Probing matter at Gbar pressures at the NIF

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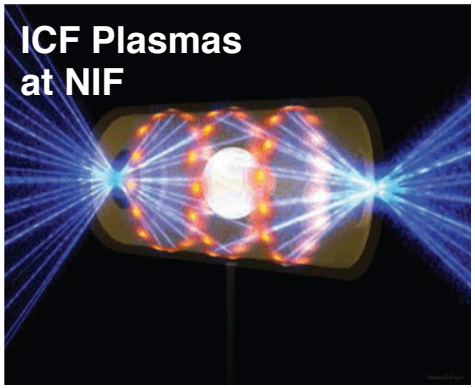
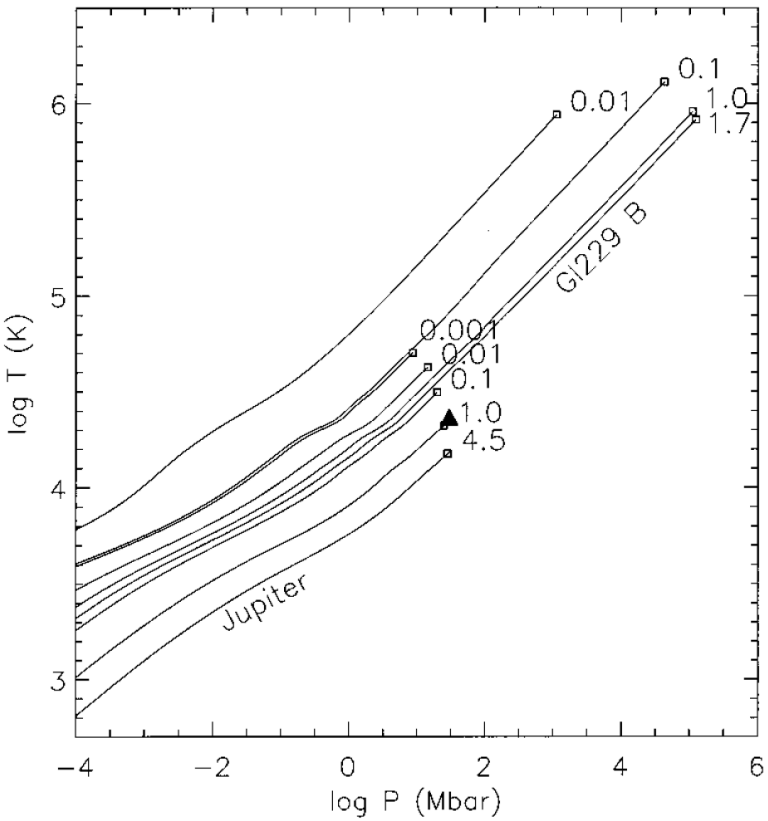
T. Doeppner, A. L. Kritcher, D. C. Swift, J. Hawreliak, D. Chapman, B. Bachmann, P. M. Celliers, G. W. Collins, T. Darling, E. Dewald, J. Eggert, L. B. Fletcher, E. Foerster, D.O. Gericke, S.H. Glenzer, S. Hamel, R. Hemley, R. Jeanloz, O. L. Landen, H. J. Lee, S. LePape, T. Ma, E. McKee, D. Milathianaki, J. Nilsen, P. Neumayer, R. Redmer, S. Rose, S. Rothman, C. Keane, and R. W. Falcone

Matter at Gbar pressure | Challenges and applications

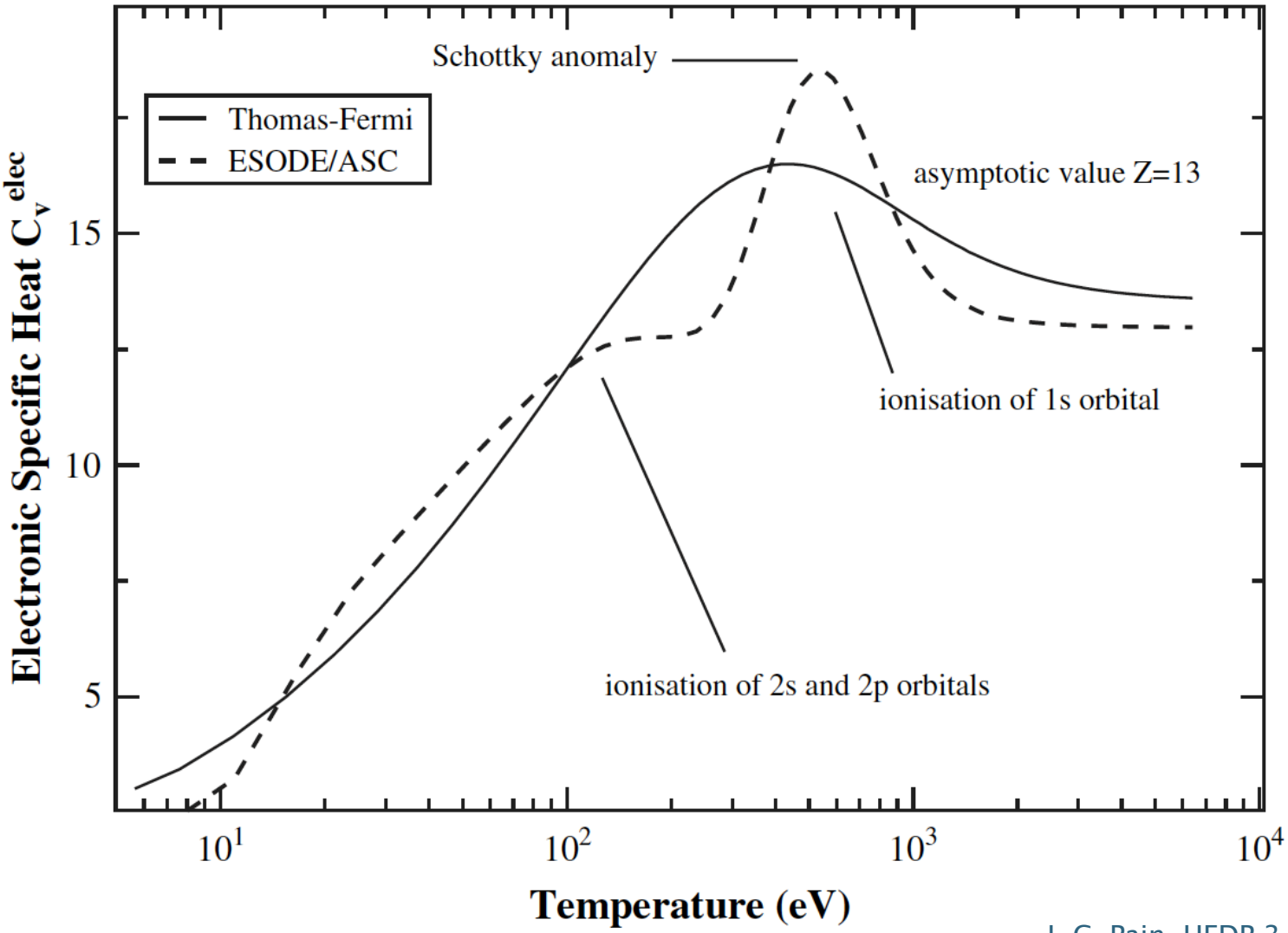
- Interplay of Coulomb pressure and electron-degeneracy pressure
- Partial ionization, shell effects
- Difficult description of compressibility and heat capacity





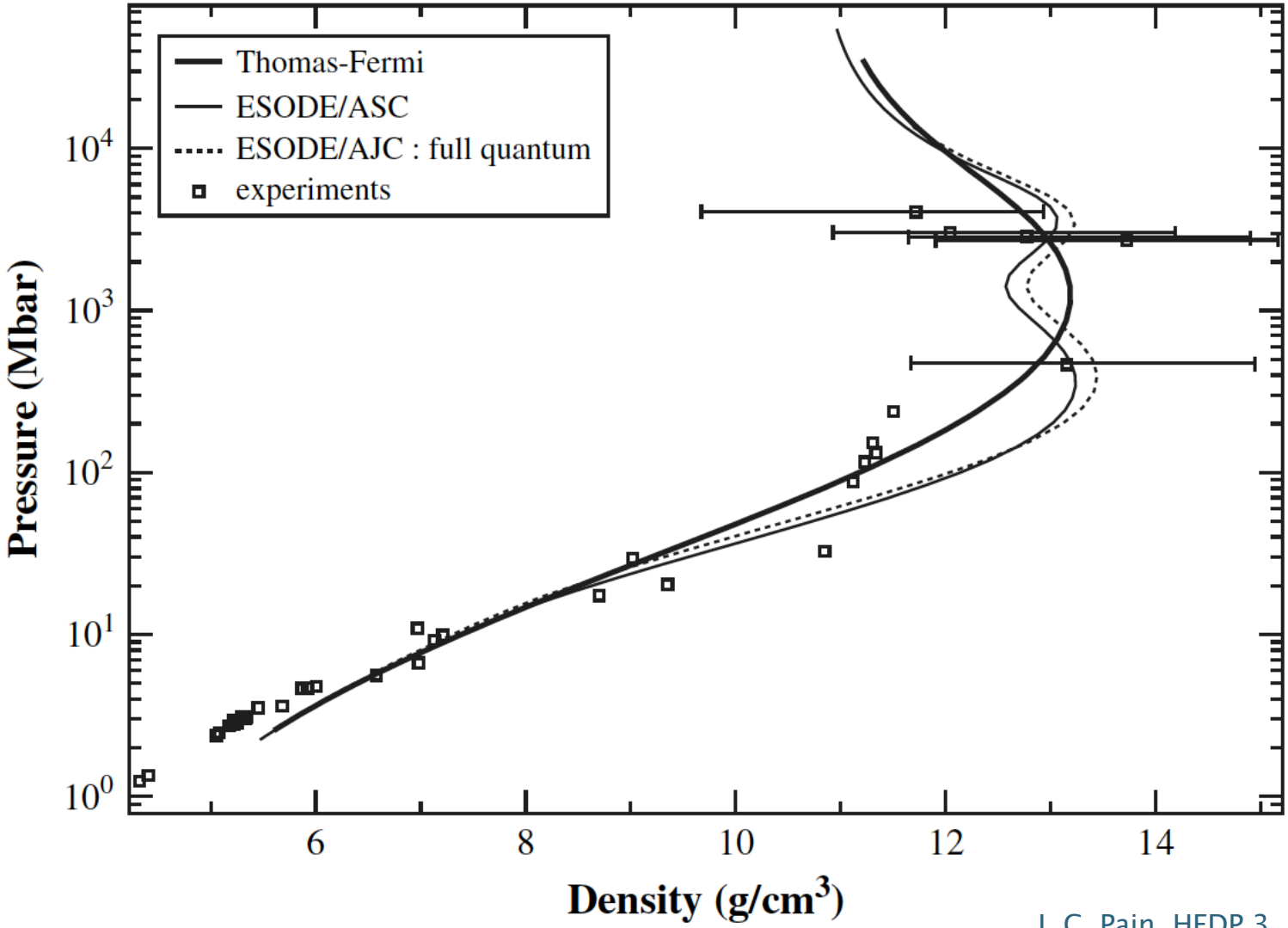
W. B. Hubbard et al, Physics of Plasmas 4, 2011 (1997)

Matter at Gbar pressure | Shell effects: heat capacity of aluminum



J. C. Pain, HEDP 3, 204 (2007)

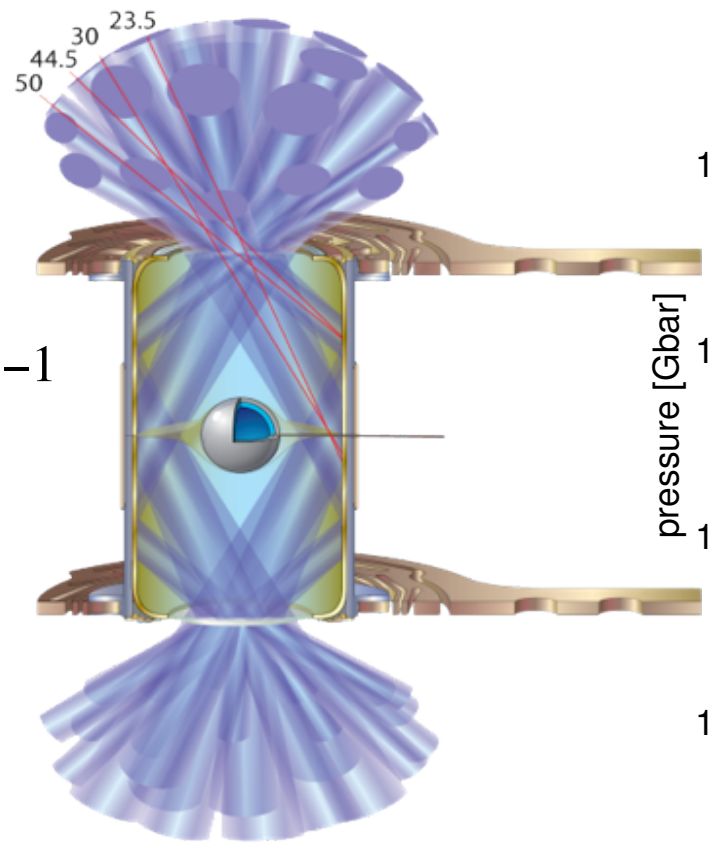
Matter at Gbar pressure | Shell effects: Aluminum Hugoniot

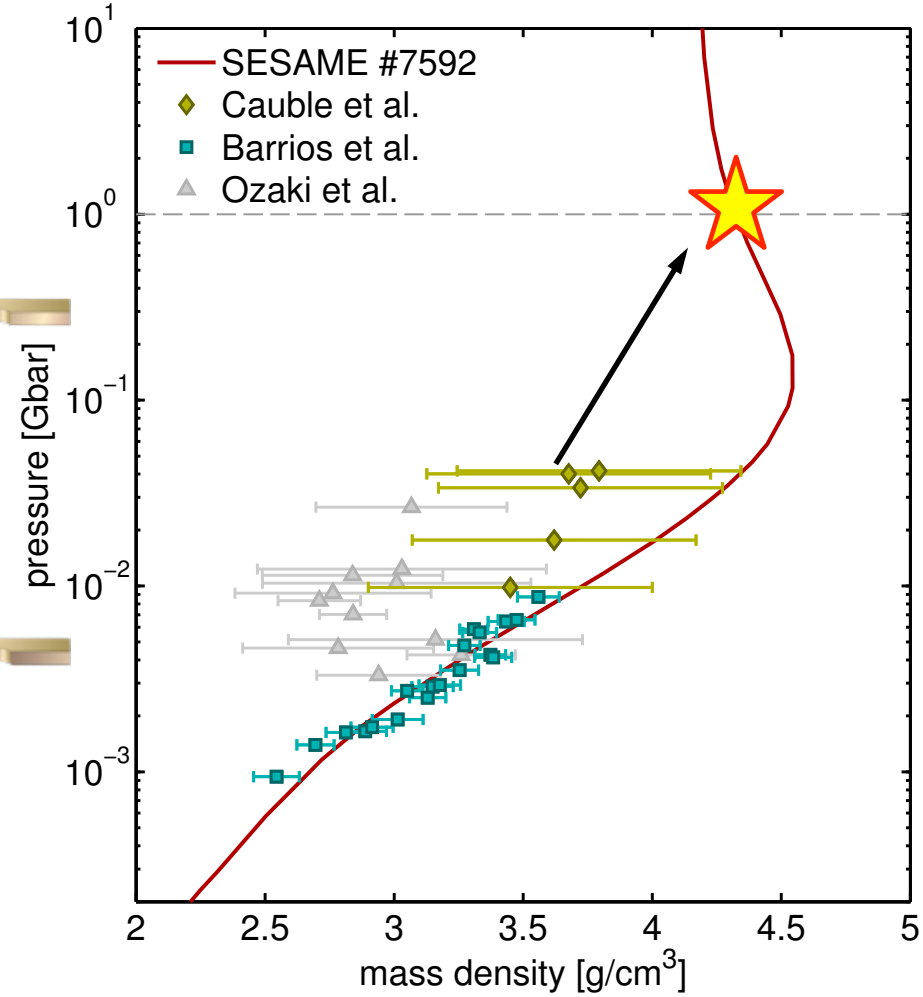


J. C. Pain, HEDP 3, 204 (2007)

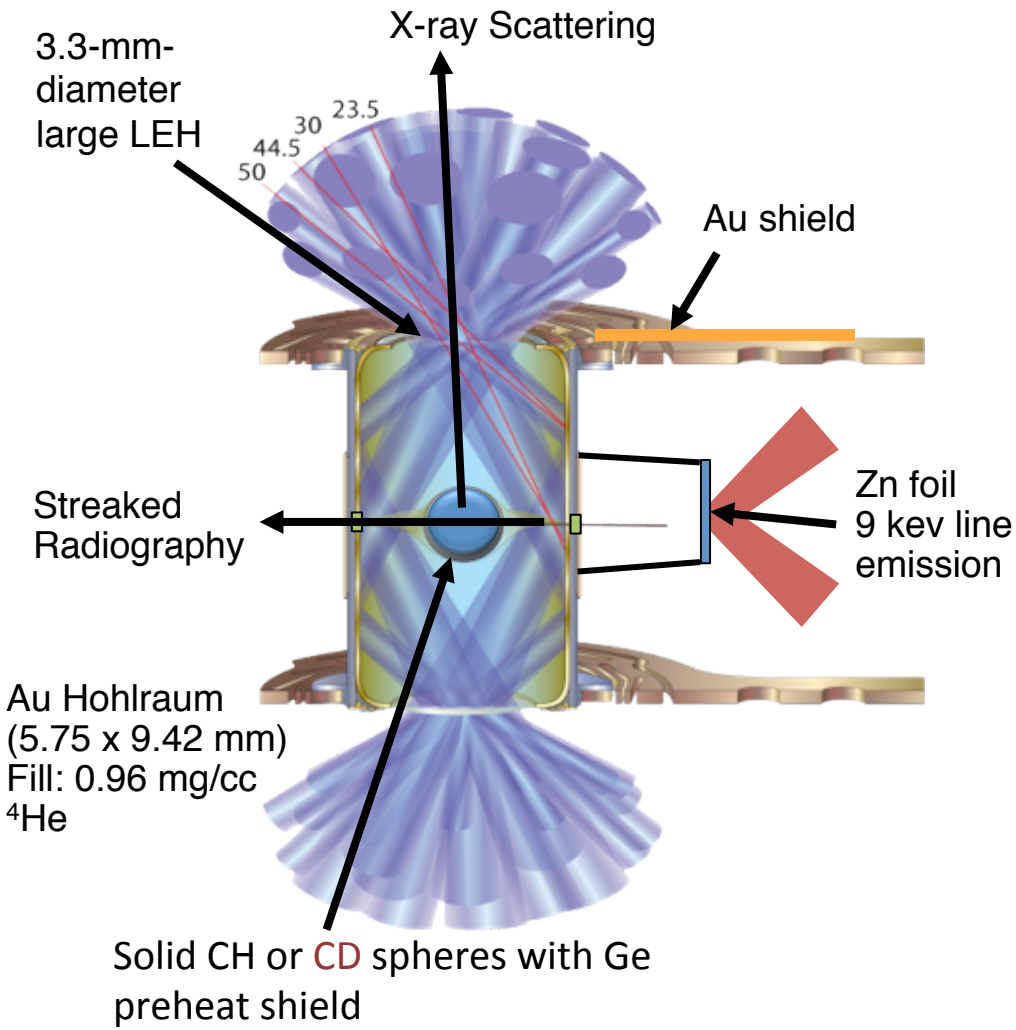
Matter at Gbar pressure | CH Hugoniot & shell structure

$$\frac{P}{P_0} \sim r^{-1}$$





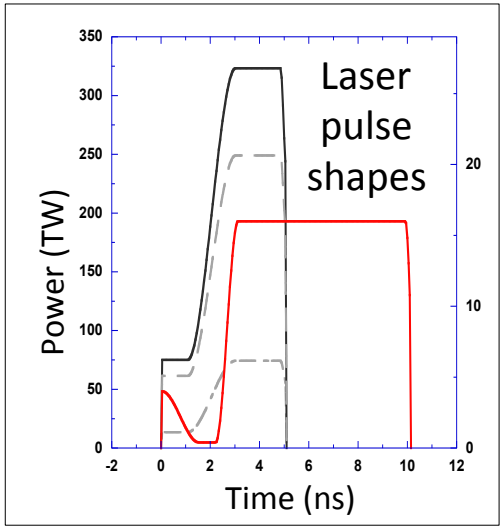
Experimental setup | X-ray radiography and scattering



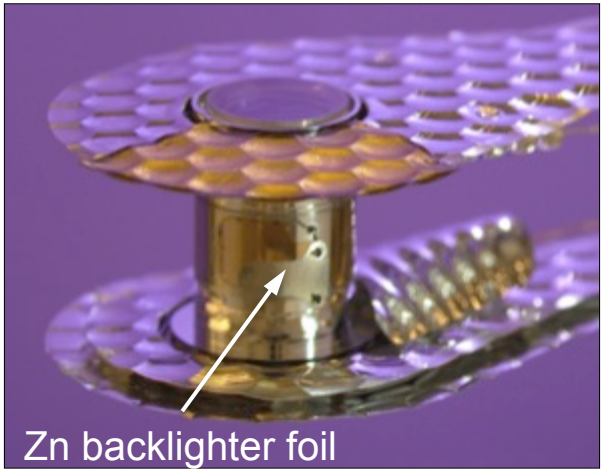
Modified existing NIF platform (1D Convergent Ablator)

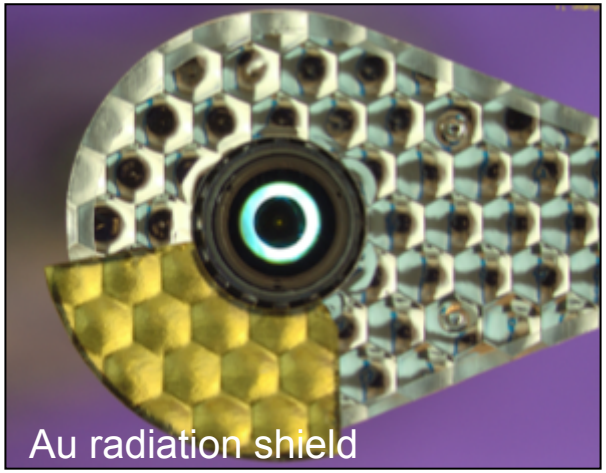
Main diagnostics:

- Streaked X-ray radiography (shock speed, mass density)
- X-ray Thomson scattering (electron temperature)

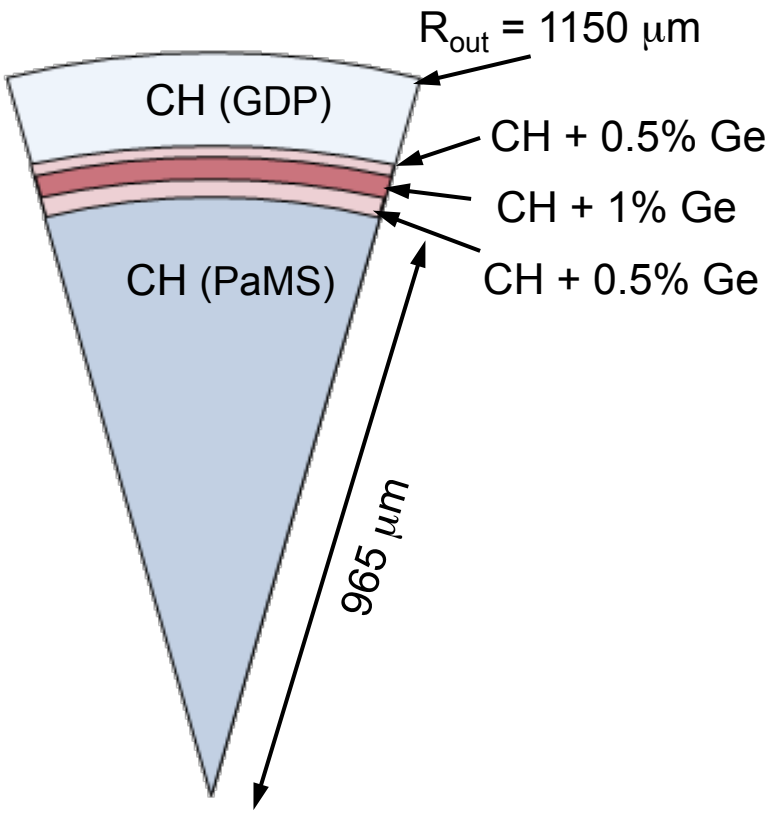


Experimental setup | Target design

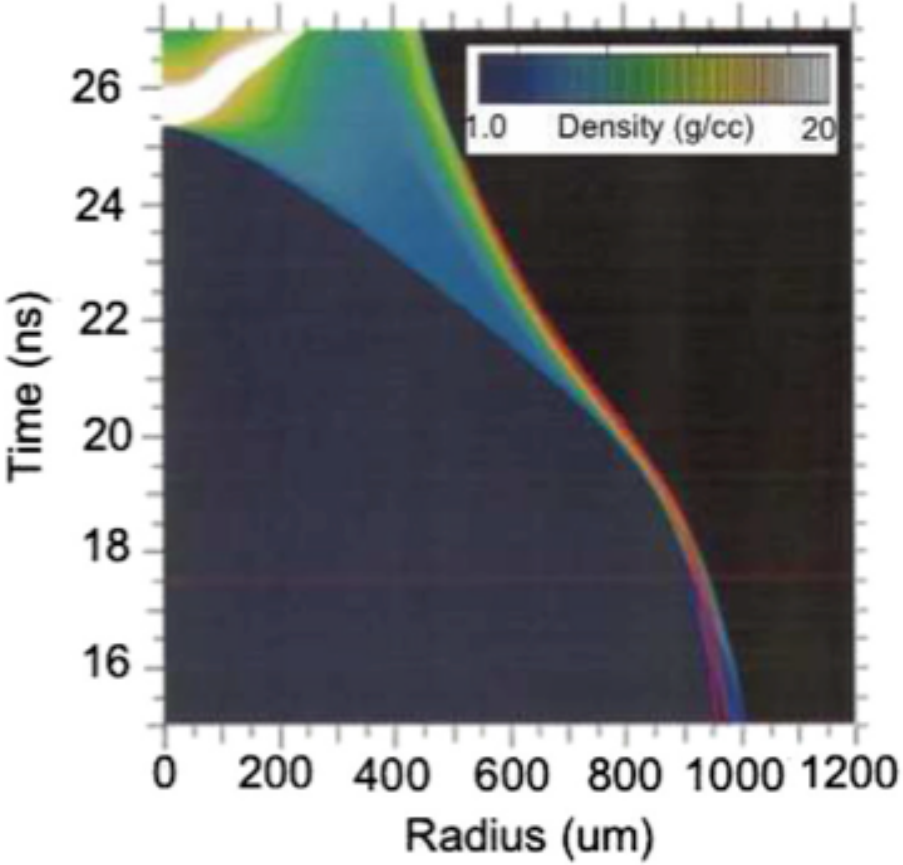




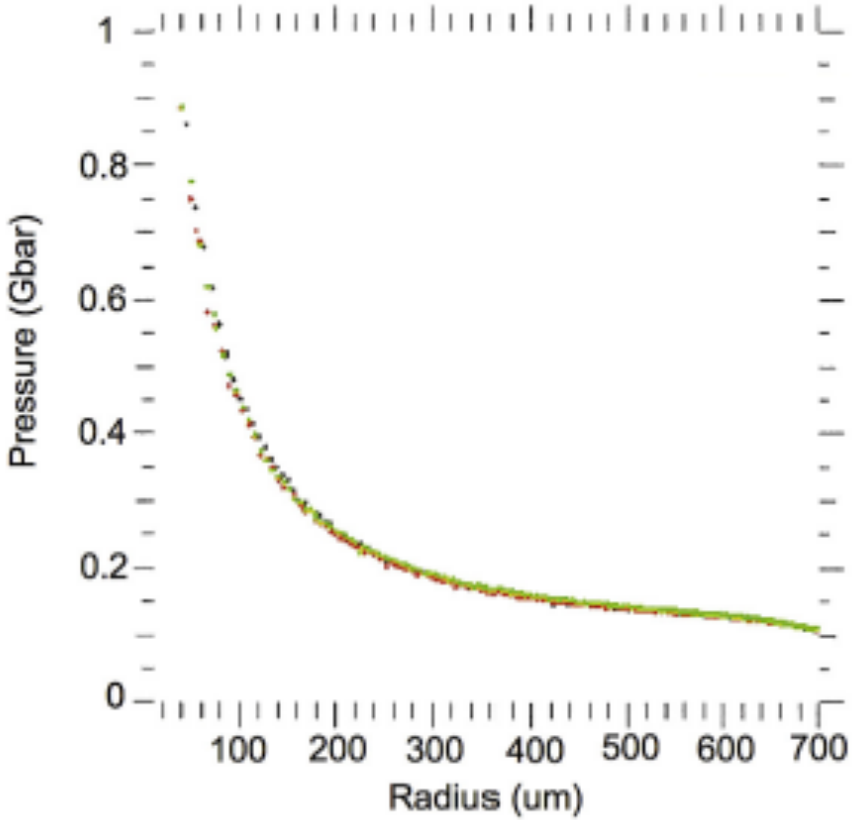
capsule design with graded Ge dopant layer



Simulations | Parameter space



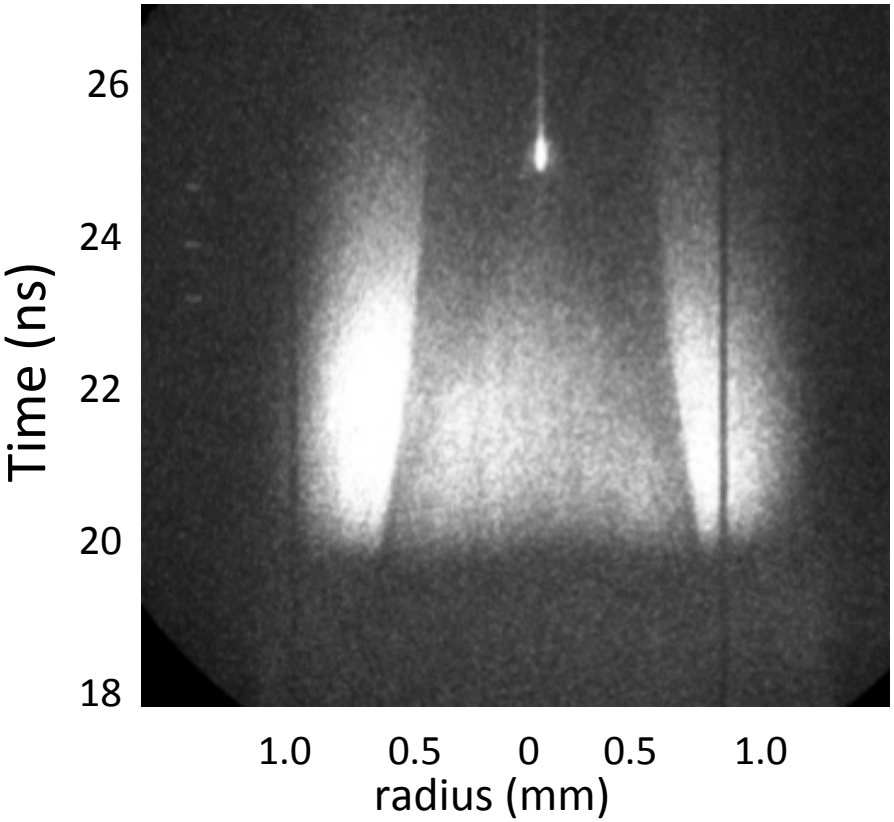
Pressure at shock front



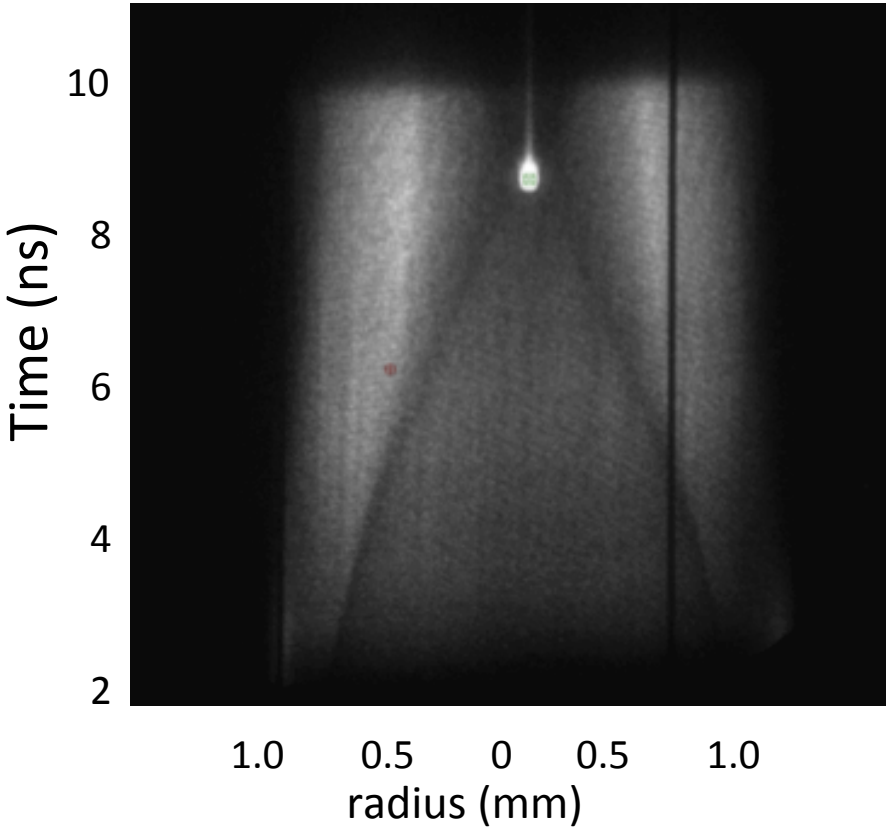
A. L. Kritcher et al., HEDP 10, 27 (2014)

X-ray radiography | Raw data

January 03, 2013

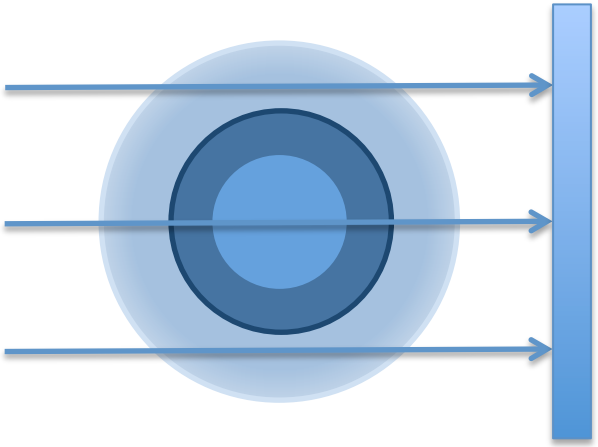


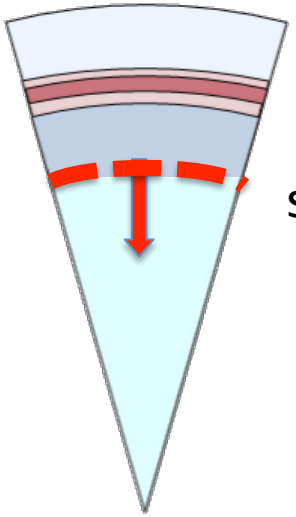
July 01, 2013



X-ray radiography | Analysis

- Profile matching to infer
  $\mu(r) = \rho(r)\ \sigma(r)$
- Movement of shock front with time gives shock velocity
- After shock passes marker layer, enclosed mass between shock front and marker layer is known
- Assuming constant density and constant opacity for first time step after passing marker layer: simultaneous density and opacity unfold
- As shock propagates: Using relative comparison to the first time step after passing the marker layer gives full density and opacity profile

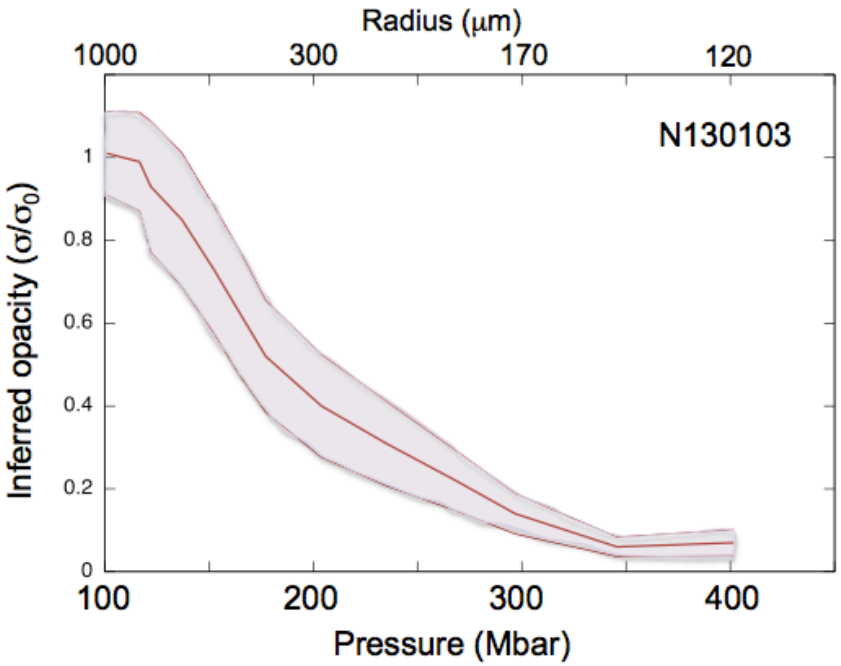




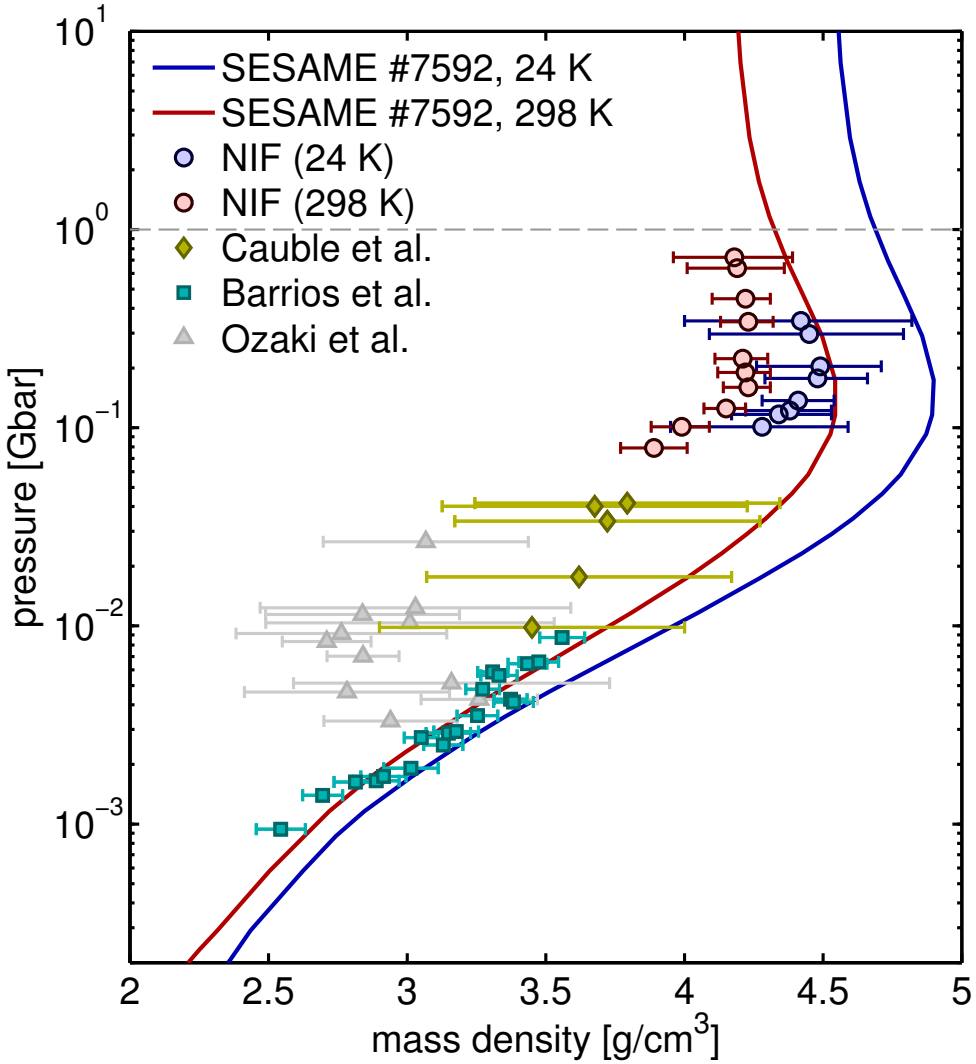
D. C. Swift et al., in prep.

X-ray radiography | Results

Inferred opacity



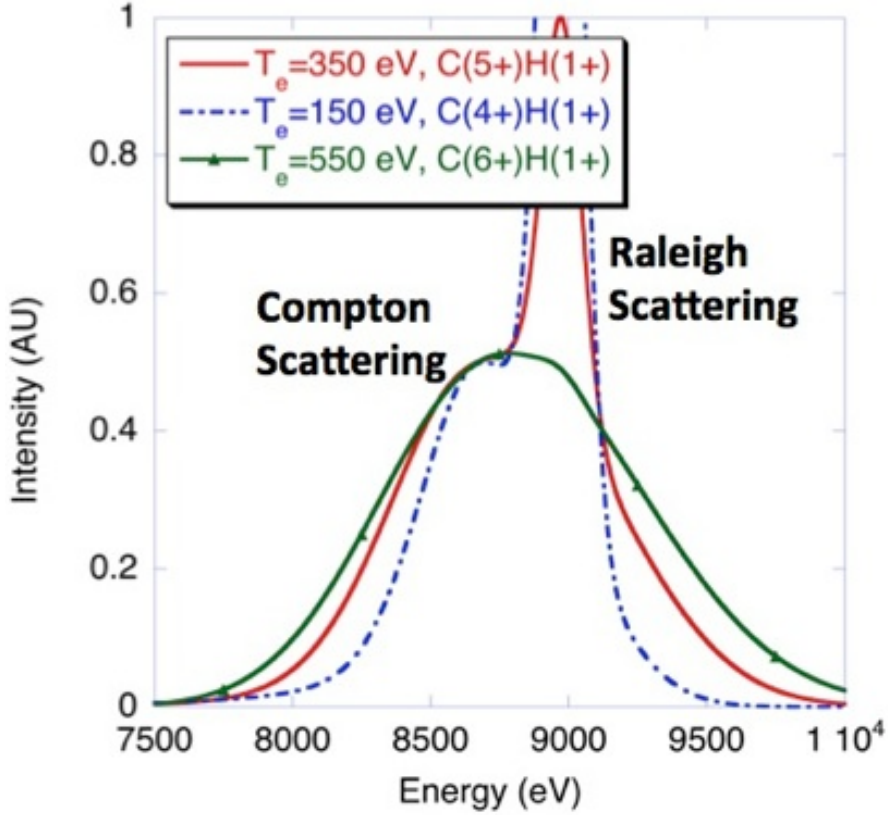
Hugoniot data



T. Doeppner et al., in prep.

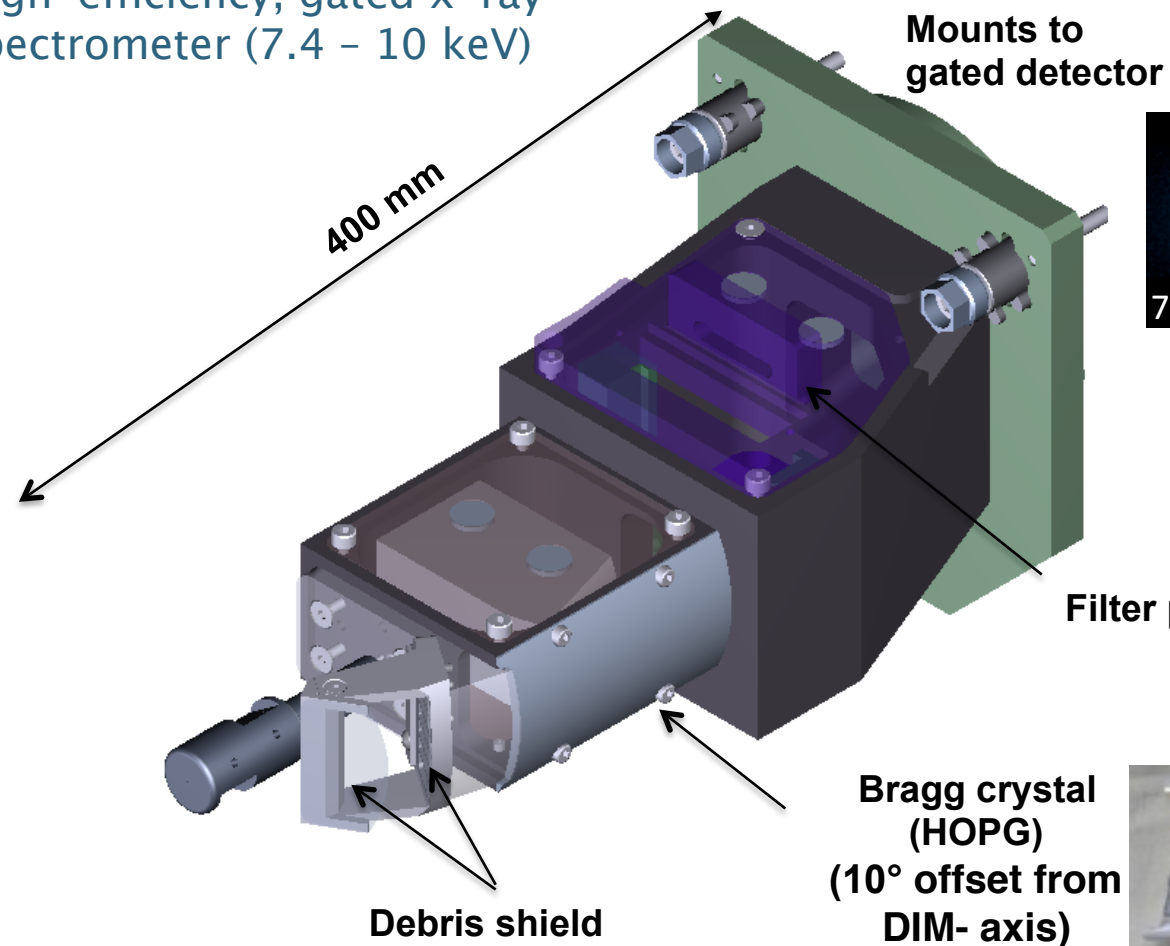
X-ray scattering | Temperature measurement

- X-rays are scattered from plasma electrons
- **Elastic (Rayleigh):** scattering from tightly bound electrons or free electrons which dynamically follow the ion motion
- **Inelastic (Compton):** scattering from free or weakly bound electrons, mirrors electron velocity distribution → T_e

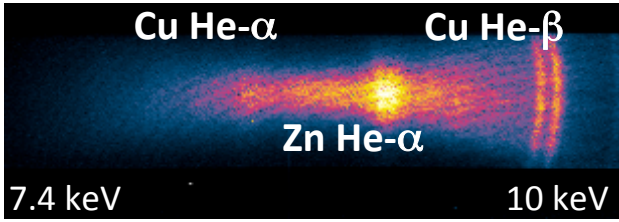


X-ray scattering | Spectrometer setup

High-efficiency, gated x-ray spectrometer (7.4 – 10 keV)

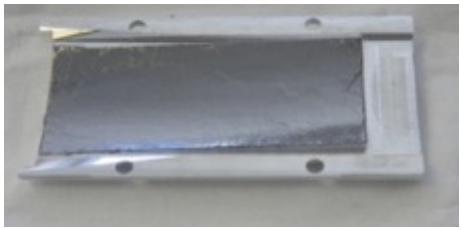


Calibration shot



Photon energy

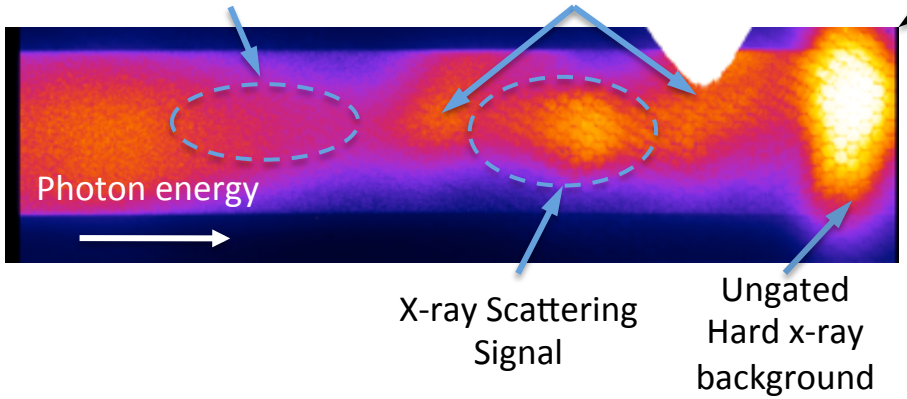
Bragg crystal (HOPG) (10° offset from DIM- axis)



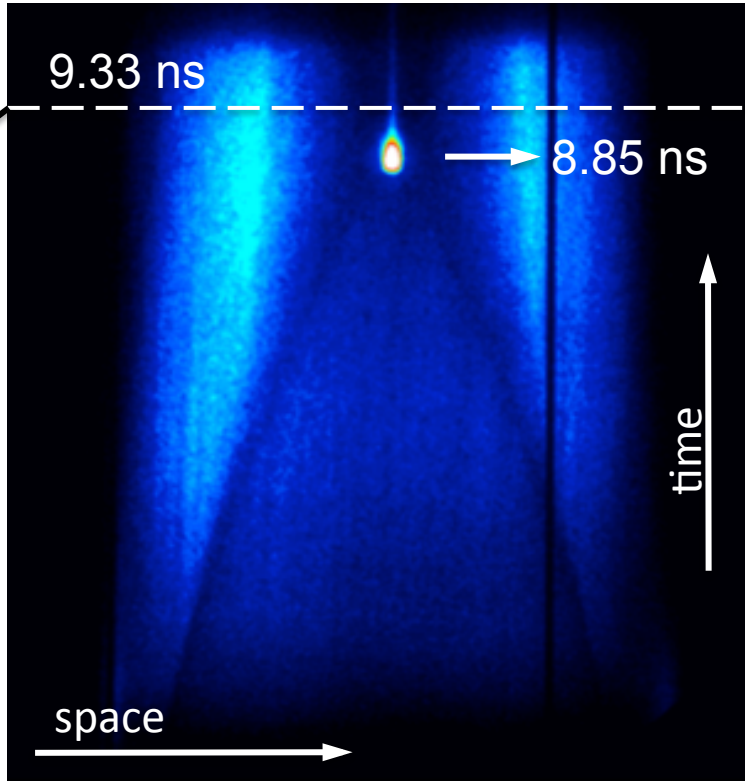
T. Doeppner et al., in prep.

X-ray scattering | Raw data

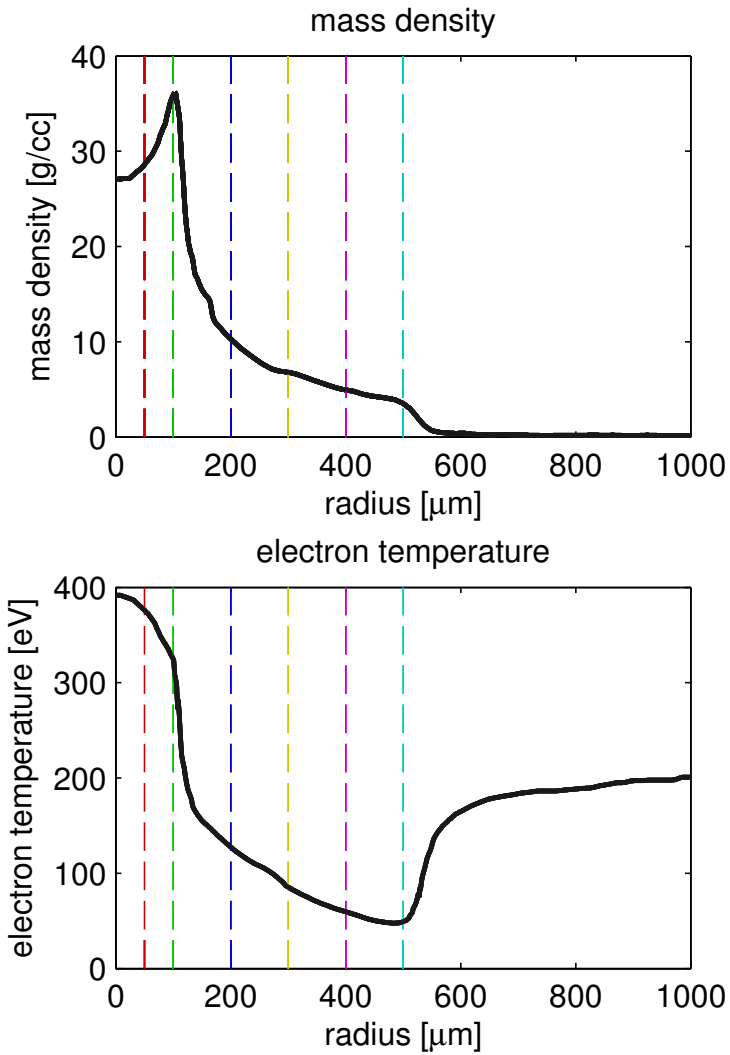
time-resolved x-ray spectrum



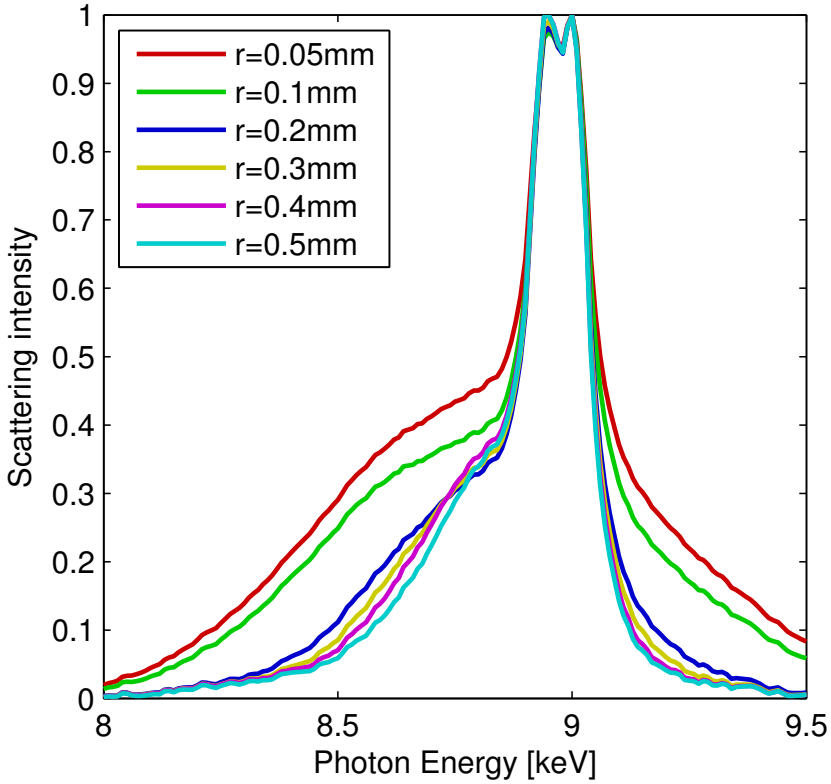
streaked radiograph



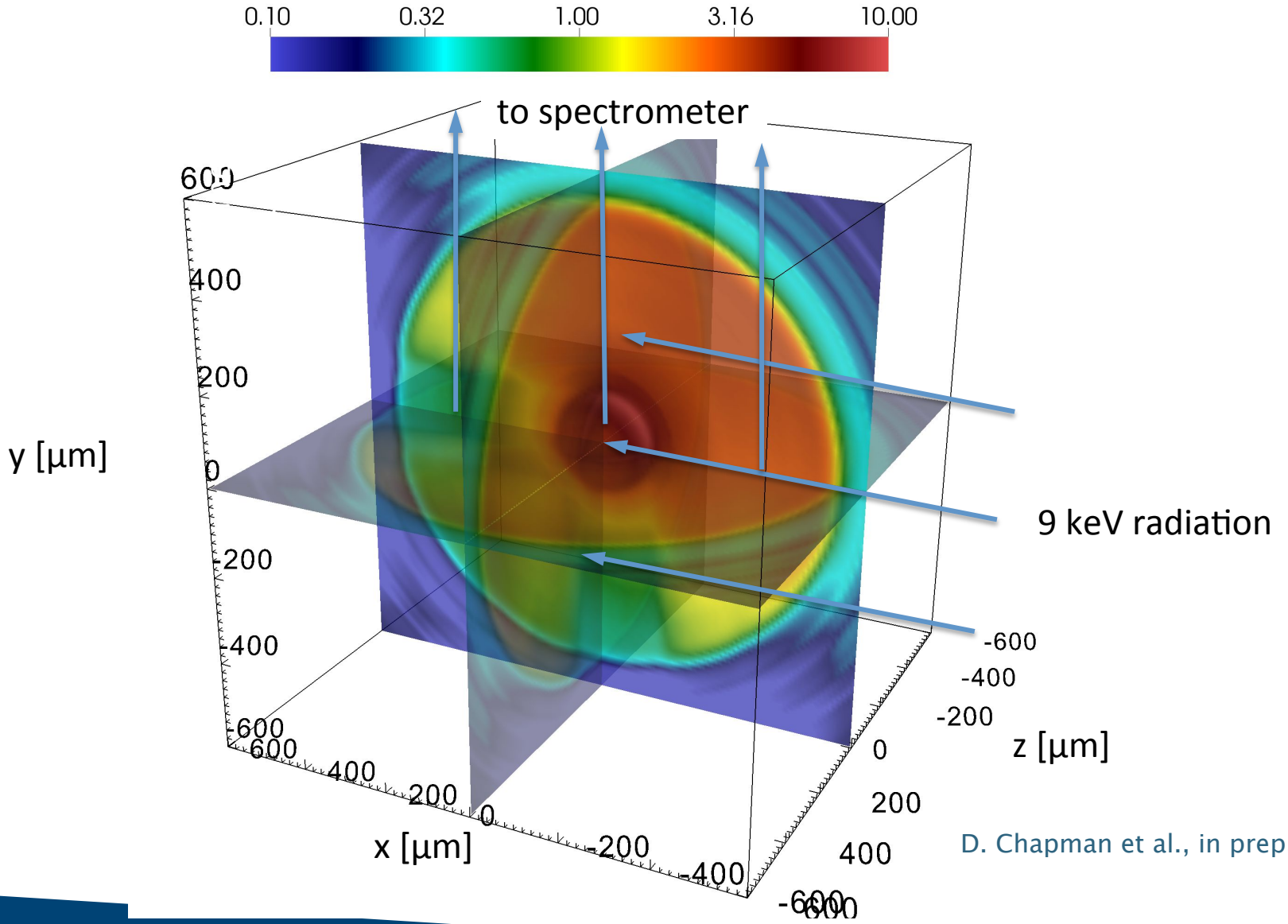
X-ray scattering | Analysis: inhomogeneous sample



Different expected X-ray scattering spectra from different radii

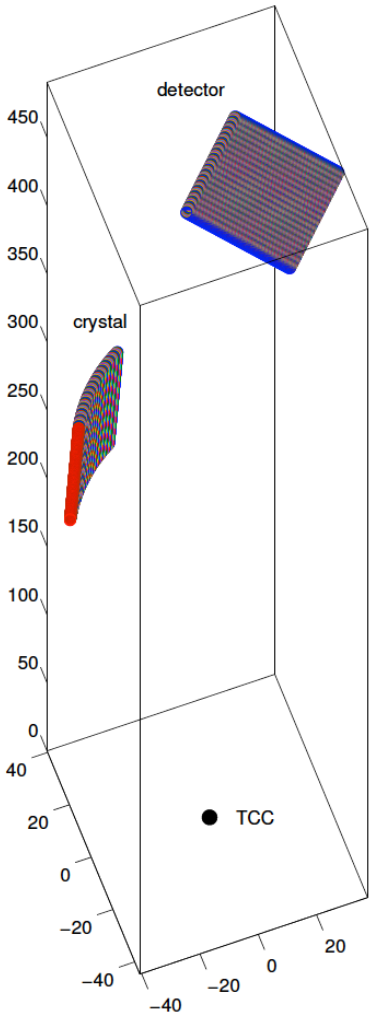


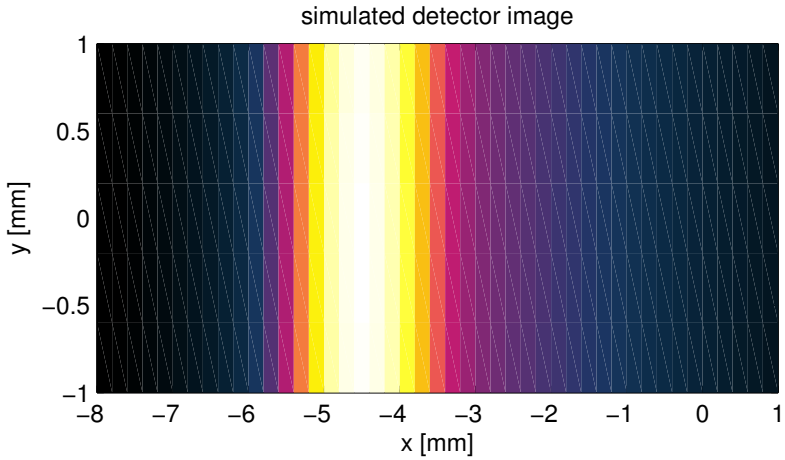
X-ray scattering | Analysis: scattering signal weighting

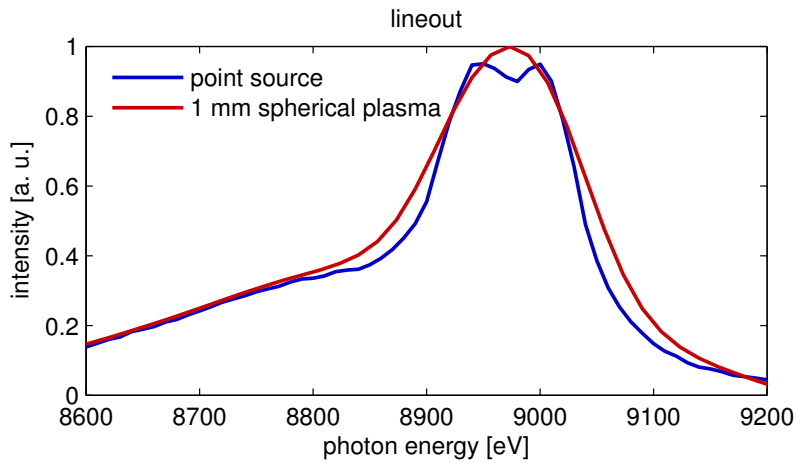


D. Chapman et al., in prep.

X-ray scattering | Analysis: spectrometer ray-tracing



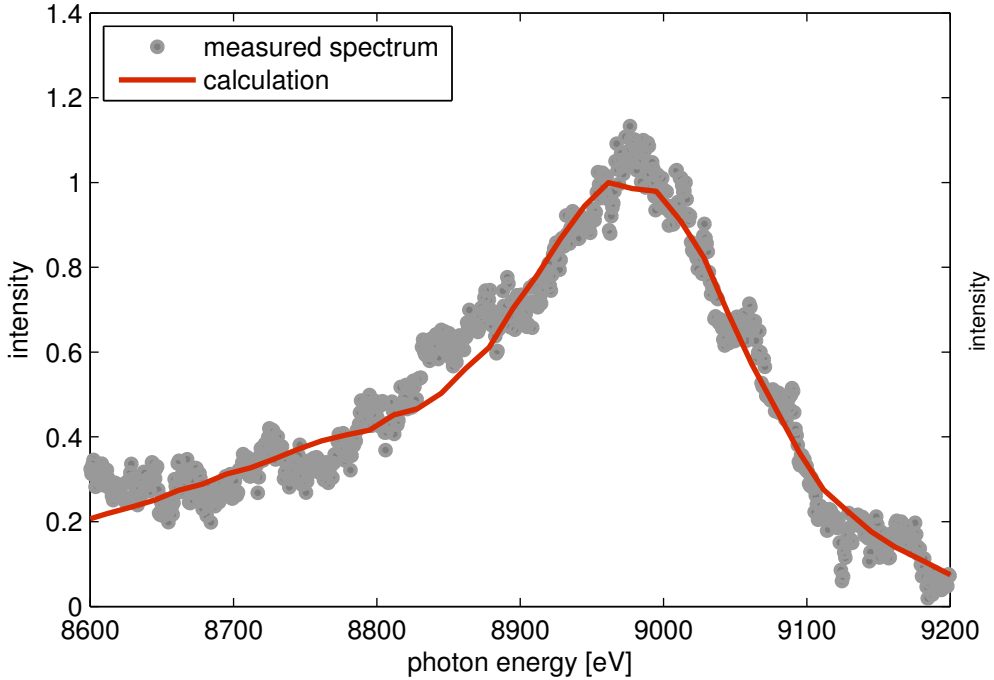


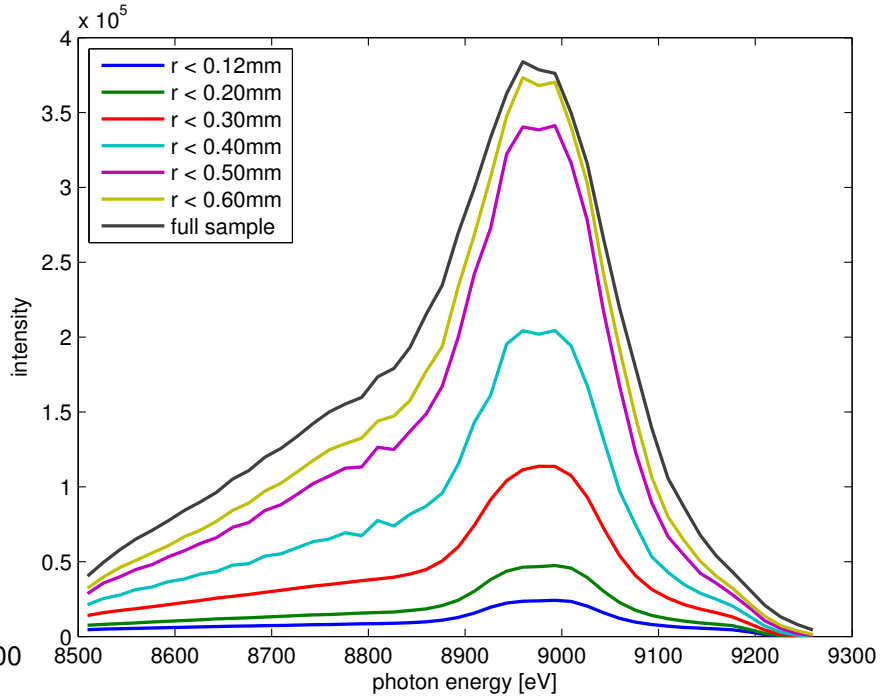


Full analysis:

- Calculate radial scattering spectrum for sample conditions
- Apply weighting maps (3D)
- Ray-tracing of weighted spectra to detector (3D)
- Compare result with measured spectrum

X-ray scattering | Results





Signal dominated by
300 μm ≤r ≤ 500 μm

at r = 400 μm (Hydra + SESAME):

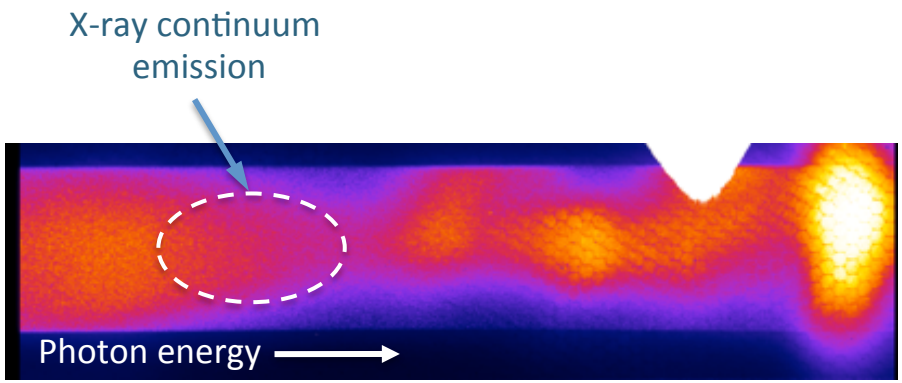
T_e = 60 eV

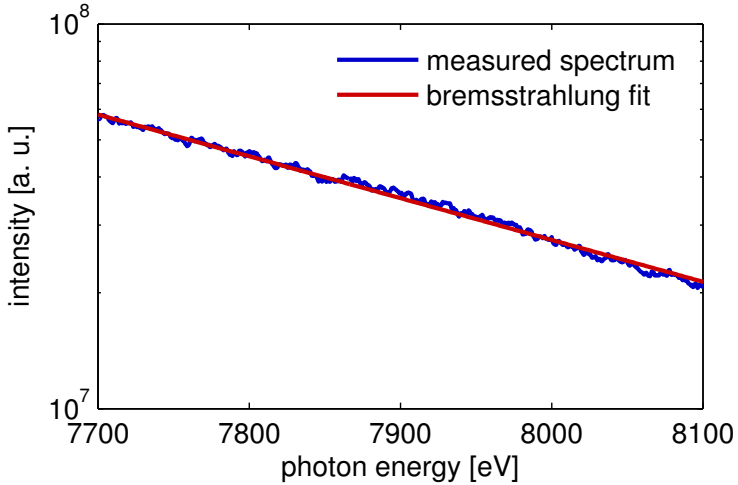
ρ = 5.0 g/cm^3

Z_C = 3.9

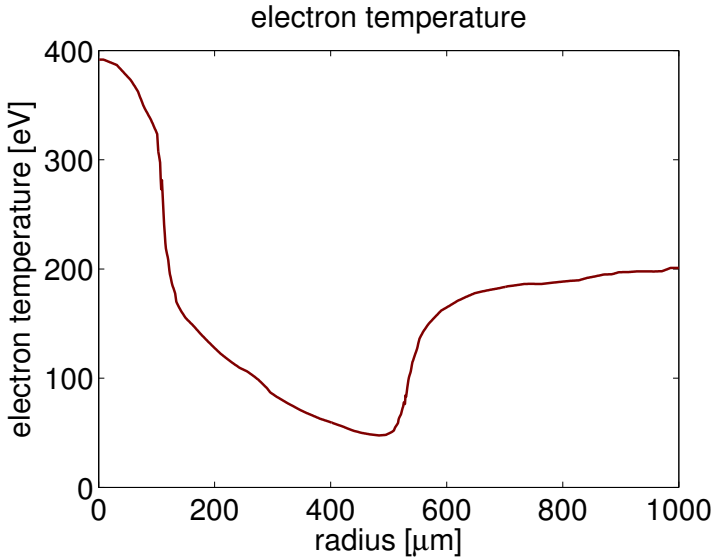
D. Kraus et al., in prep.

X-ray scattering | Bremsstrahlung continuum



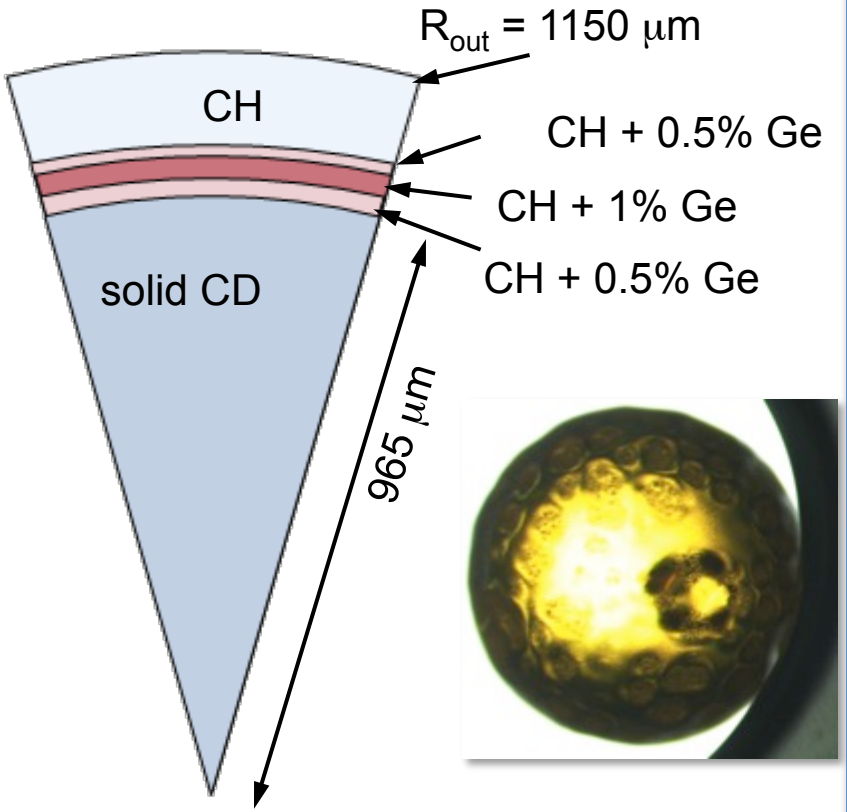


- Slope sensitive to core plasma temperature:
- Fitting slope with LTE bremsstrahlung spectrum ~ $\exp(-h\nu/kT_e)$: T_e=400 eV
- Fitting slope with Planck spectrum ~ $\nu^3 \exp(-h\nu/kT_e)$: T_e=350 eV



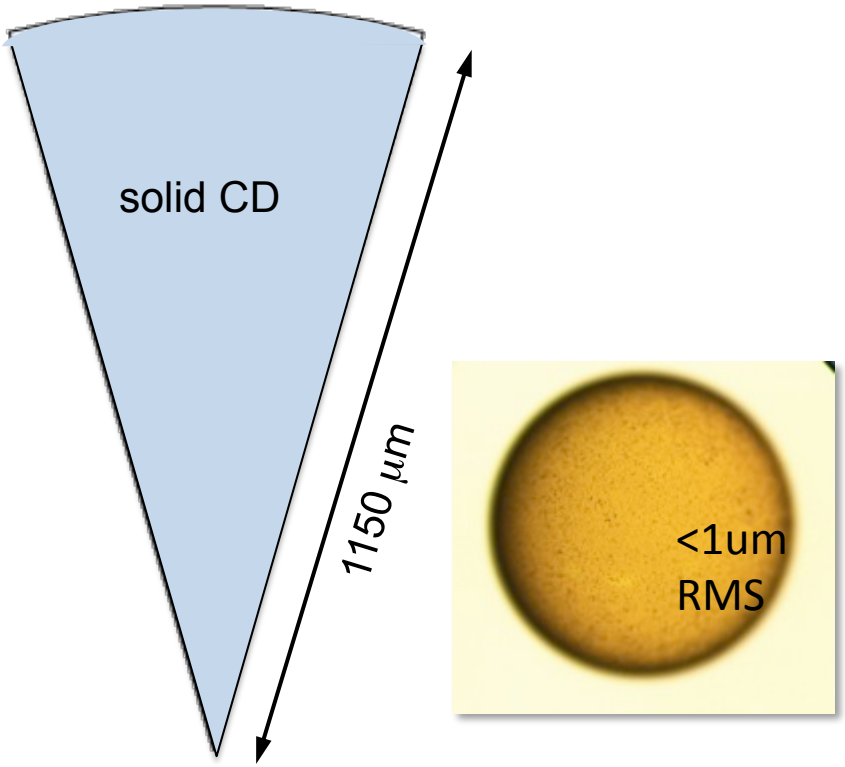
CD targets | Hotspot ion temperature via DD fusion

Capsule design: CD with a graded Ge doped ablator



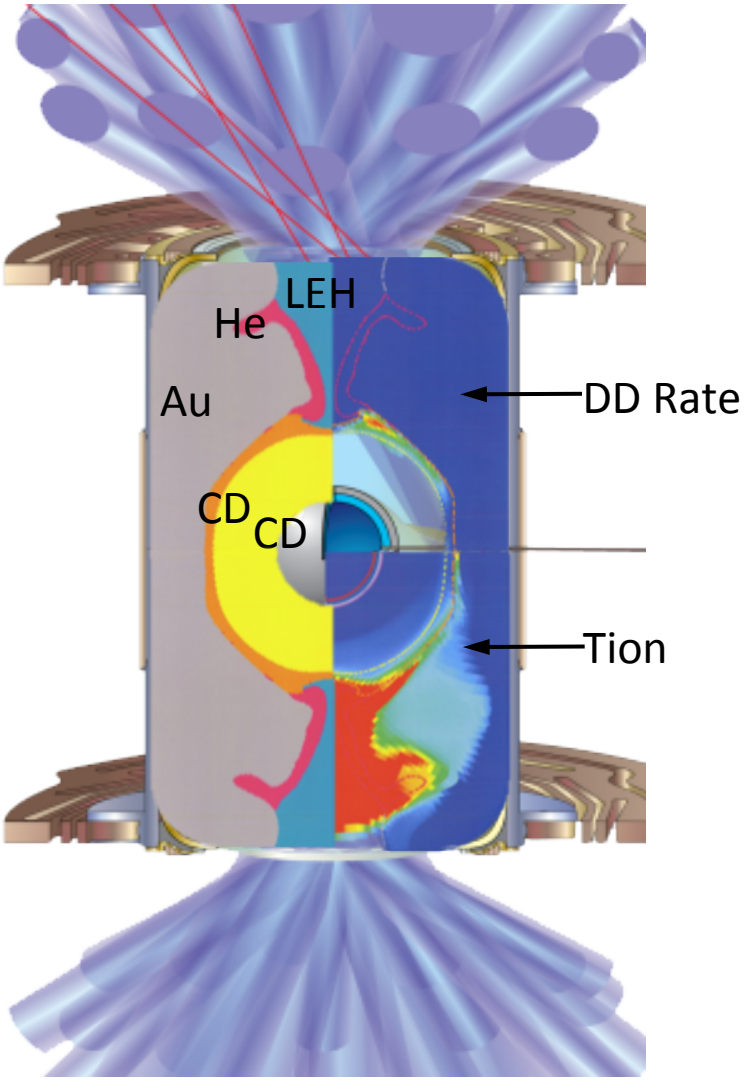
Outgassing caused wrinkles

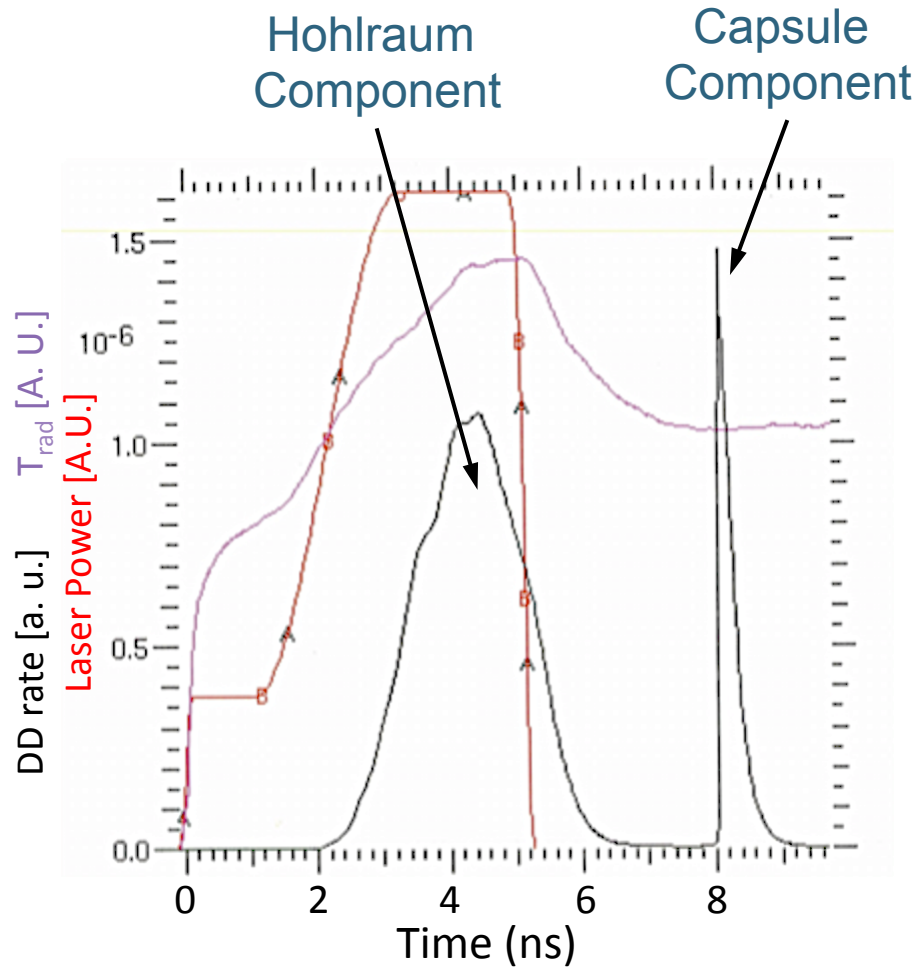
We attempted CD experiment with no ablator



$D + D \rightarrow n + {}^3He$ $E_n = 2.5$ MeV

CD targets | Hotspot ion temperature via DD fusion





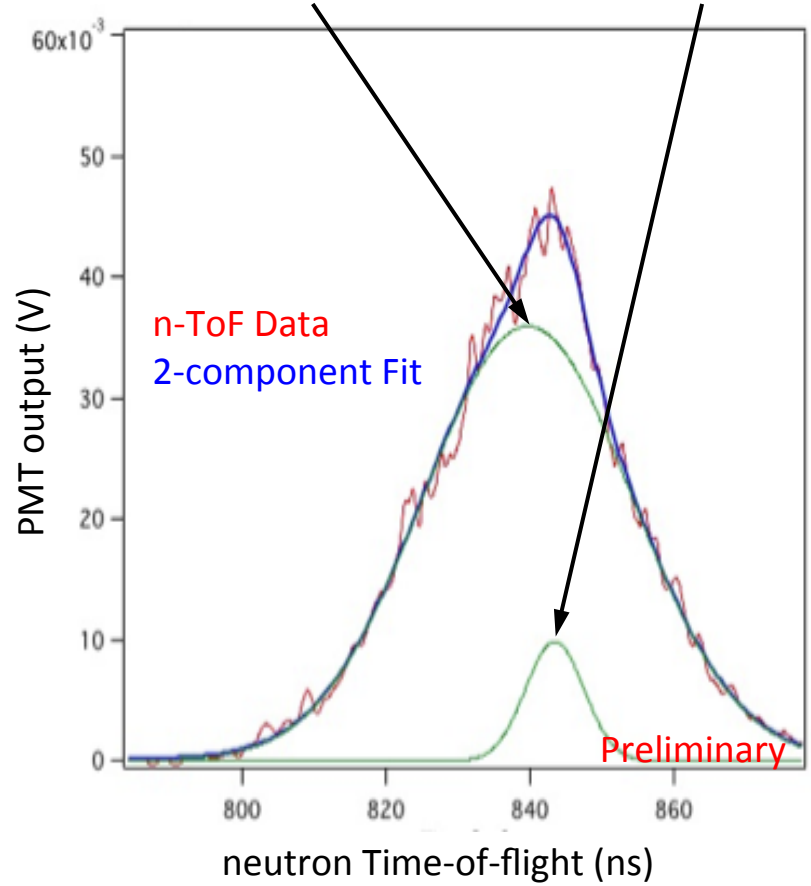
CD targets | Hotspot ion temperature via DD fusion

$D + D \rightarrow n + {}^{3}He$ $E_n = 2.5$ MeV

- neutron energy measured through time-of-flight over 18 m
- neutron energy distribution is Doppler-broadened

Hohlraum:
Tion=6(2)keV
Yield=1.29(10)e10

Capsule:
Tion=0.5(1)keV
Yield=0.1(1)e10



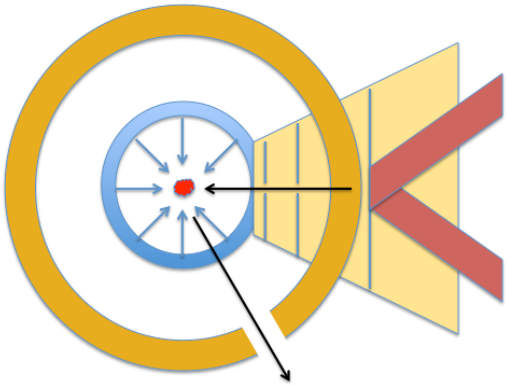
Summary

- Developed and fielded an experimental platform for absolute Hugoniot measurements up to the 1 Gbar regime

- Developed dedicated tools for data analysis for this very special and demanding experimental geometry:
  - Simultaneous density and opacity unfold of time resolved radiography images
  - 3D analysis of X-ray Thomson scattering from inhomogeneous, mm scale, multi-component dense plasma samples
    Posters M-15, T-10, T. Doeppner, D. Kraus
  - …

- First two Gbar equation of state experiments measured Hugoniot of CH up to 720 Mbar Poster T-01, J. Hawreliak

- Several approaches to experimentally constrain temperature:
  - X-ray Thomson scattering (also sensitive to ionization state)
  - DD fusion neutron yield
  - X-ray self emission spectrum
  - X-ray self emission absolute intensity Poster M-04, B. Bachmann

Outlook

- Hugoniot measurements at lower pressure (connection to NOVA data)
- Repeat of CD experiment
- Further development of temperature diagnostics
- Apply platform to different materials (HDC, …)
- Development dedicated NIF platform for X-ray Thomson scattering