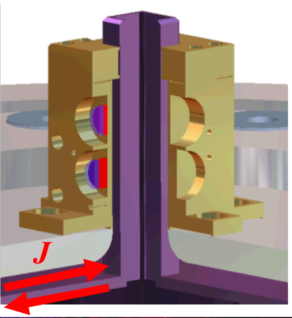
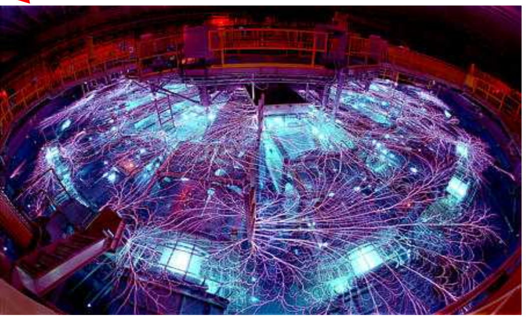
SAND2012-9517C

# X-ray sources for x-ray Thomson scattering of warm dense matter on the Z-Accelerator




ZBeamlet



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15th International Workshop on Radiative Properties of Hot Dense Matter
Santa Barbara, CA, November 4-9, 2012

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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# Overview

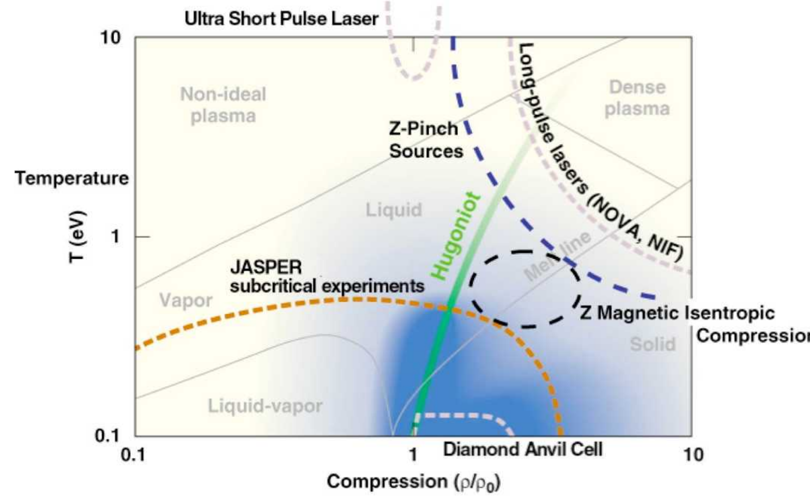
- X-ray Thomson scattering experiments on Z-accelerator in preparation
  - Implementation of ZBL with magnetically launched flyer target
  - Focusing spectrometer with spatial resolution

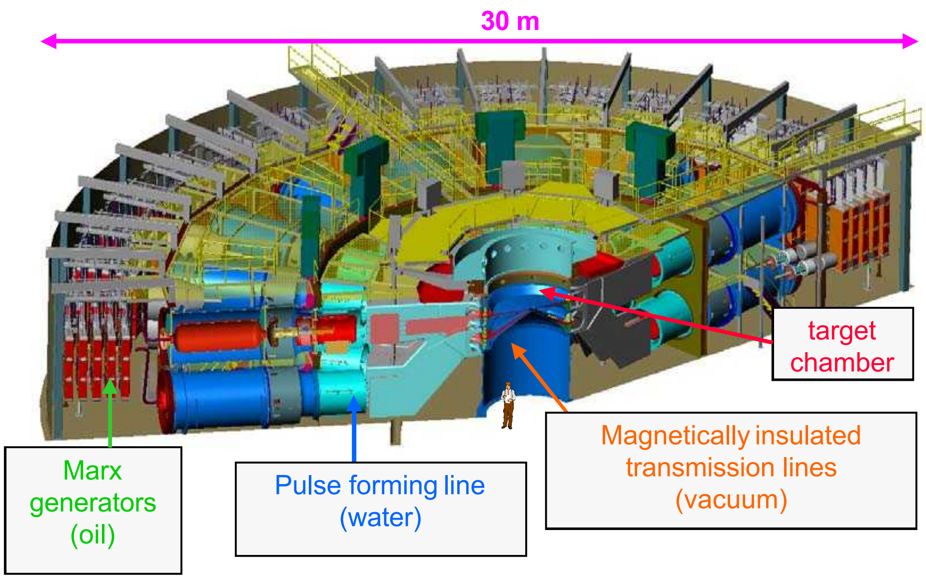
- Development of x-ray source probe
  - Mn He-$\alpha$, V He-$\beta$, Ti He-$\beta$
  - Angle dependence of emitted x-rays

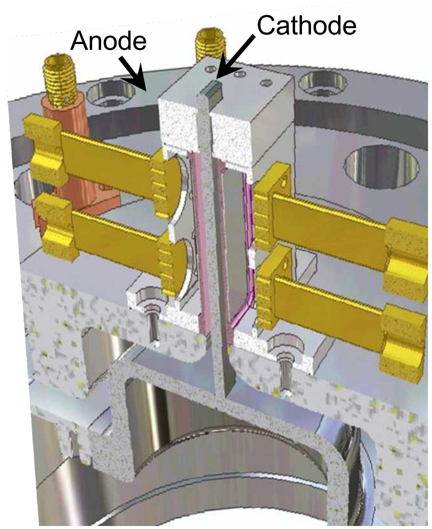
- X-ray scattering validation tests
  - Ambient TPX foam

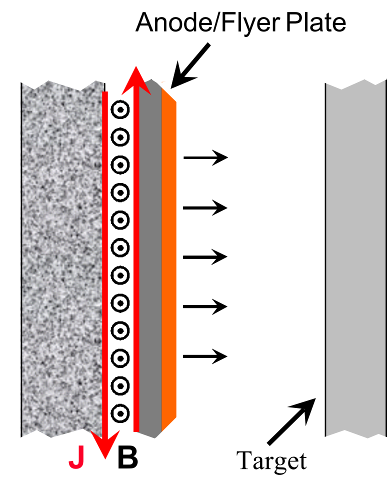
# Warm dense matter research on Z-accelerator

- Z-accelerator for Dynamic Material Properties (DMP) experiments
  - Pulsed power generator: 26 MA, 100-700 ns
  - Ramp (quasi-isentropic) compression: > 4 Mbar
  - Shock compression with magnetically launched flyer plates: 40 km/s, > 10 Mbar, several eV



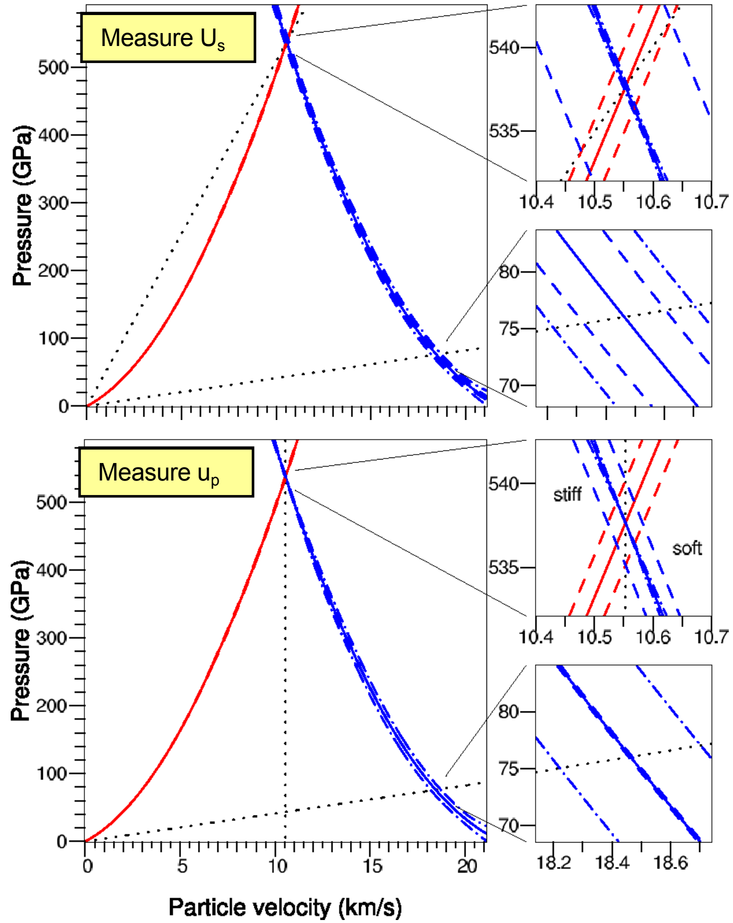




Lemke, et al., J. Appl. Phys. **98**, 073530 (2005)

# Benefits of Z-DMP experiments

- Shock-compressed state experimentally determined from flyer's impact velocity
  - Pressure and density characterized ~ 1-2 %
- Considerably larger samples enable more uniform shock state: spatially & temporally
  - Larger scattering volume for x-rays enable more accurate and precise measurements

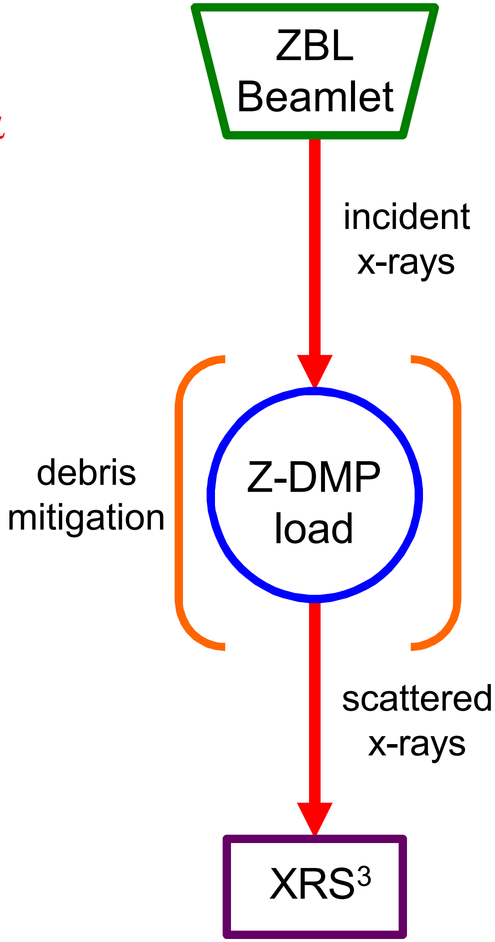
| | dimension | Z | laser | Z/laser |
|---|---|---|---|---|
| **Initial state** | thickness | 1 mm | 0.25 mm | 4 |
| | diameter | 10 mm | 1 mm | 10 |
| | | | | |
| **WDM state** | spatial extent | 200 – 400 um | 50 um | 8 – 16 |
| | scattering volume | 8 – 15 mm$^3$ | 0.04 mm$^3$ | 750 - 1500 |
| | temporal duration | 10 – 100 ns | 0.1-1 ns | 10 - 100 |




Knudson, et al., J. Appl. Phys. **94**, 4420 (2003)

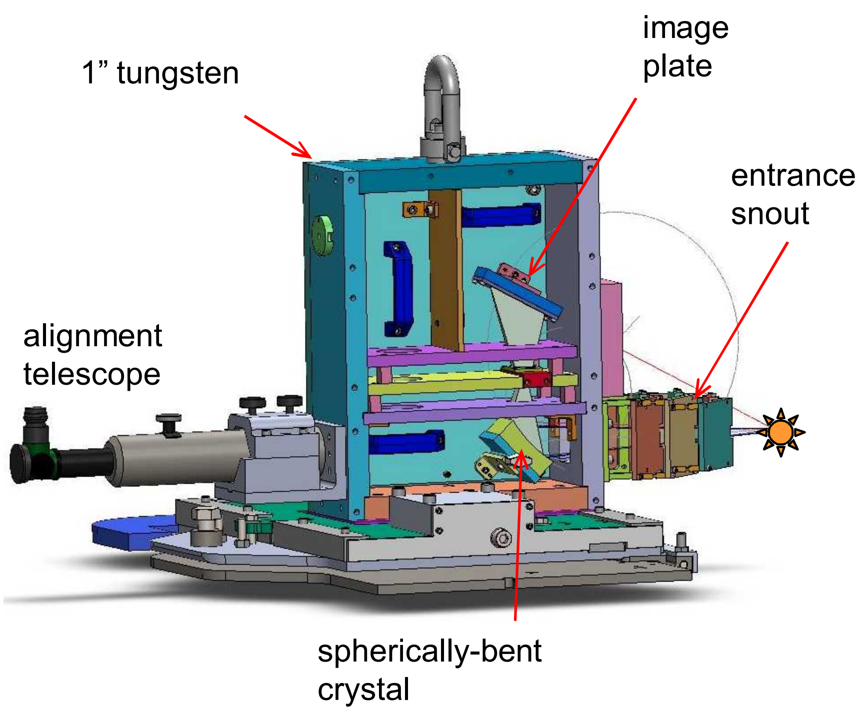
# 3 key components to x-ray Thomson scattering (XRTS) on Z-DMP experiments

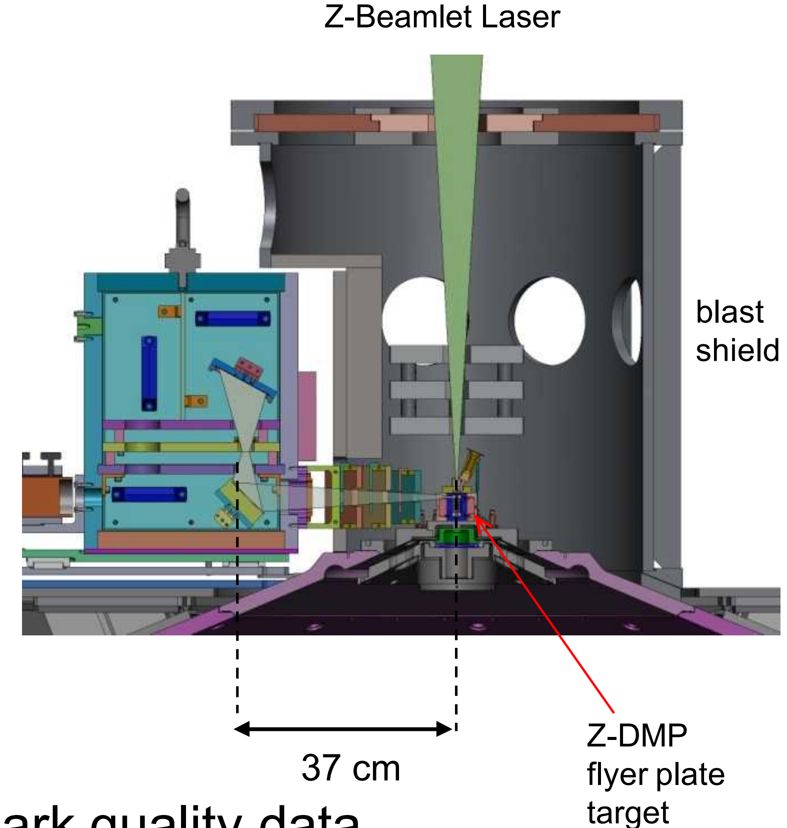
- Produce quasi-monochromatic x-rays
  - ZBL Beamlet (1.2 kJ) irradiate metal foil ➔ Mn-He-$\alpha$ (6.181 keV)
    - V-He-$\beta$ (6.117 keV), Ti-He-$\beta$ (5.580 keV)
- Generate WDM state
  - Z-Dynamic Material Properties (DMP) load using magnetically launched flyer to shock compress sample ➔ coaxial load
  - Debris mitigation to protect ZBL
- Detect scattered x-rays
  - X-ray scattering spherical spectrometer ($XRS^3$), spherically bent crystal and resolve spectrally and spatially ➔ Germanium
    - Mica, Quartz, HOPG/HAPG
  - Record x-rays ➔ image plate
    - X-ray film



# X-ray scattering spherical spectrometer (XRS$^3$) diagnostic on Z-accelerator

- Focusing spectrometer with spatial resolution (FSSR)
  - Spherically-bent single crystal
  - High spatial and spectral resolution

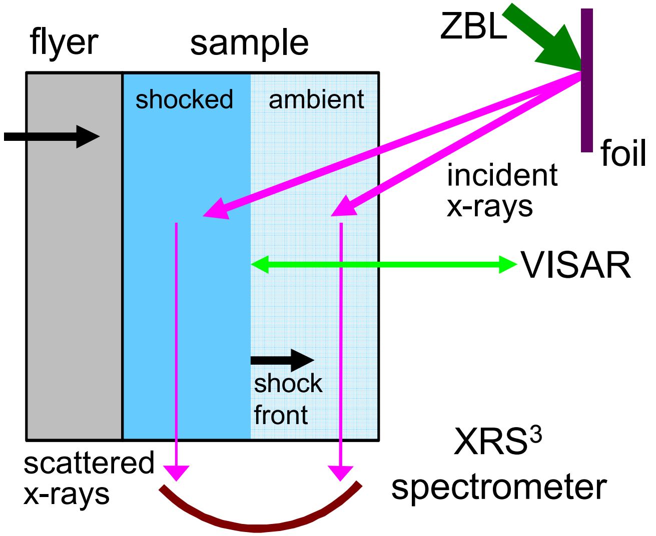


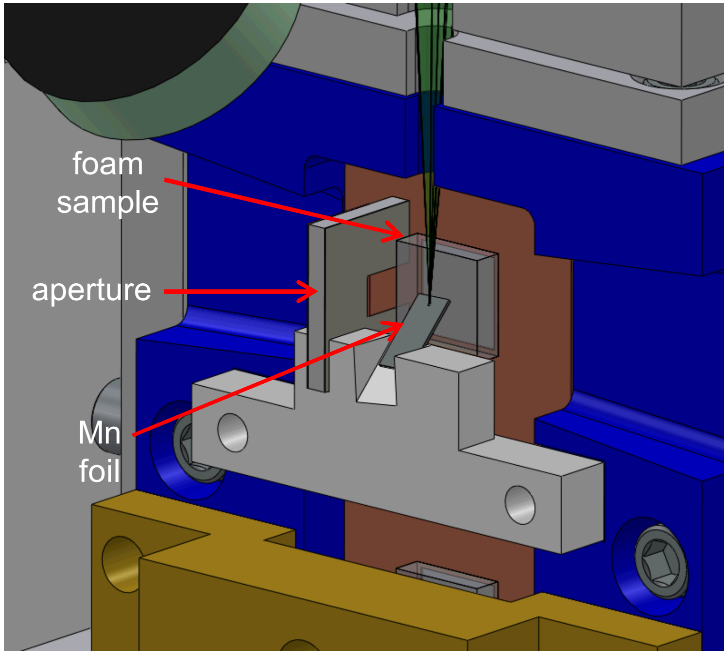




- Spatial resolution essential for benchmark quality data

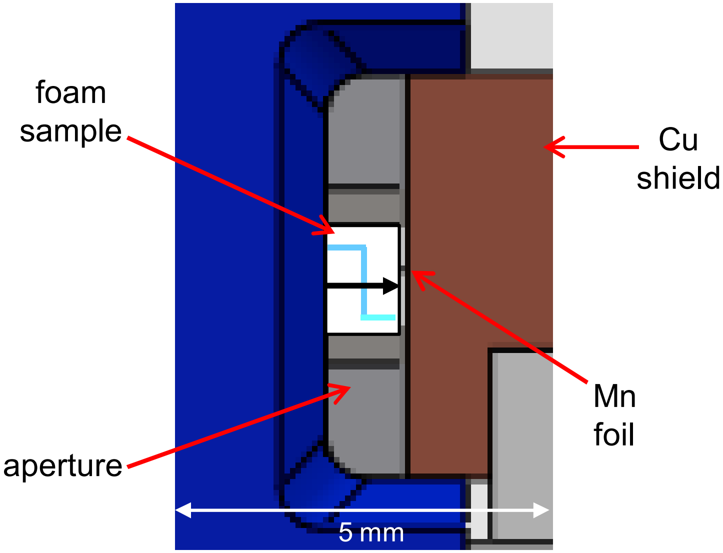
# Z-DMP experiments in preparation to measure XRTS signal from ambient & shock material, and x-ray source

- Shocked carbon foams: TPX ($CH_2$), CRF
- ALEGRA calculations with Al flyer (18 km/s)
  - 0.37 Mbar, 2.6 eV in CH foam target
  - Very large spatial extent: > 400 μm
  - Very long time duration: > 100 ns



DMP load isometric view



spectrometer view (90° scattering)

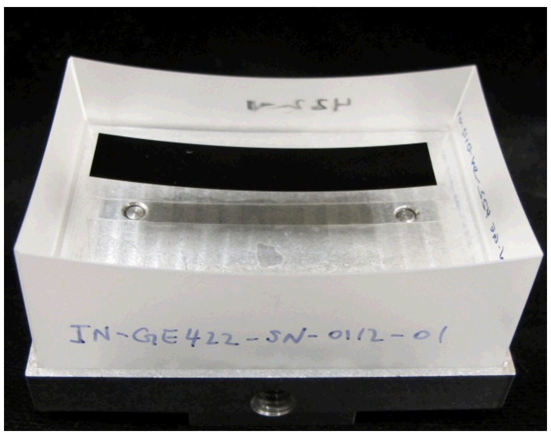
# Need to better understand laser-heated foil x-ray sources and our FSSR type spectrometers

- How does the emitted x-ray spectrum change when viewing the foil at different angles?
- What is relative intensity of the more monochromatic He-$\beta$ line compared to He-$\alpha$.
- What is the **spatial** resolution of our spectrometer?
- What is the **spectral** resolution of our spectrometer?

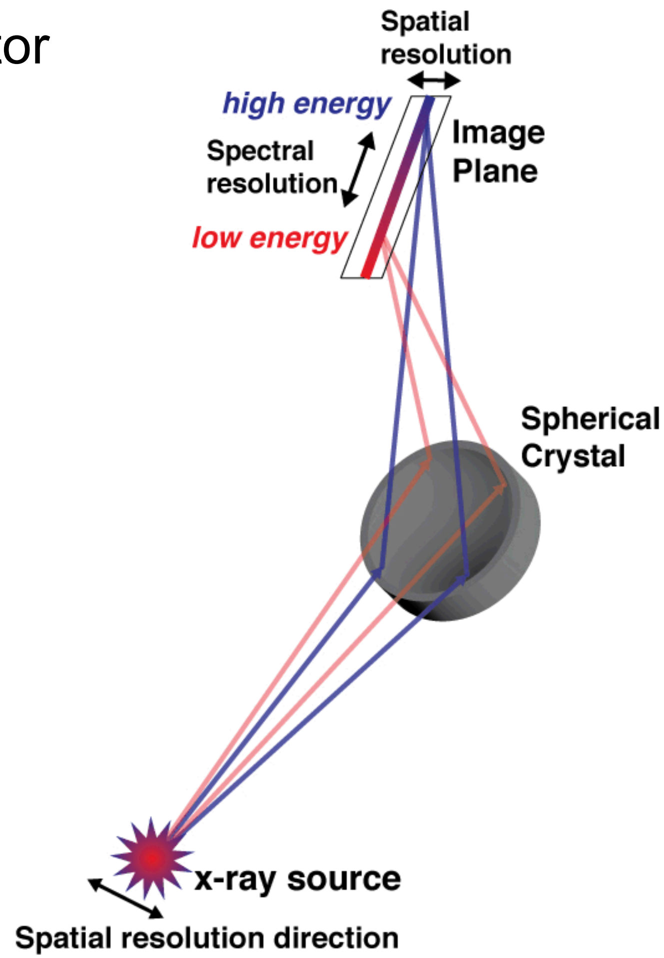
Dedicated experiments designed to address these questions using Sandia Z-Beamlet Laser.

# Spherically bent crystal spectrometer provides high spatial and spectral resolution

- To maximize image fluence place detector on Rowland circle.
- Use Germanium due to high integrated reflectivity ($R_{int}$)

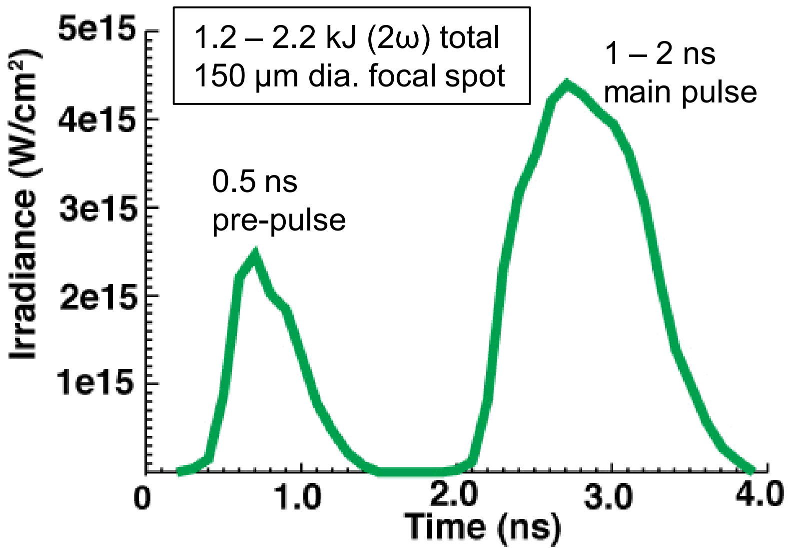


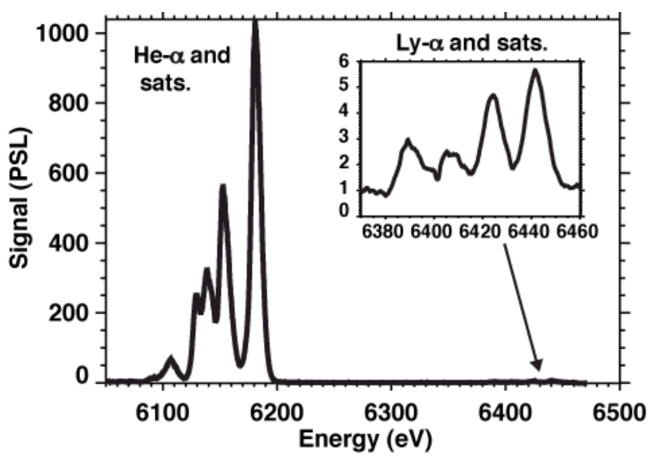

Spherically bent Ge 422 (r = 150 mm)
$R_{int}$ = 0.046 mrad (*calculated*)



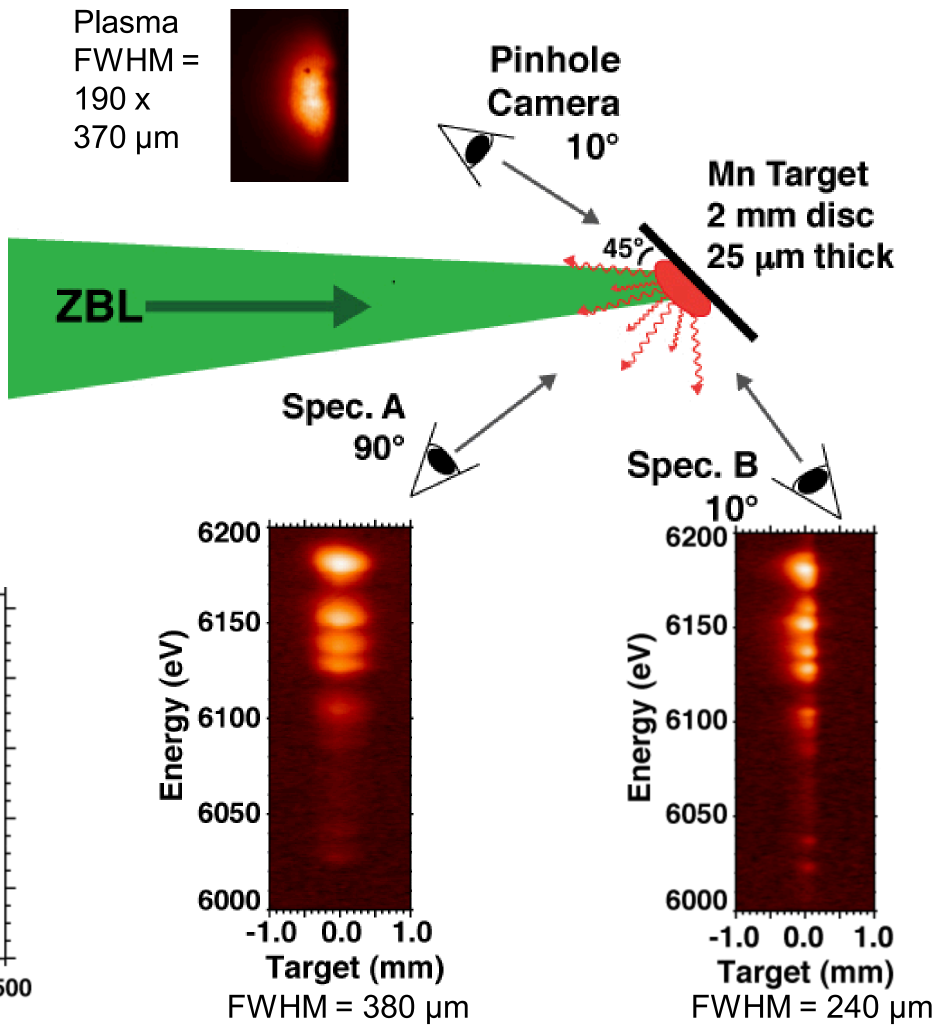
# Z Beamlet Laser (ZBL) irradiates Mn foil to provide probe x-ray source for scattering

## Laser Pulse Shape & Irradiance



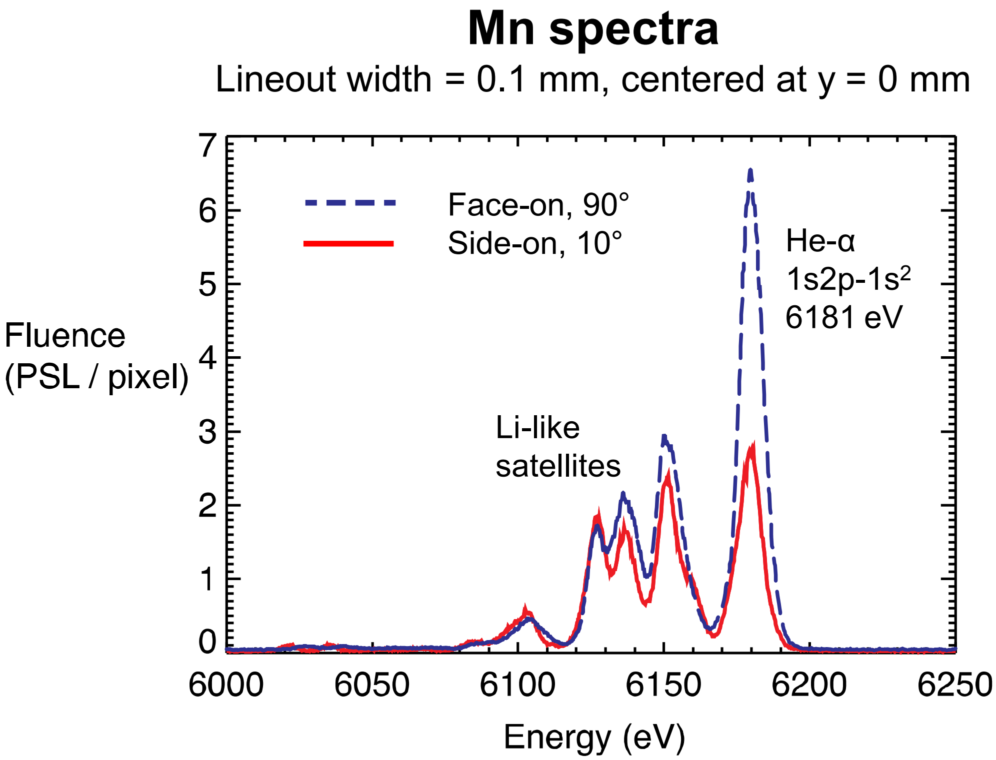

## Spectrometer Geometry



# Bright & monochromatic x-ray source needed for XRTS

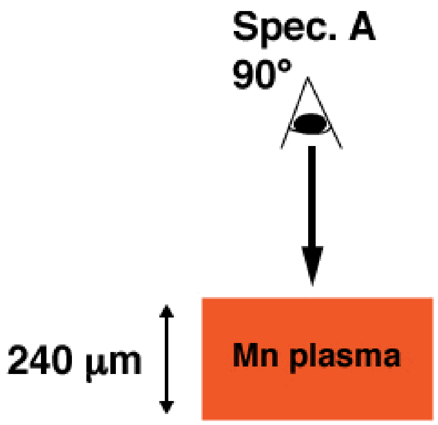
- Optimize x-ray source by modeling the simultaneously recorded spectra from multiple viewing angles

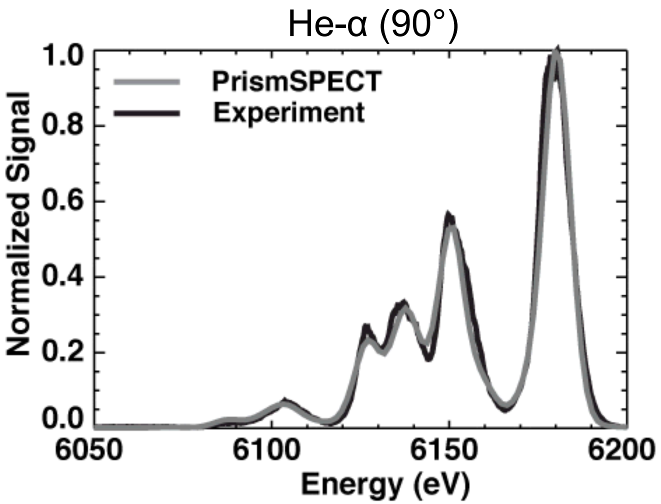
- Estimate $T_e$ and $n_e$ with increasingly complex simulations of spectra
  - 1D slab
  - 3D uniform hemi-sphere
  - Hydro simulations

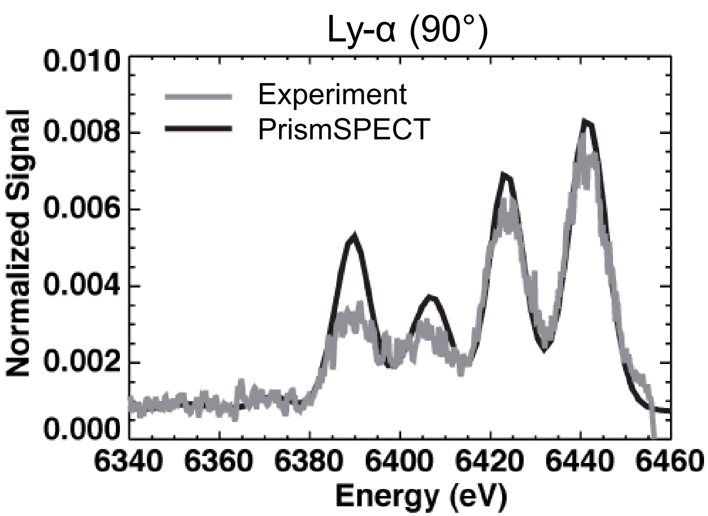


# Assuming uniform slab geometry PrismSPECT* simulations used to fit experimental spectrum

Mn PrismSPECT Model
nLTE
1D Slab
240 μm thick
$T_e = 2.2$ keV
$n_i = 6 \times 10^{18}$ cm$^{-3}$



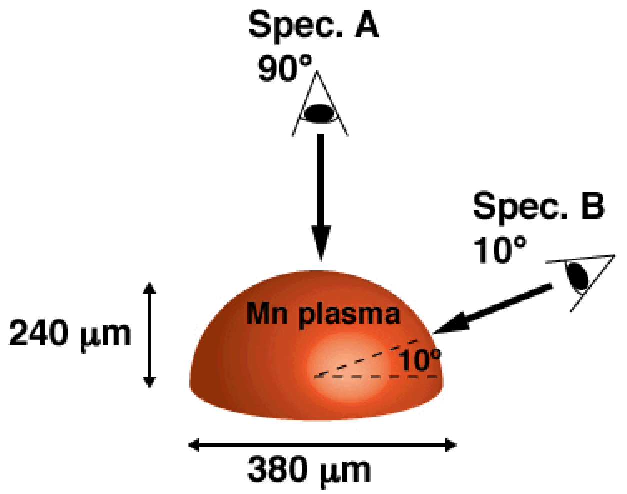



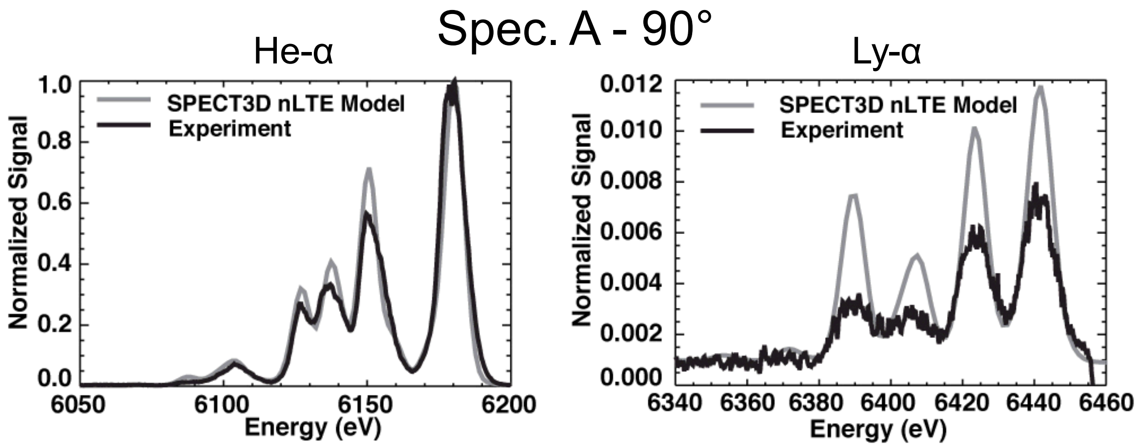



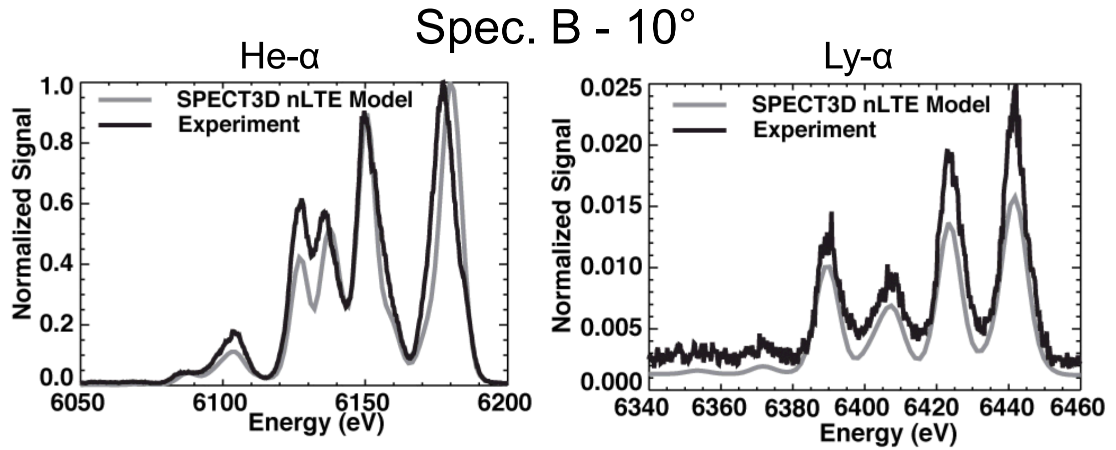

*PrismSPECT is a collisional-radiative spectral analysis code produced by Prism Computational Sciences, Inc.

# SPECT3D* used to simulate spatially resolved spectra from two spectrometer viewing angles

Mn SPECT3D Model
3D Ellipsoid Shape
nLTE
$T_e$ = 2.2 keV
$n_i$ = 6 x $10^{18}$ $cm^{-3}$



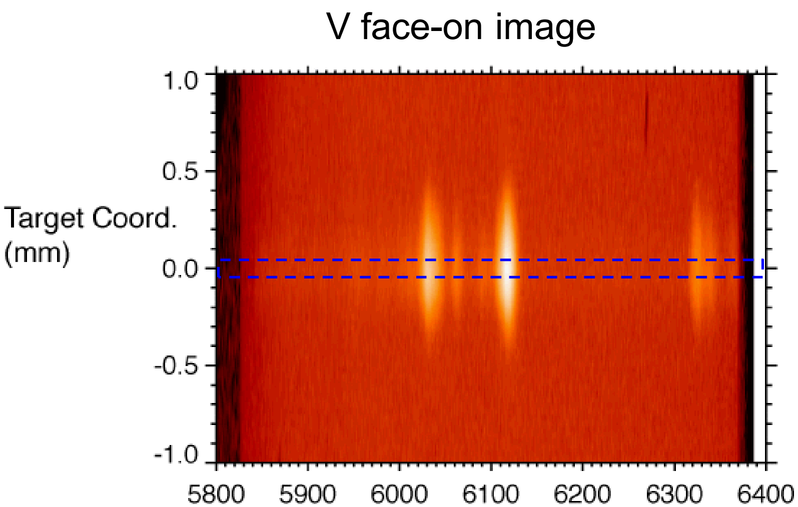



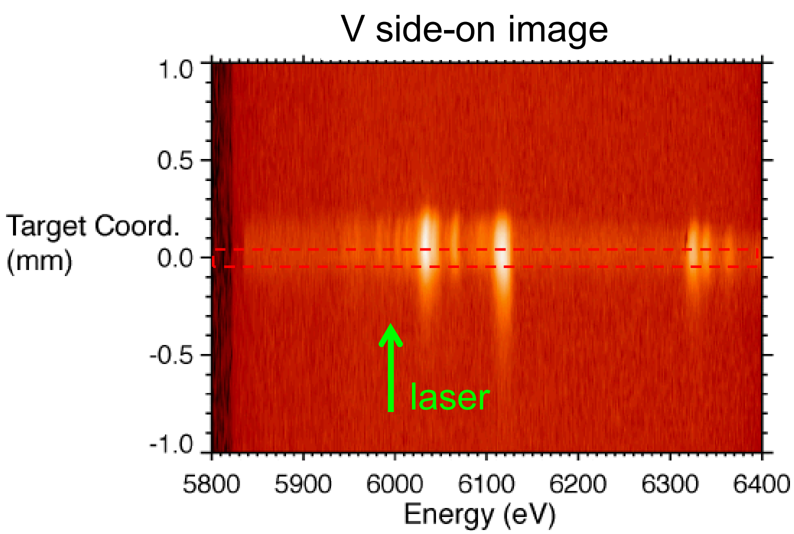

*Spect3D is a collisional-radiative spectral analysis code produced by Prism Computational Sciences, Inc.

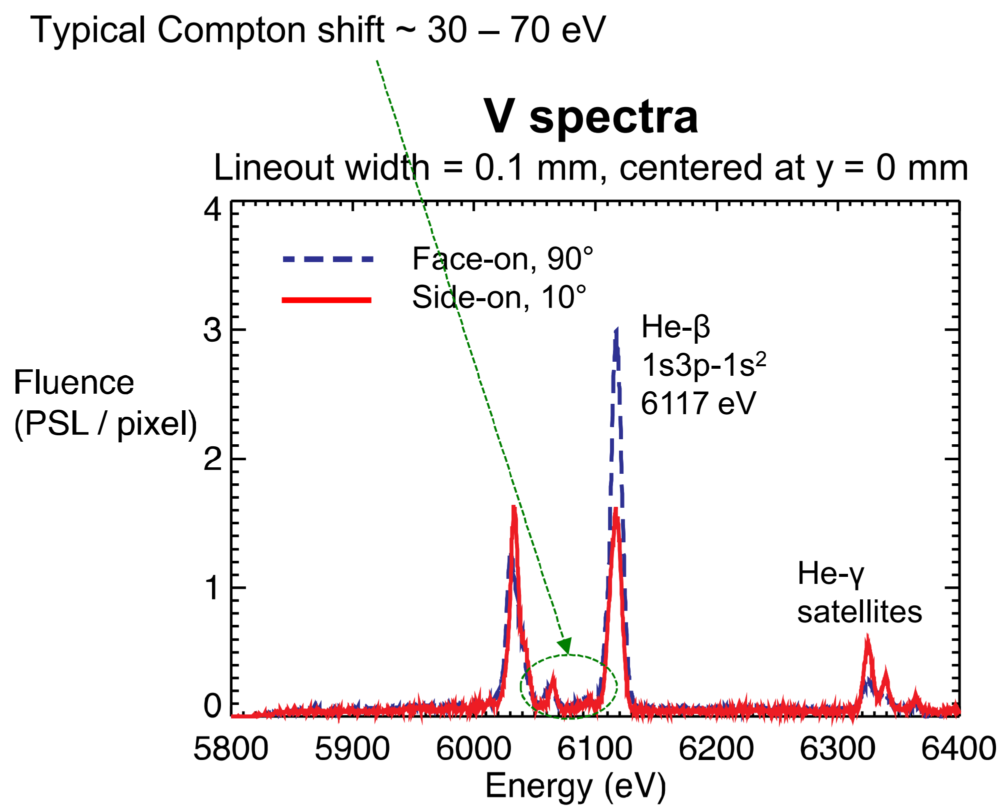
- Hydro simulations in progress

# V-He-β spectra show spectral region relatively free from satellite interference

- V-He-β half as intense as Mn-He-α



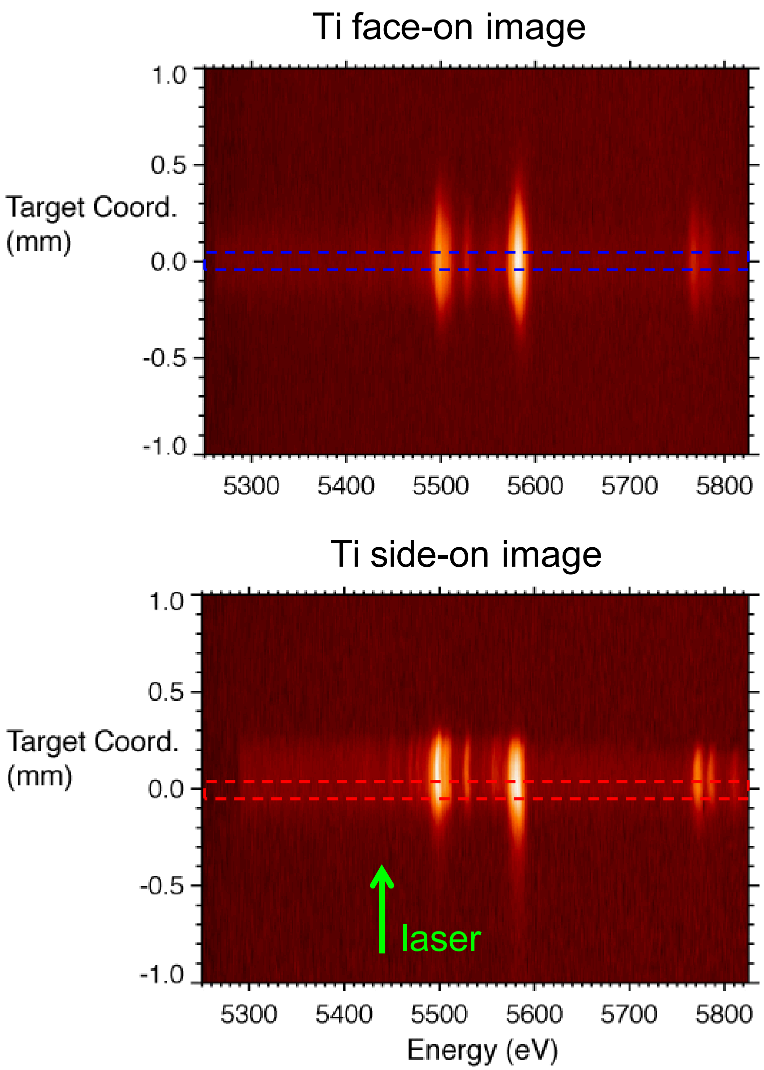



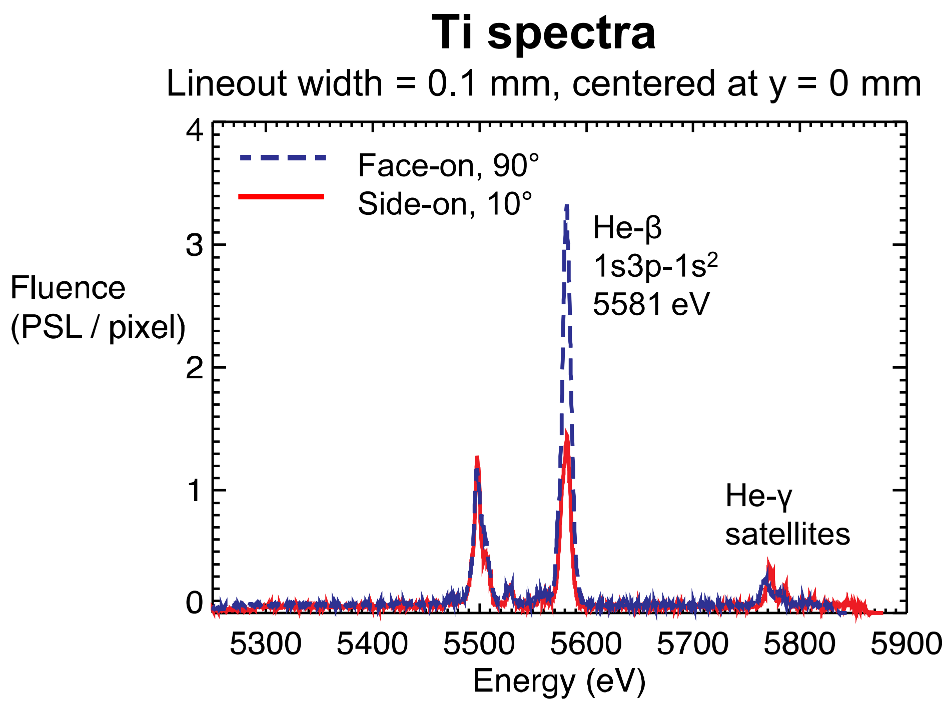

Spatial Information from vertical lineouts

Face-on FWHM: 310 μm @ 6117 eV

Side-on FWHM: 230 μm @ 6117 eV

# Ti-He-β spectra show a brighter resonance line in face-on view



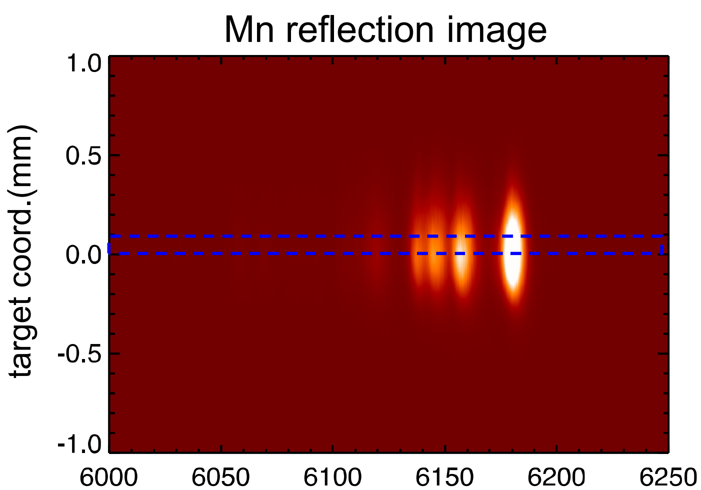

Spatial Information from vertical lineouts

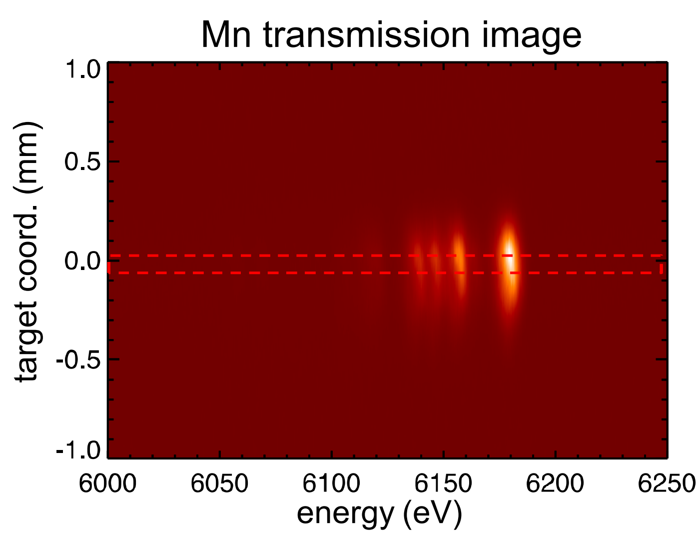
Face-on FWHM: 300 μm @ 5581 eV

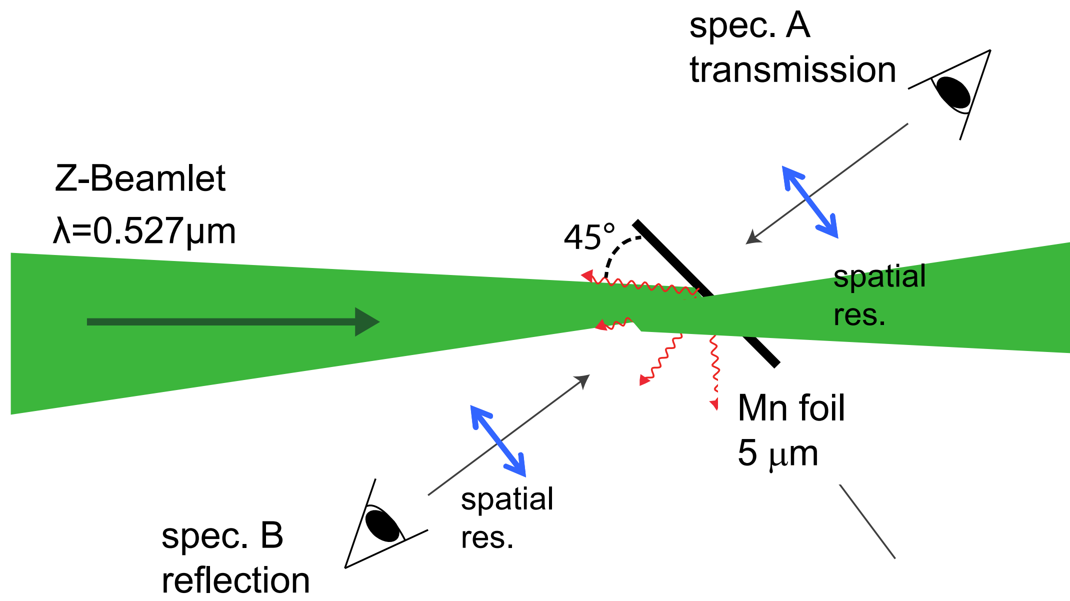
Side-on FWHM: 280 μm @ 5581 eV

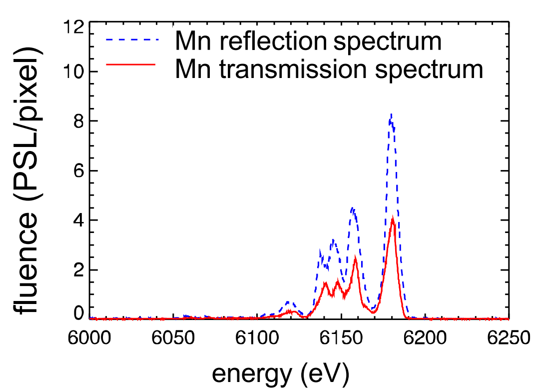
# Reflection and transmission spectra

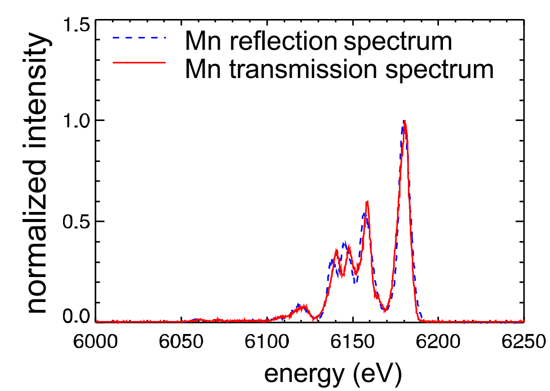
- Spectra similar but transmitted x-rays attenuated by 50% compared to reflected x-rays



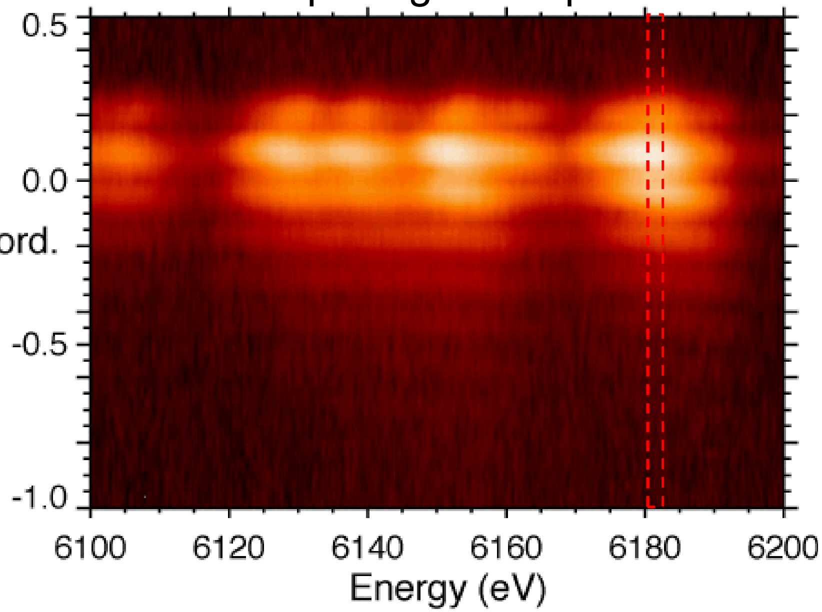



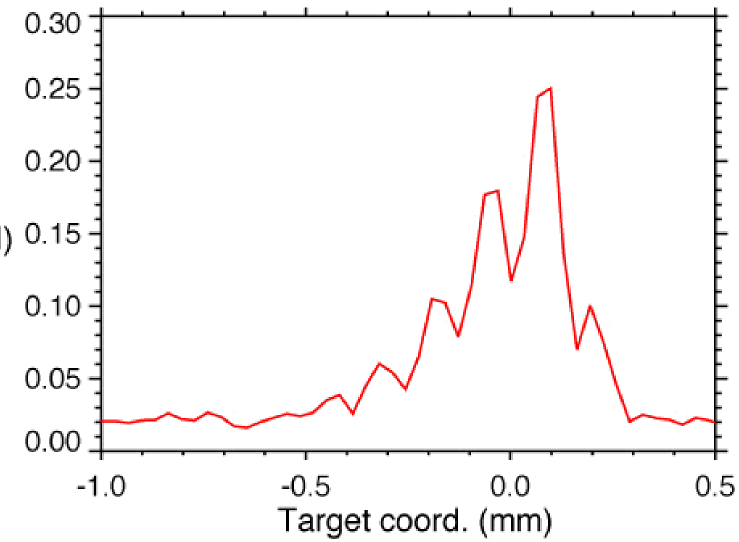



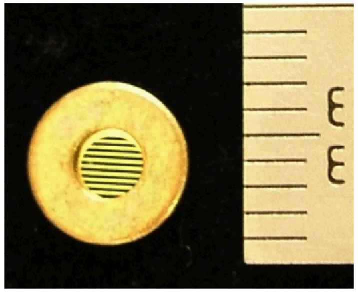
# Backlit grid images provide estimate of spatial resolution and magnification

Mn plasma backlighting Au grid
bar width = 45 μm
bar spacing = 125 μm




Vertical lineout across grid

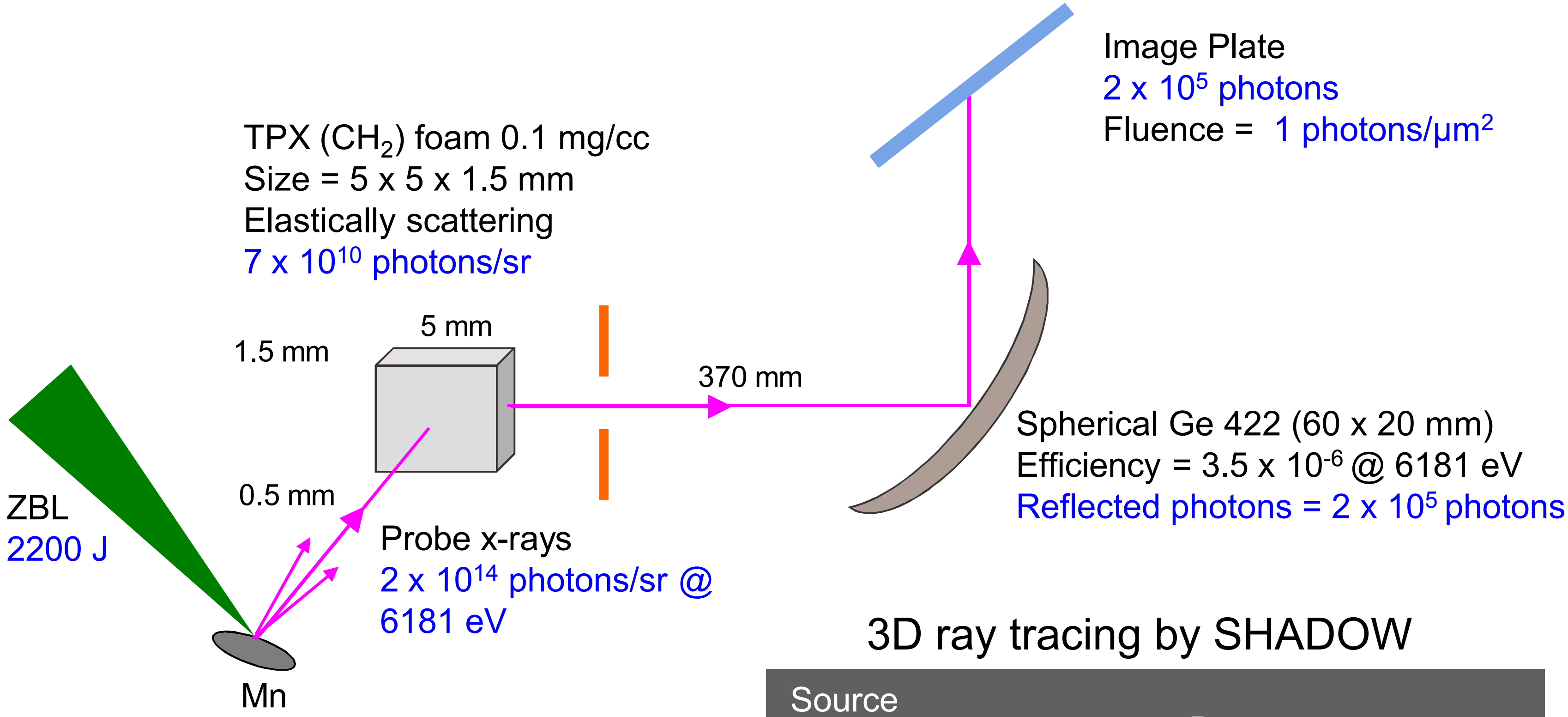


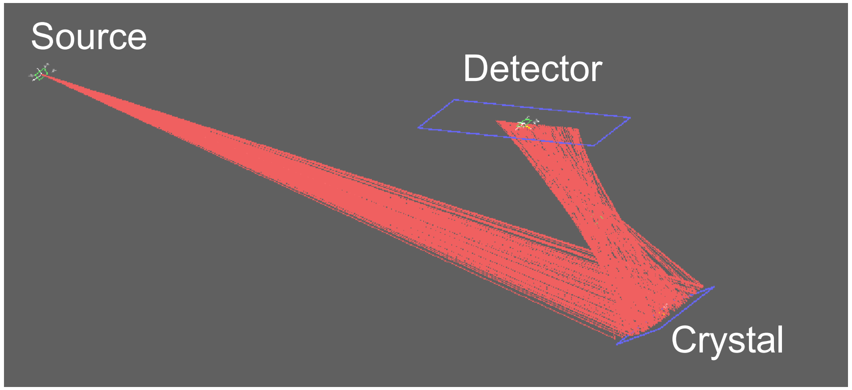
Au grid used for backlighting

Spatial resolution limited to ~75 μm by the Image Plate scanner (Fuji BAS-5000)

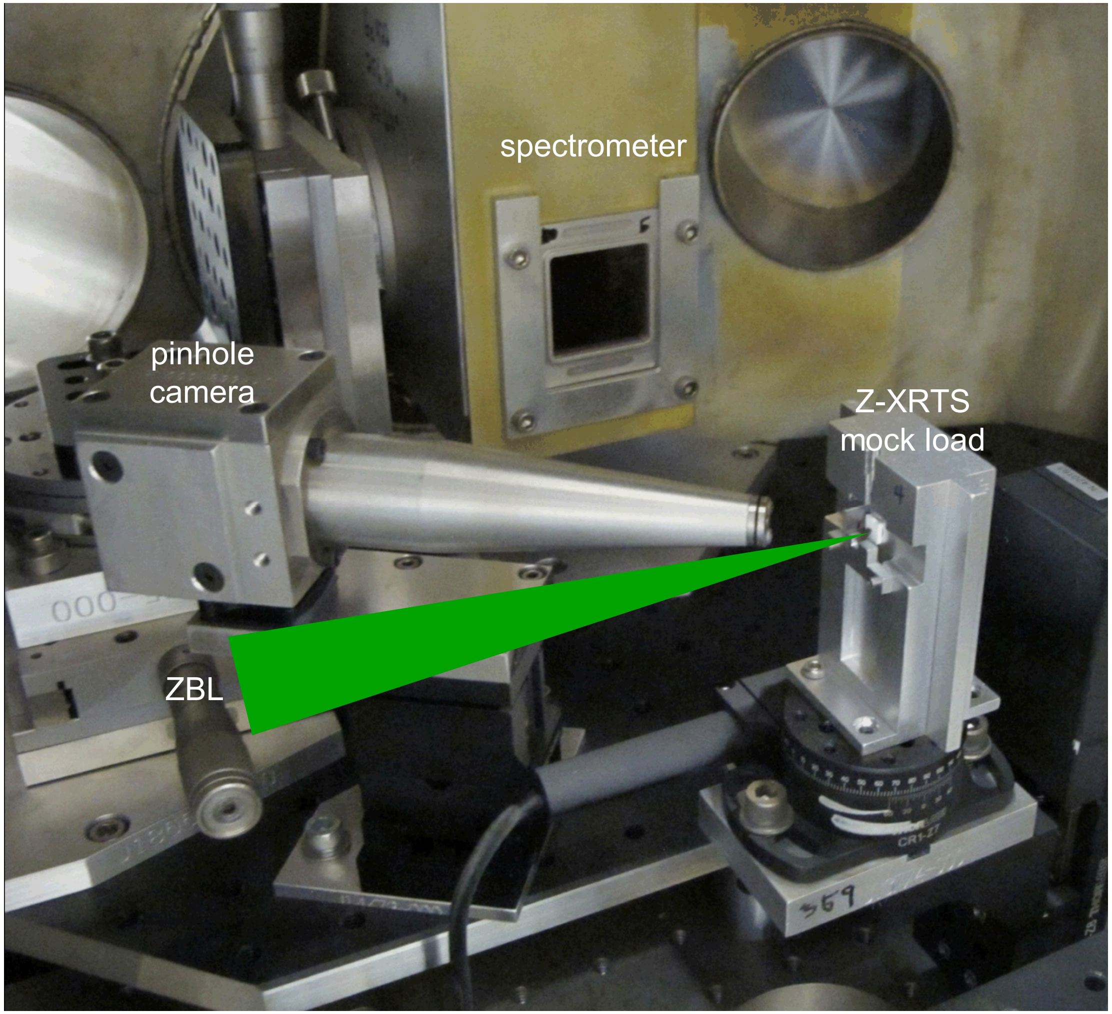
# Detailed photometric calculations and 3D ray tracings carried out to estimate scattered signal fluence



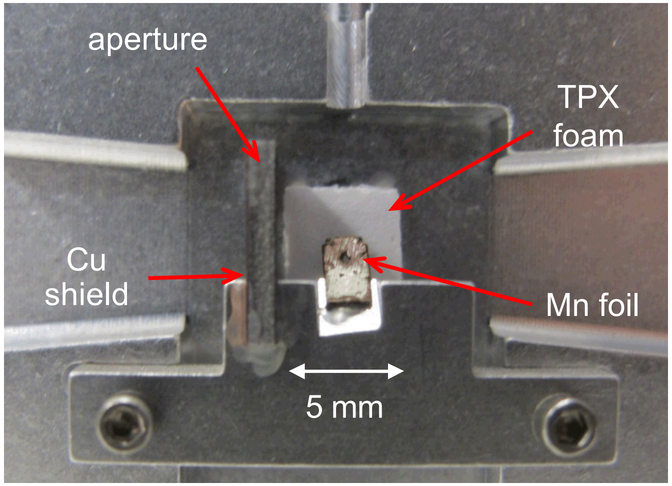

3D ray tracing by SHADOW



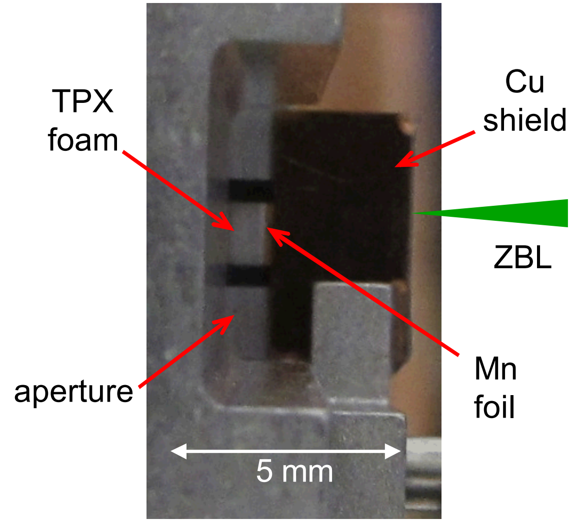
# X-ray scattering of TPX foam using Z-XRTS mock load




experimental setup

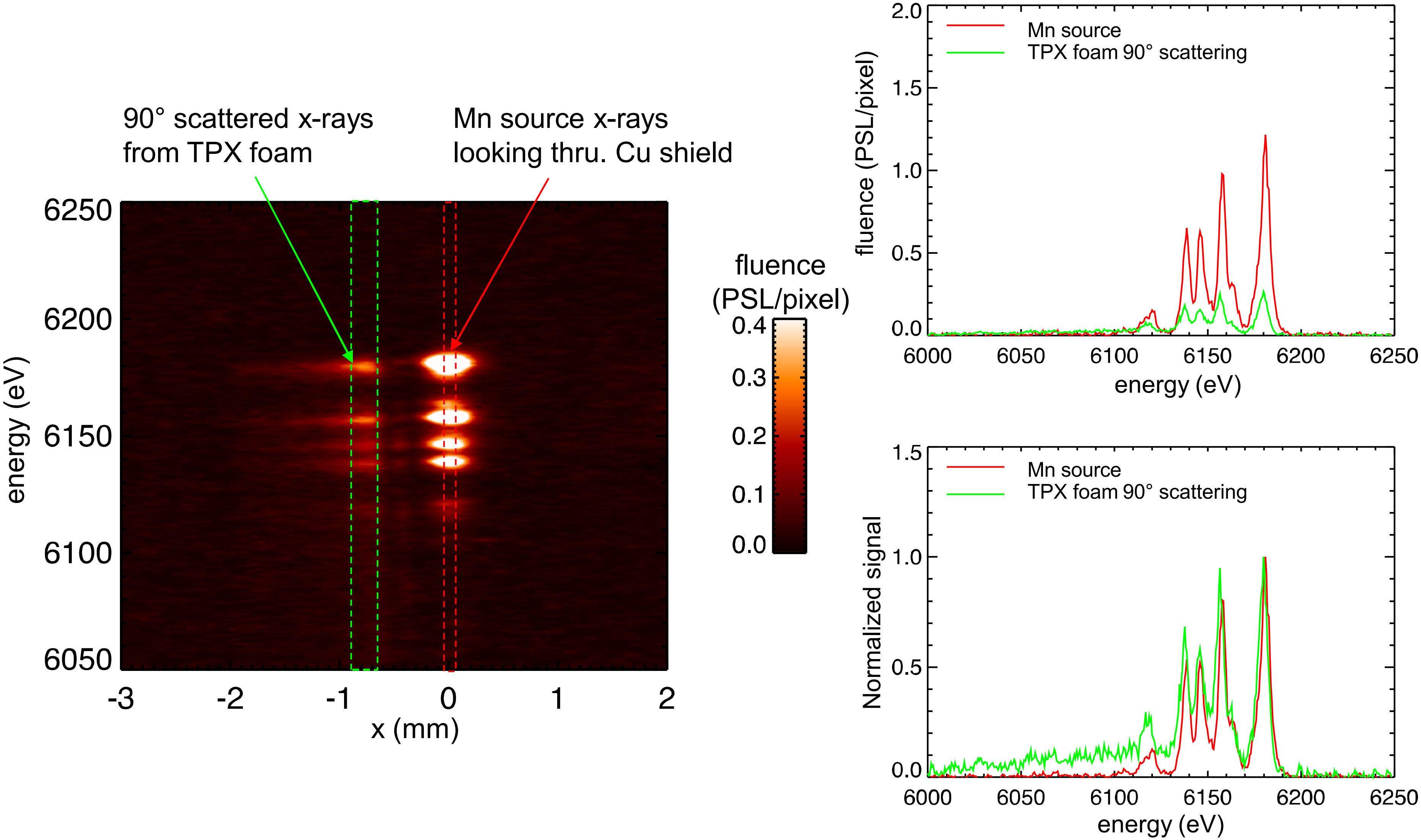



ZBL view




spectrometer view (90° scattering)

# Scattered x-rays from TPX foam and source x-rays both spectrally and spatially resolved



# Summary

- XRTS on Z-DMP experiments in preparation
  - More uniform shock state than laser-driven shock with larger spatial extent and longer duration
  - ZBL combined with $XRS^3$ diagnostic

- ZBL x-ray spectra
  - Face-on and side-on views show angle dependence of x-rays
  - V He-$\beta$ and Ti He-$\beta$ lines ~ 1/2x as bright as Mn He-$\alpha$ line, but have less interference from satellite lines
  - Reflected x-rays ~ 2x compared to transmitted x-rays

- X-ray scattering validation tests
  - Ambient TPX foam
  - Scattered and source x-rays resolved spectrally and spatially

# Future work

- 1st Z-XRTS (Nov. 14, 2012)
  - Fire Z at low charge voltage without firing ZBL
  - Debris, shock timing, x-ray background data
- 2nd Z-XRTS (Nov. 23, 2012)
  - Fire ZBL without firing Z
  - Ambient sample scattering data
- 3rd & 4th Z-XRTS (Dec. 10 – 11, 2012 )
  - Fire Z and ZBL
  - Shocked sample scattering data
- Continuing Z-XRTS development (2013)
  - X-ray source optimization
  - XRTS on Z-DMP and Z-pinch experiments