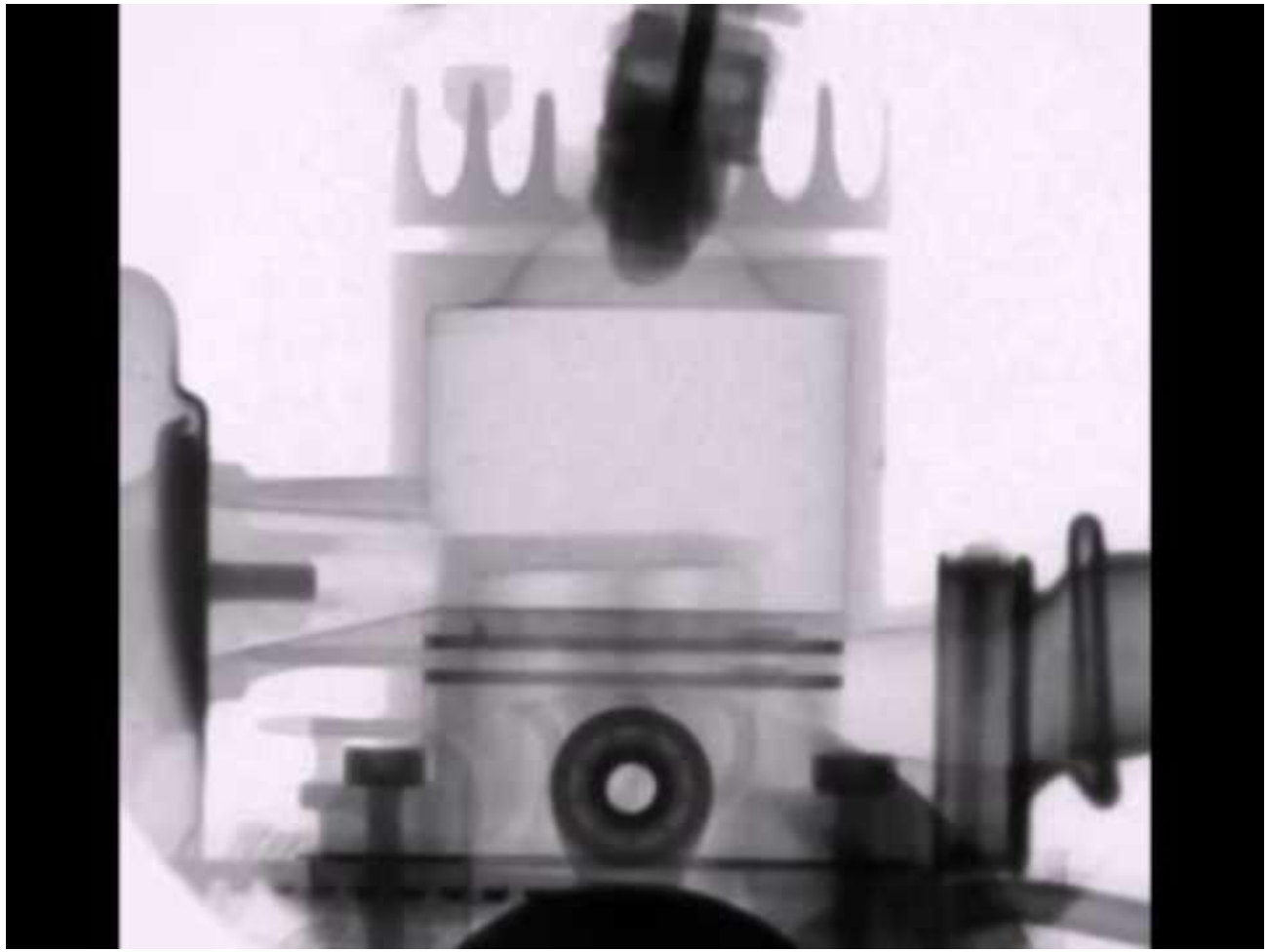
Luise Theil Kuhn, Professor, DTU Energi

Radiografi og tomografi med neutroner – direkte visualisering af materialers sammensætning og egenskaber

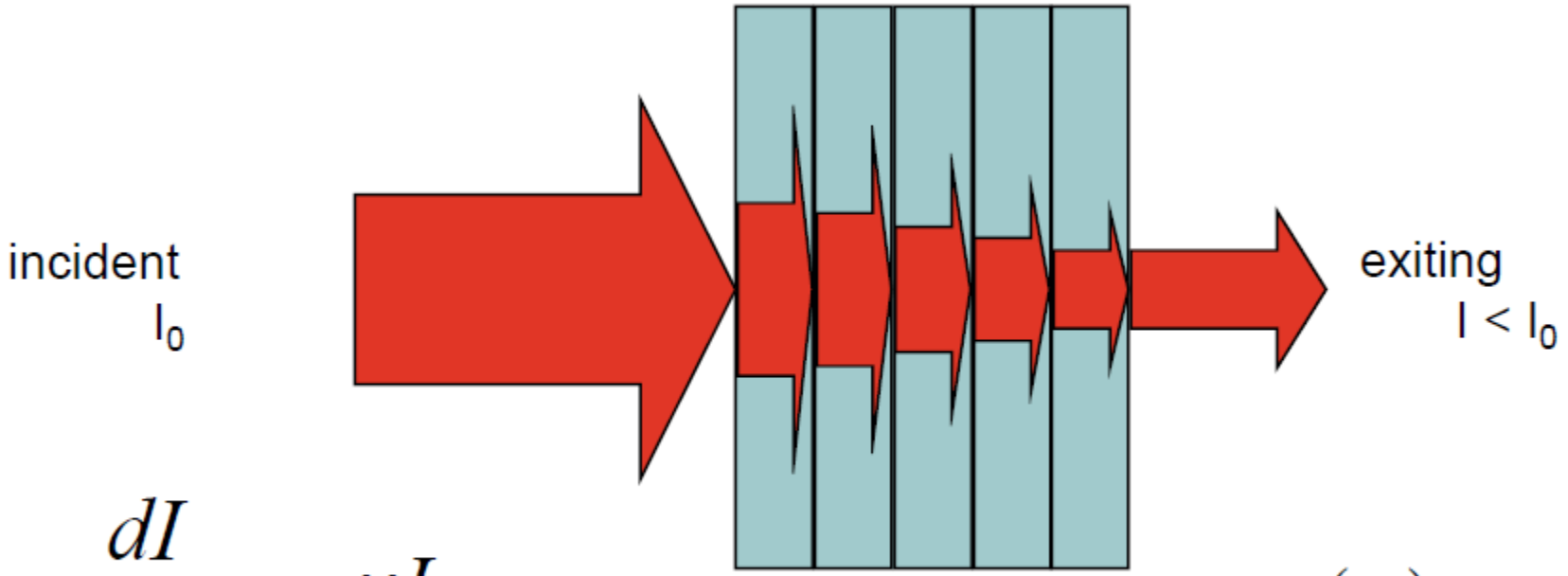
What is imaging and how is the contrast formed?

Running engine



https://youtu.be/CcJ1yrRuorA

Lambert-Beer's law for the absorption of the beam

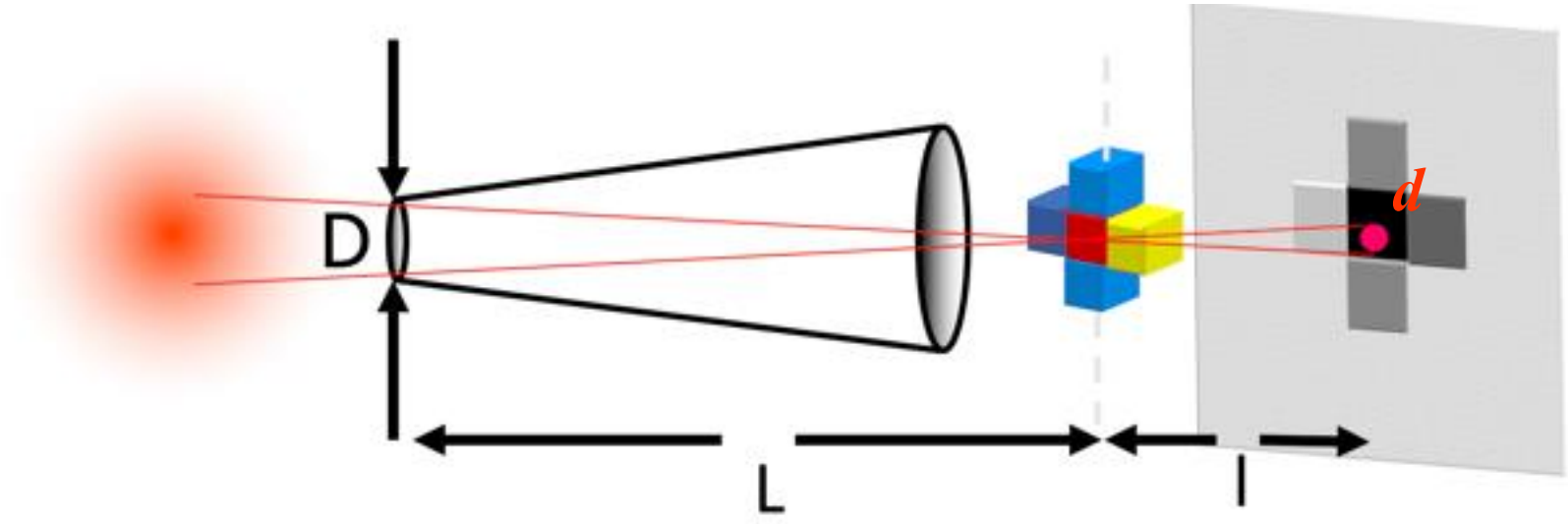


$$\frac{dI}{dx} = -\mu I$$

$$I(x) = I_0 e^{-\mu x}$$

Neutron imaging – a pinhole camera

Source Collimator Object Detector



Total neutron scattering cross section

Lambert-Beer's law:

$$\sim I_0 e^{-\int \mu(x)dx}$$

I_0 – primary beam

$\mu(x)$ – attenuation coefficient

D – Collimator aperture, pinhole

L – Distance Collimator-Object

l – Distance Object-Detector

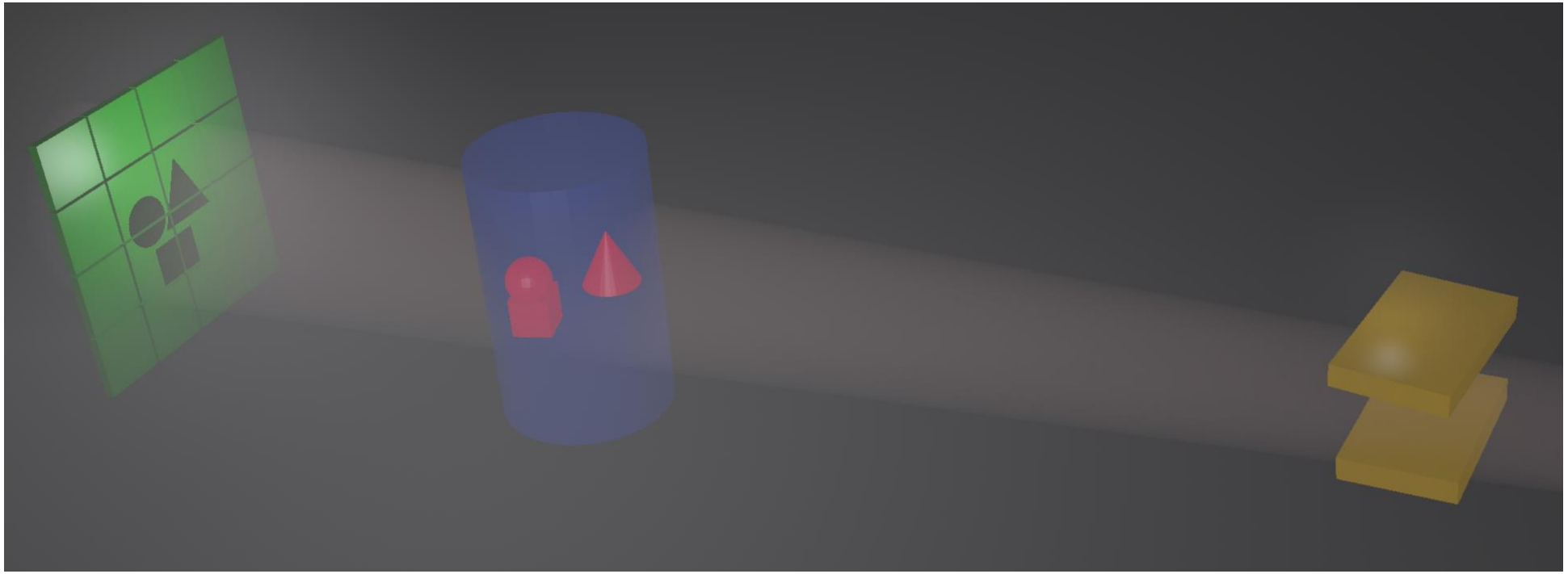
Spatial resolution

$$d = \frac{l}{L/D} \approx \frac{1\cdot10^{-3}}{10\,/1\cdot10^{-2}}\ \mathrm{m} = 1\cdot10^{-5}\ \mathrm{m}$$

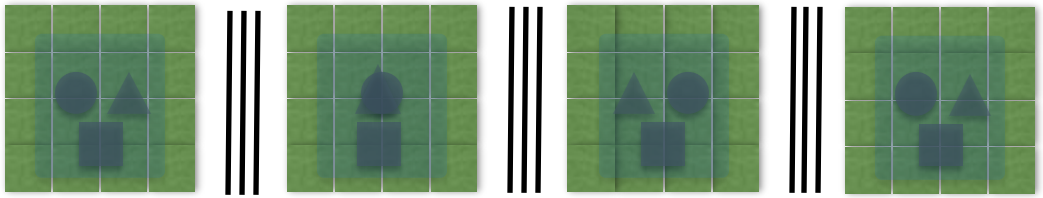
$$\mu_{total} = \mu_a + \mu_s$$

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

Tomography

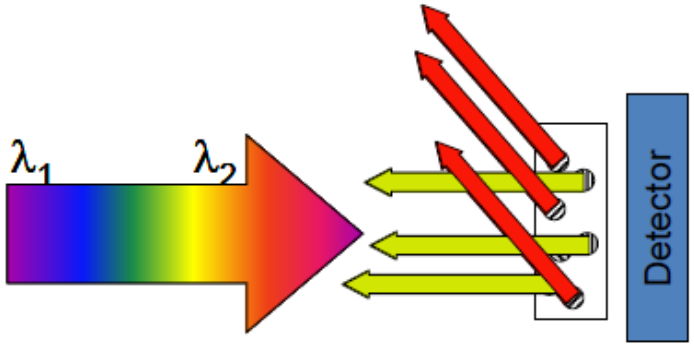


3D reconstruction



0º 90º 180º 320º

Energy-resolved neutron imaging
Bragg-edge imaging

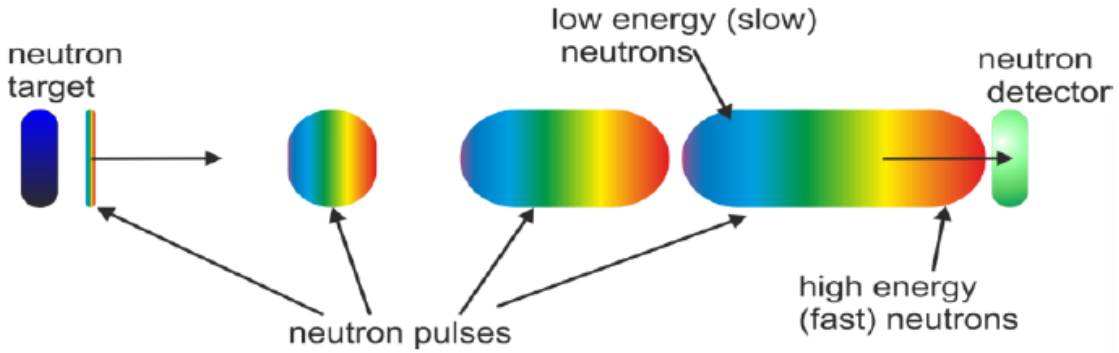


$2d_{hkl}\sin\theta=\lambda$

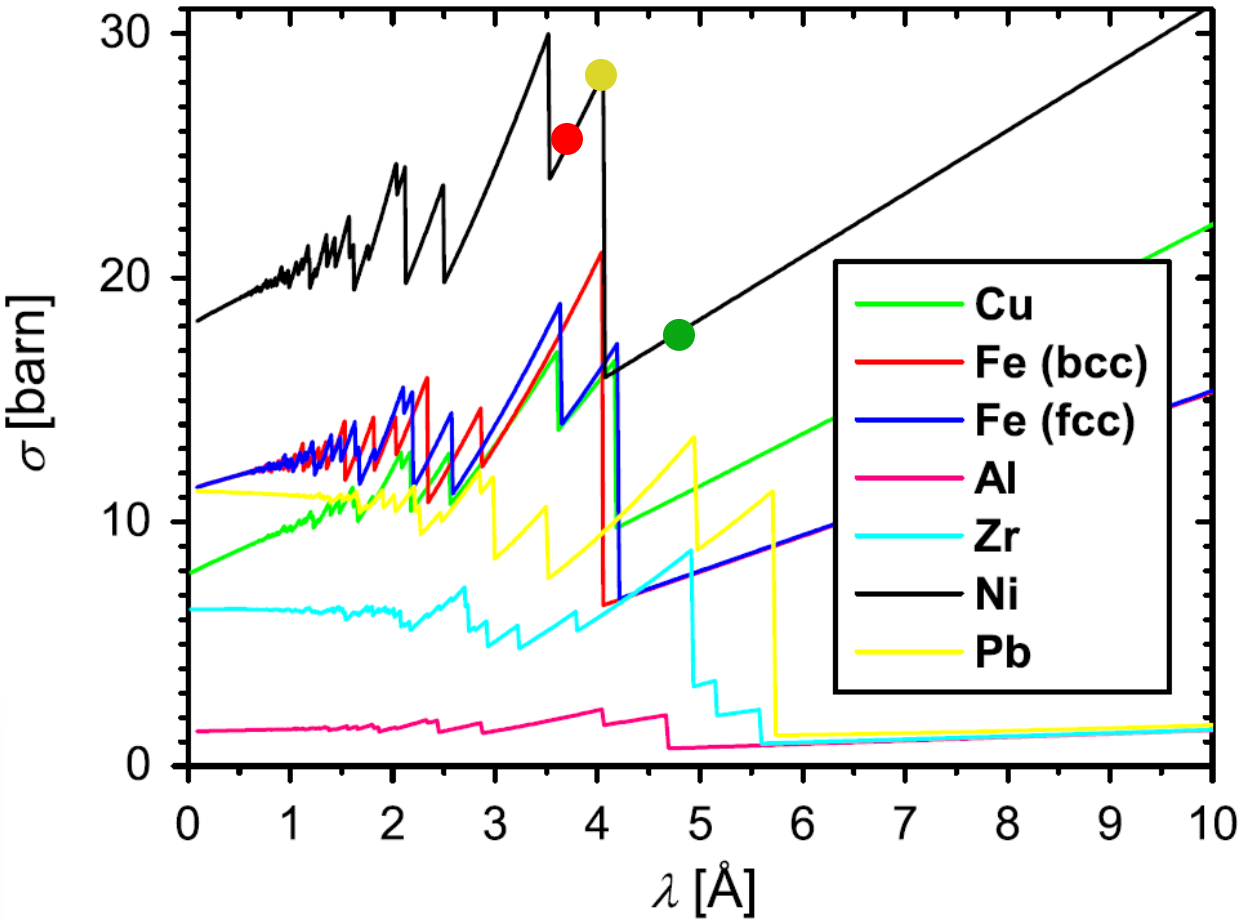
Bragg's law: $2d_{hkl}\sin 90^\circ = \lambda$

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

$$\sim I_0 e^{-\int \mu(x,\lambda)dx\, d\lambda}$$

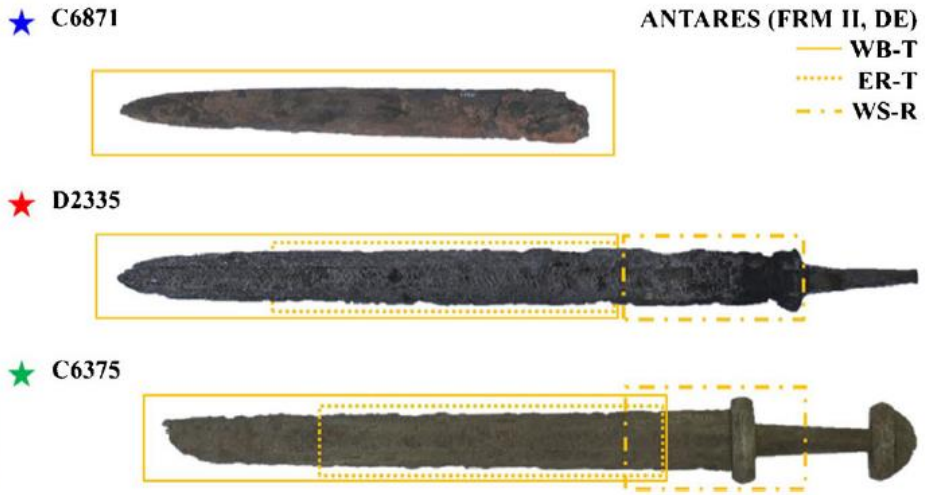


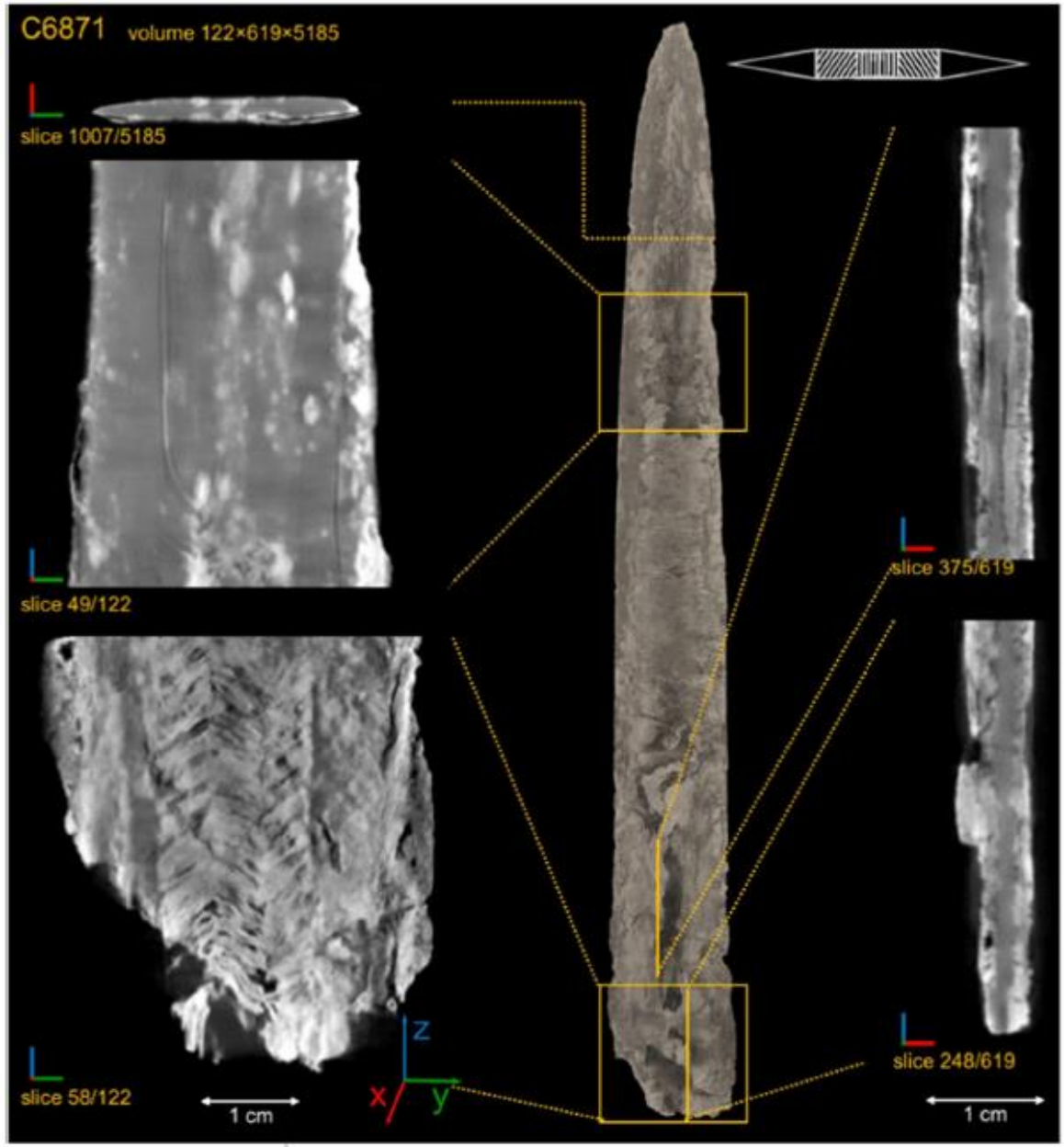
Total neutron cross section for different polycrystalline materials



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

Cases: Cultural heritage

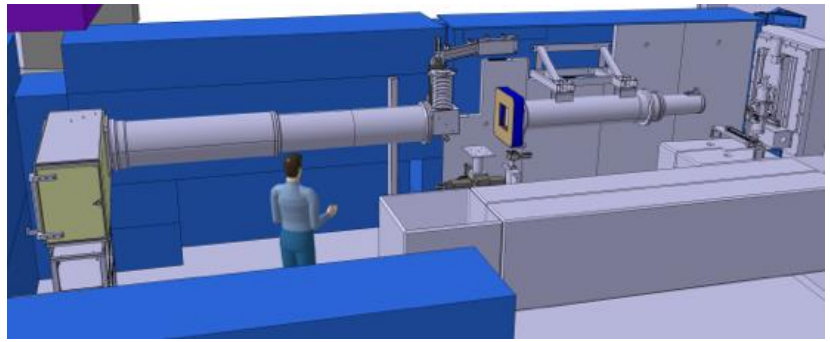


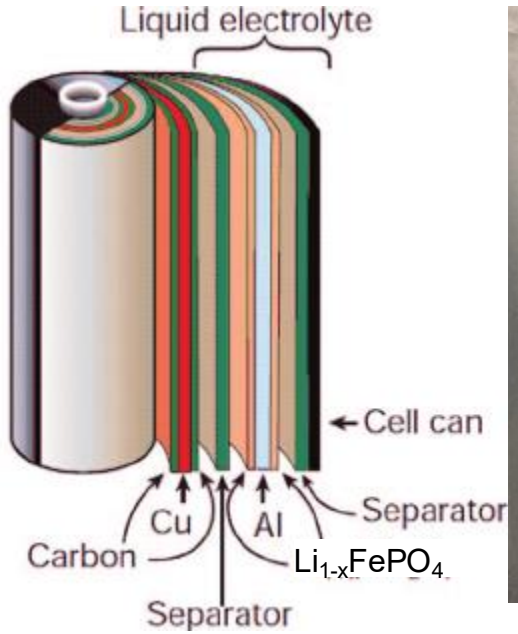


A. Fedrigo et al, *Archaeol Anthropol Sci (2018)* **10**,1249–1263

Cases:
Operando imaging of Li-ion rechargeable battery

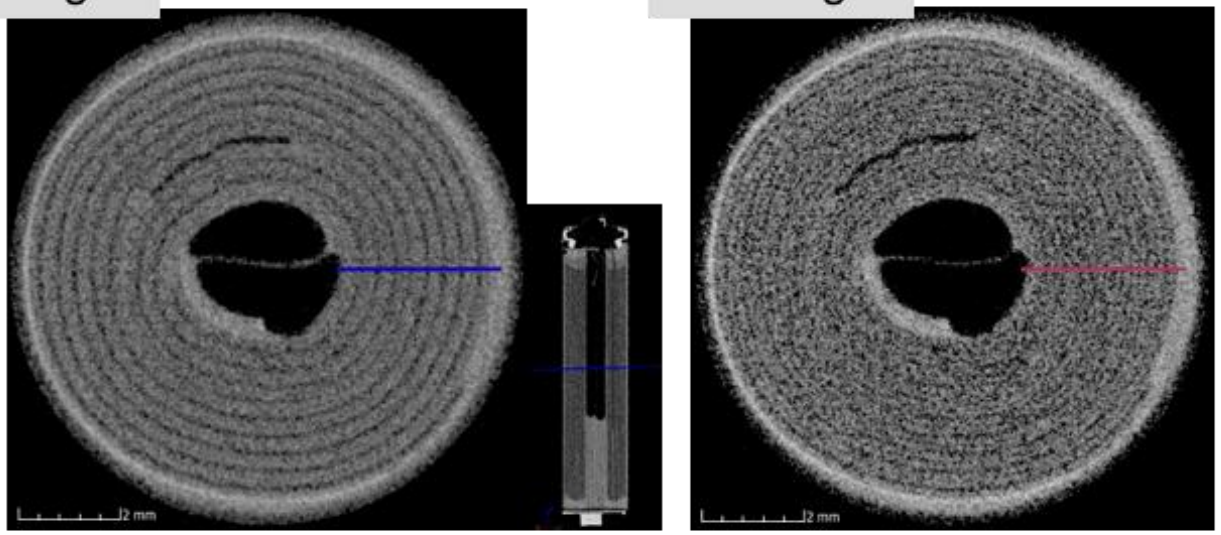
NEUTRA@PSI

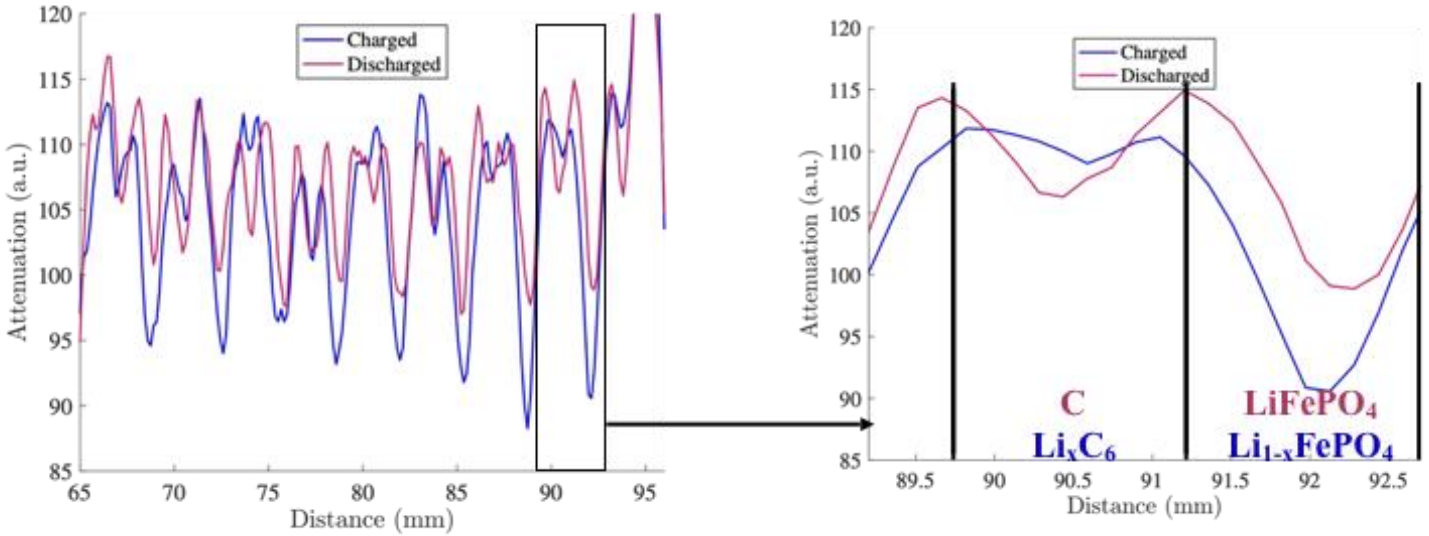




Charged

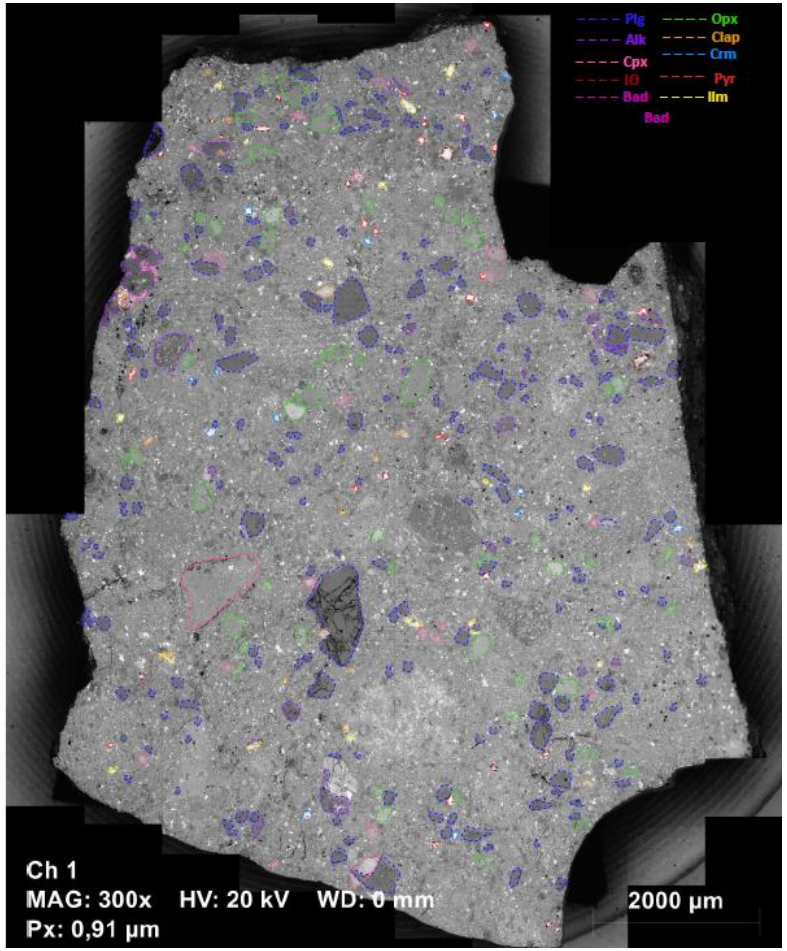
Discharged





Cases: hydrous phases in the Black Beauty Martian meteorite

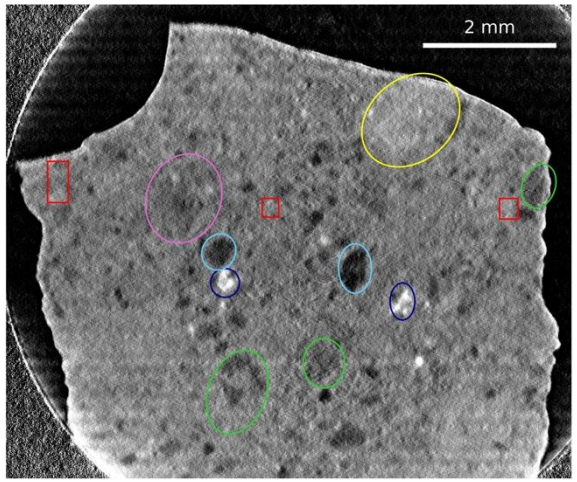
Mineral	Formula	Endmember 1	Endmember 2	Density (g/cm³)
Orthopyroxene		enstatite ($Mg_2Si_2O_6$)	ferrosilite ($Fe_2Si_2O_6$)	3.2 (enstatite), 3.95 (ferrosilite)
Clinopyroxene		diopside ($CaMgSi_2O_6$)	augite ($(Ca,Na)(Mg,Fe,Al)(Al,Si)_2O_6$)	3.4
Plagioclase	$(Na,Ca)[(Si,Al)AlSi_2]O_8$	albit (Na)	anorthite (Ca, 2xAl)	2.62 (albite), 2.73 (anorthosite)
Magnetite	Fe_3O_4			5.15
Maghemite	Fe_2O_3			
Pyrite	FeS_2			5.01
Hematite	Fe_2O_3			5.3
Perthitic feldspar	$(K,Na)AlSi_3O_8$	orthoclas (K)	albite (Na)	2.56 (orthoclase), 2.62 (albite)
Chlorapatite	$Ca_5(PO_4)_3Cl$			3.17
Ilmenite	$FeTiO_3$			4.72
Zircon	$ZrSiO_4$			
Baddeleyite	ZrO_2			
Olivine	$(Fe,Mg)_2SiO_4$	Fosterite (Mg)	Fayalite (Fe)	3.27 (fosterite), 4.39 (fayalite)
Chromite	$FeCr_2O_4$			4.79 (avg)
Spinel	$MgAl_2O_4$			3.64 (avg)
Rutile	TiO_2			



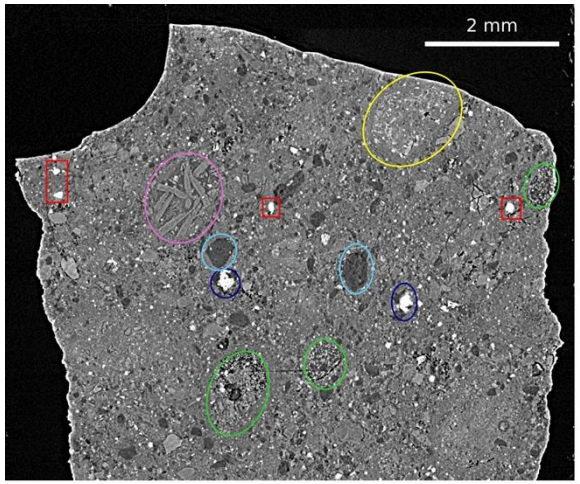
C. B. Agee et al., Science **339**,780-785(2013)

Cases: hydrous phases in the Black Beauty Martian meteorite

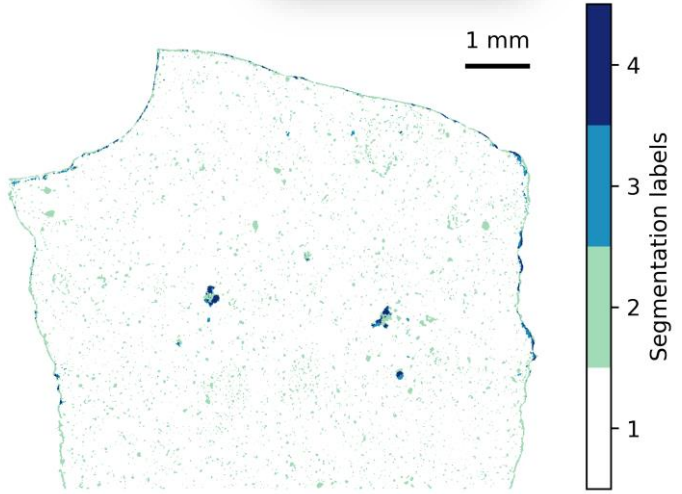
- ✓ *Non-destructive classification of water-containing minerals* in Mars meteorite for Mars return-mission.
  X-ray and neutron tomography
  - non-destructive localization and analysis of water-containing hydroxides



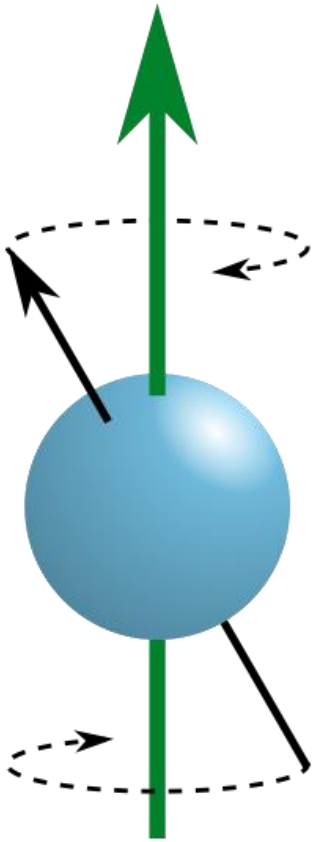
Neutron tomography

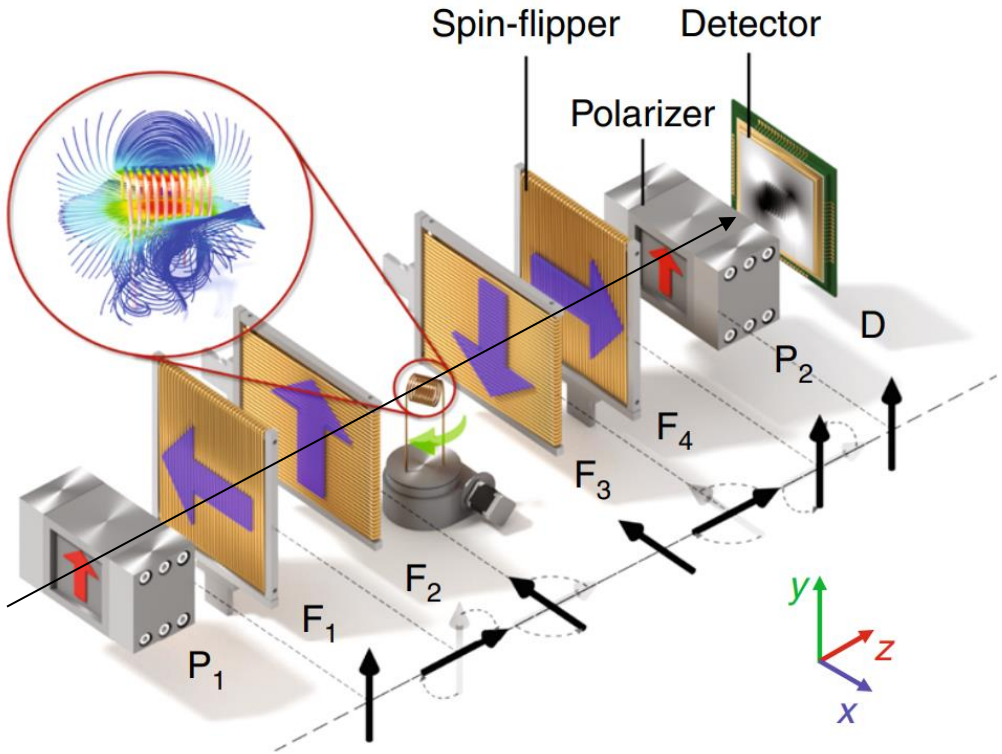


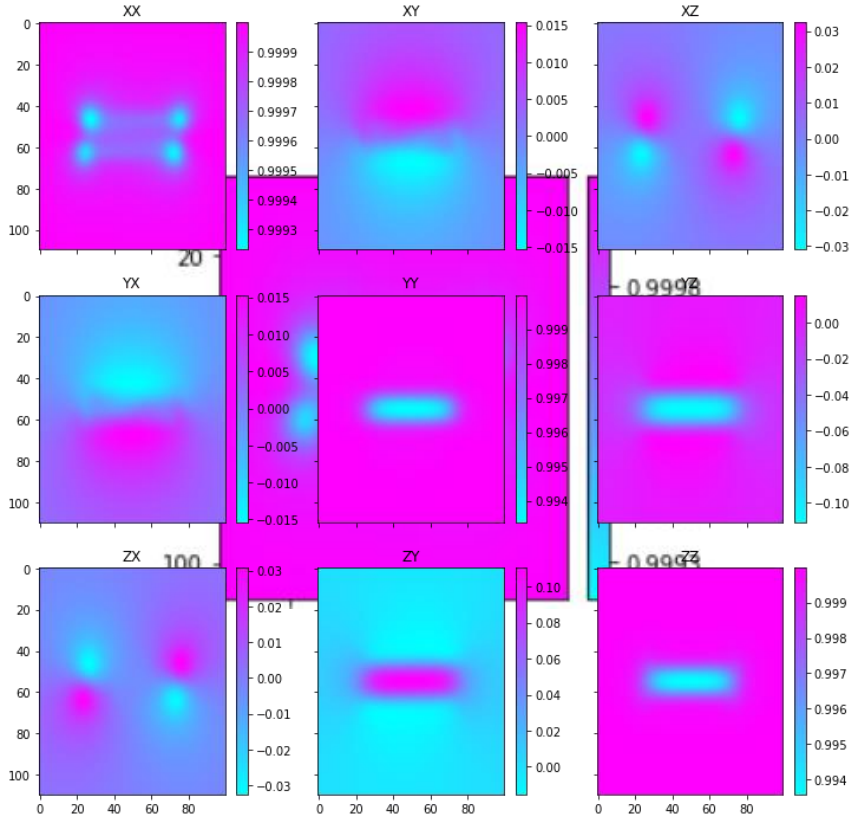
X-ray tomography



Magnetic field imaging by tracking the precession of the neutron spin





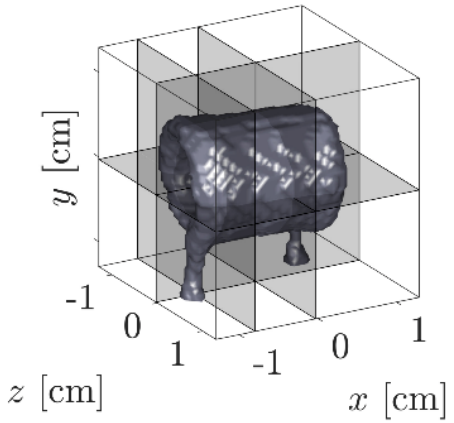


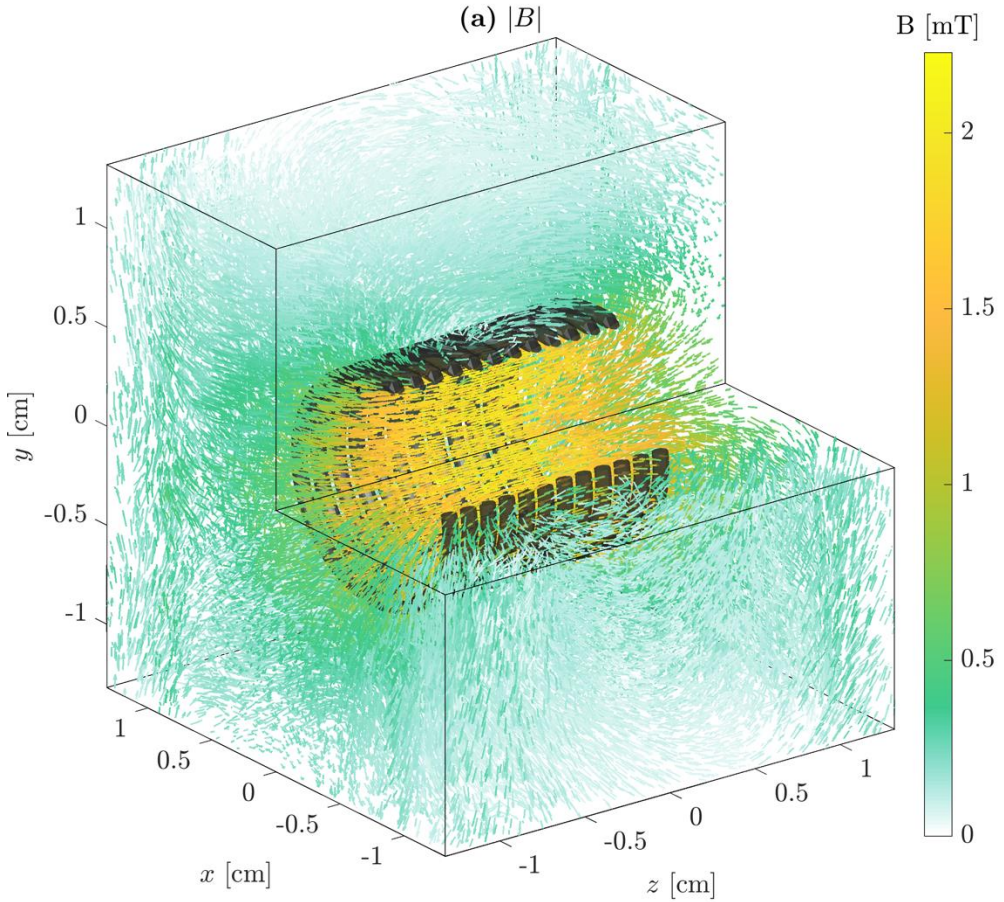
https://en.wikipedia.org/wiki/Larmor_precession

A. Hilger et al, Nature Communications, 9(1) (2018).

Cases:
Mapping of magnetic fields and currents in 3D

(a) Structural

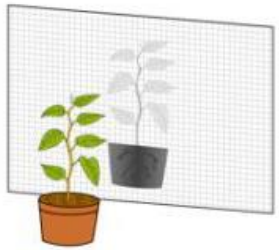




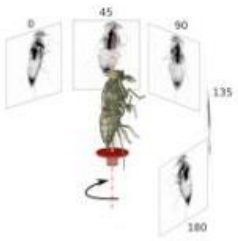
M. Sales et al, Scientific Reports, vol: 8, issue: 1, pages: 1-6, 2018

Overview of neutron imaging methods

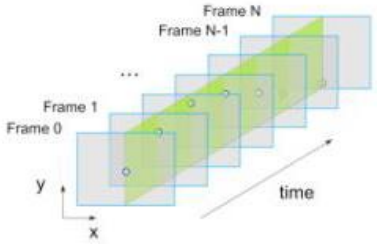
Standard techniques



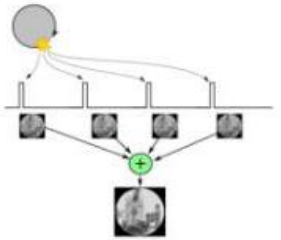
Radiography



Computed tomography

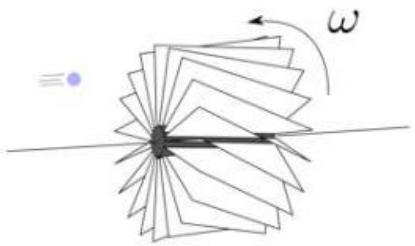


Time-series imaging

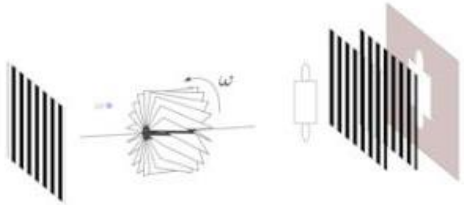


Stroboscopic imaging

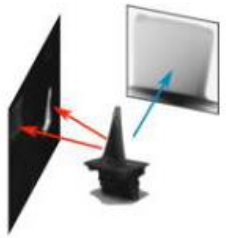
Advanced techniques



Energy selective imaging

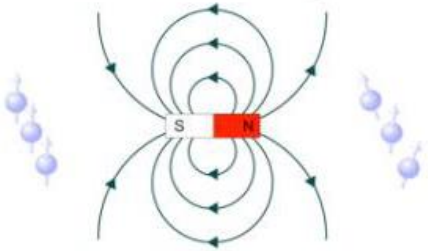


Neutron grating interferometry



Diffraction imaging

Under development



Imaging with polarized neutrons

High resolution imaging

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

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