Introduction to Neutron Radiography and Computed Tomography

Neutron Imaging Team at CG-1D:

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Data Analysis
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NX School
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Neutrons Measure Structure

### Neutron Diffraction
- SANS used to construct protein kinase A (PKA)
- Nuclear and electronic density in enzymes
- Neutron diffraction of $D_2$ sorption in $Cu_3[Co(CN)_6]_2$

### Neutron Scattering
- Characterization of biological membranes, colloids, porosity, etc.

### Neutron Microscopy
- Soil-root interface (rhizosphere)
- In Vivo Study of Embolism Formation
- Computed tomography

### Neutron Imaging
- Fluid interactions in plant-groundwater systems
- Ice/water segregation in permafrost structures

#### Inferred structure (indirect)
- $10^{-11}$
- 0.1 Å
- 1.0 nm

#### Direct structure
- $10^{-9}$
- 0.1 µm
- $10^{-7}$
- 10.0 µm
- $10^{-5}$
- 1 mm
- $10^{-3}$
- 1 mm
Introduction

- Neutron Radiography started in the mid 1930’s but only the past 30 years has it come to the forefront of non-destructive testing.
- State-of-the-art facilities in the U.S., Europe, Asia, Africa, etc.
- World conferences and workshops being held regularly
- Growing worldwide user community

<table>
<thead>
<tr>
<th>Neutron classification</th>
<th>Energy (meV)</th>
<th>Velocity (m/s)</th>
<th>λ (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultra-cold</td>
<td>0.00025</td>
<td>6.9</td>
<td>57</td>
</tr>
<tr>
<td>Cold</td>
<td>1</td>
<td>437</td>
<td>0.9</td>
</tr>
<tr>
<td>Thermal</td>
<td>25</td>
<td>2187</td>
<td>0.18</td>
</tr>
<tr>
<td>Epithermal</td>
<td>1000</td>
<td>13,832</td>
<td>0.029</td>
</tr>
</tbody>
</table>

Neutron sensitivity

Material attenuation coefficients (cf figure 2) are energy-dependent for both neutrons and x-rays. However, for many applications the energy range of neutrons used for scattering experiments, i.e. thermal and cold neutrons (around 25 meV), is more suitable for imaging.

**Figure 2.** Mass attenuation coefficients for thermal neutrons and 100 keV x-rays for the elements (natural isotopical mixture unless stated differently). (Reprinted with permission from [10]. Copyright 2008, University of Oxford Press.)

**Figure 1.** Interaction of matter with (a) x-rays and (b) neutrons.

Another factor worth considering alongside the relative penetrability of different materials with neutrons and x-rays is the spatial resolution attainable and the volume of the sample that can be imaged. Though the penetration depths achieved with thermal neutrons for a broad range of important industrial materials such as metals are significantly higher (around an order of magnitude) compared with standard x-ray energies of several tens or hundred kiloelectronvolts, the best spatial resolution available with neutrons is at least one order of magnitude lower. As a consequence of this, along with the fact that neutron beams generally have a larger cross-section than high intensity synchrotron x-ray beams, neutron (high-resolution x-ray) tomography is suited to investigating sample volumes of several cubic centimetres (millimetres).


**FigureCaption:** Courtesy of E. Lehmann, PSI
What is imaging?

- **Imaging** is the visual representation of an object: photography, cinematography, medical imaging, X-ray imaging, thermal imaging, molecular imaging, neutron imaging, etc.

- **Digital Imaging** is a field of computer science covering images that can be stored on a computer as *bit-mapped* images.
Early neutron imaging measurements

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

Discovery of neutron in 1932 by Chadwick

First neutron radiograph in 1935

Left to right: Pressure gauge with metal backplate; fire hydrant and test tubes filled with H2O and D2O imaged with gamma-rays (top) and neutrons (bottom)

\[Kallman\text{ and Kuhn, Research 1, 254 (1947)}\]

- World class dedicated imaging user facilities such as NIST, PSI, HZB, FRM-II and at many worldwide universities

- World conferences and workshops being held regularly

- Growing worldwide user community
Multiple scattering and low detector spatial resolution

[ J. Anderson et al., Br. J. Radiol. 37, 957 (1964) ]
Today: Comparison microscopy/microCT and neutron radiography

- 92% of the pixel intensities agreement between histological and neutron

Beam attenuation caused by a **homogeneous uniformly** thick sample composed of a **single isotope** is given by

\[ I(\lambda) = I_0(\lambda)e^{-\mu(\lambda)x} \]

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

\[ \sigma_t(\lambda) = \text{scattering and absorption} \]

\( \mu \) is the attenuation coefficient and \( \Delta x \) is the thickness of the sample.

\( \sigma_t(\lambda) \) is the material’s total cross section for neutrons, \( \rho \) is its density, \( N_A \) is Avogadro’s number, and \( M \) is the molar mass.
Detection of “imaging” neutrons

• Scintillator-based techniques such as $^6$Li(n,α) $^3$H
  – Good signal-to-noise (SNR) ratio
  – Large Field Of View (FOV) and 0.01 to hundreds of seconds images
  – BUT spatial resolution limited by the dissipation of particles
  – Can take a lot of neutron flux!

<table>
<thead>
<tr>
<th>1,1</th>
<th>1,2</th>
<th>1,3</th>
<th>...</th>
<th>...</th>
<th>1, ny</th>
</tr>
</thead>
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<tr>
<td>2,1</td>
<td>2,2</td>
<td>2,3</td>
<td>...</td>
<td>...</td>
<td>2, ny</td>
</tr>
<tr>
<td>3,1</td>
<td>3,2</td>
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<td>...</td>
<td>3, ny</td>
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<td>...</td>
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<tr>
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<td>nx, 2</td>
<td>nx, 3</td>
<td>...</td>
<td>...</td>
<td>nx, ny</td>
</tr>
</tbody>
</table>

Each pixel is coded using n-bit.
16-bit = pixel value is between 0 and 65535
Detection of “imaging” neutrons (cont’d)

- Pixelated detectors
  - Micro-Channel Plate (MCP)
  - In the direct path of the beam
  - Limited FOV for high spatial resolution MCPs
    - 2.8 cm x 2.8 cm at ~ 15 microns
  - Encodes events at x, y position and time of arrival, at high temporal resolution ~ 1 MHz
  - Detection efficiency has improved for both cold (~70%) and thermal (~50%) energy range
  - Absence of readout noise
  - Not as gamma sensitive
  - Becoming commercial
  - BUT: works in relatively low-signal beam!
Example: Cu, Zn and Al

<table>
<thead>
<tr>
<th>Compound</th>
<th>Abs. Coeff. [Å⁻²]</th>
<th>Inc. Coeff. [Å⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu (100%)</td>
<td>1.78E-09</td>
<td>4.65E-10</td>
</tr>
<tr>
<td>Al (100%)</td>
<td>7.75E-11</td>
<td>4.94E-12</td>
</tr>
<tr>
<td>Zn (100%)</td>
<td>4.06E-10</td>
<td>5.06E-11</td>
</tr>
</tbody>
</table>
CG-1D Neutron Imaging Facility

- Flight Tubes
- Sample
- Neutron Beam
- CCD
- ANDOR Camera: 4Mpixels – 2048x2048
- Field of view: 7.4x7.4cm² at 100 microns
- Quantum Efficiency: 95%
HFIR Neutron Imaging Facility (CG-1D)

Detector capability/spatial resolution:
ANDOR® CCD Detector ~ 100 microns
sCMOS ~ 50 microns, 100 fps
MCP(*) ~ 100 microns (and ~ 15 microns in centroiding mode), or microsecond time frames

(*) In Collaboration with Prof. Anton Tremsin, UC-Berkeley
Neutron imaging supports applied research with academia, industry and government agencies.
# The CG-1D detector suite and respective common applications

<table>
<thead>
<tr>
<th>Type of detector</th>
<th>Largest field-of-view (cm²)</th>
<th>Effective pixel size where the image is formed (microns)</th>
<th>Corresponding spatial resolution (microns)</th>
<th>Maximum Dynamic resolution (no pixel binning)</th>
<th>Dynamic range (bit)</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCD</td>
<td>7.4 x 7.4</td>
<td>36</td>
<td>~100</td>
<td>1 image/second</td>
<td>16</td>
<td>Additive Manufacturing (AM), Energy, Aerospace, Transportation Research, Geosciences, Biology, Botanical, Archeology, Medical, Food Science</td>
</tr>
<tr>
<td>sCMOS</td>
<td>3.3 x 2.8</td>
<td>13</td>
<td>&lt; 100</td>
<td>100 images/second for 4 sec max (**)</td>
<td>16</td>
<td>AM, Geosciences, Petroleum, Food Science</td>
</tr>
<tr>
<td>MCP (*)</td>
<td>2.8 x 2.8</td>
<td>55</td>
<td>~100</td>
<td>1 million images/second</td>
<td>14</td>
<td>Transportation Research, AM, Energy, Aerospace, Biology, Geosciences, Petroleum, Botanical, Food Science</td>
</tr>
<tr>
<td></td>
<td>2.8 x 2.8</td>
<td>10</td>
<td>~ 15</td>
<td>1 image/ 8 hours</td>
<td>14</td>
<td>Biology, Botanical, Medical</td>
</tr>
</tbody>
</table>

(*) The MCP detector has two modes of operation: the high time resolution and the high spatial resolution options, respectively.

(**) When binning pixels or working at lower frame rate, the limit is the 5 TB storage on the sCMOS server (each image is 10 MB). We can thus collect thousands of images.
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. Kang M. et al., Nuclear Instruments and Methods, 708, 2013]
Use of Diffusers

• 1 cm thick Graphite Powder (4 to 10 microns)
Conventional Neutron Imaging Techniques at steady-state sources

- Radiography (available at CG-1D)
- Tomography (available at CG-1D)
- Phase Contrast Imaging
- Polarized Neutron Imaging
- Stroboscopic Imaging
- Imaging of processes that happen fast
- Energy selective techniques possible with double-monochromator configuration
Data Normalization for Imaging

• 2D – Radiography
  – Normalization

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

Normalized Image

Image

Open Beam

Dark Field

Dark Field
Sample stage for nCT

- EGR Cooler
- Rotation/Translation Stage
- CCD Detector
- Neutrons
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
Computed/Computerized Tomography (CT)

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

  – Iterative Reconstruction
    • Direct approach
    • Less artifacts
    • Can reconstruct incomplete data
    • High computation time
Neutron Imaging Techniques at pulsed sources

• Energy-selective (or Time-of-Flight) imaging
  – Contrast enhancement
  – Bragg edge

• Energy resonance imaging

• Stroboscopic imaging
  – SNS has a natural clock

• Neutron Imaging at energies not accessible at reactor facilities
  – Mainly bio-medical applications
Neutron imaging techniques

- Radiography
- Computed tomography
- Bragg edge imaging
- Neutron phase imaging
- Stroboscopic imaging
- Neutron Stimulated Computed Emission Tomography or NSECT
- Polarized imaging
- Dark field imaging
- Energy resonance imaging
Bragg Edge Imaging

- **At reactors:**
  - monochromatic beams
  - Scintillator-based detection adequate

- **At spallation sources:**
  - Time-stamping of neutrons
  - Pixelated detectors such as MCPs required for time measurements

![Graph showing attenuation coefficient vs. wavelength for Fe]

- 3.9 Å
- 4.1 Å

1 cm

Courtesy of Prof. D. Penumadu, UTK and N. Kardjilov, HZB
Bragg Edge Imaging

- Strain mapping of steel screw

Strain map image of the steel screw. Strain values in μstrain

Tremsin et al., Journal of Physics, Conference Series 251 (2010) 012069
Bragg Edge Imaging

• Texture mapping

Bragg reflected neutrons result in narrow dips in the actual transmission at precise wavelengths specified by Bragg’s law:

\[ \lambda_{hkl} = 2d_{hkl} \sin \theta_{hkl} \]

where \( d_{hkl} \) is the interplanar distance for the \((hkl)\) planes and \( \theta_{hkl} \) are the Bragg angles \( \theta_{hkl} \) depends on the relative orientation of the crystal lattice to the neutron beam.

At \( \lambda_{hkl} \), creation of map of the number of crystals having any of their \((hkl)\) directions making an angle, \( \beta_{hkl} \), with the incident beam given by:

\[ \beta_{hkl} = (\pi/2) - \arcsin \left( \frac{\lambda_{hkl}}{2d_{hkl}} \right) \]

**Propagation-based Neutron Phase Imaging**

- Source needs to be spatially coherent (i.e. small pinhole and long pinhole-detector distances)
- Flux is low (up to 98% of flux is sacrificed, several hours to days for one radiograph)

![Diagram of neutron imaging setup](source.png)

- Source needs to be spatially coherent
- Flux is low

(a) Neutron attenuation radiograph (e) and phase contrast radiograph of a lead sinker mounted on an Al screw. [B. Schillinger et al., Mat. Trans. Proc. (2006) 61]

(a) Neutron attenuation radiograph (b) photograph and (c) phase contrast radiograph of a yellow jacket wasp. [B. E. Allman et al., Nature 408 (2000) 158]
Phase Radiography using Grating Interferometry

- G0 creates array of coherent sources from source \( w \)
- G1 creates diffraction patterns for each source which overlap if
  \[
  p_0 = p_2 \frac{l}{d}
  \]
- Diffraction pattern has maximum contrast when \( d \) is a integer multiple of the Talbot length, \( L_T \)
  \[
  L_T = \frac{p_1^2}{\lambda}
  \]
- Phase object cause distortion of diffraction pattern (or phase shift of incident wave \( \Phi \))
- Measure diffraction pattern by translating G2

\( p_0 \sim 1 \text{ mm}, \ p_1 \sim 10 \mu \text{m}, \ p_2 \sim 5 \mu \text{m}, \ l \sim 5 \text{ m}, \ d \sim 20 \text{ mm} \)

G0: (source) absorption grating, period \( p_0 \)
G1: phase grating, period \( p_1 \)
G2: (analyzer) absorption grating, period \( p_2 \)

[\text{Pfeiffer et al., PRL. 96 (2006) 215505}]
Magnetic field of a dipole magnet visualized by spin-polarized neutrons

N. Kardjilov et al., http://physicsworld.com/cws/article/news/33694
Stroboscopic imaging

- Makes a cyclically moving object appear to be slow moving
- Pulsed sources are by definition stroboscopic neutron sources

BMW engine, NEUTROGRAPH, ILL, France

Schillinger et al., NIM A 542 (2005) 142.
Applications at a glance

- Archeology
- Bio-medical
- Botany
- Contraband
- Cultural Heritage
- Energy
- Engineering/Materials Science
- Forensic Science
- Geology/Earth Sciences
- Homeland Security
- Paleontology
- Quality Assurance

Visualization of water transport in artificial soil sedimentation (20 s frame, 25 x 25 cm²)

`http://neutra.web.psi.ch/gallery/animations.html`

Radiography of a dry monkey skull

`http://neutra.web.psi.ch/gallery/biological.html`
A unique inside look of turbine blades produced by additive manufacturing

Scientific Achievement
Non destructive analysis of turbine blades produced by additive manufacturing reveals inside surface roughness and other printing characteristics

Significance and Impact
Neutron computed tomography provides important mapping of the finished product.

Research Details
– Comparison of engineering drawing and neutron computed tomography is ongoing
– Efforts are focused in combining neutron computed tomography with residual strain to gain information on additive manufacturing processes
– Surface roughness data may be fed back to Finite Element Analysis computation studies to determine the effect in air flow using the turbine

Advanced materials and processes March 2013 Journal Cover showing a photograph (left), a neutron radiograph (center) and a sliced computed tomography (right) of the Morris Technologies turbine blade.


Work performed at ORNL’s High Flux Isotope Reactor CG-1D and Spallation Neutron Source VULCAN beamlines was supported by Scientific User Facilities Division, Office of Basic Energy Sciences, US Department of Energy.
Fabrication tolerance studies comparing CAD drawing to neutron computed tomography

Engineering drawing + Neutron CT

In orange/yellow: AUTOCAD outline
In gray: neutron data
Comparison of Li Distribution as a function of depth of battery

Control

Li-Air (no catalyst)

Li-Air (with catalyst)

Neutron Imaging Provides the Basis for Developing Models

Non-uniform lithium distribution may limit rechargeability

- Reaction phase 3 dimensional modeling was used to predict results and compare with measurements

- Spatiotemporal reaction phase three-dimensional modeling of the electrodes also predicted a non-uniform lithium product distribution, confirming the neutron imaging result.

- Need to match resolution of neutron imaging capabilities to further improve feedback to modeling tools

Anomalous Discharge Product Distribution in Lithium-Air Cathodes

Jagjit Nanda, Hassina Bilheux, Sophie Voisin, Gabriel M. Veith, Richard Archibald, Lakeisha Walker, Srikant Allu, Nancy J. Dudney, and Sriekanth Pannala

Materials Science and Technology Division, Neutron Scattering Science Division, and Computer Science and Mathematics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, United States
Neutron Computed Tomography Characterizes Particulate Properties During Regeneration

**Scientific Achievement**

Employed neutron tomography to measure the properties of soot cake layer thickness and subsequently density during a sequential regeneration. Identified key parameters that will aid understanding of the fuel-consuming regeneration process.

**Significance and Impact**

Understanding the regeneration progression of DPFs is important in improving the efficiency of the process and to understand the correlation between pressure drop and soot level. The results from this work can directly provide model parameters to industry so they can better predict the level soot/particulate in the DPFs.

**Research Details**

- DPFs were filled to different levels (3, 5 and 7 g/L) using diesel engine
- Full DPFs analyzed with neutron tomography to determine the soot cake thickness and packing density
- Soot cake density, thickness and axial profile measured during sequential regeneration
- Highest soot cake density observed during initial 20% regeneration; layer then loses density, porosity increases and channels open up
- Different soot loading displayed same behavior during regeneration

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**Work performed at the High Flux Isotope Reactor Imaging (CG1D) beamline was supported by Scientific User Facilities Division, Office of Basic Energy Sciences, US Department of Energy.**


Neutron Tomography of Industry-Provided Cooler Tube Sections

- Slices can be collected along any plane through the cooler.
- The resolution was not high enough to measure thickness directly but we can still gather useful information about the deposit location relative to the heat exchanger geometry.

M. Lance, S. Sluder, H. Bilheux, S. Voisin, J. Gregor, J. –C. Bilheux
Ancient Craft Skills meet Modern Characterization

K. Ryzewski (PI), S. Herringer, H. Z. Bilheux, J.-C. Bilheux, B. Sheldon
Ancient Craft Skills meet Modern Characterization

K. Ryzewski (PI), S. Herringer, H. Z. Bilheux, J.-C. Bilheux, B. Sheldon
Biological and Environmental Applications
**Rapid Imbibition of Water in Fractures within Unsaturated Sedimentary Rock**

**Scientific Achievement**

Spontaneous imbibition of liquids into gas-filled fractures in variably-saturated porous media is important in a variety of engineering and geological contexts. Dynamic neutron radiography was applied to directly quantify this phenomenon in terms of sorptivity and dispersion coefficients.

**Significance and Impact**

The theory derived describes rapid early-time water movement into air-filled fractures in sedimentary rock. Both theory and observations indicate that fractures significantly increase spontaneous imbibition and dispersion of the wetting front in unsaturated sedimentary rocks. Capillary action appears to be supplemented by surface spreading on rough fracture faces. The findings can be applied in modeling hydraulic fracturing.

**Research Details**

Imbibition into unsaturated Berea sandstone cores was controlled with a Mariotte bottle setup. Images were collected using dynamic neutron radiography and analyzed using ImageJ.

Imaging and modeling of fluid flow in non-homogeneous porous media

Flint Sand Drying Process (HFIR /CG1-D)

- Measured point functions varied with column height
- Heterogeneity due to packing procedure
- Input parameters for numerical model

doi:10.2136/sssaj2011.0313
Kang, M. et al., NIM A, accepted
Point Water Retention Function: hanging water column

Brooks and Corey Parameters

- $\theta_r =$ residual water content ($\text{cm}^3\text{cm}^{-3}$)
- $\theta_s =$ saturated water content ($\text{cm}^3\text{cm}^{-3}$)
- $\psi_b =$ air entry value (cm)
- $\lambda =$ pore-size distribution index

- Point water retention function is extracted from the average water retention curve determined by hanging water column using TrueCell inverse modeling procedure
Neutron Radiography of Roots at CG1-D

- Water injected into root zone at base
- Unidentified endophyte (symbiotic) or decomposer fungi visible near roots of switchgrass (left), revealing substantial hydration of the rhizosphere
- Both fine and coarse roots are readily visible
10-d old maize seedling (A) aluminum sample chamber; (B) neutron radiograph at ~70 µm pixel resolution illustrating roots distribution (0.2-1.6 mm); C) 3D tomographic reconstruction; (D) Timing of water uptake by plant components highlighted in (B) illustrating impact of solar radiation on rate of water flux in stem and ~0.5 mm first and second order roots.

This study provides direct evidence for root-mediated hydraulic redistribution of soil water to rehydrate drier roots.
A novel approach to determine post-mortem interval using neutron radiography

Scientific Achievement
PMI was objectively estimated by measuring changes in neutron transmission correlated with H content variation in decaying tissues.

Significance and Impact
- One of the most difficult challenges in forensic research for criminal justice investigations is to objectively determine post-mortem interval (PMI).
- The estimation of PMI is often a critical piece of information for forensic sciences.
- Most PMI techniques rely on gross observational changes of cadavers that are subjective to the forensic anthropologist.

Research Details
- Tissues exposed to controlled (laboratory settings) and uncontrolled (University of Tennessee Anthropology Research Facility) environmental conditions.
- Neutron radiographs were compared to histology data to assess the decomposition stage.
- Over a period of 10 days, changes in neutron transmission through lung and muscle were found to be higher than bone by 8.3%, 7.0%, and 2.0%, respectively.

(A) Photograph, (B) gray scale and color enhanced (C) neutron radiograph of a 2 cm × 2 cm × 1 mm thick skeletal muscle tissue. (D) Neutron transmission as a function of time of skeletal muscle tissues under controlled conditions with natural logarithm fit.


Work performed at ORNL’s High Flux Isotope Reactor CG-1D and Spallation Neutron Source VULCAN beamlines was supported by Scientific User Facilities Division, Office of Basic Energy Sciences, US Department of Energy. Part of this research sponsored by NIJ.
Muscle June 2012

[A] Day 0, Day 2, Day 3, Day 4

[B] Day 0, Day 1, Day 2, Day 3, Day 4
Imaging at the Spallation Neutron Source: the future VENUS beamline
VENUS at the Spallation Neutron Source: a unique tool for basic and applied research

\[ I(\lambda) = I_0(\lambda)e^{-\mu(\lambda)x} \quad \mu(\lambda) = \sigma_t(\lambda) \frac{\rho N_A}{M} \]
(Top) For a specific neutron wavelength, $\lambda$, shorter than the Bragg edge wavelength, $\lambda_{\text{Bragg edge}}$, the incident neutron beam enters the crystalline lattice with $\theta < 90^\circ$ and is scattered with a deviation of $2\theta$. (Center) The lattice planes are aligned with the incident neutron, i.e. $\theta = 90^\circ$, which back-scattered towards the neutron source. (Bottom) For a neutron wavelength longer than the Bragg edge wavelength, there is no diffraction and the neutron beam can transmit. In this figure, $d$ is the distance between lattice planes and $\theta$ is the scattering angle.
Demonstrated that SNS’s unique pulsed source enables mapping of crystalline planes in complicated geometries including textured samples.

- Sample was Inconel 738 made by additive manufacturing
- Micro-channel plate detector (MCP) temporarily installed at VULCAN
- Time-binned (5.2 μs) data collection.

Mapping of Bragg edge and corresponding crystalline orientation in Inconel 718 structures, as identified using Time-Of-Flight imaging. “DOE” letters are polycrystalline structures and the surroundings are textured.

Work performed at ORNL’s Spallation Neutron Source VULCAN beamlines was supported by Scientific User Facilities Division, Office of Basic Energy Sciences, US Department of Energy.
Mapping of crystalline structures

Highly textured
Polycrystal
Letter contour has some texture

DOI: 10.1179/1743284714Y.0000000734
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- Anton Tremsin, University of CA - Berkeley

- Ed Perfect, Jen Gregor, University of TN – Knoxville

- Chu-Lin Cheng, University of Texas – Pan America/Rio Grande Valley

- Hui Zhou, Hong Kong Science Park

- Industry collaborators

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