ADVANCED X-RAY IMAGING OF CARBON-FIBER MICROSTRUCTURE

CO-HOSTED BY:

CKN Composites Knowledge Network

sampe Canada

compositeskn.org

nasampe.org

YOUR HOST

Toby Bond
Senior Scientist, Canadian Light Source (CLS)

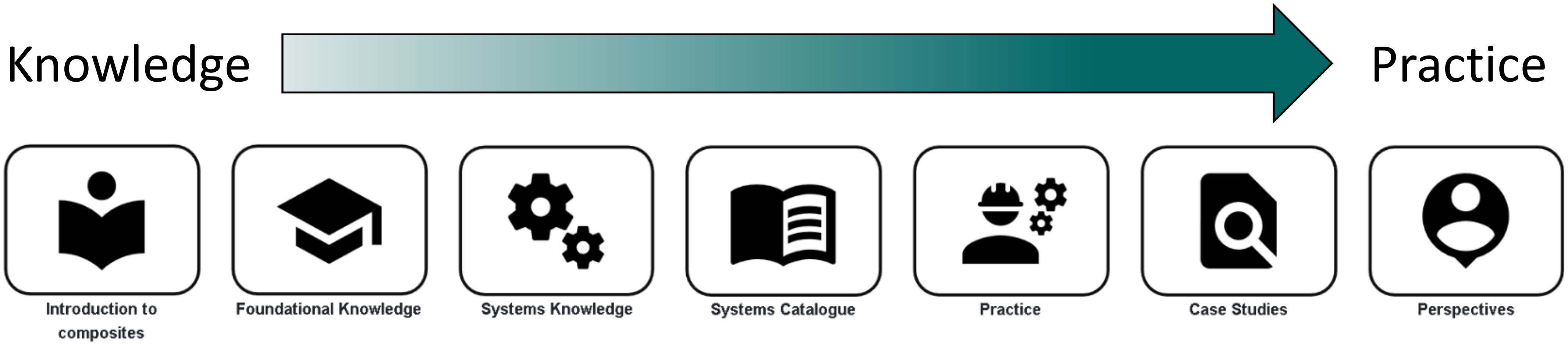
- Synchrotron X-ray imaging specialist at the CLS (Canada's national synchrotron facility)
- 10 years of experience with computed tomography and advanced x-ray-based imaging techniques
- Formal background in electrochemistry and synchrotron imaging/diffraction
- Works with industry clients who need to do synchrotron imaging at the CLS

KNOWLEDGE IN PRACTICE CENTRE (KPC)

- A freely available online resource for composite materials engineering:

compositeskn.org/KPC

- Focus on practice, guided by foundational knowledge and a systems-based approach to thinking about composites manufacturing



PAST WEBINAR RECORDINGS AVAILABLE

Today’s Webinar will be posted at:
https://compositeskn.org/KPC/A374

HOSTED BY: CKN Composites Knowledge Network

HOSTED BY: sampe Canada

TODAY'S TOPIC:

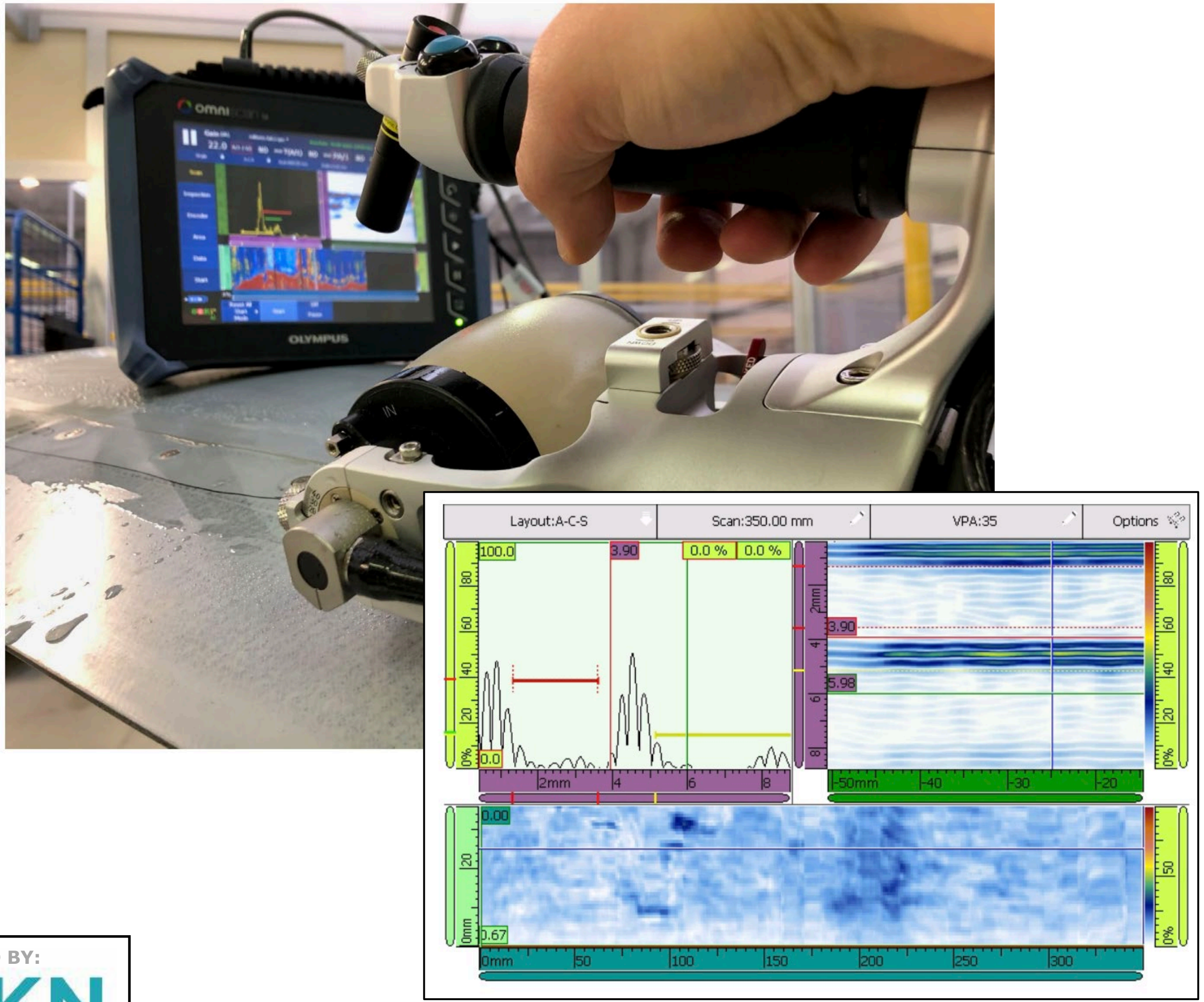
Advanced X-Ray Imaging of Carbon-Fiber Microstructure

OUTLINE

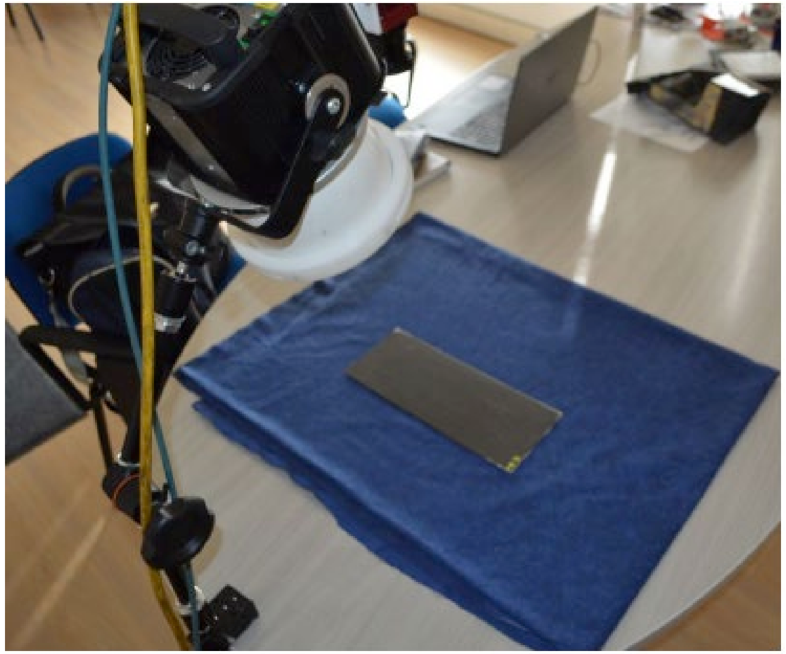
- Non-destructive Imaging
- X-ray imaging and computed tomography (CT)
- What's a synchrotron?
- Synchrotron CT
- Characterizing fiber microstructure:
  - Visible-light microscopy
  - Lab-based CT
  - Synchrotron CT: analyzing carbon fiber parts
  - Synchrotron CT: analyzing individual carbon Fibers

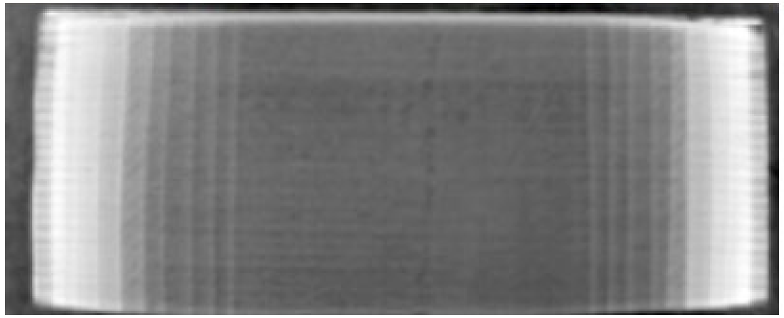
NON-DESTRUCTIVE IMAGING OF COMPOSITES

Ultrasound Imaging



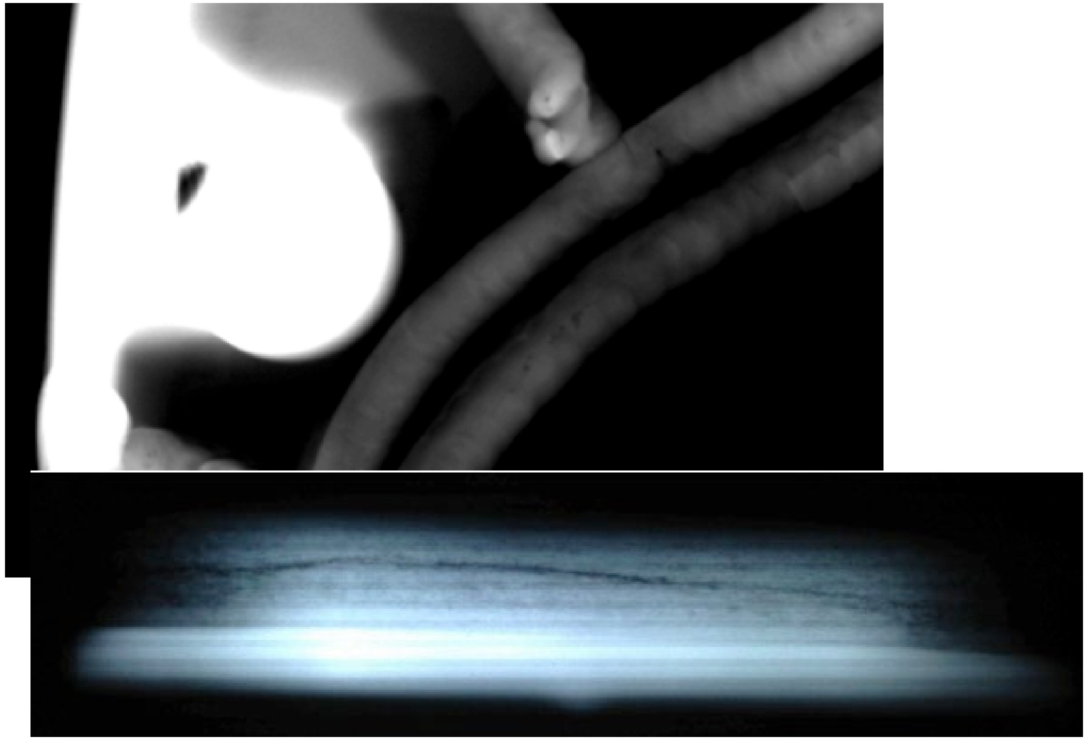
Infrared Thermography



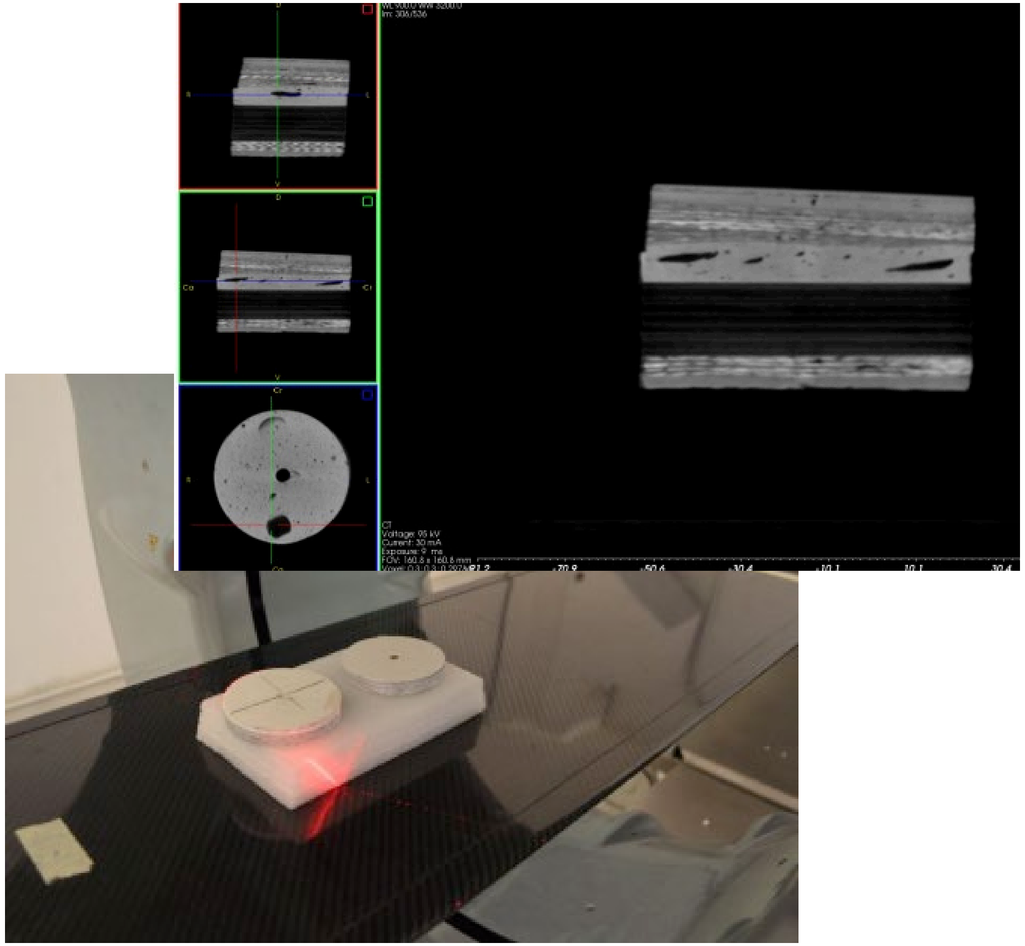


NON-DESTRUCTIVE IMAGING OF COMPOSITES WITH X-RAYS

Radiography (2D imaging)

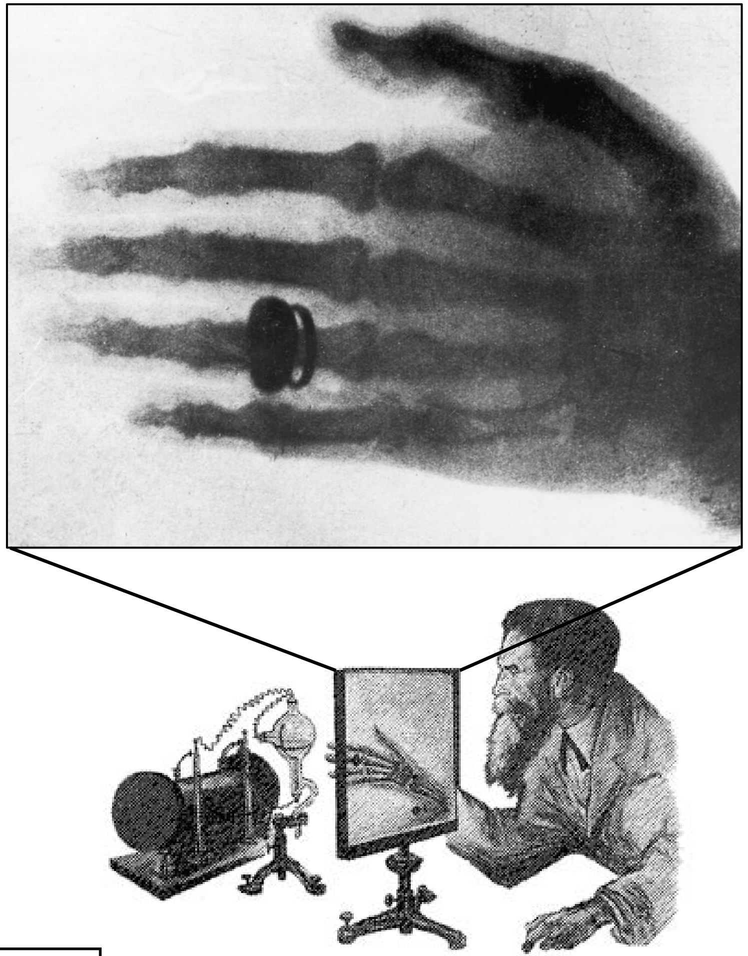


Computed tomography (3D imaging)

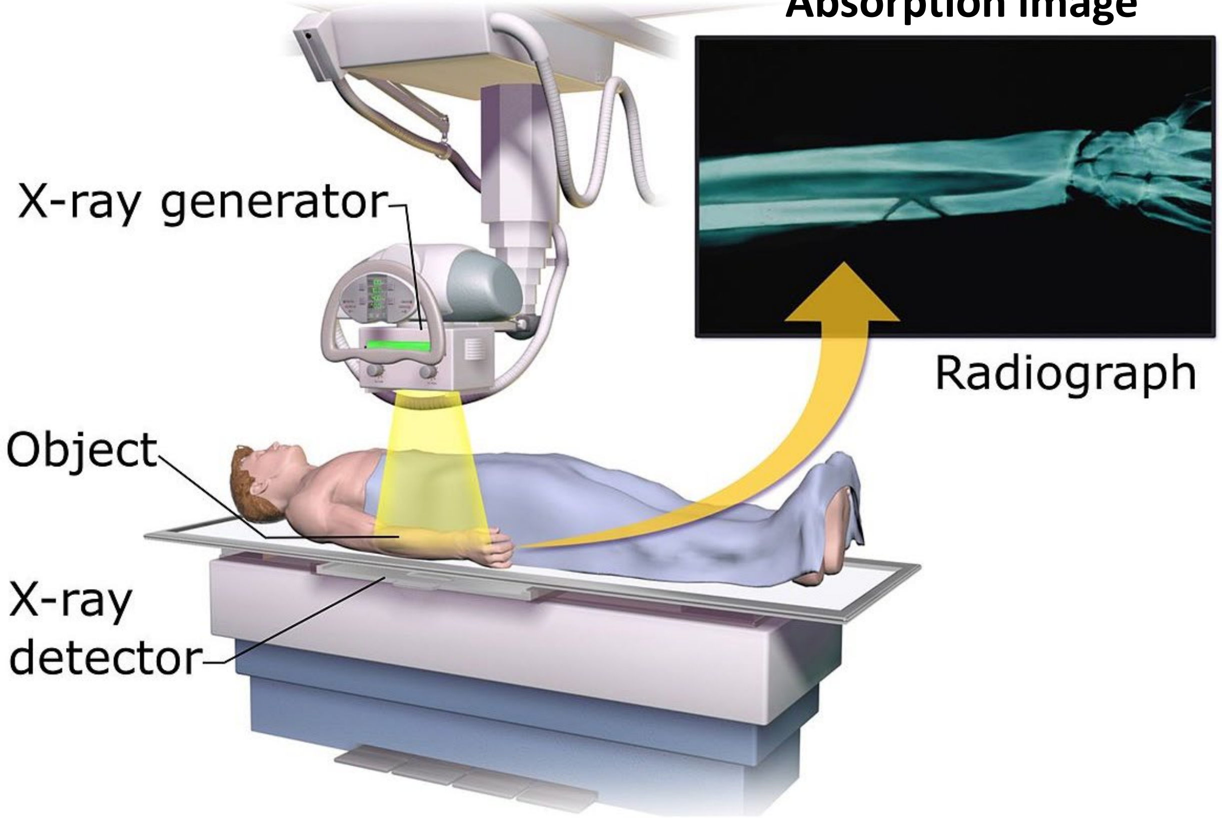


X-RAY IMAGING (RADIOGRAPHY)

Transmission image

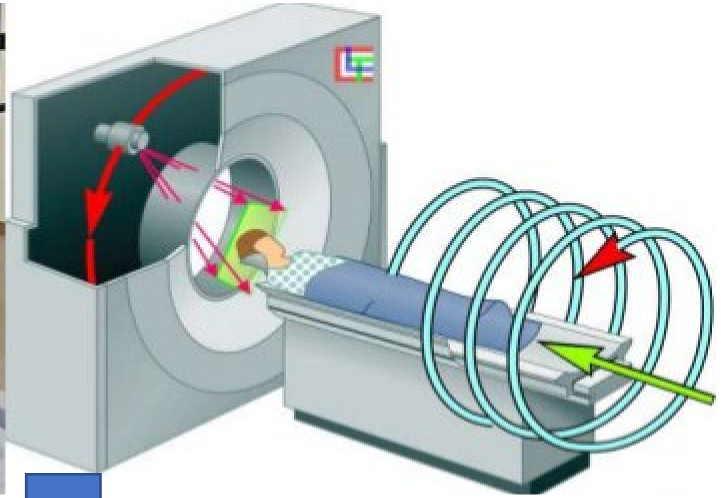


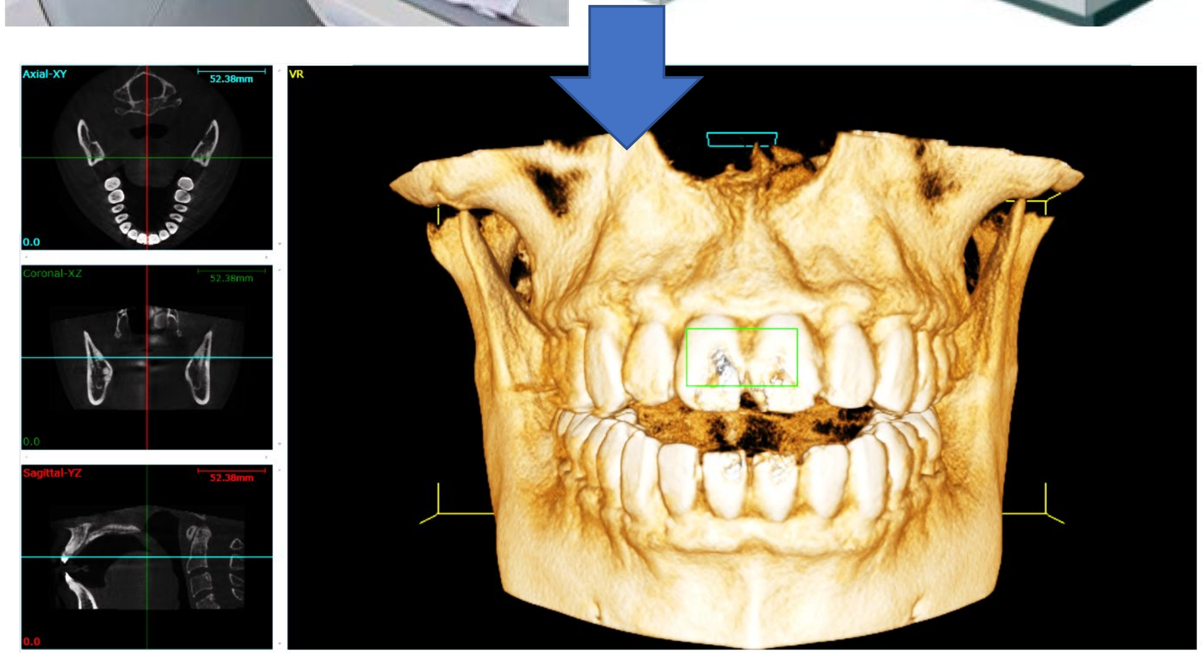
Absorption image



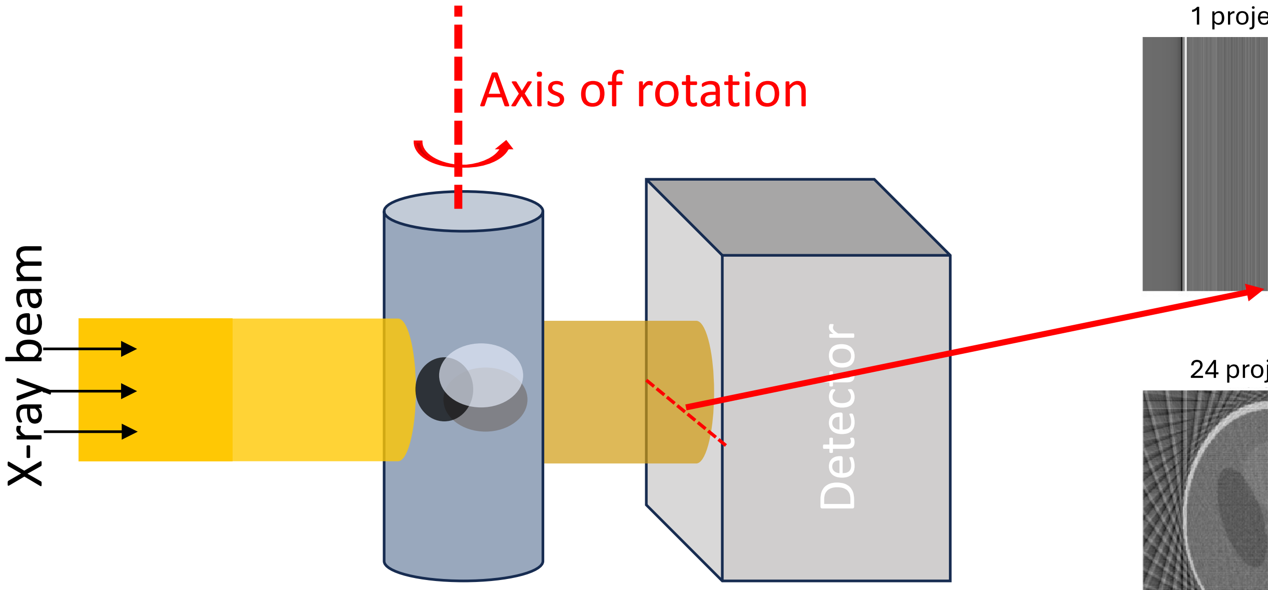
COMPUTED TOMOGRAPHY (CT)

- CT scans (aka CAT scans) are the 3D extension of x-ray projections
- Procedure:
  - Take many projections while rotating the detector and x-ray source around the patient
  - Reconstruct the projections into a digital 3D model

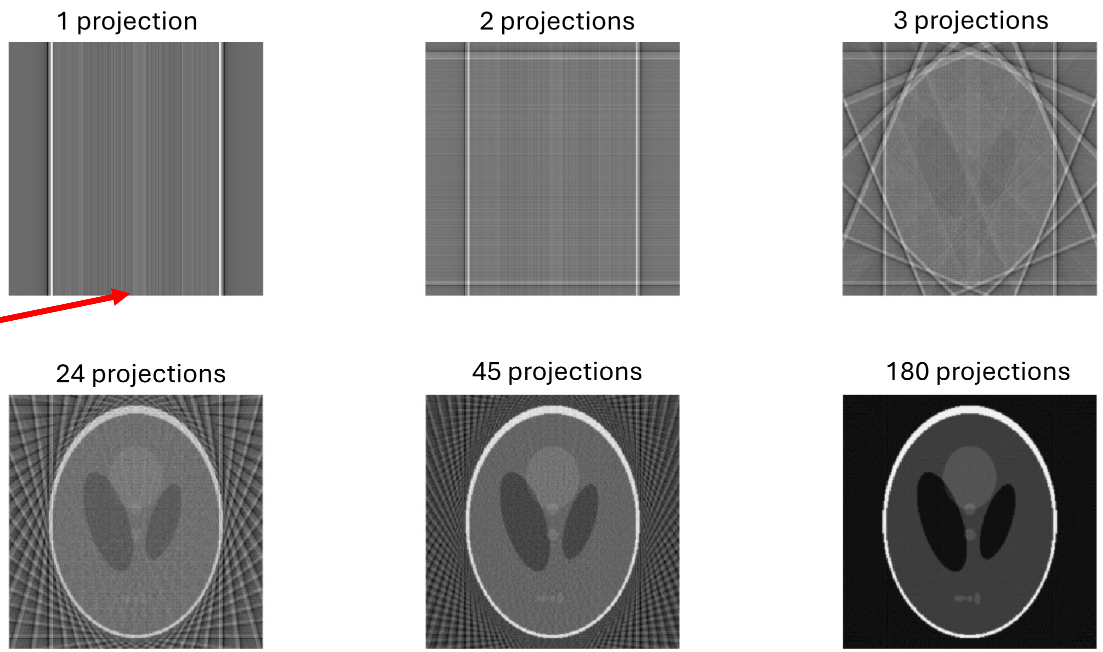




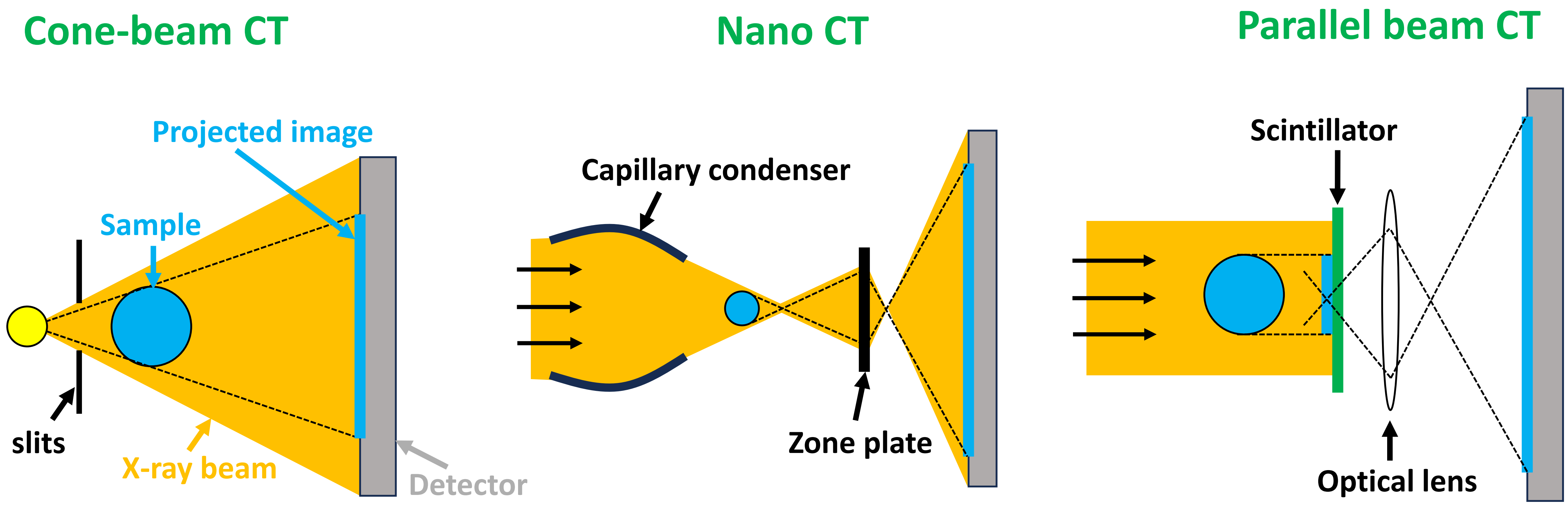
COMPUTED TOMOGRAPHY (CT)



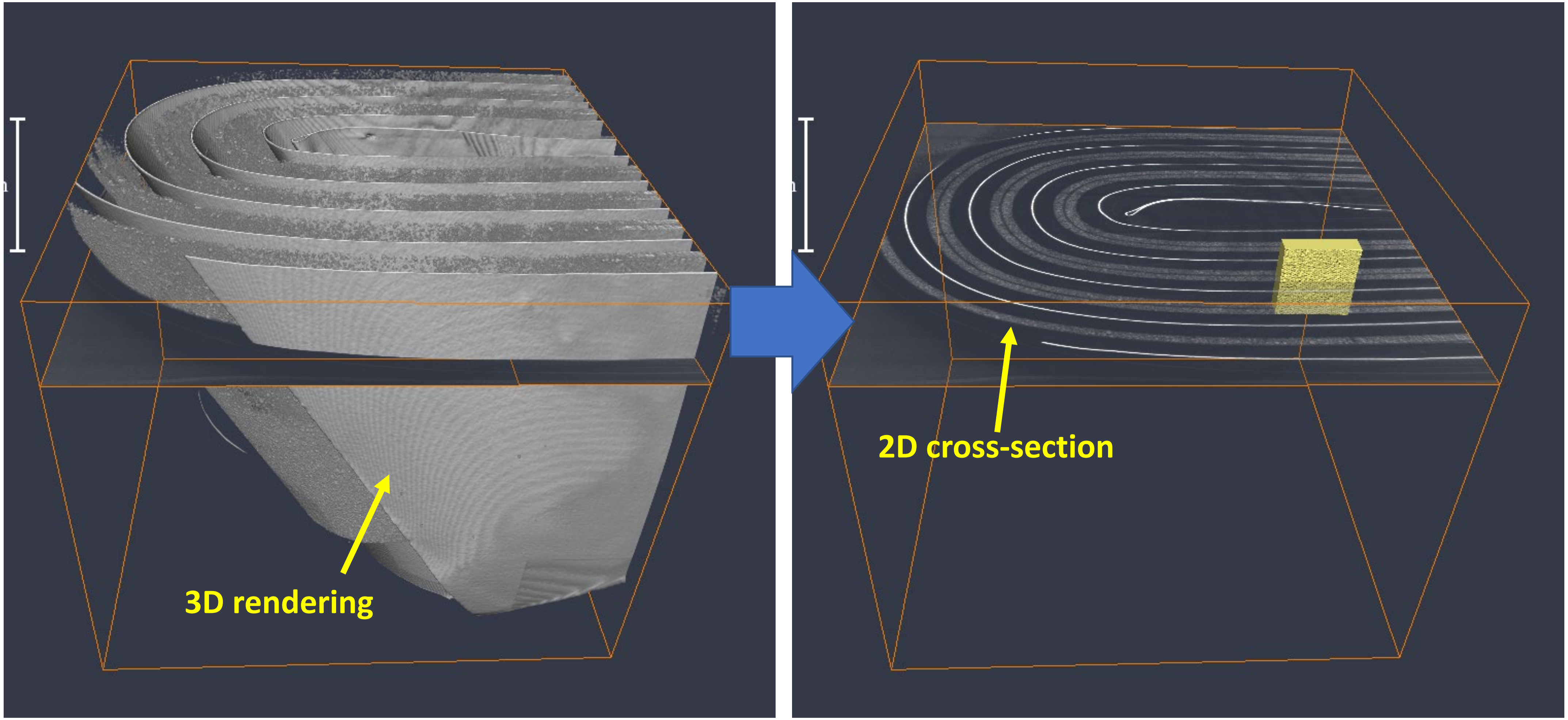
Reconstruction of a single "slice"



TYPES OF CT SYSTEMS

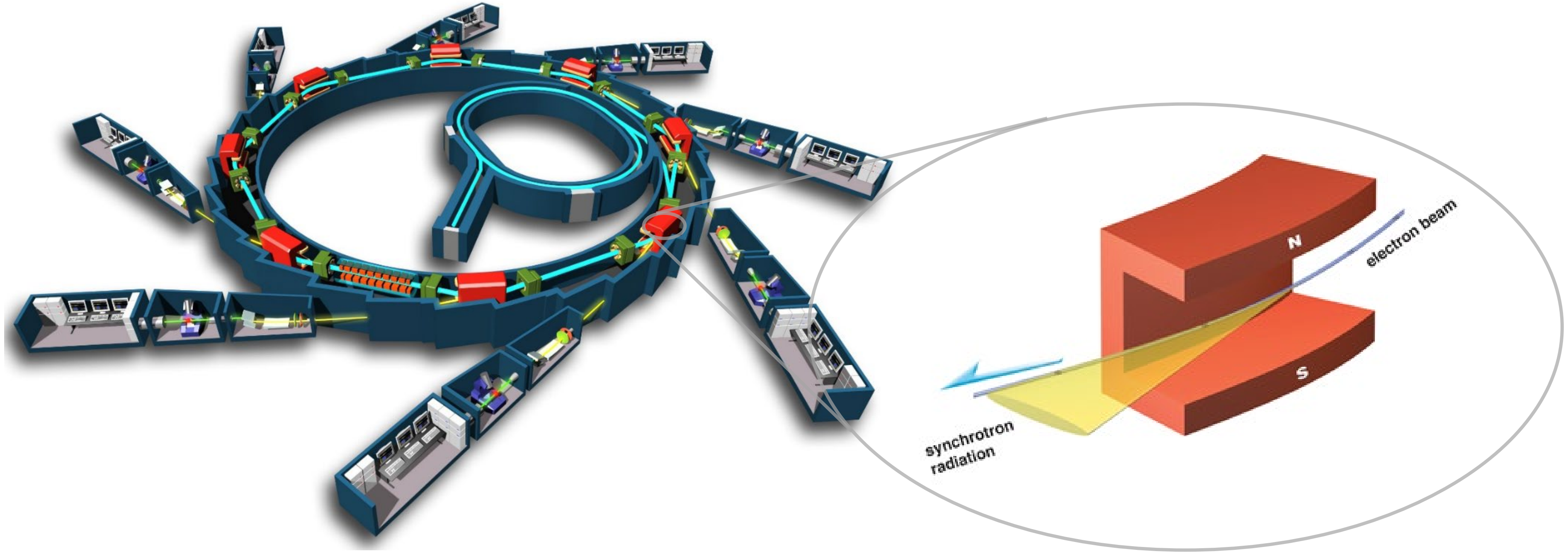


COMPUTED TOMOGRAPHY (CT)

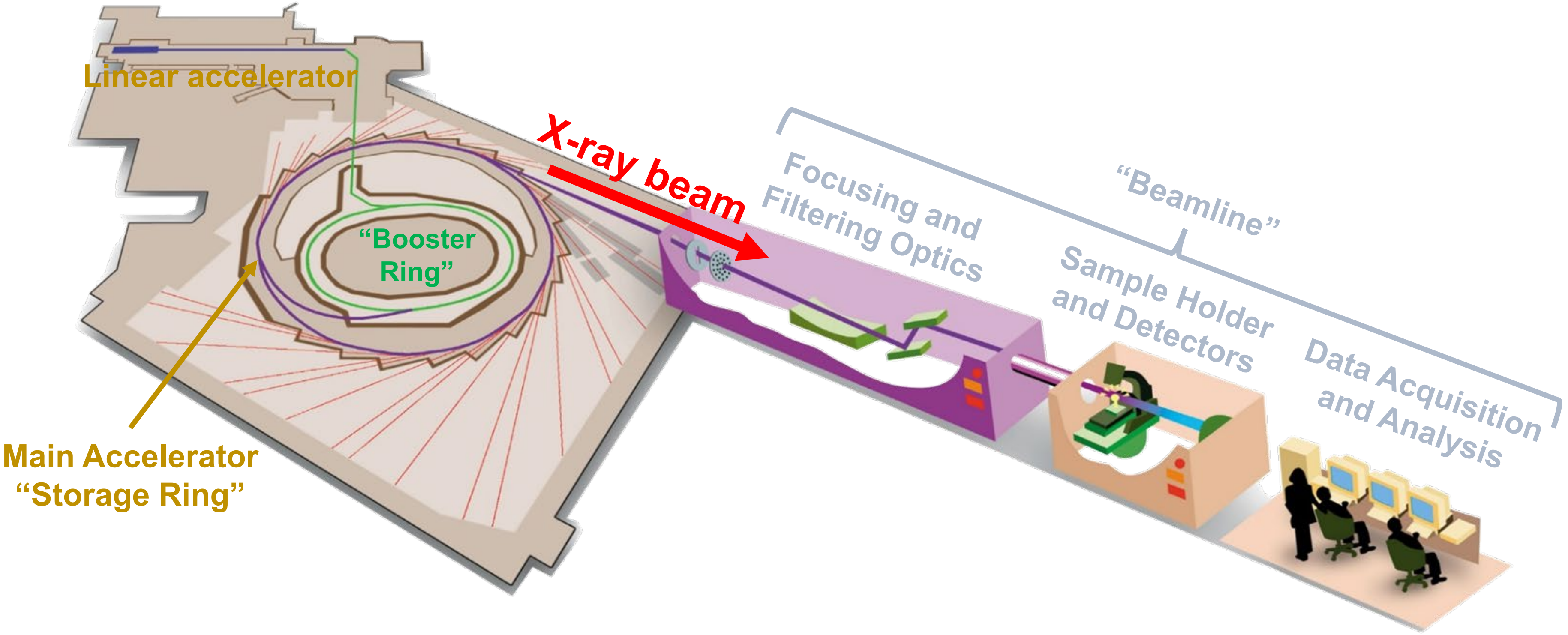


WHAT'S A SYNCHROTRON?

A synchrotron particle accelerator that is used to generate x-ray beams with unique properties



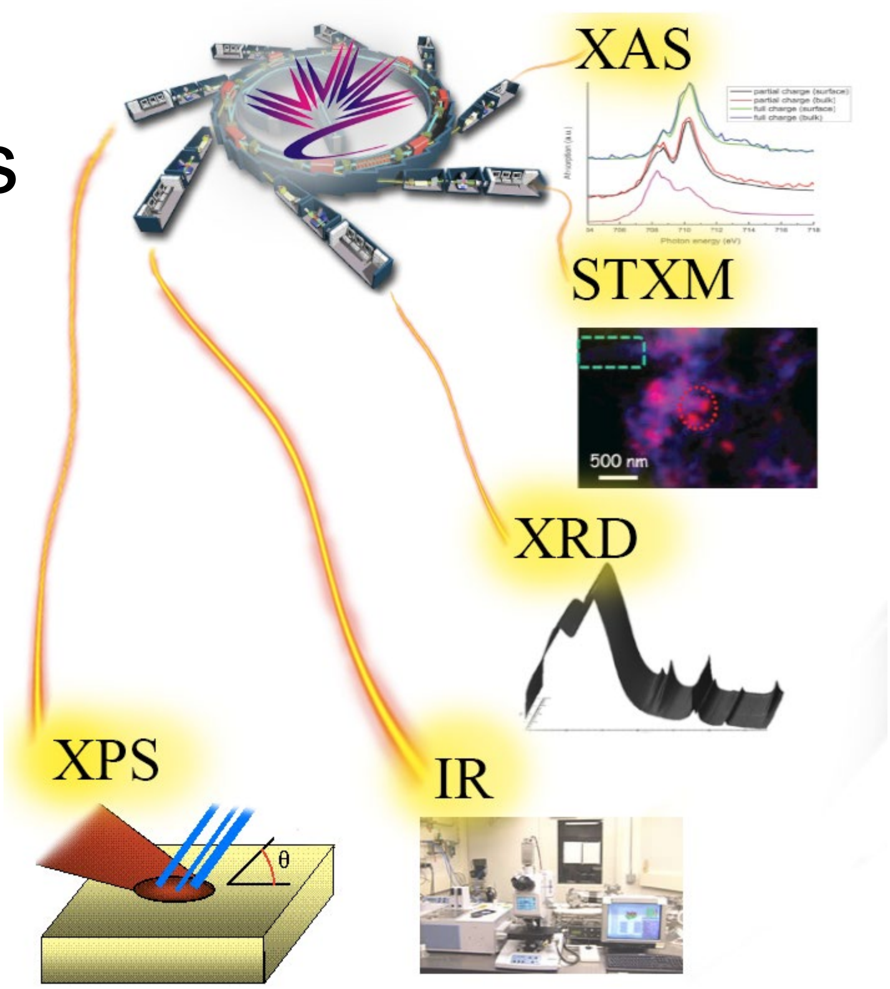
WHAT'S A SYNCHROTRON?



- Synchrotron X-ray beams are:
  - Very high-intensity
  - Highly parallel (laser-like geometry)
  - Monochromatic (narrow distribution of wavelengths)

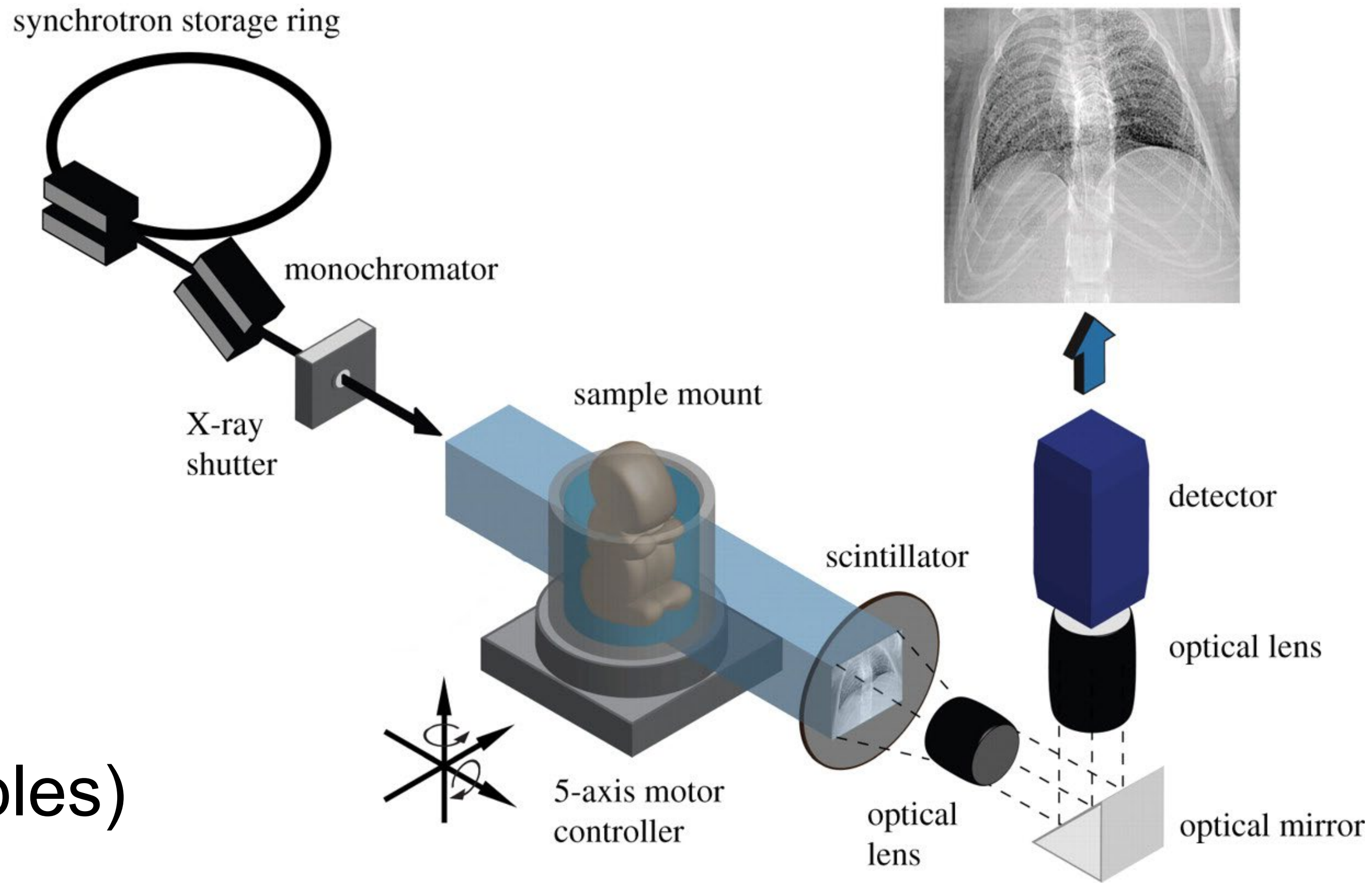
WHAT'S A SYNCHROTRON?

- Synchrotron techniques are generally:
  - **Fast**
  - **Non-Destructive**
  - **Element-Specific**
  - **High-Resolution**
  - **Low-Noise**



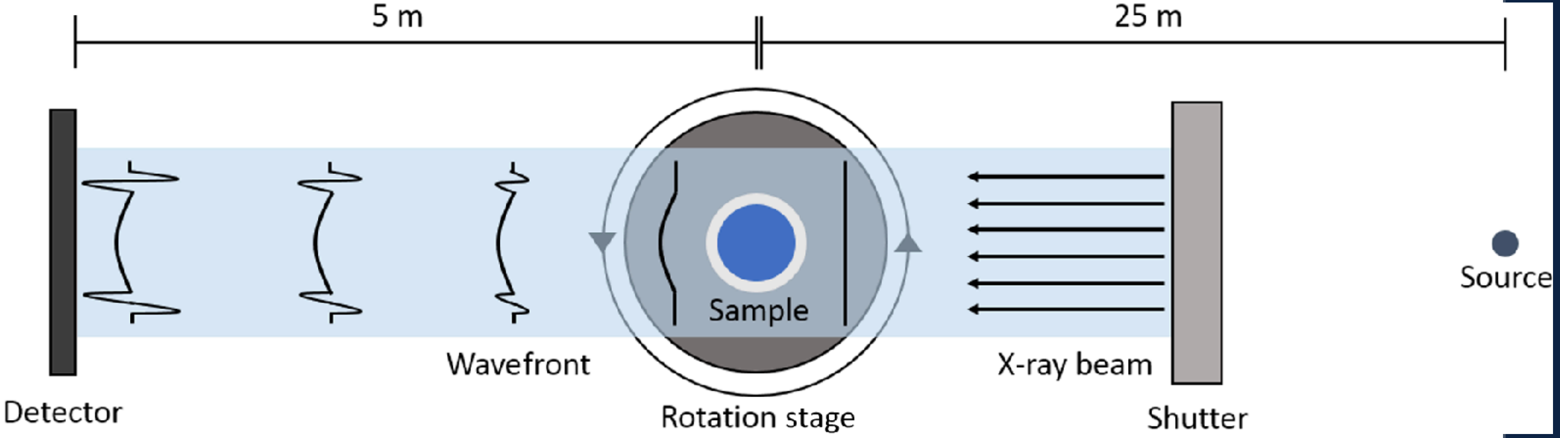
SYNCHROTRON CT

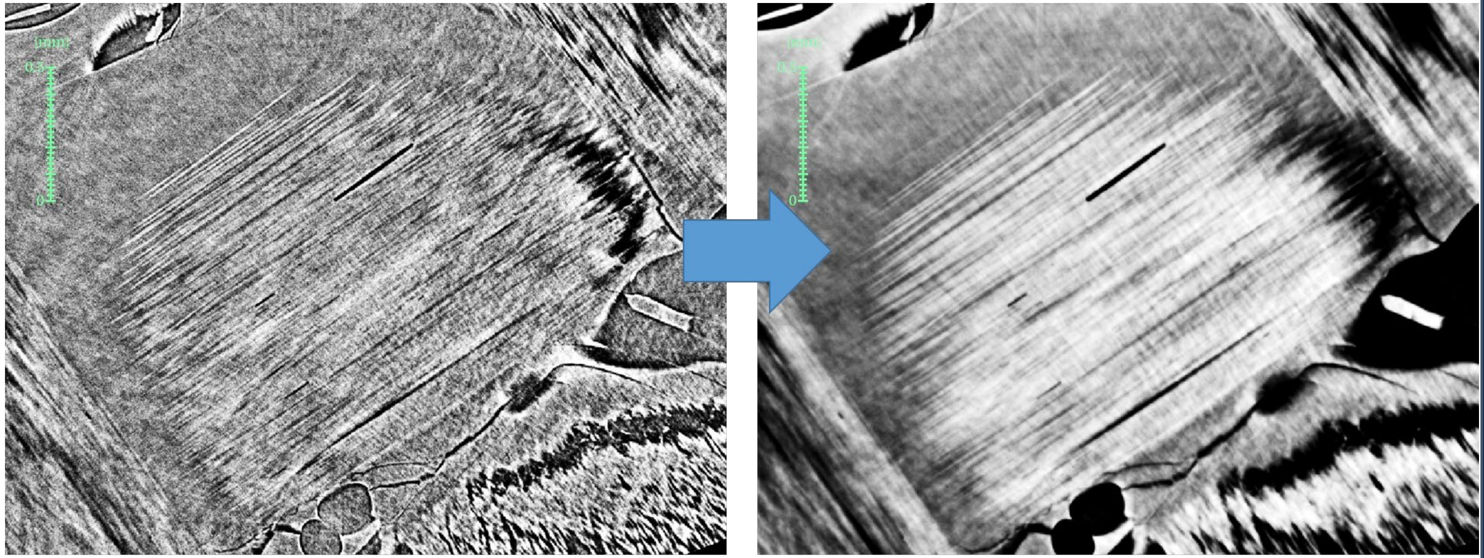
- Advantages of SR-CT:
  - Fast
  - High-contrast
  - “straight beam”
- Well-suited to:
  - Low-contrast samples
  - Time-resolved imaging
  - High-resolution imaging (especially in large samples)



PHASE-CONTRAST X-RAY IMAGING

- The high contrast of synchrotron CT comes from “phase contrast”
- This uses differences in refractive index between materials to get contrast (instead of just absorption)



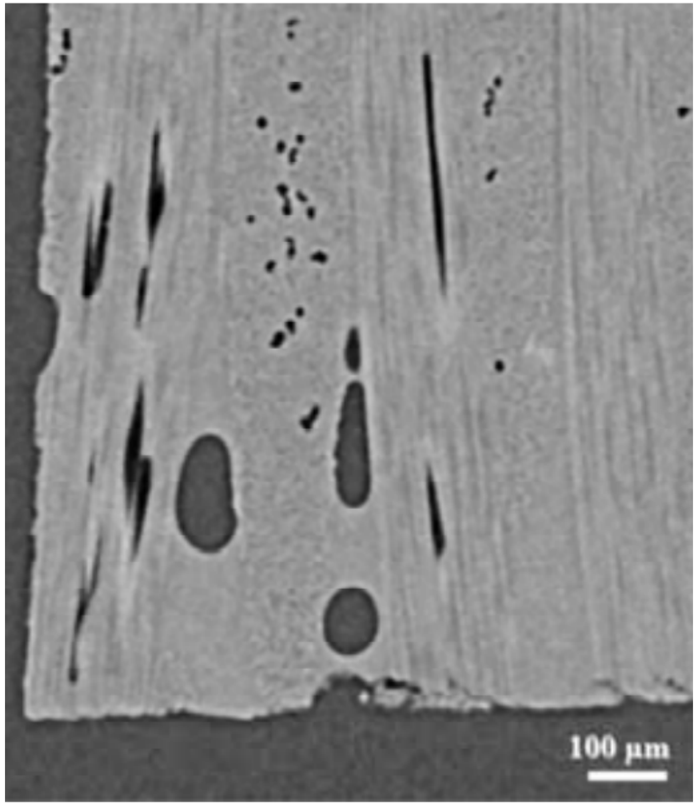


Absorption contrast **Phase contrast**

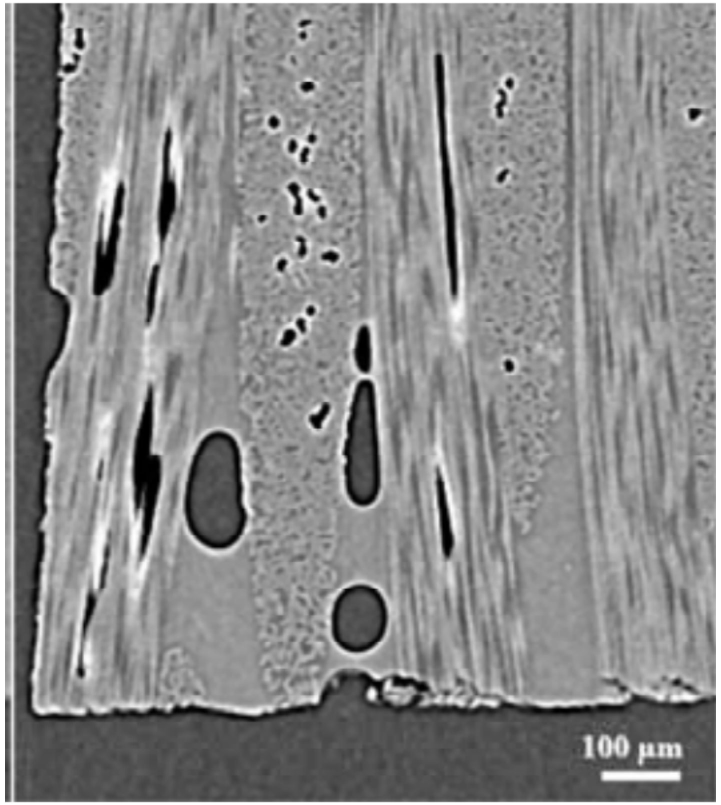
J.E. Montgomery; M. J. Wesolowski; B. Wolkowski; R. Chibbar; E. C. R. Snead; J. Singh; M. Pettitt; P. S. Malhi; T. Barboza; G. Adams. Electrochemistry Communications, vol. 59, 2015,16-19, ISSN 1388-2481.

IMAGING FIBERS: LAB CT VS SYNCHROTRON CT

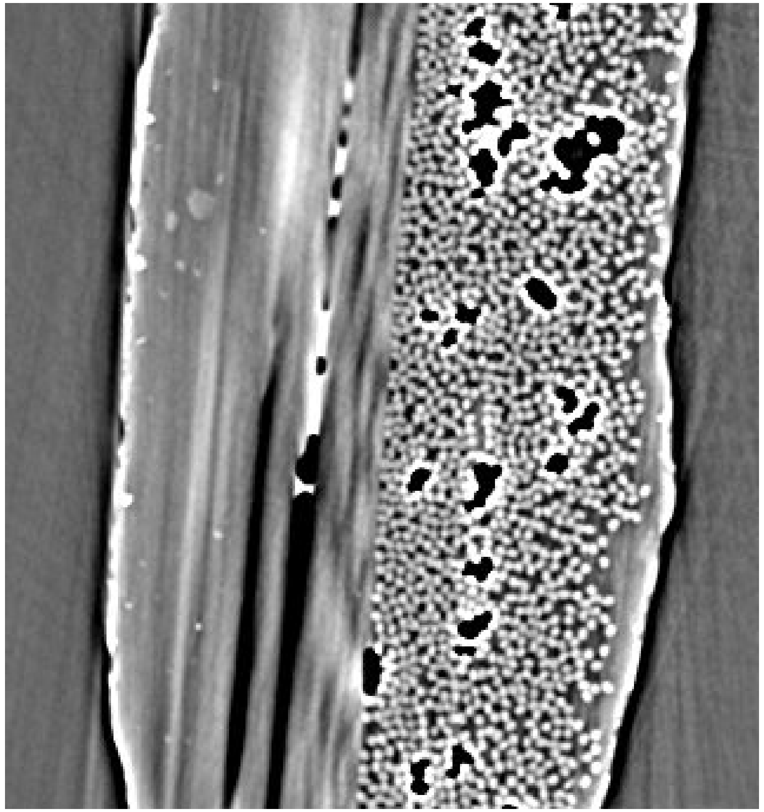
Lab CT



Lab CT (phase contrast)



Synchrotron CT (phase contrast)

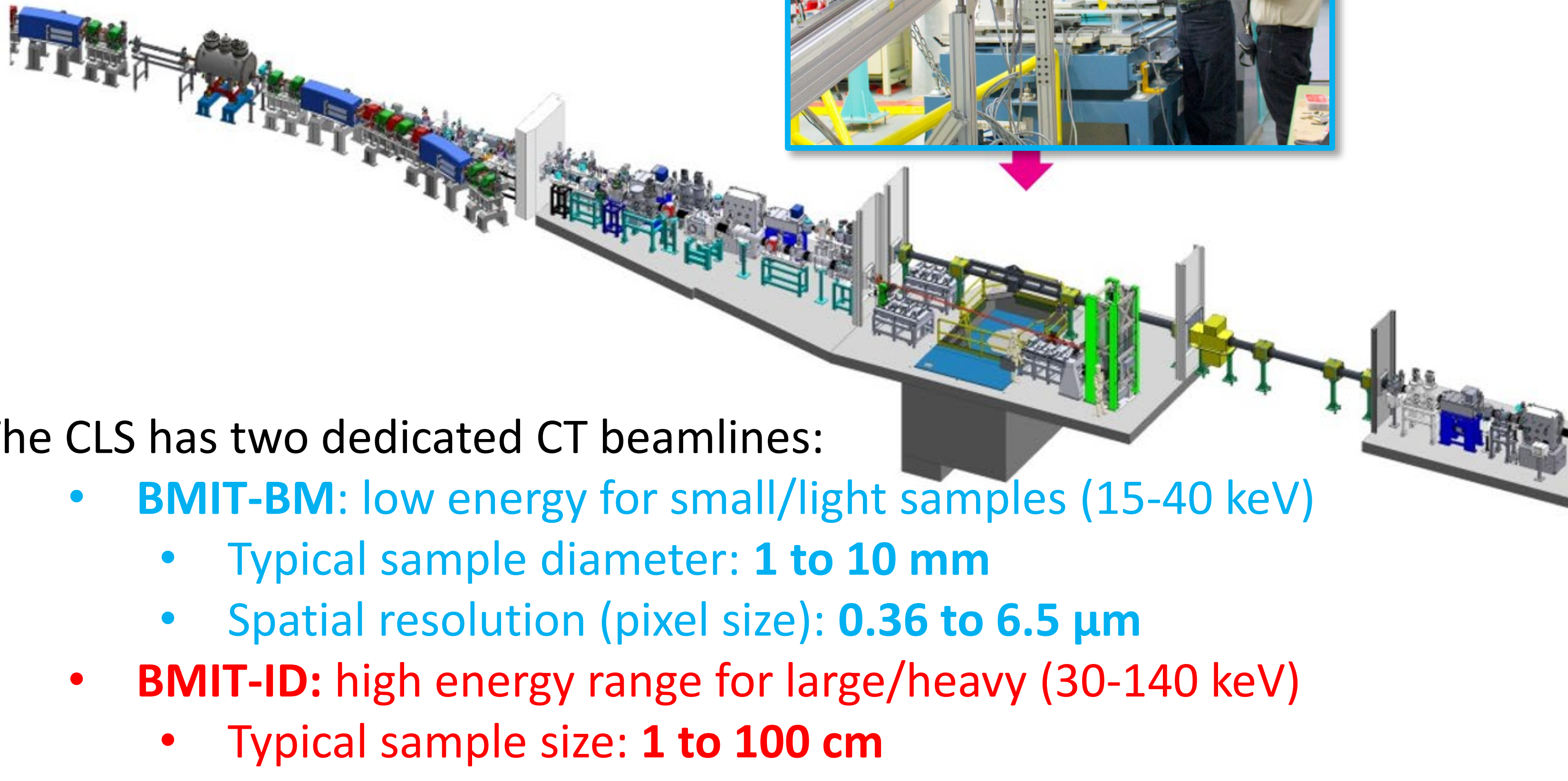


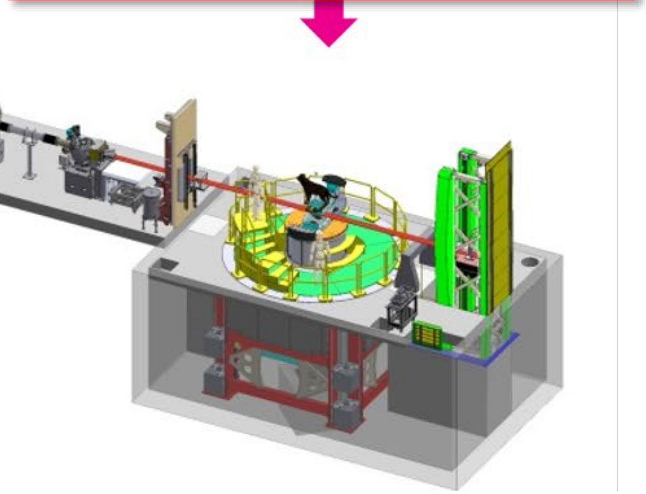
Kastner, J., Plank, B., Kottler, C., & Revol, V. (2012). Comparison of phase contrast X-ray computed tomography methods for non-destructive testing of materials. 18th World Conference on Nondestructive Testing, April 2012, Durban, South Africa . *e-Journal of Nondestructive Testing* Vol. 17(7). https://www.ndt.net/?id=12642

THE CANADIAN LIGHT SOURCE (CLS)

- The CLS is Canada's national synchrotron facility (in Saskatoon, SK)
- Commissioned in 2005
- 22 operational beamlines

CT IMAGING AT THE CLS





The CLS has two dedicated CT beamlines:

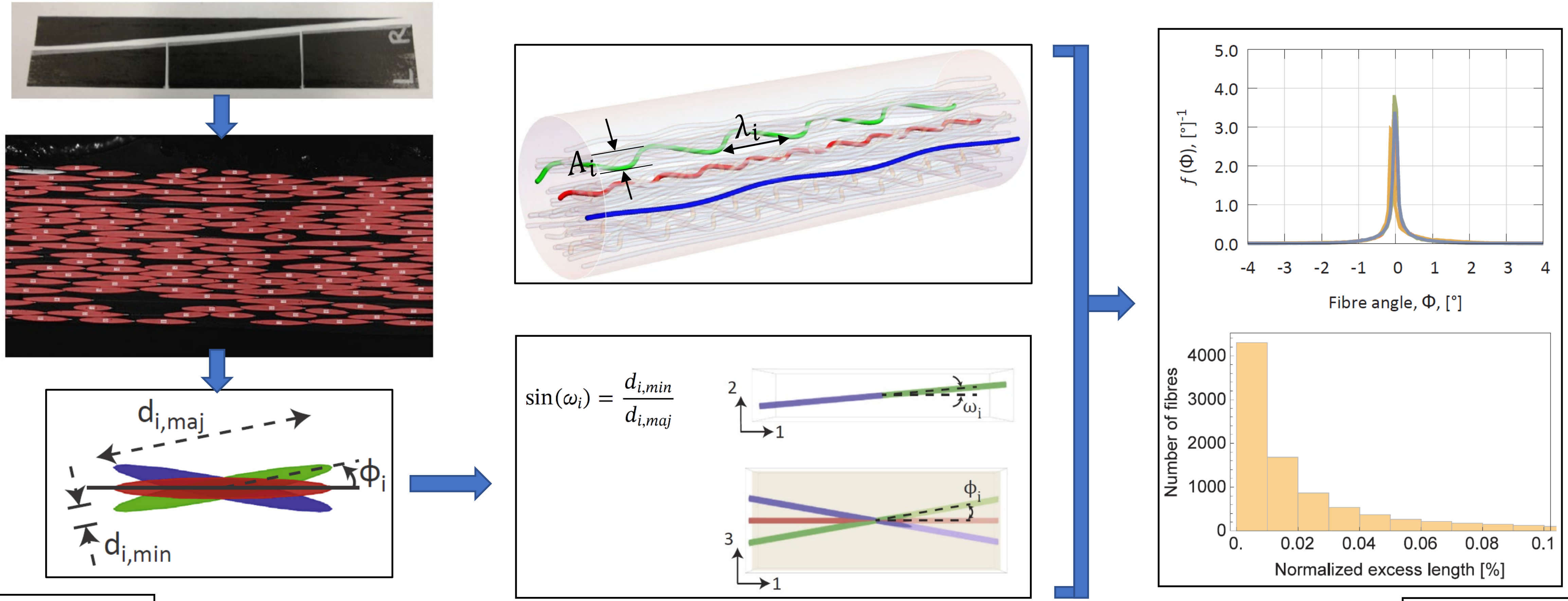
- **BMIT-BM**: low energy for small/light samples (15-40 keV)
    - Typical sample diameter: **1 to 10 mm**
    - Spatial resolution (pixel size): **0.36 to 6.5 µm**
- **BMIT-ID:** high energy range for large/heavy (30-140 keV)
    - Typical sample size: **1 to 100 cm**
    - Spatial resolution (pixel size): **1.5 to 100 µm**

OUTLINE

- Non-destructive Imaging
- X-ray imaging and computed tomography (CT)
- What’s a synchrotron?
- Synchrotron CT
- Characterizing fiber microstructure:
  - Visible-light microscopy
  - Lab-based CT
  - Synchrotron CT: analyzing carbon fiber parts
  - Synchrotron CT: analyzing individual carbon Fibers

IMAGING FIBERS WITH VISIBLE LIGHT MICROSCOPY

- Fiber microstructure can be imaged with microscopy by making cross sections (known as the Yugartis method)
- This allows for quantification of fiber orientation and excess length (discussed in coming slides), but relies on certain assumptions about the fiber wavelength

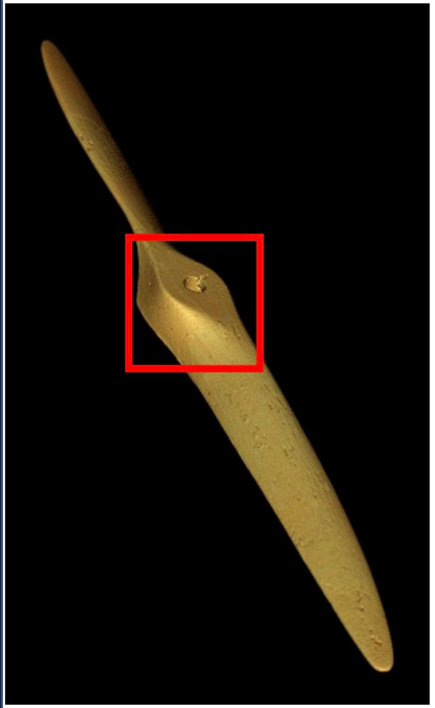


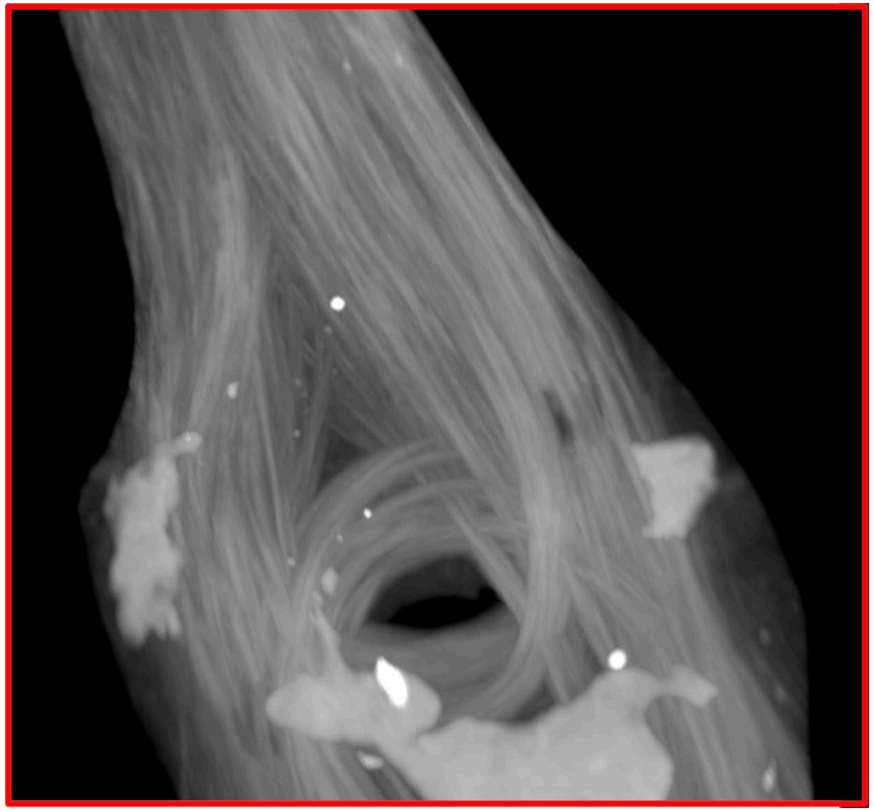
A. Stewart & A. Poursartip., *Comp. Part A.*, 2018.

IMAGING COMPOSITES WITH LAB CT

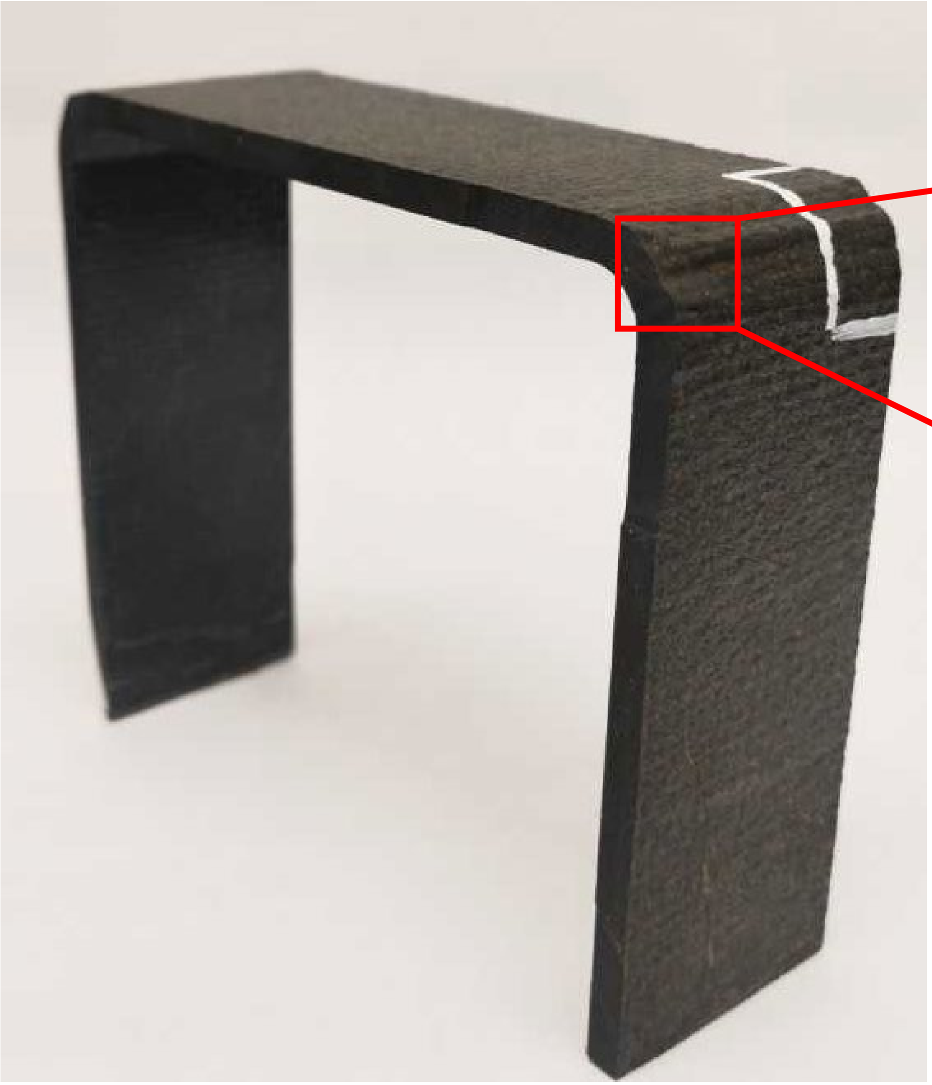
Voids and Damage

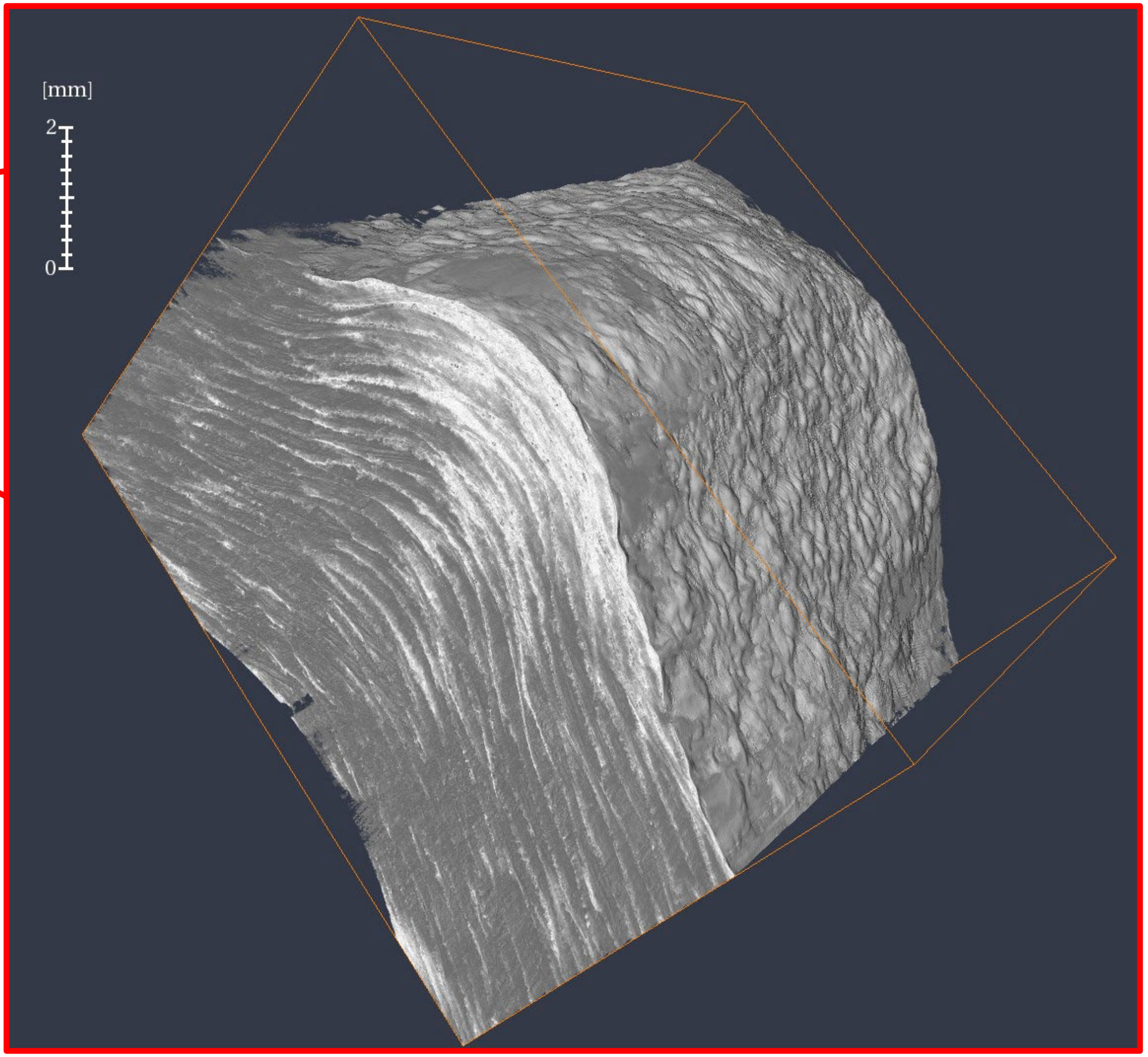
Fiberglass imaging



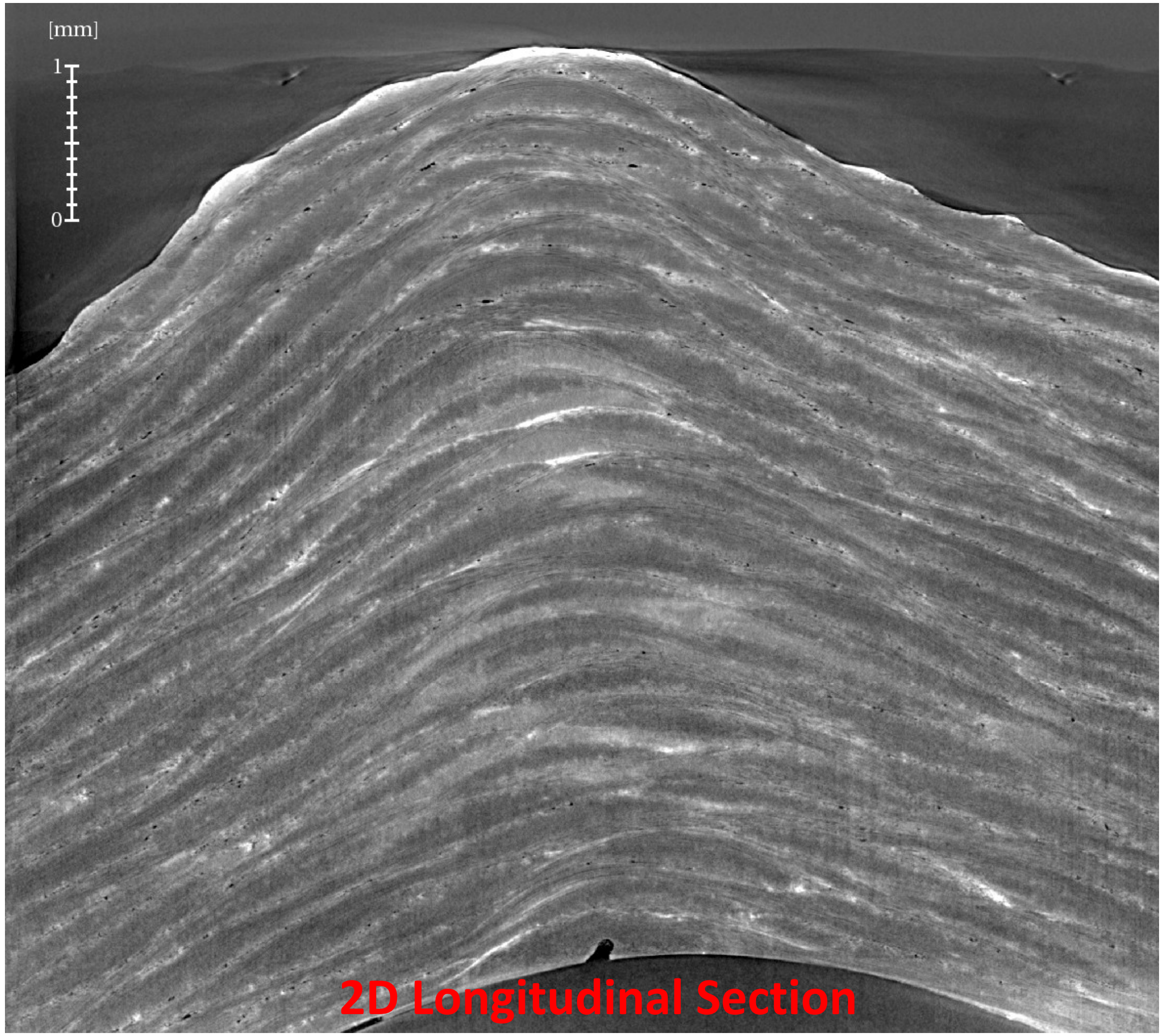


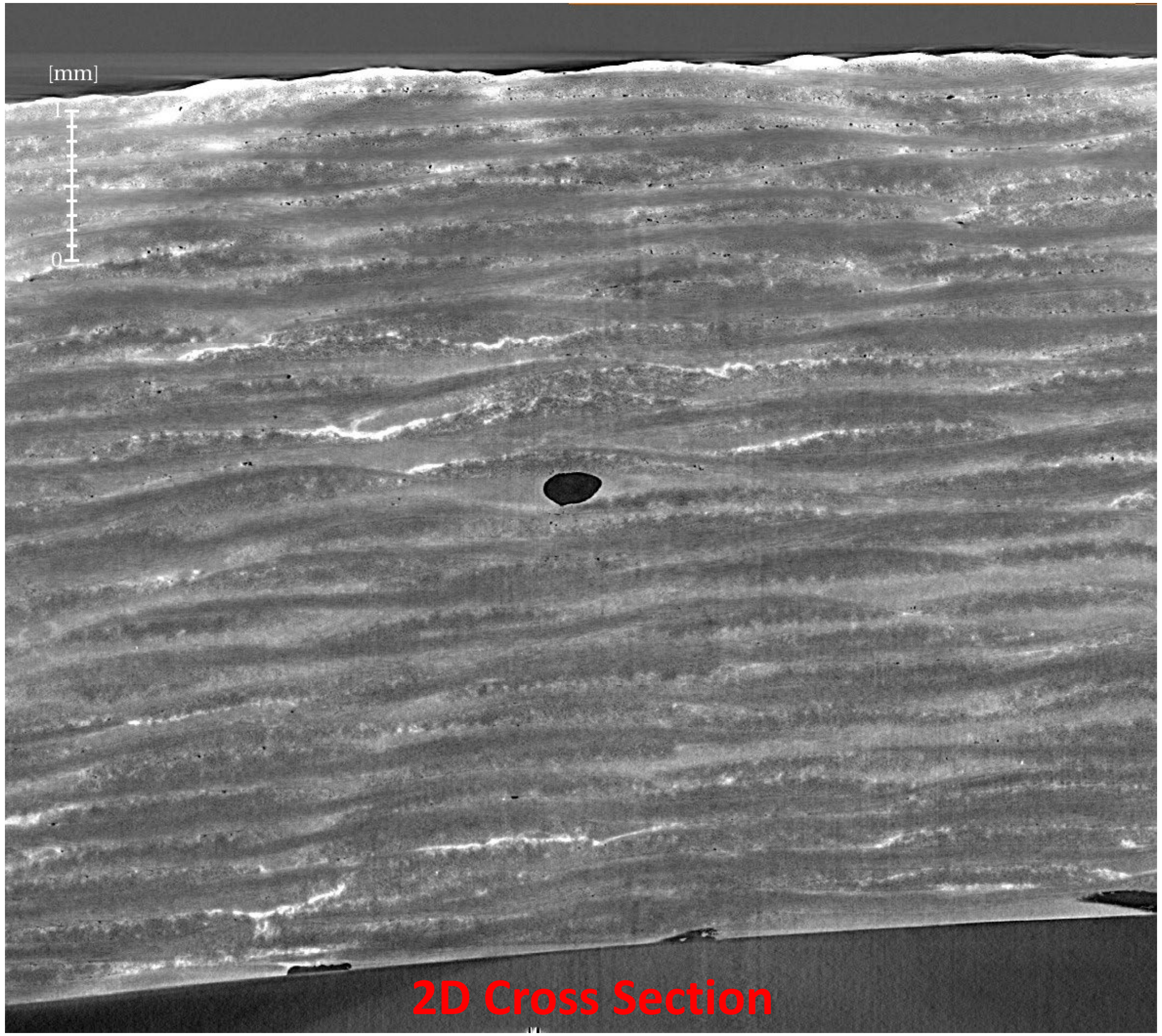
IMAGING CARBON-FIBER PARTS AT LOW RESOLUTION (10-20 μm)





IMAGING CARBON-FIBER PARTS AT LOW RESOLUTION (10-20 μm)



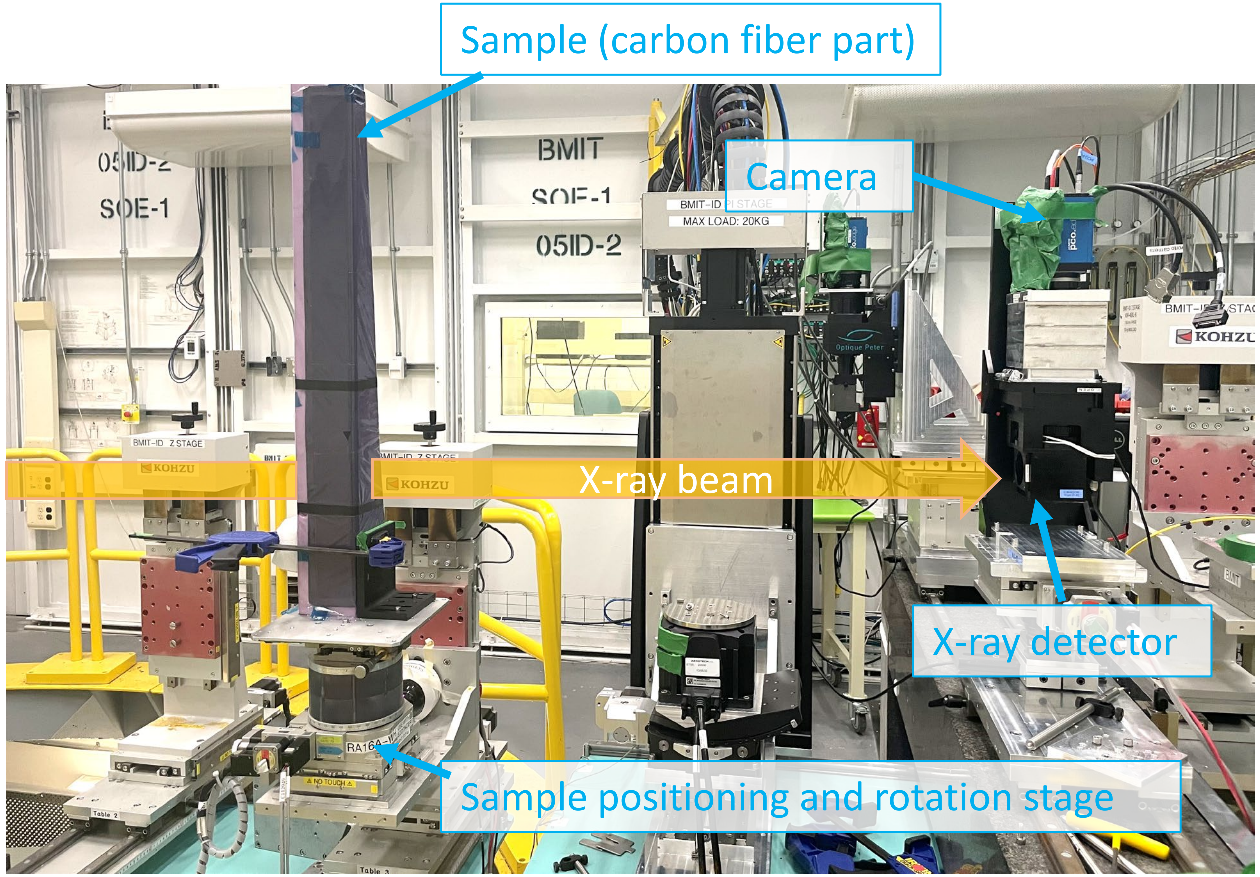


HOSTED BY: CKN Composites Knowledge Network

HOSTED BY: sampe Canada

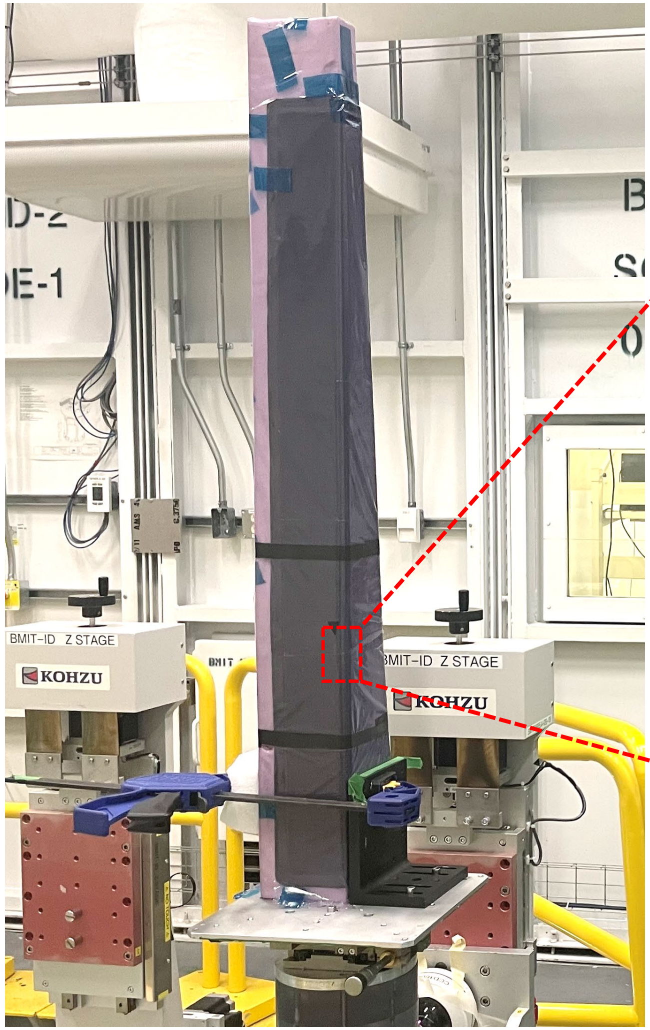
IMAGING CARBON-FIBER PARTS AT MEDIUM RESOLUTION (6.5 μm)

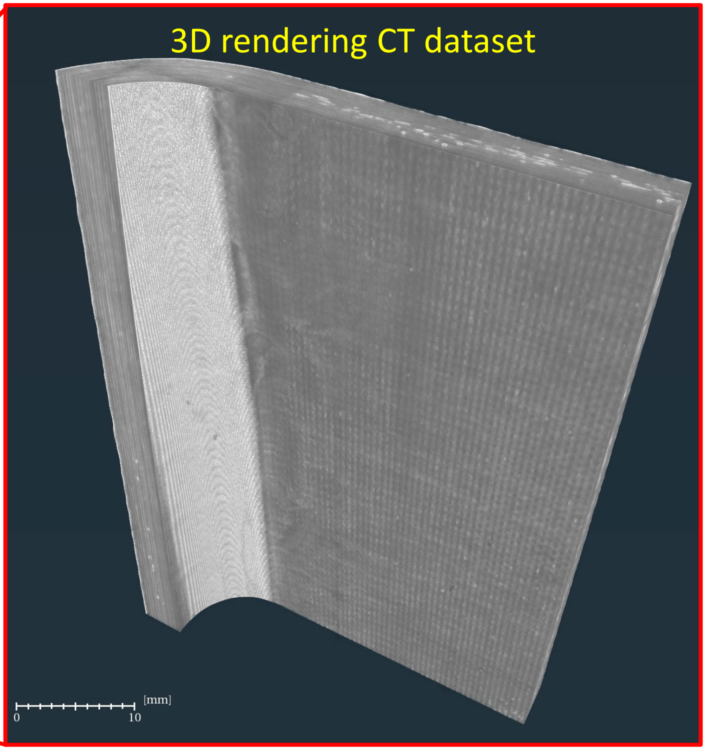
- Larger parts can also be imaged, but this requires lower resolution
- We use a different setup for this that is designed for large samples
- This work is a collaboration with Simon Hind at NRC Aerospace

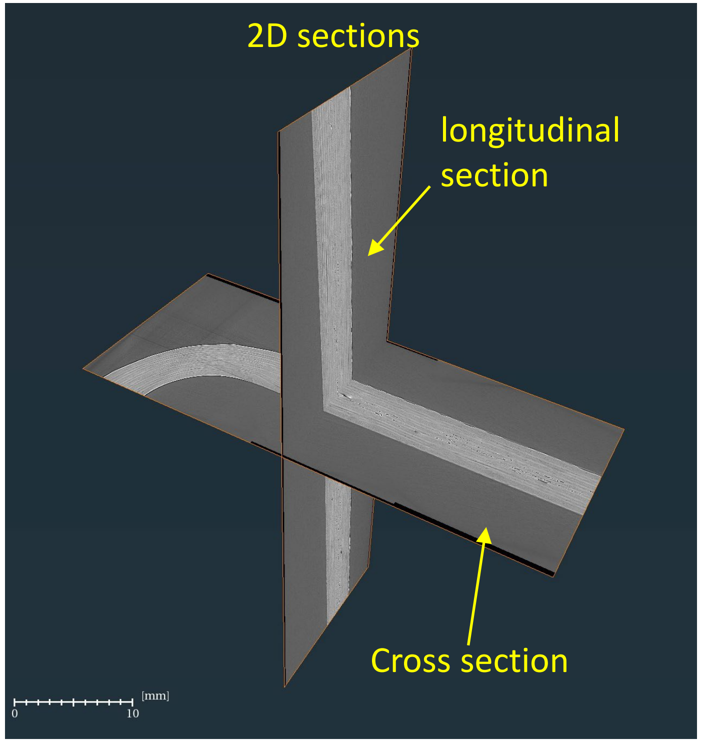


Unpublished work from collaboration between CLS and NRC (Simon Hind)

IMAGING CARBON-FIBER PARTS AT MEDIUM RESOLUTION (6.5 μm)





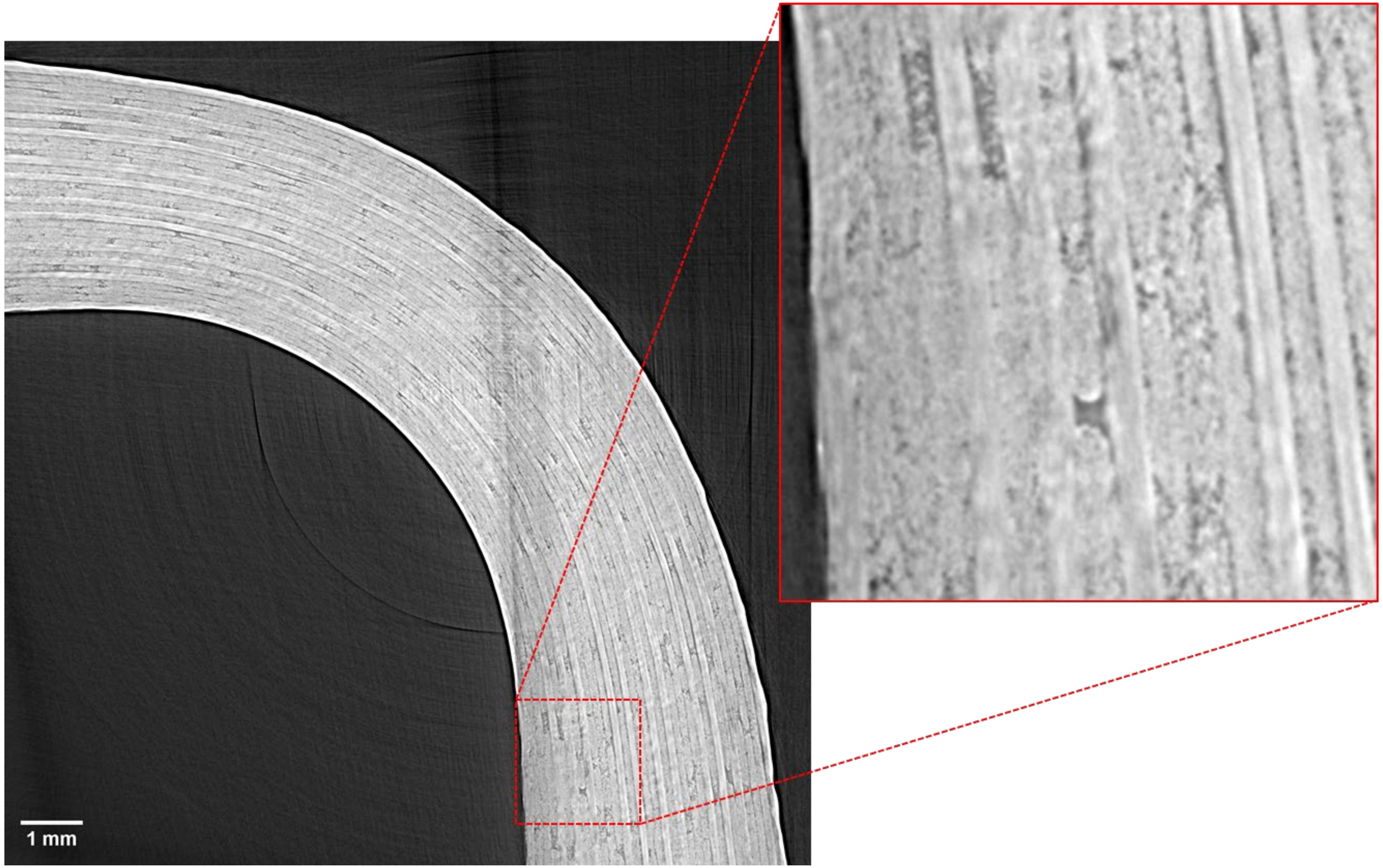


- Pixel size is 6.5 μm
- region of interest is about 60 x 40 x 16 mm (8800 x 6000 x 2500 pixels)

Unpublished work from collaboration between CLS and NRC (Simon Hind)

IMAGING CARBON-FIBER PARTS AT MEDIUM RESOLUTION (6.5 μm)

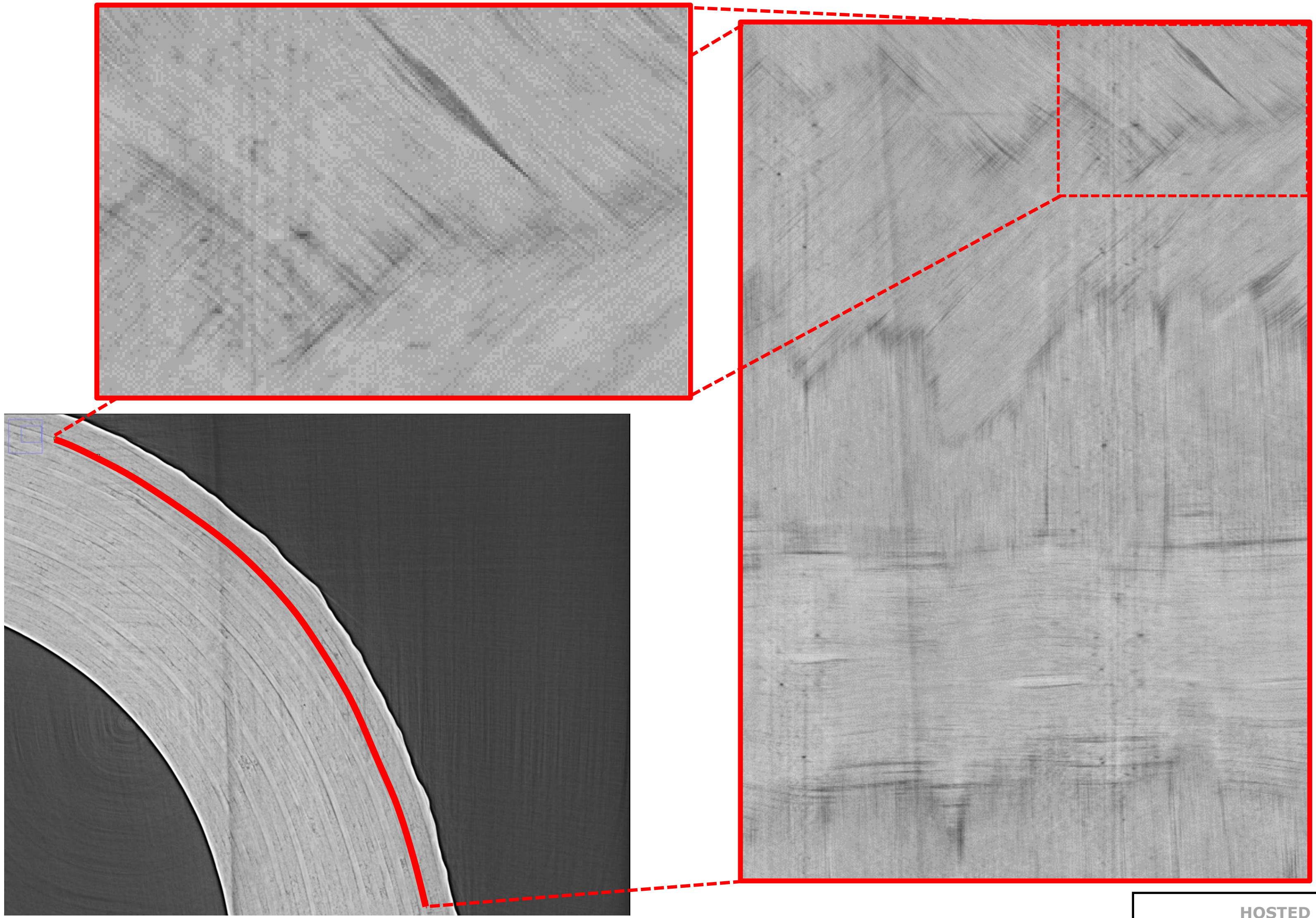
- Cross sections show that the plies are well resolved
- Resin rich areas and spaces between some tows and fibers are visible



Unpublished work from collaboration between CLS and NRC (Simon Hind)

IMAGING CARBON-FIBER PARTS AT MEDIUM RESOLUTION (6.5 μm)

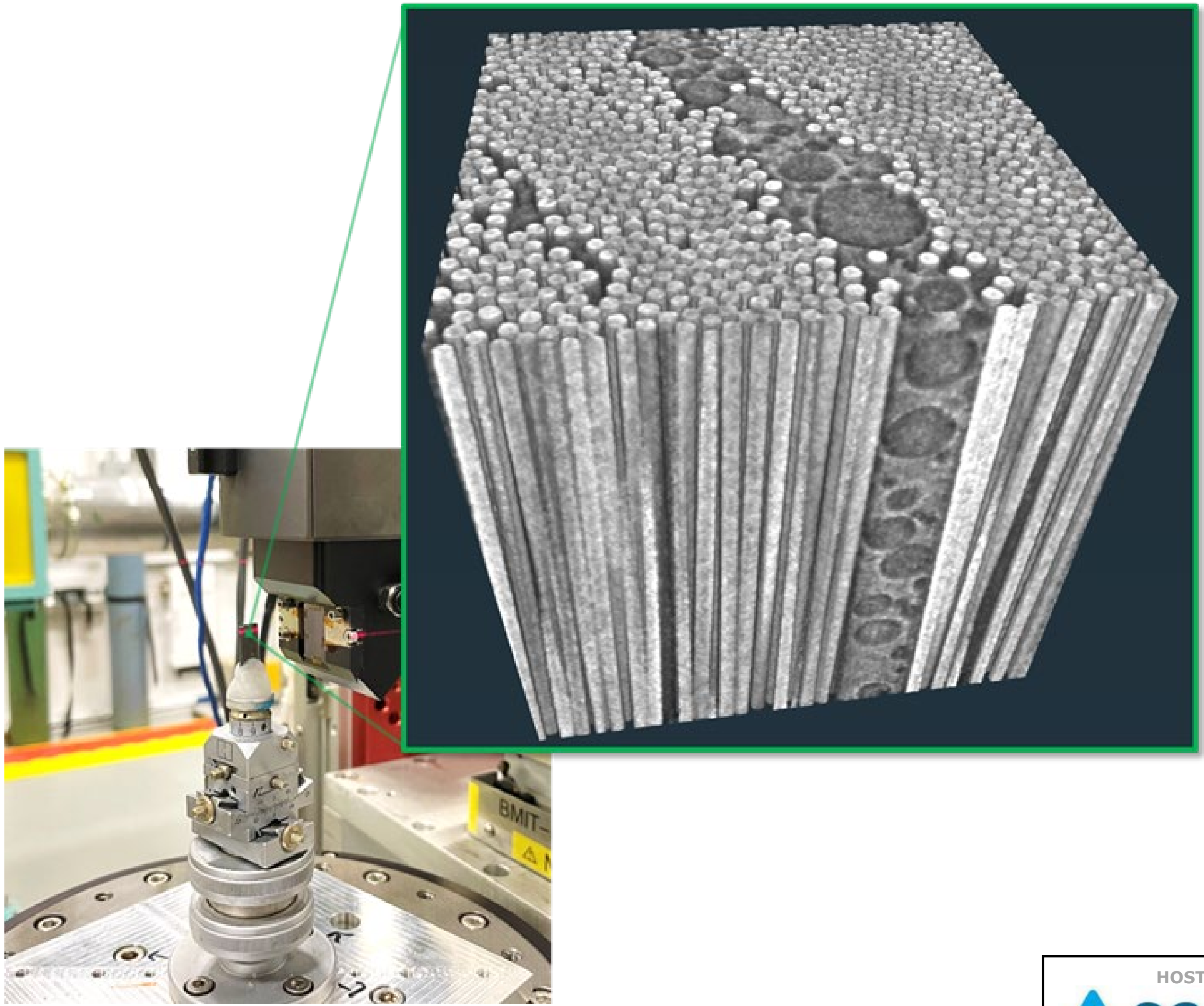
- You can create 2D sections by “unwrapping” layers that go around a curve
- This allows you to characterize fiber orientation and defects
- Individual fibers are still not visible



Unpublished work from collaboration between CLS and NRC (Simon Hind)

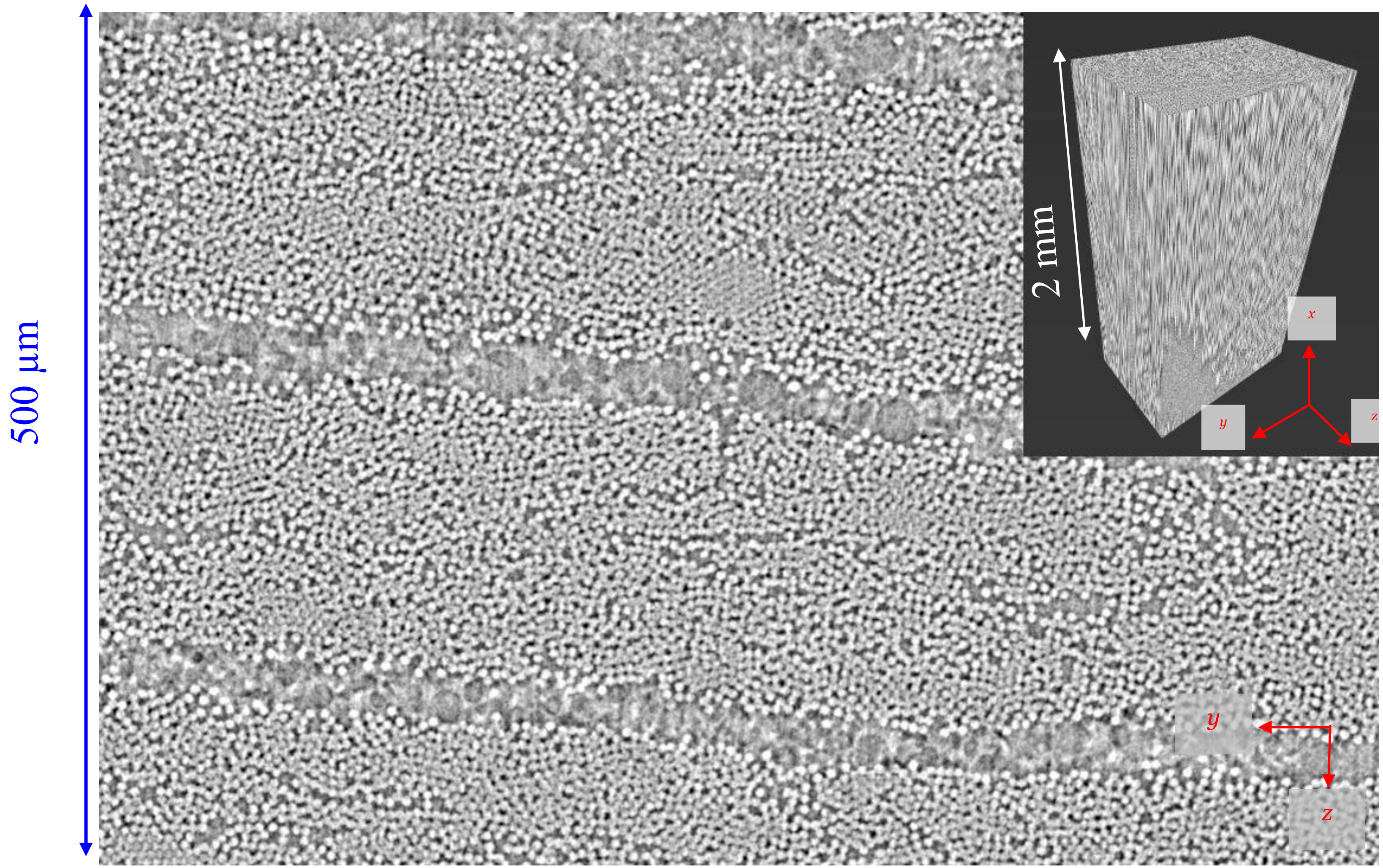
HIGH-RESOLUTION IMAGING OF INDIVIDUAL FIBERS

- To resolve to individual fibers, pixels need to be a fraction of the fiber diameter
- In these cases, we needed 360 nm pixels to properly resolve fibers
- you need to work with smaller samples (tens of mm, or ideally < 10 mm)

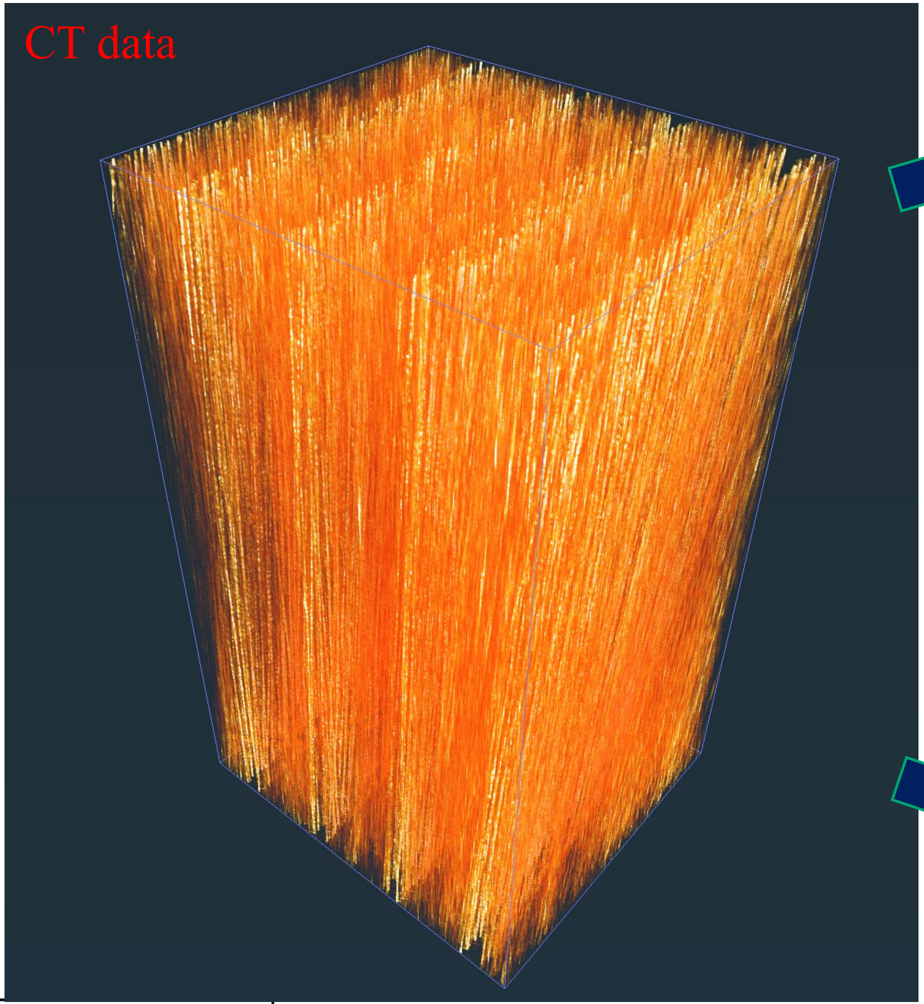


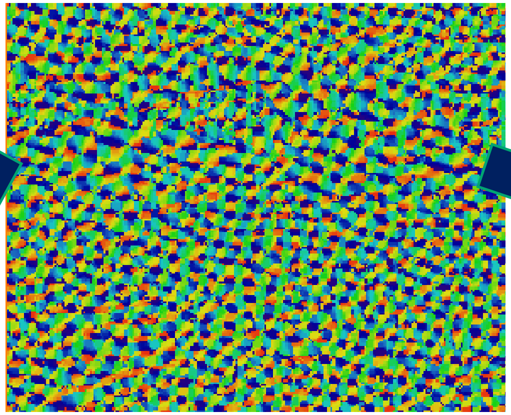
Unpublished work from collaboration between CLS and UBC/CRN (Farzad Sharifpour, Anoush Poursartip)

HIGH-RESOLUTION IMAGING OF INDIVIDUAL FIBERS



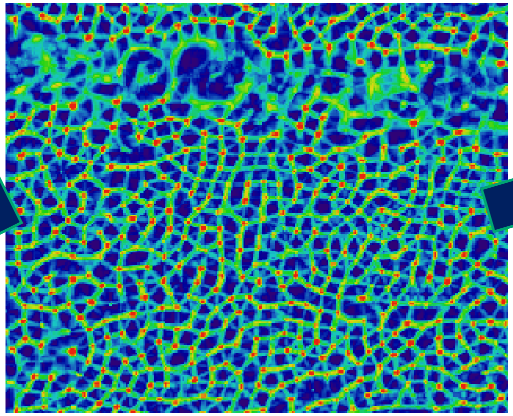
FIBER TRACING

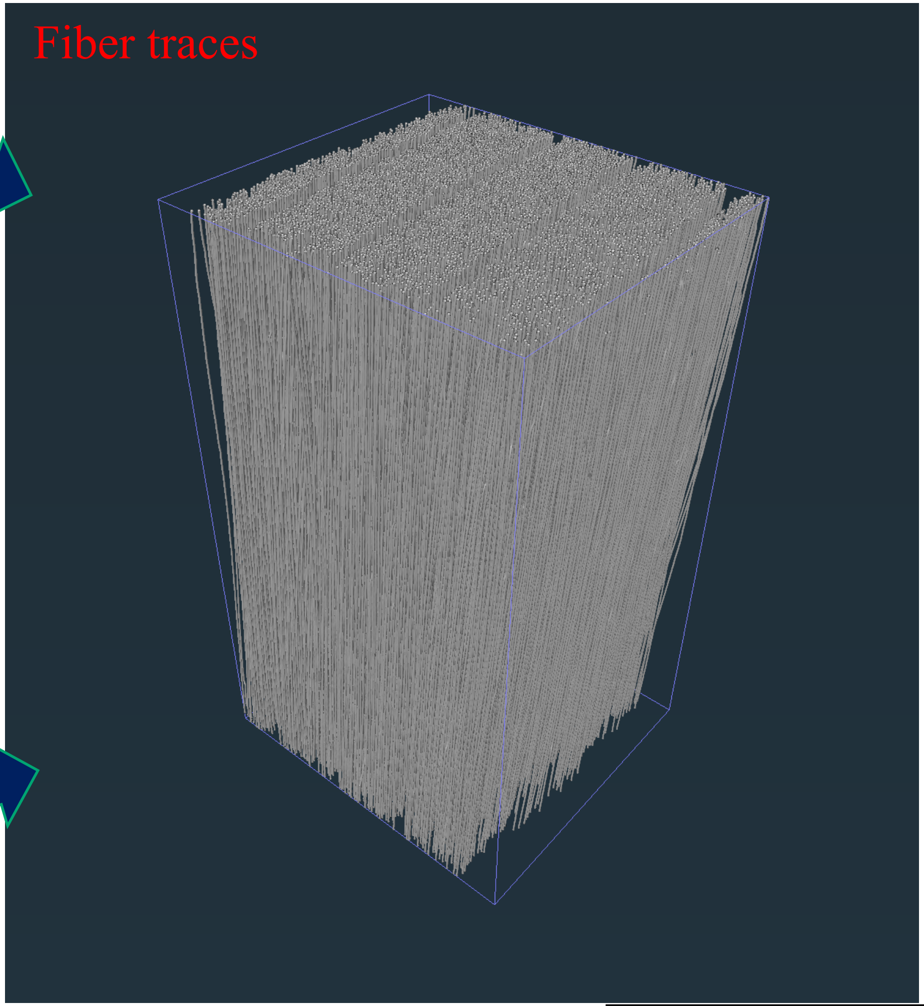




Orientation field

Correlation field

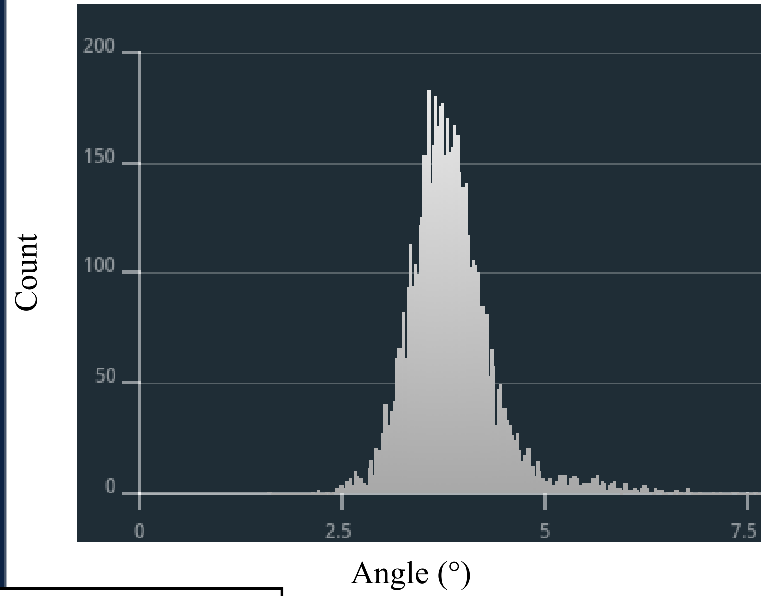


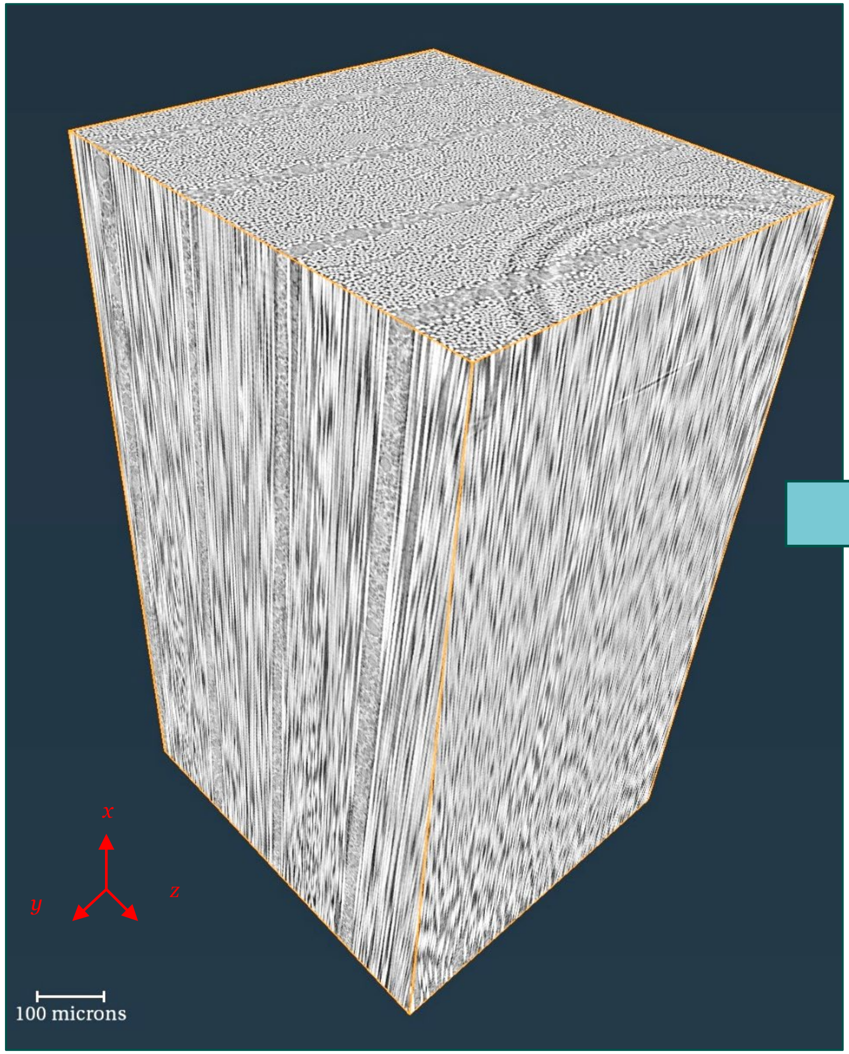


Unpublished work from collaboration between CLS and UBC/CRN (Farzad Sharifpour, Anoush Poursartip)

QUANTIFYING FIBER MISALIGNMENT

- Once the fiber is traced, you can analyze the distribution of fiber angles in both in-plane and out-of-plane directions

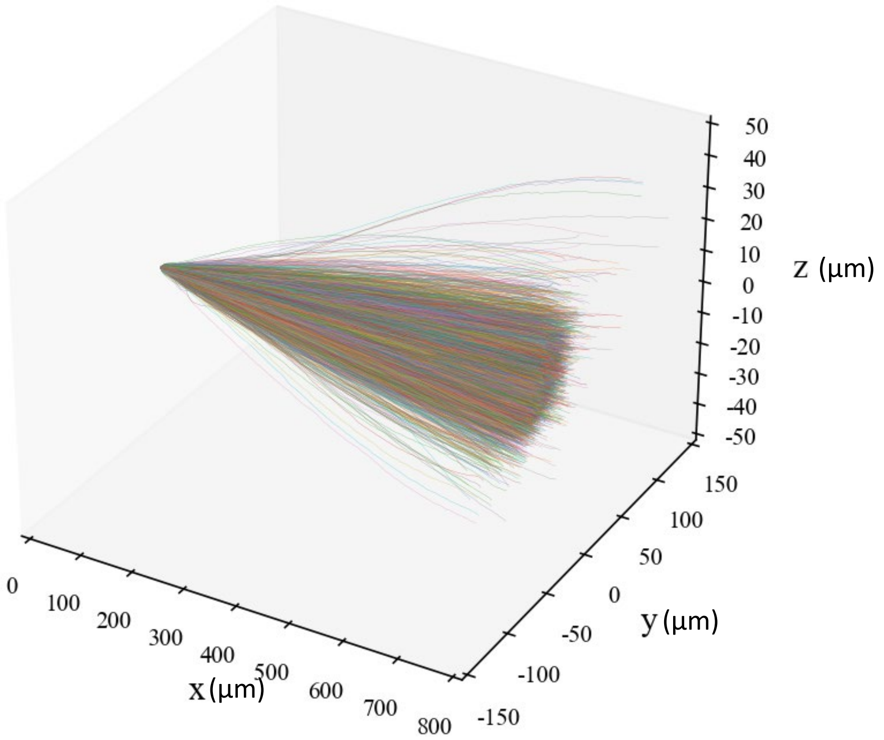




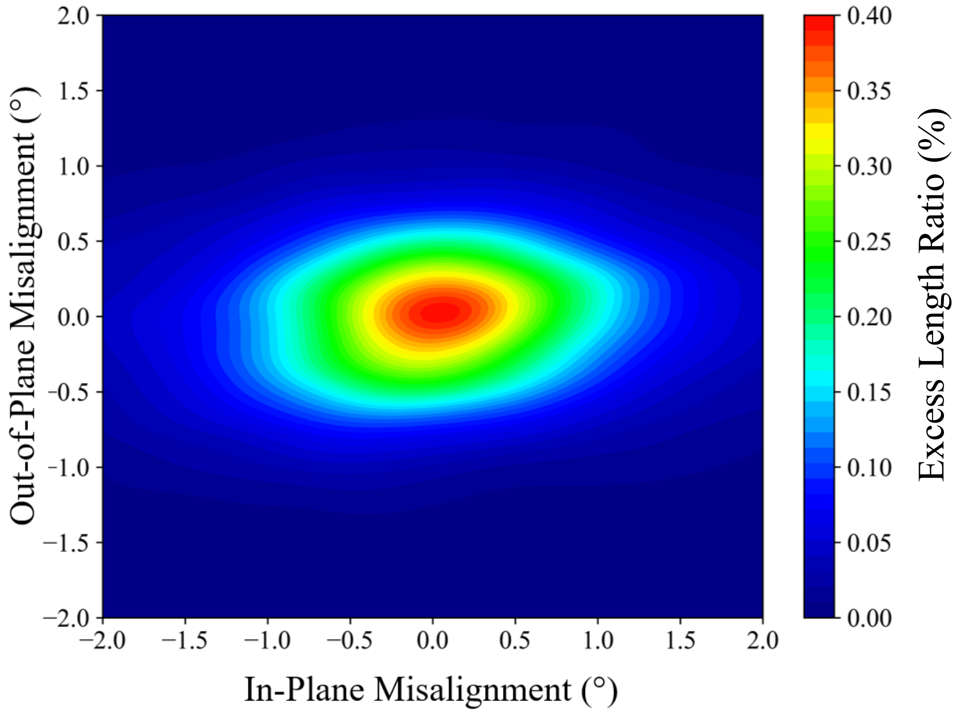
Unpublished work from collaboration between CLS and UBC/CRN (Dr Farzad Sharifpour, Anoush Poursartip)

QUANTIFYING FIBER MISALIGNMENT

- Another way to visualize this is to put all the fibers traces at the same starting point and make a heat map of the resulting angles



3D fiber shape starting at the coordinate system origin



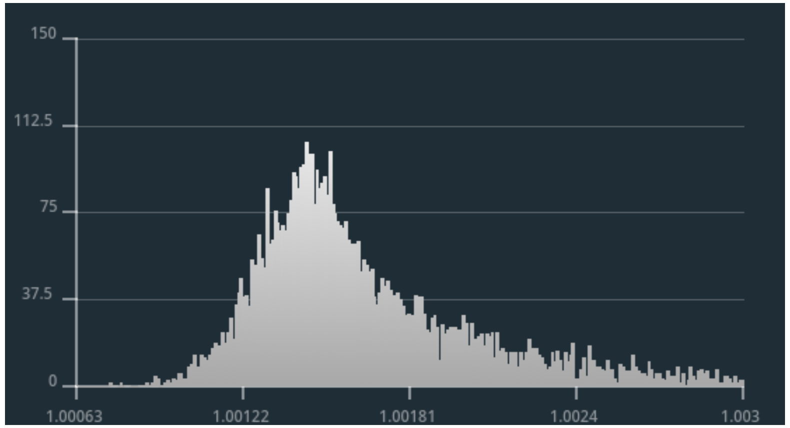
Distribution of "excess length ratio" at different degrees of misalignments

Unpublished work from collaboration between CLS and UBC/CRN (Farzad Sharifpour, Anoush Poursartip)

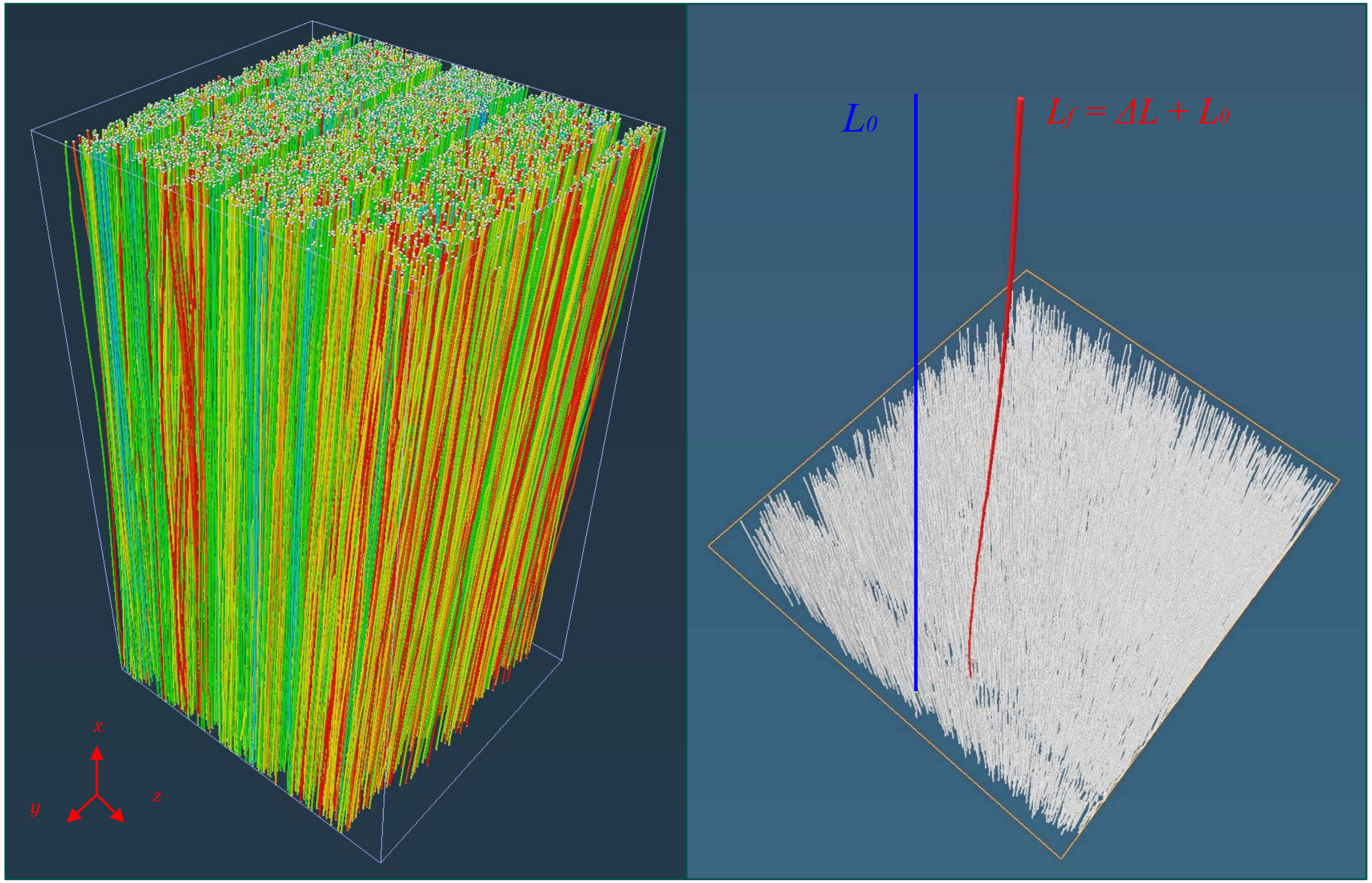
EXCESS LENGTH (AKA TORTUOSITY)

- Another metric of fiber geometry is excess length, which describes how much a fiber deviates from being a straight line
- A “twistier” fiber has greater excess length

Count



Tortuosity (µm/µm)



* Fiber with the maximum tortuosity has been indicated in this image.

HOSTED BY: CKN Composites Knowledge Network

Unpublished work from collaboration between CLS and UBC/CRN (Farzad Sharifpour, Anoush Poursartip)

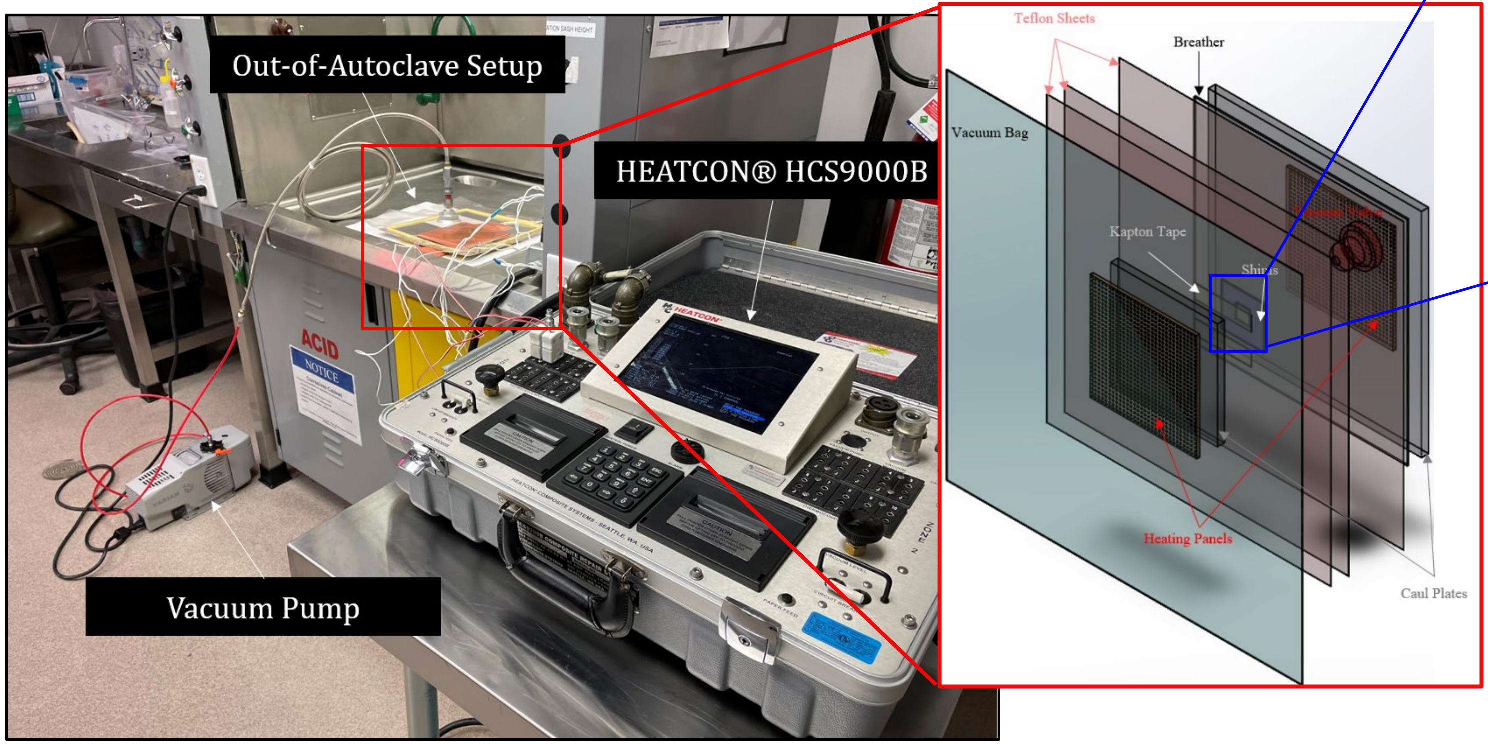
HOSTED BY: sampe Canada

EXCESS LENGTH (AKA TORTUOSITY)

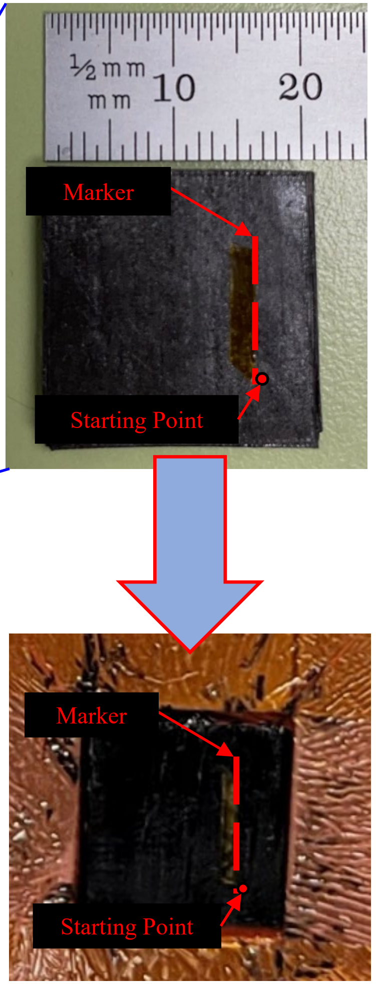
Unpublished work from collaboration between CLS and UBC/CRN (Farzad Sharifpour, Anoush Poursartip)

IN-SITU IMAGING BEFORE AND AFTER CURING

- Since CT is non-destructive, we can image a sample before and after curing
- If you carefully position the sample, you can image the same microscopic area to see how the structure changes



Developed a technique for conducting an OOA cure process on small prepregs.



Before Curing

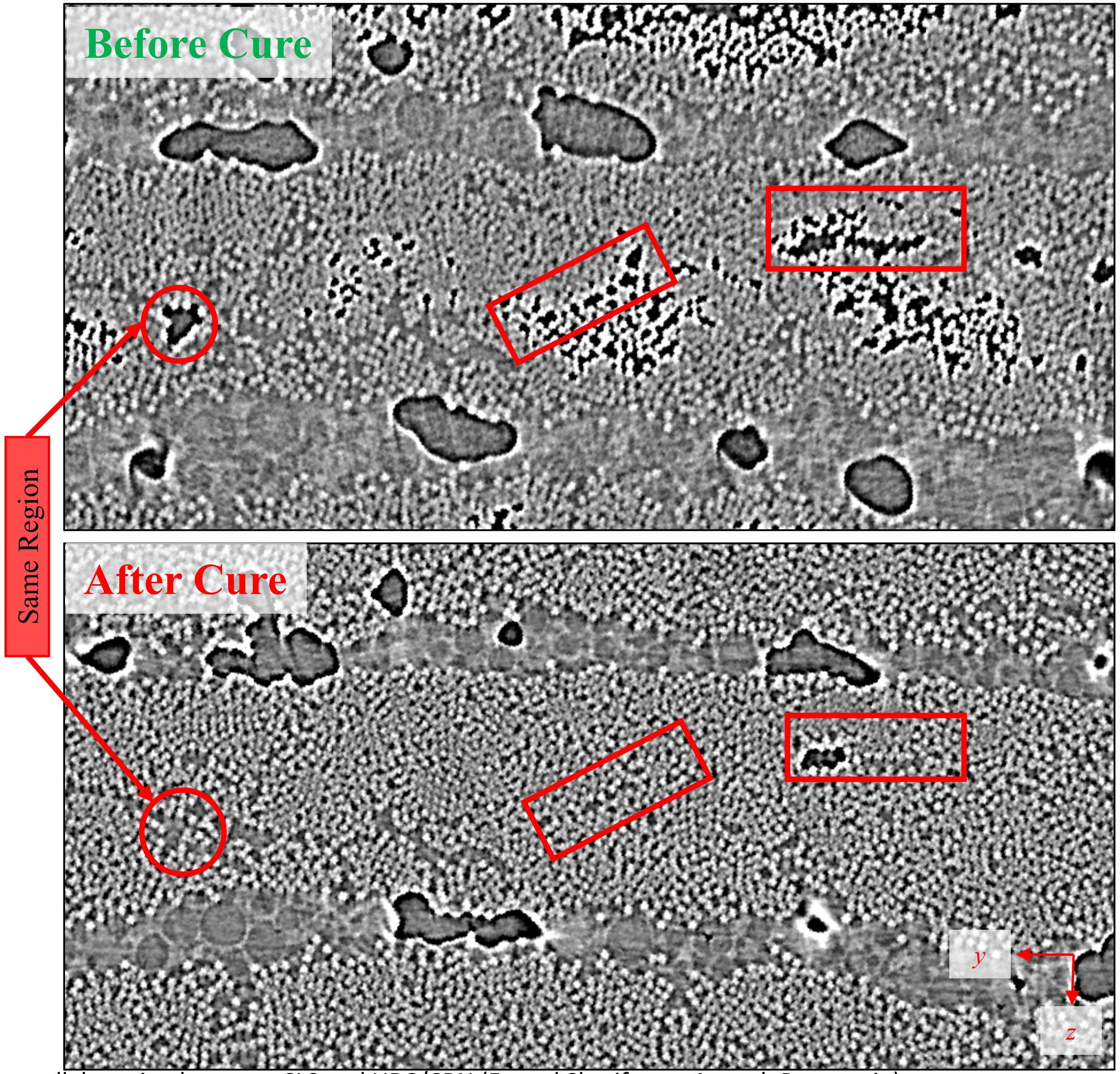
After Curing

Same location

Unpublished work from collaboration between CLS and UBC/CRN (Farzad Sharifpour, Anoush Poursartip)

IN-SITU IMAGING BEFORE AND AFTER CURING

- During curing, the pre-preg is debulked and voids disappear
- Some porosity is left behind in this case, but it has moved around
- Larger voids end up leaving behind resin-rich regions



Unpublished work from collaboration between CLS and UBC/CRN (Farzad Sharifpour, Anoush Poursartip)

SUMMARY

- CT is a very powerful tool for characterizing defects and fiber geometry in 3D
- Conventional CT can capture high-contrast features like voids and damage, but resolving fibers is difficult unless you're using fiberglass
- If you can resolve fibers, there's a lot of information contained within a CT scan that you can analyze statistically and reduce down to simple metrics
- Since CT is non-destructive, you can image processes over time like curing, resin infiltration, strain, damage, etc.
- If you're working with carbon fiber, quantitative fiber tracing and analysis really requires a synchrotron

ACKNOWLEDGEMENTS

Special thanks to:

- Farzad Sharifpour (UBC/CRN)
- Anoush Poursartip (UBC/CRN)
- Simon Hind (NRC)
- Sergey Gasilov (CLS)

The CLS offers synchrotron µCT imaging to industry clients as an analytical service. For more information, please visit: https://www.lightsource.ca/industry

Or contact me at: toby.bond@lightsource.ca

Canadian Light Source   Centre canadien de rayonnement synchrotron

Thank you for joining us!

Keep an eye out for upcoming AIM events:

Introduction to Carbon Fibre Bicycles
Hosted by Richard Mathews
January 29, 2024
https://compositeskn.org/KPC/A377

And don't forget to visit the KPC for more information:

https://compositeskn.org/KPC

Today's Webinar will be posted at:
https://compositeskn.org/KPC/A374