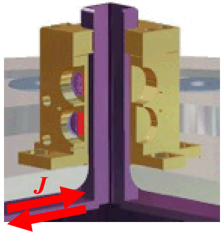
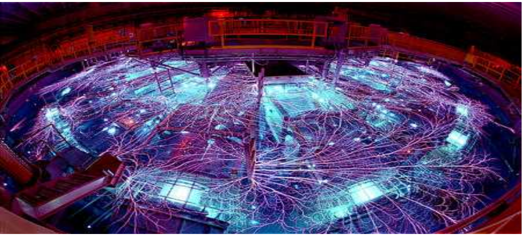
SAND2017-3540C

X-ray diagnostics for warm dense matter experiments on the Z-Accelerator





T. Ao, E. C. Harding, M. Schollmeier, J. E. Bailey, R. W. Lemke,
M. P. Desjarlais, S. B. Hansen, I. C. Smith, P. Rambo, and J. F. Benage

Sandia National Laboratories, Albuquerque, NM

9th International Workshop of Warm Dense Matter

Vancouver, BC, April 9-12, 2017

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Outline

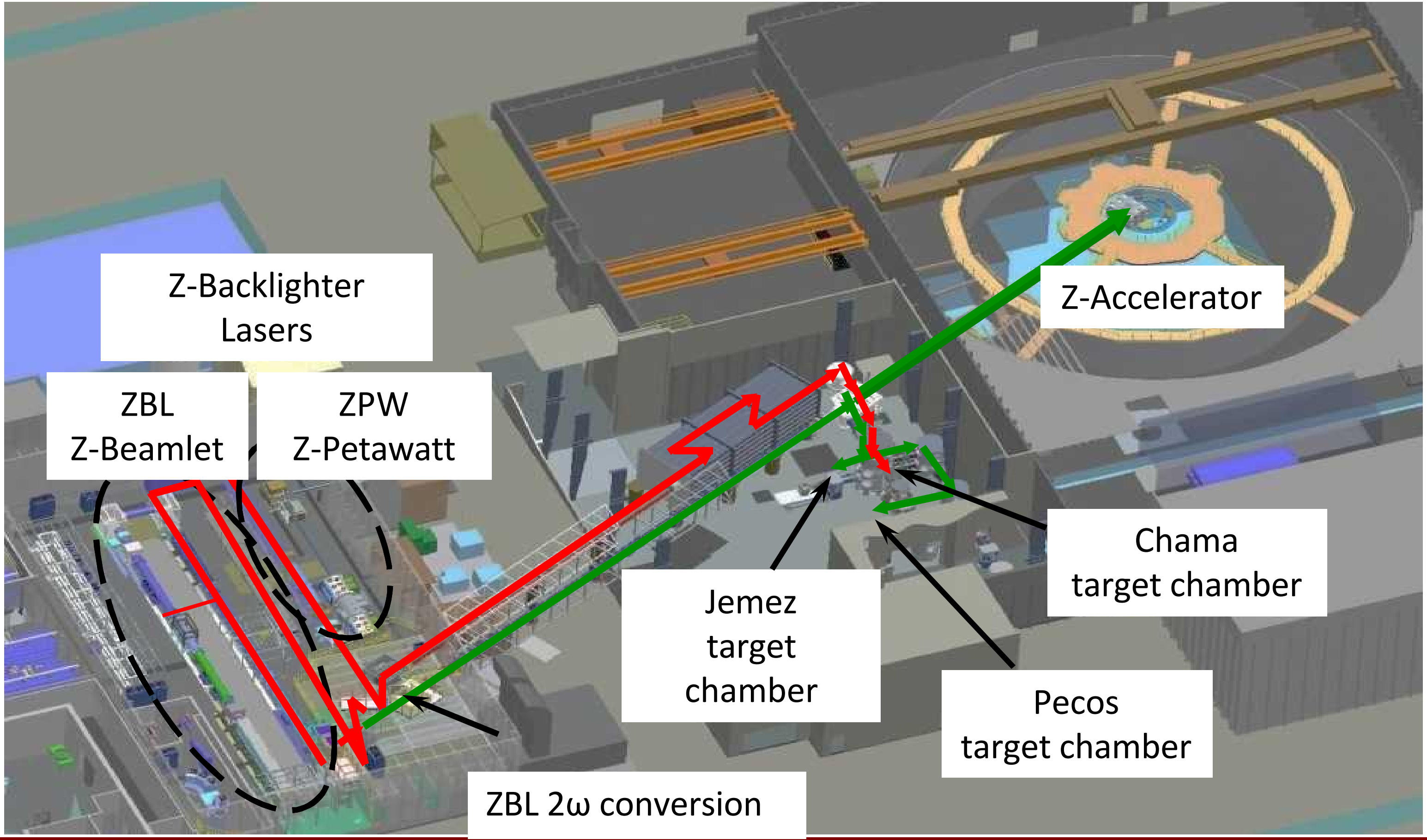
- Background
  - Z-Accelerator and Z-Backlighter lasers
  - Experimental challenges

- Recent results
  - X-ray Thomson scattering on Z

- Future developments
  - X-ray diffraction on Z
  - Higher photon energy x-ray source

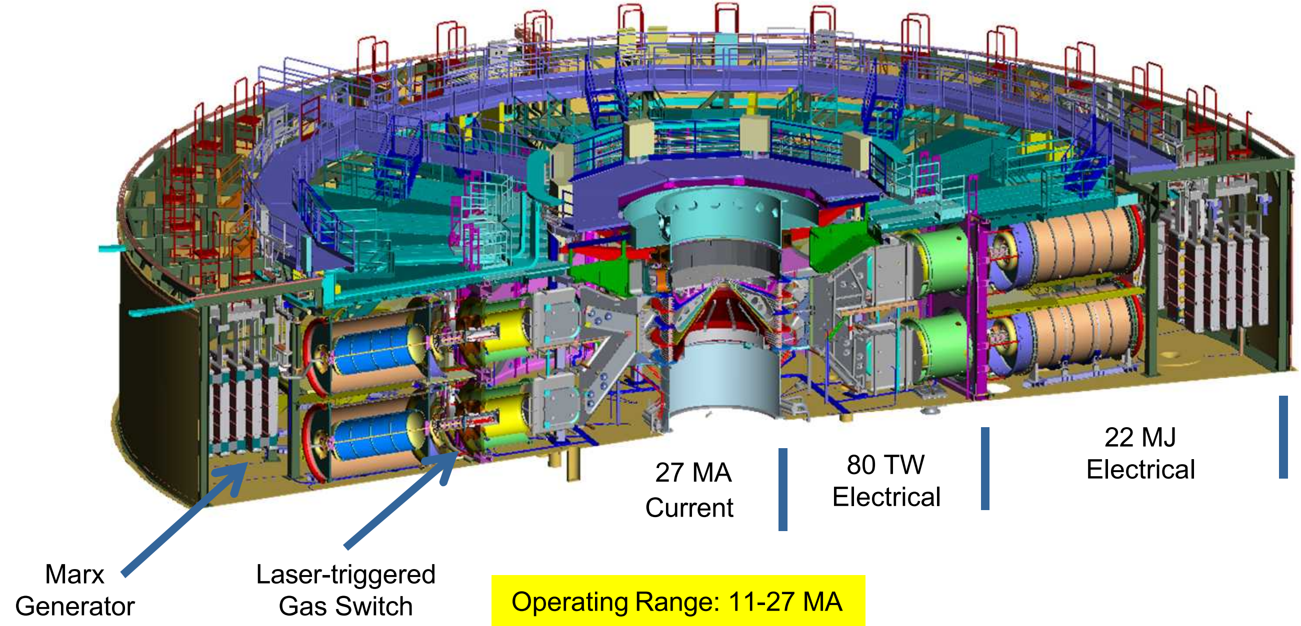
Background

Overview of Z Facility



Combining x-ray diagnostics with Z's unique warm dense matter (WDM) samples to provide benchmark quality data

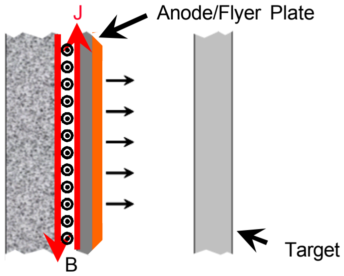
- Z's WDM samples are large, uniform, long-lived and precisely characterized
- Expand diagnostic capabilities on Z beyond pressure and density measurements

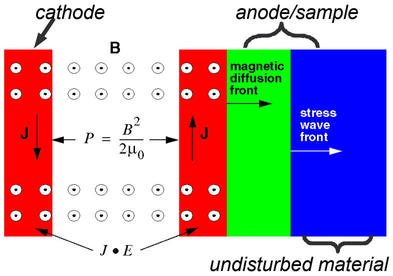


Operating Range: 11-27 MA

Z is a unique platform for WDM studies

- Dynamic material properties (DMP) experiments





- Magnetically launched flyer plates for shock compression[1]
  - Flyer impact velocities to ~ 40 km/s
  - Hugoniot states to ~ 10 Mbar; 10,000 – 50,000 K
  - Pressure and density characterized ~ 1-2 %
- Ramp (shockless) compression[2]
  - Continuous quasi-isentropic compression to ~5 Mbar
  - Strain rates ~10^6-10^7 /s
  - Lower temperature states ~ 1000 – 3000 K
- Shock-ramp compression[3]
  - Initial flyer impact followed ramp loading
  - Complex loading path access off-Hugoniot states
  - Shock melt and ramp refreeze

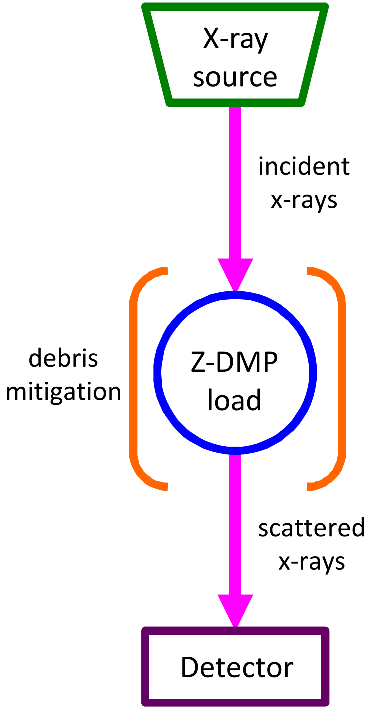
[1] R.W. Lemke *et al.*, J. Appl. Phys. **98**, 073530 (2005)

[2] J.-P. Davis *et al.*, Phys. Plasmas **12**, 056310 (2005)

[3] C. T. Seagle *et al.*, Appl. Phys. Lett. **102**, 244104 (2013)

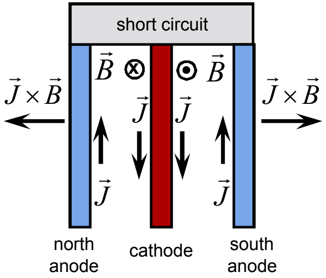
Three key components needed to implement x-ray diagnostics on Z-DMP experiments

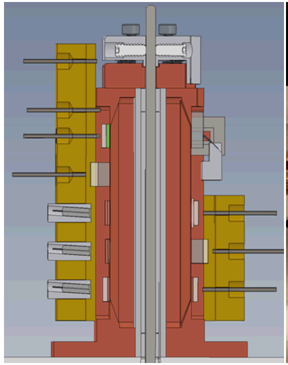
- Produce source x-rays
  - Laser (ZBL/ZPW) irradiated metal foil
- Generate high-pressure state
  - Z-DMP load
  - Debris mitigation
  - X-ray background
- Detect scattered x-rays
  - Spherical crystal spectrometer
  - Image plate
  - Scintillator/phosphor
  - CCD camera

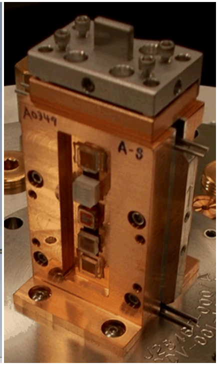


Z-DMP planar experiments

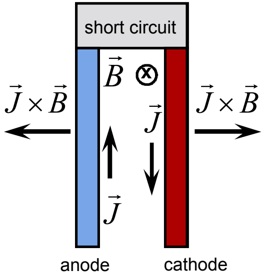
- Coaxial load
  - Cathode stalk surrounded by anode panels
  - Dual pressures possible on north and south panels
  - More sample locations
  - Enclosed magnetic fields, current and plasma flow
- Stripline load
  - Identical pressure on both cathode and anode panels
  - Higher current density and pressure
  - Open magnetic fields, current and plasma flow

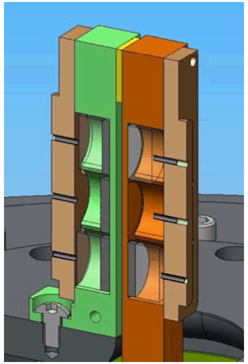






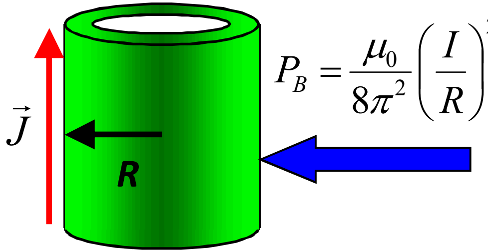
$$P = \frac{B^2}{2\mu_0}$$





Z-DMP cylindrical experiments

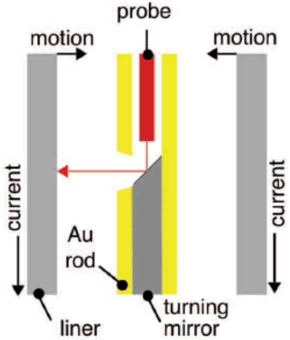
- Cylindrical implosion reaches extreme pressure states[1]
  - Current pulse shaping creates ramp-wave compression
  - Quasi-isentropic compression to 20 Mbar

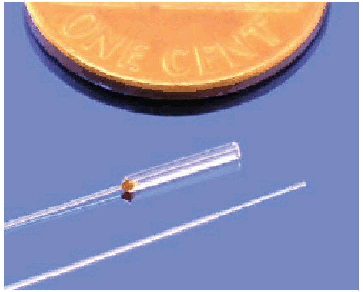


$$P_B = \frac{\mu_0}{8\pi^2}\left(\frac{I}{R}\right)^2$$

I = 20 MA
R = 1 mm
$P_B \approx$ 64 Mbar

- Diagnostics are challenging[2]
  - Limited space
  - Miniature probes
  - Velocities beyond 40 km/s





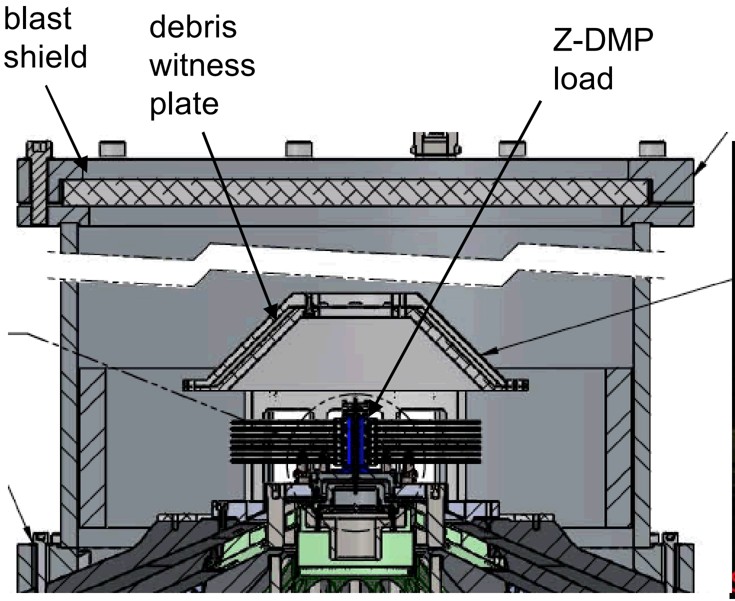
[1]M. R. Martin *et al.*, Phys. Plasmas **19**, 056310 (2012)
[2]D. H. Dolan *et al.*, Rev. Sci. Instrum. **84**, 055102 (2013)

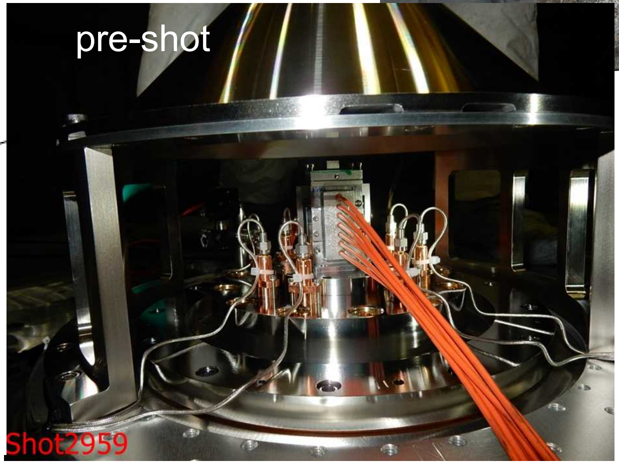
Challenges of Z-DMP experiments

- Target parameters
  - Large and thick samples
  - Reflection geometry
- Destructive environment of Z-DMP load
  - Prevent catastrophic vacuum breach
  - Protect Z-Backlighter Lasers
  - Retrieve data
- X-ray background
  - High energy photons (up to 10 MeV) produced
  - Sufficient signal-to-noise
- Electromagnetic pulse (EMP)
  - Fry electronics

Z2959: Protection and recovery of any detector near Z-DMP load highly unfeasible

- Unable to field any x-ray detector such as image plate, x-ray CCD, x-ray streak camera within blast shield (~50 cm diameter)

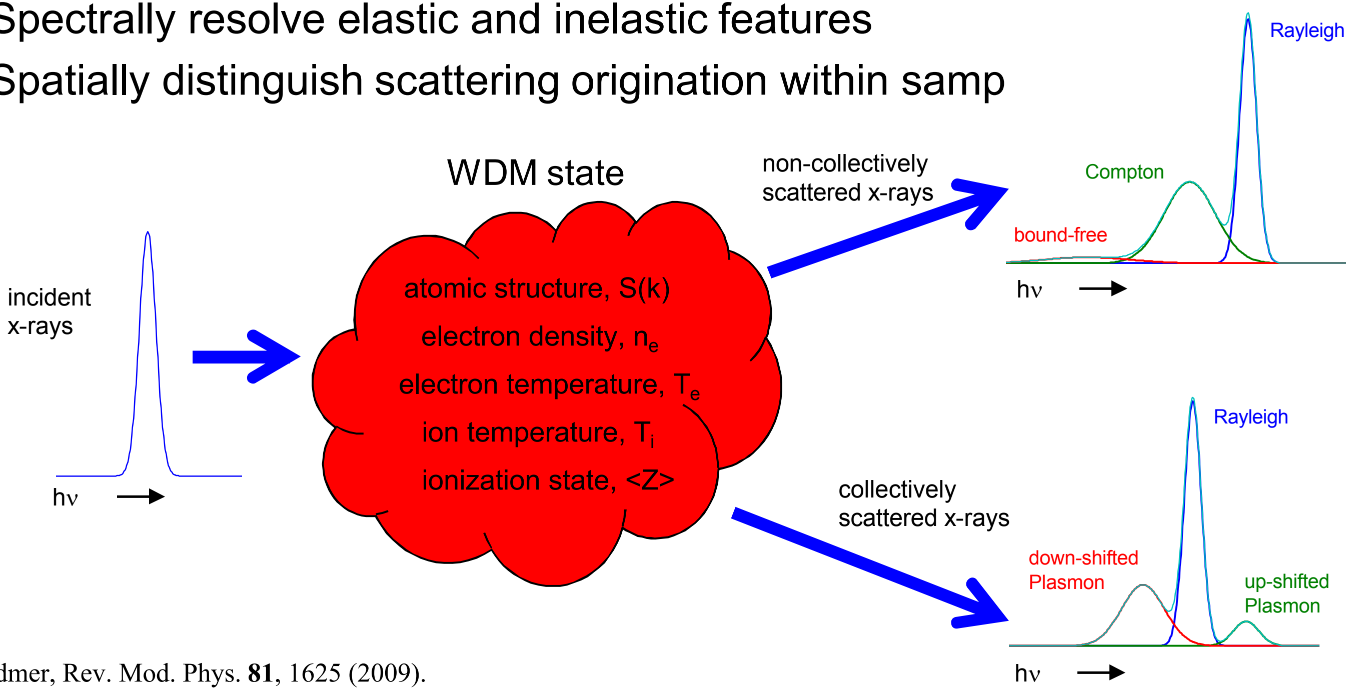




Recent results

X-ray Thomson scattering (XRTS) diagnostic has been implemented on Z

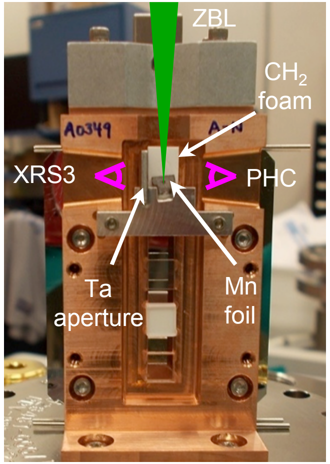
- Extract to infer n_e, T, <Z>, and phase information about sample from scattered x-rays
  - Spectrally resolve elastic and inelastic features
  - Spatially distinguish scattering origination within samp



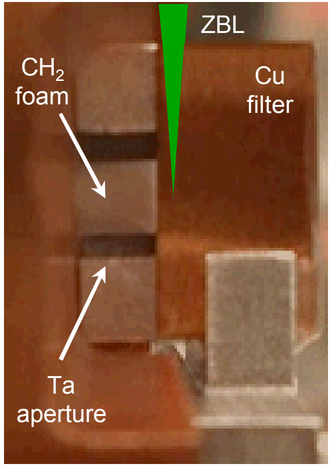
S. H. Glenzer and R. Redmer, Rev. Mod. Phys. **81**, 1625 (2009).

Experimental setup of Z-XRTS

- X-ray scattering spherical spectrometer (XRS[3])
  - Resolve scattered x-rays spectrally and spatially using spherically bent crystal → Ge 422
  - Record x-rays → image plate (IP)

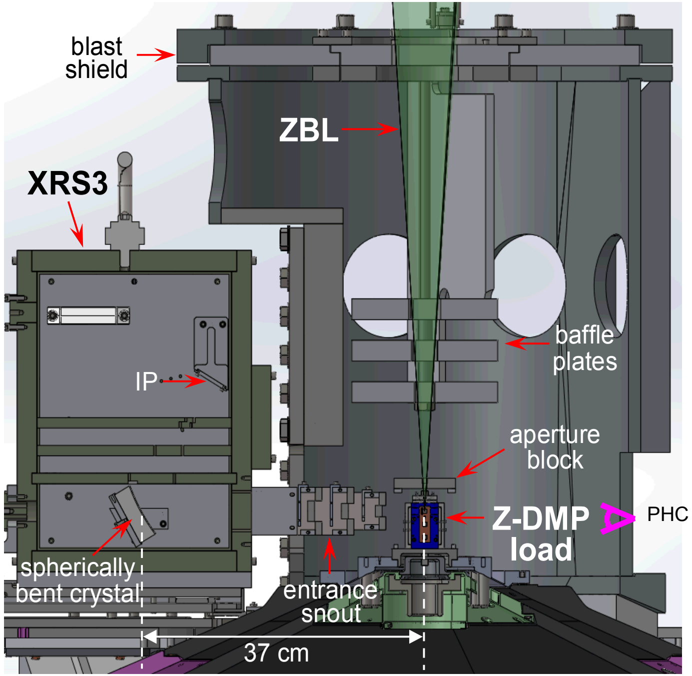


Back view



Side (XRS3) view

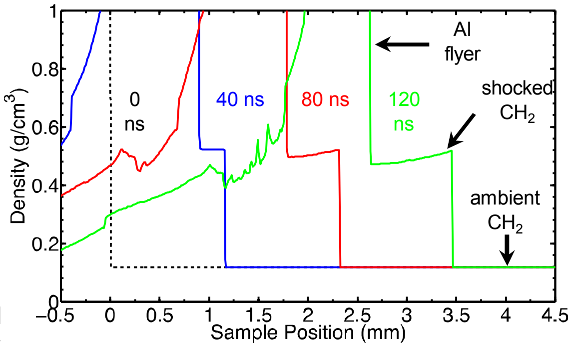
Z-DMP load



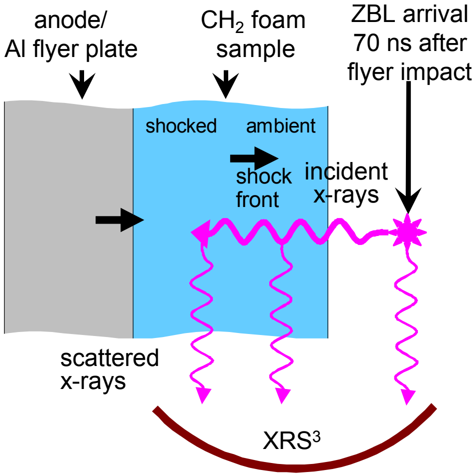
Target chamber (cross–section view)

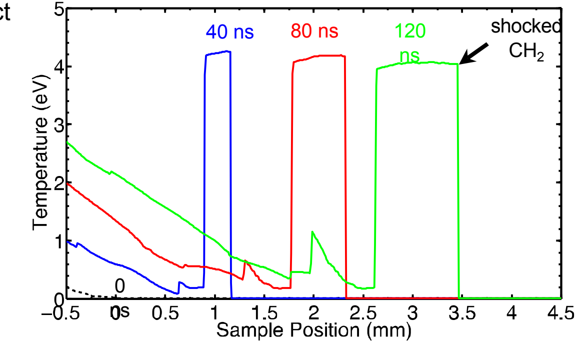
Spatial resolution is essential for benchmark quality XRTS

- ALEGRA calculations with Al flyer (25 km/s)
  - Ambient CH_2 foam:
    - (7.5 x 5 x 2.5) mm, r_0=0.12 g/cm^3
  - Shocked CH_2 foam:
    - P = 0.75 Mbar, ρ = 0.52 g/cm^3, T = 4.3 eV



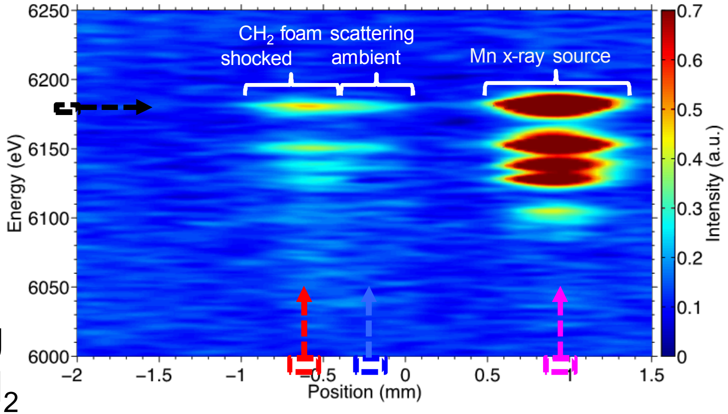
- Measure XRTS signal from ambient & shocked material, and x-ray source
  - VISAR: Al flyer impact velocity; CH_2 sample shock velocity, verify steady-state of WDM
  - XRS^3: characterize Mn x-ray probe spectrum

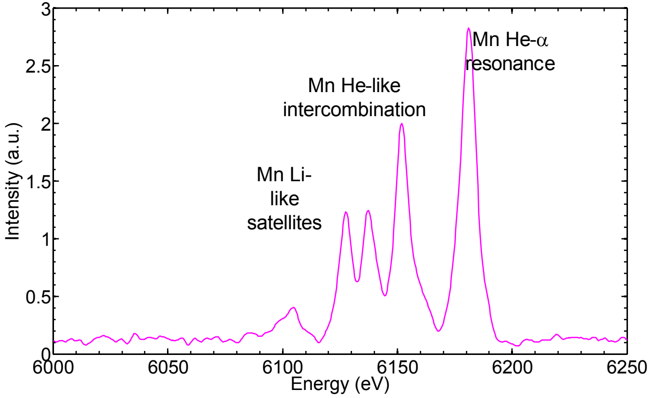


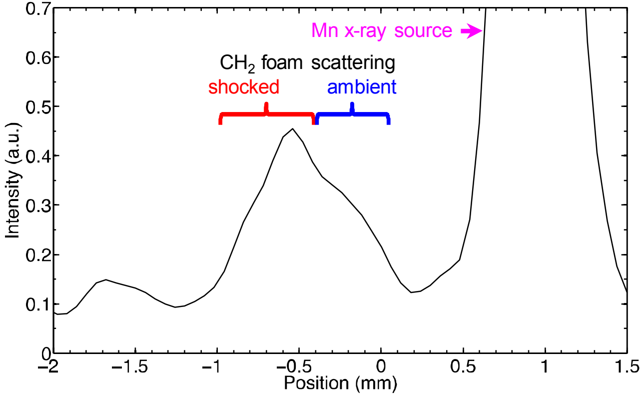


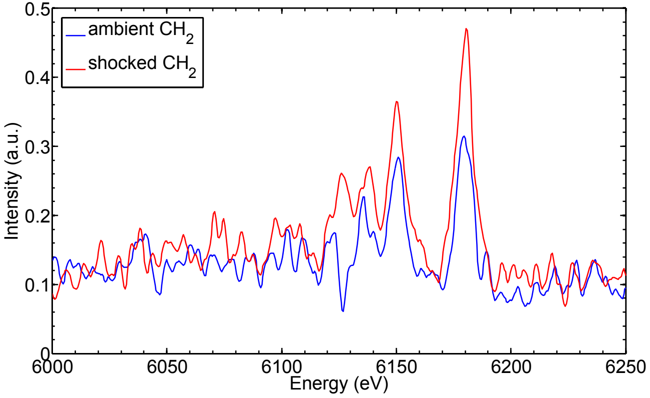
Z2661: Simultaneously recorded space-resolved scattering spectra from shocked & ambient states, and source

- Backward scattering (90°) of shocked CH_2 foam on image plate





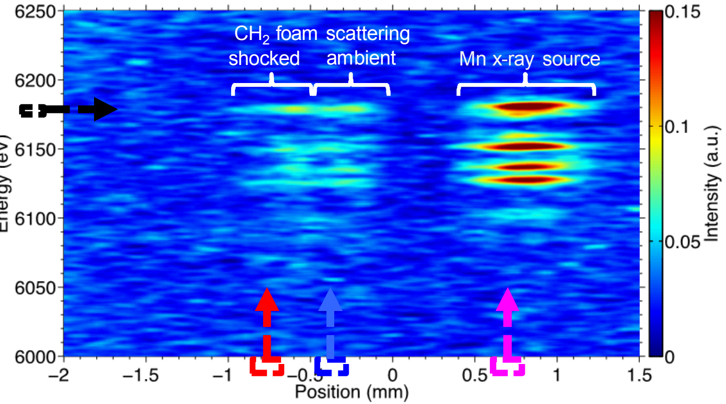


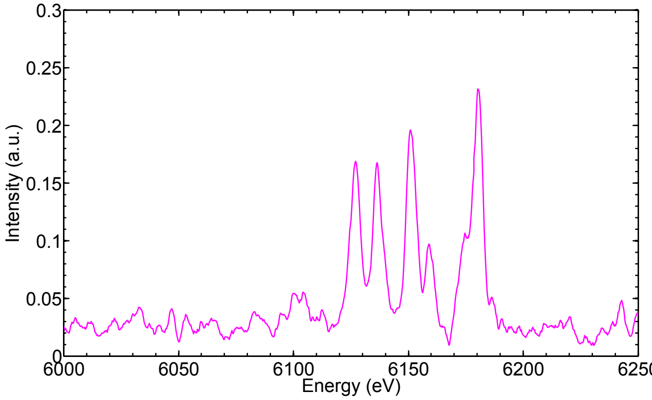


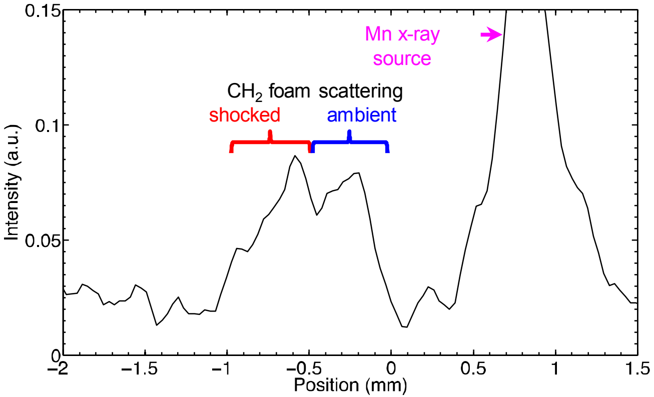
T. Ao, *et al.*, HEDP. **18**, 26 (2016).

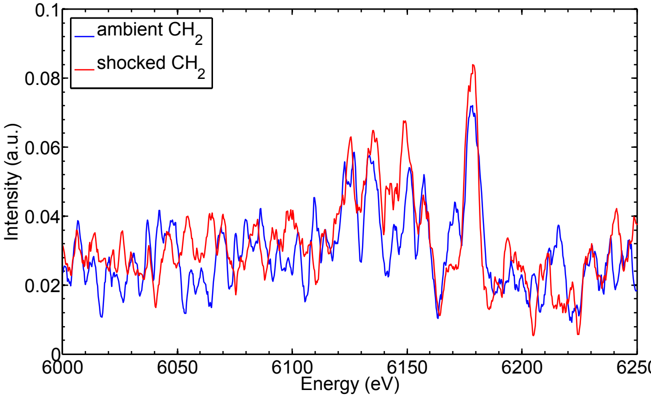
Z2704: Improved spectral and spatial resolution using x-ray film

- Backward scattering (90°) of shocked CH_2 foam on Agfa D8 film
- Reduced signal intensity





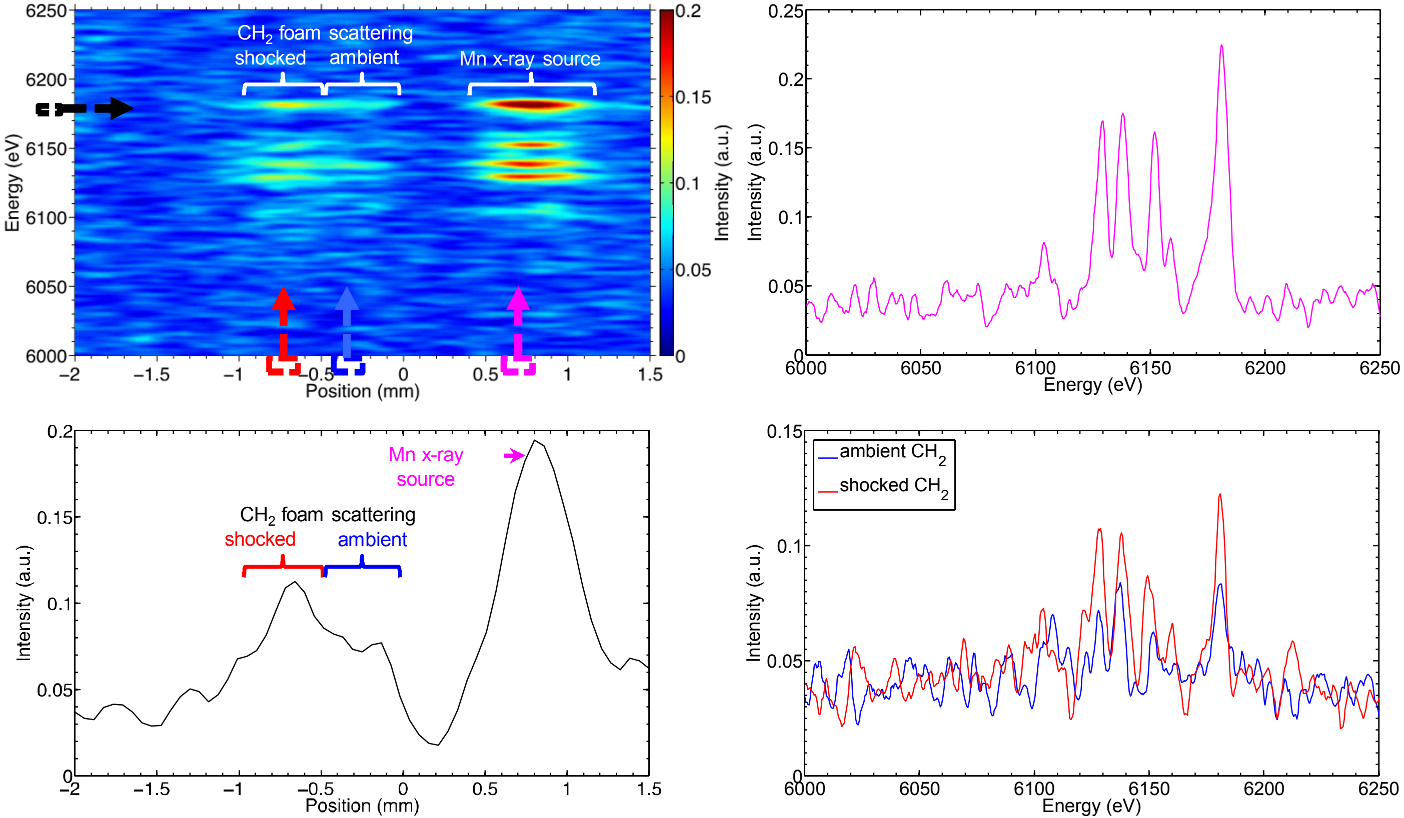




T. Ao, *et al*., HEDP. **18**, 26 (2016).

Z2750: Constrained scattering angle to reduce angular smearing

- Forward scattering (30°) of shocked CH_2 foam on image plate

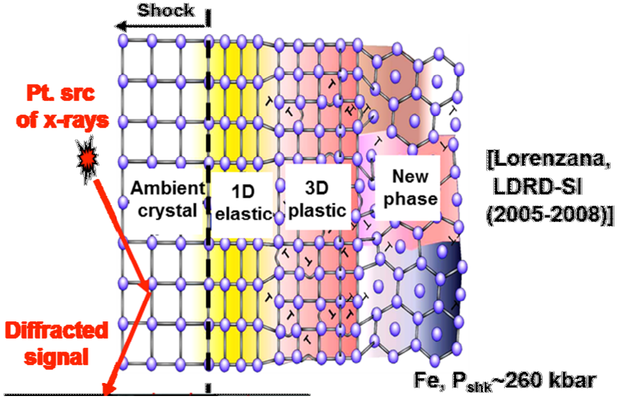


T. Ao, *et al*., HEDP. **18**, 26 (2016).

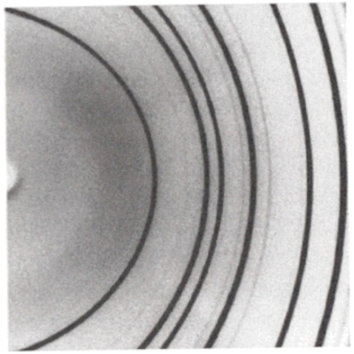
Future developments

X-ray diffraction (XRD) to diagnose material lattice dynamics during shock/ramp compression

- What?
  - Characterize phase transformations that occur in dynamically compressed condensed matter on **ns** time scales and **nm** spatial scales
- Why?
  - For most materials, there are very few constraints on existing models for phase transitions under dynamic loading
- How?
  - Perform time-resolved, x-ray diffraction measurements on dynamically compressed, polycrystalline matter

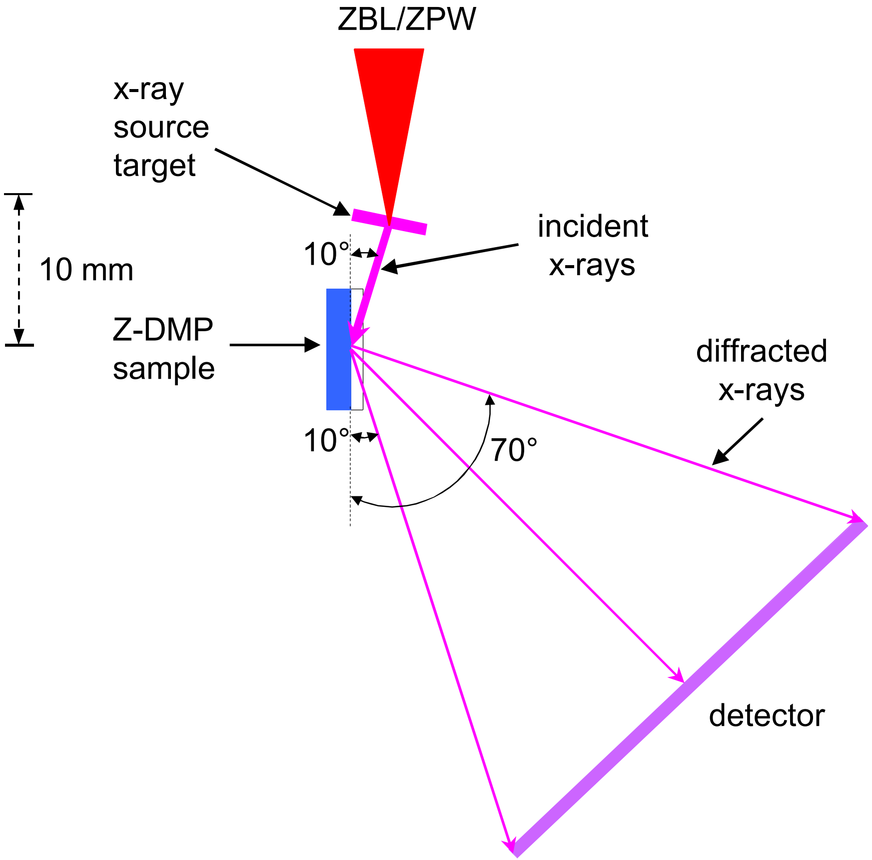


[Lorenzana, LDRD-SI (2005-2008)]



Powder x-ray diffraction pattern

General experimental design of Z-XRD

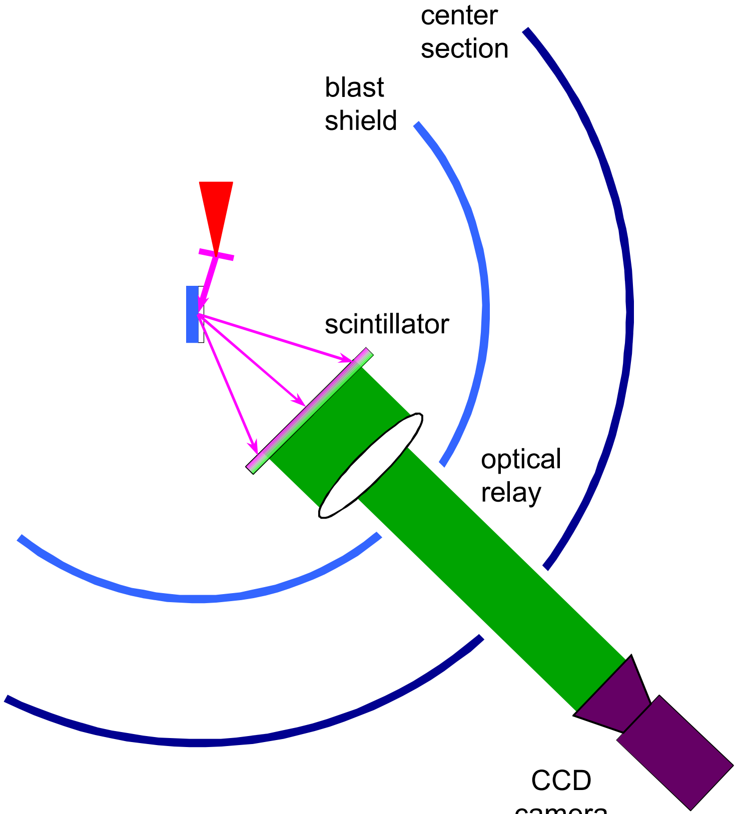


Addressing challenges of Z-XRD

- High photon energy (>6 keV), short duration (~1ns) multi-pulse x-ray sources (ZBL and/or ZPW)
  - Penetrate into thick and high Z targets
  - Temporally resolve phase transformations
- Placing image plate, x-ray CCD, or x-ray streak camera near load
  - Advanced debris mitigation
  - Robust x-ray and EMP shielding
- Convert diffracted x-rays into visible photons
  - X-ray phosphor/scintillator near load
  - Transport optical light out of load region (open optics)
  - Record light on optical CCD away from debris, x-ray background and EMP field

Z-XRD using scintillator/optical relay/CCD camera

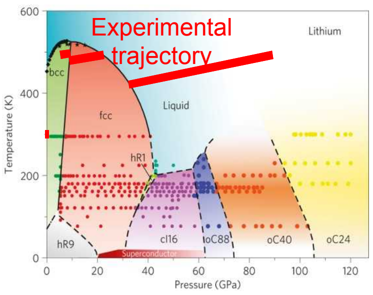
- Operation
  - Scintillator located close to sample inside blast shield
  - X-ray conversion to optical light
  - Optical relay to outside blast shield and center section onto CCD camera
- Advantages
  - Time gating, possible multiple events
- Disadvantages
  - Optical background mitigation
  - Scintillator and optics destroyed
  - Alignment considerations

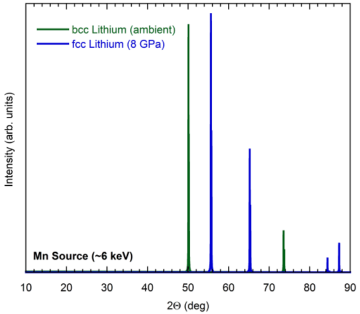


Possible 1st Z-XRD experiments with Z-Beamlet generated 6-8 keV x-rays

Lithium

- Lithium has very low mass attenuation coefficient (probe ~1 mm thickness)
- Timed correctly, a two-phase pattern (bcc/fcc) may be observed
- Free surface ramp compression with XRD diagnostic timed to probe bcc-fcc phase transition

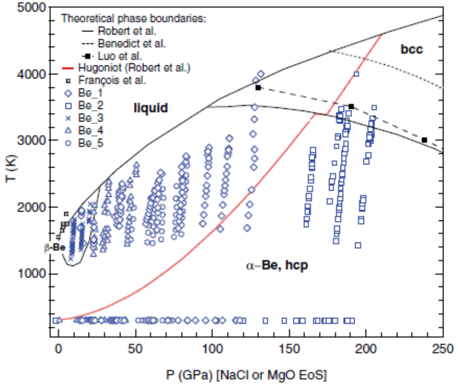




C. L. Guilliame *et al.*, Nature Physics **7**, 211 (2011)

Beryllium

- Beryllium also has low mass attenuation coefficient, but no phase transitions with ramp; XRD should see compression of the hcp lattice
- Alternatively, attempt to shock into bcc, probe before free surface breakout



Hugoniot may not intersect bcc?

A. Lazicki *et al.*, PRB **86**, 174118 (2012)

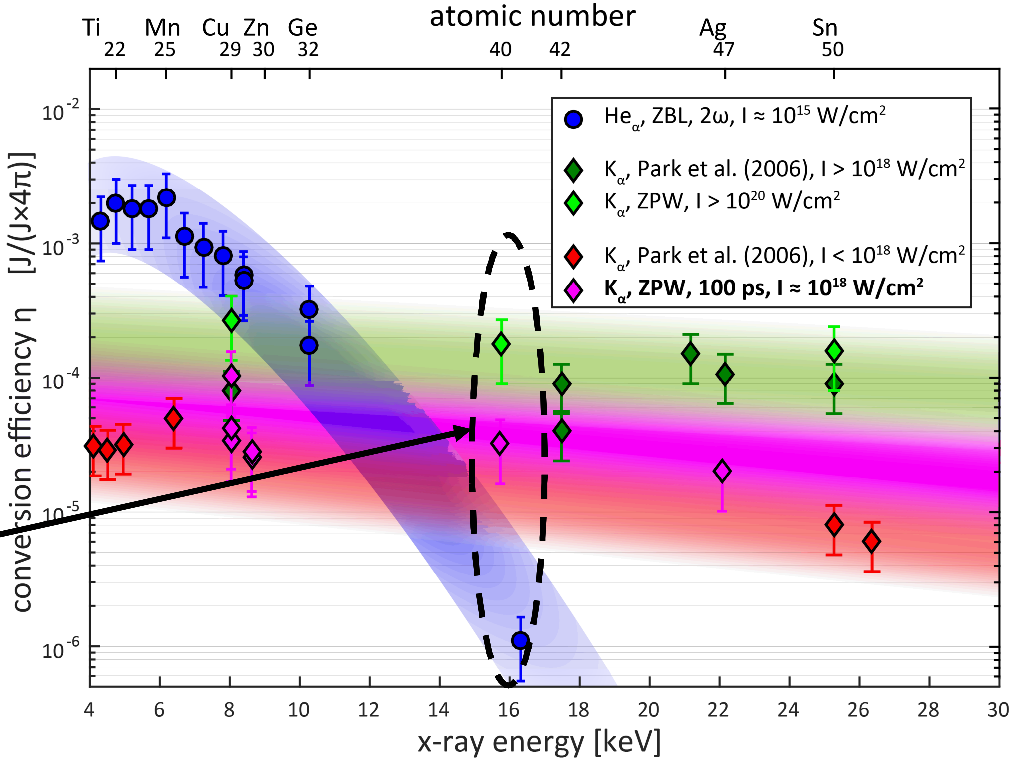
Comparison of laser-to-x-ray conversion efficiencies

- Steep drop in efficiency for long pulse (ns) laser driven He_α x-ray emission > 10 keV
- More gradual drop in efficiency for short pulse (sub-ns) laser driven K_α x-ray emission > 10 keV
  - Off-axis parabola focusing

ZPW, 0.5 ps, 100 J, 10^{20} W/cm²: $\eta \approx 2 \times 10^{-4}$

ZPW, 100 ps, 100 J, 10^{18} W/cm²: $\eta \approx 3 \times 10^{-5}$

ZBL, 1000 ps, 1000 J, 10^{15} W/cm²: $\eta \approx 10^{-6}$



Focusing ZPW with lens to generate K〈 x-ray source

- X-ray source requirements for Z-XRD
  - Above 10 keV to penetrate high Z and thick targets
  - Monochromatic (ΔE ~0.1 eV)
  - Short emission duration (< 1 ns or below)
  - Multi-pulse with >5 ns inter-pulse delays

→ use multiple Kα bursts from period-5 transition metals (15-25 keV)

- Laser and focusing hardware:
  - Multi-pulse capability
  - Sub-ns pulse duration
  - Final focusing optics well-shielded from Z debris (difficult using off-axis parabola)

→ modify ZPW for multi-pulse, 100-ps operation, use existing ZBL lens focusing

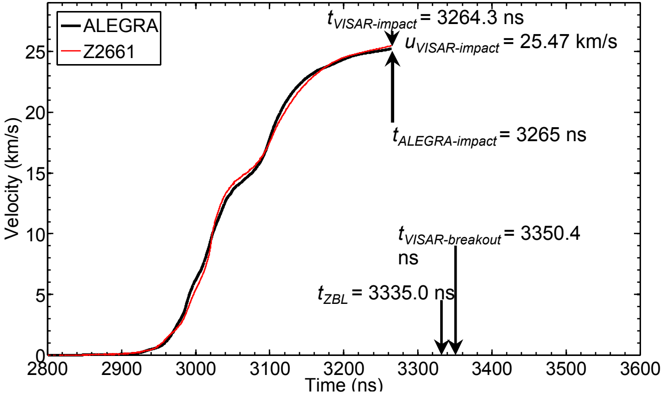
Summary

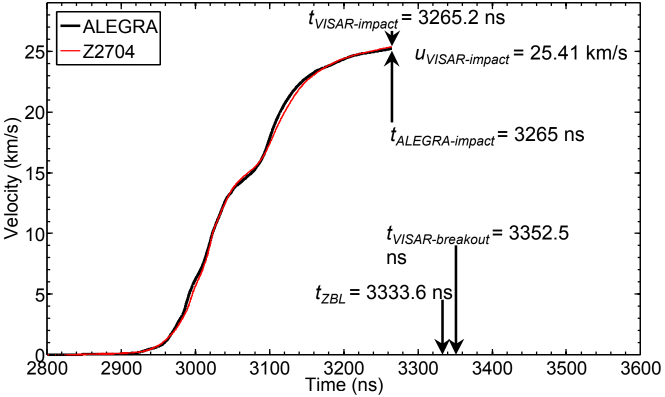
- Demonstrated spaced-resolved x-ray Thomson scattering of shocked carbon foams on Z
  - Simultaneous measurements of shocked and ambient states
  - In-situ x-ray source characterization
  - Backward and forward scattering
  - Image plate and film comparison

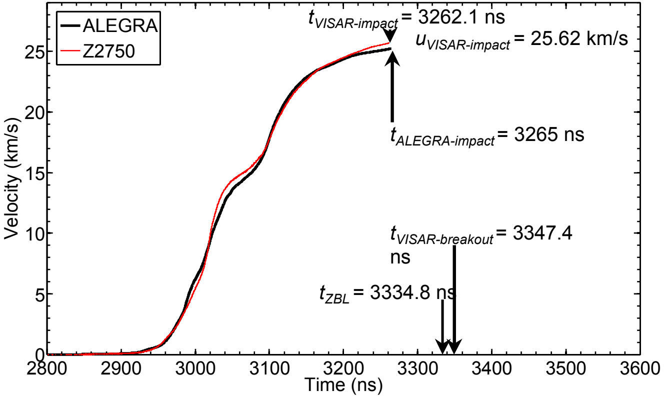
- Development of an x-ray diffraction diagnostic for Z
  - Scintillator/optical relay/CCD camera scheme
  - Higher photon x-ray source with lens-focusing of short-pulse laser

Extra slides

Reproducibility of flyer velocities, ZBL time of arrival, and shock break time of CH_2 foam (Z2661, Z2704, Z2750)

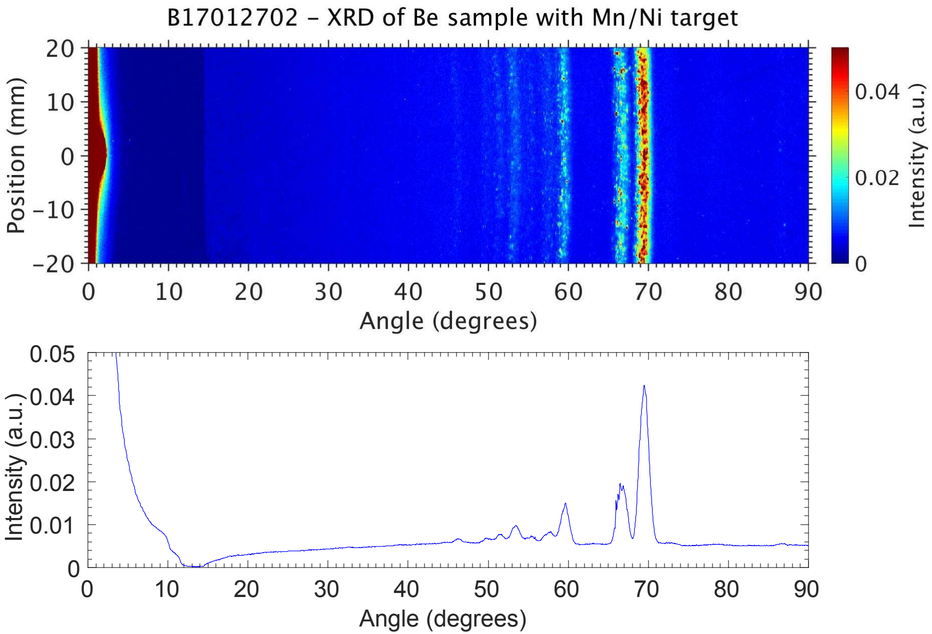






Ambient XRD of Be (hcp) sample with Z-Beamlet

- B17012702, 1085 J, Mn(88%)-Ni(12%) foil, 6.2 keV x-rays
- X-ray source: 152 mm from input pinhole
- IP: 140 mm from Be sample



- Photometrics:
  - X-ray source ~10^{16} photons
  - Photons incident on Be sample ~ 4×10^{10}
  - Be scattering fraction ~ 0.01
  - Total collected photons per pixel ~ 2.4
  - TR-IP sensitivity at 6keV ~ 3.3 mPSL/γ
  - Expected signal ~ 0.01 PSL

Optical image relay

- Open optical beam propagation
  - Z-DMP load
  - Blast shield
  - Center section