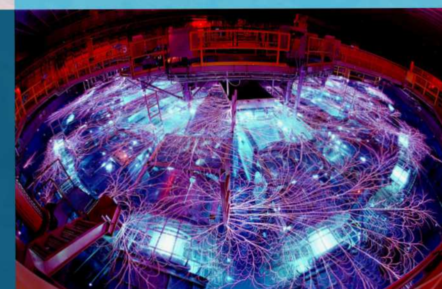
SAND2019-6549C

Sandia National Laboratories

X-RAY DIFFRACTION OF DYNAMICALLY COMPRESSED MATTER ON THE Z-ACCELERATOR



PRESENTED BY

Tommy Ao, Marius Schollmeier, Patricia Kalita

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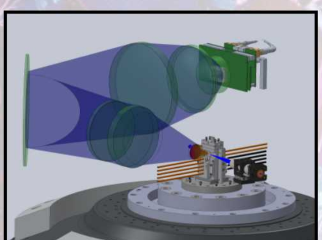
Background

- Z-Accelerator and Z-Backlighter capabilities
- Challenges of x-ray diffraction on Z

X-ray Diffraction on Z

- Spherical crystal diffraction imager
- Recent results



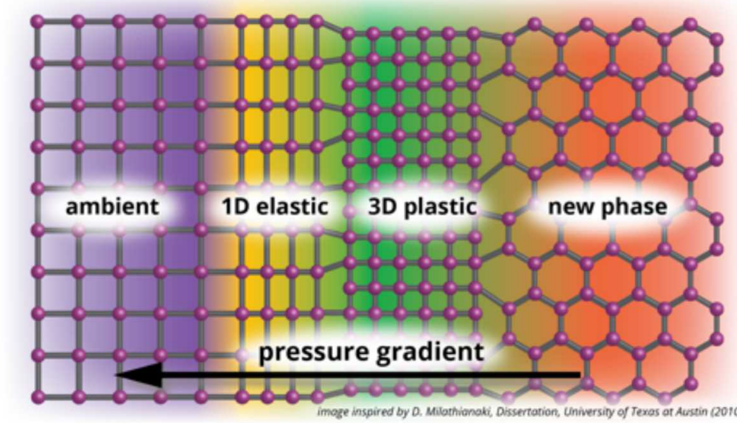
Future Developments

- X-ray sources
- X-ray diffraction detector schemes

X-RAY DIFFRACTION TO INFER DYNAMIC MATERIAL PROPERTIES

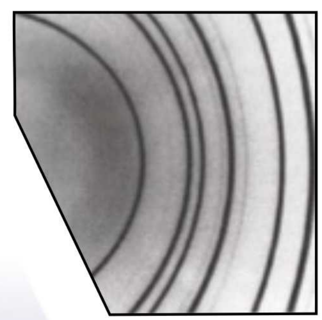
Goals

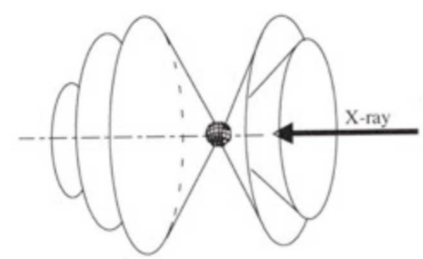
- Characterize both phase transitions and their kinetics that occur in dynamically compressed condensed matter on ns time scales and nm spatial scales
- Determine at atomic scale how materials behave under extreme pressure & temperature conditions; velocimetry gives only continuum scale information



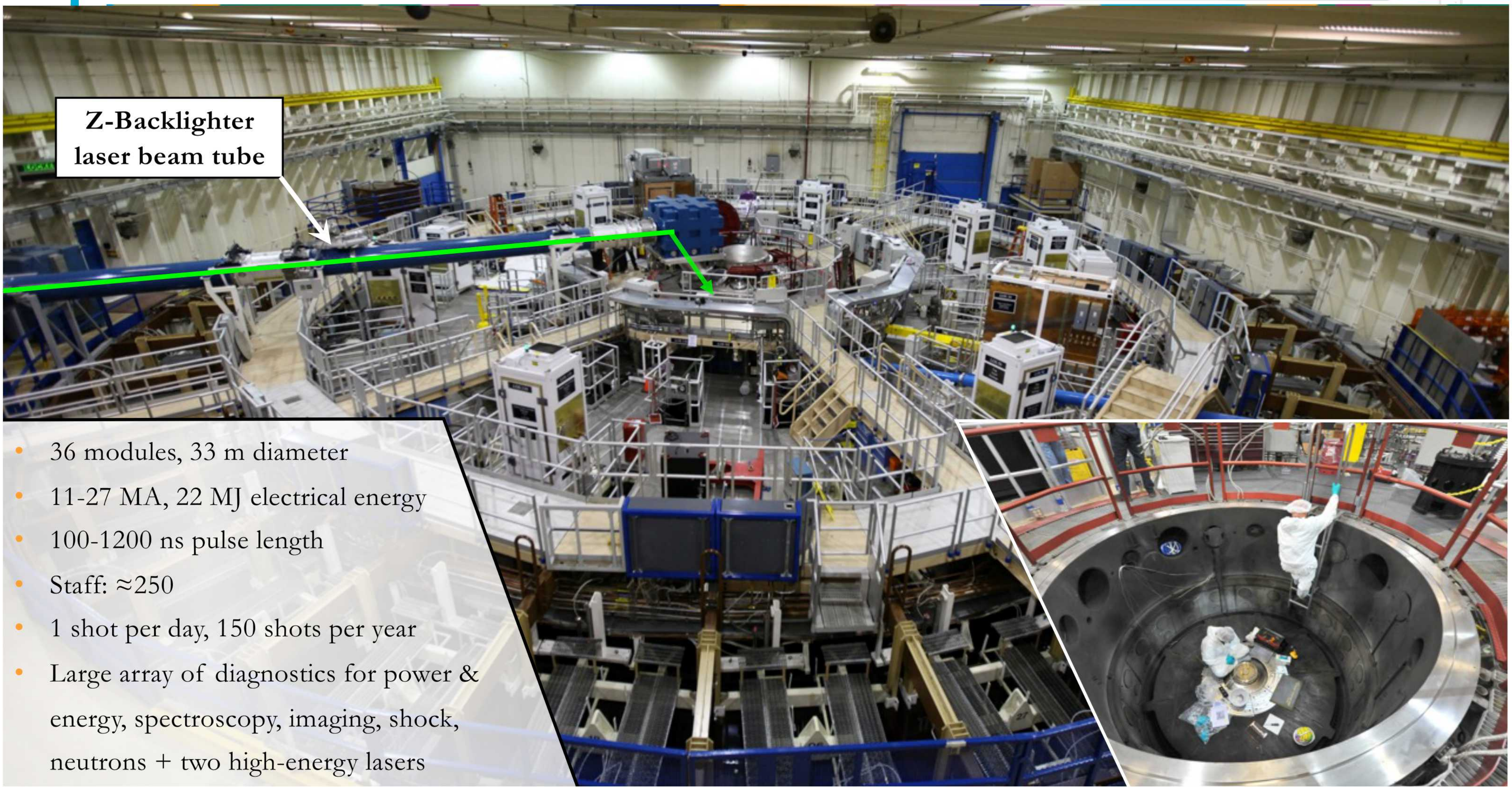
Approach

- Produce (multi-pulse) source x-rays with ZBL/ZPW
- Generate high-pressure state with Z-DMP load
- Detect diffracted x-ray pattern (time-gated)





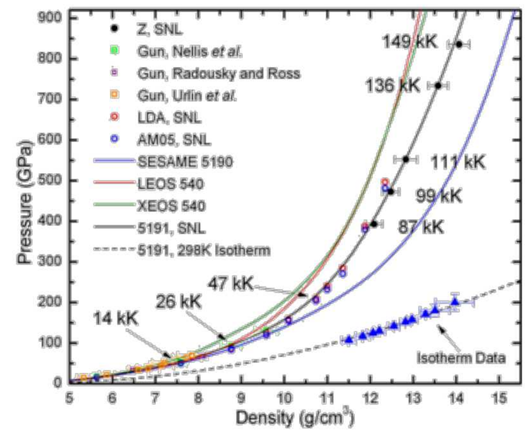
THE Z PULSED POWER FACILITY IS USED FOR HEDP RESEARCH



- 36 modules, 33 m diameter
- 11-27 MA, 22 MJ electrical energy
- 100-1200 ns pulse length
- Staff: ≈250
- 1 shot per day, 150 shots per year
- Large array of diagnostics for power & energy, spectroscopy, imaging, shock, neutrons + two high-energy lasers

Z creates high pressures without directly heating materials:

- Long time scales (100-1200 ns) with control over the time history
- Large samples (cm): HED conditions for volumes ≫ sample grain boundaries dimensions
- One Z-DMP (Dynamic Materials Properties) experiment can field 6-20 samples

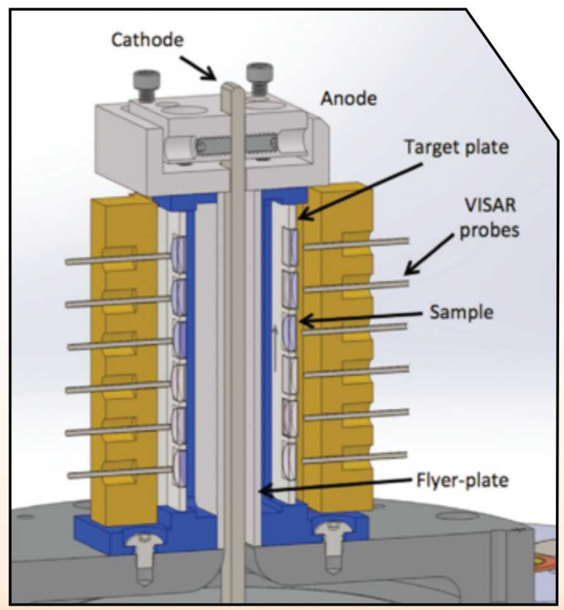


P-ρ Hugoniot plot of Xenon*

Key physics questions:

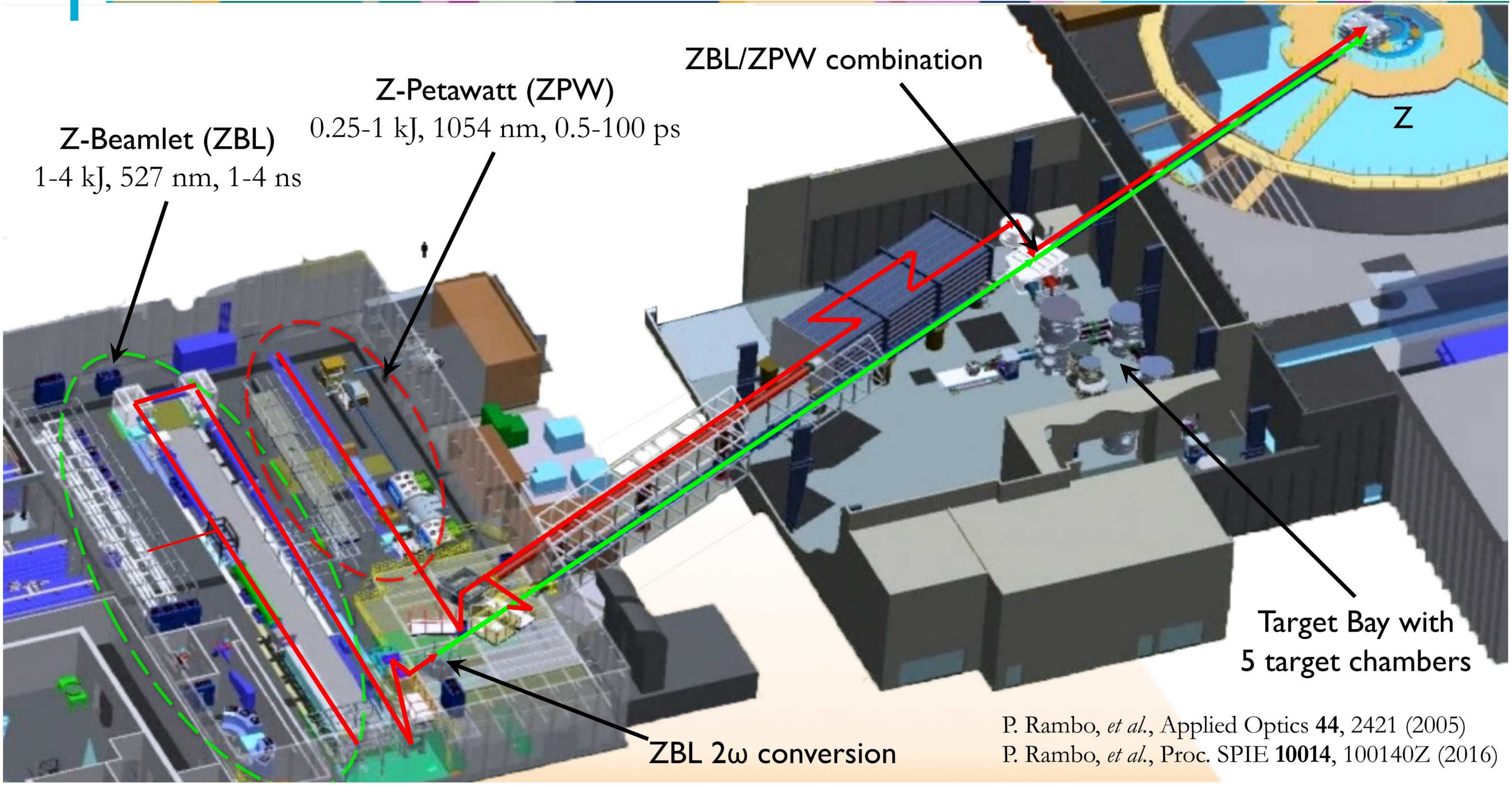
- Role of microstructure
- Kinetics and phase transitions
- Strength
- Transport properties
- Radiation shock

⟶ Theory & data almost always diverge in previously unreachable regimes



*S. Root, *et al.*, Phys. Rev. Lett. **105**, 085501 (2010)

THE Z-BACKLIGHTER FACILITY



P. Rambo, *et al.*, Applied Optics **44**, 2421 (2005)
P. Rambo, *et al.*, Proc. SPIE **10014**, 100140Z (2016)

Target parameters

- Large and thick samples; high-Z samples
- Reflection geometry limits accessible angles

Destructive environment of Z-DMP load

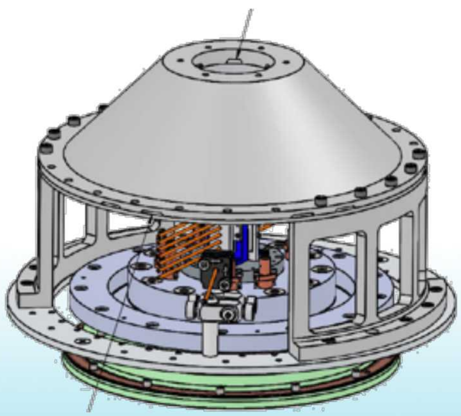
- **Minimum distance ~5 cm**
- Data retrieval?
- Protect Z-Backlighter laser optics

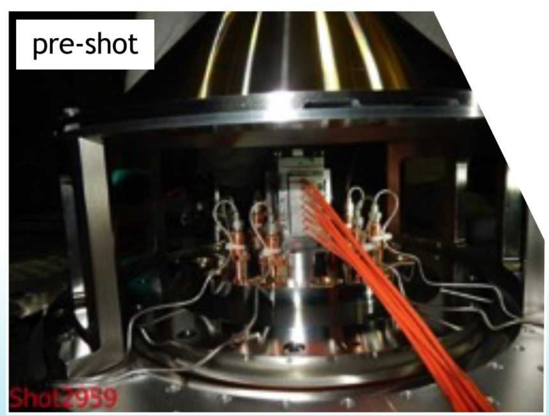
X-ray background

- High energy photons (MeV) produced near load
- Sufficient signal-to-noise?

Electromagnetic pulse (EMP)

- Fry electronics
- Early triggers

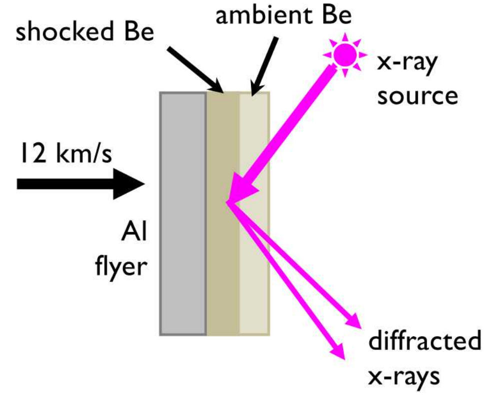


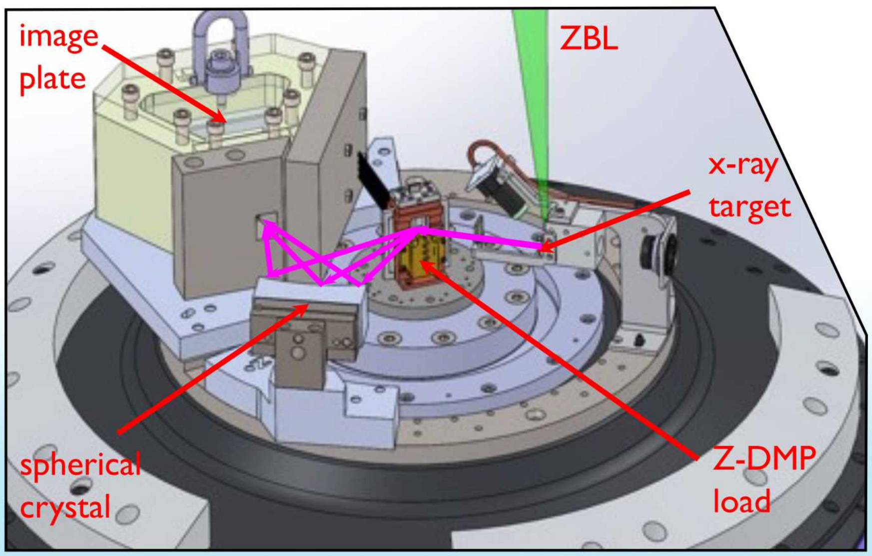


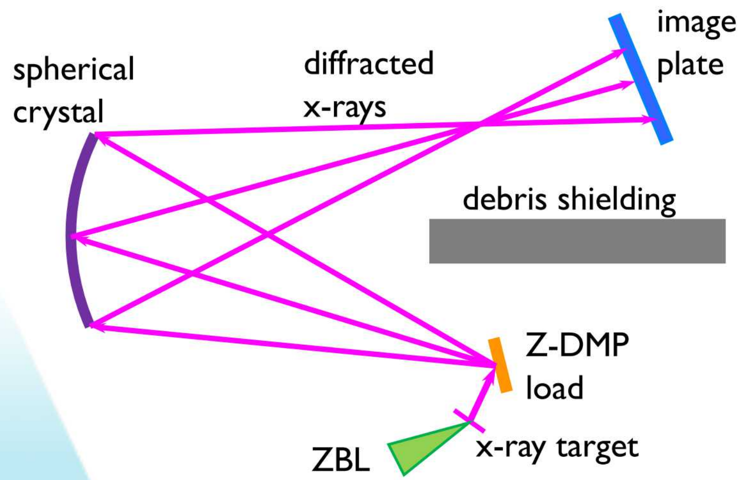
Direct x-ray detection (image plates, CCDs) is infeasible

Experimental parameters

- Z-Beamlet laser ⟶ 6-8 keV x-rays
- HOPG spherical crystal ⟶ collect and reflect diffracted x-rays
- Image plate ⟶ record data
- Be sample ⟶ low mass attenuation coefficient, high XRD cross section
  - Serves as its own x-ray window
  - Possible hcp-bcc phase transition at ~2 Mbar, 3000 K*



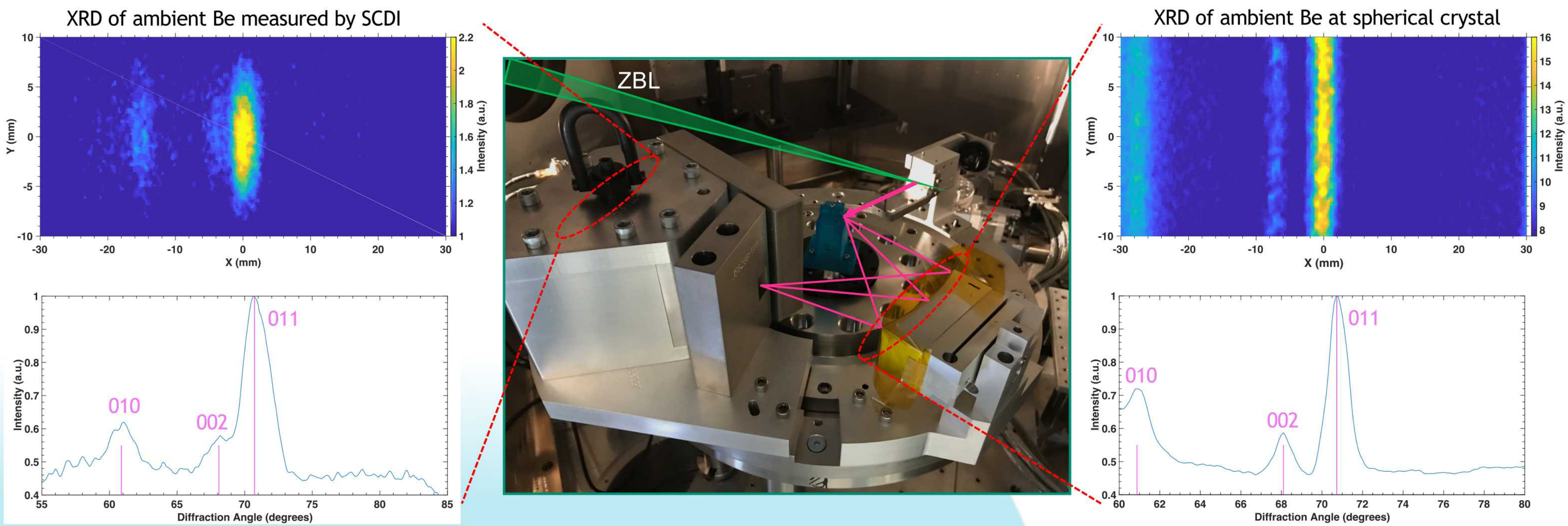




*A. Lazicki, *et al.*, PRB **86**, 174118 (2012)

Duplicate SCDI hardware with surrogate Z-DMP sample

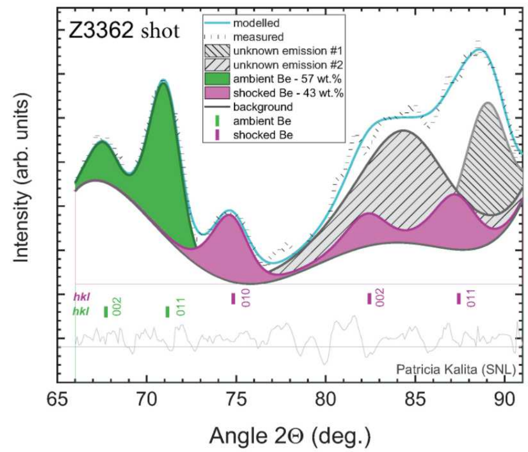
- Collected diffracted x-rays and focused into SCDI detector housing
  - Diffraction angle range: $\Delta 2\theta \sim 30\,°$
  - Angular resolution: $\Delta\theta \sim 1°$

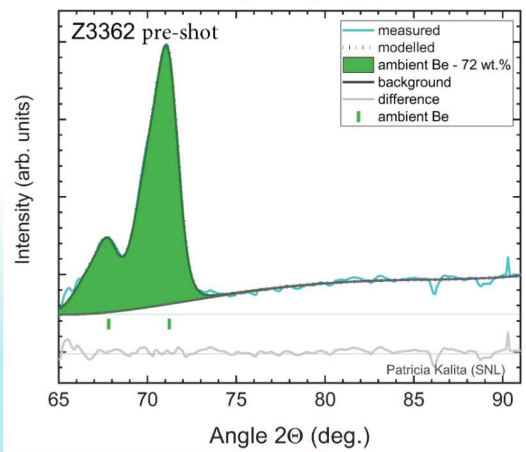


SCDI diagnostic has been commissioned on Z-DMP experiments

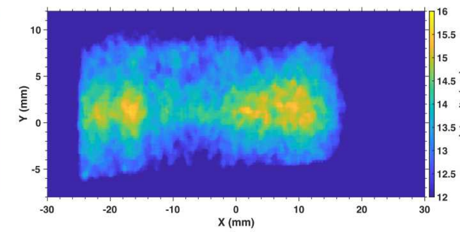
- 25-mm tungsten box with 12 x 3 mm slit
- IP survives shot, no debris penetration
- Strong, MeV-level x-ray background

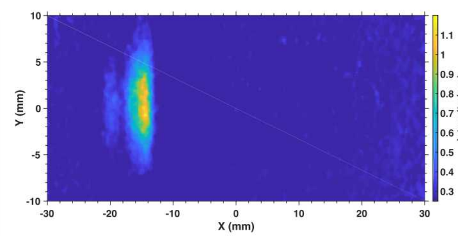
SCDI housing survives!





X-ray density of shocked Be ~ 3.1 g/cm^3

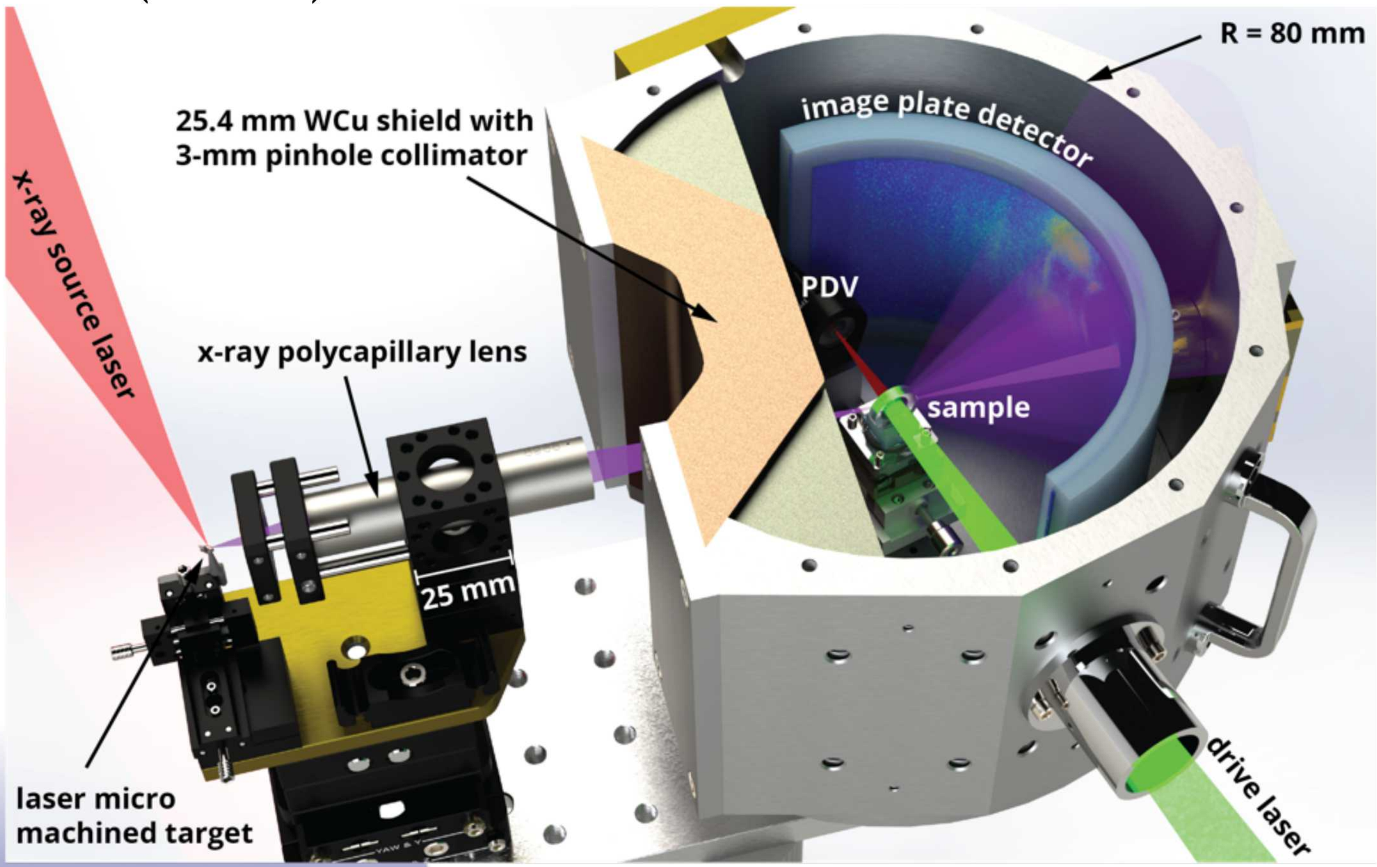




X-ray density of ambient Be ~ 1.85 g/cm^3

Z-Backlighter target chamber (Chama) used a testbed for Z shots

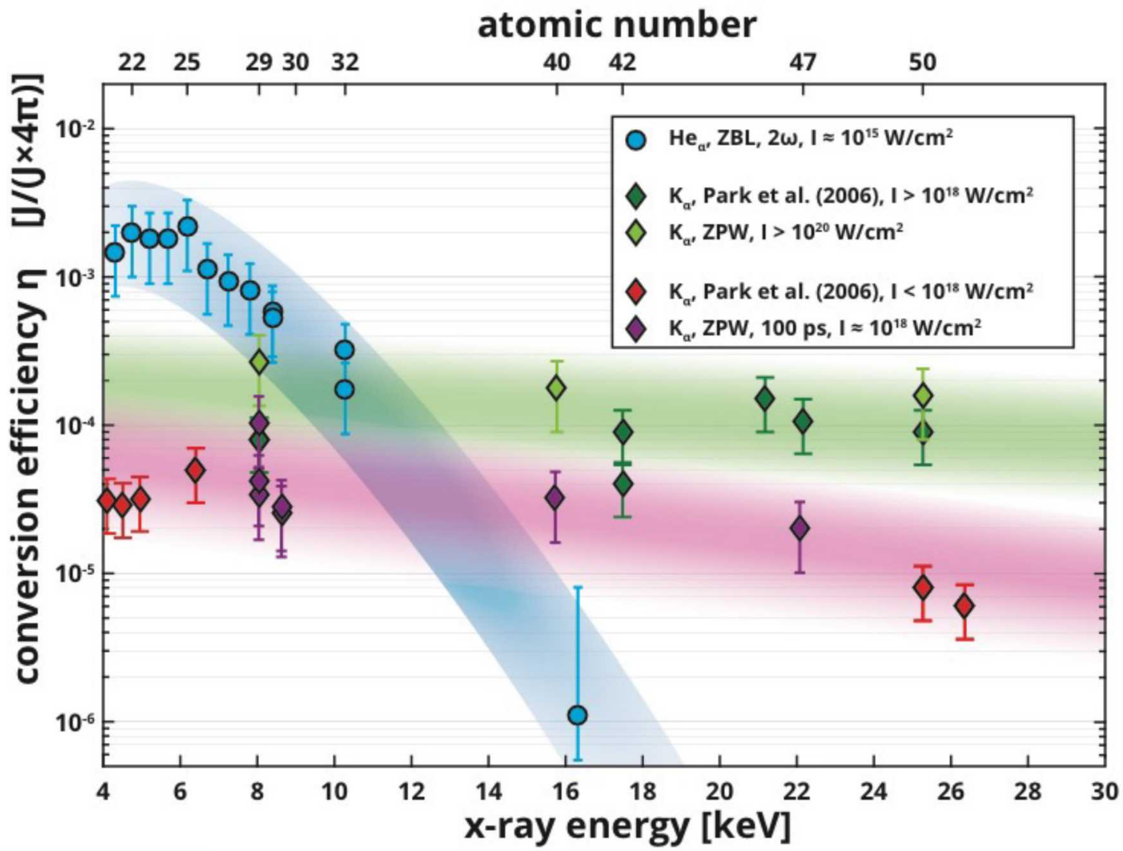
- ZPW laser x-ray source
- Laser shock drive
- 2D detector (IP, …)



PACMAN: Phase And Crystallographic Measurement ANalyzer

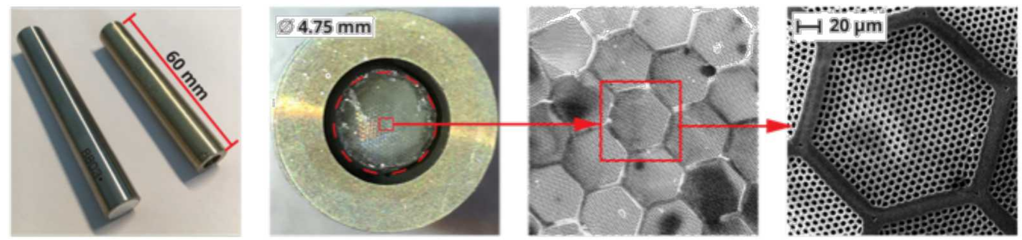
Single-shot diffraction requires both sufficient photon energy and fluence

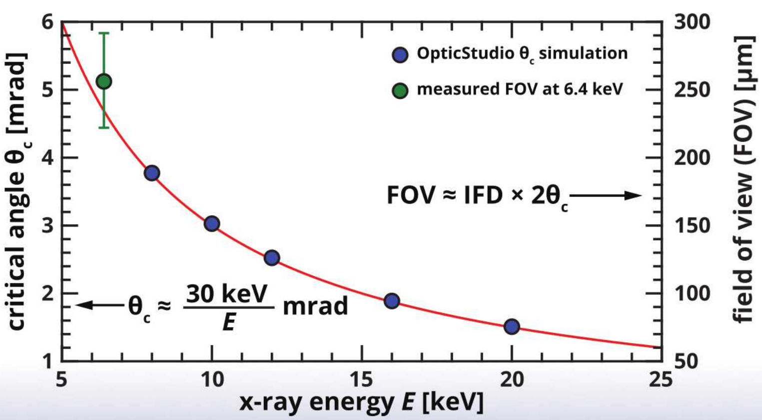
- Number of photons
  - $N_{photon} = \eta \times E_{laser} / E_{photon}$
- Z-Beamlet laser (ZBL): 1 – 4 kJ, 527 nm, 1 – 4 ns
  - 2 kJ → 6.2 keV → 10^{15} photons/4π
  - 2 kJ → 16 keV → 10^{12}
  - Minimal, low-energy background
  - Routinely used on Z
- Z-Petawatt laser (ZPW): 0.25 – 1 kJ, 1054 nm, 0.1 ns
  - 1 kJ → 16 keV → 10^{14}
  - Strong, MeV-level background
  - Not yet used on Z

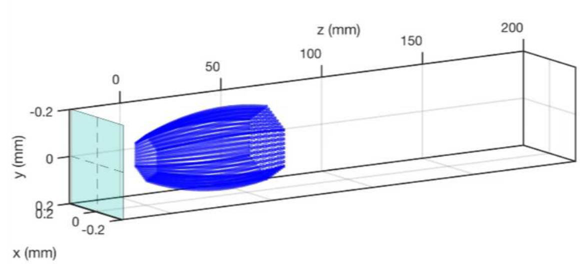


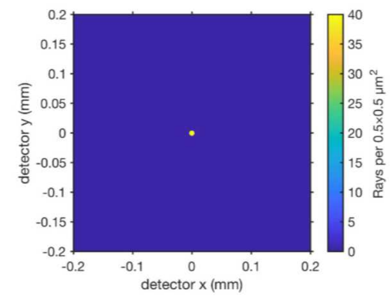
Enabling technology for ZPW XRD

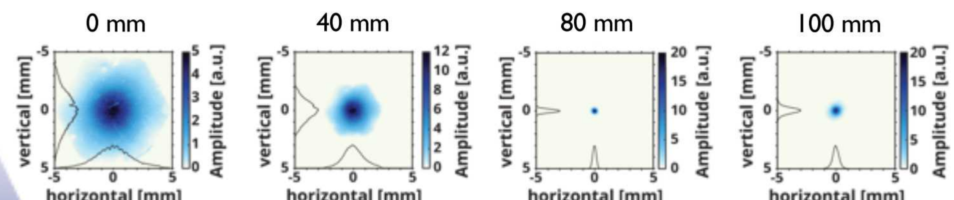
- Total external reflection focusing fiber bundle
- Throughput: $\Omega \times T \approx 5\text{x}10^{-3}$
- Number photons on sample: $10^9 - 10^{12}$
- X-ray flux gain vs. pinhole: 100 - 1000







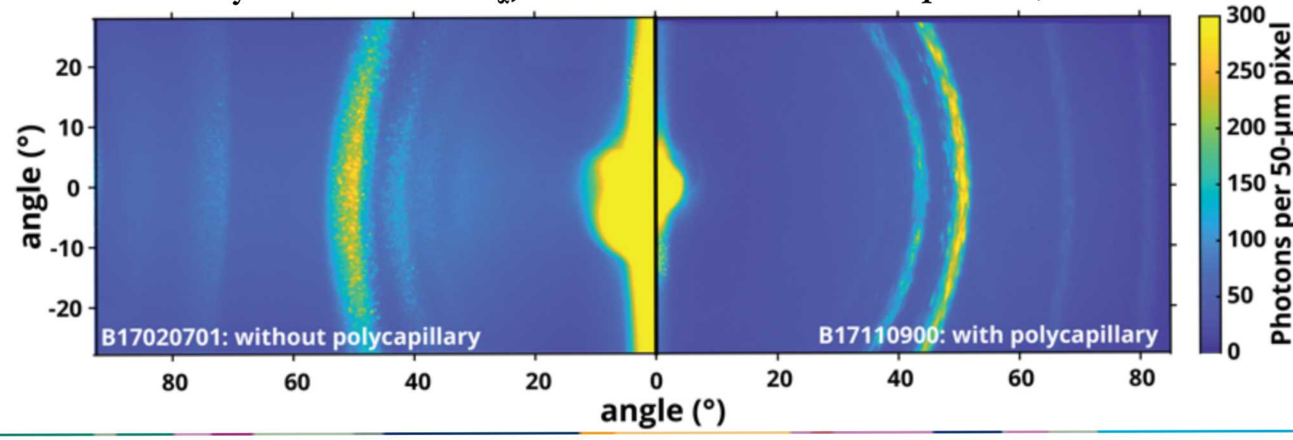




M. Schollmeier, T. Ao, *et al.*, RSI **89**, 10F102 (2018)

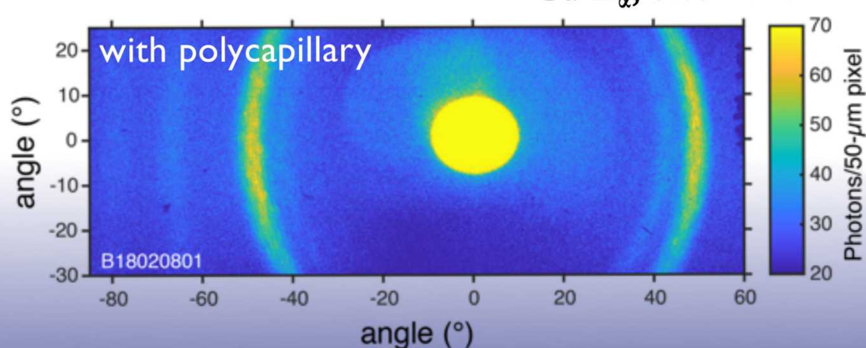
XRD DATA WITH ZBL (1 kJ, 1 ns, 10^{15} W/cm^2)

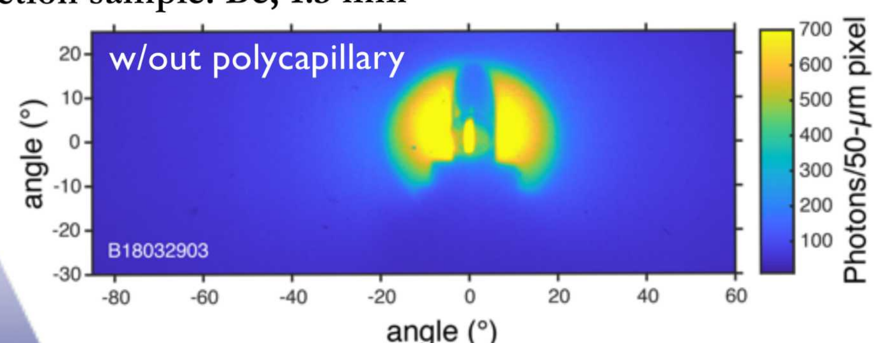
X-ray source: Cu He$_\alpha$, 8.4 keV. Diffraction sample: Be, 1.3 mm



XRD DATA WITH ZPW (250 J, 100 ps, 10^{18} W/cm^2)

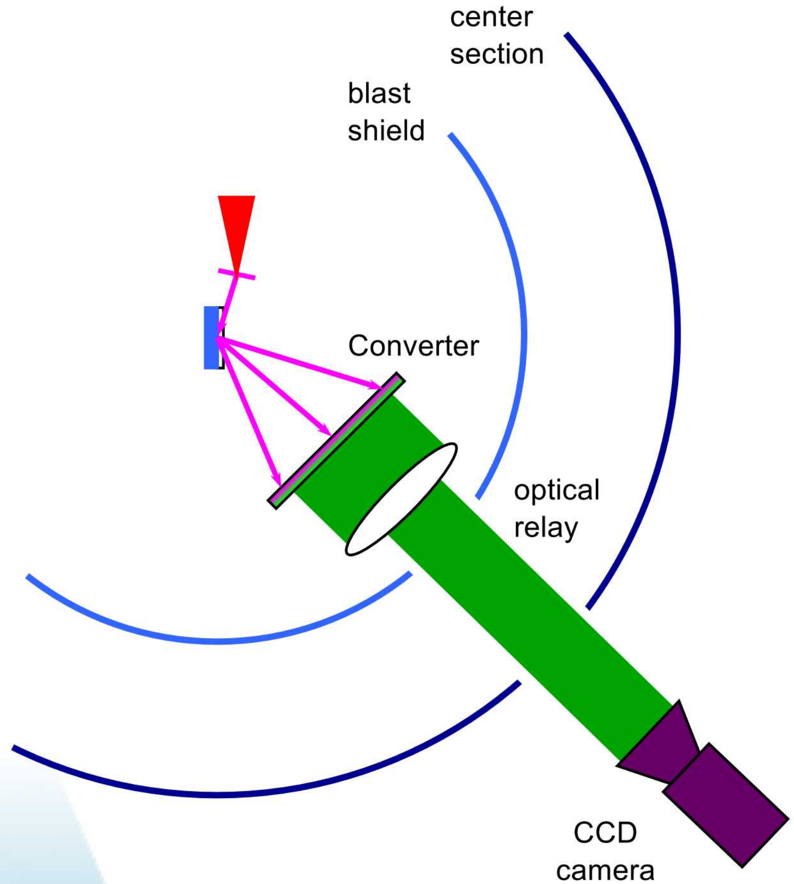
Cu K$_\alpha$, 8.05 keV. Diffraction sample: Be, 1.3 mm





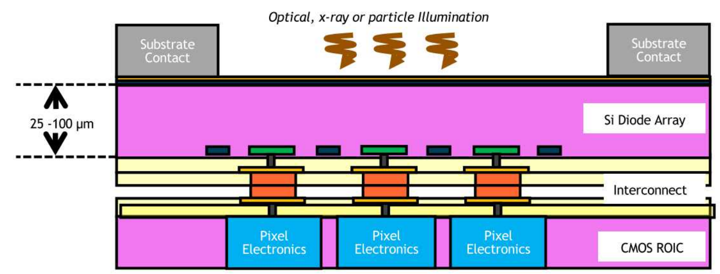
DIFFRACTION SCINTILLATOR OBJECTIVE (DISCO)

Detector	Chemical Formula	1/e Decay Time	Emission Wavelength (nm)	Light Yield (photons/keV)
Mirrored P-43	**$Gd_2O_2S:Tb$**	**1 ms**	**550**	**95**
Mirrored P-47	**$Y_2SiO_3:Ce$**	**70 ns**	**400**	**38**
Exalite 404	$C_{50}H_{58}$	3 ns	400	?
LSO	$Lu_2SiO_5:Ce^{3+}$	47 ns	400	30
PreLude420	$Lu_{1.8}Y_2SiO_5:Ce$	41 ns	420	32
BriLanCe380	$LaBr_3:Ce$	16 ns	380	63
ZnO:Ga	ZnO:Ga	0.8 ns	385	9
ScintiFast	?	< 1 ns	390	7.5
R42	?	68	510	11



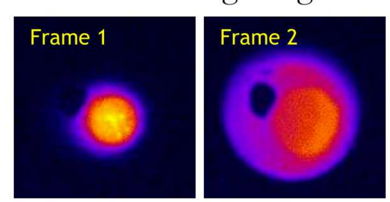
Ultrafast X-ray Imager (UXI)

- hCMOS chip composed of two layers:
  - 25-µm thick absorbing Si layer & readout integrated circuit (ROIC)
  - precisely aligned and then joined together at each pixel through indium bump bonds
- 25 µm pixels, 512 x 1024 format
- 1-20 ns exposure time, 1.5 ns inter-frame times
- 2-8 frames
- Actively fielded on Z machine for x-ray backlighting since 05/2018



CMOS Hybrid Image Sensor

X-ray emission from MagLIF gas cell on Z

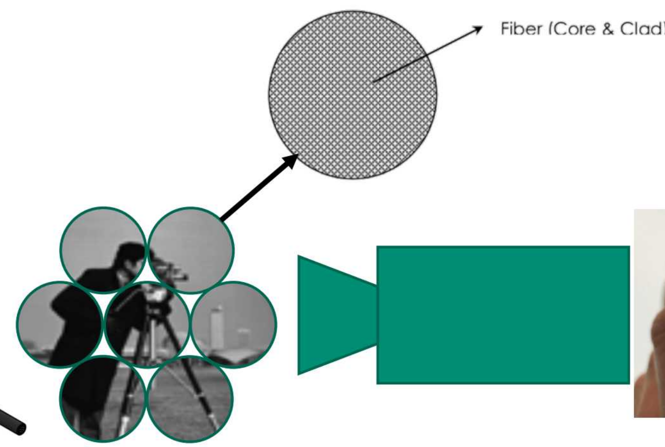


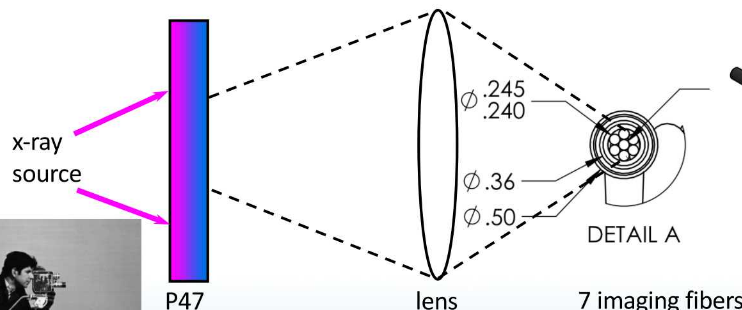
L. Claus, *et al.*, Proc. SPIE **10763**, 107630M (2018)
E. Hurd, *et al.*, Proc. SPIE **10763**, 107630L (2018)

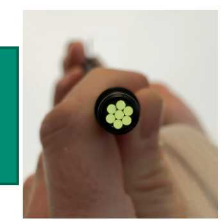
Fiber-based optical relay

- Asahi Multi-core POF MBL-2000-24 PMMA imaging fiber bundle
  - 13,000 fibers, 15 μm, 2 mm total
  - NA = 0.485
  - \$33/fiber/m → \$230/m for bundle
- Bundle of 7 registered imaging fibers
  - Hexagonal pattern
  - Effective diameter: 6 mm/ 0.24 in

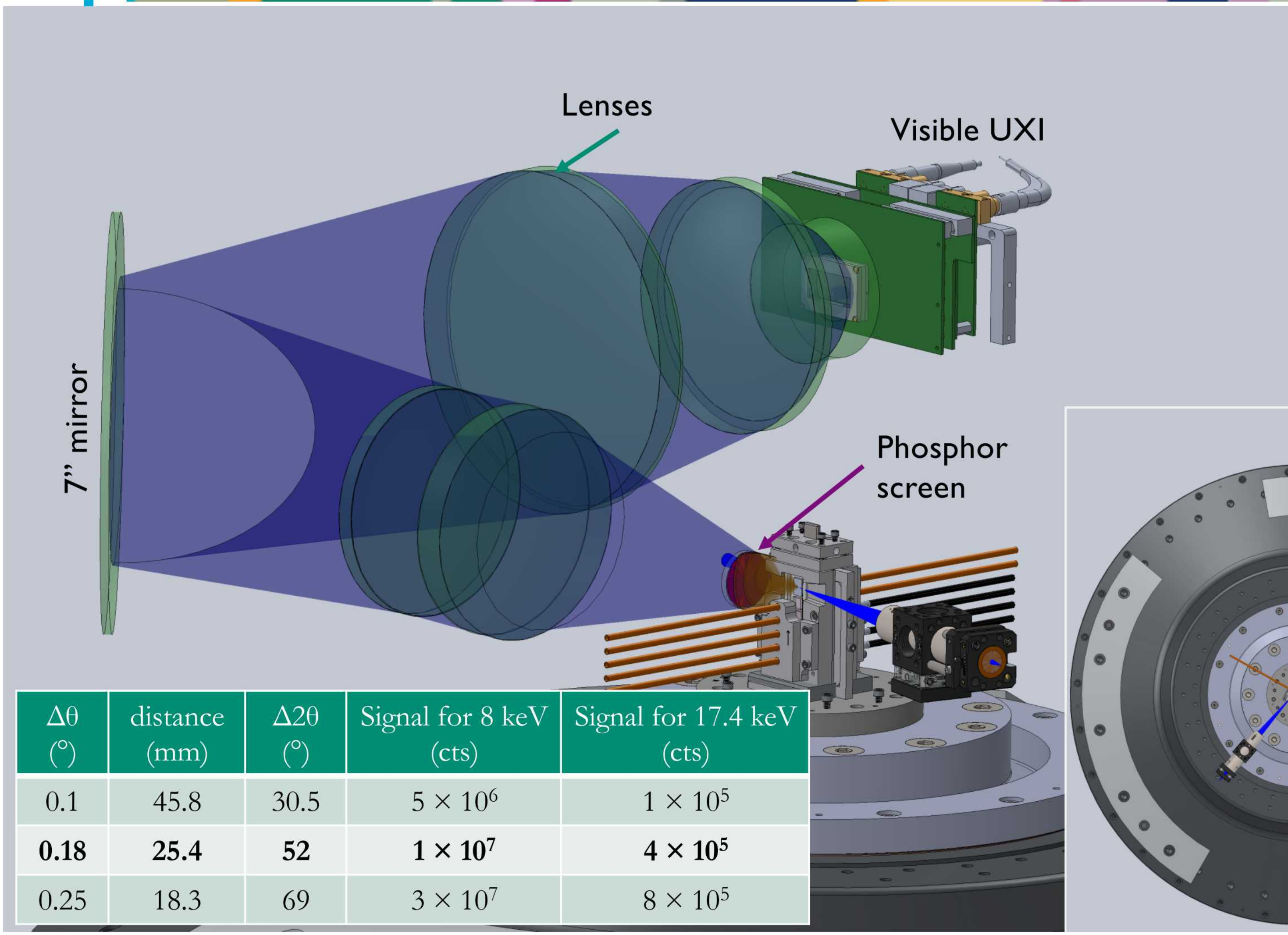
ITEM	UNIT	Specifications
Core Material		PMMA
Clad Material		Fluorinated Polymer
Fiber Diameter	μm	2000 ± 120
Core Number		13000
NA		0.5

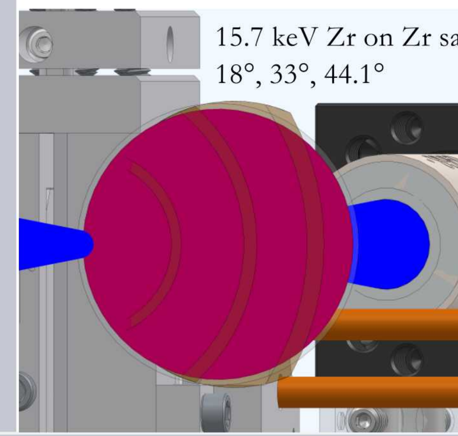


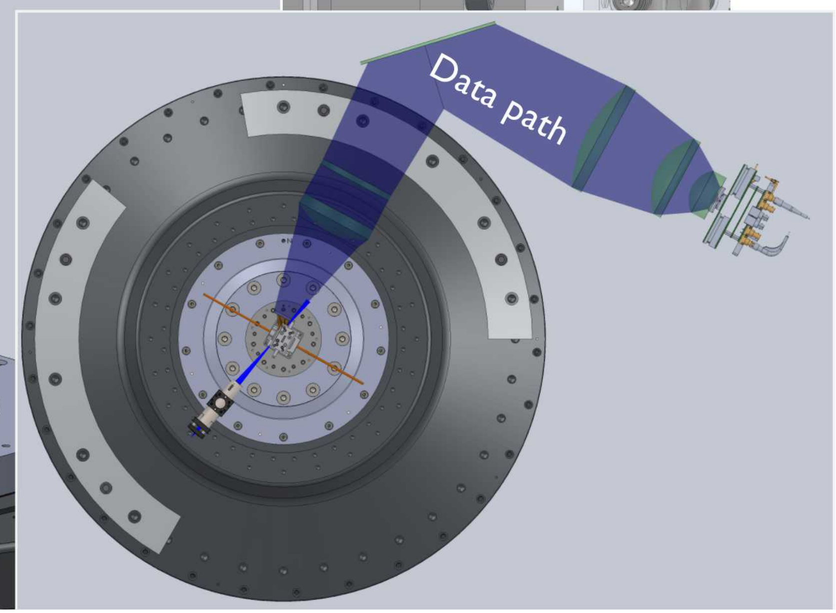




POSSIBLE Z-XRD CONFIGURATION: DISCO-UXI

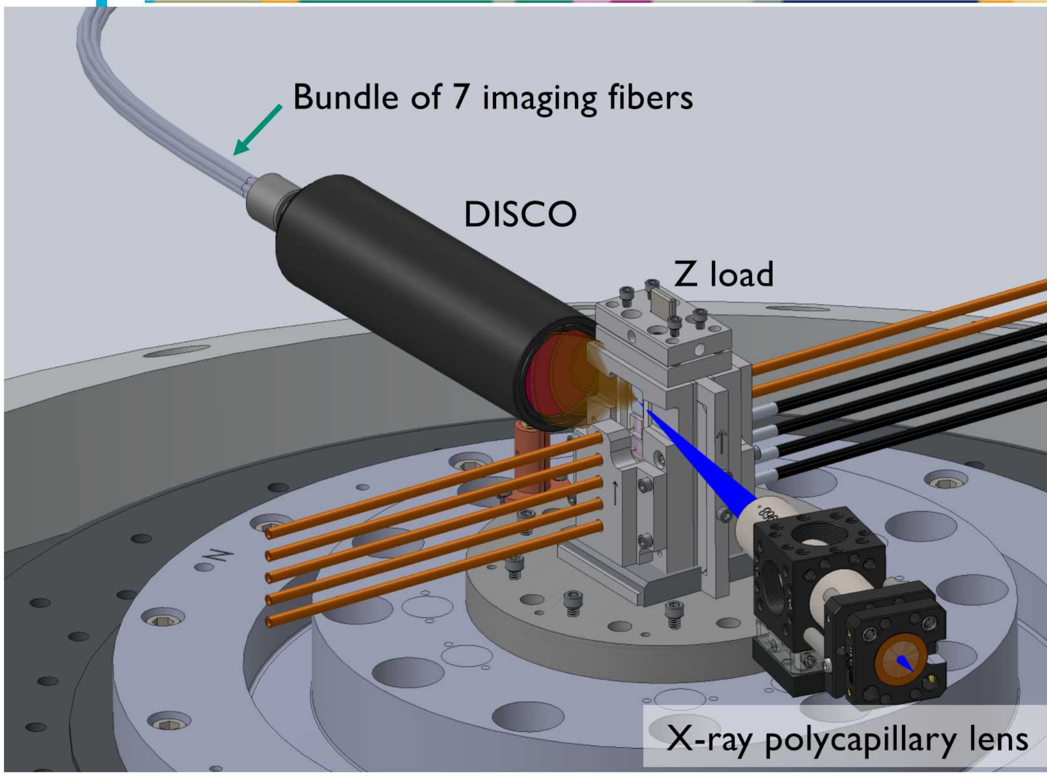


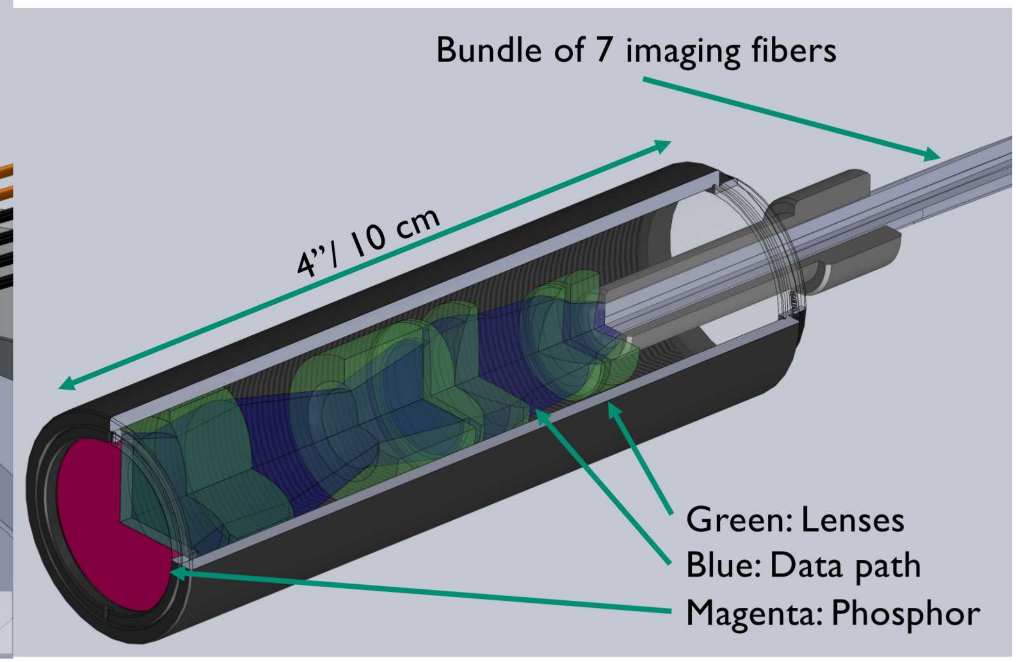




$\Delta\theta$ (°)	distance (mm)	$\Delta 2\theta$ (°)	Signal for 8 keV (cts)	Signal for 17.4 keV (cts)
0.1	45.8	30.5	5×10^6	1×10^5
0.18	**25.4**	**52**	$\mathbf{1 \times 10^7}$	$\mathbf{4 \times 10^5}$
0.25	18.3	69	3×10^7	8×10^5

POSSIBLE Z-XRD CONFIGURATION: DISCO-FIBER





$\Delta\theta$ (°)	distance (mm)	$\Delta 2\theta$ (°)	Signal for 8 keV (cts)	Signal for 17.4 keV (cts)
0.1	45.8	30.5	46,000	1,100
0.18	**25.4**	**52**	**150,000**	**4,000**
0.25	18.3	69	280,000	7,250

X-ray Diffraction on Z

- Mitigation of load debris and x-ray background challenges
- Spherical crystal diffraction imager (SCDI) enabled 1st XRD measurements on Z

Future Developments

- Higher photon energies (15-20 keV) x-ray sources using ZPW
- Polycapillary x-ray optics enhanced x-ray flux
- New detector schemes for time-resolved/gated XRD

Acknowledgements

- Paul Gard, Jim Williams, Caroline Blada, Heath Hanshaw, Ian Smith, Jon Shores, Shane Speas, Patrick Rambo, Ben Galloway, Chris Seagle, John Porter