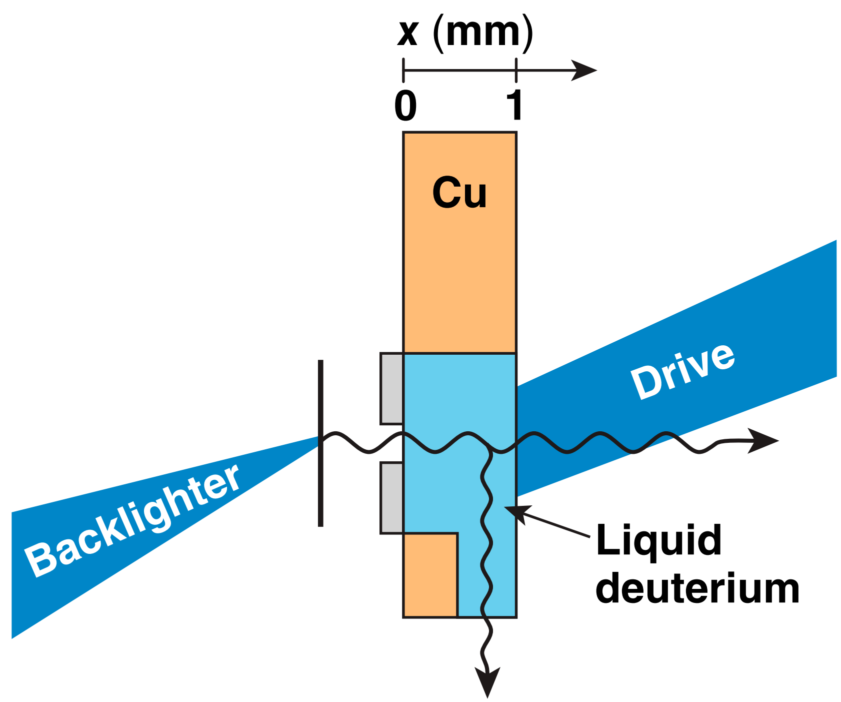
Inferring the Electron Temperature of Shocked Liquid Deuterium Using Inelastic X-ray Scattering

Planar cryogenic target

90° x-ray-scattering geometry



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Summary

Inelastic x-ray scattering is a powerful diagnostic for equation-of-state measurements

- The electron temperature (T_e) of the shocked deuterium is inferred from the spectral line shapes of the noncollective x-ray scattering.
- Initial results from the new cryogenic experimental platform are consistent with *DRACO* 2-D simulations.
  - $T_e \sim 10$ eV at $P \sim 10$ Mbar

Future experiments will combine inelastic x-ray-scattering observations with shock-velocity measurements to infer n_e, T_e, Z, ρ, and P of the shocked deuterium.

Collaborators

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The shell adiabat is an important parameter for inertial confinement fusion (ICF)

- Shell adiabat $\rightarrow$ $\alpha = \dfrac{P_{\text{fuel}}}{P_{\text{Fermi}}}$

- The shell adiabat of the target is mainly controlled by the shock-wave strength.

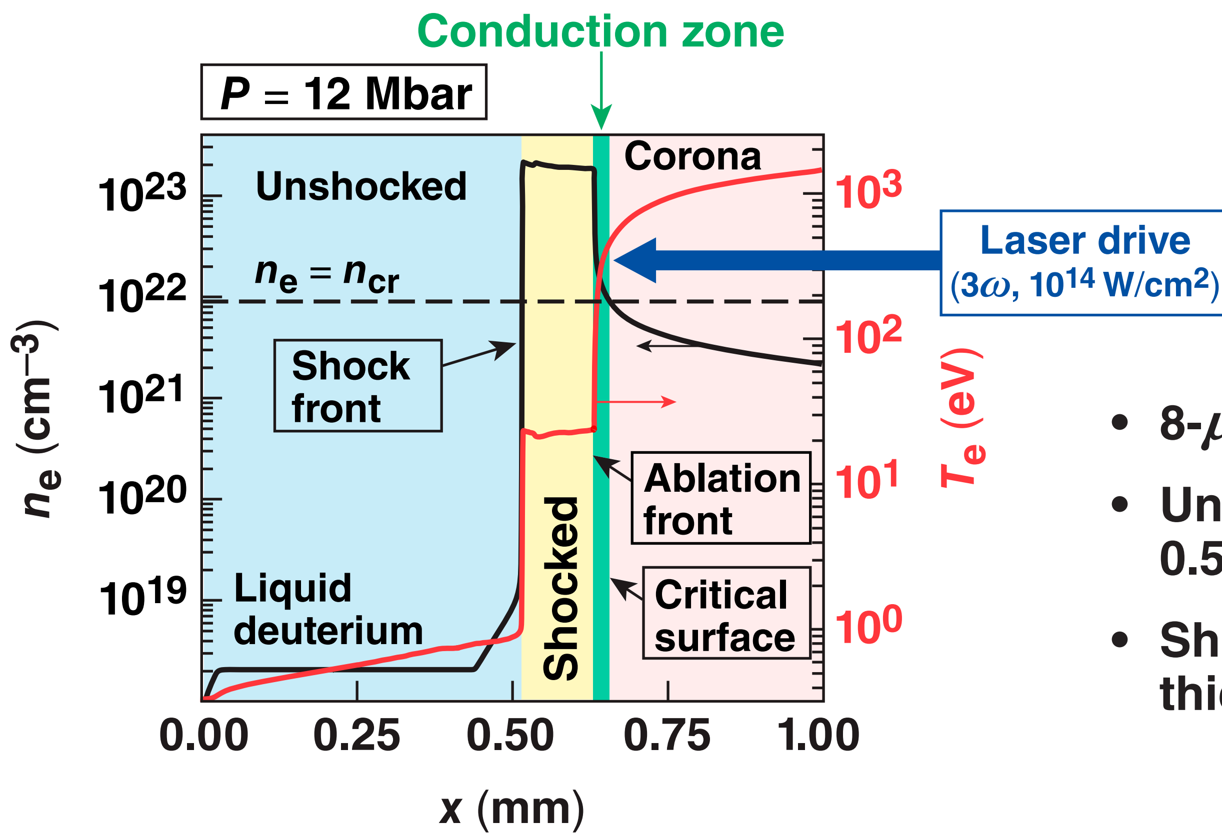
Motivation for measuring low adiabat ($\alpha \sim 1$ to 3) plasma conditions in shocked deuterium:

$E_{min} \sim \alpha^{1.8}$ (minimum laser energy for ignition)*,**

*M. C. Hermann, M. Tabak, and J. D. Lindl, Nucl. Fusion 41, 99 (2001).
**R. Betti *et al.*, Phys. Plasmas 9, 2277 (2002).

A laser-ablation–driven shock wave is launched in a planar liquid-deuterium target creating warm dense matter

LILAC[1] 1-D simulations (t = 5 ns)



- 8-μm CH ablator
- Uniform drive over 0.5-mm diam
- Shocked deuterium thickness ~100 μm

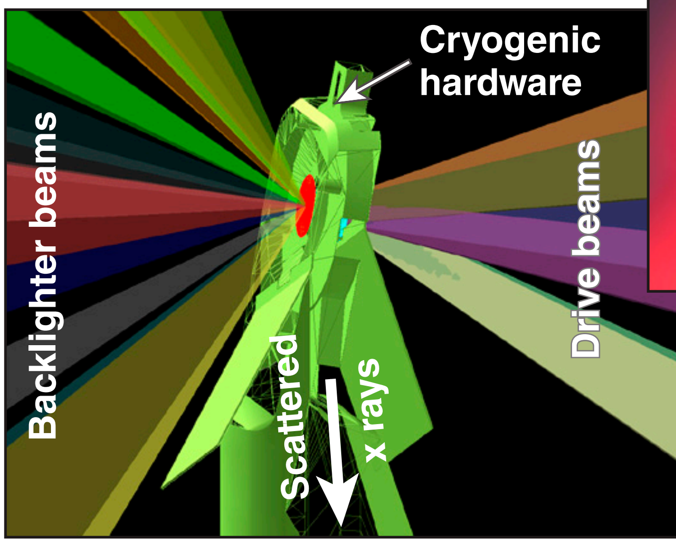
Uniform conditions with $n_e = 2.0 \times 10^{23}$ cm^{-3} ($\rho \sim 0.8$ g/cm^3) and T_e = 22 eV are predicted.

E17589b

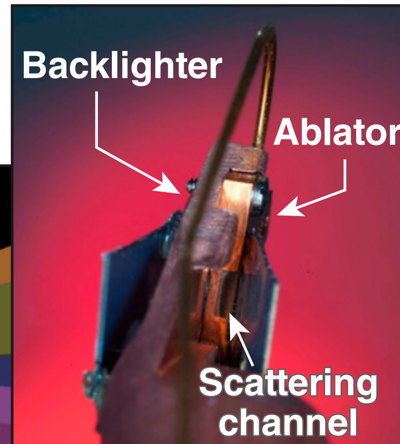
[1] J. A. Delettrez *et al*., Phys. Rev. A 36, 3926 (1987).

An experimental platform to study inelastic x-ray scattering[1] from shocked deuterium has been demonstrated

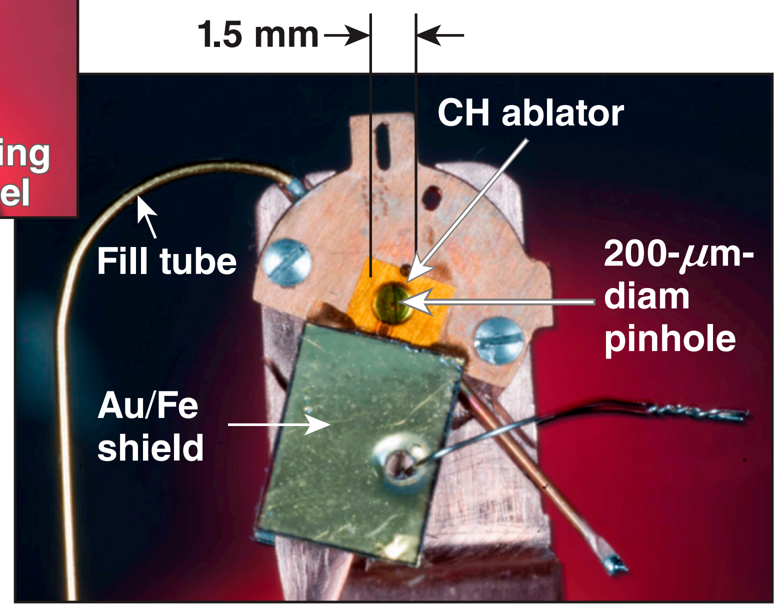
VisRad model



3 to 4 shots/day



Target images



The T_e of the shocked deuterium is inferred from the spectral line shapes of the noncollective x-ray scattering.

[1] S. H. Glenzer *et al.*, Phys. Rev. Lett. 90, 175002 (2003);
G. Gregori *et al.*, Phys. Rev. E 67, 026412 (2003);
H. Sawada *et al.*, Phys. Plasmas 14, 122703 (2007).

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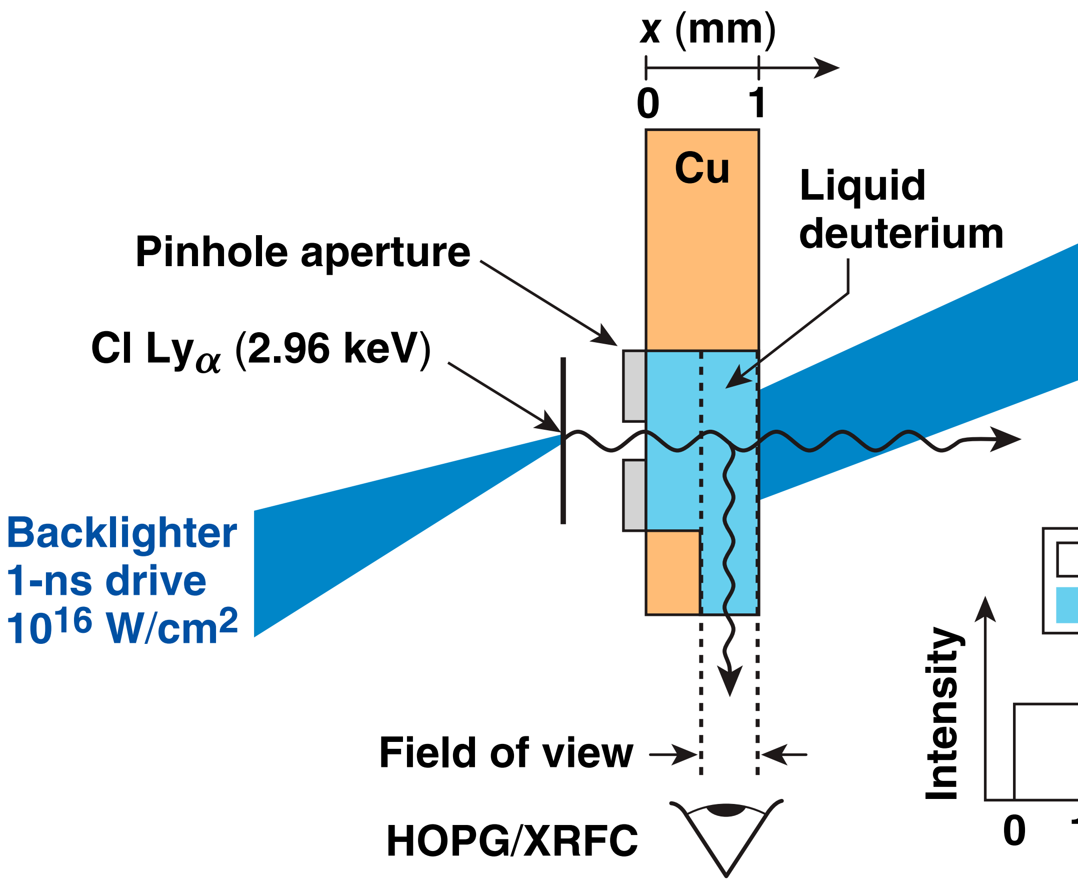
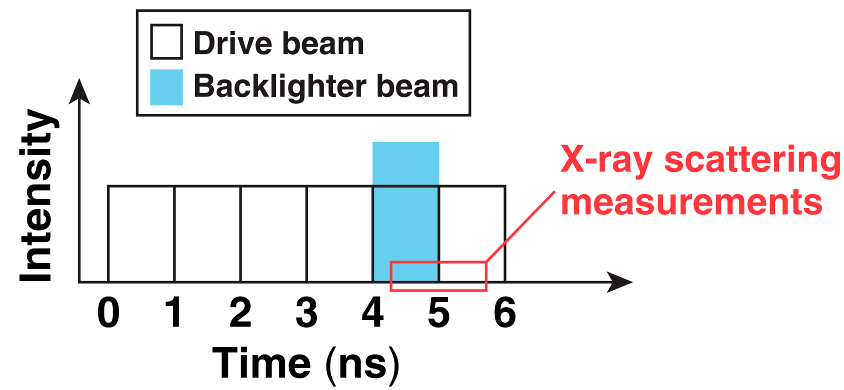
X rays scattered at 90° are recorded with a HOPG crystal spectrometer and an x-ray framing camera (XRFC)

Noncollective 90° x-ray-scattering experiment





Inelastic x-ray scattering is a powerful diagnostic for high-pressure (*P* > 10 Mbar) EOS research, which is inaccessible to optical shock-velocity measurements.

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T_e is inferred from the Doppler-broadened Compton-downshifted peak of the noncollective x-ray scattering for $T_e > T_F$*

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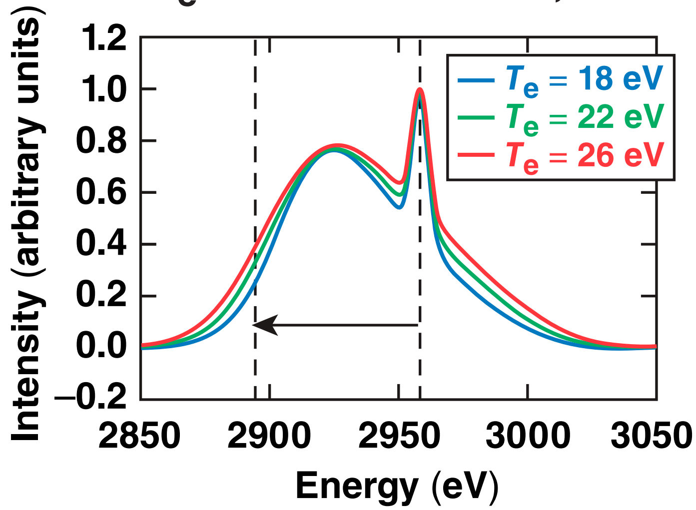
Calculated x-ray scattering from electrons ($\alpha_s \sim 0.6$)

$\theta = 90°$
$\lambda_0 = 4.188$ Å (Cl Ly$_\alpha$)
$T_e = 22$ eV
$n_e = 2.0 \times 10^{23}$ cm^{-3}, $Z = 1$



Compton downshifted energy (eV)

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

θ: scattering angle
λ_0: wavelength of probe

Scattering parameter

$$\alpha_s = \frac{1}{k\lambda_D}$$

$\alpha_s < 1$ noncollective → x rays scatter from individual electrons → T_e*
$\alpha_s > 1$ collective → x rays scatter from plasmons → n_e**

*G. Gregori *et al.*, Phys. Rev. E 67, 026412 (2003).
**S. H. Glenzer *et al.*, Phys. Rev. Lett. 98, 065002 (2007).

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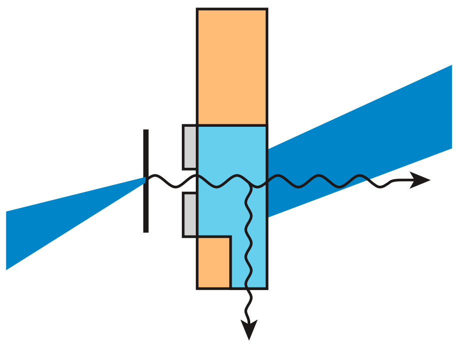
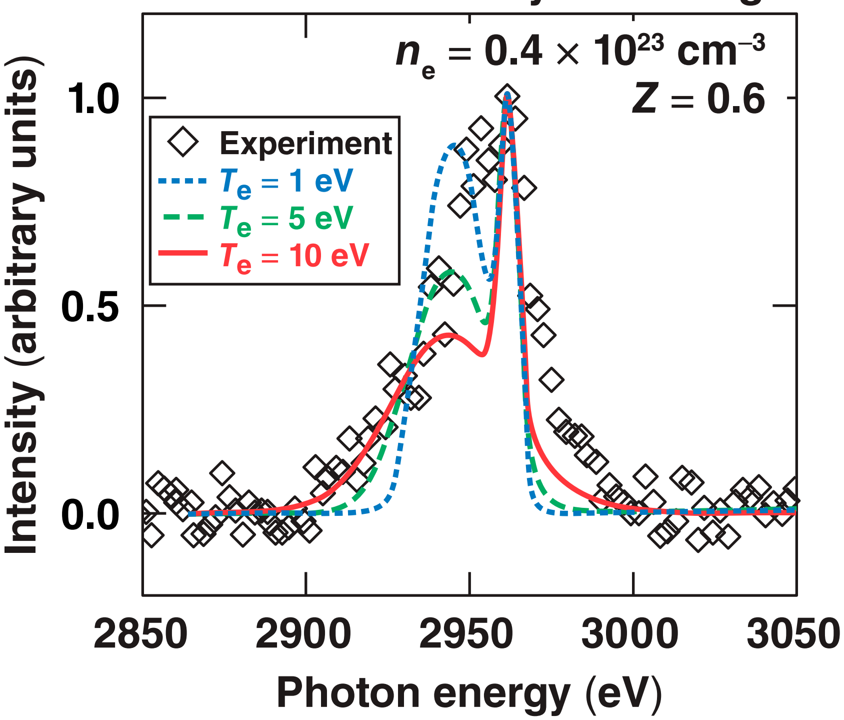
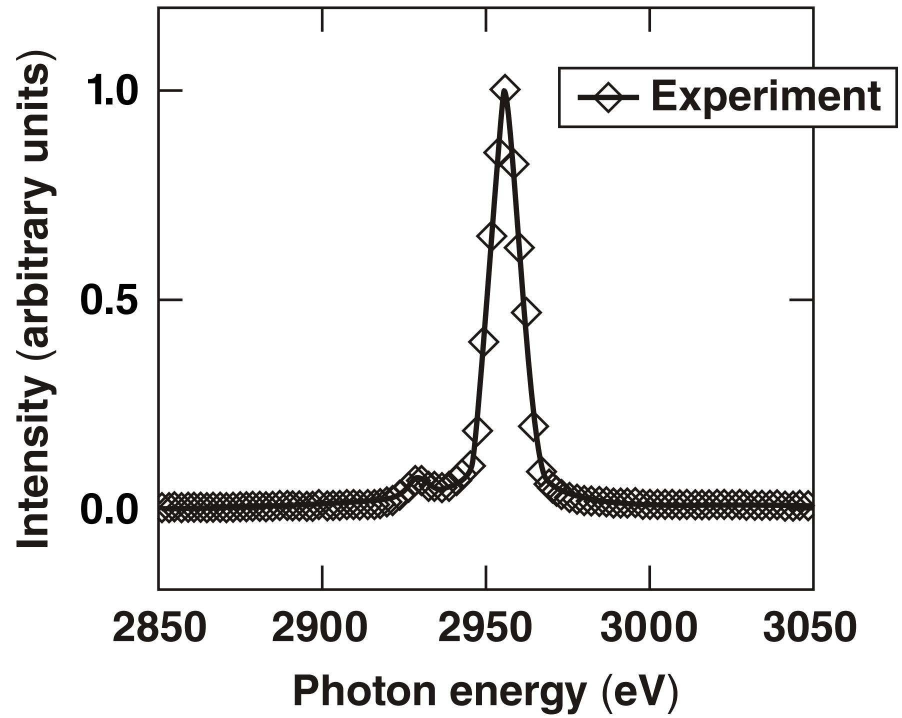
Noncollective x-ray scattering from shocked deuterium has been observed



Noncollective x-ray scattering



Transmitted x-ray spectrum



T_e (expt.) < T_e (1-D) = 22 eV:
X rays are scattered from shocked and unshocked deuterium.

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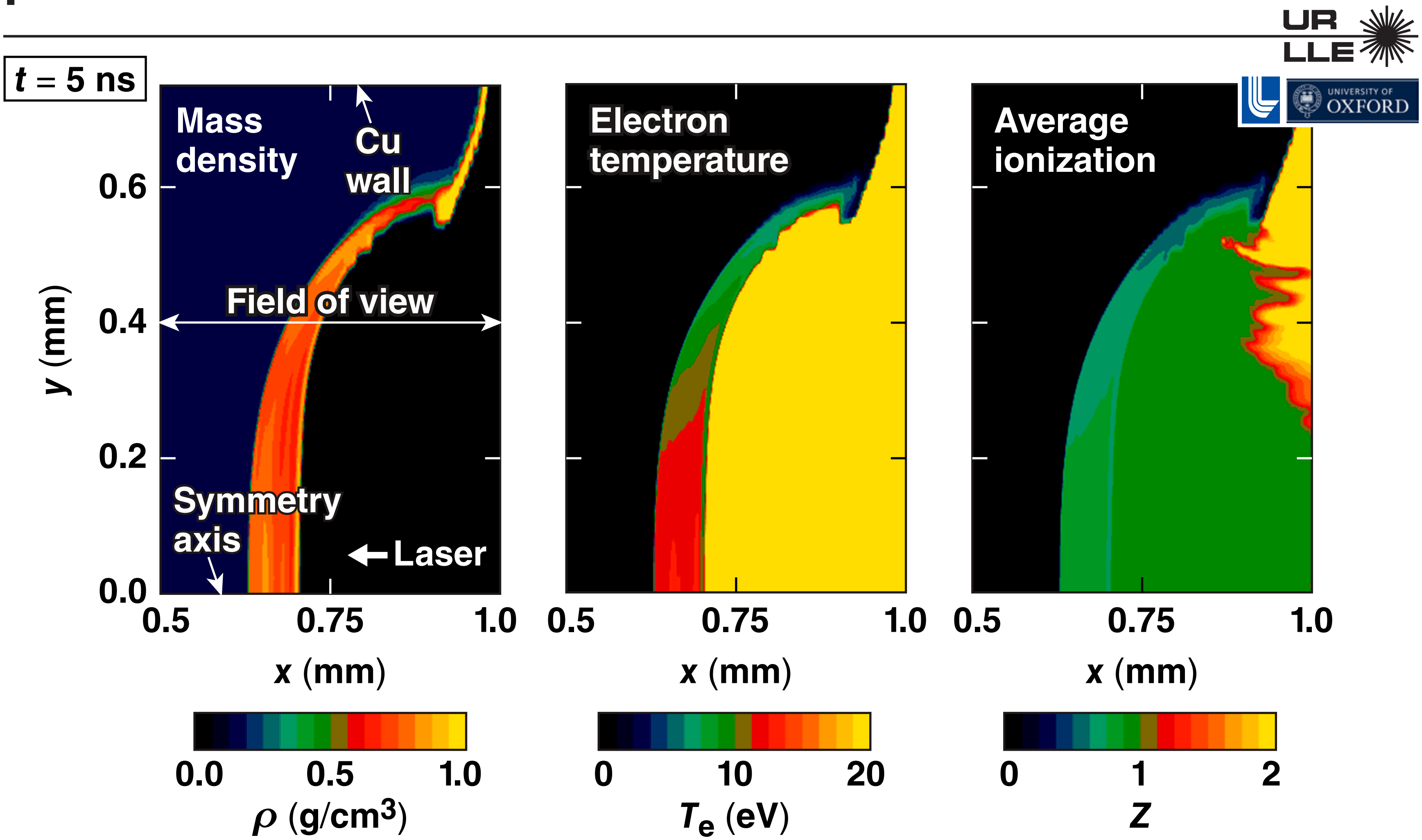
Initial results from the new cryogenic experimental platform are consistent with *DRACO** 2-D simulations



T_e (1-D) = 22 eV	→	T_e (2-D) = 5 to 15 eV	→	T_e (expt.) ~ 10 eV
Z (1-D) = 1	→	Z (2-D) ~ 0.5 to 0.8	→	Z (expt.) ~ 0.6

E18449

*P. B. Radha *et al.*, Phys Plasmas 12, 032702 (2005).

Summary/Conclusions

Inelastic x-ray scattering is a powerful diagnostic for equation-of-state measurements

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- **The electron temperature (T_e) of the shocked deuterium is inferred from the spectral line shapes of the noncollective x-ray scattering.**
- **Initial results from the new cryogenic experimental platform are consistent with *DRACO* 2-D simulations.**
  - **T_e ~ 10 eV at P ~ 10 Mbar**

Future experiments will combine inelastic x-ray-scattering observations with shock-velocity measurements to infer n_e, T_e, Z, ρ, and P of the shocked deuterium.