HZB Helmholtz Zentrum Berlin

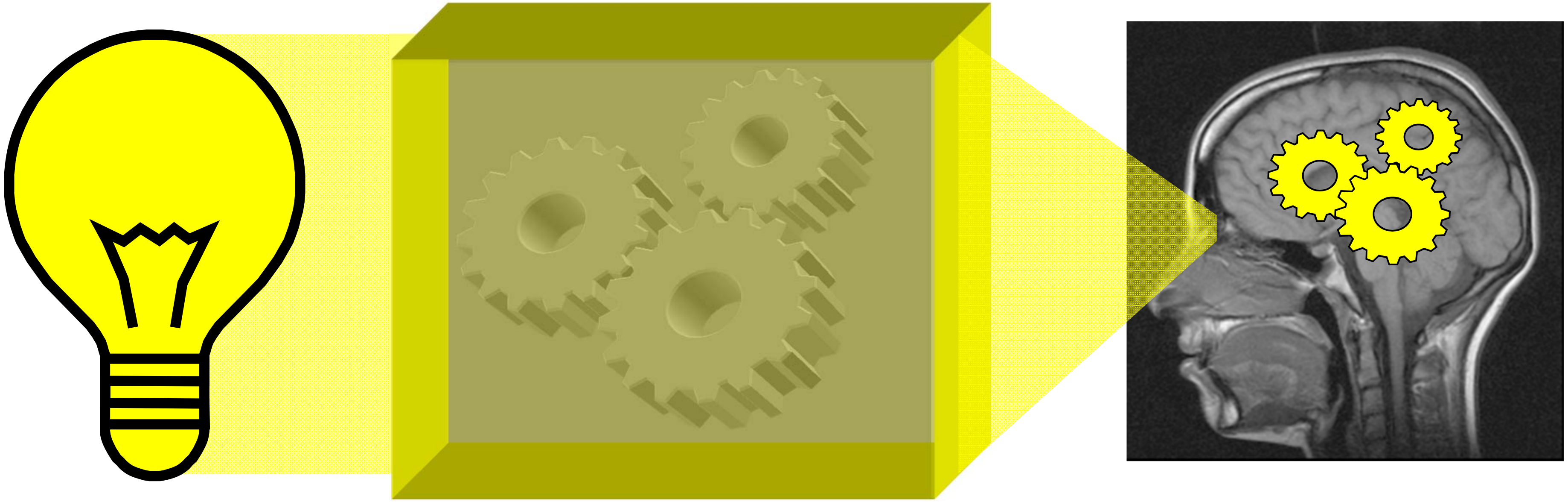
Oxford School on Neutron Scattering

Neutron imaging

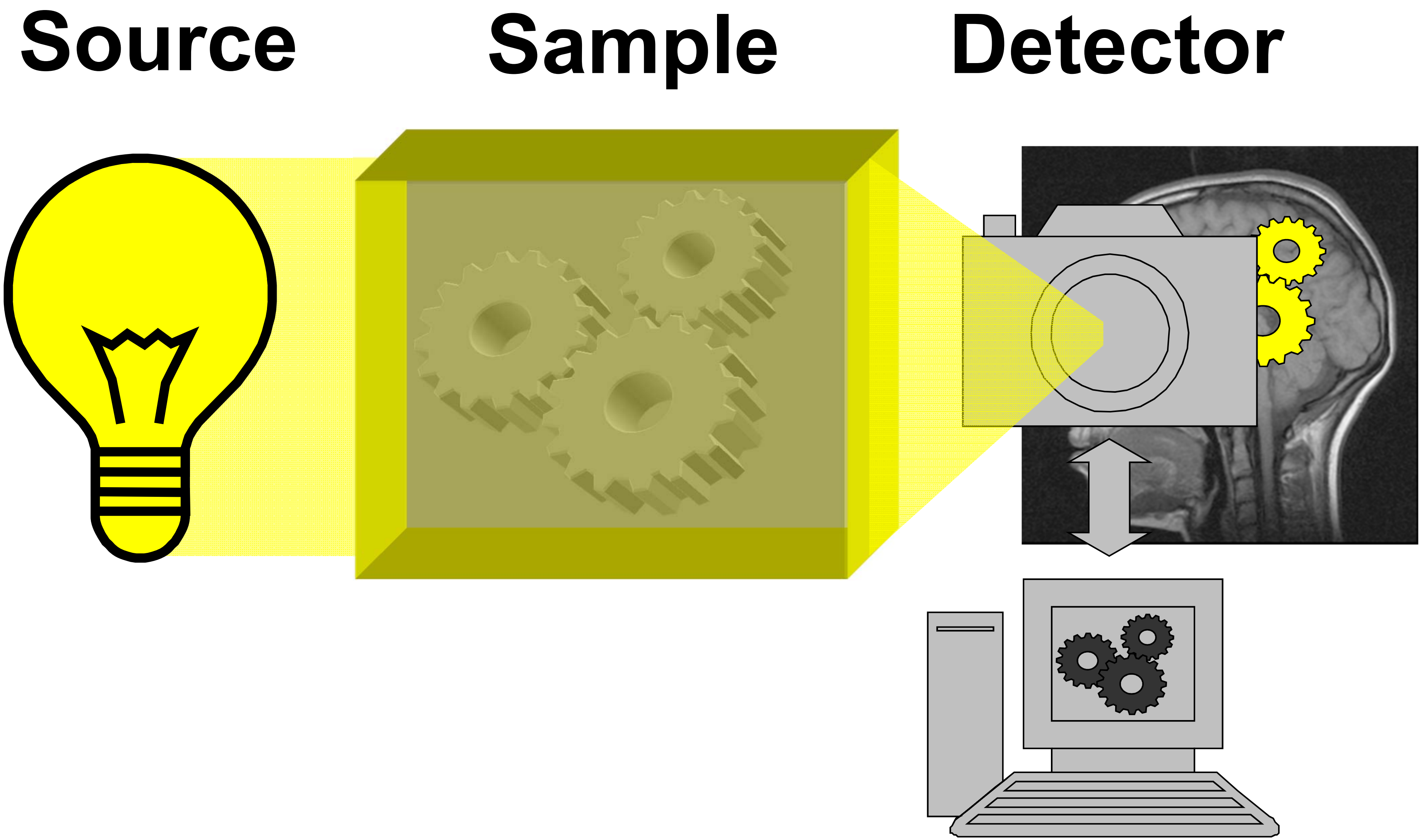
Nikolay Kardjilov

Neutron imaging

Neutron imaging



Neutron imaging



Neutron imaging

Introduction

One of the first X-ray experiments late in 1895 performed by Konrad Röntgen was a film of a hand.

The bones and also finger rings deliver much higher contrast than the soft tissue.

Neutron imaging

Introduction

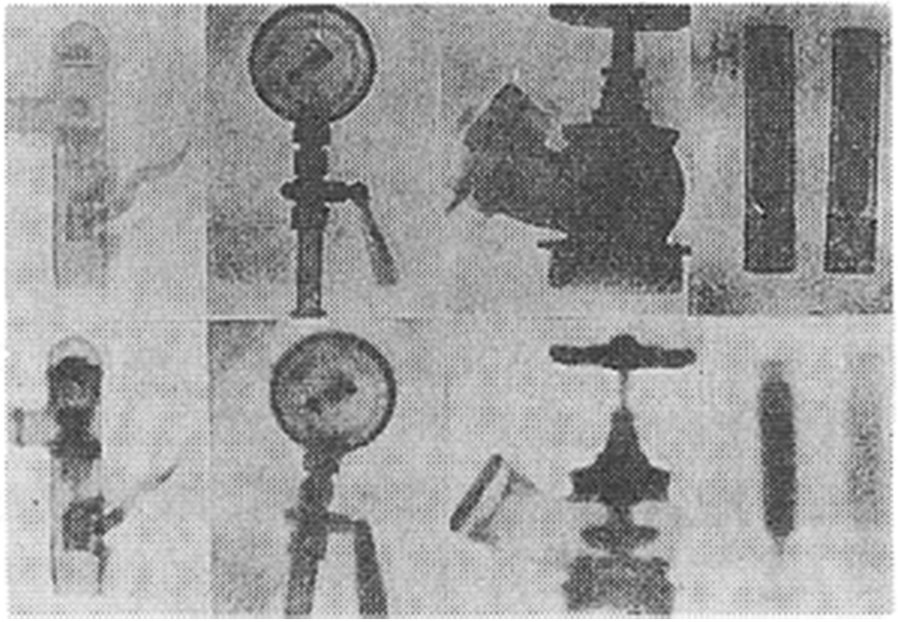
Photo of experimenters taking an X-ray with an early Crookes tube apparatus, from the late 1800s.

Roots of neutron radiography

Comparison between x-ray and neutron images

x-rays

neutrons



Berlin, 1935 – 1938
H. Kallmann & Kuhn with Ra-Be and neutron generator

Berlin until Dec. 1944
O. Peter with an accelerator neutron source

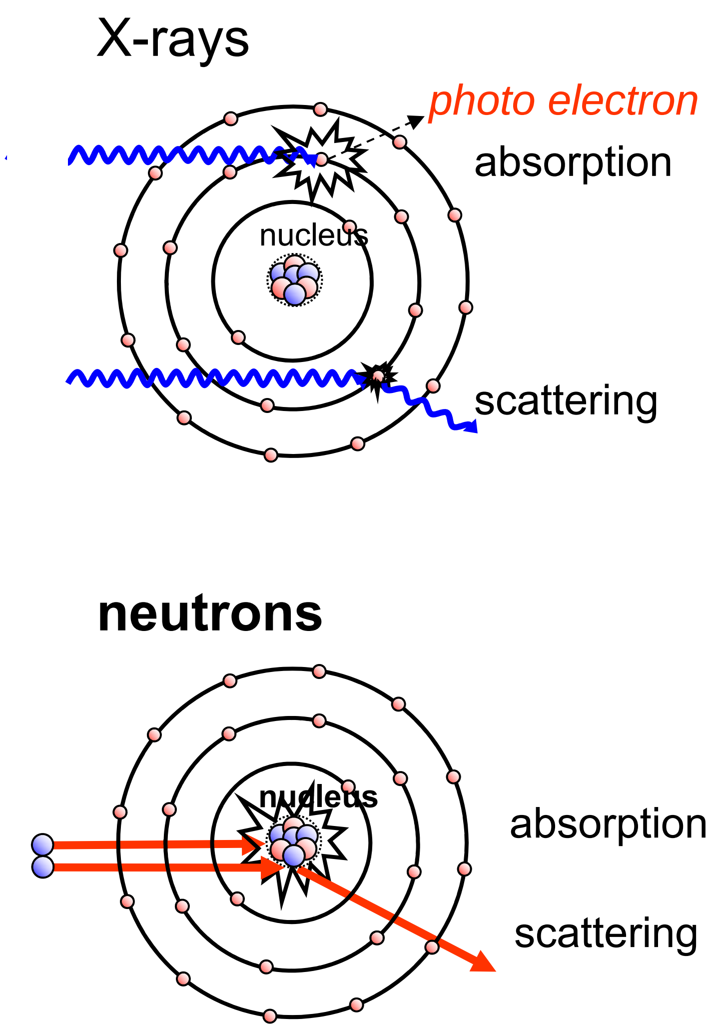
But the real programs with neutrons started after World War II at research reactors

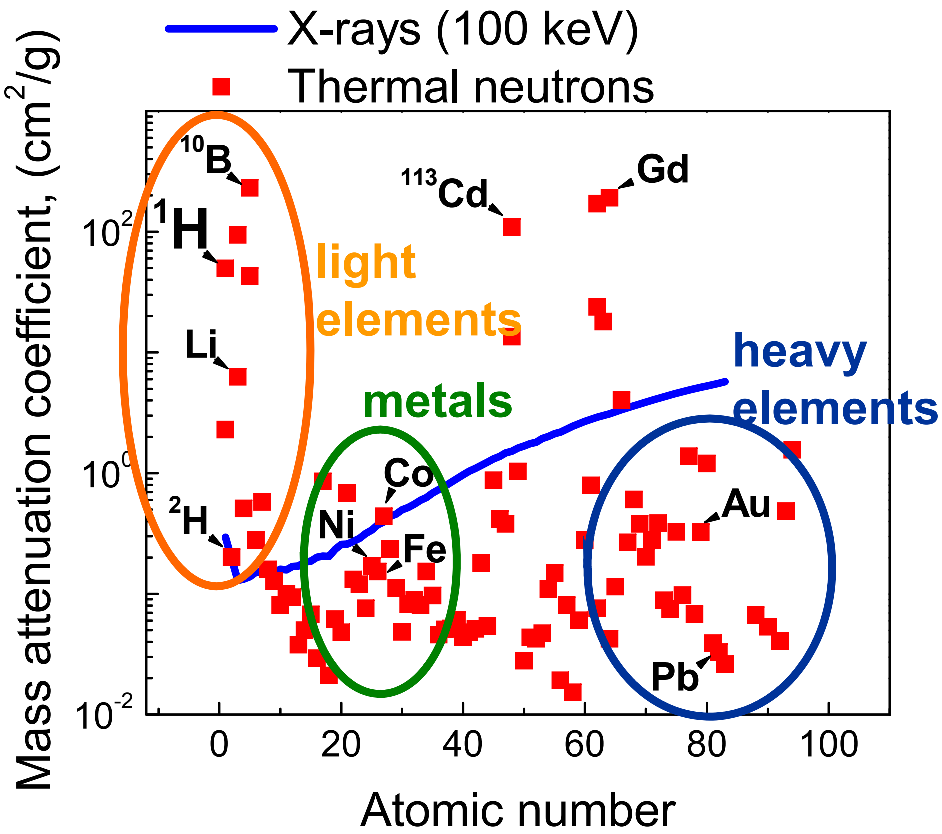
Introduction

Sample image: X-ray showing frontal view of both hands.

Neutron imaging

Neutron interaction with matter

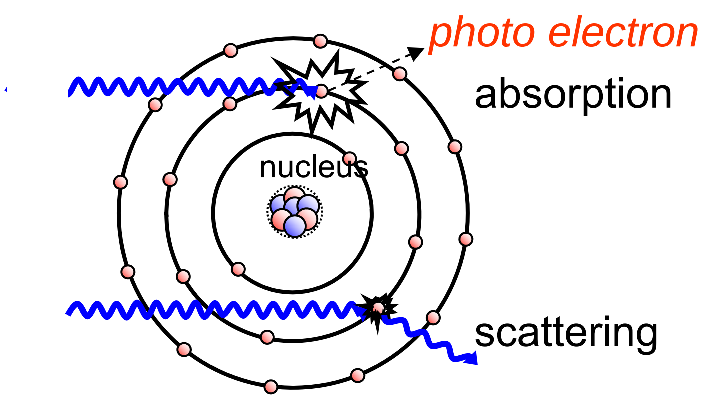




Neutron imaging

Neutron interaction with matter

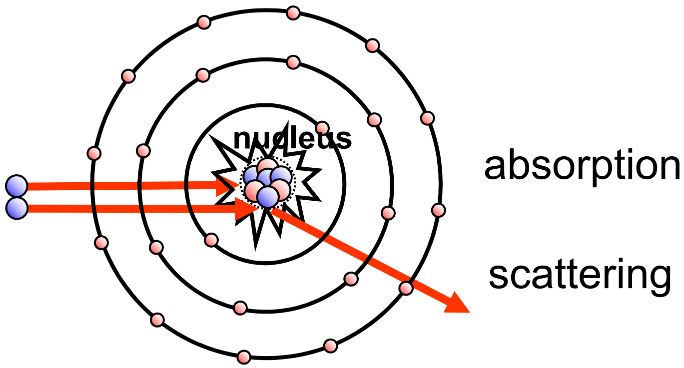
X-rays



Attenuation coefficients with X-ray [cm$?^{1}$]

1a	2a	3b	4b	5b	6b	7b	8	8	8	1b	2b	3a	4a	5a	6a	7a	0
H 0.02																	He 0.02
Li 0.06	Be 0.22											B 0.28	C 0.27	N 0.11	O 0.16	F 0.14	Ne 0.17
Na 0.13	Mg 0.24											Al 0.38	Si 0.33	P 0.25	S 0.30	Cl 0.23	Ar 0.20
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
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
Cs 1.42	Ba 2.73	La 5.04	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
Fr	Ra 11.80	Ac 24.47	Rf	Ha													
Lanthanides	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 10.91	Er 11.70	Tm 12.49	Yb 9.32	Lu 14.07			
*Actinides	Th 28.95	Pa 39.65	U 49.08	Np	Pu	Am	Cm	Bk	Vf	Es	Fm	Md	No	Lr x-ray			

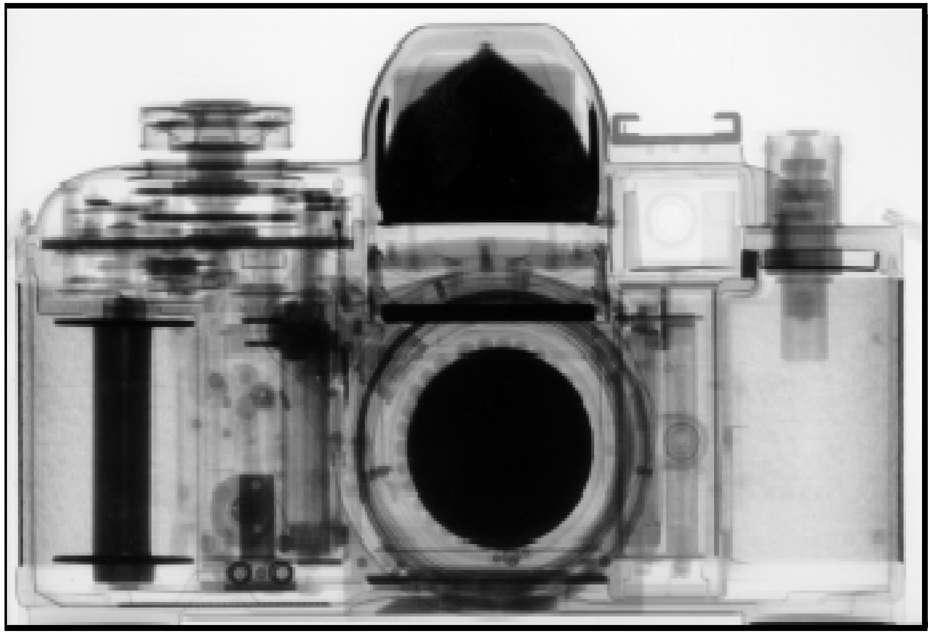
neutrons

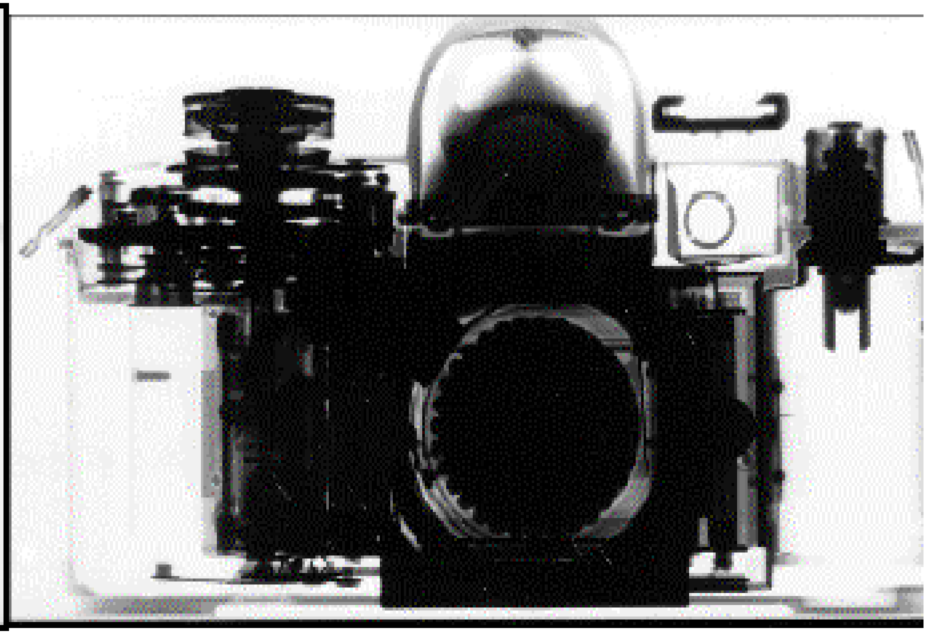


Attenuation coefficients with neutrons [cm$?^{1}$]

1a	2a	3b	4b	5b	6b	7b	8	8	8	1b	2b	3a	4a	5a	6a	7a	0
H 3.44																	He 0.02
Li 3.30	Be 0.79											B 101.60	C 0.56	N 0.43	O 0.17	F 0.20	Ne 0.10
Na 0.09	Mg 0.15											Al 0.10	Si 0.11	P 0.12	S 0.06	Cl 1.33	Ar 0.03
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
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 115.11	In 7.58	Sn 0.21	Sb 0.30	Te 0.25	I 0.23	Xe 0.43
Cs 0.29	Ba 0.07	La 0.52	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
Fr	Ra 0.34	Ac	Rf	Ha													
*Lanthanides	Ce 0.14	Pr 0.41	Nd 1.87	Pm 5.72	Sm 171.47	Eu 94.58	Gd 1479.04	Tb 0.93	Dy 32.42	Ho 2.25	Er 5.48	Tm 3.53	Yb 1.40	Lu 2.75			
**Actinides	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 neut.			

Neutron radiography - examples

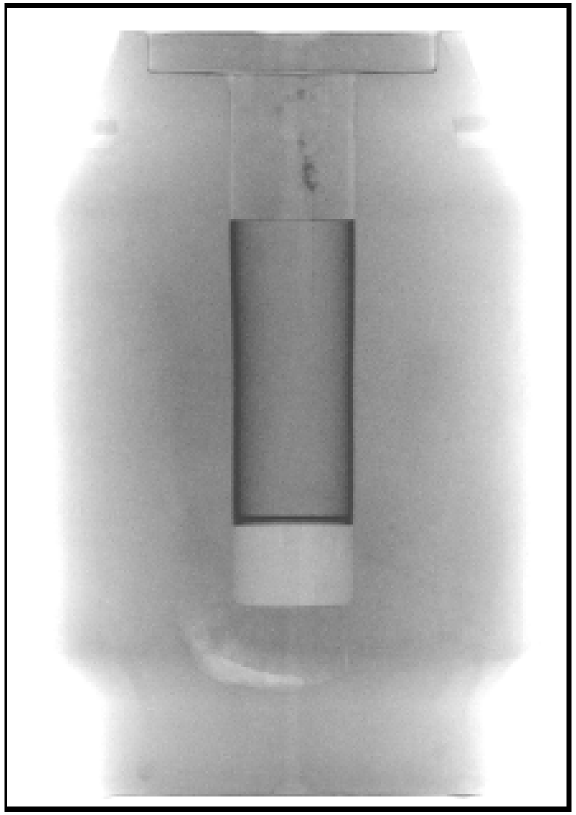


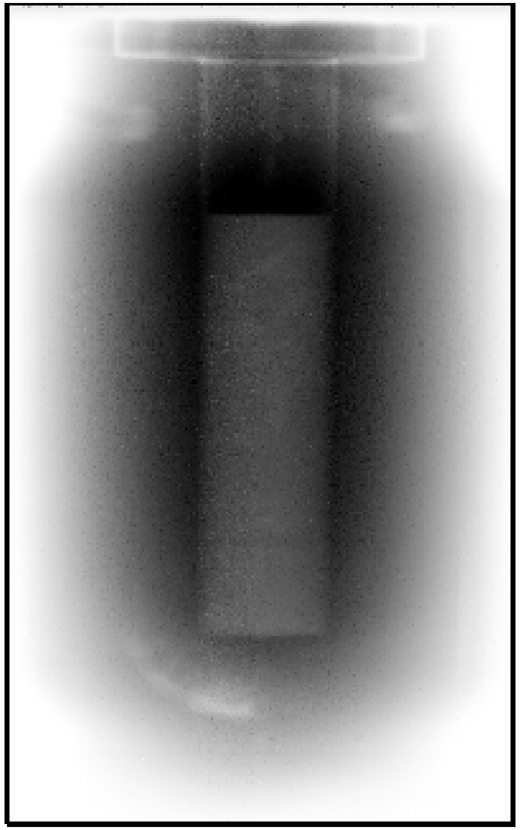


The example for a camera helps to explain differences in neutron (left) and X-ray (right) radiography. Whereas the hydrogen containing parts can be visualised with neutron even at thin layers, thicker metallic components are hard to penetrate with X-rays.

Images courtesy: Dr. Eberhard Lehmann (Paul-Scherrer-Institute, Switzerland)

Neutron imaging



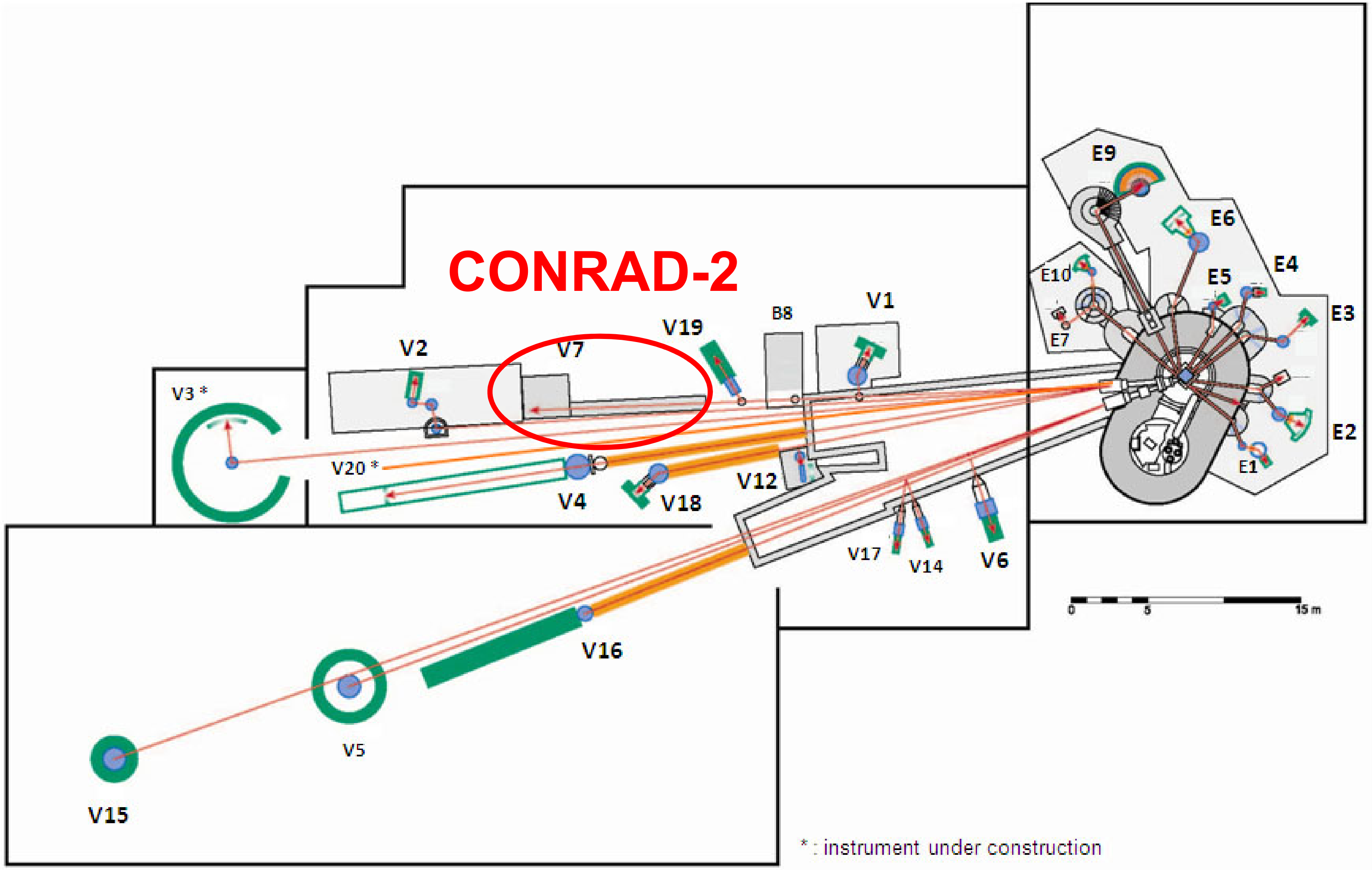


Observation of a lead container. The neutron image on the left was obtained after 20 s. On the right, the gamma radiography with Co-60 (1100 keV) needed 120 minutes of exposure.

Images courtesy: Dr. Eberhard Lehmann (Paul-Scherrer-Institute, Switzerland)

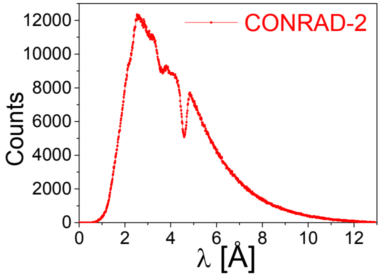
Neutron imaging

Beam optimisation



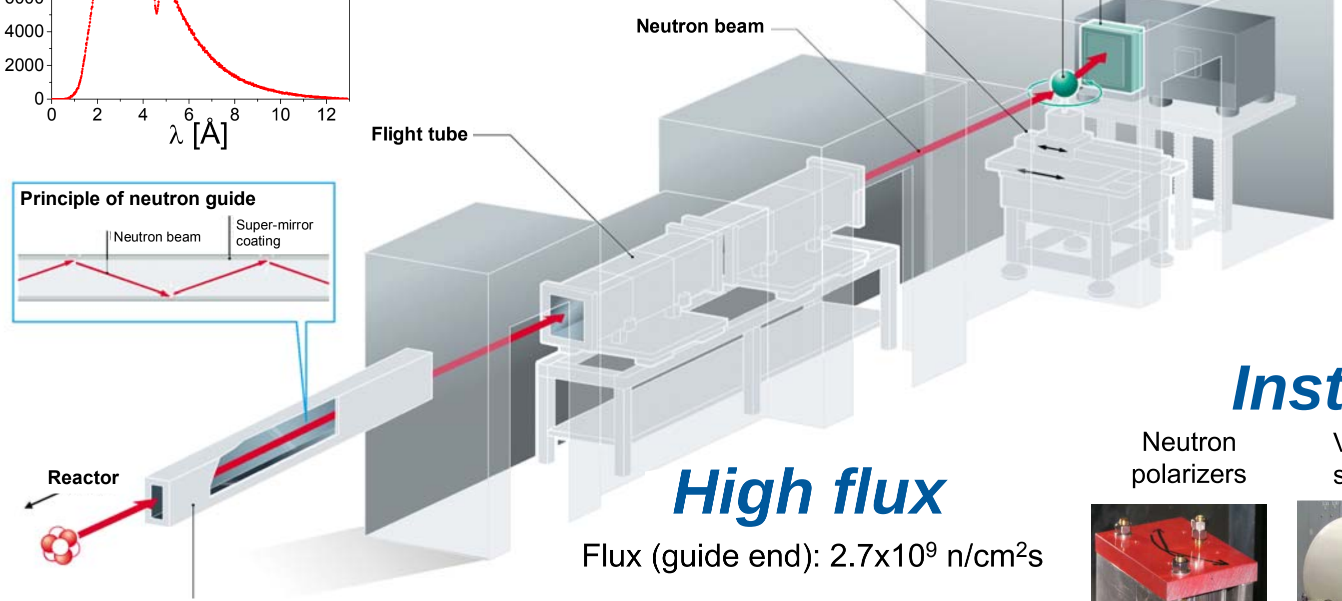
Cold neutrons

Wavelength range: 1.5 Å – 10 Å



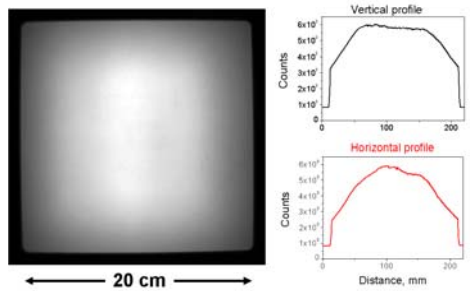
Labs

Micro-CT Lab
3D Data Analytics Lab



Large beam

Beam size: 20 cm x 20 cm



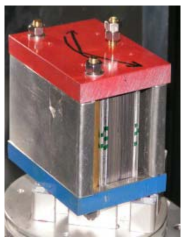
Guide system: super-mirror coated neutron guide (M=3) with a curvature of 750 m and length of 15 m followed by linear guide section (M=2) with a length of 10 m.

High flux

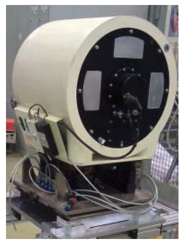
Flux (guide end): 2.7x10^9 n/cm^{2}s

Instrumentation

Neutron polarizers

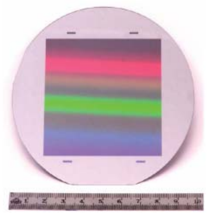


Velocity selector



Double-crystal monochromator

Grating interferometry



Contrast

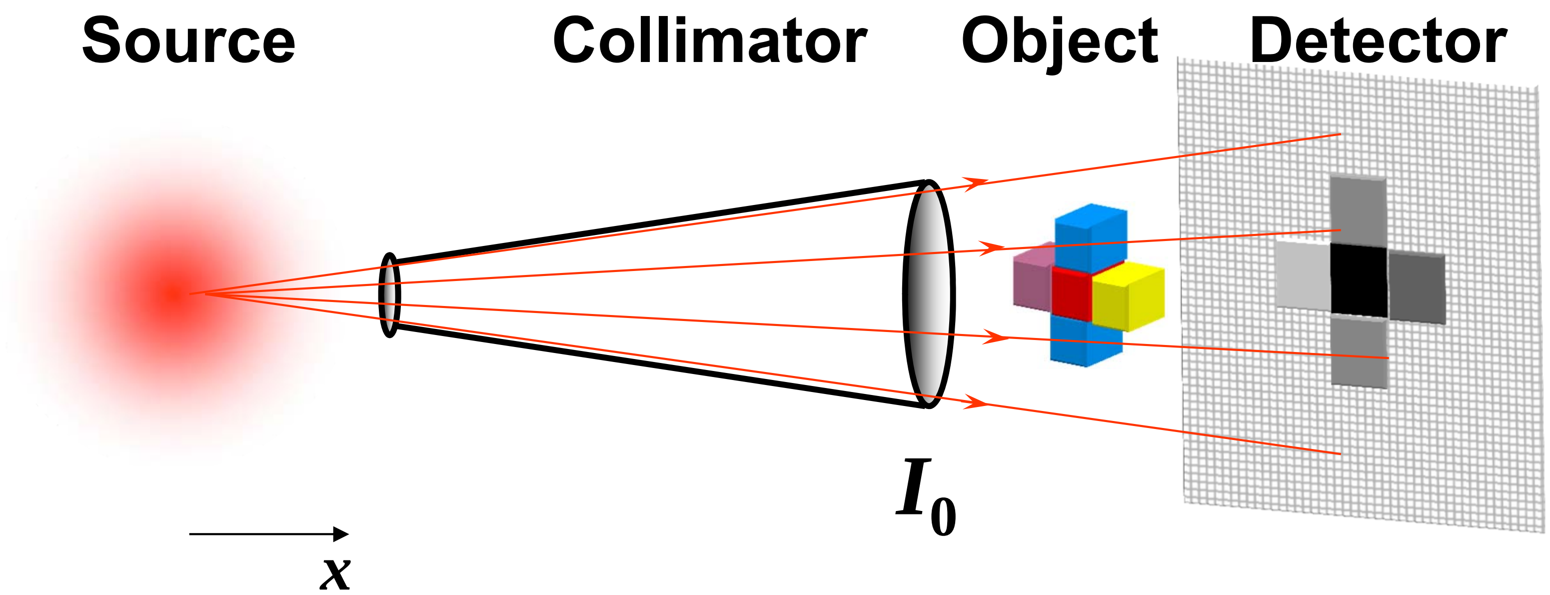
Resolution

- Beam optimisation ⇐
- Detector development

- Neutron interaction with matter
  - absorption
  - incoherent scattering
  - coherent scattering
  - magnetic interaction

Neutron imaging

Beam optimisation



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

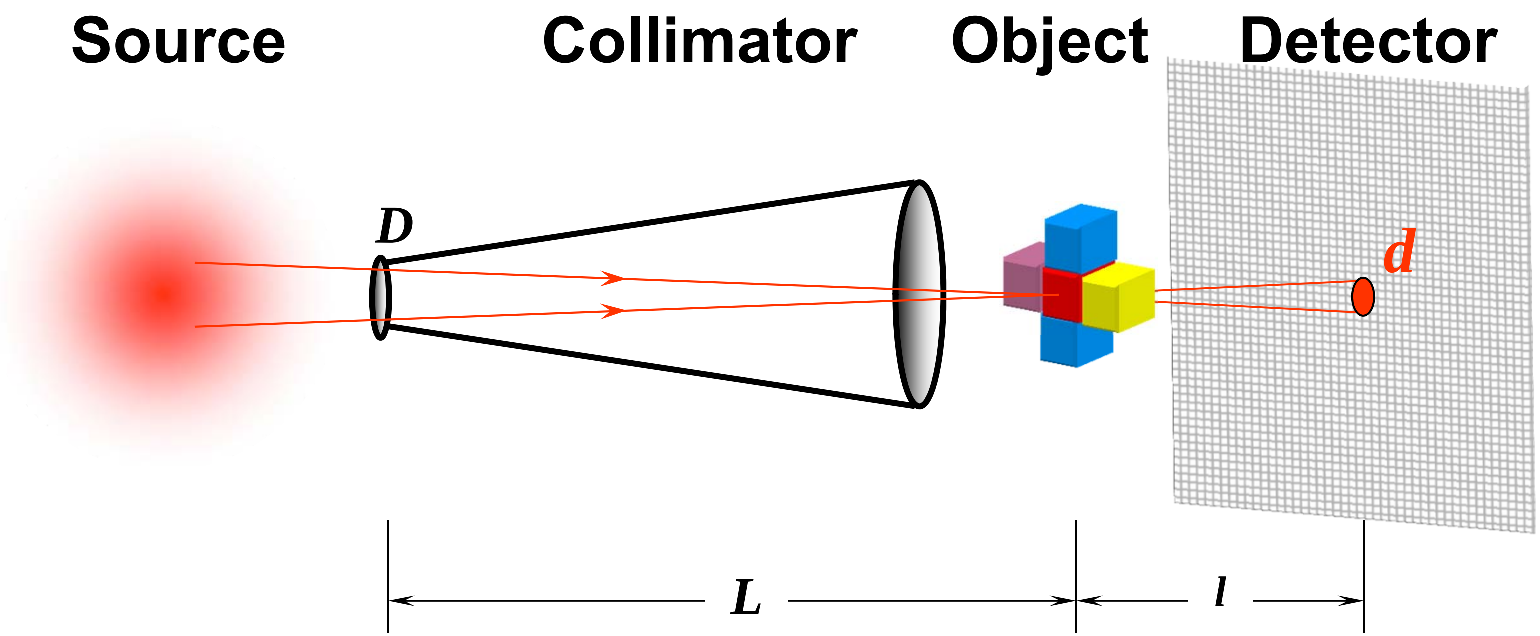
x – propagation direction

I_0 – primary beam

$\Sigma(x)$ – attenuation coefficient

Neutron imaging

Beam optimisation



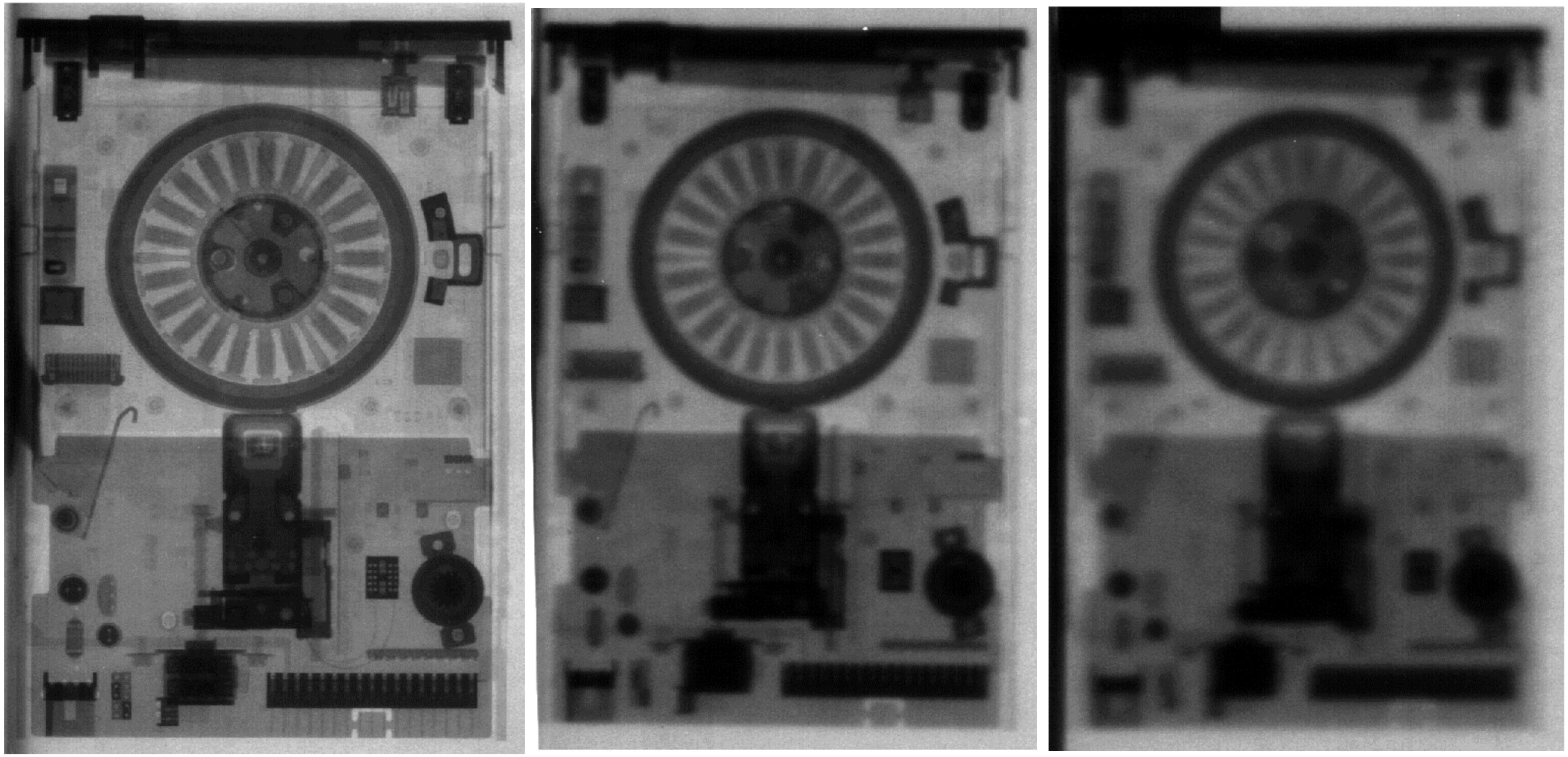
D – Collimator aperture

L – Distance Collimator-Object

l – Distance Object-Detector

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

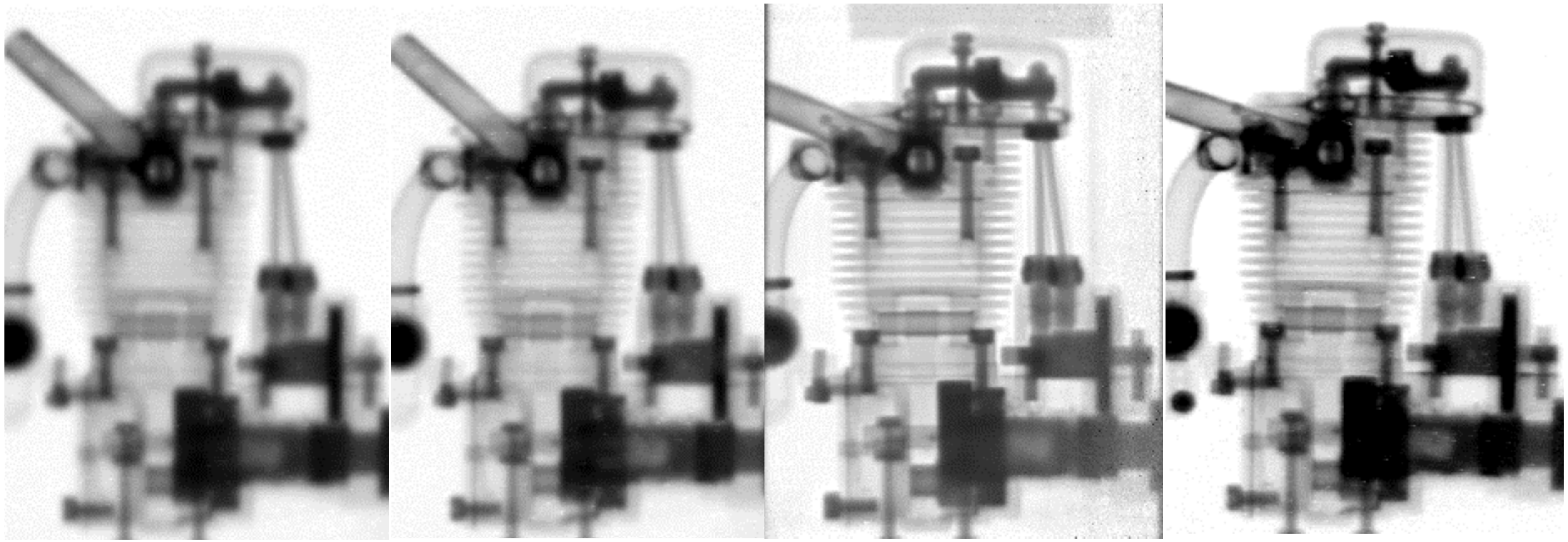
Neutron imaging



Radiographs of a 3,5" floppy drive in 0 cm, 10 cm and 20 cm distance from a film + Gd sandwich taken at a cold neutron guide with *L/D*=71.

B. Schillinger, Estimation and measurement of L/D on a cold and thermal neutron guide, in: Nondestructive Testing and Evaluation, World Conference on Neutron Radiography, vol. 16, Osaka, 1999, pp. 141–150

Neutron imaging



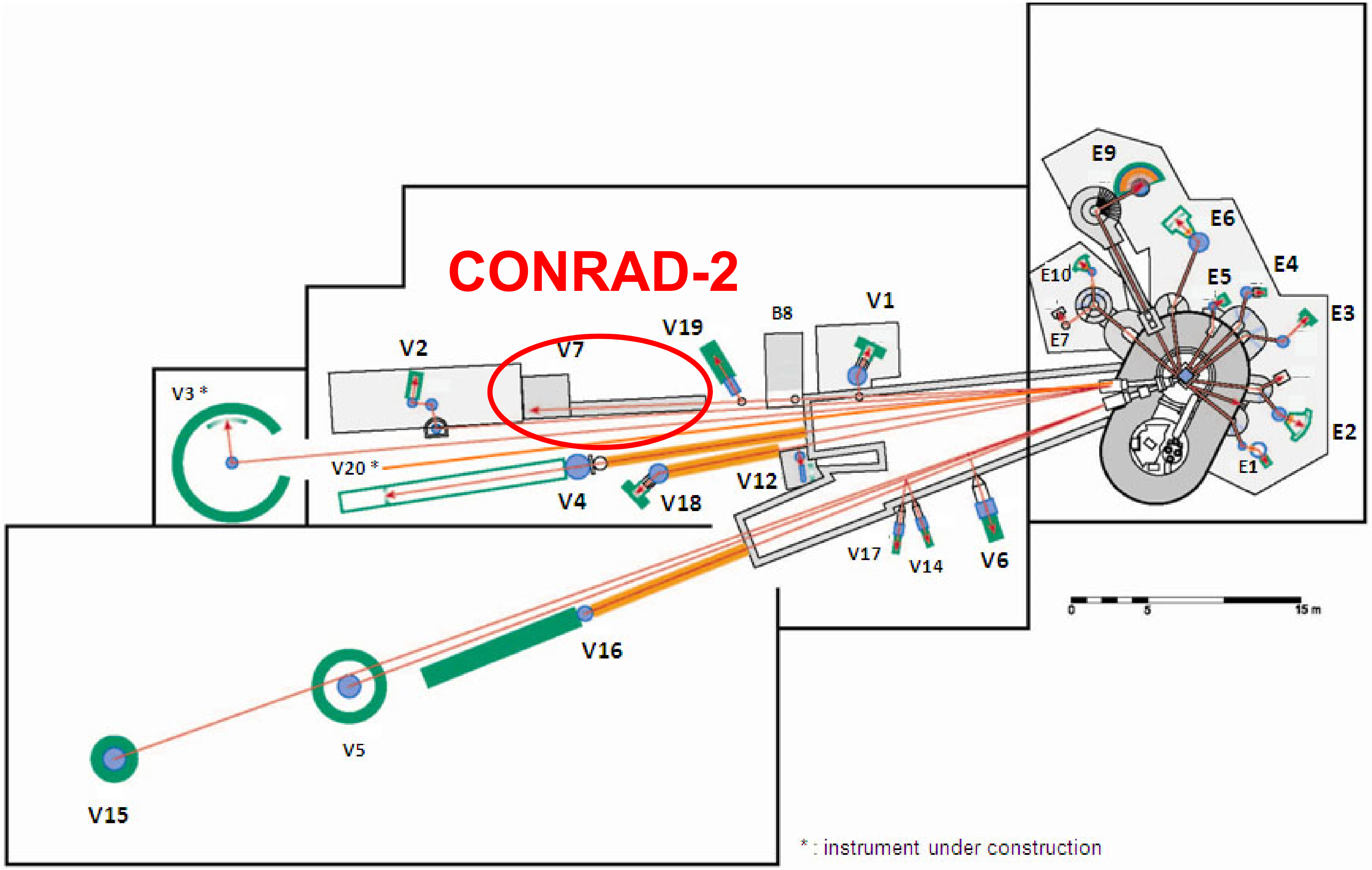
L/D=71 L/D=115 L/D=320 L/D>500.

Radiographs of a small motor taken at different beam positions with different L/D ratios.

B. Schillinger, Estimation and measurement of L/D on a cold and thermal neutron guide, in: Nondestructive Testing and Evaluation, World Conference on Neutron Radiography, vol. 16, Osaka, 1999, pp. 141–150

Neutron imaging

Beam optimisation



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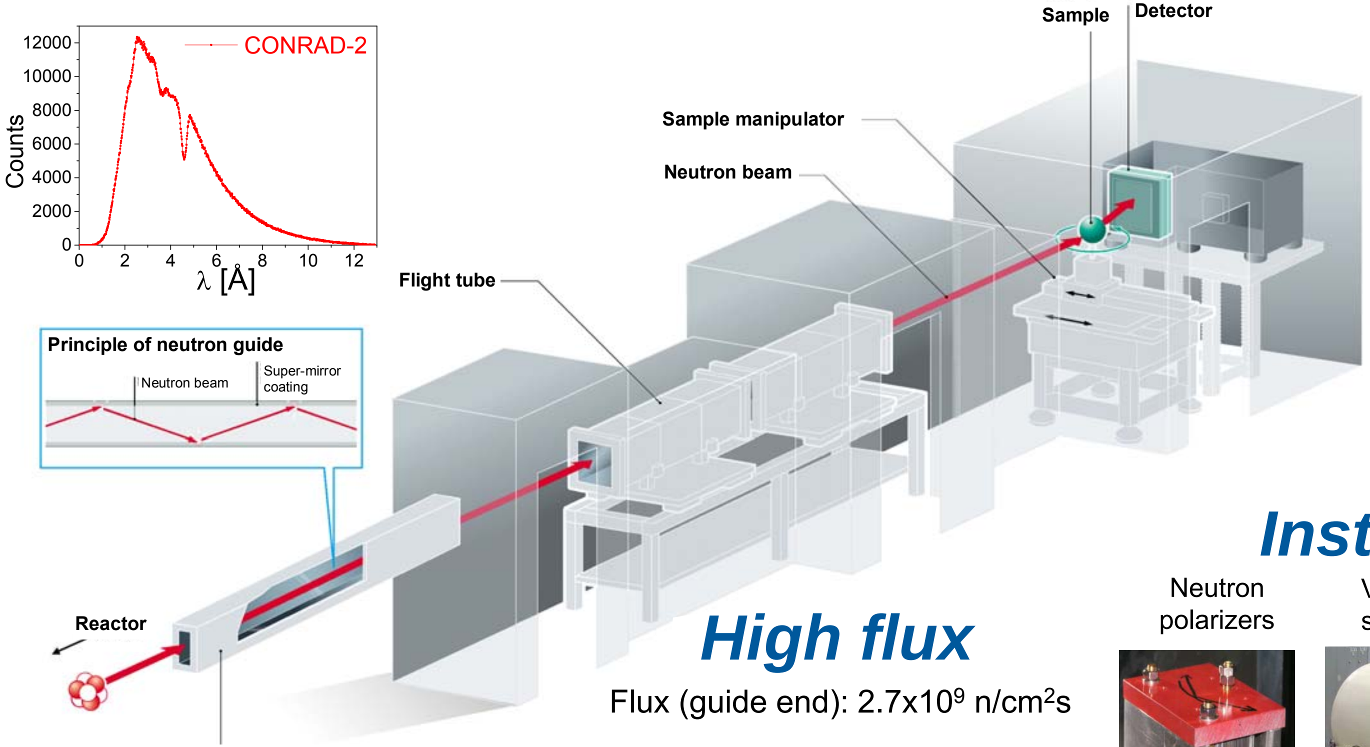
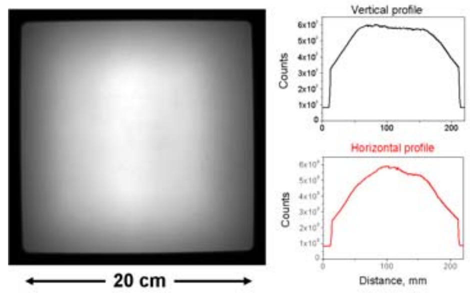


Large beam

Beam size: 20 cm x 20 cm



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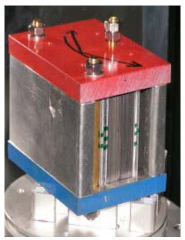

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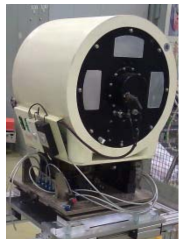
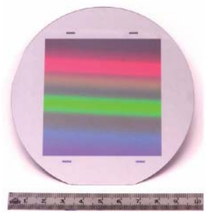


Double-crystal monochromator

Grating interferometry



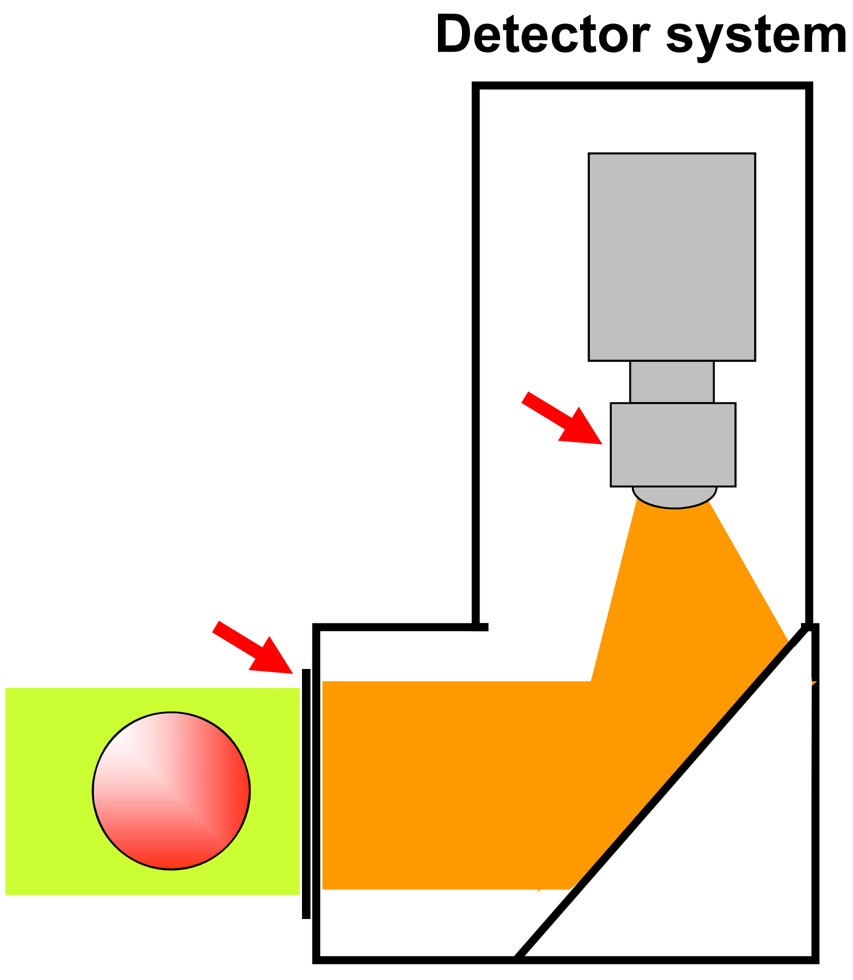
Resolution

- Beam optimisation
- Detector development ⇐

Contrast

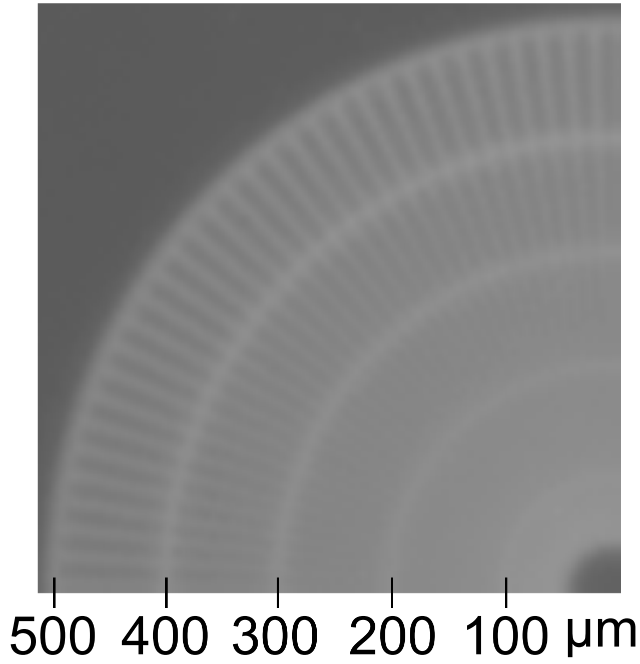
- Neutron interaction with matter
  - absorption
  - incoherent scattering
  - coherent scattering
  - magnetic interaction

Detector development



Standard setup

Scintillator: 200 µm 6LiF
Lens system: 50 mm
Pixel size: 100 µm
Exposure time: 20 s



Detector development

neutron detection for imaging

- no direct neutron detection possible
- a secondary nuclear process is needed (capture, fission, collision)
- main ***neutron imaging processes*** are using:
  - scintillation
  - photo-luminiscence by secondary particles + β, γ
  - nuclear track detection
  - chemical excitation
  - collection of charge in semiconductors from Gd conversion

Capture reactions for thermal / cold neutrons

$^{3}He + {}^{1}n \Rightarrow {}^{3}He + {}^{1}p + 0.77$ MeV

→ $^{6}Li + {}^{1}n \Rightarrow {}^{3}H + {}^{4}He + 4.79$ MeV

$^{10}B + {}^{1}n \Rightarrow {}^{7}Li + {}^{4}He + 2.78$ MeV (7%)

$\Rightarrow {}^{7}Li^{*} + {}^{4}He + 2.30$ MeV (93%)

$^{155}Gd + {}^{1}n \Rightarrow {}^{156}Gd + \gamma$´s + CE´s (7.9 MeV)

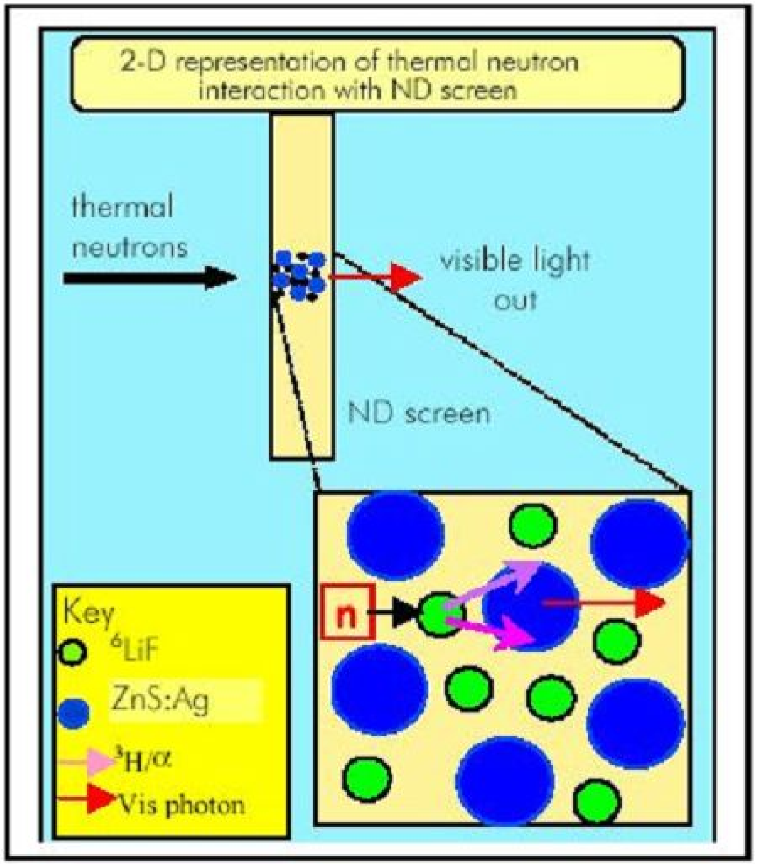
→

$^{157}Gd + {}^{1}n \Rightarrow {}^{158}Gd + \gamma$´s + CE´s (8.5 MeV)

^{235}U, ^{239}Pu $^{1}n \Rightarrow$ fission products + 80 MeV

Detector

The ZnS+^{6}LiF scintillation screen is the limit of resolution.



The reaction products of

^{6}Li(n,α) ->^{3}H + ^{4}He + 4.7 MeV

have to be stopped in the ZnS scintillation screen.
Their average range is in the order of 50-80 μm.

About 177,000 photons are generated per detected neutron.

With thinned scintillation screens, we can achieve resolution in the order of 20-30 μm.

Slide courtesy: Dr. Burkhard Schillinger (FRM-II, Munich, Germany)

Neutron imaging

Nikkor Makro-Objektiv - 105 mm - F/2.8

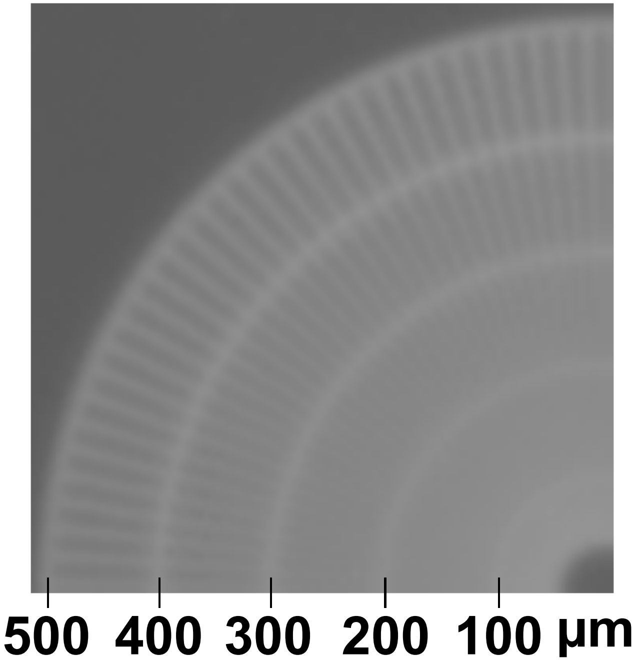
FOV_{max}: 10 cm x 10 cm, pixel size: 50 µm
FOV_{min} : 6 cm x 6 cm, pixel size: 30 µm

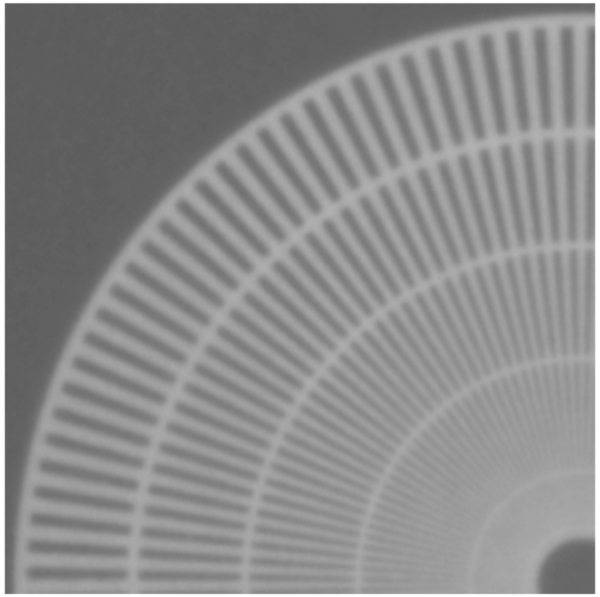
Nikon Micro Nikkor 200mm f/4 D (IF) ED

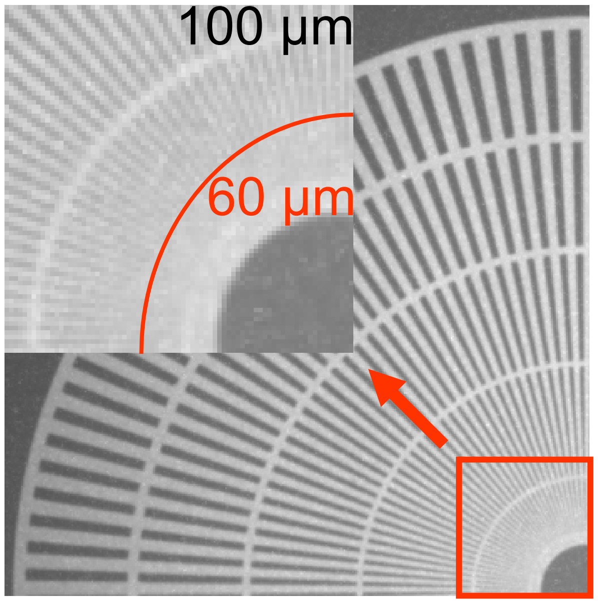
1:1 imaging
FOV_{max}: 2.8 cm x 2.8 cm, pixel size: 13.5 µm

Detector development

Standard setup	Improved lenses	+ Improved screen
Scintillator: 200 μm 6LiF Pixel size: 100 μm Exposure time: 20 s	Scintillator: 200 μm 6LiF Pixel size: 30 μm Exposure time: 20 s	Scintillator: 5 μm Gadox Pixel size: 30 μm Exposure time: 120 s



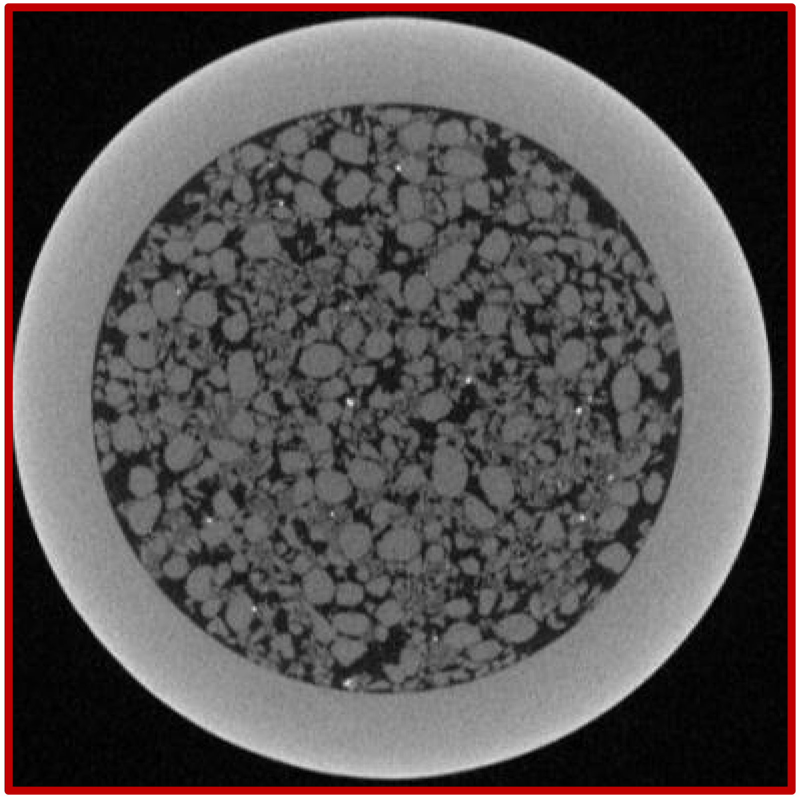




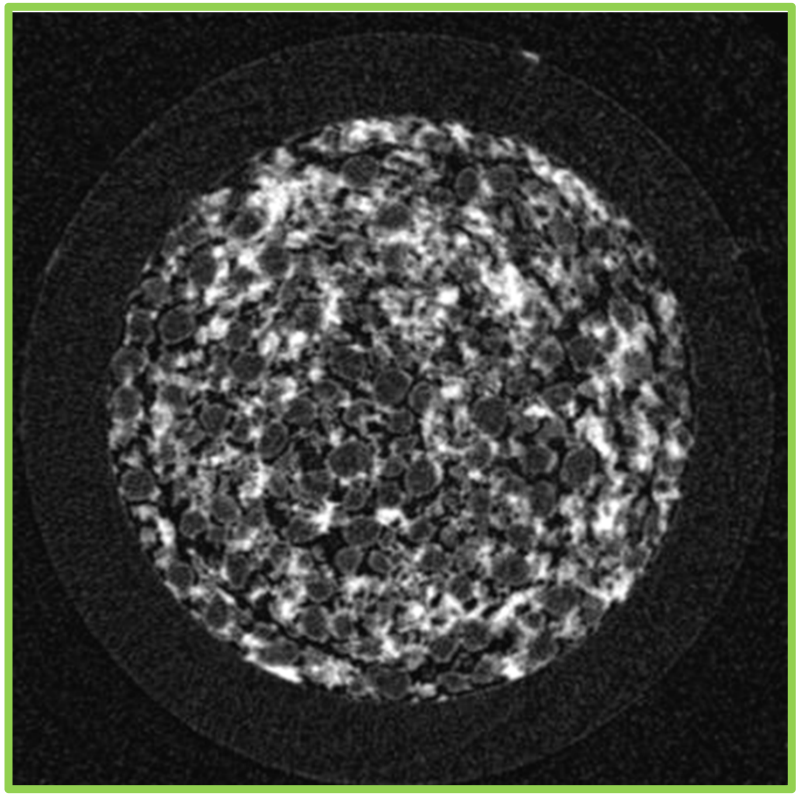
Kardjilov, N., et al. "A highly adaptive detector system for high resolution neutron imaging." *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 651.1 (2011): 95-99.

Neutron imaging

SiO_2 particles in water



X-rays, 120 kV
Pixel size: 15 µm



Cold neutrons
Pixel size: 13.5 µm (resolution: 30 µm)
Gadox 10 µm
Lens system: 200mm

Kim, F., et al. "High Resolution Neutron and X-Ray Imaging of Granular Materials." *Journal of Geotechnical and Geoenvironmental Engineering* (2012).

Resolution

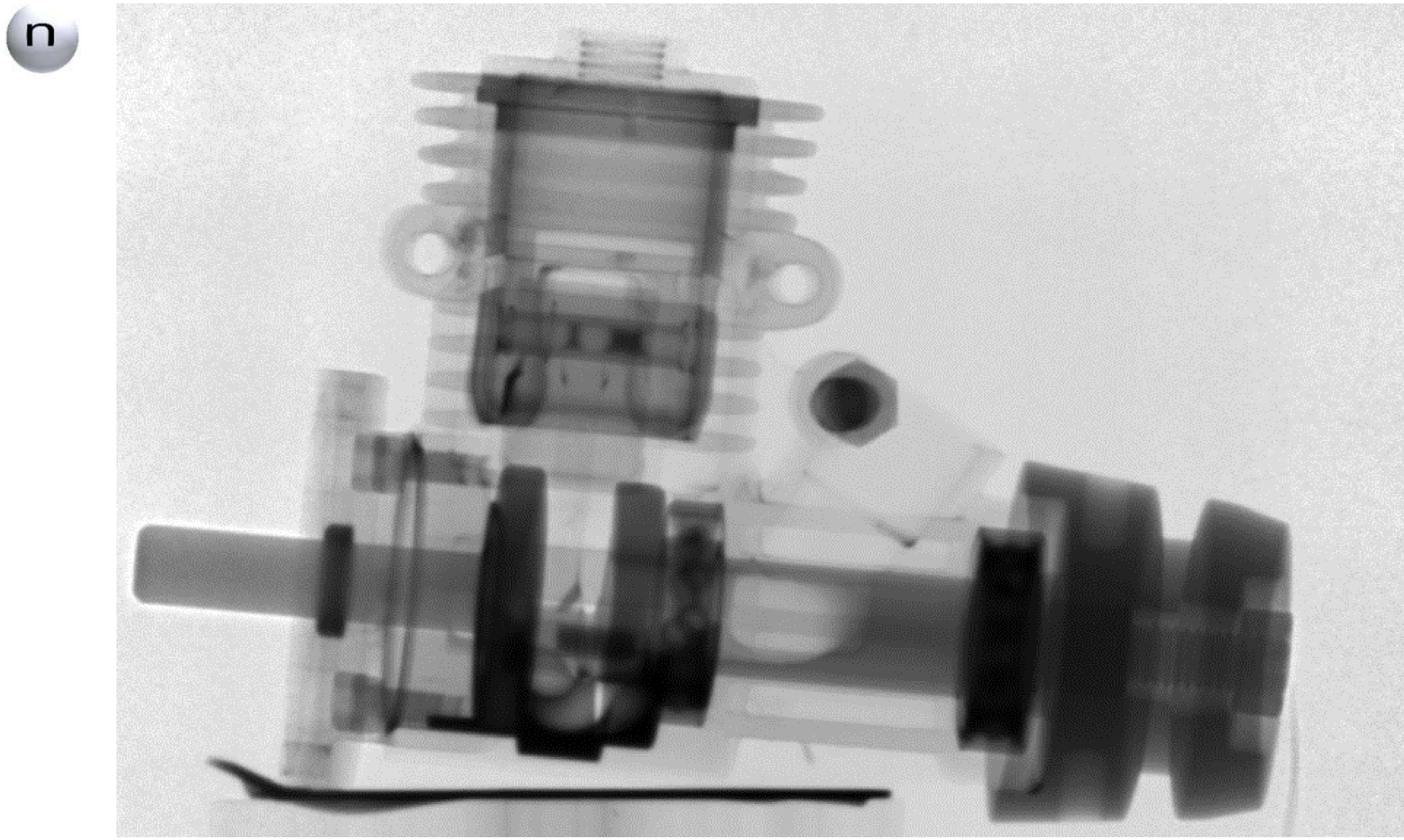
- Beam optimisation
- Detector development

Contrast

- Neutron interaction with matter

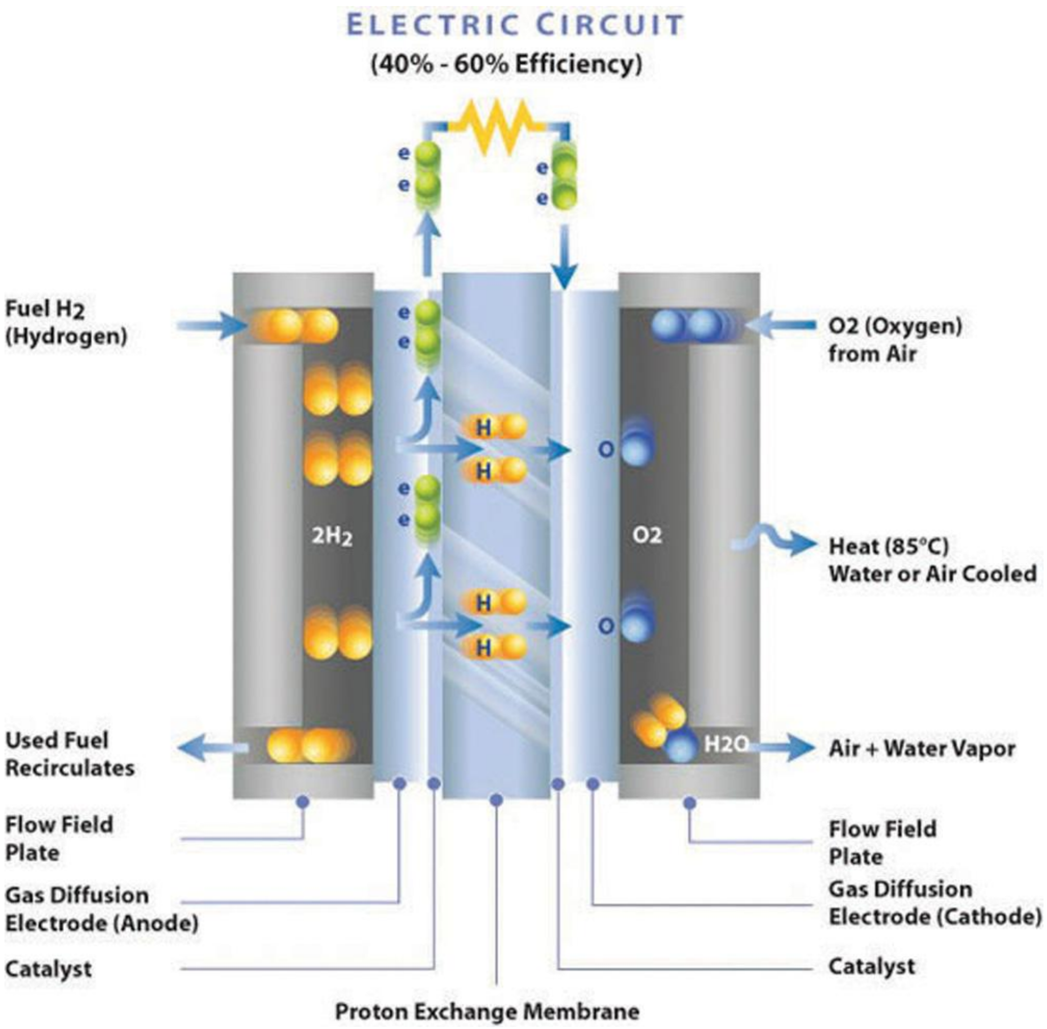
- absorption
- scattering
- magnetic interaction

Attenuation Contrast



1 cm

Application – fuel cells



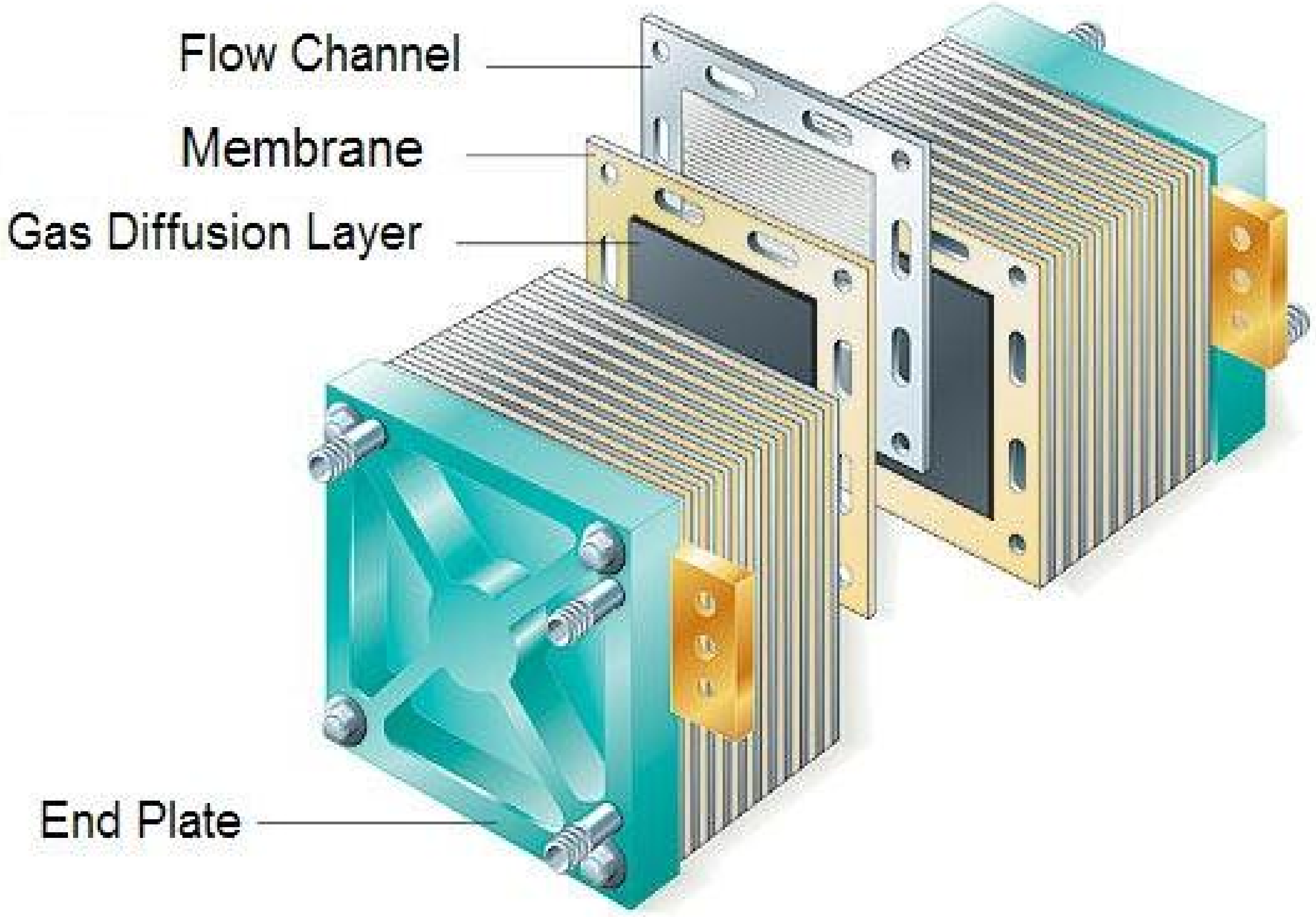
The basic elements of an individual PEM fuel cell:

Composites are used in flow field plates and gas diffusion layers that control the mix of hydrogen and oxygen in the electrochemical reaction.

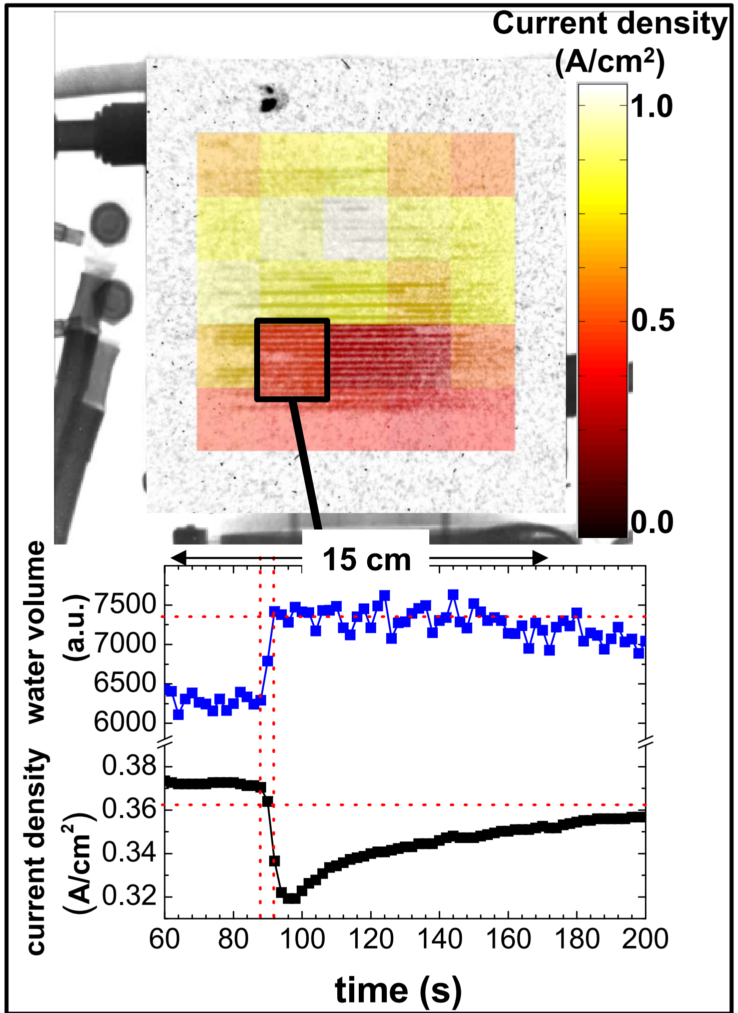
Source: Ballard Power Systems

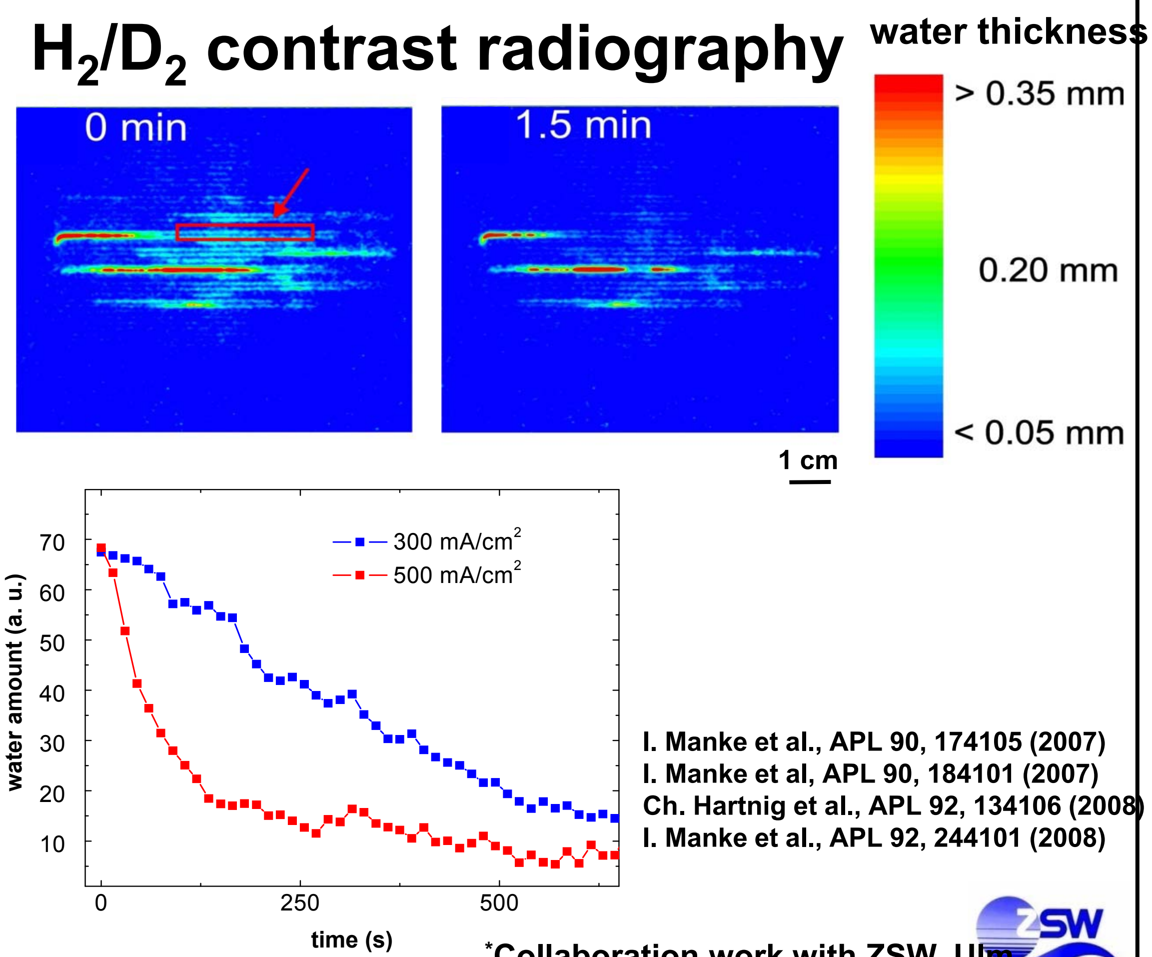
Neutron imaging

Application – fuel cells



Fuel cells



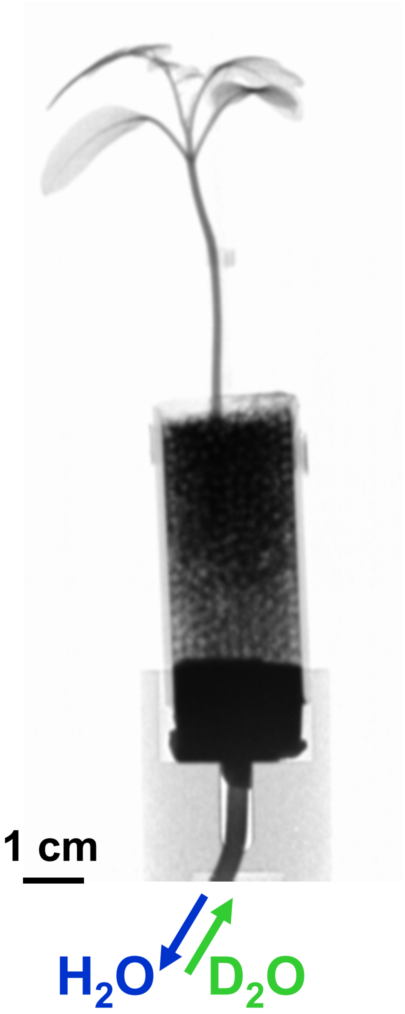


I. Manke et al., APL 90, 174105 (2007)
I. Manke et al, APL 90, 184101 (2007)
Ch. Hartnig et al., APL 92, 134106 (2008)
I. Manke et al., APL 92, 244101 (2008)

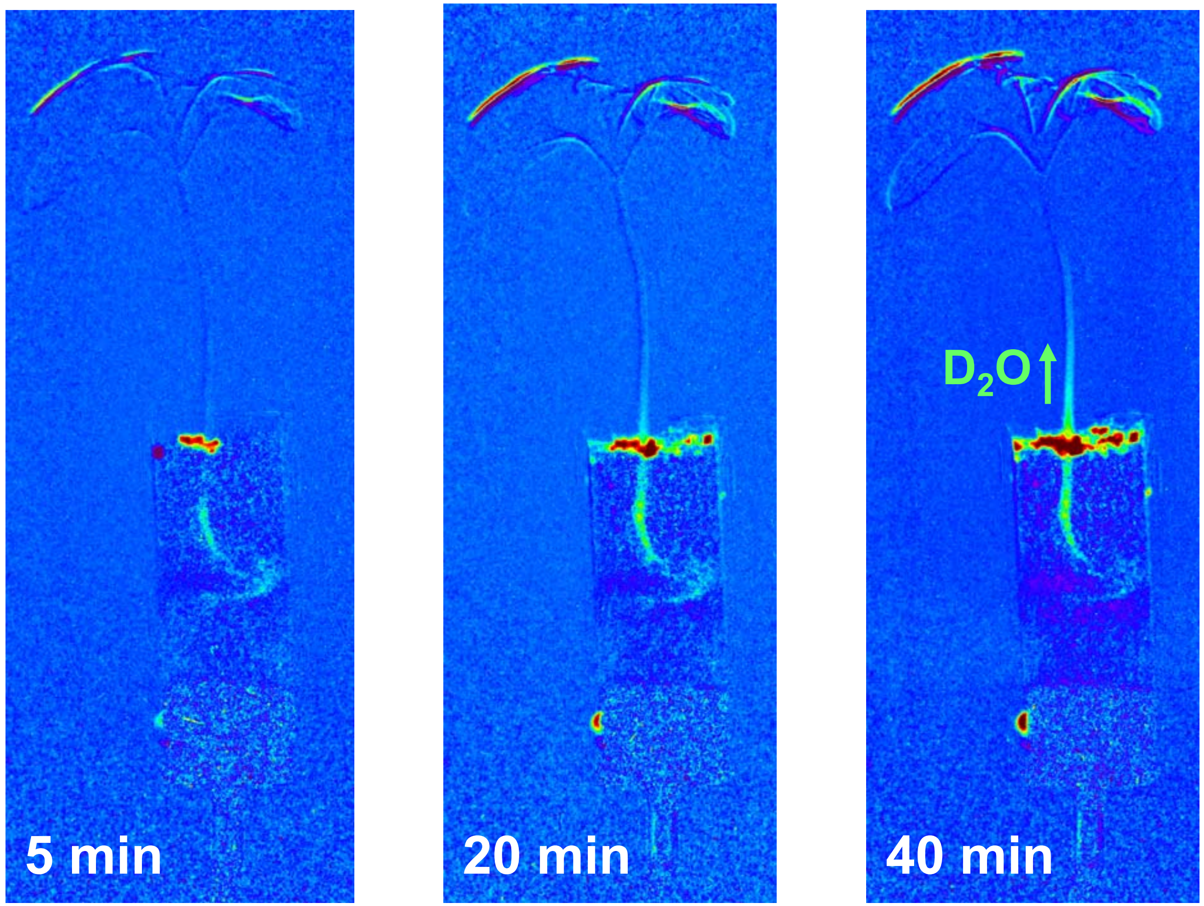
*Collaboration work with ZSW, Ulm

Neutron imaging

Application - plants



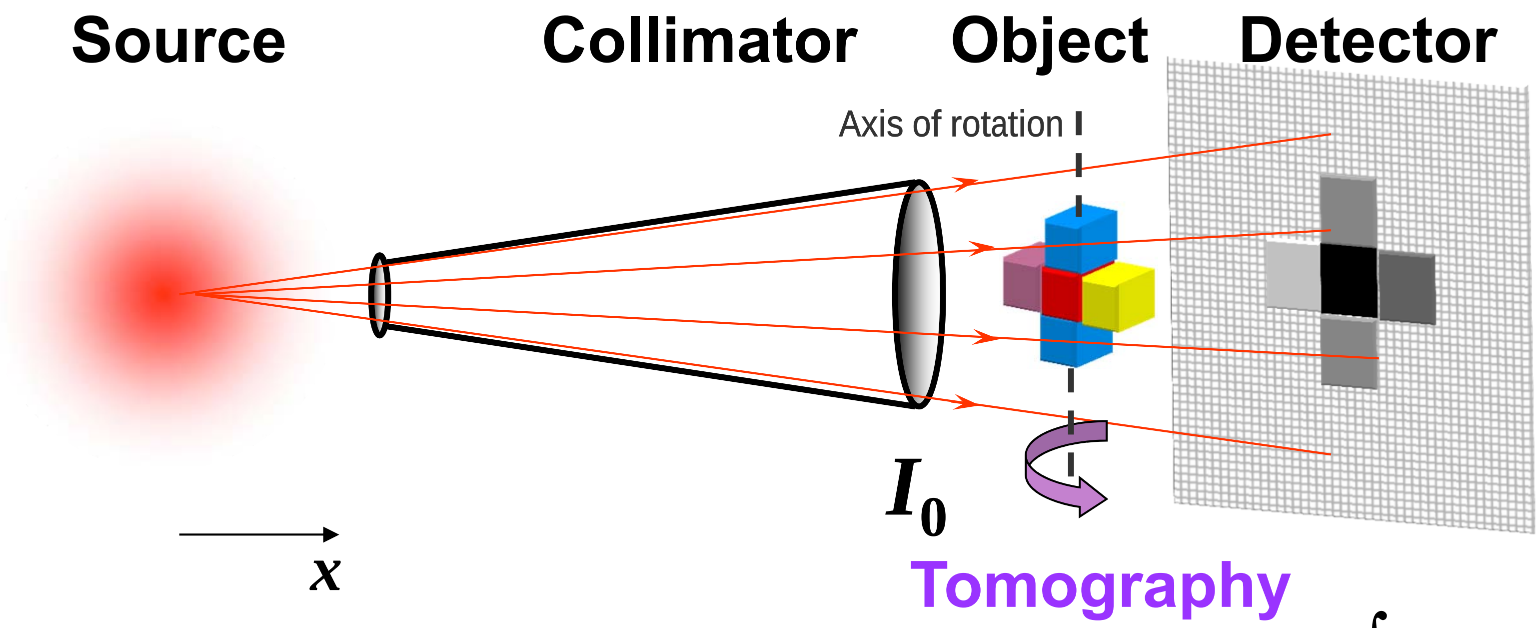
Tomato seedling



Matsushima, U., et al. "Application potential of cold neutron radiography in plant science research." *Journal of applied botany and food quality* 82.1 (2008): 90-98.

Neutron imaging

Absorption tomography



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

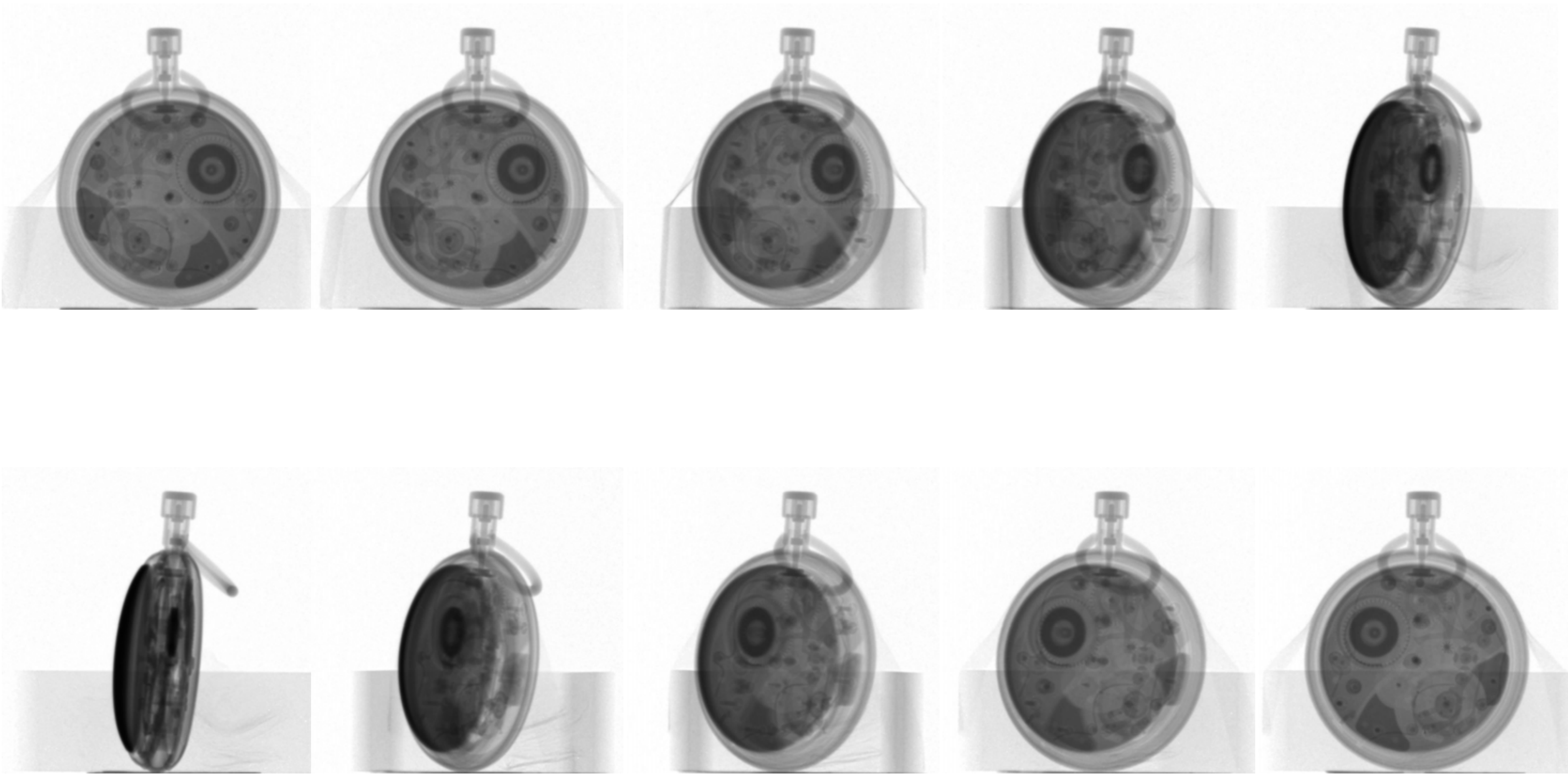
x – propagation direction

I_0 – primary beam

$\Sigma(x)$ – attenuation coefficient

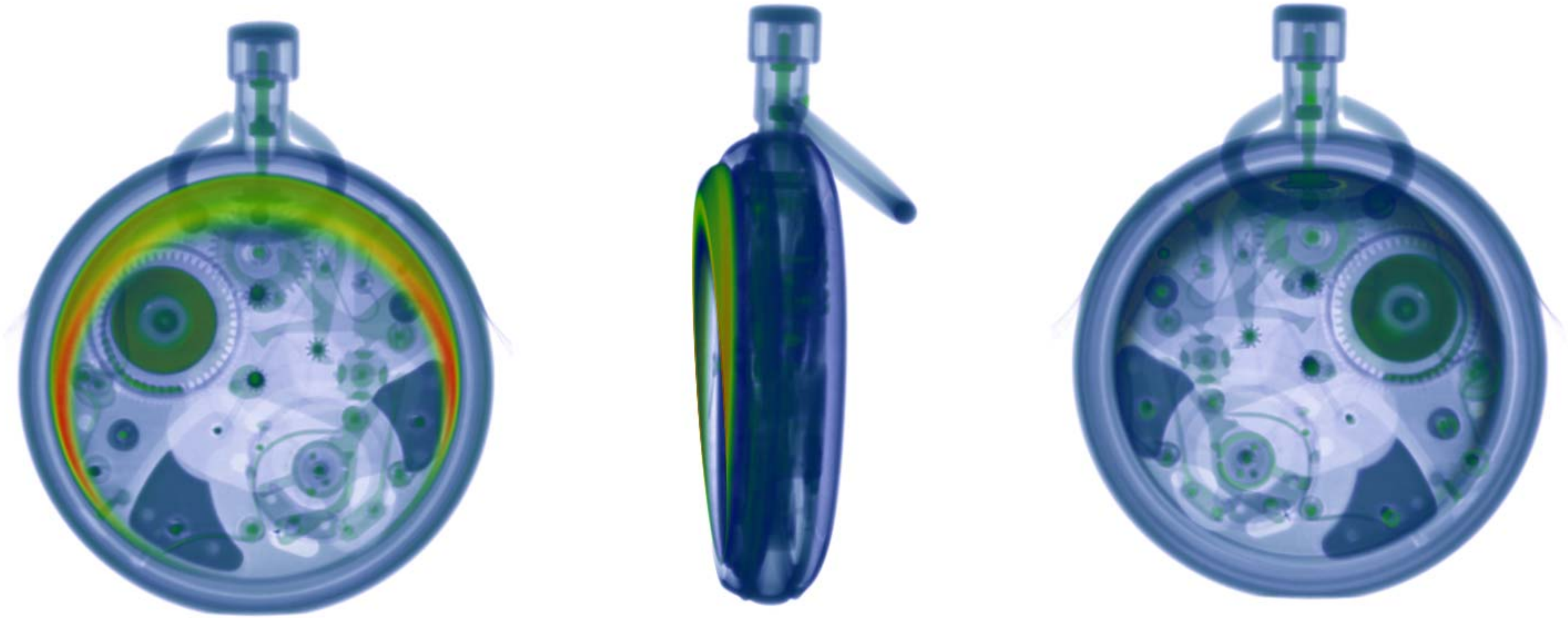
Neutron imaging

Single tomographic projections



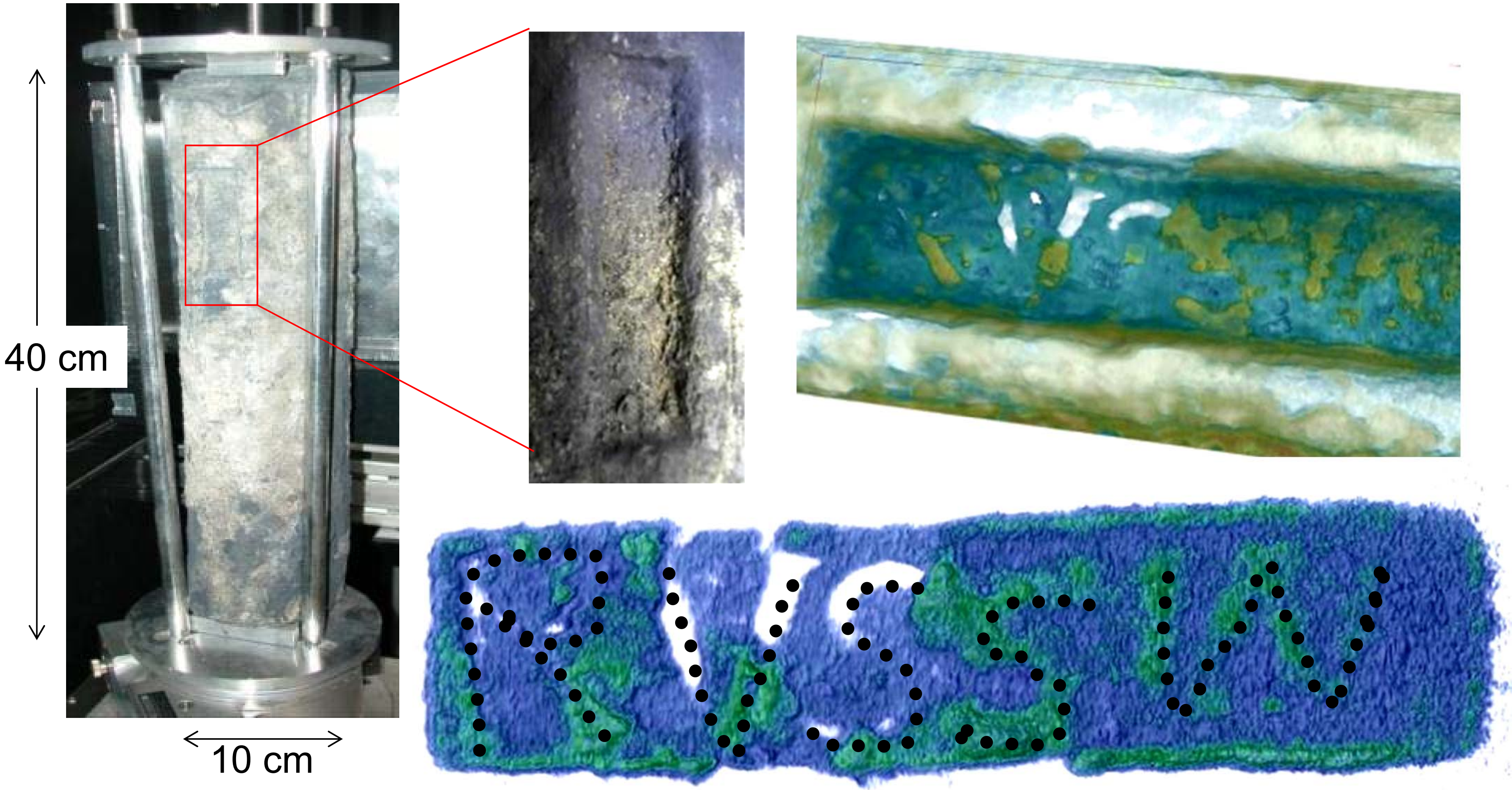
Neutron imaging

Tomographic reconstruction



Attenuation Contrast

Lead blocks recovered near the UNESCO World Heritage Site Syracuse.
Presumably I century A.D. (Roman Imperial Age).



Attenuation Contrast

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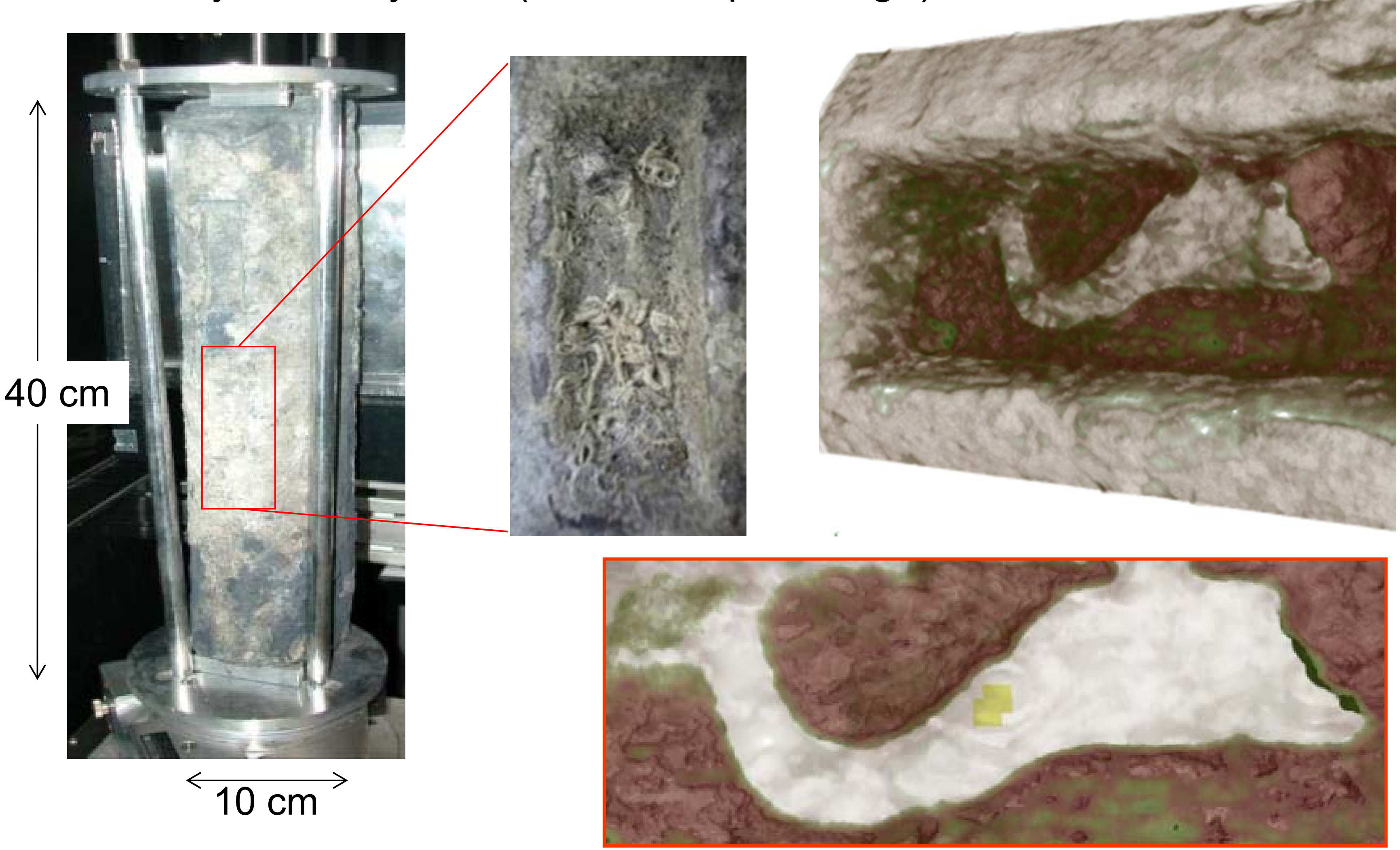
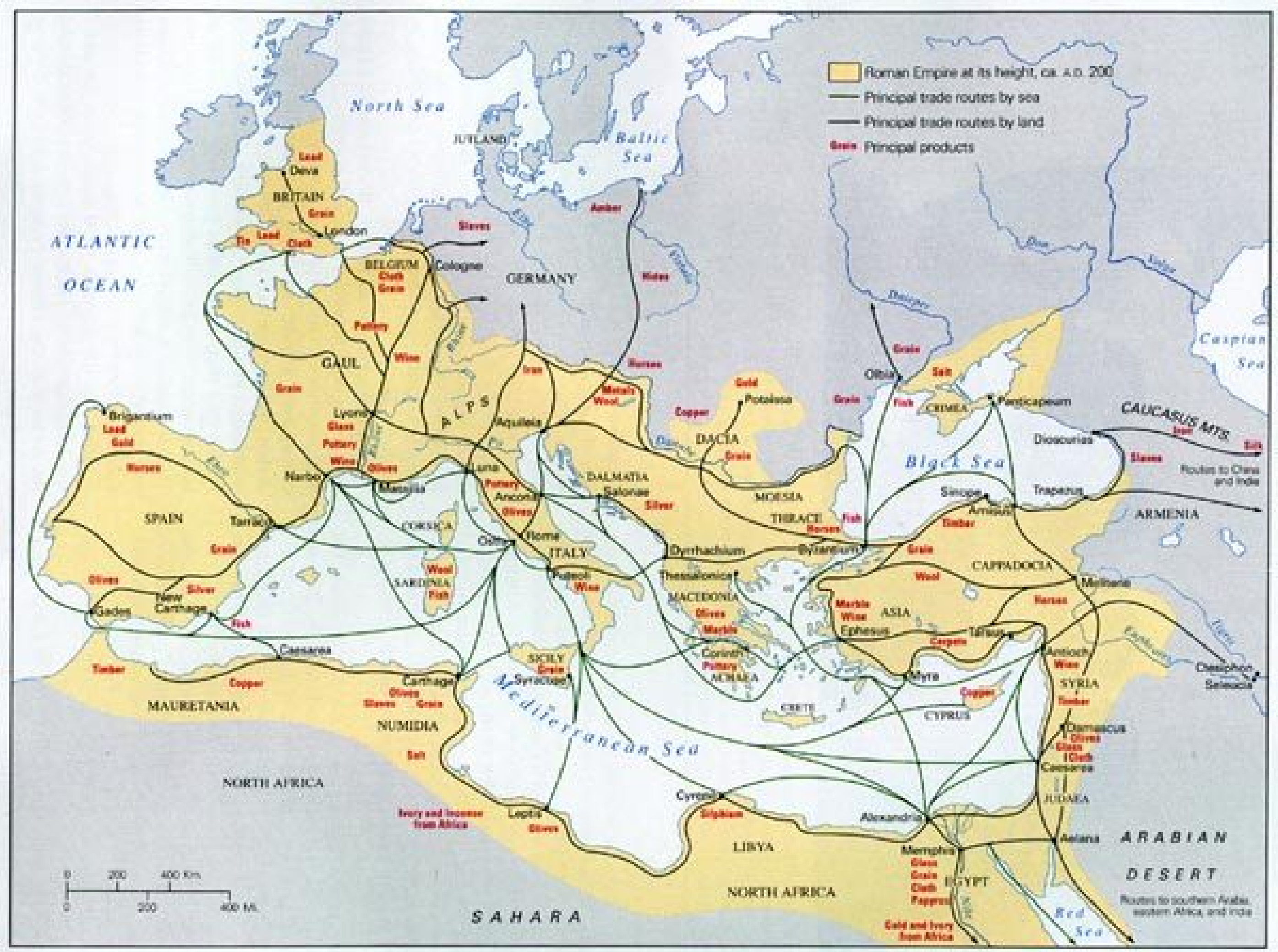
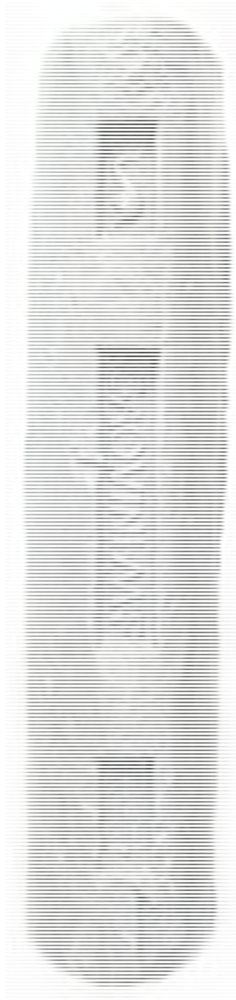


Attenuation Contrast

http://mapsontheweb.zoom-maps.com/image/64197912527





All routes lead to Rome: A map of Roman ports and trade routes

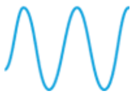
Resolution

- Beam optimisation
- Detector development

Contrast

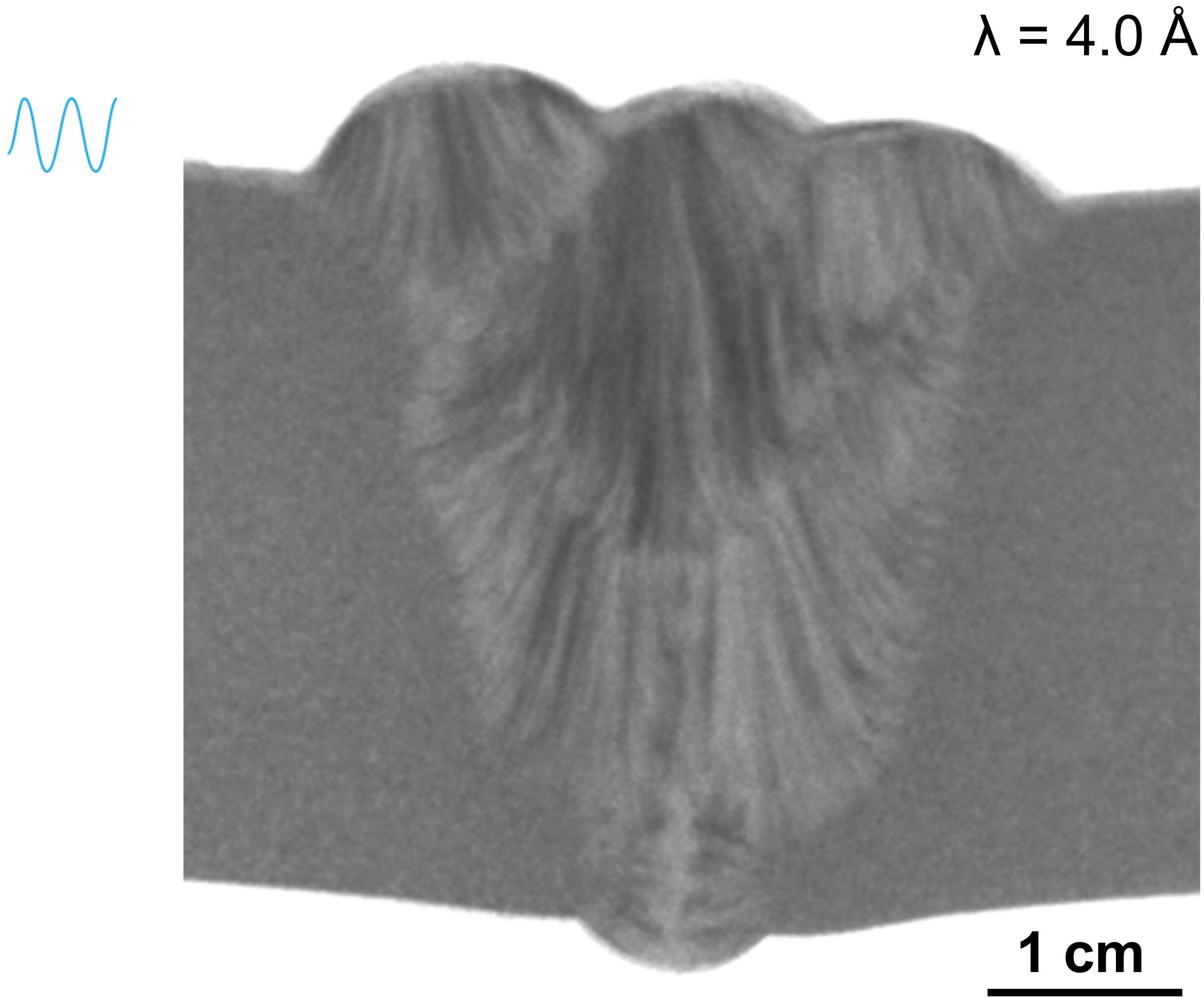
- Neutron interaction with matter

- absorption


- scattering

- magnetic interaction

Diffraction Contrast



Neutron imaging

Beam monochromatisation

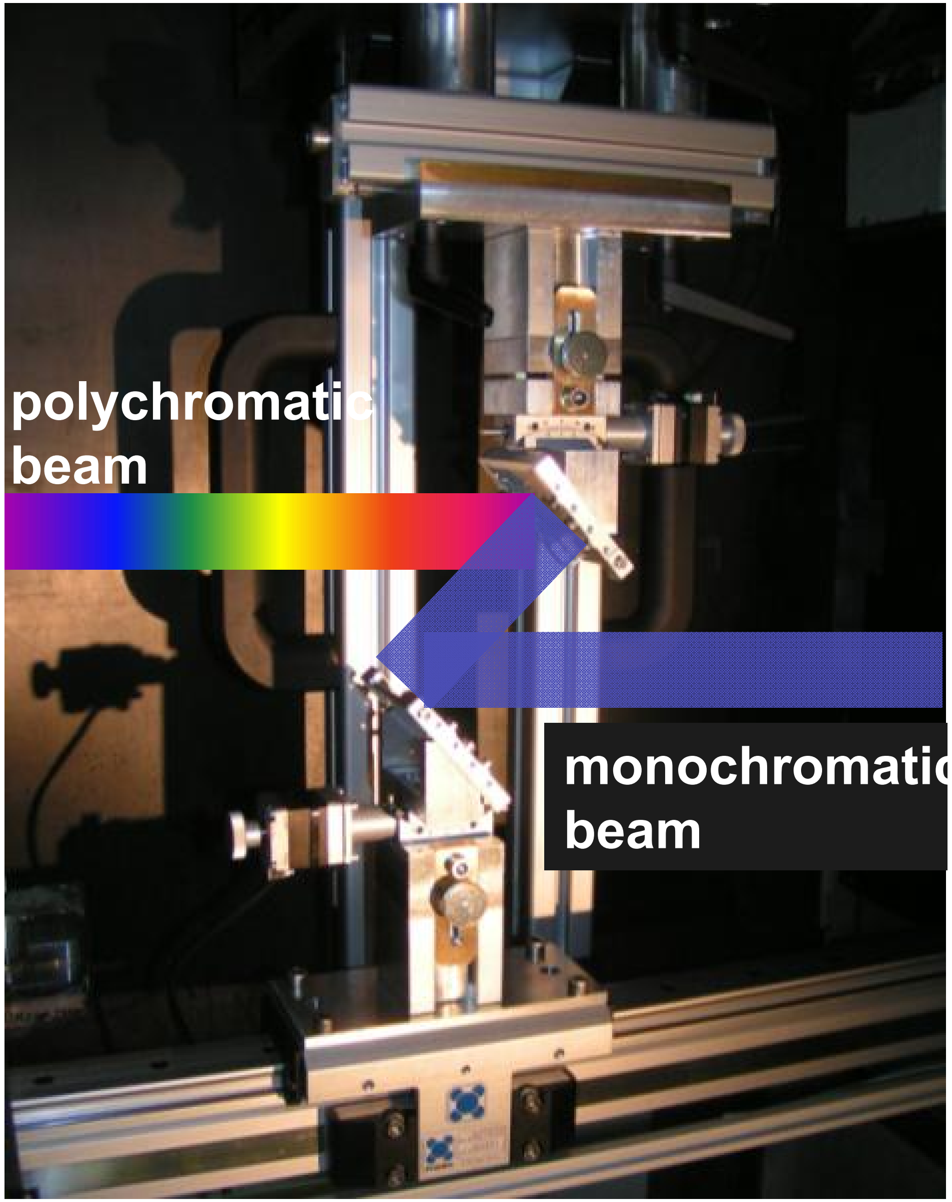
Double crystal monochromator: PCG crystals (mosaicity of 0.8°)

Range: 2.0 – 6.5 Å

Resolution ($\Delta\lambda/\lambda$): ~ 3%

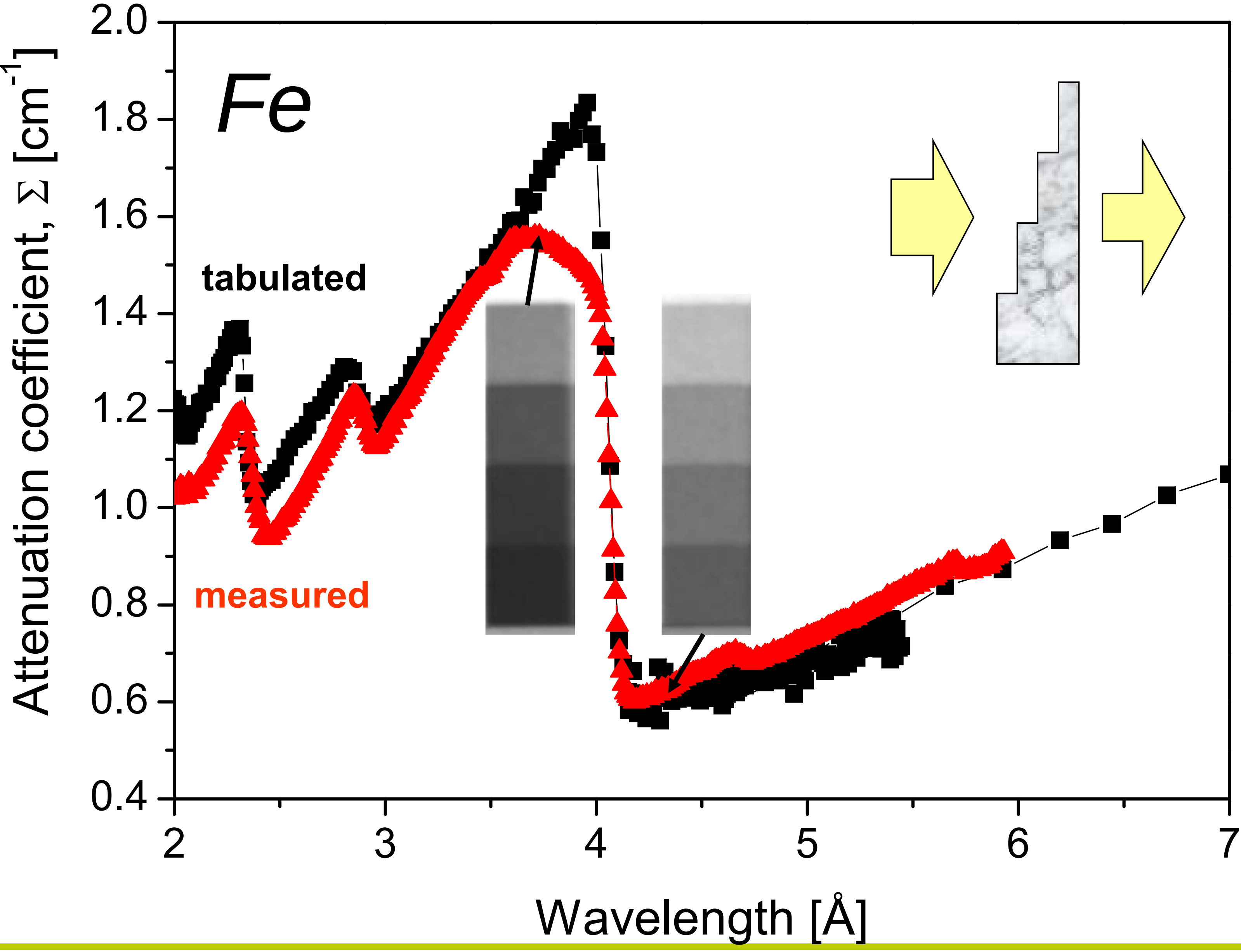
Neutron flux: ~ $4x10^5$ n/cm^2s (at λ=3.0 Å)

Beam size: 5 x 20 cm^2

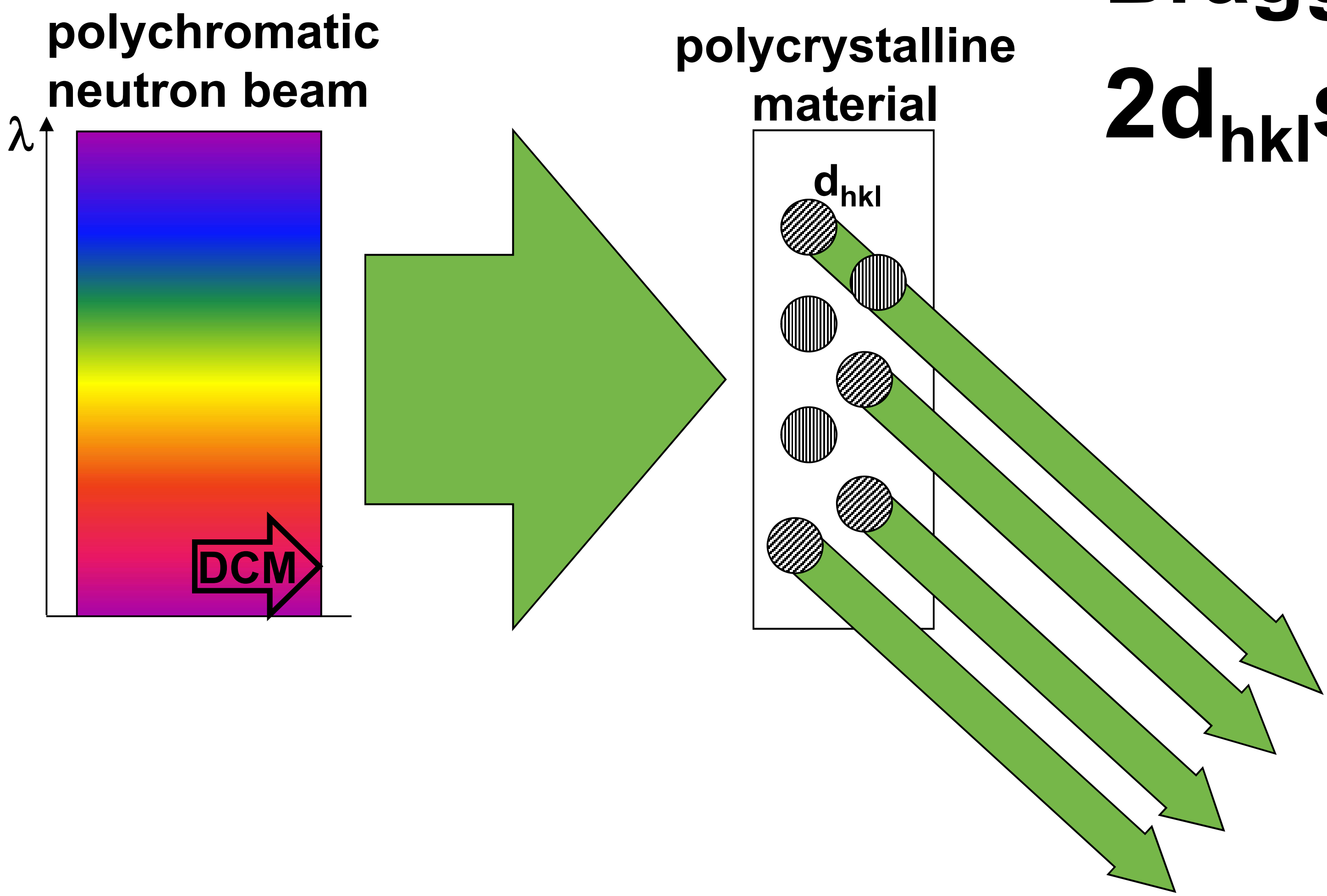


Kardjilov, Nikolay, et al. "New trends in neutron imaging." *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 605.1 (2009): 13-15.

Neutron imaging



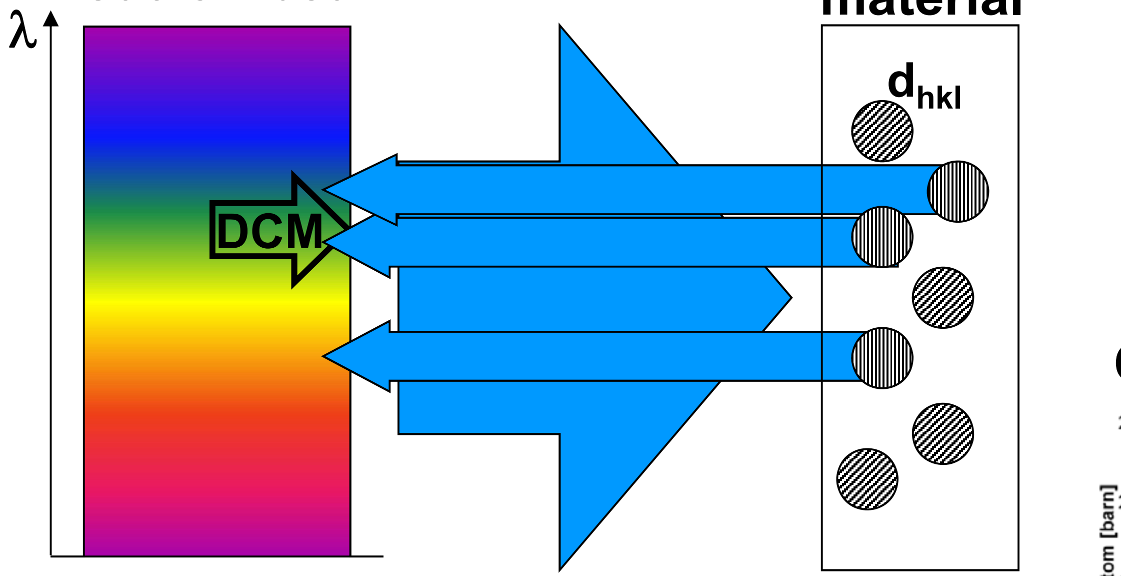
Coherent scattering – Bragg edges



Bragg's law

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

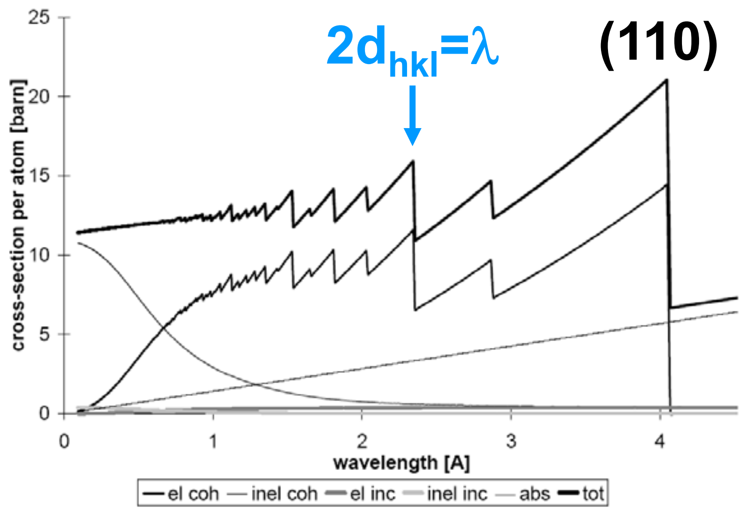
Coherent scattering – Bragg edges



Bragg‘s law

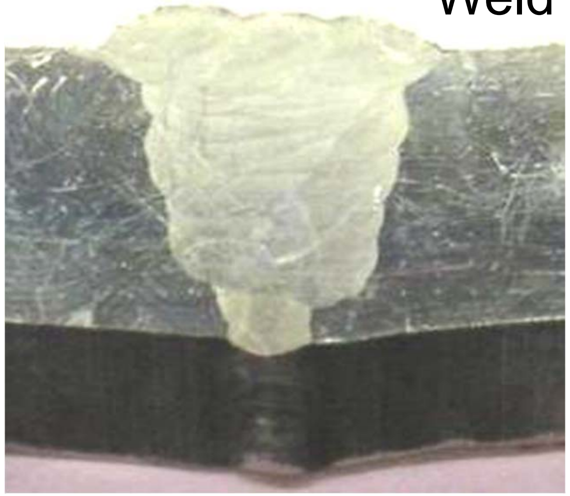
$$2d_{hkl}\sin 90° = \lambda$$

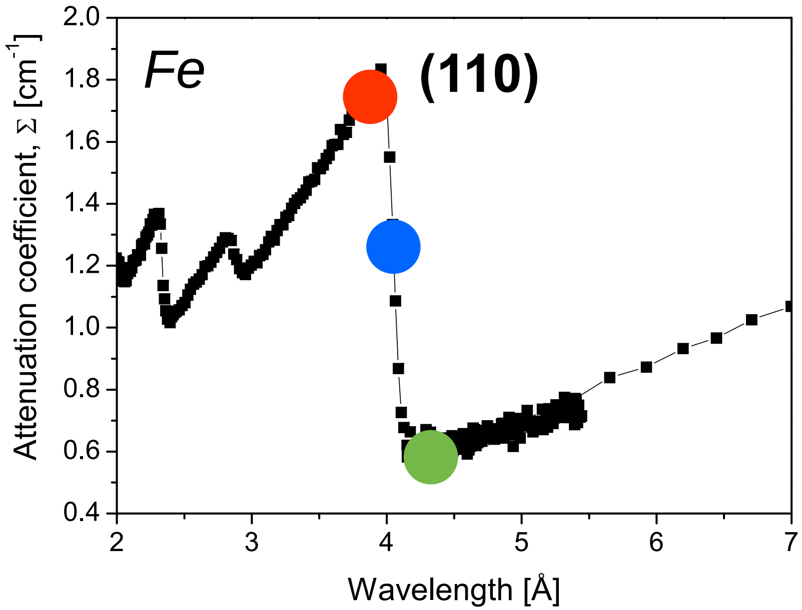
Cross-sections of iron per ator

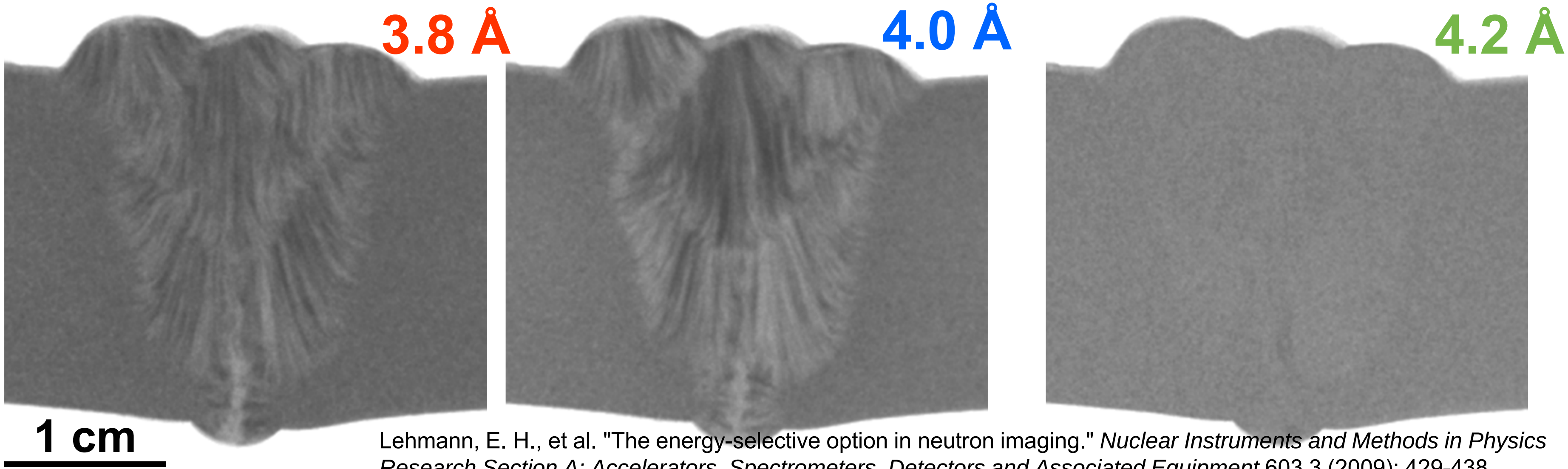


Energy-selective radiography

Weld (photo)

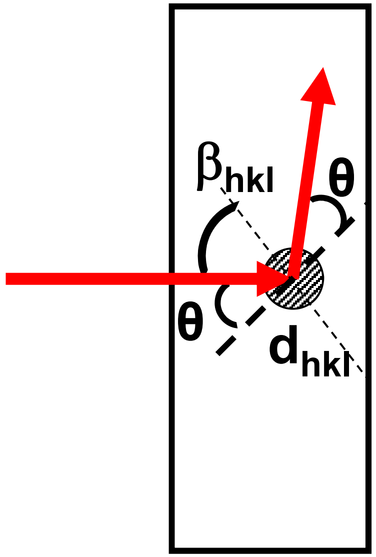




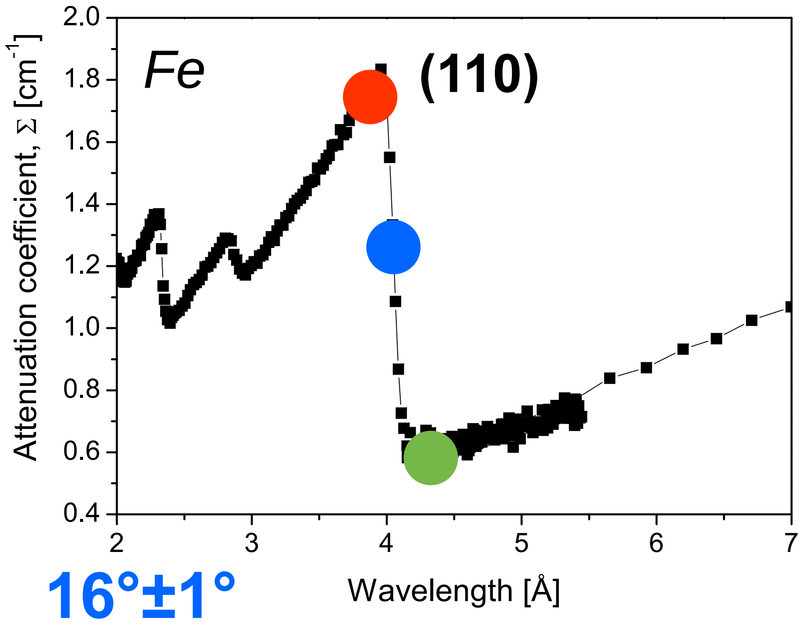


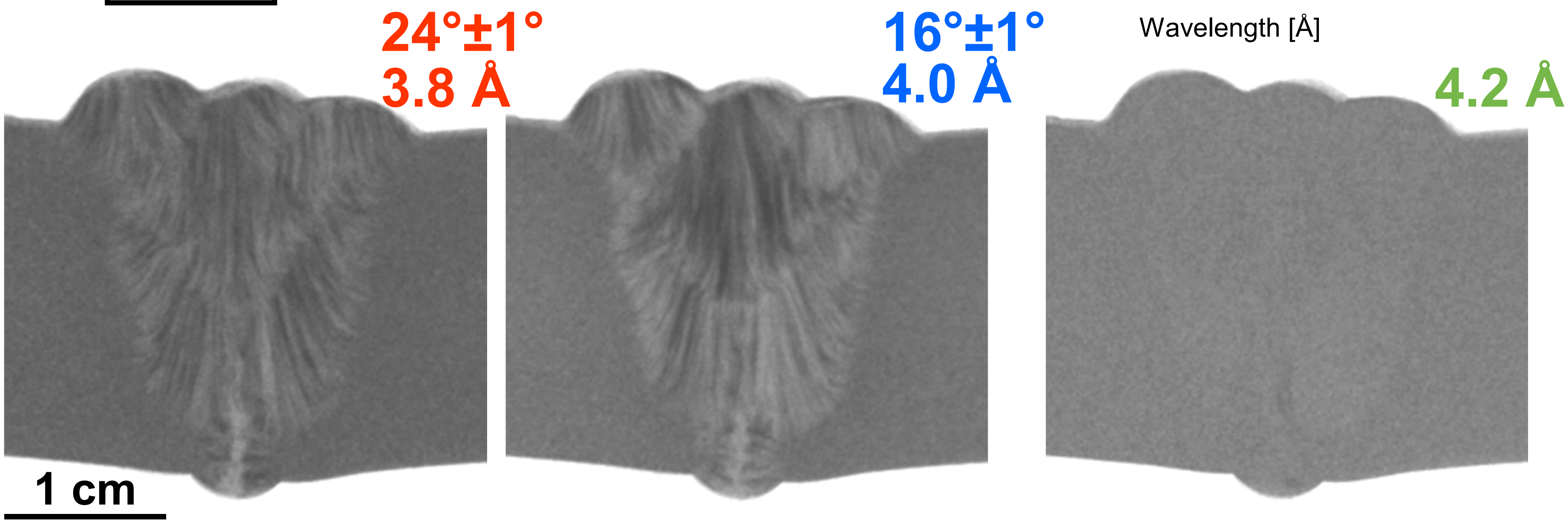
Lehmann, E. H., et al. "The energy-selective option in neutron imaging." *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 603.3 (2009): 429-438.

Neutron imaging



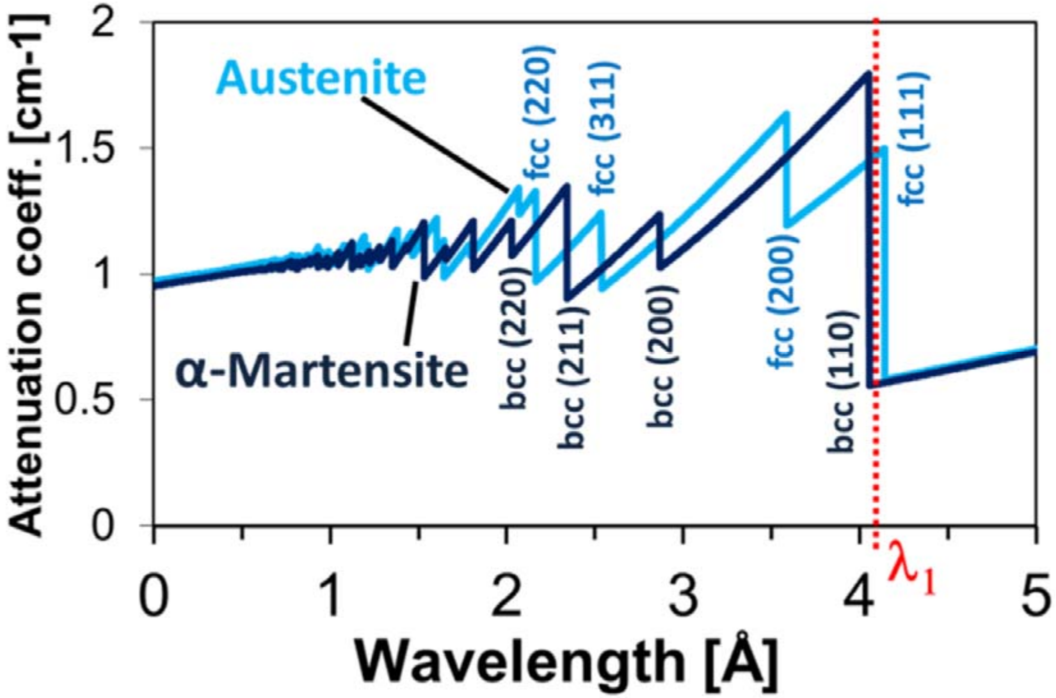
$$\beta_{hkl} = \frac{\pi}{2} - \arcsin\left(\frac{\lambda}{2d_{hkl}}\right)$$



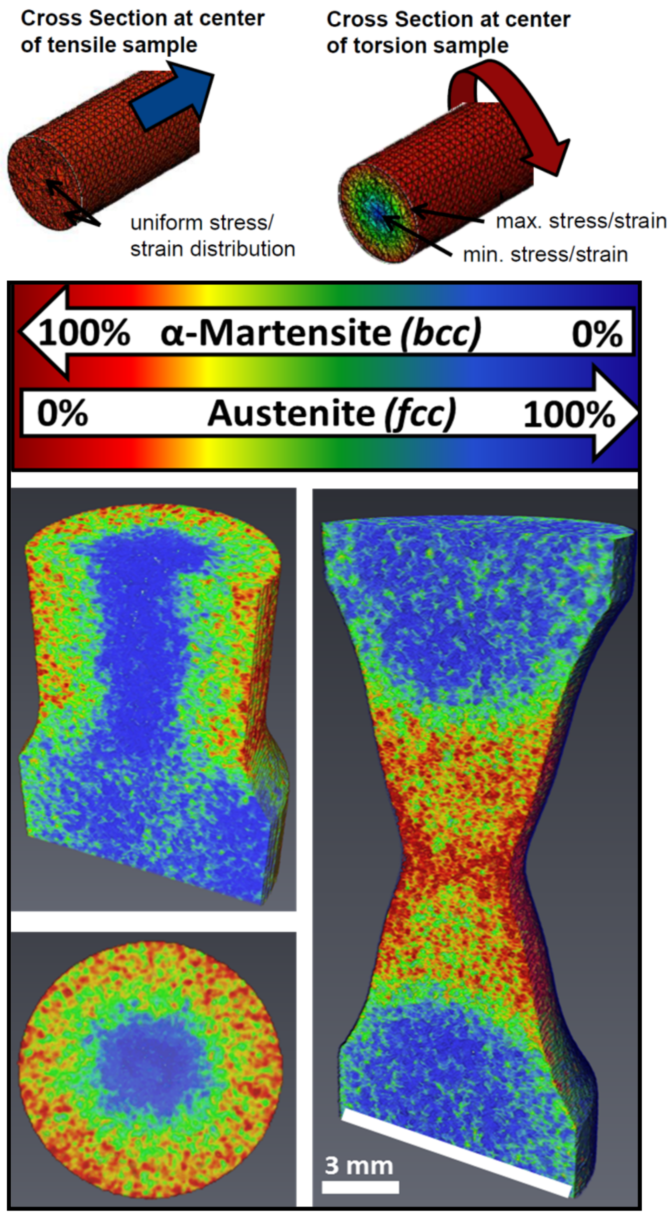


3D Phase mapping in metals

Project: Phase transitions in steels

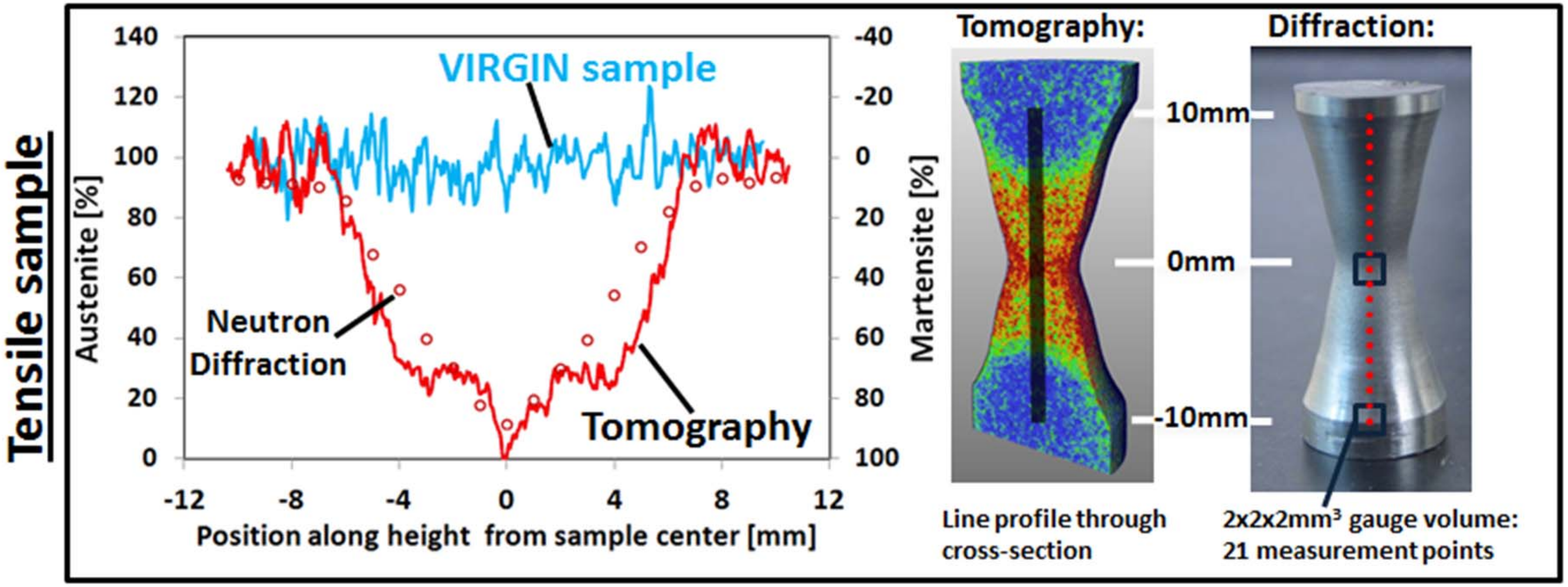


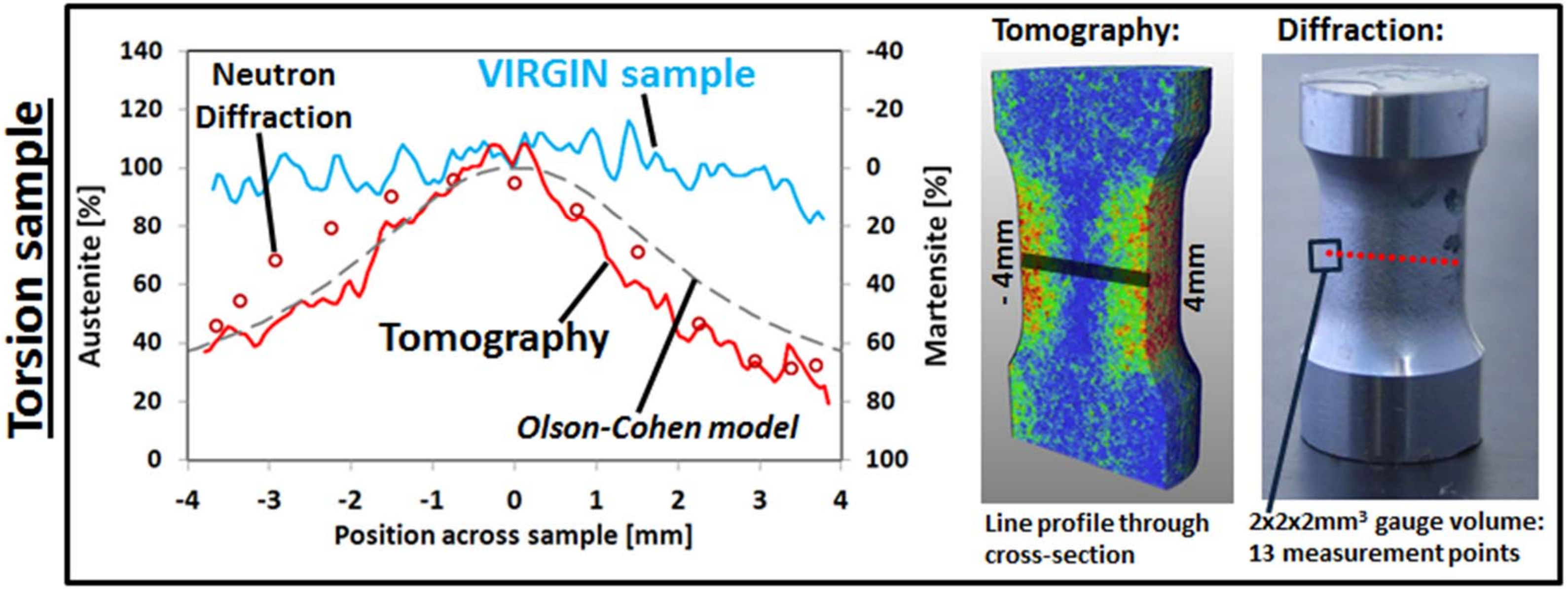
Energy-selective neutron tomography of TRIP-steel



R. Woracek et al., **Advanced Materials 26** (2014)

Diffraction Contrast





Neutron imaging

Resolution

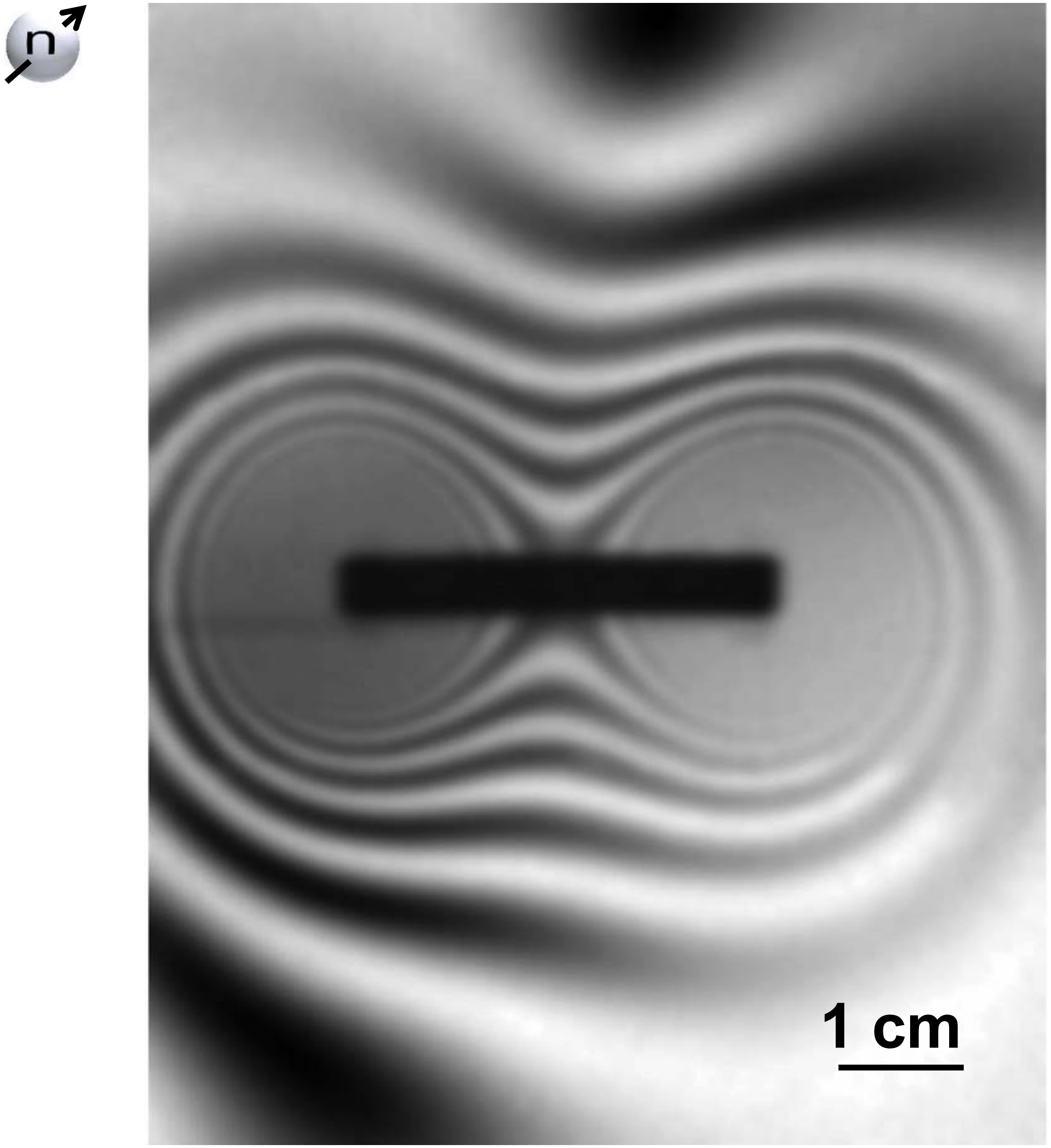
- Beam optimisation
- Detector development

Contrast

- Neutron interaction with matter

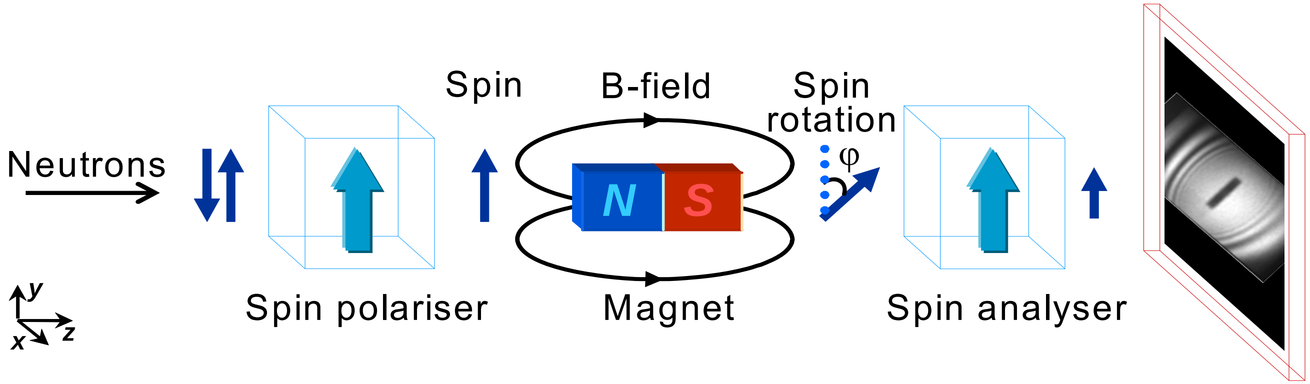
- absorption
- scattering
- magnetic interaction

Magnetic Contrast



Neutron imaging

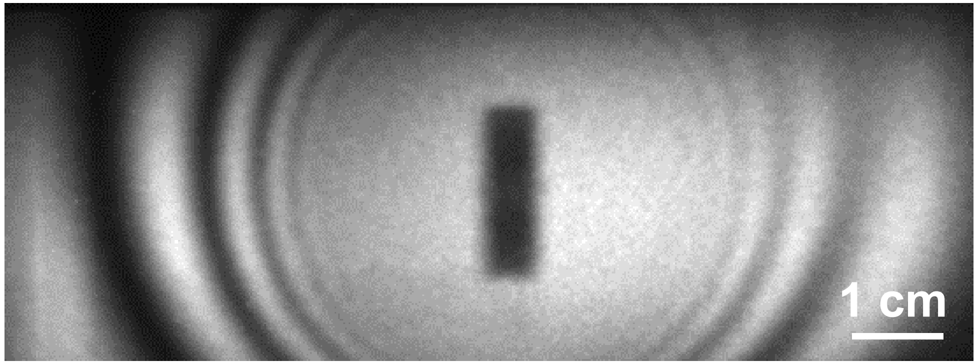
Principle



$$\varphi = \omega_L t = \frac{\gamma_L}{v} \int_{path} H ds$$

Experimental parameters

- Solid state polarazing benders
- Beam size (WxH): 20 x 4 cm^2
- Exposure times: ~10 min / image

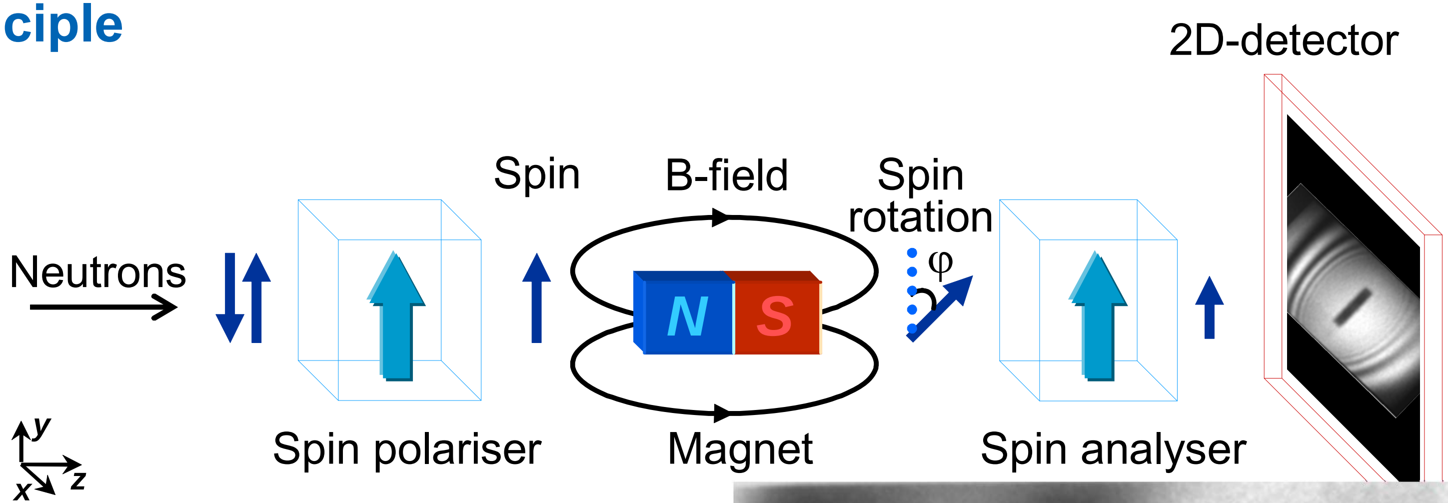


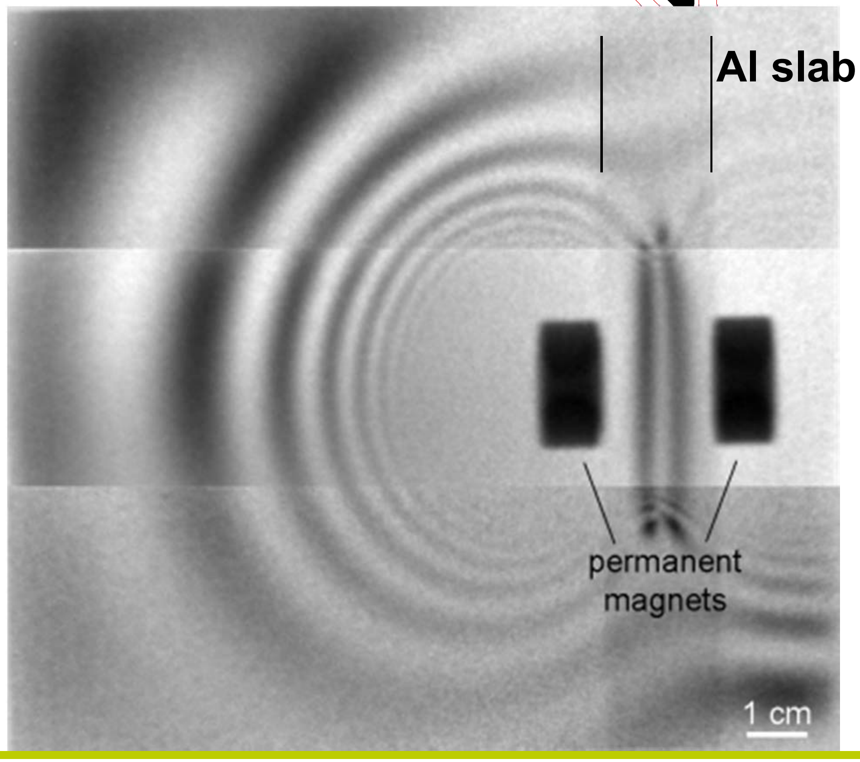
permanent magnet

N. Kardjilov et al, Three-dimensional imaging of magnetic fields with polarized neutrons, Nature Physics 4, 399, 2008

Neutron imaging

Principle





Experimental parameters

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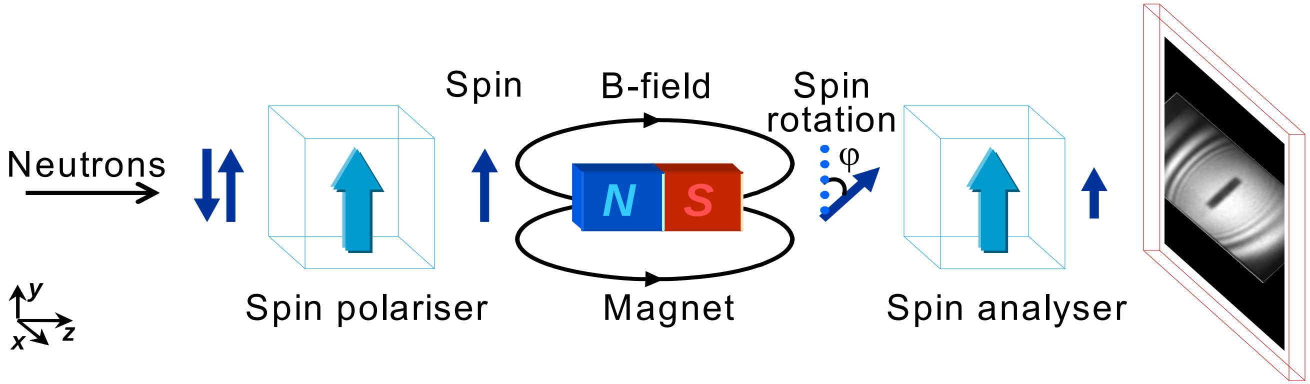
- Exposure times: ~10 min / image

Neutron imaging

Principle



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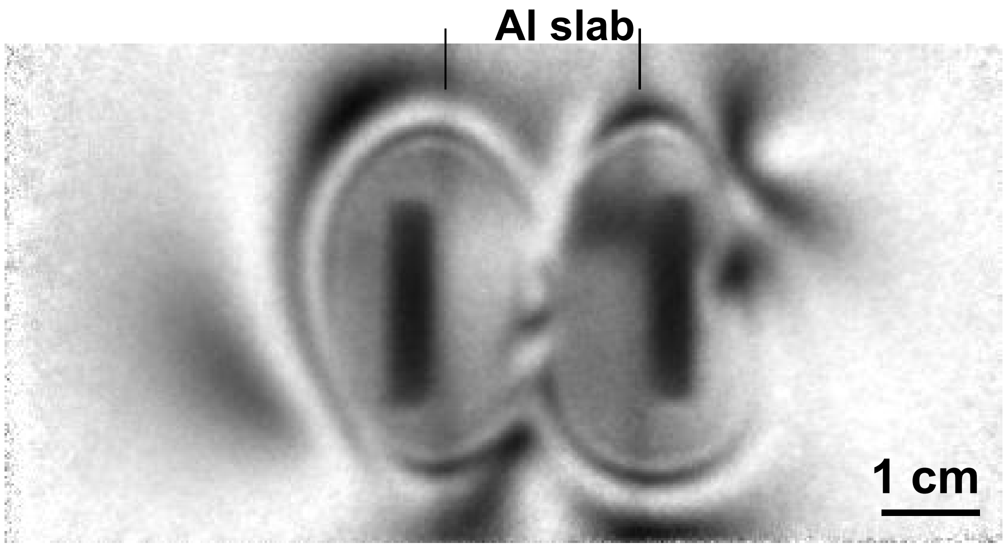
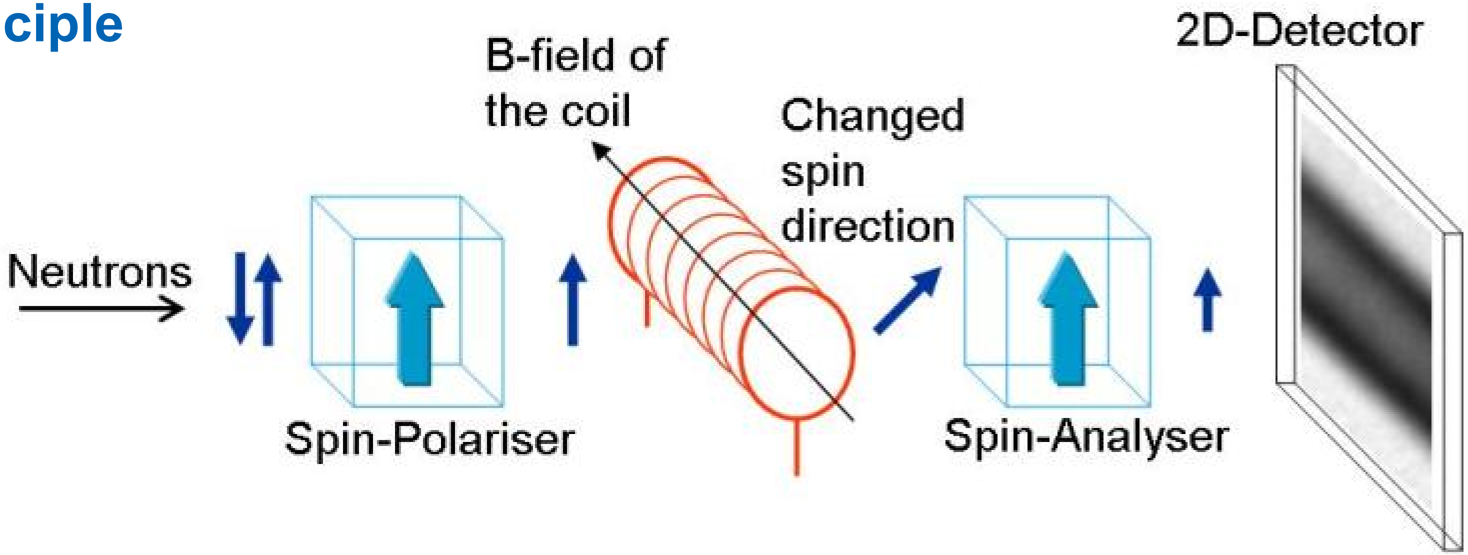


non-dipole magnets

N. Kardjilov et al, Three-dimensional imaging of magnetic fields with polarized neutrons, Nature Physics 4, 399, 2008

Neutron imaging

Principle

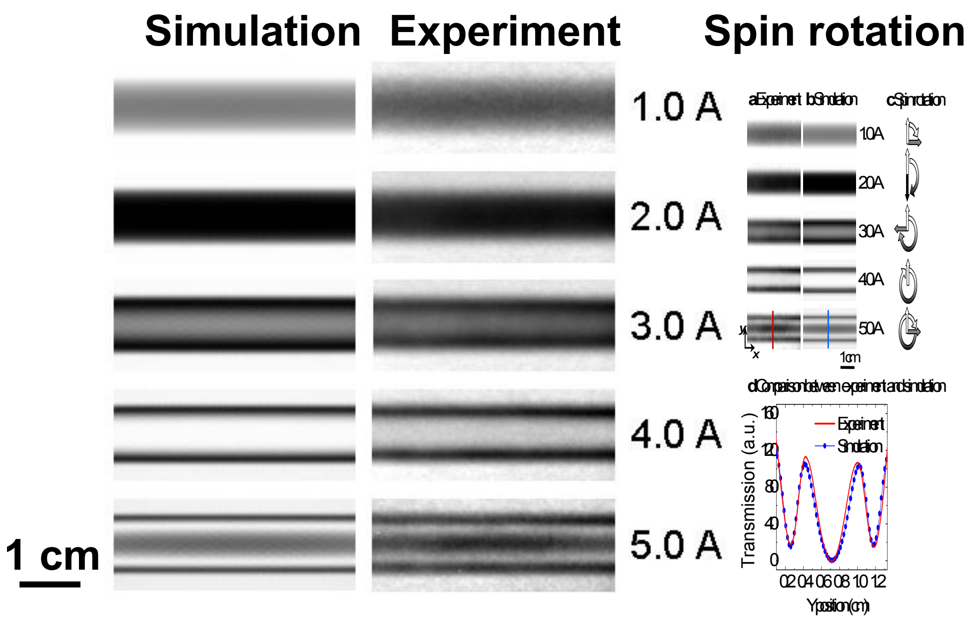


Biot-Savart law

$$d\vec{B} = \frac{\mu_0}{4\pi} \frac{Id\vec{I} \times \hat{r}}{r^2}$$

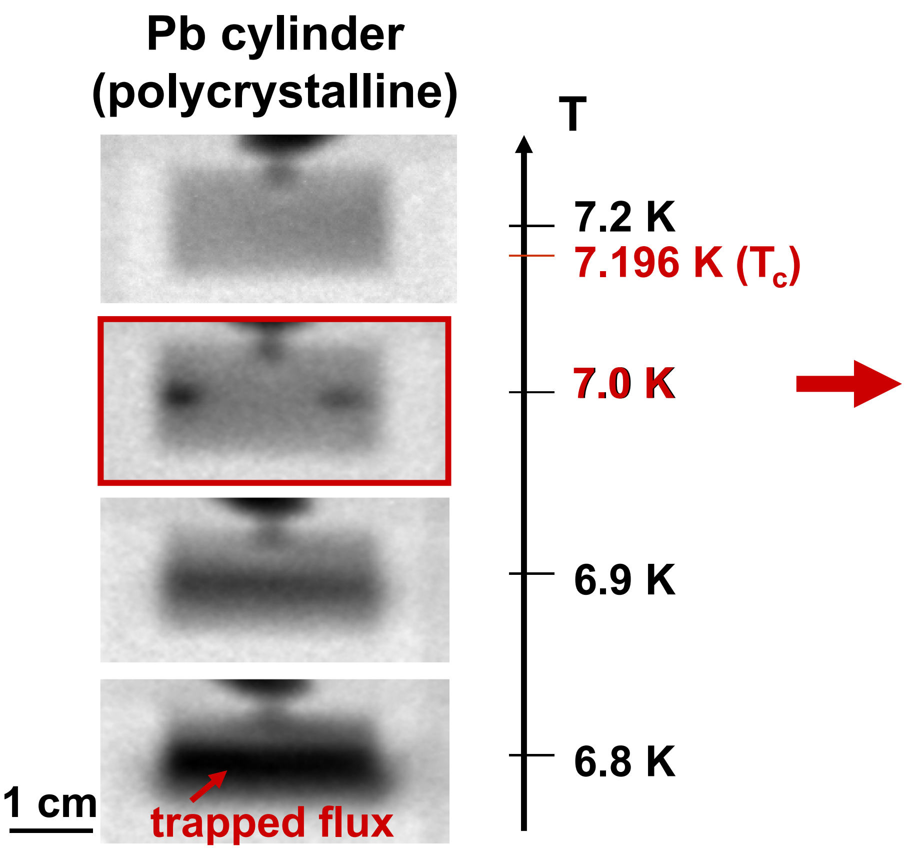
Spin rotation

$$\varphi = \frac{\gamma_L}{v} \int_{path} Bds$$

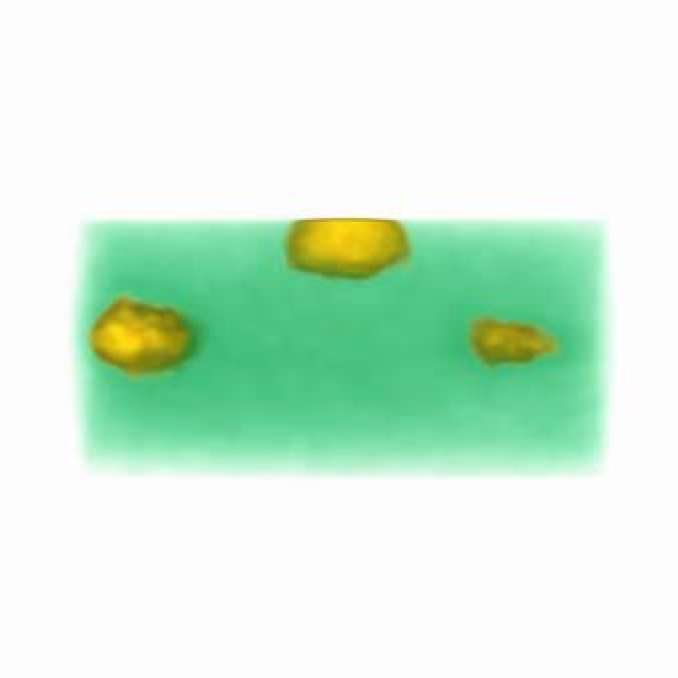


Neutron imaging

Example: Flux pinning

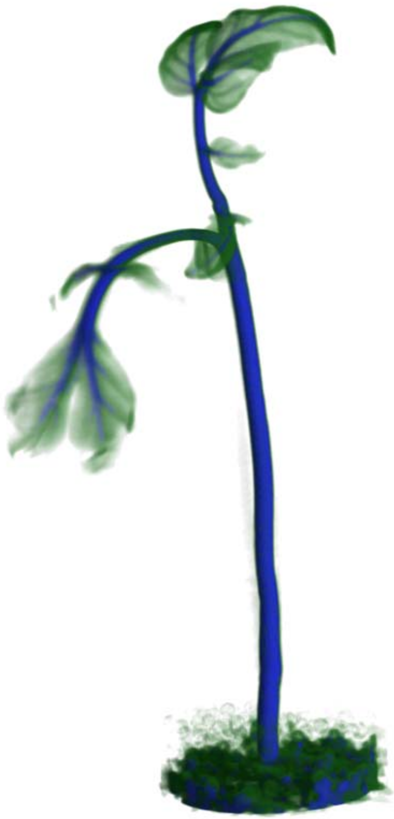


Tomography



Flux pinning at cooling down below Tc while applying a homogenous magnetic field of 10 mT perpendicular to the beam.

The images were recorded after switching off the magnetic field.



Thank you !

https://www.helmholtz-berlin.de/user/user-info/user-offices/neutrons/index_en.html