Centre for Energy Research

Neutron Radiography and Tomography

László Szentmiklósi, Zoltán Kis
Central European Training School on Neutron Techniques, Budapest, Hungary

Budapest Neutron Centre, Budapest, Hungary
szentm@bnc.hu

Nuclear Analysis and Radiography Department
Centre for Energy Research, Budapest, Hungary
szentmiklosi.laszlo@ek-ker.hu
Neutron-matter interactions

Neutrons interact with the condensed matter:

- Induce nuclear reactions (capture, fission)
- Scattering (elastic, inelastic)
- Reflection
- Unaffected neutrons pass through the sample
Attenuation ($\mu$) of the neutron beam depends on:

- absorption ($\sigma_{abs}$)
- scattering ($\sigma_s$)

$$\mu^{tot} = N_V \left( \sigma_{abs} + \sigma_s \right) = N_V \sigma^{tot}$$

$N_V$ : number of atoms per unit volume

**Principle of the radiography**

- Radiography = „Draw with radiation”
- Radiography is a direct imaging technique, where the 2D visual representation of an object is obtained nondestructively by detecting the modification of an incident beam as it passes through the matter
- **Transforms invisible radiation into visible images**
Attenuation coefficient (note the logarithmic scale) of elements for thermal neutrons (separate dots - black), for 1 MeV gamma-ray (dotted line), for 150 kV X-ray (solid line) and for 60 kV X-ray (dashed line)
Total microscopic cross section $\sigma$ [barn] for photons with an energy of 100 keV (the interaction takes place with the electron shell)

Total microscopic cross section $\sigma$ [barn] for neutrons with an energy of 25 meV (the interaction takes place with the atomic nucleus)
• Mass attenuation coefficient (m²/kg):

\[ \mu_m = \frac{\mu}{\rho}, \]

\( \rho \): sample density (kg/m³),
\( \mu \): linear attenuation coefficient (1/m)
It has the same value for the solid, liquid or gaseous state of a given element.

• Mass-thickness (kg/m²):

\[ d_m = \rho \times d \]

\( d \): sample thickness (m)

• Beer-Lambert law
valid for a point detector and a well-collimated, thin pencil beam without buildup effect

\[ \frac{I_{tr}}{I_0} = \exp(-\mu_{tot} \cdot d) = \exp(-\mu_{m}^{tot} \cdot d_m) \]
Chronology of neutron radiography

1935 - Kallmann and Kuhn awarded a US Patent in January 1940
Neutron imaging begins with the work of Hartmut Kallmann and Ernst Kuhn

1945 - Thewlis utilized a high flux reactor neutron beam
McDonough produced earliest reactor quality neutron radiograph
Barton develops the divergent collimator
Tochilin reports on fast neutron radiography
Neutron radiography commercial services begin
Personnel qualification SNT-TC-1A published
First neutron radiography standard published ASTM E54S

1955 - WCNR1 - San Diego, CA, USA

1965 - Radiography with Neutron Conference - U. of Birmingham, UK
Kawasaki reports neutron generator real-time images
Beiger reports results of "neutron television"
Barton images with cold & epithermal neutrons
First application neutron radiographs of radioactive fuel

1975 - ITMNR1 - Penbroke, Ontario, Canada
Radiography Station at the MVA
KFKI Atomic Energy Research Institute in Budapest, Hungary
International Society for Neutron Radiography founded

1985 - AEC of South Africa SAFARI-1, Pretoria, South Africa
ANTARES neutron imaging facility
FRM II Garching, Germany
Fuji patents photostimulable phosphor plates for CR

1995 - Neutron Imaging Facility (NIF) at the NIST in Gaithersburg, Maryland

2005 - NEUTRA station at Paul Scherrer Institut spallation neutron source SINQ
Treimer demonstrates scattering contrast in NCT

J.S. Brenizer / Physics Procedia 43 (2013) 10 – 20
## Classification of neutrons

<table>
<thead>
<tr>
<th>Neutrons</th>
<th>Energy range</th>
<th>Wavelength [Å]</th>
<th>Velocity [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ultra cold</td>
<td>( \leq 300 ) neV</td>
<td>( \geq 500 )</td>
<td>( \leq 8 )</td>
</tr>
<tr>
<td>very cold</td>
<td>300 neV - 0.12 meV</td>
<td>52.2 – 26.1</td>
<td>7.5 – 152</td>
</tr>
<tr>
<td>cold</td>
<td>0.12 meV - 12 meV</td>
<td>26.1 – 2.6</td>
<td>152 – 1515</td>
</tr>
<tr>
<td>thermal</td>
<td>12 meV - 100 meV</td>
<td>2.6 - 0.9</td>
<td>1515 - 4374</td>
</tr>
<tr>
<td>epithermal</td>
<td>100 meV - 1eV</td>
<td>0.9 - 0.28</td>
<td>4374 - 13.8 (10^3)</td>
</tr>
<tr>
<td>intermediate</td>
<td>1eV - 0.8MeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>fast</td>
<td>( &gt; 0.8) MeV</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Neutron sources for imaging

• Research reactor (ILL, FRM-II, BNC, ...)
• Spallation sources (ISIS, SINQ, SNS, ...)
• Radioactive nuclides (Cf, Ra-Be, Sb-Be)
• Accelerator sources (D-D, D-T reactions)

<table>
<thead>
<tr>
<th>Source type</th>
<th>Nuclear reactor</th>
<th>Neutron generator</th>
<th>Spallation source</th>
<th>Radio isotope</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reaction</td>
<td>fission</td>
<td>D-T fusion</td>
<td>spallation by protons</td>
<td>gamma-n-reaction</td>
</tr>
<tr>
<td>used material</td>
<td>U-235</td>
<td>deuterium, tritium</td>
<td>high mass nuclides</td>
<td>Sb, Be</td>
</tr>
<tr>
<td>gain: primary neutron intensity [1/s]</td>
<td>1.00E+16</td>
<td>4.00E+11</td>
<td>1.00E+15</td>
<td>1.00E+08</td>
</tr>
<tr>
<td>beam intensity [cm^-2 s^-1]</td>
<td>10^6 to 10^9</td>
<td>10^6</td>
<td>10^8 to 10^7</td>
<td>10^3</td>
</tr>
<tr>
<td>neutron energy</td>
<td>fast, thermal and cold</td>
<td>fast, thermal</td>
<td>fast, thermal and cold</td>
<td>24 keV, thermal</td>
</tr>
<tr>
<td>limitation of use</td>
<td>burn up</td>
<td>life time tube</td>
<td>target life time</td>
<td>half life Sb-124</td>
</tr>
<tr>
<td>typical operation cycle</td>
<td>1 month</td>
<td>1000 h</td>
<td>1 year</td>
<td>0.5 year</td>
</tr>
<tr>
<td>costs of the facility</td>
<td>high</td>
<td>medium</td>
<td>very high</td>
<td>low</td>
</tr>
</tbody>
</table>
Components of a neutron imaging facility

7. Sample manipulator  8. Detector  9. Shielding + beam dump
Geometry of the collimation
**Collimator ratio: L/D**

The **collimator** forms a shaped and directional beam out of the neutron source (e.g. reactor)

\[
\Phi = \frac{\Phi_0 A}{4\pi L^2}
\]

\[
A = \frac{\pi D^2}{4}
\]

\[
\frac{\Phi_0}{\Phi} = \frac{\text{incoming flux}}{\text{outcoming flux}} = 16 \left(\frac{L}{D}\right)^2
\]
Beam formation

- pre-collimator
- filter
- diaphragm
- Outer-collimator

Filters

Pinhole collimators

Outer-collimator

1st collimator

2nd collimator
Neutron Velocity Selector
a device that allows neutrons of defined velocity to pass while absorbing all other neutrons, used for the purpose of producing a monochromatic neutron beam. The blades are coated with a strongly neutron-absorbing material.

Double crystal monochromator
Pyrolytic graphite (002) crystals
- Mosaicity 0.7°
- $\Delta \lambda / \lambda = 1\% \ldots 3\%$
- Wavelength band: 2.7 … 6.5Å

E. Calzada, ANTARES II, FRM II, Garching
Vacuum, or He gas to reduce the loss of neutrons
How close the beam geometry is to the ideal point-source configuration?

A larger L/D ratio provides better image resolution because image blur (d) is smaller.
Neutron guide

The definition of L/D for a simple flight tube is no longer valid.

Beam div $\sim \gamma_c$
tot. refl. angle for Ni-nat:

$\gamma_c = 1.73 \times 10^{-3}\text{ rad/Å or } 0.1^\circ/\text{Å}$

$\frac{L}{D} = \frac{1}{\tan[2\gamma_c(\lambda)]}$

Energy dependent!

Flight tube

Collimators should be positioned in the flight tube

Collimators:
- shaping field of view
- less flux
- improving L/D

Sample & Tomograph

Neutrons hit the screen (e.g. 2:1 mixture of ZnS/6LiF)

Conversion into visible light

That is collected on the CCD of a camera

Light-proof box containing mirror and CCD optics and camera
Neutron Periscope @ FRM II
Impact of the beam quality on the image sharpness

Radiographs of a small motor taken at different beam positions with different L/D ratios.

The radiographs were taken at a cold guide, a thermal guide, a cold guide with a consecutive 15 mm pinhole and 4.8 m flight tube and at a classical 20 mm pinhole and 10 m flight tube arrangement.
The curved lines represent constant values of the neutron flux per solid angle.

From PhD. Thesis of A. Van Overberghe
Beam profile of guided beams always have horizontal and vertical stripe structure. More homogenous beam can be obtained with a scatterer - N. Kardjilov (HMI Berlin)

Without graphite  |  5mm graphite  |  10mm graphite
--- | --- | ---
Intensity: 100 % | 95 % | 82 %
Sample manipulator

Heavy-load sample manipulator
(up to few hundred kg)

small sample table (few kg)
Neutron detection

- No direct neutron detection possible
- A secondary nuclear process is needed: capture, fission, collision
- Main neutron imaging processes are using:
  - scintillation
  - photo-luminiscence by secondary particles +\(\beta, \gamma\)
  - nuclear track detection
  - chemical excitation
  - charge collection in semi-conductors

Performance parameters of neutron imaging detectors

- Spatial resolution
- Time resolution
- Signal-to-Noise Ratio
- Dynamic Range
- Read-out behaviour
- Sensitivity, efficiency
- Stationarity
- Trigger options

E. Lehmann

To be optimized for the specific problem!
The **result** of (digital) radiography:

- 2D image with linear scale (e.g. black/white)
  Integrating all layers of the object in beam direction suitable for image post-processing

- Data set as matrix of pixel values containing intensity information
  Suitable for quantitative evaluation of the sample content

The **limitation** of neutron radiography:

- **Spatial resolution** (finally given by the detection process)
  But also limited by the beam collimation, the pixel size and optical systems

- Frame rate (exposure time and readout time)
  Limited by the beam intensity, the detector sensitivity and the electronic readout

- Sample size (by the transmission properties of the sample material)
  Can be overcome with fast neutrons …
Detectors for Neutron Imaging

(under the conditions at the NEUTRA facility)

- Intensified real-time camera
- Amorphous-Si flat panel
- CCD camera + scintillator
- CMOS pixel detector
- N-imaging plates
- X-ray film + converter
- Track etch foils

More neutrons → Detector development!!!

Time resolution [s]

E. Lehmann
The Image Plate is a film-like radiation image sensor comprised of specifically designed phosphors that trap and store the radiation energy. The stored energy is stable until scanned with a laser beam, which releases the energy as luminescence.

Photostimulated luminescence (PSL)

- very small crystals (grain size: about 5 μm) of photo-stimulable phosphor [BaFBr:Eu$^{2+}$ (X-Ray), $^{10}$B-enriched lithium-borate glass + BaCl$_2$:Eu$^{2+}$ or Gd$_2$O$_3$ (0.1 %) + BaFBr:Eu$^{2+}$ (neutron)] are uniformly coated on a polyester support film.
• Application sequence: expose, read, clear

• Off-line readout, clearing with light illumination

• Spatial resolution is limited by scattering and the range of the conversion electrons (tens of um)

e.g. Fujifilm BAS-ND
CCD or sCMOS camera with a scintillator
The digital image detector of RAD
Components of a scintillator-based digital image detector

- The impinging neutrons are converted to visible light using a $^6$LiF/ZnS or Gadox scintillator layer
- The light is reflected out of the neutron beam direction with a mirror
- Collected with optical lenses and detected with a pixelized CCD or sCMOS camera
- Stored as a grayscale image with 16-bit depth (e.g., TIFF)
Optics for CCD/sCMOS camera

Table 2. Magnification (M), effective pixel size (P_{eff}), Field of View (FOV) and neutron flux of several objective/imaging lens combinations with three available pinhole diameters.

<table>
<thead>
<tr>
<th>Obj. Lens/Img. Lens</th>
<th>M</th>
<th>P_{eff} (\mu m)</th>
<th>FOV (mm)</th>
<th>Neutron flux (n/s/pixel)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>D = 3 cm</td>
<td>D = 2 cm</td>
</tr>
<tr>
<td>105 mm / 50 mm</td>
<td>2.10</td>
<td>6.429</td>
<td>13.2 \times 13.2</td>
<td>9.9</td>
</tr>
<tr>
<td>200 mm / 100 mm</td>
<td>2.00</td>
<td>6.750</td>
<td>13.8 \times 13.8</td>
<td>10.9</td>
</tr>
<tr>
<td>200 mm / 50 mm</td>
<td>4.00</td>
<td>3.375</td>
<td>6.9 \times 6.9</td>
<td>2.7</td>
</tr>
</tbody>
</table>

S. H. Williams et al, J. of Instrumentation (2012)
Microchannel plate

- microchannel plate is an emerging method that is a digital semiconductor detector array with very small pixel sizes
- MediPix collaboration (CERN -> Nova Scientific, WidePix)
- 5 micron channels spaced on 6 micron centers
- pixel detector readout chip working in single photon counting mode
- resolution about 100 μm, 30 frames per second
Light from a point source passing through the lens interferes with itself (diffraction from a circular aperture) creating a ring-shape diffraction pattern, known as the **Airy pattern**. The Airy pattern is observable in the far field:

**Rayleigh criterion** (the **angular resolution** of an optical system, $\Theta$):

Two point sources are regarded as just resolved when the principal diffraction maximum of one image coincides with the first minimum of the other.

At $r_{\text{Airy}}$:

$$\sin \Theta = 1.22 \frac{\lambda}{a}$$

$\Theta$, angle of observation

$\lambda$, wavelength

$a$, is the diameter of the entrance pupil of the aperture or lens
The spatial resolution of an imaging system

- Methods to measure the spatial resolution in 2D:
  - Gd Siemens Star test pattern:
    - labeled spoke periods of concentric rings
    - The pattern gives a qualitative measurement of resolution capability of the system
  - Measurements based on a sharp Gd foil edge:
    - Distance across the Edge Spread Function (ESF) as defined from 10% to 90% of full intensity
    - Full width at half maximum (FWHM) of the Gaussian peak fit to the Line-Spread Function (LSF)
    - Inverse of the spatial frequency when Modulation Transfer Function (MTF) = 10%
- Spatial resolution in 3D: pile of Ti spheres
Example: CCD camera + optics + $^6$LiF/ZnS(Ag) scint. in different thicknesses

- The spatial resolution is measured by a sharp edge of a 25-µm-thick Gadolinium foil placed directly on the aluminum plate of the scintillator.
- ESF was determined from a line profile perpendicular across the edge.
- Spatial resolution was determined by calculating the mean value of the 10%-90% responses.

![Graph showing ESF and resolution data.]

**Spatial resolution and relative efficiency of the detection system using $^6$LiF/ZnS:Ag scintillators with various thicknesses**

<table>
<thead>
<tr>
<th>Thickness (mm)</th>
<th>Resolution (mm)</th>
<th>Relative efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.42</td>
<td>0.54 ± 0.02</td>
<td>100</td>
</tr>
<tr>
<td>0.20</td>
<td>0.34 ± 0.01</td>
<td>85</td>
</tr>
<tr>
<td>0.10</td>
<td>0.24 ± 0.01</td>
<td>64</td>
</tr>
</tbody>
</table>

Fig. 1. ESF of three converter screens with different thickness.
Spatial resolution vs. scintillator thickness

Fig. 3. Radiographs of a relay, 24 × 30 mm², taken with (a) 0.40-mm-thick converter; and (b) 0.10-mm-thick converter.

Several exchangeable scintillator screens to properly detect neutrons and X-rays

Thickmess: compromise between exposure time and spatial resolution
Tomography is an extension of radiography, where the 3D visualization of the object is achieved using computational algorithms from a series of radiographic projections acquired as the object is rotated in small angular increments.
Intensities detected:

- $I_{\text{openbeam}}$, $I_{\text{darkbeam}}$, $I_{\text{transmitted}}$

Projections have to be corrected for:

- inhomogeneity of the beam and the detector
- dark current of the camera

Neutron flux transmitted $\rightarrow$ grayscale

$$\frac{I_{\text{tr}}}{I_0} = \frac{I_{\text{transmitted}} - I_{\text{darkbeam}}}{I_{\text{openbeam}} - I_{\text{darkbeam}}}$$

- real sample = $\Sigma$ (small, homogeneous samples)

$$\frac{I_{\text{tr}}}{I_0} = e^{-\int_{\text{beam path}} \mu_{\text{tot}}(x,y) \, ds}$$

Projections (Radon transform):

- line integrals of the attenuation coefficient $\mu(x,y)$
- perpendicular to $t$ (along $s$) taken at angle $\Theta$
- through a slice

**Intensities in grayscale values**

$$P_\Theta(t) = -\ln \frac{I_{\text{tr}}(\Theta,t)}{I_0(\Theta,t)} = \int_{\text{line}} \mu(x, y) \, ds = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \mu(x, y) \cdot \delta(t - x \cos \Theta - y \sin \Theta) \, dx \, dy$$
The 1D Fourier Transform of a parallel projection $P_\theta(t)$ of a distribution $\mu(x,y)$, taken under an angle $\theta$ is equal to a single line (a slice) within the 2D Fourier Transform of the distribution $\mu(x,y)$ that encloses the angle $\theta$ with the u-axis.

Filling up the frequency domain: measurement at multiple angles
Image reconstruction step-by-step

Reverse transformation to the space domain:

- from interpolated mesh data
- inverse 2D Fourier transform

\[ S(\omega, \Theta) \rightarrow S(u,v) \]

\[ \mu(x, y) = \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} S(u,v) e^{2\pi i (ux + vy)} \, du \, dv \]

**BUT:**
- Direct reverse transformation is too slow
- Cannot measure infinite number of projections to fill up the Fourier space
- There is always noise, scattering
- We need filters: **Filtered Backprojection (FBP)**
- \( S(\omega, \Theta) \rightarrow S(u,v) \), and weight by \(|\omega|\)
  (ramp filter)
Image processing in tomography

Object

$P_0(t)$

Projections at multiple angles

$\mu(x,y)$

Slices of the object

$\mu(x,y,z)$

Visualization in the 3D space

Object Image processing in tomography

Visualization in the 3D space
Merovingian style iron belt buckle

Disk fibula with garnet inlays
Data processing can be a very labor- and computationally intense task

- Image referencing: Minutes, hours
- 3D reconstruction: Minutes, hours
- Image processing: Hours
- Visualization: Hours, days
IAEA – PSI tomography contrast phantom
Iron blocks with Al placeholder sheets inbetween
PSI 3D resolution phantom: pile of Ti spheres

a: Ø4.997 mm
b: Ø2.09 mm
c: Ø1.00 mm and Ø0.704 mm
State-of-the-art European facilities
<table>
<thead>
<tr>
<th>Application</th>
<th>Number of RR involved</th>
<th>Involved / Operational, %</th>
<th>Number of countries</th>
</tr>
</thead>
<tbody>
<tr>
<td>Education &amp; Training</td>
<td>161</td>
<td>67</td>
<td>51</td>
</tr>
<tr>
<td>Neutron Activation Analysis</td>
<td>122</td>
<td>51</td>
<td>54</td>
</tr>
<tr>
<td>Radioisotope production</td>
<td>90</td>
<td>37</td>
<td>44</td>
</tr>
<tr>
<td><strong>Neutron radiography</strong></td>
<td><strong>68</strong></td>
<td><strong>28</strong></td>
<td><strong>40</strong></td>
</tr>
<tr>
<td>Material/fuel testing/irradiations</td>
<td>60</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Neutron scattering</td>
<td>48</td>
<td>21</td>
<td>32</td>
</tr>
<tr>
<td>Nuclear Data Measurements</td>
<td>42</td>
<td>18</td>
<td>20</td>
</tr>
<tr>
<td>Gem coloration</td>
<td>36</td>
<td>15</td>
<td>22</td>
</tr>
<tr>
<td>Si doping</td>
<td>35</td>
<td>15</td>
<td>22</td>
</tr>
<tr>
<td>Geochronology</td>
<td>26</td>
<td>11</td>
<td>21</td>
</tr>
<tr>
<td>Neutron Therapy</td>
<td>20</td>
<td>8</td>
<td>13</td>
</tr>
<tr>
<td>Other</td>
<td>95</td>
<td>40</td>
<td>29</td>
</tr>
</tbody>
</table>

IAEA Research Reactor Database – D. Ridikas
Neutron imaging facilities around the world

Table 2
Neutron imaging facilities with state-of-the-art properties and conditions (without claim for completeness); given parameters are raw values that can be varied only by changing beam conditions.

<table>
<thead>
<tr>
<th>Country</th>
<th>Location</th>
<th>Institution</th>
<th>Facility</th>
<th>Neutron source</th>
<th>Thermal/cold flux (cm⁻² s⁻¹)</th>
<th>L/D ratio</th>
<th>Field of view</th>
</tr>
</thead>
<tbody>
<tr>
<td>Austria</td>
<td>Vienna</td>
<td>Acom Institut</td>
<td>Imaging beam line</td>
<td>TRIGA Mark-II, 250 kW</td>
<td>1.00E+05</td>
<td>125</td>
<td>90 mm diam.</td>
</tr>
<tr>
<td>Brazil</td>
<td>Sao Paulo</td>
<td>IFEN</td>
<td>Imaging beam line</td>
<td>IRE-1M 5 MW</td>
<td>1.00E+06</td>
<td>110</td>
<td>25 cm diam.</td>
</tr>
<tr>
<td>Germany</td>
<td>Garching</td>
<td>TU Munch</td>
<td>ANTARES</td>
<td>RMR-II 25 MW</td>
<td>9.40E+07</td>
<td>400</td>
<td>32 cm diam.</td>
</tr>
<tr>
<td>Germany</td>
<td>Garching</td>
<td>TU Munch</td>
<td>NECTAR</td>
<td>RMR-II 25 MW</td>
<td>3.00E+07</td>
<td>150</td>
<td>20 cm diam.</td>
</tr>
<tr>
<td>Germany</td>
<td>Berlin</td>
<td>HZB</td>
<td>CONRAD</td>
<td>BER-II 10 MW</td>
<td>6.00E+06</td>
<td>500</td>
<td>10 cm x 10 cm</td>
</tr>
<tr>
<td>Hungary</td>
<td>Budapest</td>
<td>KFKI</td>
<td>Imaging beam line</td>
<td>WRS-M 10 MW</td>
<td>6.00E+05</td>
<td>100</td>
<td>25 cm diam.</td>
</tr>
<tr>
<td>Japan</td>
<td>Osaka</td>
<td>Kyusho University</td>
<td>Imaging beam line</td>
<td>MTR 5 MW</td>
<td>1.20E+06</td>
<td>100</td>
<td>16 cm diam.</td>
</tr>
<tr>
<td>Japan</td>
<td>Tokai</td>
<td>JAGA</td>
<td>Imaging beam line</td>
<td>JRRM-3M 20 MW MTR</td>
<td>2.60E+08</td>
<td>123</td>
<td>23 cm x 30 cm</td>
</tr>
<tr>
<td>Korea</td>
<td>Daejon</td>
<td>KAERI</td>
<td>Imaging beam line</td>
<td>HANAR 30 MW</td>
<td>1.00E+07</td>
<td>190</td>
<td>25 cm x 30 cm</td>
</tr>
<tr>
<td>Switzerland</td>
<td>Villigen</td>
<td>PSI</td>
<td>NEUTKA</td>
<td>SINQ spallation source</td>
<td>5.00E+06</td>
<td>500</td>
<td>40 cm diam.</td>
</tr>
<tr>
<td>Switzerland</td>
<td>Villigen</td>
<td>PSI</td>
<td>ICON</td>
<td>SINQ spallation source</td>
<td>1.00E+07</td>
<td>350</td>
<td>15 cm diam.</td>
</tr>
<tr>
<td>USA</td>
<td>Pennsylvania State University</td>
<td>University</td>
<td>Imaging beam line</td>
<td>TRIGA 2 MW</td>
<td>2.00E+06</td>
<td>100</td>
<td>23 cm diam.</td>
</tr>
<tr>
<td>USA</td>
<td>Gaithersburg</td>
<td>NIST</td>
<td>CNR</td>
<td>NBSR 20 MW</td>
<td>2.00E+07</td>
<td>500</td>
<td>23 cm diam.</td>
</tr>
<tr>
<td>USA</td>
<td>Sacramento</td>
<td>McCleanan RC</td>
<td>Imaging beam line</td>
<td>TRIGA 2 MW</td>
<td>2.00E+07</td>
<td>100</td>
<td>23 cm diam.</td>
</tr>
<tr>
<td>South Africa</td>
<td>Pelindaba</td>
<td>NIECSA</td>
<td>SANRAD</td>
<td>SAFARI-1 20 MW</td>
<td>1.60E+06</td>
<td>150</td>
<td>36 cm diam.</td>
</tr>
</tbody>
</table>
NEUTRA: NEUtron Transmission RAdiography
ICON: Imaging with COld Neutrons

Extreme good resolution (25 \( \mu \text{m} \)) for small objects

Position for large objects

Space for Selector or Chopper

Beam limiters

variable apertures 1 … 80 mm, Be filter
• Beam accessible along flight path
• More possibilities than ANTARES I
• Higher flexibility
• New & lighter shielding material
• Space for experiments & sample environment
• All components on rail system
• He-filled flight tubes,
• Highly flexible concept for moving, combining parts and removing parts from the flight tube
Fast neutron imaging with a uranium converter

T. Bücherl (2011)
• Beamline D50
• 2D and 3D neutron imaging with a field of view of up to 170x170 mm$^2$, and real pixel resolution of 10 microns.
• Complementary 2D and 3D X-ray imaging with a field of view of 250x300 mm$^2$, and real pixel resolution of 5 microns.
• approved in 2013 as one of the three first instruments for construction at the European Spallation Source, Lund, Sweden
• unique combination of high flux and specific time structure (energy-selective imaging)
• Novel event-based imaging detectors not to waste valuable neutrons
BNC Neutron imaging facilities

Budapest Research Reactor (10 MW)

NORMA

RAD

TRADITIONAL NEUTRON INSTRUMENTS:
- RAD: Dynamic Gamma & Static Radiography
- BOR: Perturbed-Beam Neutron Radiography
- ARTIS: Material Testing Reactor Actinometry
- TRS: EPR, ESR, Electron Spin Resonance

COLD NEUTRON INSTRUMENTS:
- IN6: Polarized Neutron Reflectometer
- IN4: In-Beam Mössbauer Spectrometer
- GANS: Small Angle Neutron Scattering Spectrometer
- FNSA: Prompt Gamma Activation Analysis
- IN26: Neutron Induced Prompts Gamma Spectrometer
- RIF: Reflectometer
Primary aperture to screen distance: 463 – 539 cm
Flux: $4.6 - 3.38 \times 10^7 \text{ cm}^{-2} \text{ s}^{-1}$
L/D = 170 – 195
Diameter: 195 – 230 mm
$\Phi_{\text{sub Cd}} / \Phi_{\text{epi}} = 52$

Available modalities:
- Thermal neutron
- Gamma beam: ~ 8.5 Gy/h
- X-ray tube: 25-225 keV, max. 10 mA

Detector options:
- 16-bit 4 Mpx sCMOS camera
- Highly sensitivity TV-camera
- Image plate

Imaging options:
- Radiography or Tomography of larger objects
- Small FOV, better resolution
- (Sapphire filter to get rid of fast neutrons)
Neutron, X-ray imaging at RAD

- **static imaging:**
  - radiography and tomography based on digital sCMOS camera (Andor Neo 5.5)
  - neutron: Li$_6$F/ZnS, Gadox; X-ray: Gadox; gamma-ray: NaI(Cs) crystal

- **dynamic imaging:**
  - radiography based on low-level-light analog TV camera (Vidicon tube) and digi

- **different field of views:**
  - 250×250 mm$^2$ (Sigma 50mm)
  - 100×100 mm$^2$ (Nikon 105mm)
  - 40×40 mm$^2$ (Nikon 300mm)
  - 60-250 μm spatial resolution
  - 1-35 s temporal resolution
Combination of local element analysis by prompt gamma activation analysis and structure analysis by neutron radiography/tomography.

Unique instrument

Commissioned in 2012 at the cold neutron guide hall

Flux: $2.7 \times 10^7$ cm$^{-2}$ s$^{-1}$
Resolution: 230 $\mu$m
Field of view: 40x40 mm
L/D ratio: 233
Variable L/D ratio at NIPS-NORMA

- Higher L/D through less D’s:
  - Changeable primary apertures at the end of the neutron guide
  - Available sizes: 550 mm² (25×22 mm²), 121.54 mm² (Ø12.44 mm), 9.95 mm² (Ø3.54 mm)
  - L/D values measured by Gd-foil edge method: 233, 500, 1800

- More uniform neutron flux distribution using scatterers:
  - Changeable graphite scatterer sheets upstream to primary apertures
  - Available thicknesses: 3 mm, 2 mm and no scatterer in the beam
Variable L/D ratio at NIPS-NORMA

L/D = 233 → L/D = 1832

Less uniform

More uniform

Advantages:
- Better spatial resolution farther from the screen (tomography of larger objects!)
- More uniformly irradiated field of view

Disadvantages:
- Longer exposure times
Applications
Breakdown of use

Which methods are used mostly in present applications?

What are the specific requests for the improvement of the existing facilities?

Applications: science + industry

Neutron Imaging
- Materials research
- Wood- and soil-chysts
- (Hydro-) geology
- Nuclear technology
- Two-phase flow
- Structural integrity and performance
- Adhesive connections

Neutron Imaging
- Combustion engines
- Welding, soldering and brazing
- Fuel cell properties

PSI NIAG
A predynastic cemetery was excavated near Gerzeh by **G.A. Wainwright** and **J.P. Bushe-Fox** in **1911**

**Principal Proposer: Thilo Rehren – UCL London**
• to be determined the nature of the iron from which these earliest iron beads are made - can we demonstrate that they are meteoritic in origin, as has been speculated based on their early date?

• All three artefacts have a central hole along their long axis, not visible during visual inspection due to their corrosion. It demonstrate that the beads were made from rolled iron sheet, with areas of overlapping metal visible at the centre of the seam UC10740.

• This would have required repeated hammering with intermittent annealing.

Egyptian Vase from the Pharao age

DOI 10.1007/s00339-014-8779-3
Bronze Monkey - Visualization of regions with different neutron attenuations

B. Maróti et al, J Radioanal Nucl Chem (2017) 312:36
Cultural heritage – Early Iron Age bronze shield

Do we see contrast? Cases if:

1. X-ray – yes, neutron – yes: e.g. bronze (rivet fragments)
2. X-ray – yes, neutron – no: high atomic number (e.g. lead)
3. X-ray – no, neutron – yes: low atomic number (e.g. organic)
A bronze spearhead (Inv. nr.: HNM 75.1893.1200)

Gábor Tarbay, Hungarian National Museum

neutron image

- Hollow is filled with different materials

X-ray image

- Not seen in the X-ray images \(\rightarrow\) organic

1. small fibrous-like material
2. a sharp, long and slim wand
3. next to 2 a similar but thicker wand
4. around the bottom of wands a fibrous-like substance
Bimodal imaging of a snail shell

Bimodal imaging
Neutron activation Autoradiography (NAAR)

**Example:** Panczyk et al., INCT – Warsaw

**IRRADIATION**
Uniform cold / thermal neutron field

**MEASURE**
Delayed $\gamma$ "2D image"

**SENSITIVITY**
High: trace elements (Cu, Mn, Fe, Hg)

**APPLICATIONS**
paintings, pigments

**NAAR system at ‘MORIA’ reactor, Warsaw**

Graphite scatterer

**Neutron beam**

**J. Tintoretto** (1519-1594)
"Portrait of a Venician admiral"

Autoradiograph, 12 min after irradiation. Irradiation time: 3h. Blackening mainly due to $^{56}$Mn and $^{64}$Cu
Non-destructive reverse engineering of internal objects

1. Surface – 3D scan
2. Segmentation of the tomogram
3. Engineering analysis of the segmented dinosaur model
4. 3D-printed dinosaur model

Excavation kit – a plastic dinosaur skeleton within gypsum
Pore volume distribution based on the NT

- Photo of the wagon's part made of bronze
- Tomogram of the whole object
- A longitudinal cut showing pores, cracks, voids

Histogram of the pore's volume distribution

1 voxel = 70 476 micron$^3$
Pore size distribution, wall thickness distribution

E. Solórzano et al., Nuclear Instruments and Methods B 324 (2014) 29–34
Hawaii basalt – visualization of air bubbles
Neutron Tomograph
Red is high neutron attenuation
Red indicates very high H conc.
Image has had low attenuation regions subtracted

X-ray Tomography
Left: Tomograph of core surface
Right: 3D perspective with low X-ray attenuating material subtracted
Red indicates zones of high density

NOTE: X-RAY IMAGE SHOULD REPRESENT THE OPPOSITE TO NEUTRON IMAGE.
THUS: Neutron "sees" hydrocarbon; X-ray "sees" matrix
Lapis lazuli – visualization of heterogeneities
Engineering – Virtual cuts / real fracture face

S3D (stereoscopic 3D) visualization
Turbine blade inspection – visualization of casting template remains

Images from DNR vs. NORMA

Contrast enhancement with a Cd-solution
• Process leading accidental situation in NPPs: loss of coolant accident (LOCA)

• NR: H-distribution in Zr fuel rod cladding around the burst
Mi-24 military chopper rotor blade

- 19 sectors,
- 9.85 m long,
- 700 mm wide,
- 65 mm thick,
- total weight 115 kg

M. Balaskó
Industrial Quality control

welding of metals

- Macroscopic objects

- Micro-tomography: FOV 27×27 mm², 1:1 Lens
- Pixel size 9 μm, 10 μm Gadox scintillator, Scan times 15-20 h

Quality control of explosive devices for space applications

Comparison of neutron radiography and X-ray radiography of an ARIANE cartridge fuse (DASSAULT-AVIATION)
• 100Cr6 high-carbon chromium steel, organic grease -> problem for X-rays

• Unexpected damage observed during use of a double row bearing, due to insufficient lubrication

• Before taking it apart for further studies (e.g., diffraction), the exact geometry can be recorded

• Collaborator: Rogante Engineering Office, Italy
Probing local density via neutron imaging

- Spray-dried refractory carbide and metal powder mixtures, containing tungsten carbide, is compacted and sintered during the production of conventional cutting tool inserts.

- The friction between the pressing tool and the powder results in density gradients in the powder compact, and uneven shrinkage during sintering.

- To validate the finite element simulation of the pressing procedure, the density gradients in the powder compacts must be measured with a high spatial resolution.

- Since Tungsten has a high atomic number, it is hard to penetrate with X-rays and even cold neutrons.

- Calibration of the neutron attenuation vs. thickness using homogeneous pellets.

https://www.youtube.com/watch?v=0QrynzuLZ4
Finite element simulations and experimental imaging results are in close agreement.

Collaborators:
Hjalmar Staf,
Bartek Kaplan,
Erik Olsson,
Per-Lennart Larsson
a) 50, 

b) 75,  
c) 100,  
d) 150,  
e) 200 keV X-ray beam  

f) thermal neutron beam
Composite Image segmentation
Cell phone in 3D
Capillary rise in a brick

\[ y = k \cdot x + c \]
\[ c = 0.048 \pm 0.022 \times 10^{-5} \]
\[ k = (7.051 \pm 0.004) \times 10^{-5} m/\sqrt{s} \]

Z. Kis et al, Materials and Structures (2017) 50:159
Time-resolved imaging

High-speed imaging of very fast, singular processes requiring several thousand frames per second

Example: Gun shot - hardly feasible for neutrons!

Problems:
- the number of neutrons/photons in one time window becomes very low, below the detector noise
- in classic detectors, the number of detector pixels that can be read out in one time window becomes very small, drastically decreasing resolution

But: New detectors are becoming fast enough (see below), the neutron flux is the main limiting factor!

Stroboscopic imaging of very fast but repetitive processes

Example: Fuel injection / oil flux in a combustion engine

Advantage:
- the number of neutrons/photons in one time window is still very low, but many exposures of the same time window of the periodic process may be accumulated on the detector before read-out, thus increasing the available intensity

Disadvantage:
- Only one time window of the periodic process can be recorded in one sequence, the periodic process has to be recorded in a sequence of many consecutive time window accumulations, sacrificing most neutrons.

Physical limitations
- Available neutron/photon flux in a time window
- Decay time of scintillation light
- Readout speed of the detector
- Gating time of the detector (if applicable)
Real-time neutron imaging

A. Kaestner and E. Lehmann, IAEA TM on Regional RR Users’ Networks: advances in neutron imaging, 26-29 Nov. 2012, Jakarta, Indonesia
• Real-time visualization of an engineering object
• p,T,v parameters external controlled
• ANCARA – experimental loop to study the behaviour of SCW
• For an improved efficiency of future energy production

M. Balaskó, L. Horváth et al,
Physics Procedia 43 (2013) 254 – 263
Supercritical water @ RAD

A. Kiss, Annals of Nuclear Energy
100 (2017) 178–203
Fuel cell in situ @ RAD
Gas formation during charge cycle of Li ion battery

H. Sommer
Stroboscopic imaging – Image acquisition

• The camera is triggered by an event in the process
• Many short time exposures accumulated per frame
• Cyclic processes can be faster than real-time imaging
• Different positions can be reached by delay

Common-rail diesel injector nozzle
• Fired two-stoke engine running idle at 3000 RPM
• 40 frames created from 32 images each.
• 1 ms exposure time/frame
The contrast can be adjusted by selecting different wavelengths.
Neutrons act as waves; due to wave-particle dualism neutrons can also be described by matter waves with a certain wavelength.

In the case of the phase contrast method, one uses the fact that the waves which transverse an object have a different velocity to those which do not, and therefore have a different wavelength.

The resulting displacement of the wave maxima leads to a change of the propagation direction and therefore to an angular change.
Imaging of magnetic field with polarized neutrons

A radiograph showing the field lines surrounding a bar magnet. The magnetic field decreases in strength with distance from the magnet, resulting in a series of maxima and minima, where the beam polarization is sequentially parallel or antiparallel to the analyzer.

Very close to the magnets (where the field is strongest) the field lines are too close together to be spatially resolved (N. Kardjilov)
Conclusions

• Neutron imaging is a popular and capable tool in nondestructive material testing
• 2D/3D Images with 10-200 μm resolution
• Contrast scatters substantially by elements
• User facilities operated at large neutron centres

• BNC: RAD and NORMA
Thank you for your attention!