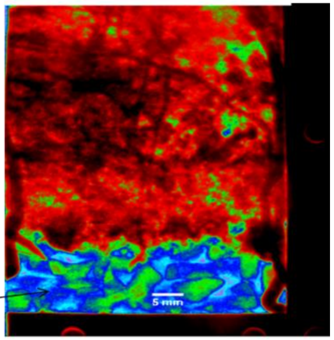
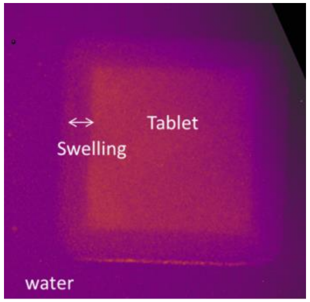
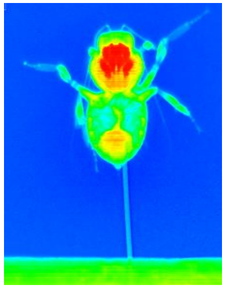
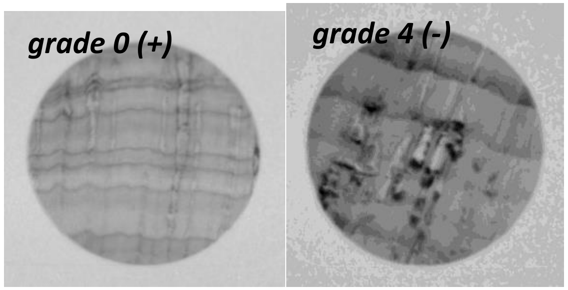
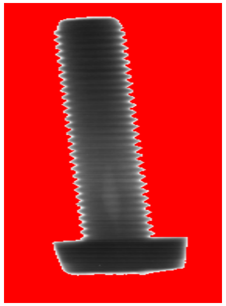
Neutron imaging and tomography



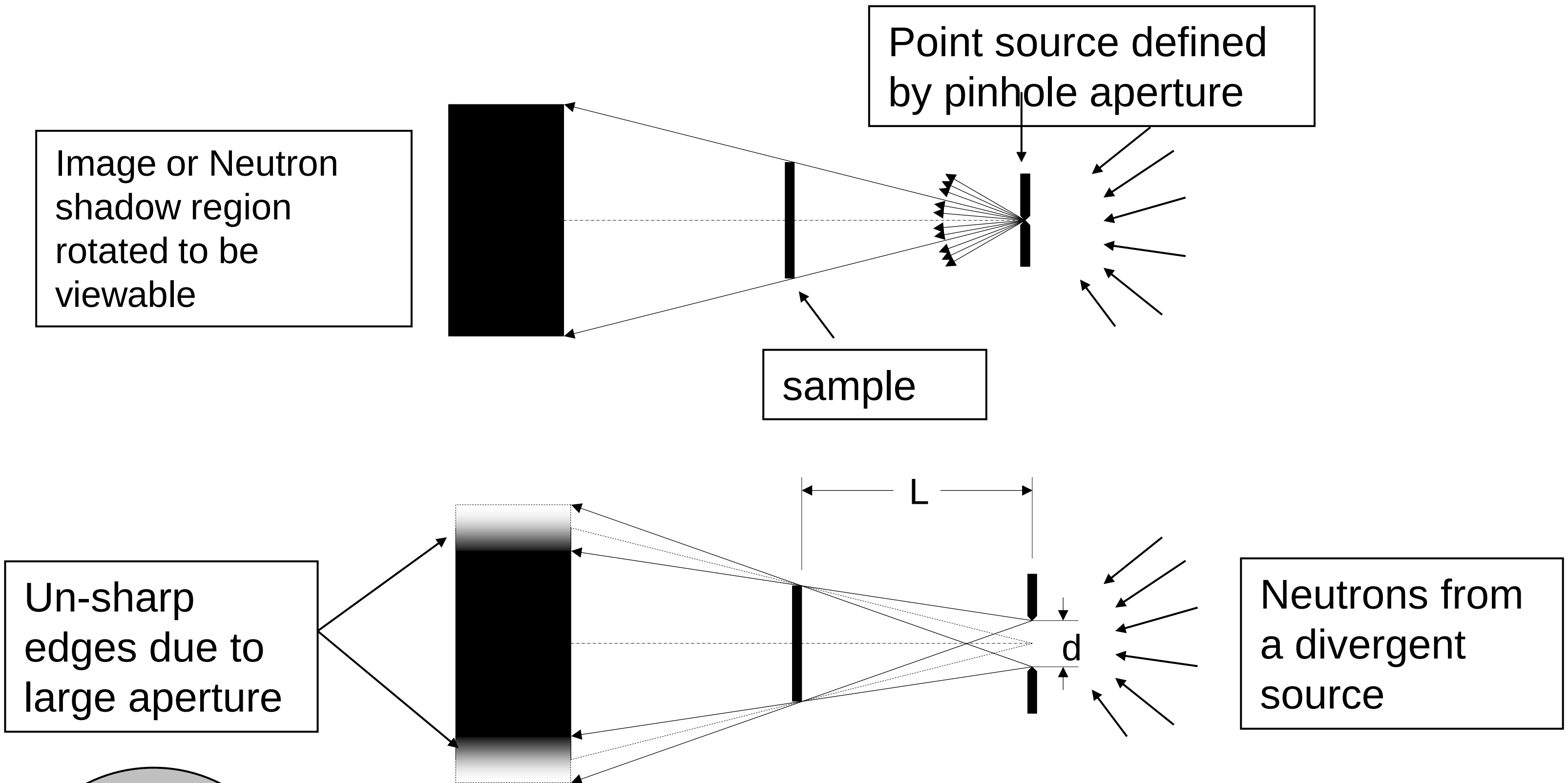


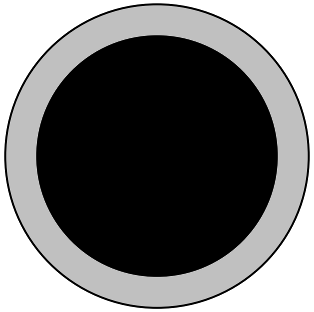






PRINCIPLE : TRANSMISSION IMAGING





Source has a finite size (~10mm)

Neutrons have wavelengths in the range 1-10A°

ABSORPTION CONTRAST

Measurement of the attenuation coefficient in transmission

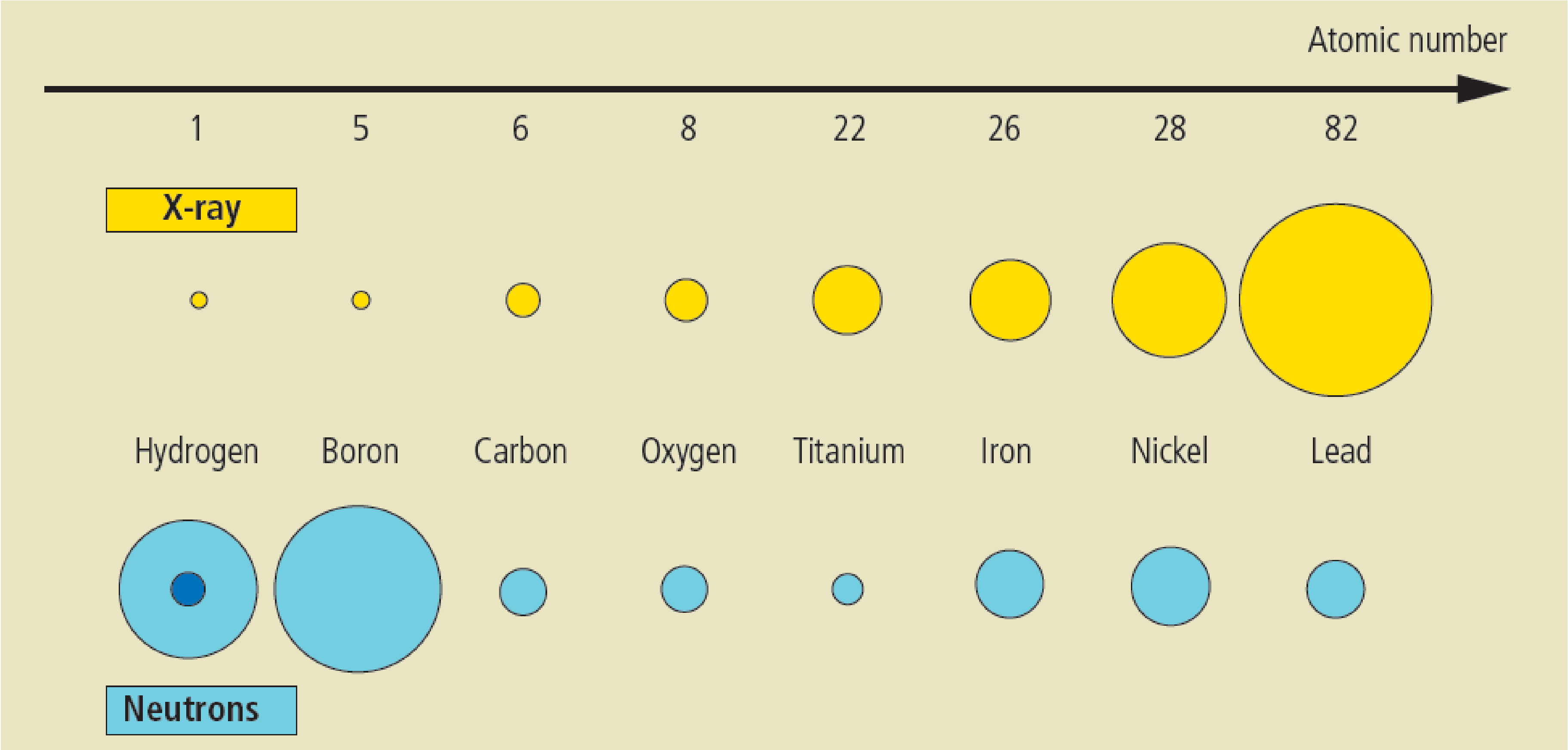
- Beer-Lambert's Law: $$I = I_0 \, e^{-\mu d}$$

Attenuation sources

- absorption
- incoherent scattering by nuclear spins (Hydrogen in particular)
  - possibility of isotopic labelling H/D
- diffraction by crystallites
  - Bragg edge imaging
- SANS
- Refraction effects

} Phase contrast imaging

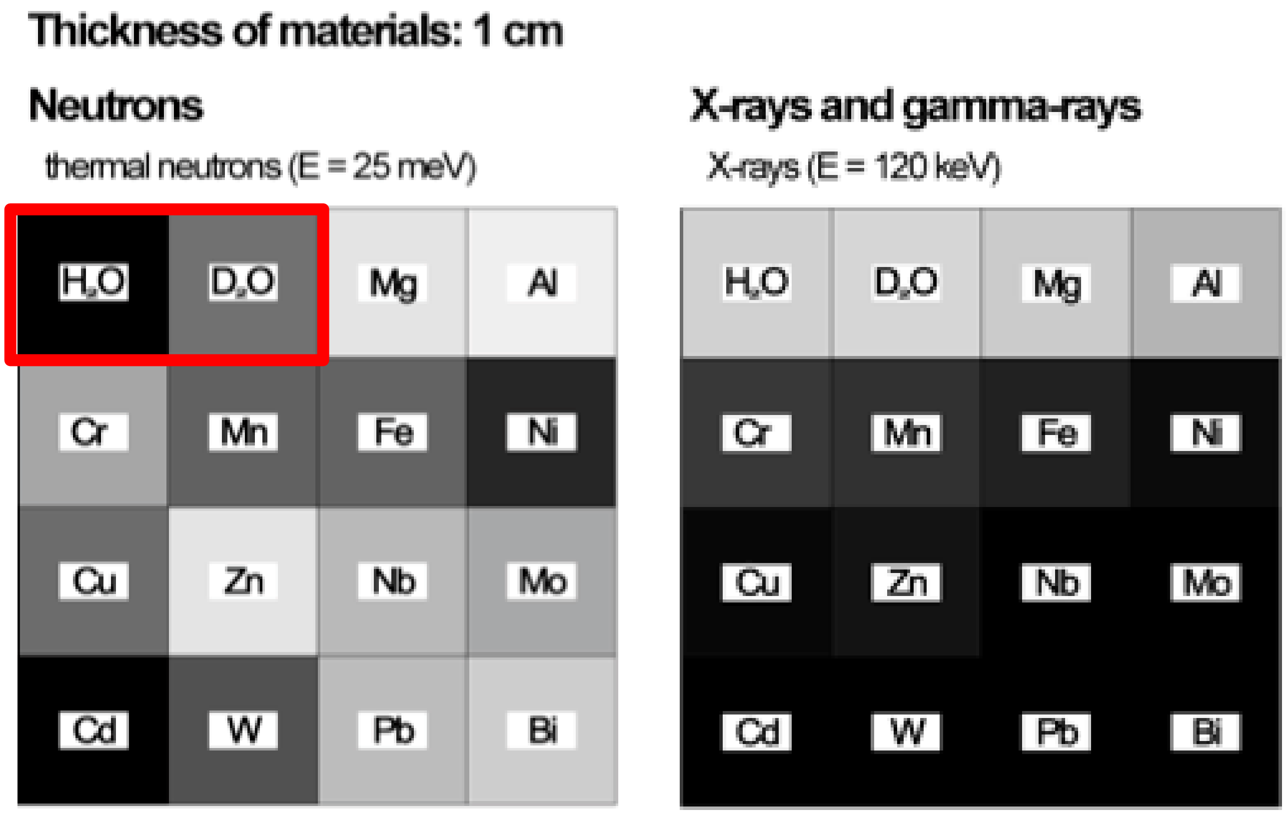
COMPARISON X-RAYS - NEUTRONS



STRENGTHS AND DRAWBACKS OF NEUTRONS

Very high sensitivity to Hydrogen

- High water sensitivity
- Quantitative



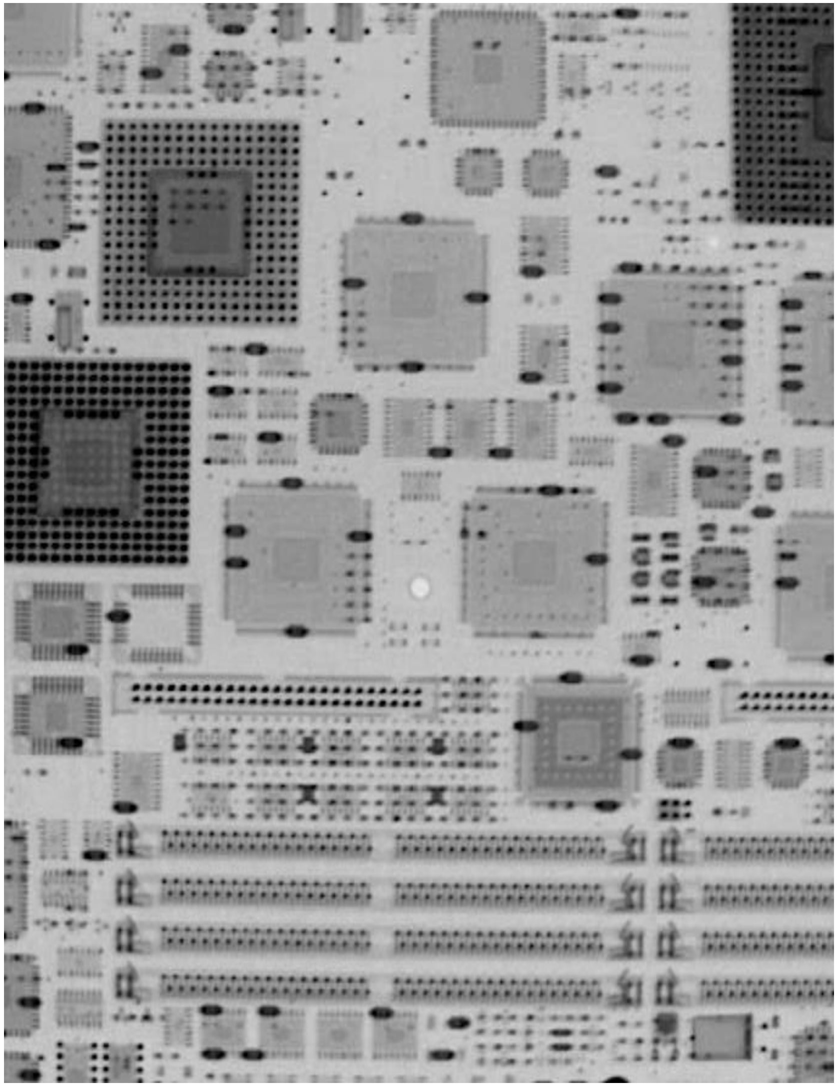
Strong penetration

Low flux (10^7 – 10^8 n/cm²/s)

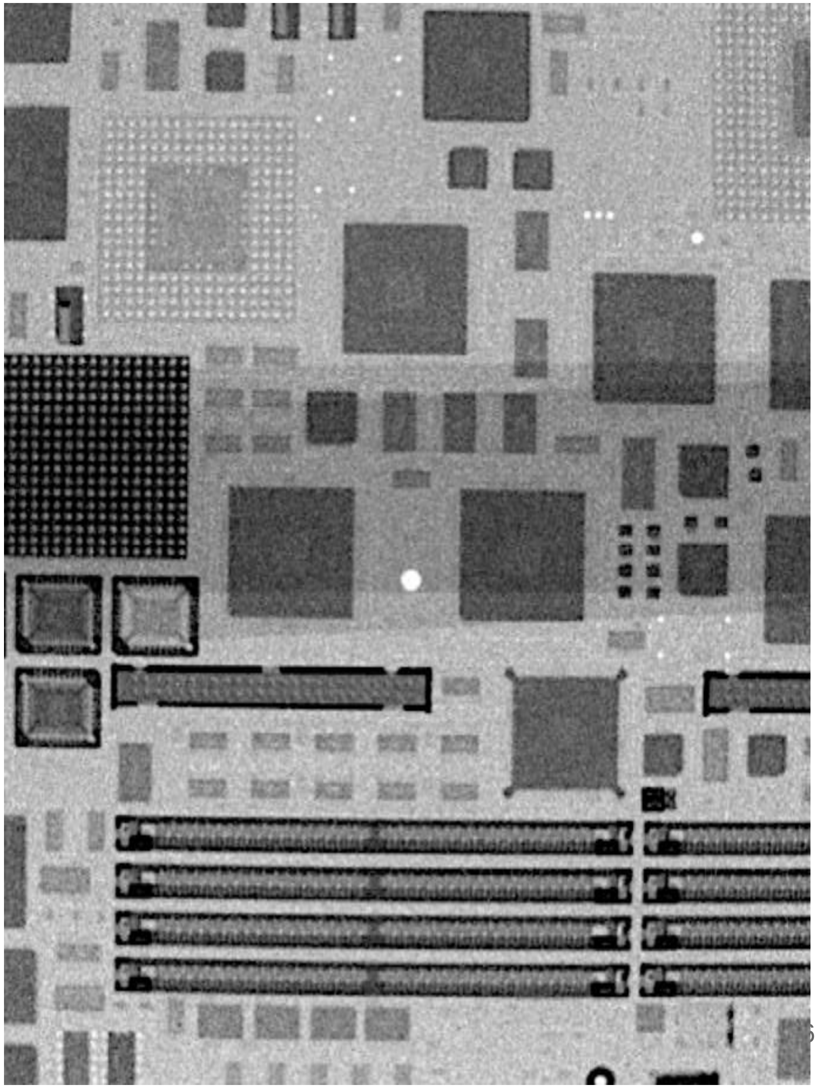
Limited spatial resolution : 10-20 µm (at very best)

EXAMPLES

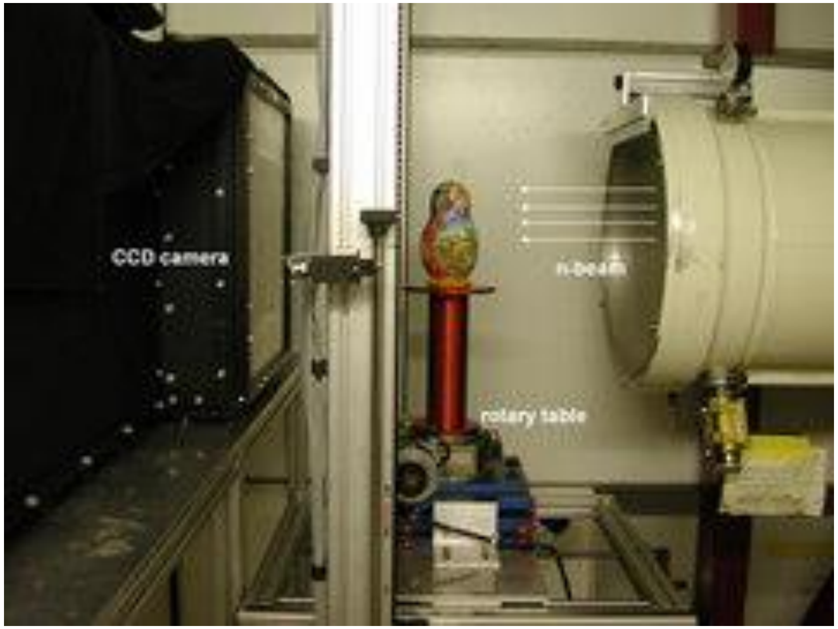
X-rays



neutrons

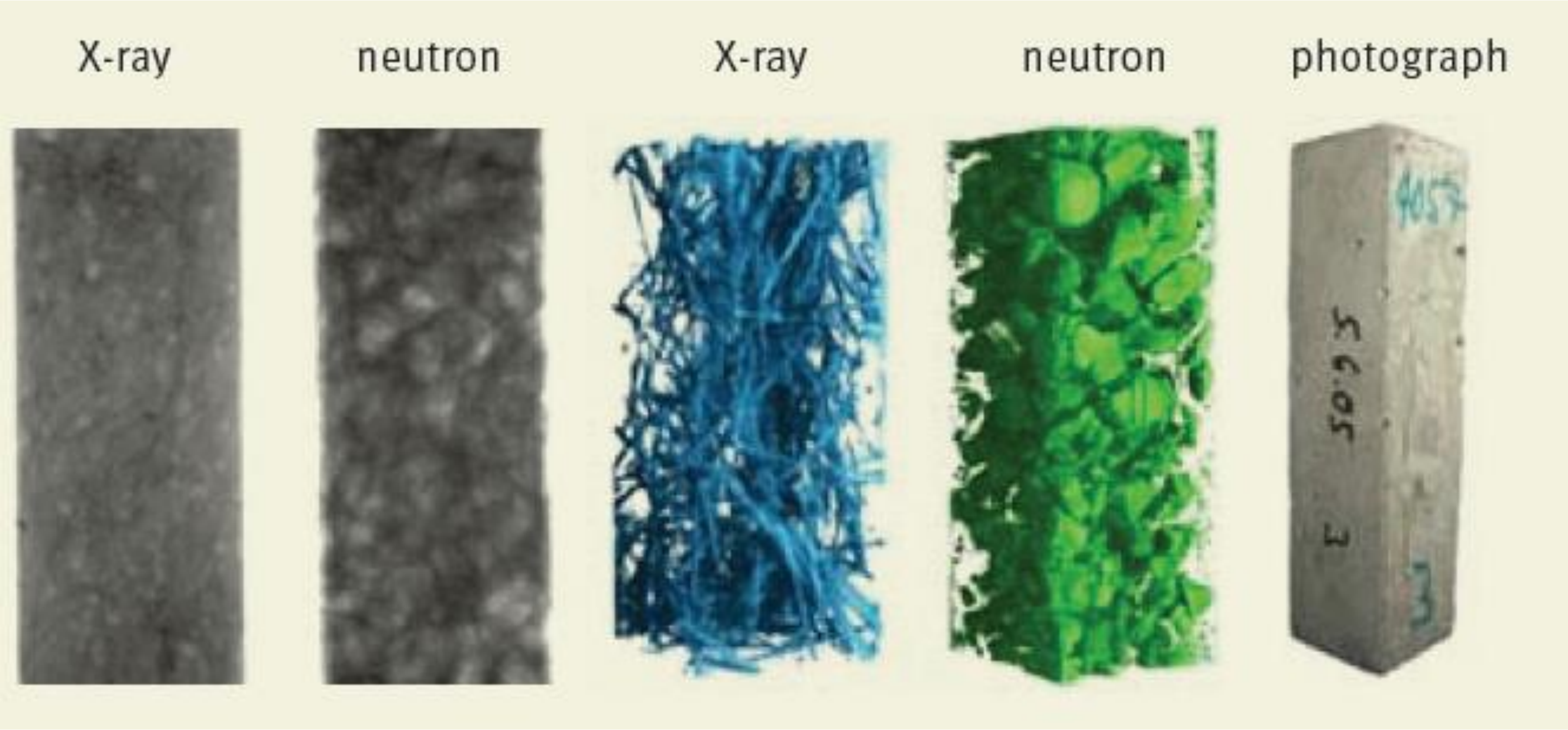


POSSIBILITY TO PERFORM TOMOGRAPHY



Tomography and radiographies performed at PSI

Transmission radiographs (left) and tomographic views (middle) made from a concrete sample embedded with steel fibres with X-ray and neutrons.
(credit Paul Scherrer Institute)



MORE ADVANCED TECHNIQUES

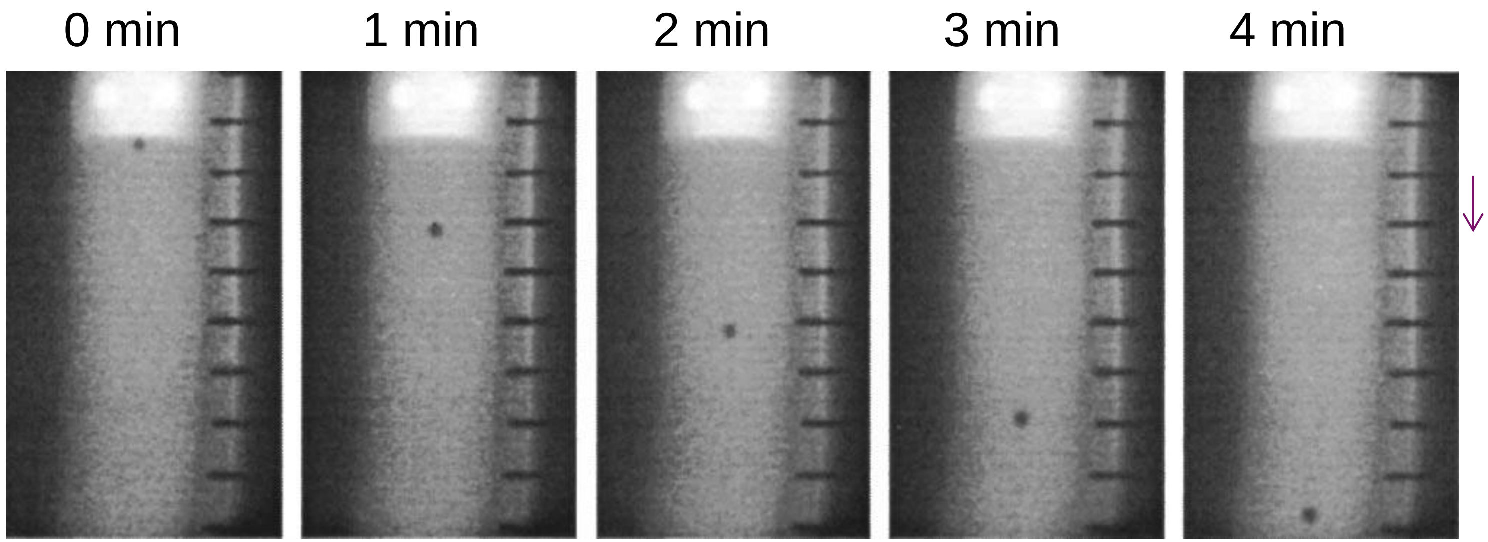
Stroboscopic Imaging

Bragg edge imaging

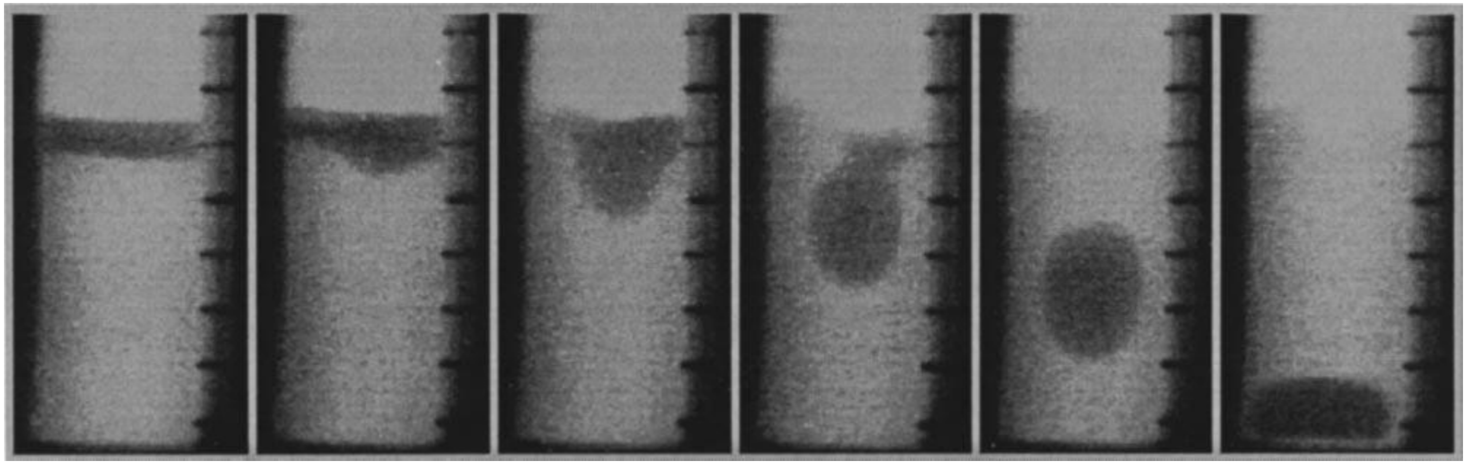
Phase Contrast Imaging

Polarized Neutron Imaging

TIME RESOLVED IMAGING



Falling Hf sphere in a silicate melt at 1600K

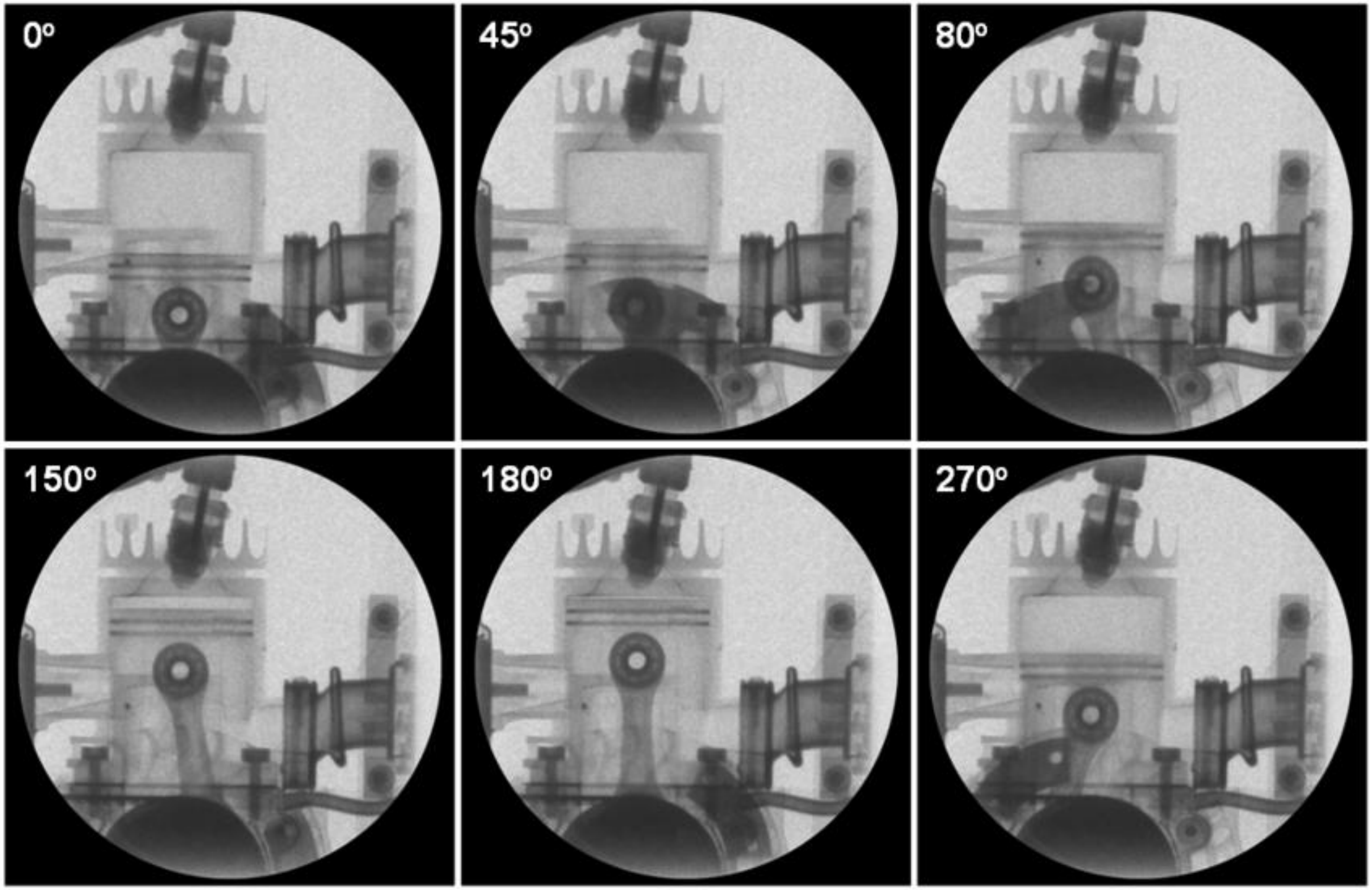


Falling brass melt in a silicate melt at 1450K

A. Kahler et al, RSI 2003 (performed on G45 at the LLB)

FASTER MEASUREMENTS

Stroboscopic (50µs resolution) (1000 images = 50ms)

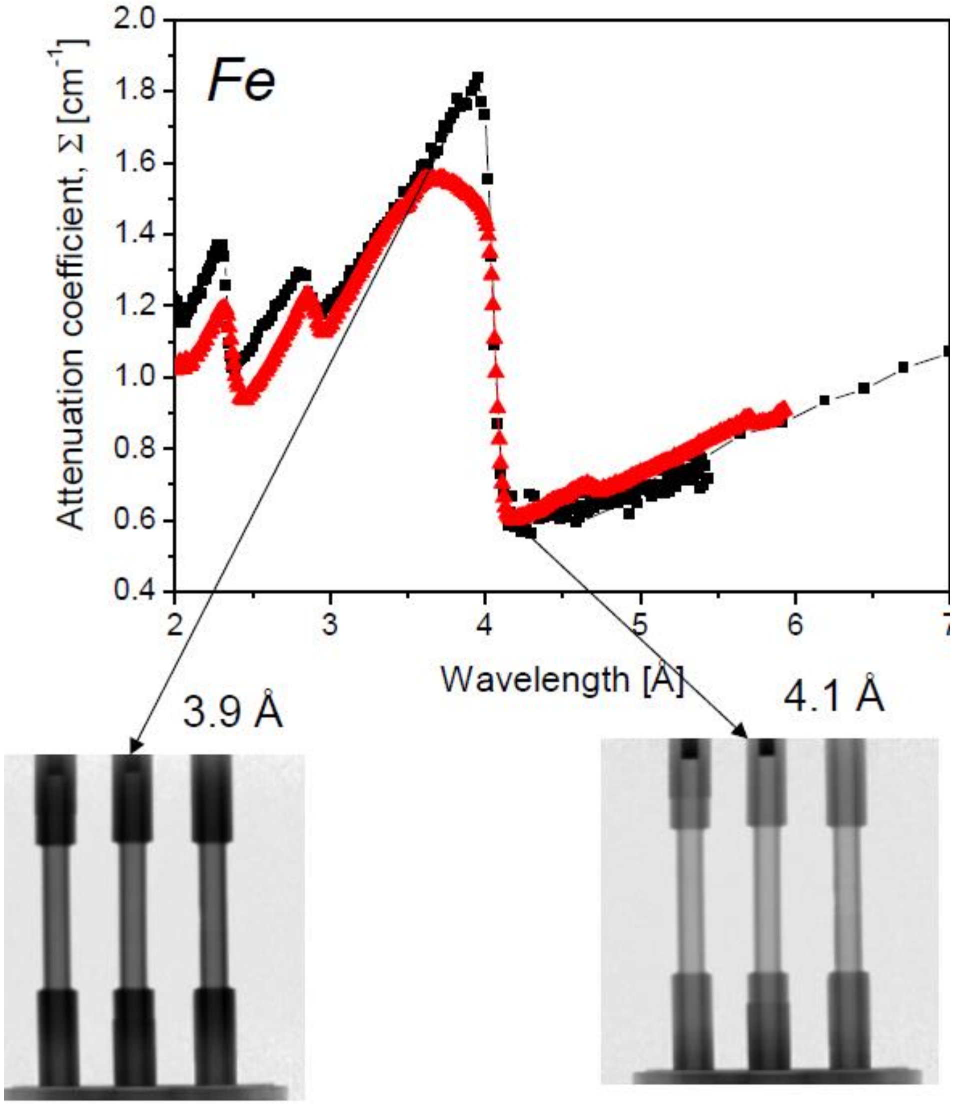


« ULTRA FAST » MEASUREMENTS

Single shot images at very best in 0.1s

- with low resolution 100-200µm
- In theory, tomogram feasible in 20s
  - No known example
  - In real life, there are often limitations due to the sample environment
  - People prefer measurements with better statistics
- At high resolution (20-50µm) : typical measuring time on the order of the hour
  - Losses due to fact that one uses cold neutrons to achieve such high resolution
  - Scintillators need to be thinner to achieve high resolutions
  - Geometry less favorable

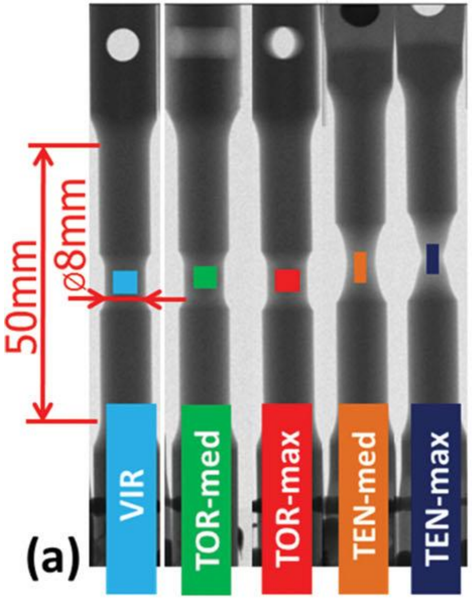
BRAGG EDGE IMAGING

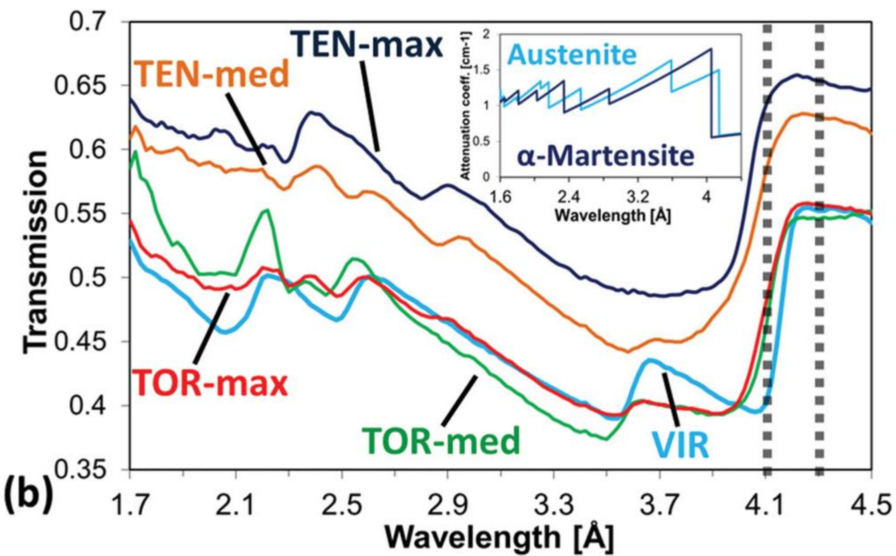


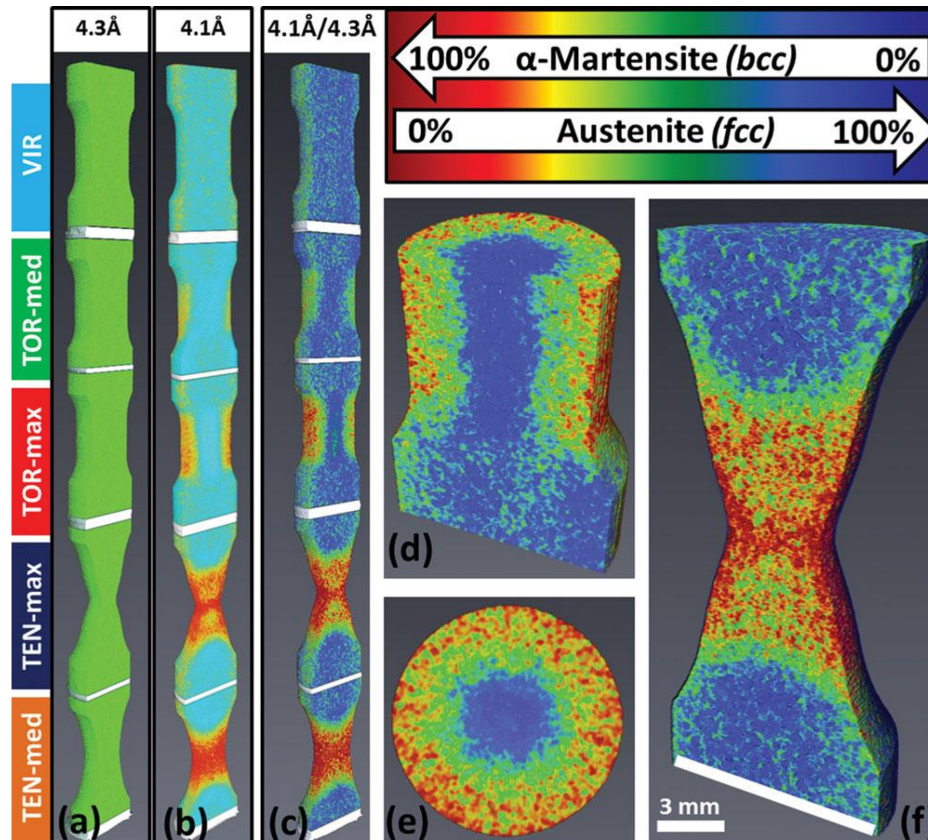
Courtesy of Prof. D. Penumadu, UTK and N. Kardjilov, HZB

ENERGY SELECTIVE NEUTRON IMAGING

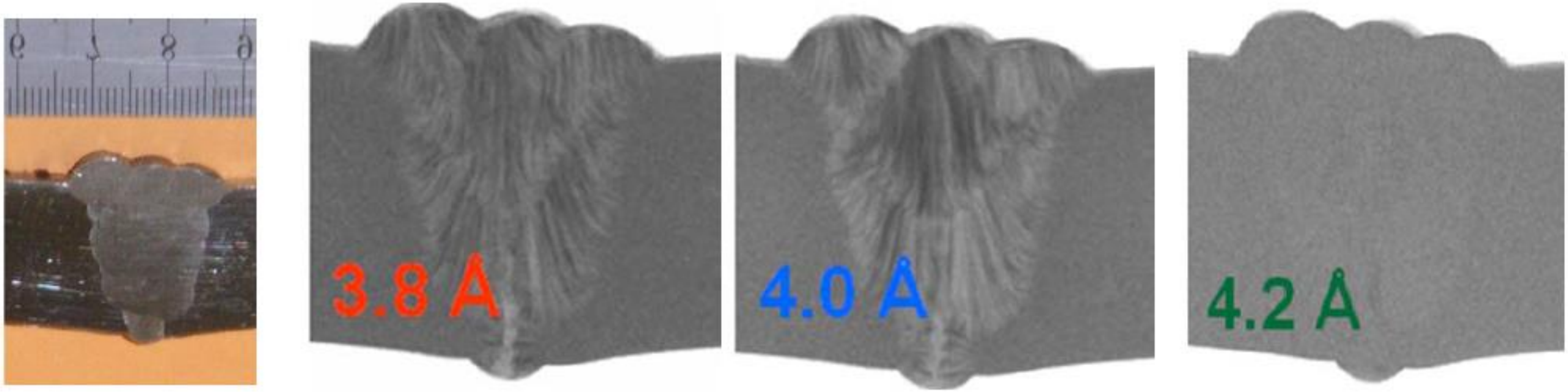
R. Woracek, Adv. Mater. 2014







BRAGG EDGE IMAGING : TEXTURE MAPPING

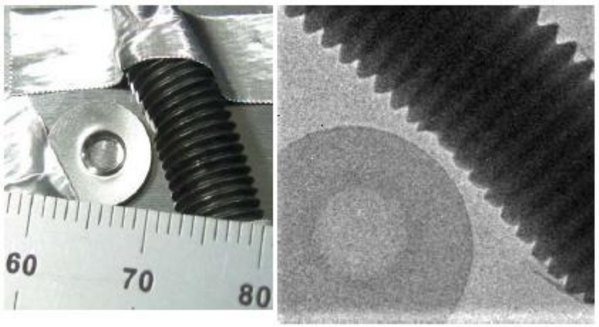


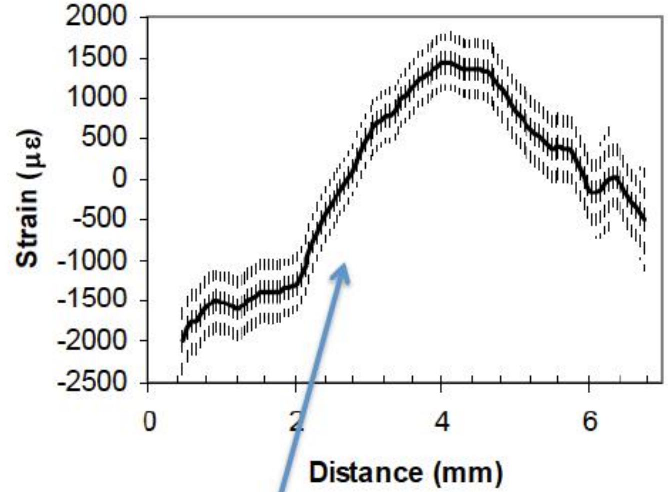
Kockelmann et al, NIM A, vol 578 (2007) 421

BRAGG EDGE IMAGING

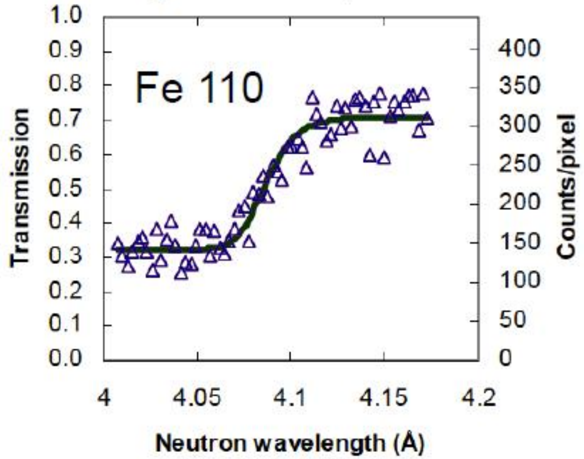
Bragg Edge Imaging

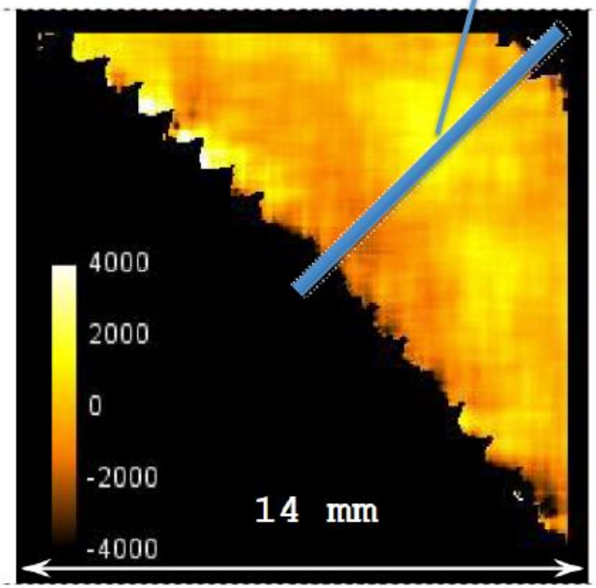
- Strain mapping od steel screw





5 min exposure, 1 μs time res.





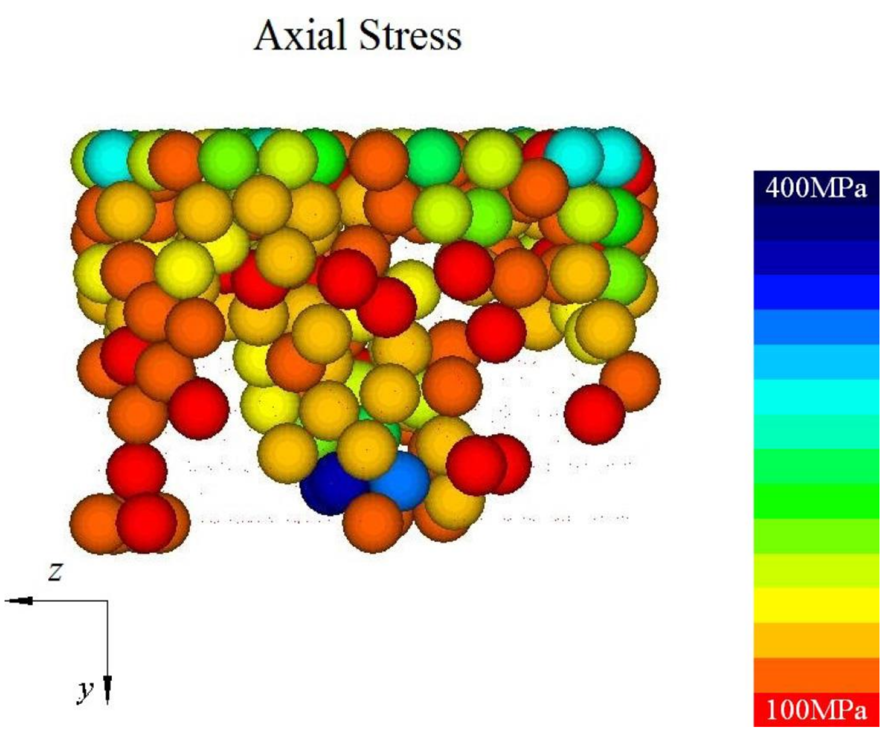
Strain map image of the steel screw. Strain values in μstrain

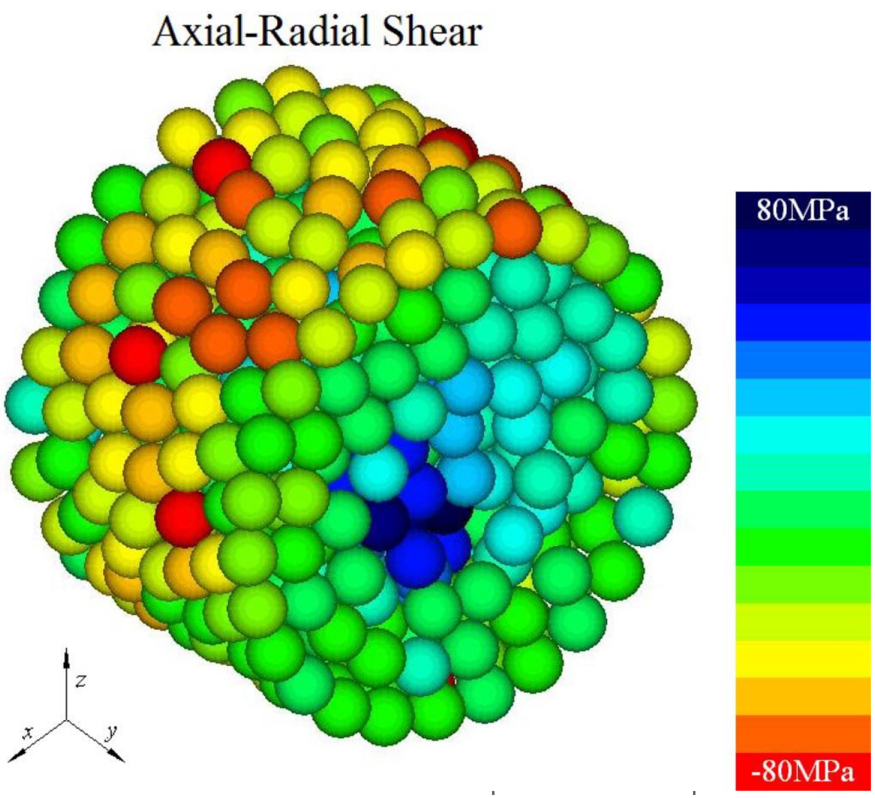
Hassina Bilheux

Tremsin et al., Journal of Physics, Conference Series 251 (2010) 012069

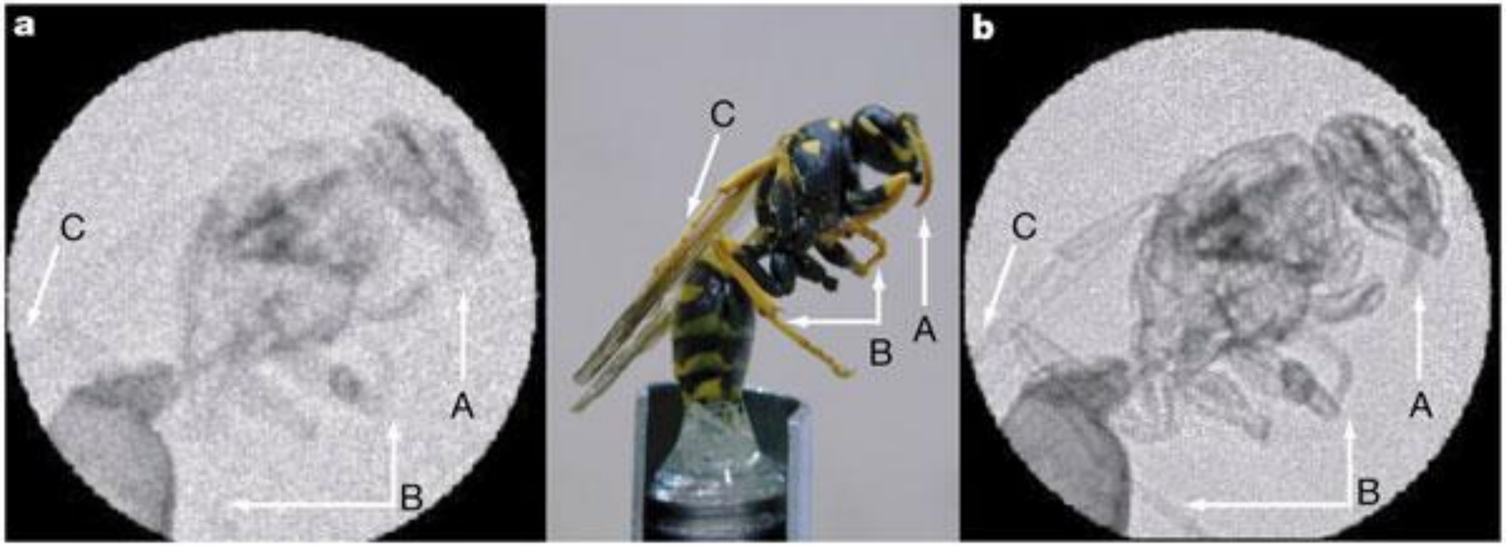
STRAIN FIELDS IN COMPACTED BEADS

Wensrich, Phys. Rev. E (2014)
Force chains in monodisperse spherical particle assemblies
(3mm beads)



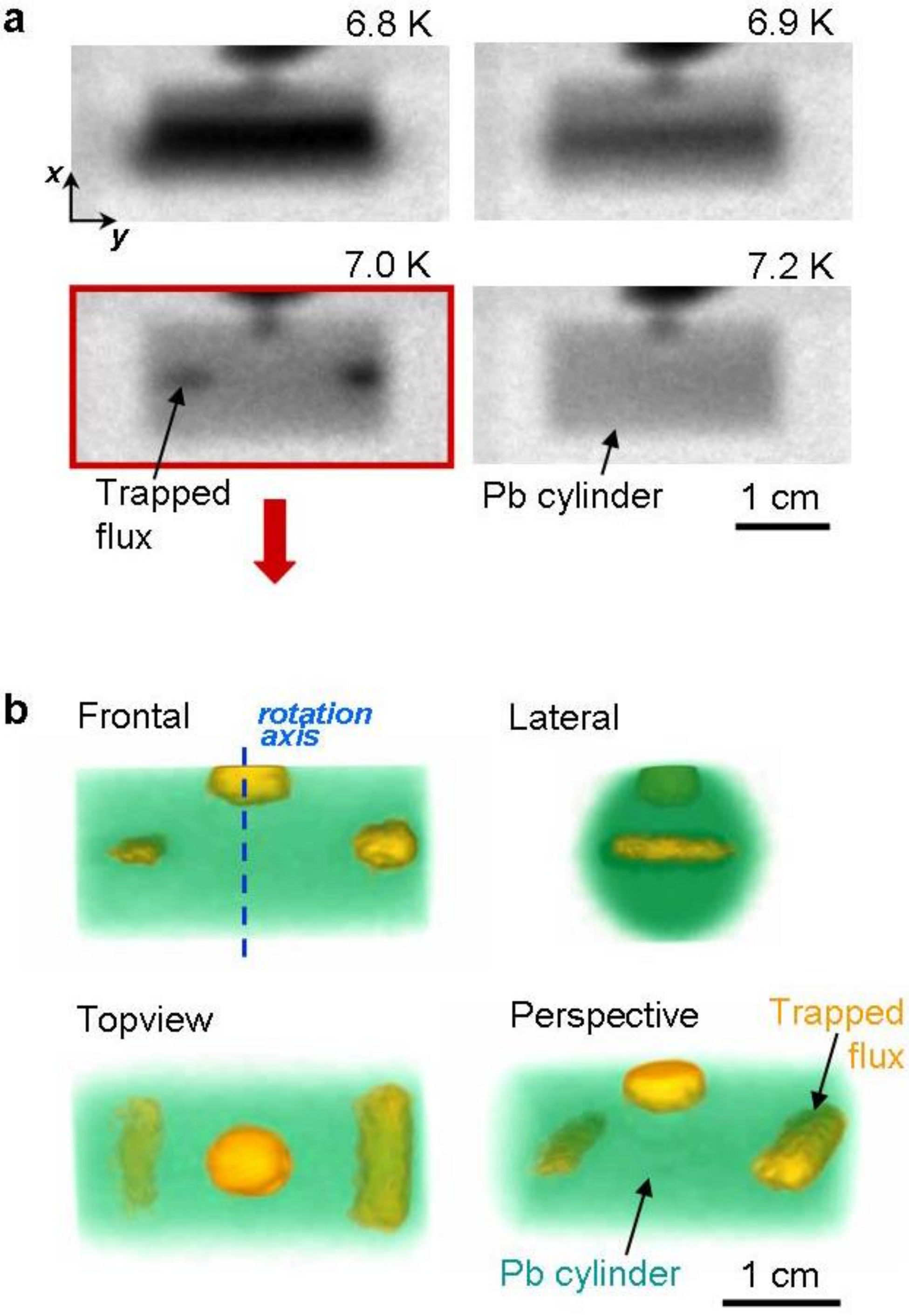


NEUTRON PHASE IMAGING



(a) Neutron attenuation radiograph (b) photograph and (c) phase contrast radiograph of a yellow jacket wasp.
*[B. E. Allman et al., **Nature** 408 (2000) 158]*

MAGNETIC IMAGING



N. Kardjilov,
Nature Physics 4(5), 399–403 (2008)

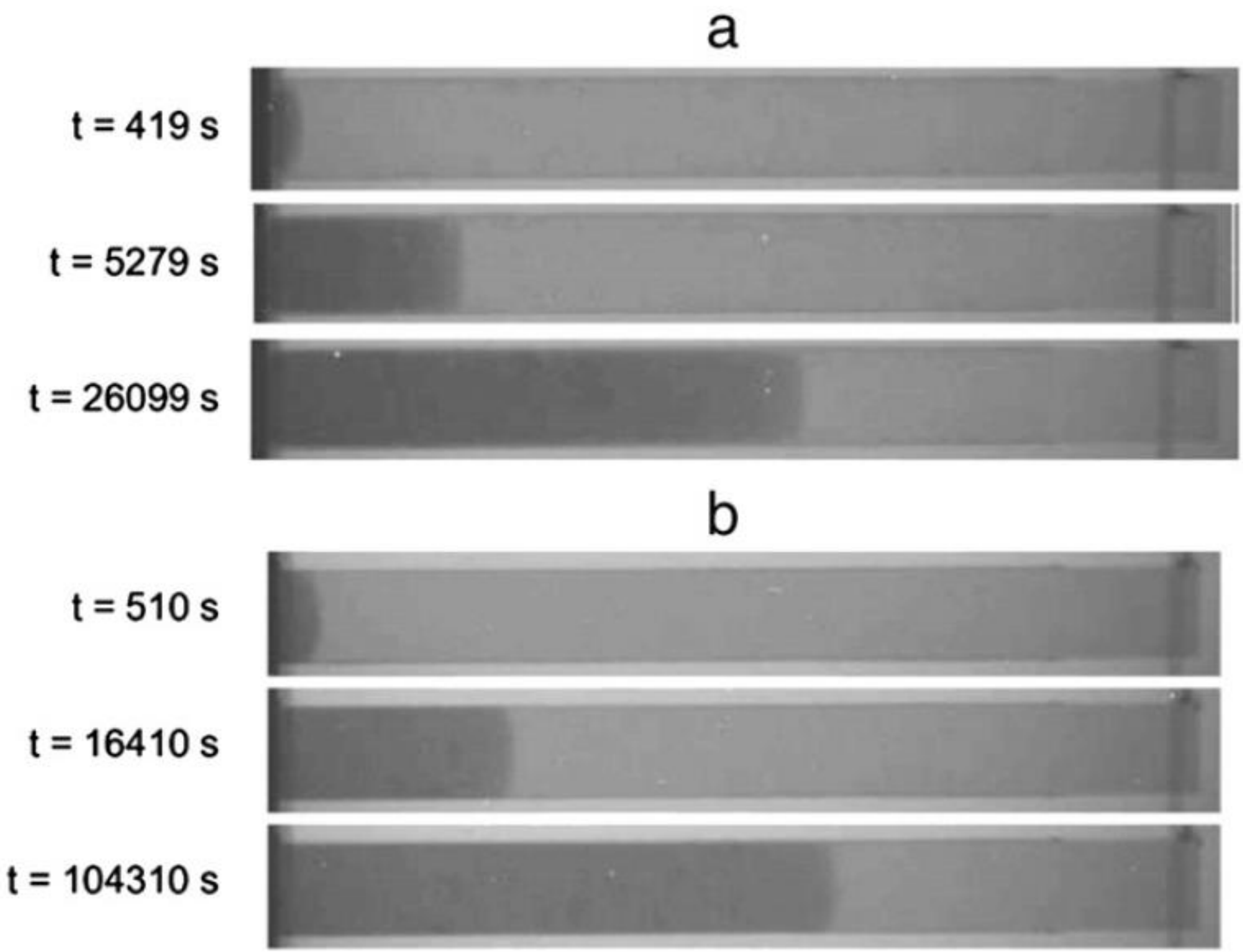
APPLICATIONS FOR GEOMATERIALS AND POROUS MEDIA

The major interest of neutrons is to observe water in porous materials

Order of magnitude : $\mu \sim 0.8/mm$

1% absorption <=> 10µm of water

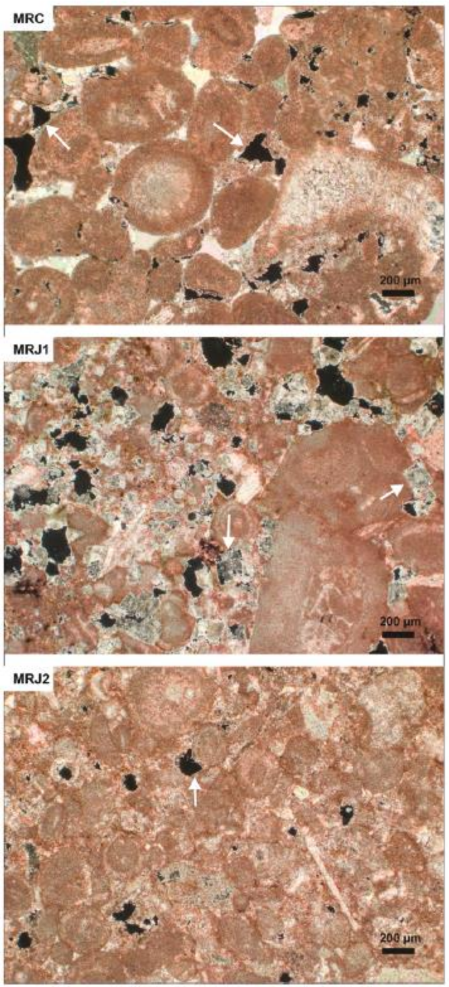
WATER FLOW IN CLAY (A) AND SILICEOUS BRICKS (B)



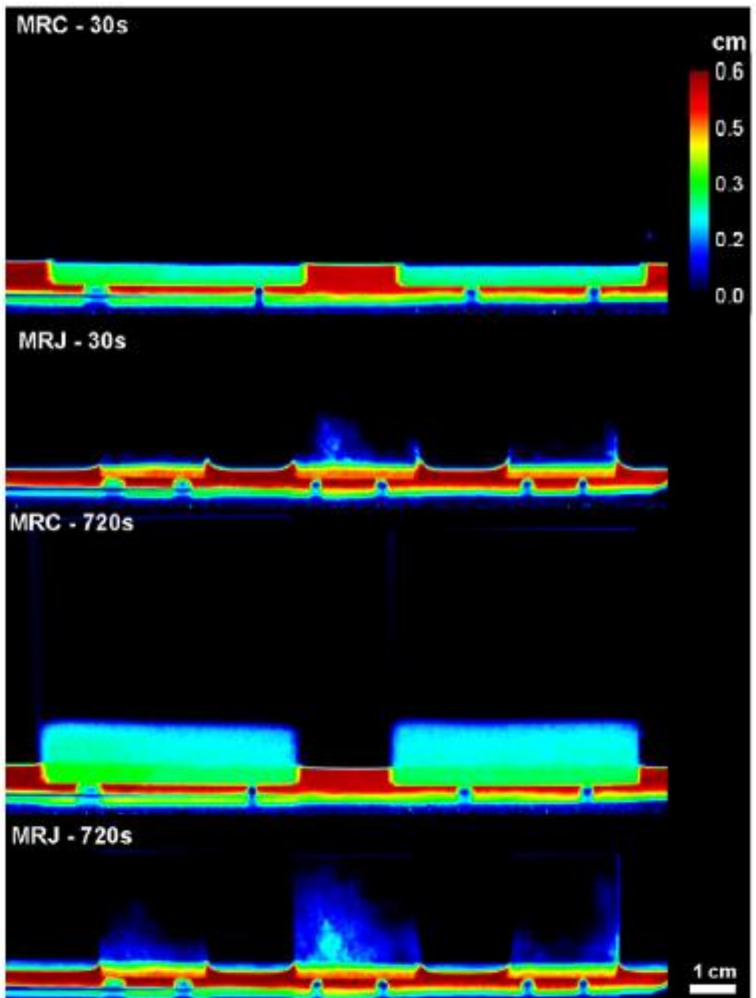
El Abd et al, 2005

MASSANGIS ROCHE CLAIRE (MRC) AND MASSANGIS ROCHE JAUNE (MRJ)

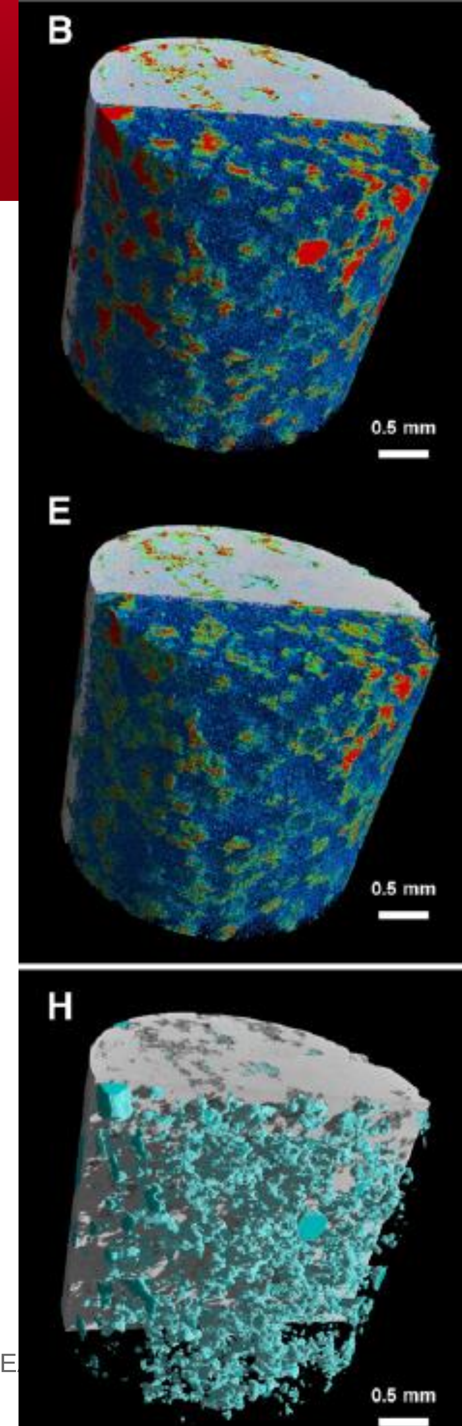
M.A. Boone, *Material Characterization* (2014)



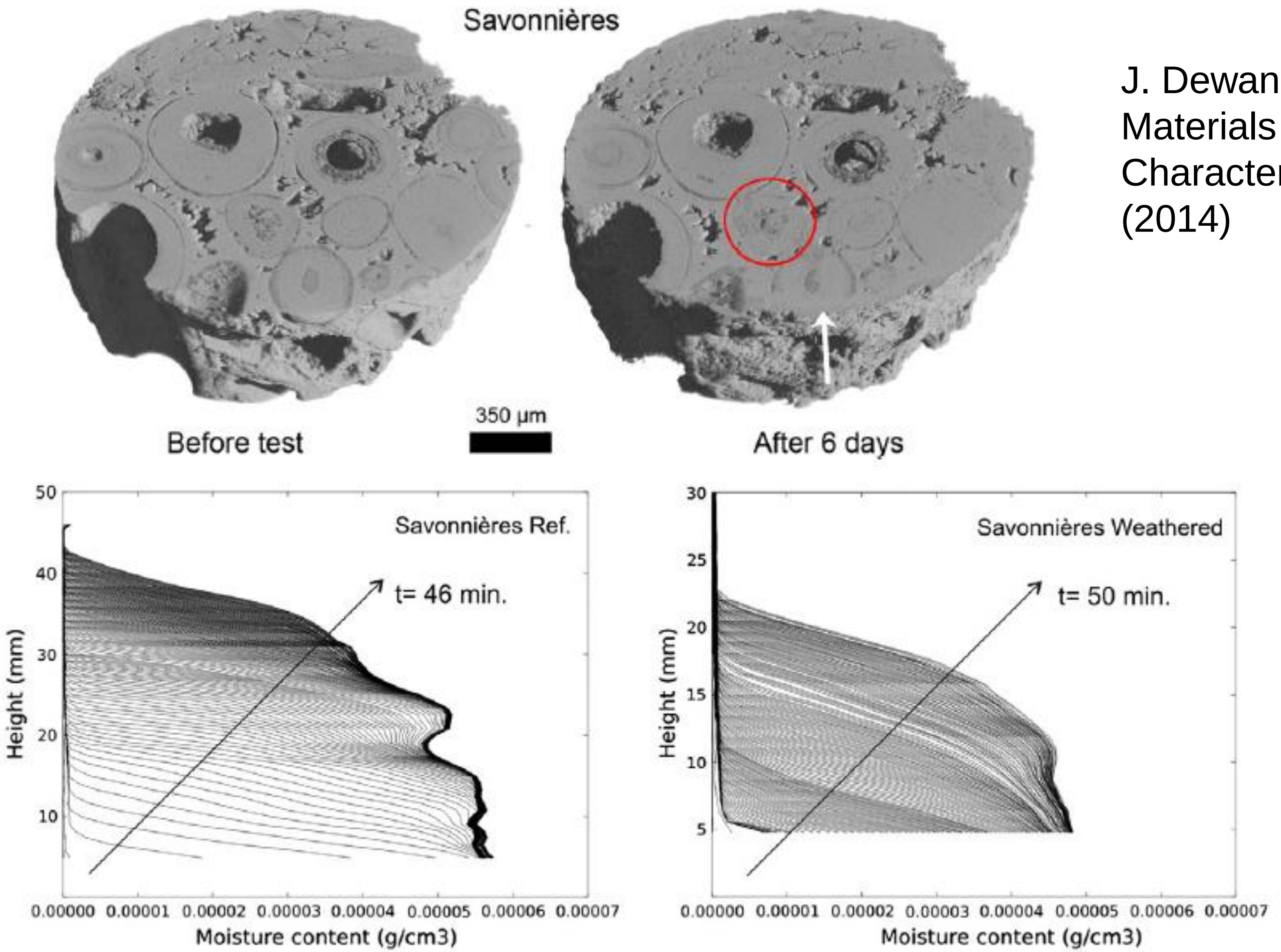
Neutron radiograph



MCT
(water + CsCl)



WATER UPTAKE IN WEATHERED LIMESTONE (EUVILLE AND SAVONNIÈRES LIMSTONE)

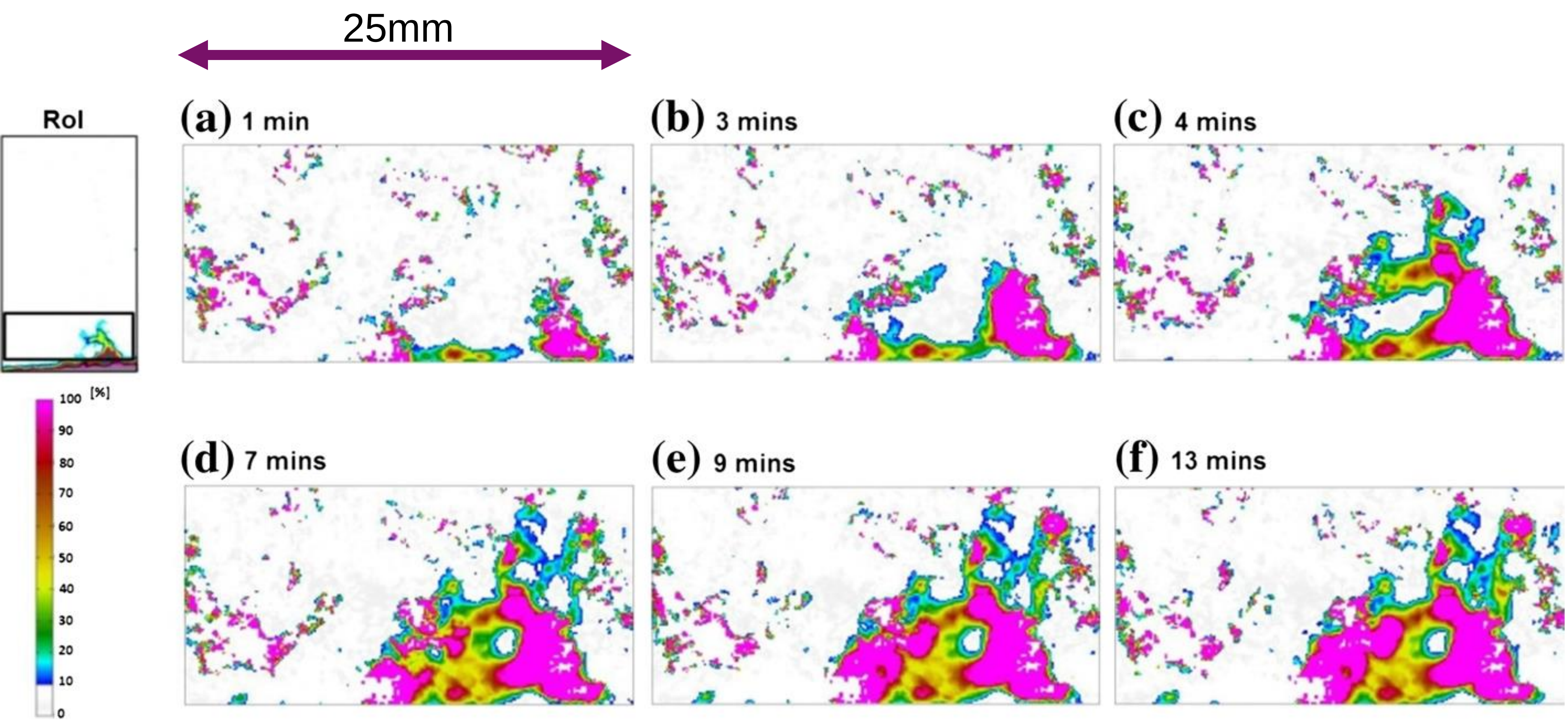


J. Dewanckele et al, Materials Characterization (2014)

WATER UPTAKE IN POROUS ASPHALT CONCRETE

Lal, Transport in Porous Media (2014)

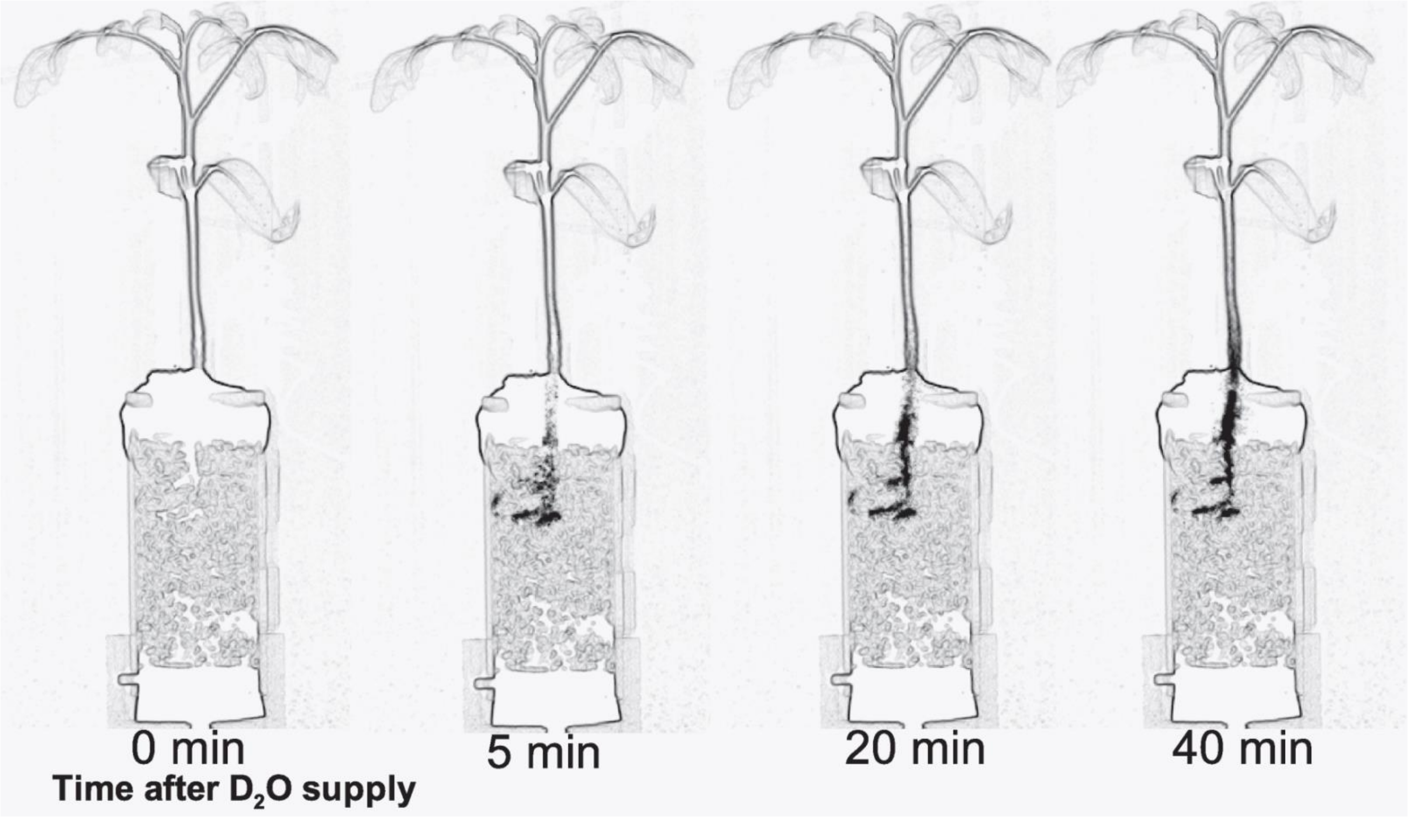
Sample size 45 x 25 x 10 mm3



ISOTOPIC LABELLING

Exchange H2O/D2O:

- **U. Matsushima, Journal of Applied Botany (2008)**



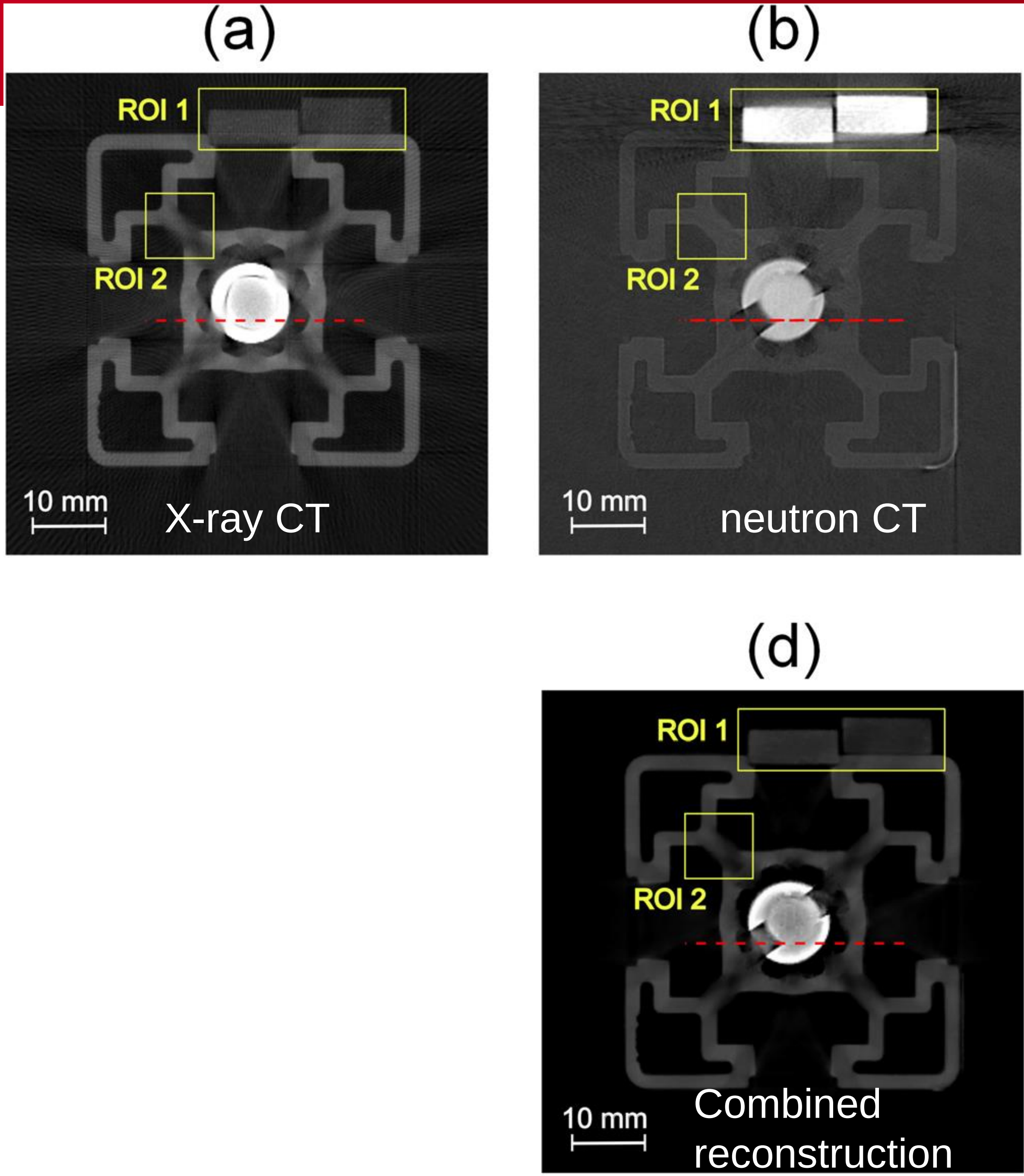
Transposable au mélange de 2 fluides (1 hydrogéné, l'autre deutéré)

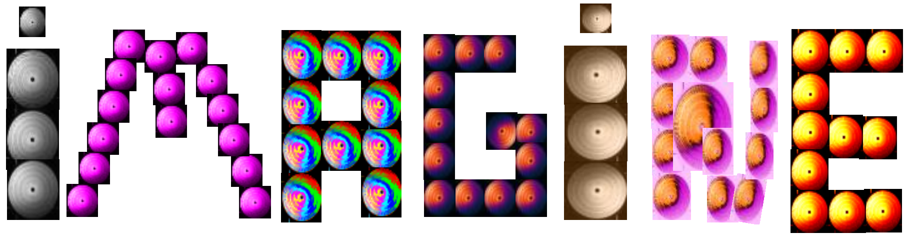
DATA FUSION

Schrapp et al, JAP 2014

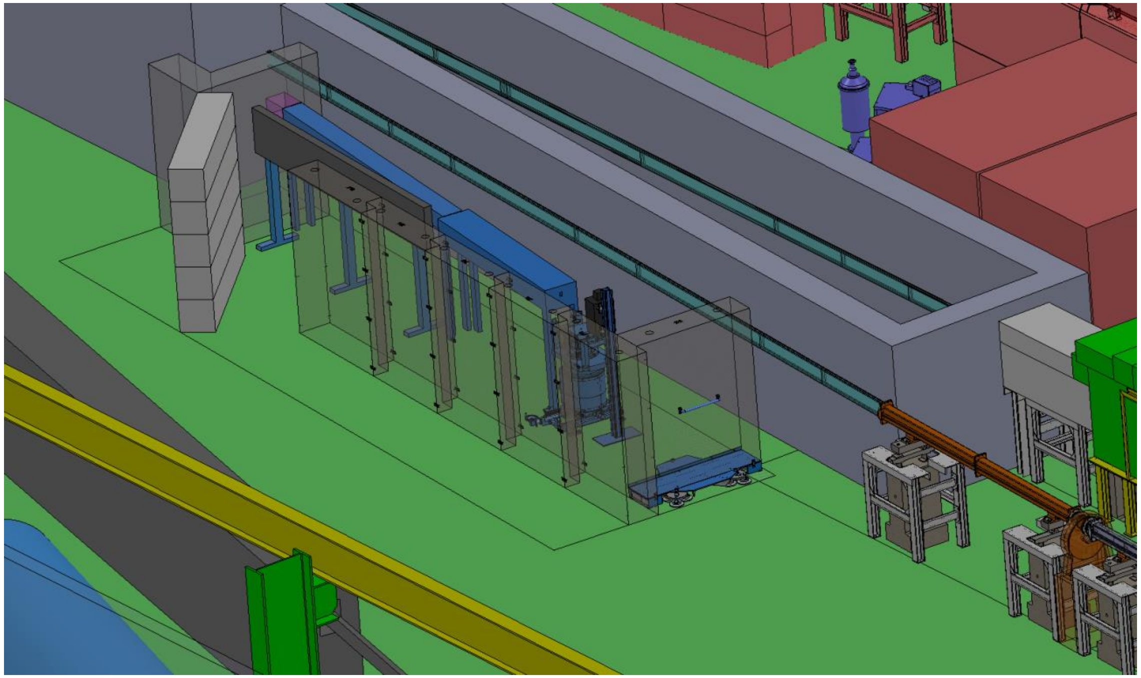
Iterative method

- SART
  Simultaneous Algebraic Reconstruction Technique





Imaging Station with cold neutrons



IMAGING AT THE LLB

An imaging station has been running for 30 years at the LLB : G45

- Installed at the end of a cold neutron guide
- Uses films and image plates: spatial resolution ~50µm
- Very wide field of view (500x250mm²) (defined by the image plate size)
- The station is operated by the company A+ RTD (~3 operators)
- Used mostly for explosive materials (~5000 pieces / year)

Limitation

- Access difficult for LLB physicists
- Access not allowed for external users
- The configuration is fixed to make sure the « industrial » configuration is not modified
    - Key requirement for qualification issues with industrialists
- Very difficult to setup dedicated sample environments

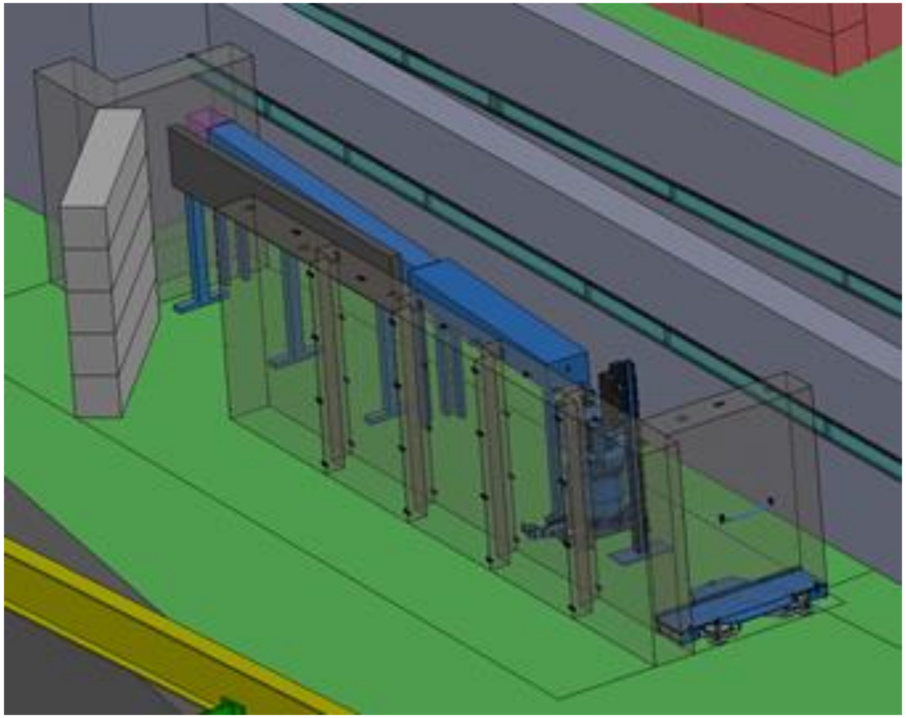
A facility dedicated to experimentalists was required

IMAGINE : IMAGING STATION WITH COLD NEUTRONS

- Main scientific driver : agro-food applications
- + possibility to perform Bragg edge imaging
- + possibility to perform magnetic imaging
- + possibility to perform Time-Of-Flight imaging

- Main interest : high resolution imaging

- Installed on the cold neutron guide G3bis

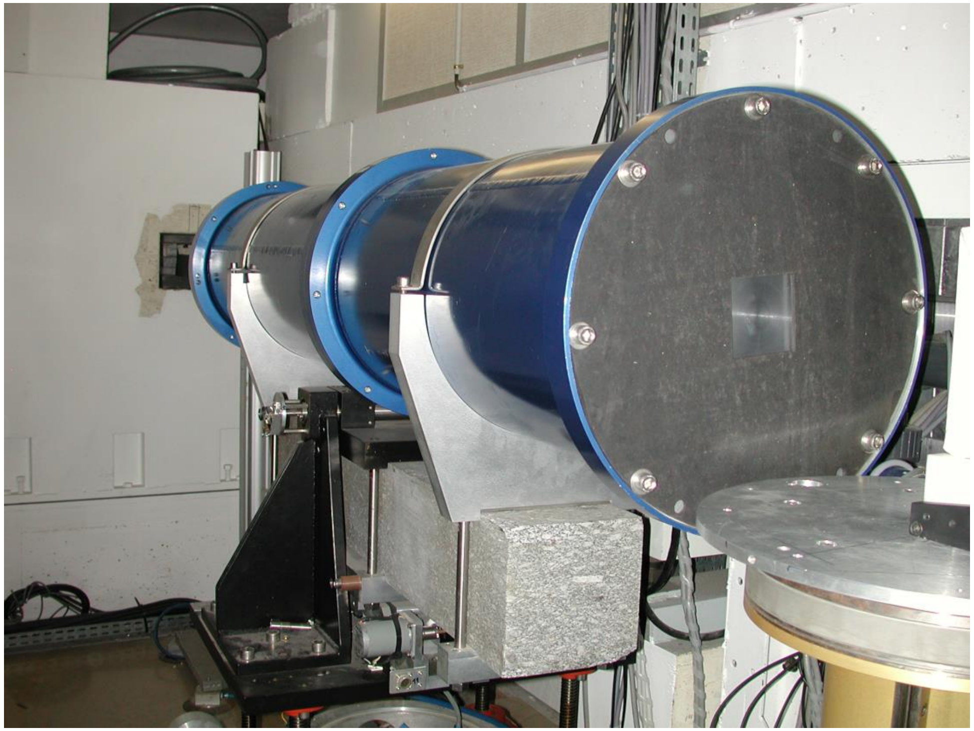


TECHNICAL CHARACTERISTICS

- Cold neutron guide G3bis: neutron spectrum ranging from 3A° to 20A°
- Whole experimental area on tanzboden
  - All elements of the spectrometer can be moved around on air-cushion and can be easily swapped (collimator, sample table, detector)
- Source size from 6 to 25mm in diameter
  Flight path from 3-10m
  - L/D ratio from 100 to 1000
- Flux in a typical configuration (FOV = 80mm, source 20mm diameter, L = 4m): $2x10^7$ neutrons/s/cm².
- Very low background noise
- The spatial resolution is presently limited to 200µm.
  - Limitation due to the very wide aperture optical lens (f/0.95)
  - Optics is being changed to go down to 50µm

PHOTOS

PHOTOS



SAMPLE ENVIRONMENTS

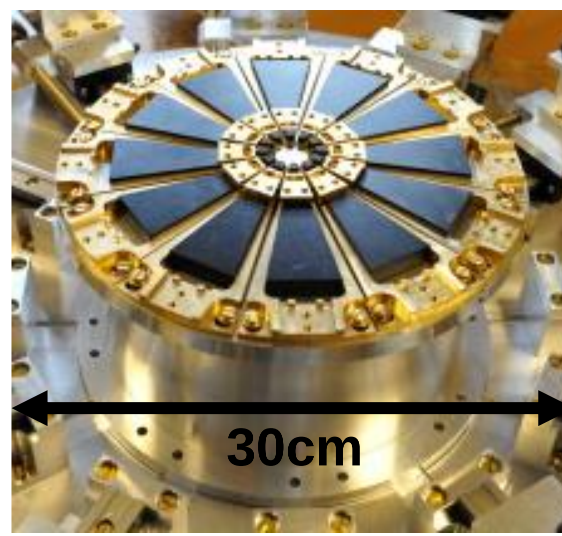
Heavy load
sample table

Humidity chamber
k€40 obtained from the
Labex to setup a new one

Furnace
+ electrical measurements

Coupled MRI +
neutron imaging

P. Judenstein (LLB)
D. Sakellariou (NIMBE)



H

FORESEEN UPGRADES

- Large areas detector
  - Requested by some users
  - Fuji image plate (500x250mm²) + off-line Scanner
  - Reuse of MAR image plate from TPA (300x300mm²) (as soon as TPA get a new detector)
- Microchannel plate detector
  - Further increase in spatial resolution and detection efficiency
  - Possibility to perform Time-Of-Flight measurements
  - Price ? k€100-150
- Time-of-flight measurements
  - Chopper is readily available
  - Make use of the microchannel plate

DATA PROCESSING

Base

- ImageJ
- Matlab

Tomography

- Octopus (commercial) + GPU computing
  - WBP Weighted Back Projection

- TomoJ (Institut Curie) + GPU computing (3s par reconstruction 512^3)
  - WBP Weighted Back Projection
  - Iterative reconstruction (SART)

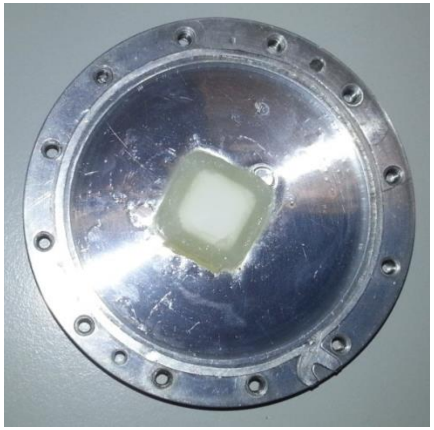
- In practice, WBP provides good results since the data sets are complete (200-400 images over 180°)

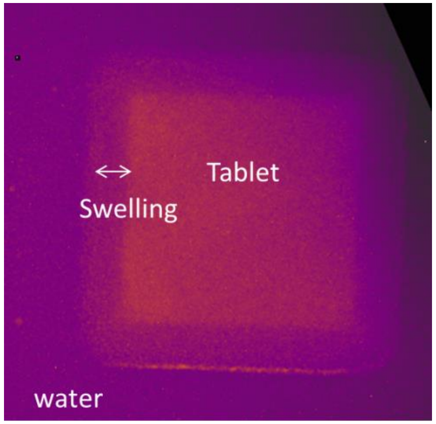
- Avizo for vizualization

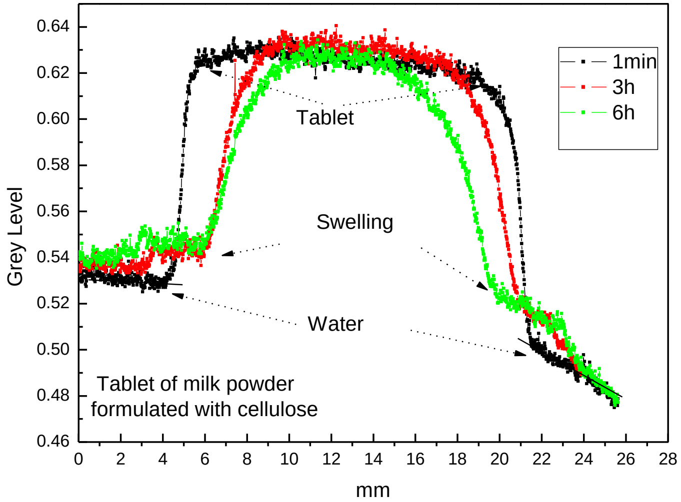
SOME SCIENCE

MILK POWDERS DISSOLUTION IN WATER: IMPACT OF AGGLOMERATION AND FORMULATION

Camille Loupiac[1,2] and Ali Assifaoui[1]
Equipe PAPC, UMR PAM, AgroSup Dijon-Université de Bourgogne, Dijon, France
Laboratoire Léon Brillouin CEA/CNRS UMR 12, CEA Saclay, Gif sur Yvette, FRANCE





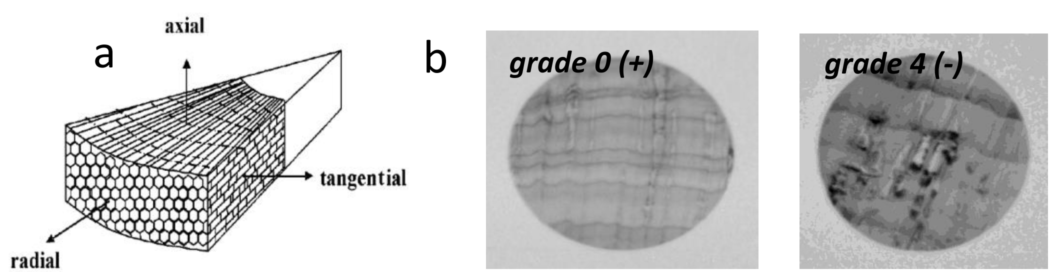


(left) tablet of milk powder after few minutes of hydration in the aluminium cell; (right) neutron radiography performed on this sample with IMAGINE (40 s exposure, 100 µm scintillator).

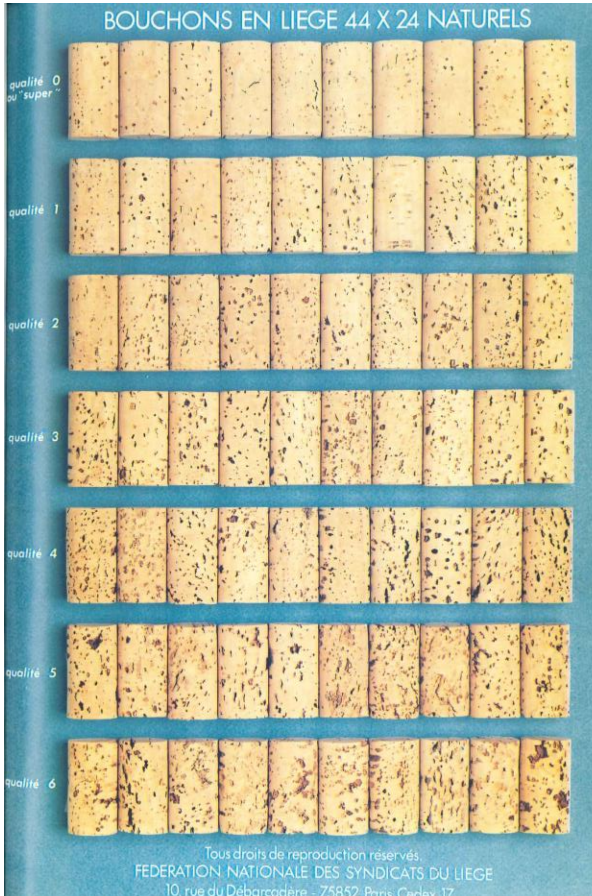
Quality grading of cork stoppers: amount of defects inside the material

Aurélie Tachon[1,2,3], Thomas Karbowiak[1], Camille Loupiac[1,2], Régis Gougeon[1,3], Jean-Pierre Bellat[4]

Equipe PAPC, UMR PAM, AgroSup Dijon-Université de Bourgogne, Dijon, France
Laboratoire Léon Brillouin CEA/CNRS UMR 12, CEA Saclay, Gif sur Yvette, FRANCE
Institut Universitaire de la Vigne et du Vin, Université de Bourgogne, Dijon, France
Laboratoire Interdisciplinaire Carnot de Bourgogne, UMR 6303, Université de Bourgogne, Dijon France



(left) three dimensional structure of the cork from Silva et al. 2005 / (right) Neutron radiographies of two cork stoppers slides of different qualities (IMAGINE instrument, 120 s exposure, 100 µm scintillator).



GRAPEVINE ROOT GROWTH: BENEFICIAL EFFECTS OF ARBUSCULAR MYCORRHIZAL FUNGI

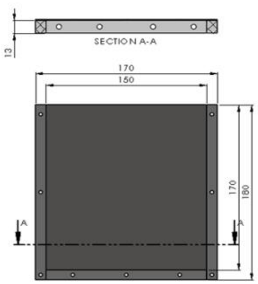
Marielle Adrian[1], Sophie Trouvelot[1], Eric Bernaud[1], Daniel Wipf[1], Laurent Bonneau[1], Christophe Salon[1], Camille Loupiac[2,3], Régis Gougeon[2,4]

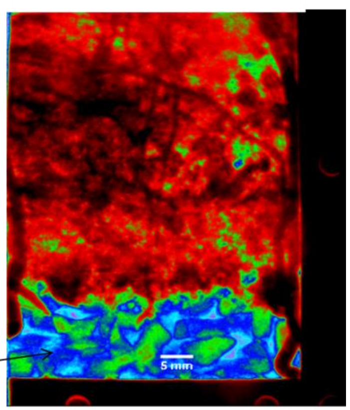
1- UMR1347 Agroécologie, AgroSup dijon –INRA-Université de Bourgogne, 17 rue Sully, Dijon, France

2-Equipe PAPC, UMR PAM, AgroSup Dijon-Université de Bourgogne, Dijon, France

3-Laboratoire Léon Brillouin CEA/CNRS UMR 12, CEA Saclay, Gif sur Yvette, France

4-Institut Universitaire de la Vigne et du Vin, Université de Bourgogne, Dijon, France





Neutron images of a grapevine herbaceous cutting cultivated by the AgroEcology team (Dijon) in an aluminium flat container. The left « black and white » image has been performed with an image plate detector (LLB neutronography station) and the right color one comes from the IMAGINE station (40 s of exposure).

CONCLUSION

Nous devons développer une expertise car l'imagerie est une technique nouvelle au LLB

Les sujets abordés sont très variés

- Agro-alimentaire
- Sciences du sol
- Archéologie
- Magnétisme

Nous souhaitons répondre aux besoins d'un maximum d'utilisateurs