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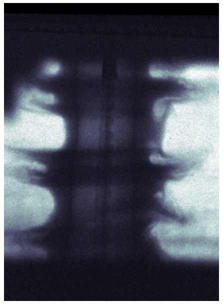

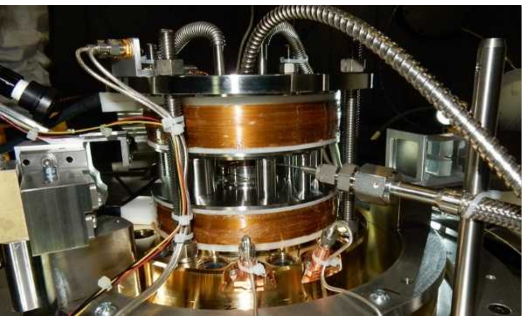

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Exceptional service in the national interest

Spherical Crystal Backlighting at Z

Marius Schollmeier, P.F. Knapp, D.F. Ampleford, G.P. Loisel, E.C. Harding, G. Robertson, J.E. Shores, I.C. Smith, C.S. Speas, J.L. Porter, R.B. McBride

Workshop on Spectral Imaging and X-ray Doppler Velocimetry of ICF Plasmas
Tuesday, August 30, 2016
Lawrence Livermore National Laboratory, CA, USA

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Current two-color, two-frame x-ray backlighting capabilites at Z

X-ray sources:

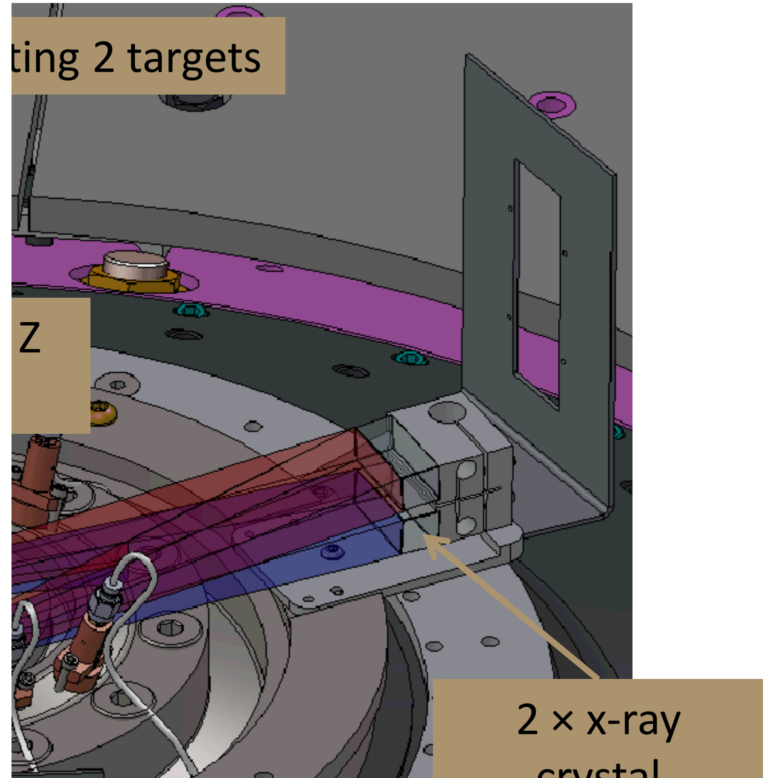
- Si He_α (1.865 keV) and/or
- Mn He_α (6.151 keV)

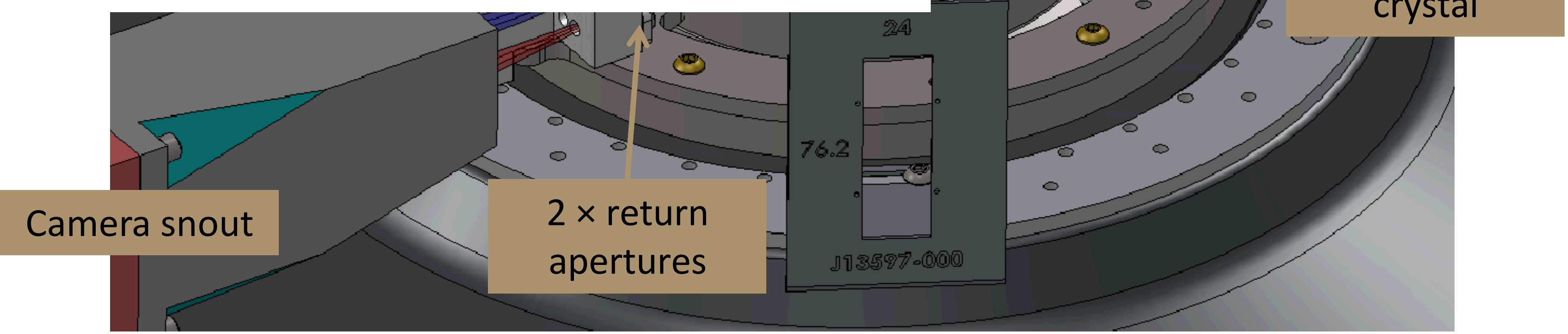
X-ray crystals:

- Qz $(10\underline{1}1)$, $\vartheta_B = 83.9°$
- Qz $(22\underline{4}3)$, $\vartheta_B = 83.19°$

Imaging parameters:

- FOV: 11.7 x 4 mm
- Magnification: 5.8
- Spatial resolution: 12 µm





Z backlighter camera housing

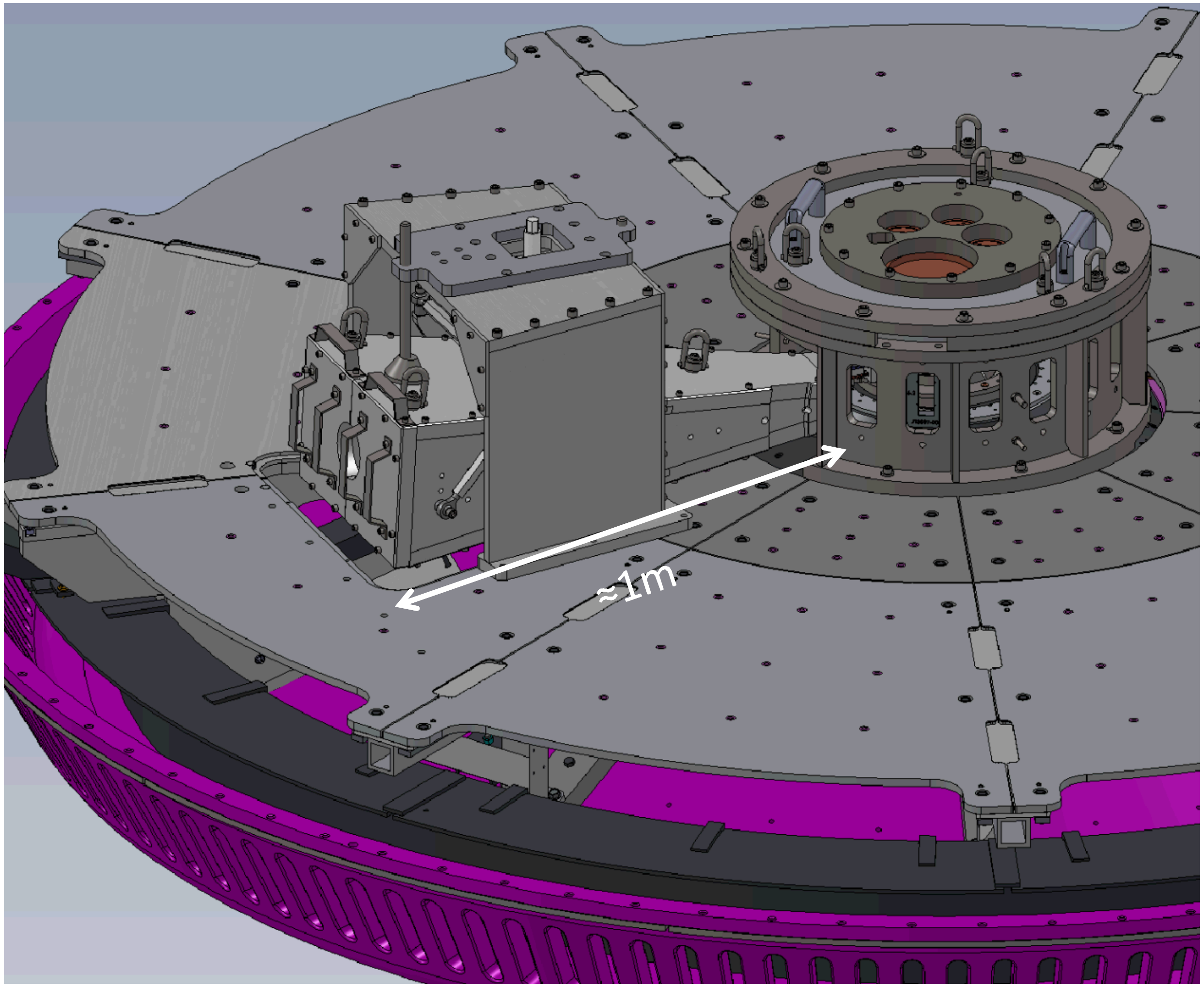
- Can accommodate 2x large-format image plates
- Allows for hCMOS sensor placement

- Detector shielding: 2.54 cm tungsten everywhere

- Weight: 400 kg, Costs: ≈$250k just in materials

- Position fixed due to cut-out in base plate and interference with other diagnostics

- Limits Bragg angles to $\vartheta_B = (83.5 \pm 1)°$



The majority of backlighting shots are for Magnetized Liner Inertial Fusion (MagLIF)*

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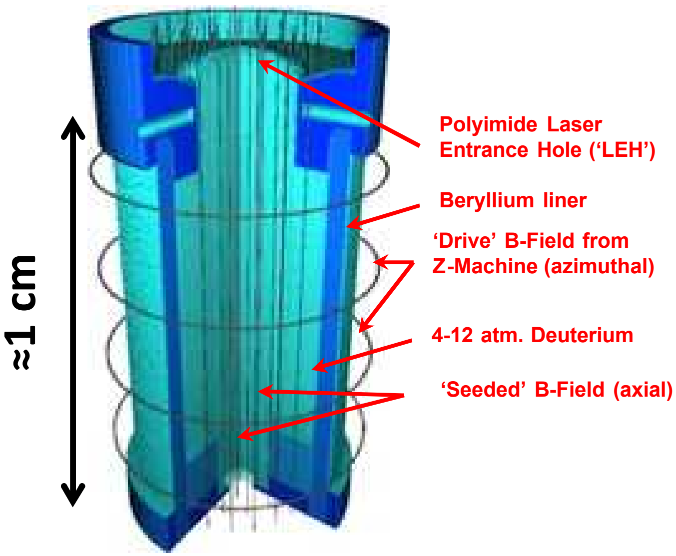
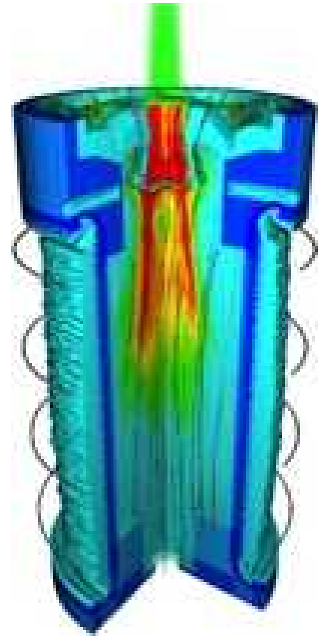
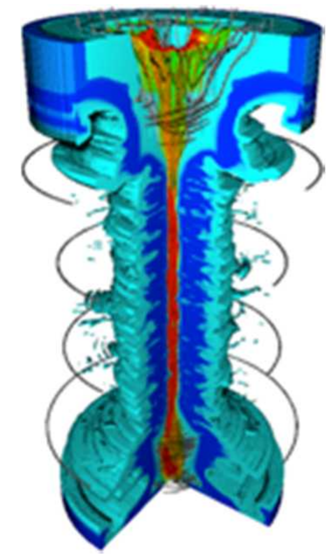


Initialize axial magnetic field (B_0 = 10-30 T)



Laser heating of fuel (E_L = 2-4 kJ)



Magnetic compression of fuel

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*S.A. Slutz et al.: Physics of Plasmas **17**, 056303 (2010); S.A. Slutz & R.A. Vesey, Phys. Rev. Lett (2012); A.B. Sefkow *et al.*, Phys. Plasmas (2014)

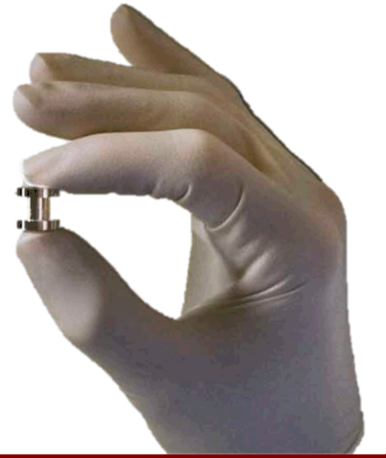
Slide 4

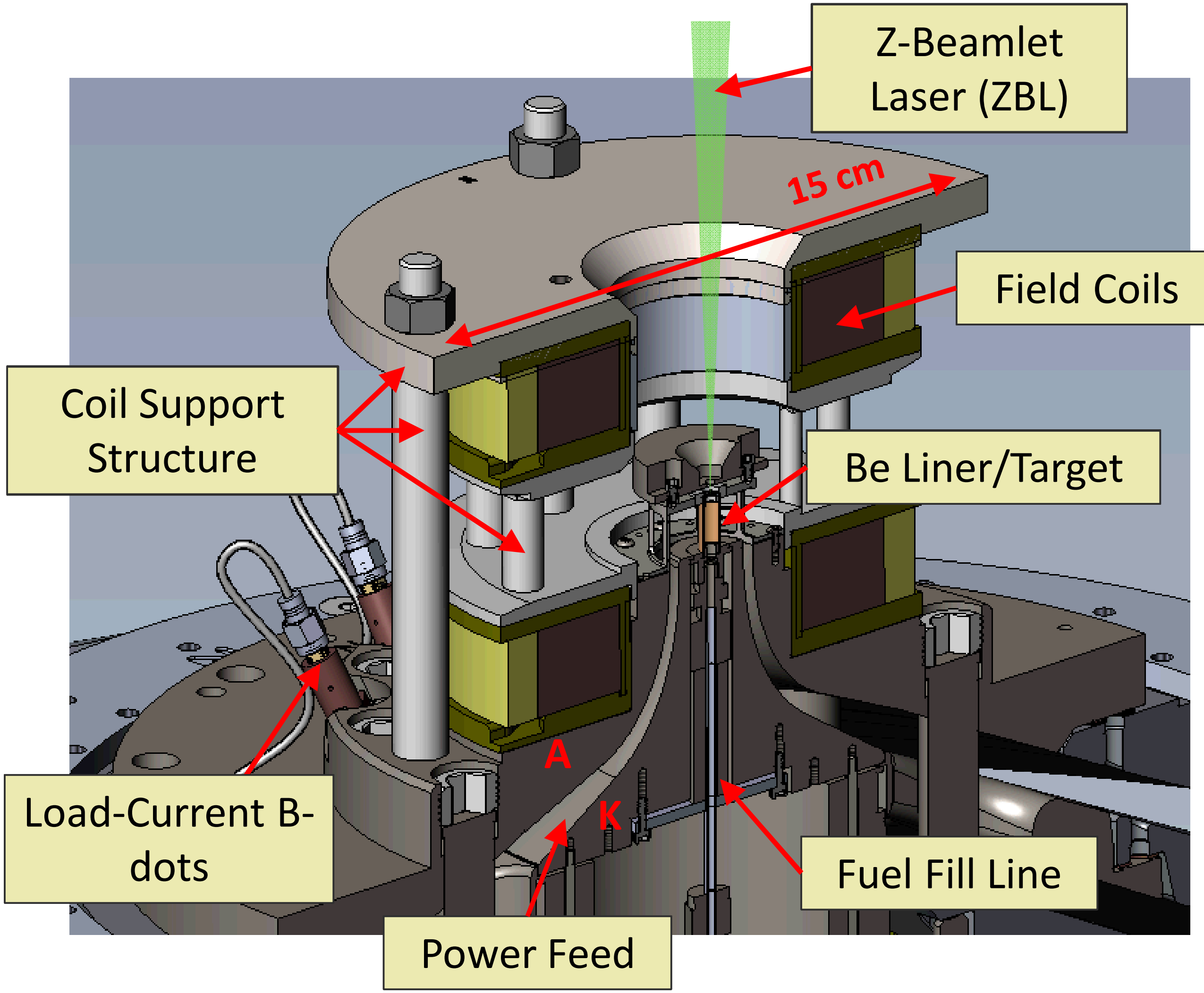
Office12 remove. I borrowed the slide from Dan; the simulations were done by Chris Jennings. You could acknowledge Chris for the pretty pictures.

Microsoft Office User, 8/22/2016

Anatomy of a MagLIF Experiment

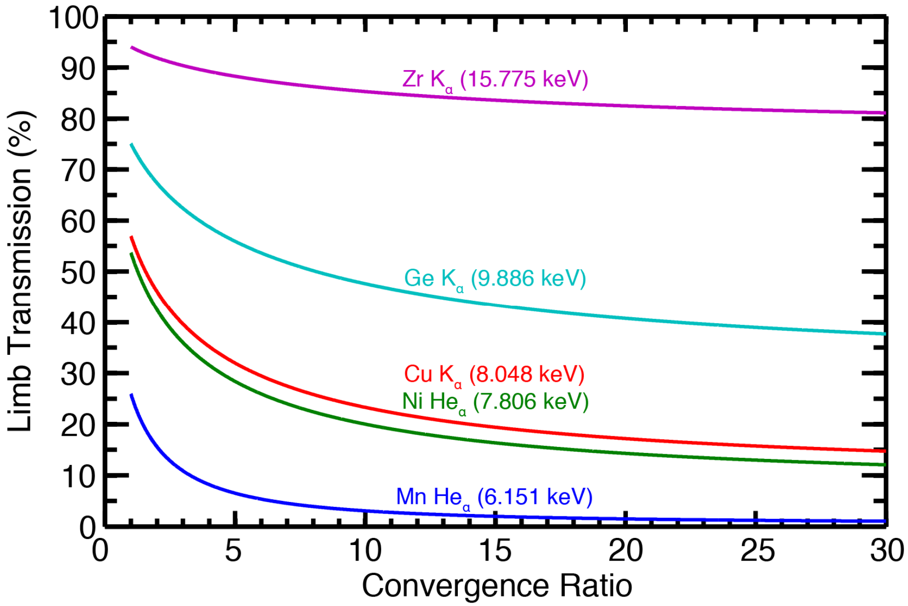
- **Field Coils**: Helmholtz-like coil pair, 10-30 T axial field w/ ≈3 ms rise time
- **ZBL**: 1-4 kJ green laser, 1-4 ns square pulse w/ adjustable prepulse
- **Power Feed**: Up to 24 MA (typical ≈18 MA) in 120 ns

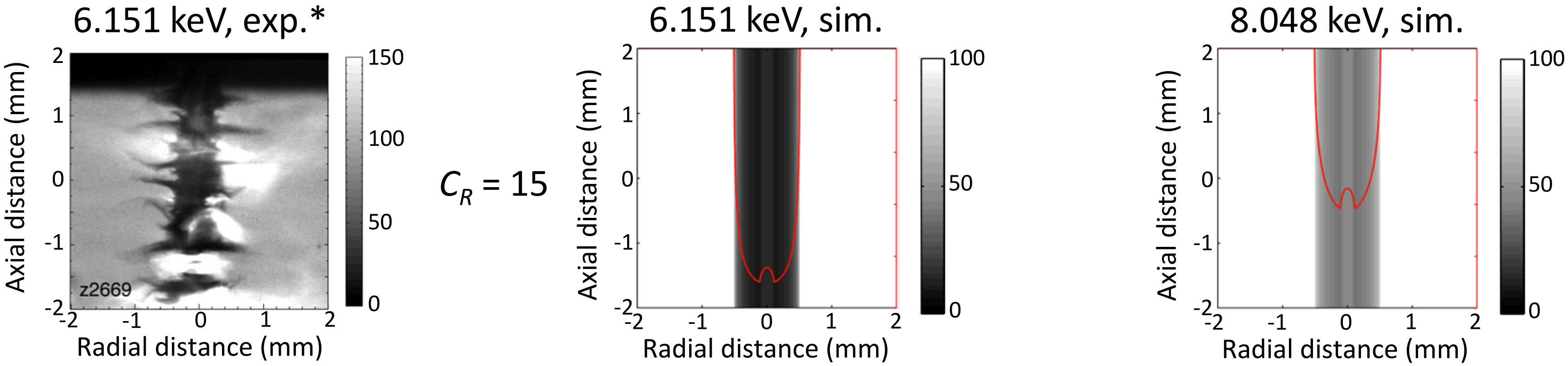




Requirements for improvements

- **MagLIF-style liner implosions require 7-10 keV backlighter for enhanced contrast and penetration**
- **Self-emission at stagnation further compromises the radiographs**
- **Goals:**
  - **find a higher-energy backlighter at 83° for Z**
  - **develop multi-frame, single LOS gated imaging**





$C_R = 15$

[1] M.S. Schollmeier et al., Appl. Opt. 54, 5147 (2015) [2] J.A. Koch, et al., Appl. Opt. 54, 10227 (2015) *Image courtesy of Pat F. Knapp

Systematic search for spectral line/crystal combinations*

Description	Quantity
Elements	Ne – Sn (Z = 10 – 50)
Spectral lines	He-like resonance and intercombination, $K_{\alpha 1}$, $K_{\alpha 2}$
Energy range	0.848 – 26.027 keV
Crystals	α-Quartz, Ge, Si, Mica, GaAs, InAs
Miller index ranges (*h, k, l*)	0 – 20 each
Possible combinations tested	9,112,824
Total number of matches with $R_{int} > 0$	**37,265**

General search and down-selection process:

- **Use Python script to iterate through all combinations**
- **call XOP to calculate R_{int} for matches, then calculate N_{phot} and I_d**
- **Find highest reflectivity crystals for each element & x-ray energy**
- **Identified ~21,000 matching combinations for backlighting and 1,000 for self-emission imaging with $\vartheta \geq 87°$**

Further down-selection for Z application:

- **$6 < E < 10$ keV to ensure good contrast and good penetration**
- **Bragg angle within (83.5 ± 1)°**
- **High reflectivity for good signal-to-noise ratio**

*publication in preparation

Imaging crystals for Z

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)**	**83.2**	**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

red = already used combinations
blue = interesting combinations

*PSL = PhotoStimulated Luminescence; estimated using Z-Beamlet parameters (527 nm, 1 kJ, 1 ns) and 6× magnification

Laser-only tests demonstrate feasibility using Ge (335)

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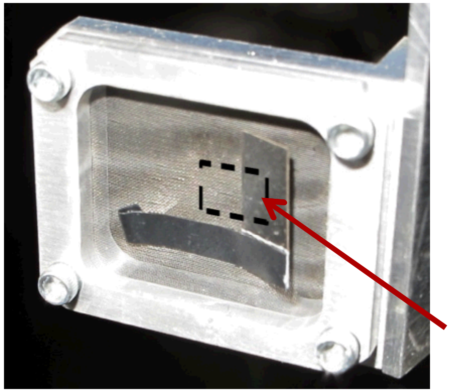
Measurements:

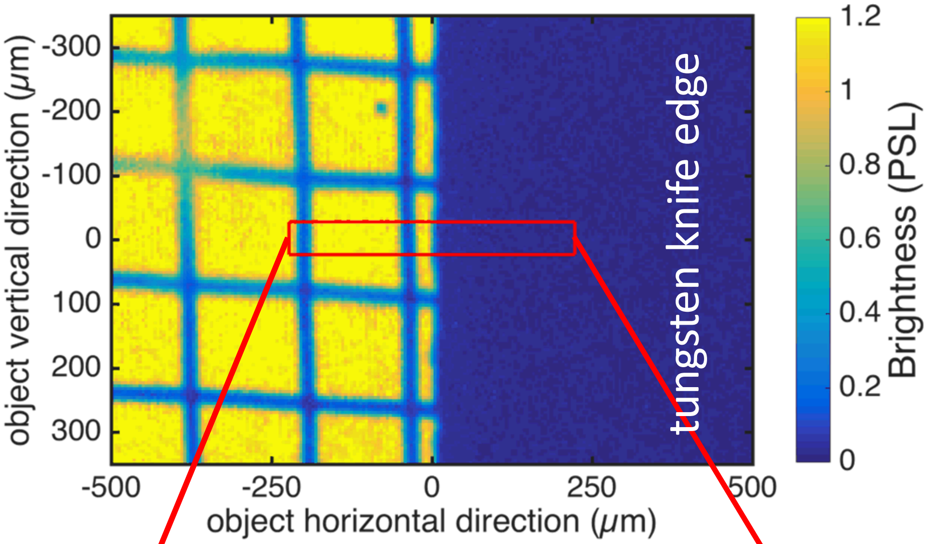
- Meridional ESF = (12.5 ± 0.5) µm
- Sagittal ESF = (16 ± 0.5) µm
- Brightness: 1500 phot./px

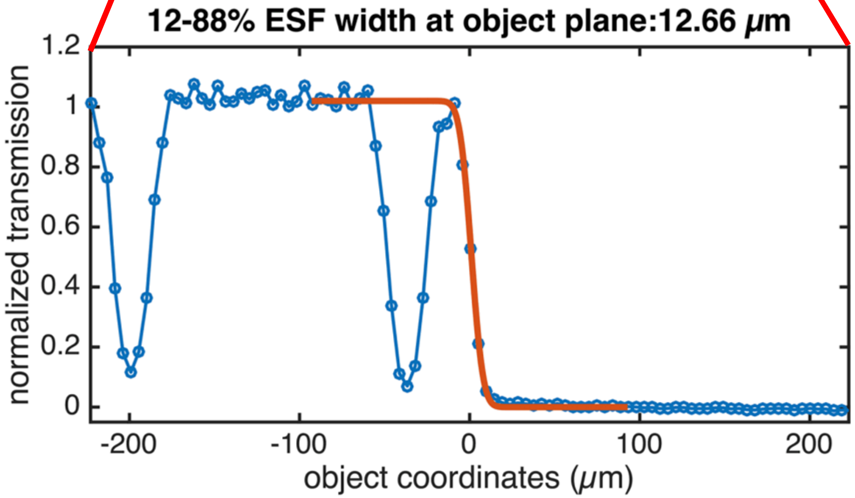
Ray-tracing model:

- Using 65 µm Gaussian PSF for detector [1]
- Meridional ESF: (12 ± 1) µm
- Sagittal ESF: (15 ± 2) µm
- Brightness: 750 phot./px



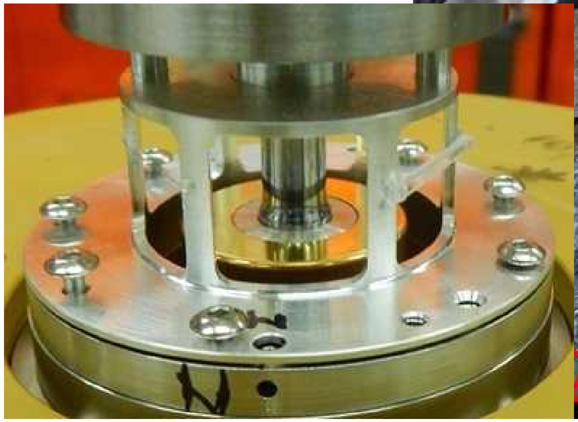
0.5 mm thick tungsten knife edge on 150 lpi mesh



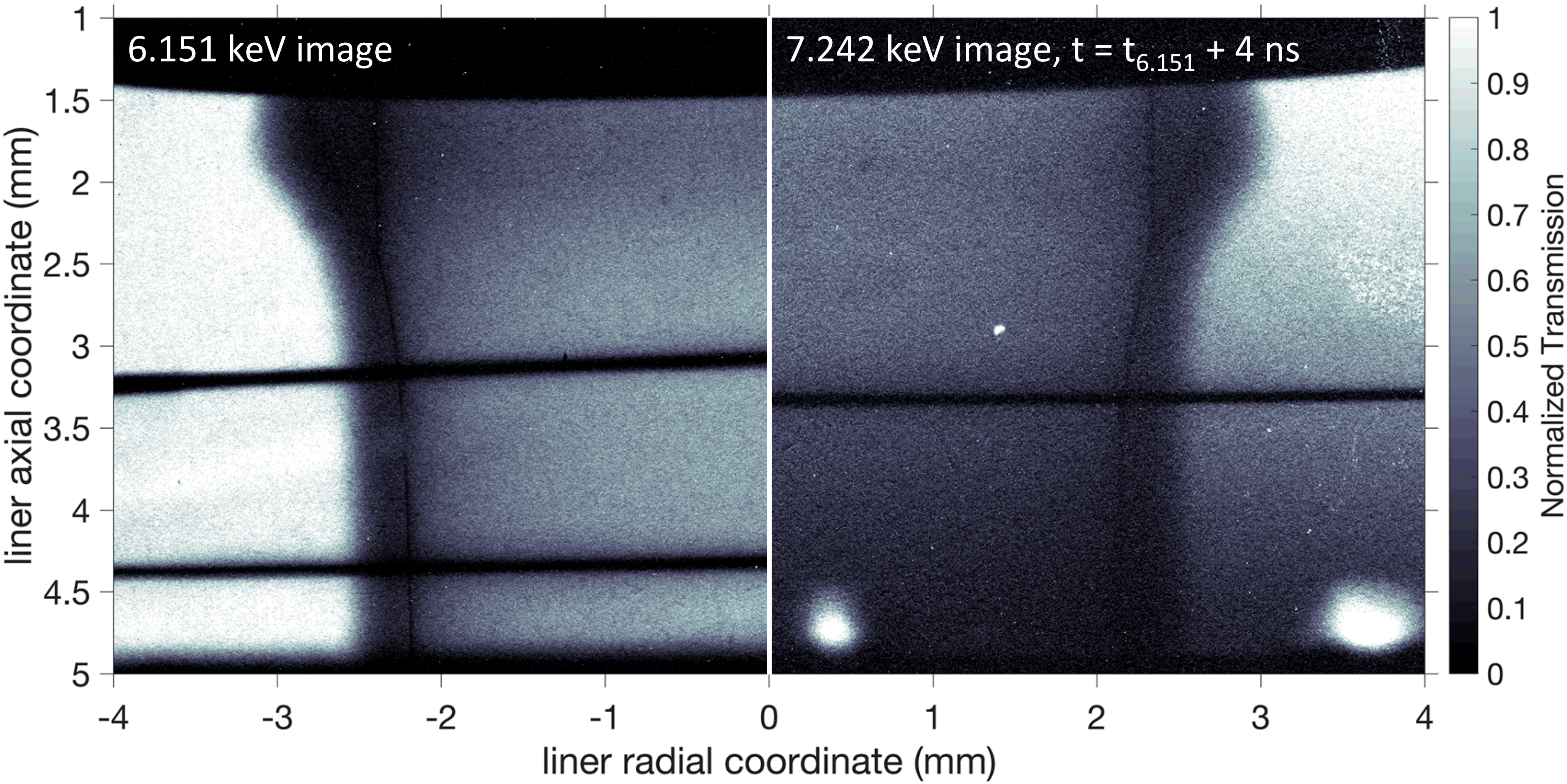


[1] T. Ao et al., JQSRT 144, 92-107 (2014)

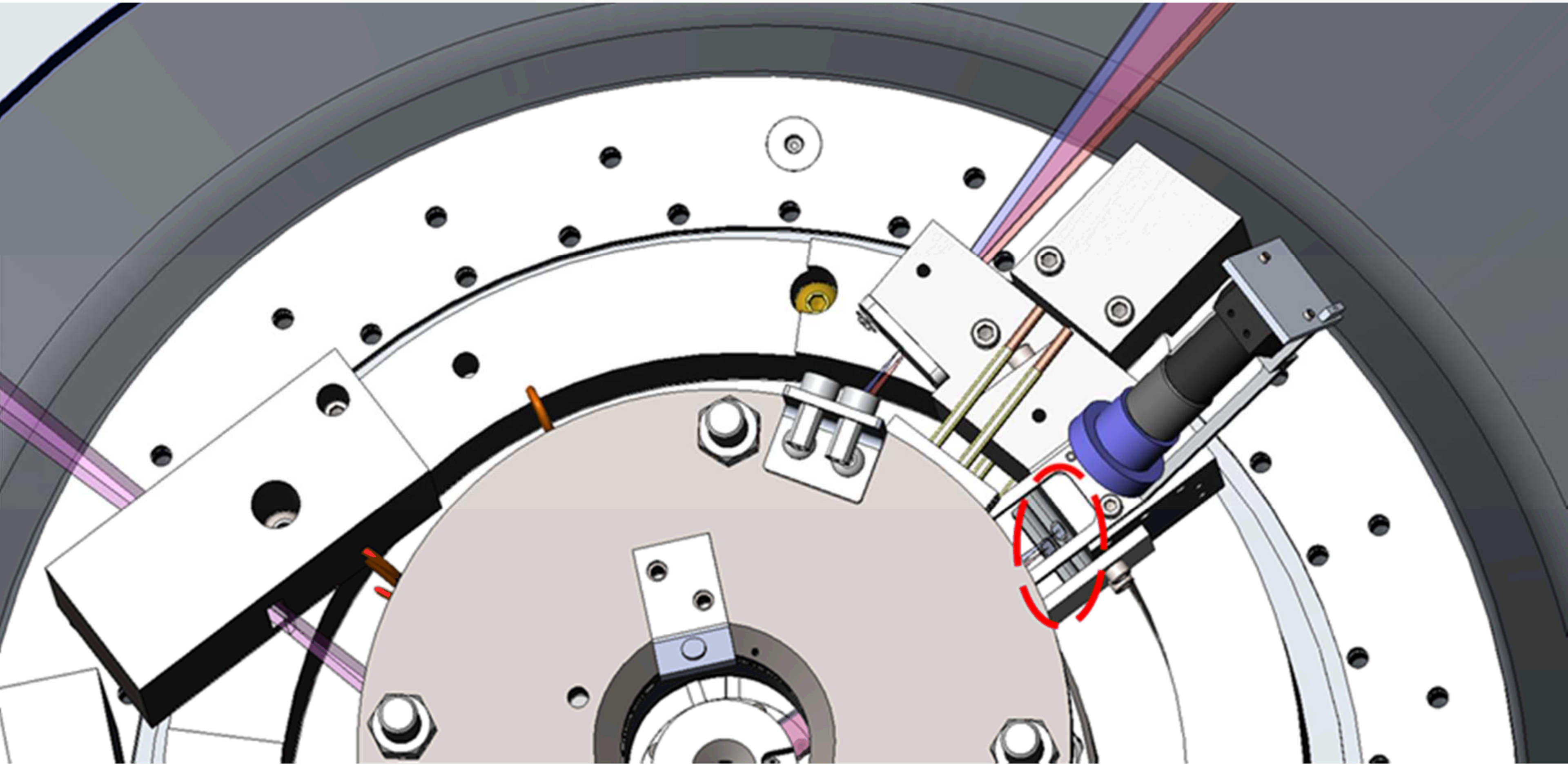
6.2 and 7.2 keV two-color or 7.2 keV two-frame x-ray backlighter system for Z



6.2 and 7.2 keV two-frame radiographs at early time of implosion

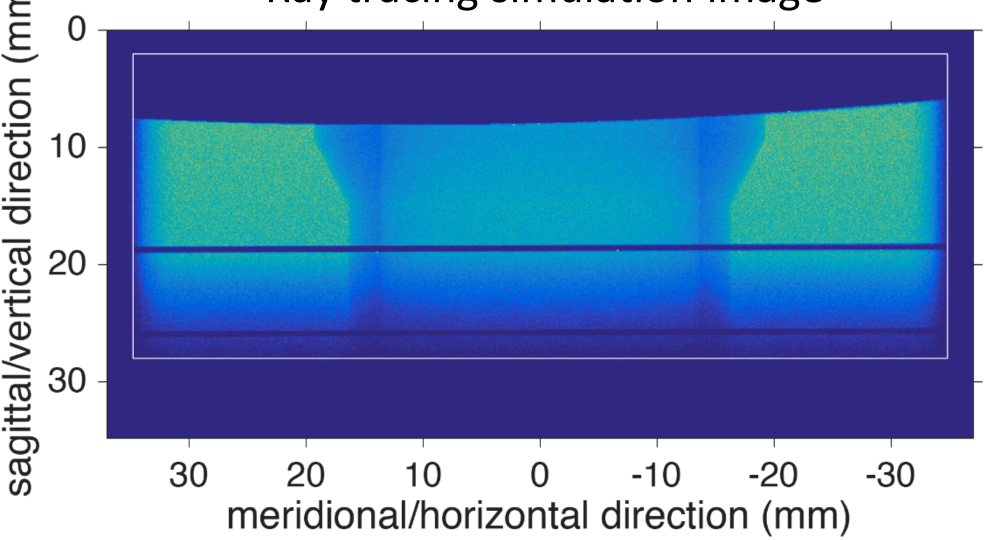


Laser targets are in close proximity to magnetic field coils

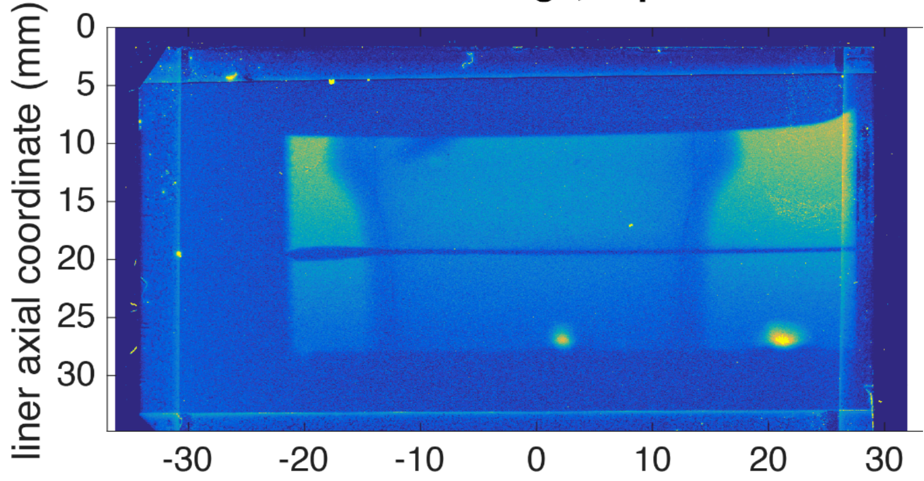


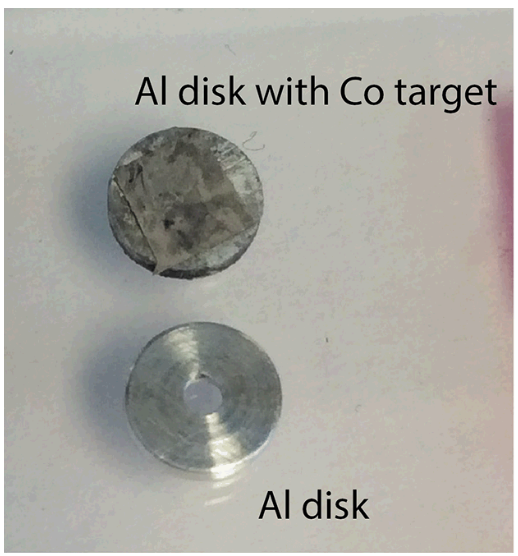
Applied magnetic field affects Co x-ray source

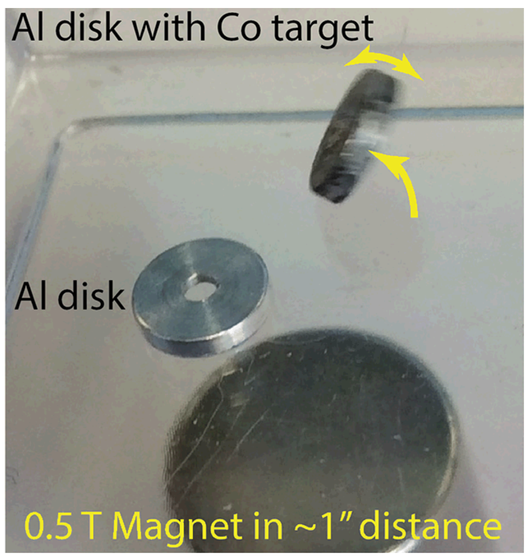
Ray tracing simulation image

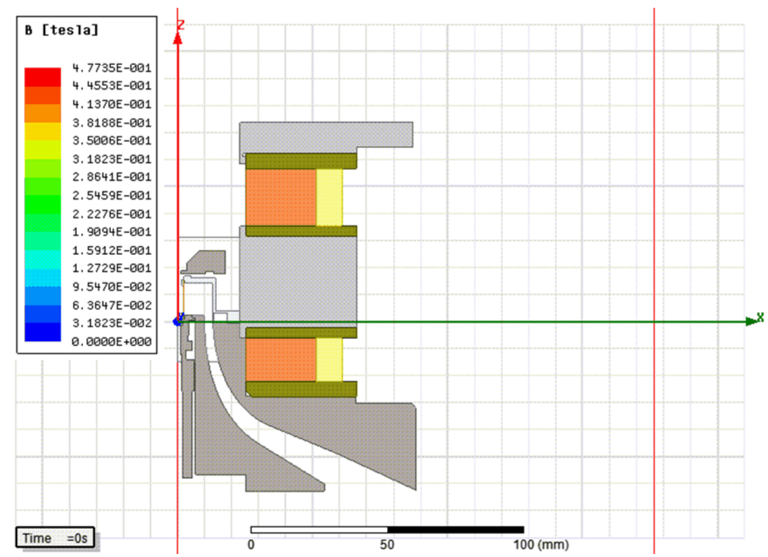


7.242 keV image, experiment









A 2.5x magnification crystal configuration for multi-frame, single LOS hCMOS imaging

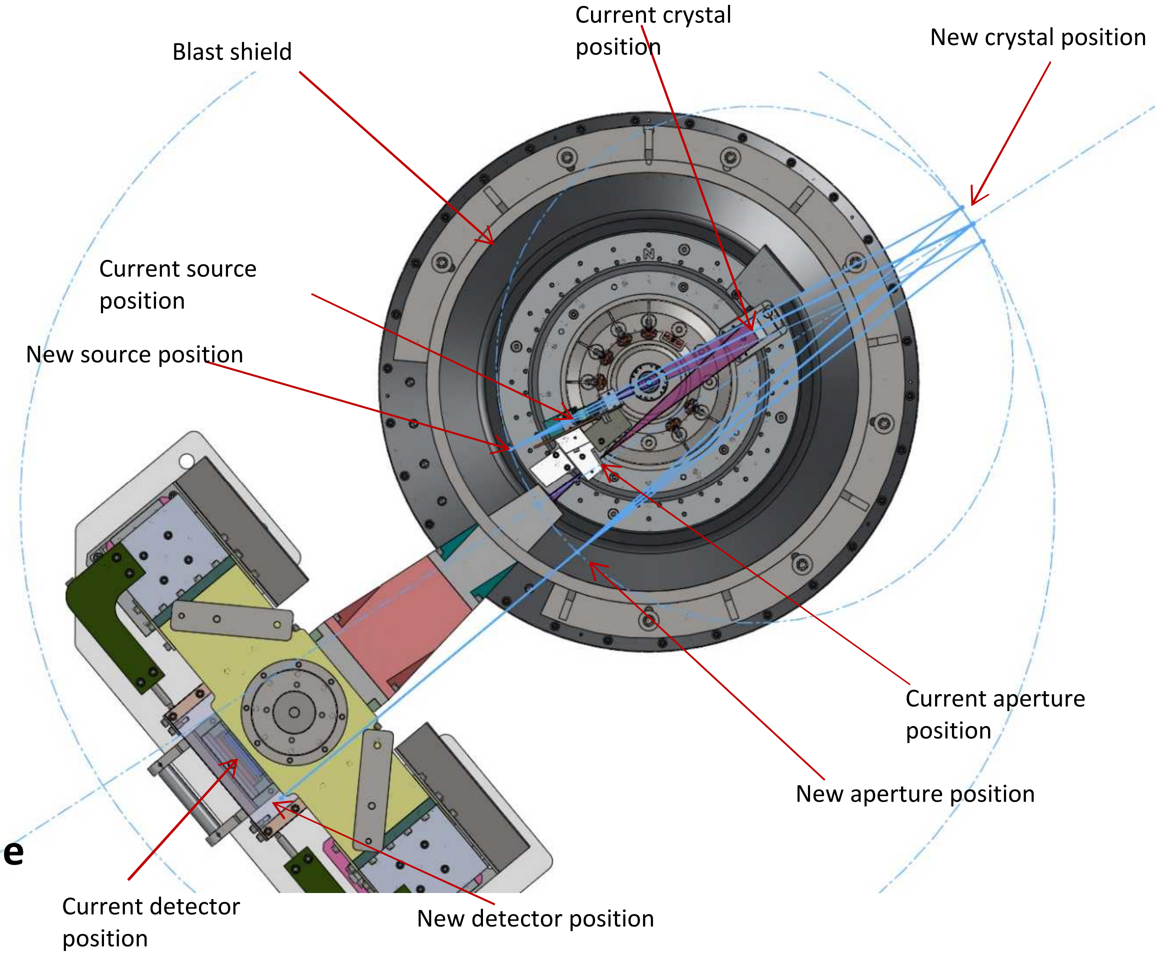
Crystal parameters:

- Quartz 22-43, 2d = 2.03 Å
- Aperture: 38 × 14 mm
- R = 650 mm
- M = 2.5

Calculated distances:

- Source-to-object: 194.2 mm
- Object-to-crystal: 453.1 mm
- Detector-to-crystal: 1132.8 mm

- Keeps detector at approximately the same distance (known background and shielding)
- Reduces image size to match hCMOS chip size



Experiments: Comparison to 5.8x BL

- single shot results, both backlighter systems were operated simultaneously; same IP type and filtering.
- Images at object plane, detail of mesh radiograph
- 2.5x image is even slightly brighter

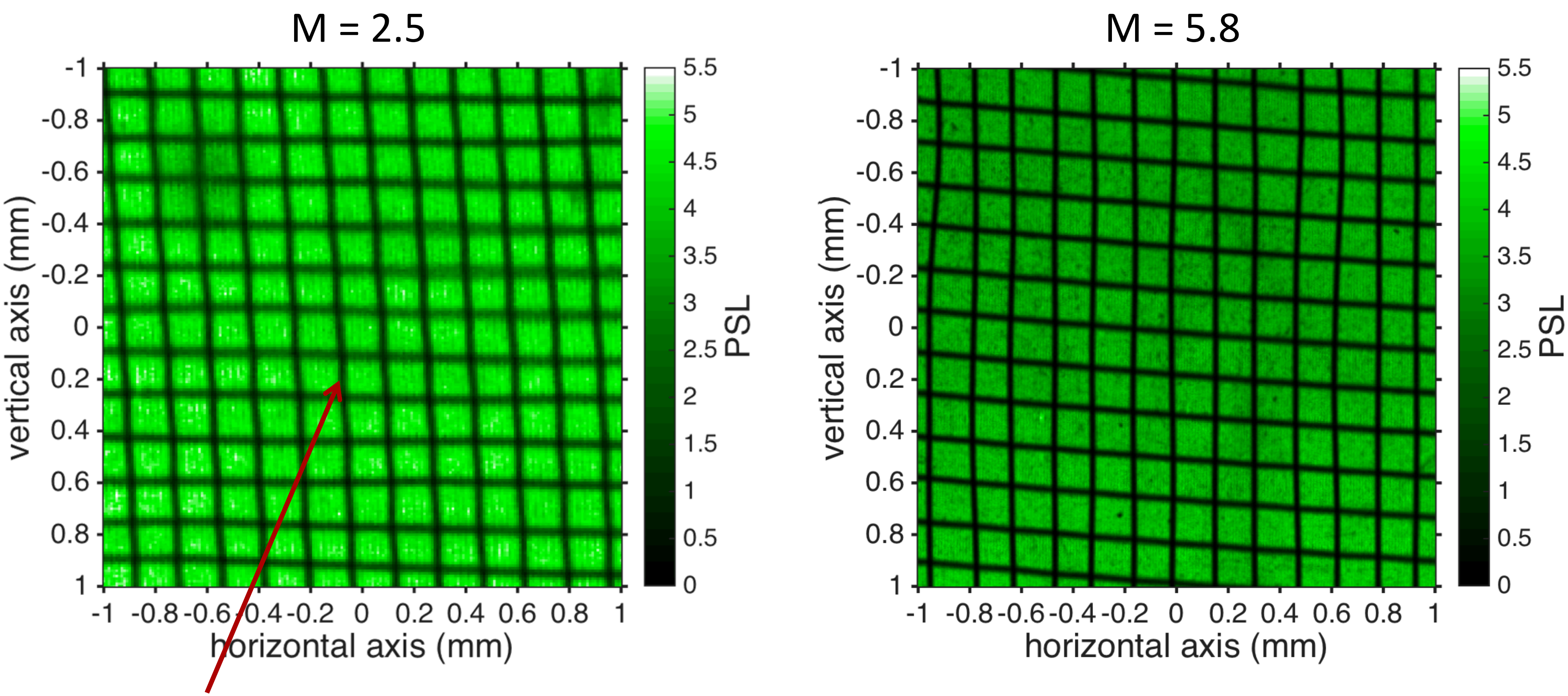
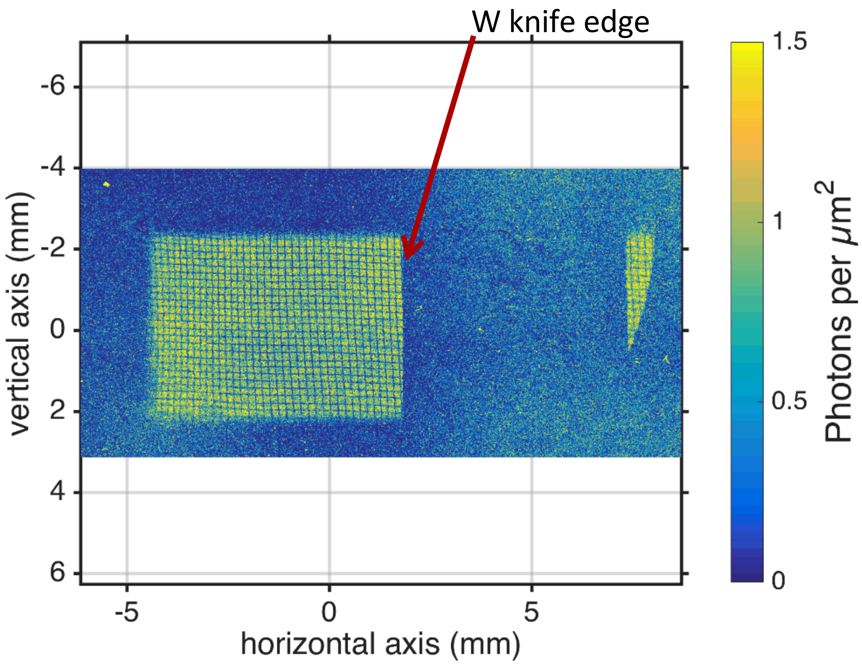
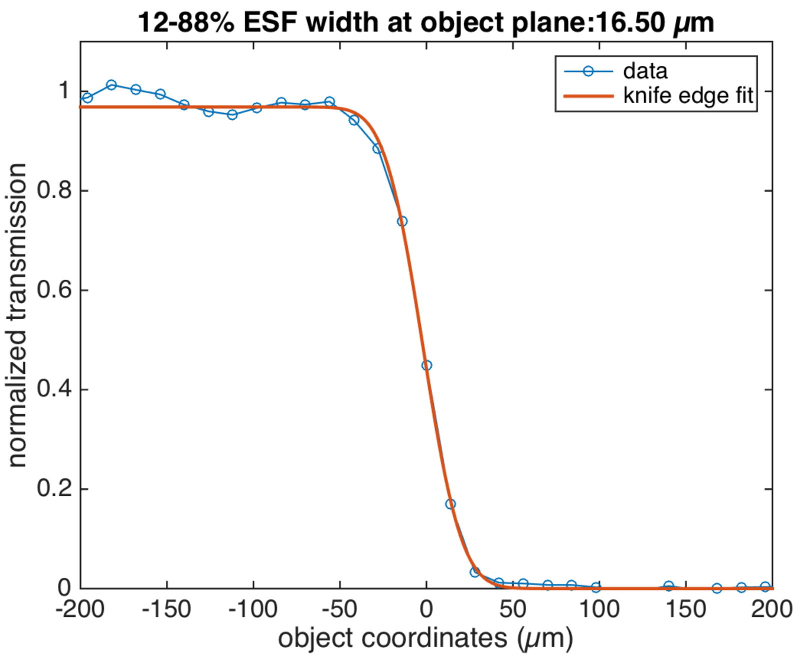


Image blurred due to IP detector

Experiments: Knife edge measurement with X-ray film



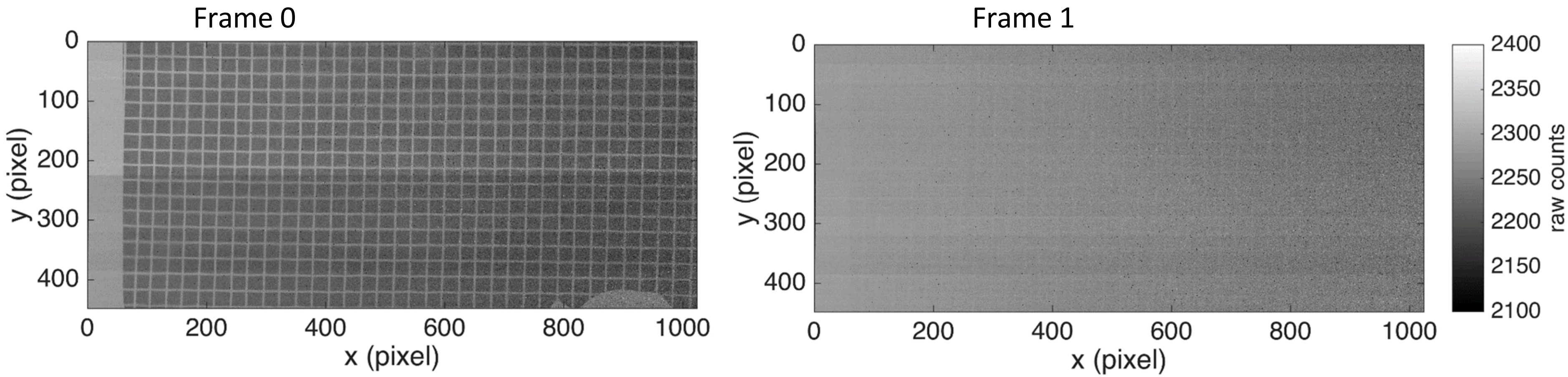


- The film was scanned with 14 µm pixel size; it has about 20 µm spatial resolution (5.6 µm pixel size and 8 µm resolution in the object plane)
- 12-88% width of knife edge lineout in the center of the image: 16.5 µm in the object plane*
- At the edges of the image the knife edge width increases to 18.5 µm

*There is some contribution to broadening from the film and scanner, which was not corrected for

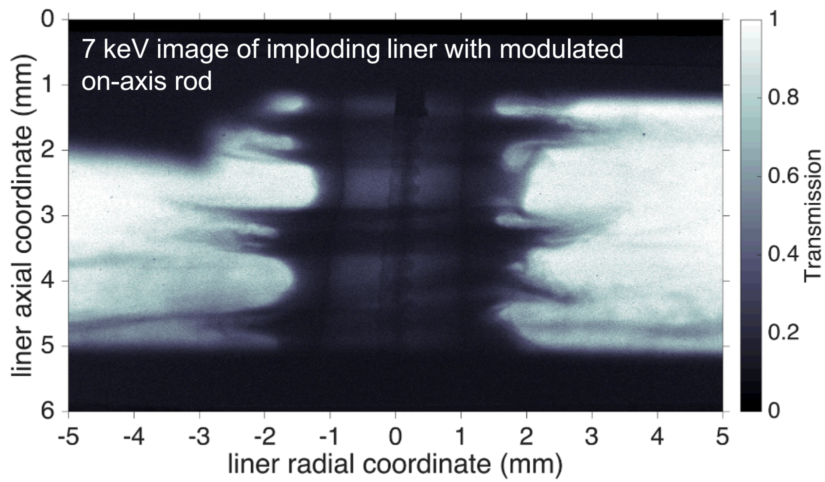
Experiments: Time-gating demonstrated with FURI sensor

- A FURI hCMOS sensor was put in a vacuum ante-chamber and mounted to the outside of the JEMEZ chamber
- Due to the increased distance from the crystal, the magnification had to be increased to M ≈ 4, thus lowering the overall image brightness
- The hCMOS sensor trigger and exposure was adjusted to have the full 1-ns backlighter signal in the first frame, and no x-ray exposure in the 2nd frame



Summary

- A systematic evaluation was performed to find spectral line and spherical-crystal matches suitable for high-resolution imaging
- A 7.2 keV backlighter system was developed for the Z facility
  - Utilizes existing infrastructure for spherical crystal backlighting
  - Enables two-color radiography and reduces unwanted higher-order self-emission
  - 6 Z shots to date:
    - 2× two-color for 'thick-end' liner radiography
    - 4× two-frame for deceleration MRT instability radiography
- Time-gating of high-resolution, 6 keV backlighting with a FURI sensor was demonstrated
- Some future developments:
  - Reliability (laser target holder, laser energy balance)
  - Multi-frame, single line-of-sight backlighting at Z
  - Laser-target coupling to enhance yield
  - After Gareth Hall and Inrad have reported success:
    - Backlighting at 8.9 keV Zn *w* with InAs (1 5 7)



BACKUP SLIDES

X-ray backlighting with spherical crystals

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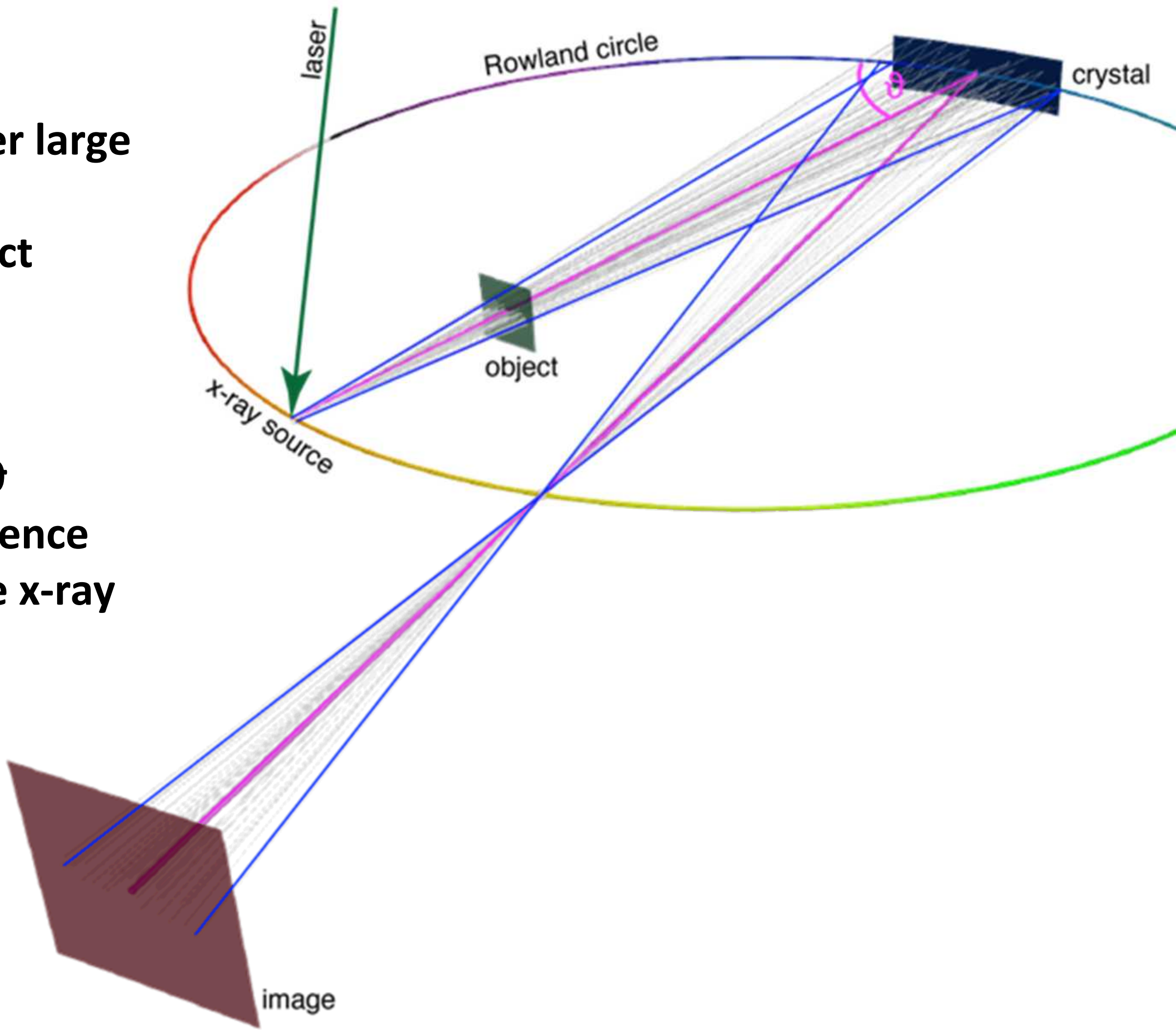
Advantages:

- high sensitivity
- monochromatic
- <20 µm spatial resolution over large field-of-view (>1 cm)
- no direct line-of-sight to object (debris/noise)

Limitations:

- Bragg condition: $m\lambda = 2d \sin \vartheta$
- Astigmatism: off-normal incidence
- Source: needs to emit suitable x-ray spectral line



Literature survey

Spectral line	Energy [keV]	Crystal material	Miller indices hkl	$2d$ [Å]	ϑ [°]
Al He_β	1.468	Quartz	1 0 0	8.510	82.85
Mg Ly_α	1.473	Quartz	1 0 0	8.510	81.53
Al K_α	1.487	Quartz	1 0 0	8.510	78.39
Dy	1.494	Quartz	1 0 0	8.510	77.21
Si He_α	1.865	Quartz	1 0 1	6.687	83.80
Al H, He-like	1.927	Mica	0 0 6	6.647	75.25
Ar K_α	2.956	Quartz	2 0 0	4.255	80.00
Ar He_α	3.124	Ge	2 2 0	4.000	82.83
Ar He_α	3.140	Quartz	2 0 1	3.959	85.80
Ti K_α	4.505	Quartz	2 0 3	2.749	88.90
Sc Ly_α	4.542	Quartz	2 0 3	2.749	83.21
Mn He_α	6.151	Quartz	2 2 3	2.030	83.19
Ni He_α	7.806	Quartz	5 0 2	1.624	77.97
Cu K_α	8.048	Quartz	4 2 2	1.541	88.70
Ta L_α	8.141	Mica	0 0 26	1.534	83.17
Zr $K_{\alpha 2}$	15.691	Quartz	2 3 4	0.79126	86.98
Zr $K_{\alpha 1}$	15.775	Quartz	9 3 0	0.7868	87.34
Ru He_α	19.717	Ge	15 7 7	0.6296	87.15

Comparison to existing 6.151 keV system

	6.151 keV	7.242 keV
Crystal	Quartz (22$\underline{4}$3)	Ge (335)
Crystal size	28 × 10 mm	28 × 10 mm
Reflection order	1st	1st
Next possible higher order	2nd (12.302 keV)	3rd (21.726 keV)
X-ray source	Mn He y	Co He w
Bragg angle	83.19°	82.83°
Magnification	5.8	5.8
Crystal-to-Object distance	146.6 mm	146.55 mm
Crystal-to-Detector distance	850 mm	850 mm