Neutron imaging and tomography at the IFE Kjeller research reactor

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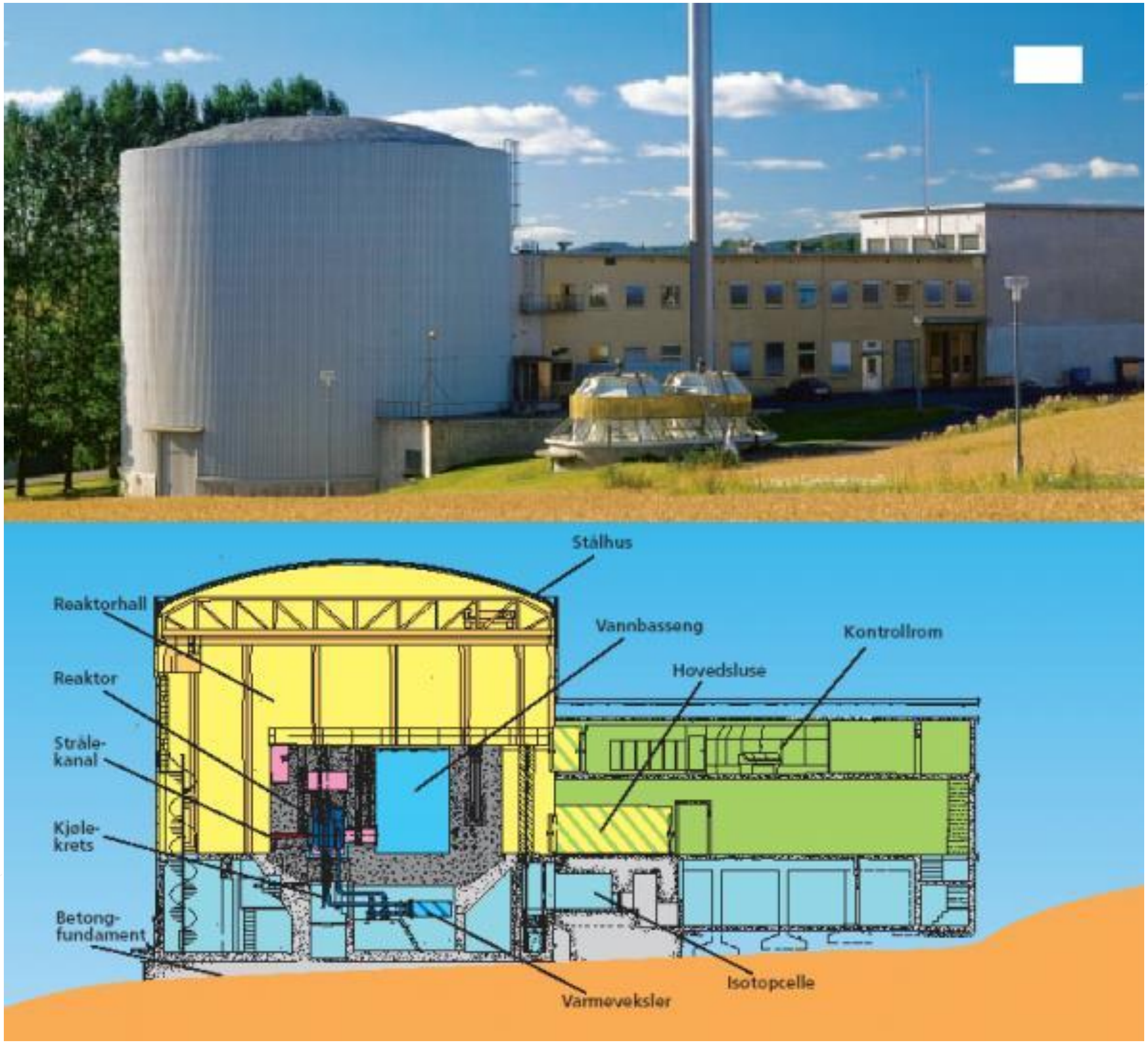
Institute for Energy Tecnology - IFE

- Located at Kjeller near Lillestrøm
- Operating two nuclear research reactors (Kjeller og Halden)
- Nuclear technology, materials & renewable energy, petroleum technology
- > 600 employees

The JEEP-II reactor at IFE, Kjeller

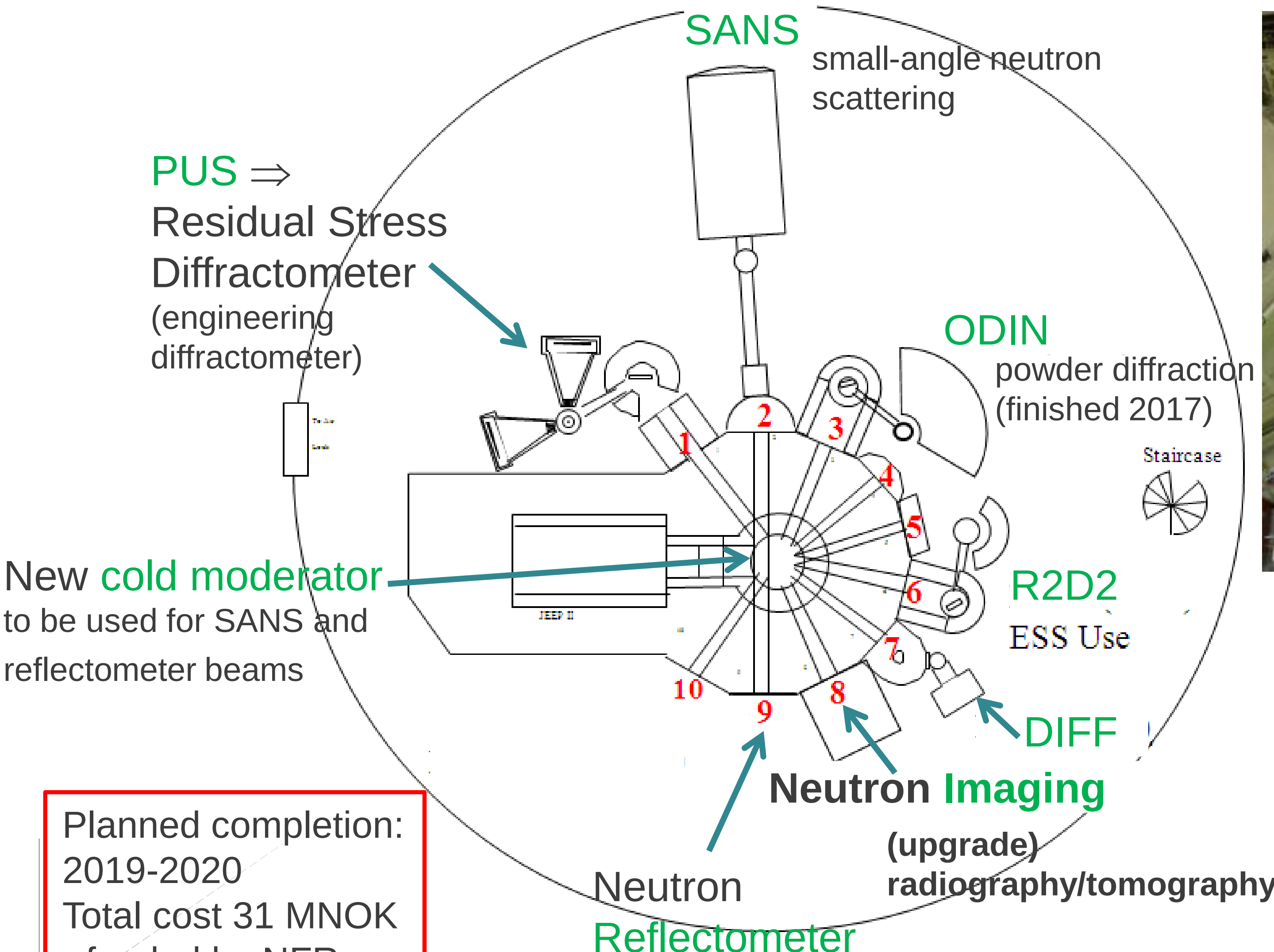


250 kg UO_2

D_2O moderated

2 MW thermal power

NcNeutron: New and planned instrumentation in the IFE reactor



Planned completion:
2019-2020
Total cost 31 MNOK
- funded by NFR

NcNeutron
NORWEGIAN CENTER FOR NEUTRON RESEARCH

Why use neutron scattering?

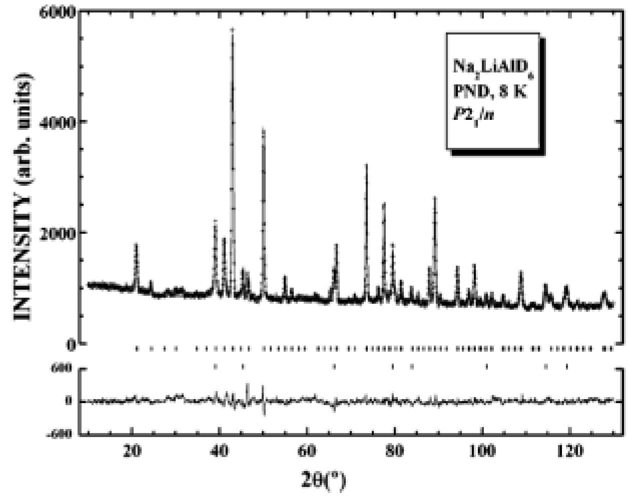
- Thermal neutron beams from fission or spallation sources have the same wavelength as interatomic spacings ⇒ can be used to find atomic structure of materials
- Kinetic energy of neutrons comparable to energy level separation in crystalline materials ⇒ can be used to study dynamics, i.e. what atoms do
- Neutron beams are very penetrating ⇒ can study properties deep inside an object or inside furnaces, cryostats or sample cells
- Neutrons can “see” magnetic structures and magnetic ordering
- Can be used to study samples in solvent (e.g. water) – organic or biomolecules
- Neutron beams are particularly sensitive to the light elements (H, C, O, …)

Challenge:

- Need a reactor neutron source or spallation source in order to get neutron beams
- Very few neutron sources available in Northern Europe, IFE-reactor the only one in the Nordic countries
  BUT: European Spallation Source – ESS – will come in Lund (SE) in 2023 !!

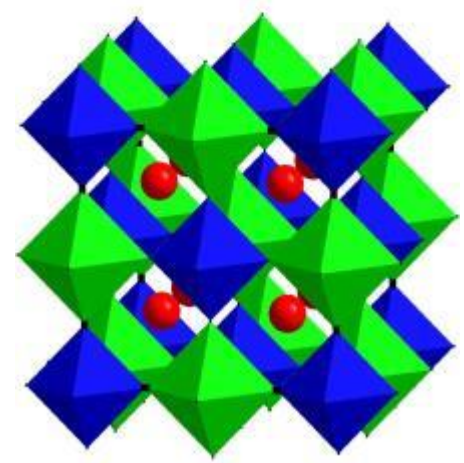
Typical neutron scattering instrument:

PUS – high-resolution powder diffractometer

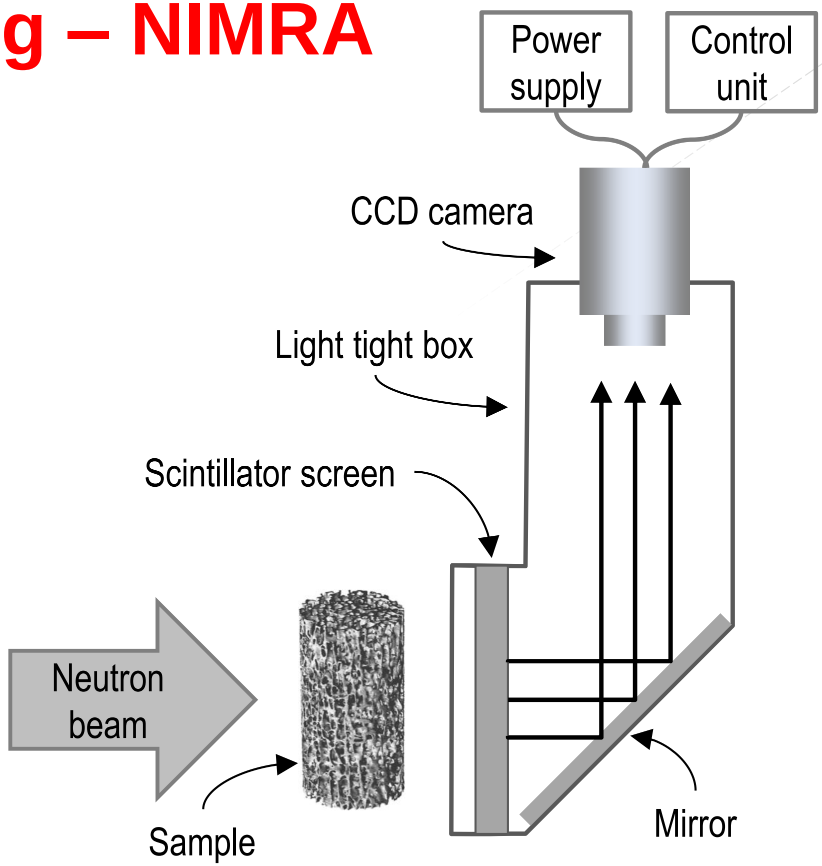


- 2 detector units, each 7 position sensitive detectors
- λ = 0.75 – 2.60 Å (typically 1.55 Å)
- T = 9-1300 K, controlled atomsphere (0-8 bar)

- For powder samples: metal hydrides (H-storage), battery materials, magnetic materials



Upgrade: Neutron Imaging – NIMRA



NIMRA

Some applications:

- Energy materials and systems (hydrogen storage, fuel cells, batteries)
- Concrete
- Porous materials (clays)
- Welding - cracks

- digital image acquisition system
- adapted to fit test samples with a variety of sizes
- rotating sample stage
- area of the neutron beam increased 15cm x 15cm
- expected resolution after upgrade ≈ 50 µm

X-ray imaging vs. neutron imaging

Main differences:

- Sensitivity to the various elements is different
- Beam penetration depth much larger for neutrons ⇒ thicker samples

1/e attenuation length:

	X-ray		Neutron	
	10 keV	30 keV	thermal	fast
SiO_2	210 μm	4.9 mm	3.50 cm	3.53 cm
Al_2O_3	159 μm	3.7 mm	2.64 cm	2.69 cm
H_2O	2.0 mm	31 mm	0.18 mm	0.18 mm

Use of neutron imaging:

H.K. Jensen et al., Prog. Nucl. Energy 72, 55 (2014)

Copyright:

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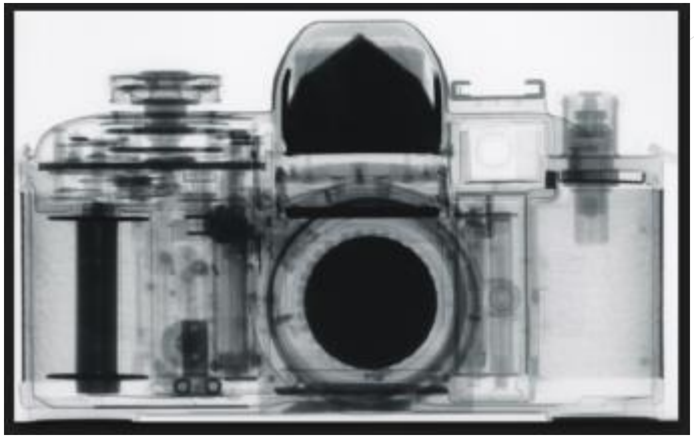

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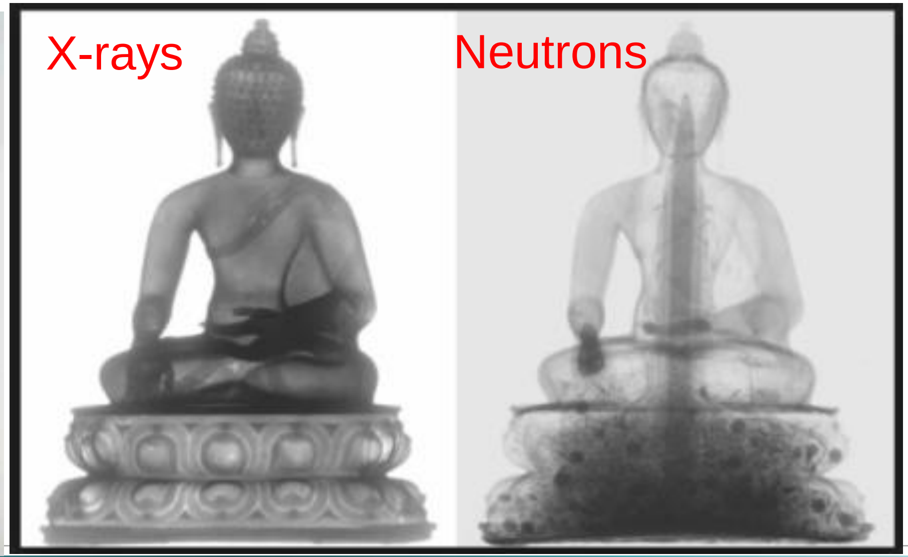

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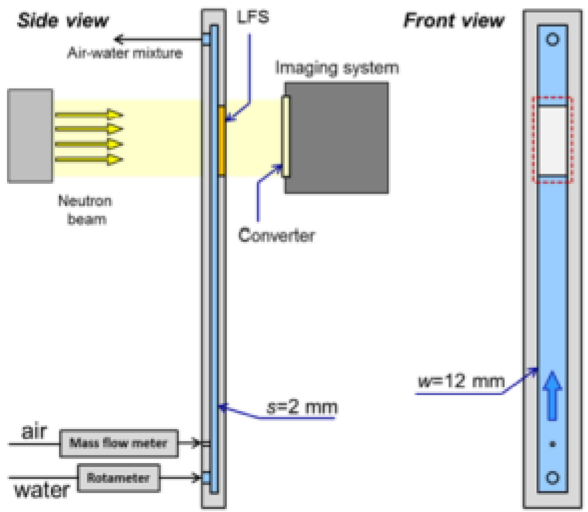
Neutron imaging:
examples from recent literature

Examples: Two-phase flow using neutron imaging



Air-water two-phase flow in channel (Ito et.al. 2015)
Resolution 0.16 mm, 200 fps

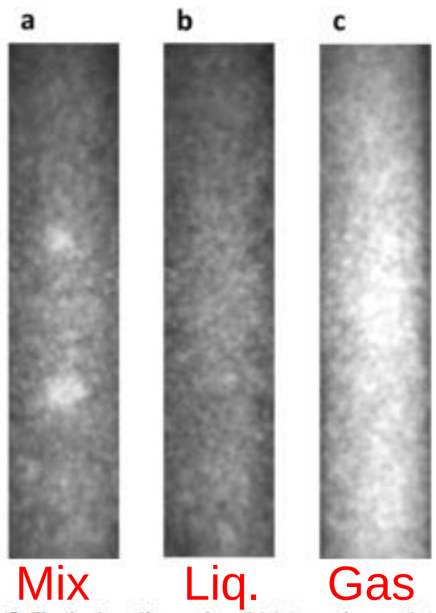
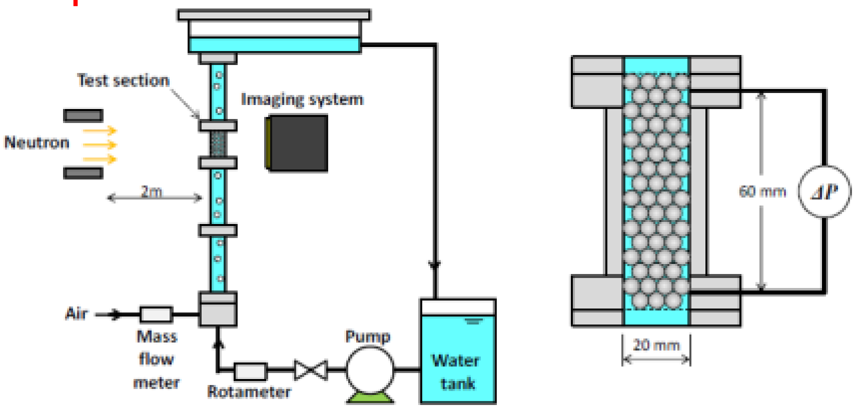
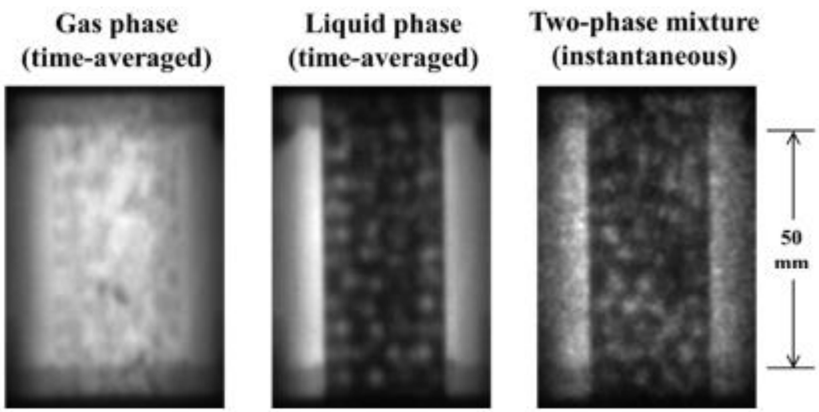


Fig. 5. Typical radiographs of (a) two-phase mixture, (b) liquid phase and (c) gas phase,

In a packed bed



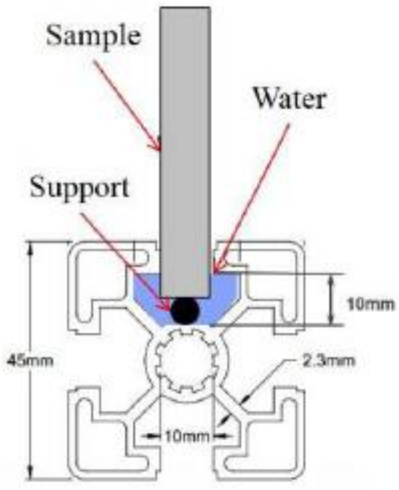


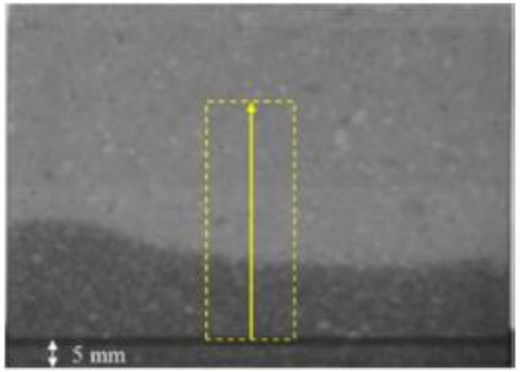
Ito & Saito 2015
Compared imaged void fraction to pressure drop

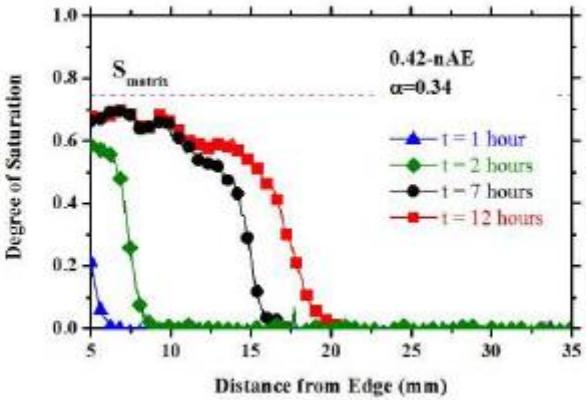
Fig. 3. Typical radiographs for the gas phase, the liquid phase and the two-phase mixture in the packed bed of spheres.

Water transport and saturation in cement based mortar

Lucero et.al. 2015



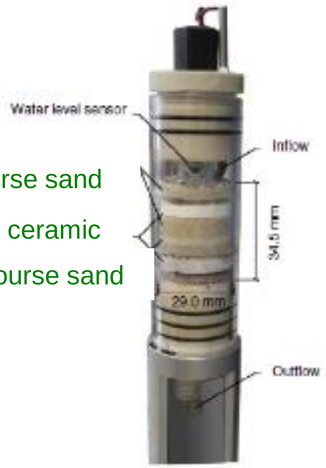




Moisture profile of mortar vs. time

Water-air redistribution in porous system (ceramic + coarse + medium coarse sand)

Sacha et al. 2015



course sand

fine ceramic

medium course sand

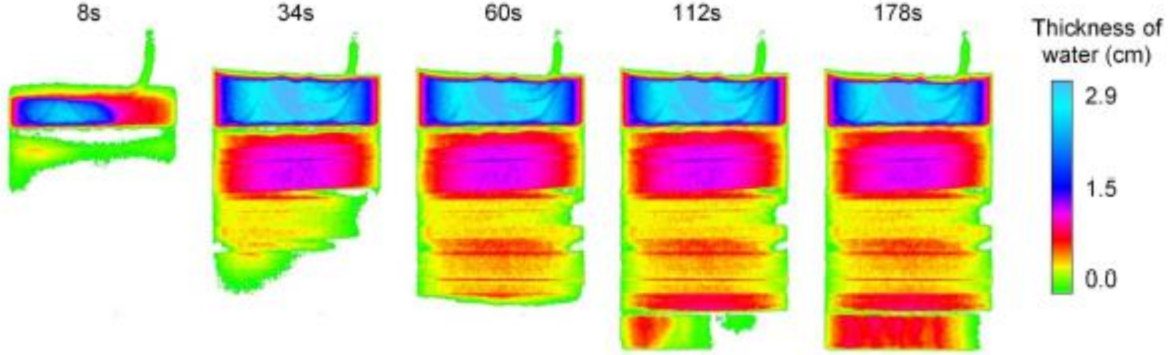


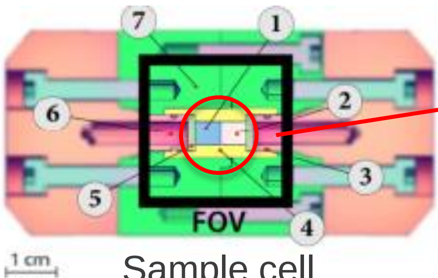
Fig. 2: A sequence of neutron radiography images illustrating the process of progress of the wetting front at the start of infiltration

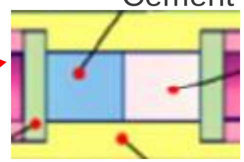
Pixel resolution 45x45 μm^2, 0.1 fps

C. Lucero et al., Physics Procedia 69 (2015) 542
J. Sacha et al., Physics Procedia 69 (2015) 530

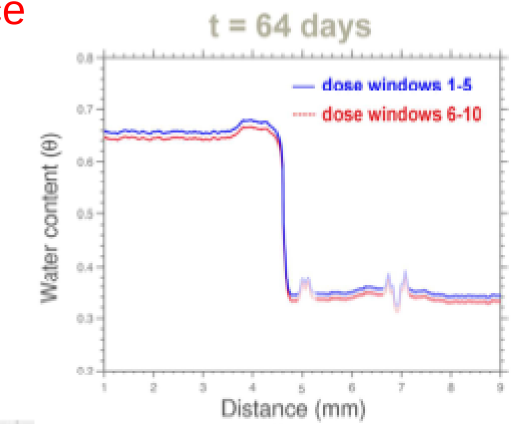
Quantification of water content across a cement-clay interface

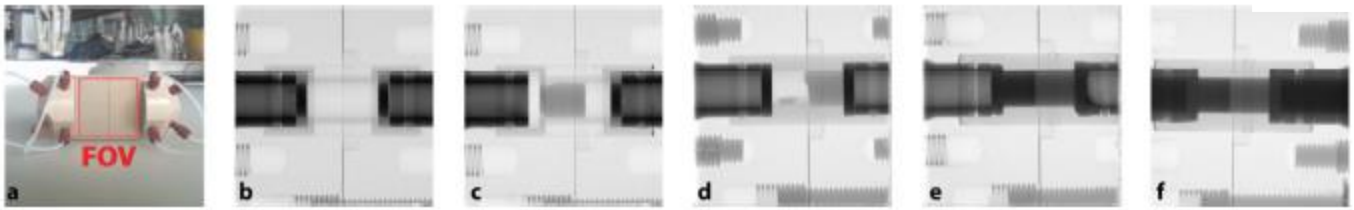
Shafizadeh et al. (2015)





Sample cell



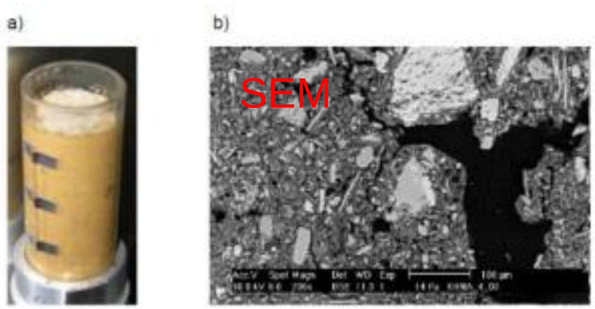


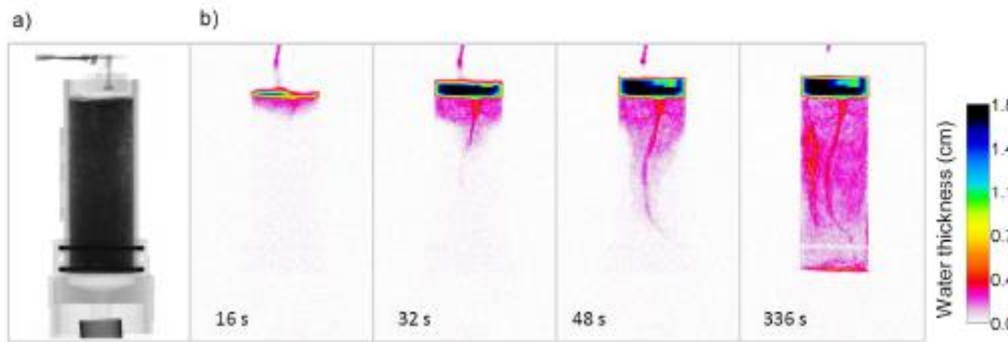
Empty cell | Dry cement | Dry clay | Cement-clay

t= 64 days | t= 104 days

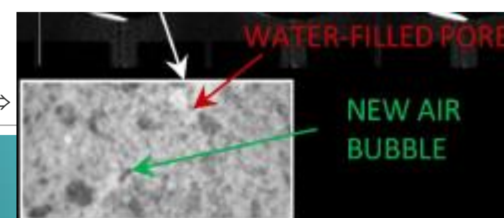
Preferential flow in a near-saturated intact soil sample

Snehota et al. 2015





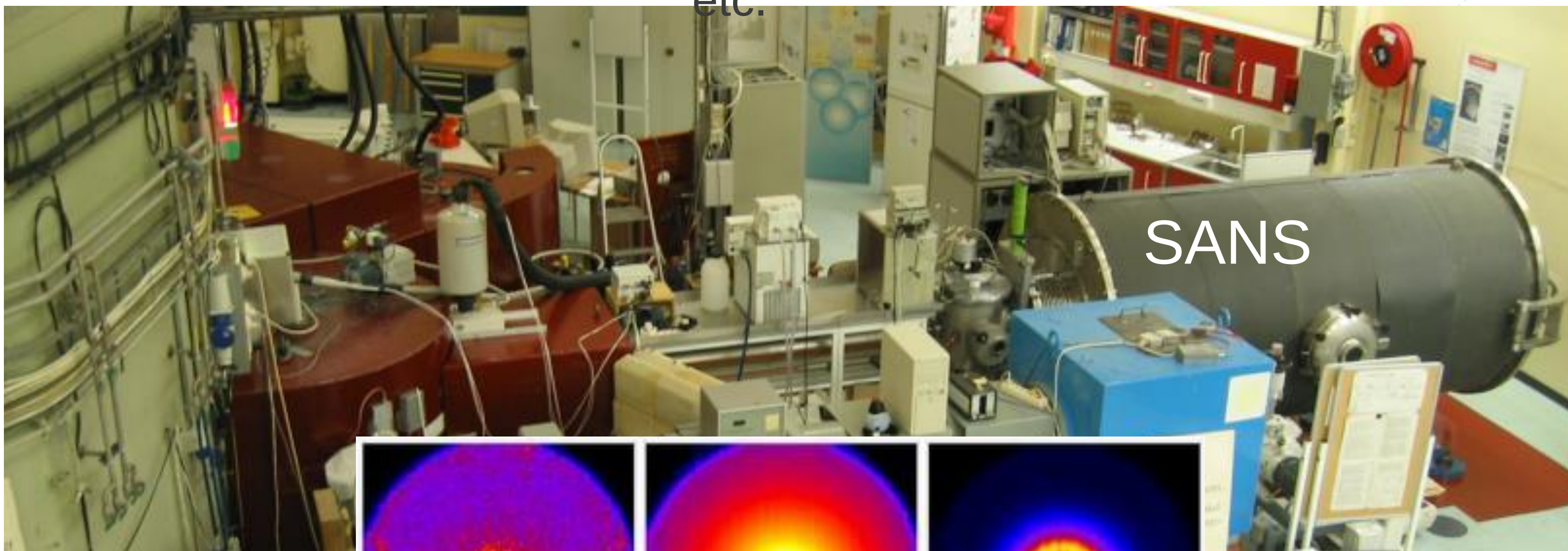
Water ~ white
Air ~ dark grey ⇒



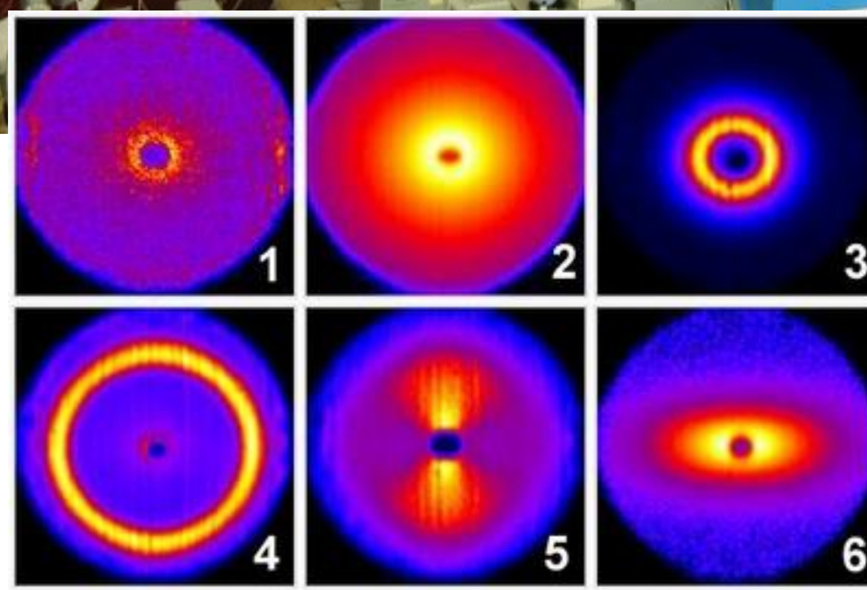
A. Shafizadeh, Physics Procedia 69 (2015) 516
M. Snehota et al., Physics Procedia 69 (2015) 496

Other techniques: **SANS – Small-Angle Neutron Scattering**

For soft / nanoporous materials: polymers, nanoparticles in solution, fluids, gels etc.



Carbon nanotubes



Microemulsions

SANS:
Typical “particle”-size 10-100 nm

Layered silicate particles

Silver nanoparticle solution

⇒ Shape and size of nano-objects (1-100 nm)

Magnetic nanoparticles

New: Strain/stress measurements

Residual Stress Diffractometer - NEST

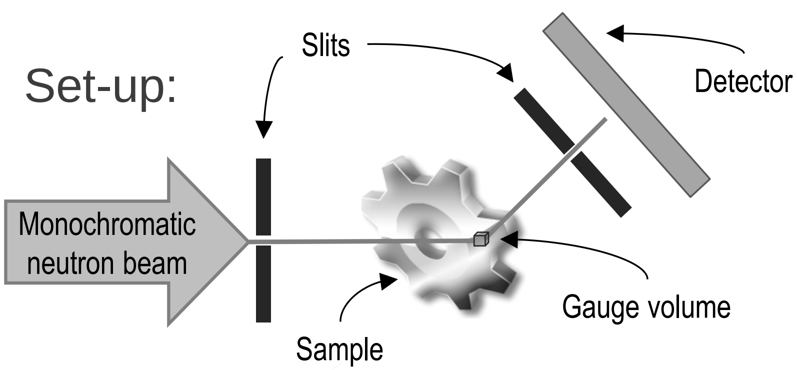
Neutrons beams very penetrating

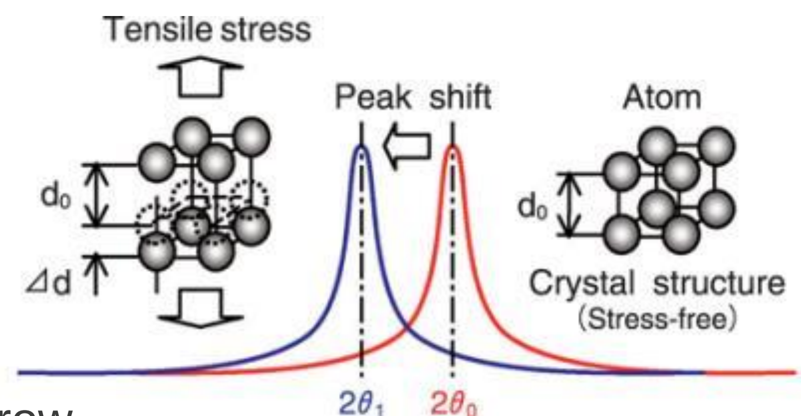
⇒ can probe the strain deep inside thick samples

Beam transmission:

Metal	**Neutron** (1.0 Å) Sample **tickness=100 mm** Intensity ratio **I/I_0**	**Neutron** (1.0 Å) **t=10 mm** **I/I_0**	**X-rays** (1.0 Å) **t=1 mm** **I/I_0**
Mg	0.983	0.998	0.021
Al	0.923	0.992	0.008
Fe	0.301	0.887	$4.2 \cdot 10^{-14}$

Set-up:





- Use narrow neutron beam and narrow detector window
- Scan beam-spot across sample volume
- Finished 2020

Strain:

$\varepsilon = \Delta d/d = -\cot\theta \; \Delta\theta$

Summary

- Neutron imaging / tomography can be a useful tool for studying porous materials and flow in pores
- Neutrons are more strongly attenuated by light elements, e.g. water, than by heavy elements – e.g. rocks
- At IFE, Kjeller a new instrument for neutron imaging is currently under construction – **input from potential users wanted!**
- Also other instruments in the new **NcNeutron** research center can be useful for study of micro- and nano-porous materials (SANS) or fracturing of materials (NEST instrument – finished 2020)

The NcNeutron team:
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Stefano Deledda
Christoph Frommen
Isabel Llamas-Jansa
Geir Helgesen

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