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Neutron imaging

Monitoring and quantifying water in porous media

GRK 2075 :: TU Braunschweig :: October 6th, 2017

Outline

- Introduction
- Neutron imaging
- Imaging with water
- New possibilities
- Summary

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Introduction

Water is everywhere…

The role of water in construction materials

Production

Maintenance and Preservation

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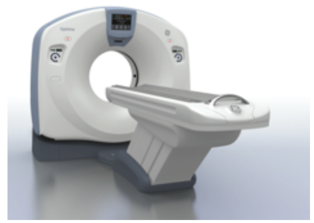
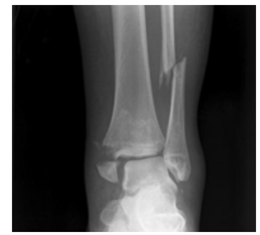
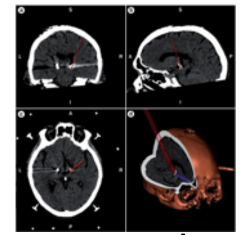
What is the link to imaging?

When most people hear the words Radiography and Tomography . . .
. . . they think about applications in hospitals

- X-rays
- Broken legs
- Head scans
- . . .



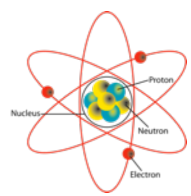




[Hyam et al., 2012]

… and when they hear about neutrons they think about

- Something very small
- Bombs
- Nuclear power



These are not the topics of this seminar . . . but there are connections.

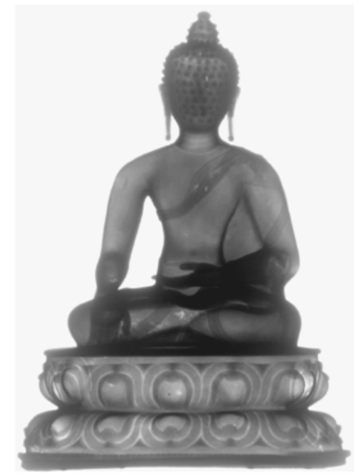
You can see through samples and observe processes

X-ray - Neutrons what's the difference?

Neutrons

Group → / ↓ Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	H 3.44																	He 0.02
2	Li 3.30	Be 0.79											B 101.6	C 0.56	N 0.43	O 0.17	F 0.20	Ne 0.10
3	Na 0.09	Mg 0.15											Al 0.1	Si 0.11	P 0.12	S 0.06	Cl 1.33	Ar 0.03
4	K 0.06	Ca 0.08	Sc 2.00	Ti 0.60	V 0.72	Cr 0.54	Mn 1.21	Fe 1.19	Co 3.92	Ni 2.05	Cu 1.07	Zn 0.35	Ga 0.49	Ge 0.47	As 0.67	Se 0.73	Br 0.24	Kr 0.61
5	Rb 0.08	Sr 0.14	Y 0.27	Zr 0.29	Nb 0.40	Mo 0.52	Tc 1.76	Ru 0.58	Rh 10.88	Pd 0.78	Ag 4.04	Cd 115.1	In 7.58	Sn 0.21	Sb 0.30	Te 0.25	I 0.23	Xe 0.43
6	Cs 0.29	Ba 0.07		Hf 4.99	Ta 1.49	W 1.47	Re 6.85	Os 2.24	Ir 30.46	Pt 1.46	Au 6.23	Hg 16.21	Tl 0.47	Pb 0.38	Bi 0.27	Po -	At -	Rn -
7	Fr -	Ra 0.34		Rf -	Db -	Sg -	Bh -	Hs -	Mt -	Ds -	Rg -	Uub -	Uut -	Uuq -	Uup -	Uuh -	Uus -	Uuo -
Lanthanides				La 0.52	Ce 0.14	Pr 0.41	Nd 1.87	Pm 5.72	Sm 171.47	Eu 94.58	Gd 1479.0	Tb 0.93	Dy 32.42	Ho 2.25	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 2.86	Cm -	Bk -	Cf -	Es -	Fm -	Md -	No -	Lr -

X-rays



Group → / ↓ Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	H 0.02																	He 0.02
2	Li 0.06	Be 0.22											B 0.28	C 0.27	N 0.11	O 0.16	F 0.14	Ne 0.17
3	Na 0.13	Mg 0.24											Al 0.38	Si 0.33	P 0.25	S 0.30	Cl 0.23	Ar 0.20
4	K 0.14	Ca 0.26	Sc 0.48	Ti 0.73	V 1.04	Cr 1.29	Mn 1.32	Fe 1.57	Co 1.78	Ni 1.96	Cu 1.97	Zn 1.64	Ga 1.42	Ge 1.33	As 1.50	Se 1.23	Br 0.90	Kr 0.73
5	Rb 0.47	Sr 0.86	Y 1.61	Zr 2.47	Nb 3.43	Mo 4.29	Tc 5.06	Ru 5.71	Rh 6.08	Pd 6.13	Ag 5.67	Cd 4.84	In 4.31	Sn 3.98	Sb 4.28	Te 4.06	I 3.45	Xe 2.53
6	Cs 1.47	Ba 2.73		Hf 19.70	Ta 25.47	W 30.49	Re 34.47	Os 37.92	Ir 39.01	Pt 38.61	Au 35.94	Hg 25.88	Tl 23.23	Pb 22.81	Bi 20.28	Po 20.22	At -	Rn 9.77
7	Fr -	Ra 11.80		Rf -	Db -	Sg -	Bh -	Hs -	Mt -	Ds -	Rg -	Uub -	Uut -	Uuq -	Uup -	Uuh -	Uus -	Uuo -
Lanthanides				La 5.04	Ce 5.79	Pr 6.23	Nd 6.46	Pm 7.33	Sm 7.68	Eu 5.66	Gd 8.69	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 28.95	Pa 39.65	U 49.08	Np -	Pu -	Am -	Cm -	Bk -	Cf -	Es -	Fm -	Md -	No -	Lr -

Why are neutrons good?

High contrast water vs. matrix

- No contrast enhancement required.
- D2O can be used to observe diffusion and transport

Can penetrate metal containers and still see the water.

- Strong pressure cells can be used
- Often sufficient resolution (spatial and temporal)

. . . more about this later.

Al	H	O	C	K	Si	Ca	N	Ti	Fe	Na
0.1	3.44	0.17	0.56	0.06	0.11	0.08	0.43	0.60	1.19	0.09

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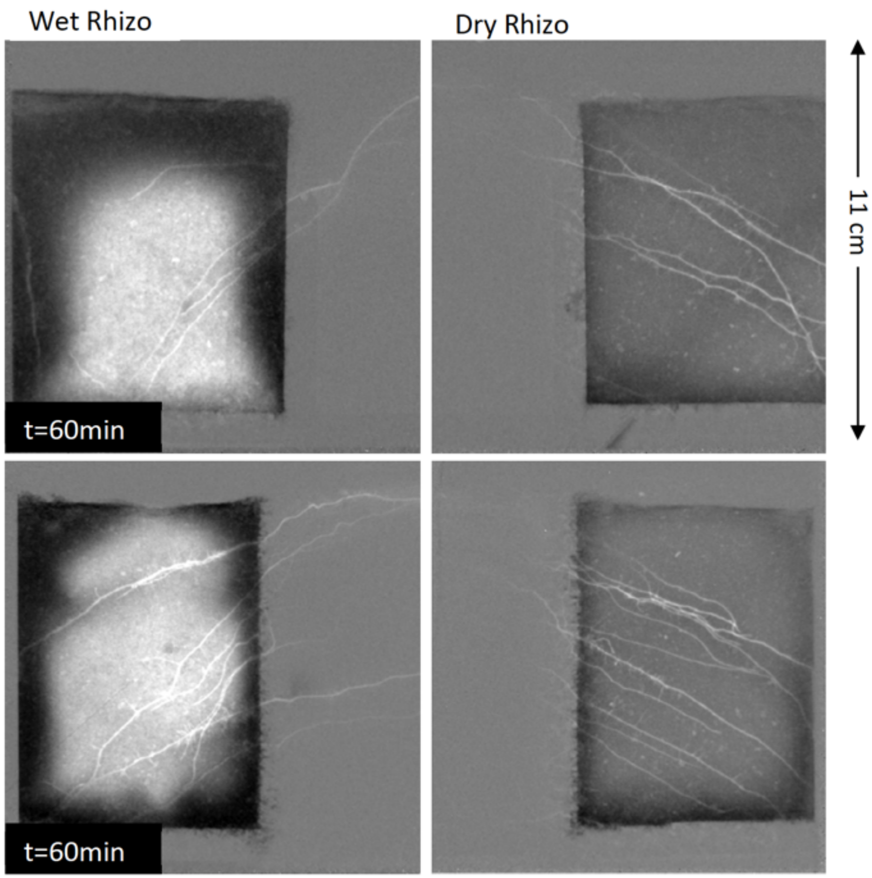
... and in particular neutron imaging?

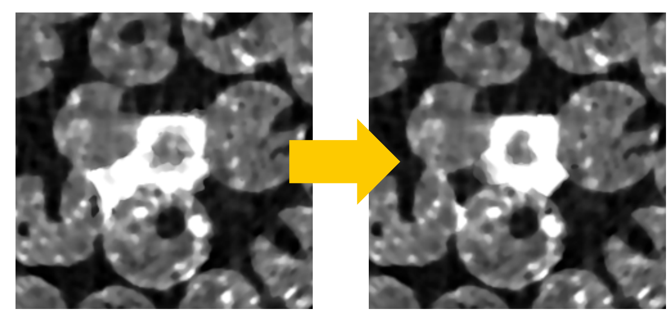
The sensitivity to water and isotope sensitivity!

Radiography time series



[Zarebanadkouki et al., Plant and Soil Nutrition, 2013]

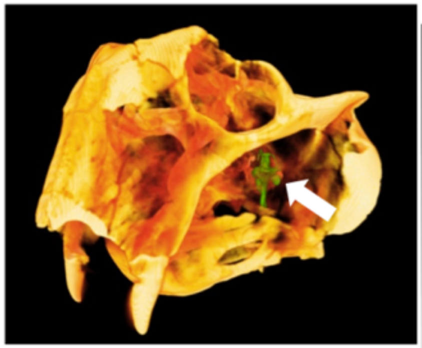
Tomography time series



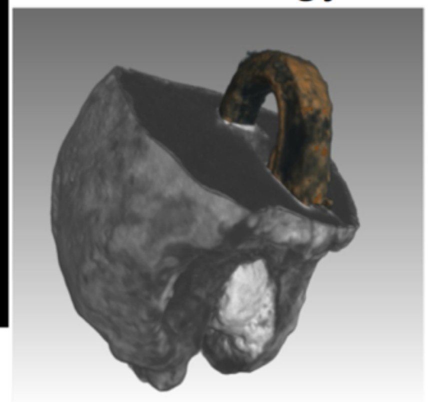
[Kazantsev et al., Inv. Problems and Imaging, 2015]

Neutron imaging examples

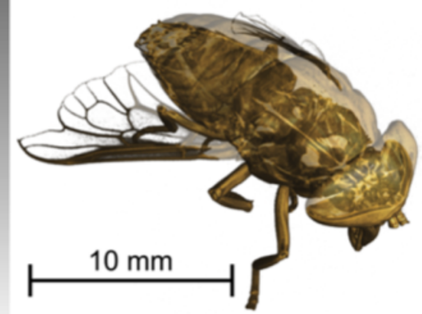
Palaeontology



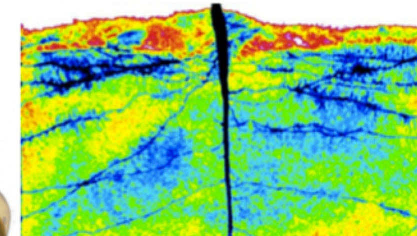
Archeology



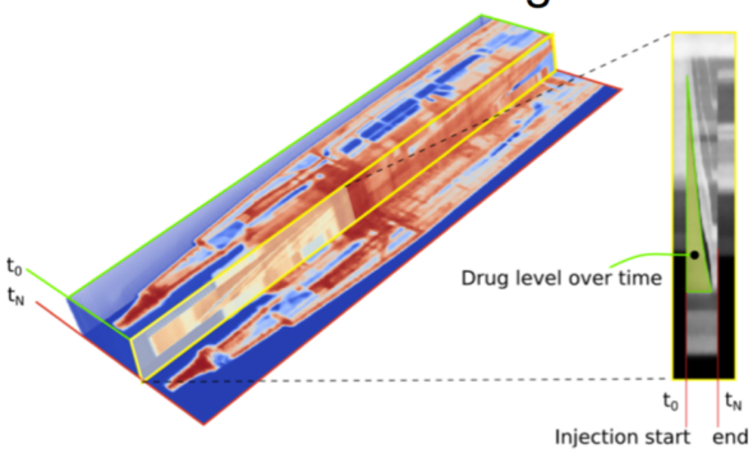
Biology



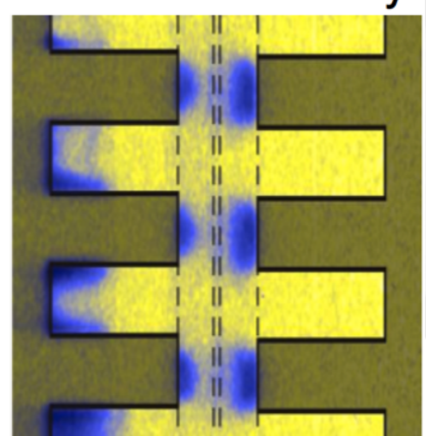
Soil and plants



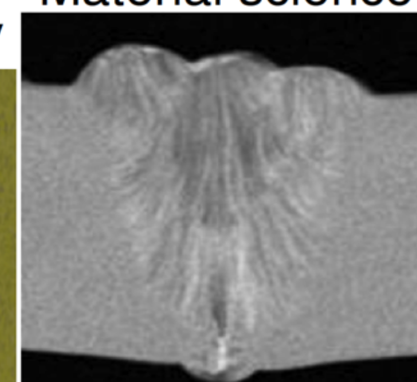
Material testing



Electrochemistry



Material science

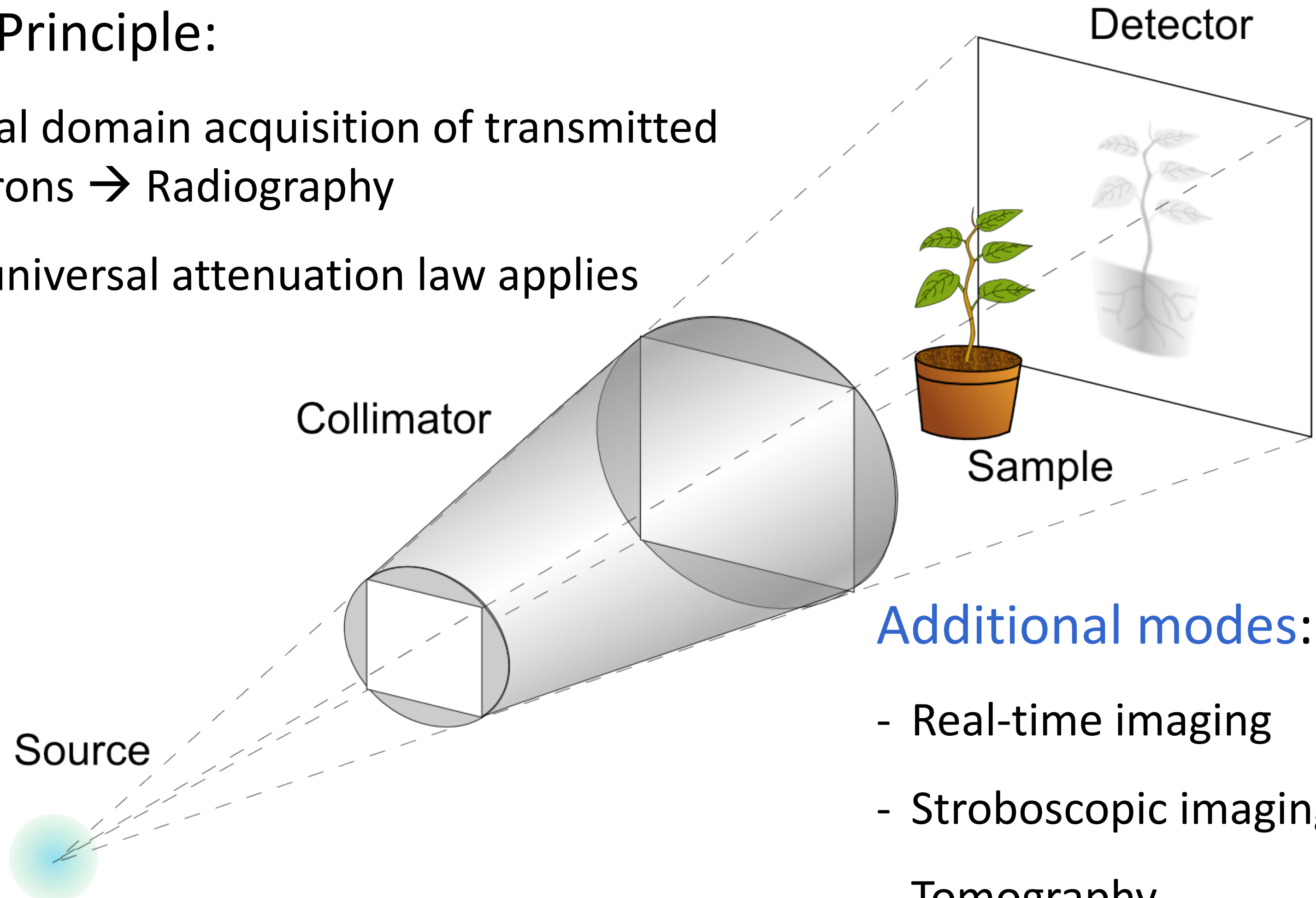


Neutron imaging

Neutron imaging

Basic Principle:

- Spatial domain acquisition of transmitted neutrons → Radiography
- The universal attenuation law applies

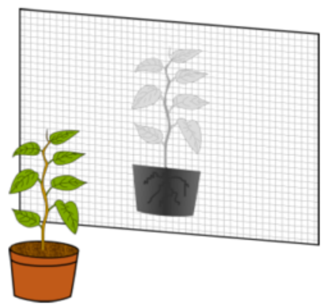


Additional modes:

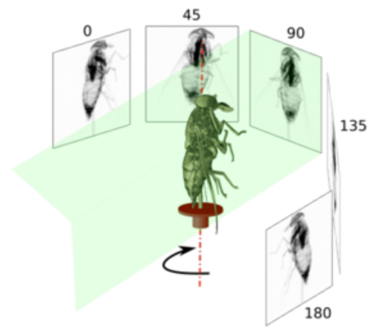
- Real-time imaging
- Stroboscopic imaging
- Tomography
- Energy selective imaging
- Grating interferometry

Neutron imaging methods

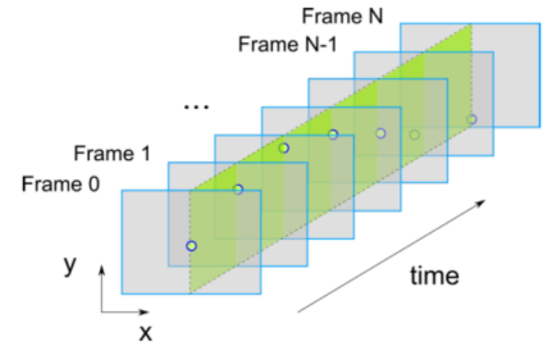
Radiography



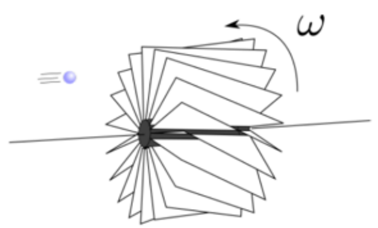
Tomography



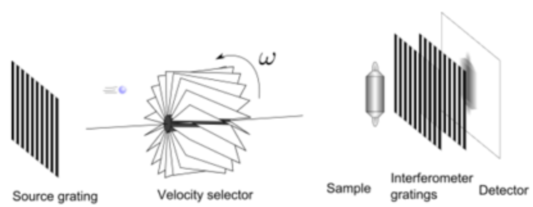
Time series



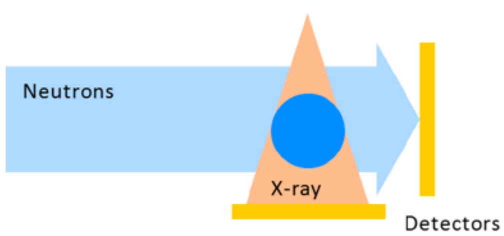
Spectral imaging



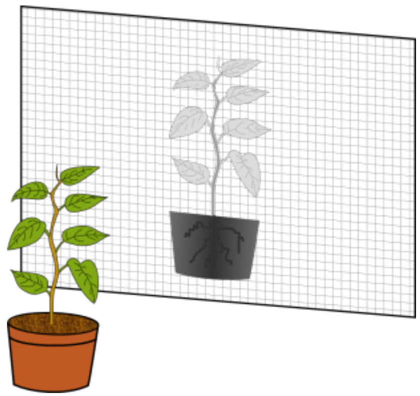
Grating interferometry

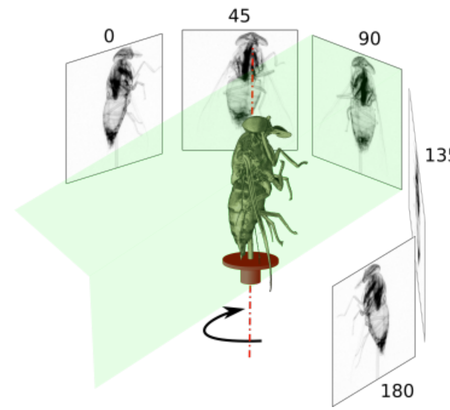


Multi modality



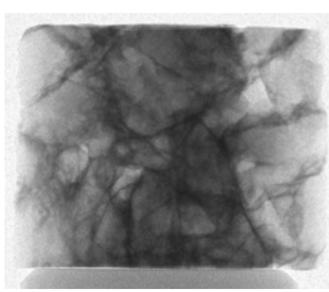
Difference between radiography and CT





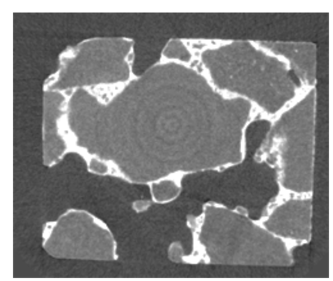
Radiography

- 2D Projection
- No depth information
- Fast acquisition



Tomography

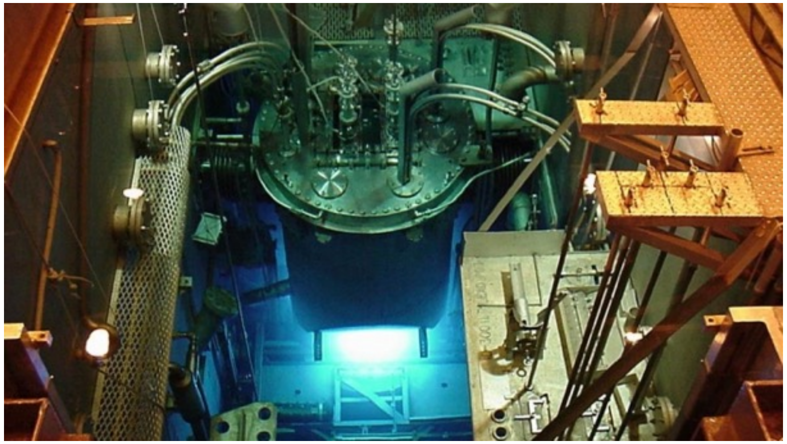
- Volume information
- Requires multiple radiographs
- Acquisition by scanning
- Higher local contrast



Neutron sources

Neutron imaging require high fluxes - 10^6 neutrons/cm^2/s and more

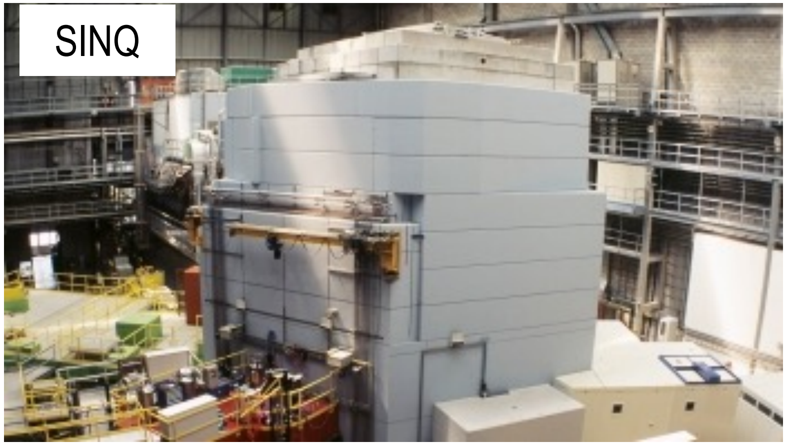
Research reactors



Main process: Fission

Requires: Uranium

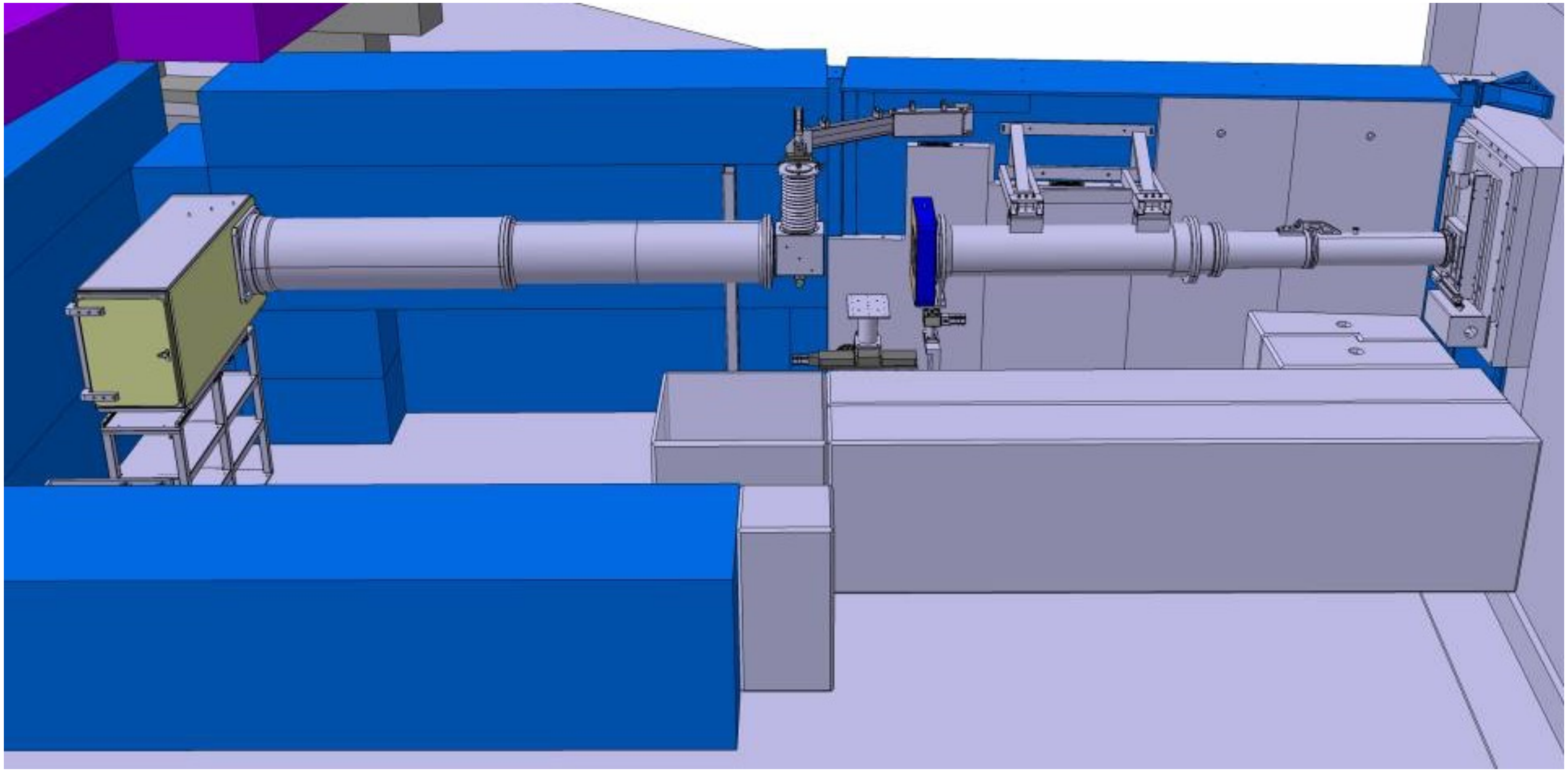
Spallation neutron sources



Main process: Spallation

Requires: High energy proton beam

Neutron imaging beamlines at PSI - NEUTRA



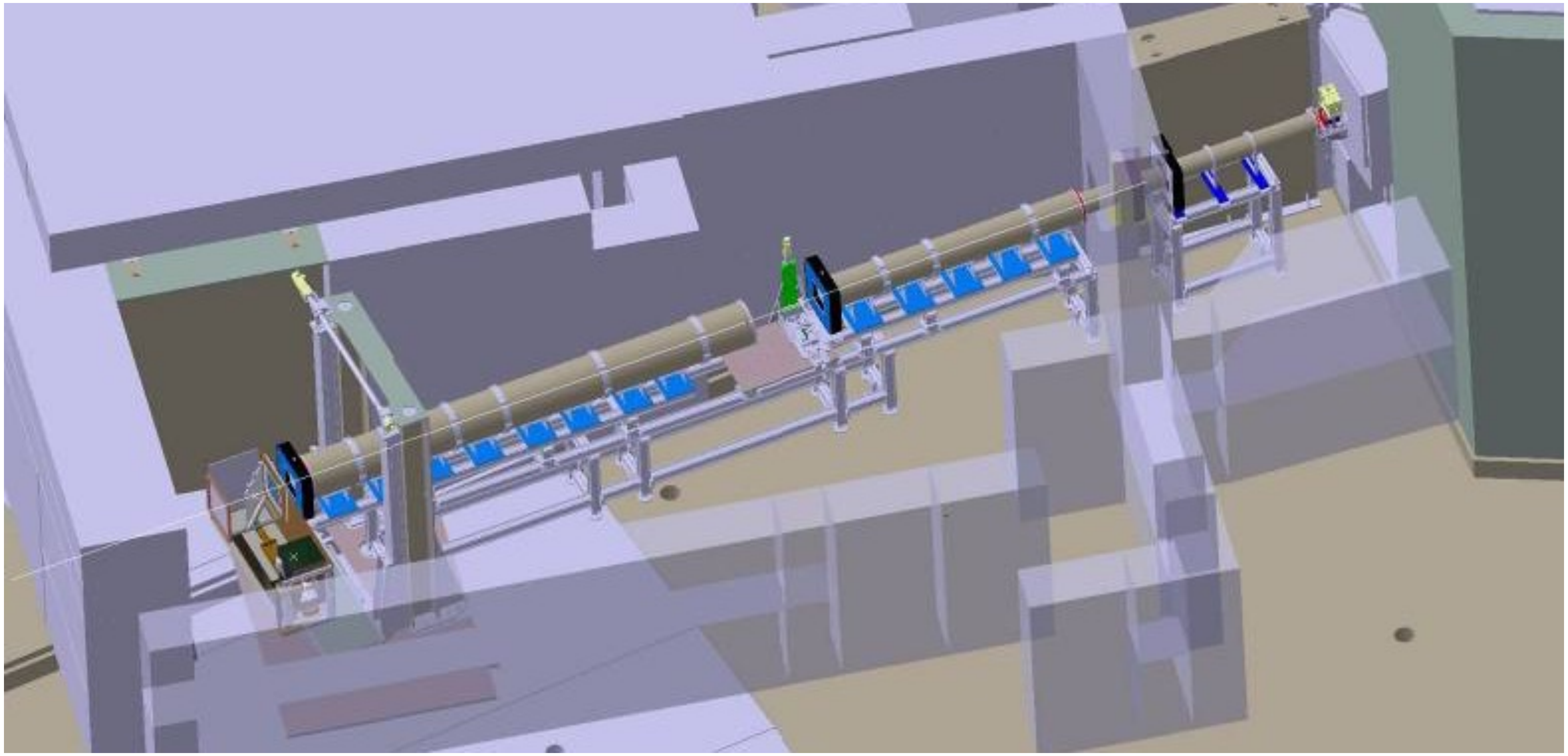
Thermal neutrons

X-rays inline

Support for imaging with high active samples

FOV: $50x50mm^2 \rightarrow 300x300mm^2$

Neutron imaging beamlines at PSI - ICON



Cold neutrons
X-rays oblique
High resolution imaging

FOV: 5x5mm^2 → 250x250mm^2

Energy selective imaging
Grating interferometry
Diffraction imaging

Neutron imaging in the world

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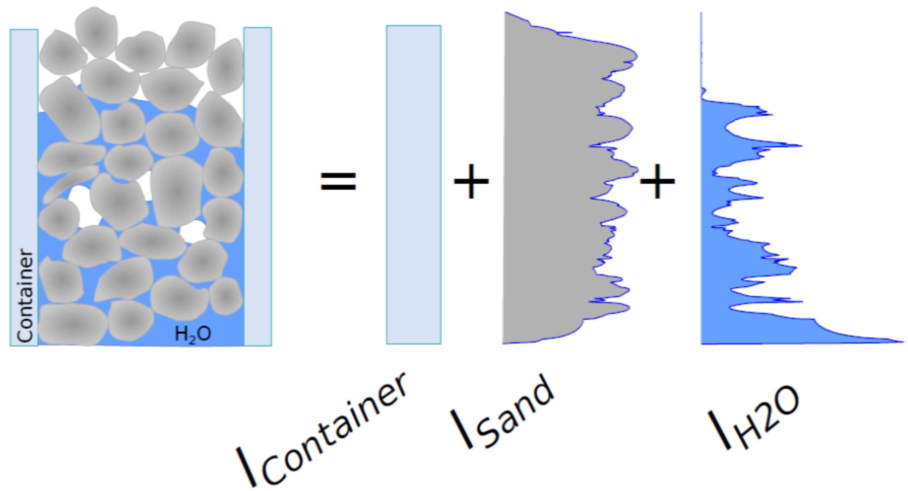
Imaging with water

How we measure water content…

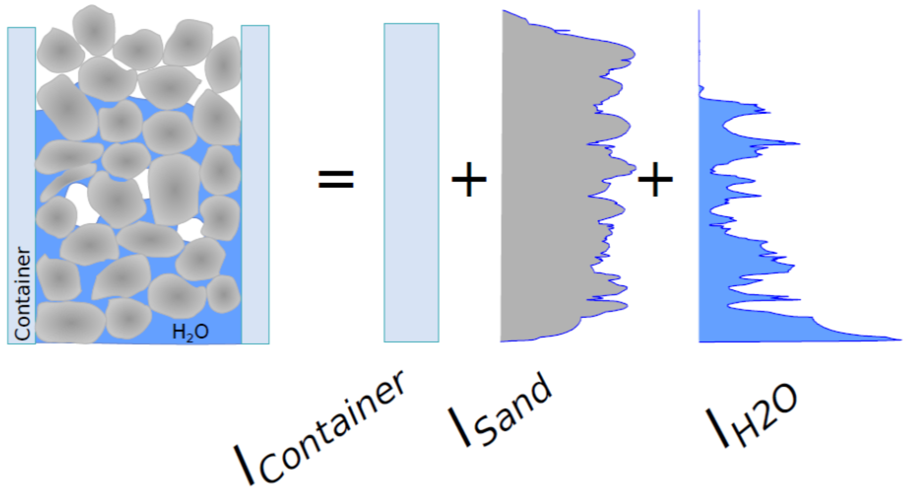


From Beer-Lambert's law we get

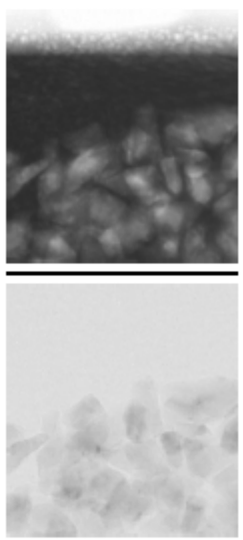
$$I_{dry} = I_0\, e^{-\Sigma_{media}\, l_{media} - \Sigma_{Contatiner}\, l_{Container}}$$

$$I_{wet} = I_0\, e^{-\Sigma_{media}\, l_{media} - \Sigma_{H_2O}\, l_{H_2O} - \Sigma_{Contatiner}\, l_{Container}}$$

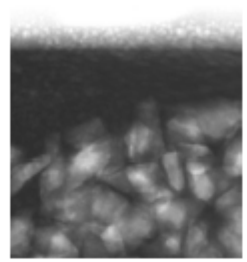
Quantifying changes – Image referencing



$$\frac{I_{wet}}{I_{dry}} =$$

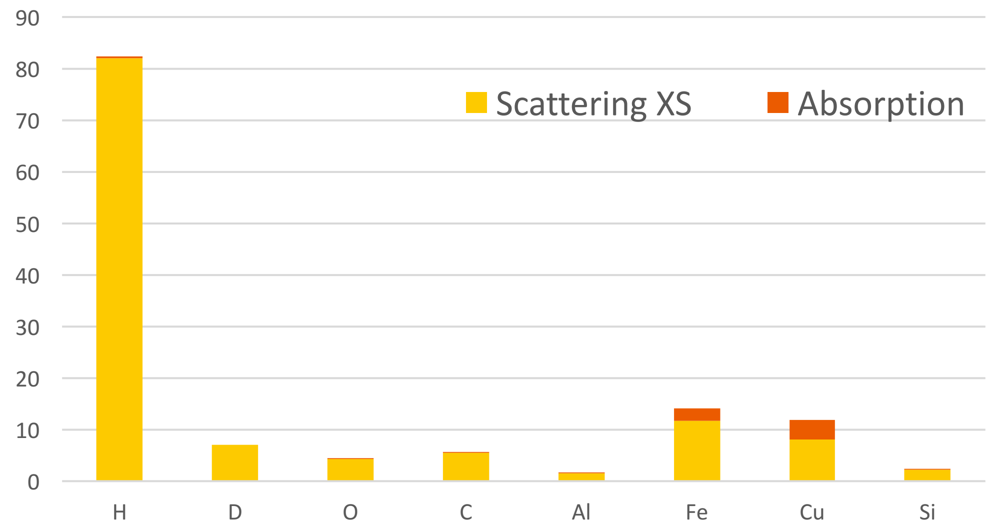


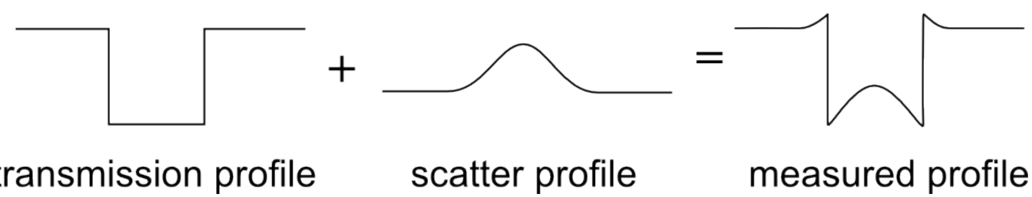
$$=$$



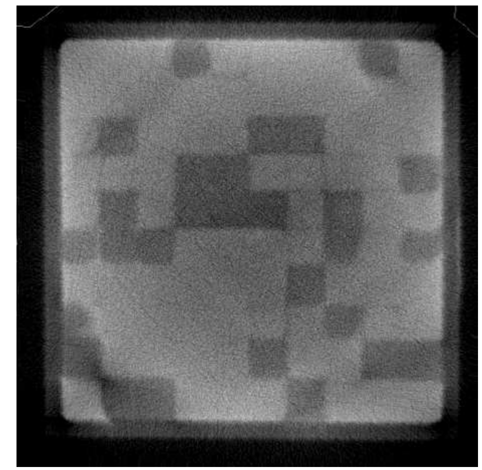
$$= e^{-\Sigma_{H_2O}\, l_{H_2O}}$$

Scattering correction – Getting closer

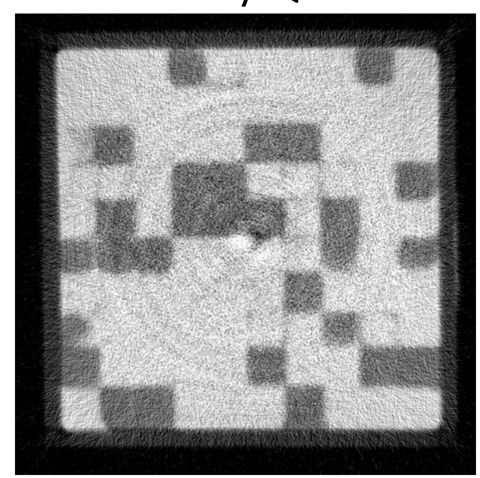




Original CT slice



Corrected by QNI

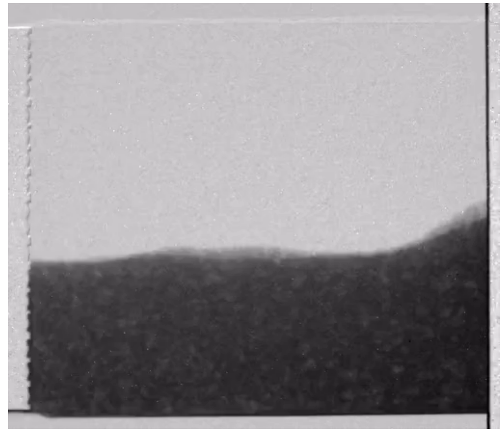


[R. Hassanein, , PhD. Thesis, ETH, Zürich, 2006]

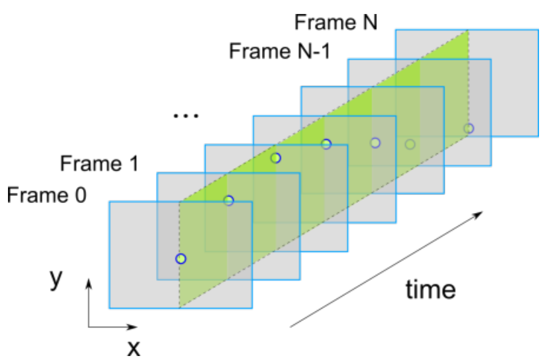
Time series of radiographs

Time series of images

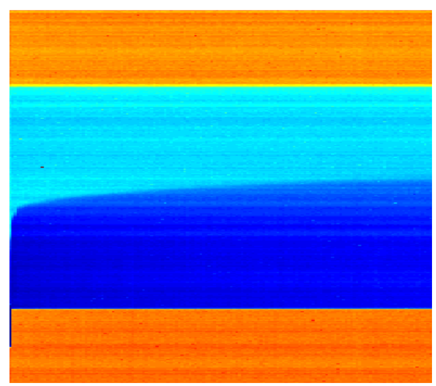
Vertical position



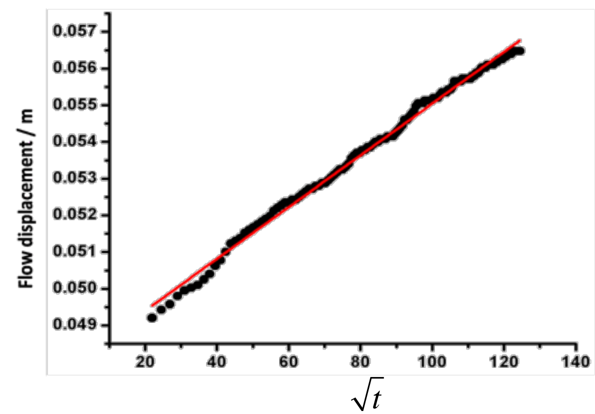
Horizontal position



Vertical position



Time

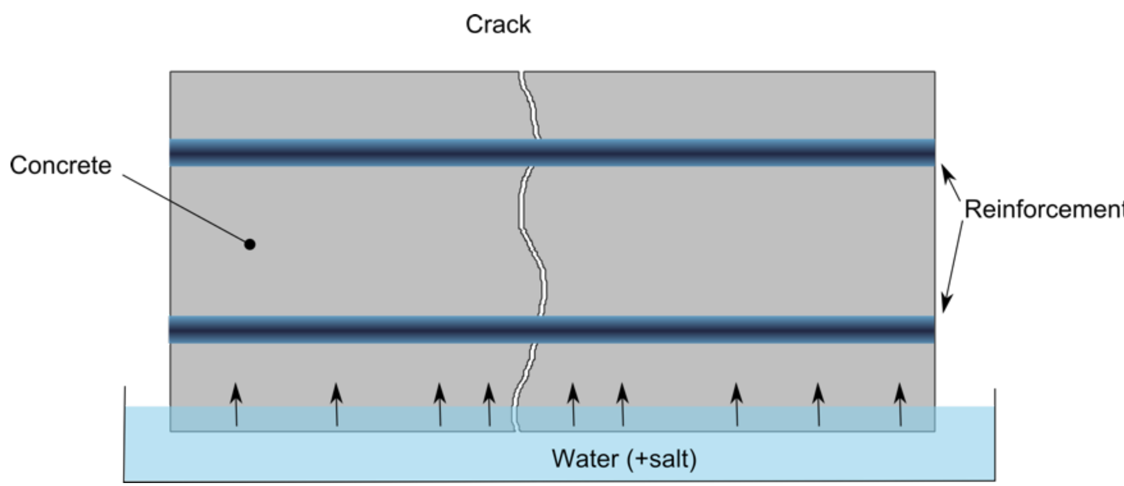


[PSI Summer school experiment 2013]

Salt transport in concrete

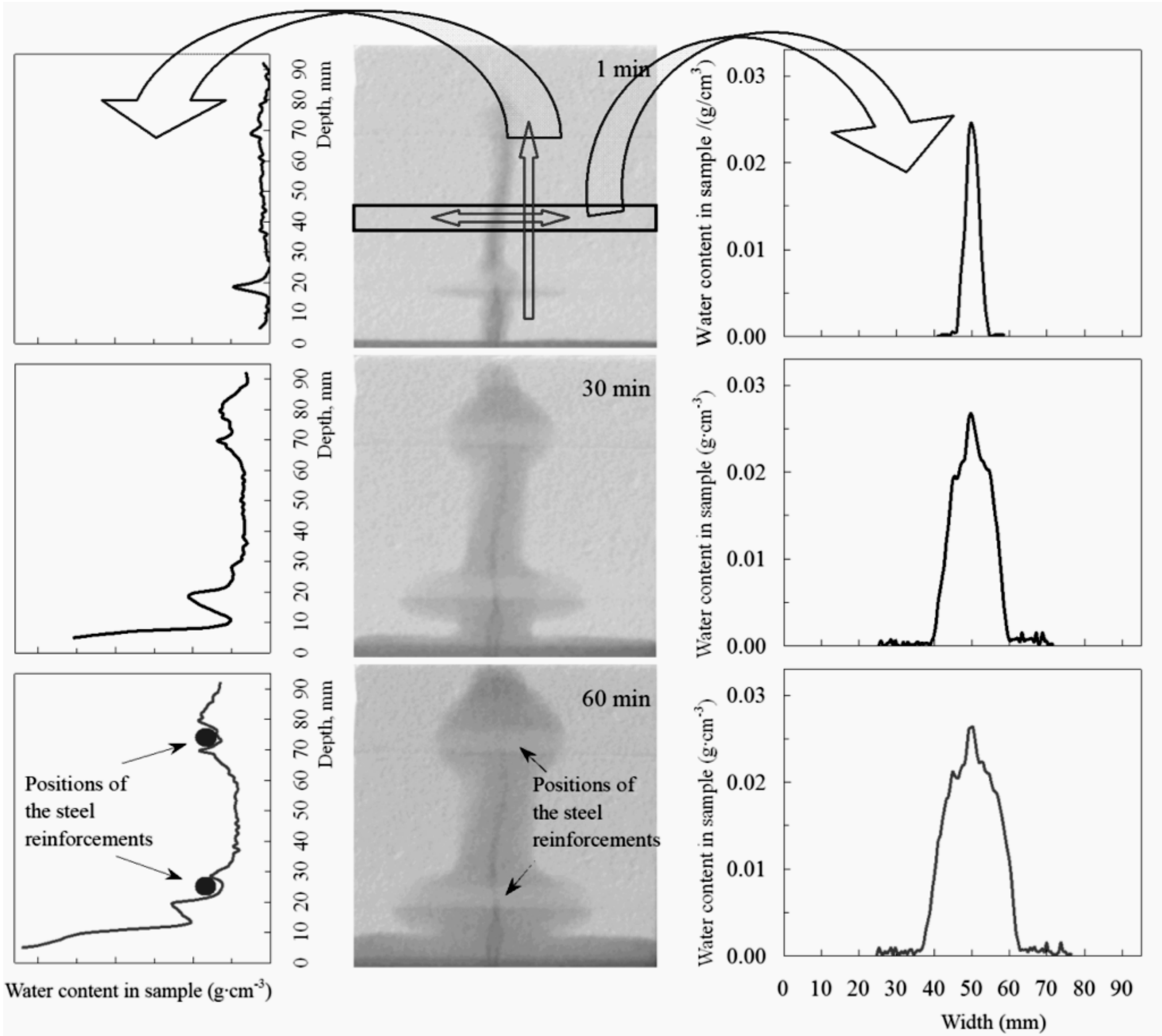
Reality

Experiment configuration

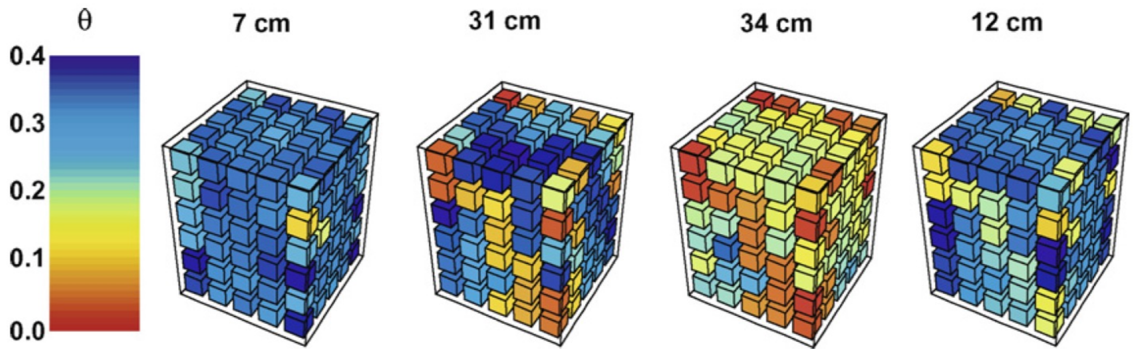


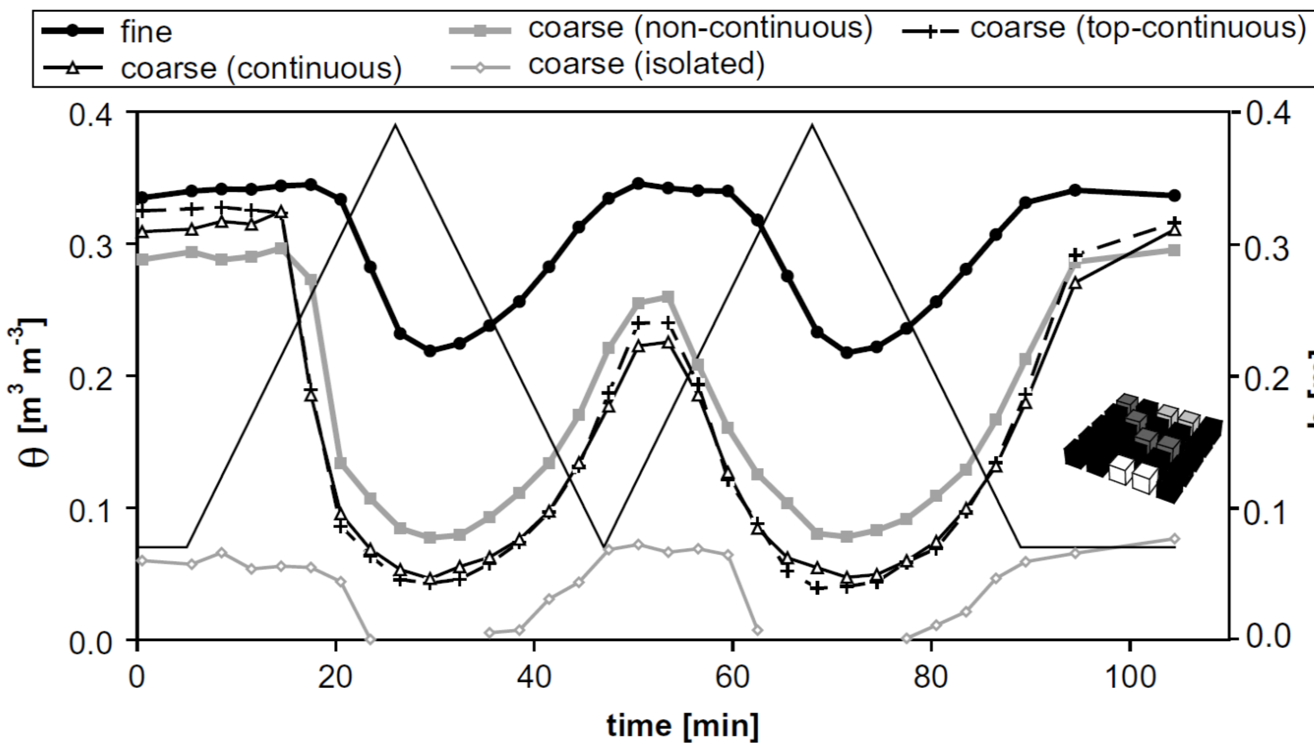
P. Zhang et al., Physica B: Condensed Matter, 405(7), pp 1866-1871, 2010

Salt transport in concrete – Imaging



3D water distribution in sand



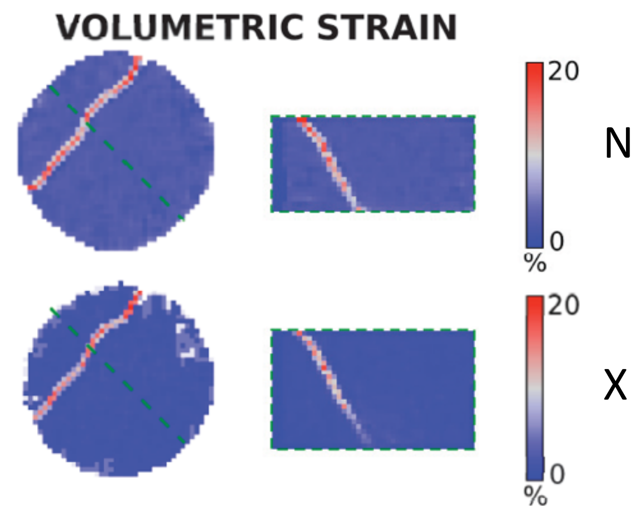


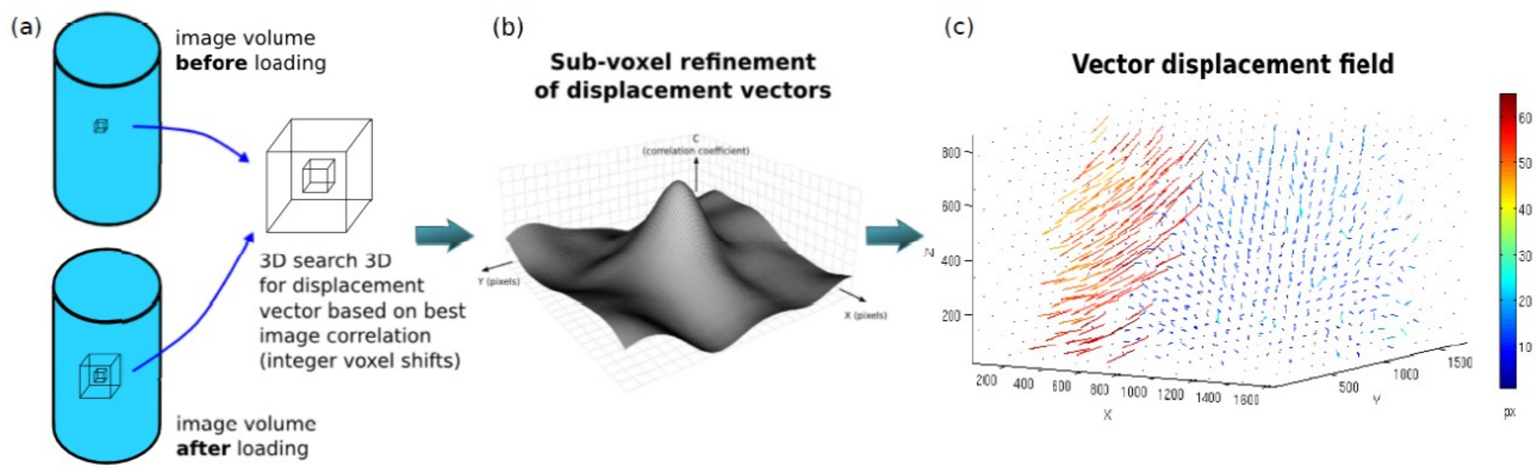
[P. Lehmann et al., AWR, 2008]

Displacement analysis

Digital Image Correlation

- Identifies small displacements using correlation
- Useful for deforming samples



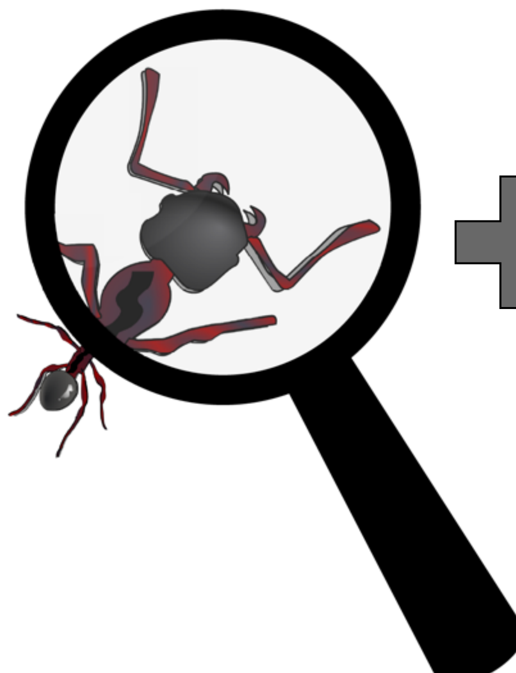


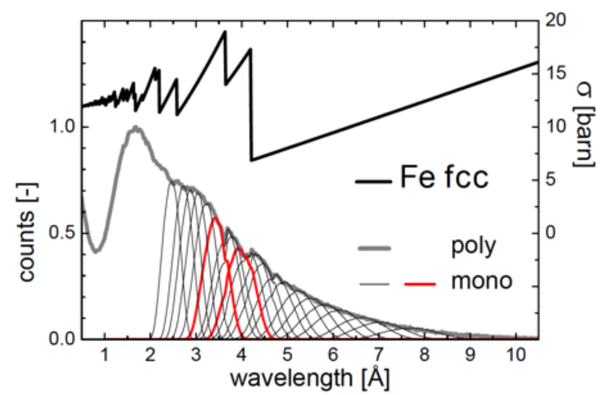
[Tudisco et al., Physics Procedia, 2015]

New posibilities

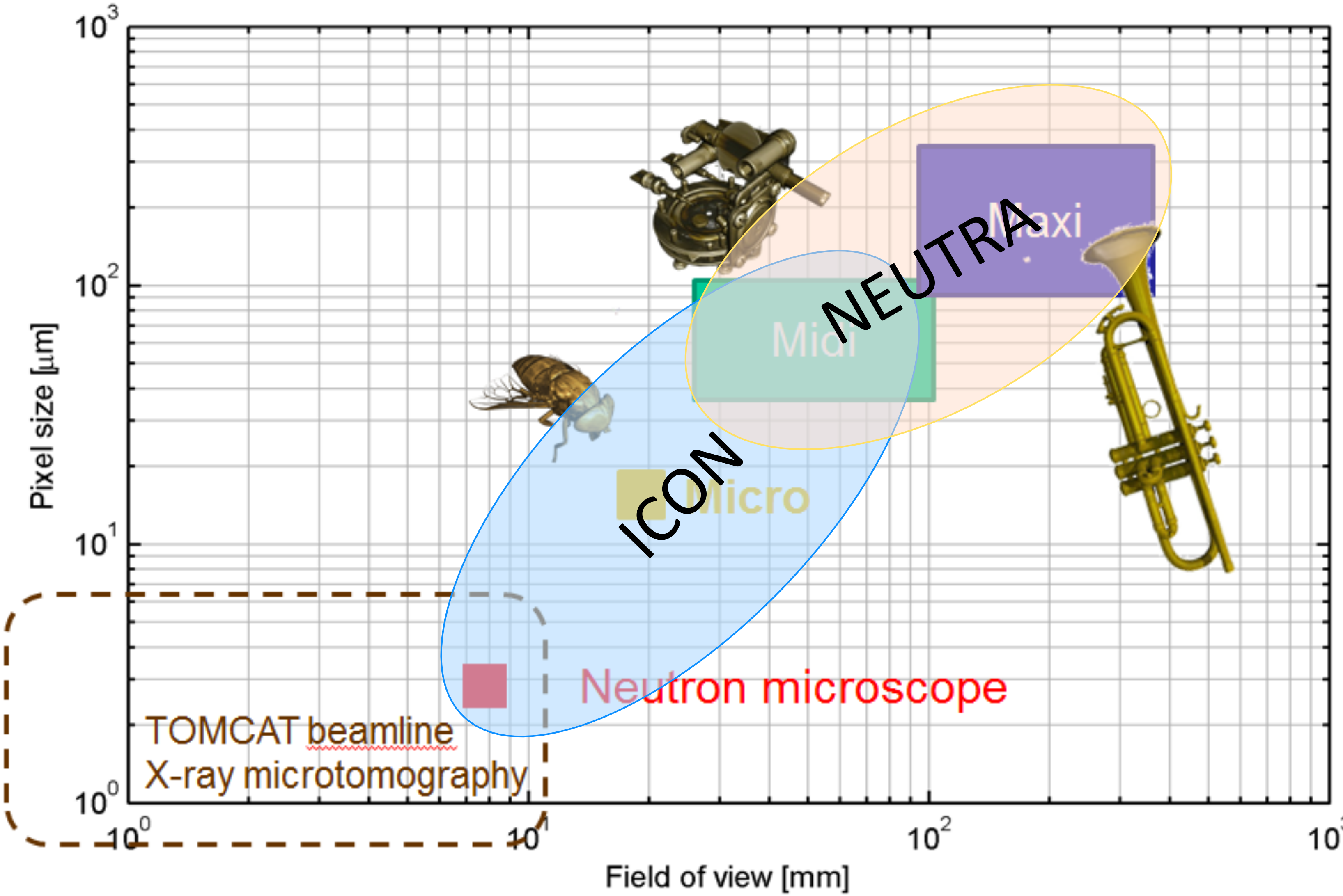
The challenge

- Many users want to …
- measure fast
- see small details in 3D
- with a monochromatic beam





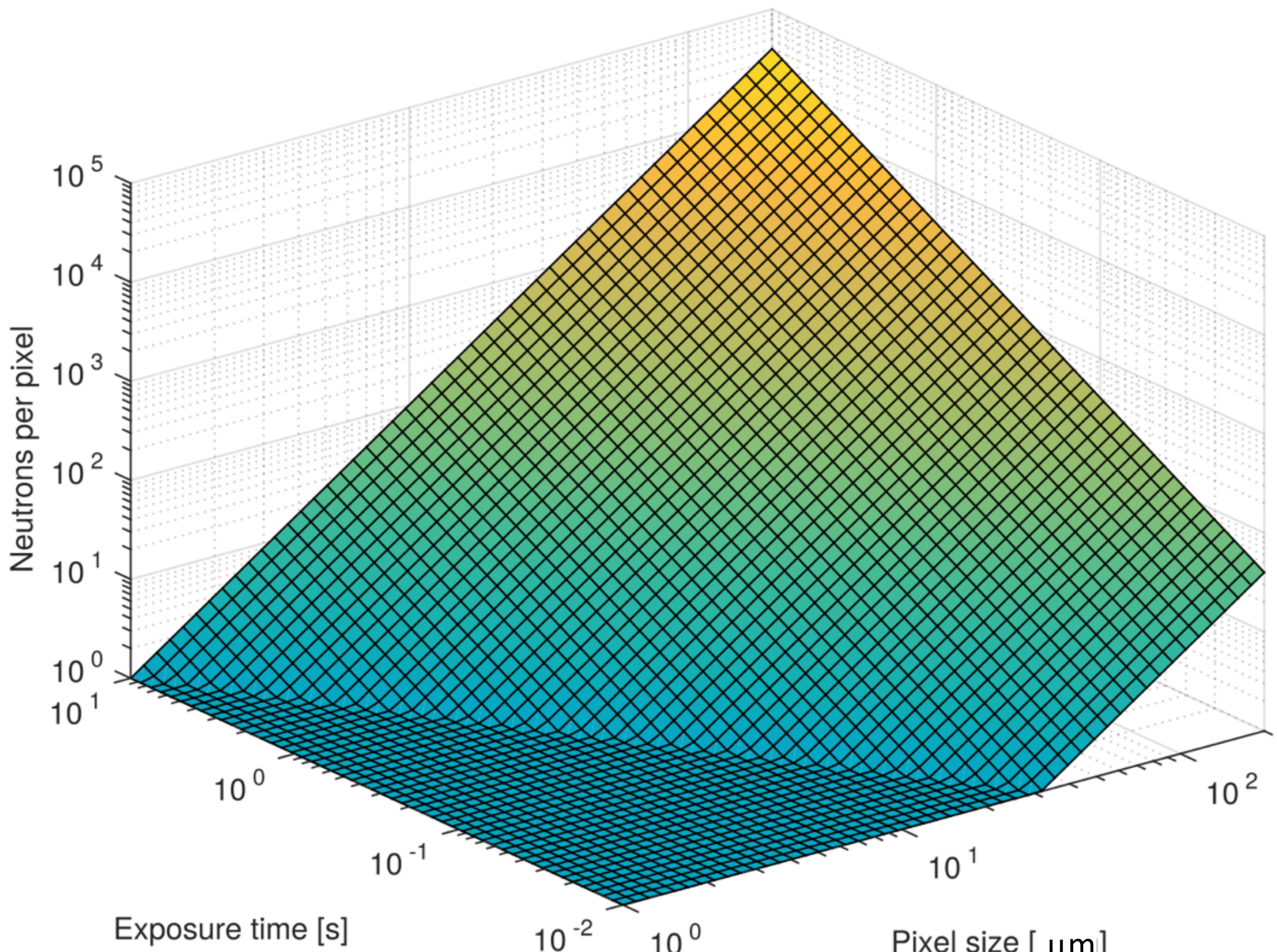
Resolutions in space



Courtesy: P. Trtik, PSI

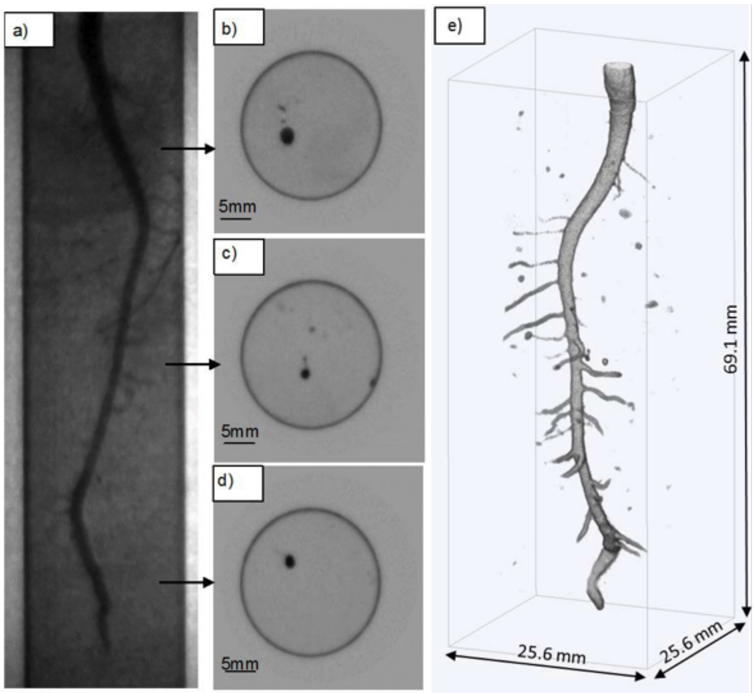
Spatial or temporal resolution

Neutron statistics (pixels and time)



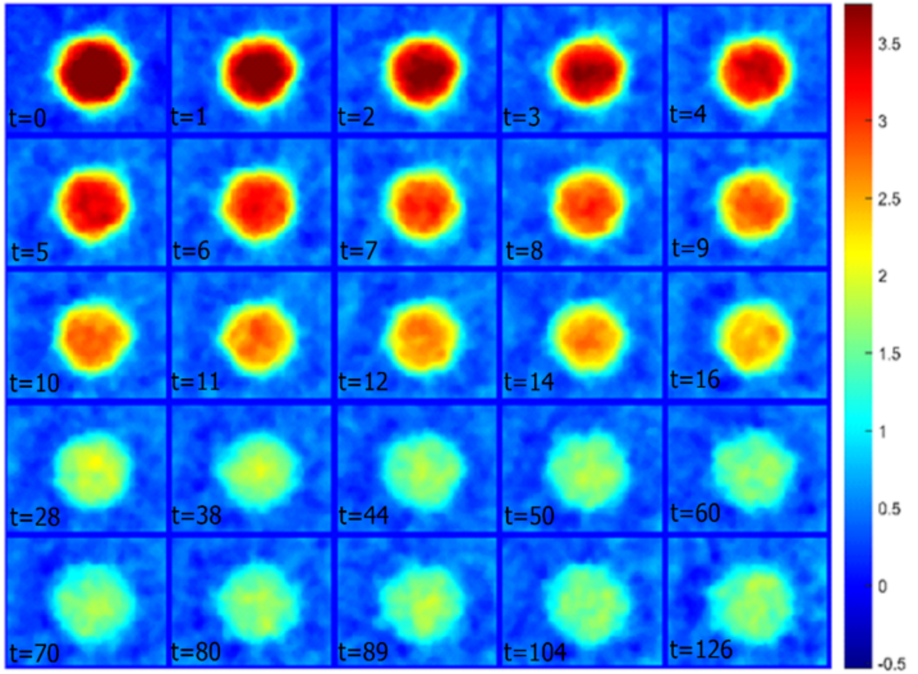
[Kaestner et al., Solid Earth, 2015]

On-the-fly CT – High volume rates



[Zarebanadkouki et al., Physics Procedia, 2015]

D_2O uptake in a root
Volume rate 1/min @ 46μm voxels

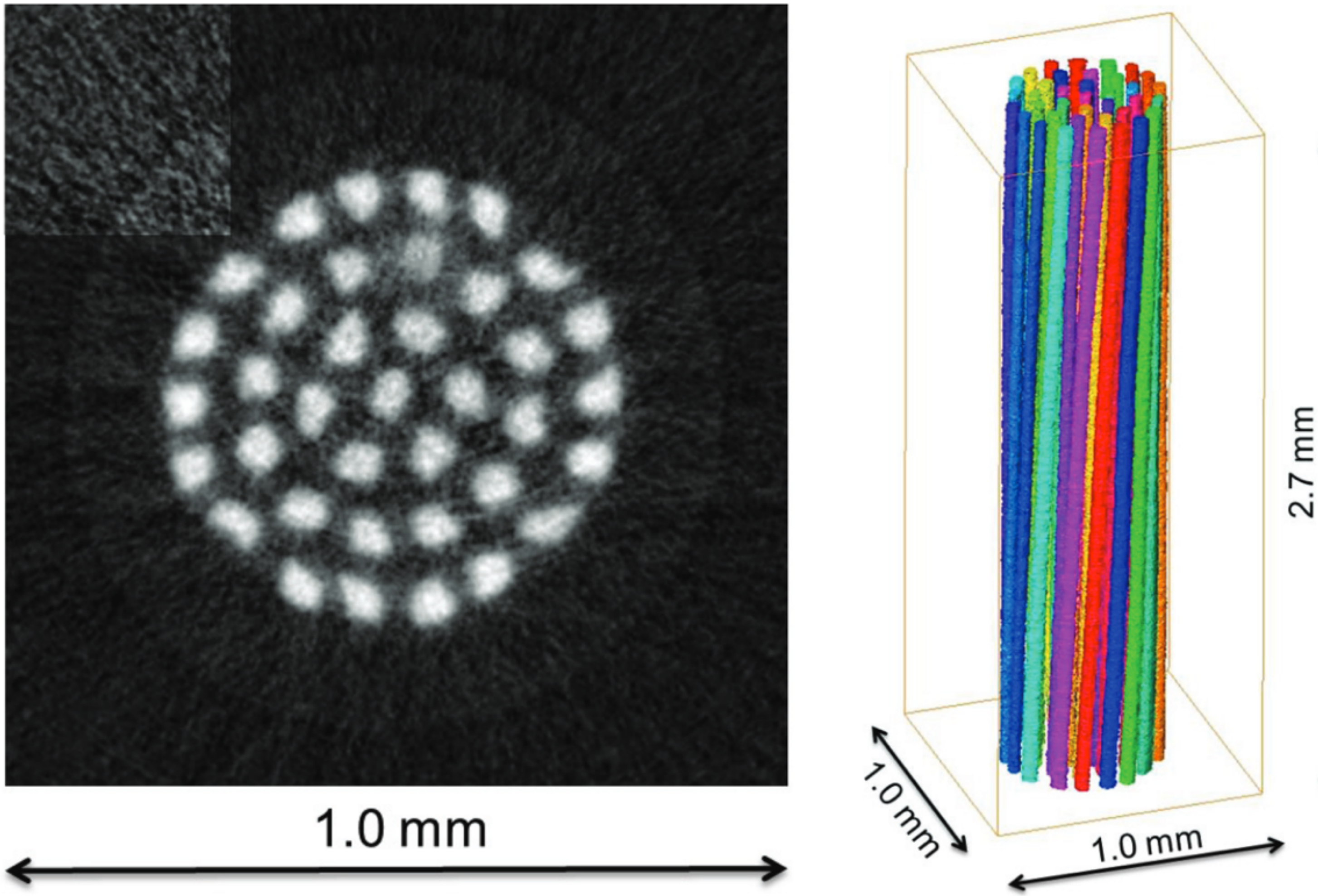


[Kaestner et al., Solid Earth, 2015]

D2O is an ideal tracer in water (contrast difference ~1:10)

High spatial resolution neutron CT

MgB2 superconducting multifilament wire, voxel size 2.7μm



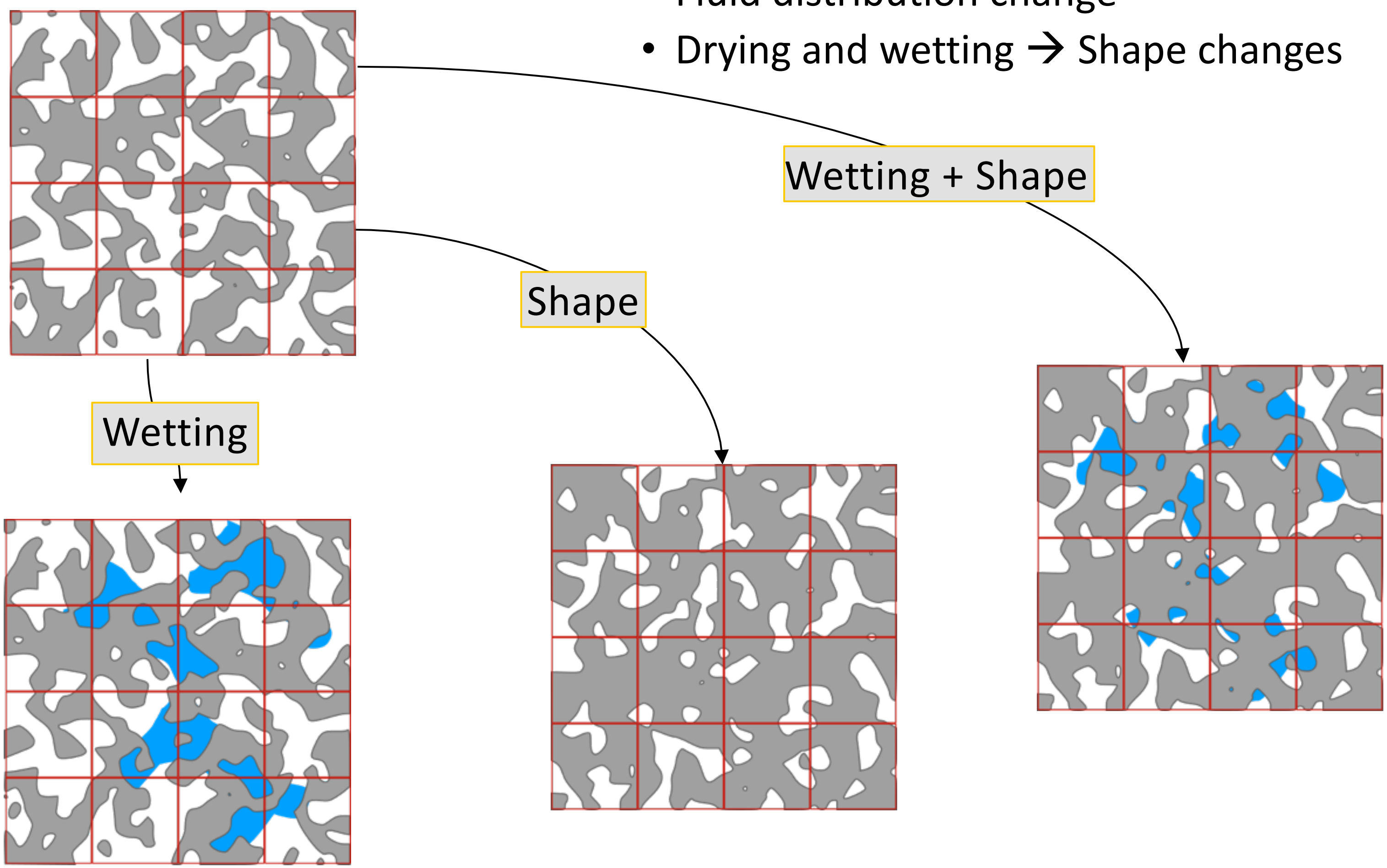
[Trtik et al., Physics Procedia, 2015]

Challenge with porous samples

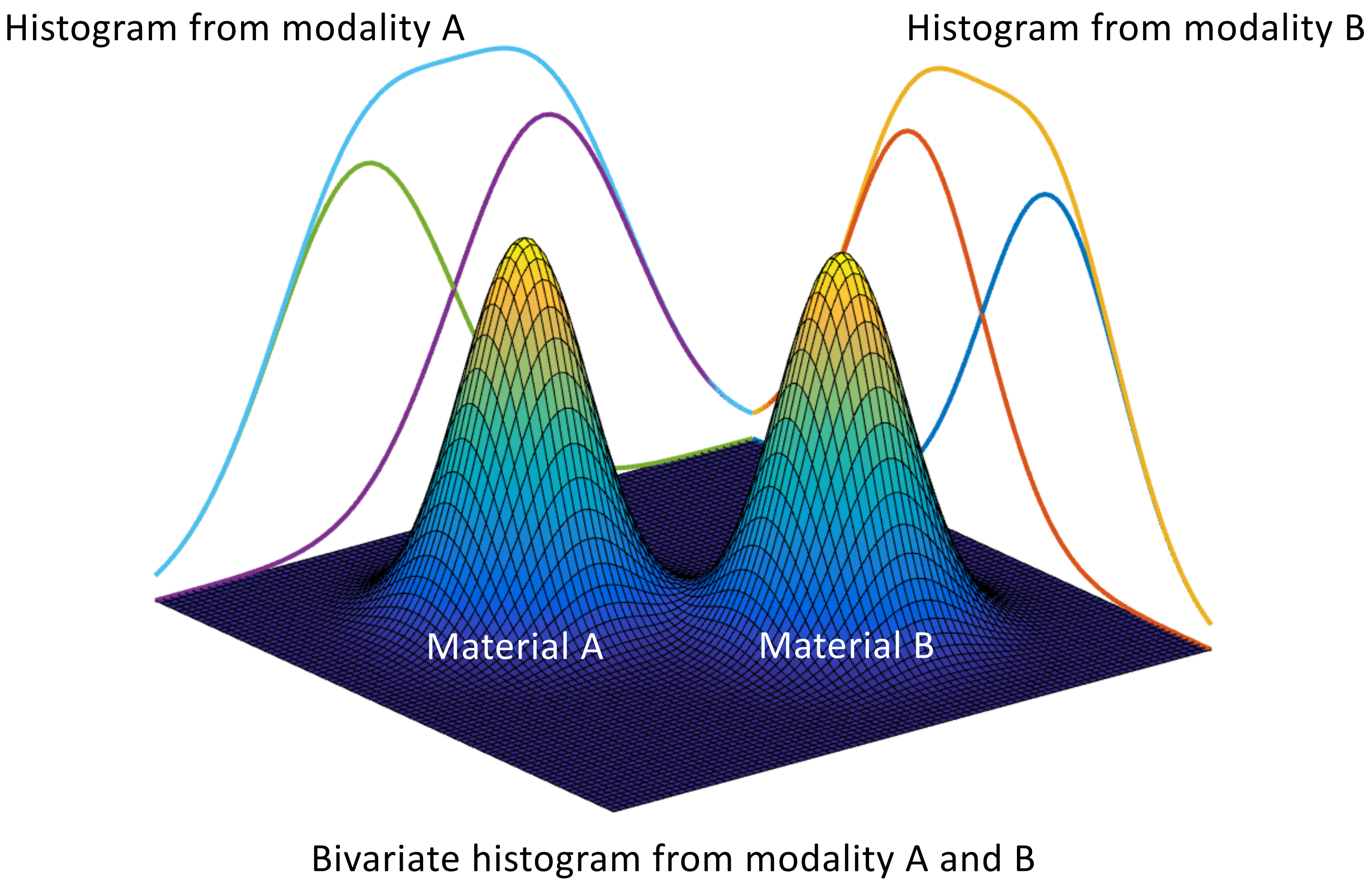
What are the contributions to a pixel intensity?

- Partial volume effects
- Fluid distribution change
- Drying and wetting → Shape changes

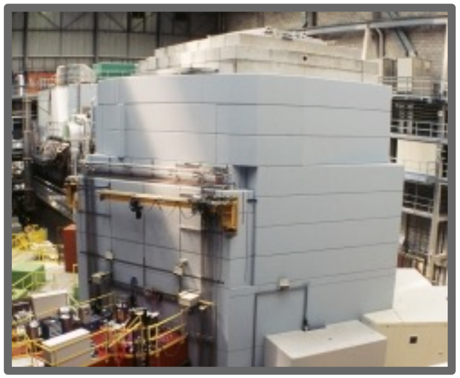
Original state



Working with two modalities



Different approaches to NX-imaging :: Off-site



Neutrons

+

Synchrotron

OR

Lab-based X-ray

Pros
- Different resolutions
- Optimized acquisition times
- Access to equipment (at home)

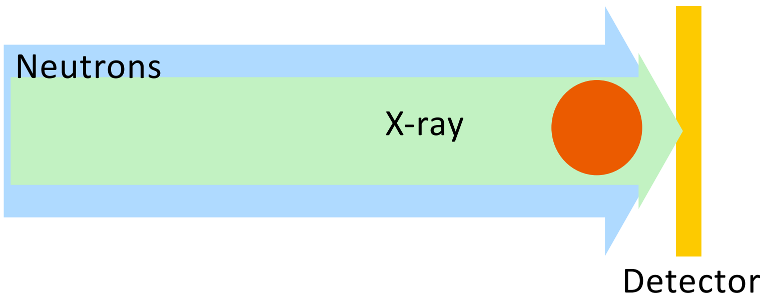
Cons
- Sample transport (sample activation etc.)
- No simultaneous acquisition
- Coordination

Different approaches to NX-imaging :: On-site

Inline

NEUTRA

Beam geometry XTRA option



Pros

- Same detector
- Pixel wise comparable
- Sample is not repositioned
- Strong X-ray source

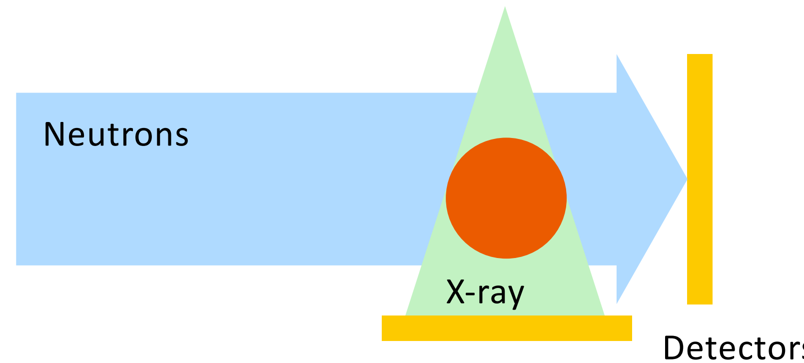
Cons

- No simultaneous acquisition

Perpendicular

ICON

Beam geometry μXTRA option



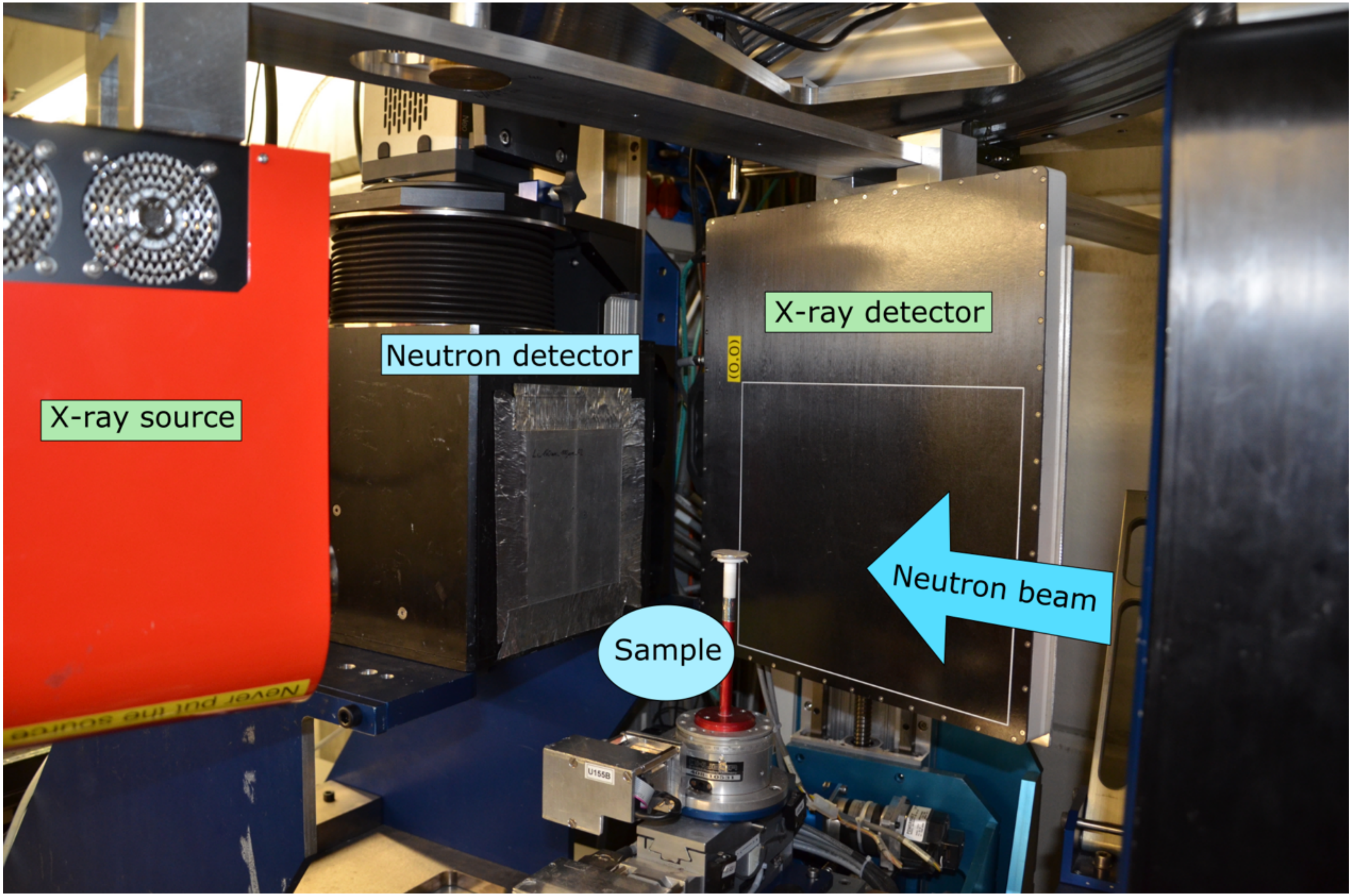
Pros

- Optimized detectors
- Magnification (X-rays)
- Simultaneous acquisition
- Sample is not repositioned

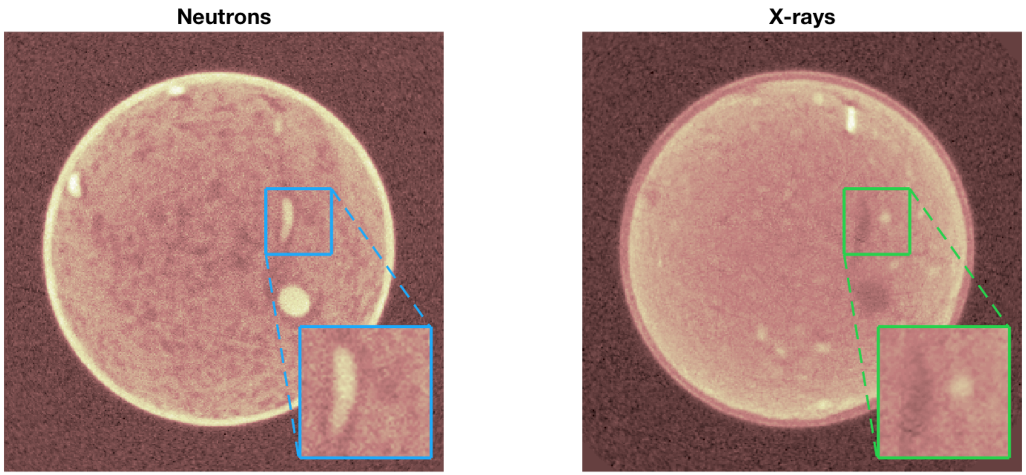
Cons

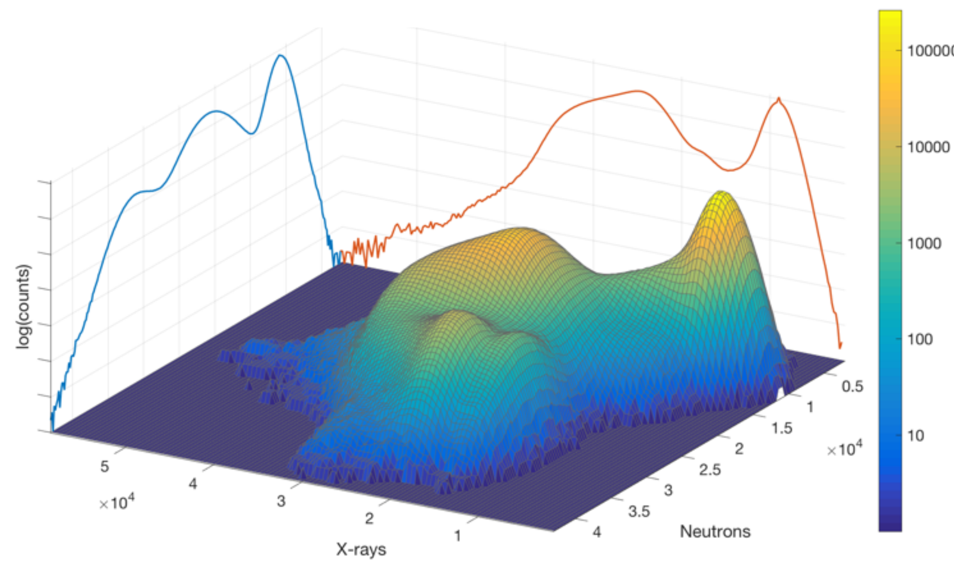
- Different coordinate systems

The perpendicular installation at ICON



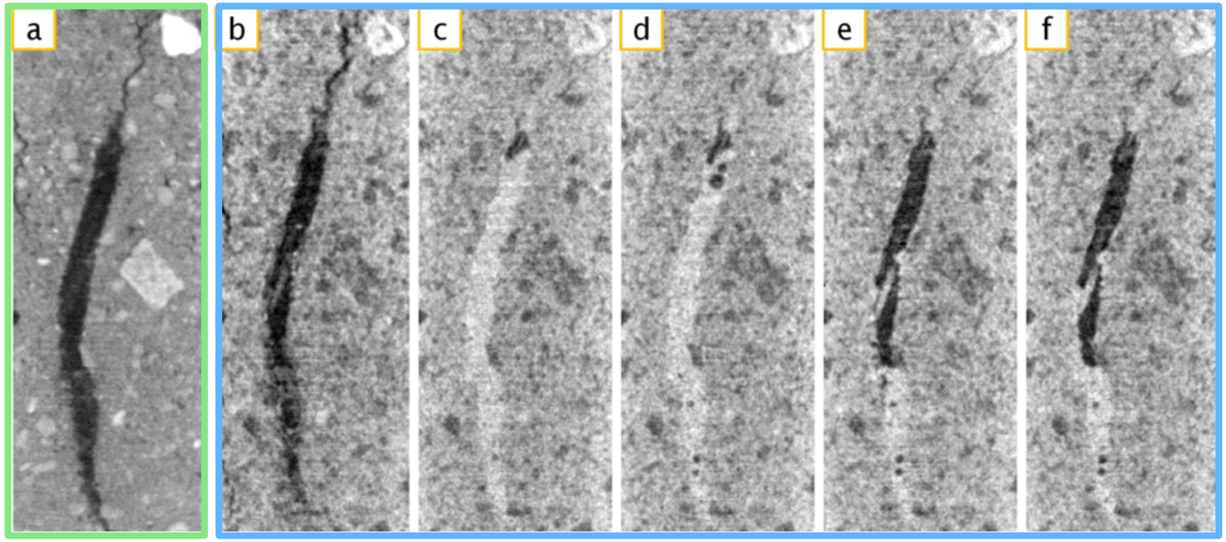
Roots and soil

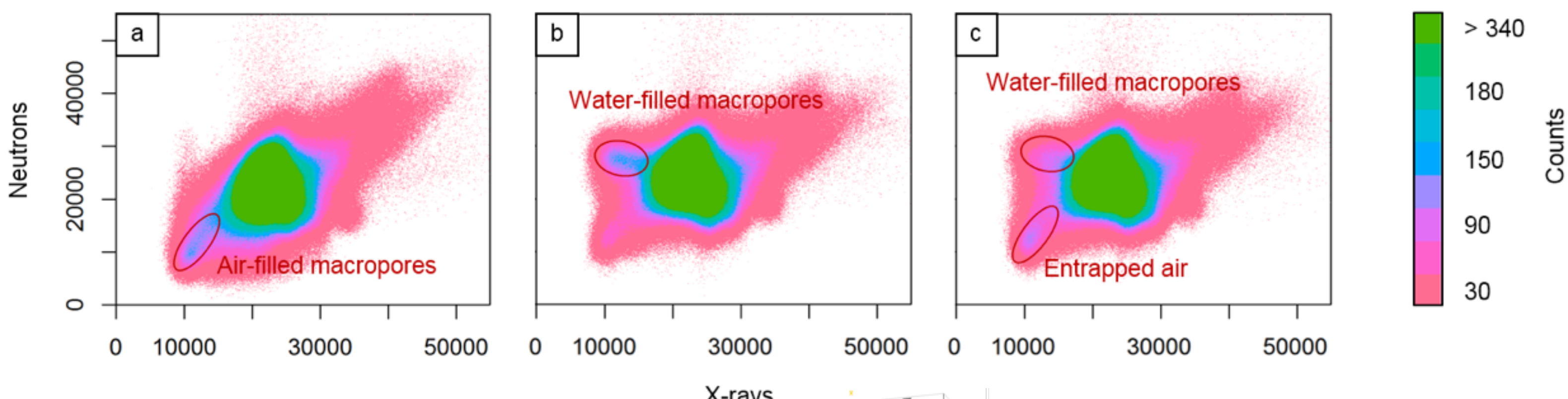


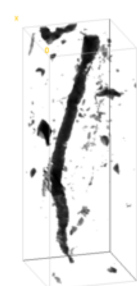


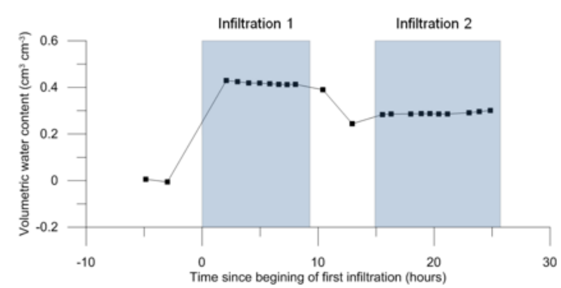
A. Kaestner et al. Physics procedia 2017

Dynamic study of water in soil





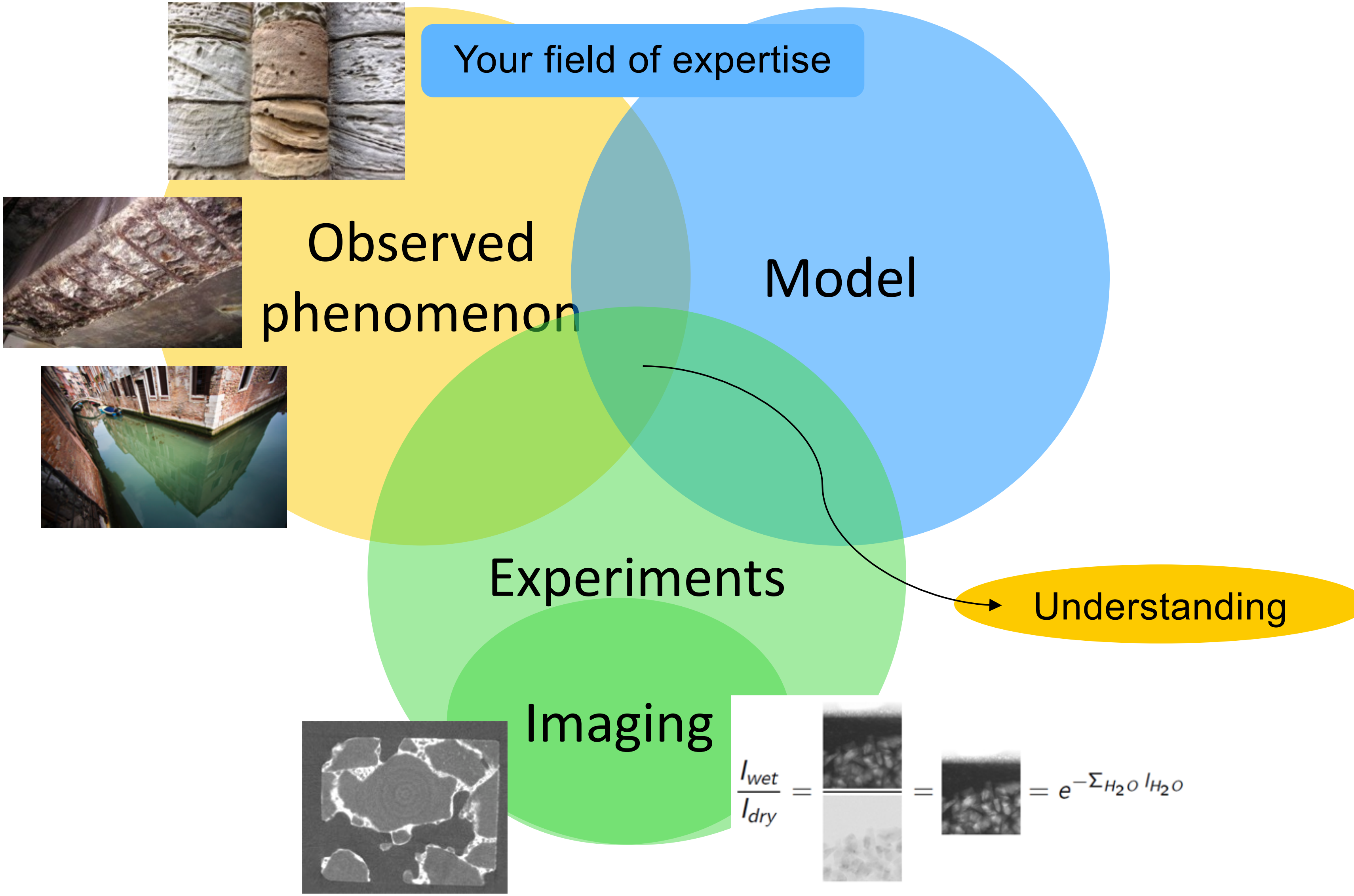




A. Kaestner, …, M. Snehota et al. Solid Earth, 2016

Summary

Summarizing schematic



Neutron imaging …

… is a well-used tool for porous media research.

… has high sensitivity to fluids.

… method development allow new insights.

You are welcome to submit proposals:
https://duo.psi.ch/duo/
Next deadline:

Wir schaffen Wissen – heute für morgen

My thanks go to

- The Neutron Imaging activation Group, PSI
- Our user community