SAND2011-5315C

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# Potential and Progress in X-ray Thomson Scattering of Warm Dense Matter on the Z-Accelerator

2011 Workshop and User Meeting on Fundamental Science using Pulsed Power and High Power Laser
July 28 – 30, 2011
Santa Fe, NM

**T. Ao**

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# Acknowledgements


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  - Experimenters: Jim Bailey, Eric Harding
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  - Experimental support: Dan Sinars, Marcus Knudson, Seth Root, Dave Ampleford
  - Designers: Dave Wenger, Paul Gard, Paul Mix, Dave LePell, Dustin Romero, Devon Dalton
  - ZBL experiments: Ian Smith, Jon Shores, Verle Bigman, Robin Broyles, Larry Ruggles, Diana Schroen, Gary Smith


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# Outline

- Background
  - Warm dense matter (WDM)
  - X-ray Thomson scattering (XRTS)
- Research goals
  - Explore WDM with XRTS by utilizing the advantages of Z
- X-ray calibrations
  - Spherically bent crystals
  - X-ray scattering spherical spectrometer ($XRS^3$)
- ZBL experiments
  - X-ray source development
  - X-ray scattering
- Z experiments
  - Dynamic materials properties (DMP)
  - Radiatively driven (Z-pinch)



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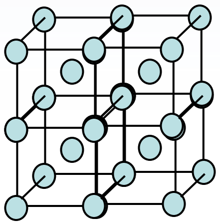
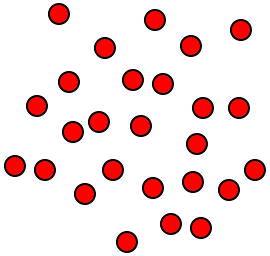
# Fundamental science of warm dense matter (WDM)

- Condensed matter
  - Solid and liquids (crystalline and amorphous)
  - Low temperature
  - High degree of ordering

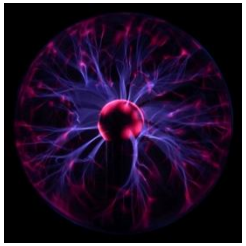


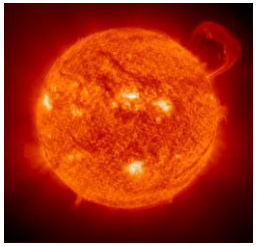
Cold lattice (bcc)

- Plasma
  - Ionized gas
  - High temperature
  - Low degree of ordering

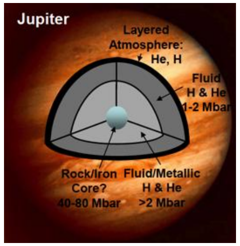


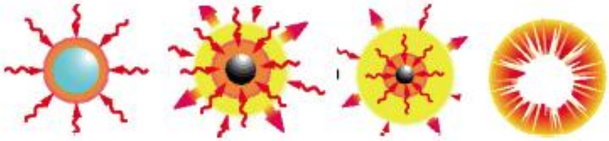
Hot plasma





- Warm dense matter
  - Convergence between condensed matter & plasma
  - Large planetary cores, preliminary stages of fusion, intense laser-target interactions & particle beam-target interactions
  - High temperature condensed matter (?)
  - Strongly coupled plasma (?)



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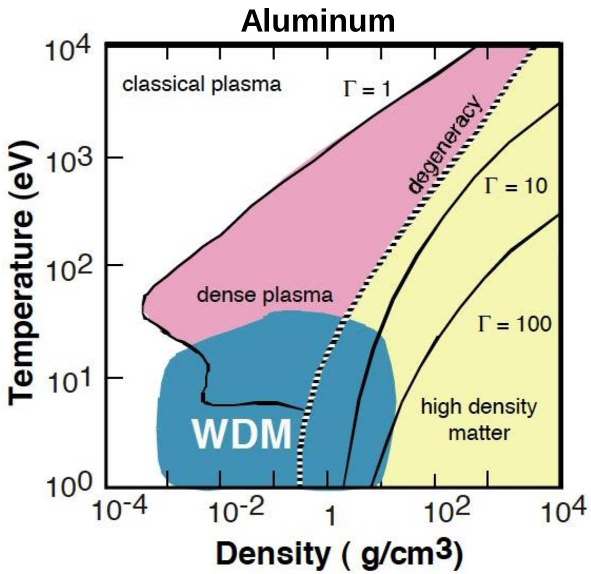
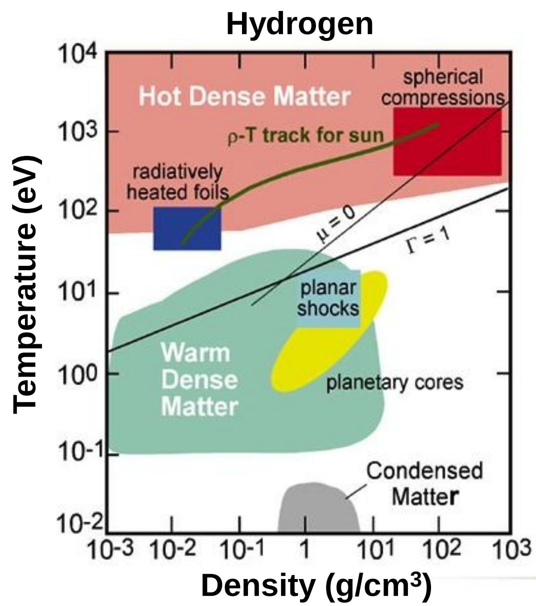
# Warm dense matter is an interesting but difficult regime to study

- High-temperature condensed matter
  - Disordered system whose description requires detailed knowledge of excited states, structure factors and dynamics of strongly interacting electrons and ions
- Strongly coupled plasma
  - Dominated by ion-ion correlations, it cannot be treated with conventional Debye screening & perturbative approaches
- Comparable Fermi & thermal energy and strong ion-ion coupling $G=\frac{E_{Coulomb}}{k_B T} \gg 1$
  - Densities from ~ 0.1 – 10 times solid density
  - Temperatures from ~ 1 – 100 eV

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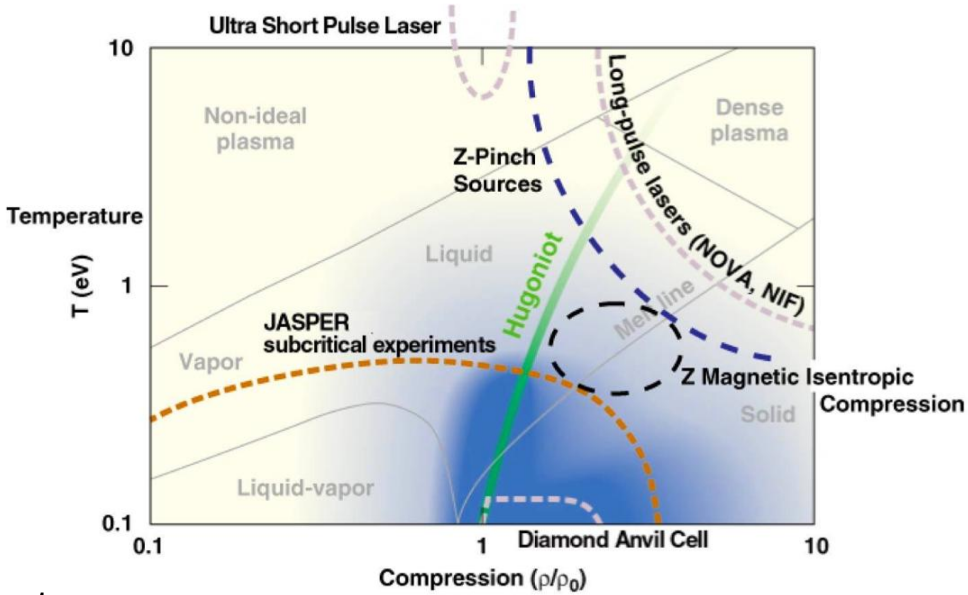
# Experimental techniques to study WDM

- Generating WDM extreme states
  - Isochoric heating: ion beams, short-pulse lasers, high-energy-density lasers, radiation-synchrotron sources (XFEL)
  - Shock compression: laser-driven shock, high velocity flyer impact
- Diagnostics for probing WDM
  - VISAR
  - Streaked optical pyrometry (SOP)
  - X-ray Thomson scattering (XRTS)
  - X-ray diffraction
  - X-ray & proton radiography
  - Extended x-ray absorption fine structure spectroscopy (EXAFS)




- Facilities for XRTS-WDM experiments
  - NIF (LLNL), Laser Megajoule (CEA), OMEGA (LLE)
  - LULI 2000 (Ecole Polytechnique), Vulcan (Rutherford), Titan (LLNL), Trident (LANL), LIL (France), Xingguang II (China), Gekko (Japan), Phelix (Germany)
  - LCLS (SLAC-Stanford), FLASH (DESY-Germany), SACLA (RIKEN-Japan)

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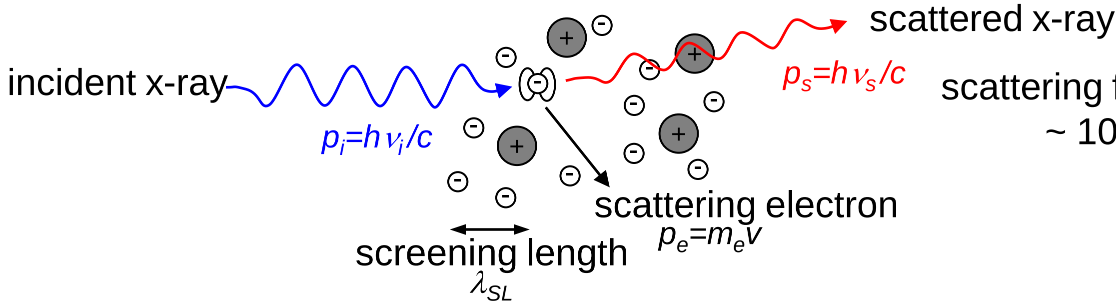
# X-ray scattering to diagnose WDM

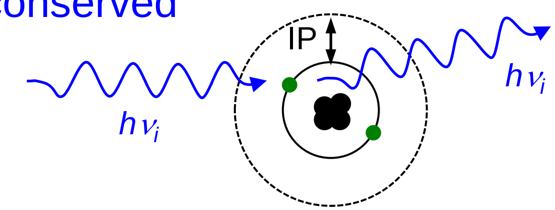
- X-rays scattered from electrons determine plasma parameters
  - Electrons absorb x-ray photon, oscillate and re-emit x-ray photon



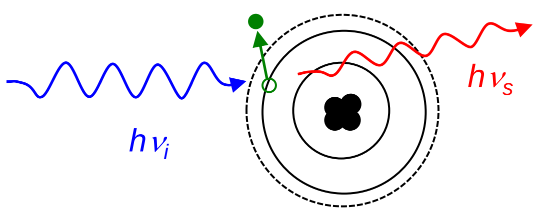

scattering fraction
~ $10^{-4}$

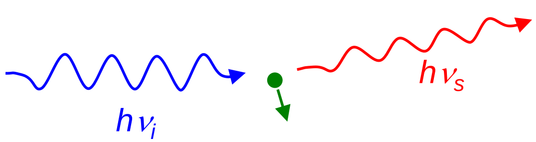
$$E_C = \frac{\hbar^2 k^2}{2m_e}$$

- Elastic (Rayleigh): energy of incident photon conserved
  - Tightly bound e$^-$
    - Binding energy > Compton energy ($E_C$)




- Inelastic (Compton or Plasmon): energy of incident photon not conserved
  - Weakly bound e$^-$
    - Binding energy < Compton energy ($E_C$)
  - Free e$^-$




O. L. Landen, *et al.*, J. Quant. Spectrosc. Radiat. Transf. **71**, 465 (2001)

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# Non-collective and collective regimes of x-ray scattering

- Plasma screening length: $\lambda_{SL}$

Classical plasma

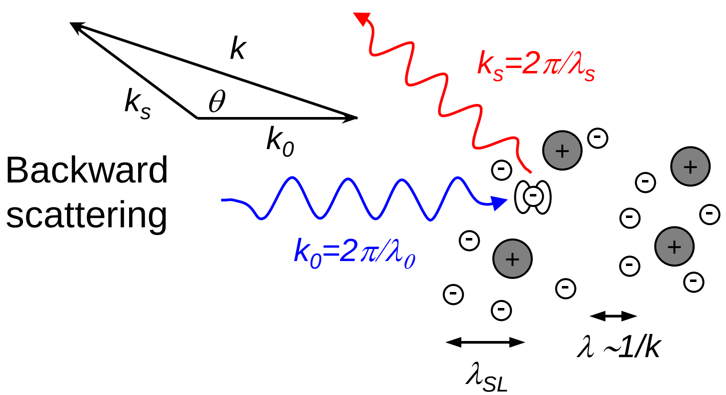
$$\lambda_D = \left(\frac{\varepsilon_0 k T_e}{n_e e^2}\right)^{1/2}$$

Fermi-degenerate plasma

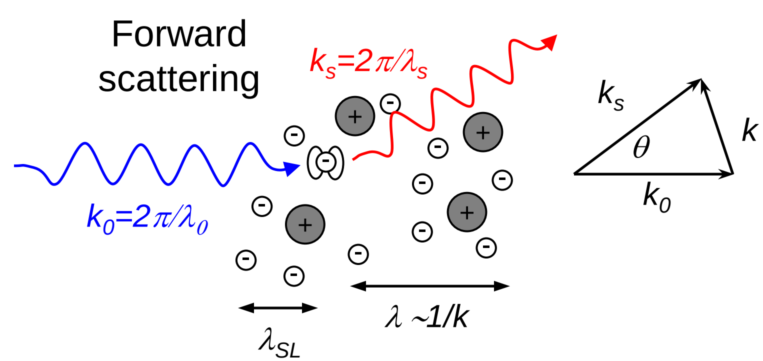
$$\lambda_{TF} = \left[\frac{\pi \varepsilon_0 \hbar^2}{m_e e^2}\left(\frac{\pi}{3 n_e}\right)^{1/3}\right]^{1/2}$$

- Scattering parameter: $\alpha = \frac{1}{k\lambda_{SL}} \propto \frac{\lambda}{\lambda_{SL}}$ $\quad k = \frac{2\pi}{\lambda} = \frac{4\pi}{\lambda_0}\sin\left(\frac{\theta}{2}\right)$

- Non-collective scattering
  - $\alpha < 1, \ (\lambda < \lambda_{SL})$




- Collective scattering
  - $\alpha > 1, (\lambda > \lambda_{SL})$




O. L. Landen, *et al.*, J. Quant. Spectrosc. Radiat. Transf. **71**, 465 (2001)

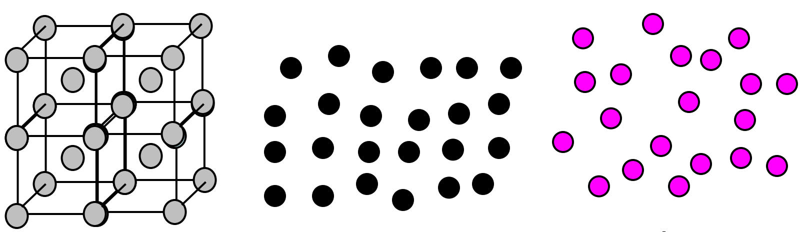
# Scattering related to dynamic structure factor of material

- Total cross-section includes free, tightly and weakly bound electron states

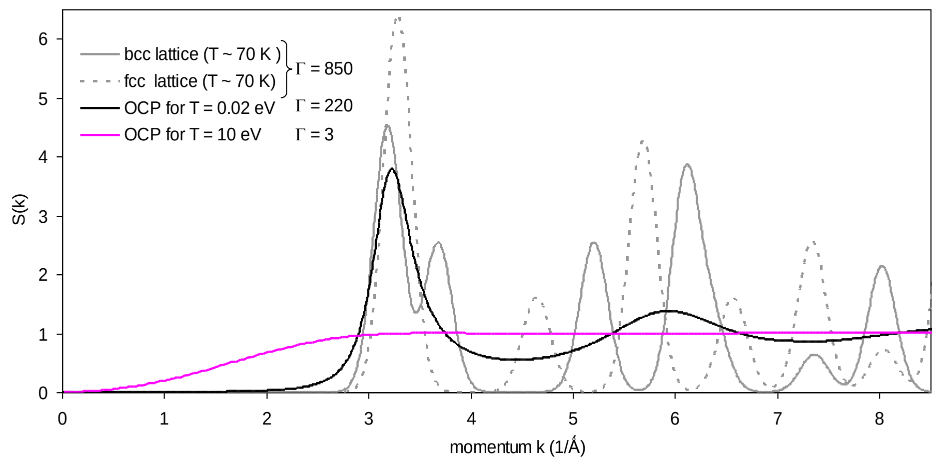
$$\frac{d^2\sigma}{d\Omega d\omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Th} \frac{k_1}{k_0} S(k,\omega)$$

- Dynamic structure factor S(k,ω)
  - Fourier transform of probability of finding a particle at a given distance from another particle
  - Less structured atoms higher probability of scattering at an arbitrary angle, S(k,ω) becomes constant

$$S(k,\omega) = \underbrace{\left|f_I(k)+q(k)\right|^2 S_{ii}(k,\omega)}_{\text{ion feature}} + \underbrace{Z_f S^0_{ee}(k,\omega)}_{\text{electron feature}} + \underbrace{Z_b \int \tilde{S}_{ce}(k,\omega-\omega')S_S(k,\omega')d\omega'}_{\text{bound-free feature}}$$



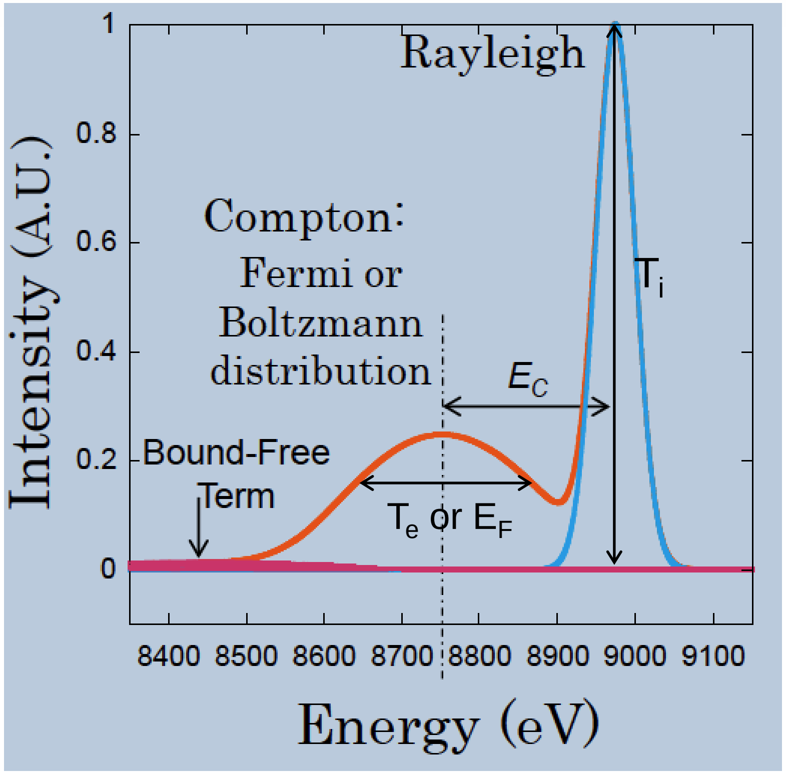
bcc lattice    liquid    plasma




J. Chihara, J. Phys. Condens. Matter **12**, 231 (2000)

# Extracting information from non-collective XRTS

- Electron density
  - For Fermi-degenerate plasma, width of Compton $\mu\ E_F^{1/2}\ \mu\ n_e^{1/3}$
- Electron temperature
  - For non-degenerate plasma, Compton reflect Maxwell-Boltzmann distribution which provide $T_e$
- Ion temperature
  - From intensity of Rayleigh which increases with increasing $T_i$
- Ionization state
  - From profile distribution & intensity of inelastic feature due to bound-free scattering

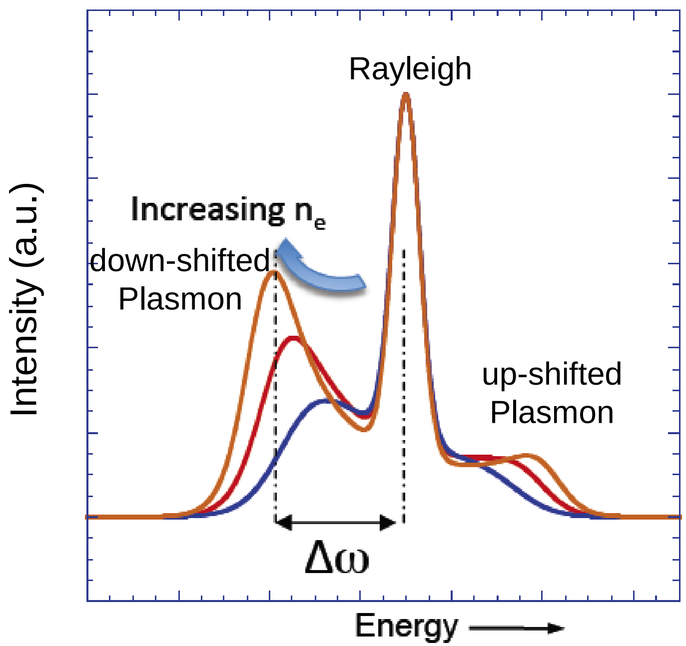



O. L. Landen, *et al.*, J. Quant. Spectrosc. Radiat. Transf. **71**, 465 (2001)

# Extracting information from collective XRTS data

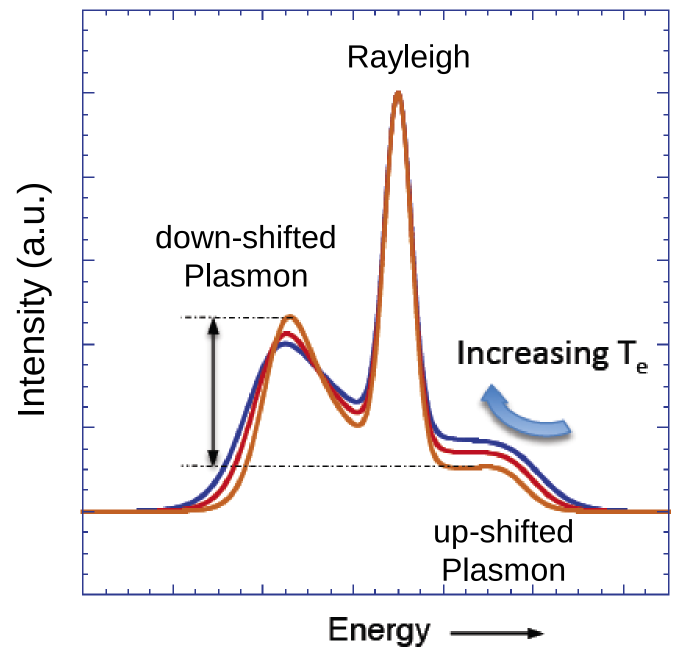
- Electron density
  - From plasmon frequency shift from Rayleigh peak via dispersion relation

$$\Delta\omega \approx \omega_{pe} \propto n_e^{1/2}$$




- Electron temperature
  - From ratio of up- to down-shifted plasmons from detailed balance

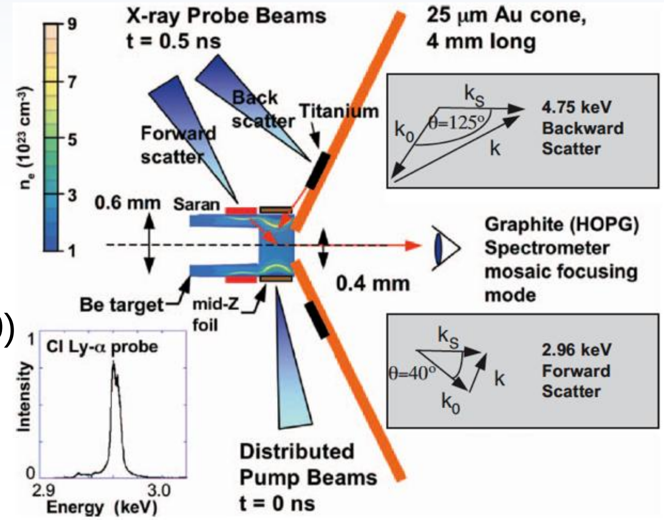
$$\frac{S(k,\omega)}{S(-k,-\omega)} = \exp\left(-\frac{\hbar\omega}{kT_e}\right)$$



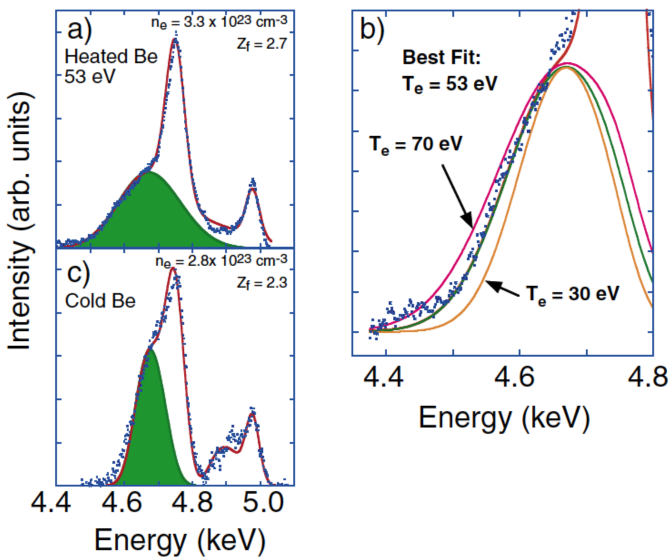

O. L. Landen, *et al.*, J. Quant. Spectrosc. Radiat. Transf. **71**, 465 (2001)

# Laser isochorically heated XRTS-WDM experiment

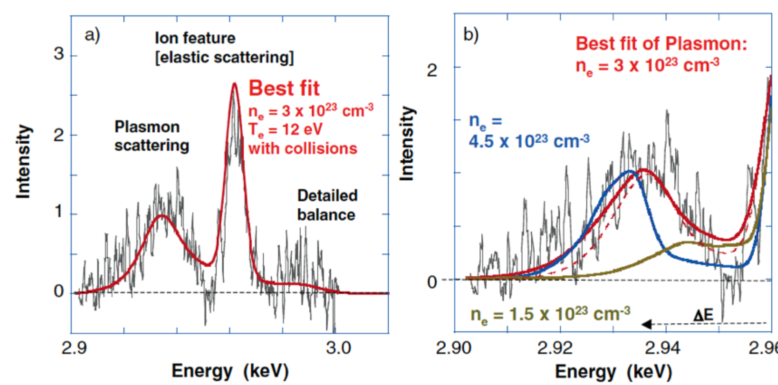
- Be target: 300 μm long x 600 μm diameter cylinder
  - OMEGA: 1 ns heater (10-15 kJ), 1 ns probe (3.5-7 kJ)
  - LASNEX: $T_e$ = (30-60) & (10-15) eV, $n_e$ = (2-3) $\times 10^{23}$ $cm^{-3}$
  - Ti-He-$\alpha$ 4.75 keV, 125° scattering
  - Cl-Ly-$\alpha$ 2.96 keV, 40° scattering
  - HOPG spectrometer-gated microchannel plate (E/ΔE ~ 500)




- Best fit to non-collective scattering data
  - $T_e$ = 53 eV (± 10%)
  - $n_e$ = 3.3 $\times 10^{23}$ $cm^{-3}$ (± 10%)




- Best fit to collective scattering data
  - $T_e$ = 12 eV (± 50%)
  - $n_e$ = 3 $\times 10^{23}$ $cm^{-3}$ (± 20%)




S. H. Glenzer, *et al.*, PRL **90**, 175002 (2003); S. H. Glenzer, *et al.*, PRL **98**, 065002 (2007)

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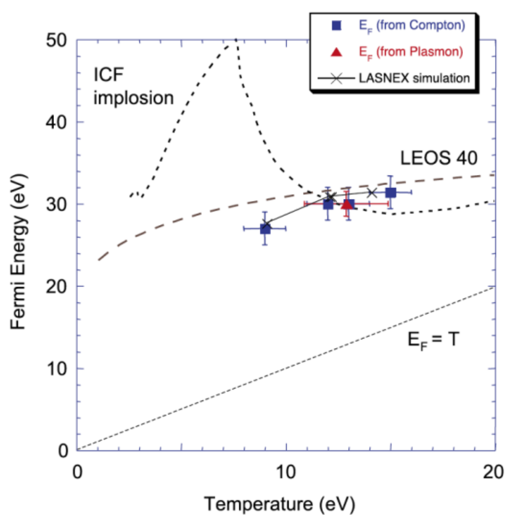
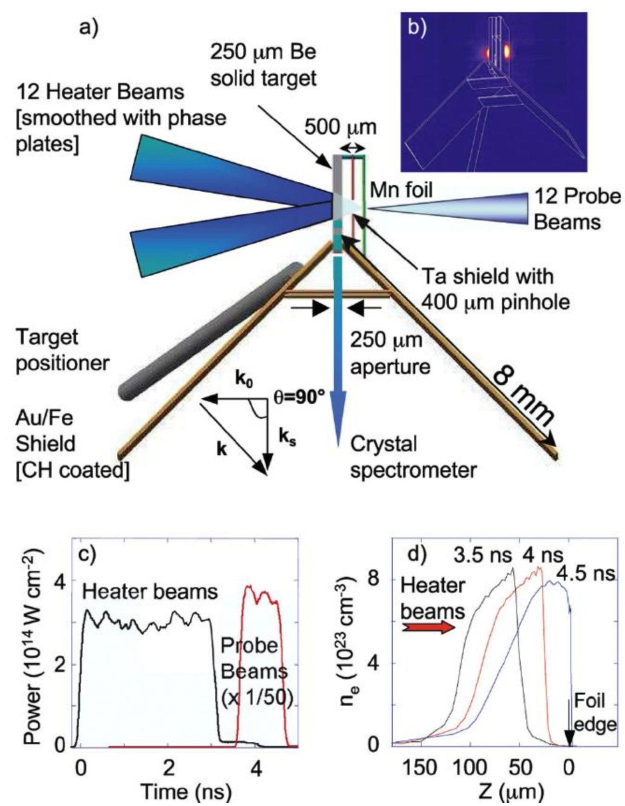
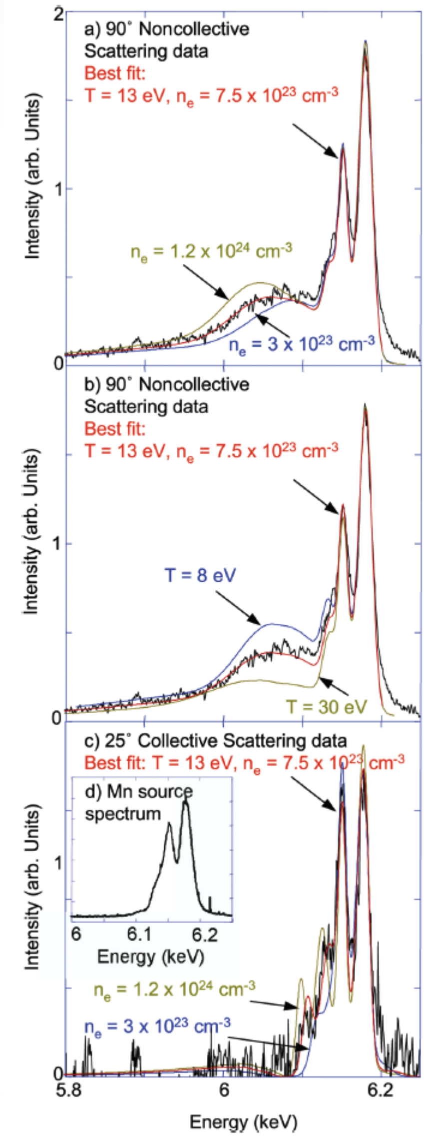
# Laser driven shock XRTS-WDM experiment

- Be target: 250 μm thick x 1 mm diameter spot
  - OMEGA: 3 ns heater ($3\times10^{14}$ W/cm$^2$), 1 ns probe ($2\times10^{16}$ W/cm$^2$)
  - LASNEX: 20-35 Mbar, 3x compressed
  - Mn-He-$\alpha$ 6.181 keV, 90° & 25° scattering
  - HOPG spectrometer-gated microchannel plate ($E/\Delta E \sim 500$)
- Best fit to data
  - $T_e$ = 13 eV ($\pm$ 20%)
  - $N_e$ = $7.5\times10^{23}$ cm$^{-3}$ ($\pm$ 7%)
  - Z = 2 ($\pm$ 25%)
  - $E_F$ = 30 eV ($\pm$ 7%)




H. J. Lee, *et al.*, PRL **102**, 115001 (2009)

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# Expanding the scientific capabilities of Z (temperature, phase, structure factor, ionization)

- Measure temperatures of shock, ramp, and complex-path loading states
  - Constrain thermal contribution to EOS for high-pressure experiments
  - Measure temperature for ramp or complex-path loading through a phase boundary
  - Temperature range: 0.3-20 eV; accuracy: 5-20%
- Phase identification and characterization on ramp and shock loading
  - Measure changes in crystal structure (and ultimately isotropy, heterogeneity) along a dynamic loading path
- Quantify the influence of correlations on the EOS by measuring the structure factor, S(k), as function of wave vector for warm dense matter
  - Reconcile non-physical assumptions of previous XRTS work (OCP approximation)
- Measure ionization for dynamically compressed materials at transition from insulator to conductor

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# XRTS-WDM LDRD project research activities

- Design experiment through synthesizing prior work and using simulations
- Create a uniform warm dense matter sample on Z
- Design, fabricate, calibrate a high sensitivity x-ray spectrometer
  - X-ray scattering spherical spectrometer ($XRS^3$)
- Create of an intense x-ray probe source
- Implement complementary diagnostics on Z
- Develop analysis methods, theory, and simulations that connect the experiment results with a physical picture and exploit the results to advance physics knowledge

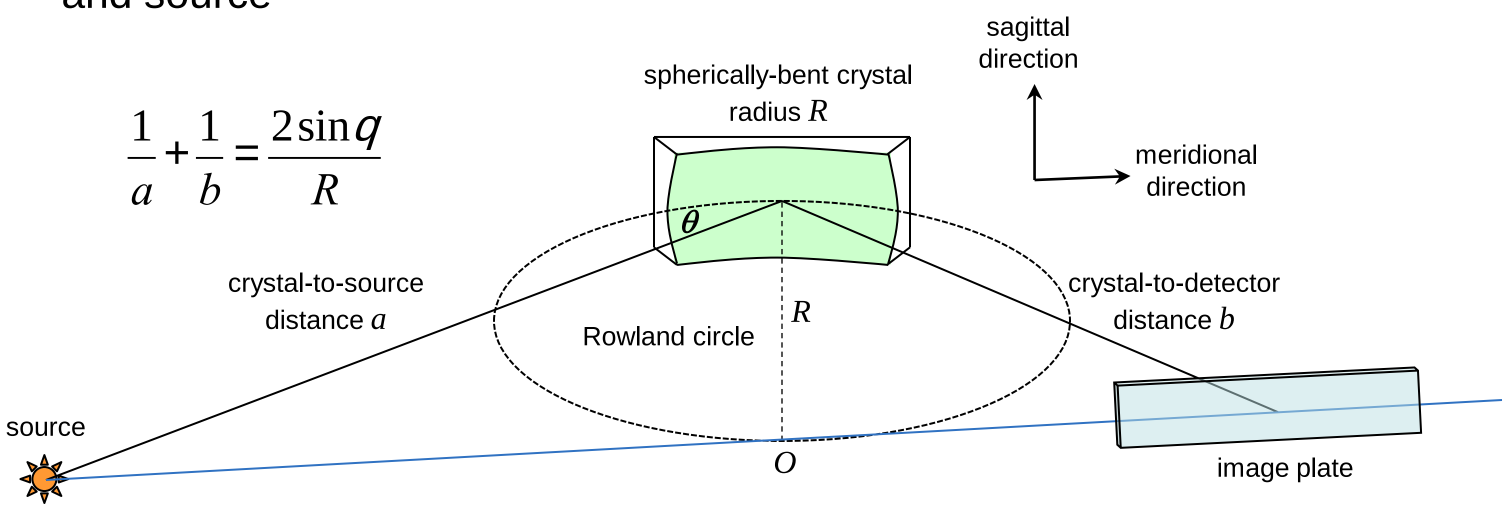
# XRS³ design based on FSSR (focusing spectrometer with spatial resolution)

- Spherically bent crystal enables double focusing
  - Simultaneously obtain high spectral and high spatial resolution
  - X-rays from source dispersed from crystal according to Bragg equation

$$nl = 2d\sin q$$

- Source-crystal-detector setup
  - Source located outside Rowland circle
  - Detector (image plate) outside Rowland circle on line passing through point *O* and source

$$\frac{1}{a}+\frac{1}{b}=\frac{2\sin q}{R}$$




D. B. Sinars, *et al.*, J. Quant. Spectrosc. Radiat. Transf. **99**, 595 (2006)

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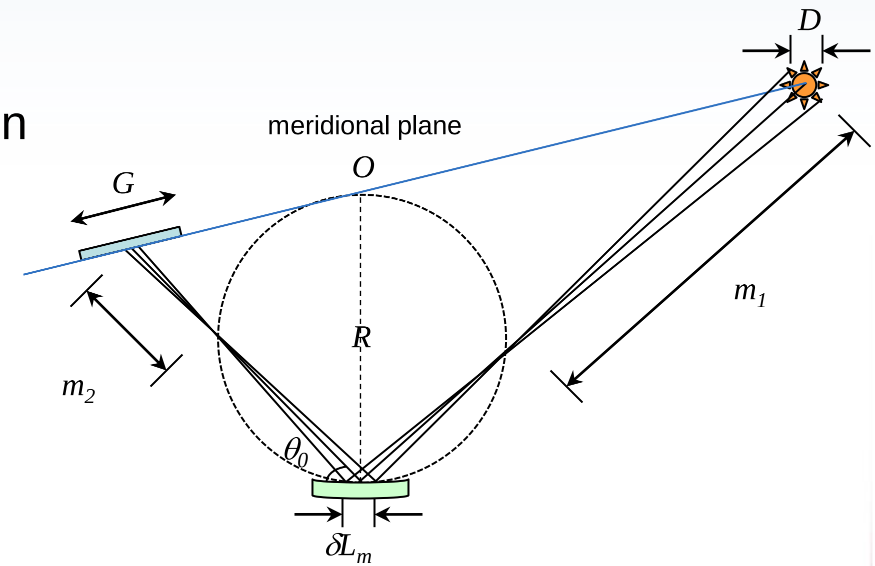
# FSSR provides spatial imaging in sagittal direction and spectral dispersion in meridional direction

- Magnification along meridional direction

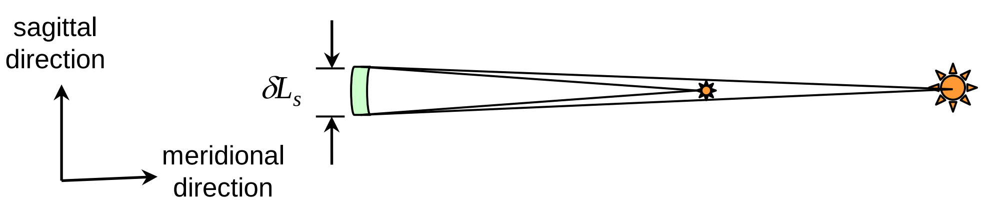
$$M_{mer} = \frac{m_2}{m_1}$$

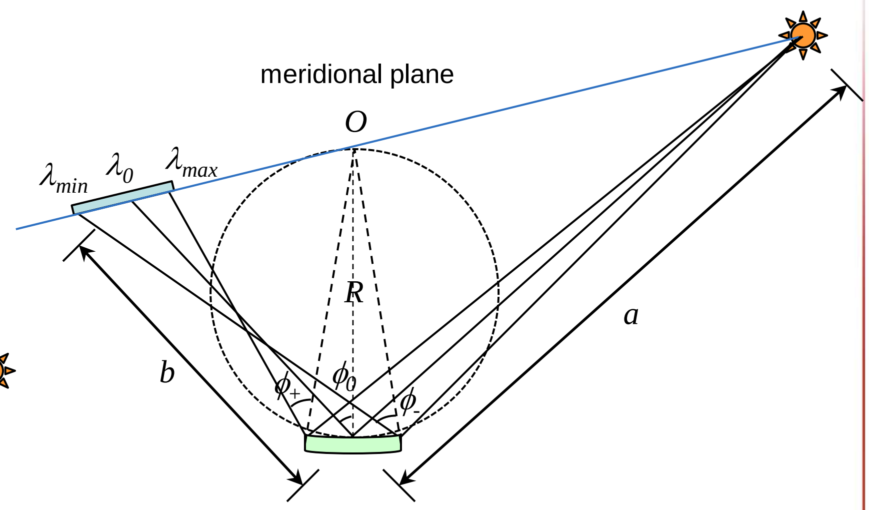
$$d\lambda(G) = \left(D M_{mer} \sin\theta_G\right)\left\{\frac{\partial\lambda}{\partial G}\right\}$$




- Magnification along sagittal direction

$$M_{sag} = \frac{b}{a} = \frac{R}{2a\sin\theta - R}$$

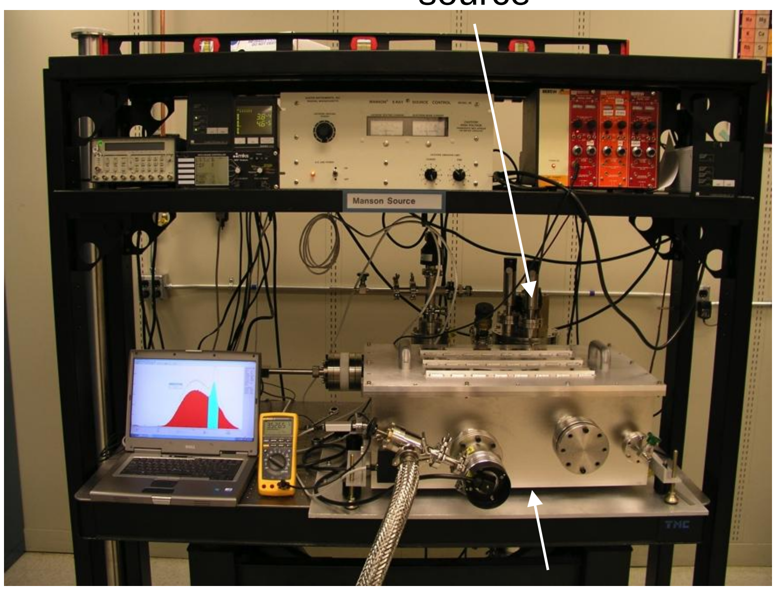


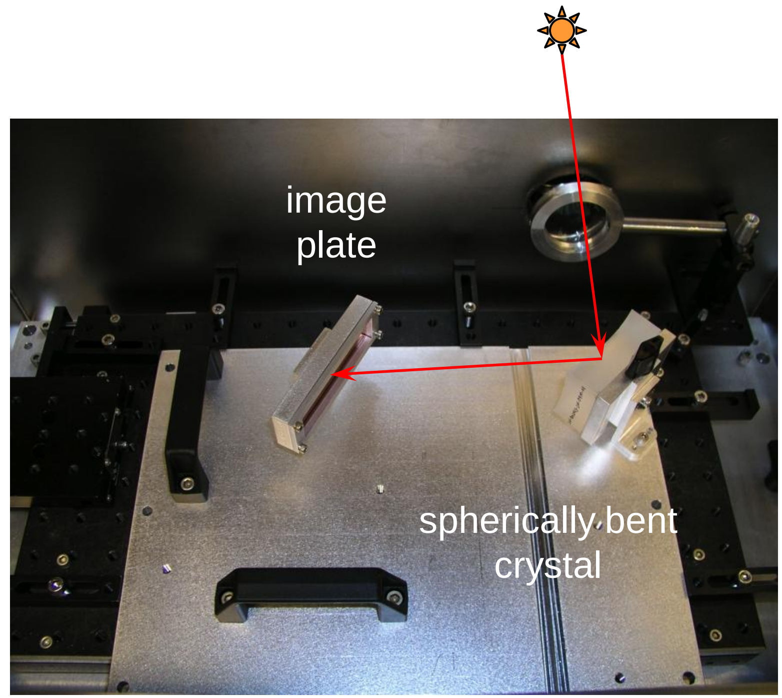




D. B. Sinars, *et al.*, J. Quant. Spectrosc. Radiat. Transf. **99**, 595 (2006)

# Crystal characterizations performed on Manson x-ray source

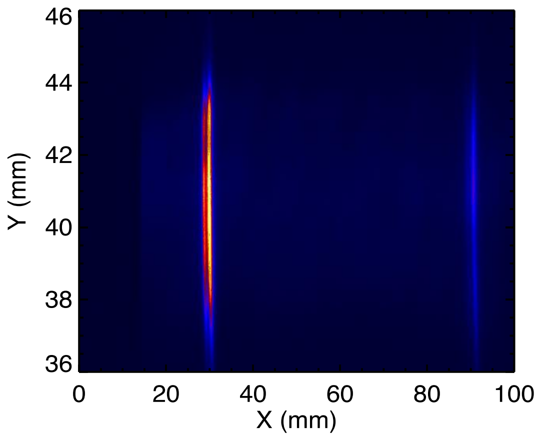
- Manson x-ray source
  - Mn anode: K-α (5.899 keV) & K-β (6.491 keV)
- Crystal characterization parameters
  - Relative reflectivity
  - Spectral resolution E/ΔE > 1000
  - Spatial resolution < 100 μm

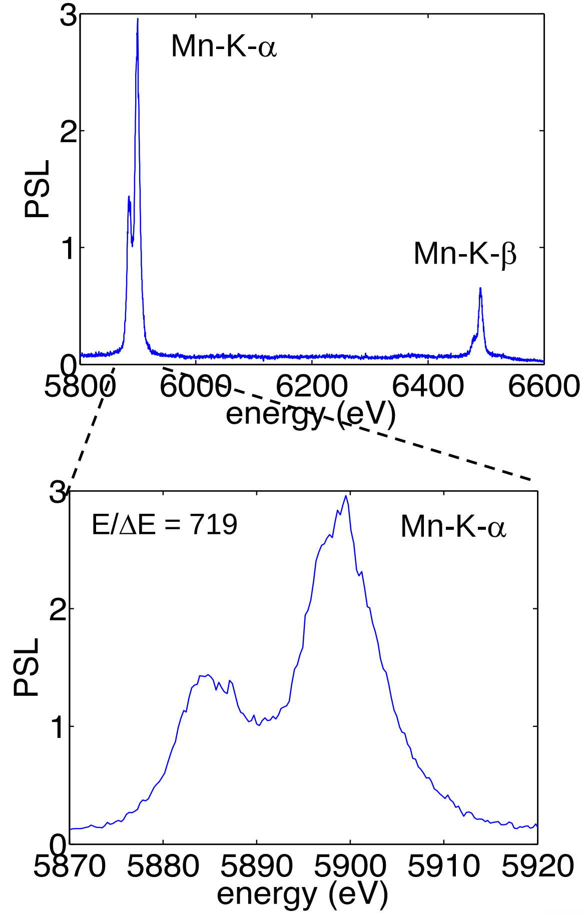


# Highly orientated polygraphite (HOPG) crystals commonly used in XRTS-WDM experiments

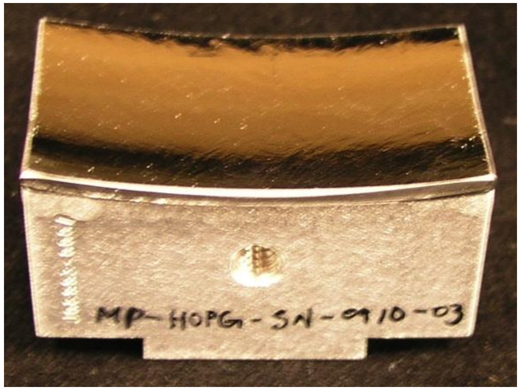
- HOPG provides no spatial information and moderate spectral resolution
  - Cylindrically bent HOPG, $\theta_B = 37°$ , 30x50 mm, r = 150 mm, mosaic focusing

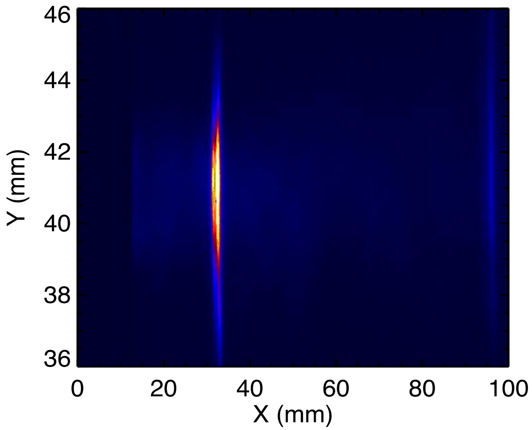



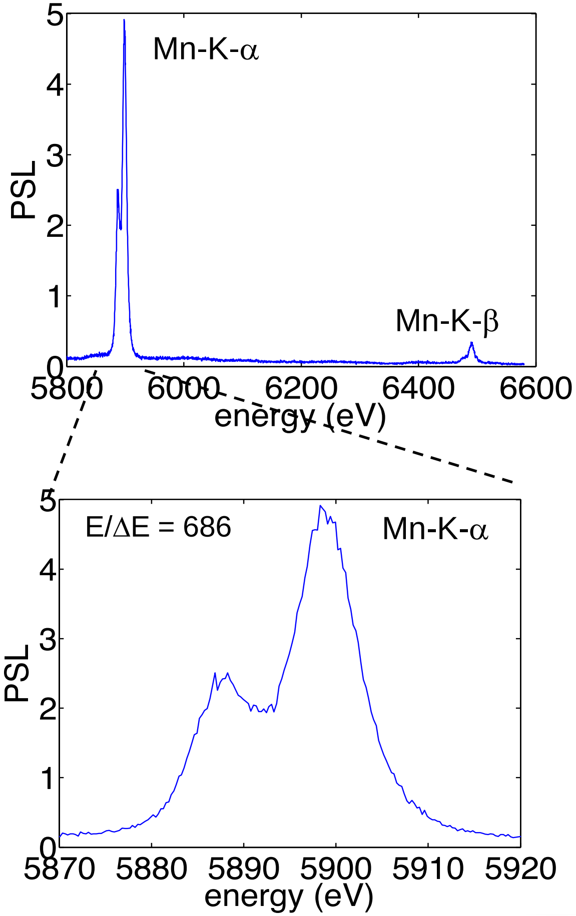



# Spherically bent HOPG crystal increases x-ray collection but still provides no spatial information

- Spherically bent HOPG, $\theta_B = 37^\circ$
  - 30x50 mm, r = 150 mm, mosaic focusing

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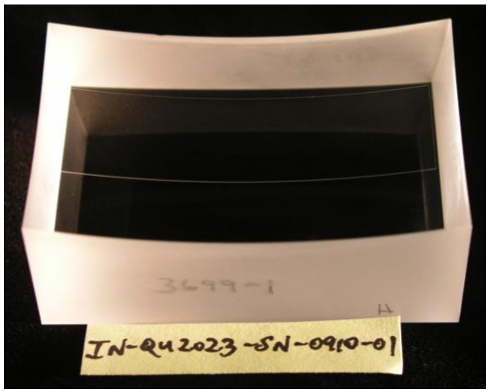
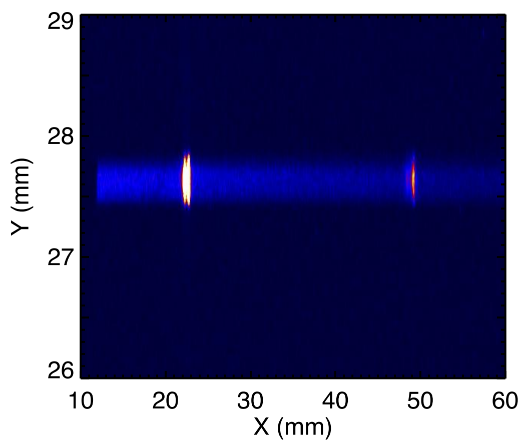
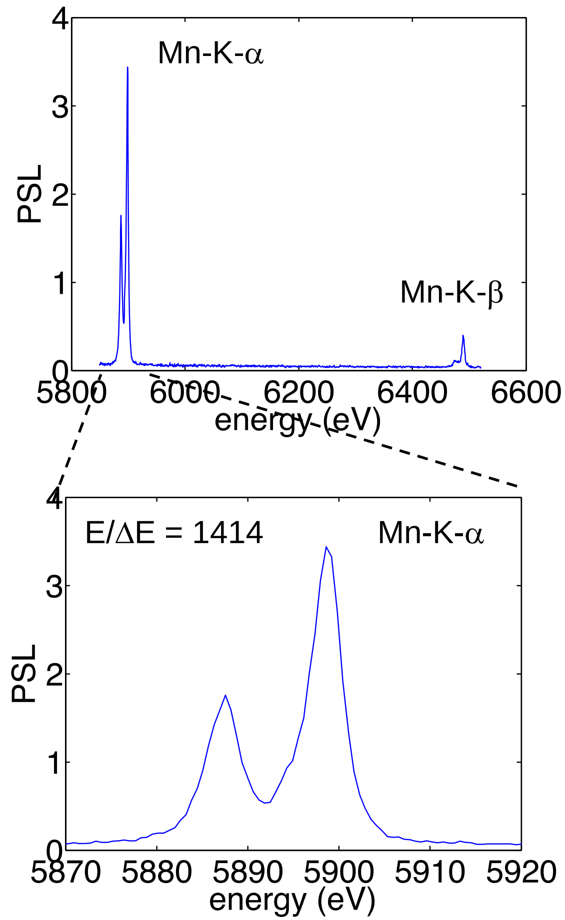
# Spherically bent single crystal provide both high spatial and spectral resolution

- Quartz $20\bar{2}3$ (Inrad), $\theta_B = 46^\circ$
  - Single crystal: 18 mm x 60 mm, r = 150 mm




- ~1/20x total collected signal of cylindrical HOPG

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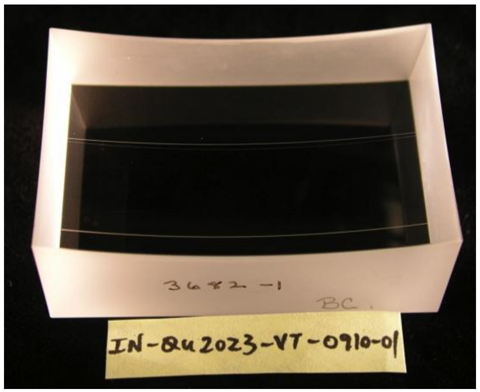
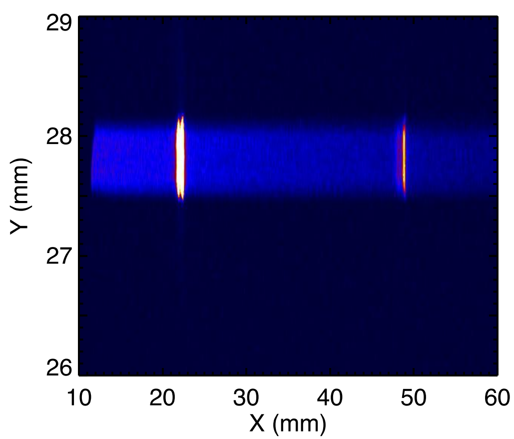
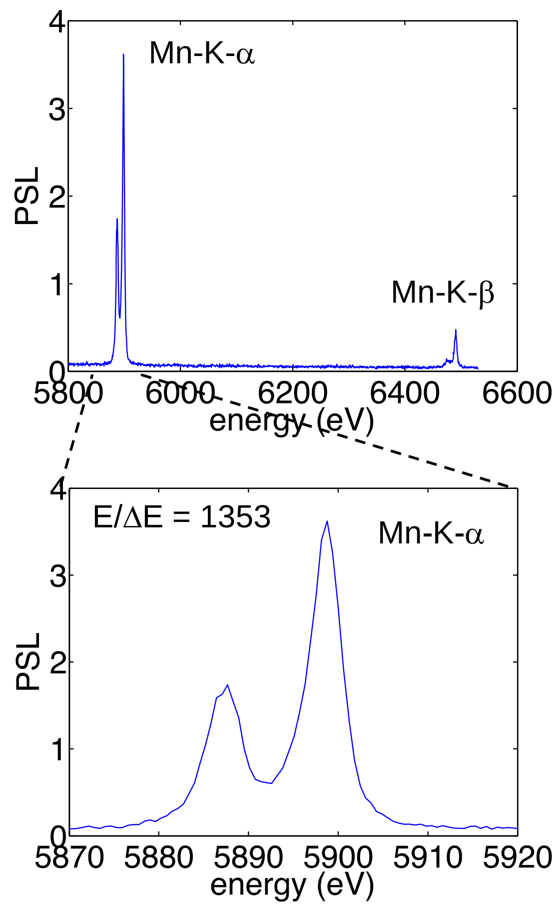
# Vertical tiling of crystals to increase reflecting area

- Quartz $20\bar{2}3$ (Inrad), $\theta_B = 46^\circ$
  - Two crystals vertically tiled: 36 mm x 60 mm, r = 150 mm
  - Multiple images due to crystals bent on slightly different spherical surfaces




- ~1.8x total collected signal of single Quartz $20\bar{2}3$



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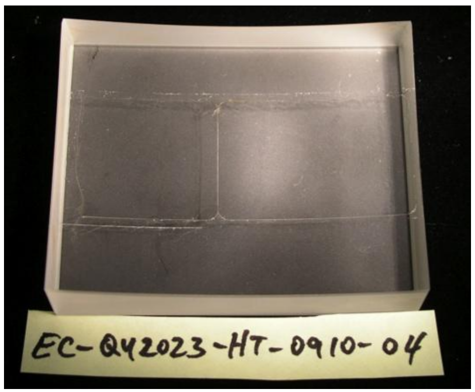
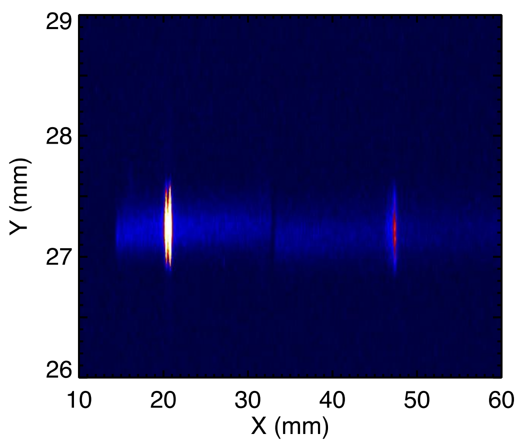
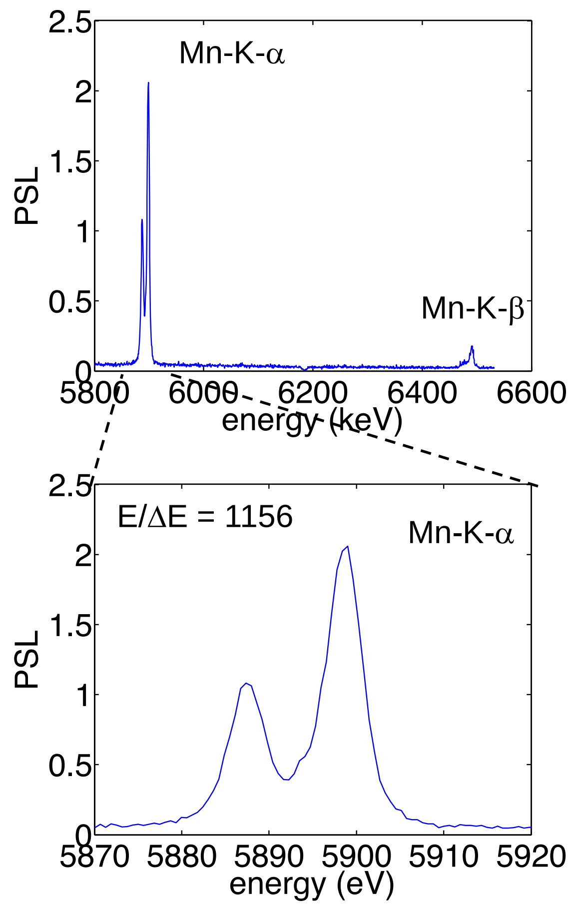
# Horizontal tiling of crystals to increase reflecting area

- Quartz $20\bar{2}3$ (Ecopulse), $\theta_B = 46^\circ$
  - Two crystals horizontally tiled: 20 mm x 50 mm, r = 150 mm
  - Missing information at the edges of adjacent crystals

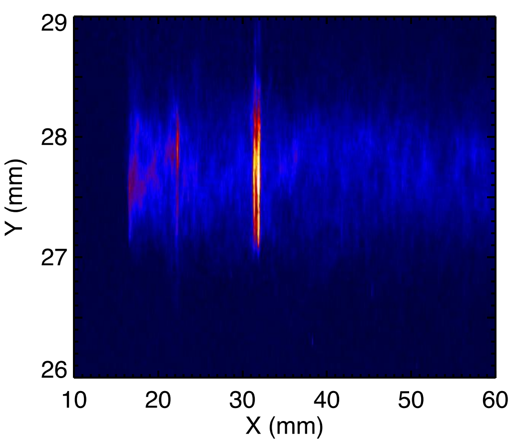


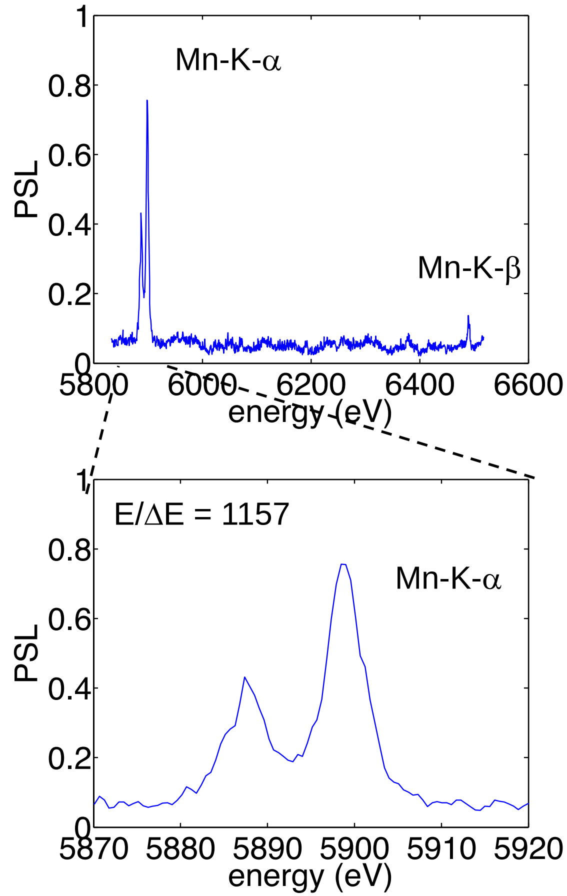



# Mica crystal would be versatile due to its multiple orders of reflections

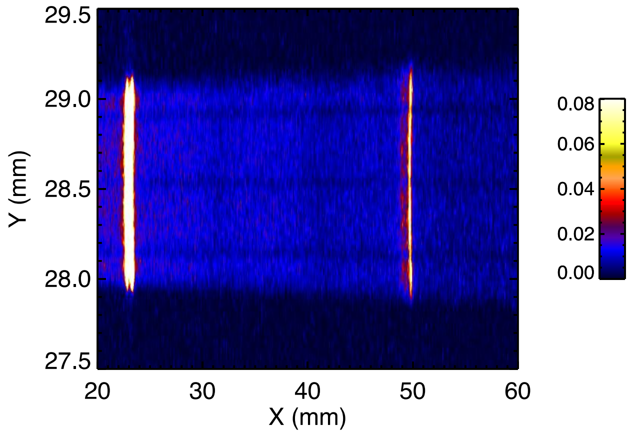
- Mica (Ecopulse), 7th order, $\theta_B = 37^\circ$
  - Two crystals vertically tiled: 30 mm x 50 mm, r = 150 mm
  - Poor focusing due to quality of Mica



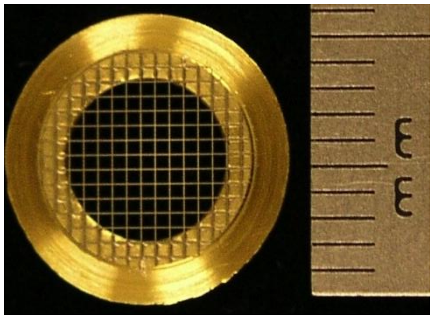



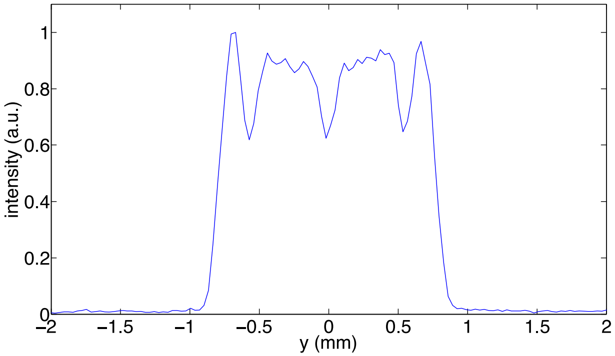
# Spatial resolution of spherically bent crystal

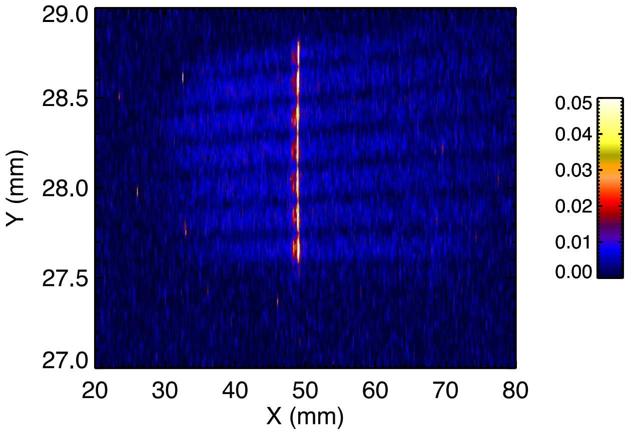
- Quartz $20\bar{2}3$ (Inrad), $\theta_B = 46°$
  - Single crystal: 18 mm x 60 mm, r = 150 mm



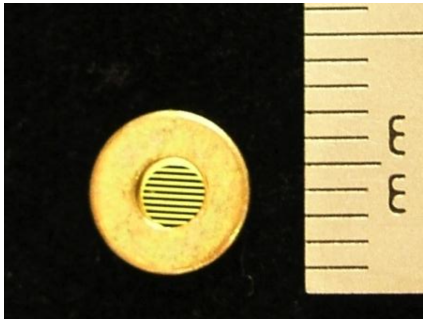

66 µm Ni wires, 494 µm spaces

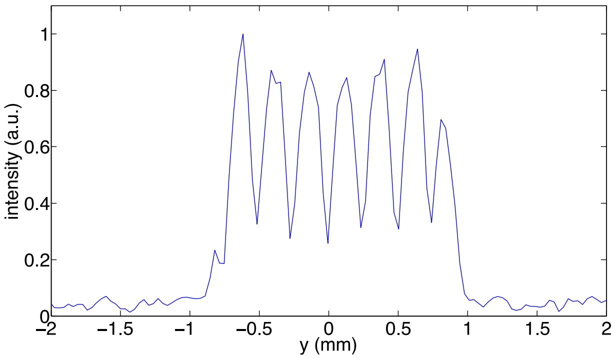





65 µm Au wires, 180 µm spaces






- Image plate and crystal spatial resolution: ~ 75 µm



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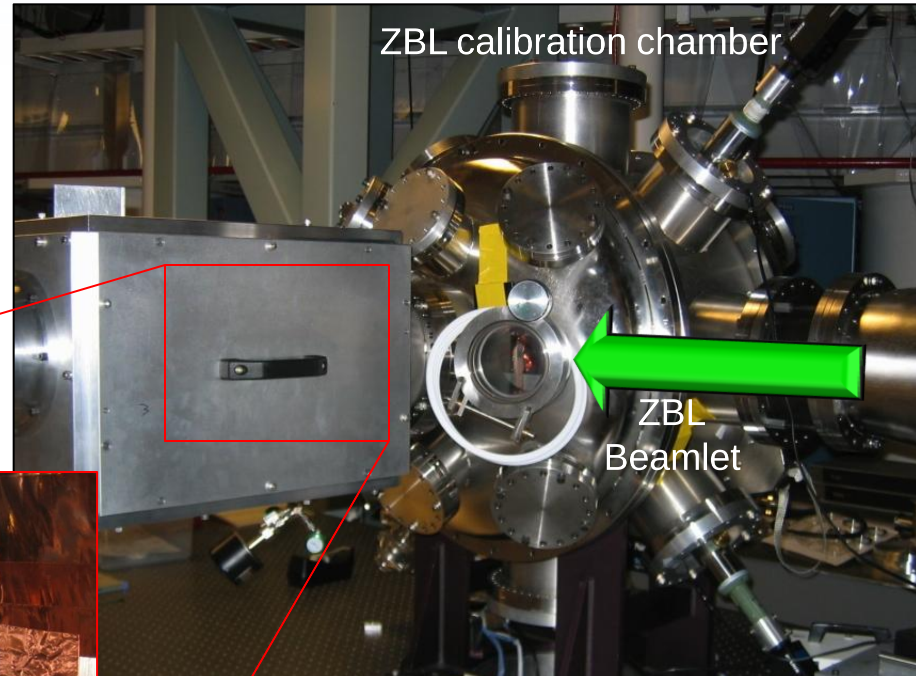
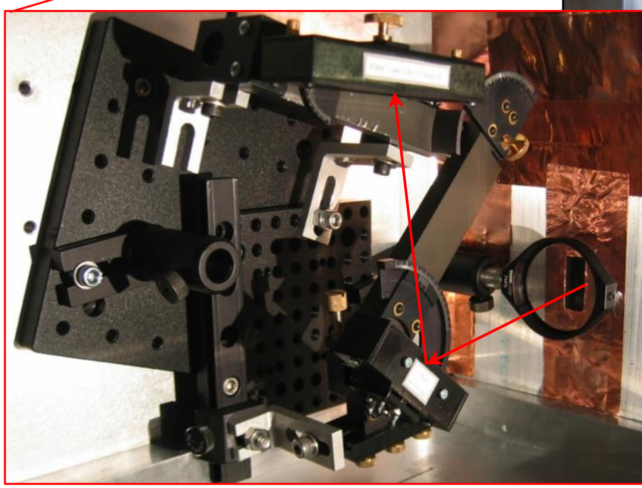
# Crystal calibration results and future work

- Quartz $20\bar{2}3$ crystals have been evaluated
  - Spectral and spatial resolutions met design criteria
  - Vertical tiling of crystals needs tolerances can be tightened
  - Horizontal tiling of crystals could result in missing information
- HOPG's high x-ray collection useful for low scattering signals
  - Sacrifice spatial imaging and has poor spectral resolution
  - Thin (<100 $\mu$m) HOPG/HAPG could provide better spectral resolution
- Mica could still prove useful if better quality crystals are found
- Germanium crystal have been shown to be 3x reflective than Quartz

# 1st XRTS-ZBL experiments (August 2010)

- X-ray source characterization
- XRTS from ambient CH & $CH_2$ foam and Al foils

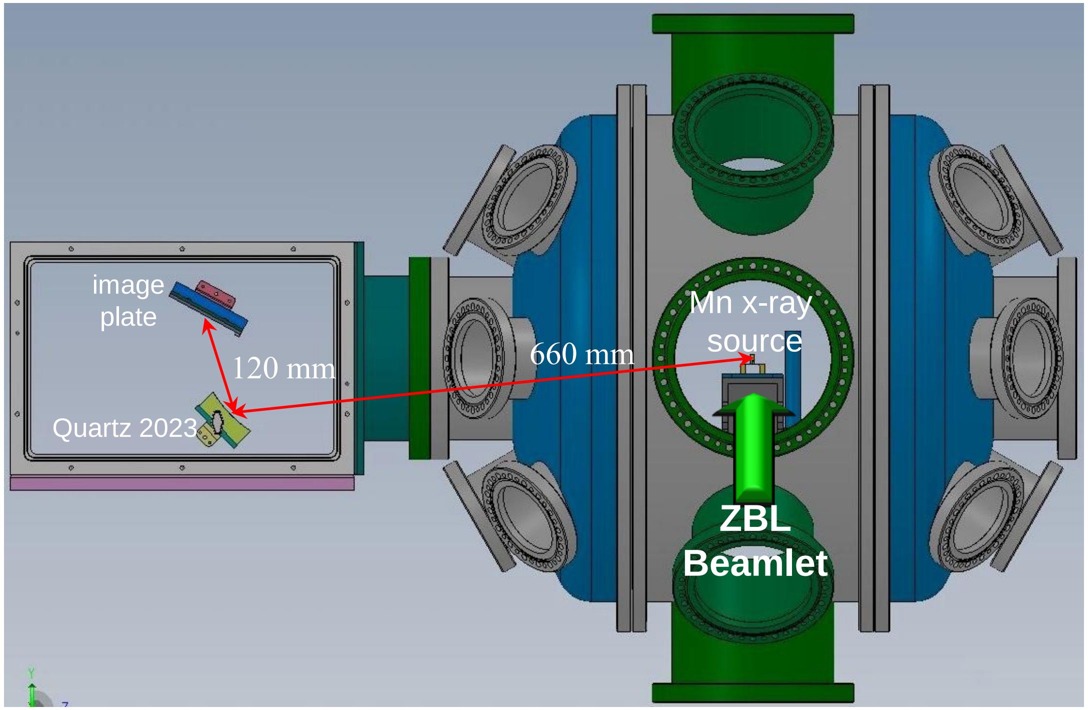


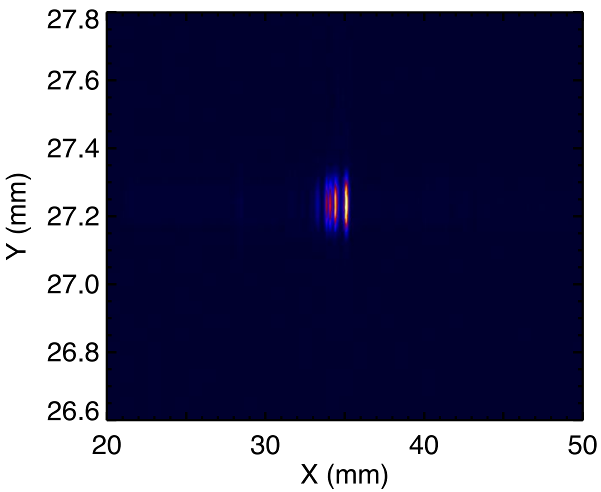



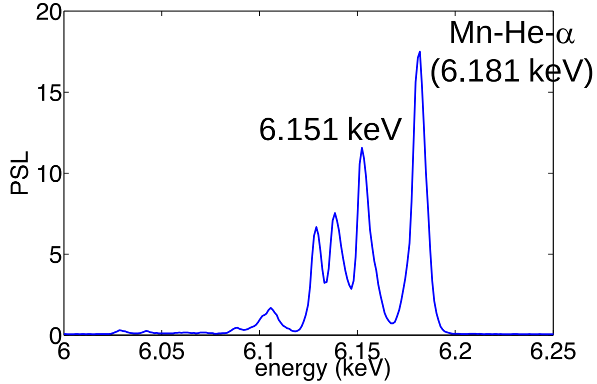
focusing spectrometer with spatial resolution (FSSR)
Quartz $20\bar{2}3$, r = 150 mm

# Spectrally resolve Mn x-ray source with FSSR

- Mn-He-α (6.181 keV) and satellites (6.151 keV for Z backlighter imaging)

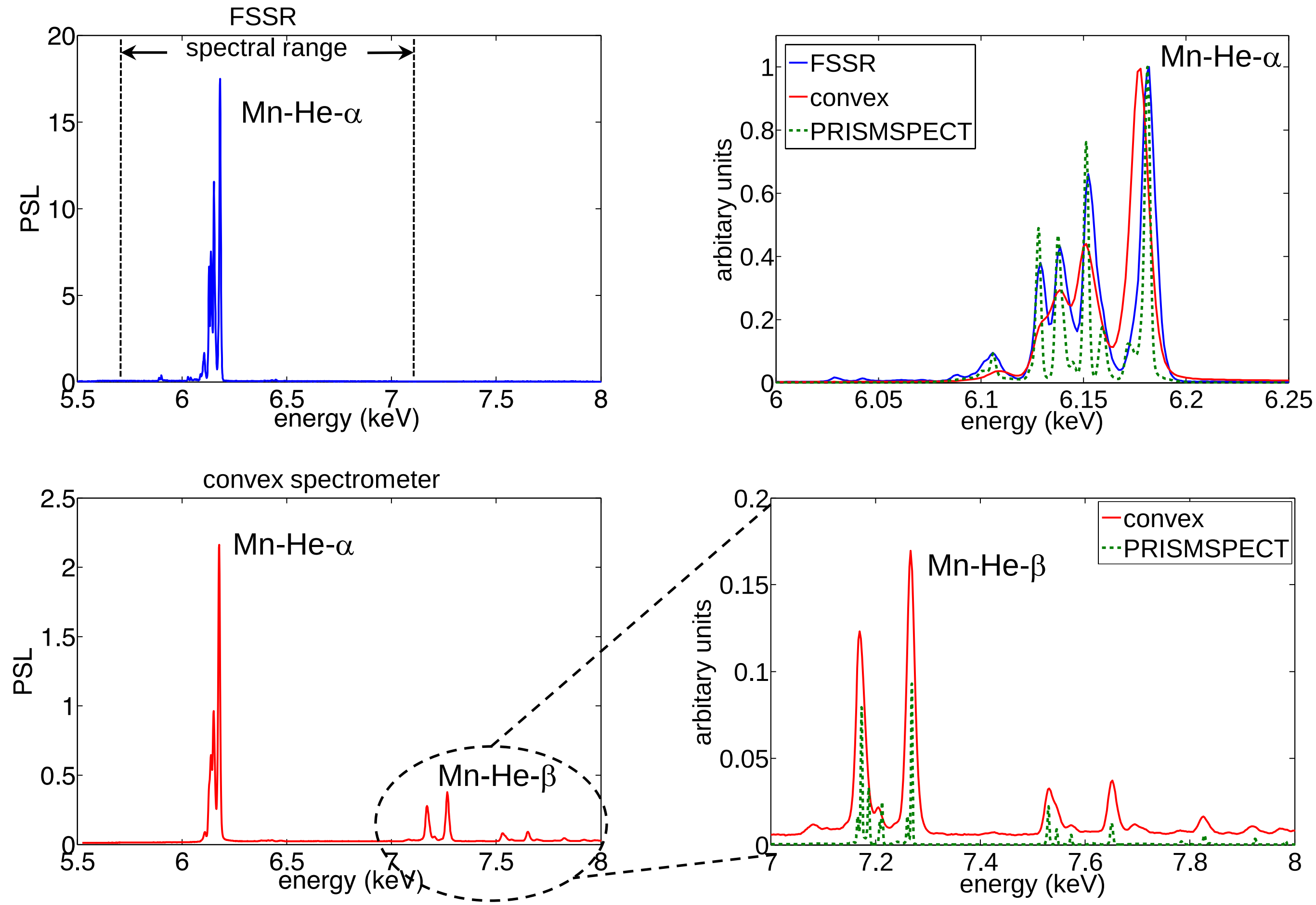


# Comparison of FSSR spectra with convex spectrometer and PRISMSPECT calculations

- PRISMSPECT
  - Mn plasma, $T_e$ = 1800 eV, d = $10^{-5}$ cm, $n_e$ = 4.6 x $10^{21}$ $cm^{-3}$

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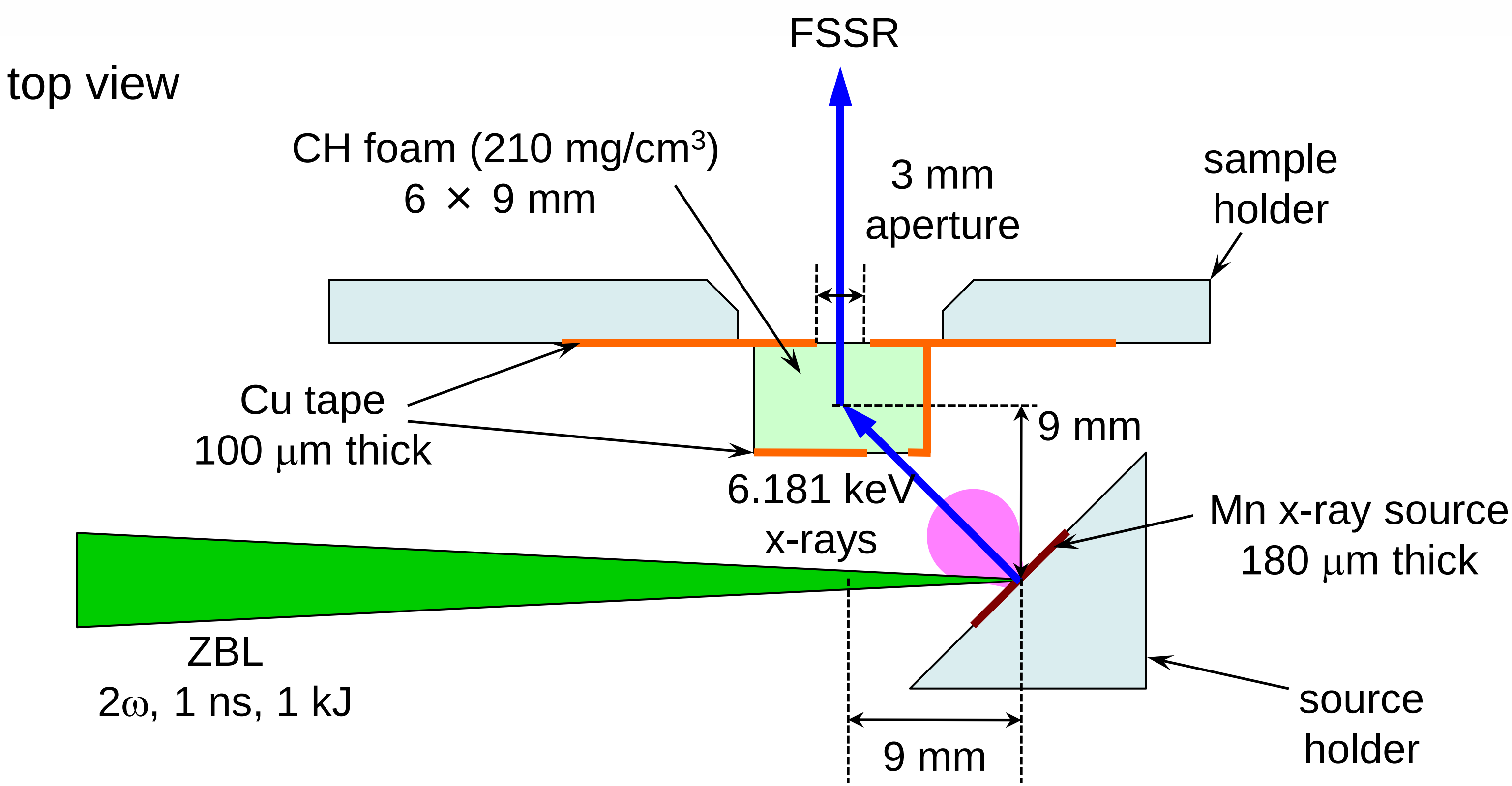
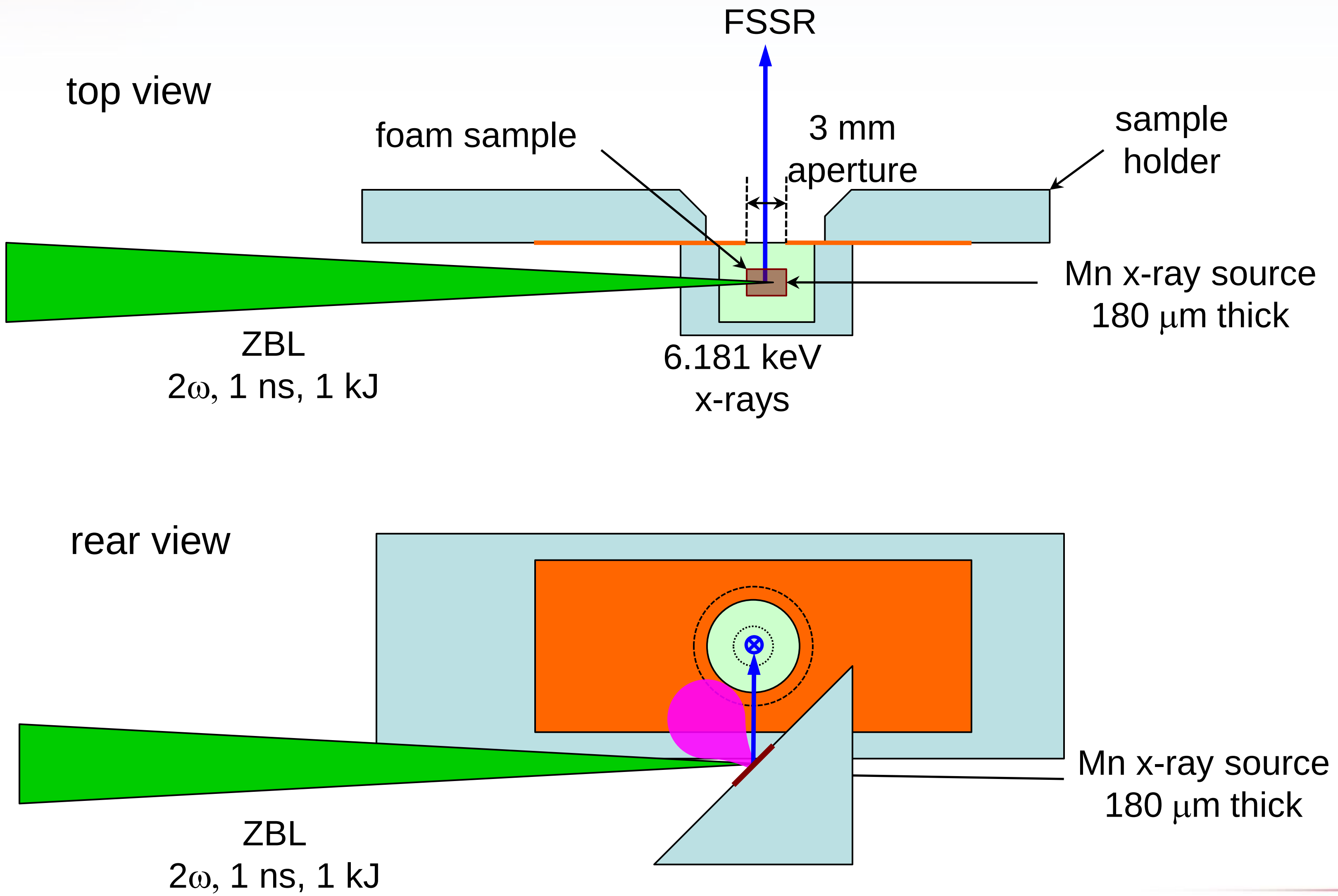
# Forward scattering experimental setup



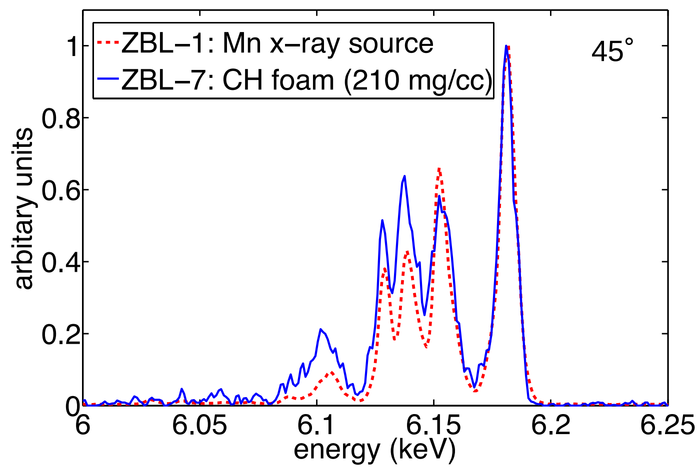
# Backward scattering experimental setup

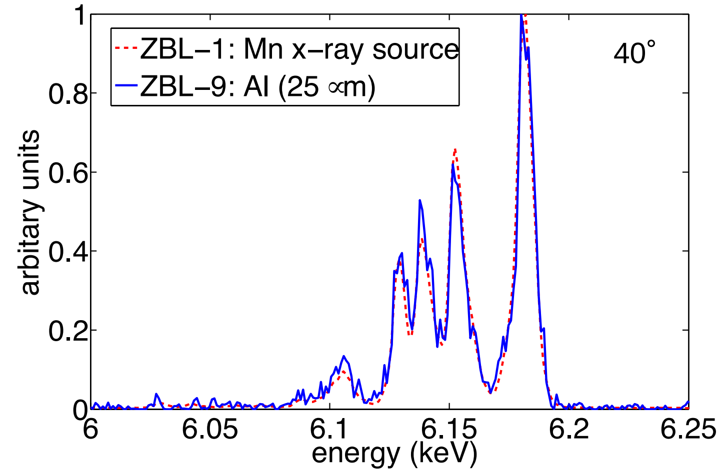


# Encouraging signal levels from x-ray scattering of cold targets

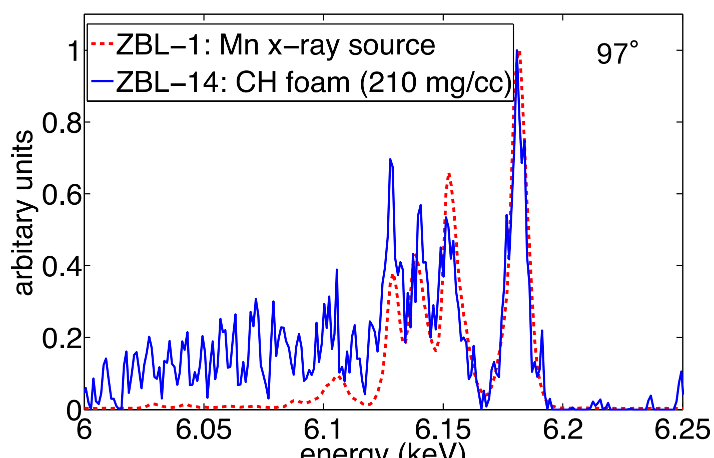
CH foam (210 mg/cm$^3$) | Al (2.7 g/cm$^3$)

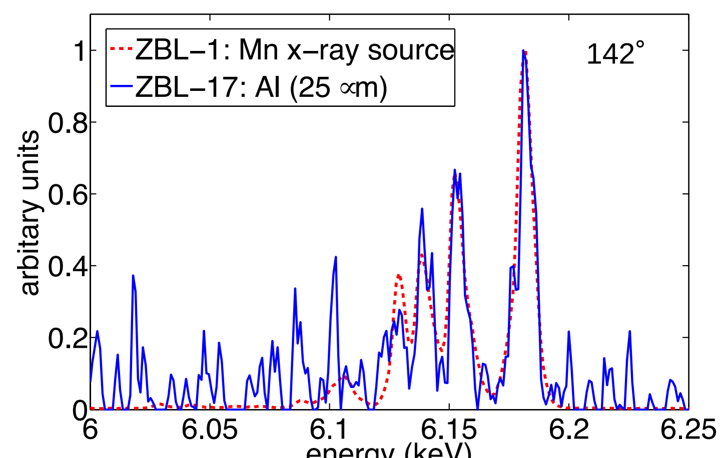
- Forward scattering




- Backward scattering

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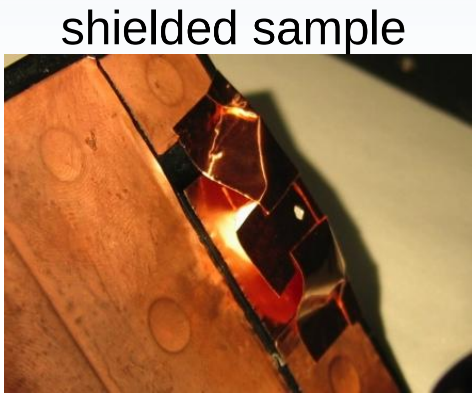
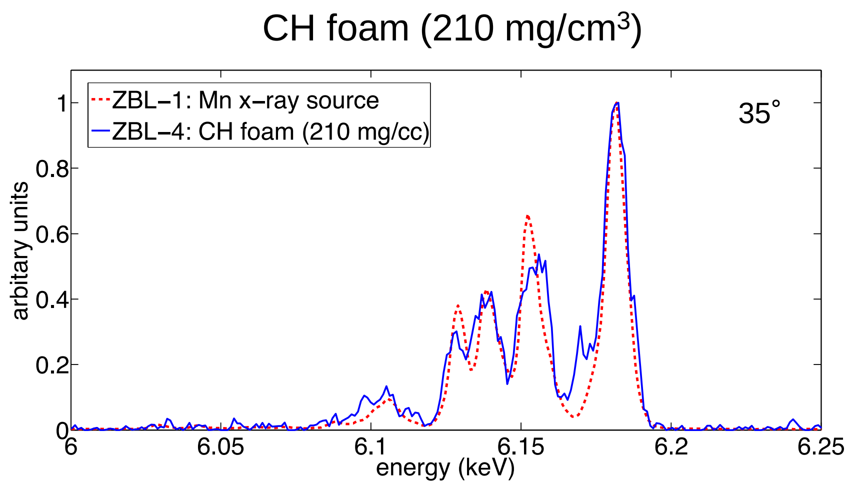
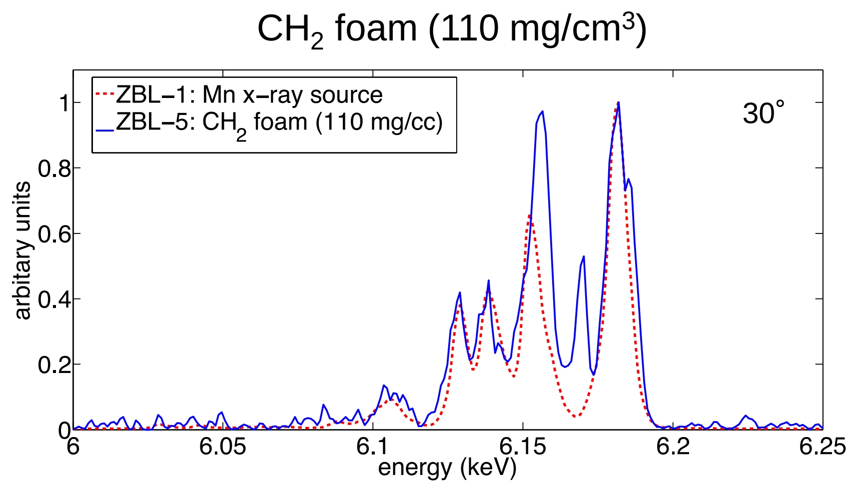
# X-ray scattering of “heated” samples


- X-ray scattering of bare samples unintentionally heated by x-rays and/or ZBL laser light (forward scattering)

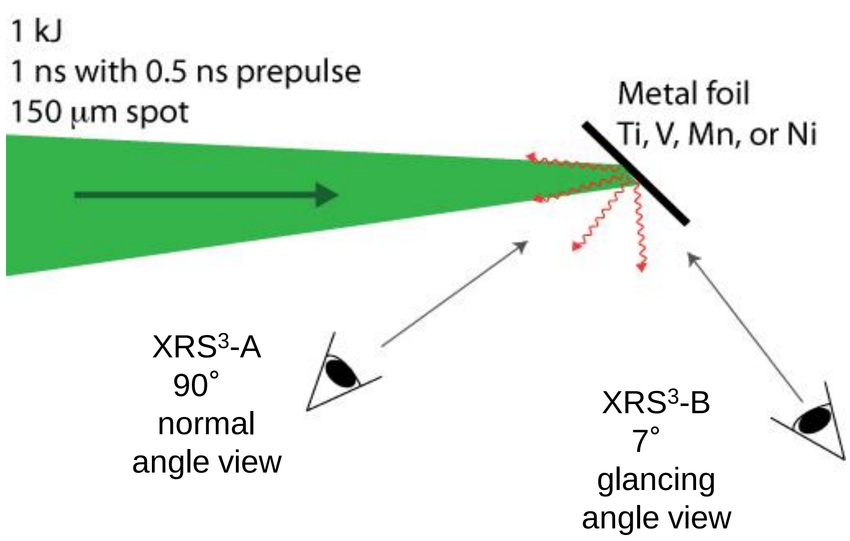


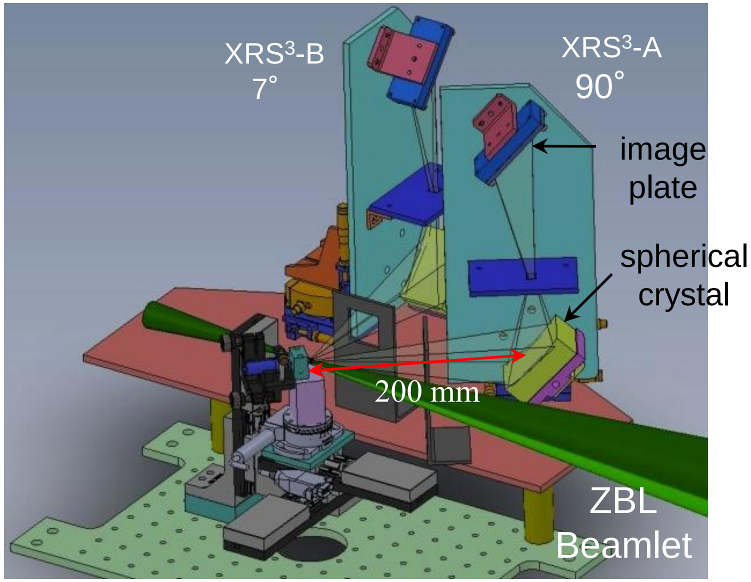




- Inelastic Compton shift (~15 eV) due to weakly bound electrons

# 2nd XRTS-ZBL experiments (May-June 2011)

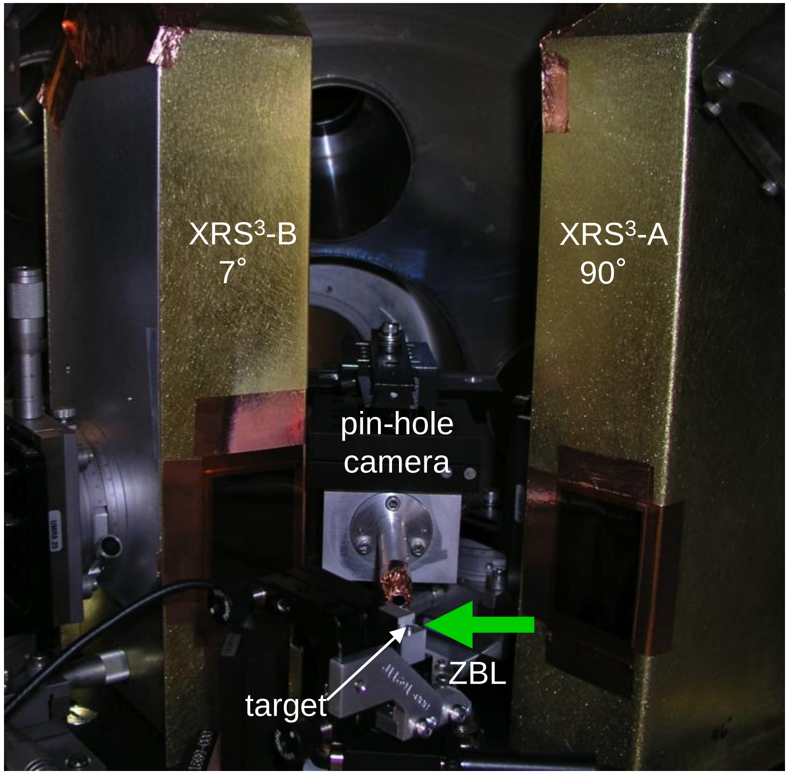
- X-ray source development for x-ray Thomson scattering
  - Investigate more monochromatic x-ray lines (e.g. V-He-β)
  - Study angular dependence of x-ray spectra



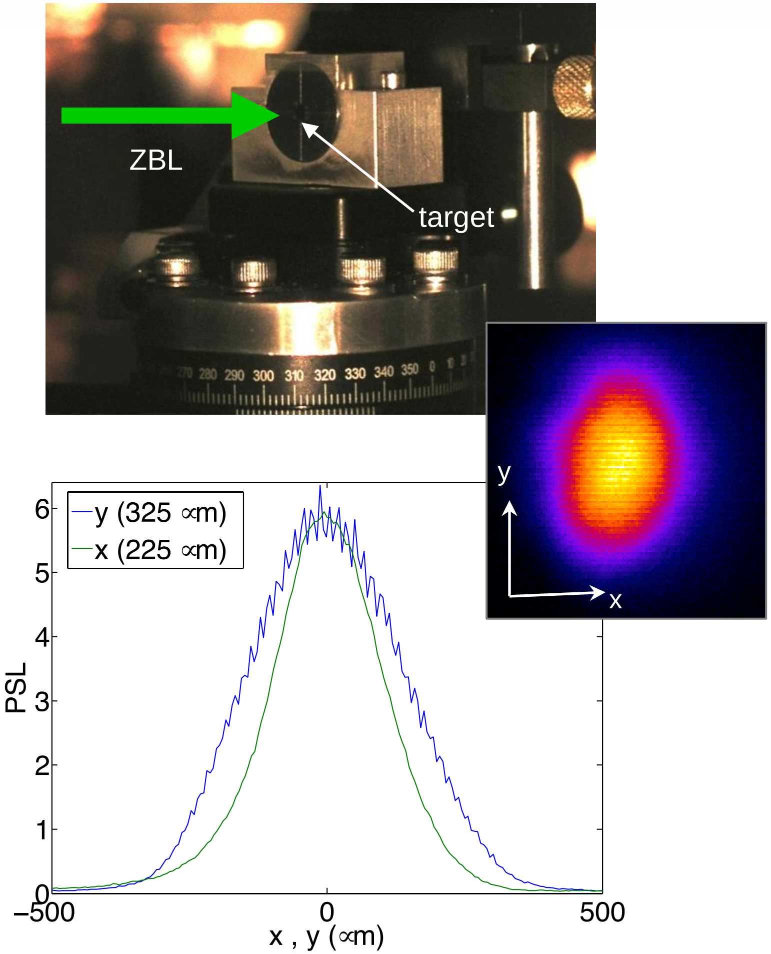



# X-ray source monitored with x-ray pin-hole camera

- X-ray pin-hole camera views target at 45°
  - 4.375x magnification




X-ray pin-hole camera view

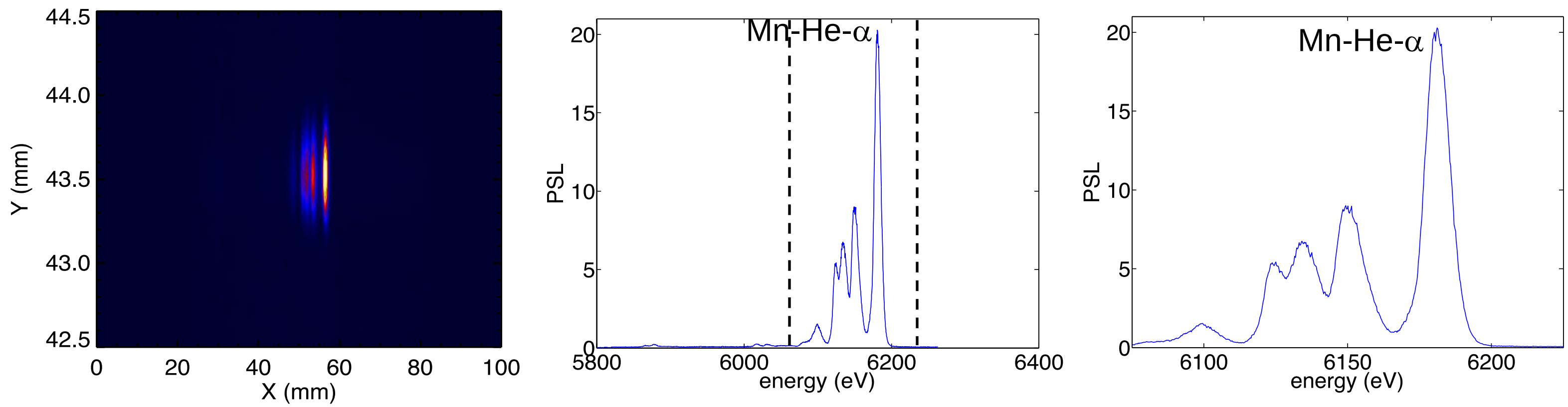


# Current x-ray source for Z backlighting
# Mn-He-α (6.181 keV)

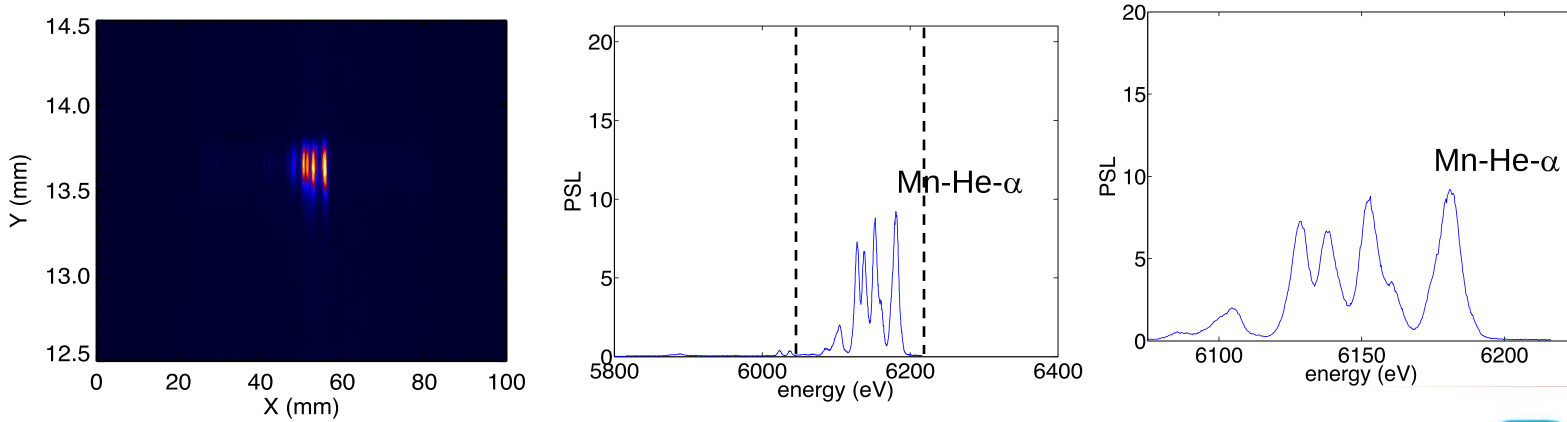
- X-ray spectra noticeably different at normal and glancing viewing angles
- Satellites next to main line complicate inelastic scattering features

- XRS$^3$-A ($\theta$ = 90° )

ZBL: 1185 J, Quartz $20\bar{2}3$: 46°




- XRS$^3$-B ($\theta$ = 7° )

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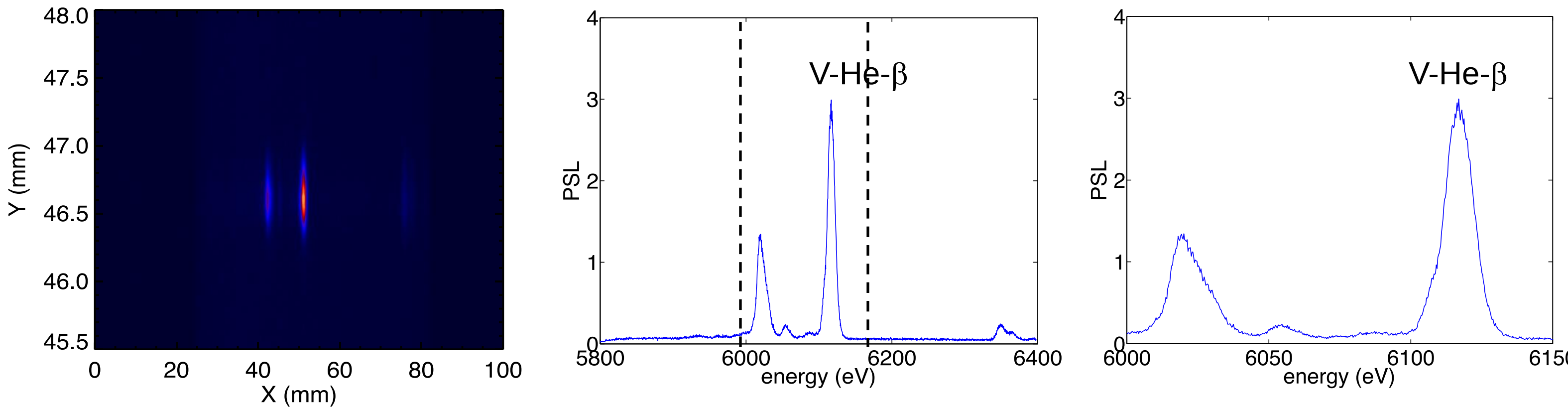
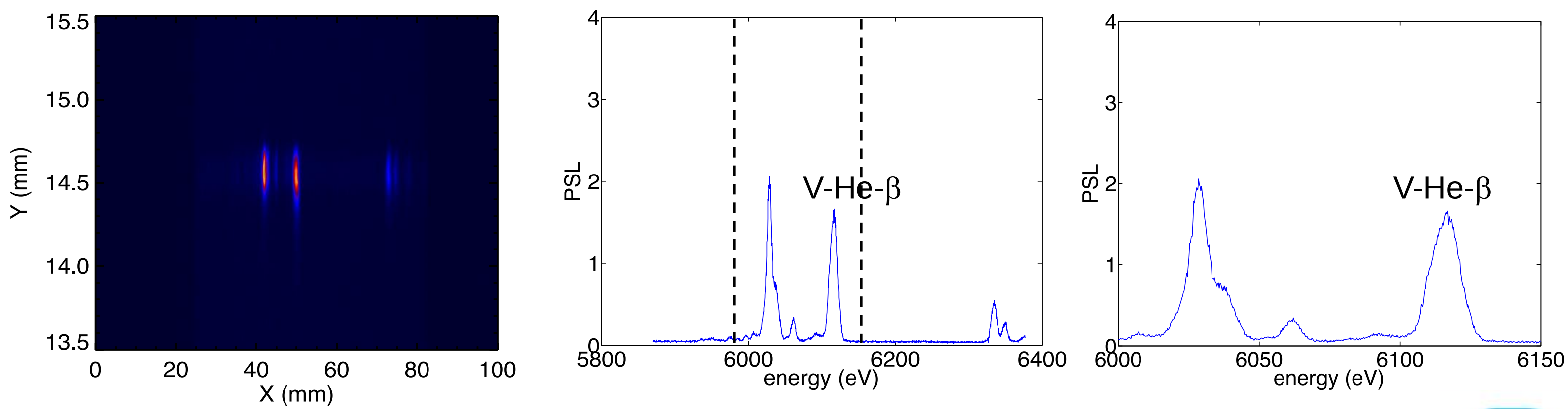
# More monochromatic x-ray source
# V-He-β (6.117 keV)

- Having a region free of satellites allow unobstructed view of inelastic scattering features
  - About 1/6x intense as Mn-He-α
  - XRS[3]-A ($\theta$ = 90° ) ZBL: 1162 J, Quartz $20\bar{2}3$: 46°




  - XRS[3]-B ($\theta$ = 7° )

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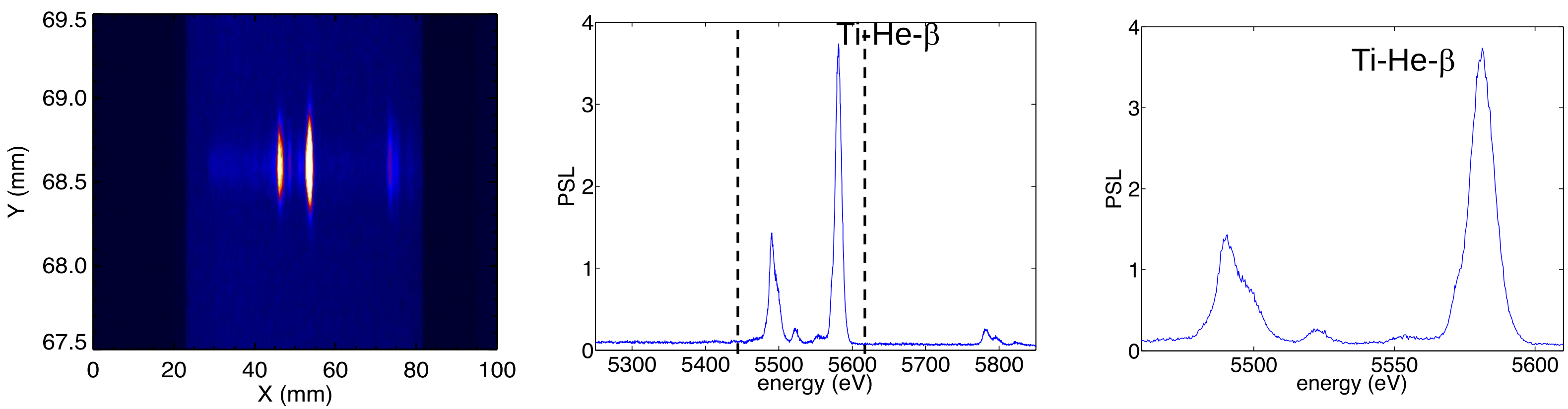
# Lower photon energy x-ray source
# Ti-He-β (5.580 keV)

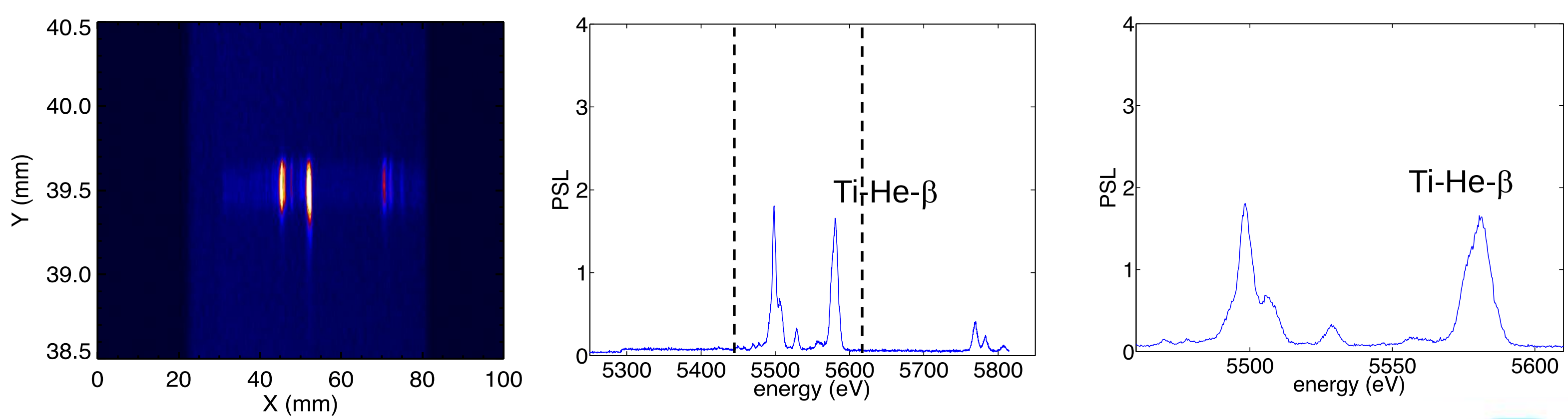
- Slightly lower energy x-ray source but brighter and satellite free region

- $XRS^3$-A ($\theta = 90°$)

ZBL: 1286 J, Quartz $20\bar{2}3$: 54°




- $XRS^3$-B ($\theta = 7°$)

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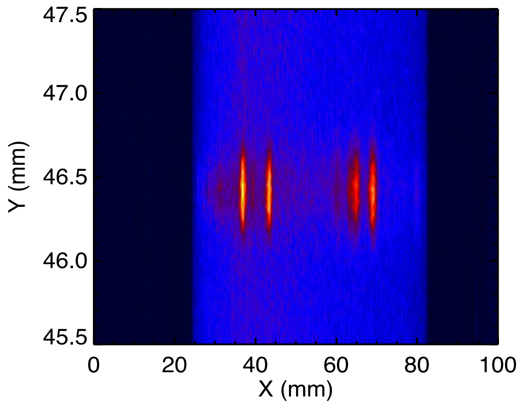
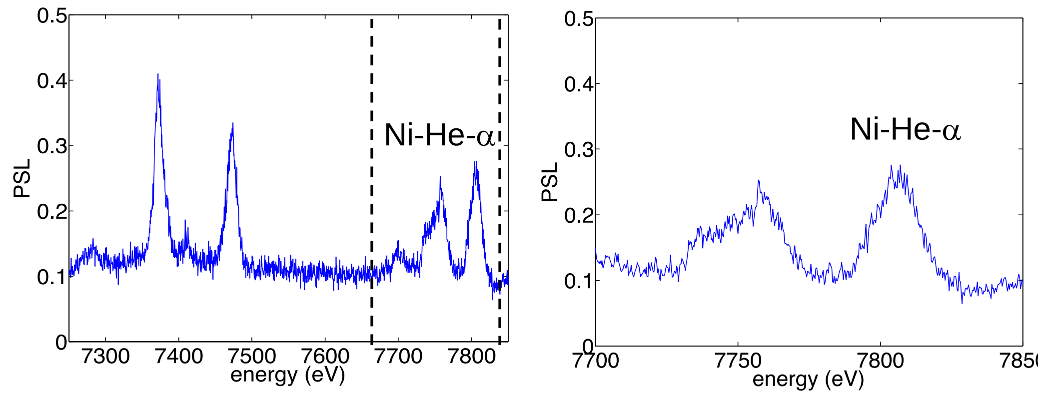
# Higher photon energy x-ray source
# Ni-He-α (7.806 keV)

- Weak x-ray spectra
  - Multiple spectra due to multiple reflection orders of Mica

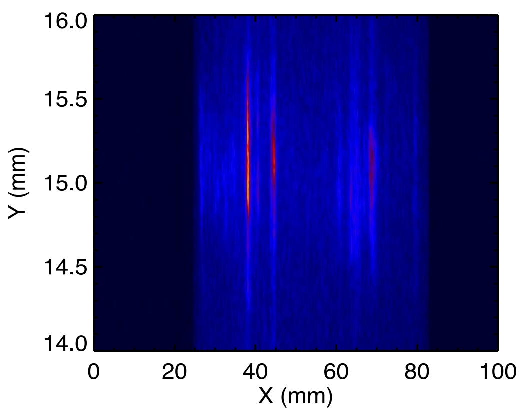
ZBL: 1385 J, Mica 9th order: 46°

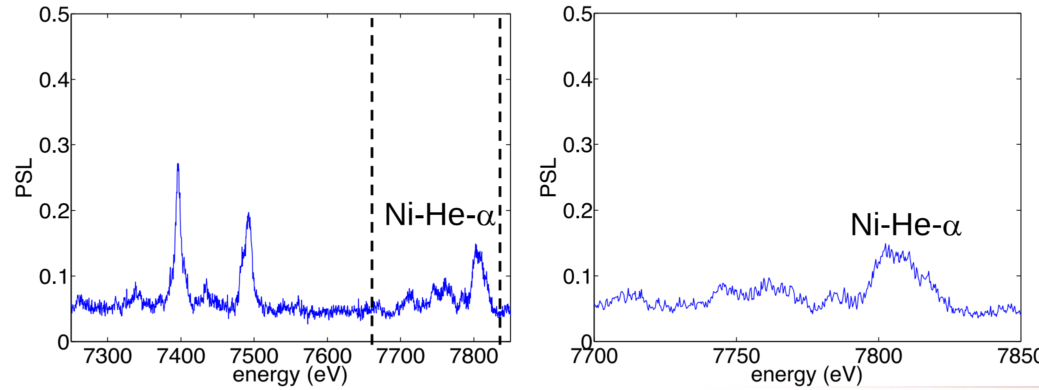
- XRS$^3$-A ($\theta$ = 90° )



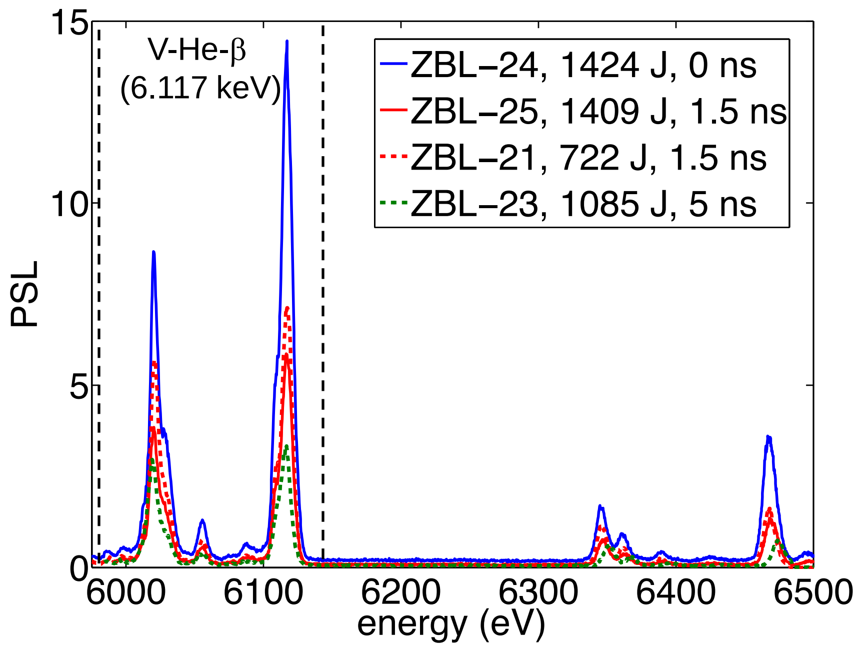

- XRS$^3$-B ($\theta$ = 7° )

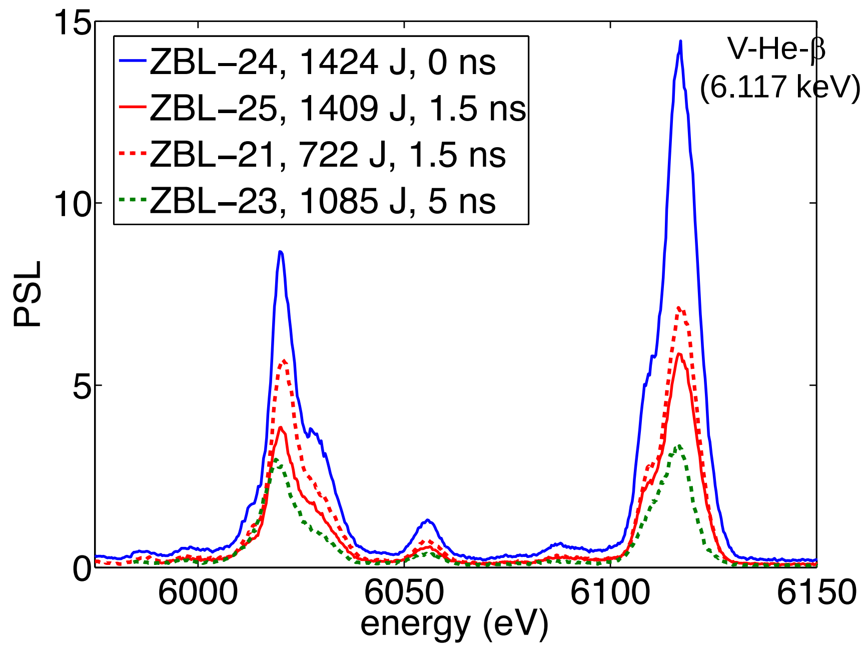


# Examination of ZBL pre-pulse for V-He-β (6.117 keV)

- Varied pre-pulse delay:
  - 0 (no pre-pulse)
  - 1.5 ns (standard pre-pulse)
  - 5 ns
- For V-He-β pre-pulse possibly not necessary for optimal x-ray production unlike the results shown for Mn-He-α




D. B. Sinars, *et al.*, RSI **77**, 10E309 (2006)

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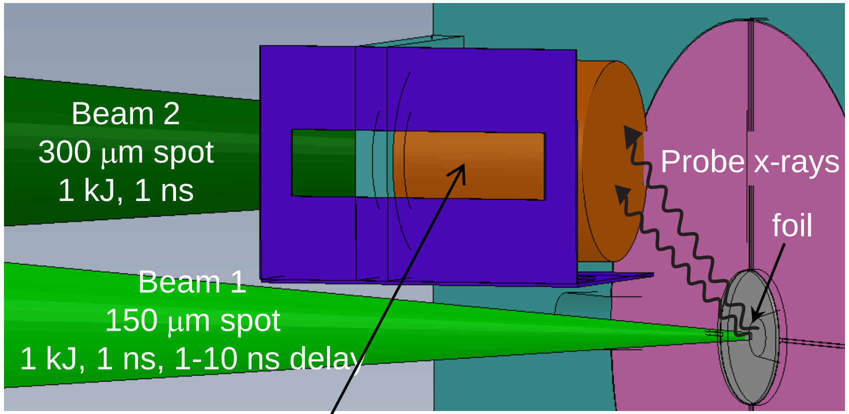
# Next XRTS-ZBL experimental campaign

- X-ray scattering with room temperature carbon foam targets
  - Investigate x-ray scattering physics from a room temperature target
  - Learn to optimize future scattering experiments

- X-ray scattering from heated carbon foam targets
  - Investigate x-ray scattering physics from warm dense matter
  - Develop methods for ZBL x-ray scattering experiments

<u>Foam Scattering setup</u>
(Room temp. experiment uses the same setup, except Beam 2 is turned off.)




Carbon foam (0.1 g/cc; orange) behind Au slit.
Spectrometer 2 views directly into slit.
Spectrometer 1 monitors probe x-rays.

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# ZBL experiments results and future work

- X-ray source development
  - V-He-$\beta$ and Ti-He-$\beta$ provide more monochromatic spectral lines free from interference from satellite lines
  - Angle dependence of x-ray spectra provide insight into x-ray production and optimization
  - Investigate pre-pulse optimization for V-He-$\beta$ type lines
  - Higher energy x-ray spectra to be further investigated

- X-ray scattering
  - Initial scattering signals from cold CH foam and Al samples are encouraging
  - Unintentional “heating” of CH and $CH_2$ samples stimulate discussions on WDM
  - More carefully designed scattering experiments planned for both cold and heated samples

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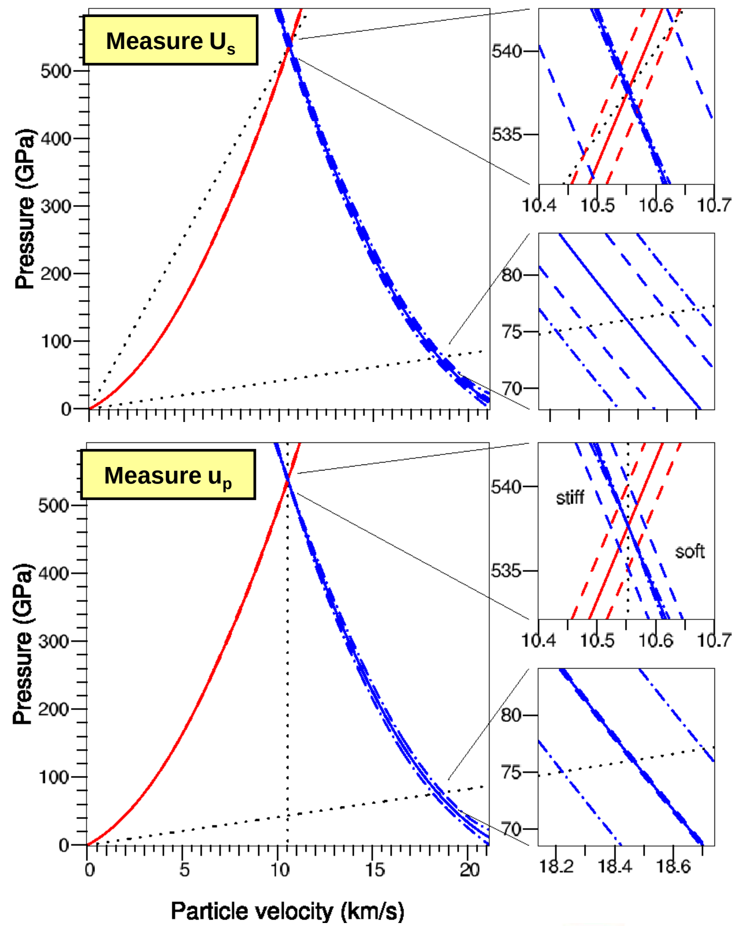
# Advantages of XRTS-WDM experiment on Z-DMP load

- Shock-compressed state experimentally determined from flyer's impact velocity
  - Laser-driven shock experiment relies upon hydrodynamic simulations to calculate the shock-compressed state
  - Z experiment allow pressure and density to be characterized ~ 1-2 %

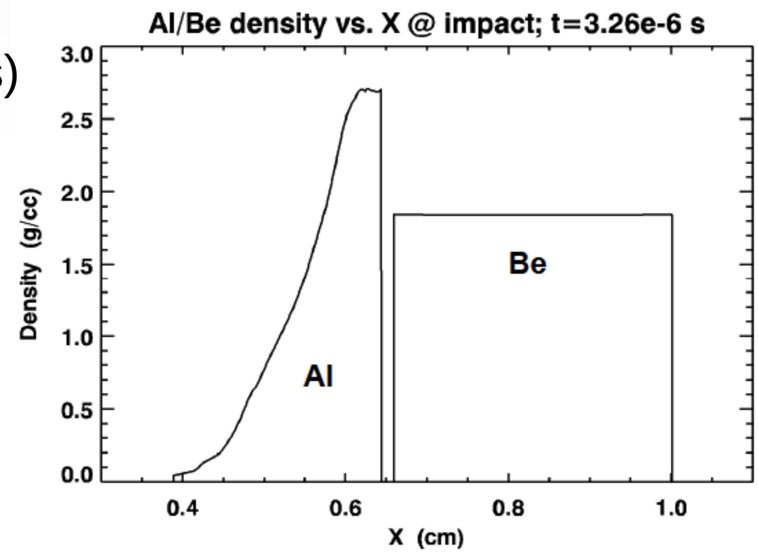
- Considerably larger samples means more uniform shock state: spatially & temporally
  - Larger scattering volume for x-rays enable more accurate and precise measurements of the warm dense matter properties

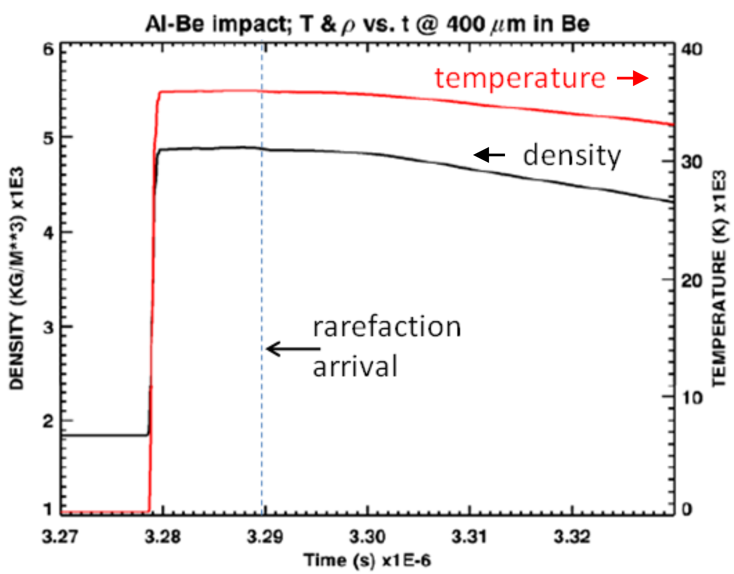
| | dimension | Z | laser | Z/laser |
|---|---|---|---|---|
| **target** | thickness | 1 mm | 0.25 mm | 4 |
| | diameter | 10 mm | 1 mm | 10 |
| | | | | |
| **steady state** | spatial extent | 200 – 400 um | 25 um | 8 – 16 |
| | scattering volume | 15 – 30 $mm^3$ | 0.02 $mm^3$ | 750 - 1500 |
| | temporal duration | 10 – 100 ns | 1 ns | 10 - 100 |

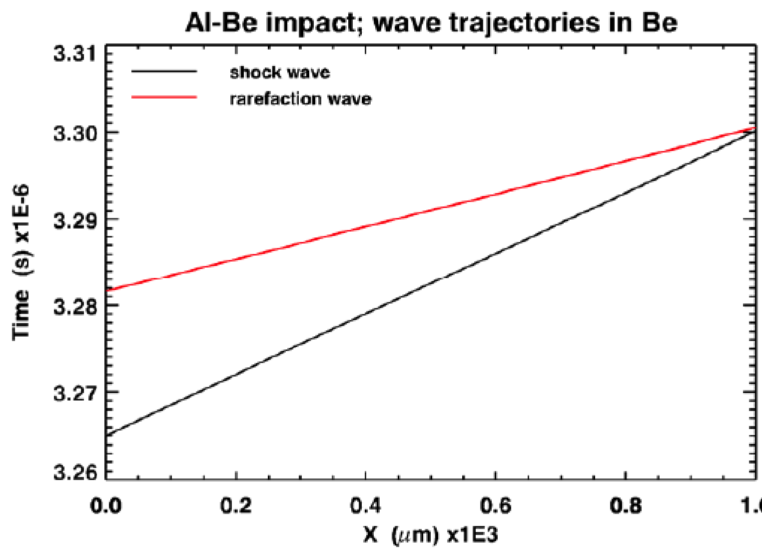


# XRTS of shocked Be on Z allow comparison with previous XRTS results

- ALEGRA calculations with Al flyer (40 km/s)
  - 14 Mbar, 3 eV in Be target
  - Large spatial extent: > 200 μm
  - Long time duration: > 10 ns
- Attenuation length of 6.18 keV x-rays
  - Be (1.85 g/cm$^3$): 2.44 mm
  - Be (4.8 g/cm$^3$): 0.94 mm




ALEGRA simulations by R. Lemke

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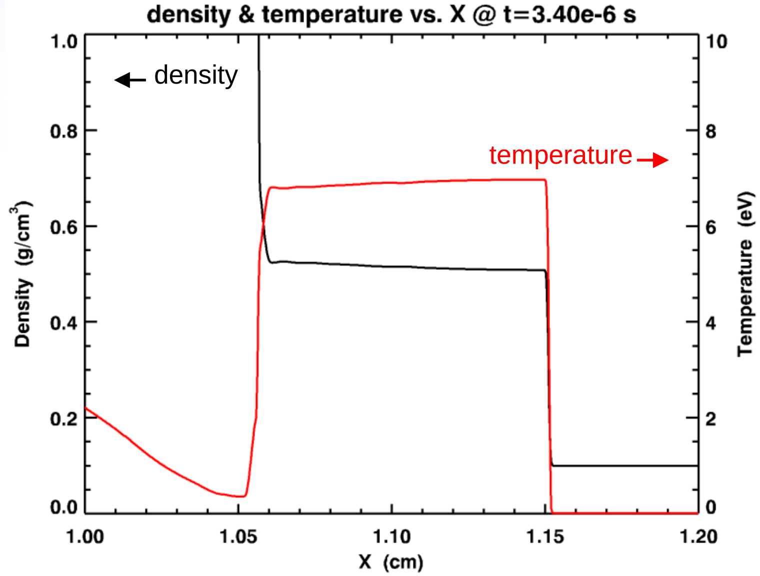
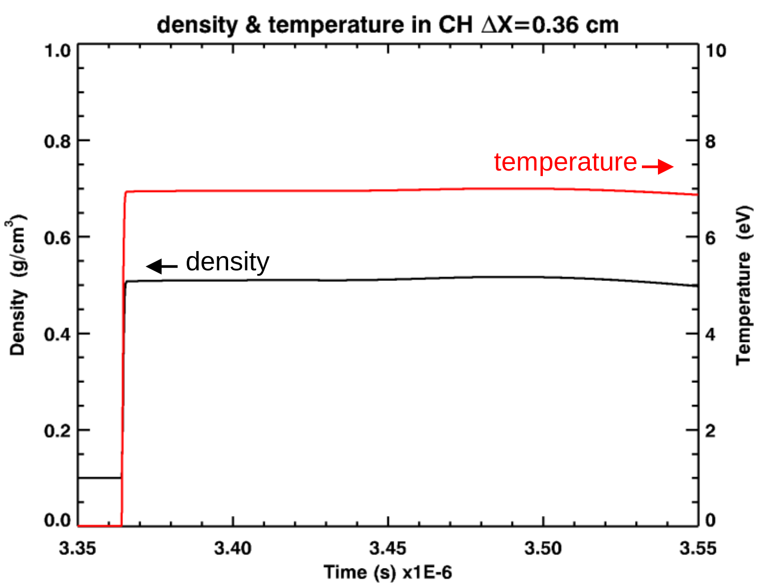
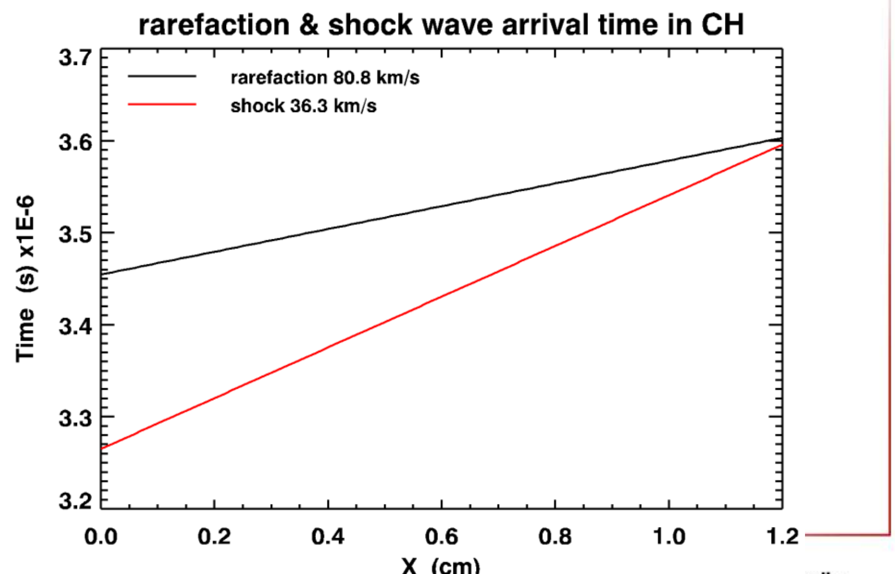
# XRTS of shocked CH foam on Z allow greater control of generated WDM state

- ALEGRA calculations with Al flyer (30 km/s)
  - 0.8 Mbar, 7 eV in CH foam target
  - Very large spatial extent: > 400 μm
  - Very long time duration: > 100 ns
- Attenuation length of 6.18 keV x-rays
  - CH (0.1 g/cm$^3$): 11.0 mm
  - CH (0.7 g/cm$^3$): 1.57 mm



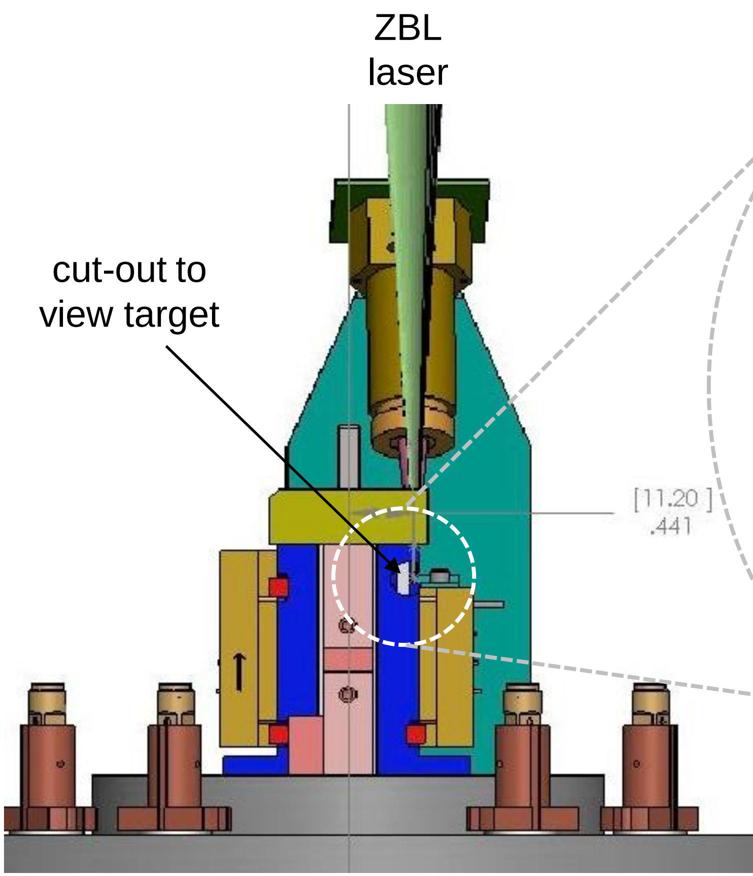



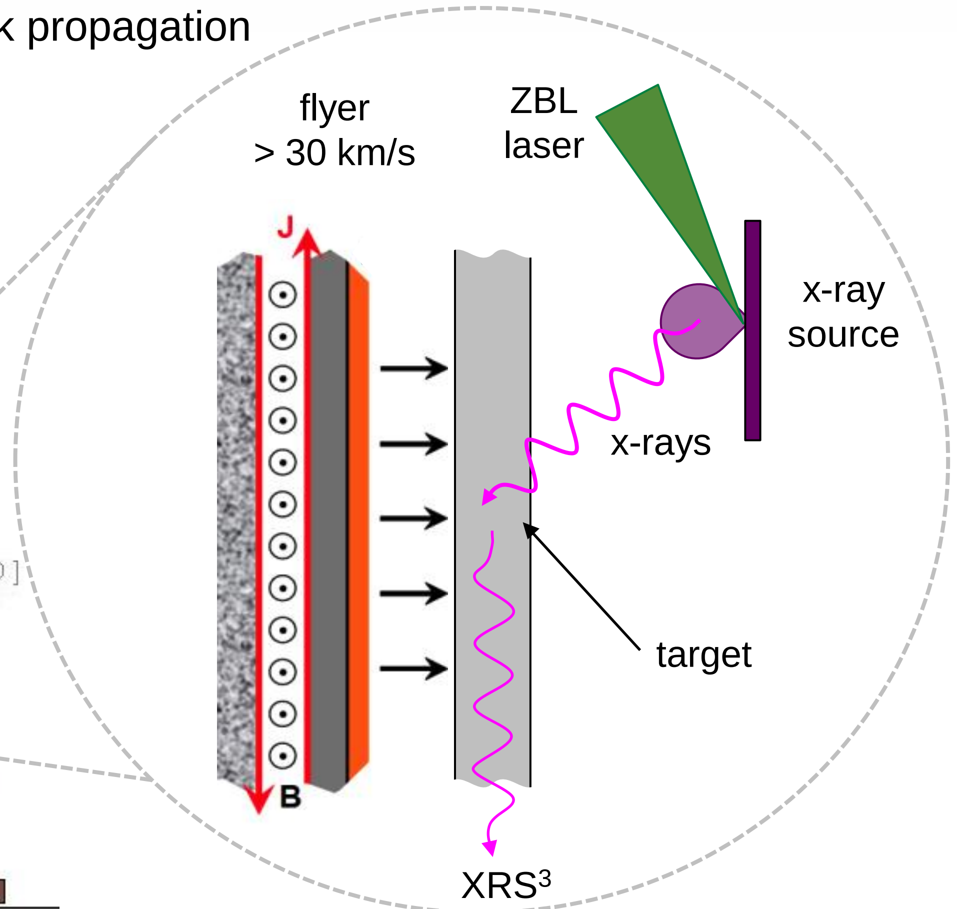

ALEGRA simulations by R. Lemke

# Experimental design of XRTS on Z-DMP load

- Collection of scattered x-rays from both ambient and shocked material of a coaxial load
  - XRS³ view perpendicular to shock propagation



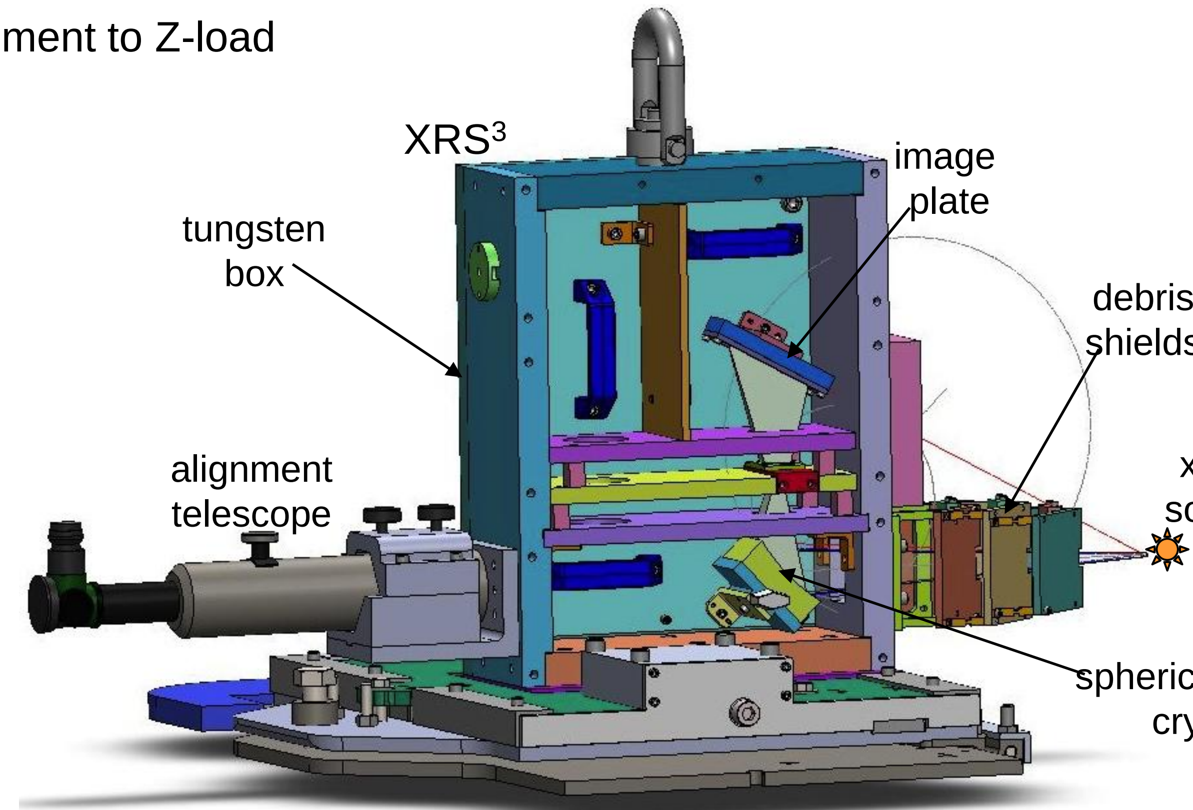

XRS³ line-of-sight view




Z load top view

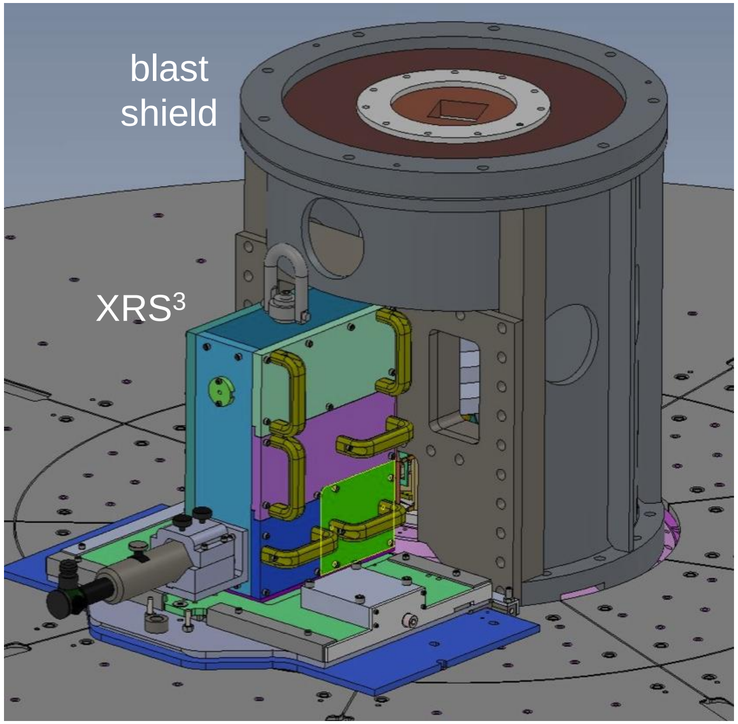
# X-ray scattering spherical spectrometer (XRS$^3$)

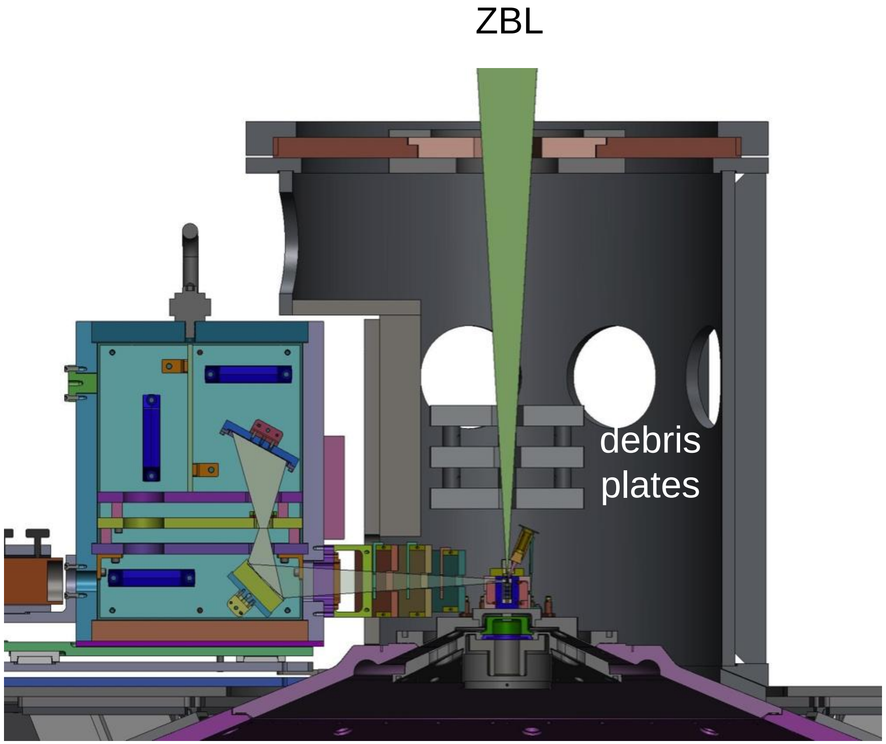
- Experimental design considerations
  - Protection of spherically-bent crystal and image plate detector
  - Tungsten shielding of x-rays from Z
  - Mitigation of load debris
  - Alignment to Z-load



# Ride-along experiments needed on Z-DMP shots

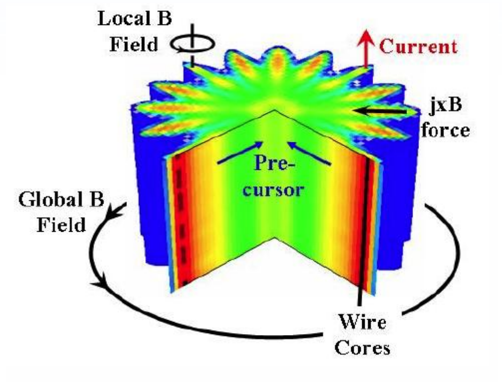
- New blast shield for mitigation of debris to ZBL
- Shielding of x-ray background from Z
- Alignment of ZBL to x-ray source target on DMP load

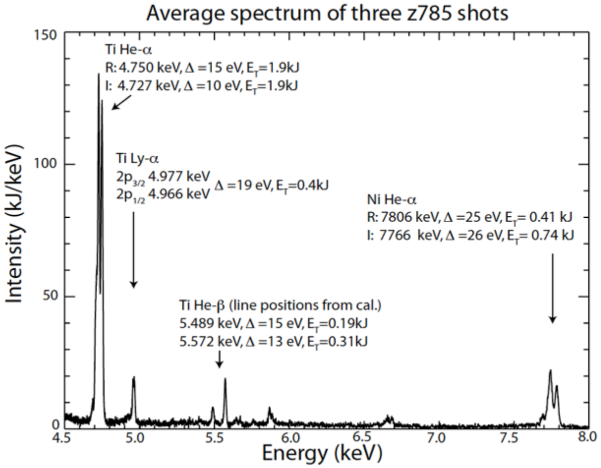


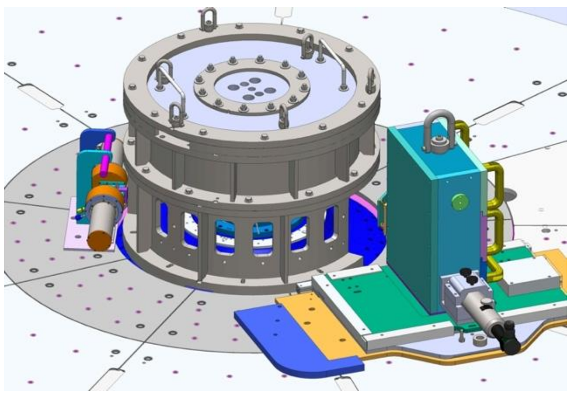



# Radiatively heated XRTS ride-along experiment on Z-pinch shots

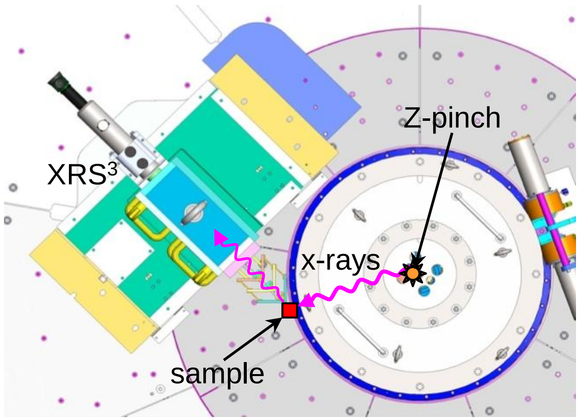
- Immense radiation from Z-pinch
  - Isochorically heat sample with broadband x-rays
  - Probe warm dense matter with intense spectral line: Ti-He-$\alpha$ (2 kJ)
  - Sample located far from x-ray source
  - Highly collimated x-rays allow small angle forward scattering



Z-pinch load isometric view




Z-pinch load top view

X-ray spectra from D. Ampleford

Sandia National Laboratories

# XRTS-WDM summary and future direction

- Potential of XRTS on Z
  - Critical diagnostic to expand the scientific capabilities of Z
  - Temperature, phase, dynamic structure factors, and ionization information
- Progress of XRTS work
  - X-ray scattering spherical spectrometer
  - Spherically bent crystal calibrations
  - ZBL x-ray source and scattering experiments
- Preparation activities on Z
  - Blast shield tests on DMP
  - X-ray background characterization of DMP and Z-pinch loads
  - ZBL alignment on DMP load