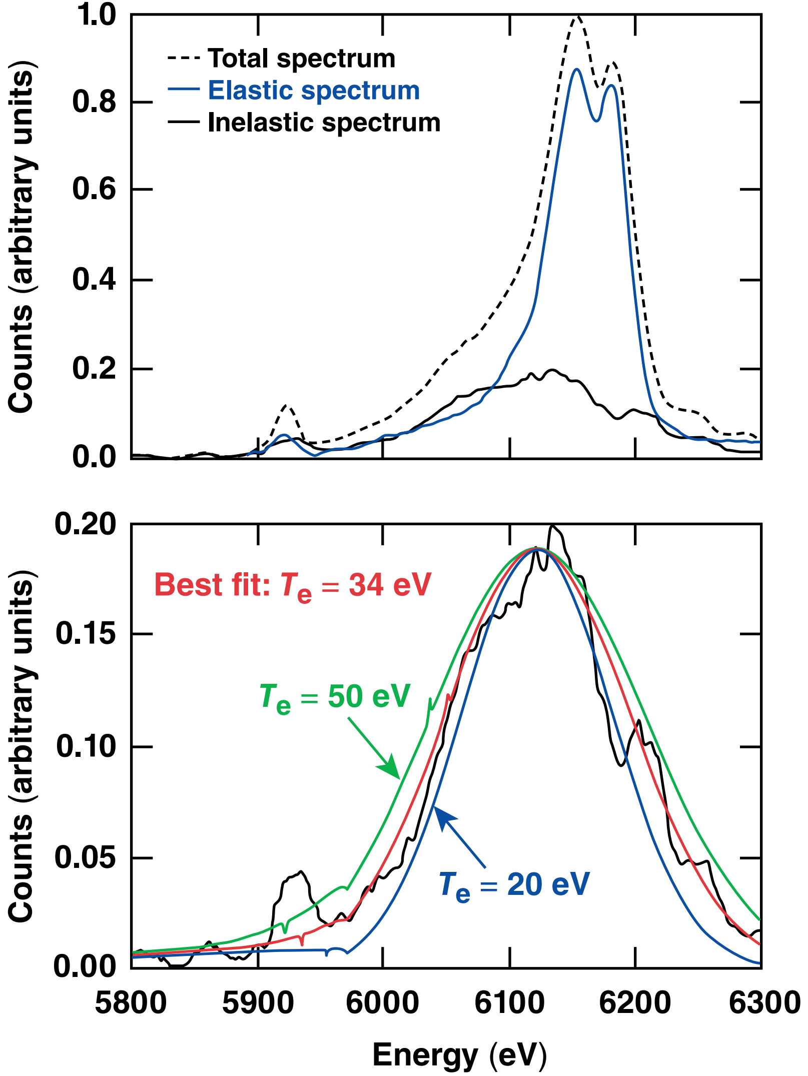
The shocked CH has a peak at 3.5 Å^{-1}, which can be modeled when ion screening is included.

B. Barbrel *et al*., Phys. Rev. Lett. 102, 165004 (2009).

A radiative shock wave in Ar was diagnosed with XRTS on OMEGA

Ar radiative shock experiment





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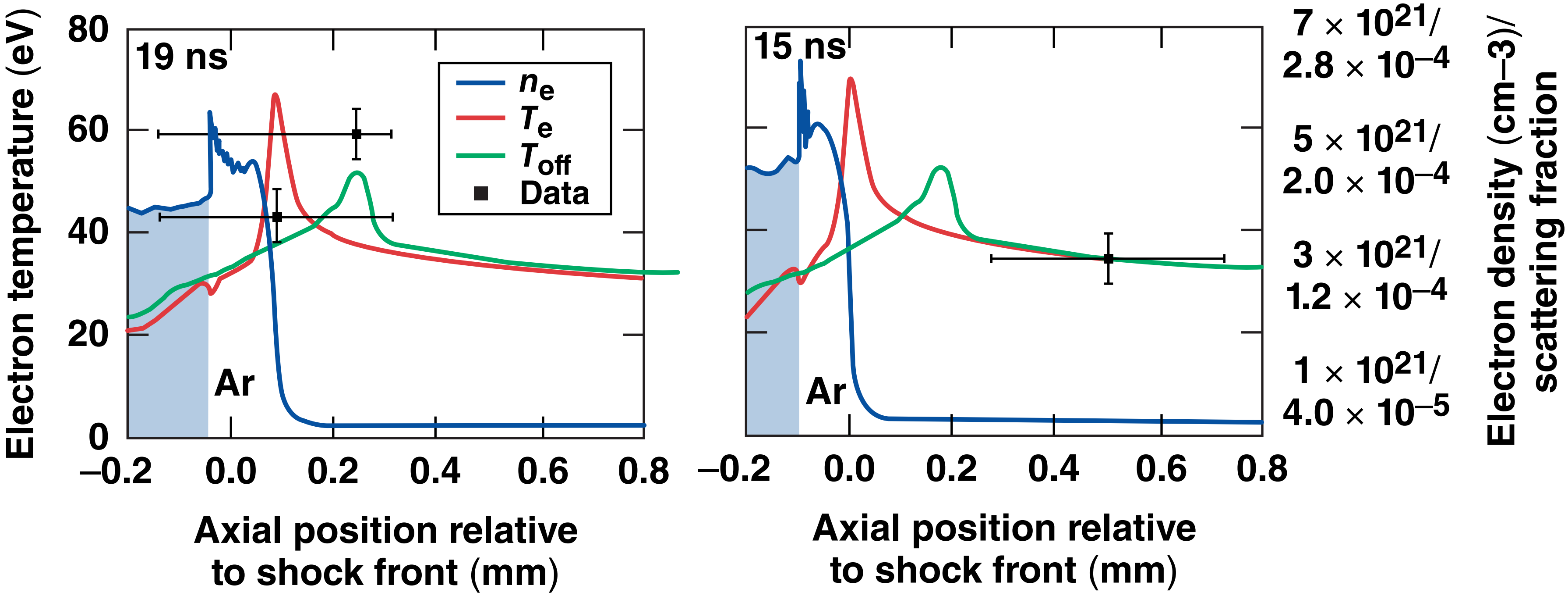
*A. J. Visco, *et al.,* PRL. 108, 145001 (2012).

The electron temperature in the shocked region is higher than in the radiative precursor



The predictive capability of radiative shock waves is validated in the laboratory with XRTS and x-ray radiography.

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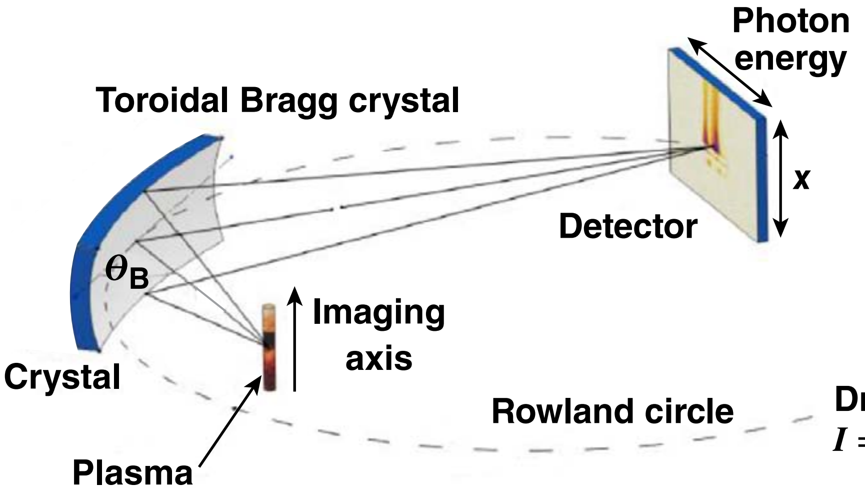
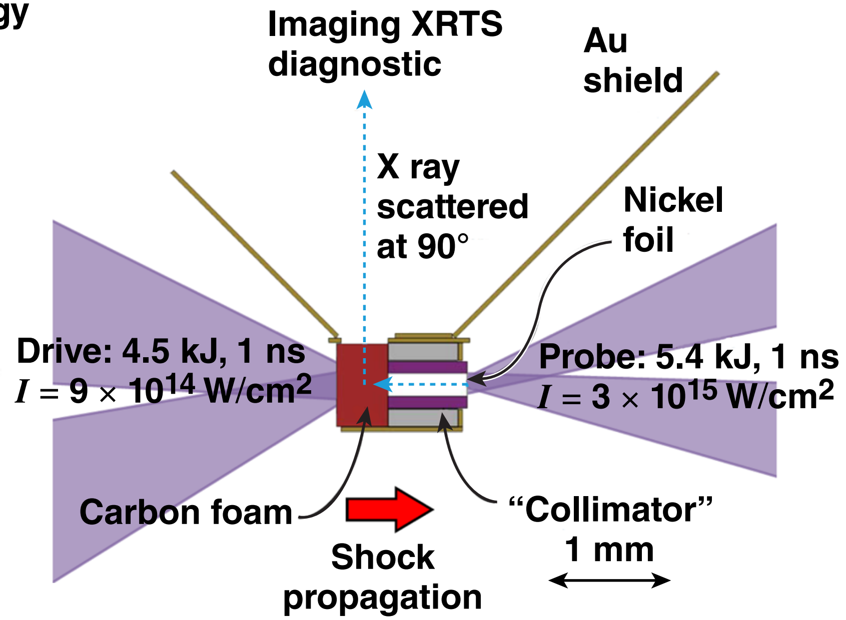
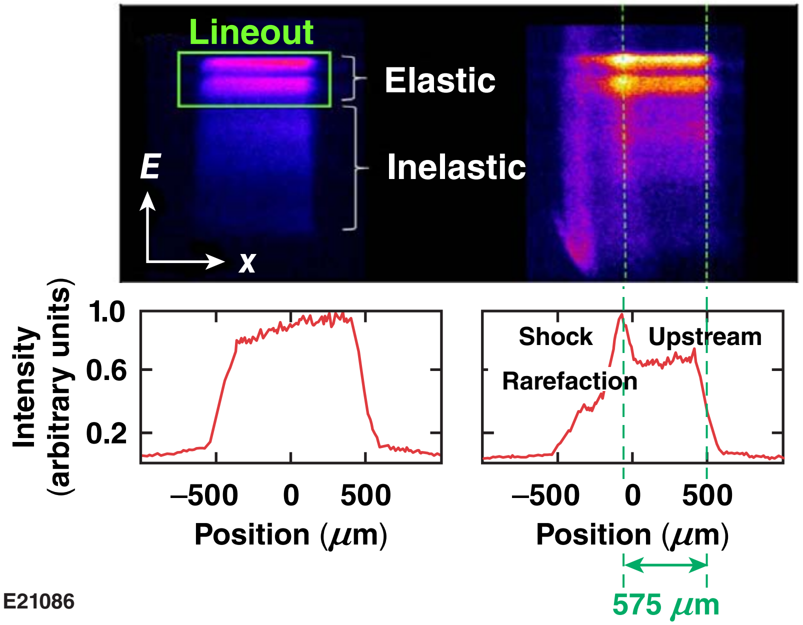
*A. J. Visco, *et al.,* PRL. 108, 145001 (2012).

The University of Michigan and LANL have deployed an imaging spectrometer for XRTS on OMEGA







Spatially resolved XRTS ($dx \sim 50$ μm) was recorded.

Gamboa *et al.*, to be presented at the 19th Topical Conference on High Temperature Plasma Diagnostics, Monterey, CA 6–10 May (2012).

Outline

- Motivation
- XRTS
- Experiments
- **Future**

A spatial resolution of ~10 μm for spectral measurments would greatly benefit many XRTS experiments

- General-use spectral imaging diagnostic
- Development of brighter backlighters
- Improve accuracy of target alignment
  - install foreground lighting on OMEGA Target Viewing System

OLUG could help to develop specifications for next-generation XRTS measurements on OMEGA.

Summary/Conclusions

X-ray Thomson scattering* (XRTS) is a primary diagnostic for high-energy-density-physics (HEDP) experiments

- The conditions of dense plasmas are probed with XRTS, especially warm, dense matter with $T_e \sim T_F$ and the ratio of potential energy to kinetic energy of the ions greater than unity
- The elastic and inelastic x-ray scattering features are spectrally resolved
  - scattering from electrons (noncollective) → T_e, Z
  - scattering from plasmons (collective) → n_e
  - elastic scattering → structure of matter
- A review of XRTS experiments is presented
  - inertial confinement fusion (ICF)
  - radiation heated
  - shock heated and compressed
  - proton heated
  - laboratory astrophysics (radiative shocks and planetary interiors)

Many XRTS experiments need spatially resolved spectral measurements.

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*S. H. Glenzer and R. Redmer, Rev. Mod. Phys. 81, 1625 (2008).
O. L. Landen *et al*., J. Quant. Spectrosc. Radiat. Transf. 71, 465 (2001).
G. Gregori *et al*., Phys. Rev. E 67, 026412(2003).