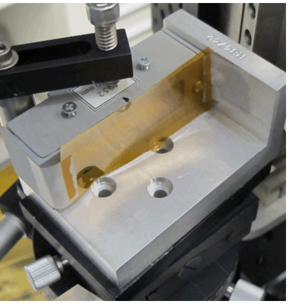
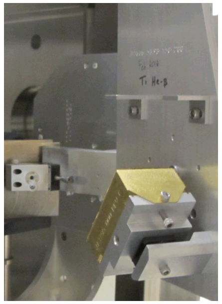
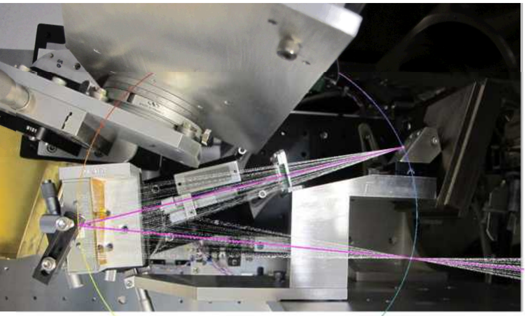
SAND2015-7881C







2-20 keV x-ray imaging and backlighting with spherical crystals

Marius Schollmeier, Guillaume P. Loisel, M. Geissel, E.C. Harding, P.K. Rambo, J. Schwarz, J.E. Shores, I.C. Smith, C.S. Speas, M. Vargas, and J.L. Porter

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Sandia National Laboratories

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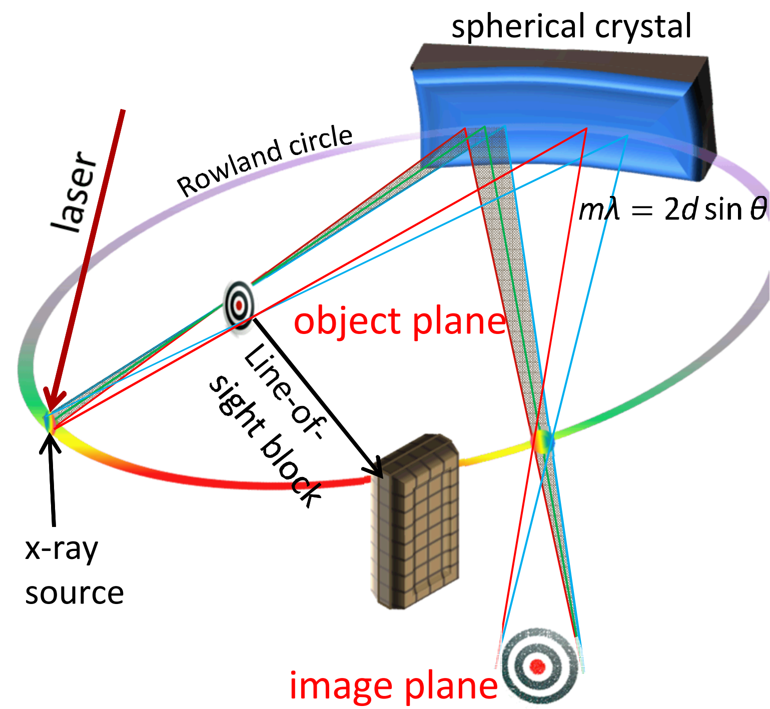
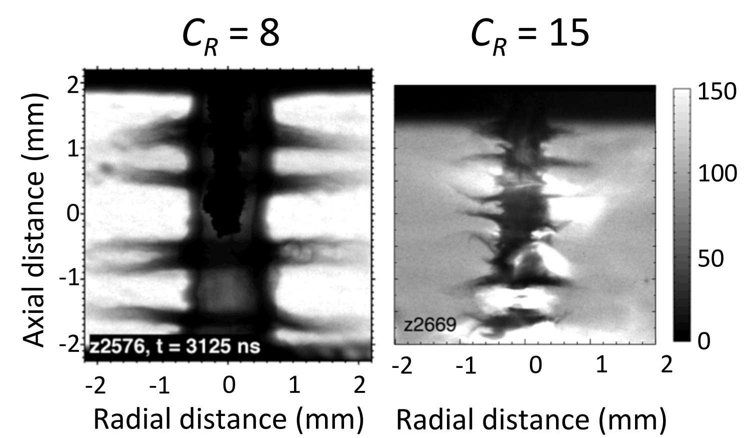
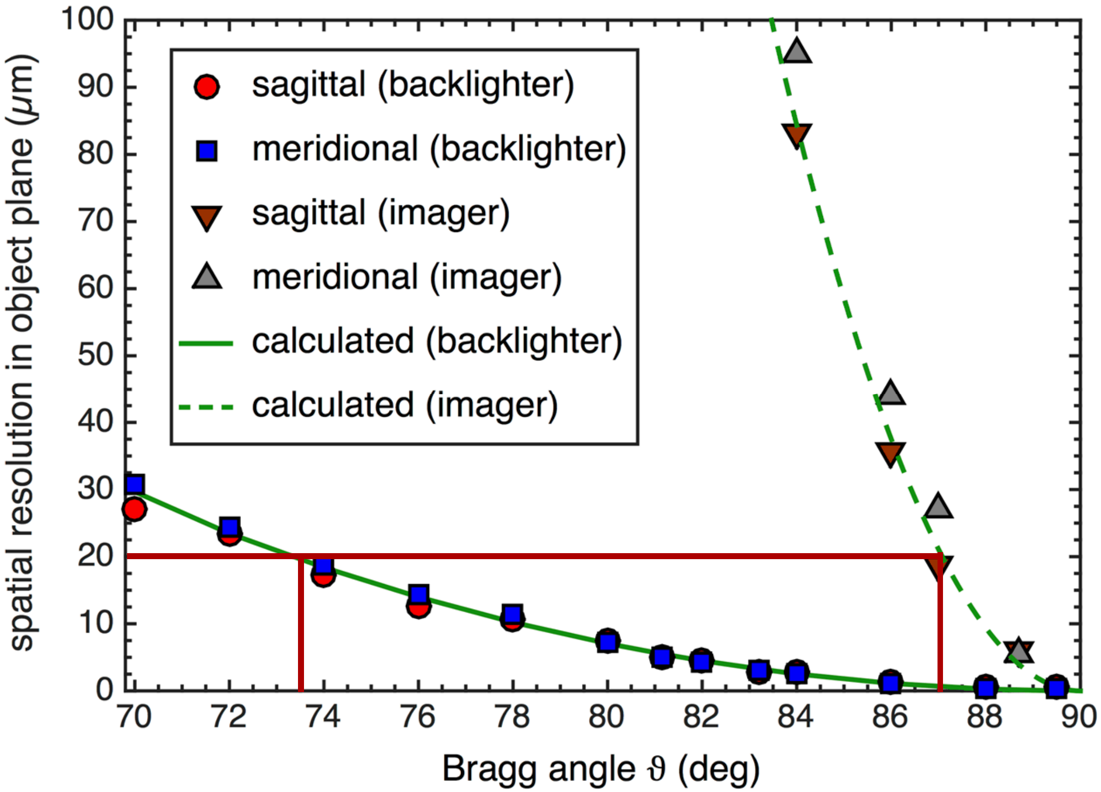
Motivation

- High C_R liner experiments at the Z Pulsed Power Facility require >6 keV backlighter x-ray energies
- Literature survey (see e.g. [1]) reveals only few known working systems, such as:
  - Si Heα (1.865 keV) and Quartz ($10\underline{1}1$)
  - Mn Heα (6.151 keV) and Quartz ($22\underline{4}3$)
  - Cu Kα (8.048 keV) and Quartz ($21\underline{3}1$)
  - Ti Kα (4.511 keV) and Quartz ($20\underline{2}3$)
  - Zr Kα (15.775 keV) and Quartz ($23\underline{5}4$)
  - Is that all??
- Earlier work by Jeffrey A. Koch (1998):
  - systematic study using selected Quartz, LiF, Si, Ge cuts and a few “exotic” crystals
  - no attempt was made to rank the crystals in terms of suitability for imaging [3]
- What limits use of spherical crystal imagers?
- How to find all possible combinations and rank them?





Bragg angle limits the spatial resolution



Spatial resolution scales as:

$$\sigma = \sqrt{2}\, L_s \left(\frac{M+1}{M}\right)(1 - \sin\vartheta_B) \quad [1]$$

Backlighter:

- Magnification M = 6
- Crystal: R = 250 mm
- r = 100 μm source
- $L_s \approx 0.29$ mm

$\Longrightarrow \quad \sigma < 20$ μm for $\vartheta_B \gtrsim 75°$

Imager:

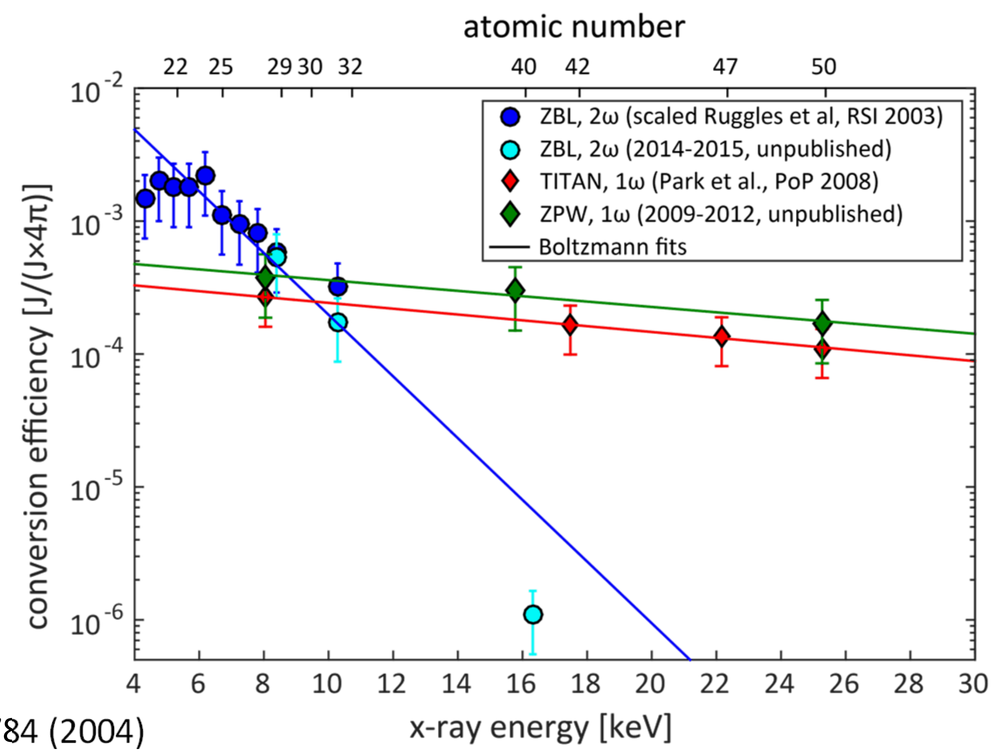
- M = 10
- Crystal: R = 250 mm, 10 × 10 mm
- $L_s = 10$ mm

$\Longrightarrow \quad \sigma < 20$ μm for $\vartheta_B \gtrsim 87°$

[1] M.S. Schollmeier, Applied Optics 54, 5147 (2015)

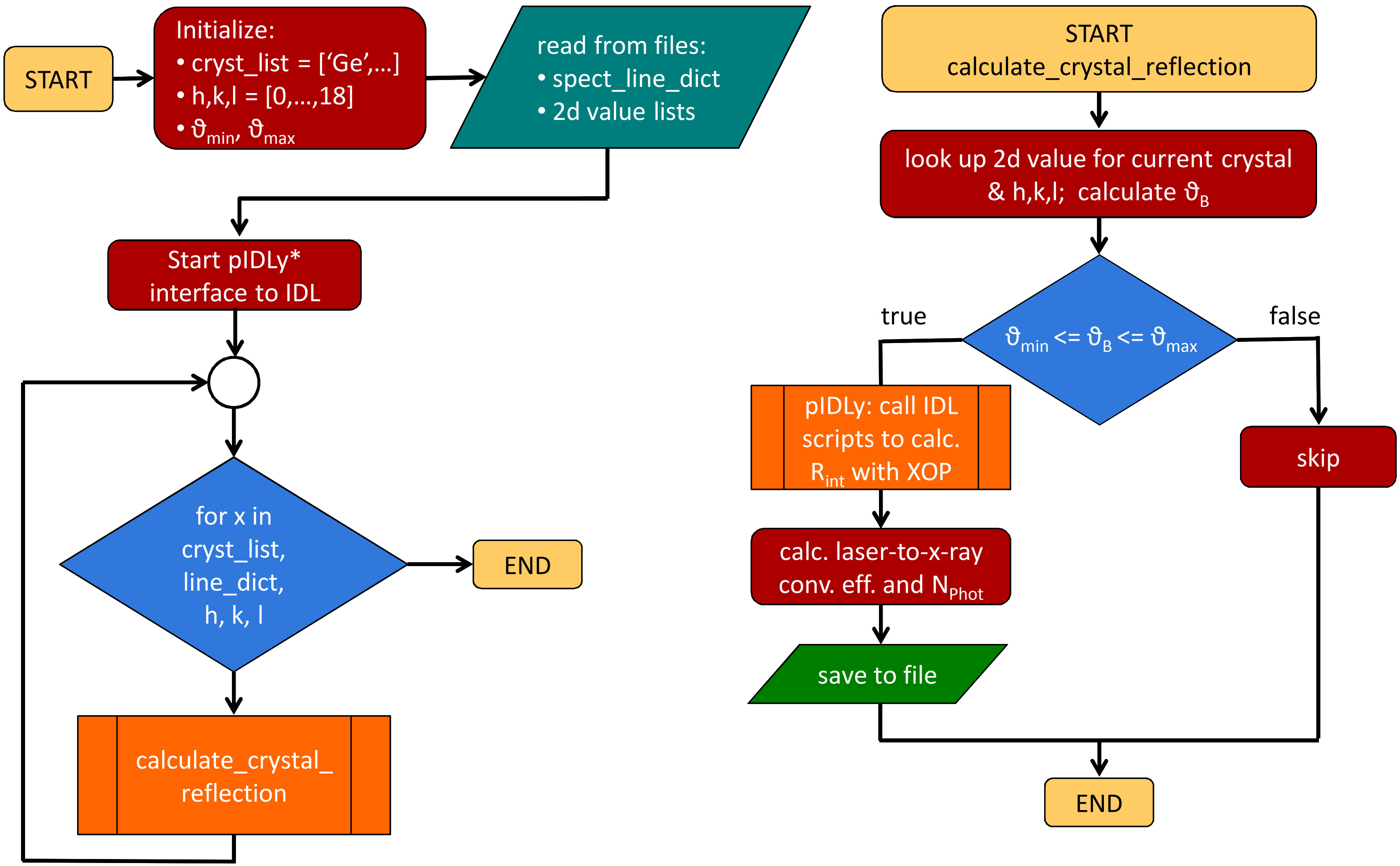
Source efficiency and crystal reflectivity limit the image brightness

- Image brightness $I_d = \eta \dfrac{N_{\mathrm{phot}}\Omega}{4\pi A_{\mathrm{obj}} M^2}$ [1]
- Reflection efficiency η depends on rocking curve, spectral linewidth and source size:
  - use XOP [2] to calculate rocking curve
  - use linewidth and source size from experiments
- Source yield N_{phot} depends on laser-to-x-ray energy conversion:
  - Measure conversion efficiency
  - Fit Boltzmann distributions to measured data:
    $$N_{\mathrm{phot}} = P_1 \times \exp(-E/P_2)$$
  - Use those fits to interpolate N_{phot} in estimates for I_d



[1] M.S. Schollmeier, Applied Optics 54, 5147 (2015)
[2] M. Sanchez del Rio and R.J. Dejus, AIP Conf. Proc. 705, 784 (2004)

Use Python & XOP to perform systematic search for spectral line/crystal combinations



pIDLy: https://github.com/anthonyjsmith/pIDLy XOP: M. Sanchez del Rio and R.J. Dejus, AIP Conf. Proc. 705, 784 (2004)

Search code input parameters

Description	Quantity
Elements	Si – Ag, without P, S, Tc, Ru, Rh
Spectral lines	He-like resonance and intercombination, $K_{\alpha 1}$, $K_{\alpha 2}$
Energy range (*E*)	1.74 – 22.85 eV
Crystals	α-Quartz, Ge, Si, Mica, GaAs, InAs
Miller index ranges (*h, k, l*)	0 – 18 each
Possible combinations tested	4,609,248
Script execution time on 3 GHz CPU	22.5 h
Total number of matches w/ R_{int} > 0	**18,484**

General trend: More matches found for higher x-ray energies (deeper penetration), e.g., 2 for Si at 3 keV vs. 500 for Ag at 22 keV

Down-selection process:

- **Find highest reflectivity crystal for each element/ x-ray energy**
- **Calculate N_{phot} for Sandia's Z-Beamlet laser parameters; spatial resolution due to astigmatism**
- **Sort by x-ray energy and N_{phot}; then by Bragg angle/astigmatism for equal efficiencies**

Results: Backlighting with He$_\alpha$ lines, $\vartheta_B = 75^\circ - 90^\circ$

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useful range (Z = 14–29)

efficiency too low (Z = 30–47)

Z	element	energy [kev]	crystal	hkl	reflection order	ϑ_B [deg]	R_{int} [µrad]	Photons per µm²	Astigmatism [µm]
14	Si	1.865	Quartz	(0 1 $\underline{1}$ 1)	1	83.86	421	203	5
14	Si	1.865	Quartz	(1 0 $\underline{1}$ 1)	1	83.86	185	90	5
17	Cl	2.790	Quartz	(1 1 $\underline{2}$ 1)	1	83.53	65	14	6
18	Ar	3.124	Ge	(2 2 0)†	1	82.80	843	206	7
20	Ca	3.883	Si	(3 1 1)†	1	77.16	82	21	24
21	Sc	4.295	Quartz	(1 1 $\underline{2}$ 3)	1	83.48	53	5	6
22	Ti	4.727	Si	(2 0 0)†	2	75.01	77	12	33
24	Cr	5.655	Si	(4 2 2)†	1	81.46	142	6	10
25	Mn	6.151	Quartz	(2 2 $\underline{4}$ 3)	1	83.27	86	2	6
25	Mn	6.151	InAs	(1 3 5)*	1	81.05	88	3	11
26	Fe	6.668	Si	(2 2 0)†	2	75.56	74	3	31
27	Co	7.242	Si	(6 2 0)*	1	85.49	257	1	3
28	Ni	7.766	Quartz	(5 0 $\underline{5}$ 2)	1	79.57	91	1	16
29	Cu	8.347	GaAs	(6 4 2)*	1	79.43	100	1	16
30	Zn	8.999	GaAs	(7 3 3)†	1	85.83	144	0	2
31	Ga	9.575	GaAs	(7 5 1)*	1	82.63	66	0	8
32	Ge	10.280	Si	(8 4 0)*	1	83.31	62	0	6
33	As	10.889	Ge	(4 2 2)†	2	80.40	39	0	13
34	Se	11.652	InAs	(2 2 0)†	4	85.73	87	0	3
35	Br	12.372	InAs	(4 4 2)†	2	84.98	38	0	4
36	Kr	13.026	InAs	(6 2 0)*	2	85.81	43	0	2
37	Rb	13.880	Ge	(6 2 0)*	2	86.97	29	0	1
38	Sr	14.562	InAs	(2 2 0)†	5	85.89	36	0	2
39	Yt	15.482	InAs	(6 4 2)*	2	83.15	19	0	7
40	Zr	16.318	InAs	(13 9 1)*	1	85.67	17	0	3
41	Nb	17.036	InAs	(8 2 0)*	2	83.86	17	0	5
42	Mo	18.062	InAs	(6 6 2) †	2	82.49	12	0	8
46	Pd	21.622	InAs	(18 10 4)*	1	85.11	10	0	3
47	Ag	22.609	Ge	(18 10 0)*	1	86.36	10	0	2

red = known in literature

† = also any other cyclic permutation of h,k,l

*** = also any permutation of h,k,l**

Total matches with $R_{int} > 0$: 6,087

Results: Backlighting with cold K_α lines, ϑ_B = 75° - 90°

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useful range

efficiency too low

Z	element	energy [keV]	crystal	hkl	reflection order	ϑ_B [deg]	R_{int} [µrad]	Photons per µm²	Astigmatism [µm]
14	Si	1.740	Mica	(1 1 3)	1	82.69	8	0.4	8
17	Cl	2.622	Mica	(1 3 3)	1	83.12	78	2.2	7
18	Ar	2.958	InAs	(2 2 0)†	1	79.16	594	24.5	17
20	Ca	3.692	Ge	(3 1 1)†	1	79.88	260	7.7	15
21	Sc	4.086	Quartz	(1 2 1)	1	79.83	67	1.8	15
22	Ti	4.505	GaAs	(2 0 0)†	2	76.80	206	6.6	25
22	Ti	4.511	Quartz	(1 2 2)	1	83.96	133	1.8	5
24	Cr	5.406	GaAs	(4 2 2)†	1	83.59	275	3.1	6
24	Cr	5.406	Ge	(4 2 2)†	1	83.27	263	3.1	6
25	Mn	5.899	InAs	(2 2 0)*	2	80.04	118	1.9	14
26	Fe	6.391	GaAs	(2 2 0)	2	76.06	84	1.9	29
27	Co	6.930	Quartz	(1 2 5)	1	85.64	102	0.6	3
28	Ni	7.461	Si	(6 2 0)*	1	75.39	67	1.3	32
29	Cu	8.028	Si	(1 1 1)	4	80.11	94	1.0	14
30	Zn	8.616	Si	(6 4 2)*	1	82.51	105	0.8	8
31	Ga	9.225	InAs	(4 2 0)*	2	84.75	116	0.5	4
32	Ge	9.855	GaAs	(4 2 0)*	2	84.34	136	0.6	5
32	Ge	9.855	Ge	(4 2 0)*	2	83.98	132	0.6	5
33	As	10.508	InAs	(8 6 2)*	1	85.37	109	0.4	3
34	Se	11.222	Si	(4 2 2)†	2	85.29	59	0.2	3
35	Br	11.878	InAs	(8 8 2)†	1	83.44	20	0.1	6
36	Kr	12.649	Quartz	(1 1 0)	5	85.98	38	0.1	2
36	Kr	12.598	Si	(10 4 2)*	1	83.02	22	0.1	7
37	Rb	13.395	Si	(8 6 6)†	1	83.62	17	0.1	6
38	Sr	14.098	InAs	(12 6 2)*	1	81.19	18	0.1	11
49	Yt	14.883	InAs	(6 4 0)*	2	84.41	26	0.1	4
40	Zr	15.691	Ge	(2 2 0)†	5	80.97	8	0.0	12
41	Nb	16.521	InAs	(2 0 0)†	8	84.07	19	0.0	5
42	Mo	17.479	InAs	(2 2 0)†	6	85.67	22	0.0	3
46	Pd	21.177	InAs	(8 6 2)*	2	81.56	6	0.0	10
47	Ag	21.990	InAs	(14 14 8)†	1	85.81	11	0.0	2

Total matches with R_{int} > 0: 6,225

Results: Self-emission imagers, $\vartheta_B = 87^\circ - 90^\circ$

$K_{\alpha1,2}$ combinations

Z	element	energy [keV]	crystal	hkl	reflection order	R_{int} [µrad]
20	Ca	3.688	Mica	(2 4 1)	1	26
21	Sc	4.086	Mica	(1 0 5)	2	698
22	Ti	4.511	Quartz	(2 0 $\underline{2}$ 3)	1	881
23	V	4.952	Mica	(1 1 15)	1	2
24	Cr	5.406	Mica	(0 4 15)	1	9
25	Mn	5.888	Mica	(1 3 17)	1	174
26	Fe	6.404	Mica	(1 9 3)	1	210
27	Co	6.915	Quartz	(1 2 $\underline{3}$ 5)	1	206
28	Ni	7.478	Quartz	(0 1 $\underline{1}$ 3)	2	451
29	Cu	8.048	Quartz	(1 2 $\underline{3}$ 1)	2	189
29	Cu	8.048	Quartz	(2 1 $\underline{3}$ 1)	2	38
30	Zn	8.616	Quartz	(0 5 4)	1	214
31	Ga	9.225	Mica	(1 6 5)	2	116
32	Ge	9.886	Si	(1 5 7)*	1	447
33	As	10.508	Quartz	(1 3 $\underline{4}$ 0)	2	23
34	Se	11.222	Mica	(3 15 7)	1	91
35	Br	11.878	Quartz	(0 6 7)	1	28
36	Kr	12.649	Mica	(4 5 6)	2	9
37	Rb	13.336	Mica	(2 9 1)	2	16
38	Sr	14.098	Quartz	(4 7 $\underline{11}$ 1)	1	19
39	Yt	14.883	GaAs	(2 6 12)*	1	39
~~40~~	~~Zr~~	~~15.691~~	~~Quartz~~	~~(2 3 5 4)~~	~~2~~	~~8~~
40	Zr	15.775	Quartz	(3 1 $\underline{4}$ 0)	3	5
41	Nb	16.521	GaAs	(3 7 13)*	1	75
42	Mo	17.374	GaAs	(1 9 13)*	1	34
46	Pd	21.177	Si	(2 12 14)*	1	8
47	Ag	22.163	GaAs	(4 14 14)†	1	18

red = known in literature

† = also any other cyclic permutation of h,k,l

*** = also any permutation of h,k,l**

He_α combinations

Z	element	energy [keV]	crystal	hkl	reflection order	R_{int} [µrad]
14	Si	1.854	Mica	(0 1 2)	2	239
15	Cl	2.775	Quartz	(1 1 1)	1	159
21	Sc	4.316	Mica	(1 1 5)	2	60
22	Ti	4.727	Mica	(2 4 9)	1	1
23	V	5.180	Mica	(1 1 3)	3	157
24	Cr	5.682	Mica	(3 1 13)	1	10
25	Mn	6.181	Mica	(0 8 9)	1	3
26	Fe	6.668	Mica	(1 7 14)	1	140
27	Co	7.206	Mica	(1 0 4)	4	116
28	Ni	7.766	Mica	(5 7 2)	1	109
29	Cu	8.392	Mica	(3 9 13)	1	20
30	Zn	8.950	Mica	(0 12 11)	1	10
31	Ga	9.628	Quartz	(1 0 $\underline{1}$ 4)	2	88
32	Ge	10.280	Ge	(6 6 4)†	1	1084
33	As	10.889	Mica	(4 0 7)	2	30
34	Se	11.652	Si	(8 6 2)*	1	93
35	Br	12.372	Mica	(9 7 9)	1	25
36	Kr	13.114	InAs	(1 9 9)†	1	151
37	Rb	13.880	Mica	(10 6 15)	1	42
38	Sr	14.669	Quartz	(7 3 6)	1	38
39	Yt	15.482	InAs	(3 7 13)*	1	48
40	Zr	16.189	InAs	(12 10 2)*	1	48
41	Nb	17.036	InAs	(1 7 15)*	1	52
42	Mo	17.907	Ge	(5 11 11)†	1	39
46	Pd	21.622	InAs	(7 13 15)*	1	22
47	Ag	22.609	GaAs	(18 10 0)*	1	12

Total matches with R_{int} > 0: 612

Higher-energy backlighter for Be liner implosions on Z

- Design constraints:
  - 6 < E < 10 keV to ensure good contrast and good penetration
  - about 1 PSL per 25 μm pixel on Fuji TR image plate
  - existing hardware limits Bragg angles to $\vartheta_B = (83.5 \pm 1)^\circ$

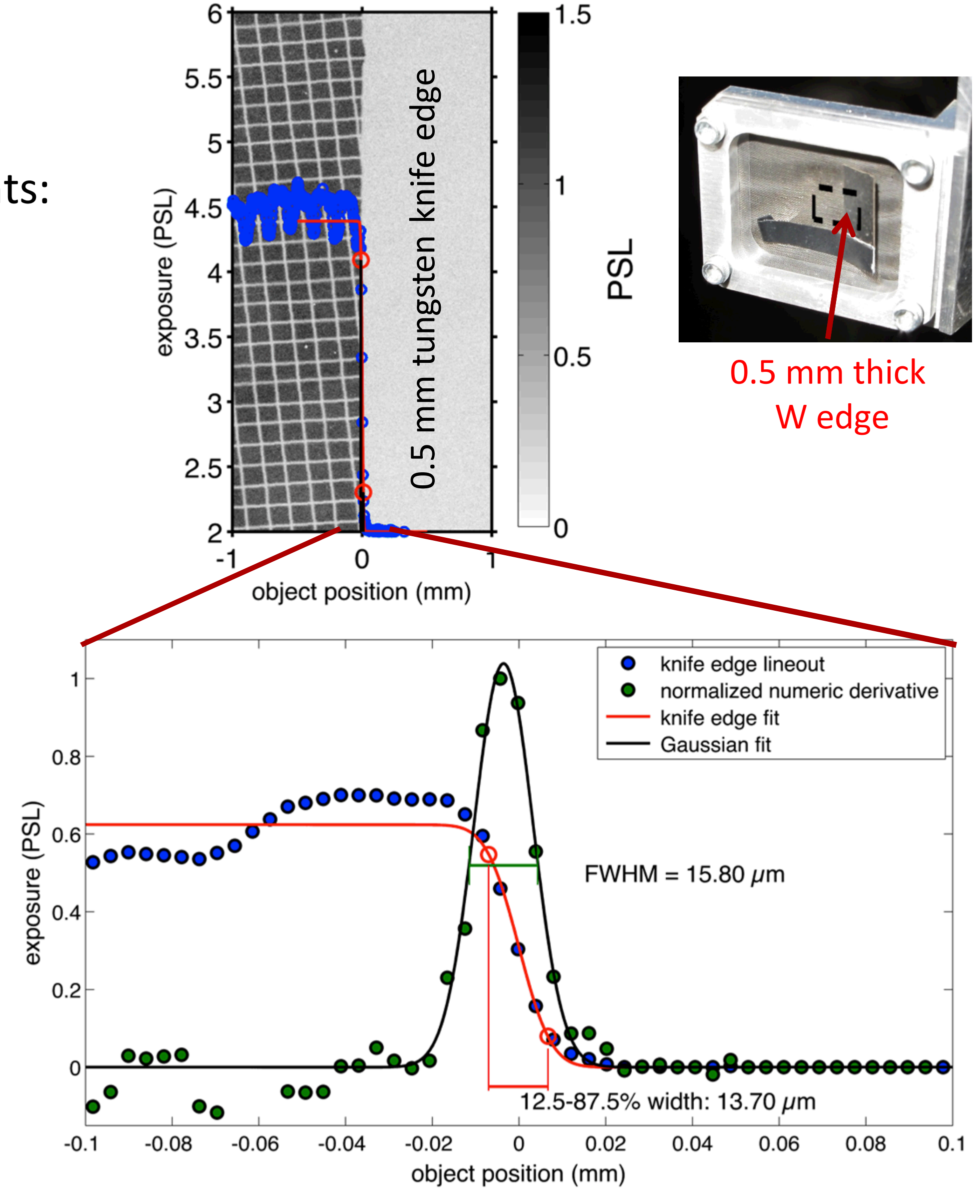
index	element	x-ray energy [eV]	crystal	Miller indices (h k l)	ϑ_B [°]	R_{int} [μrad]	PSL per 25 μm px
1	Si	1865	Quartz	(0 1 1)	83.9	421.17	143
2	**Si**	**1865**	**Quartz**	**(1 0 1)**	**83.9**	**185.40**	**63**
3	Cl	2789.8	Quartz	(1 1 1)	83.5	64.93	9.5
4	**Ar**	**3124**	**Ge**	**(2 2 0)**	**82.8**	**843.15**	**145**
5	Ca	3883	Quartz	(1 2 0)	83.1	11.25	1
6	Sc	4295	Quartz	(1 1 3)	83.5	52.98	3.2
7	**Mn**	**6151**	**Quartz**	**(2 2 3)**	**83.3**	**85.98**	**1.4**
8	**Co**	**7242**	**Ge**	**(3 3 5)**	**82.8**	**118.60**	**0.7**
9	**Ni**	**7766**	**Quartz**	**(2 4 0)**	**83.1**	**63.32**	**0.4**
10	Zn	8999	InAs	(1 5 7)	83.6	69.50	0.2
11	Zn	8950	Quartz	(2 1 7)	84.4	20.34	0.07
12	Ga	9628	Quartz	(1 6 0)	82.9	26.48	0.03
13	Ga	9575	Quartz	(4 3 3)	83.2	16.93	0.03
14	Ge	10280	Si	(8 4 0)	83.3	62.12	0.05
15	Ge	10221	Quartz	(3 0 8)	83.9	46.81	0.05

Astigmatism: 5-8 μm, w/ IP resolution: 12-14 μm

† = also any other cyclic permutation of h,k,l
*** = also any permutation of h,k,l**
red = already used combinations
blue = interesting combinations

Benchmark: Backlighting w/ He-like Ni

- Z-Beamlet: 1-4 kJ, 1-4 ns, 2ω
- 7.8 keV, Qz (50$\underline{5}$2) backlighter measurements:
  - Reflection order: 1, ϑ = 79.44°, M = 6
  - Meridional ESF = (13.4 ± 0.4) μm
  - Sagittal ESF = (19 ± 2) μm
  - Brightness: (400 ± 80) phot./px
- Calculations & ray-tracing model:
  - Using actual distances
  - With XOP rocking curve
  - Image plate: 65 μm Gaussian PSF [1]
  - Meridional ESF: (12 ± 1) μm
  - Sagittal ESF: (19 ± 2) μm
  - Brightness: (900 ± 450) phot./px



[1] T. Ao et al., JQSRT 144, 92-107 (2014)

Benchmark: Imaging and backlighting w/ Zr K_α

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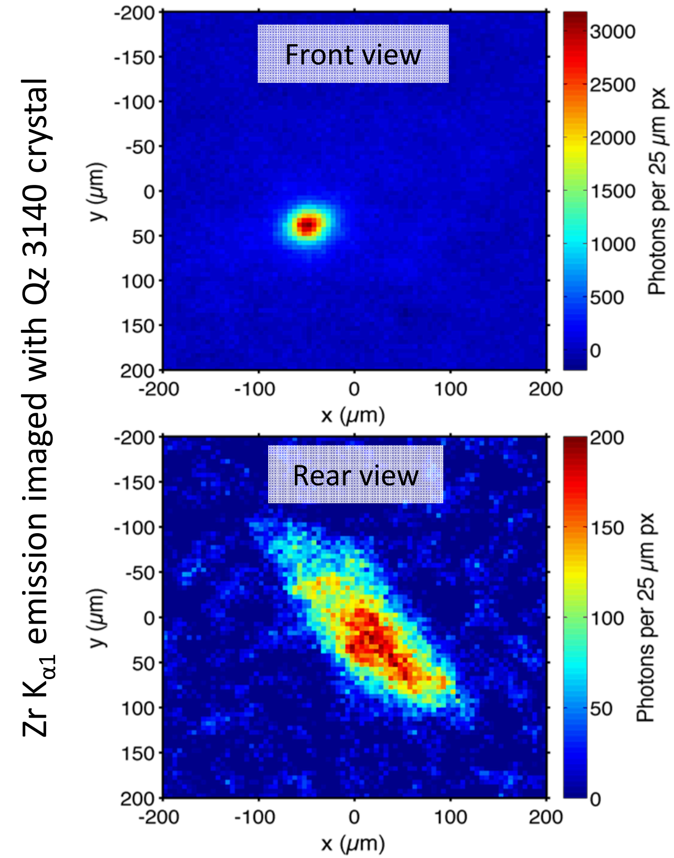
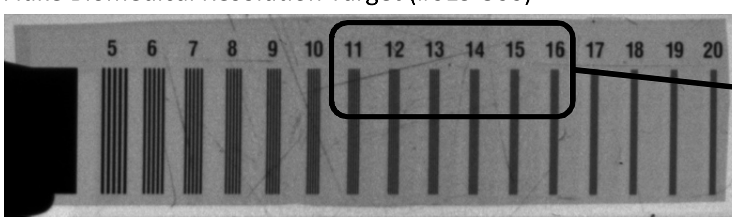
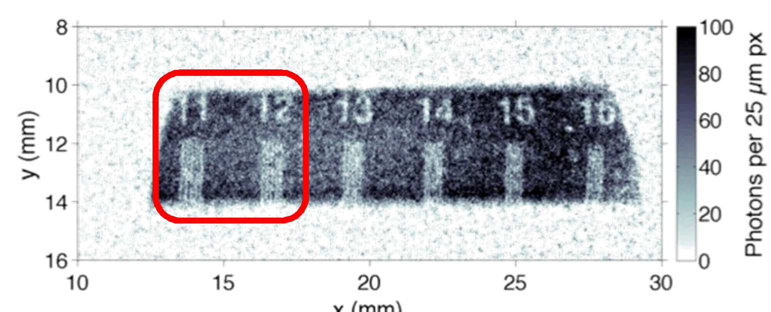
- 100 TW arm of Z-Petawatt: 70 J, 500 fs or 200 J, 15 ps
- 15.7 keV, Ge 220 backlighter measurements:
  - Reflection order: 5, ϑ = 79.22°, M = 2.15
  - Spatial resolution: ≈11-12 lines/mm ⟶ 80-90 µm
  - Image brightness: (60 ± 15) phot./px
  - Ray-tracing model with XOP rocking curve:
    - Spatial resolution with IP: 75 µm
    - Without IP: 20 µm
    - Brightness: (80 ± 20) phot./px



Fluke Biomedical Resolution Target (#019-500)





Summary

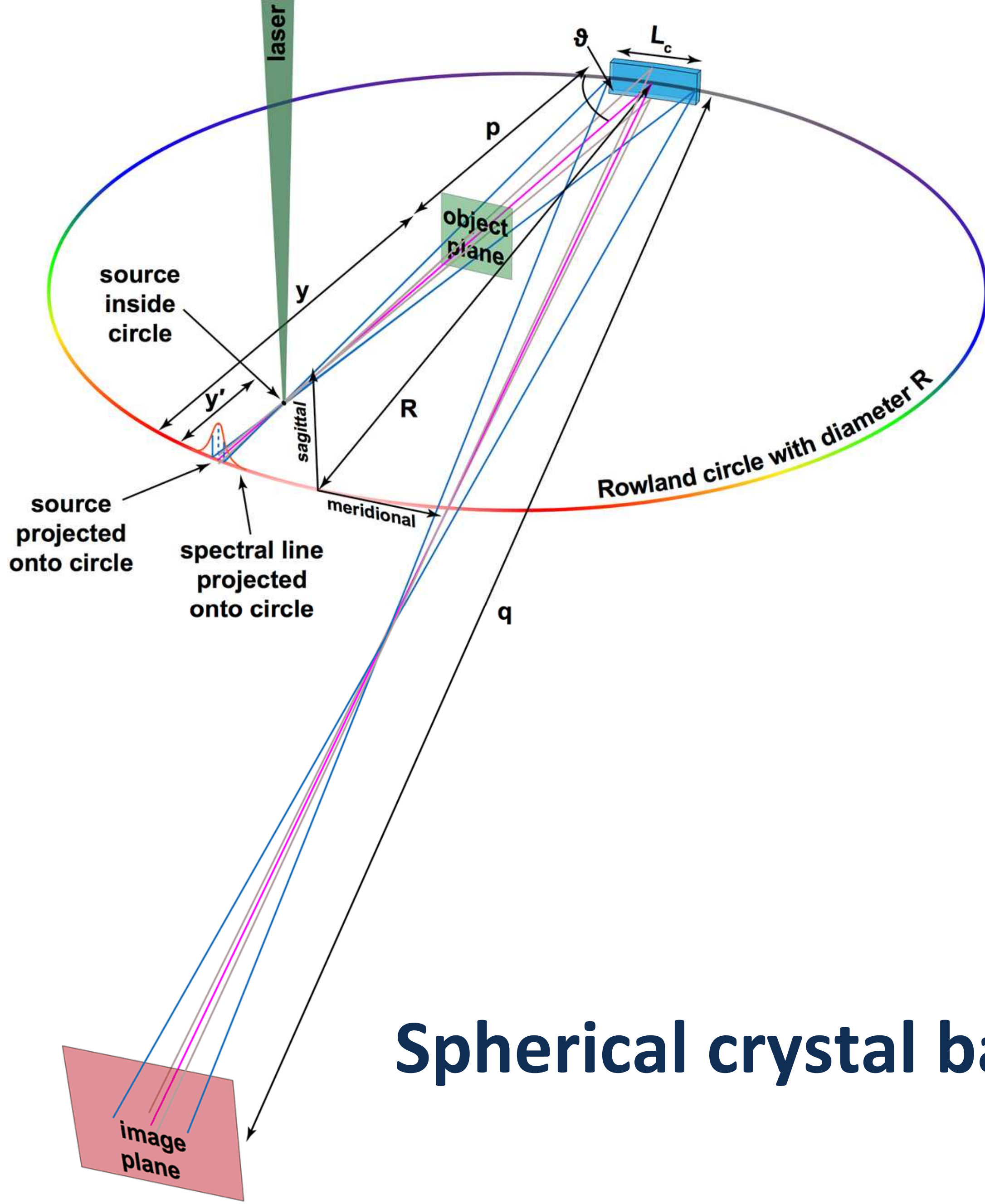
- Systematic search for spectral line and crystal combinations suitable for backlighting and self-emission imaging reveals 1000's of matches using well-known crystal substrates

- There is a match for almost all He-like and Kα spectral lines for elements between Si and Ag, at low reflection order and with sufficient reflectivity for applications
  - Self-emission imagers dominated by Quartz and Mica
  - Backlighters w/ E<10 keV dominated by Quartz and Si; E>10 keV dominated by Ge and InAs

- Python script allows to perform systematic search within narrow design constraints, e.g., to extend backlighting at Z towards higher energies

- Comparison between calculations and experiments shows agreement within a factor of 2 for image brightness; spatial resolution as calculated

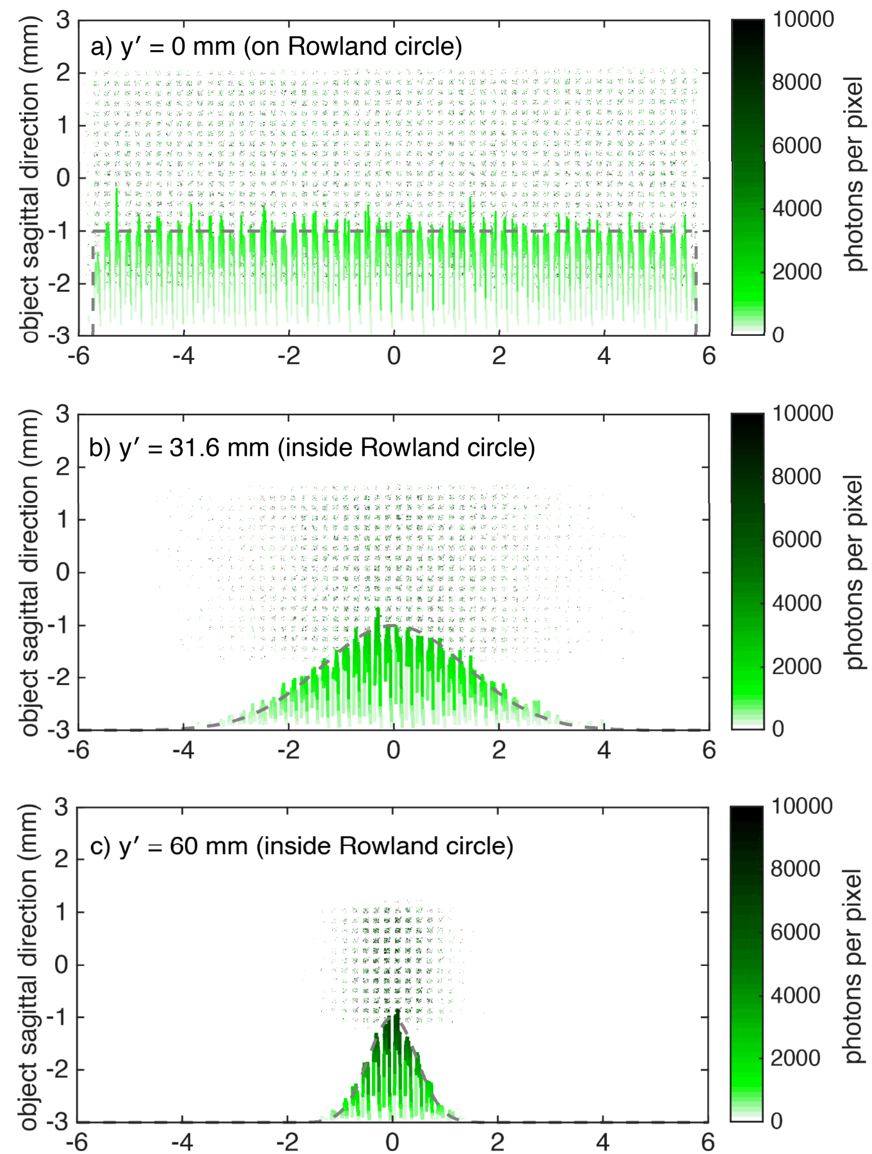
BACKUP SLIDES



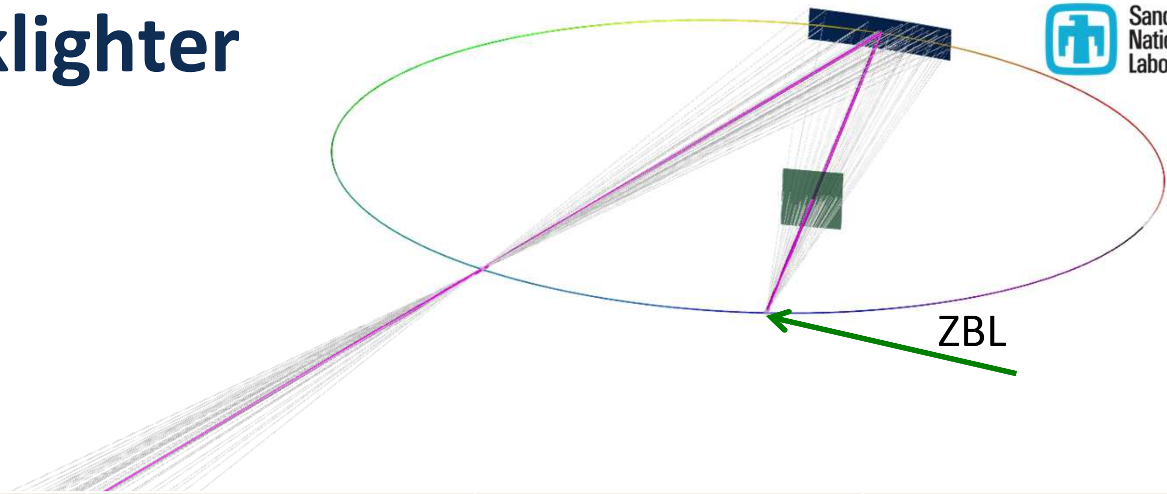
Spherical crystal backlighting

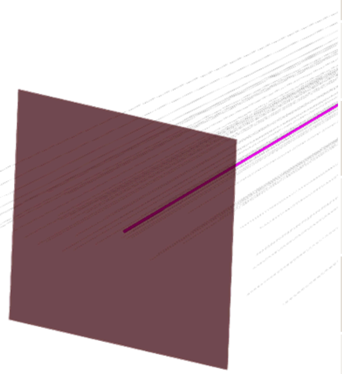
How does the field of view scale?

- FOV depends on crystal size, source position and spectral linewidth
- Image brightness 2 × higher at 31.6 mm, but FOV ≈3 × smaller
- Does not make much sense to move source much inside the Rowland circle



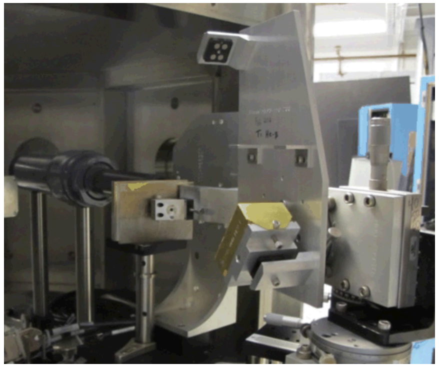
7.766 keV backlighter

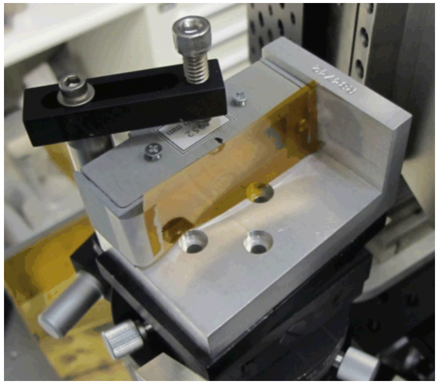


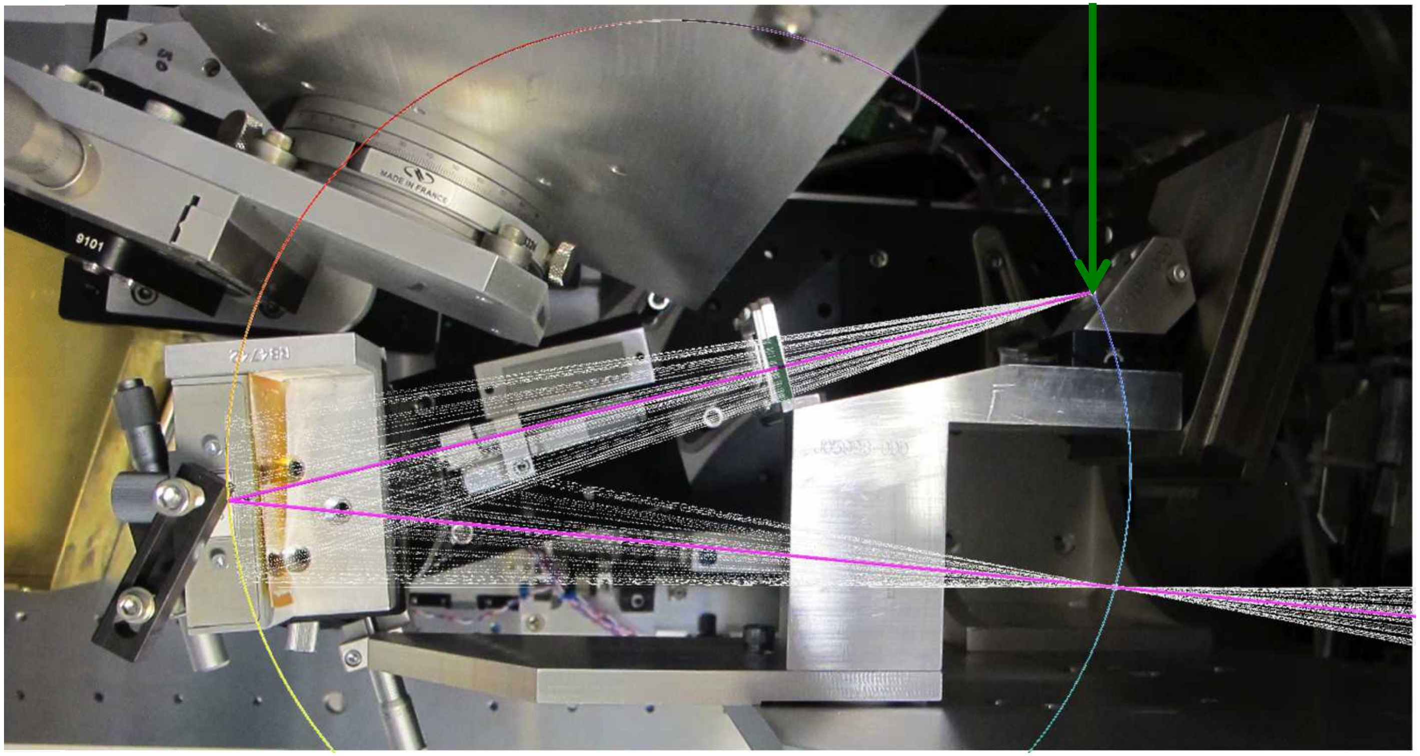


	6.151 keV	7.766 keV (I)	7.766 keV (II)
Crystal	Quartz (223)	Quartz (502)	Ge (444)
Crystal size	28 × 10 mm	28 × 10 mm	28 × 10 mm
X-ray source	Mn He y	Ni He y	Ni He y
Bragg angle	83.19°	79.44°	77.86°
Magnification	5.8	6.1 × 5.6	
Crystal-to-Object distance	146.6 mm	146.3 mm	146.3 mm
Crystal-to-Detector distance	850 mm	860 mm	860 mm

7.766 keV BL implementation

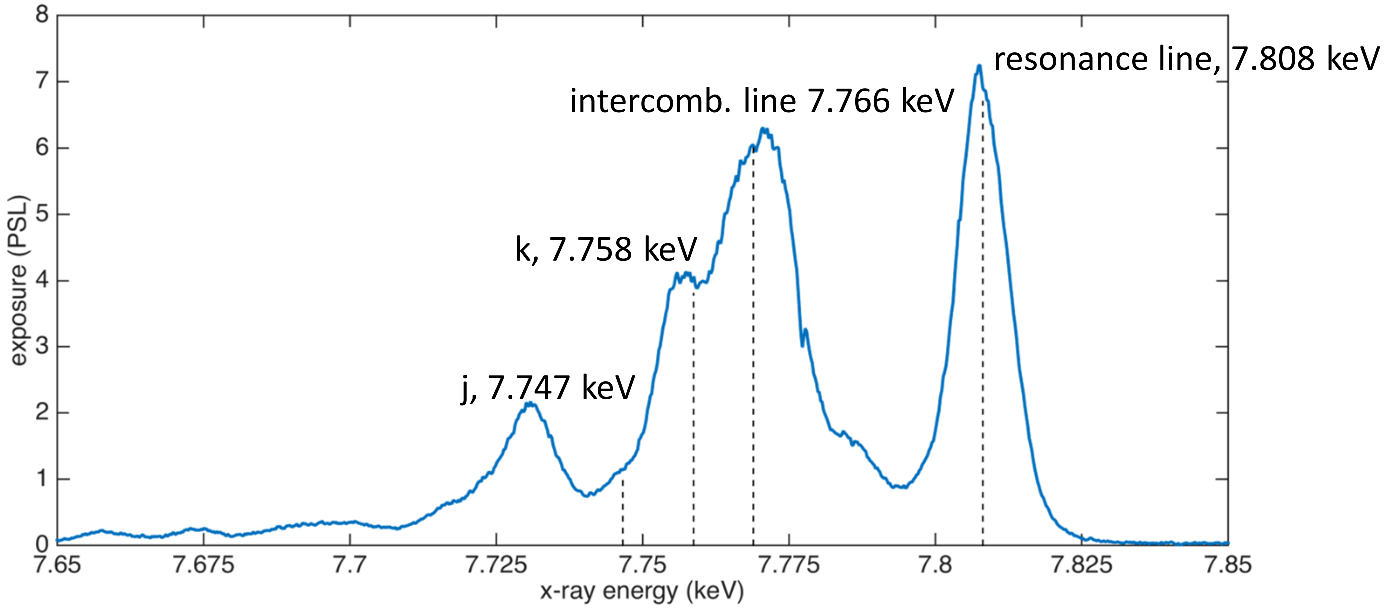


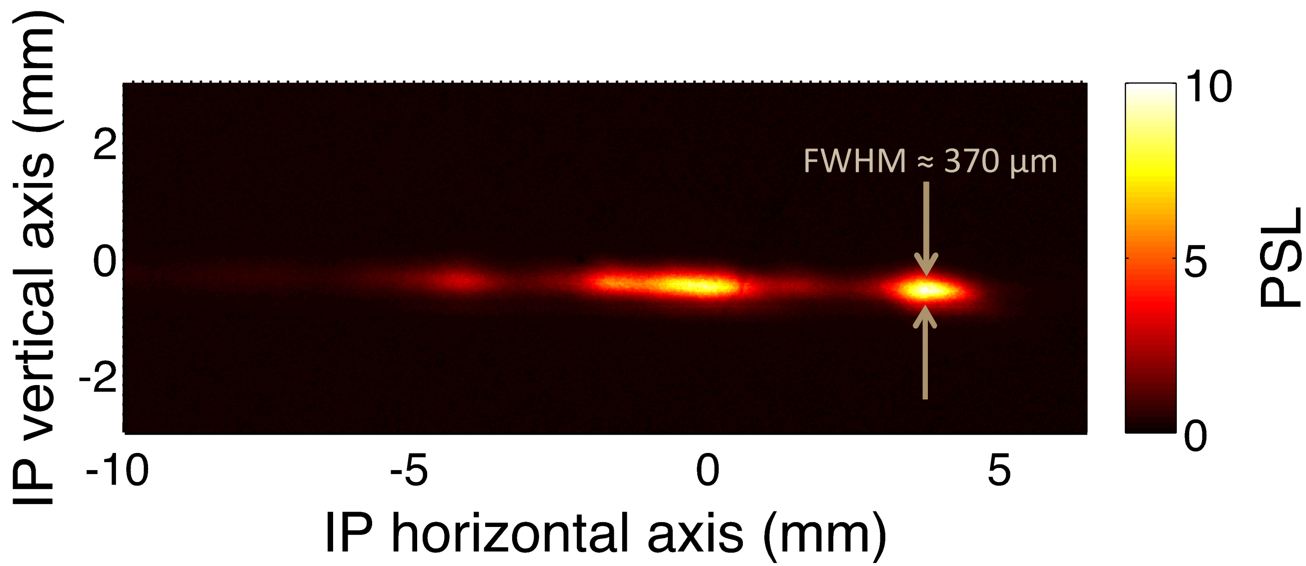




- No return aperture yet
- Crystal in perpendicular plane compared to Z

Ni source spectrum (Ge 220 crystal)





Shot B14080502, 2.5 ns delay p-p, 2 ns main, 2.485 kJ total. Spectrometer resolution: E/ΔE > 500

Image brightness

- Net image exposure: local maximum of the histogram's brightest pixels (Gaussian fit) minus average background
- Exposure error: FWHM of Gaussian