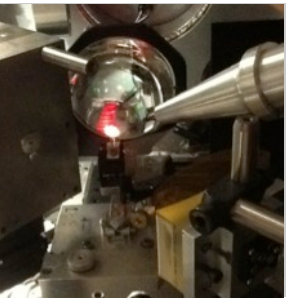
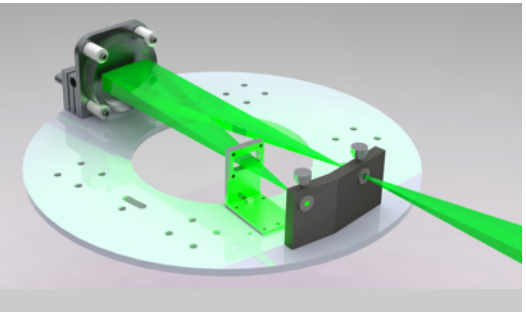
SAND2014-19001C





Laser-driven 6-16 keV x-ray imaging and backlighting with spherical crystals

Marius Schollmeier, Patrick K. Rambo, Jens Schwarz, Ian C. Smith, and John L. Porter

56th Annual Meeting of the APS Division of Plasma Physics
New Orleans, Louisiana, USA
Oct 27-31, 2014

Sandia National Laboratories

Exceptional service in the national interest

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

ZBacklighter

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Backlighting for EOS measurements on Z

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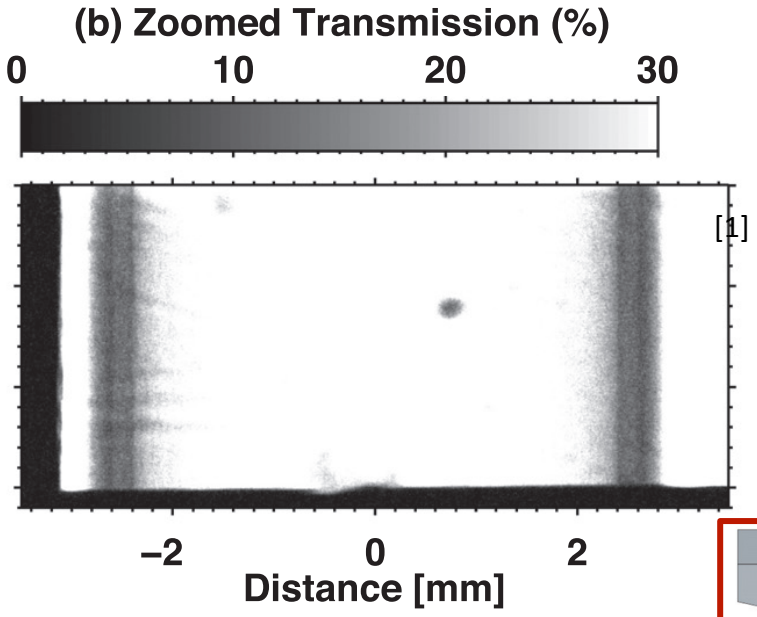
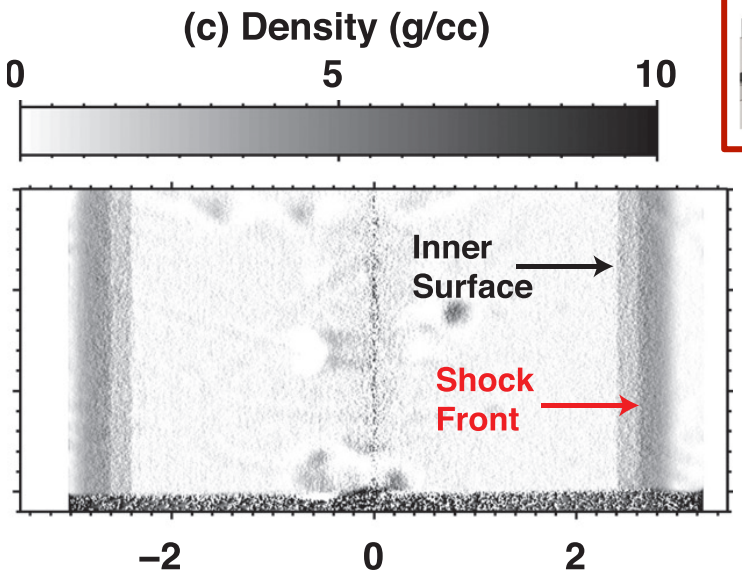
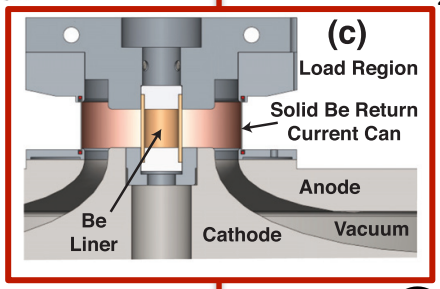
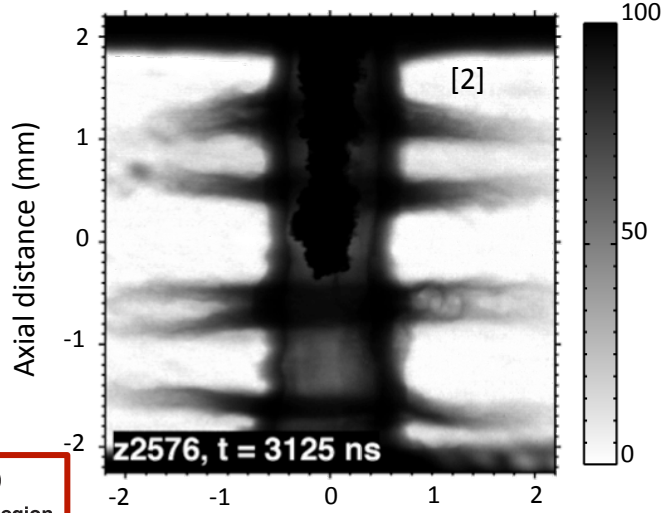
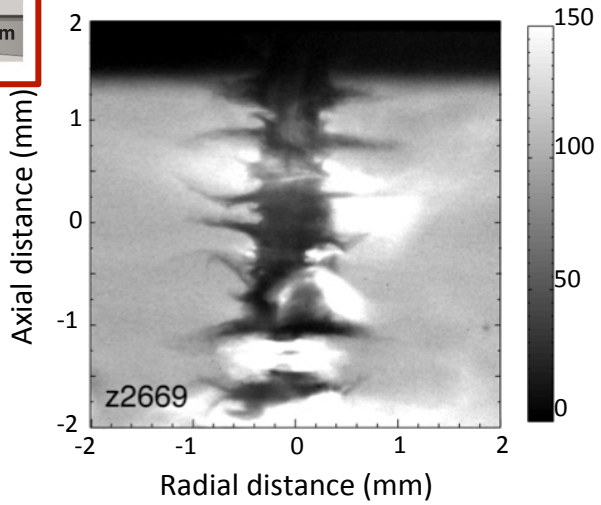








$C_R = 8$



$C_R = 15$

[1] images from R.D. McBride, Phys. Plasmas **20**, 056309 (2013), [2] images courtesy of P.F. Knapp, SNL

X-ray backlighting with spherical crystals

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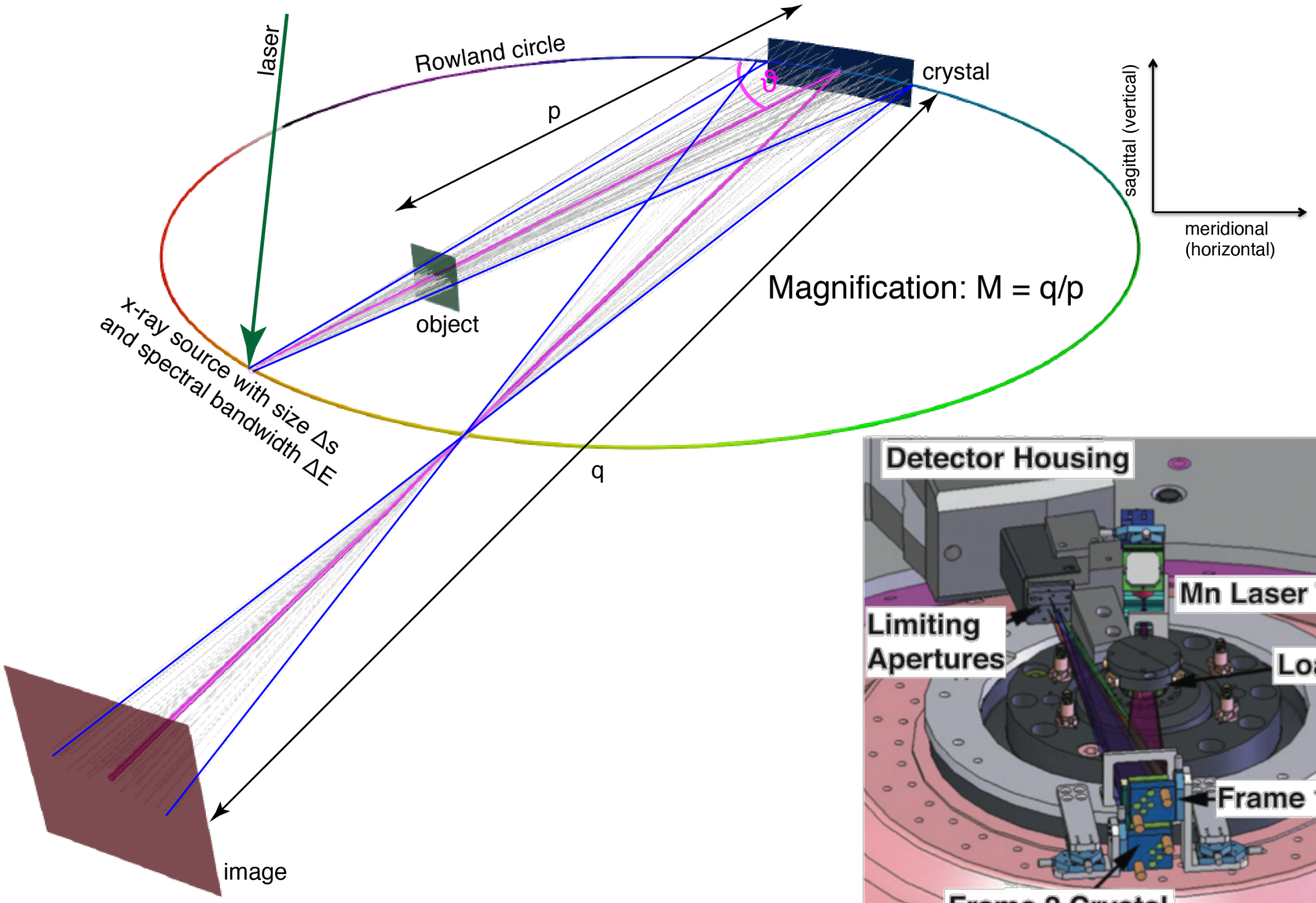
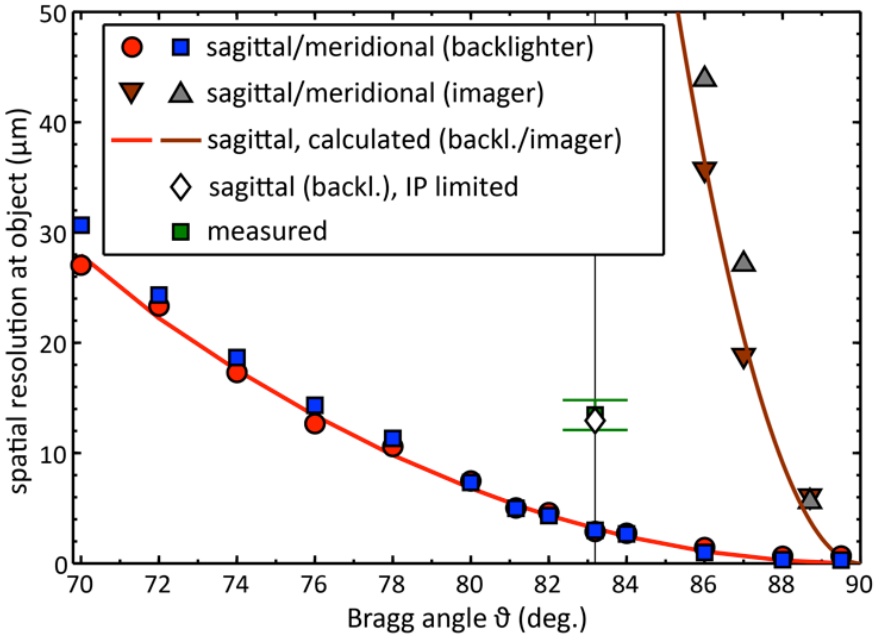
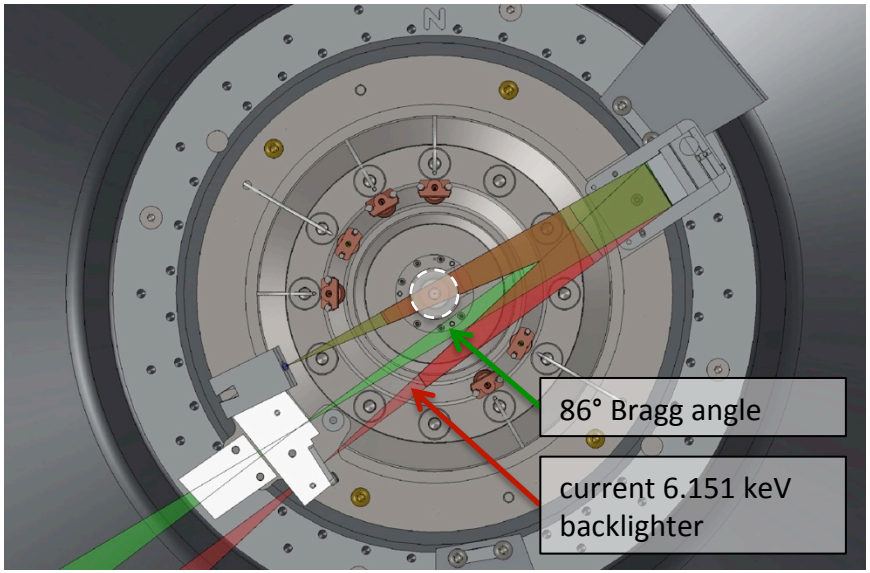


Crystal imaging: Incidence angle constraints

Lowest achievable Bragg angle



Largest achievable Bragg angle



ESF width scales as: $\sigma = 0.7\, L_s \left(1 + \frac{1}{M}\right)(1 - \sin^2 \vartheta)$ [1]

- Backlighter:
  - M = 6
  - Crystal: R = 250 mm
  - r = 100 μm source
  - $L_s \approx 0.29$ mm
- Imager:
  - M = 10
  - Crystal: R = 250 mm, 10 × 10 mm
  - $L_s = 10$ mm

[1] D.B. Sinars, Applied Optics 42, 4059 (2003)

Search for line & crystal combinations

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Description	Quantity
Elements	Mn, Fe, Co, Ni, Cu, Zn, Ga, Ge, As, Se, Br, Kr, Rb, Sr, Y, Zr
Nuclear charges	Z = 25 - 40
Spectral lines	He resonance, He intercombination, $K_{\alpha 1}$, $K_{\alpha 2}$, K_{β}
Energy range (*E*)	5.8 – 17.7 keV
Crystals (*2d*)	α-Quartz, Ge, Si, Mica
Reflection orders (*m*)	1 – 5 (for Si, Ge, Mica) 1 – 3 (for Quartz)

$$\vartheta = \arcsin\left(\frac{m\,hc}{2d\,E}\right)$$

Possible combinations: 6320
Total number of matches: 92
Total number of $K_{\alpha,\beta}$ matches: 52
Total number of He_{α} matches: 40

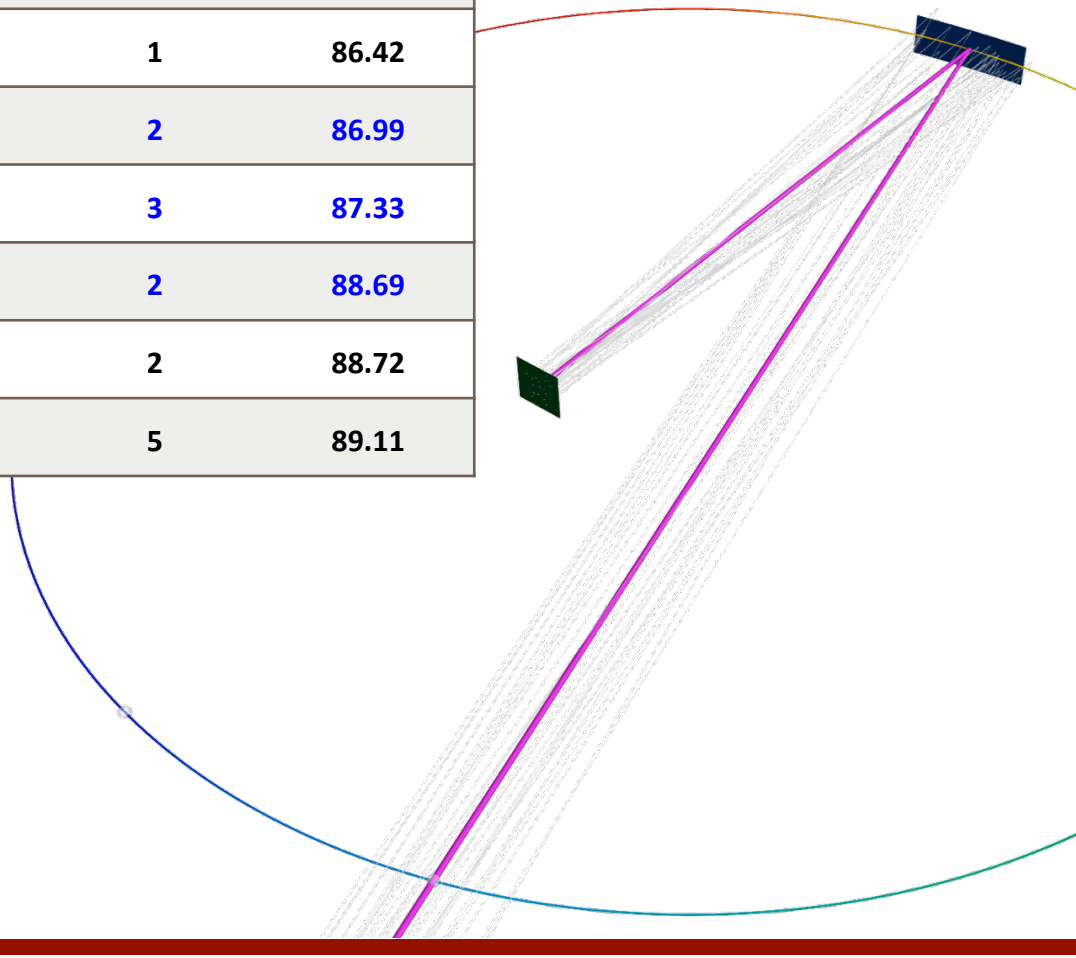
Post-search selection criteria:

- Imager:
  - $\sigma < 30\ \mu m \Rightarrow \vartheta \gtrsim 86°$
- Backlighter:
  - $\vartheta = [76°, 90°]$
  - α-Quartz: m = 1
  - no K_{β}

Crystal	Miller indices
α-Quartz	10$\underline{1}$0
	10$\underline{1}$1
	10$\underline{1}$2
	11$\underline{2}$0
	11$\underline{2}$2
	20$\underline{2}$0
	20$\underline{2}$3
	21$\underline{3}$1
	22$\underline{4}$0
	22$\underline{4}$3
	23$\underline{5}$4
	31$\underline{4}$0
	50$\underline{5}$2
Mica	002
	331
Si	111
	220
Ge	400
	111
	220
	422

Self-emission imager combinations

Line	Energy [keV]	Crystal	2d spacing [Å]	Reflection order	Bragg angle [°]
Zr He 2p $^3P_1$	16.189	Si (220)	3.8403117	5	85.65
Co K_β	7.649	α-Qz (5052)	1.624	1	86.42
Zr $K_{\alpha 2}$	15.691	α-Qz (2354)	1.5825	2	86.99
Zr $K_{\alpha 1}$	15.775	α-Qz (3140)	2.3604	3	87.33
Cu $K_{\alpha 1}$	8.048	α-Qz (2131)	3.082	2	88.69
As $K_{\alpha 2}$	10.508	α-Qz (3140)	2.3604	2	88.72
Ge $K_{\alpha 1}$	9.886	Si (111)	6.2712	5	89.11



Backlighter line & crystal combinations

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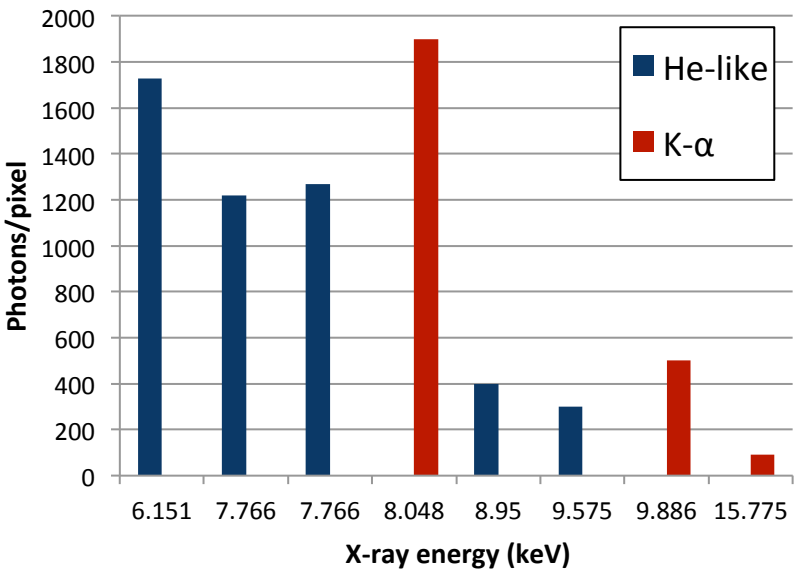
X-ray energy ↓

Line*	Energy [keV]	crystal	refl. order	Bragg angle [deg]	photons in 4π (×10^{14})‡	photons/ pixel§
Mn He$_\alpha$	6.151	Qz (2243)	1	83.19	5	1730
Ni He$_\alpha$ (y)	7.766	Ge (111)	4	77.86	2.4	1220
Ni He$_\alpha$ (y)	7.766	Qz (5052)	1	79.44	2.4	1270
Cu K$_{\alpha1}$	8.048	Si (111)	4	79.31	2	1900
Zn He$_\alpha$	8.950	Ge (400)	2	78.44	0.5	400
Ga He$_\alpha$	9.575	Ge (220)	3	76.18	0.4	300
Ge K$_{\alpha1}$	9.886	Si (220)	3	78.45	1	500
Zr K$_{\alpha1}$	15.775	Ge (220)	5	79.22	0.8	90

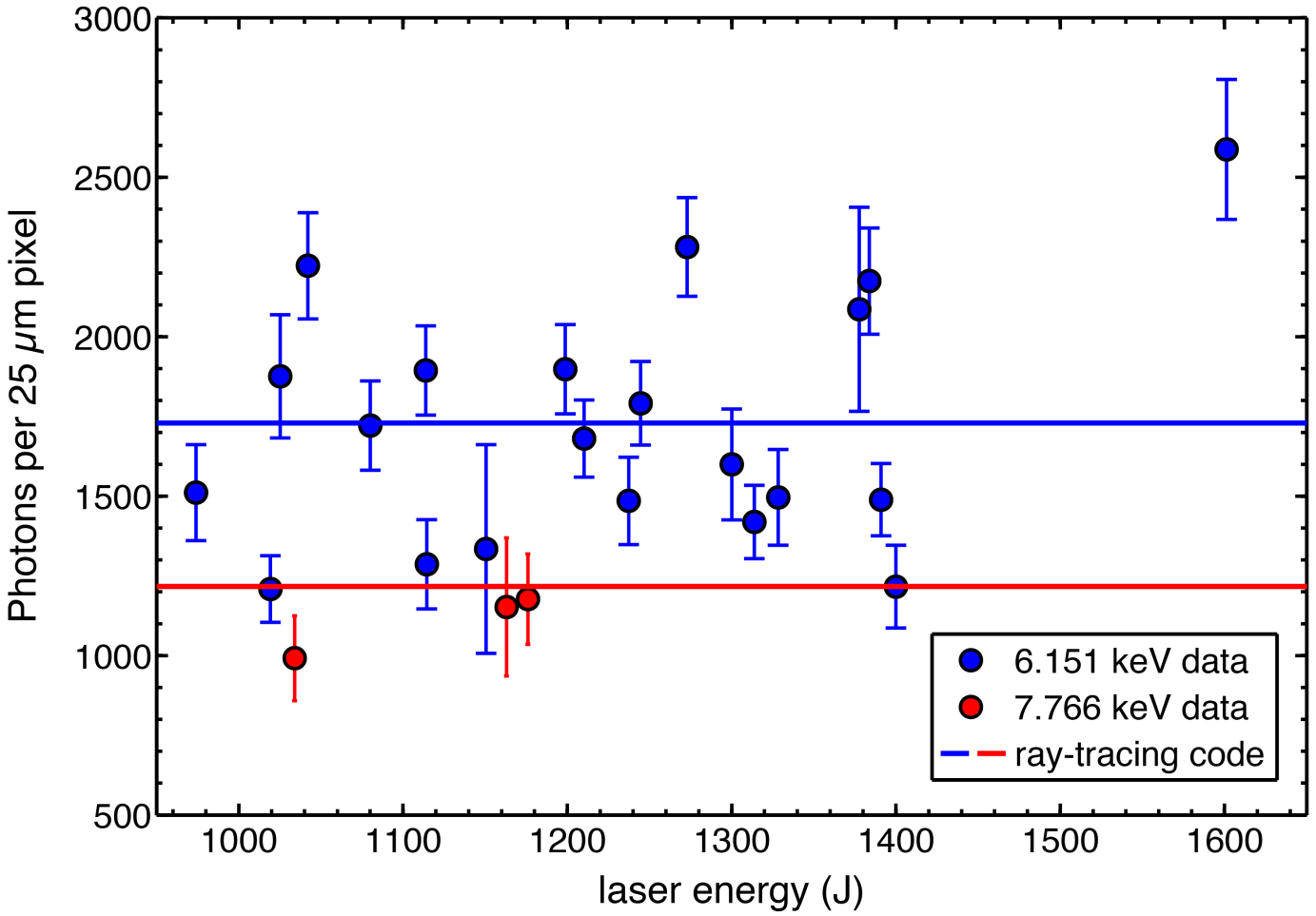


*For most cases only resonance lines and K$_{\alpha1}$ are shown, intercombination line (y) and K$_{\alpha2}$ will work as well. K$_\beta$ is generally too inefficient.

‡**Assume 1 kJ laser energy.** Conversion efficiencies taken from L. Ruggles et al., Rev. Sci. Instrum. 74, 2206 (2003), H.-S. Park et al., Phys. Plasmas 15, 072705 (2008) and own data. C.e. into individual lines determined with PrismSPECT simulations.

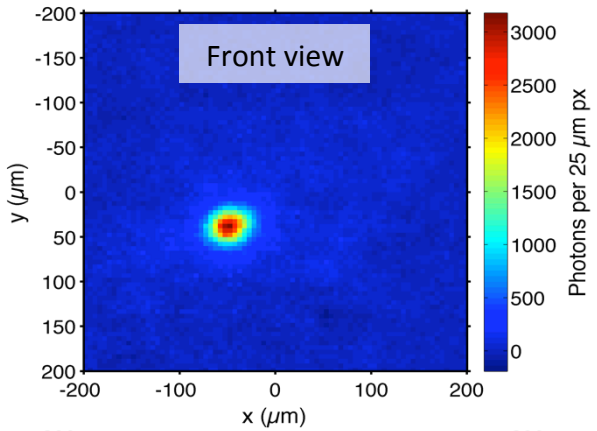
§R = 250 mm, 6x magnification, 3 eV FWHM spectral line width, 25 µm detector pixel size.

Benchmark to experiments: Brightness

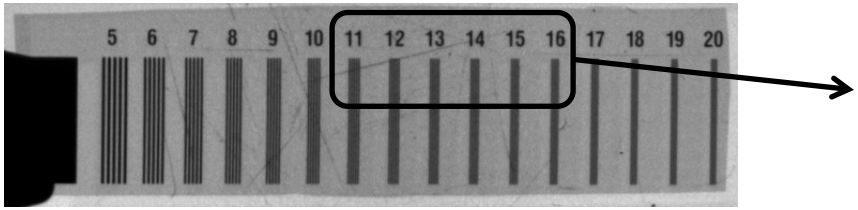


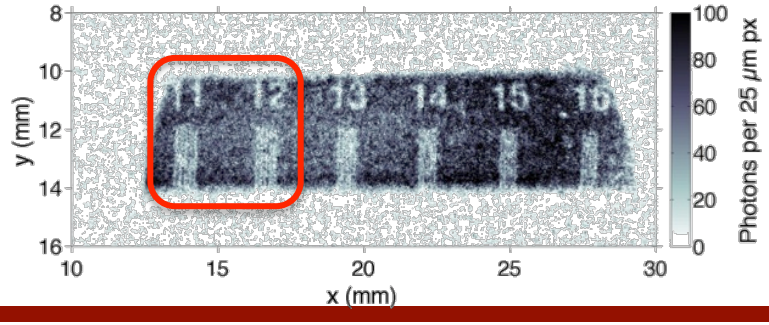
Benchmark: 15.7 keV backlighter

- Initial tests with 100 TW arm of Z-Petawatt: 70-200 J, 500 fs or 15 ps
- X-ray source: Zr $K_{\alpha 1}$: 15.775 keV
  - Total K_{α} photons: $(1.1 \pm 0.3) \times 10^{13}$
  - Zr $K_{\alpha 1}$ emission imaged with Qz 3140 crystal
- 15.7 keV, Ge 220 backlighter:
  - Reflection order: 5, $\vartheta = 79.22°$, M = 2.15
  - **Spatial resolution:**
    - **Experiment: ≈11-12 lines/mm → 80-90 µm**
    - **Ray-tracing with IP broadening: 75 µm**
    - Ray-tracing without IP broadening: 37 µm
    - Ray-tracing with optimized positions: 20 µm
  - **Image brightness:**
    - **Experiment: ≈ 60 phot./px**
    - **Ray-tracing: ≈ 80 phot./px**



Fluke Biomedical Resolution Target (#019-500)





Summary

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- Spectral line and x-ray crystal survey for backlighting and self-emission imaging
- For x-ray energies between 6 and 16 keV:
  - 7 self-emission imager combinations
  - 9 backlighter combinations
- Demonstration of 15.7 keV shortpulse backlighting
    - ≈0.6 phot./px/J at detector for M = 2
    - Brightness scales with target area
    - ≈80 µm spatial resolution (detector limited)
    - 20 µm geometrical limit
- 15.7 keV self-emission imaging
  - Use Qz 3140 instead of Qz 2354
  - 15.7 keV: strong emission at laser focus, almost nothing elsewhere
  - Good point source for imaging

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Backup Slides

6.151 vs. 7.766 keV backlighting

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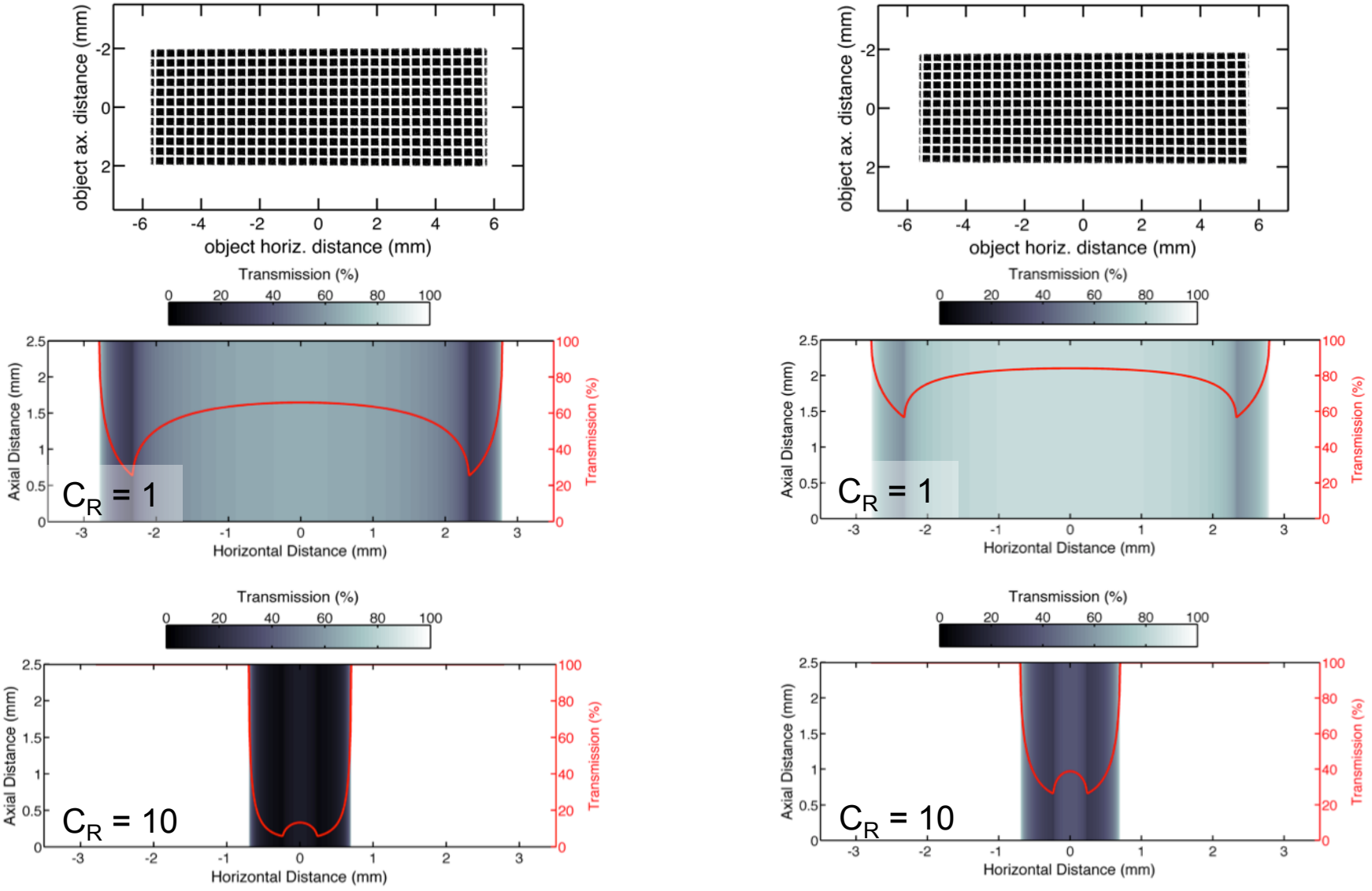
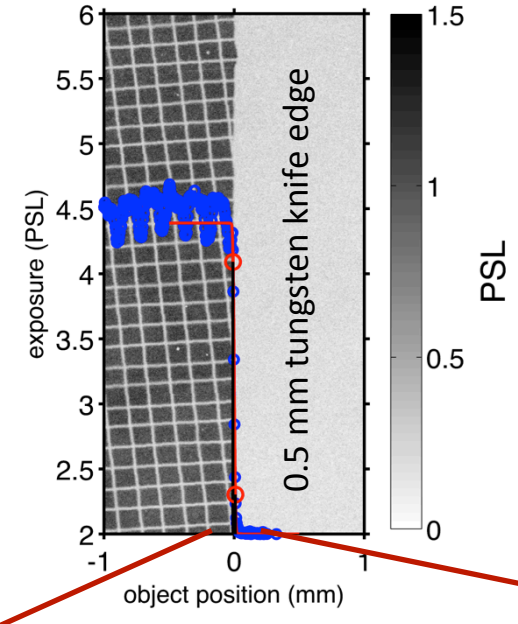
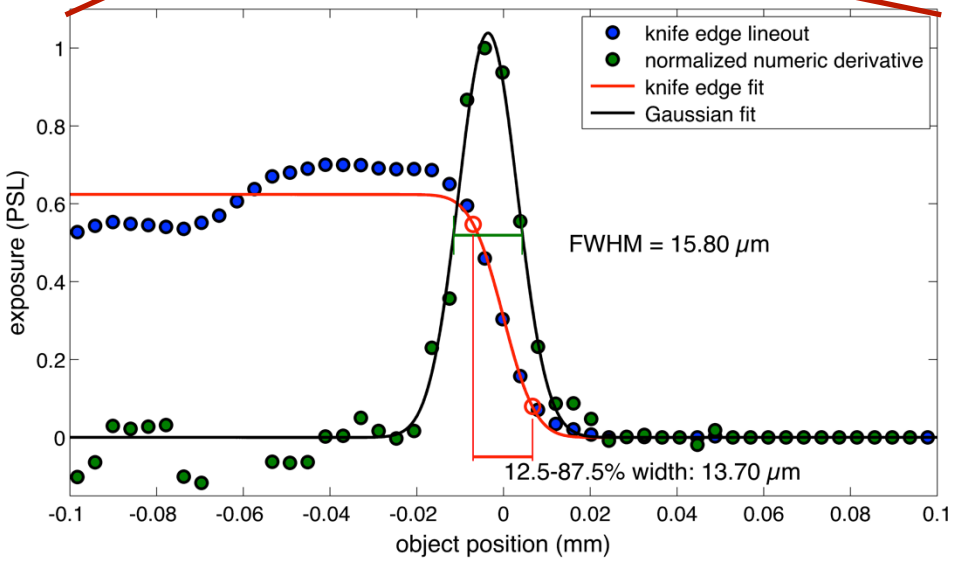


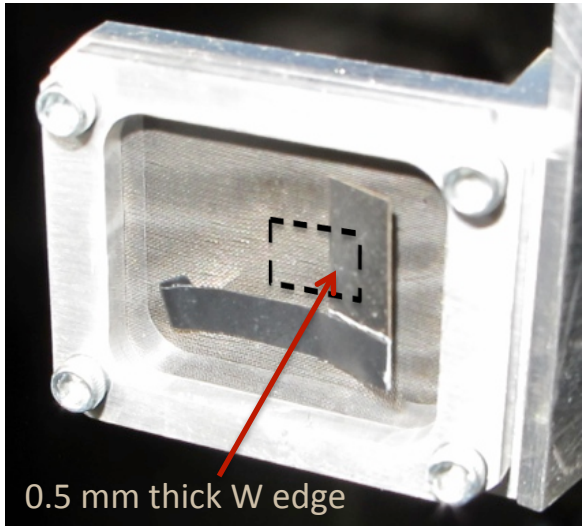
MagLIF-type Be liner

Ni backlighter: Spatial resolution



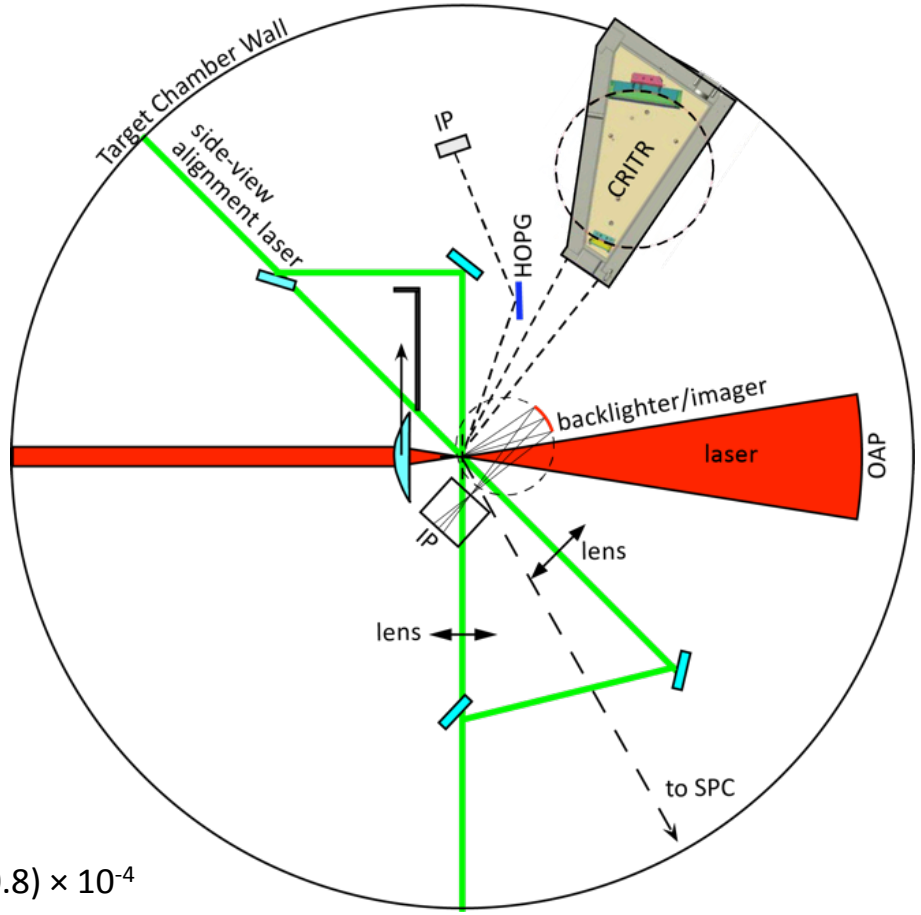


- Knife edge measurements:
  - Meridional ESF = (13.4 ± 0.4) μm
  - Sagittal ESF = (19 ± 2) μm
- Post-shot ray-tracing:
  - r = 200 μm source
  - using actual distances
  - with rocking curve
  - with IP resolution (ESF = 106 μm)
  - Meridional ESF: (12 ± 1) μm
  - Sagittal ESF: (19 ± 2) μm



Experiments with Z-Petawatt (ZPW)

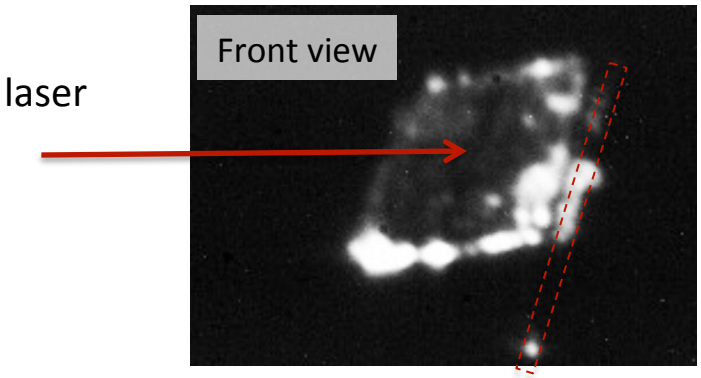
- Laser parameters:
  - 70-200 J, 500 fs or 15 ps
  - $I \approx 7 \times 10^{18}$ - 2×10^{20} W/cm^2
  - 45° *s*- or 45° *p*-polarization
- X-ray spectrometers:
  - flat HOPG: ZYA grade, 2nd order
  - CRITR: cylindr. α-Quartz 10$\underline{1}$1
  - Single Photon Counter (SPC)
- X-ray imagers:
  - 15.7 keV Ge 220 backlighter
  - 15.7 keV Quartz 3140 imager
  - 8 keV Quartz 2131 imager

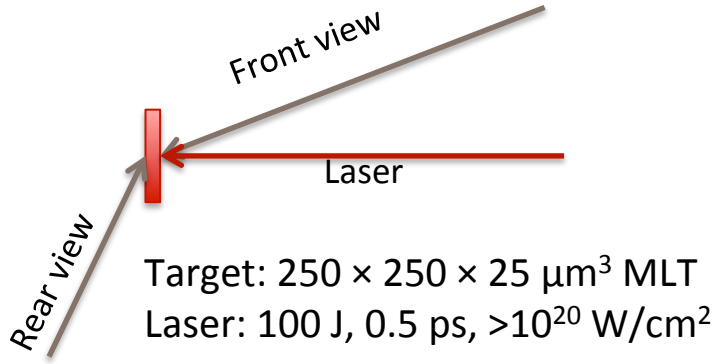


- Total number of K_α photons: $(1.1 \pm 0.3) \times 10^{13}$
- Laser-to-photon energy conversion efficiency: $(2.8 \pm 0.8) \times 10^{-4}$

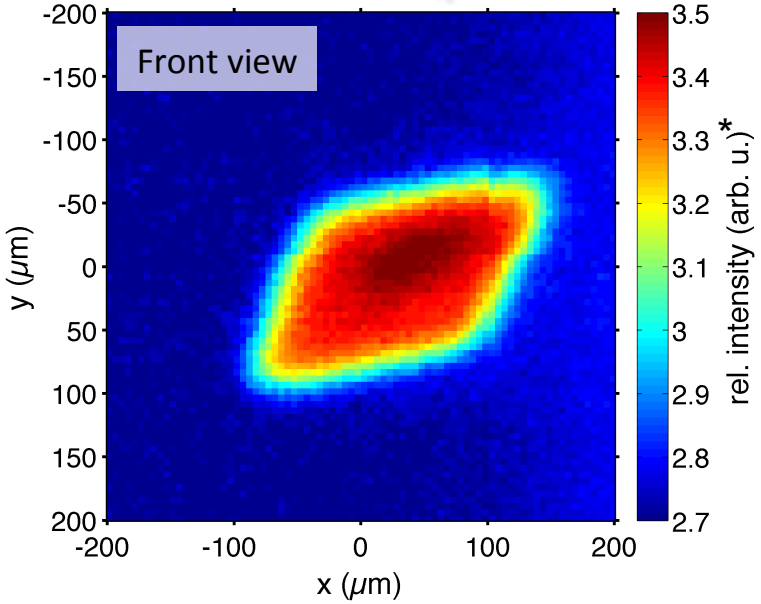
CRITR: Compact, rugged in-chamber transmission spectrometer

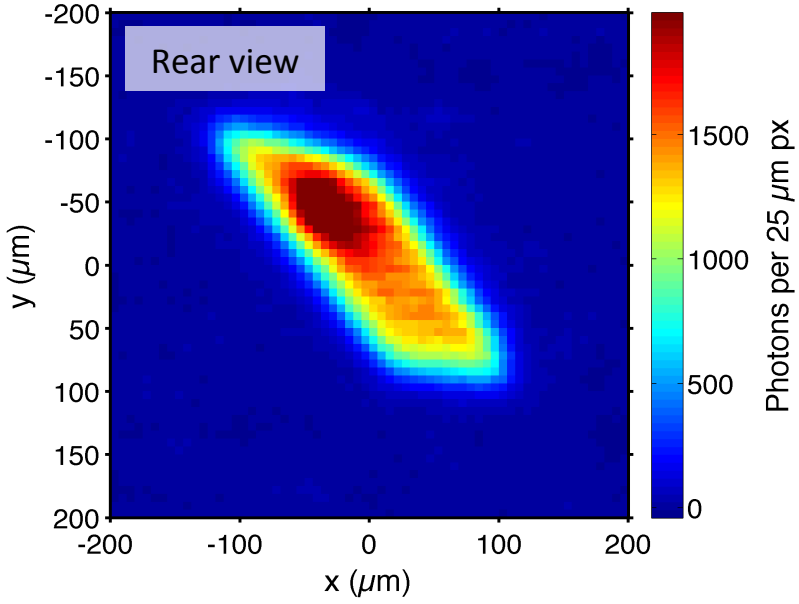
Self Emission Imaging: Copper





Target: 250 × 250 × 25 μm^3 MLT
Laser: 100 J, 0.5 ps, >10^{20} W/cm^2





*IP over-exposed on first scan

Self Emission Imaging: Zirconium

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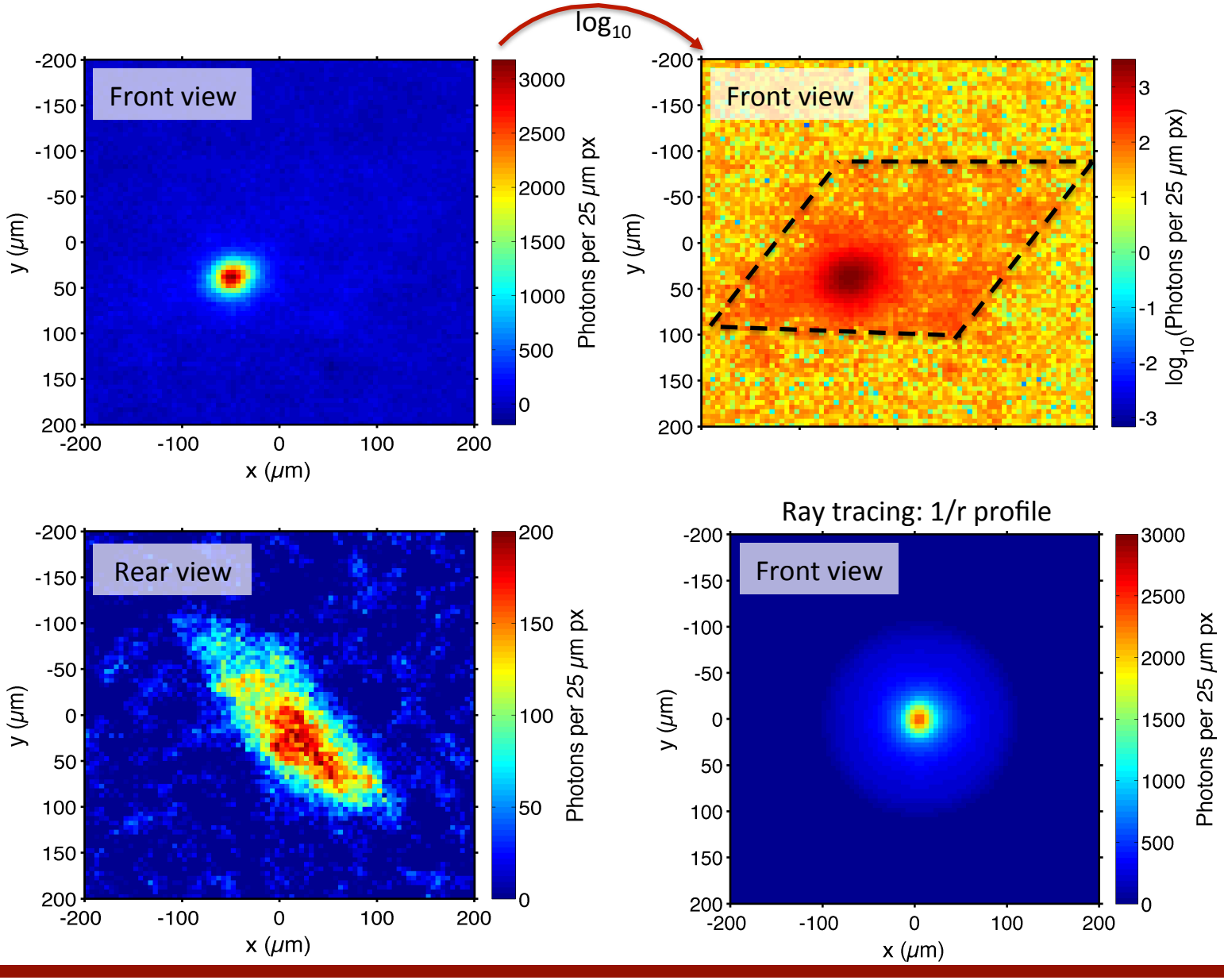
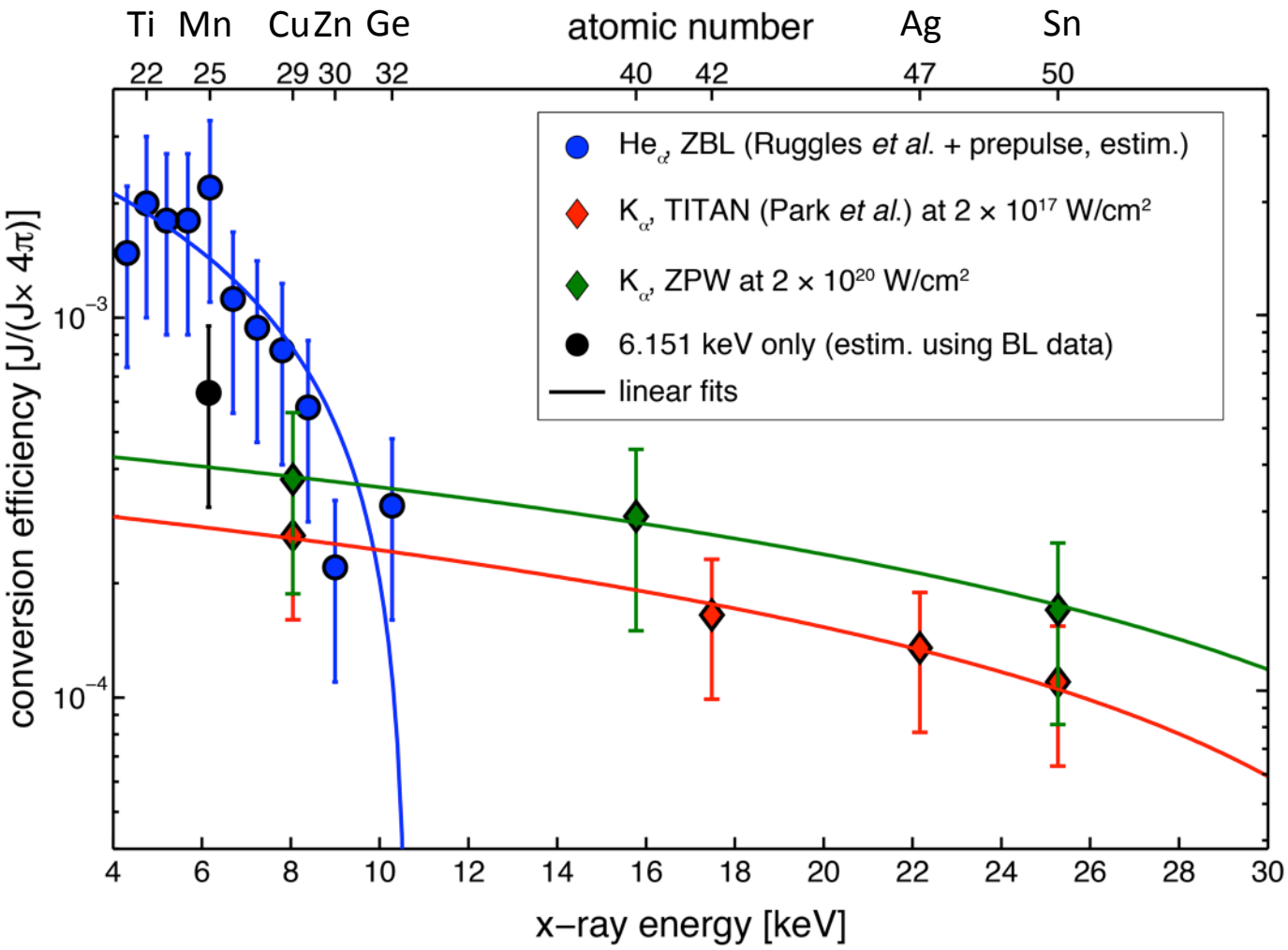


Almost no large-area K_α emission ⟶ no e^- recirculation?

Efficiency scaling with atomic number



L. Ruggles et al., Rev. Sci. Instrum. 74, 2206 (2003)
H.-S. Park et al., Phys. Plasmas 15, 072705 (2008)