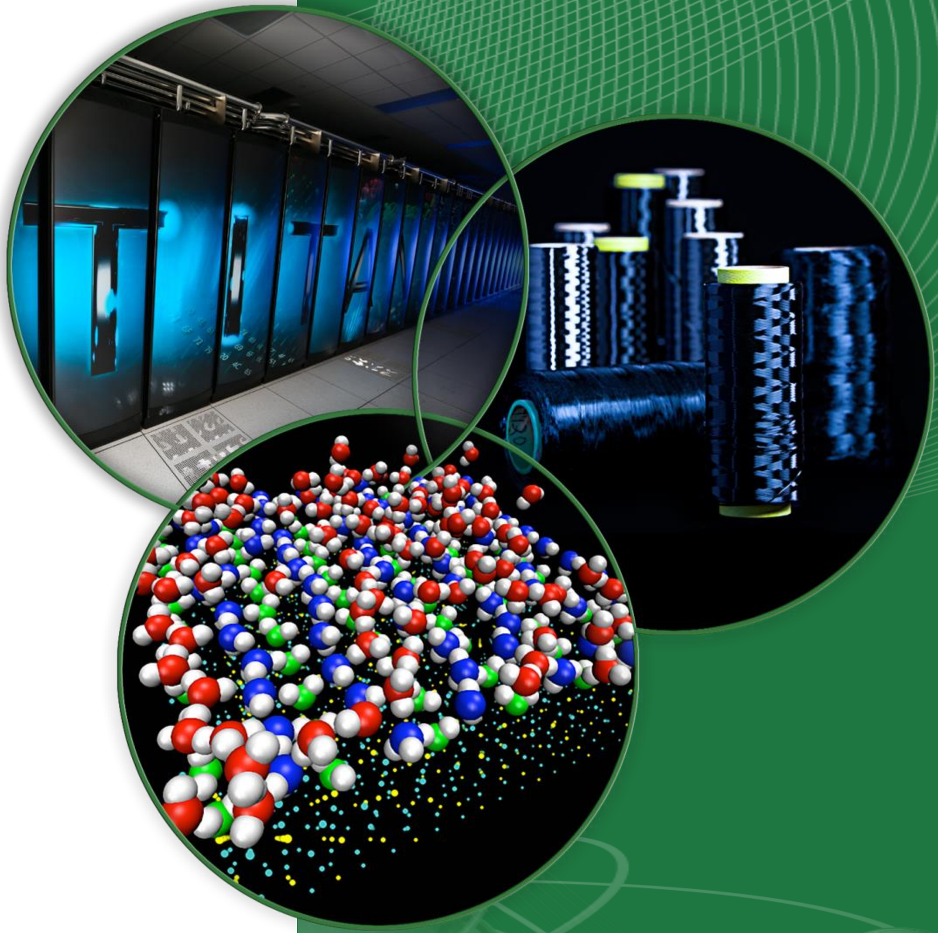
Imaging with Neutrons



Lou Santodonato
Instrument Scientist
Neutron Imaging Team

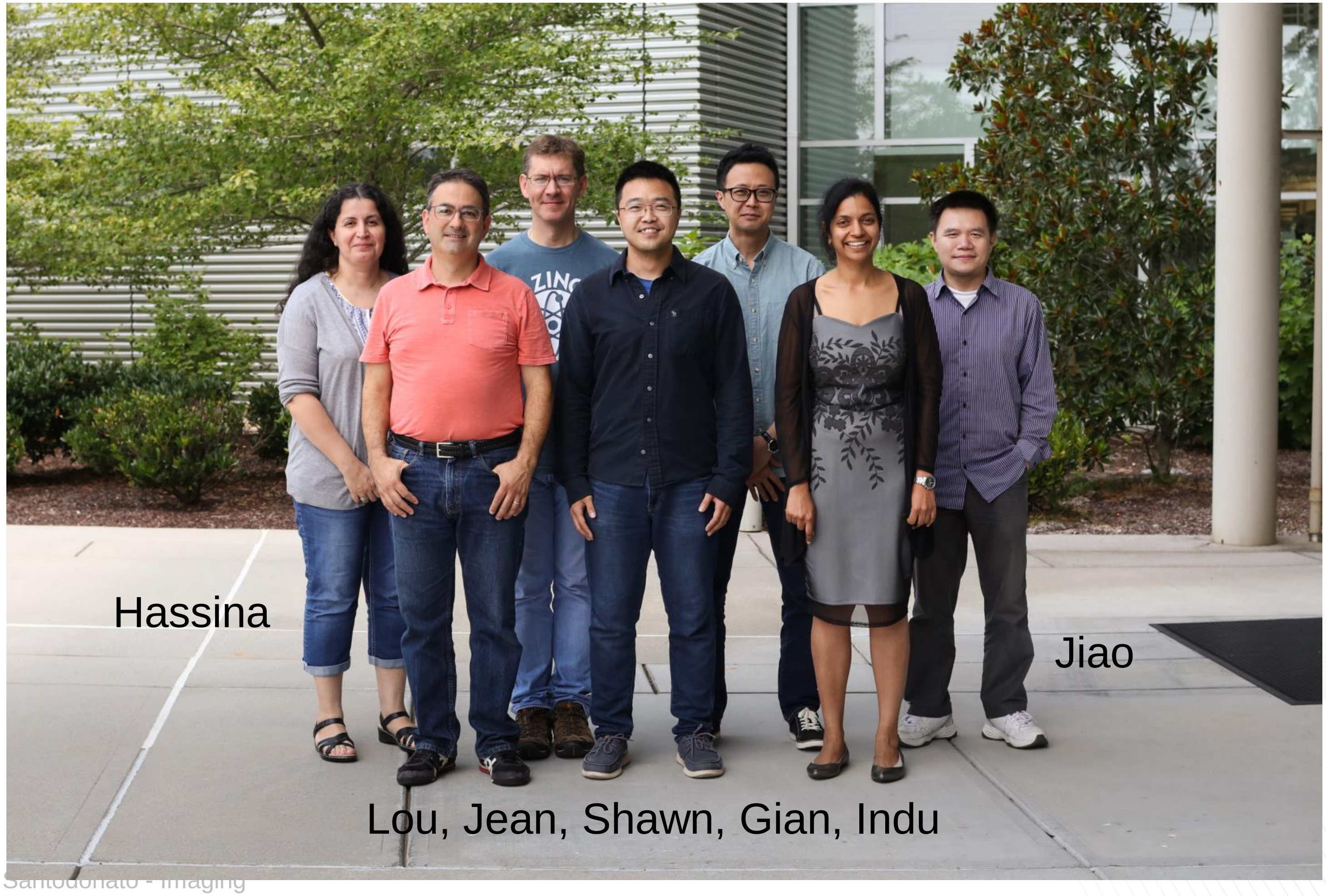
19th National School on
Neutron and X-ray Scattering
August 5-19, 2017

ORNL is managed by UT-Battelle
for the US Department of Energy

OAK RIDGE
National Laboratory

Acknowledgement

- The Neutron Imaging Team



Hassina

Jiao

Lou, Jean, Shawn, Gian, Indu

Goals

- Compare neutron imaging to other imaging techniques, and know when to choose it

- Understand the basic instrument layout and principals of neutron image acquisition and analysis

- Learn by example
    - Review some recent neutron imaging projects

Imaging throughout Nobel Prize History

- 1901: Roentgen, FIRST Nobel Prize in Physics, Discovery of X-rays
- 1979: Cormack and Hounsfield, Nobel Prize in Medicine, Computed Tomography (CT)
- 1986: Ruska, Binnig, Rohrer, Nobel Prize in Physics, Electron Microscopy
- 2003: Lauterbur and Mansfield, Nobel Prize in Medicine, Magnetic Resonance Imaging (MRI)
- 2009: Boyle and Smith, Nobel Prize in Physics, Imaging semi-conductor circuit, the CCD* sensor

- (*) Charge-Coupled Device

What about Neutron Imaging?

- The Nobel Prize for neutron imaging has yet to be won
  - An opportunity for you!

- NI started in the mid 1930’s but only the past 30 years has it come to the forefront of non-destructive testing

- World conferences and workshops being held regularly

Obtaining a Transmission Image

Medical Imaging

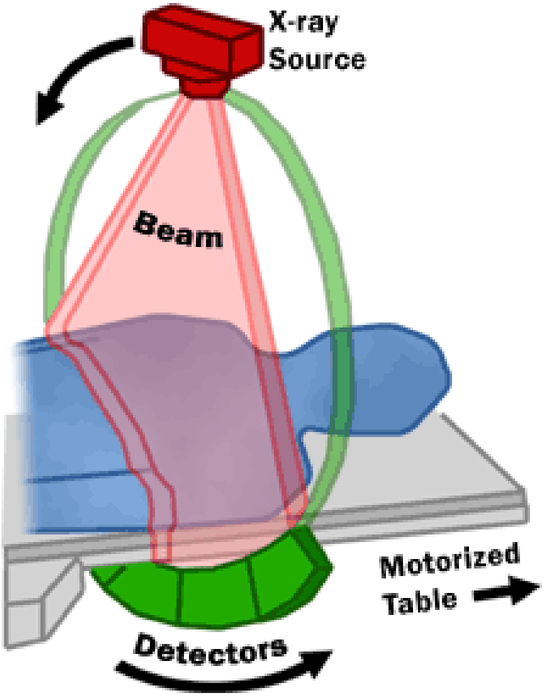
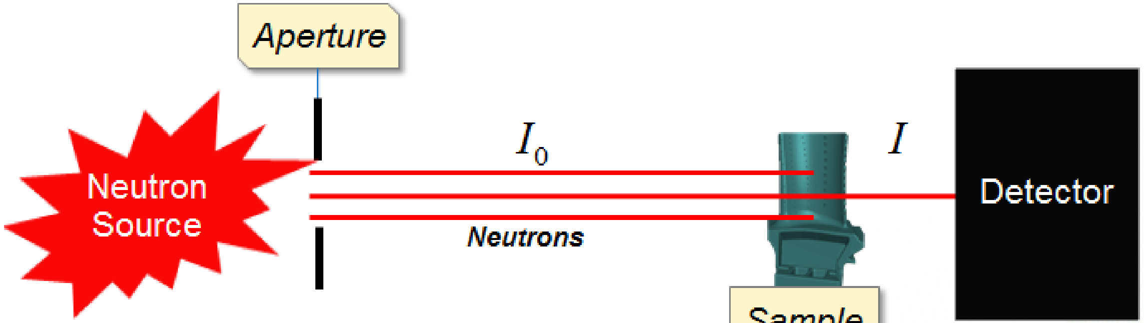


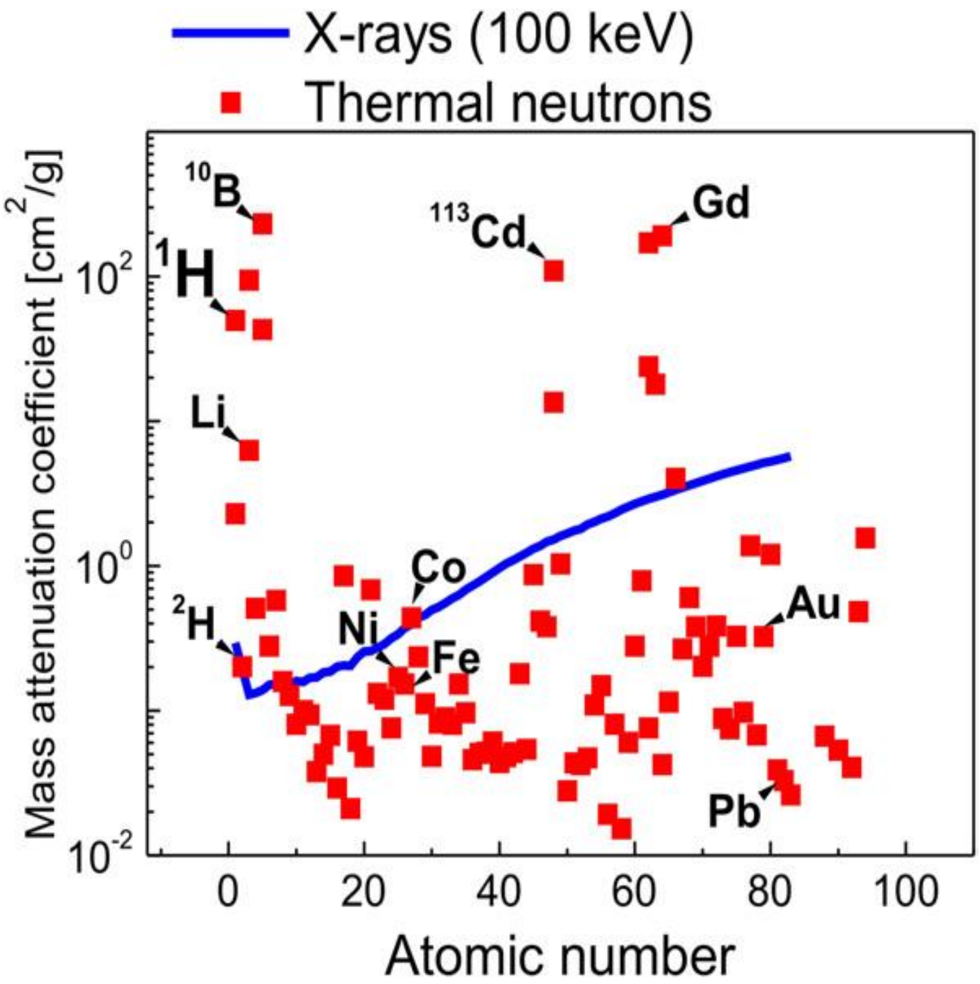
Figure from http://www.fda.gov

Neutron Imaging

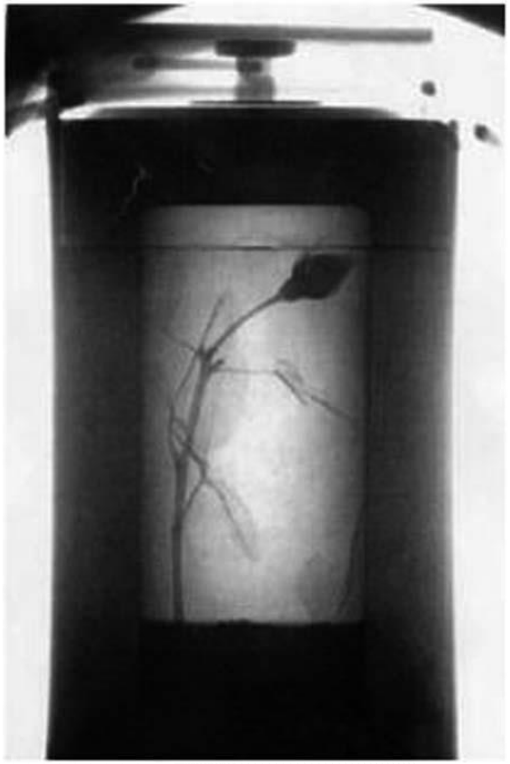
- Measures "shadows" based on neutron attenuation through the object
- One shadow is a radiograph
- These "shadows" are collected at different angles and reconstructed in 3D, called the computed tomography or CT



Distinctive Features of Neutron Imaging



[M. Strobl et al., J. Phys. D: Appl. Phys. ***42*** *(2009) 243001]*

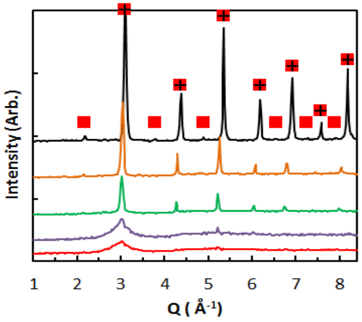


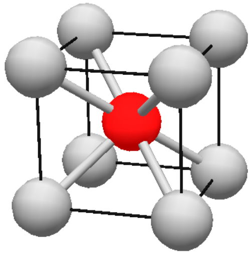
Neutron Radiograph of Rose in Lead Flask!

Courtesy of E. Lehmann,PSI

Distinctive Features of Neutron Imaging

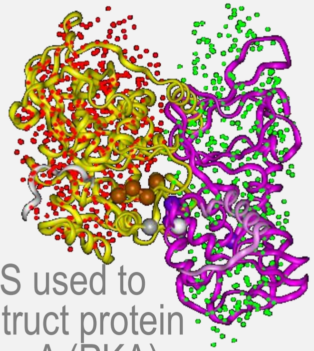
Diffraction



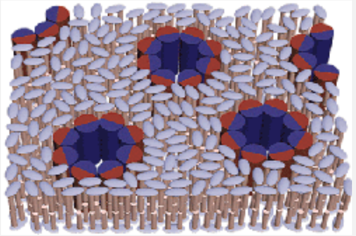


Crystal structures

Scattering



SANS used to construct protein kinase A (PKA)



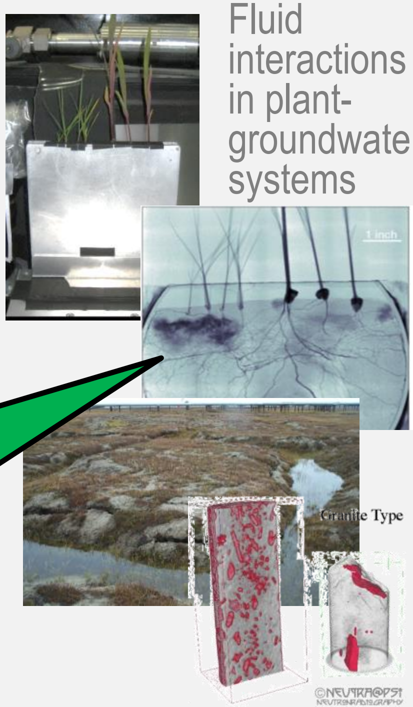
Characterization of biological membranes, colloids, porosity, etc.

Inferred structure (indirect)

You can directly see the structure.

How easy!

Real-space imaging



Fluid interactions in plant-groundwater systems

Ice/water segregation in permafrost structures

Direct structure

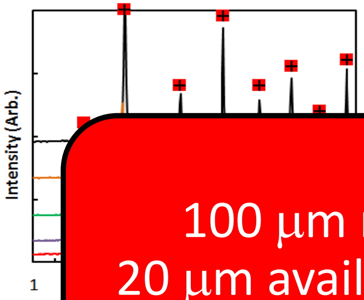
10^{-11}	10^{-9}	10^{-7}	10^{-5}	10^{-3}
0.1Å	1.0nm	0.1μm	10.0μm	1mm

Dimension (meters)

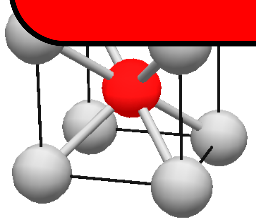
OAK RIDGE National Laboratory

Distinctive Features of Neutron Imaging

Diffraction

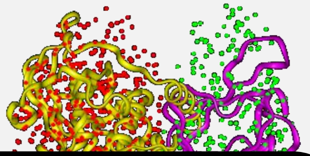


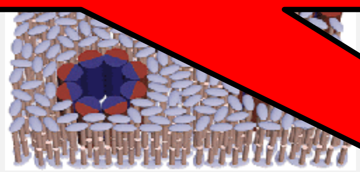
100 μm routinely available
20 μm available with trade-off in field-of-view and acquisition times



Crystal structures

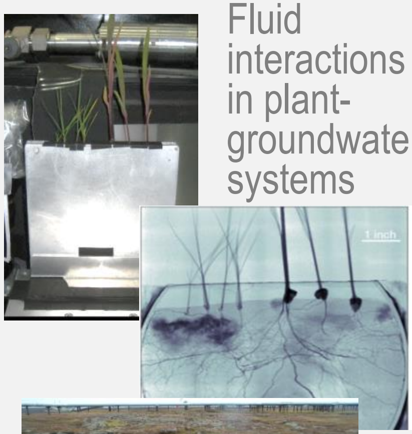
Scattering



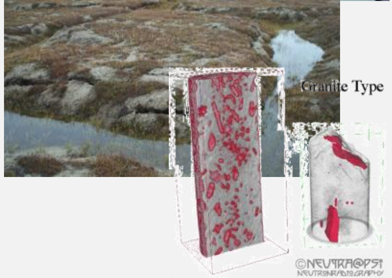


Characterization of biological membranes, colloids, porosity, etc.

Real-space imaging



Fluid interactions in plant-groundwater systems



Ice/water segregation in permafrost structures

Inferred structure (indirect)

Direct structure

10^{-11}	10^{-9}	10^{-7}	10^{-5}
0.1Å	1.0nm	0.1μm	10.0μm

Dimension (meters)

Spatial resolution is limited!

Quantitative Neutron Imaging

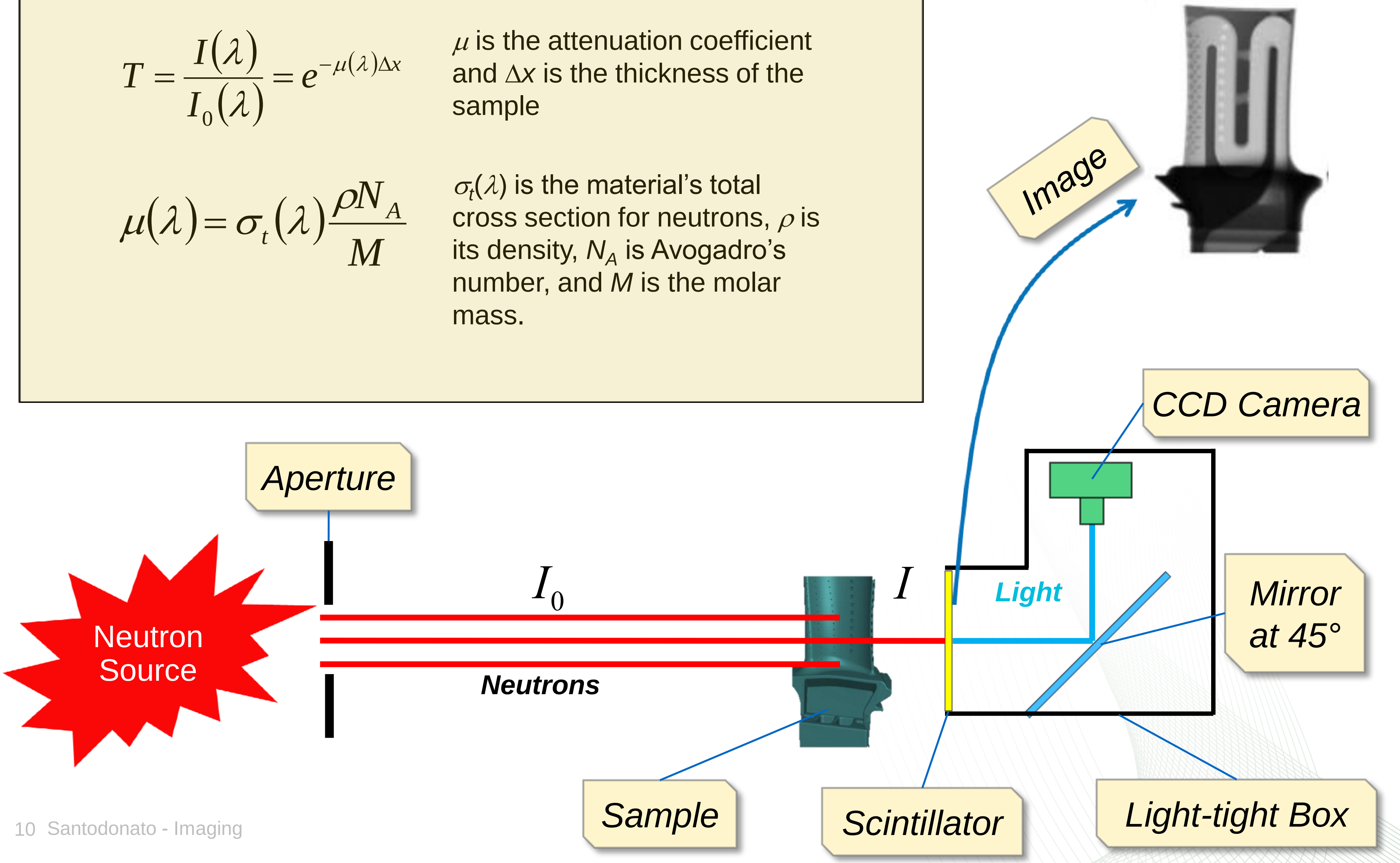
Lambert-Beer Law:

$$T = \frac{I(\lambda)}{I_0(\lambda)} = e^{-\mu(\lambda)\Delta x}$$

μ is the attenuation coefficient and Δx is the thickness of the sample

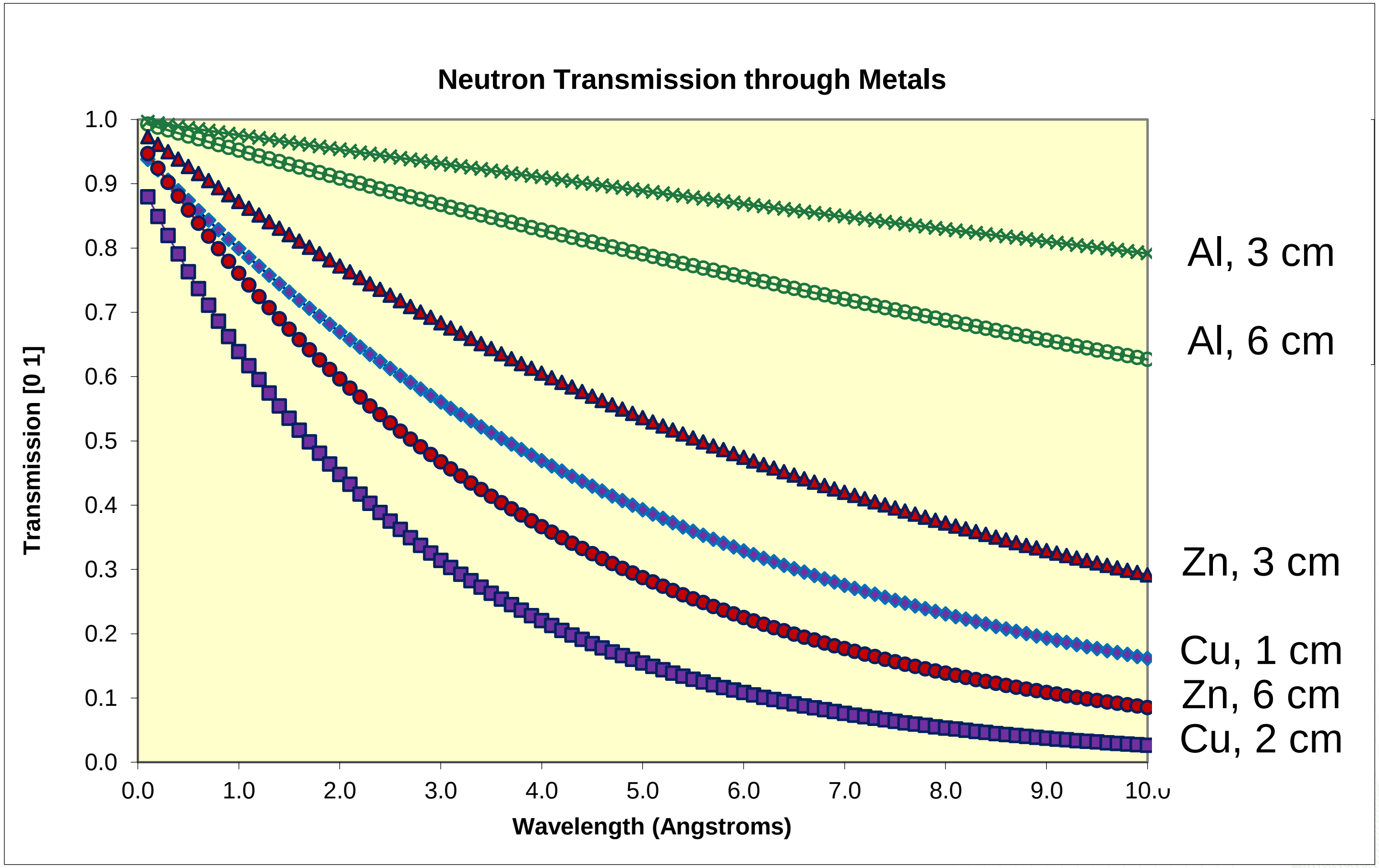
$$\mu(\lambda) = \sigma_t(\lambda)\frac{\rho N_A}{M}$$

$\sigma_t(\lambda)$ is the material's total cross section for neutrons, ρ is its density, N_A is Avogadro's number, and M is the molar mass.



Neutron Transmission Depends Upon . . .

- Sample composition, thickness, and neutron wavelength



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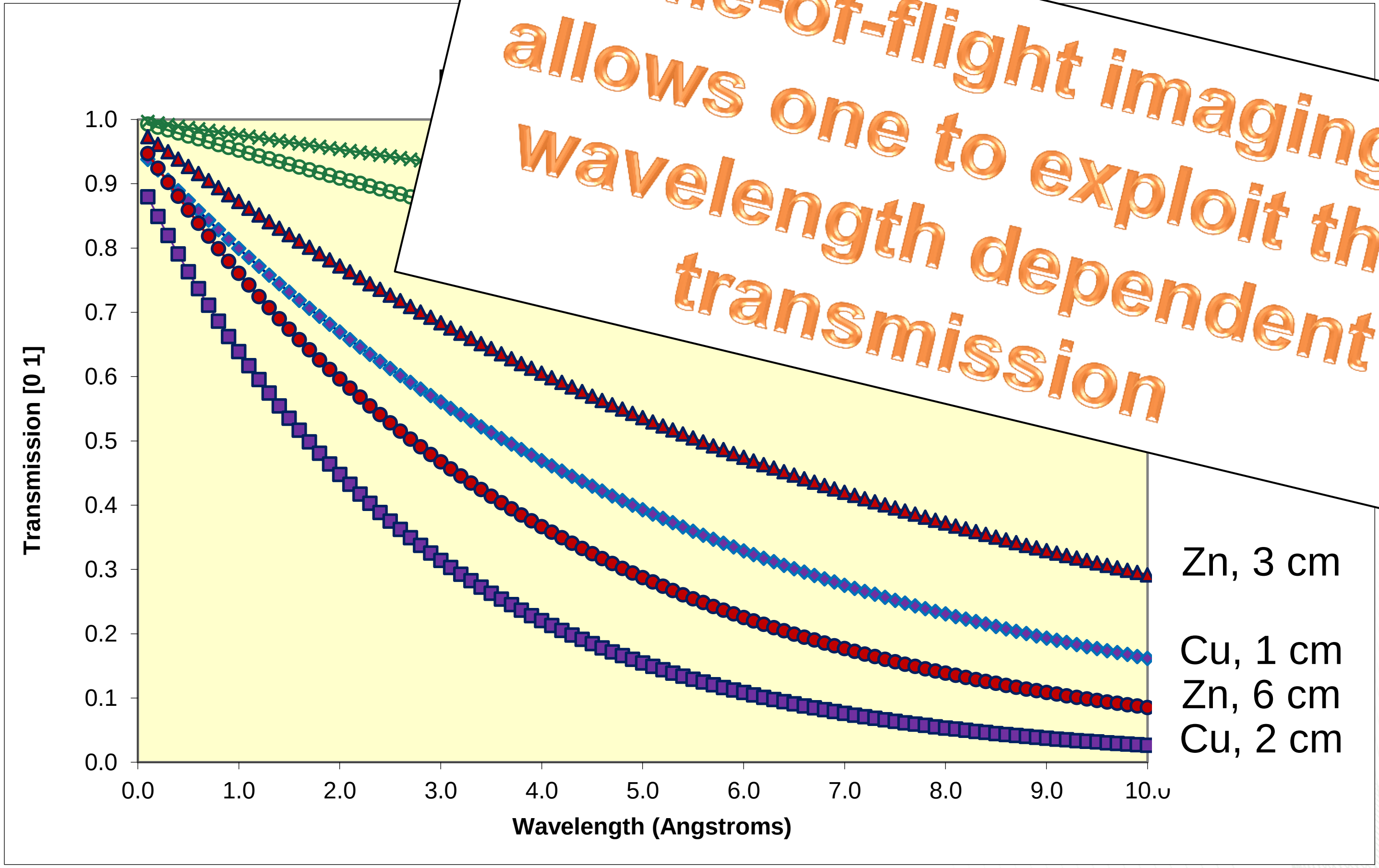


Time-of-flight imaging allows one to exploit the wavelength dependent transmission

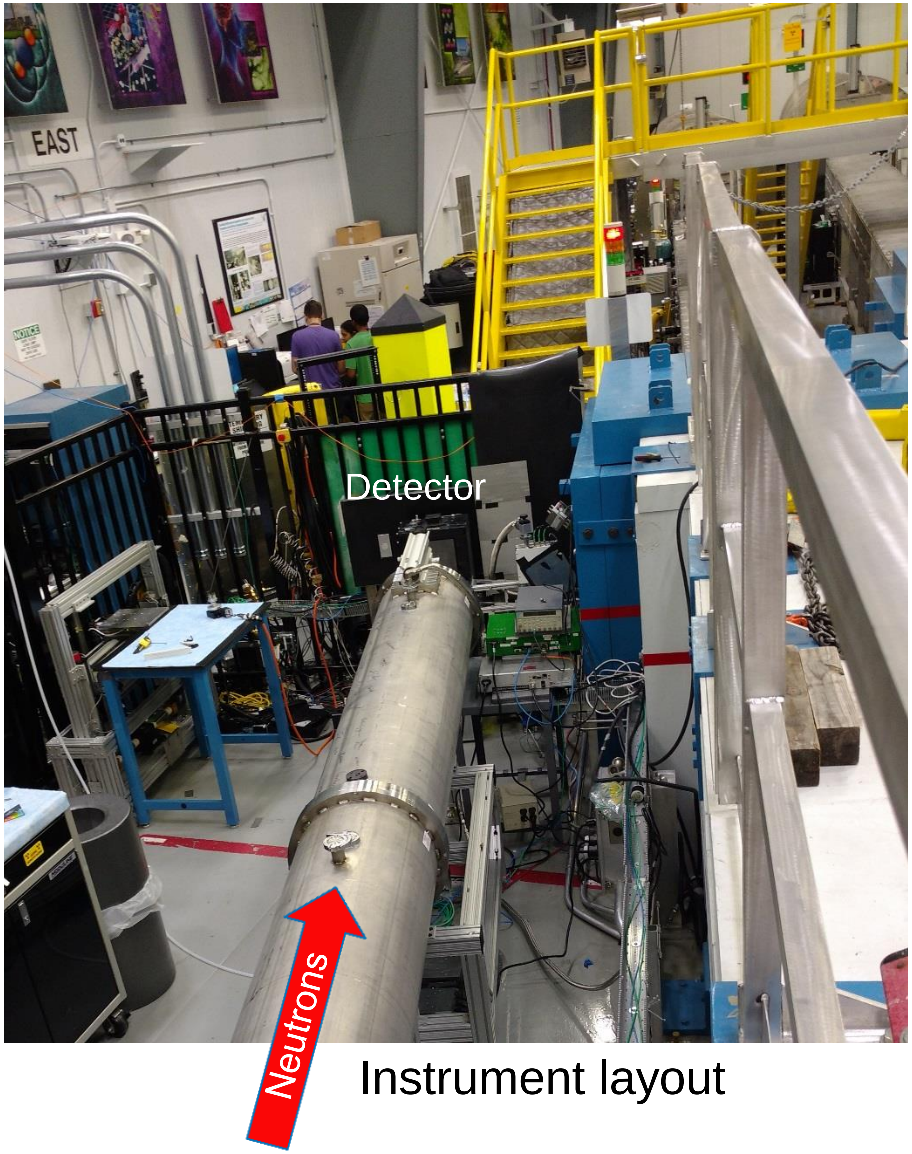
Goals

- Compare neutron imaging to other imaging techniques, and know when to choose it

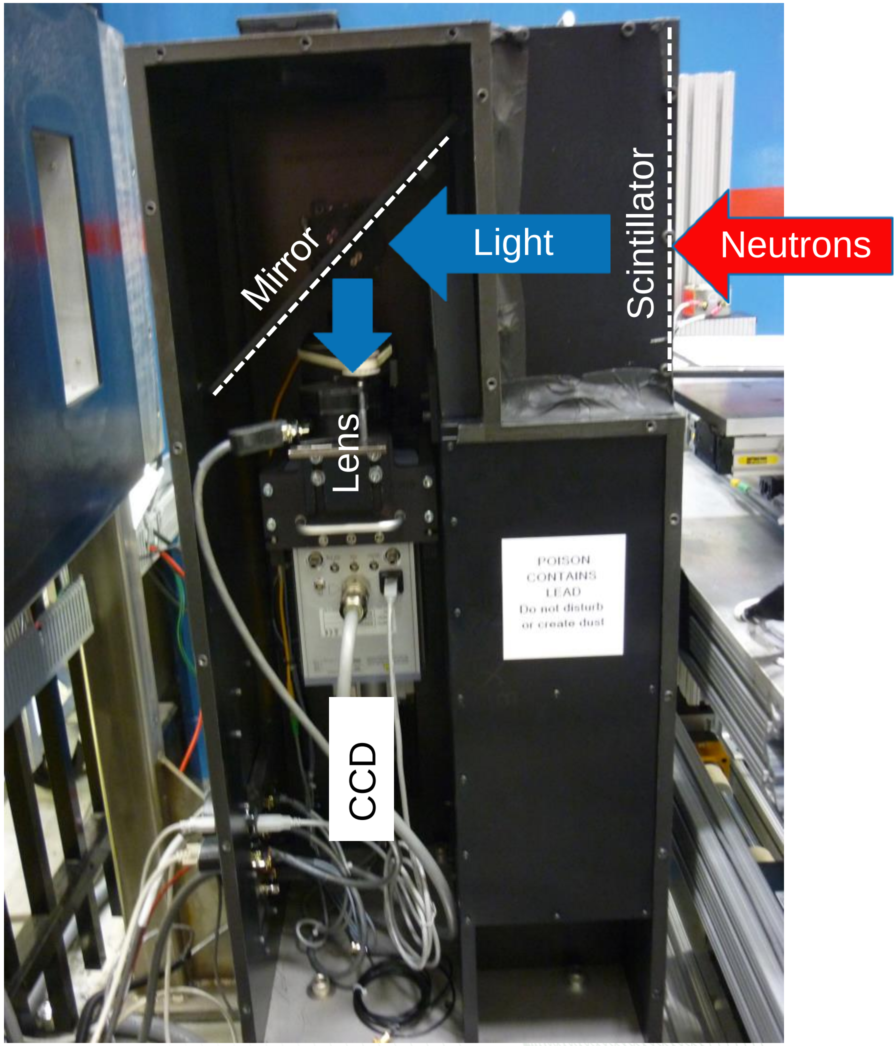
- Understand the basic instrument layout and principals of neutron image acquisition and analysis

- Learn by example
  - Review some recent neutron imaging projects

CG-1D Neutron Imaging Facility

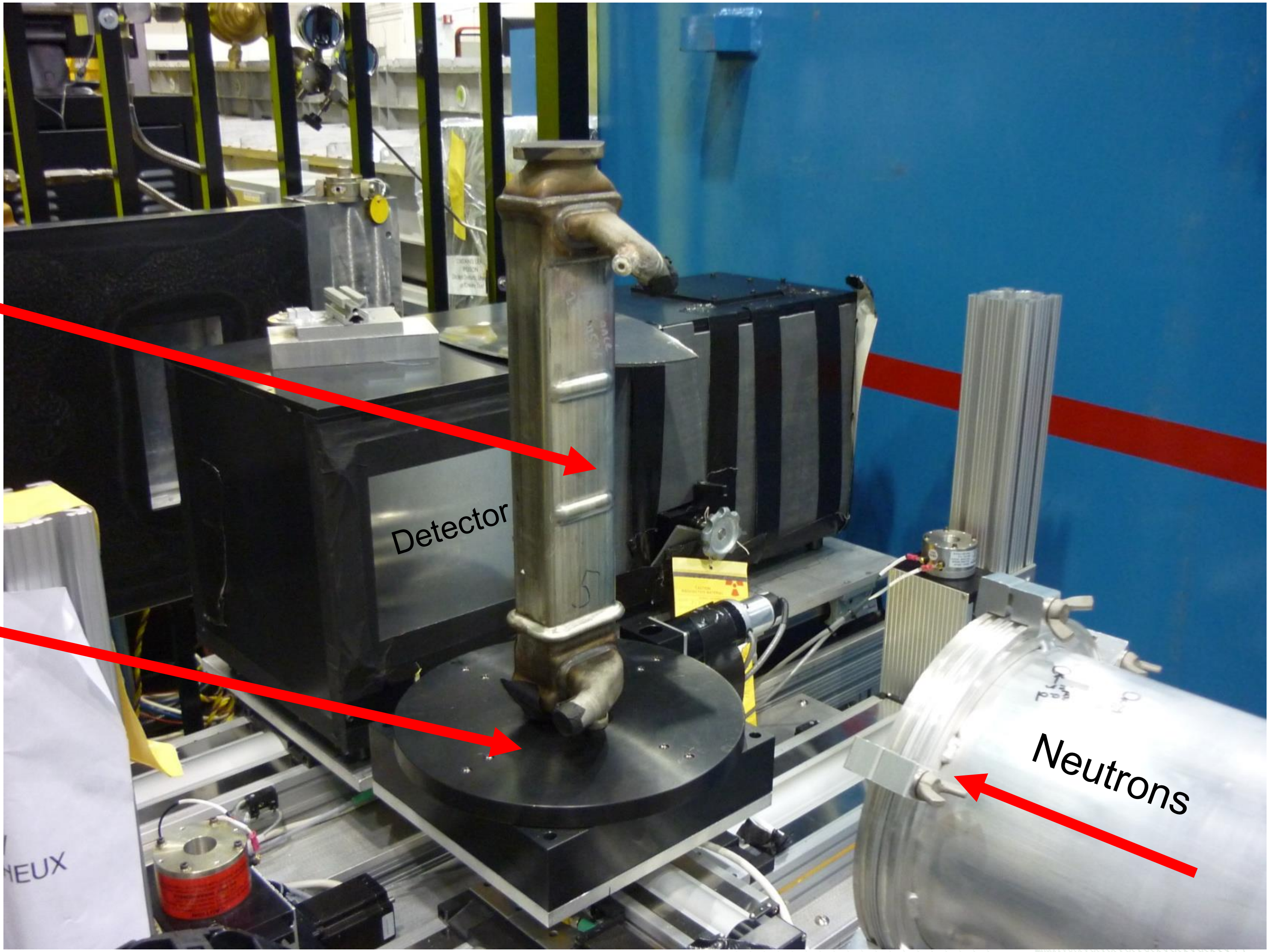


Instrument layout



Detector assembly (side view)

Sample Area

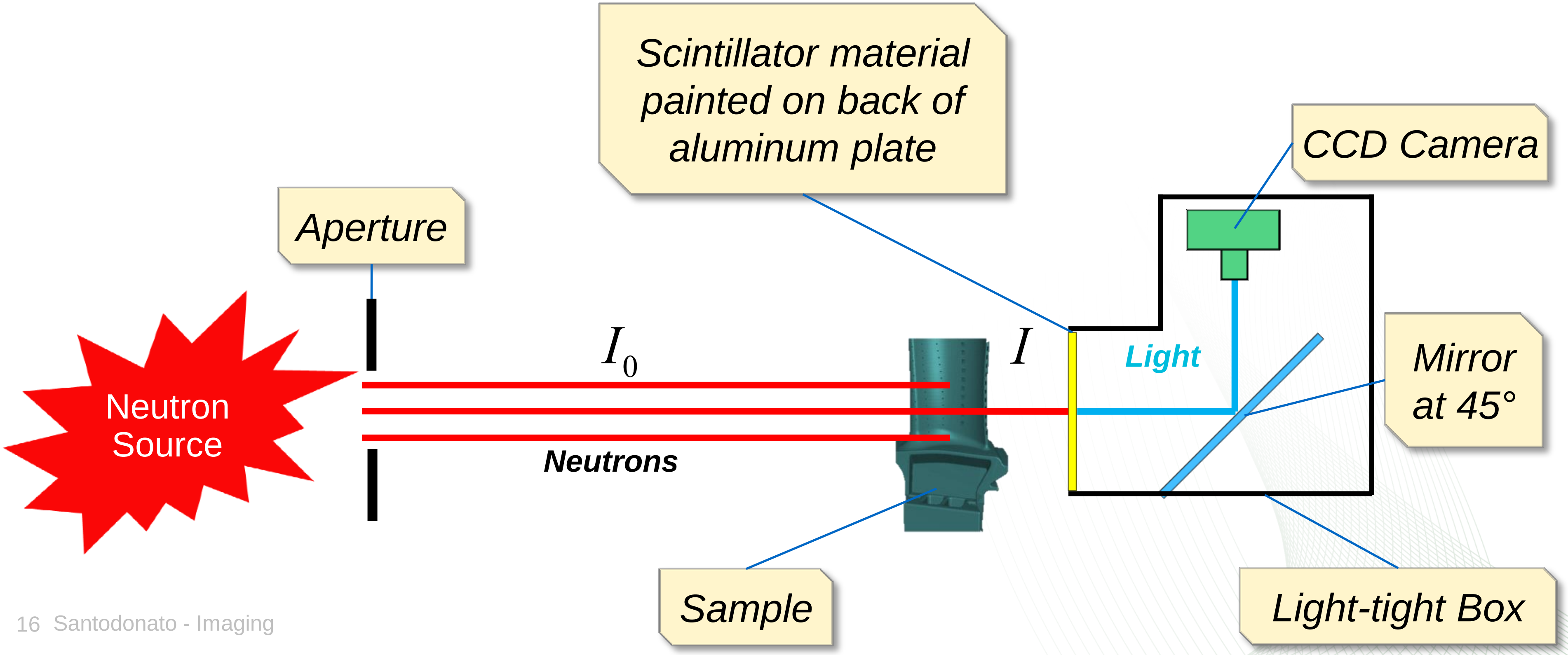


Sample (Automobile part)

Rotation/ Translation Stage

Detection of “Imaging” Neutrons

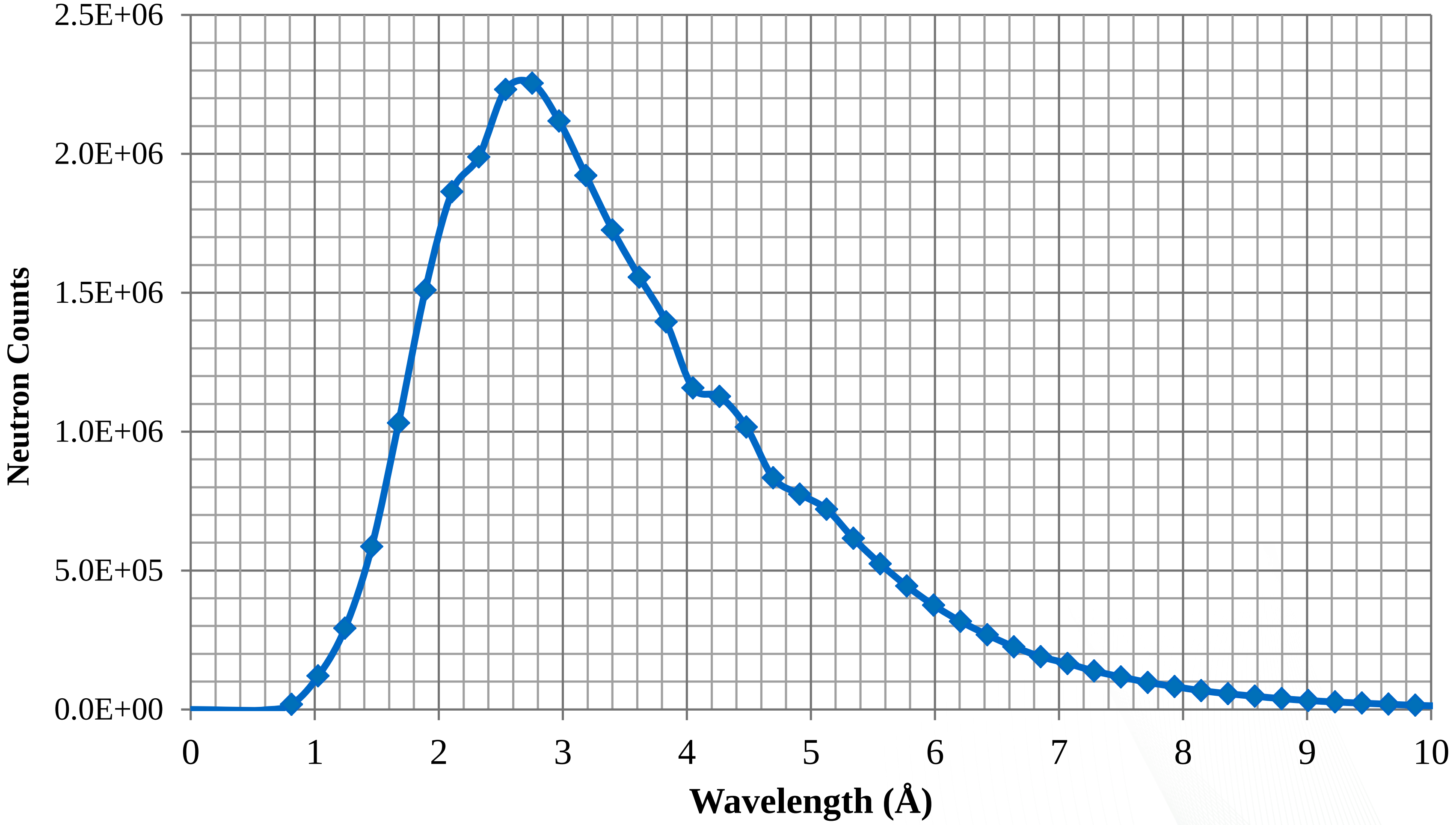
- Neutron scintillators
  - Emit light after capturing neutrons
  - Good signal-to-noise ratio
  - Large Field Of View
  - Spatial resolution limited by the dissipation of particles



Detection of "Imaging" Neutrons (cont'd)

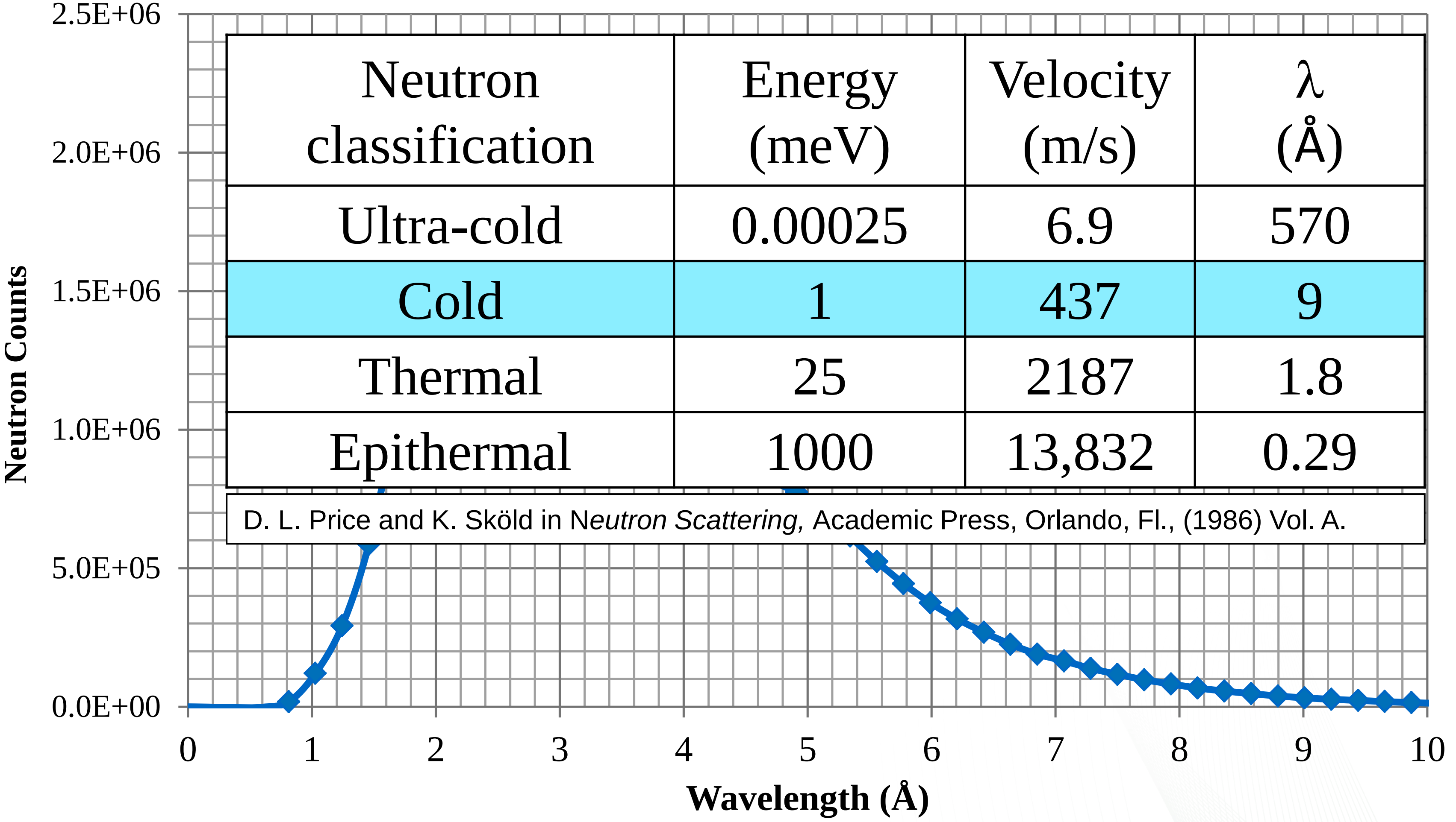
- Micro-Channel Plate (MCP)
  - In the direct path of the beam
  - Encodes events at x, y position and time of arrival, at high temporal resolution ~ 1 MHz
    - Enables time-of-flight imaging
  - Detection efficiency has improved for both cold (~70%) and thermal (~50%) energy range
  - Absence of readout noise
  - Not as gamma sensitive
  - Becoming commercial
  - Limited FOV

CG-1D polychromatic beam



CG-1D spectrum measured with the MCP detector at a flight path distance of approximately 5.5 m, with the chopper running at a frequency 40 Hz and an 5 mm aperture. *[Bilheux et al., ITMNR-7, Canada, June 2012]*

CG-1D polychromatic beam



Neutron classification	Energy (meV)	Velocity (m/s)	λ (Å)
Ultra-cold	0.00025	6.9	570
Cold	1	437	9
Thermal	25	2187	1.8
Epithermal	1000	13,832	0.29

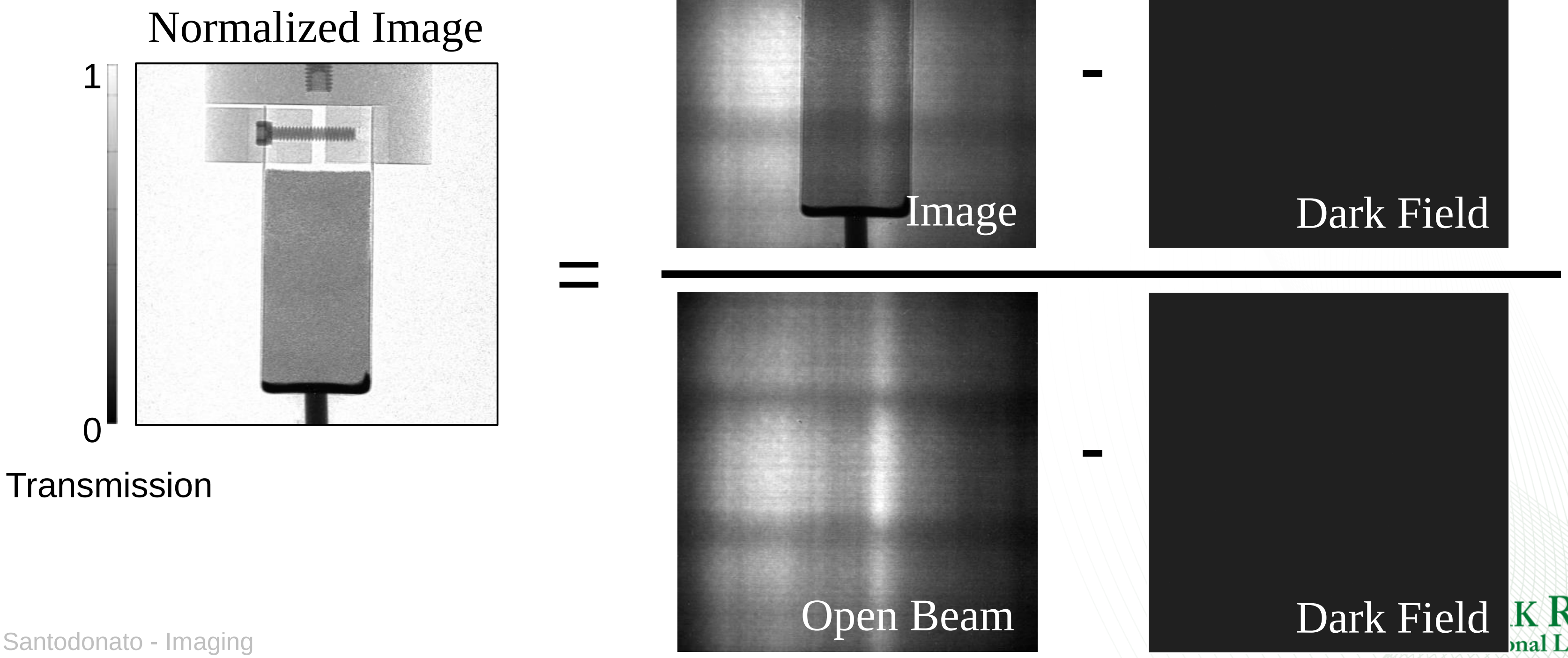
D. L. Price and K. Sköld in *Neutron Scattering,* Academic Press, Orlando, Fl., (1986) Vol. A.

CG-1D spectrum measured with the MCP detector at a flight path distance of approximately 5.5 m, with the chopper running at a frequency 40 Hz and an 5 mm aperture. *[Bilheux et al., ITMNR-7, Canada, June 2012]*

Data Normalization for Imaging

- 2D – Radiography
  - Normalization

$$I_N(i,j) = \frac{I(i,j) - DF(i,j)}{OB(i,j) - DF(i,j)}$$



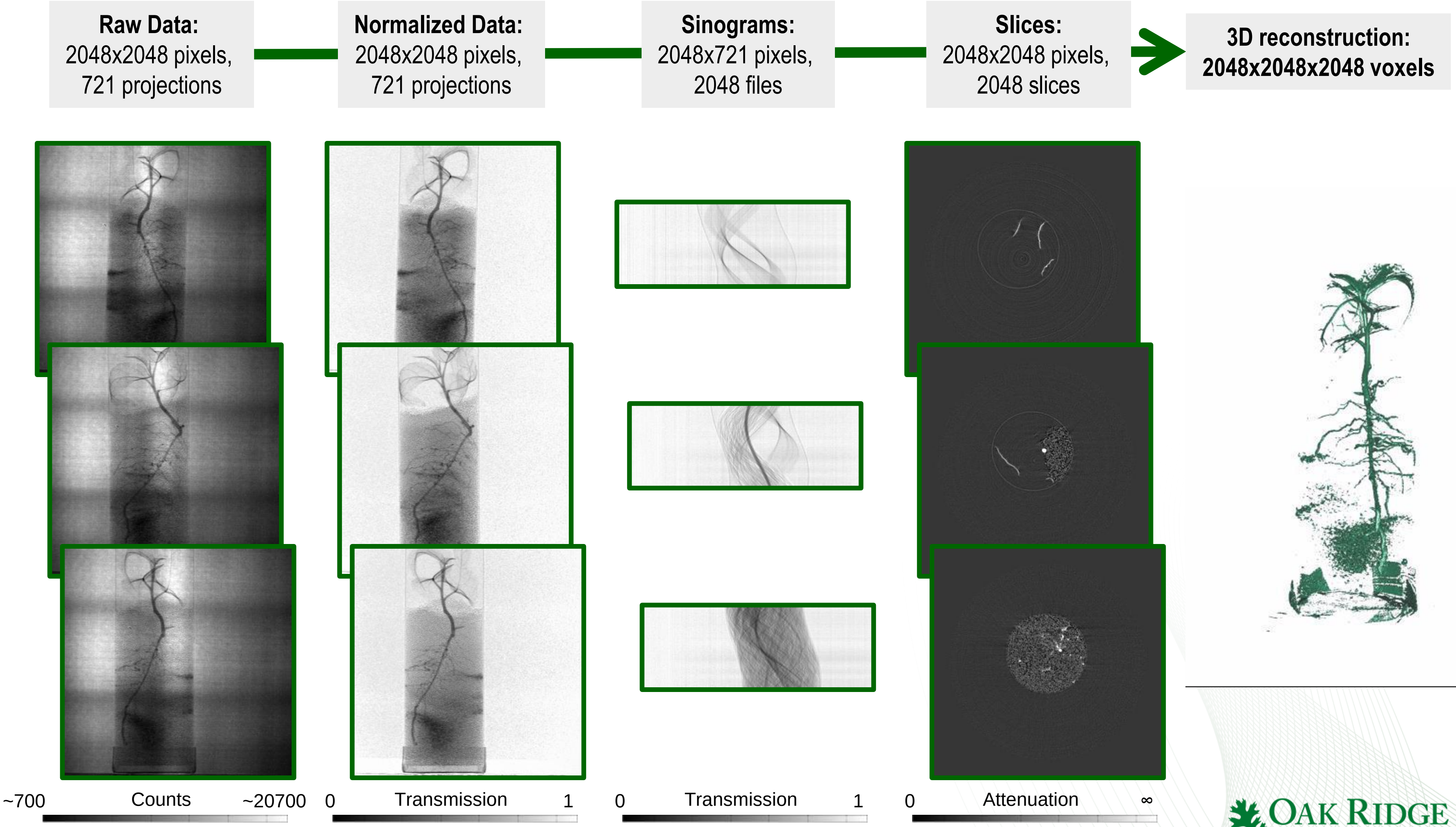
Computed/Computerized Tomography (CT)

- Several techniques:
  - Filtered Back Projection
    - Radon transform
    - Works well with high signal to noise ration measurements
    - Easy-to-use commercial, semi-automated software available
    - Quick

  - Iterative Reconstruction
    - Direct approach
    - Less artifacts
    - Can reconstruct incomplete data
    - High computation time

Computed/Computerized Tomography (FBP)

- Filtered back projection method



Raw Data:
2048x2048 pixels,
721 projections

Normalized Data:
2048x2048 pixels,
721 projections

Sinograms:
2048x721 pixels,
2048 files

Slices:
2048x2048 pixels,
2048 slices

3D reconstruction:
2048x2048x2048 voxels

Conventional Neutron Imaging Techniques at Steady-State Sources

- Radiography
- Tomography

Routinely available at CG-1D

- Stroboscopic Imaging
- Imaging of processes that happen fast

Available at CG-1D using the MCP detector

- Polarized Neutron Imaging
- Energy selective techniques possible with double-monochromator configuration

Newly implemented at CG-1D

- Phase Contrast Imaging
  - Under development

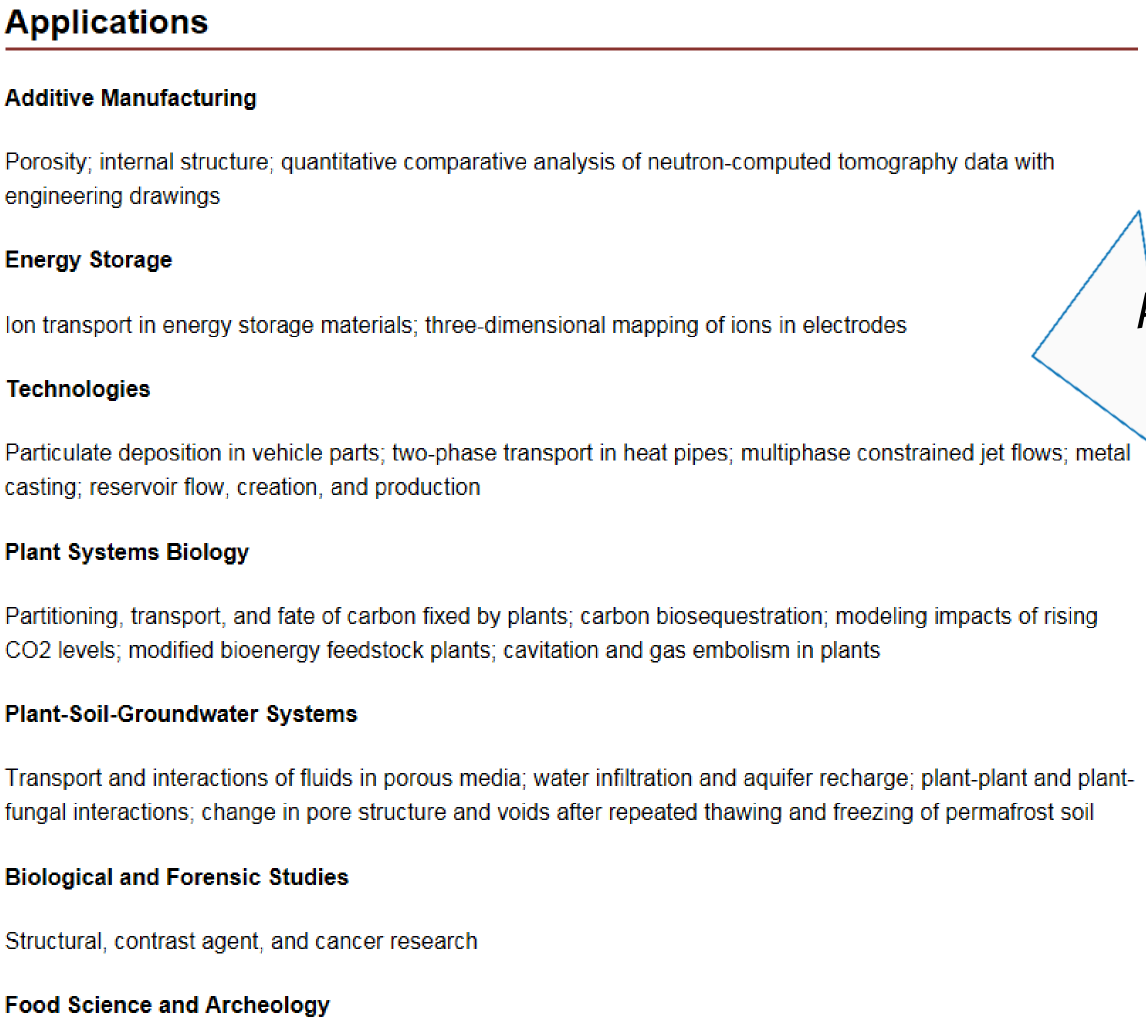
Goals

- Compare neutron imaging to other imaging techniques, and know when to choose it

- Understand the basic instrument layout and principals of neutron image acquisition and analysis

- Learn by example
  - Review some recent neutron imaging projects

A Wide Range of Applications



Applications

Additive Manufacturing

Porosity; internal structure; quantitative comparative analysis of neutron-computed tomography data with engineering drawings

Energy Storage

Ion transport in energy storage materials; three-dimensional mapping of ions in electrodes

Technologies

Particulate deposition in vehicle parts; two-phase transport in heat pipes; multiphase constrained jet flows; metal casting; reservoir flow, creation, and production

Plant Systems Biology

Partitioning, transport, and fate of carbon fixed by plants; carbon biosequestration; modeling impacts of rising CO2 levels; modified bioenergy feedstock plants; cavitation and gas embolism in plants

Plant-Soil-Groundwater Systems

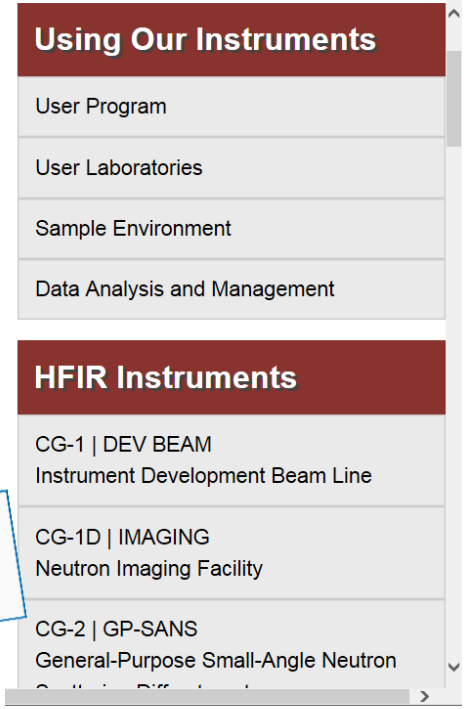
Transport and interactions of fluids in porous media; water infiltration and aquifer recharge; plant-plant and plant-fungal interactions; change in pore structure and voids after repeated thawing and freezing of permafrost soil

Biological and Forensic Studies

Structural, contrast agent, and cancer research

Food Science and Archeology

Applications include . . .



Using Our Instruments

- User Program
- User Laboratories
- Sample Environment
- Data Analysis and Management

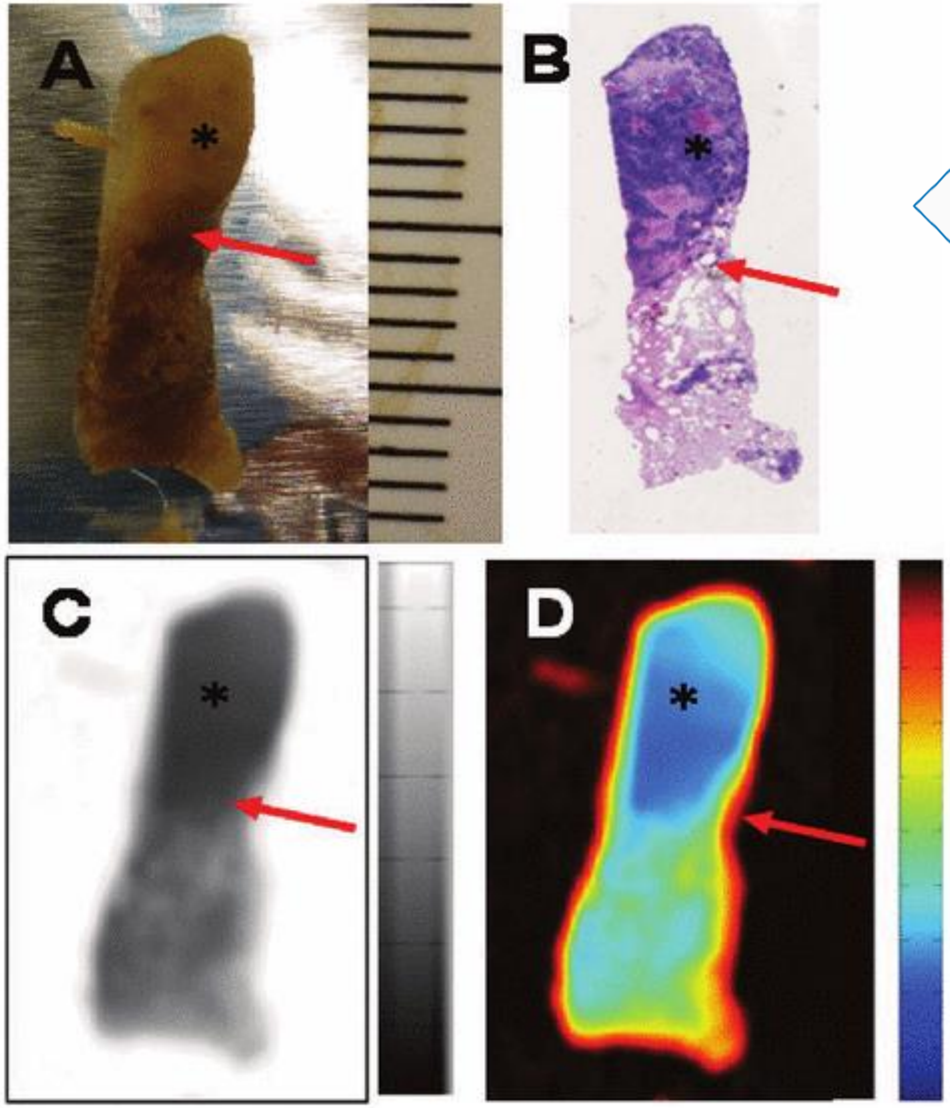
HFIR Instruments

- CG-1 | DEV BEAM
  Instrument Development Beam Line
- CG-1D | IMAGING
  Neutron Imaging Facility
- CG-2 | GP-SANS
  General-Purpose Small-Angle Neutron

CG-1D Cancer Research Application

Photograph of tissue sample

Photo of stained tissue slice



Greyscale neutron image

Colorized* neutron image

Cekanova M., Donnell R.L., Bilheux H.Z., Bilheux J., Neutron Imaging: Detection of cancer using animal model *Biomedical Science and Engineering Center Conference (BSEC), 2014 Annual Oak Ridge National Laboratory*, (2014).

Several Biological Tissues Have Been Studied at CG-1D

- No animals are ever hurt or sacrificed for these experiments
- Post mortem studies help researchers battle disease
- Neutrons reveal important features
- Non-destructive 3D evaluation

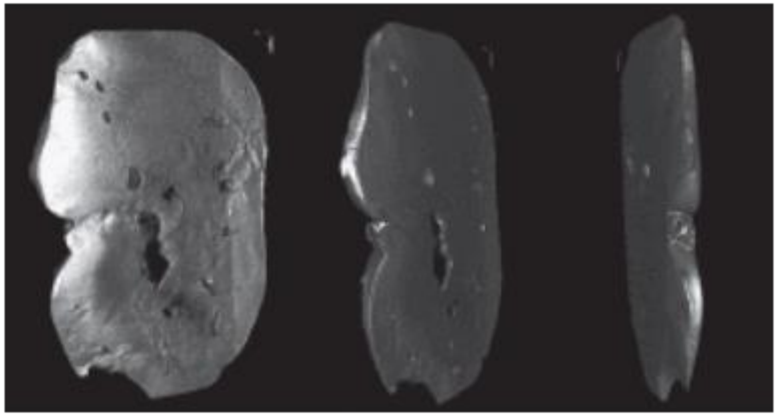
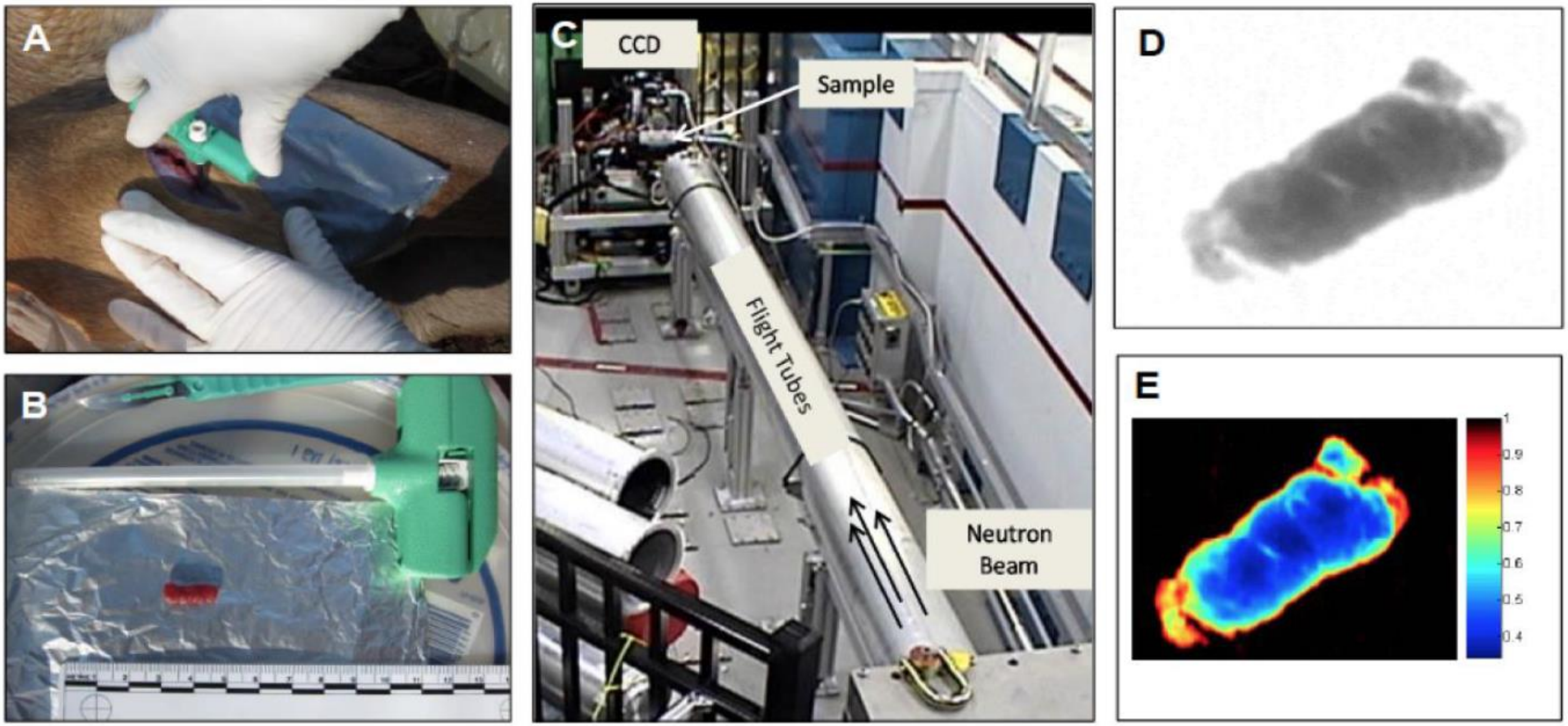


Fig. 5.
Volume rendered images computed tomogram of the canine kidney slice from fig. 5.

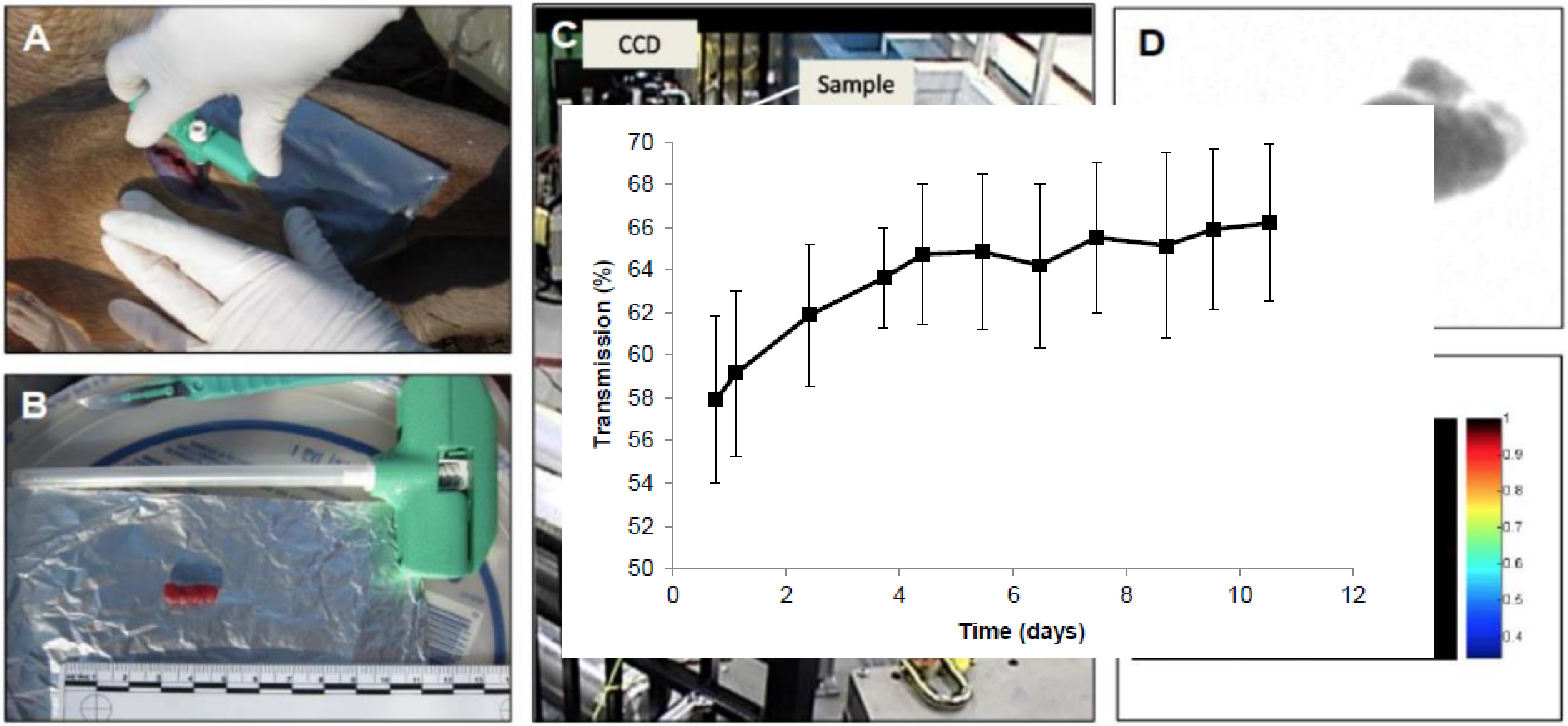
Bilheux H.Z., Bilheux J., Bailey W.B., Keener W.S., Davis L.E., Harwig K.W., Cekanova M., Neutron Imaging at the Oak Ridge National Laboratory: Application to Biological Research *Biomedical Science and Engineering Center Conference, Oak Ridge, TN,* (2014).

Forensic Science Example



Bilheux H.Z., Cekanova M., Vass A., Nichols T., Bilheux J., Legendre A., Donnell R.L., Investigation of a Novel Approach to Forensic Analysis Using Neutron Imaging Techniques *U. S. Department of Justice* 24845 (2014).

Forensic Science Example



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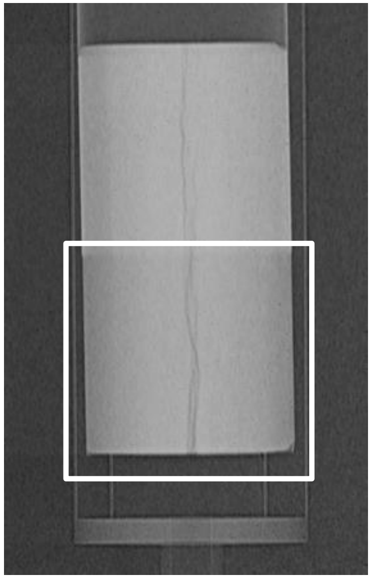
Rapid Imbibition of Water in Fractures within Unsaturated Sedimentary Rock



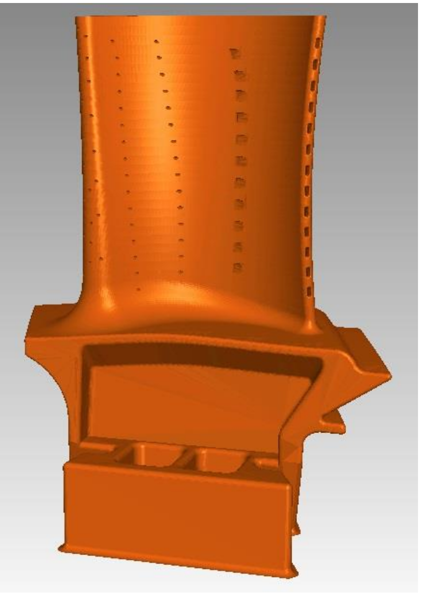
Time sequence of neutron radiographs showing the rapid uptake of water into a longitudinal, air-filled fracture zone in Berea sandstone. FOV is ~28 x 28 mm^2.

- **Dynamic neutron radiography**
  - **Directly quantify the sorptivity and dispersion coefficients of liquids in fractured, porous media**
  - **The findings can be applied in modeling hydraulic fracturing**

Work performed at the High Flux Isotope Reactor Imaging beam line (CG1D) was supported by the Scientific User Facilities Division, Office of Basic Energy Sciences, U.S. Department of Energy.

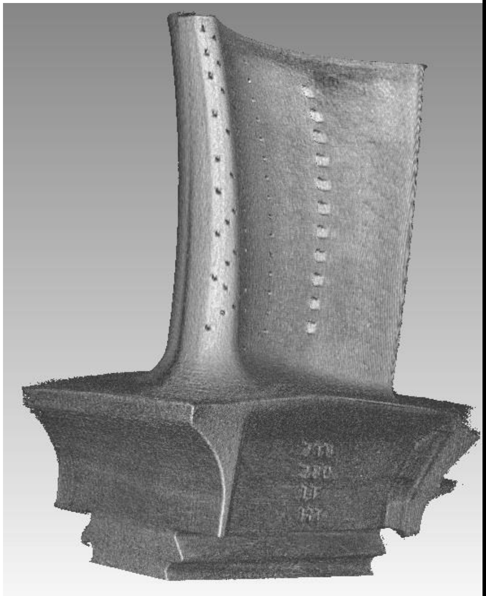
Cheng C. -L., Perfect E., Donnelly B., Bilheux H. Z., Tremsin A. S., McKay L. D., DiStefano V. H., Cai J. C., Santodonato L. J., Rapid imbibition of water in fractures within unsaturated sedimentary rock. 2015. Advances in Water Resources, Volume 77, Pages 82–89 <http://dx.doi.org/10.1016/j.advwatres.2015.01.010>

Fabrication tolerance studies comparing CAD drawing to neutron computed tomography

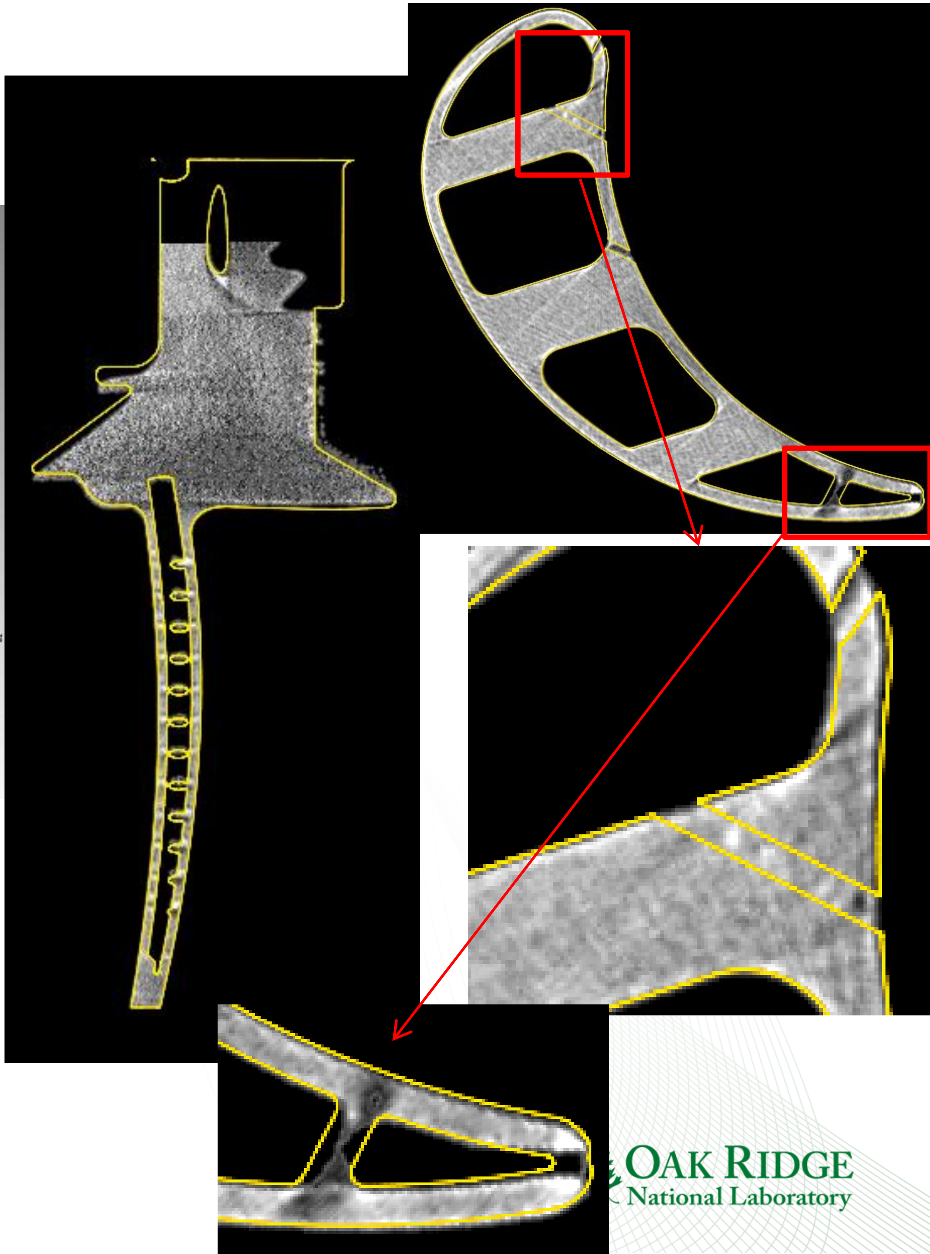


Engineering drawing

+



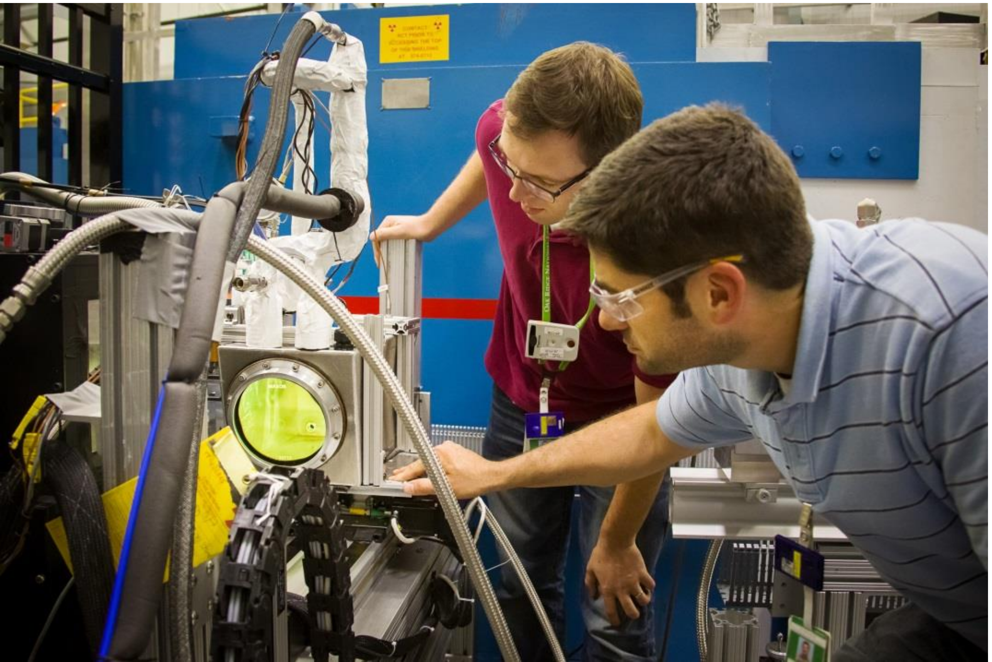
Neutron CT



In orange/yellow: AUTOCAD outline
In gray: neutron data

Time-resolved studies

- Rapid image acquisition and synchronization with operating devices
  - Micro-channel plate detector technology
- Recent applications include fuel injector operation and water propagation through porous media



Researchers setup a fuel Injector chamber

Oak Ridge National Laboratory

More Examples

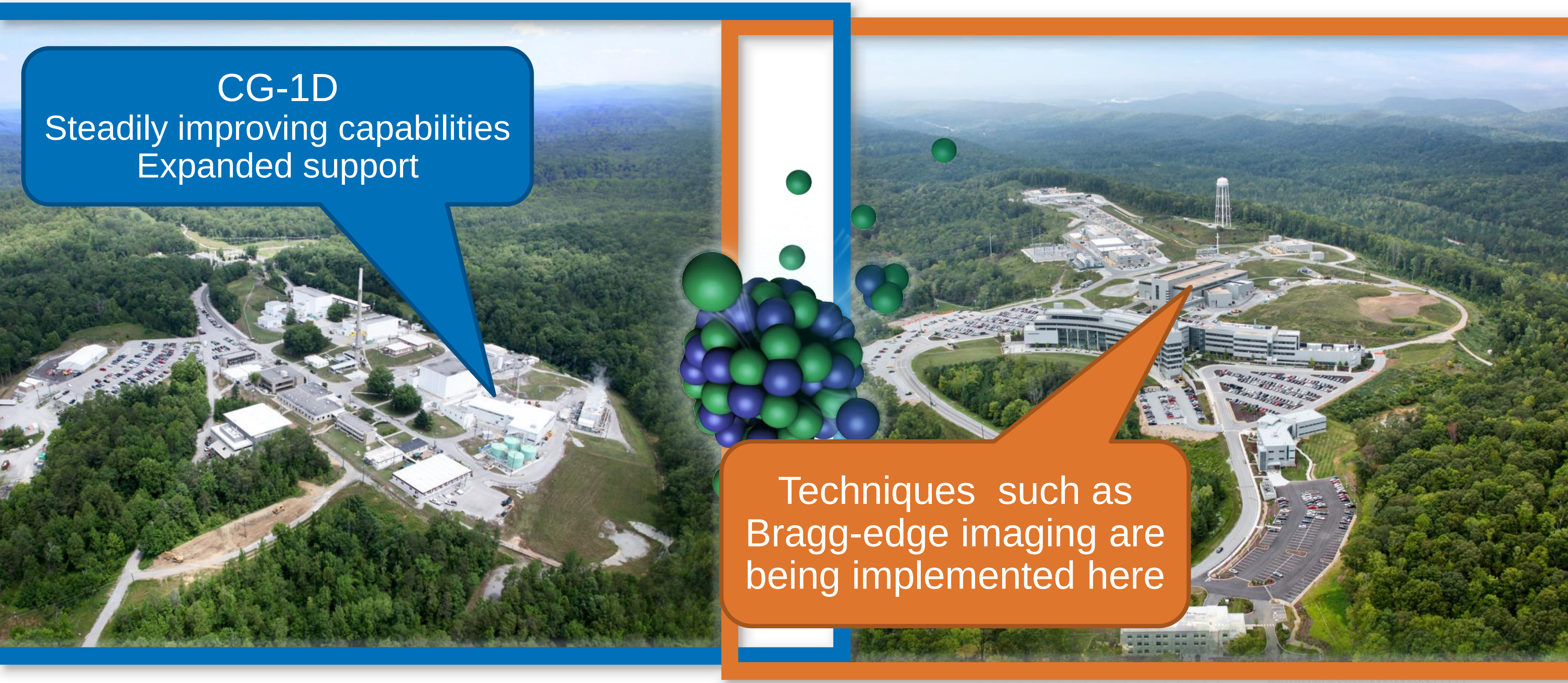
- More examples may be presented at the live talk

Summary

Imaging is a Small but Growing Part of the ORNL Neutron Program

High Flux Isotope Reactor (HFIR)
Intense steady-state neutron flux
and a high-brightness cold neutron source

Spallation Neutron Source (SNS)
World’s most powerful
accelerator-based neutron source



CG-1D
Steadily improving capabilities
Expanded support

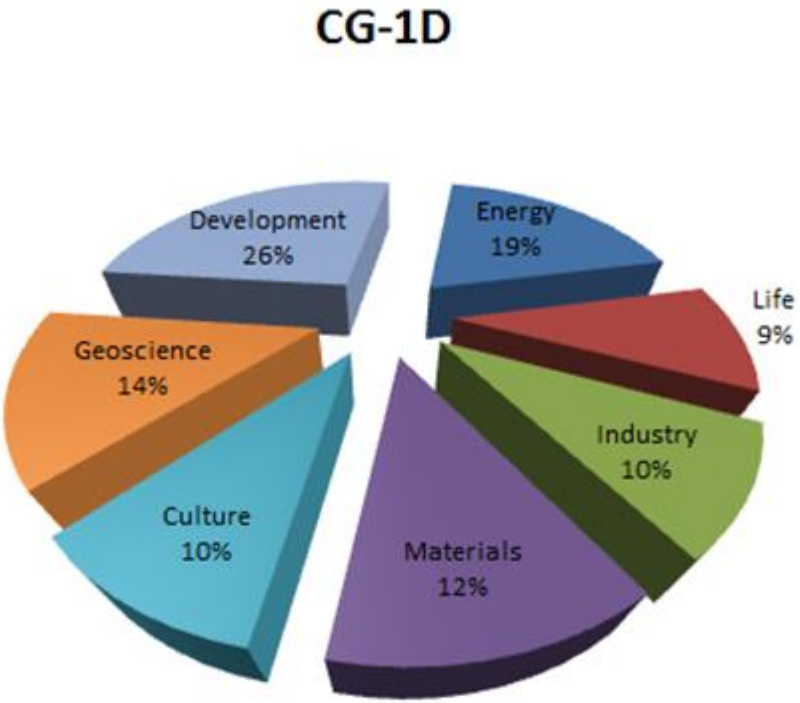
Techniques such as Bragg-edge imaging are being implemented here

HFIR

SNS

Diverse Science and Engineering Applications

- Trends at CG-1D are similar other facilities
- Are we missing any opportunities? Your science!



Based upon recent publications

Summary

- Neutrons are ideal for *certain* imaging applications, especially those requiring
  - Sensitivity to hydrogen and other light elements
  - Isotope sensitivity
  - Penetration into large samples and/or sample environments

- Spatial resolution is a key consideration
  - CG-1D routine capability of ~ 80 μm
  - Radiography at ~ 20 μm (with the trade-off of long counting time) is now available

- Imaging capabilities are steadily improving

Thank you

- Lou Santodonato SantodonatoL@ornl.gov
- Hassina Bilheux bilheuxhn@ornl.gov