SAND2012-3724C

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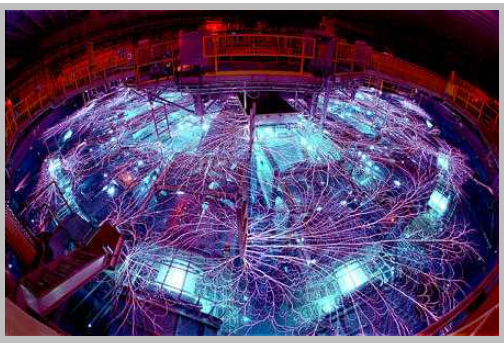

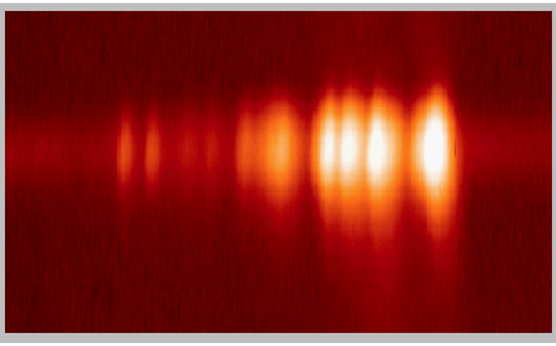

Experimental X-ray Spectra from Ti, V, Mn, and Ni Foils Irradiated with the Z-Beamlet Laser

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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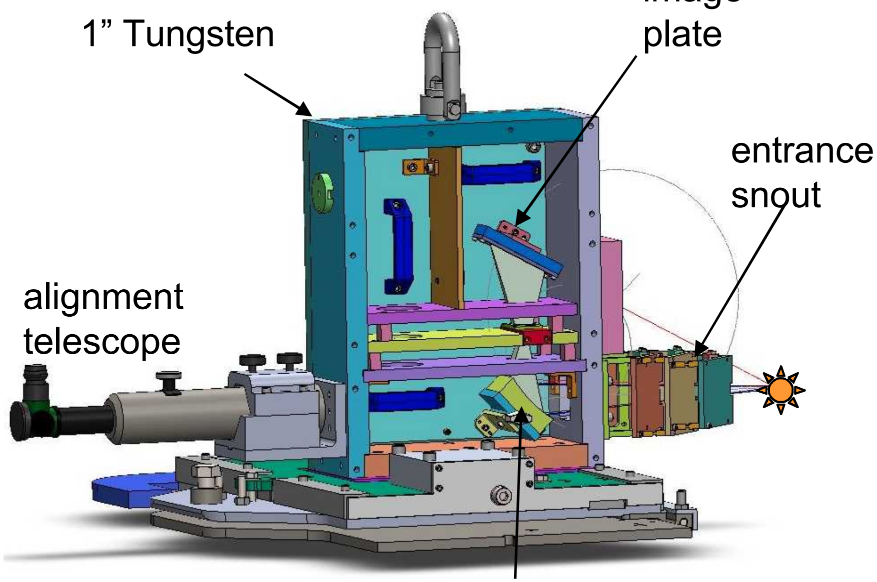
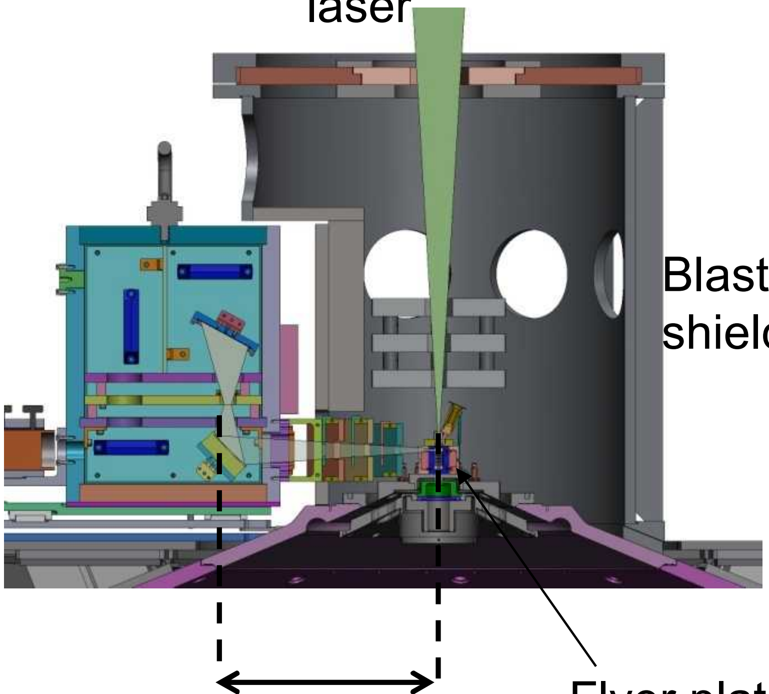
A new focusing spectrometer with spatial resolution (FSSR*) has been built for operation in the Z-machine.

- This spectrometer has been designed to diagnose Z experiments using the X-ray Thomson Scattering technique.





*see Belyaev LM, Instrum. Exper. Tech. 1977 and Pikuz et. al.

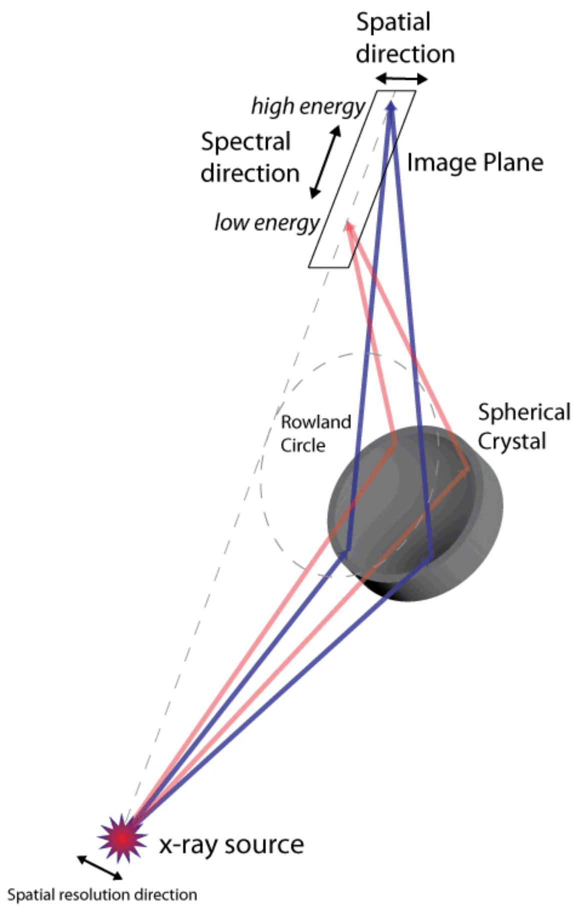
The experiments presented here are motivated by the need to better understand laser-heated foil x-ray sources and our FSSR type spectrometers.

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

Dedicated experiments were designed to answer these questions using the Z-Beamlet laser at Sandia.

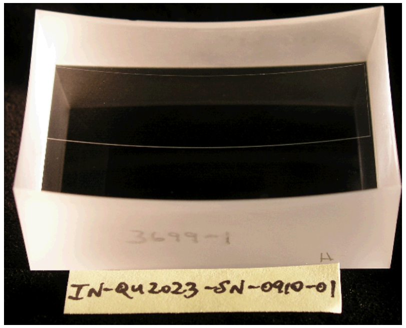
The FSSR spectrometers use a spherically bent crystal to provide spectral and spatial resolution.

FSSR spectrometer



FSSR Experimental Setup

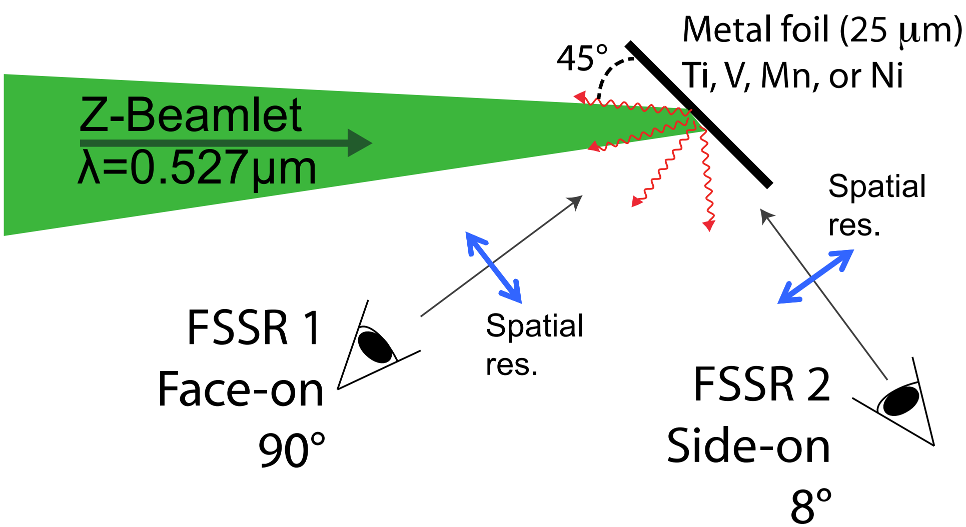
Crystal: Quartz 2023, Spherically bent, Radius = 150 mm
Central Bragg angle: 46°
Source-to-crystal : 20 cm
Crystal-to-Detector : 21.8 cm
Spatial Mag.: ~ 1x
Energy Range: 5800 – 6400 eV
Detector: Fuji Image Plate (TR)



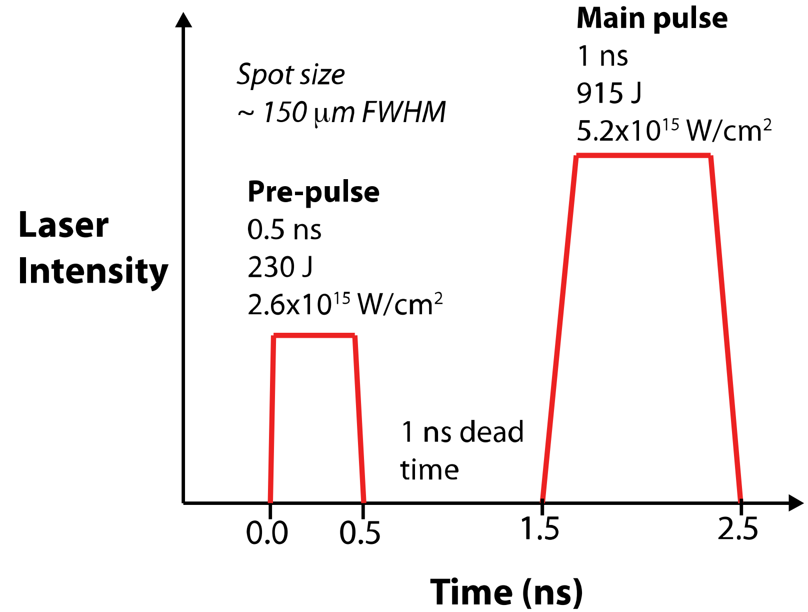
Quartz 2023 on BK7
Size ~ 58 x 18 mm

Two FSSR spectrometers simultaneously viewed a laser irradiated foil at 90° ("Face-on") and 8° ("Side-on").

Spectrometer Geometry



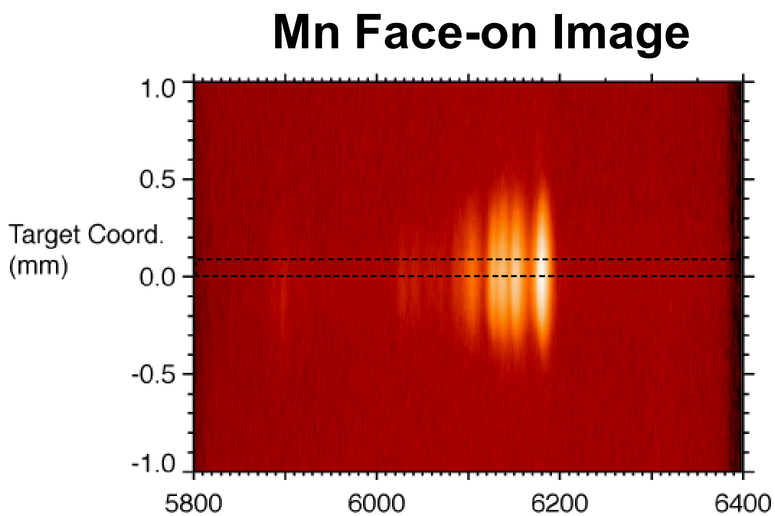
Laser Pulse Shape & Irradiance

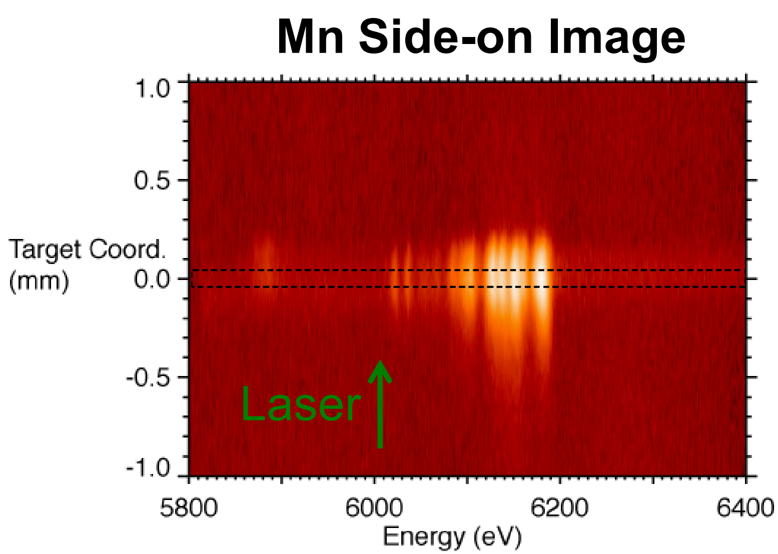


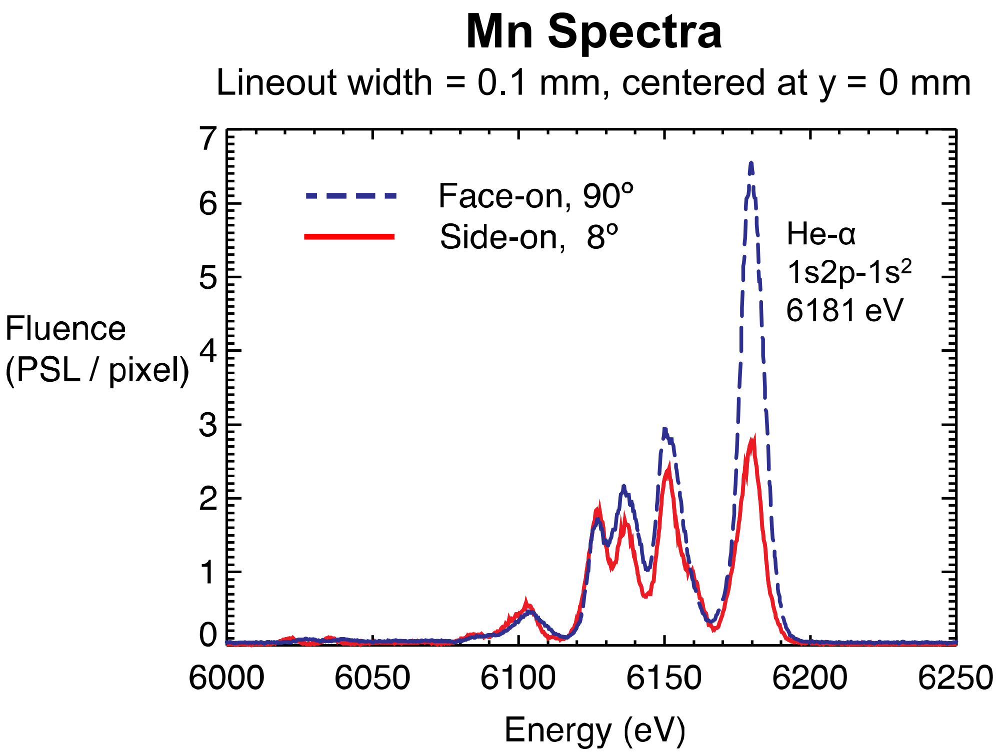
We investigated the following spectral lines:

Ti He-β (5586 eV)
V He-β (6117 eV)
Mn He-α (6181 eV)
Ni He-α (7804 eV)

The Mn spectrum exhibits a clear difference in shape between the Face-on and Side-on views.



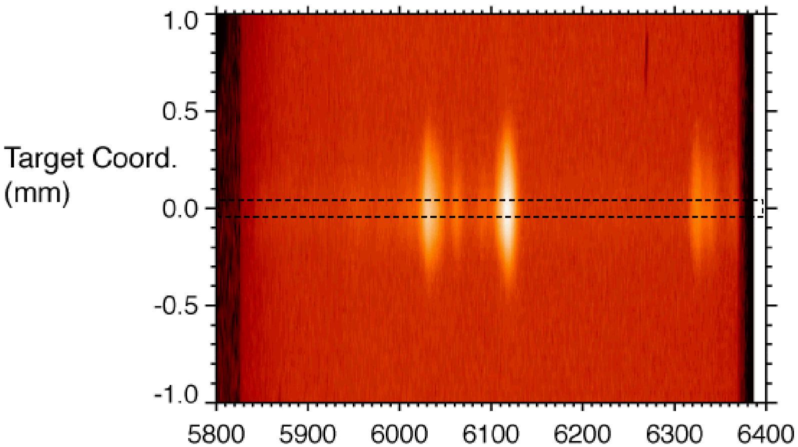




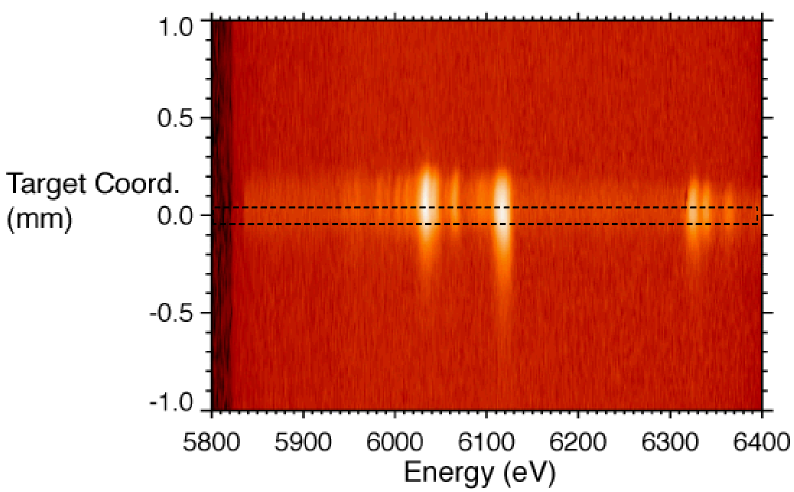
Spatial Information from vertical lineouts
Face-on FWHM: 340 μm @ 6181 eV
Side-on FWHM: 220 μm @ 6181 eV

The V He-β spectra also show differences between the two viewing angles.

V Face-on Image

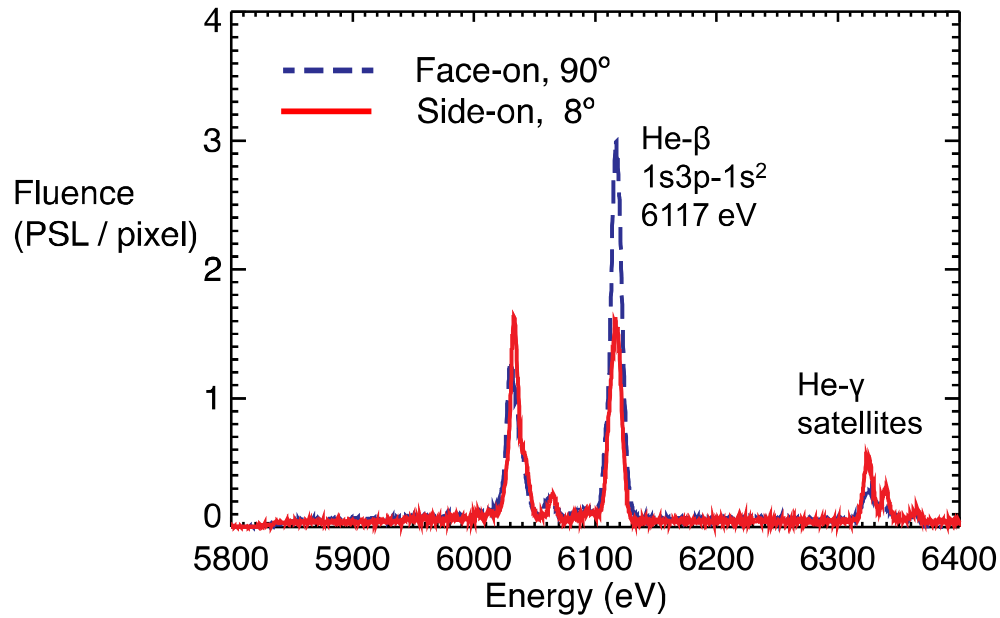


V Side-on Image



V Spectra

Lineout width = 0.1 mm, centered at y = 0 mm

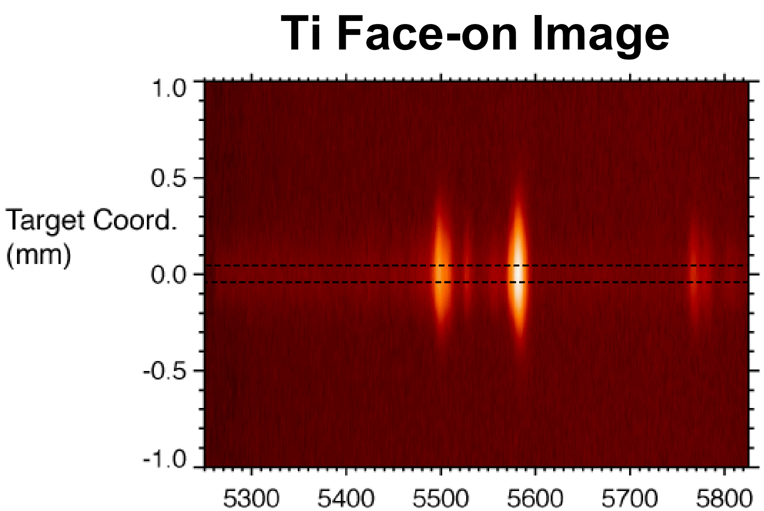


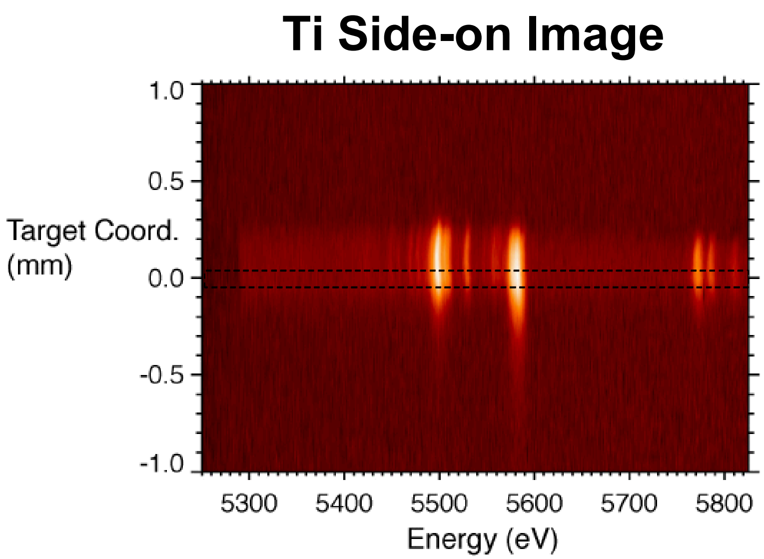
Spatial Information from vertical lineouts

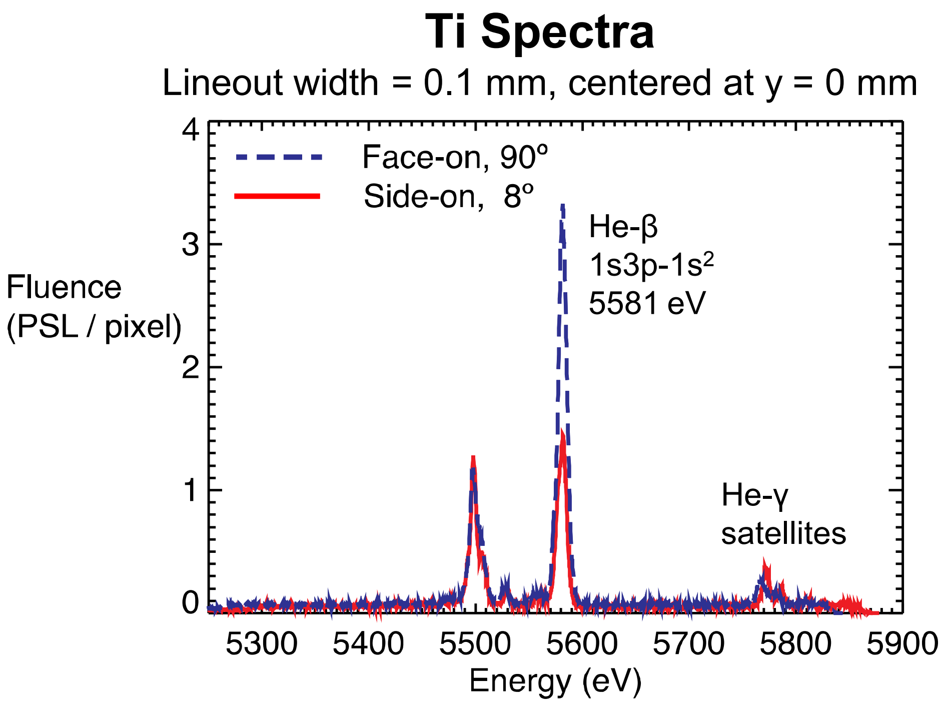
Face-on FWHM: 310 μm @ 6117 eV

Side-on FWHM: 230 μm @ 6117 eV

The Ti He-β spectra show a brighter resonance line in the Face-on view.







Spatial Information from vertical lineouts

Face-on FWHM: 300 μm @ 5581 eV

Side-on FWHM: 280 μm @ 5581 eV

The Ni He-α configuration used two different Mica crystals (9th order, Bragg = 46°). The Side-on crystal produced a poor spatial focus.

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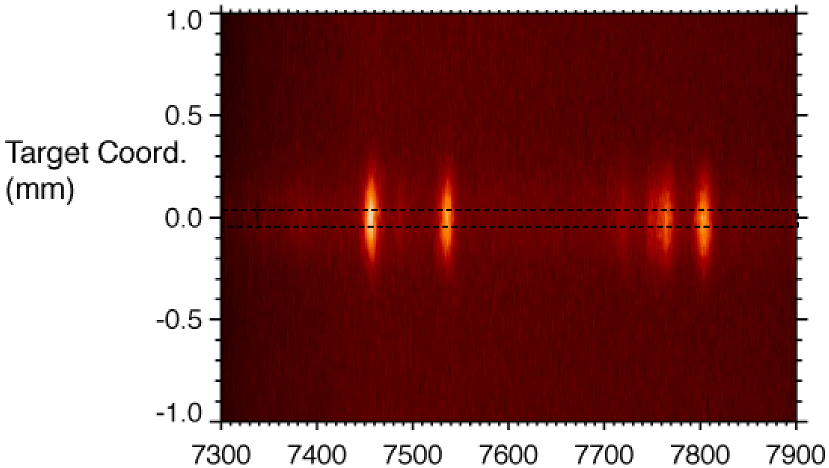
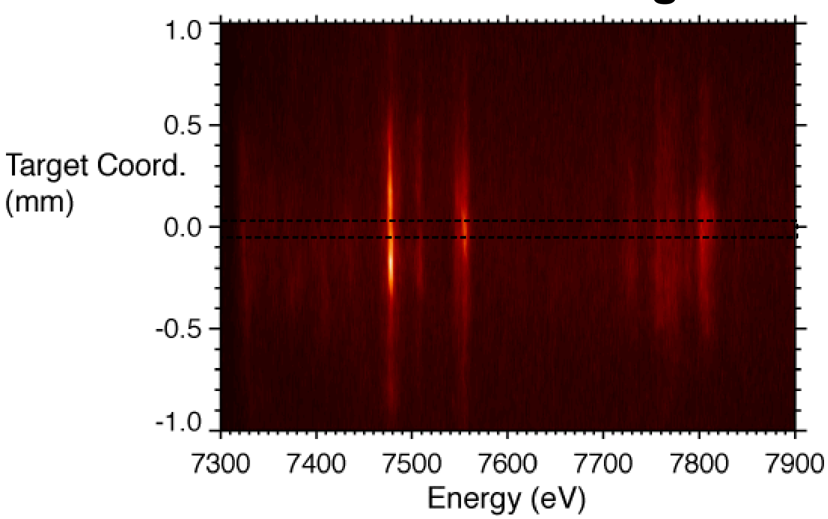
Ni Face-on Image

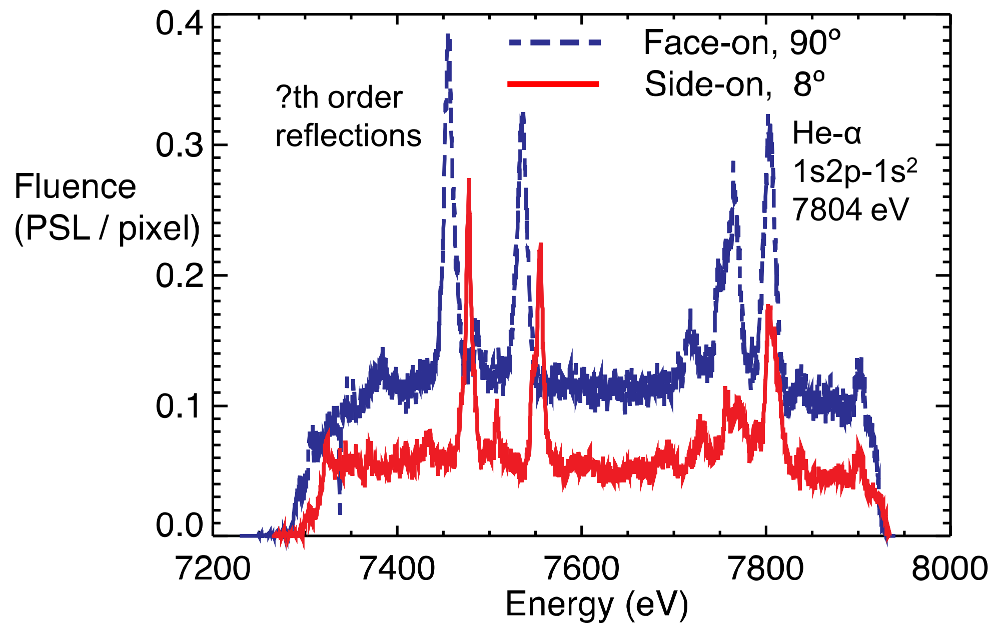


Ni Side-on Image



Ni Spectra

Lineout width = 0.1 mm, centered at y = 0 mm



Spatial Information from vertical lineouts

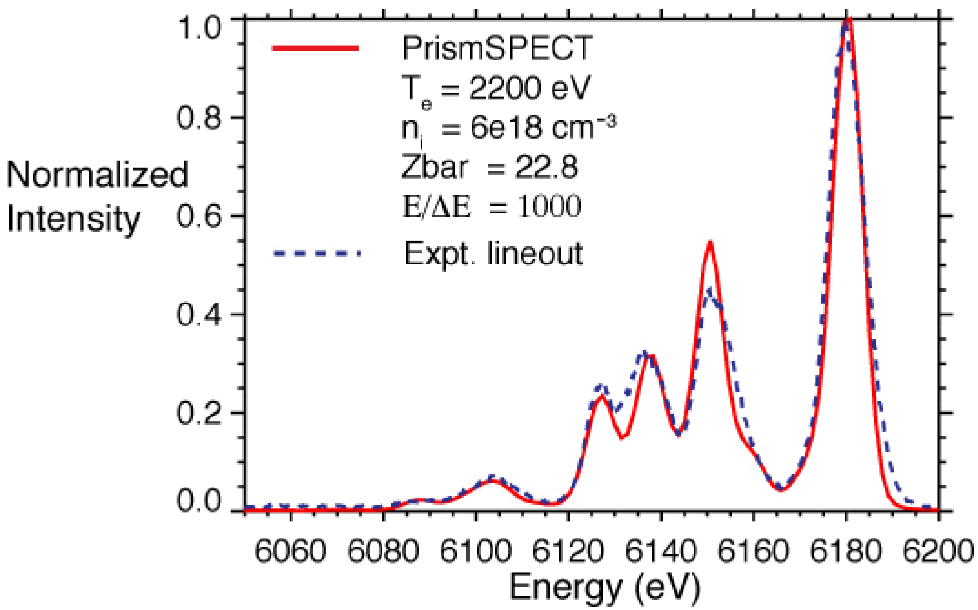
Face-on FWHM: 340 μm @ 7804 eV

Side-on FWHM: NA due to poor focusing of the Mica crystal

PrismSPECT NLTE simulations of Mn at T_e = 2.2 keV and n_i = 6 x 10^{18} cm^{-3} show good agreement with the Face-on spectrum.

Mn PrismSPECT model and Experiment

Intensity normalized to He-α Res. line.



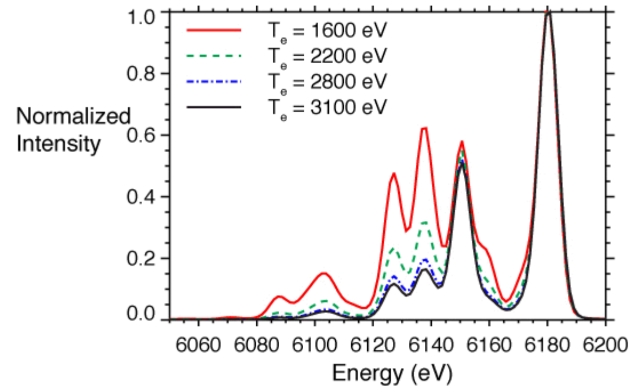
PrismSPECT indicates that our spectrometer has E/ΔE =1000.

PrismSPECT gives n_e = 1.4e20 cm^{-3} which is 30x lower than n_{cr} (4e21 cm^{-3}).

Mn Li-sat. to He-α ratio provides T_e measurement

Plasma slab 200 μm thick, n_i = 6e18 cm^{-3}

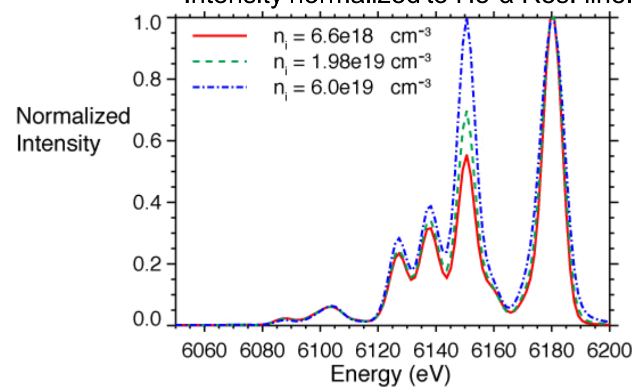
Intensity normalized to He-α Res. line.



Mn Inter. Comb. line to He-α ratio provides n_i measurement

Plasma slab 200 μm thick, T_e = 2.2 keV

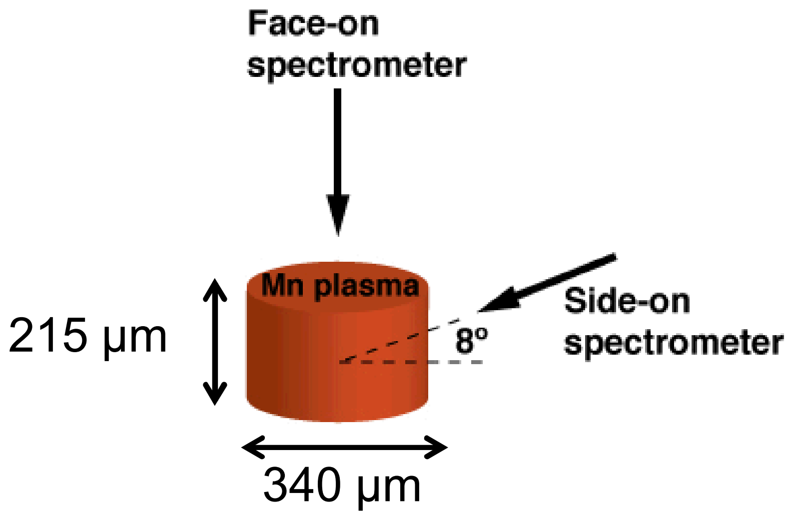
Intensity normalized to He-α Res. line.



SPECT3D* NLTE simulations were used to simulate both Face-on and Side-on views.

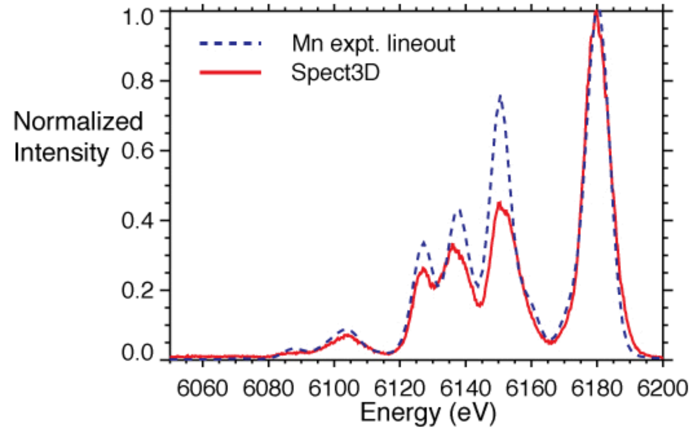
SPECT3D Model Setup

T_e = 2200 eV
n_i = 6e18 cm^{-3}
Plasma geometry = Disk
Spatially resolving detectors (res.= 100 μm)



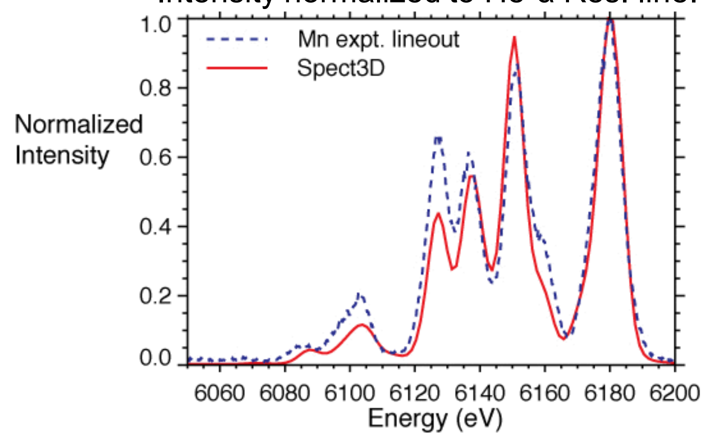
Mn SPECT3D and Experiment Face-on view

Intensity normalized to He-α Res. line.



Mn SPECT3D and Experiment Side-on view

Intensity normalized to He-α Res. line.

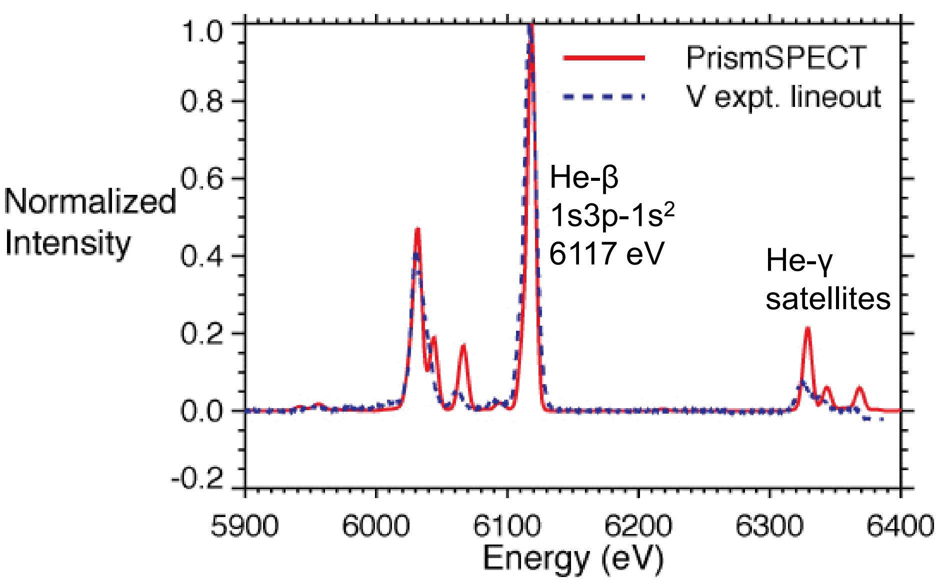


*Spect3D and PrismSPECT are collisional-radiative spectral analysis codes produced by Prism Computational Sciences, Inc.

Using the same T_e & n_i as the Mn best fit, PrismSPECT was used to generate Ti and V He-β spectra.

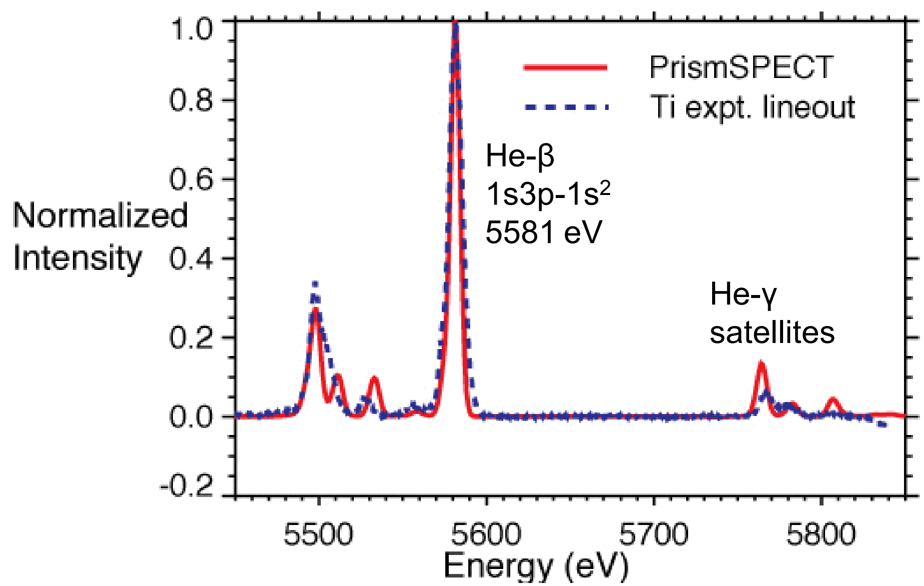
PrismSPECT Setup
T_e = 2200 eV
n_i = 6e18 cm^{-3}
Thickness = 200 μm
E/ΔE =1000

V PrismSPECT and Experiment



Zbar = 20.9, n_e= 1.3e20 cm^{-3}

Ti PrismSPECT and Experiment



Zbar = 20.1, n_e= 1.2e20 cm^{-3}

Turning off the laser pre-pulse increased the intensity the V He-β line by 2.5x when viewing at 45°.

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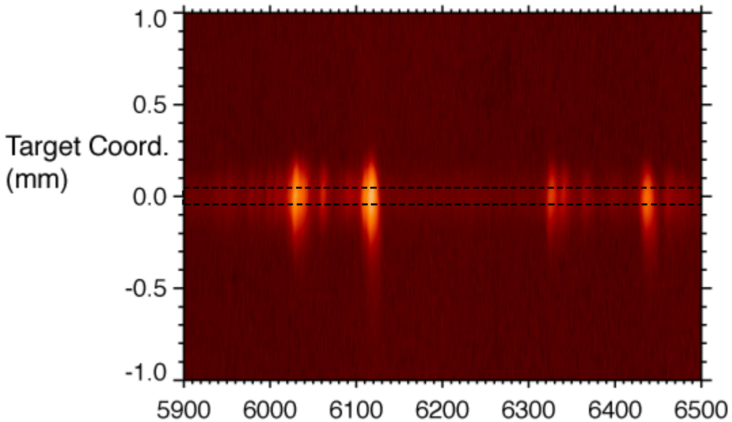
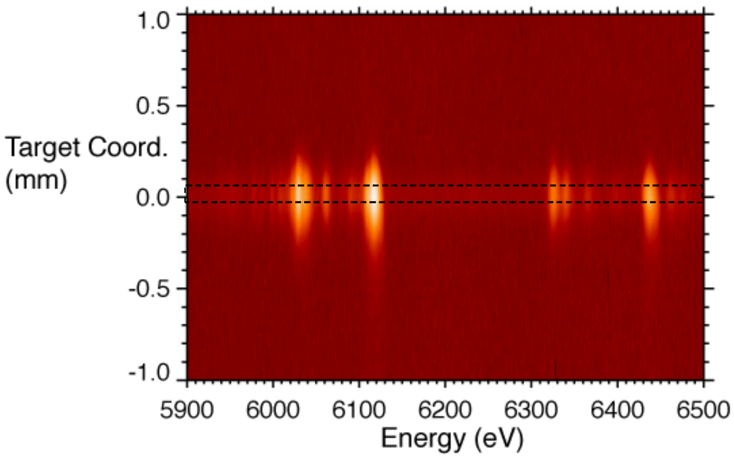
V foil, Standard Laser Pre-pulse

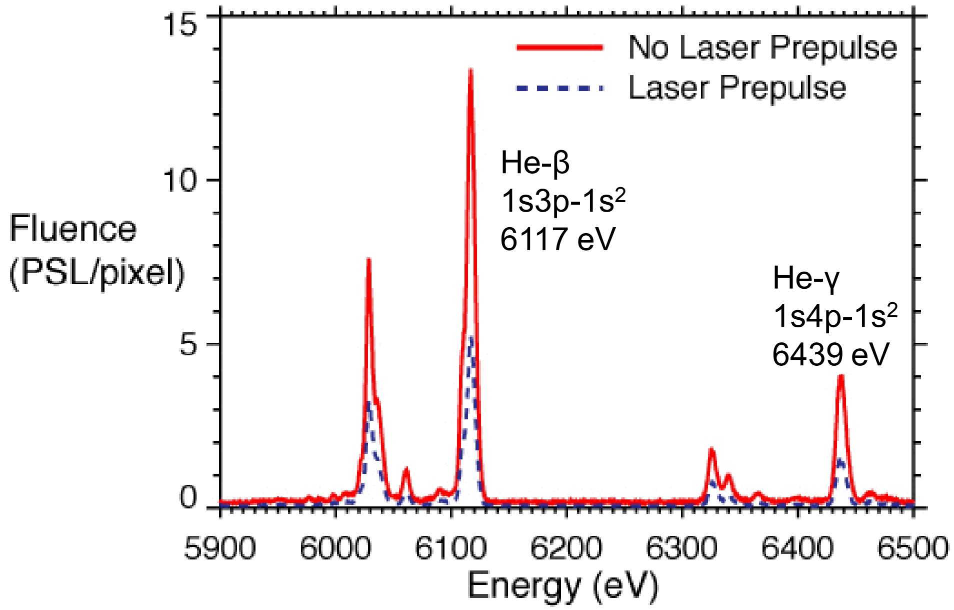


V foil, No Laser Pre-pulse



V Spectra

Lineout width = 0.1 mm, centered at y = 0 mm



<u>Spatial Information from vertical lineouts</u>

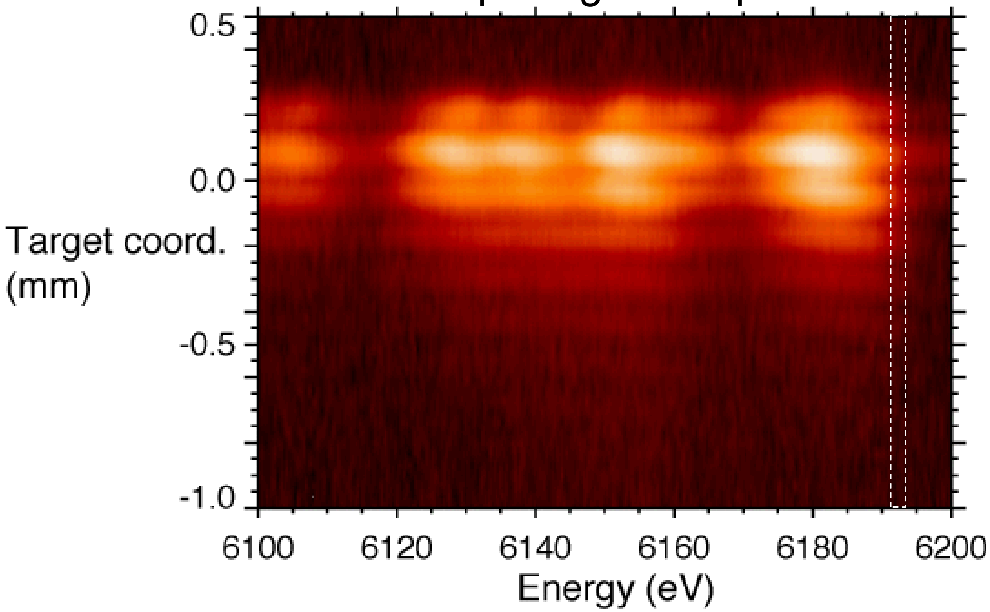
With Pre-Pulse: 200 μm FWHM @ He-β

No Pre-Pulse: 195 μm FWHM @ He-β

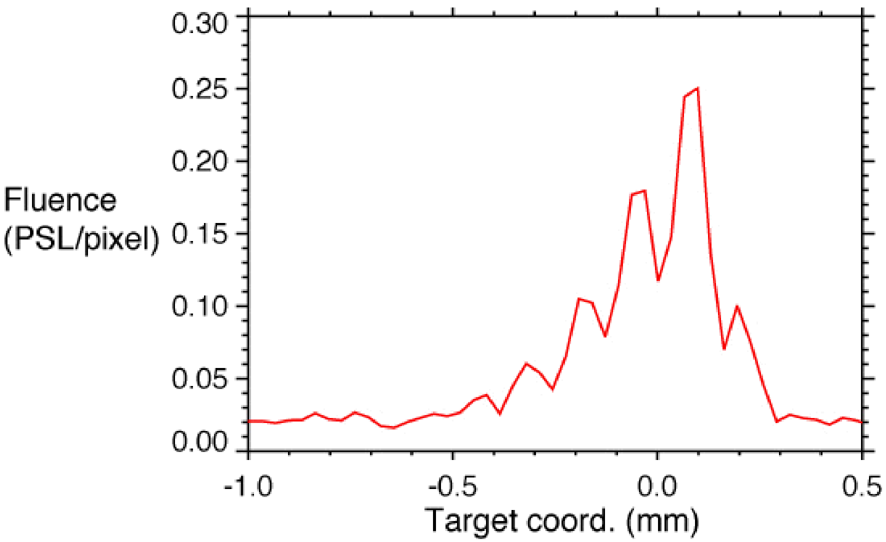
Emitting plasma appears to be the same size in both cases.

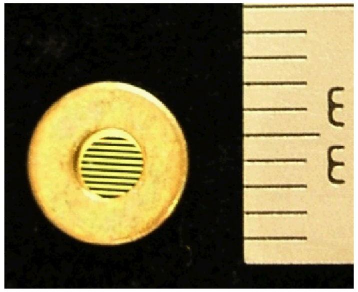
Backlit grid images provide an estimation of the spatial resolution and the magnification.

Mn plasma backlighting a Au Grid
Bar width = 45 μm
Bar spacing = 125 μm



Vertical lineout across grid





Au Grid used for backlighting

Spatial Resolution limited to ~100 μm by the Image Plate scanner (Fuji BAS-5000)

These initial experiments suggest the spectrometer must be modified so that it produces a more concentrated image (i.e., smaller footprint).

- The image size is controlled by the magnifications in the sagittal and meridonal planes, M_{sag} and M_{mer} respectively.

$$M_{sag} = \frac{R}{2s_o \sin(\theta_B) - R} = \left(\frac{s_0}{f_{sag}} - 1 \right)^{-1}$$

$$M_{mer} = \frac{s_i - R\sin(\theta_B)}{s_o - R\sin(\theta_B)}$$

where s_o = object distance, s_i = image distance, θ_B = Bragg angle, f_{sag}= sagittal focal length, R = crystal radius of curvature.

- M_{mer} is reduced by moving the detector onto the Rowland circle. Here M_{mer} = 0, and the spectral image width is determined by the spectral line width and not the object size.

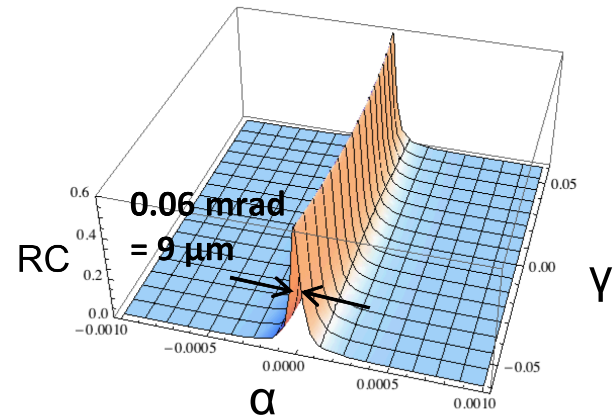
The fluence [photons/μm^2] of the x-ray image is also controlled by the active solid angle of the crystal.

- The active solid angle (ASA) is the total solid angle of the crystal that is responsible for reflecting incident x-rays.
- The ASA can be calculated by integrating the crystal's rocking curve over the entire crystal surface.*

$$ASA = \left[\int_{\alpha_{min}}^{\alpha_{max}} \int_{\gamma_{min}}^{\gamma_{max}} RC[\theta_B - \theta(\alpha,\gamma)] d\alpha d\gamma \right] \left[\left(\frac{R}{s_o} \right)^2 \sin(\theta_B) \right]$$

Where RC is crystal rocking curve, θ_B = Bragg angle, θ = local grazing angle, R=crystal radius, s_o= object distance, and α = crystal polar angle and γ = crystal azimuthal angle as defined from the center of the crystal sphere.

Example surface plot of RC[θ_B- $\theta(\alpha,\gamma)$] for:
Quartz 2023, 6181 eV, R = 150mm, s_o= 20 cm,
θ_B = 46°



*See T. Missalla et. al., RSI 1999
E.J. Gamboa, et. al., JINST 2011

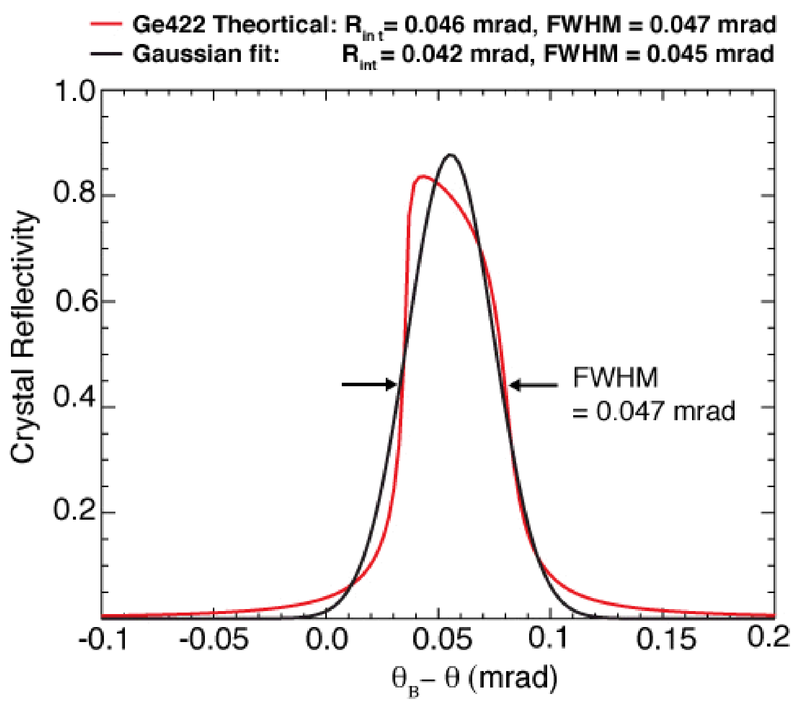
Once ASA, M_{mer}, and M_{sag} are calculated we can estimate the fluence of the x-ray image.

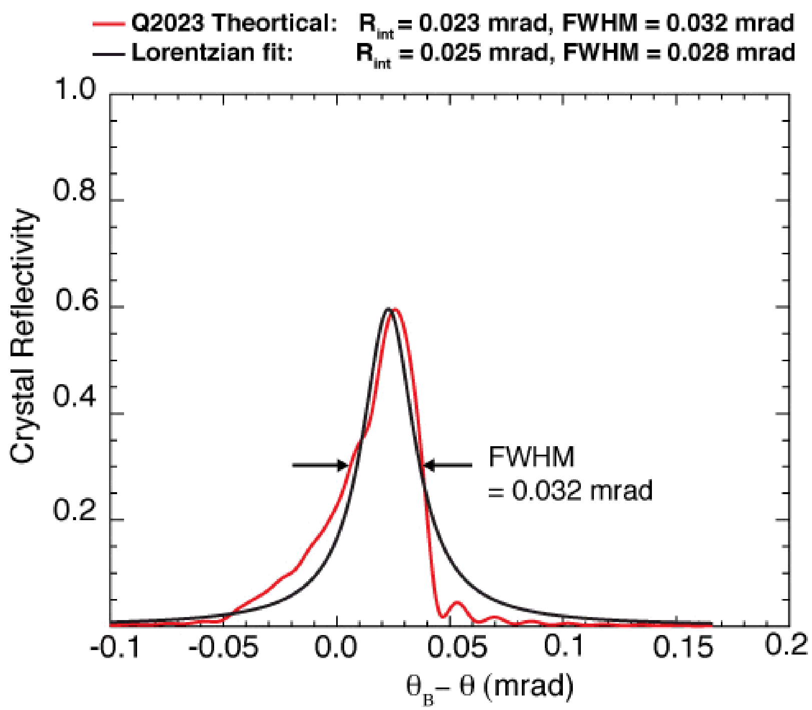
$$Fluence\left[\frac{photons}{\mu m^2}\right] \approx \left(\frac{E_L}{E_x}\frac{\eta T}{4\pi}\right)\left(\frac{ASA}{L_{sag}M_{sag}\sqrt{\left(\frac{L_{mer}M_{mer}}{cos(\phi)}\right)^2+\left(\frac{\Delta E}{D}\right)^2}}\right)$$

Where E_L= laser energy on target, E_x = single photon energy, η = laser to x-ray spectral line conversion efficiency into 4π, T = filter transmission, ASA = active solid area of crystal, L_{mer} = object size in meridional plane, L_{sag} = object size in sagittal plane, M_{mer}= meridional magnification, M_{sag}= sagittal magnification, ϕ = angle between the reflected ray and the image plane normal, ΔE = intrinsic spectral line width, D = spectrometer dispersion [energy/mm].

The crystal rocking curves were calculated using the multi-lamellar theory contained in XOP.*

- Crystal thickness = 65 µm, R = 150 mm, X-ray energy = 6181 eV (Unpolarized).



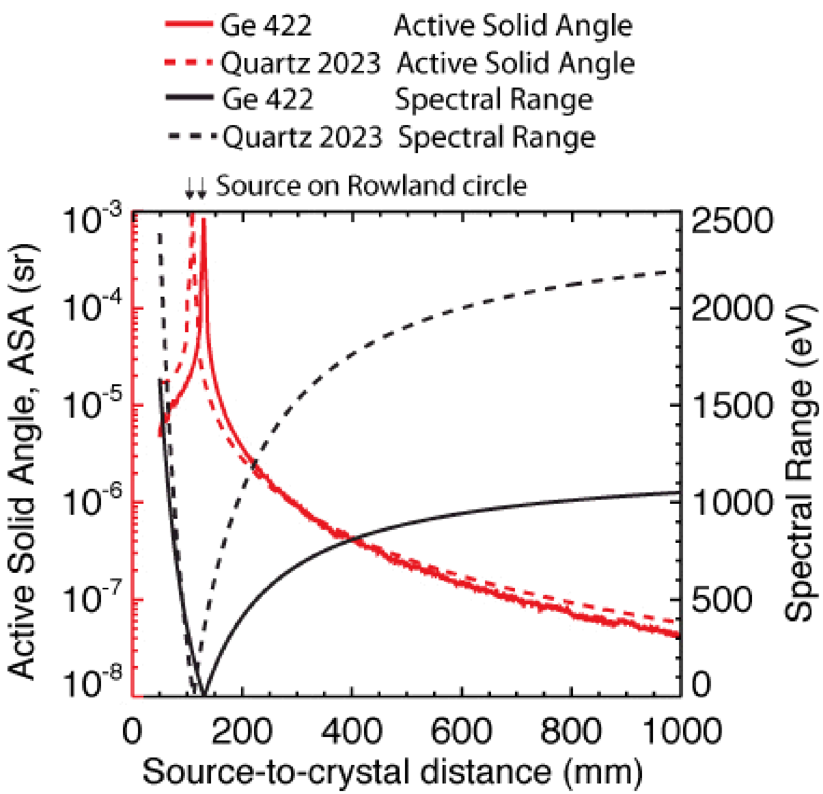


*X-ray Orientated Programs
M. Sanchez del Rio, et. al., SPIE vol. 3151, 1997

Here are two examples of calculated ASA values for Quartz 2023 and Ge 422 at 6181 eV.

- Quartz dimensions: 60 x 18 mm, R = 150 mm, θ_B=46.86°

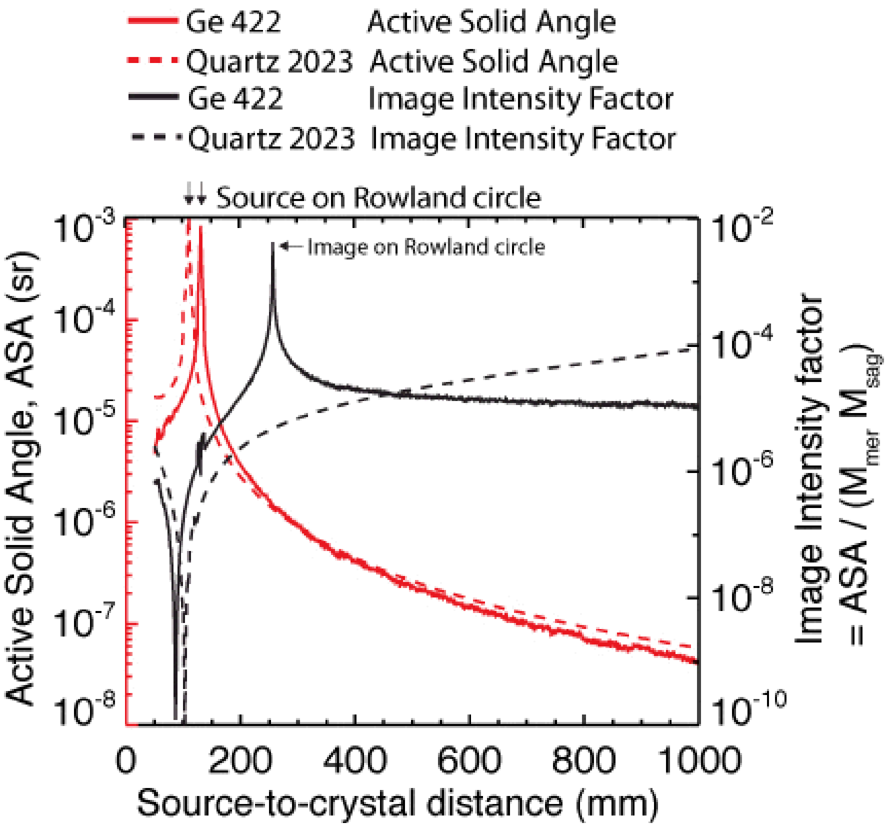
  Ge dimensions: 50 x 10 mm, R = 150 mm, θ_B=60.27°



- ASA is largest when the source is on the Rowland circle. However, the spectrometer will have no spectral range.

The fluence of the x-ray image is maximized when the image is formed on the Rowland circle.

- Quartz dimensions: 60 x 18 mm, R = 150 mm, θ_B=46.86°
  Ge dimensions: 50 x 10 mm, R = 150 mm, θ_B=60.27°



- The Quartz intensity factor peaks at 1687 mm which is off this plot. At this distance the spatial magnification is 0.07. This would prohibit us from obtaining spatial information.

Predicted fluence values are 3x larger than the experimentally measured values for two different source distances for 6181 eV with Quartz 2023.

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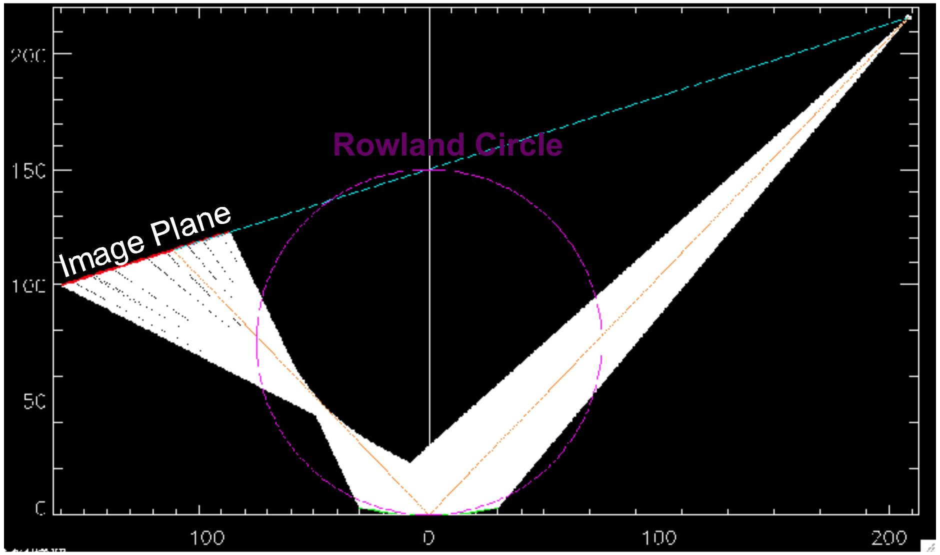
	Source dist. 20 cm	Source dist.66 cm
Laser Energy	1.15 kJ	0.84 kJ
Conv. Eff.	0.1%	0.1%
Active Solid Angle (ASA)	2.8×10^{-6}	7.2×10^{-8}
M_{sag}	1.02	0.18
M_{mer}	1.13	0.02
Object size	300 µm dia.	300 µm dia.
Image size	320 x 630 µm	50 x 110 µm
Predicted fluence	**286 PSL** (135 photons/µm²)	**1540 PSL** (840 photons/µm²)
Experiment fluence	**96 PSL** (~1/3 predicted)	**480 PSL** (~1/3 predicted)

- As an initial estimate this not bad considering several parameters are not well known. For instance, x-ray-to-laser conversion efficiency could easily be off by a factor of 2 or 3. The spectra line width and image plate calibration are also not well known.

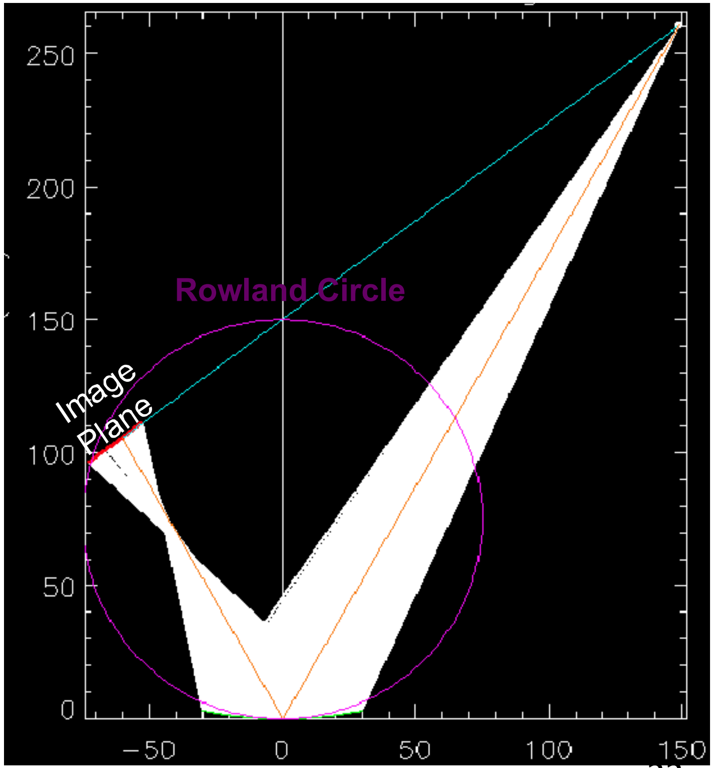
By switching to Ge 422 we can further increase the fluence. This is desirable for future scattering experiments that will use a probe energy of 6181 eV.

- Ge 422 (2d=2.31 Å) allows the image plane to be placed near the Rowland circle for reasonable object distances and crystal bending radii.

Quartz 2023 configuration



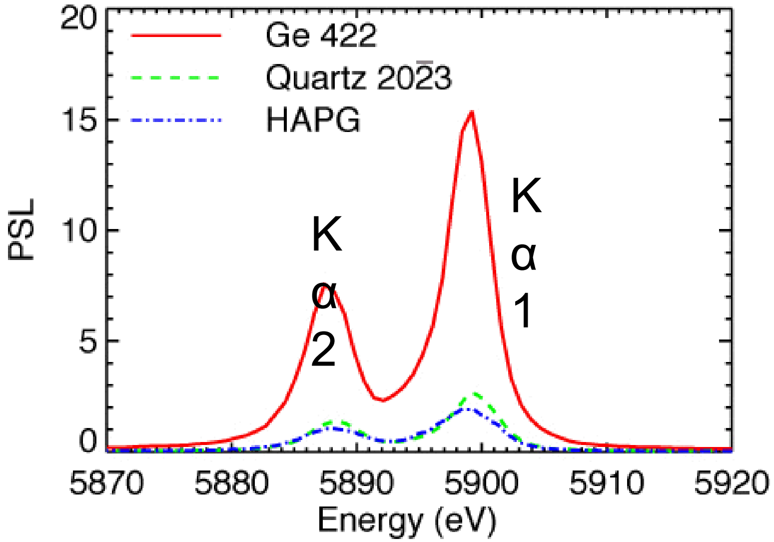
Ge 422 configuration



Manson source calibrations at 5898 eV (Mn anode) confirmed that the Ge 422 configuration produces a brighter image (4x) than Quartz 2023.

- A HAPG from Optigraph was also tested in mosaic focusing mode, but it lacked good spatial focusing.

	Quartz 2023	**Ge 422**	**HAPG**
Crystal Size (mm)	60 x 18	50 x 10	35 x 25
Image FWHM(spatial x spectral)	160 x 180 μm	200 x 140 μm	630 x 530 μm
ASA	9.5×10^{-7} sr	1.5×10^{-6} sr	?
Peak PSL	**3.50**	**14.4**	**1.60**



Summary

- In preparation for future x-ray Thomson scattering experiments on Z, we have begun experiments to better understand laser-heated foil x-ray sources.
- Using two FSSR spectrometer placed at 90° and 8° Mn, V, and Ti spectra were observed with $E/\Delta E = 1000$ and a spatial resolution = 100 µm.
- The intensity & shape of the emitted x-ray spectrum has an angular dependence.
- The V He-β line appeared brighter with no laser pre-pulse.
- PrismSPECT and SPECT3D were used to diagnose the density and temperature of the plasma.
- Using Ge 422 the spectrometer design has been further optimized to produce a greater image fluence.