Luise Theil Kuhn
Head of Section “Imaging and Structural Analysis”

# Neutron Imaging

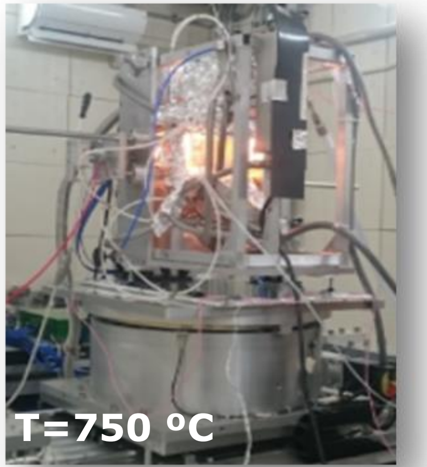
**A basic and recent text on neutron imaging: 50th IFF Spring School ”Scattering! Soft, Functional and Quantum Materials” (Forschungszentrum Jülich 2019)**
Download here:
https://www.fz-juelich.de/pgi/EN/Leistungen/SchoolsAndCourses/SpringSchool/History/SpringSchool2020/Lecture-Notes/_node.html

# Motivation

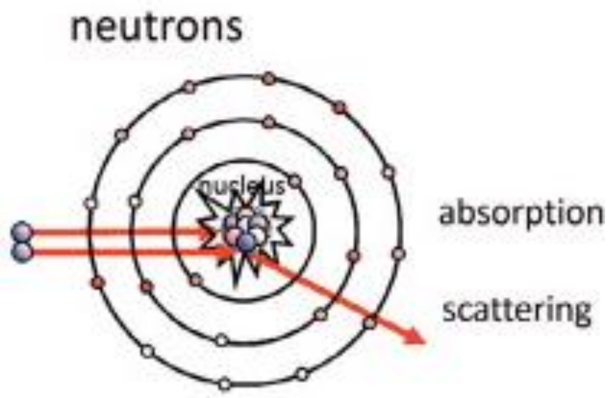
# This module's important concepts

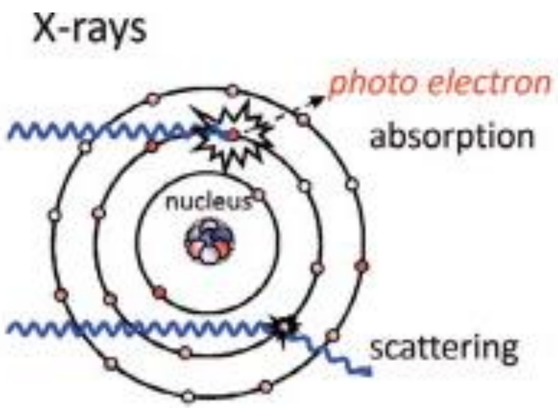


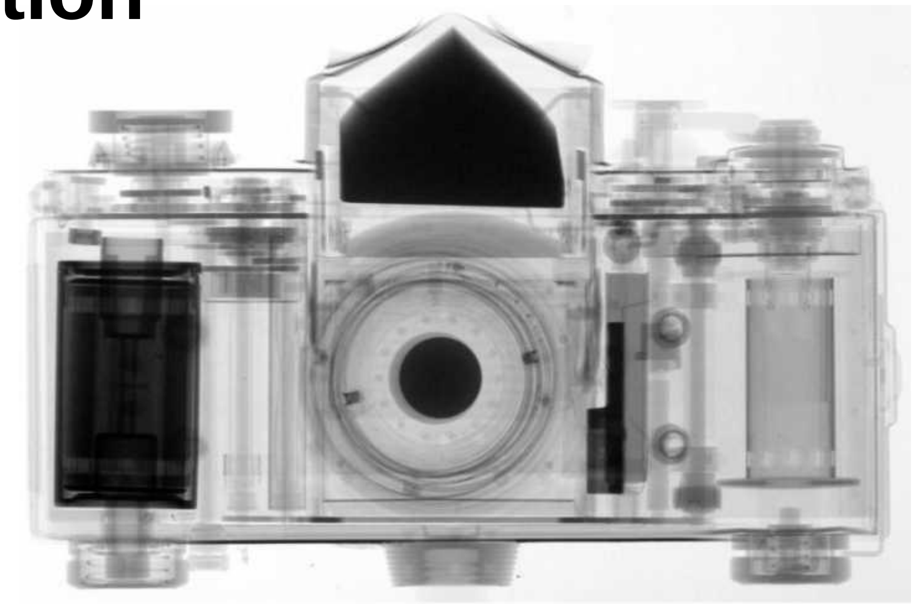
- Instrumentation
- Radiography
- Tomography
- In operando
- Virtual Imaging experiment

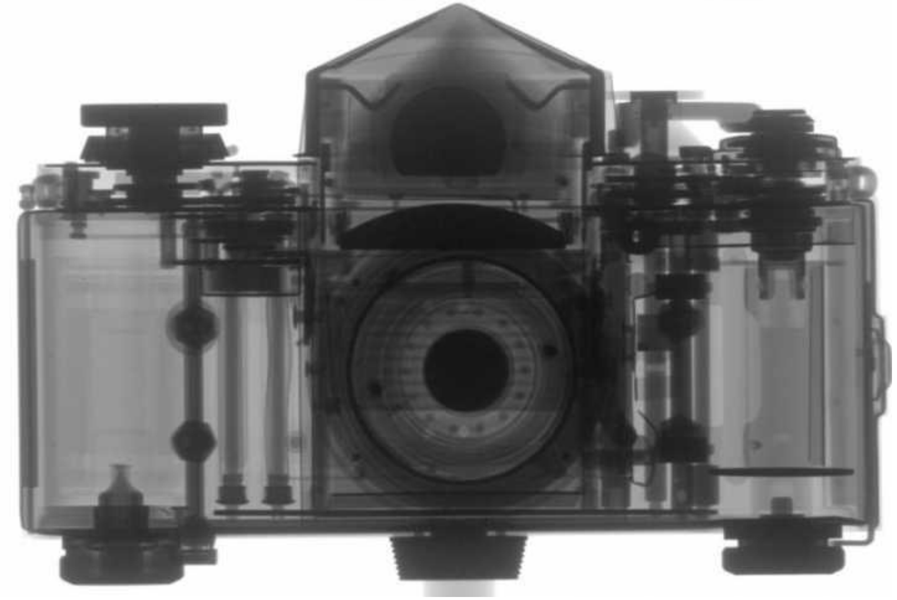


# Image and contrast formation

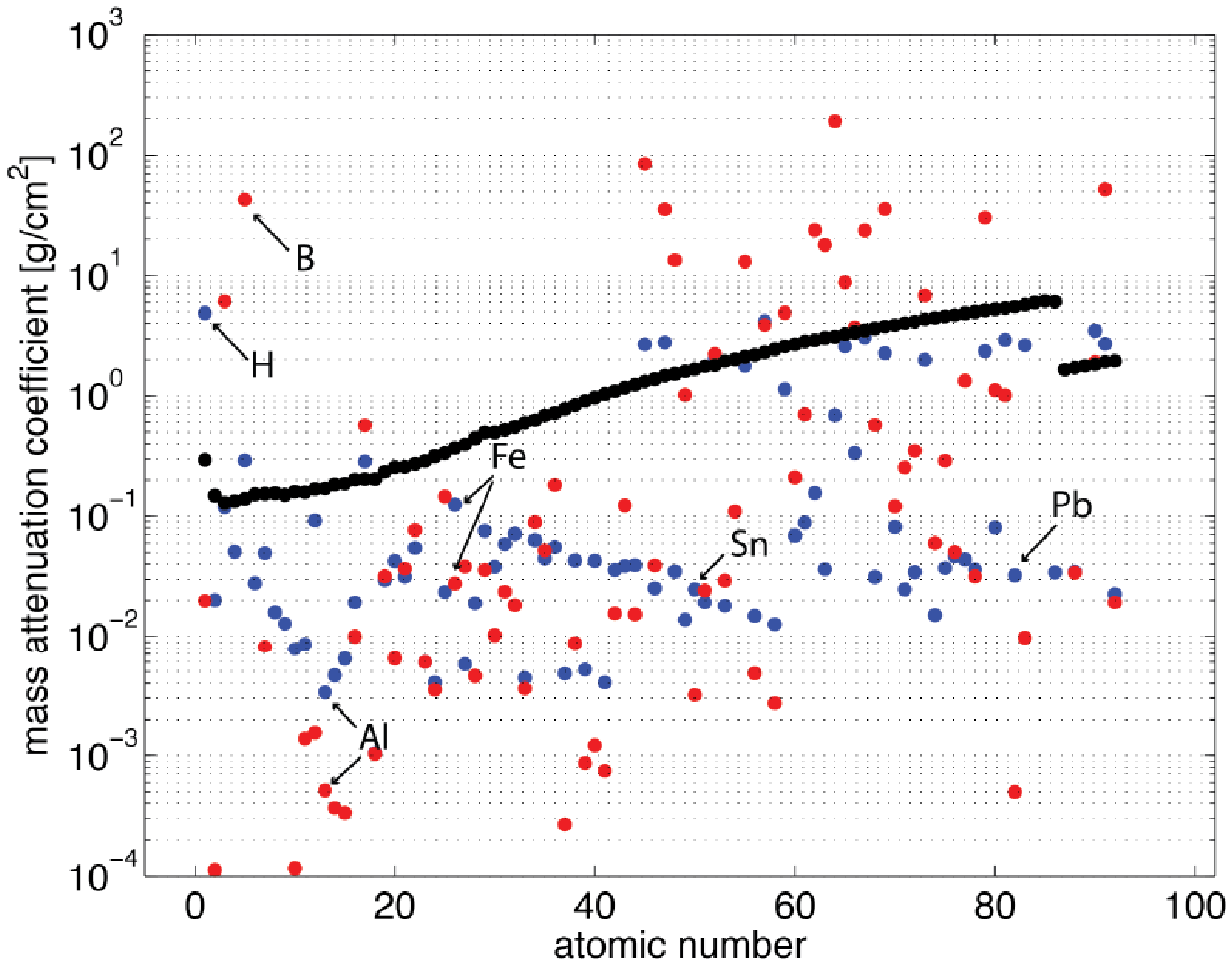


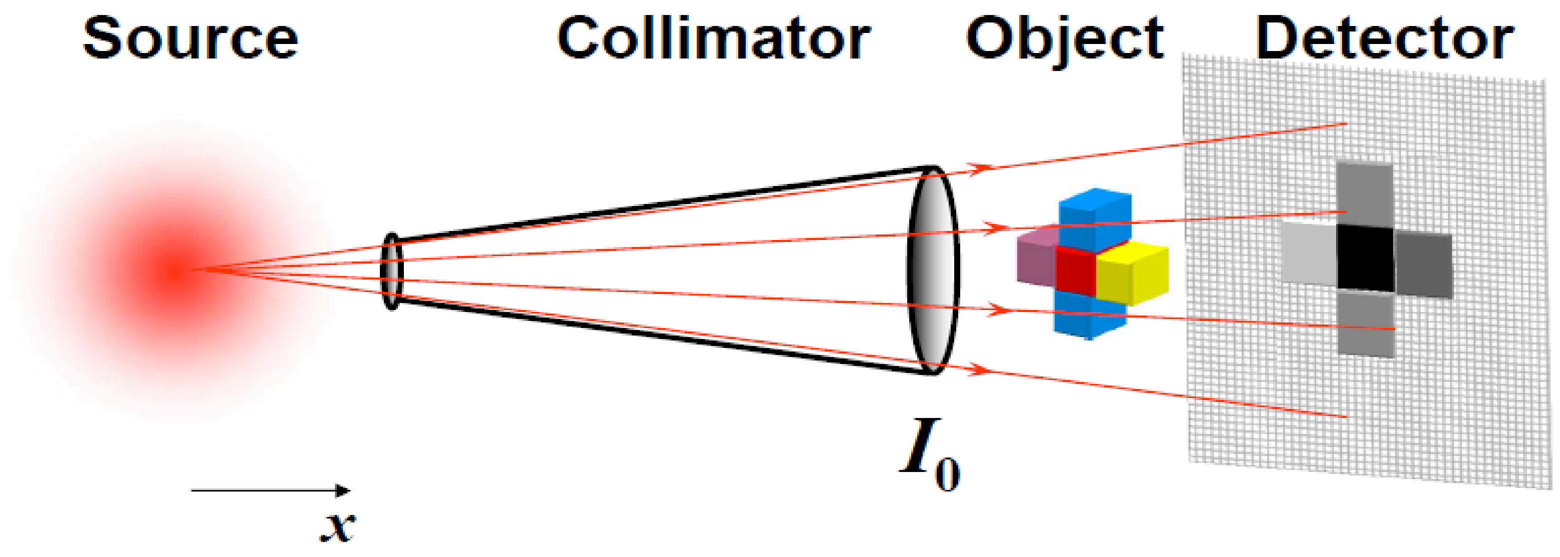


# Image and contrast formation




$$\frac{\mu}{\rho} = \frac{N_a}{M}\sigma$$

# Radiography




Beer-Lambert law: $\sim I_0 e^{-\int \mu(x)dx}$

$x$ – propagation direction

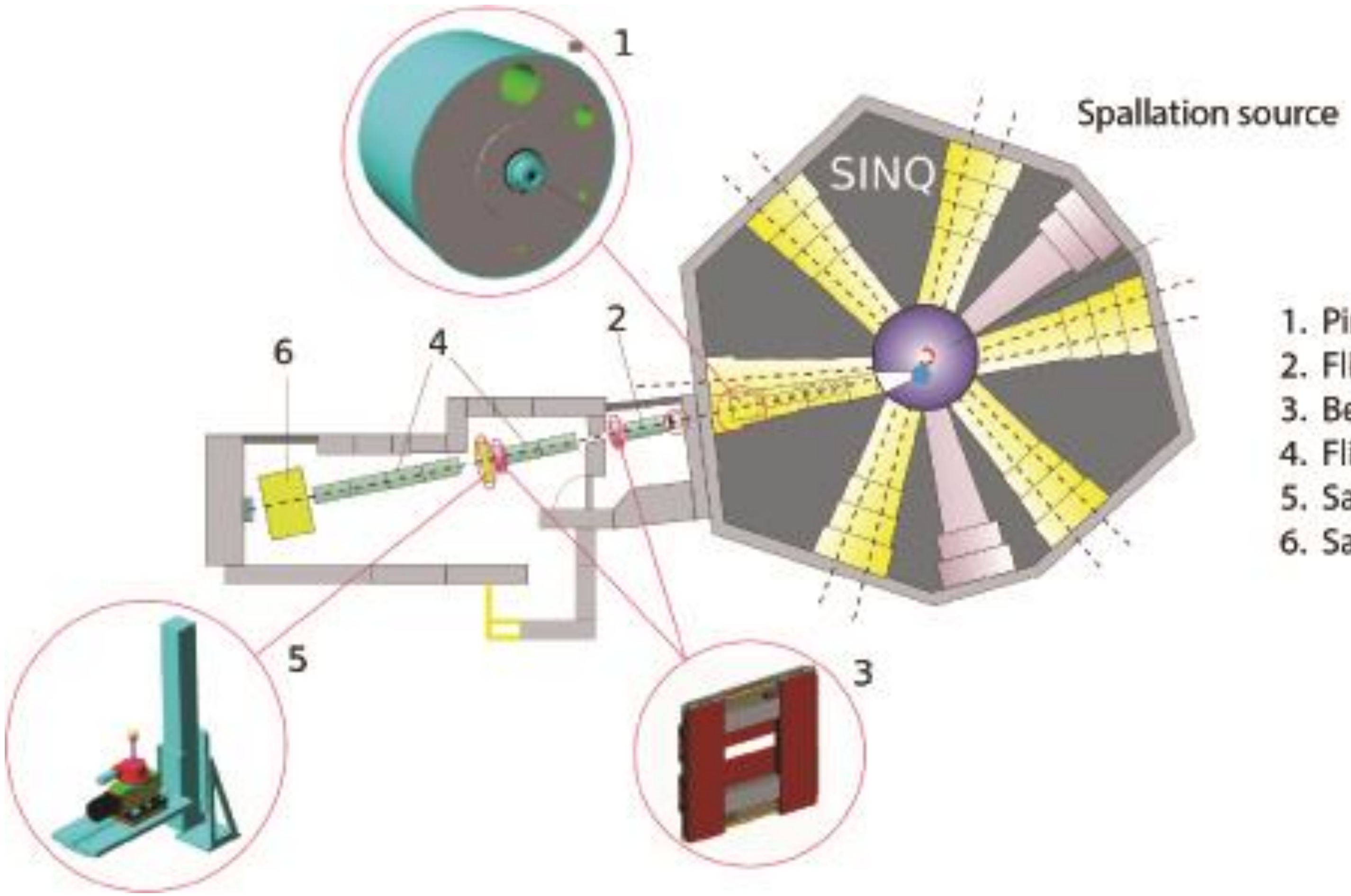
$I_0$ – primary beam

$\mu(x)$ – attenuation coefficient

$\mu_{total} = \mu_a + \mu_s$

Strobl, M. et al. (2009). *J. Phys. D. Appl. Phys.* **42**, 243001.

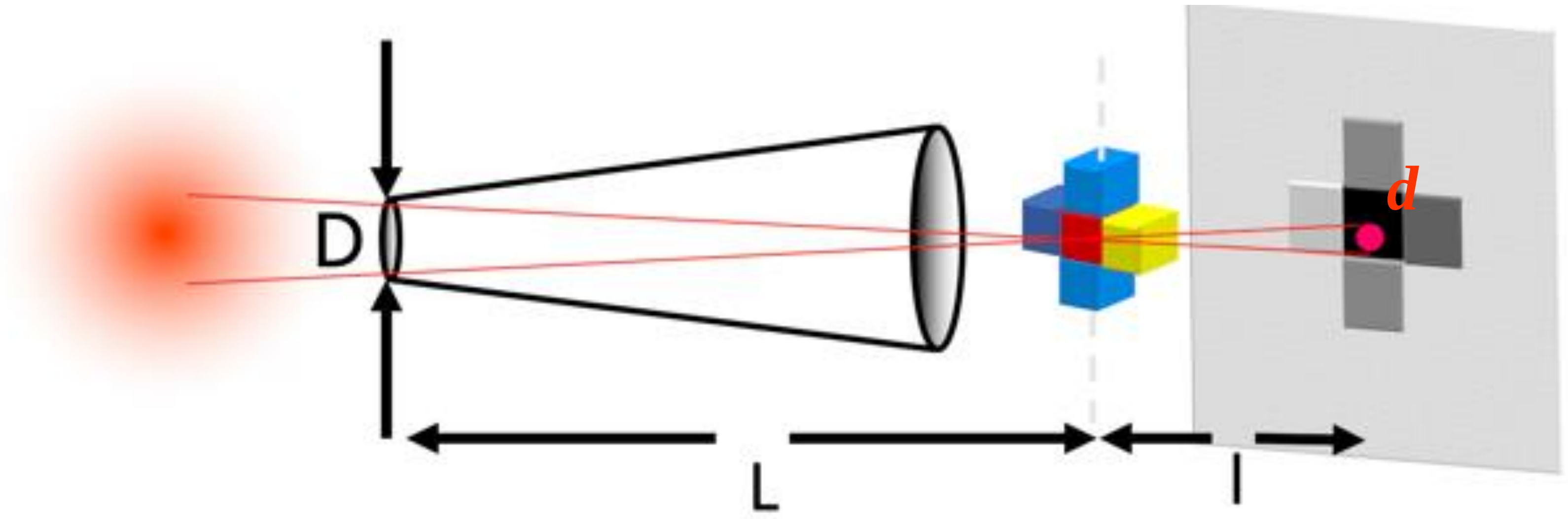
# Setup: ICON @ PSI

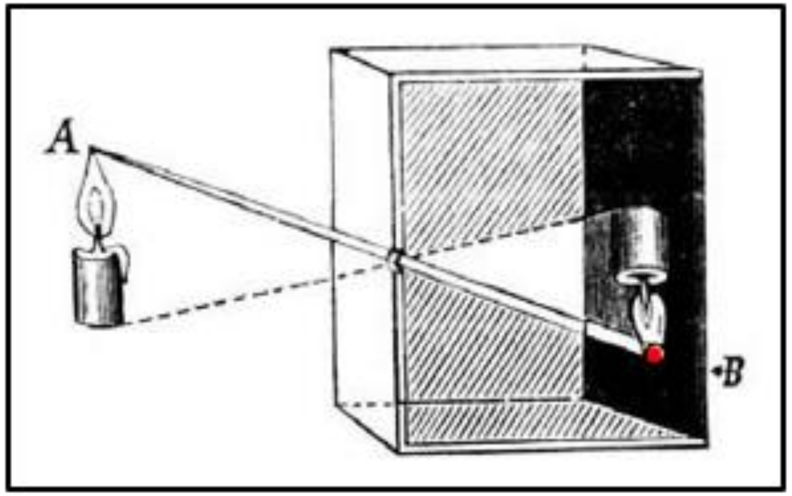



1. Pinhole
2. Flight tube
3. Beam limiters
4. Flight tube
5. Sample stage for small samples
6. Sample stage for large samples

# Spatial resolution

**Source Collimator Object Detector** **Camera obscura**




$D$ – **Collimator aperture, pinhole**

$L$ – **Distance Collimator-Object**

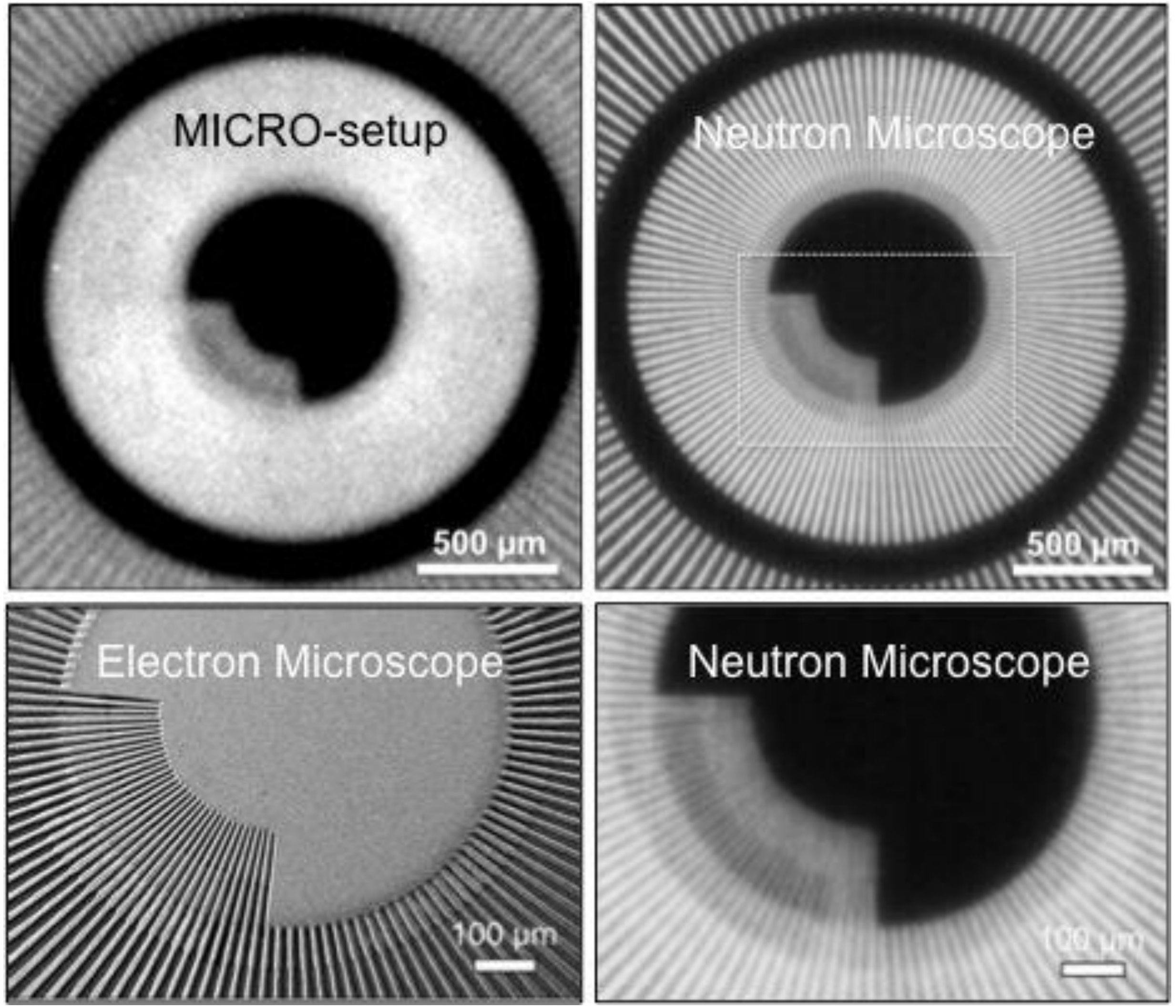
$l$ – **Distance Object-Detector**

$$d = \frac{l}{L/D}$$

Strobl, M. et al. (2009). *J. Phys. D. Appl. Phys.* **42**, 243001.

# Spatial resolution - Siemens star

32.9 μm

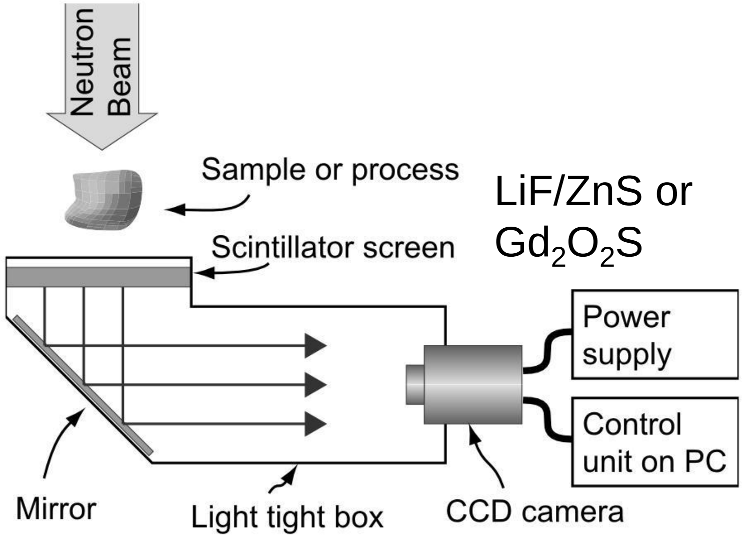



7.6 μm

Trtik, P. et al. (2015). *Physics Procedia.* **69**, 169.

# Detectors

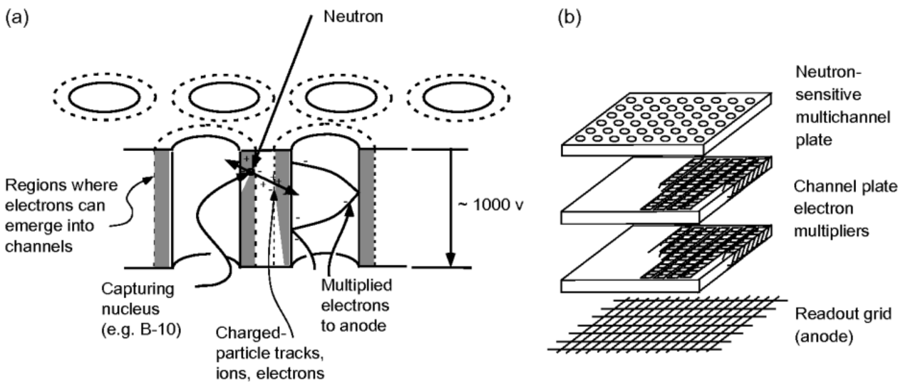
## Charged Coupled Device



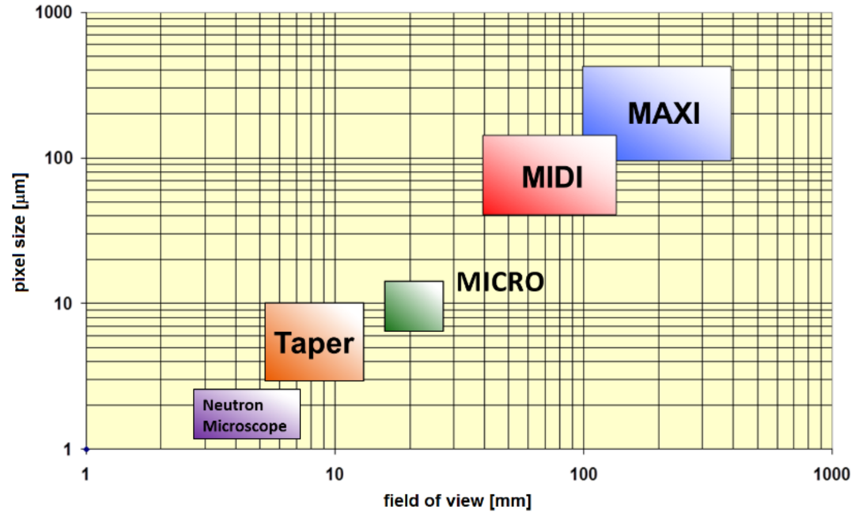

LiF/ZnS or $Gd_2O_2S$

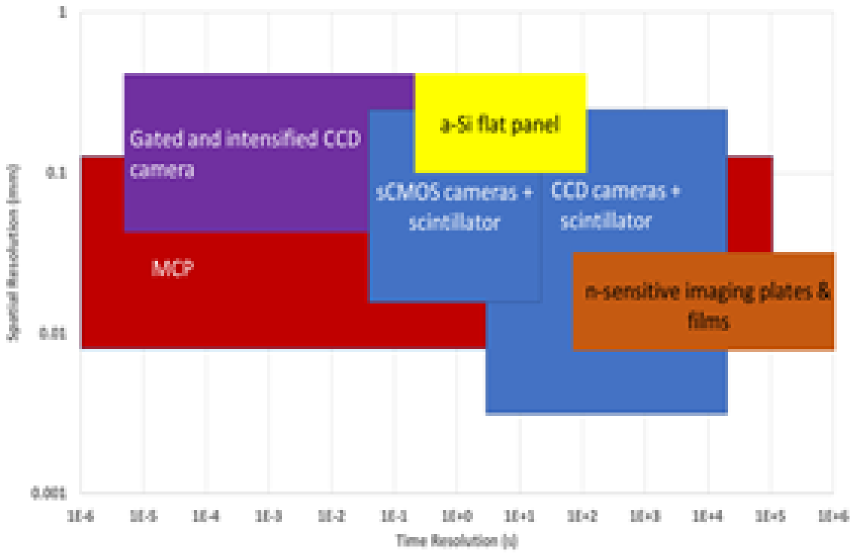
FOV: 0.5x0.5 $m^2$ to 5x5 $mm^2$
Pixelsize: 500x500 $\mu m^2$ to 1.5x1.5 $\mu m^2$

## Multi Channel Plate




*http://www.novascientific.com/technology/*



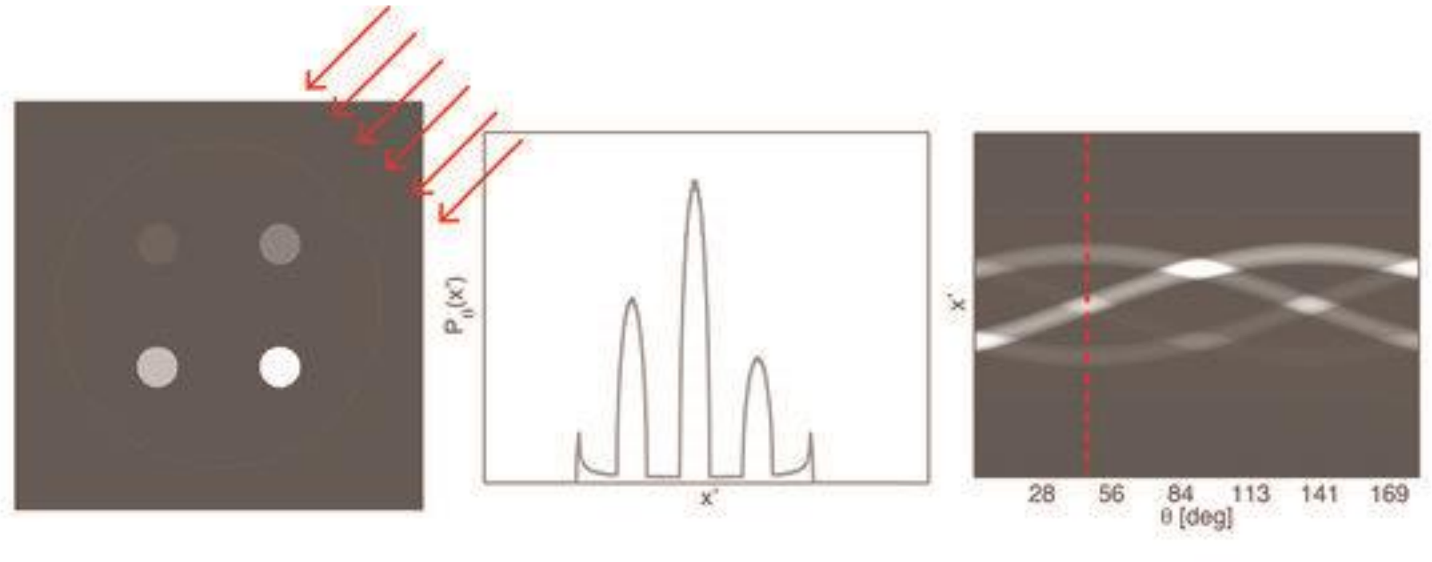



# Principle for data acquisition in imaging experiment

1. Raw image, $I_\theta$
2. Dark field image (no beam), correct for dark-current in detector system, *DF*
3. Flat-field image (open beam), correct for inhomogeneities in beam-profile and in detector screen, *FF*
4. Image, $T_\theta$

$$T_\theta = \frac{I_\theta - DF}{FF - DF}$$

# Tomography

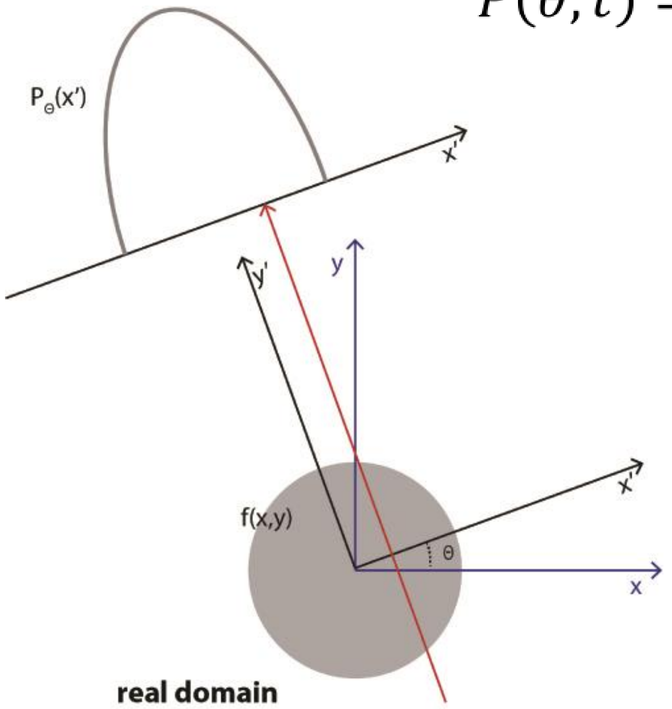



2D sample | Projection image $T_\theta$ | Sinogram

no. of projections $n$ with resolution $d$ of object with size $R$

$$n = \frac{\pi}{2}\frac{R}{d}$$

# Tomographic reconstruction – Radon transform

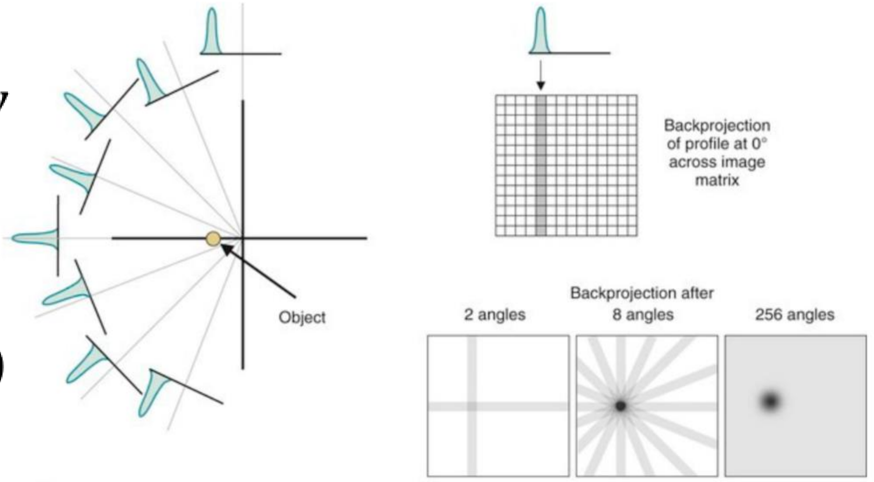


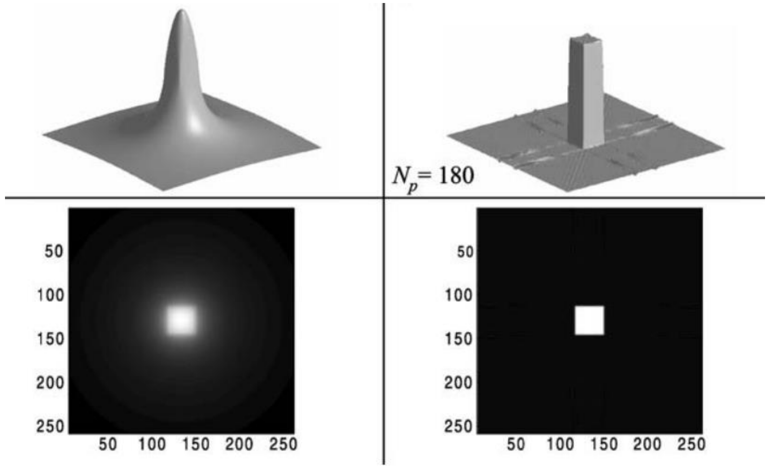

$$P(\theta,t) = \int\int f(x,y)\delta_D(x cos\theta + y sin\theta - t)dxdy$$

$$f'(x,y) = \frac{1}{n}\sum_{i=1}^{n} P(\theta_i, x cos\theta_i + y sin\theta_i)$$

$$\hat{P}(\theta_i,\omega) = \int P(\theta_i,\omega)e^{-i2\pi\omega t}dt$$

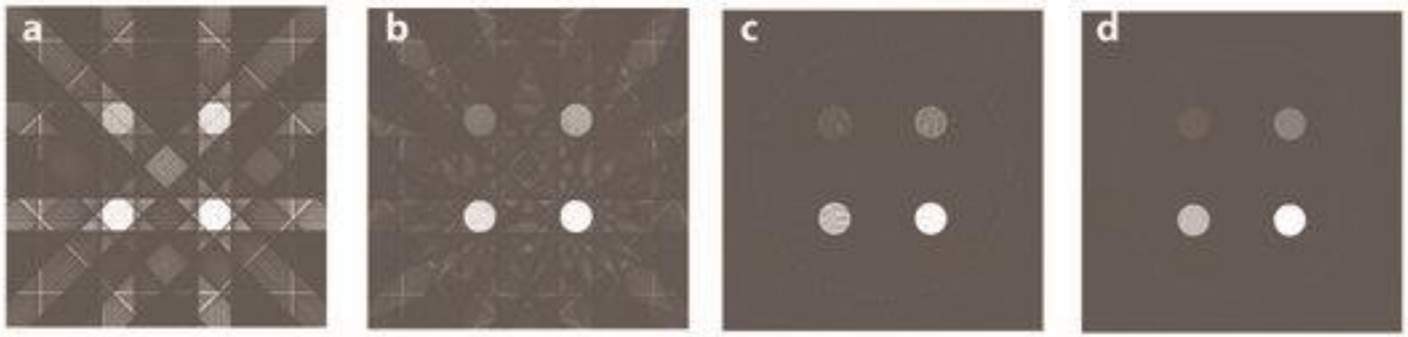
$$P_f(\theta_i,\omega) = \int \hat{P}(\theta_i,\omega)\, e^{-i2\pi\omega t}|\omega| d\omega$$



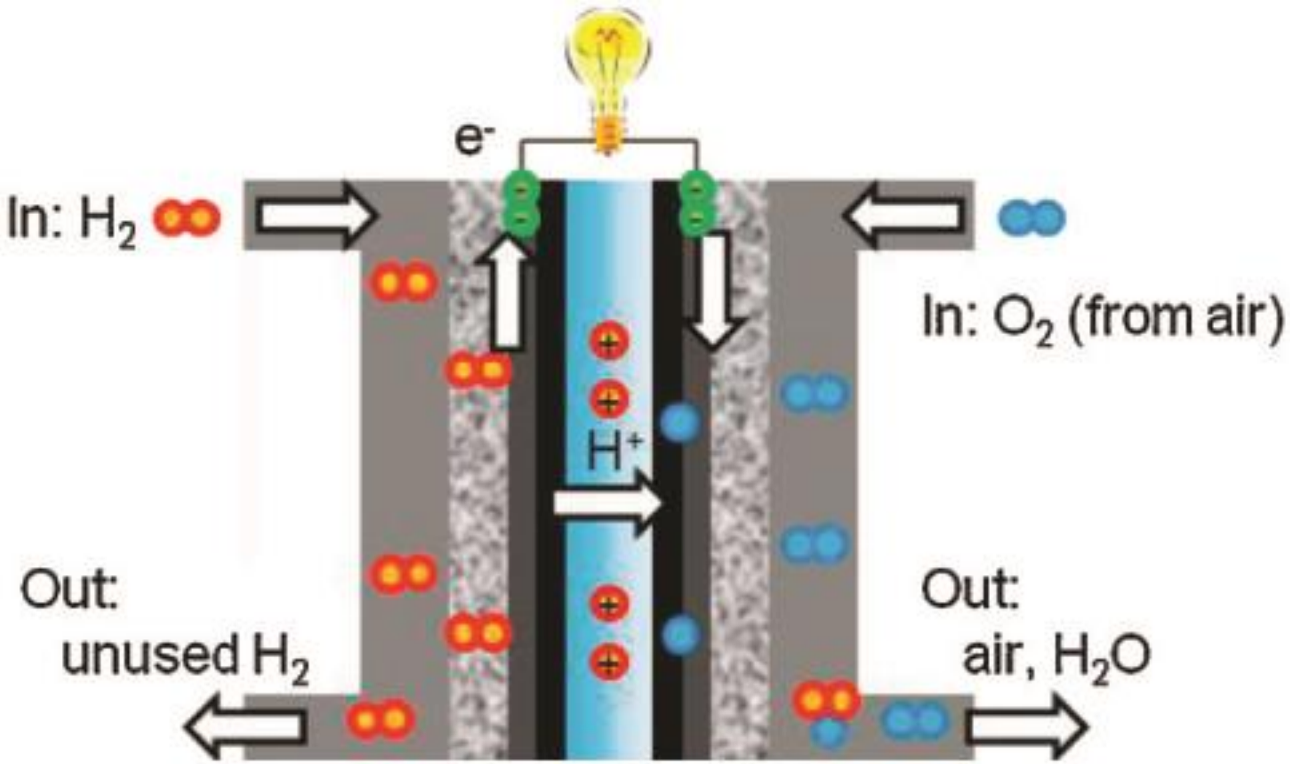
# Principle for tomographic reconstruction

1. Collect projections, $P_\theta(x')$, for several angles
2. Calculate the Fourier transform of each projection
3. Apply the Fourier filter to approximate the ideal case
4. Find the inverse Fourier transformation of the filtered projection
5. Sum over all angles to make the reconstruction



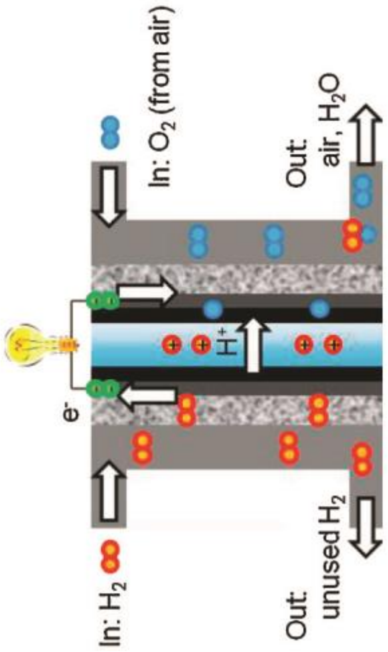

4 projections    8 projections    32 projections    128 projections

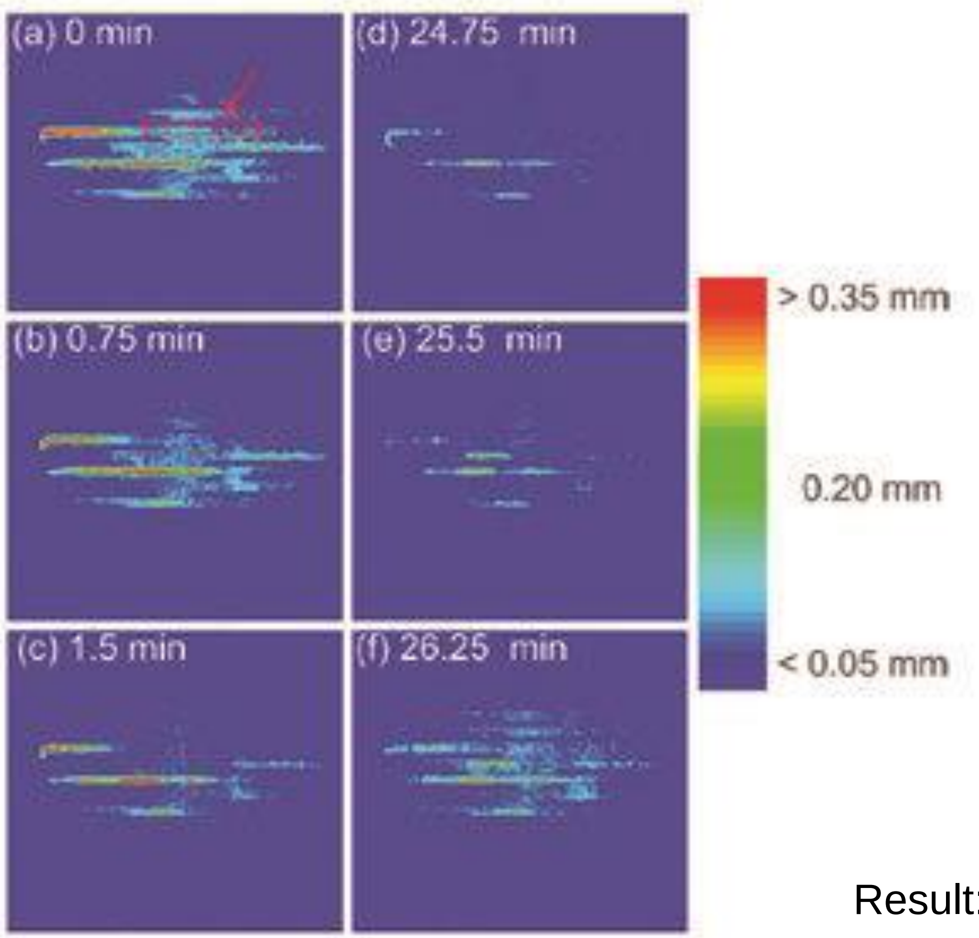
# Cases:
# Polymer Electrolyte Membrane Fuel Cell (PEMFC)



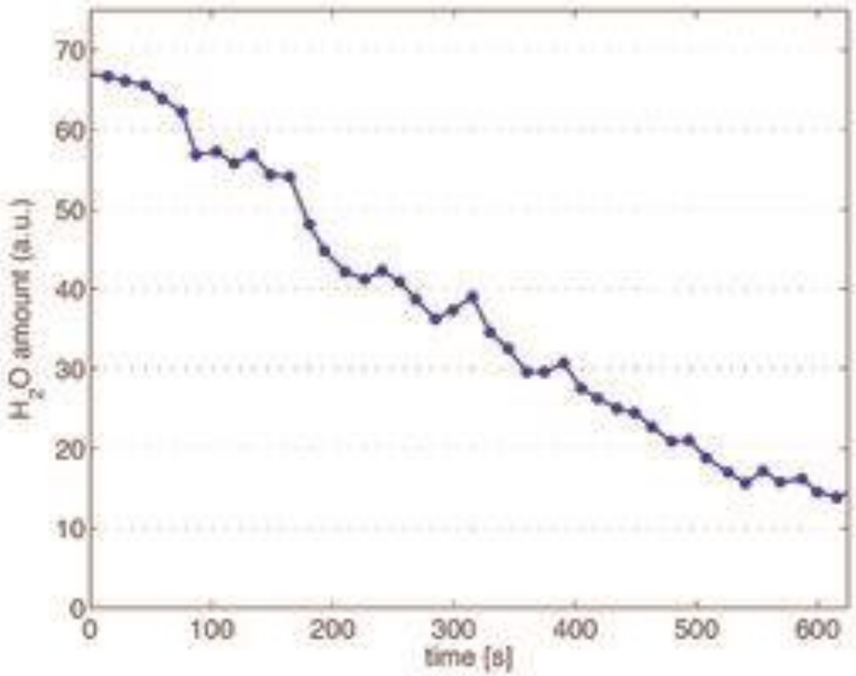

Mischler, J. et al. (2010). *Electrochimica Acta.* **75**, 1.

# Cases: In-situ study of water in PEMFC



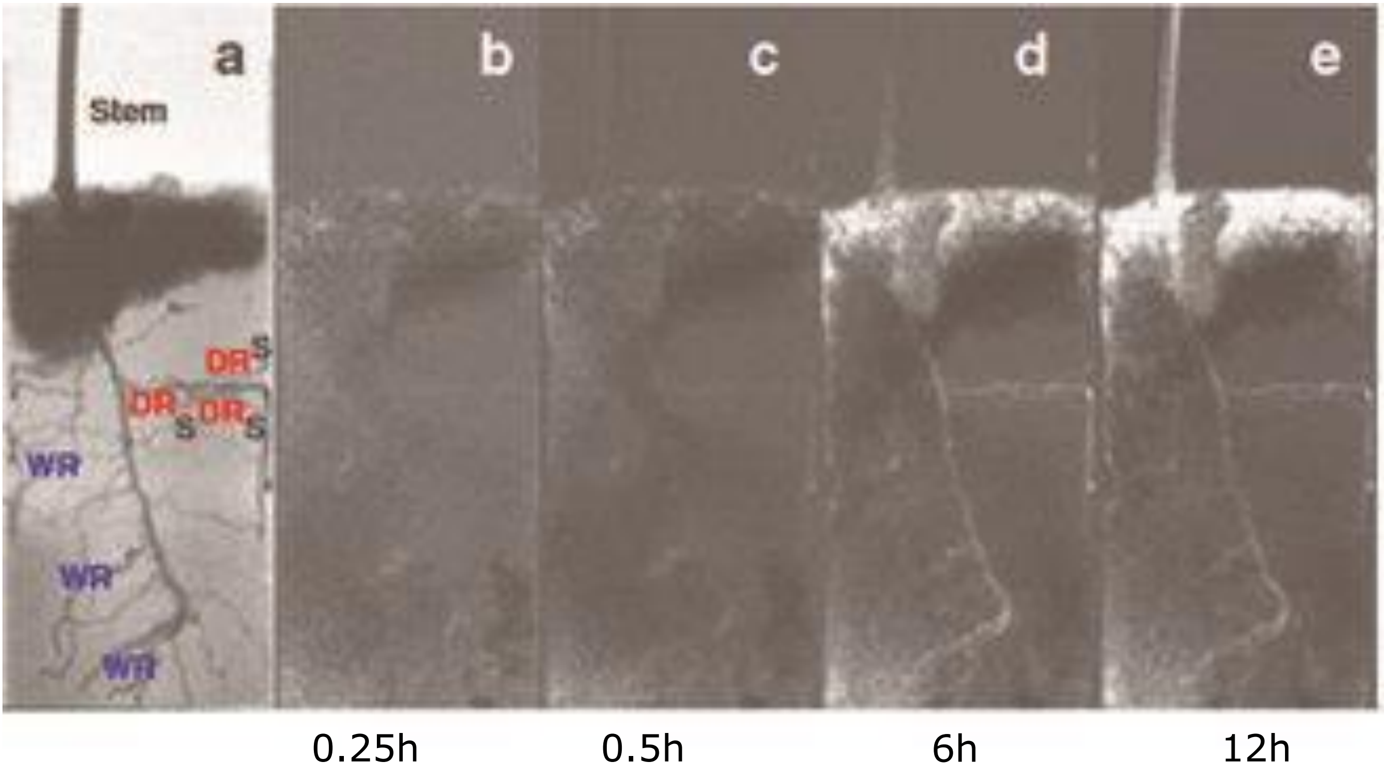

$D_2$

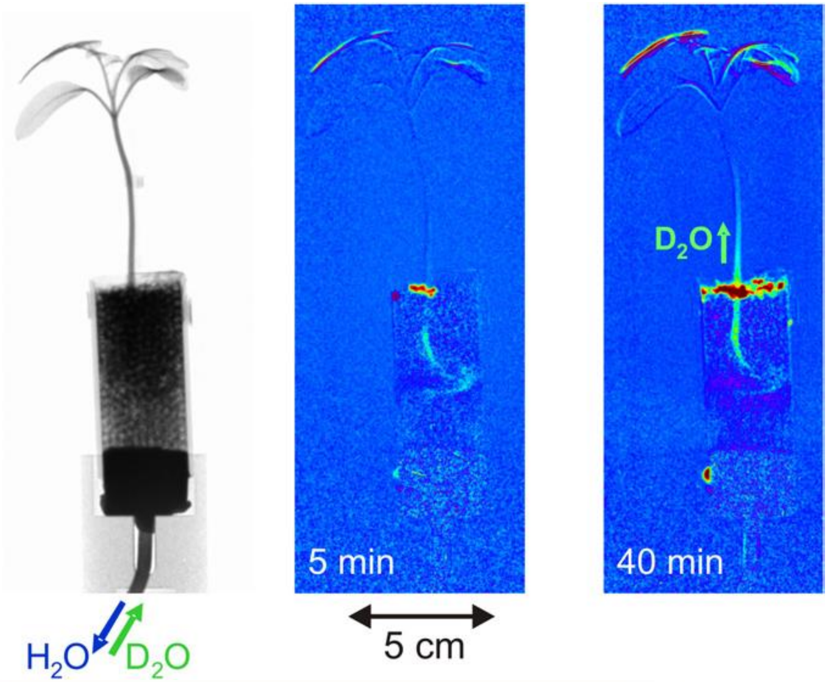


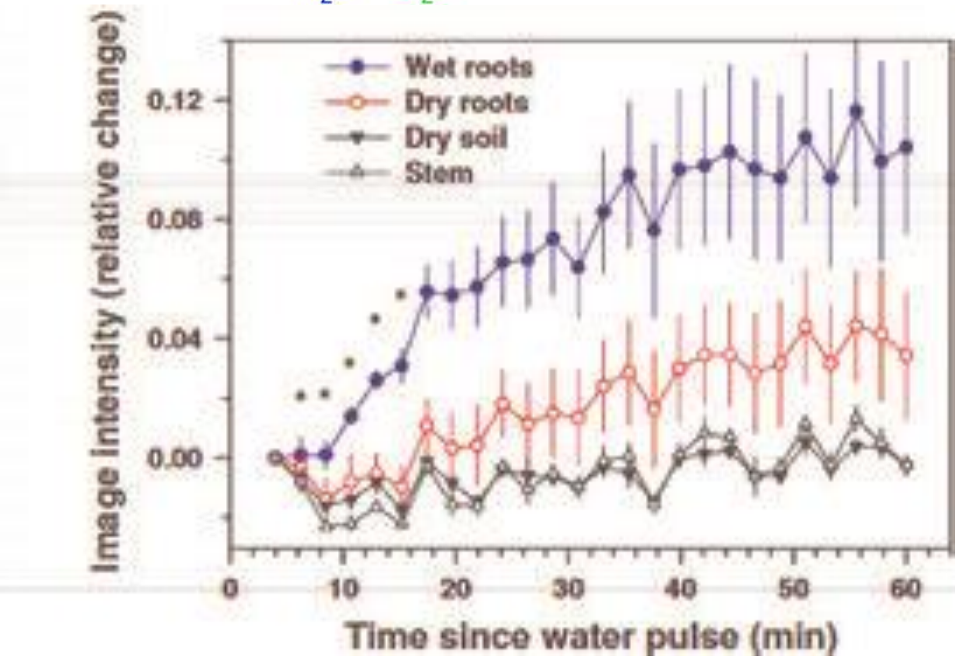

Result: a new model for two-phase flow

Manke, I. et al. (2009). *Appl. Phys. Lett.* **92**, 244101.

# Cases: water uptake in plants



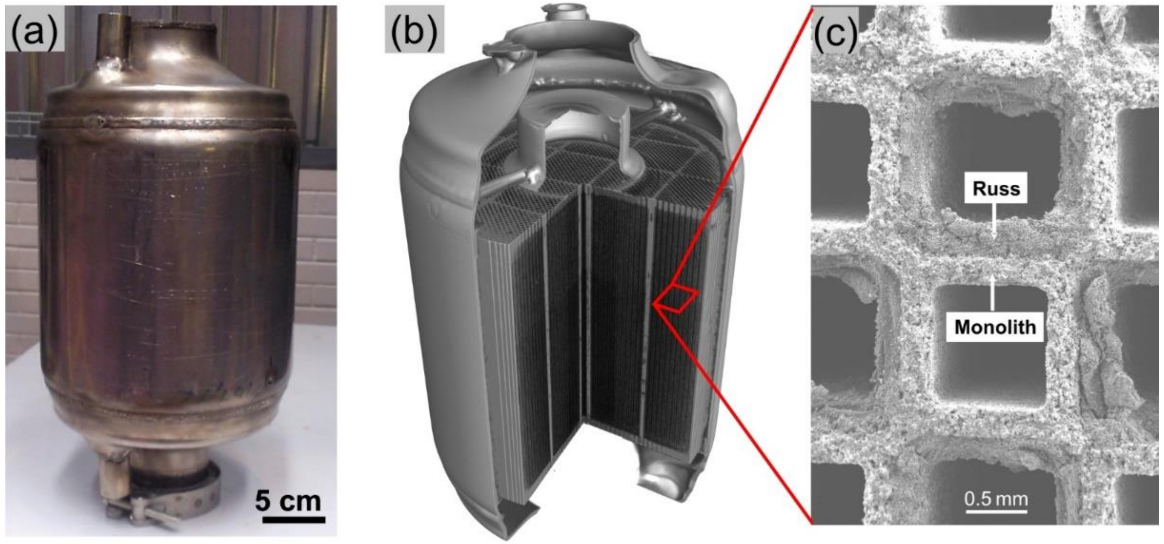



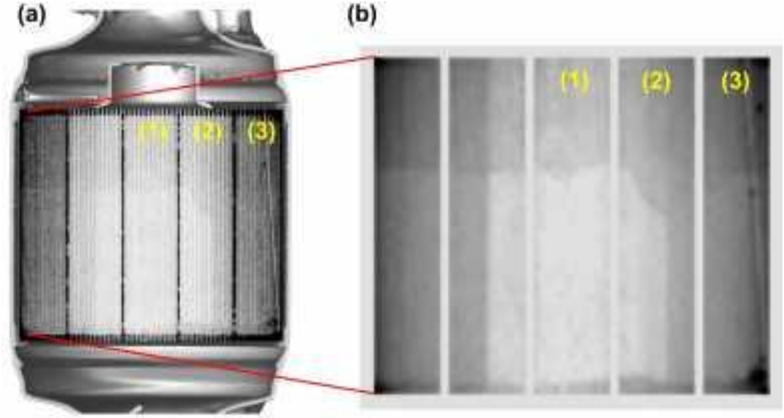



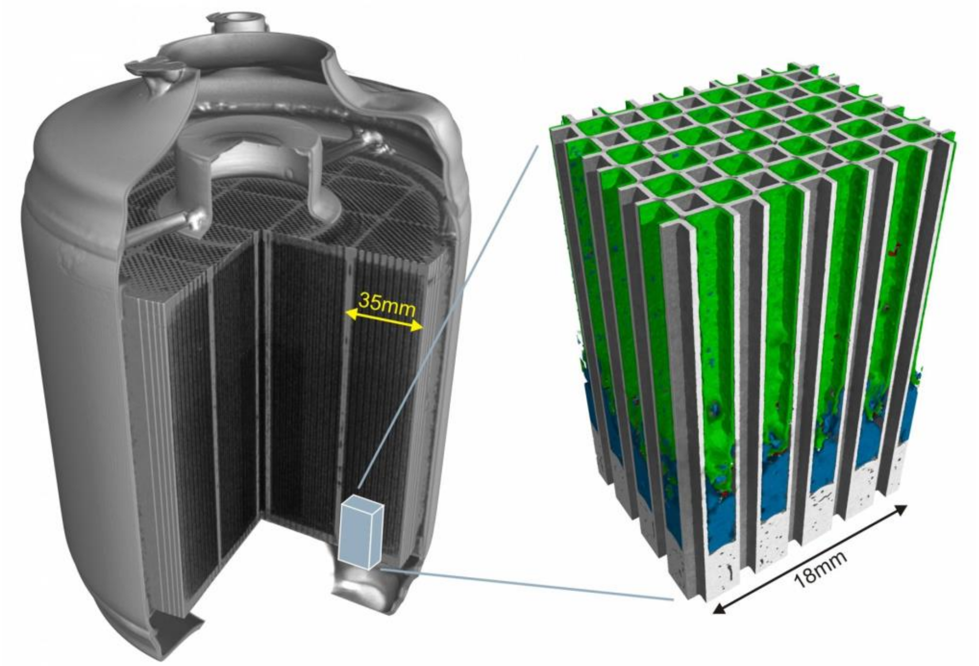

Strobl, M. et al. (2009). *J. Phys. D. Appl. Phys.* **42**, 243001.

DTU

# Cases:
# Soot in particulate filter for diesel engine



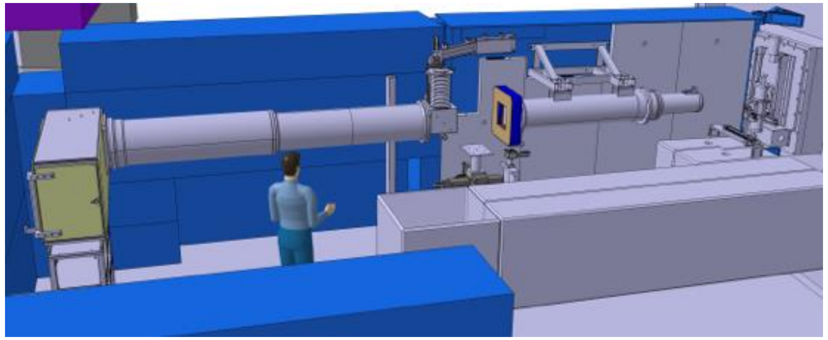



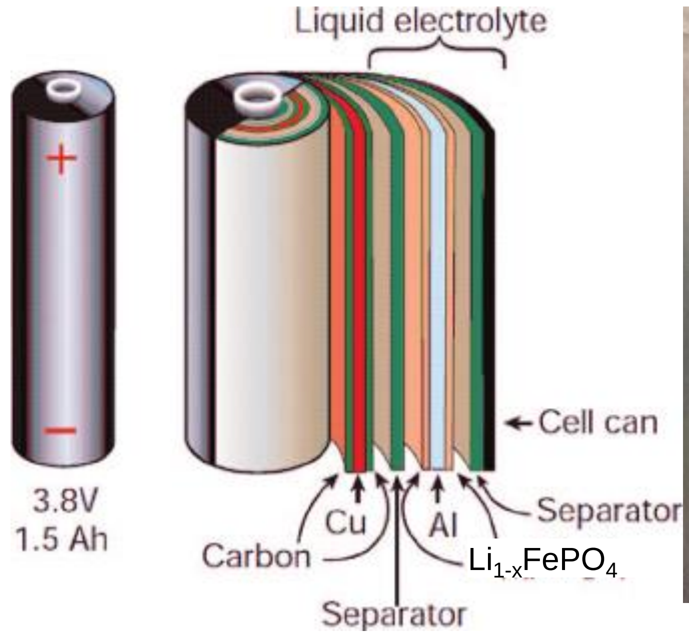



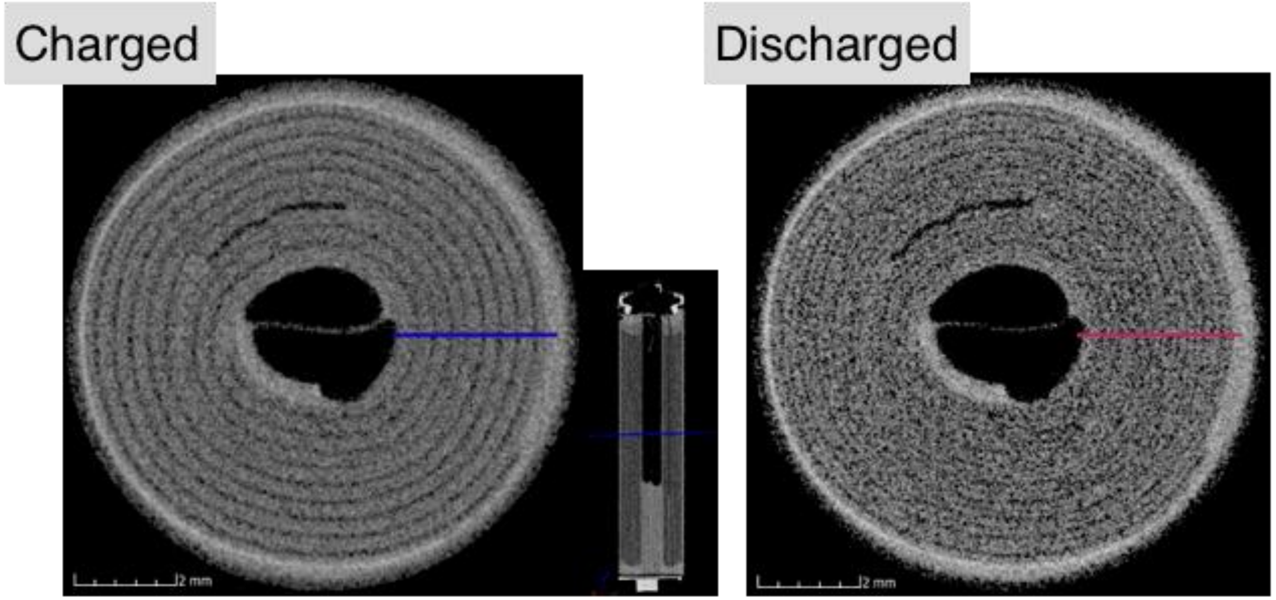

*https://www.psi.ch/media/distribution-of-soot-particles-in-particulate-filters-of-diesel-vehicles*

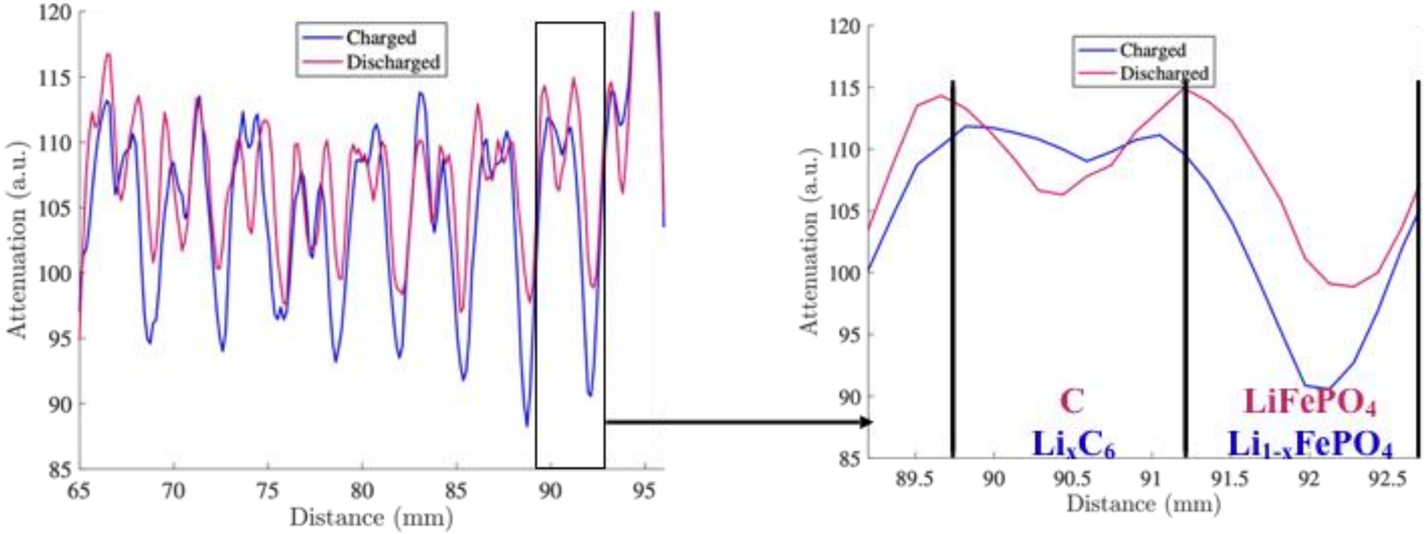
# Cases: Aging of Li-ion rechargeable battery

NEUTRA@PSI

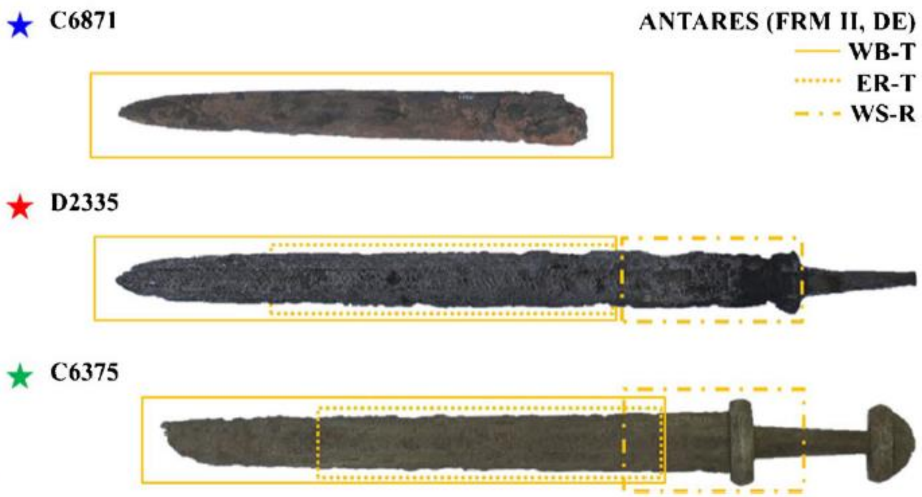


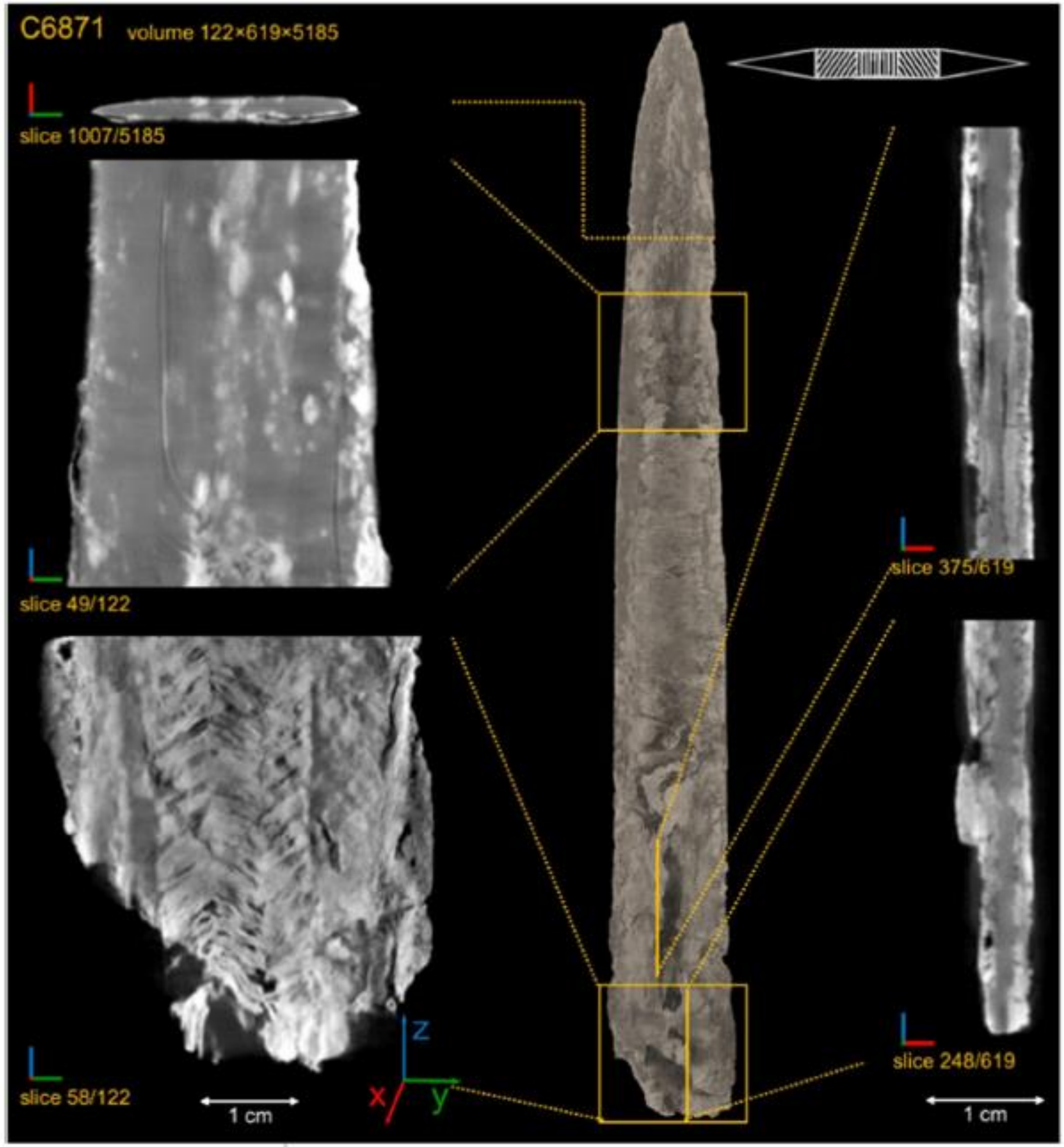


# Cases: Cultural heritage

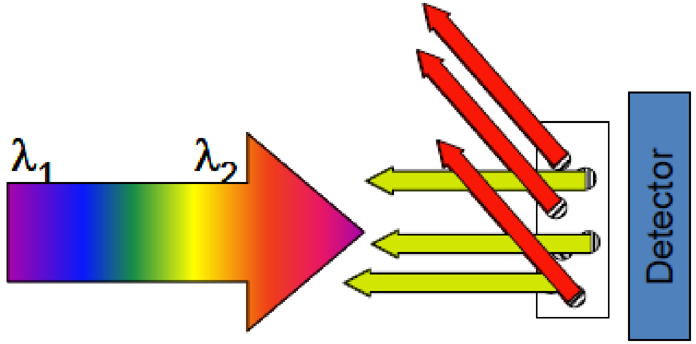




A. Fedrigo et al, Archaeol Anthropol Sci (2018) 10:1249–1263

# Break – 10 min

clipartpng.com

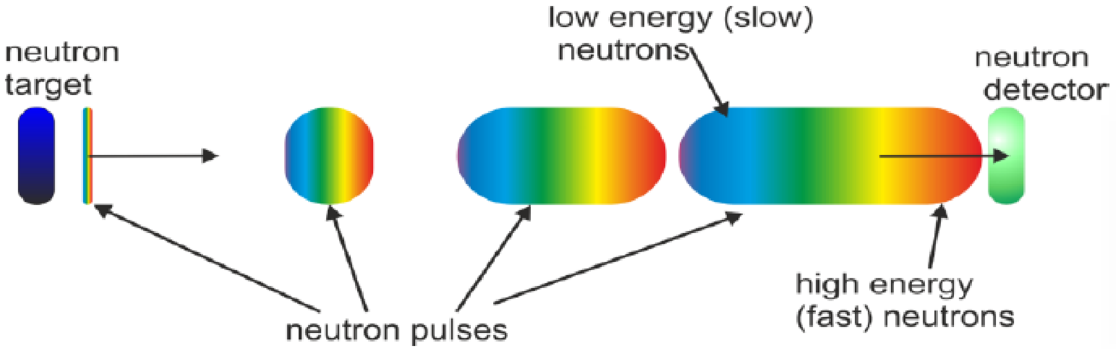
# Energy-resolved neutron imaging
# Bragg-edge imaging



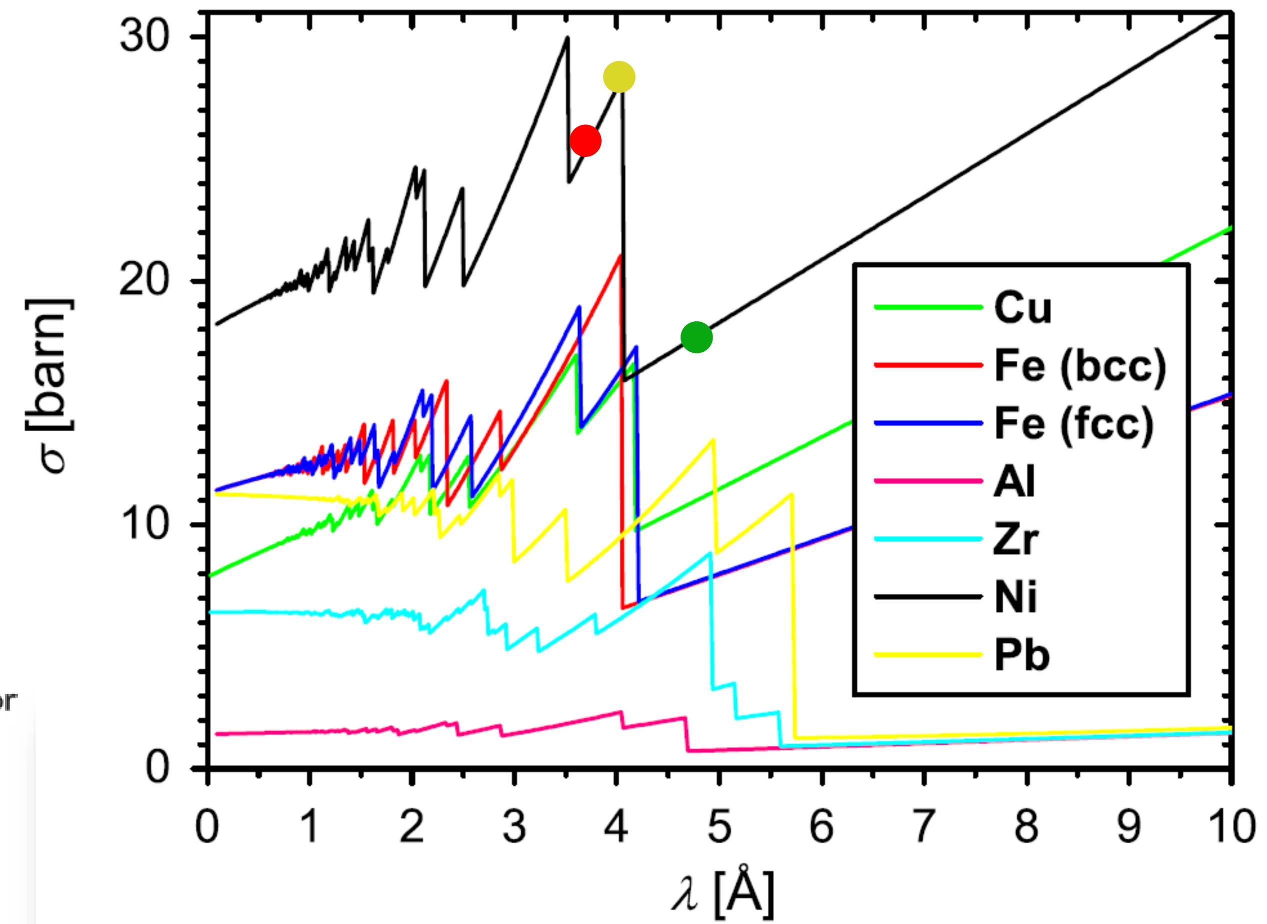

$2d_{hkl}\sin\theta=\lambda$

*Bragg's law*: $2d_{hkl}\sin 90^{\circ}=\lambda$

$2d_{hkl}\sin\theta<\lambda$

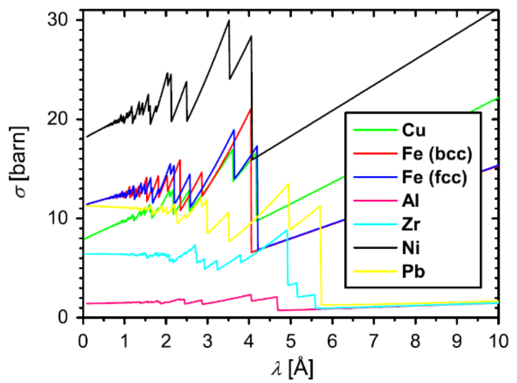



**Total neutron cross section for different polycrystalline materials**



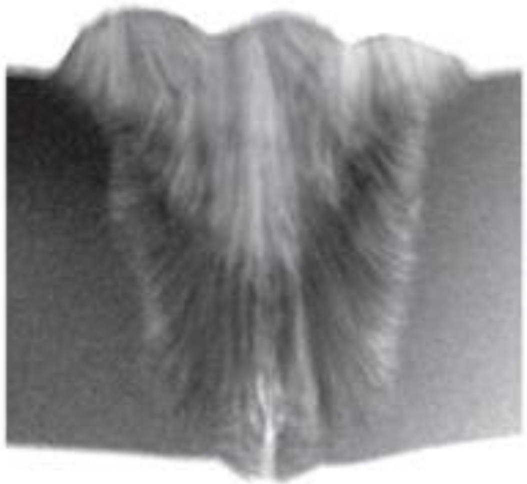

Josic, L. et al (2011). *Nucl. Instruments Methods Phys. Res.* **651**, 166.

# Energy-resolved neutron imaging
# Case: welding of steel





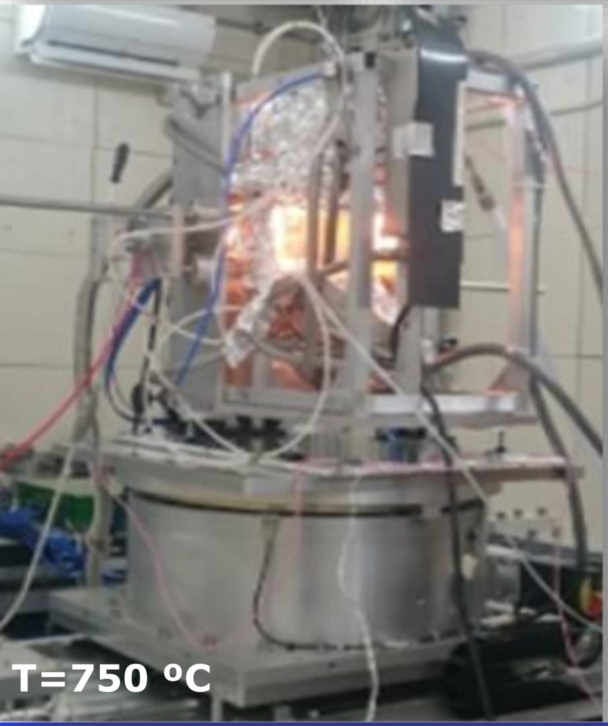
3.4 Å

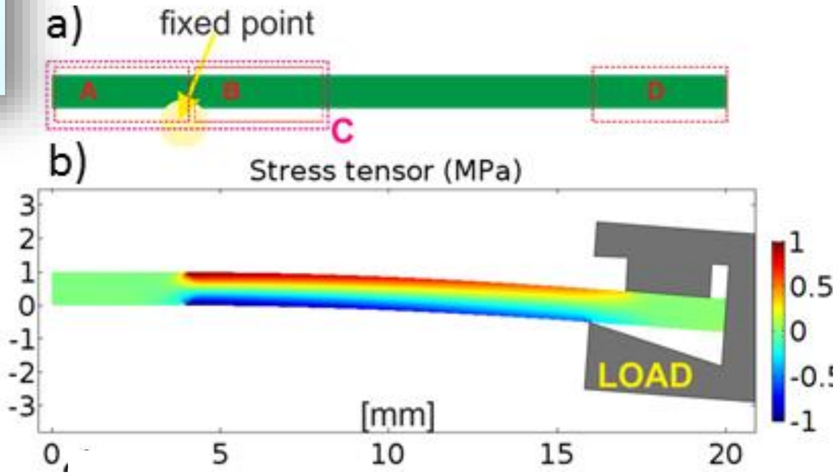


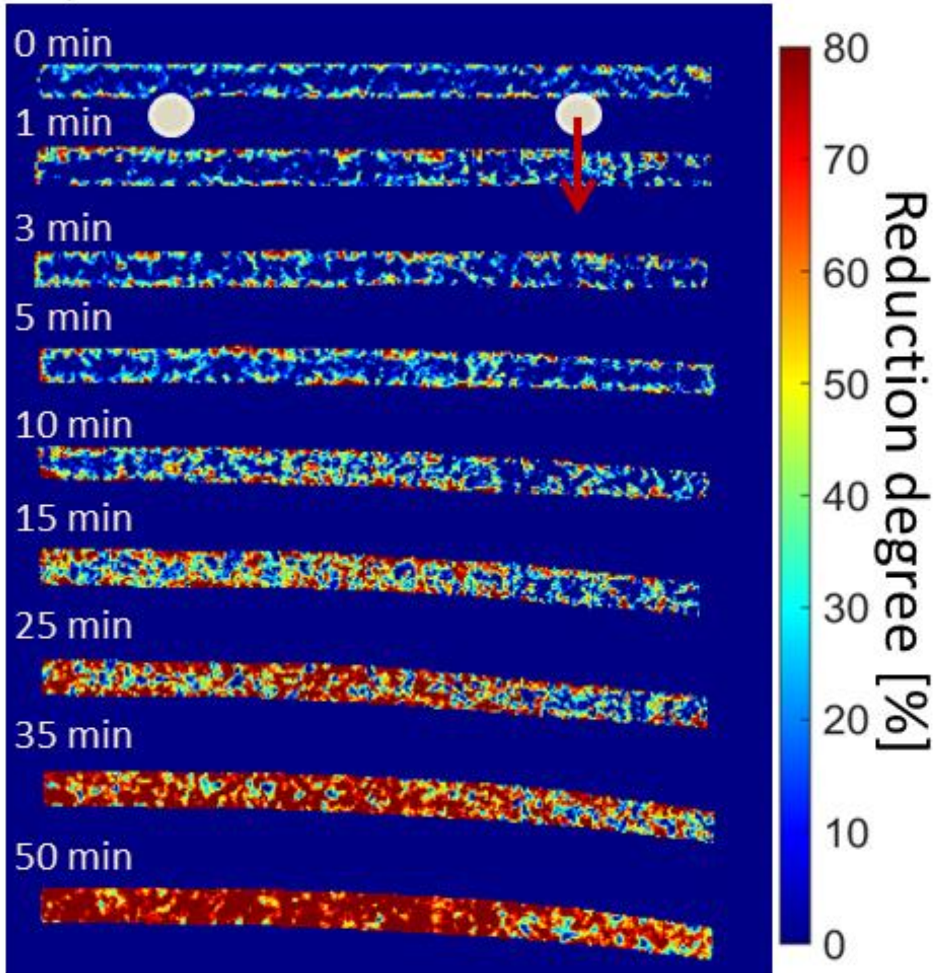
4.0 Å

4.4 Å

# Cases: In-situ Bragg-edge imaging linking strain and NiO reduction in Solid Oxide Fuel/ Electrolysis Cell electrodes



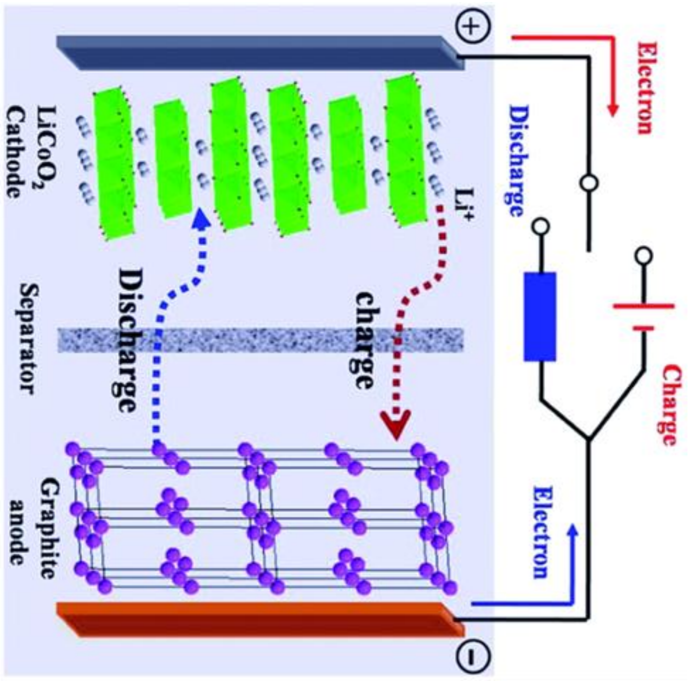



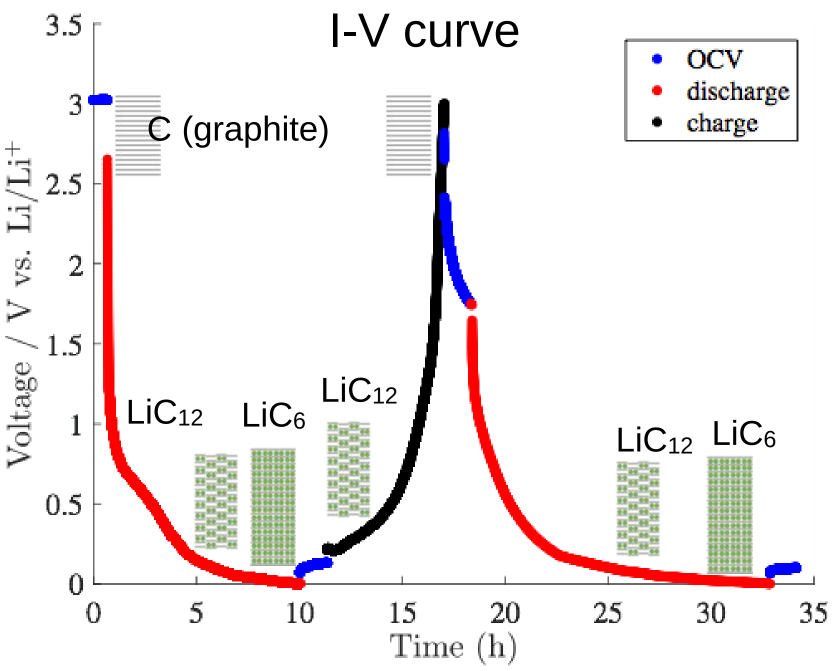



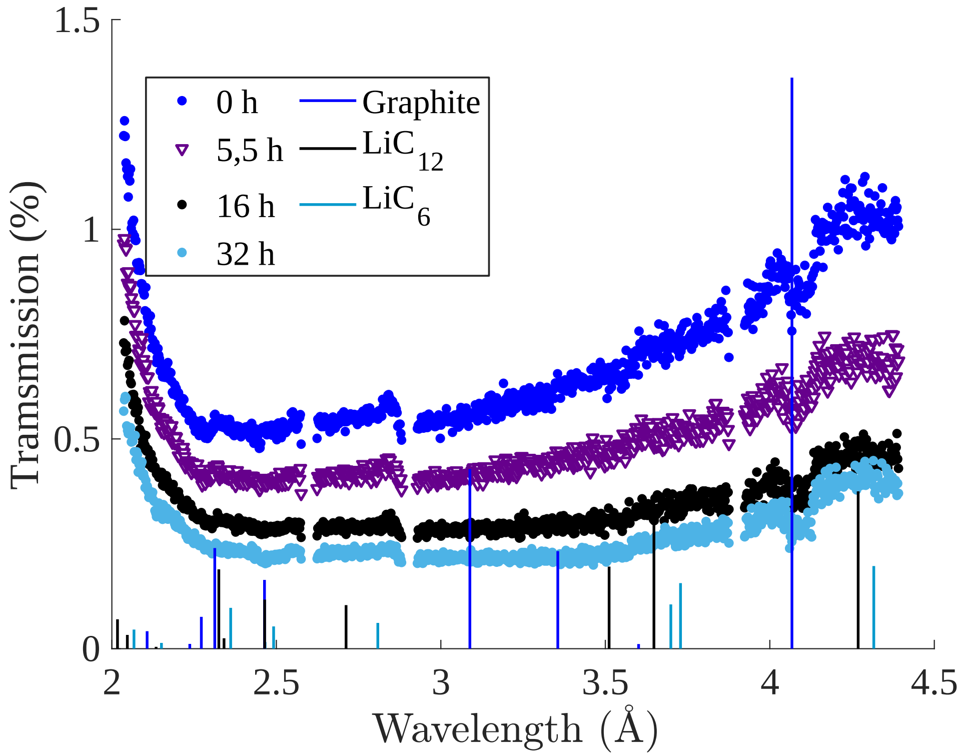

*M. Makowska et al, J.Appl.Cryst.* ***48****, 401(2015)*

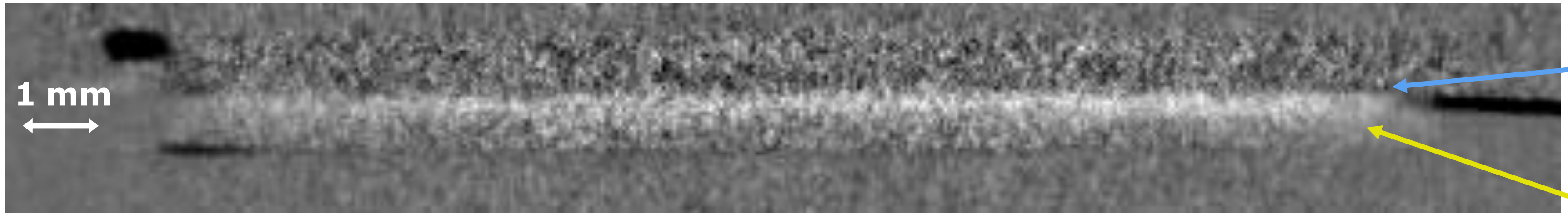
*M. Makowska et al, J. Appl. Cryst.* ***49****, 1674 (2016)*

# Cases: Discharge – charge of model Li-ion battery



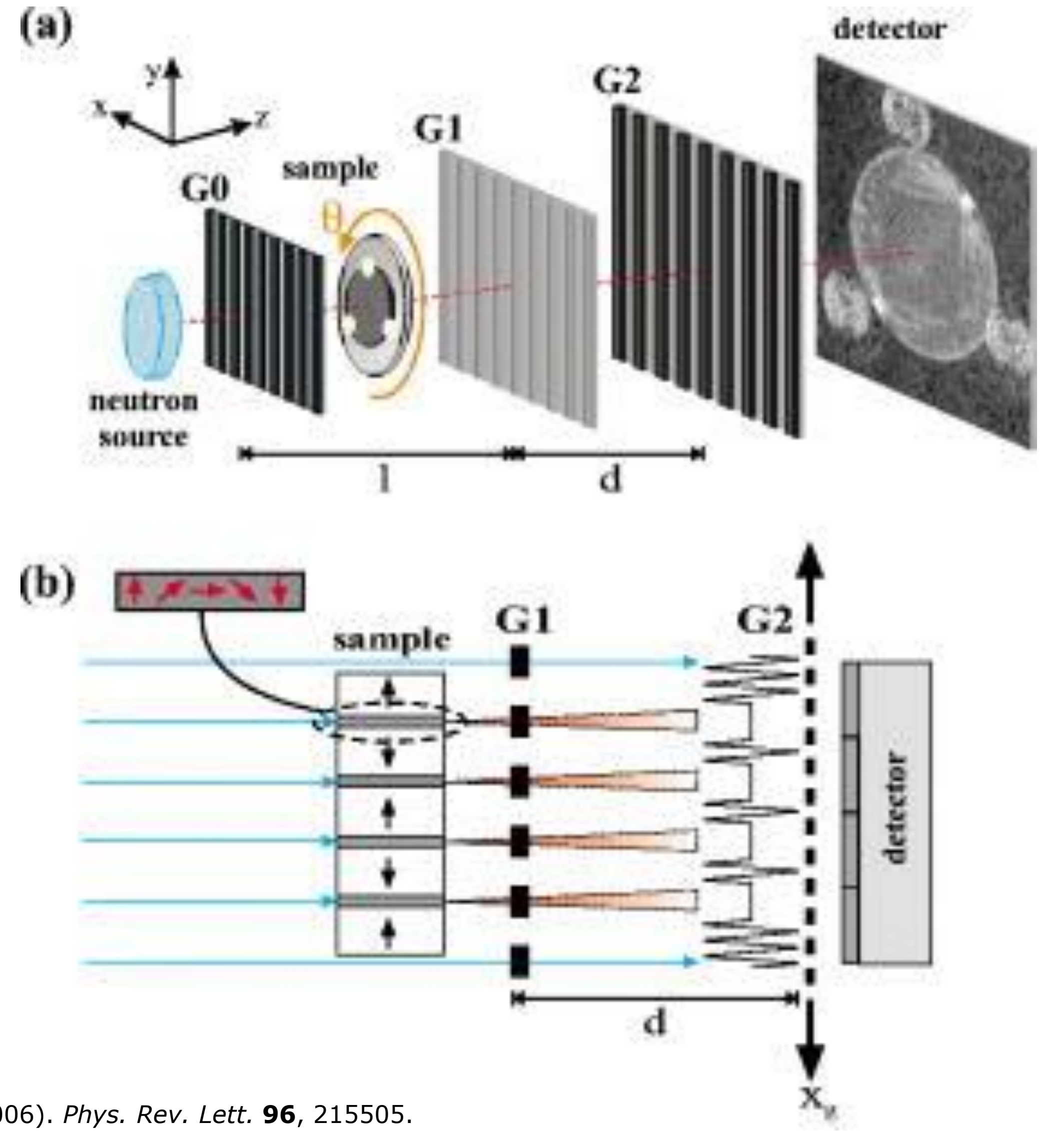



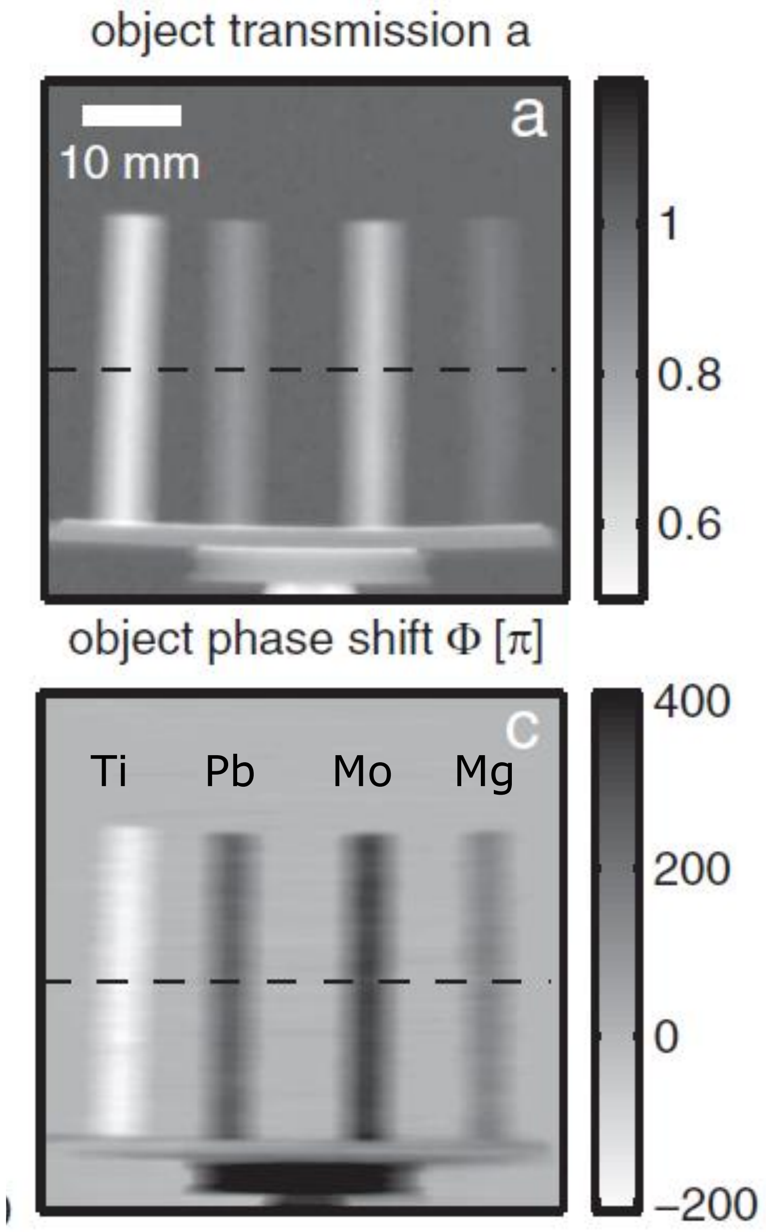

Counter Electrode, Li

Working Electrode, Graphite pellet

# Neutron grating interferometry

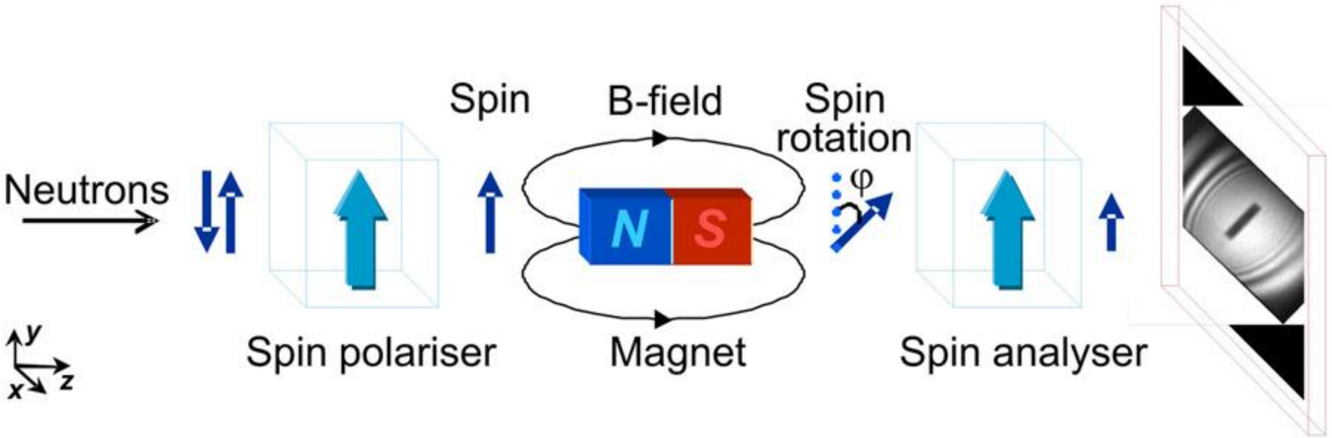


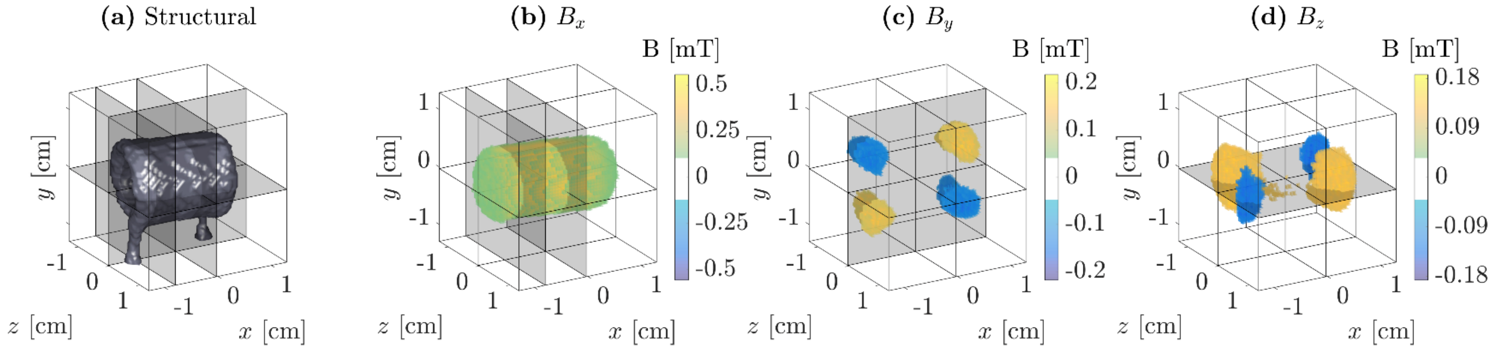

Grünzweig, C. et al. (2006). *Phys. Rev. Lett.* **96**, 215505.




Grünzweig, C. et al. (2008). *Appl. Phys. Lett.* **93**, 112504.

# 3D polarimetric neutron tomography of magnetic fields and current distributions

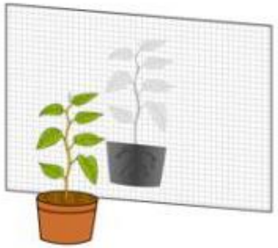


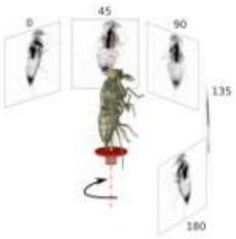

*M. Sales et al, Scientific Reports, vol: 8, issue: 1, pages: 1-6, 2018*

# Summary

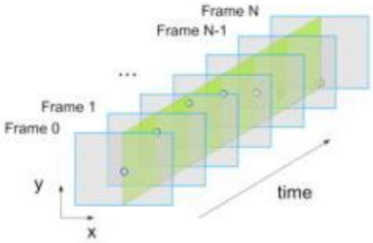
*Standard techniques*



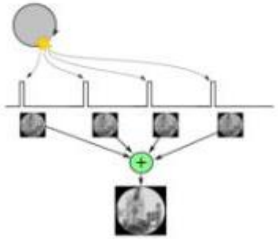
Radiography




Computed tomography

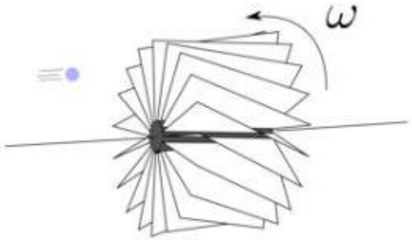



Time-series imaging

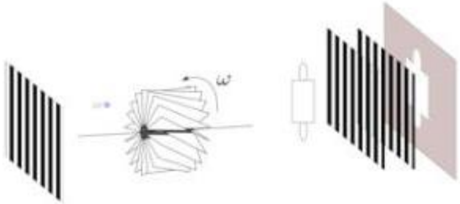


Stroboscopic imaging

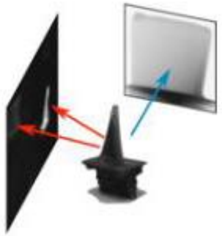
*Advanced techniques*




Energy selective imaging

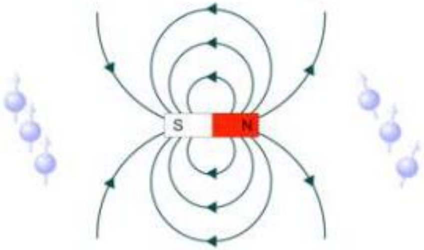



Neutron grating interferometry



Diffraction imaging

*Under development*




Imaging with polarized neutrons

High resolution imaging

Lehmann, E. et al. (2017). *Phys. Proc.* **88**, 5.

# Learning objectives

A student who has successfully completed this module should be able to:

- Describe how the image and contrast is formed during neutron imaging and how it differs from X-ray imaging
- Explain the contributions to the neutron attenuation, and explain the relationship between the attenuation coefficient and the scattering cross section
- Explain the principles behind various types of neutron imaging methodologies
- Decide which combination of pinhole diameter, pinhole-sample distance, and sample-detector distance gives the best spatial resolution for a given experimental setup

# Learning objectives

A student who has successfully completed this module should be able to:

- Decide which of the experimental parameters pinhole diameter, pinhole-sample distance, and sample-detector distance you should modify to reduce the blur at a given neutron flux and divergence

- Evaluate the quality of a tomographic reconstruction by applying the filtered back-projection algorithm

- Evaluate the advantages of neutron radiography compared to neutron tomography

- Give design principles for a neutron imaging setup for 2D and 3D analysis of a given type of sample

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