Overview of Imaging at LANSCE and LANL

Ron Nelson
P-27, LANL
LANSCE User Group Meeting
Santa Fe, NM
November 2, 2015
Coauthors

- **LANL**
  - James Hunter, Michelle Espy, Tim Ickes, Bill Ward (AET-6)
  - Richard Schirato (ISR-1)
  - Alicia Swift (XCP-3)
  - Sven Vogel (MST-8)
  - Sanna Sevanto, Turin Dickman, Michael Malone (EES-14)

- **University of California at Berkeley**
  - Anton Tremsin, Adrian Losko
Introduction – Neutron Imaging Advances at Los Alamos

- Many types of imaging are in use at LANL
  - Photon (Microtron – to 15 MeV, DARHT)
  - Proton (800 MeV) short pulse, dynamic imaging, primary beam
  - Neutron (thermal-epithermal, high-energy), secondary beams
  - Muon – using natural cosmic ray background
- Goal is to observe properties of objects and phenomena that can’t be seen with other probes – non-destructive evaluation (NDE)
- Photons (x-rays) scattering depends on atomic number
- Protons are sensitive to material density
- Neutrons have a scattering dependence that varies widely with energy and element/isotope
- All of these probes are complementary, combined “multi-probe” imaging can be a very powerful technique
Imaging comparison

- X-Ray – good for small higher-Z objects in lower-Z materials e.g. bones or metal in the human body
- Thermal neutrons – good for hydrogenous materials in heavier materials e.g. a rose in a lead shielded container, water or oil in metal systems
- High-energy neutrons – hydrogenous materials in dense, fissionable materials
- New – epithermal neutrons with energy-selective imaging, e.g. fission products in uranium fuel rods
- Muons – sensitive to high-Z materials, good for large objects and radiation sensitive objects (or people) that are not amenable to other techniques
# Comparison of Imaging Characteristics of Different Probes

<table>
<thead>
<tr>
<th>Probe</th>
<th>Source example</th>
<th>Typical Imaging Time Scale</th>
<th>Sensitive to</th>
<th>Resolution</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photon</td>
<td>LANL Microtron</td>
<td>s</td>
<td>Electrons, density</td>
<td>100 µm</td>
<td>High intensity, economical</td>
</tr>
<tr>
<td>Proton</td>
<td>LANSCE Area C</td>
<td>ns – µs repetition</td>
<td>density</td>
<td>10-100 µm</td>
<td>High Intensity, fast, repetitive, focusing</td>
</tr>
<tr>
<td>Thermal Neutron</td>
<td>NIST/PSI</td>
<td>ms - s</td>
<td>nuclei</td>
<td>10-100 µm</td>
<td>Good intensity</td>
</tr>
<tr>
<td>Thermal+Epithermal Neutron</td>
<td>LANSCE Target 1 Lujan Ctr</td>
<td>10-100s</td>
<td>nuclei</td>
<td>55-100 µm</td>
<td>Fair intensity, nuclear resonance selection</td>
</tr>
<tr>
<td>High-Energy Neutron</td>
<td>LANSCE Target 4 WNR</td>
<td>10-100s</td>
<td>nuclei</td>
<td>100 µm – 1mm</td>
<td>Fair intensity, very penetrating, energy range selection</td>
</tr>
<tr>
<td>Muon</td>
<td>Cosmic Rays</td>
<td>Hours/Days</td>
<td>Electrons, density</td>
<td>cm</td>
<td>Low intensity, very penetrating, large objects</td>
</tr>
</tbody>
</table>
Technical Details

- Beam Resolution L/D
  - D = collimator diameter
  - L = distance from collimator to sample
- Field of View – beam spot size
- Intensity – time to get an image with enough counts
- Detectors – resolution (pixel size), efficiency, energy response, timing
- Neutron converters – scintillator screens
Neutron Imaging at LANL – History and Recent Developments

- At LANSCE, thermal, epithermal, and high energy neutrons are available from two spallation sources at the 800 MeV proton accelerator
  - Neutron imaging was investigated using these sources in the 1990s
  - Good and useful images were obtained, but for a variety of reasons the capability was not continued
- Improvements in detectors and computing have enabled new capabilities that use the pulsed beam properties at LANSCE
  - Time-of-flight (TOF) neutron energy selection
Accelerator Layout Showing Imaging Locations

- **Lujan Center – Thermal-Epithermal Neutrons**
  - 8 & 60 m flight paths (typical)

- **WNR Facility – High-Energy Neutrons**
  - 20 m flight path (typical)

- **Proton Radiography**
- **800 MeV Proton Linear Accelerator**
- **Muon Radiography**
Proton Beam Time Structure and Pulse Widths

- **WNR Facility (Target 4)**
  - Width micropulses < 1 ns (FWHM) typical
  - Spacing 1.8 $\mu$s (typical) variable but greater spacing reduces time-averaged intensity
  - Macro pulses 650 $\mu$s (typical), 8.3 ms spacing

- **Lujan Center (Target 1)**
  - Width ~ 125 ns (FWHM)
  - Spacing 50 ms (typical)
The WNR Pulsed Proton Beam

Typical WNR Proton Beam Parameters

- Energy = 800 MeV
- Average Current ~ 5 μA
- Protons/Micropulse ~ 7x10^8
- “Micropulses”
- “Macropulse”

Energy = 800 MeV
Average Current ~ 5 μA
Protons/Micropulse ~ 7x10^8
Time Structure of High-Energy Proton Accelerators in Operation

- SINQ (PSI, Switzerland) – CW – thermal and cold neutron beams
- J-PARC (Japan) – 3 ns or chopped, but chopped operation is limited due to intensity demands
- ISIS (RAL, United Kingdom) – double-pulsed
- LANSCE (LANL, U.S.) Single pulses
  - Advantages in pulse width and spacing for energy-selective neutron imaging
Neutron Total Cross Section Comparisons – H, D, C
Neutron Total Cross Section Comparisons – $^{56}$Fe, Co
Neutron Total Cross Section Comparisons – $^{186}\text{W}$, $^{238}\text{U}$
Detectors in Use at LANSCE

- The following give highest intensity in our experiments
- (1) Medical X-ray image flat panel amorphous silicon (aSi) detector with PP+ZnS(Ag or Cu) neutrons – no TOF but short imaging times, gamma-ray-insensitive
- (2) aSi flat panel with Gadolinium Oxysulfide (Gadox) scintillator screen for thermal neutrons
- (3) intensified Charge-Coupled Device (iCCD) or plastic scintillator and mirror – gives large field of view and TOF or scatter rejection (mono-energetic source), used for high-energy neutrons at present
- (4) B/Gd-doped Micro-Channel Plate (MCP) with Time-Pix (CERN) fast readout - measures data for all neutron energies of interest at the same time, used at the moderated source at present
A Multi-Element Object Used to Compare Images from Photons, Low-Energy, and High-Energy Neutrons

- Object is a cylinder consisting of steel, tungsten, molybdenum, nylon and polypropylene parts

![Diagram of the multi-element object with dimensions and material labels.]
Radiograph Comparison for a Multi-Component Object about 16 cm tall

6-MeV X-Ray (Microtron)

Low Energy Neutron (FP-5)

High Energy Neutron (FP15R)

Note: Radiographs are not at identical angular orientation or scale
Three examples demonstrate some of the applications of neutron imaging

- (1) Trees
  - Water flow in living specimens
- (2) Nuclear reactor fuel rods
  - Inclusions and fission products in uranium oxide
- (3) Phantom in thick uranium metal
  - Aluminum, steel, and polyethylene of varying thicknesses behind a thick uranium plate
Combining Capabilities to Reveal How Trees Transport Water

- Using the Lujan Center Flight Path 5, 60 meter station (the Silo) simultaneous NMR and neutron radiography measurements were made with low RF background.
- The neutron images were acquired over periods of up to ~12 hours while the pinon and juniper branches soaked up H$_2$O or D$_2$O
- Analysis of the neutron images allows calibration of the NMR signal
Liquid Flow in a Juniper Branch

- $\text{D}_2\text{O}$ and $\text{H}_2\text{O}$ flow in a juniper branch
- ~6 hours experiment duration
- NMR probe
- Not amenable to x-ray imaging
Energy-Resolved n-Rad and n-CT Can Select Elements and Isotopes

- A new capability under development at LANSCE exploits the short (~125 ns FWHM) proton beam pulses that produce epithermal neutrons
- Detector: Micro Channel Plate
- Resolution: < 100 um
- Technique uses nuclear resonances that are isotope specific
- Nuclear fuel pin mockups with W inclusions demonstrate technique
High-Energy Neutron Imaging at WNR Using aSi Flat Panel with ZnS(Ag) Scintillator Screen

Steel, Al, poly phantom in dU slabs

Neutron image of phantom in U through no poly (top) & 4 inches of poly
High-Energy Neutron Computed Tomography (CT) Scan of a Multi-Element Item with W, Polyethylene, etc.

Bolt for position reference
First Results Using the Time-Gated iCCD Camera Setup
Energy-Selective High-Energy Neutron Imaging

Features not seen in other time bins

No halo illustrates partial scatter rejection

Halo from scatter

Mid energy neutrons
- t = 476.5 to 1059 ns
- E = 10 to ~2.5 MeV

Low energy neutrons and scatter
- t = 1059 to 1784 ns
- E = 2.5 MeV to 100s of keV

Total low energy neutrons
- t = 476.5 to 1784 ns
- E = ~10 MeV to 100s of keV
High Energy Neutron Radiography
Work in Progress

- Improved neutron converter/scintillator screens for faster tomography with flat panel and iCCD imagers
- Continuing studies of water transport in plants – both roots and stems (pinyons & junipers at present)
- CT scans of objects for defense program needs
- iCCD camera (< 10 ns time gating) with fast scintillator screen and mirror enables selection of neutron energy range for optimum contrast and penetration
  - Determine useful and best energies for imaging objects of interest before construction of a full test accelerator and imaging system
Examples of Uses for Energy-Resolved Neutron CT

- Selectively image carbon using MeV range resonances to find diamonds in bulk ore
- Determine the structure and chemical composition of meteorites and geological samples
- Examination of a high-power, heavy duty cathode assembly for failure mechanisms
- Non-Destructive Evaluation of a Variety of Dense, Thick Objects
- Determination of chemical element and isotope distributions in materials, e.g. nuclear fuel rods, scintillator crystal doping, semiconductor device fabrication, …
- More
LANSCE has Unique Advantages for Energy-Selective Neutron Imaging

- Fast proton pulses for good neutron energy resolution – Targets 1 (moderated) and 4 (high-energy)
- Good L/D ratios for spatial resolution, intensity
- State-of-art detectors and computing
- Proposed Target 1 modifications further enhance capabilities for Energy-Selective neutron imaging in the important keV resonance region
- X-ray & neutron images combined are even more powerful for non-destructive evaluation (multi-probe imaging)
Thank you for your attention!