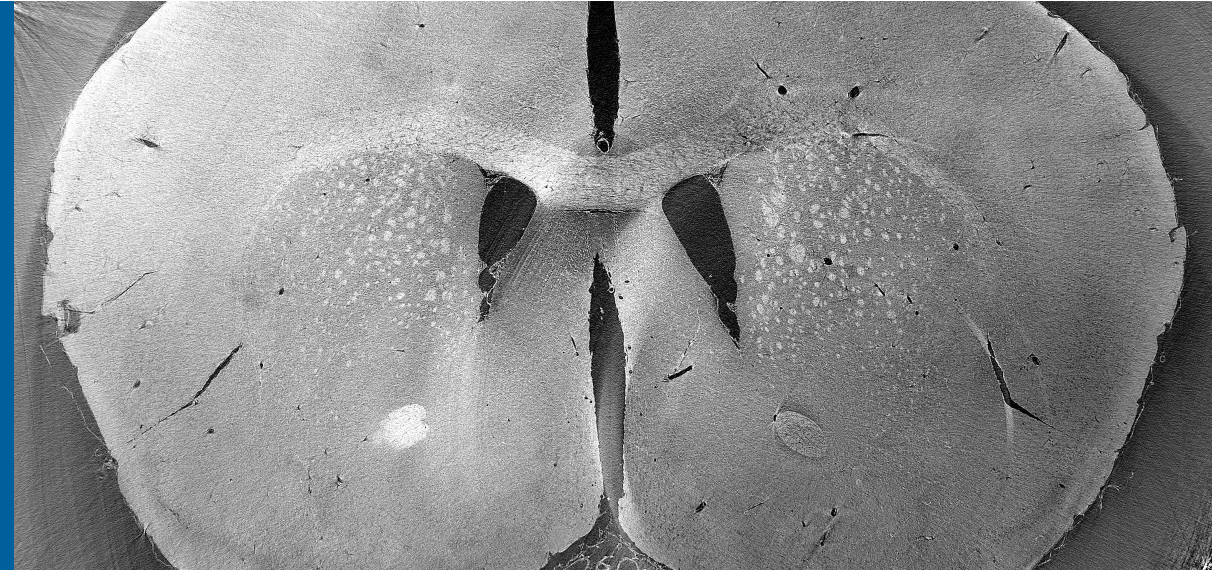
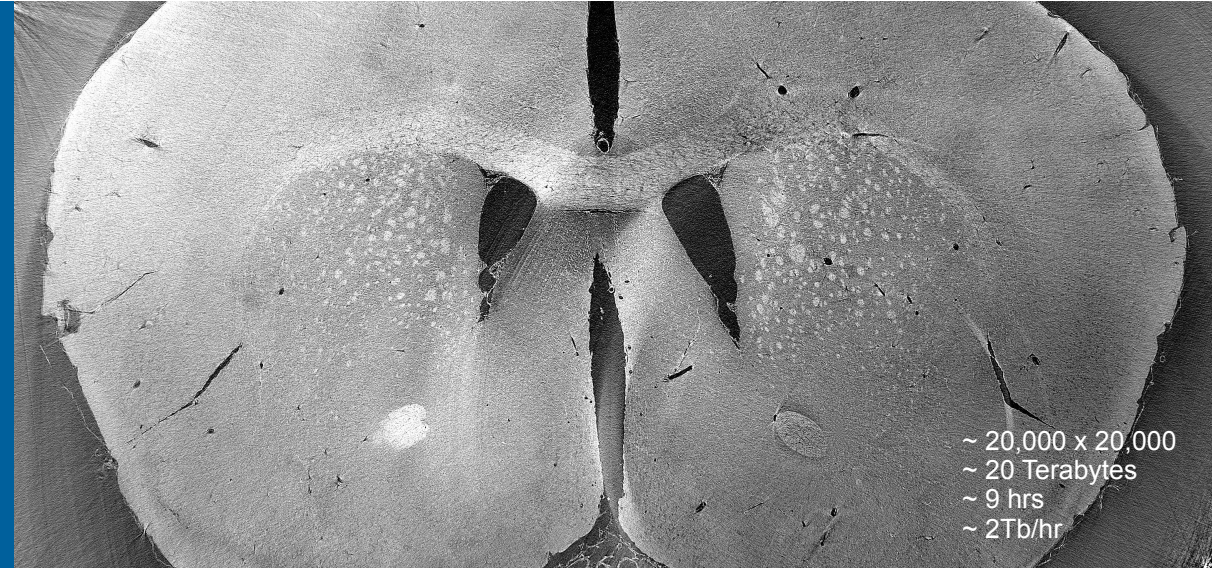


X-RAY FULL-FIELD IMAGING AT THE ADVANCED PHOTON SOURCE



Francesco De Carlo
Imaging Group, Advanced Photon Source

X-RAY FULL-FIELD IMAGING AT THE ADVANCED PHOTON SOURCE

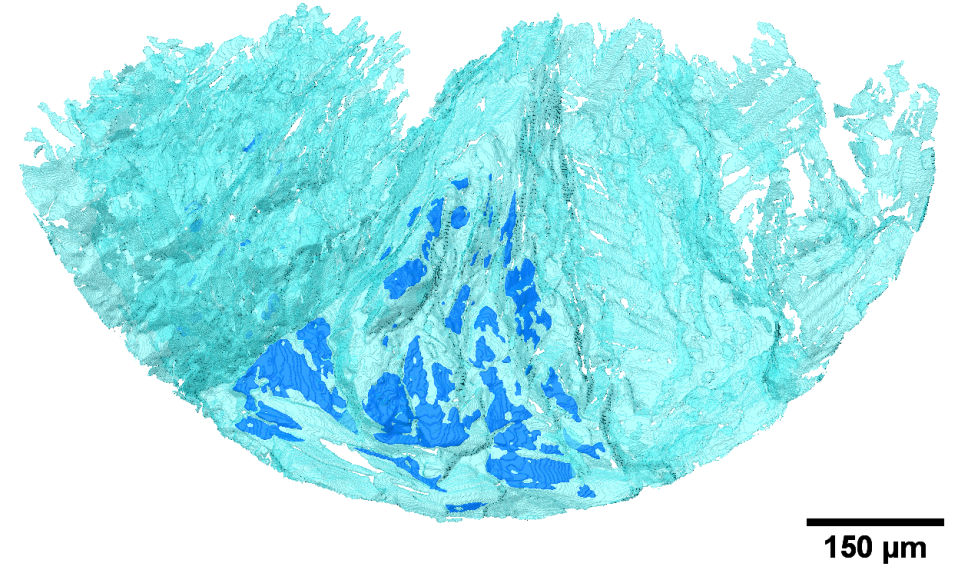


~ 20,000 x 20,000
~ 20 Terabytes
~ 9 hrs
~ 2Tb/hr

Francesco De Carlo
Imaging Group, Advanced Photon Source

X-RAY FULL-FIELD IMAGING AT THE ADVANCED PHOTON SOURCE

Francesco De Carlo
Imaging Group, Advanced Photon Source

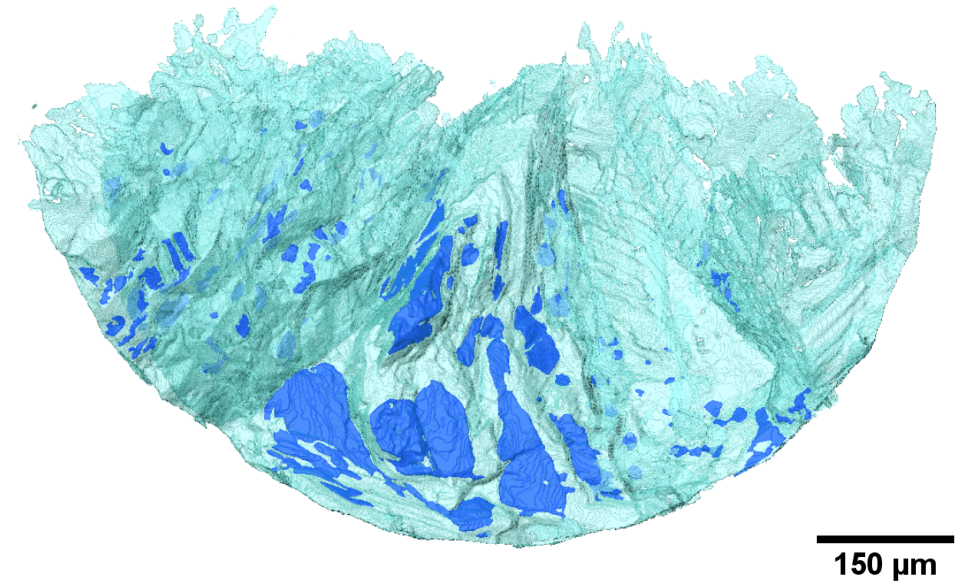


12 MPa

**ALUMINUM 7475 CORROSION
FATIGUE WITHIN THE CYCLE 5150**

X-RAY FULL-FIELD IMAGING AT THE ADVANCED PHOTON SOURCE

Francesco De Carlo
Imaging Group, Advanced Photon Source

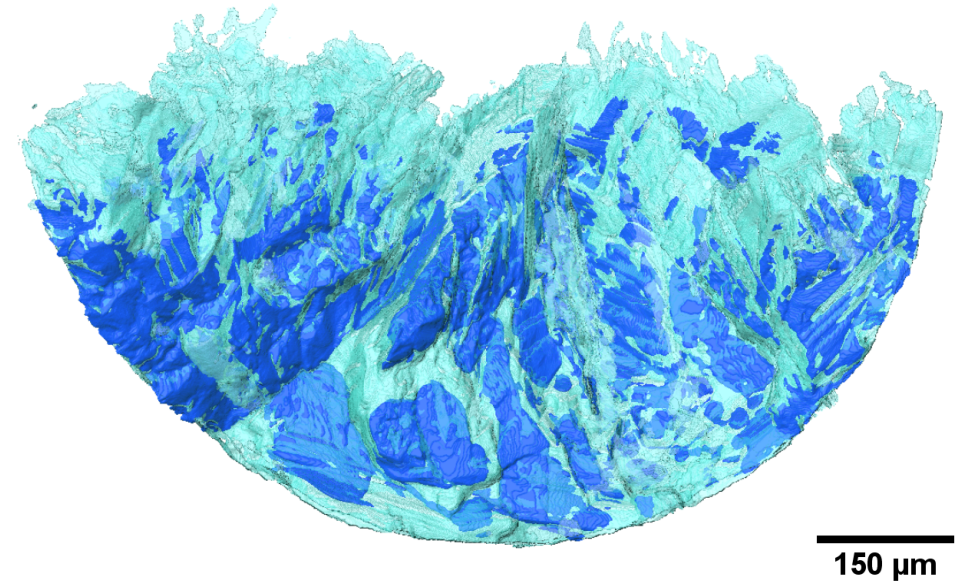


71 MPa

**ALUMINUM 7475 CORROSION
FATIGUE WITHIN THE CYCLE 5150**

X-RAY FULL-FIELD IMAGING AT THE ADVANCED PHOTON SOURCE

Francesco De Carlo
Imaging Group, Advanced Photon Source

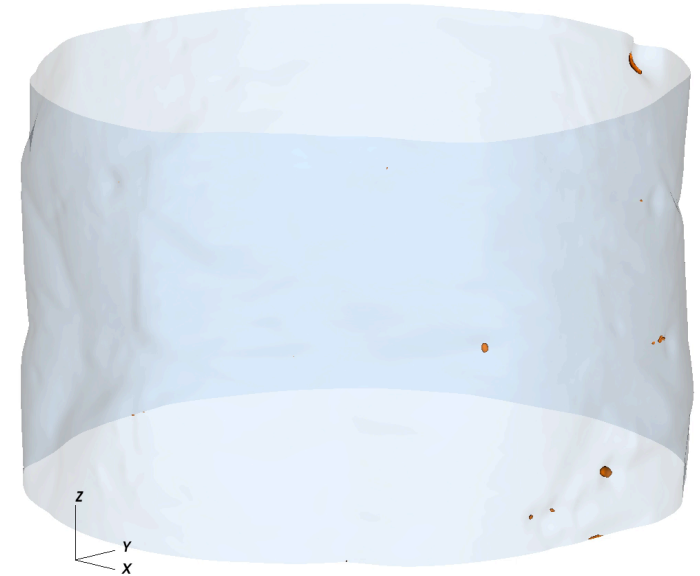


120 MPa

ALUMINUM 7475 CORROSION
FATIGUE WITHIN THE CYCLE 5150

X-RAY FULL-FIELD IMAGING AT THE ADVANCED PHOTON SOURCE

Francesco De Carlo
Imaging Group, Advanced Photon Source



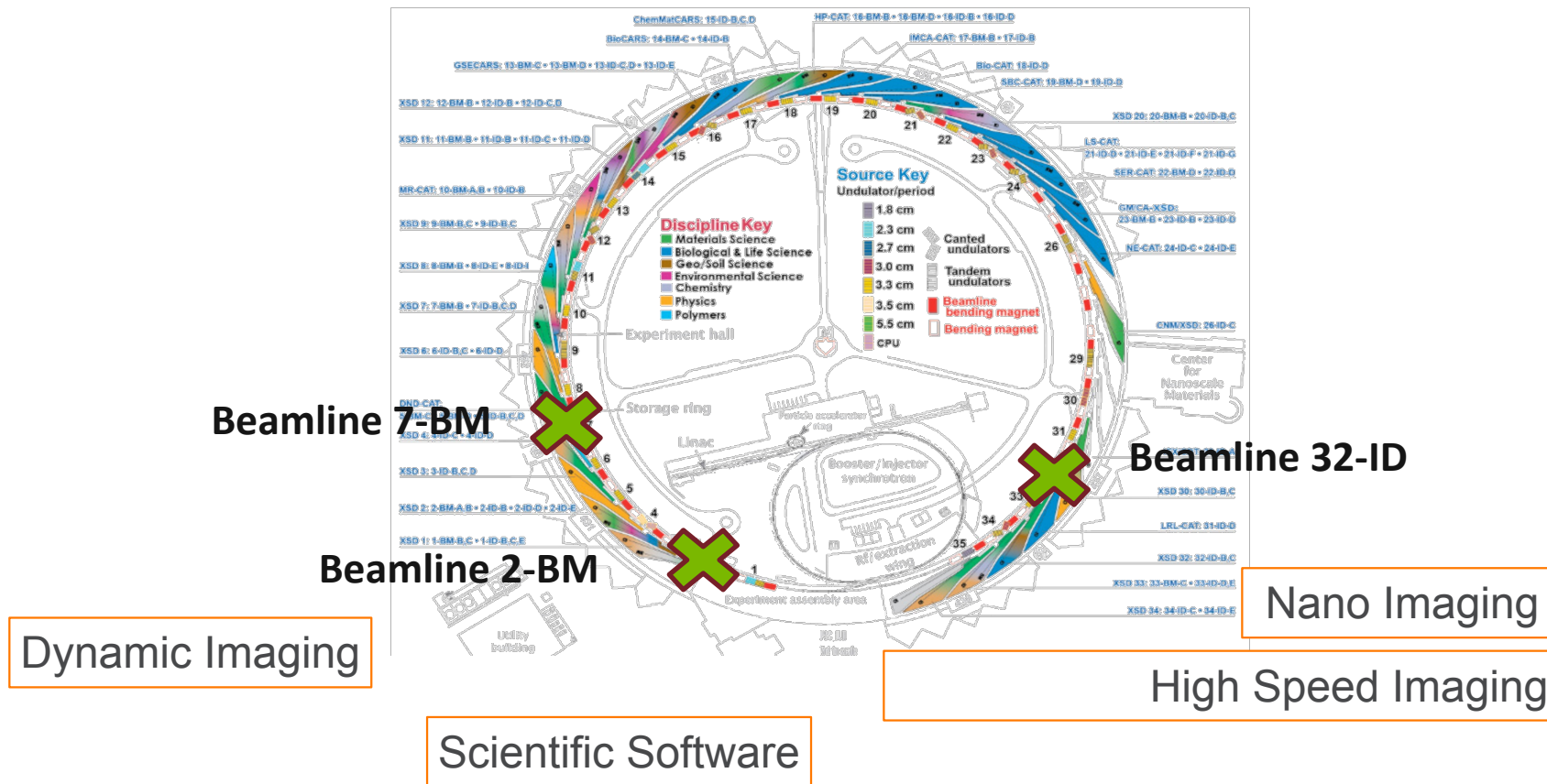
OVERVIEW

- Introduction
 - X-ray Full-field Imaging (the last ~1-2 years)
 - 2D/3D Dynamic Imaging
 - APS Upgrade opportunities
 - Challenges in increasing temporal and spatial resolution
 - Real-time Data Analysis and Experimental Steering
 - Streaming Data Analysis

INTRODUCTION

ADVANCED PHOTON SOURCE

X-ray Imaging



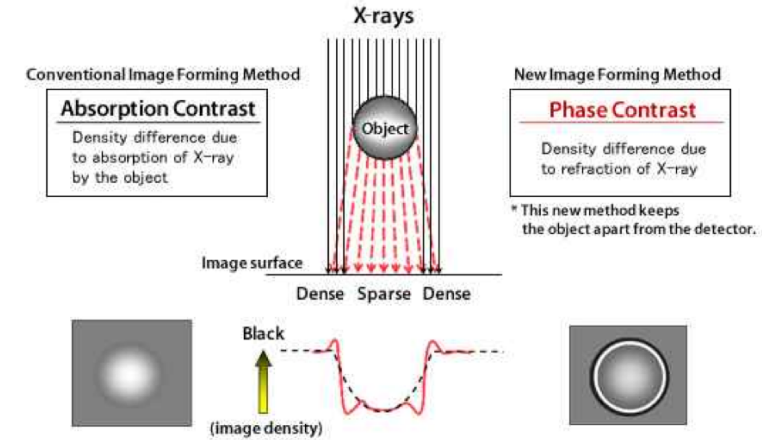
- 2-BM <https://docs2bm.readthedocs.io/>
- 7-BM <https://docs2bm.readthedocs.io/>
- 32-BM <https://docs2bm.readthedocs.io/>

IMAGING GROUP CURRENT TECHNIQUES

X-RAY IMAGING

Current techniques

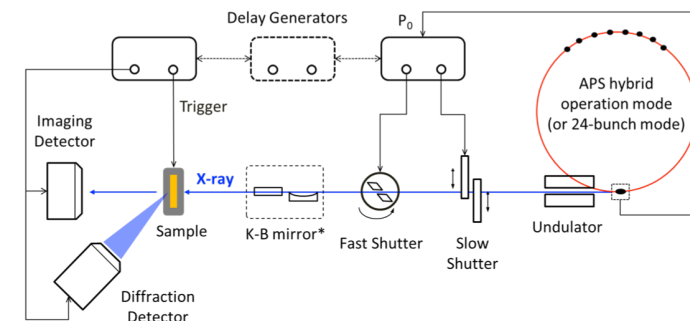
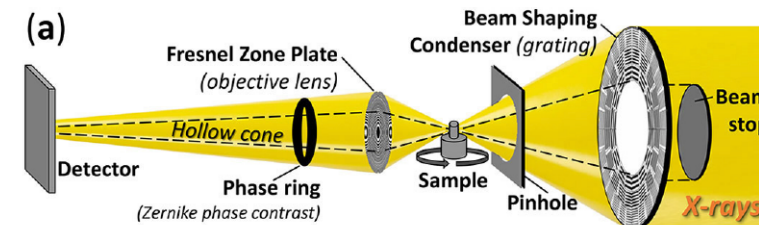
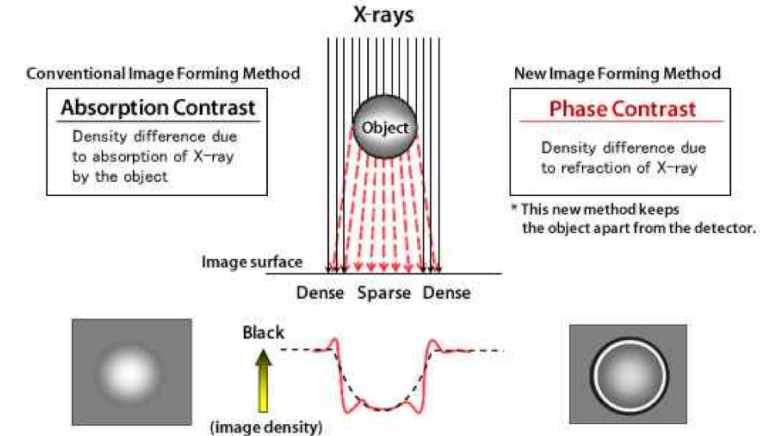
- Parallel Beam Imaging (PBI)
 - Phase and absorption
 - Spatial resolution: 1 μm
 - Temporal resolution:
 - 2D: 10.0 MHz, 100 ps
 - 3D: kHz projection



X-RAY IMAGING

Current techniques

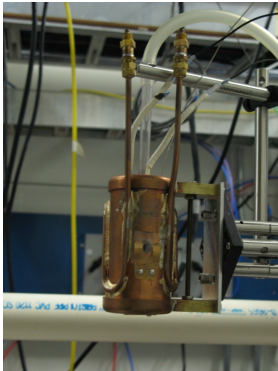
- Parallel Beam Imaging (PBI)
 - Phase and absorption
 - Spatial resolution: $1\ \mu\text{m}$
 - Temporal resolution:
 - 2D: 10.0 MHz, 100 ps
 - 3D: kHz projection
- Transmission X-ray Microscopy
 - Zernike and absorption
 - Spatial resolution: $< 10\ \text{nm}$
 - Temporal resolution:
 - 3D: 5 Hz projection
- Complementary technique:
 - High speed diffraction
 - XANES



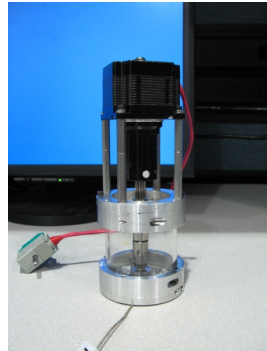
DYNAMIC IMAGING

DYNAMIC IMAGING

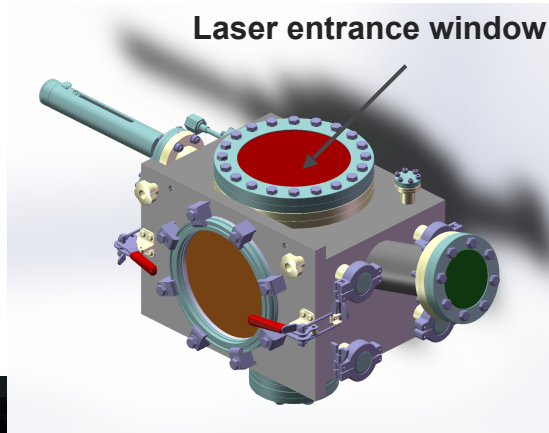
Environment Control Cells



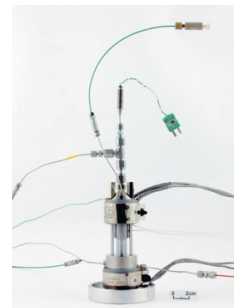
Large Hot-zone Furnaces
T Range: 25 – 1200 °C
Accuracy: 0.5 °C



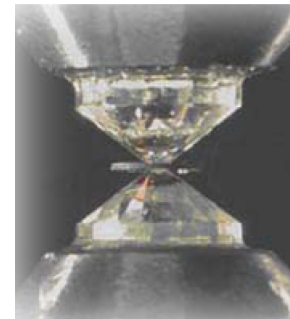
Uniaxial Load fixture
Load: up to 50N
Cyclic Load Freq: 2Hz



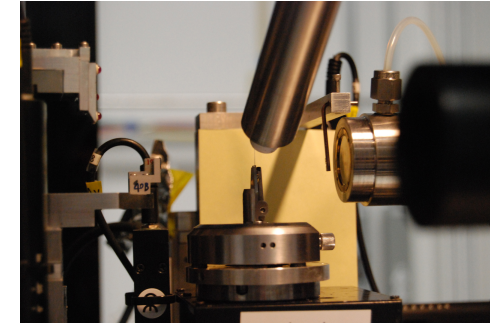
AM cells



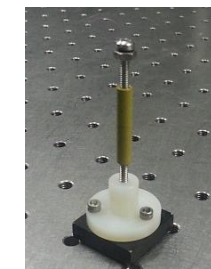
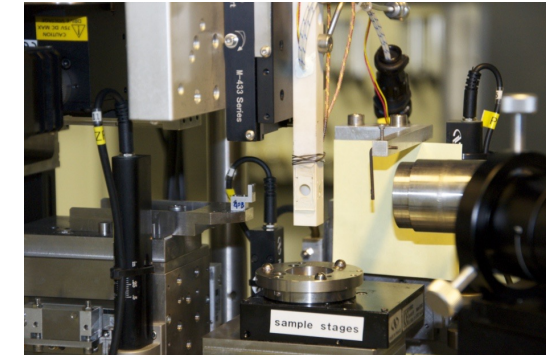
High T High P cell
T Range: up to 250 °C
P Range: up to 25 MPa



Diamond Anvil Cell



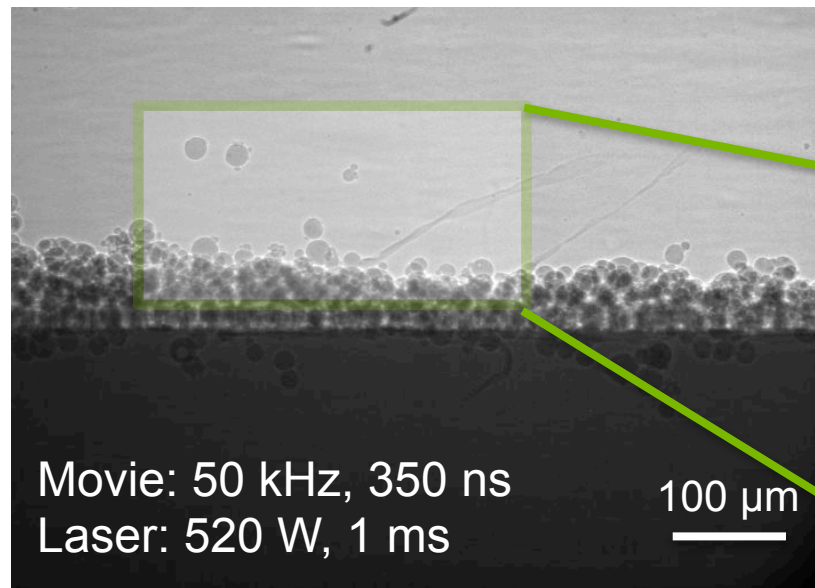
in situ nano imaging cells



in situ LiB cells

DYNAMIC IMAGING

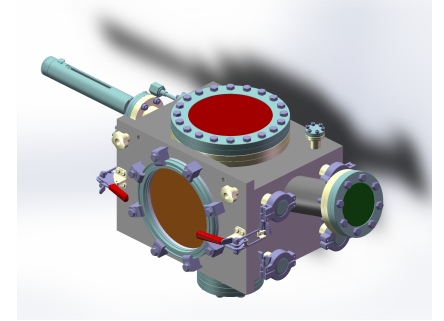
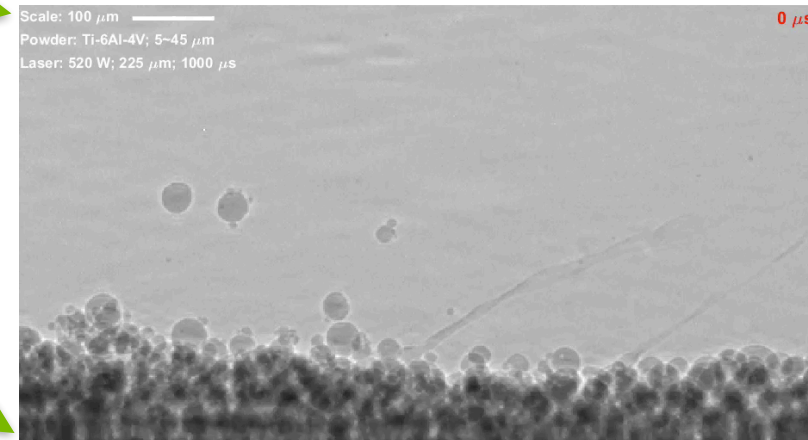
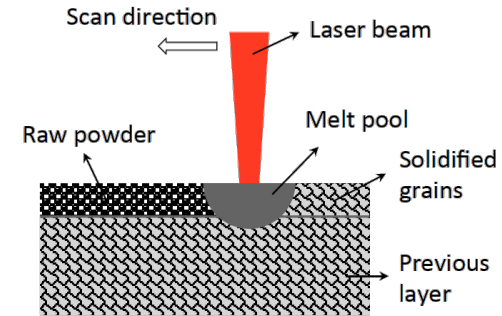
High-speed x-ray imaging of laser powder bed fusion



Ar

Ti64
powders

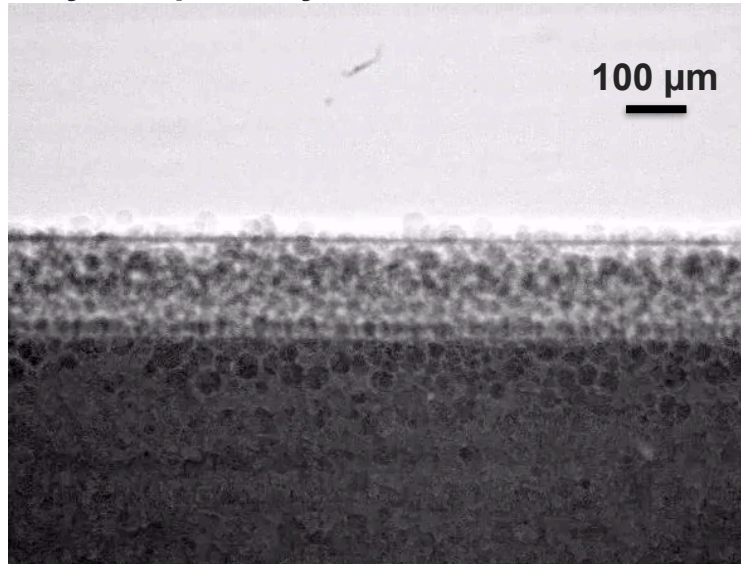
Ti64
base



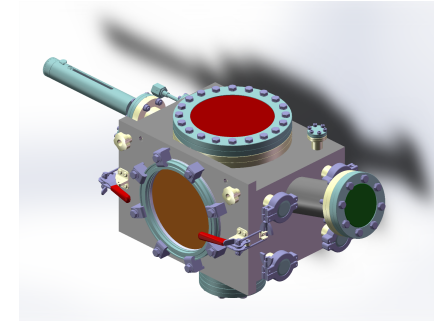
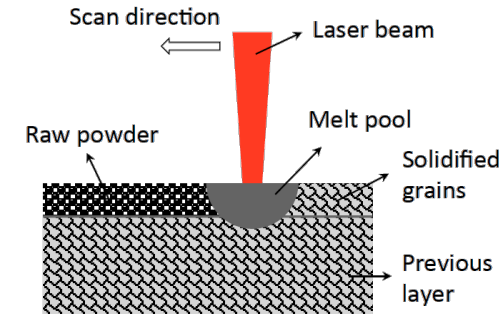
DYNAMIC IMAGING

High-speed x-ray imaging of laser powder bed fusion

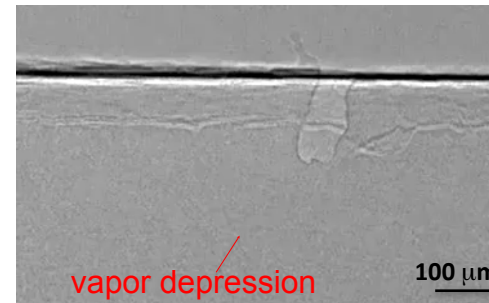
Single-pulse x-ray imaging of keyhole porosity formation



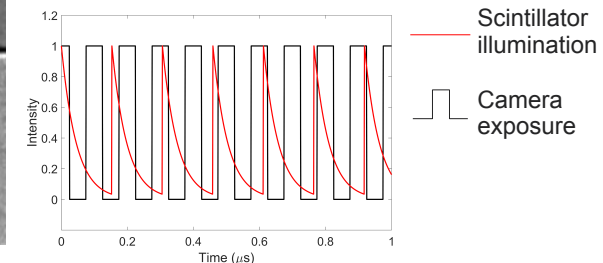
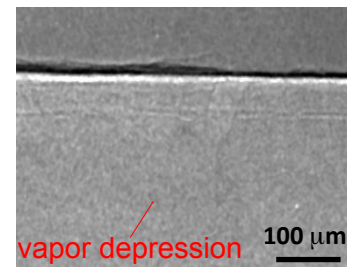
Material: Ti-6Al-4V
Recording rate: 45,000 fps
Exposure time: 0.1 ns
Video timespan: 7 ms



MHz imaging of vapor depression dynamics



Material: Al6061 alloy
Recording rate: 1,080,000 fps
Exposure time: 0.1 ns

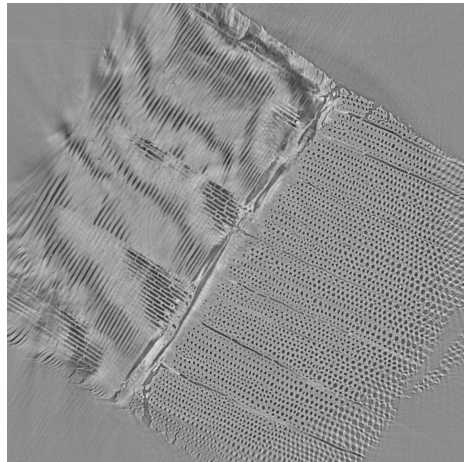
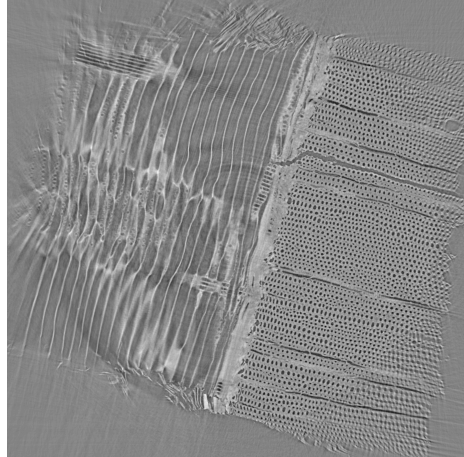


Material: Al6061 alloy
Recording rate: 10,000,000 fps (6.5 MHz pulse rate)

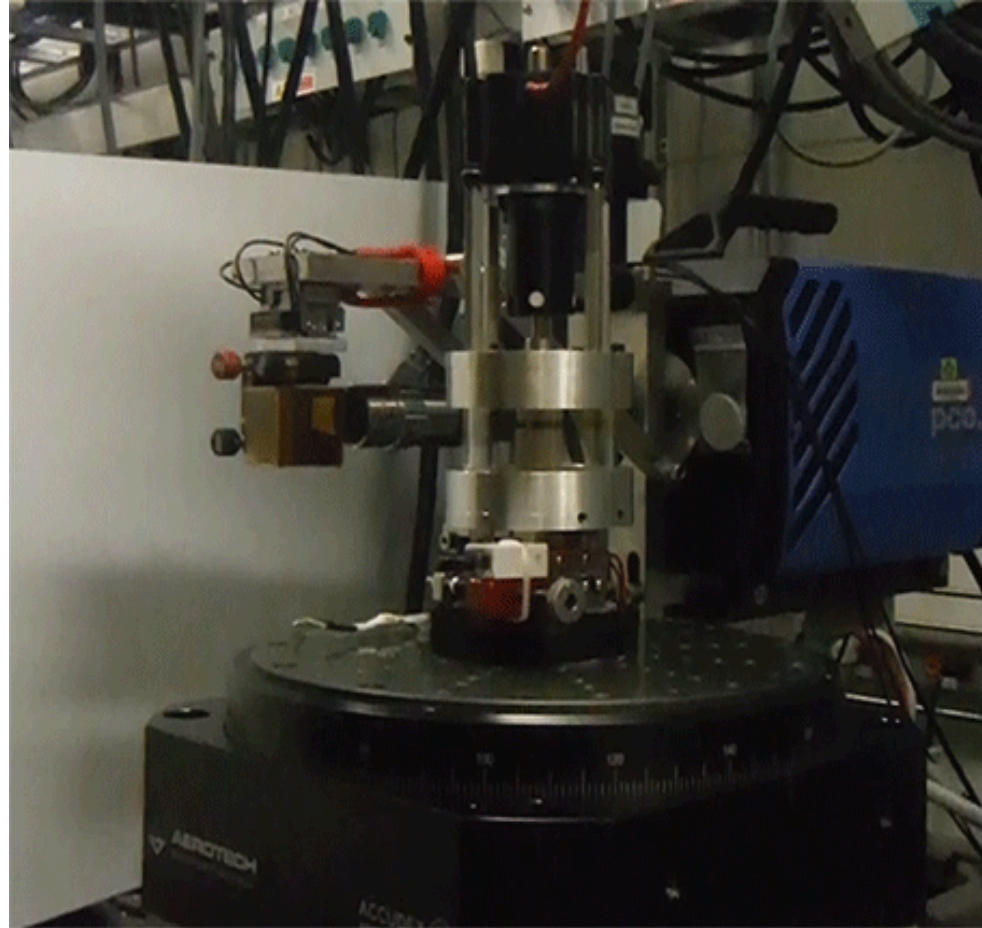
3D DYNAMIC IMAGING

DYNAMIC IMAGING

3D imaging of dynamic systems



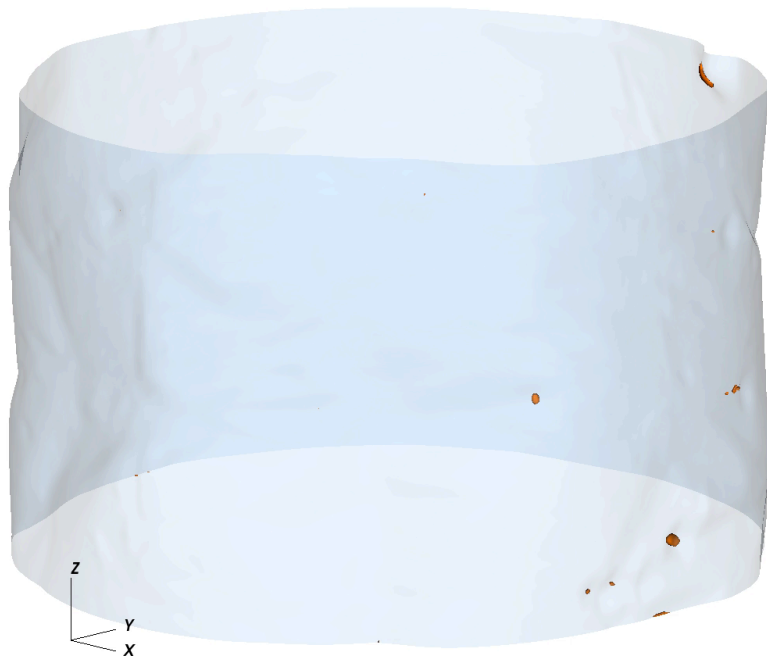
Wood adhesive bondline swelling and shrinking
J. Jakes, USDA Forest Service, Forest Products Laboratory,
Madison, WI



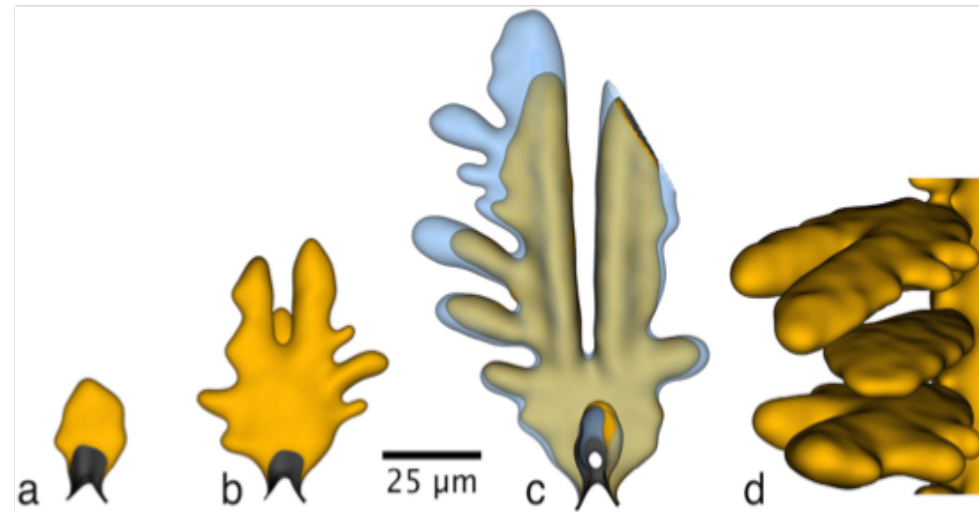
DYNAMIC IMAGING

3D imaging of dynamic systems

Growth of Al-rich dendrite in Al-Cu alloy
Cooling rate 1K/min from 550 K. 3D tomographic dataset in 1.6 s



J.W. Gibbs, et al. Sci. Rep. 5, 11824-1-11824-9 (2015)



Evolution of a split tip of a secondary dendrite arm. (a) and (b) are one dendrite arm at 7.2, and 9.0 s and show the evolution of a splitting event. (c) shows a different arm at 10.8 s in yellow and at 14.4 s in a semi-transparent blue; this shows the large groove depths that are achievable and that the groove is very slow to evolve. (d) is a view of multiple branches showing the unusual morphology of the secondary arms.

3D NANO IMAGING

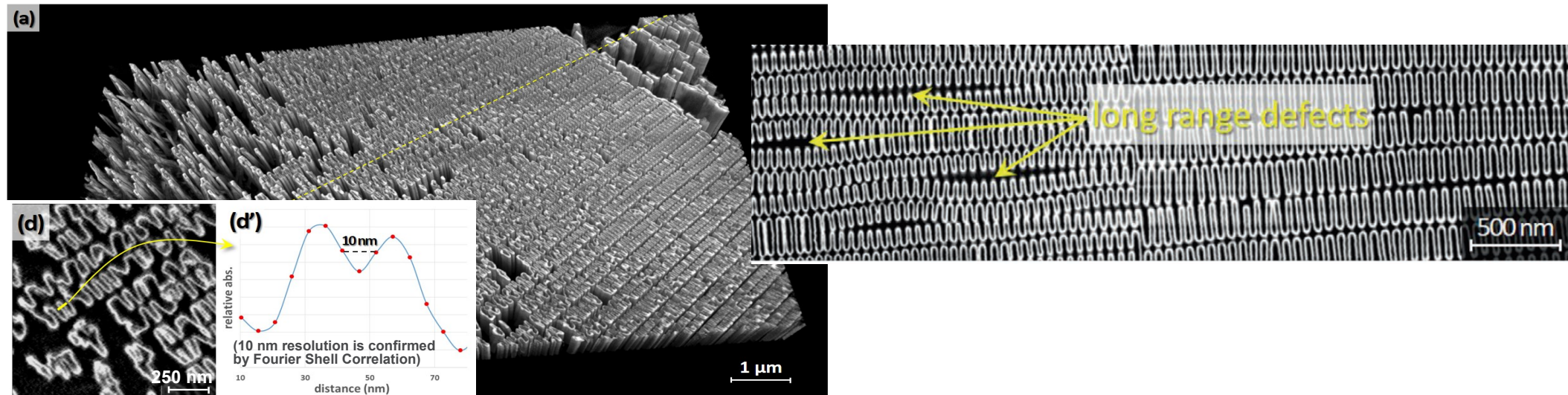
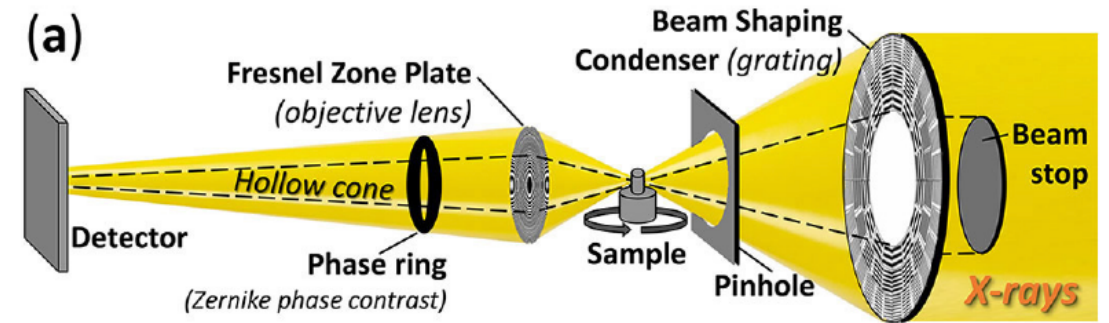
NANO IMAGING

9.4 nm 3D spatial resolution

Achieved through in-house R&D on X-ray optics, opto-mechanical components & advanced algorithms

Nanolithography application:

- Non invasive characterization of 3D nano-fabricated objects (no sectioning or cleavage)
- Resolving **16 nm** large walls and **10 nm** large defects in Fresnel Zone Plates
- Data acquisition time **85 min**



V. De Andrade et al. "Fast X-ray Nanotomography with Sub-10 nm Resolution as a Powerful Imaging Tool for Nanotechnology and Energy Storage Applications." *Advanced Materials* (2021): e2008653 (1-11)

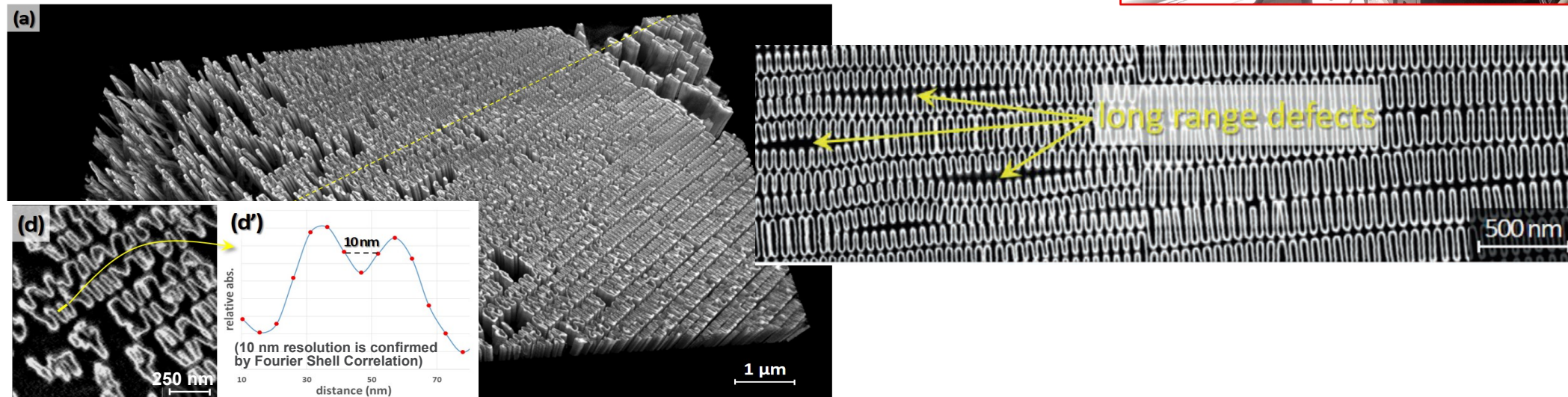
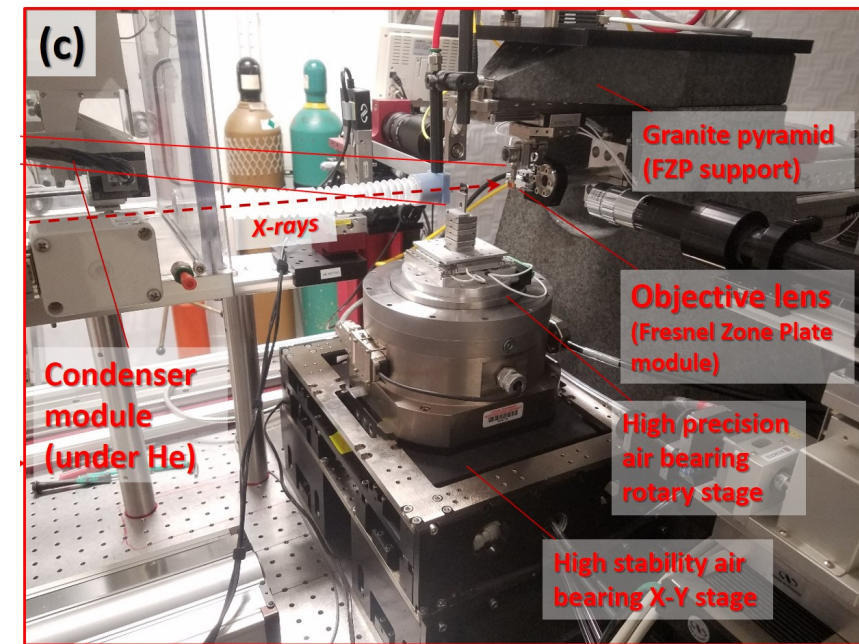
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V. De Andrade et al. "Fast X-ray Nanotomography with Sub-10 nm Resolution as a Powerful Imaging Tool for Nanotechnology and Energy Storage Applications." *Advanced Materials* (2021): e2008653 (1-11)

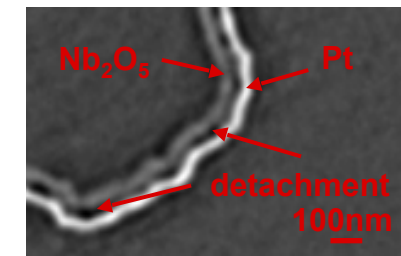
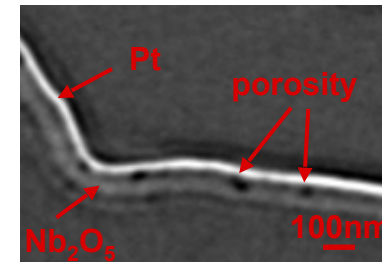
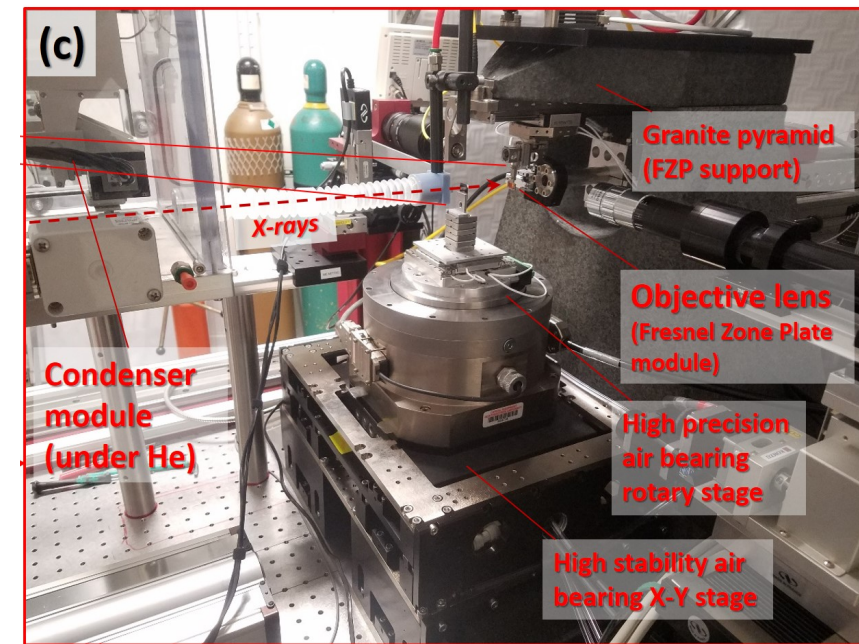
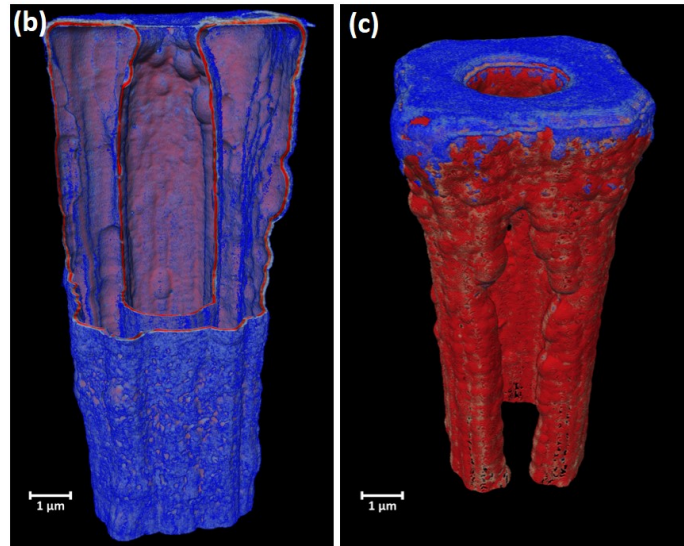
NANO IMAGING

9.4 nm 3D spatial resolution

Achieved through in-house R&D on X-ray optics, opto-mechanical components & advanced algorithms

Energy storage application:

- Studying a new class of miniaturized electrochemical capacitor with high energy densities and high rates capabilities
- Made of **30 nm** thick Pt film scaffold
- Nano-CT confirms **10-15 nm** pores formation on a 3D scaffold
- Data acquisition time **85 min**



Reconstructions were done with an advanced algorithm involving projection data alignment by using optical flow². Reconstruction time is 5 h on a single GPU-based (Tesla A100) ALCF node, scalable to tens of minutes on a larger cluster.

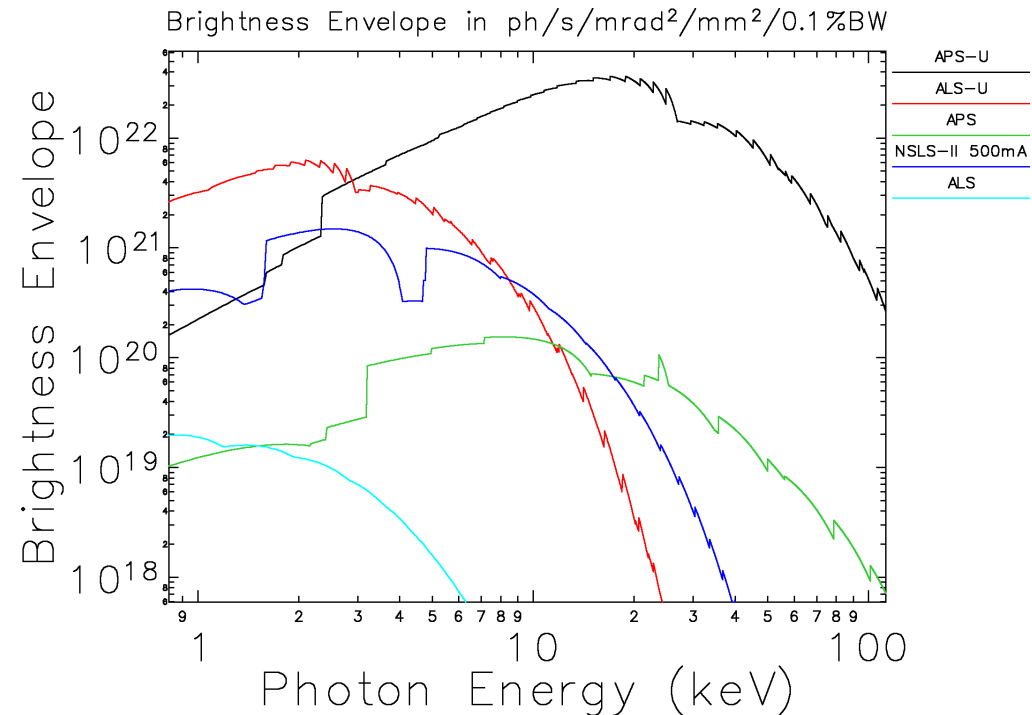
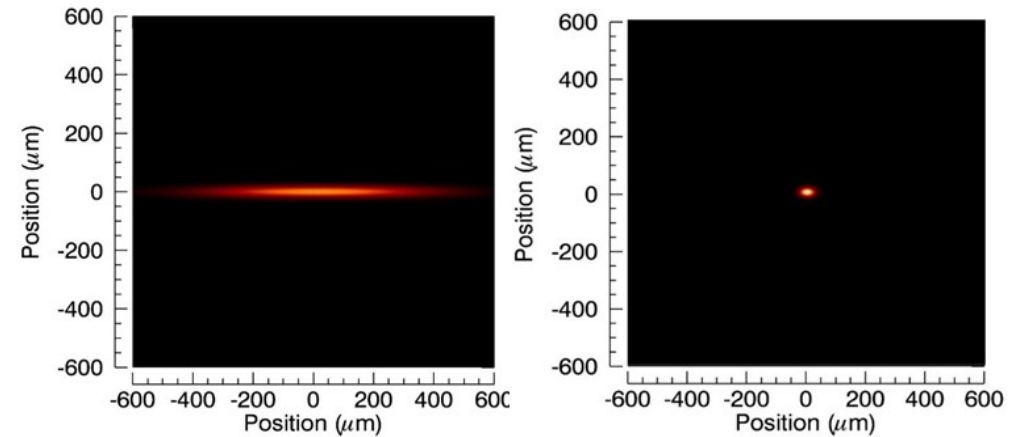
V. De Andrade et al. "Fast X-ray Nanotomography with Sub-10 nm Resolution as a Powerful Imaging Tool for Nanotechnology and Energy Storage Applications." *Advanced Materials* (2021): e2008653 (1-11)

APS UPGRADE

APS UPGRADE

Electron emittance reduced from
3000 pm-rad to 42 pm-rad

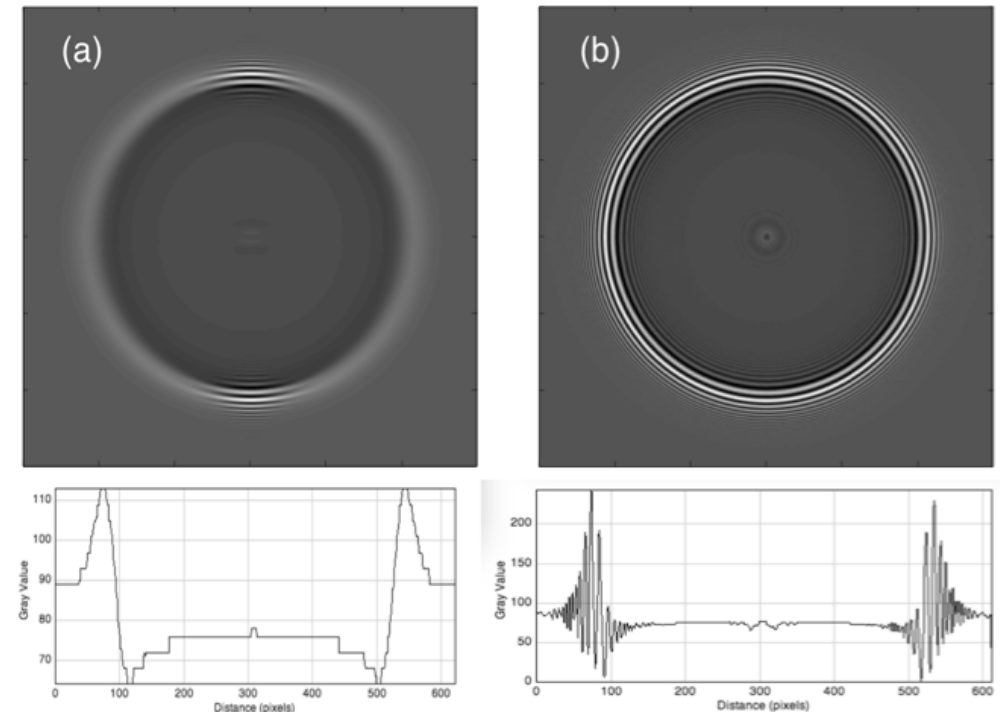
- >200x higher brightness
- micro/nanoprobe: increased flux
- smaller spot sizes
- imaging: increased contrast
- greatly enhanced stability



APS UPGRADE

Electron emittance reduced from
3000 pm-rad to 42 pm-rad

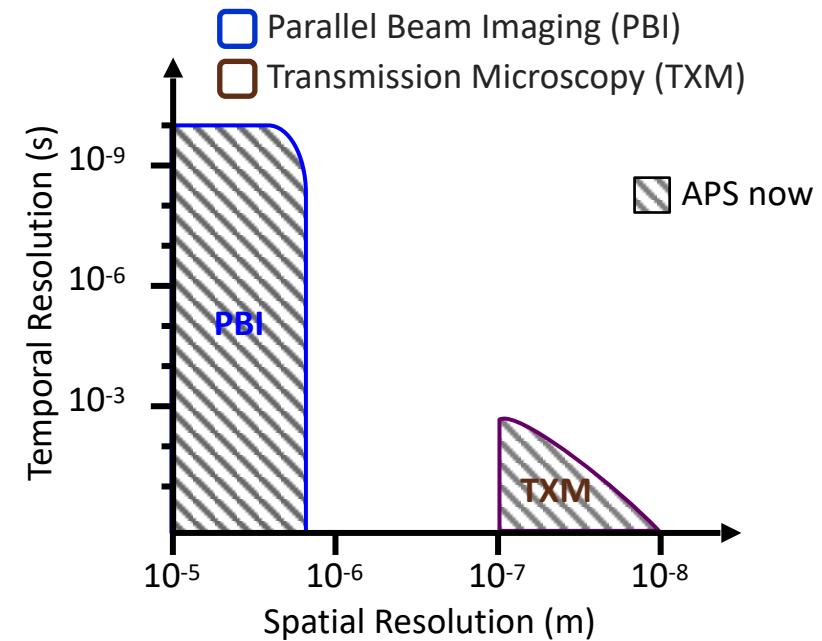
- >200x higher brightness
- micro/nanoprobe: increased flux
- smaller spot sizes
- **imaging: increased contrast**
- greatly enhanced stability



Source size effects in PCI. Simulated images of a water drop (0.4 mm diameter) with an air bubble inside (2 μm diameter) at 15 keV. (a) With current APS lattice, (b) with future MBA lattice.

APS UPGRADE

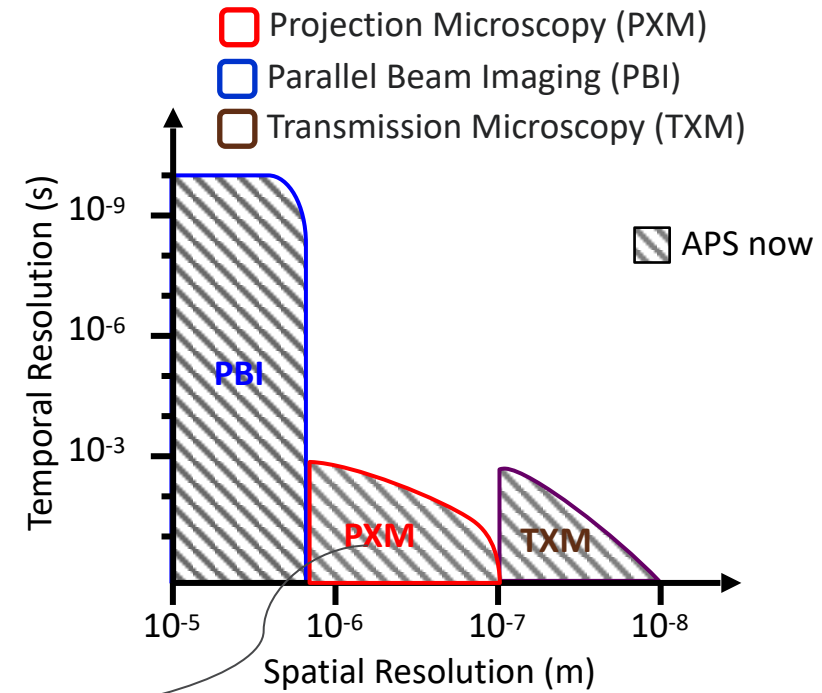
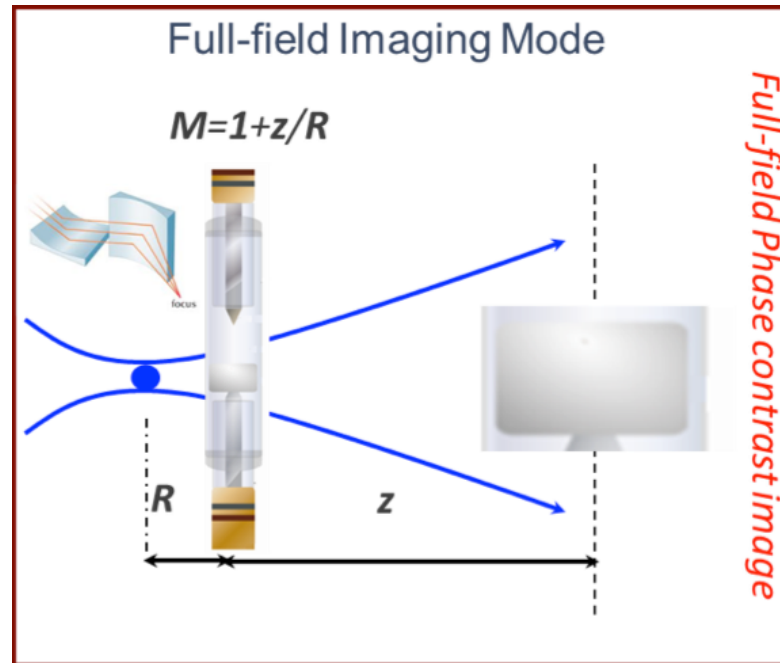
- Resolution: dynamic $> 1 \mu\text{m}$
- Lack of integrated multimodality
 - Different time scales



Temporal and spatial resolution range for the proposed APS-U imaging beamline.

APS UPGRADE

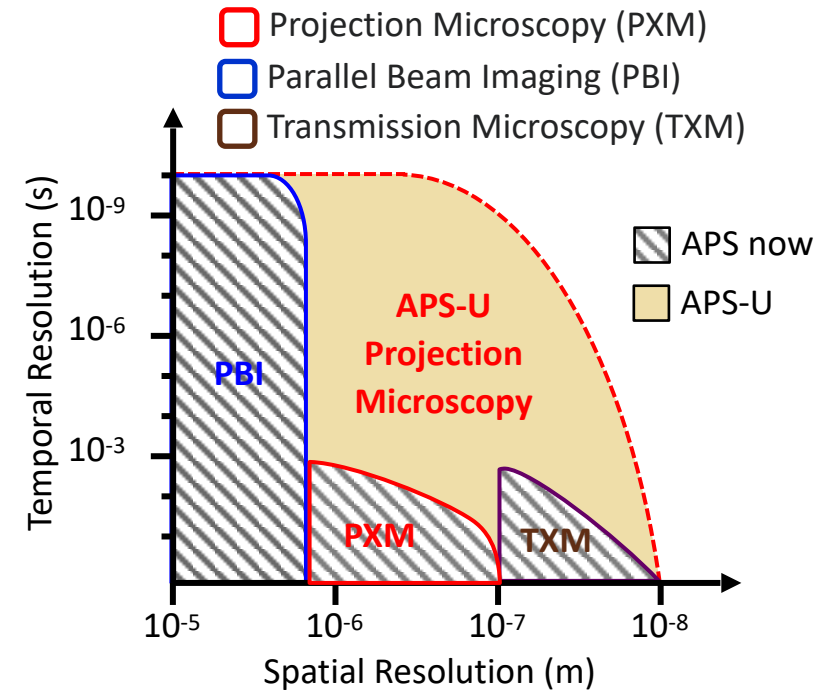
- Resolution: dynamic > 1 μm
- Lack of integrated multimodality
 - Different time scales



Temporal and spatial resolution range for the proposed APS-U imaging beamline.

APS UPGRADE

- Hierarchical characterization of dynamic systems and materials with spatial resolution below 1 μm , without a sacrifice in time resolution nor the field of view.

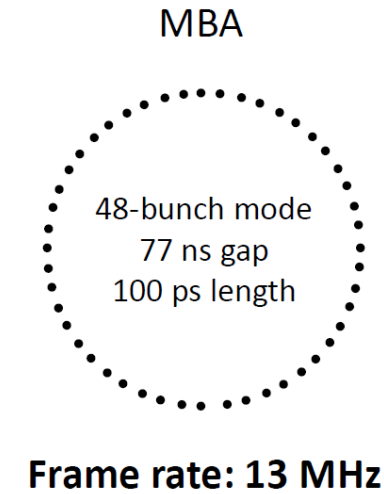
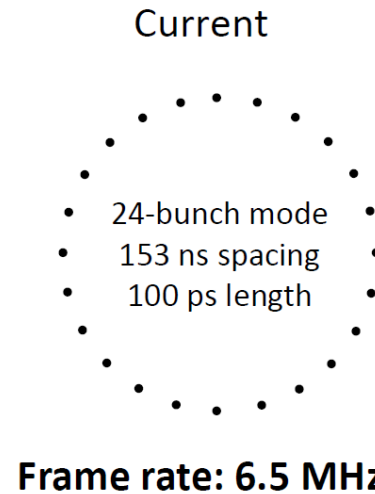


Temporal and spatial resolution range for the proposed APS-U imaging beamline.

APS UPGRADE

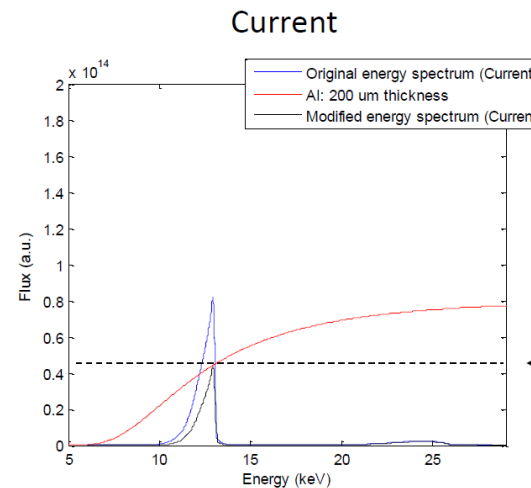
■ Increase of maximum frame rate

- Current: 6.5 MHz (24-bunch mode)
- MBA: 13 MHz (48-bunch mode)
- *Ultimately: 88 MHz (324-bunch mode) with improved detectors*

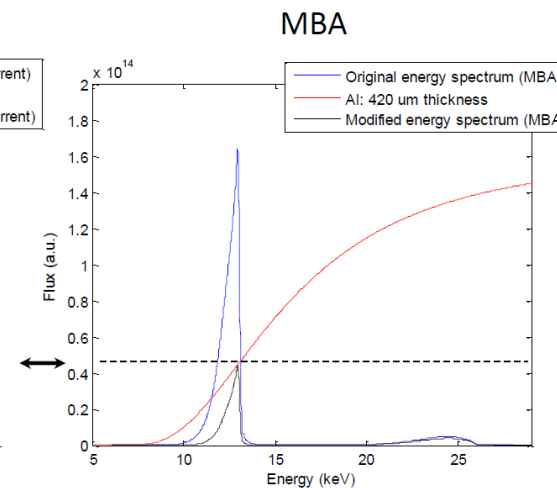


■ Increase of sample thickness (e.g. aluminum, undulator gap 30 mm, single pulse, intensified CCD)

- Current: 200 μm
- MBA: 420 μm



Thickness: 200 μm



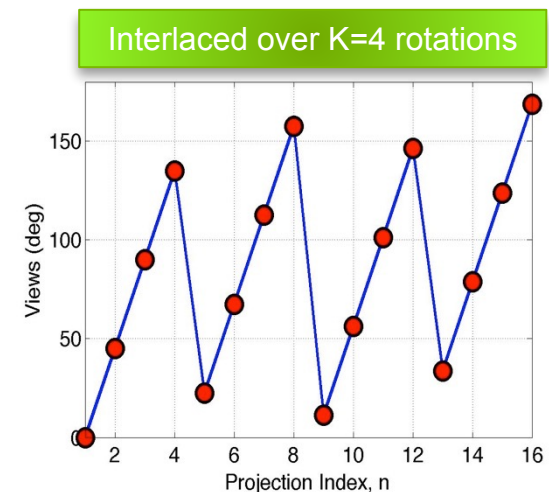
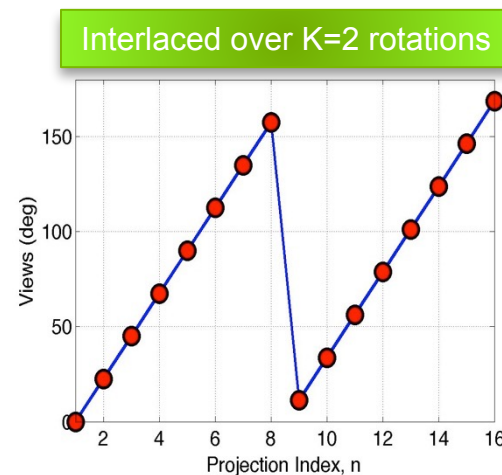
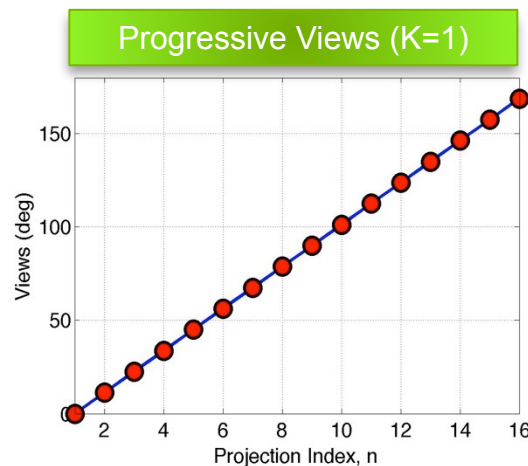
Thickness: 420 μm

CHALLENGES

CHALLENGES

Extend temporal and spatial resolution

- Many experimental parameters need to be optimized depending on the target sample/experiment
 - Dynamic features, dose sensitive samples, region of interest, temporal and spatial resolution requirements ...
- Parameters are guessed (experience) and then optimized (repeated experiments)



CHALLENGES

Extend temporal and spatial resolution

- Many experimental parameters need to be optimized depending on the target sample/experiment
 - Dynamic features, dose sensitive samples, region of interest, temporal and spatial resolution requirements ...
- Parameters are guessed (experience) and then optimized (repeated experiments)
- Data analysis happens after experiment is finalized
 - Post 3D reconstruction data reduction
 - Instrument error correction
 - Dose reduction
 - Integrate data from different techniques and scale length
- **Data collection is often done in the dark**

STREAMING DATA ANALYSIS AND EXPERIMENTAL STEERING

TOMOSCAN+TOMOSTREAM MODEL

Highlights

Streaming data collection + Streaming reconstruction

Real-time reconstruction of 3 orthogonal slices with dynamic selection of the X-Y-Z sample cut

On demand, event driven, simultaneous data saving

Programmable pre-event data saving

Simple visualization using ImageJ

New opportunities

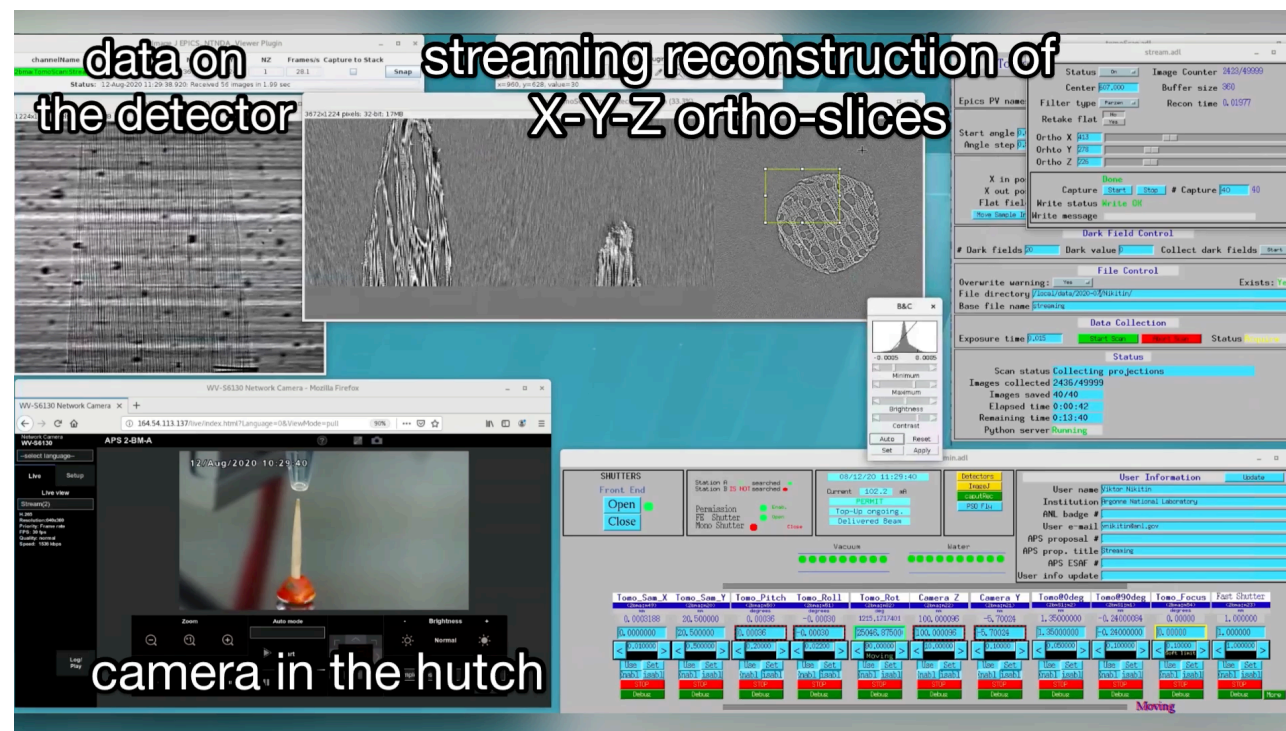
Real-time:

alignment of the acquisition system

positioning of the sample

adjustment of acquisition parameters

monitoring of sample changes

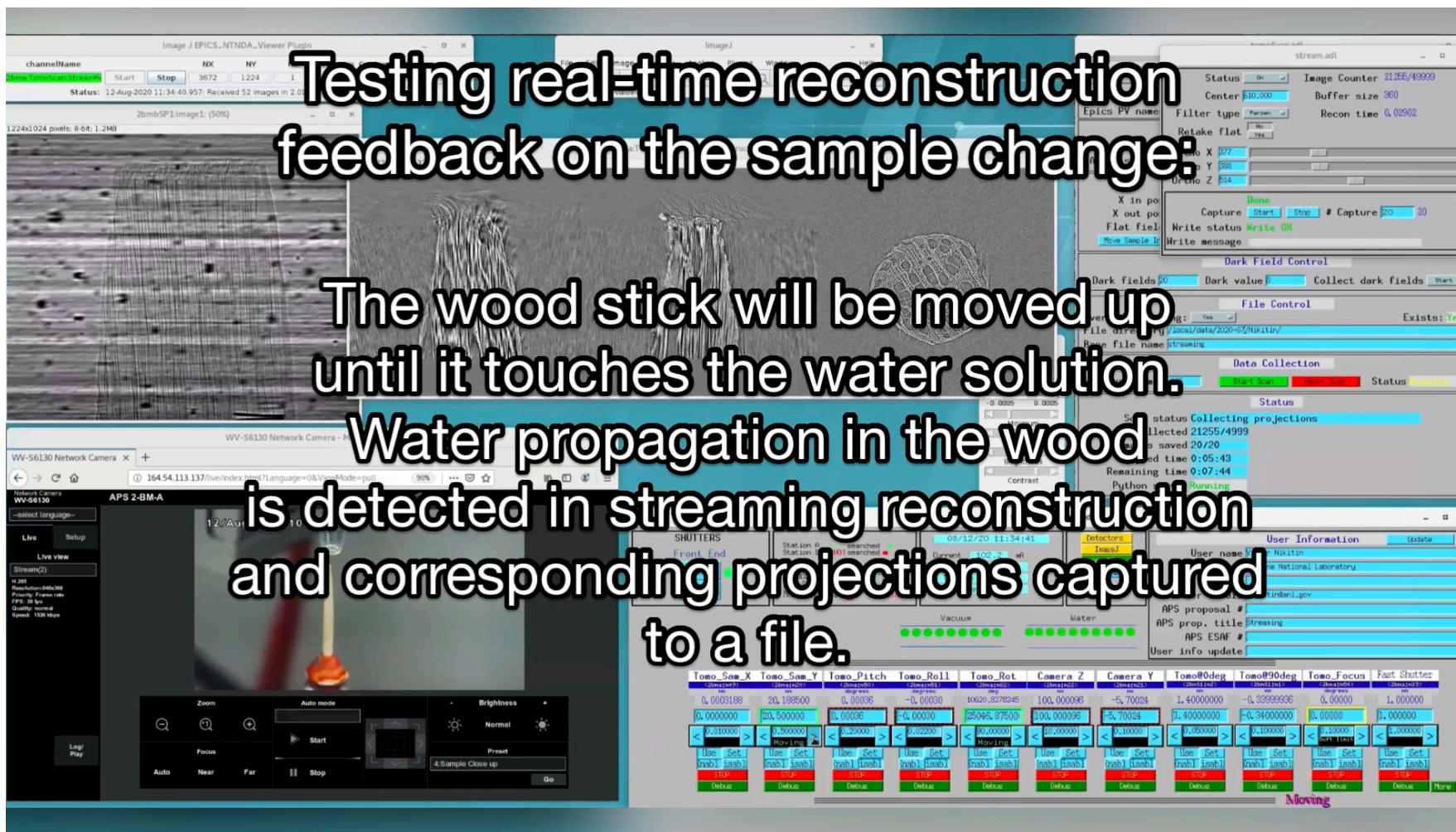


Highlights

The wood stick will be moved up until it touches the water solution.



Water propagation in the wood is detected in streaming reconstruction and corresponding projections captured to a file.



REFERENCE

- tomoPy <http://tomopy.readthedocs.io>
- tomoScan <https://tomoscan.readthedocs.io/>
- tomoStream <https://tomostream.readthedocs.io/>
- tomoBank <http://tomobank.readthedocs.io>
- DXchange <http://dxchange.readthedocs.io>
- DXfile <http://dxfile.readthedocs.io>
- XDesign <http://xdesign.readthedocs.io>



<https://github.com/tomography/>
<https://github.com/xray-imaging/>

ACKNOWLEDGMENTS:

Viktor Nikitin, Pavel Shevchenko, Kamel Fezzaa, Tao Sun, Samuel Clark, Vincent De Andrade, Alex Deriy, Xianghui Xiao,

Döga Gürsoy, Tekin Bicer, Daniel Ching, Michael Wojcik

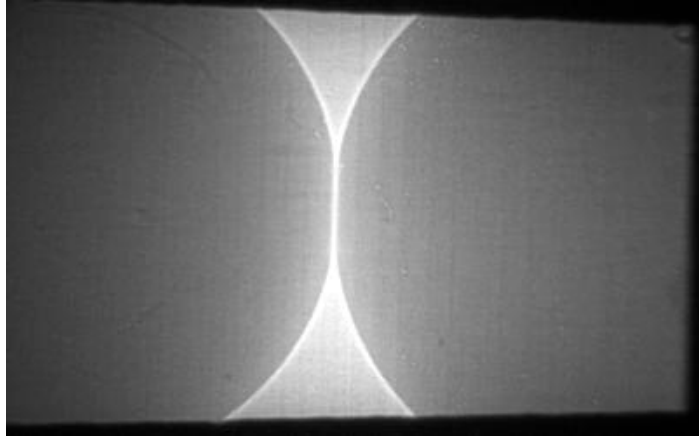
Stuart Stock (NWU)

Nik Chawla (ASU), Peter W. Voorhees (NWU)

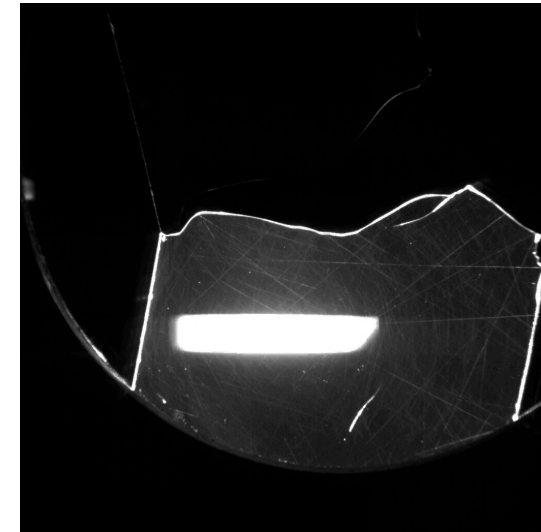
Aditya Mohan, S.V. Venkatakrishnan, Charles A. Bouman (Purdue Uni.)

Daniel Pelt (CWI Amsterdam)

THANK YOU FOR YOUR ATTENTION



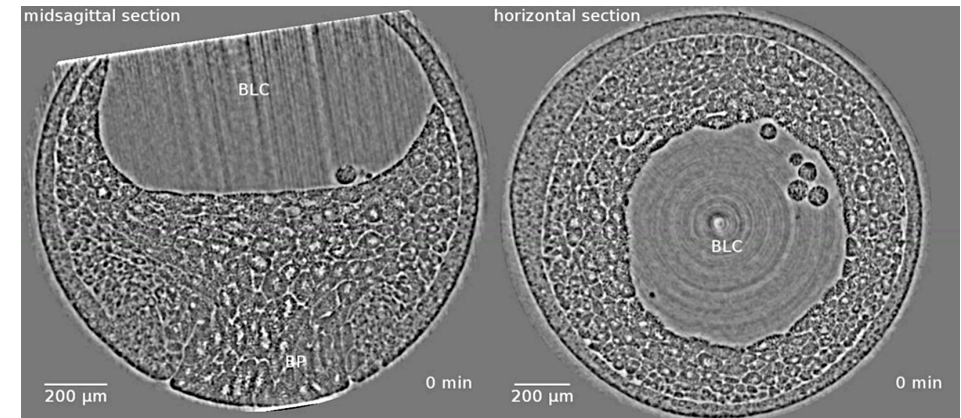
2 mm glass beads crushing @ 6.5 MHz
R. H. Coridan, et al., ACS Appl. Mater. Interfaces 8, 24612 (2016)



Scintillator screen heat load
K. Fezzaa, Imaging Group, Advanced Photon Source



Air bubble entrapment upon water
drop impact on solid @ 271 kHz
J. Lee, et al., Phys. Rev. Lett. 109, 204501 (2012)



3D time-lapse series of *X. laevis* embryo during mid-gastrulation
J. Moosmann et al., Nature 497, 394 (2013)