Neutron Imaging – Principles and Status

Historical and theoretical introduction to neutron imaging techniques
NEUTRONS IMAGING

- Current situation of neutron imaging facilities
- Principle to build a state-of-the-art system
- Methodical and topical challenges
- Our approach at PSI
- Conclusions
European Photon & Neutron Science Campus
PSI’s large scale facilities

PSI

SINQ

SLS
What about Imaging?
Beamlines for imaging

ID16A Nano-Imaging
ID16B Nano-Analysis
ID17 Bio-medical
ID19 Microtomography
ID21 X-ray microscopy & microanalysis

5 out of 44 > 10%
ILL Grenoble

0 out of 41 = 0%
1 out of 20 = 5%
**NEUTRA: NEUtron Transmission Radiography (since 1997)**

Neutron flux (@ 1.2 mA proton current) = $3 \cdot 10^6 \div 2 \cdot 10^7$ cm$^{-2}$s$^{-1}$ [thermal neutrons]

**ICON: Imaging with Cold Neutrons**

Start of operation in June 2005 [cold neutrons]

2.x out of 17 > 10%
Neutron imaging - all submitted proposals @ PSI

indication for a high demand, in particular for advanced techniques
What are the reasons?

How to overcome?

We need more good neutron imaging facilities!
Reasons for the still unsatisfactory situation in NI

- The investment for a neutron imaging beam line is not done
- Competition to other user groups (neutron scattering, irradiation technology) – no access for the neutron imaging community
- Missing user program and applications
- Limited know how and technical infrastructure in the particular country
- Missing experienced staff and education

It is possible (and needed) to use the potential at existing sources for neutron imaging with a suitable investment

New examples: LLB (F), IBR-2 (Ru), Kjeller (N), ANSTO (Aus), HFIR (USA)…
Historical overview

1895: discovery of X-rays (Röntgen) – first images
1914: X-ray diffraction (Laue)
1915: X-ray diffraction (Bragg)
1932: discovery of the neutron (Chadwick)
1936: powder diffraction (Debye)
1942: first reactor (Fermi)
1945: neutron diffraction (Wollan, Shull, Clifford)
1947: first neutron images (Kalman, Kuhn)
1956: neutron imaging at research reactor (Thewlis)
1970: X-ray tomography in hospitals
1980: 1990: digital neutron imaging
1995: neutron tomography
2000: 2016: SwissFEL (PSI, CH)
2005: phase contrast neutron imaging
2020: ESS operational
neutrons vs. X-rays (time lines)

- free neutrons were discovered **37 years** after the X-rays were found
- neutron imaging started **50 years** after first X-ray images were made
- neutron diffraction comes **30 years** later than X-ray diffraction
- neutron tomography comes **25 years** later than X-ray tomography in hospitals
- phase contrast imaging with neutrons comes **10 years** later than with X-rays
- neutron imaging is **now** a competitive and complementary method compared to the X-ray techniques
New source for neutron scattering

- backscattering spectrometer
- neutron reflectometer
- small angle scattering
- triple axis spectrometer (cold)
- residual stress diffractometer
- spin echo spectrometer
- time-of-flight spectromter
- triple axis spectrometer (therm.)
- neutron imaging facility
- single crystal diffractometer
- powder diffractometer
- USANS
- neutron reflectometer
New source for neutron imaging

- real-time imaging facility
- neutron optics development
- cold neutron radiography
- cold micro-tomography
- phase contrast imaging
- energy selective neutron imaging
- thermal neutron radiography
- combined diff.-imaging beam line
- X-ray reference facility
- resonance imaging with epi-thermal n.
- imaging with fast neutrons
- imaging with polarized neutrons
Neutron imaging at ILL now?

- backscattering spectrometer
- neutron reflectometer
- small angle scattering
- triple axis spectrometer (cold)
- residual stress diffractometer
- time-of-flight spectrometer
- neutron imaging facility?
- single crystal diffractometer
- powder diffractometer
- USANS

Spin echo spectrometer
**Principle of transmission imaging**

\[ I = I_0 \cdot e^{-\Sigma \cdot d} \]

- \( I_0 \) = initial beam intensity
- \( I \) = beam intensity behind the sample
- \( d \) = sample thickness in beam direction
- \( \Sigma \) = attenuation coefficient of the material

→ quantification of the involved materials
Neutrons vs. X-rays (interaction scheme)

- Neutrons
  - Incident neutron with energy $E_0$
  - Absorption
  - Scattering

- X-Rays
  - Incident x-ray photon with energy $E_0$
  - Photoelectron
  - Absorption
  - Scattering
Comparison N ↔ X (example: hard-disk drive)
Attenuation of X-rays (100 keV) – material dependent

<table>
<thead>
<tr>
<th>Group</th>
<th>Period</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
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<tr>
<td>1</td>
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<td>Na</td>
<td>K</td>
<td>Rb</td>
<td>Cs</td>
<td>Fr</td>
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<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>He</td>
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<td>Mg</td>
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<td>Ra</td>
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<td>V</td>
<td>Cr</td>
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</table>

Lanthanides: La (5.04), Ce (5.79), Pr (6.23), Nd (6.46), Pm (7.33), Sm (7.68), Eu (5.66), Gd (8.89), Tb (9.46), Dy (10.17), Ho (10.17), Er (11.70), Tm (12.49), Yb (9.32), Lu (14.07)

Actinides: Ac (24.47), Th (28.05), Pa (39.65), U (49.08), Np ( - ), Pu ( - ), Am ( - ), Cm ( - ), Bk ( - ), Cf ( - ), Es ( - ), Fm ( - ), Md ( - ), No ( - ), Lr ( - )
### Attenuation of thermal neutrons – material dependent

| Group | Period | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
|-------|--------|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|
|       |        | H | Li| Be| B | C | N | O | F | Ne| Na | Mg | Al | Si | P  | S  | Cl | Ar |   |
| 1     | 1      | 3.44 | 3.30 | 3.09 | 2.20 | 1.21 | 1.19 | 2.05 | 1.07 | 0.35 | 0.49 | 0.47 | 0.47 | 0.67 | 0.73 | 1.33 | 0.24 | 0.61 | He |
| 2     | 2      | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 |   |
| 3     | 3      | 0.09 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 |   |
| 4     | 4      | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 |   |
| 5     | 5      | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 |   |
| 6     | 6      | 0.29 | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 |   |
| 7     | 7      | 0.34 | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   |   |

**Lanthanides**

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<th>La</th>
<th>Ce</th>
<th>Pr</th>
<th>Nd</th>
<th>Pm</th>
<th>Sm</th>
<th>Eu</th>
<th>Gd</th>
<th>Tb</th>
<th>Dy</th>
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<td></td>
<td>0.52</td>
<td>0.14</td>
<td>0.41</td>
<td>1.87</td>
<td>5.72</td>
<td>171.47</td>
<td>94.58</td>
<td>1479.0</td>
<td>0.93</td>
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**Actinides**

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<th>Pa</th>
<th>U</th>
<th>Np</th>
<th>Pu</th>
<th>Am</th>
<th>Cm</th>
<th>Bk</th>
<th>Cf</th>
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<td>8.46</td>
<td>0.59</td>
<td>0.82</td>
<td>9.80</td>
<td>50.20</td>
<td>2.86</td>
<td>-</td>
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neutron utilization for research

<table>
<thead>
<tr>
<th>ADVANTAGES</th>
<th>DISADVANTAGES</th>
</tr>
</thead>
<tbody>
<tr>
<td>• no charge: often deeper penetration</td>
<td>• neutron intensity limited</td>
</tr>
<tr>
<td>• magnetic moment: magnetic interaction with nuclei → polarized neutrons</td>
<td>• no direct detection – secondary process is needed</td>
</tr>
<tr>
<td>• high sensitivity for light elements</td>
<td>• no charge: no focusing and guiding by el.-magnetic fields possible</td>
</tr>
<tr>
<td>• different isotopes can be distinguished (D:H, B-10:B-11, Li-6:Li-7, U-235:U-238)</td>
<td>• activation risks of samples</td>
</tr>
<tr>
<td>• energy selection using time-of-flight (at pulsed sources)</td>
<td></td>
</tr>
</tbody>
</table>
NEUTRON SOURCES

required: beam of thermal or cold neutrons with
- high intensity
- high collimation
- narrow spectrum
- large field of view
- homogenously illuminated

available: research reactors (power up to 80 MW)
spallation neutron sources (pulsed or stationary)
accelerator driven sources
radio-isotopes (e.g. Cf)

delivered: <intensity at sample ~10^7 cm^-2 s^-1
<collimators reduce intensity
<mono-chromatizers reduce intensity
<divergent beam needed to have large FOV
Detector options for neutron imaging

1. Camera based systems in conjunction with scintillators

2. \( n \)-sensitive imaging plates (Gd or Dy doped)

3. amorphous Si flat panels (with scintillators)

4. pixel detectors with B-10, Li-6 or Gd direct conversion to charge

5. 2D counting devices (He-3, B-10 based)

**performance issues:** spatial resolution, time resolution, sensitivity for gammas, fixed position \( \rightarrow \) tomo abilities
Neutron Imaging - Setup

- Moderator
- Primary source
- Second moderator (cold source)
- Filter
- Shutter
- Aperture
- Beam limiter
- Sample manipulator
- Detector
- Beam dump
Neutron Imaging TODAY: Definition

• Dedicated beam line at a (most) powerful neutron source → intensity

• Well defined thermal or cold spectrum

• Best possible beam collimation (L/D>100) → spatial resolution

• Reasonable large field-of-view (diameter > 10 cm) - homogenous

• DIGITAL IMAGING DETECTION SYSTEM

• Experimental infrastructure (remote control of processes, radiation protection, access control, …)

• Prepared for user access
GLOBAL SITUATION

ISNR + IAEA Data Base for Neutron Imaging Facilities

http://www.isnr.de
241 research reactors operational in 56 countries
188 with power > 1 kW; 110 with power > 1 MW
51 facilities claim to perform neutron scattering
77 facilities claim to perform neutron radiography!
Evaluation of the situation in respect to NI facilities

Neutron Imaging Facilities - worldwide (according to Research Reactor Data Base IAEA)

- TOP; 10
- shutdown; 3
- unknown questionable; 15
- potential; 32
- OK; 18

+ facilities at spallation sources
# State-of-the-art Neutron Imaging User Facilities Worldwide

<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>Atominstitut</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>IPEN</td>
<td>imaging beam line</td>
<td>IEA-R1M 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 Munich</td>
<td>ANTARES</td>
<td>FRM-II 25 MW</td>
<td>9.40E+07</td>
<td>400</td>
<td>32 cm diam.</td>
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<tr>
<td>Germany</td>
<td>Garching</td>
<td>TU Munich</td>
<td>NECTAR</td>
<td>FRM-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 * 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>Kyoto 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>JAEA</td>
<td>imaging beam line</td>
<td>JRRM-3M 20 MW MTR</td>
<td>2.60E+08</td>
<td>125</td>
<td>25 cm * 30 cm</td>
</tr>
<tr>
<td>Korea</td>
<td>Daejon</td>
<td>KAERI</td>
<td>imaging beam line</td>
<td>HANABO 30 MW</td>
<td>1.00E+07</td>
<td>190</td>
<td>25 cm * 30 cm</td>
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<tr>
<td>Switzerland</td>
<td>Villigen</td>
<td>PSI</td>
<td>NEUTRA</td>
<td>SINQ spallation source</td>
<td>5.00E+06</td>
<td>550</td>
<td>40 cm diam.</td>
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<tr>
<td>Switzerland</td>
<td>Villigen</td>
<td>PSI</td>
<td>ICON</td>
<td>SINQ spallation source</td>
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<td>350</td>
<td>15 cm diam.</td>
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<tr>
<td>USA</td>
<td>PennState Univ.</td>
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<td>imaging beam line</td>
<td>TRIGA 2 MW</td>
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<td>100</td>
<td>23 cm diam.</td>
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<td>USA</td>
<td>Gaithersburg</td>
<td>NIST</td>
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<td>USA</td>
<td>Sacramento</td>
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<td>23 cm diam.</td>
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<td>South Africa</td>
<td>Pelindaba</td>
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<td>SAFARI-1 20 MW</td>
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<td>36 cm dia.</td>
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<td>USA</td>
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<td>ORNL</td>
<td>CG-1D</td>
<td>HFIR</td>
<td>1.00E+06</td>
<td>500</td>
<td>7 cm</td>
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About 15 TOP facilities available worldwide among them, the performance is still different.
Total: 44 facilities; only about 15 „user facilities“
Spallation neutron source SINQ @ PSI

- In operation since 1997
- Driven by 590 MeV protons on a Pb target
- Intensity about 1.2 mA, corresponding to 1MW thermal power
- Installations for research with thermal and cold neutrons

Still the world’s strongest stationary spallation source
Beamlines layout

SINQ top view

NEUTRA
SINQ – Layout, Imaging Beam Lines
ICON-beam line @ SINQ

- Micro-Tomography-Position
- Space for Selector or Chopper
- Beam limiters
- Position for large objects
- Variable apertures 1 ... 80 mm, Be filter
## Performance of the Imaging Beam Lines at PSI

<table>
<thead>
<tr>
<th>ICON</th>
<th>NEUTRA</th>
<th>BOA</th>
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<tbody>
<tr>
<td>cold neutrons</td>
<td>thermal neutrons</td>
<td>very cold neutrons</td>
</tr>
<tr>
<td>higher contrast</td>
<td>higher penetration</td>
<td>high beam intensity</td>
</tr>
<tr>
<td>variable aperture, Bi-filter option</td>
<td>more homogenous illumination for large objects</td>
<td>polarized neutrons</td>
</tr>
<tr>
<td>two beam positions</td>
<td>two beam positions</td>
<td></td>
</tr>
<tr>
<td>micro-tomography-setup</td>
<td>two detector boxes</td>
<td>UNDER CONSTRUCTION</td>
</tr>
<tr>
<td>tilted detector option</td>
<td>X-TRA option (320 kV tube, high current) for referencing</td>
<td></td>
</tr>
<tr>
<td>two detector boxes</td>
<td>option for the inspection of highly activated materials</td>
<td></td>
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<tr>
<td>turbine energy selector</td>
<td></td>
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<tr>
<td>fuel cell infra-structure</td>
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</table>
Flexibility: FOV and pixel size for the detector systems

Detector options with CCDs:
- MAXI
- MIDI
- MICRO

Field-of-View [mm] vs. pixel size [mm]

- MAXI: Large FOV and medium pixel size
- MIDI: Medium FOV and pixel size
- MICRO: Small FOV and pixel size
Micro-Tomographie-Setup an ICON

Specifications
- FOV: 2.7cm * 2.7cm
- Pixel size: 13µm
- CCD with 2048*2048 pixels
- Scintillator 10 µm thick
- L/D>1000
Virtual Reality

Micro-Tomography with cold neutrons
Example: Sensor Diagnostik

- Inconel Membrane (718)
- 17-4PH “Front Cap”
- "Soot" Accumulation

Dimensions:
- 132mm
- 18.5mm
- 6mm
- 6.7mm Ø
Soot particle filter, Maxi-setup

Tomography

Projections: 675 over 360°

Exposure time per projection: 20 s

Pixel resolution: 150 µm
Soot particle filter, Maxi-setup
New trends in neutron imaging

**current base line:**
- digital
- 2D and 3D
- with white cold or thermal beams
- on macro (40 cm Ø) and micro scales (13 μm pixel size)

**new approaches:**
- energy selection (selection devices, TOF)
- time-dependence (sequential or stroboscopic)
- diffractive imaging
- neutron interferometry (phase and “dark-field” imaging)
- edge enhancement by neutron refraction
- data fusion (e.g. to X-ray imaging)
- resonance imaging with epithermal neutrons
- polarized neutron imaging
qualified manpower!

2.x beam lines  100 projects/year  new methods development
Conclusions

• It has been shown that neutron imaging has a high potential for scientific and applied studies, complementary to the more established X-ray techniques.

• The challenge is to use the currently running and future sources to provide the best possible imaging performance to customers.

• The highest potential is seen to go for cold neutrons (high contrast) and high intensity (spatial resolution, time sequences).

• More “exotic” options like polarized and phase contrast imaging are still under development and optimization.
The facilities at PSI are prepared to host your projects on demand

Please, send your proposal to https://duo.psi.ch/duo/