Neutron Imaging
... and options for quantification ...

Eberhard H. Lehmann
:: Neutron Imaging & Activation Group :: Paul Scherrer Institut

19th HERCULES Specialized Course on «Quantitative Imaging»
Eberhard H. Lehmann

German, working in Switzerland

Education: reactor physicist

PhD: physics of the fast breeder reactor

Active in neutron imaging since 1995

Group leader «Neutron Imaging & Activation»

Operating facilities at the Swiss spallation source
1. Historical background: X-rays vs. Neutrons - the “mirrored” techniques
2. Neutrons and their interaction with matter
3. Setup of a neutron imaging facility
4. Status in a world-wide context
5. Methods in neutron imaging - overview
6. Data processing - Quantification
7. Fields of applications
8. Future developments
9. Summary & Conclusions
X-rays vs. neutrons

- 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.
From radiography to tomography

H. Kallmann (reported by O. Peter) **about 1947**
Film radiography using an accelerator based neutron source

**2015:** high resolution tomography at the Swiss spallation source SINQ (Y. Wang)
Smartphone

destructive imaging
Smartphone: Radiography mode

Similar image quality
Complementary information
Combined N and X: components visible

camera forward

main board and electronics

SIM card

laudspeaker

music?

connector network

main switch

light diode

phone

interface

plastics

camera back

Li-ion battery

cylindre (Ta condensator?)

connector head phones

metal cover

interface

plastics

connector network

main switch

light diode

phone

interface

plastics

camera back

Li-ion battery

cylindre (Ta condensator?)

connector head phones

metal cover
Neutrons & X-ray Imaging

Heavily corroded nail from the Roman period (age: 2000 years)

- Same image quality
- Complementary information
- High resolution
- Tomography (now standard)
- Option for «data fusion»

Neutron-CT

X-ray-CT
Properties of the free neutron

- **Size:** \(1.6 \times 10^{-15} \text{ m}\)
- **Mass:** \(1.674927351(74) \times 10^{-27} \text{ kg}\)
- **Charge:** 0
- **Spin:** \(\frac{1}{2}\) (two states possible)
- **Velocity:** few m/s (ultra cold) to speed of light (very fast)
- **Elementary composition:** 3 Quarks up-down-down
- **Magnetic moment:** \(-1.913 \, \mu_N\)
- **Interaction with matter:** nuclear reactions: absorption, scattering, fission
- **Classification:** Baryon, Fermion
- **Half-life:** 881.5 s
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with relevance for neutron imaging
Neutrons vs. X-rays (interaction scheme)

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

**X-Rays**
- Incident x-ray photon with energy $E_0$
- Absorption
- Scattering
- Photoelectron
X-rays vs. Neutrons

X-Rays

Incident x-ray photon with energy $E_0$

A

Photoelectron

Absorption

B

Scattering

Mass attenuation coefficient [1/cm]

Atomic number

X-rays (100 keV)
X-rays vs. Neutrons

Neutrons

Incident neutron with energy $E_0$

Absorption
Scattering

Mass attenuation coefficient $[1/cm]$

Atomic number

X-rays (100 keV)
Thermal neutrons

Light Elements
Metals
Heavy Elements

B
H
Li
Cd
Fe
Co
Ni
Pb
Au

Thermal neutrons
### Attenuation of X-rays (100 keV)

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#### Lanthanides

- La
- Ce
- Pr
- Nd
- Pm
- Sm
- Eu
- Gd
- Tb
- Dy
- Ho
- Er
- Tm
- Yb
- Lu

#### Actinides

- Ac
- Th
- Pa
- U
- Np
- Pu
- Am
- Cm
- Bk
- Cf
- Es
- Fm
- Md
- No
- Lr
Attenuation of thermal neutrons

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**Lanthanides**
- La 0.52
- Ce 0.14
- Pr 0.81
- Nd 1.87
- Pm 5.72
- Sm 171.47
- Eu 0.58
- Gd 1479.0
- Tb 0.93
- Dy 32.42
- Ho 22.5
- Er 5.48
- Tm 3.53
- Yb 1.40
- Lu 2.75

**Actinides**
- Ac -
- Th 0.59
- Pa 8.46
- U 0.82
- Np 9.80
- Pu 50.20
- Am 2.88
- Cm -
- Bk -
- Cf -
- Es -
- Fm -
- Md -
- No -
- Lr -
Duality of neutrons – visible in imaging

de Broglie: \( \lambda = \frac{h}{m \cdot v} \)

**neutron as particle**
- single neutrons can be counts on the detector
- description with Monte-Carlo codes (cross-sections as interaction probability) per neutron
- scattering and absorption adequately confirmed

**neutron as wave**
- phase effects at edges – refraction or total reflection
- refraction index based on wave functions
- interference of waves as interpretation
- coherence can play an essential role
Interaction principle of neutrons with matter

• Neutrons interact with the **nuclei** of the atoms only

• The interaction can be: **collision** (scattering), **absorption** (creation of radioactive isotopes) or **fission** (with fissile materials)

• The strength of the interaction with matter is expressed by „**microscopic cross-sections**“ – **σ**, the unit is „barn = 10^{-24} \text{ cm}^{-2}“

• The „**macroscopic cross-section**” **Σ**, also called „**attenuation coefficient**” is defined as : **Σ** = **N*** **σ**, the unit is cm^{-1}

• **N** = nuclear density = \((\rho* A)/M\) (A=Avogadro‘s number, M=mass)
Neutron interactions with matter

- Interactions
  - Scattering
    - Elastic
    - Inelastic
  - Absorption
    - Fission
    - Capture
Neutron interactions with matter

Ultra cold  Cold  Thermal  Moderation  Fission and spallation
Neutron interactions with matter
absorption vs. scattering

- **Normalized absorption cross section**
- **Normalized scattering cross section**
Interaction principle of neutrons with matter

- The cross-sections can differ by orders of magnitude from material to material.
- The interaction probability is much higher for slow neutrons.
- Thermal and cold neutrons are the preferred tools in neutron imaging (E~meV).
Neutron Utilization for Research

**ADVANTAGES**

- no charge: often deeper penetration
- magnetic moment: magnetic interaction with nuclei → polarized neutrons
- high sensitivity for light elements
- different isotopes can be distinguished (D:H, B-10:B-11, Li-6: Li-7, U-235:U-238)
- energy selection using time-of-flight (at pulsed sources)

**DISADVANTAGES**

- neutron intensity limited
- no direct detection – a secondary process is needed (limiting spatial resolution)
- no charge: no focusing and guiding by el.-magnetic fields possible
- activation risks of samples
Neutron Imaging Principle

simplified setup for imaging in transmission mode

flux $\phi(E)$
gammas

Collimator

Source

Detector

Sample

field of view FOV

L/D ratio

$D$
Transmission process

- direct attenuation
- no phase effects
- interpretation with the particle picture

Neutrons
X-rays

Plants/roots in soil
To use the interaction of (thermal / cold) neutrons with matter to get information about composition, structure and status of the object on the macro scale.

It is mostly the attenuation of a wide, homogenous beam by the object and the analysis of the transmitted beam fraction to be analyzed.

The efficient detection of the transmitted beam component determines the performance of the neutron imaging setup.

Advanced NI methods deal with the scattered neutrons also.
Lenght scale in neutron research

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**scattering**
- atomic and magnetic structures
- internal strain

**imaging**
- organic molecules
- surfaces and multilayers inhomogeneities
- micelles, proteins, polymers
- magnetic defects, pharmaceuticals, supermolecules
- cracks, pores, precipitates
- critical phenomena, cracks and voids
- systems and components

**Diffraction regime**
- Internal strains
- Crystalline phases, textures

**SANS and Dark-field imaging regime**
- Polymers, microstructure, magnetic domain structures

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Conventional imaging regime

**Length scale in nm**
- 0.01
- 0.3
- 1.0
- 3.0
- 10
- 100
- 1000
- 10000
- 100000

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Courtesy: M. Strobl ESS
In the past: Neutron Radiography = a method for non-destructive testing

Now: Neutron Imaging = research tool for many fields of scientific applications, including material research, using more advanced methods too

New aspects: digital output, data sets more than «pictures»

importance of image-processing
Neutron Imaging – Setup & Components

**Advanced components:**
- E-selector
- Polarizer
- Grating interferometer

**Safety requirements:**
- Access control
- Shielding
- Dosimetry
Research Reactors – Design (example FRM-2)

- Moderator tank (D₂O)
- Reactor pool (H₂O)
Research Reactors – Design (example FRM-2)

Moderator tank (D₂O)

Beamline

Reactor pool (H₂O)
ANTARES and NECTAR @ FRM-2

ANTARES = cold neutrons

NECTAR = fast neutrons
Spallation Neutron Source – example SINQ, PSI

- installations for research with thermal and cold neutrons
- about 20 beam lines
- including 2.x for imaging
- approximately parallel beam
Beamlines layout

ICON  BOA  SINQ top view

NEUTRA
19 Instruments: 15 User facilities (>2 Imaging beam lines) + 4 Test facilities
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
Spectra at PSI/SINQ Neutron Imaging beamlines

Higher contrast

Higher penetration
State-of-the-art Neutron Imaging User Facilities world-wide

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**only about 15 TOP facilities available world-wide**

among them, the performance is still different

**It should be the goal for ILL to become member of the «club» !**
Neutron Detectors for Imaging

situation before 1995

X-ray film + converter
track etch foils
Analogue neutron imaging – 1 frame per hour

about 1994
Neutron Detectors for Imaging

- Intensified real-time camera
- CCD camera + scintillator
- CMOS pixel detector
- X-ray film + converter
- amorphous-Si flat panel
- n-imaging plates
- track etch foils

Current situation

Spatial resolution [mm]

Time resolution [s]
Digital – 1 frame per second

about 2012
Neutron Detectors for Imaging

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

Development!!!

Detector development!!!
Neutron Imaging: different settings wrt resolution

Pixel size [micro-meter] vs. Field of View [mm]

- MAXI
- MIDI
- MICRO

Legend:
- Green dot: Representative setting for high-resolution imaging
- Red circle: Typical settings for different field-of-view requirements

Graph shows the relationship between pixel size and field of view for different imaging settings.
Camera-detector MIDI (medium FOV)

FOV between 15 and 3 cm
Detection Efficiency for Neutron Converters

Absorption at 1.8 A

Absorption vs. Thickness (um)

- Gd-157
- Li-6 F
- Gd, B-10
- $^{10}$B
- Gadox
- $^{157}$Gadox
- B-10
- Gd
- $^{157}$Gd
- GGG
- $^{157}$GGG
- $^6$LiF
Neutron imaging methods @ PSI

Classic neutron imaging methods
- Radiography
- Tomography
- Real-time imaging
- Stroboscopic imaging

Advanced neutron imaging methods
- Energy selective imaging
- Neutron grating interferometry
- Diffraction imaging

Under preparation:
- Imaging with polarized neutrons (BOA)
- Project neutron microscope
- N/X data fusion
many

SCIENTIFIC CASES!

archaeology

engineering

metallurgy

geoscience

composites

biology

numismatic
Increased Data Volume

Data volume per tomography set

- 512 pixels: 268 MB
- 1024 pixels: 2.15 GB
- 2048 pixels: 17.2 GB
- 4096 pixels: 137 GB

High RAM and Disk space requirements
Neutron imaging methods @ PSI

Classic neutron imaging methods

- Radiography
- Tomography
- Real-time imaging
- Stroboscopic imaging

Advanced neutron imaging methods

- Energy selective imaging
- Neutron grating interferometry
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Under preparation:

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Quantification in Neutron Imaging

= non-invasive determination of the sample’s content
Attenuation in transmission mode

initial beam \( I_0 \)

sample

material properties (density, composition)

\( \Sigma \cdot d \)

transmitted beam \( I \)

detector plane

thickness
Analytical description of the transmission process

• Beer-Lambert law

\[
T = \frac{I}{I_0} = e^{-\Sigma \cdot d} = e^{-\sigma \cdot N \cdot d}
\]

Transmission

and inverted ...

\[
\Sigma \cdot d = \ln\left(\frac{I_0}{I}\right)
\]

Thickness \(d\) can be obtained when \(\Sigma\) is known

Density or composition derived if thickness \(d\) is known
Final results of neutron imaging in transmission mode

Two dimensional **pixel-matrix** $\Sigma(x, y)$ of averaged macroscopic cross-sections integrated over the length in beam direction $z$

\[
\Sigma_{\text{eff}} = N \cdot \frac{\int dE \cdot \varepsilon(E) \cdot \sigma(E) \cdot \phi(E)}{\int_{E} dE \cdot \varepsilon(E) \cdot \phi(E)}
\]

In the case of **neutron tomography** the 3$^{\text{rd}}$ dimension is resolved and a **voxel-matrix** $\Sigma(x, y, z)$ can be derived
**Physics:**

- attenuation coefficients, detector response and flux distribution are energy dependent $\rightarrow$ beam hardening artifacts are possible

- multiple scattering in the sample can distort the result

- Cross-section data for comparison are complex (Bragg edges), depend on materials properties (e.g. texture) and have uncertainties

**Imaging Technique:**

- **Detector:** background of scattered light; afterglow of scintillator; background from gamma-radiation are disturbing

- **Signal/noise** ratio can limit the accuracy
The attenuation law assumes that the beam is absorbed ... but most of the interaction is due to Scattering!
1. **Correction of the scattered neutrons** contributions by means of Monte-Carlo simulations (mainly focused on **hydrogen**)

2. **Changing sample-detector distances** for the determination of the scattering contribution

3. Using the «**black-body**» correction tools (cases of low transmission)
The scattering pretends a higher transmission value behind the sample, which is mistaken for less mass thickness.
Approximation of the Point Scattered Functions

\[
P\text{ScF}(r) = S_A \cdot \frac{d_A}{4\pi (d_A^2 + r^2)^{3/2}} \cdot \frac{1 - e^{-\Sigma_D \cdot s_D \sqrt{d_A^2 + r^2}}}{1 - e^{-\Sigma_D \cdot s_D}}
\]
QNI – the correction tool

Based on PhD work of Rene Hassanein

- MCNP based
- Programmed in IDL
- Available for other users

Basic principle: superposition of the «point scattering functions»
QNI - Iterative Algorithm

- Corrected transmission image = radiography – sample scattering

- With the corrected image, a more precise base for the choice of the PScF is available and the computation is repeated.

- After about 4 iterations the algorithm converges in the range of ±1 %. 
Water Content in Sand Columns (radiography mode)

45° view: before after correction

→ 6.5 cm diagonal
→ 14 cm diagonal
Water Content in Sand Columns (tomography mode)

- uncorrected slice
- corrected slice
- more noise induced
- Some more artefacts
Water migration in sandstones

The error in the quantification can be up to 100%!
Structural materials
Cross-sections of crystalline structural materials

![Graph showing neutron absorption cross-sections for various elements.](image)

- **σ [barn]**
- **Neutron wavelength [Å]**

Elements represented:
- Fe
- Cu
- Pb
- Zr
- Al
- Ni

Absorption range indicated.
Energy-selective Imaging

Phase information
Increased sensitivity
Texture
Increased penetration
Absorption range (quantification)

Strain Imaging

Spatially resolved
rolled Al plate (with weld) – texture analysis

Neutron radiography images

\[ \sum_{\lambda} \] [cm\(^{-1}\)]

\( \lambda_1 \) → white beam image

\( \lambda_2 \)

\( \lambda_3 \)
rolled Al plate (with weld) – texture analysis

Neutron radiography images

Al

\[ \sum [\text{cm}^{-1}] \]

\[ \lambda_1 \]

\[ \lambda_2 \]

\[ \lambda_3 \]

\[ \lambda \text{ [A]} \]

\[ \text{total} \]

Photo
Al structure – and their interpretation

Transmission image at 4.8 Å

EBSD – measurement at the surface

→ Different grain size and orientation in bulk and weld

Data: L. Josic, H. Leber, PSI
To avoid geometrical blurring, the samples have to be measured close to the detector.

To avoid the high contribution of scattered neutrons to the signal, the samples have to be measured in a certain distance.

To combine both approaches helps to overcome the problems in quantification for the observed materials Fe, Cu, V, ...
Why is scattering correction needed?

ETP Copper

$r = 12.5 \text{ mm}$

$t = 10 \text{ mm}$

Photography of a copper cylinder
Why is scattering correction needed?

\[
\frac{I}{I_0} = e^{-\Sigma t} \quad \rightarrow \quad \Sigma = \ln \left( \frac{I}{I_0} \right) t
\]

Sample at distance = 0 mm

Sample at distance = 55 mm

ETP Copper

r = 12.5 mm

t = 10 mm
Why is scattering correction needed?

Photograph

Distance = 0 mm

Distance = 55 mm
Forward scattering for coherent scatterers

**Bragg law**

\[ n\lambda = 2d \cdot \sin(\theta) \rightarrow 2\theta = 2\sin\left(\frac{n\lambda}{2d}\right) \]

<table>
<thead>
<tr>
<th>Metal</th>
<th>Largest d-spacing [Å]</th>
<th>Smallest 2θ [°]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>2.08</td>
<td>28</td>
</tr>
<tr>
<td>Iron</td>
<td>2.02</td>
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<td>2.55</td>
<td>23</td>
</tr>
</tbody>
</table>

*Examples of minimum scattering angles for structural metals*
Forward scattering for coherent scatterers

<table>
<thead>
<tr>
<th>λ=1Å</th>
<th>n=1</th>
<th>Largest d-spacing [Å]</th>
<th>Smallest 2θ [°]</th>
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*Examples of minimum scattering angles for structural metals*
Angular distribution of the scattered neutrons
Quantifying the scattering

- Close, Distance = 0 cm

- Far, Distance = 55 mm

- Close - Far

\[
\frac{I_{\text{Transmitted}} + I_{\text{Scattered}}}{I_0}
\]

\[
\frac{I_{\text{Transmitted}}}{I_0}
\]

\[
\frac{I_{\text{Scattered}}}{I_0}
\]
Quantifying the scattering: Coin

Close

Far

Close - Far

Close-Far
Quantifying the scattering: Coin

Close

Gaussian fit

Corrected
Correcting the scattering: Coin

![Graph showing thickness and radial position with uncorrected and corrected data.]
The «black body» approach
Camera-detector MIDI
(medium FOV)

FOV between 15 and 3 cm
Mirror back-scattering
Scintillator substrate scattering
Special guest ...

O’Ref

(= Optical Reflexion)
How much do they contribute?

Elimination or Correction

WANTED

Sim Scatt

REWARD: 2%

Elimination or Correction

WANTED

Al Scatt

REWARD: 1%

Elimination or Correction

WANTED

O’Blurry

REWARD: < 0.5%

Elimination or Correction

WANTED

O’Ref

REWARD: 2%

Up to 15-20% depending on setup !!!
Recomendation for the experiments

- Black body grid in front of the sample

- Dose correction region inside the grid

- **For tomographies**: Image of BB with open beam and image of BB at 25 different angles

- **For time series**: Image of BB with open beam and image of BB at one reference state
The correction process

0 Nomenclature

- $I^*_n$: Measured sample image
- $I_n$: True sample image
- $I_{n, BG}$: Background of sample image
- $I_{n, n}$: Normalised true sample image
- $I_{n, BG}$: Normalised background of sample image
- $D$: Dose operator (average value of normalising region)
- $I_{DC}$: Dark current image
- $I_{OB}$: Open beam image
- $I_{n, BB}$: Sample image with black body pattern (mean pattern transmission $\tau_{BB} \in (0,1)$)
- $I_{OB, BB}$: Open beam image with black body pattern (mean pattern transmission $\tau_{BB} \in (0,1)$)

\[
\frac{I_n}{I_{OB}} = \frac{I^*_n - I_{DC} - I_{n, n, BB}^{BG}}{D\left(I^*_n + \left(\frac{1}{\tau_{BB}} - 1\right)I_{n, n, BB}^{BG} - I_{DC}\right)\tau_{BB}}
\]

\[
\frac{I_{n, n}}{I_{OB, BB}} = \frac{D(I^*_n - I_{DC} - I_{n, n, BB}^{BG})}{D\left(I_{OB, BB} + \left(\frac{1}{\tau_{BB}} - 1\right)I_{OB, BB}^{BG} - I_{DC}\right)\tau_{BB}}
\]

\[
\frac{I_{OB}}{I_{OB}^*} = \frac{D\left(I^*_n - I_{DC} - I_{n, n, BB}^{BG}\right)}{D\left(I_{n, BB} + \left(\frac{1}{\tau_{BB}} - 1\right)I_{n, BB}^{BG} - I_{DC}\right)\tau_{BB}}
\]
Example – Lead Sphere Tomo

Without BB correction

With BB correction
Neutron imaging methods @ PSI

Classic neutron imaging methods
- Radiography
- Tomography
- Real-time imaging
- Stroboscopic imaging

Advanced neutron imaging methods
- Energy selective imaging
- Neutron grating interferometry
- Diffraction imaging

Under preparation:
- Imaging with polarized neutrons (BOA)
- Project neutron microscope
- N/X data fusion
Neutron Imaging: Improvement in spatial resolution

- Pixel size [micro-meter]
- Field of view [mm]

- MAXI
- MIDI
- MICRO
- n-Microscope
- TOMCAT
Diffractometer mit 3 koaxialen Antriebsachsen. Winkelgenauigkeit +/- 1 Bogensekunde

Neutron Microscope (layout)

Prototype already tested – real device ready since May 2016
MgB$_2$ multifilament wire in Ni casing

- 4-binned, 5.2 um pixel size,
- 180 projections
- about 4.5 hours acquisition time

Sample courtesy of Ch. Scheuerlein (CERN)
The Future of Neutron Imaging

• More access to prominent and useful neutron sources (ILL?)

• New installations with high performance

• Further methodical progress, oriented to the user profile

• Qualification of new and young operators of the facilities with respect to image processing and quantification

• Standardization of the processes to attract more industrial customers
New imaging facilities under development (or upgrade)

- **Argentina**: new reactor Buenos Aires
- **Czech Republic**: beam line in Rez
- **China**: CARR reactor with 2 beam lines
- **France**: IMAGINE at Saclay reactor
- **Europe (ILL)**: D50 cold guide shared with reflectometer
- **Norway**: beam line upgrade at Halden reactor
- **Netherlands**: project FISH
- **Jordan**: new reactor under construction – with NI facility
- **South Africa**: upgrade to SANRAD-2
- **Russia**: improvements at Dubna pulsed reactor
- **South Korea**: upgrades
- **Hungary**: improvements and upgrades → «club members»
Neutron Imaging @ Spallation Sources

- **SINQ**: NEUTRA, ICON, *BOA* operational
- **JPARC**: RADEN 2015
- **ISIS**: *IMAT* 2016
- **SNS**: *VENUS* 2018 ?
- **ESS**: *ODIN* 2019 ?
Outlook: Trends in Neutron Imaging

• colder neutrons
• energy selectivity → pulsed sources, higher E - resolution
• polarized neutrons
• combination of imaging with diffraction
• symbiosis of neutron with X-ray imaging
• highest possible intensities → higher temporal and spatial resolution
Smartphone – Tomography mode

X-rays

neutrons
Thanks to: NIAG Team (2/2017)
Visit PSI and Switzerland ... for collaboration and utilization