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M. Strobl - Neutron Imaging & Applied Materials Group :: Paul Scherrer Institut

Neutron Imaging

Oct. 2018

markus.strobl@psi.ch

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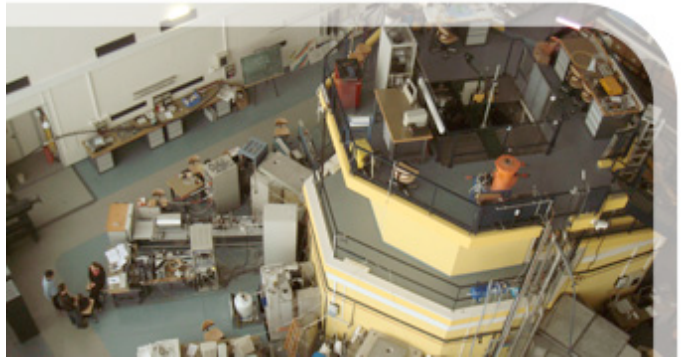
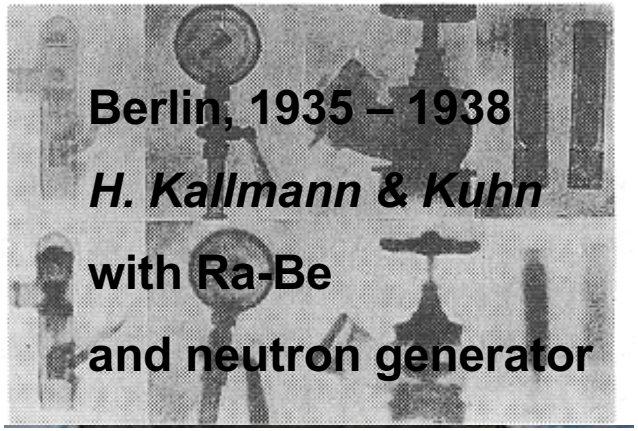
Vienna

ATOMINSTITUT



Berlin

Helmholtz Zentrum



Lund

Copenhagen

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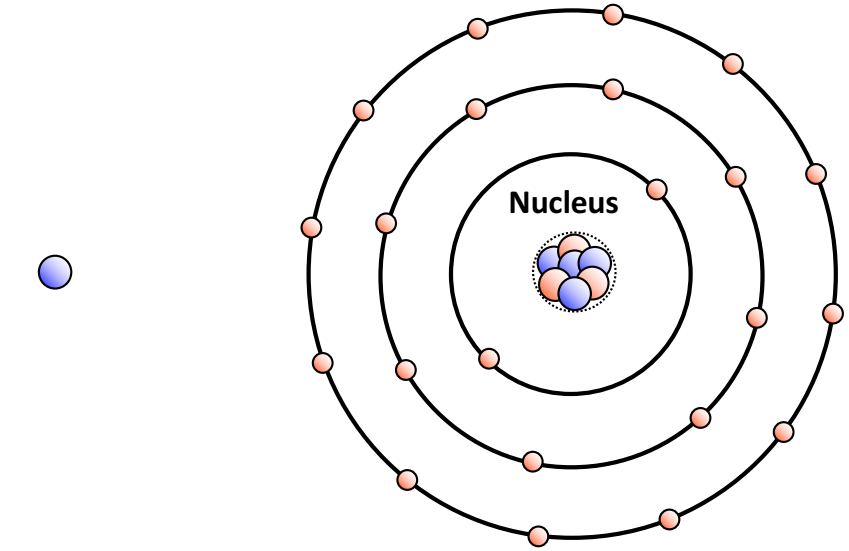
The neutron



Classification	Baryon
Composition	1 up quark, 2 down quarks
Statistics	Fermionic
Interactions	Gravity, weak, strong, electromagnetic
Symbol	n, n^0, N^0
Antiparticle	Antineutron
Theorized	Ernest Rutherford[1] (1920)
Discovered	James Chadwick[2] (1932)
Mass	$1.674\,927\,471(21) \times 10^{-27}$ kg[3] 939.565 4133(58) MeV/c^2[3] 1.008 664 915 88(49) u[3]
Mean lifetime	881.5(15) s (free)
Electric charge	0 e $(-2 \pm 8) \times 10^{-22}$ e (experimental limits)[4]
Electric dipole moment	$< 2.9 \times 10^{-26}$ e·cm (experimental upper limit)
Electric polarizability	$1.16(15) \times 10^{-3}$ fm^3
Magnetic moment	$-0.966\,236\,50(23) \times 10^{-26}$ J·T^{-1}[3] $-1.041\,875\,63(25) \times 10^{-3}$ μ_B[3] −1.913 042 73(45) μ_N[3]
Magnetic polarizability	$3.7(20) \times 10^{-4}$ fm^3
Spin	$\frac{1}{2}$

Neutron imaging

disadvantages

Low phase space density – slow

☹

Expensive

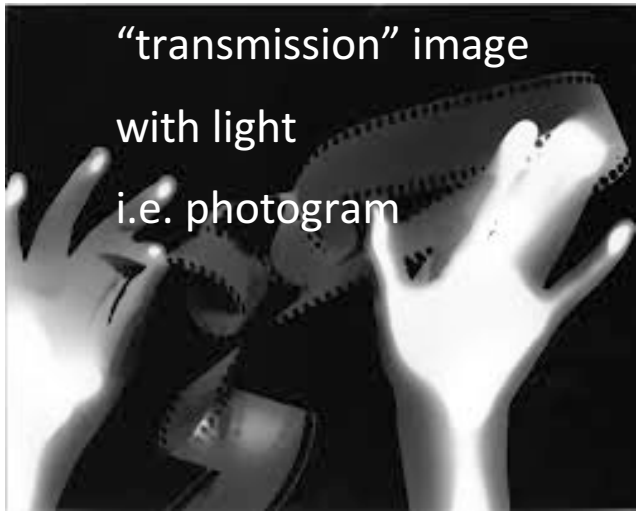
☹

No efficient optics

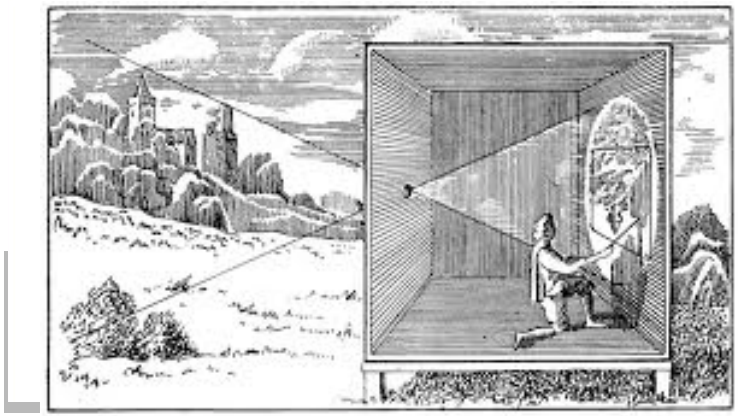
☹

transmission

reflection

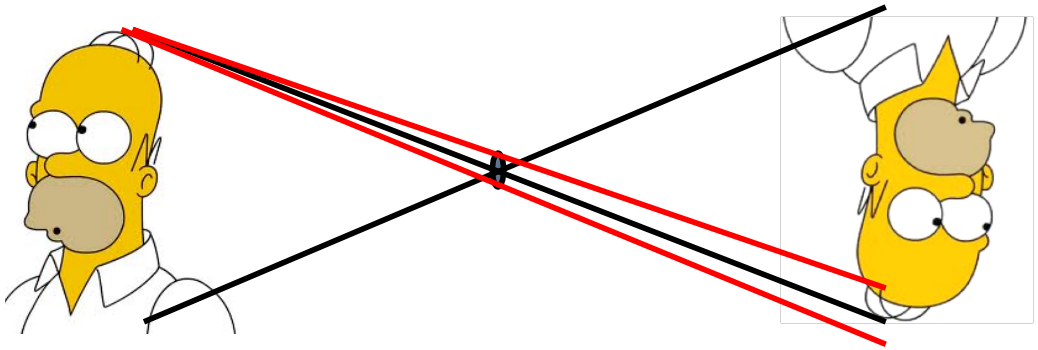


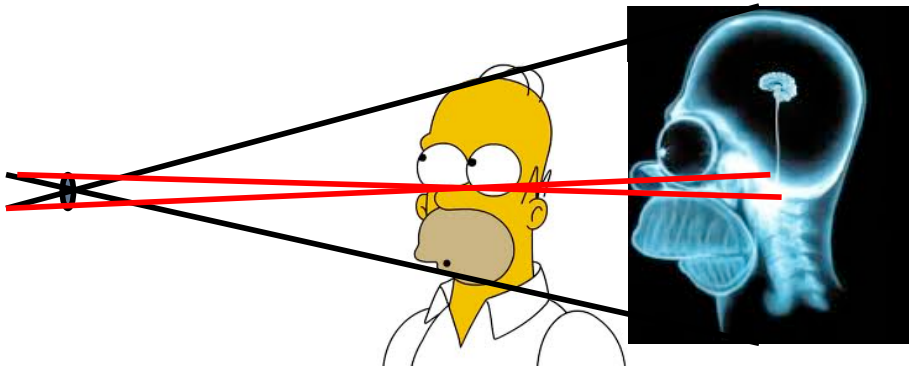
No optics



Camera obscura

No optics

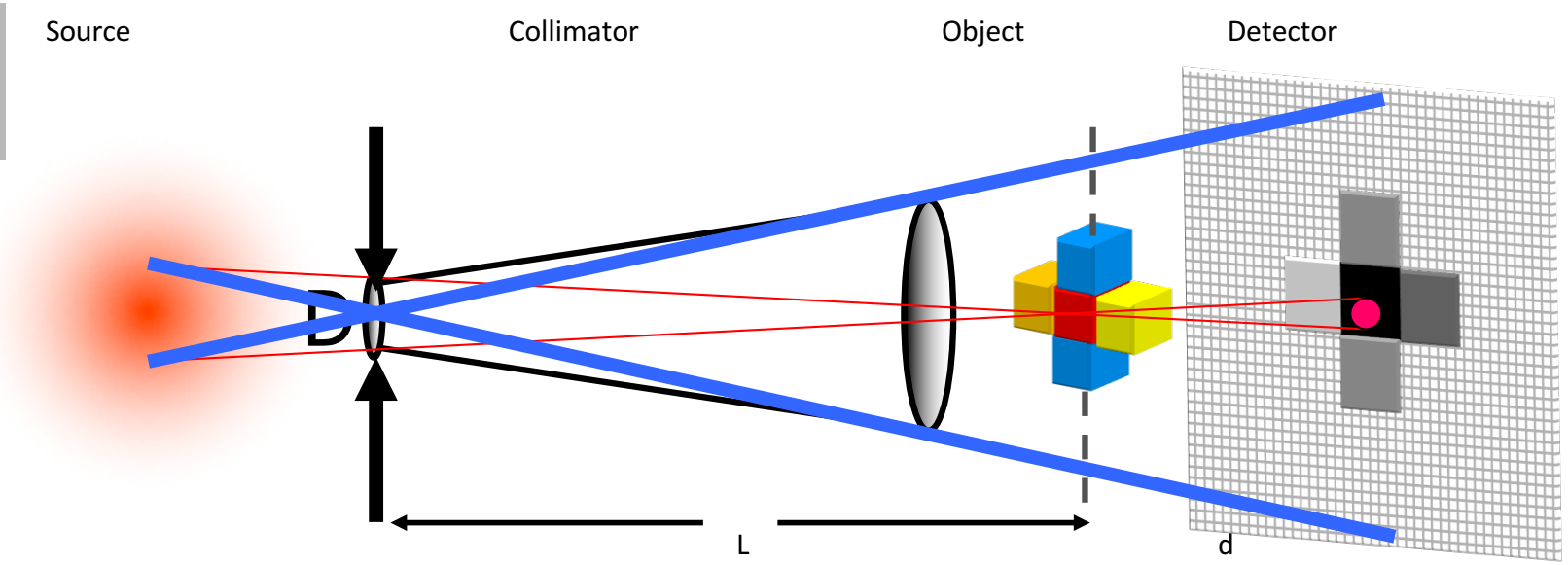




But spatial resolution!

Clearly a condition for imaging!

Resolution



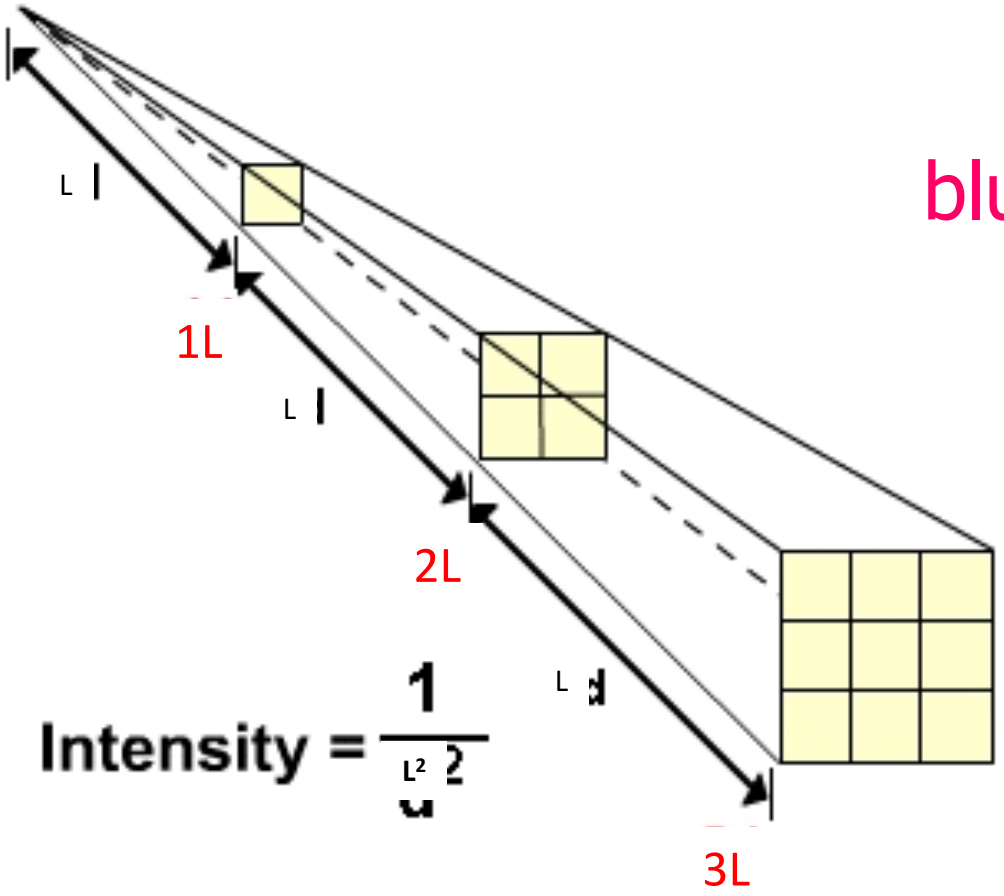
blur

collimation ratio $b = \frac{d}{L/D}$ typical: several 100

Resolution

flux limitations

10^9 $cm^{-2}s^{-1}$



blur

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

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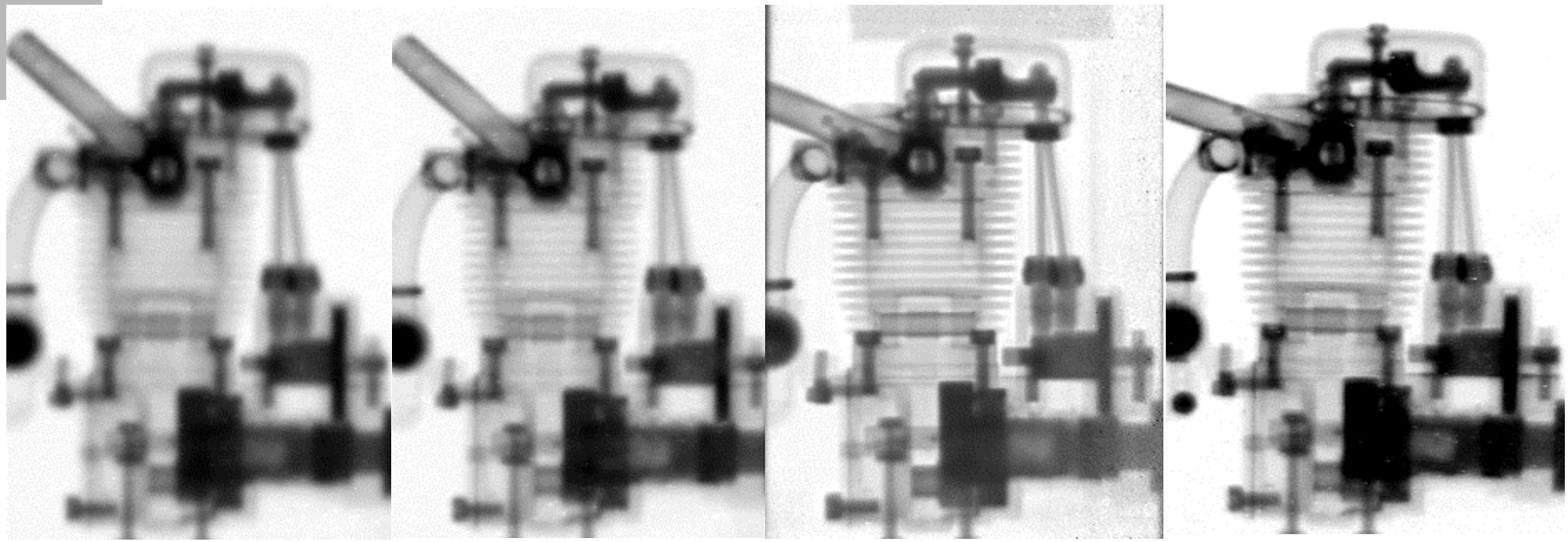
Resolution



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.

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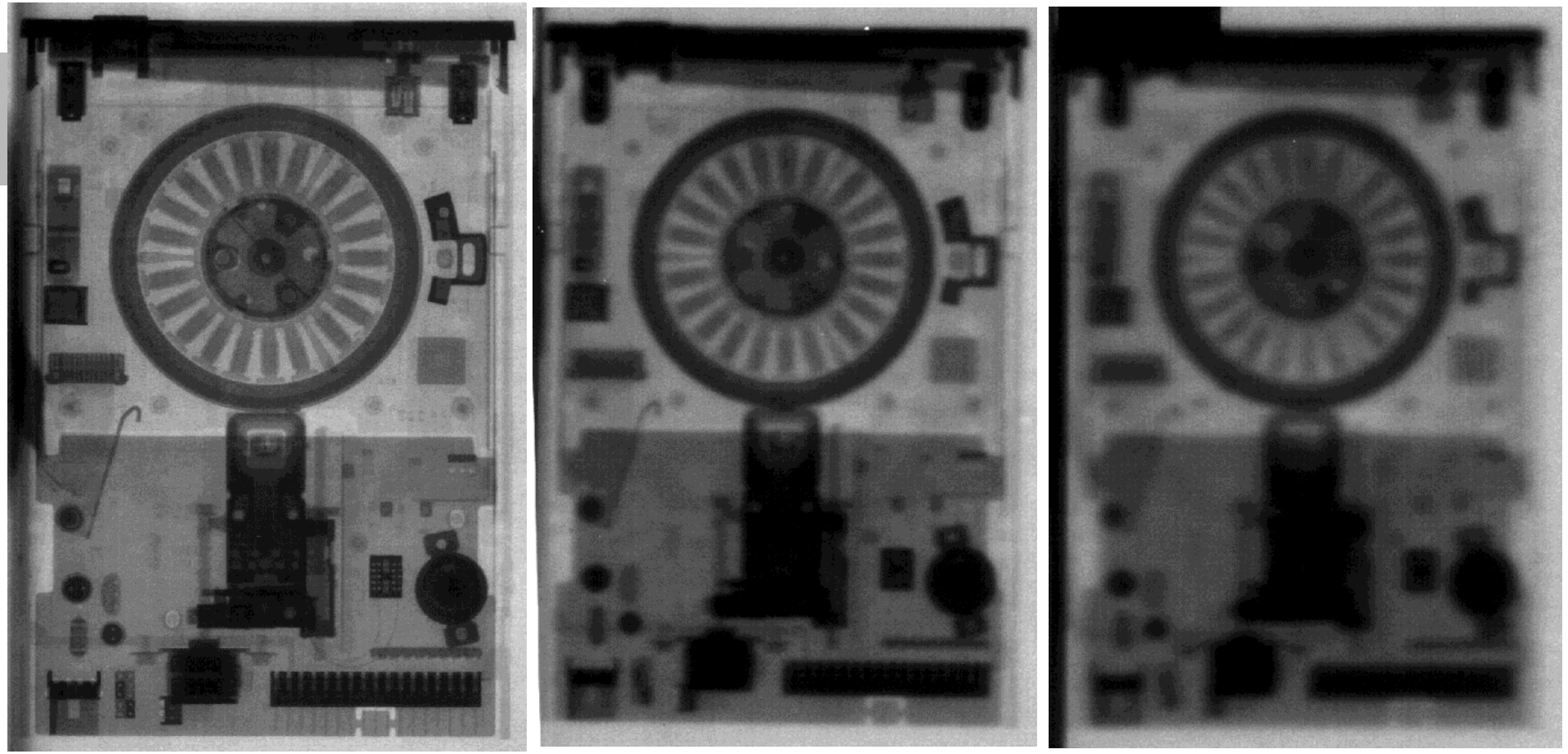
Resolution



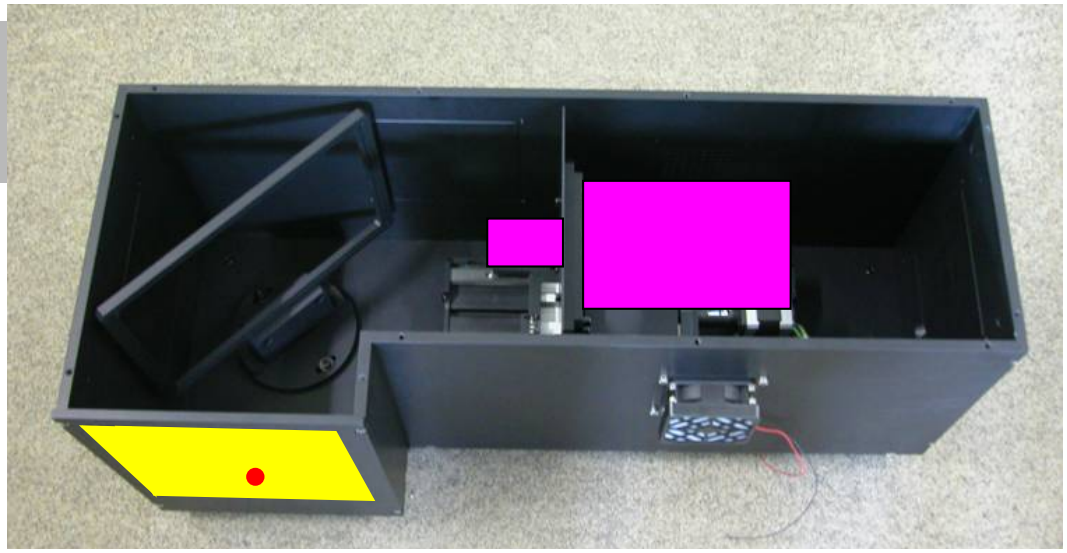
Radiographs of a 3,5" floppy drive in 0 cm, 10 cm and 20 cm distance from a film + Gd sandwich taken at a cold neutron guide with *L/D*=71.

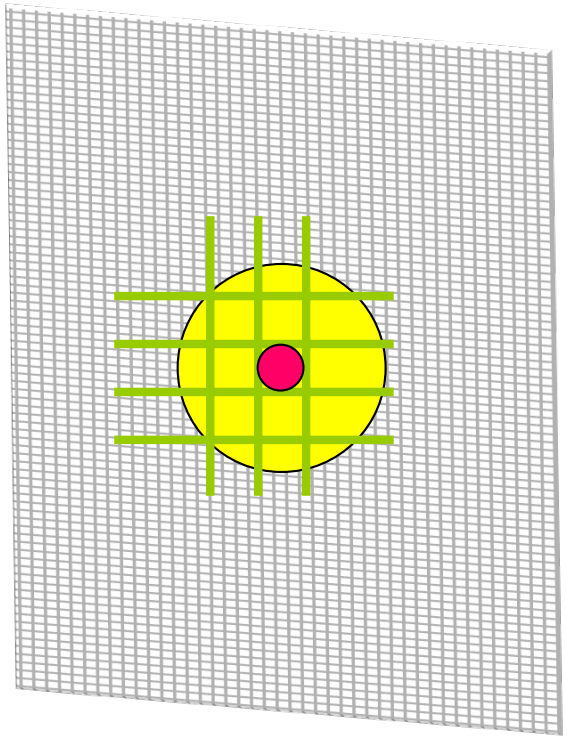
Detection?

No optics

Resolution

Detector





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

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

LiF-ZnS/Ag

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

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

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

GADOX

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

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

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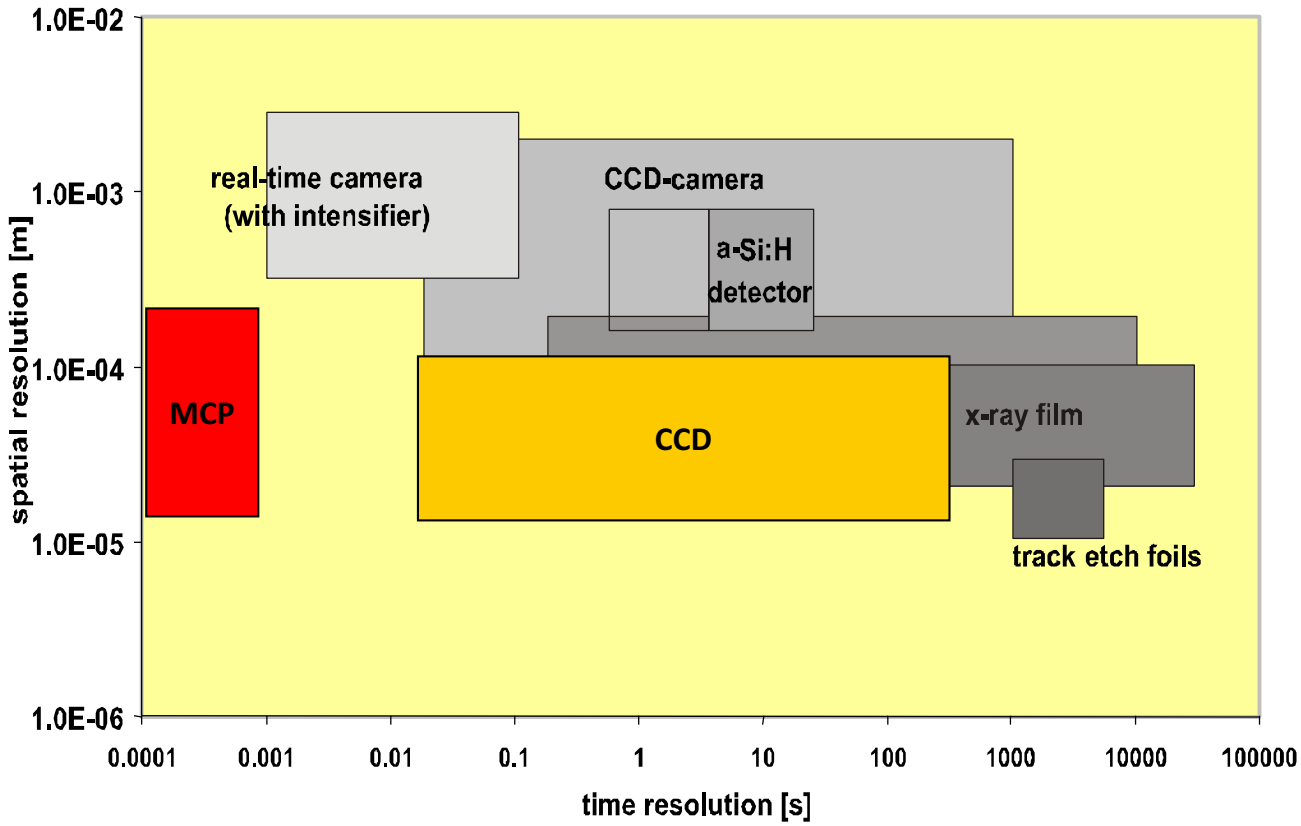
Resolution

Imaging Detectors



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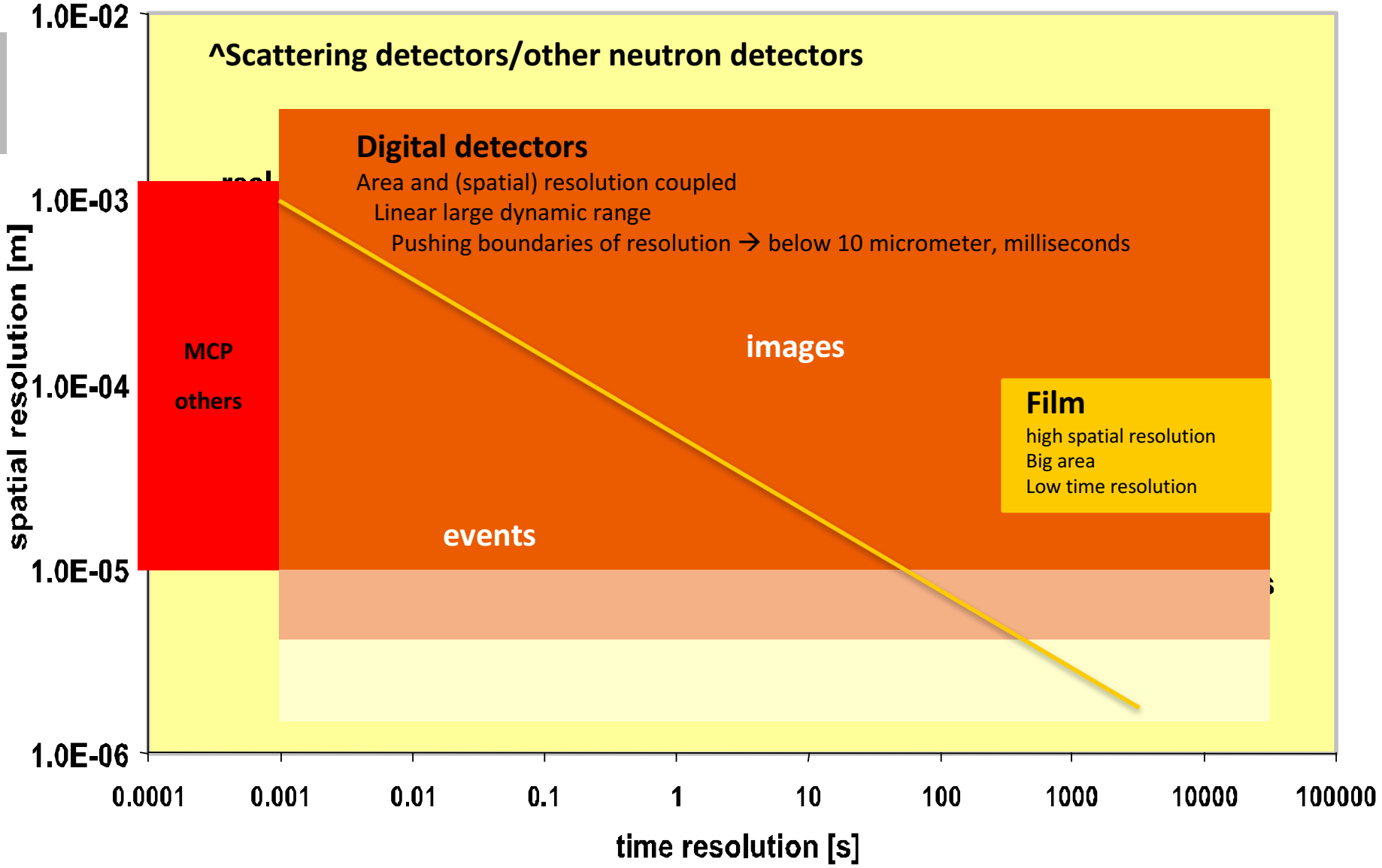
Resolution



Resolution of DIGITAL detectors

Routine resolution today 50 µm

Best today **<10µm**

Aiming at **1µm**

Firearm Cartridge

Cartridge type 7.5 × 55mm Swiss
Sample size ø12.65mm × 77.7mm
Voxel size 13.2µm

Recorded at

ICON
Imaging with Cold Neutrons

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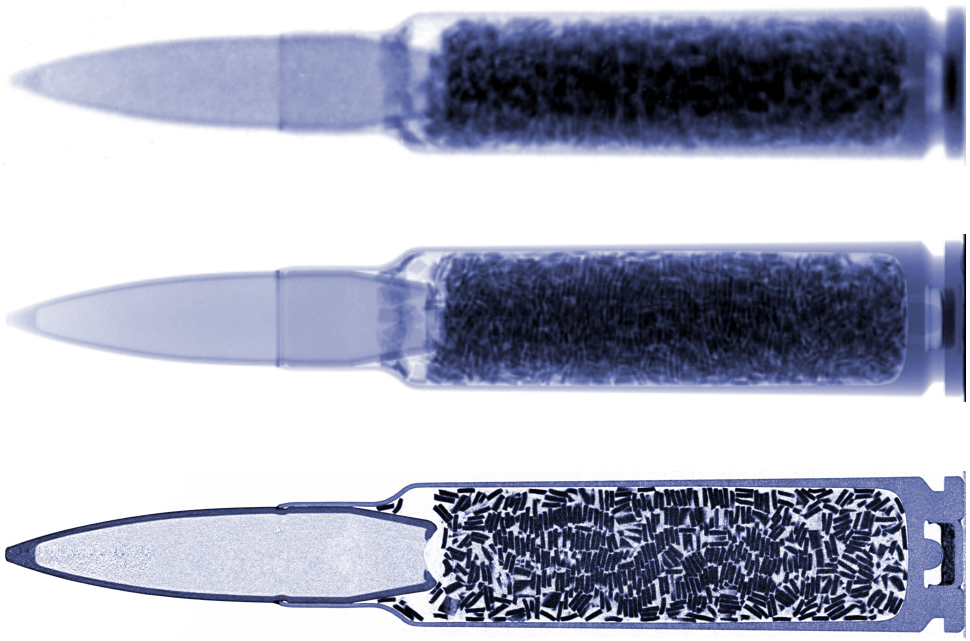
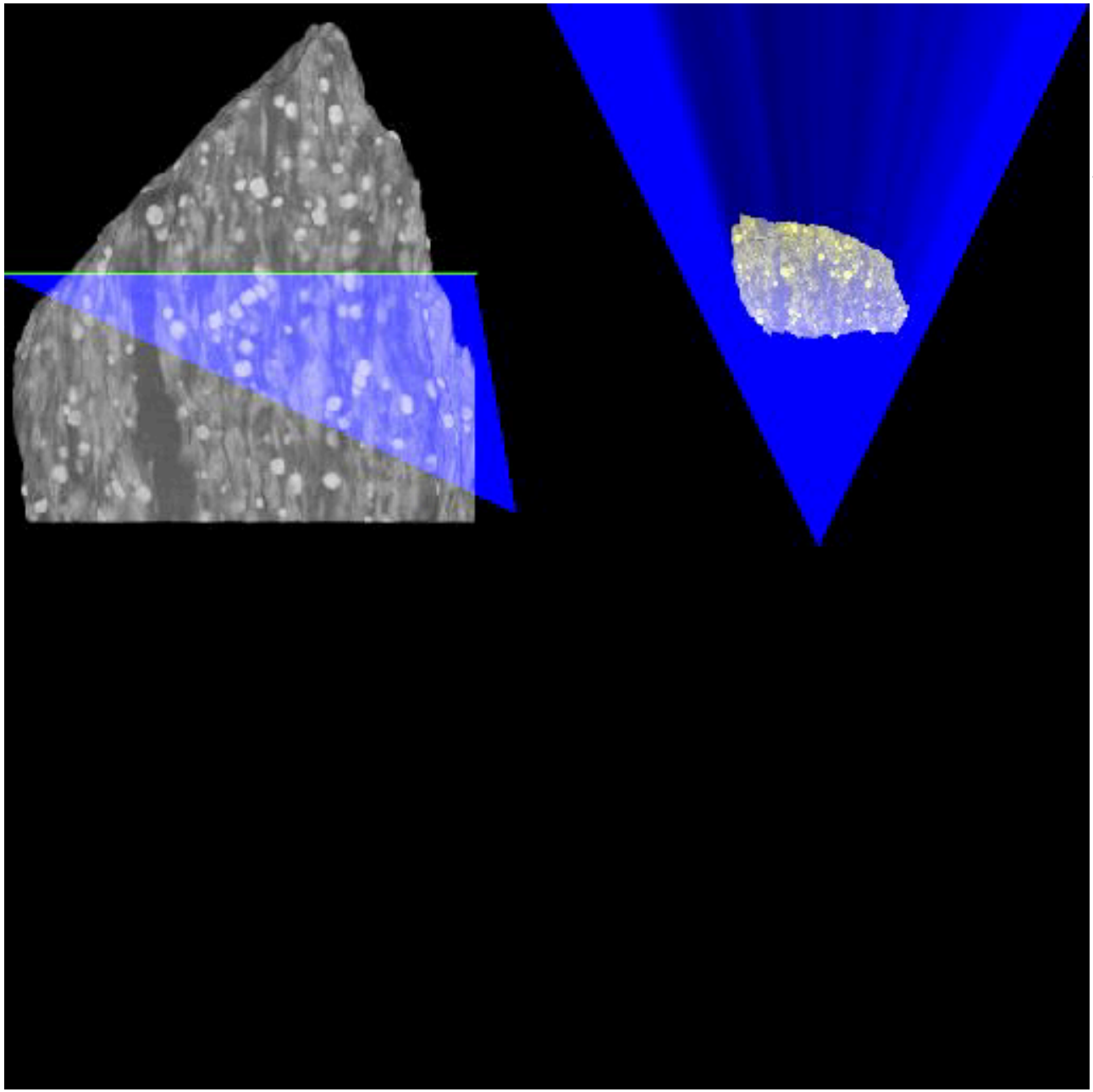


2D to 3D – tomography reconstruction

Radon Transform



Fourier Slice Theorem

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Neutron imaging

disadvantages

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☹

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Low spatial resolution

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Why neutrons then?

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Neutron Imaging for safety

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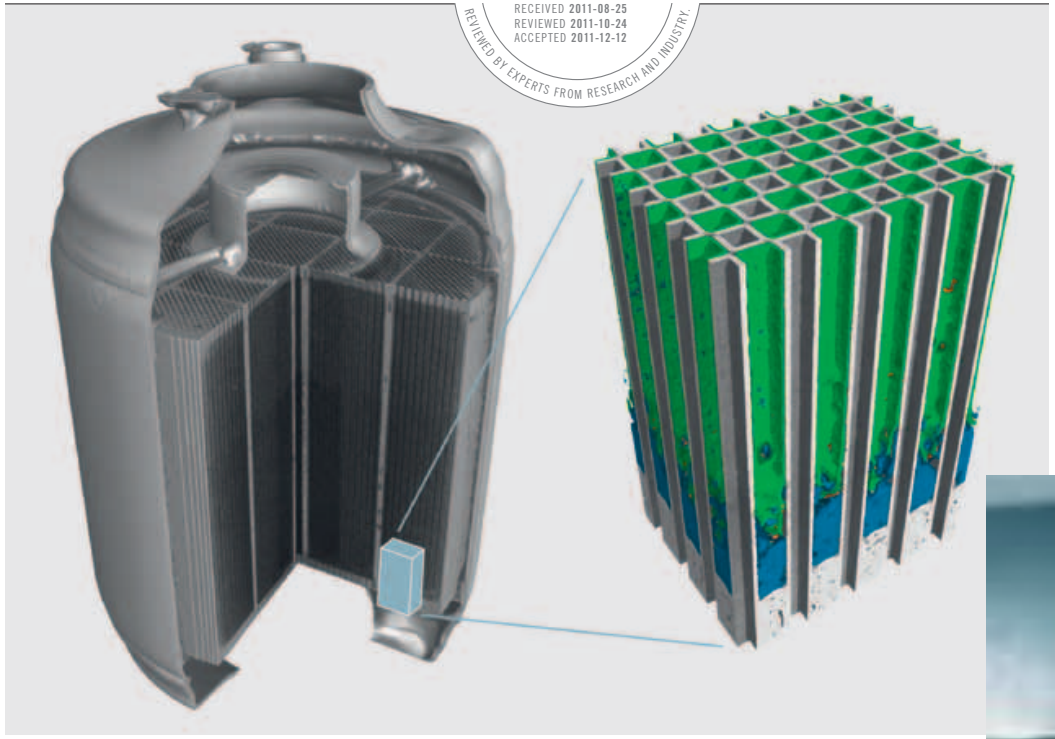
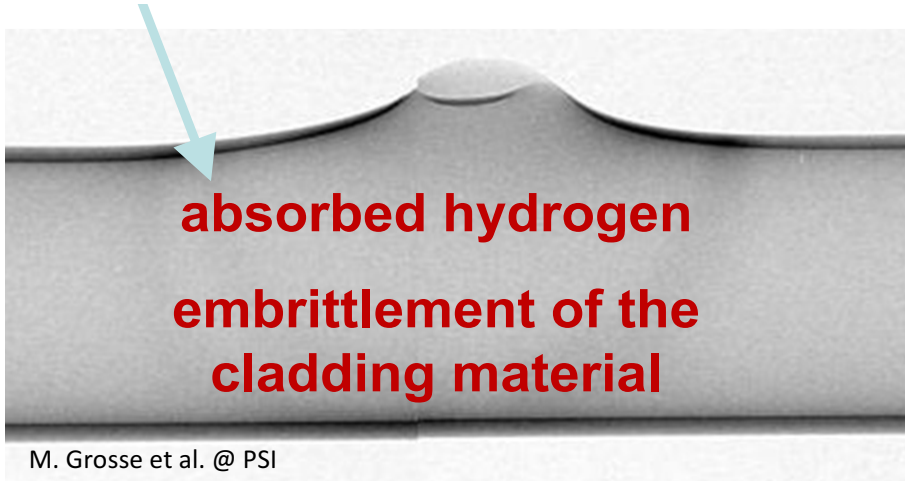
Neutron Imaging for environment

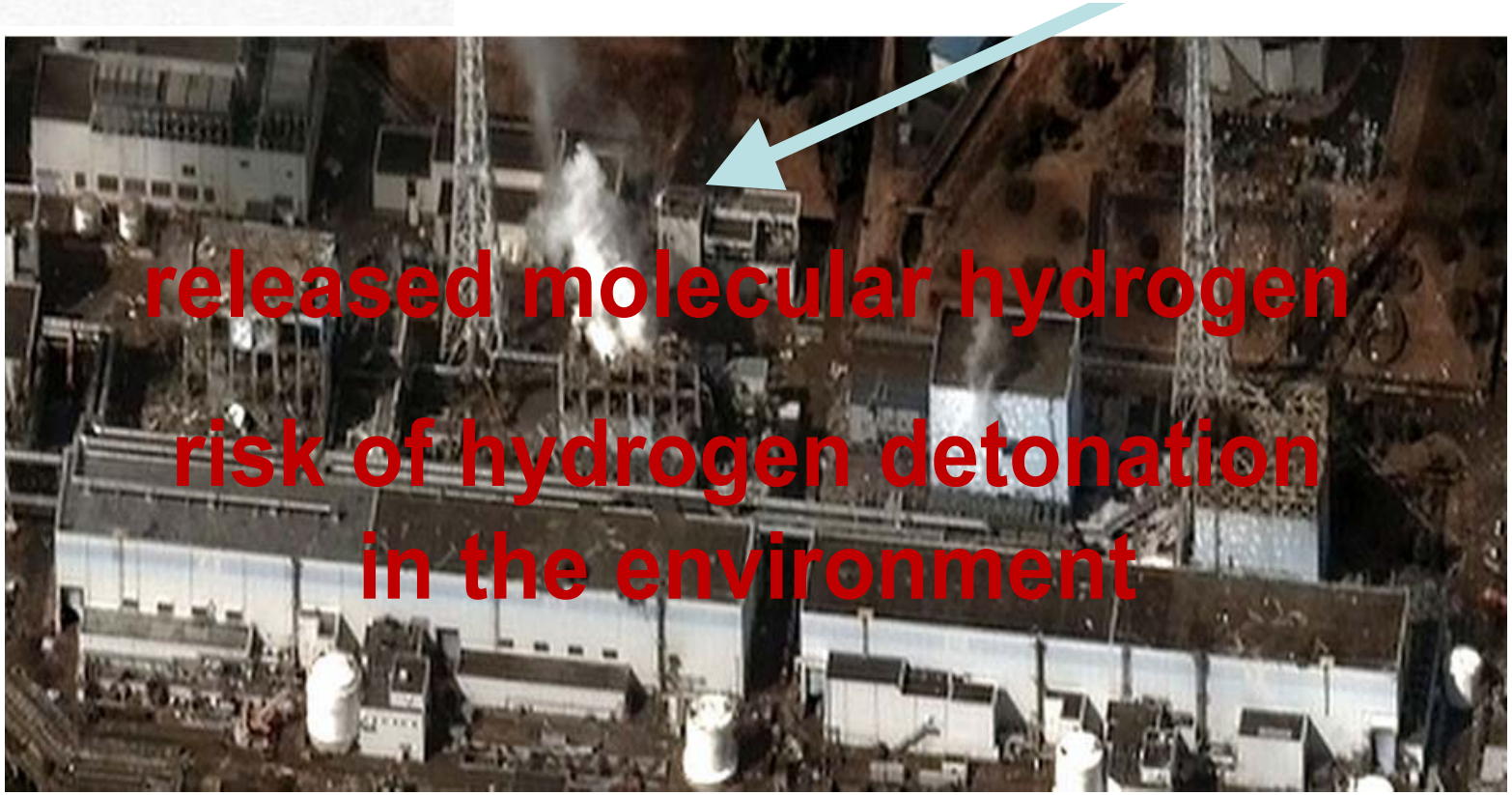


C. Gruenzweig
et al. MTZ 2011

Neutron Imaging for Nuclear Energy/Safety



M. Grosse et al. @ PSI



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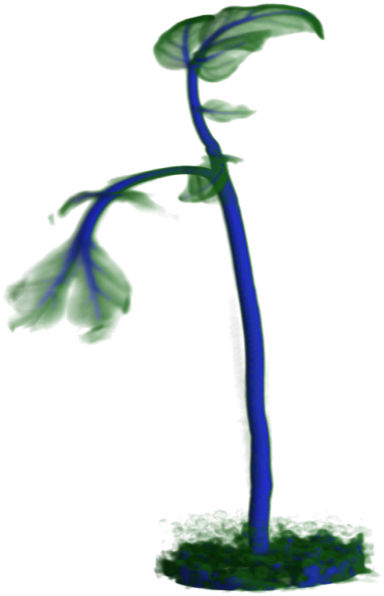
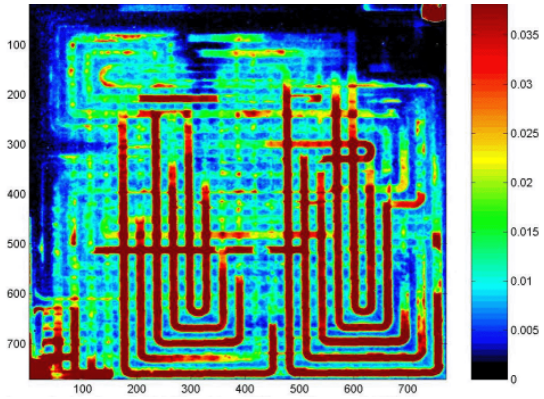
Neutron Imaging for….





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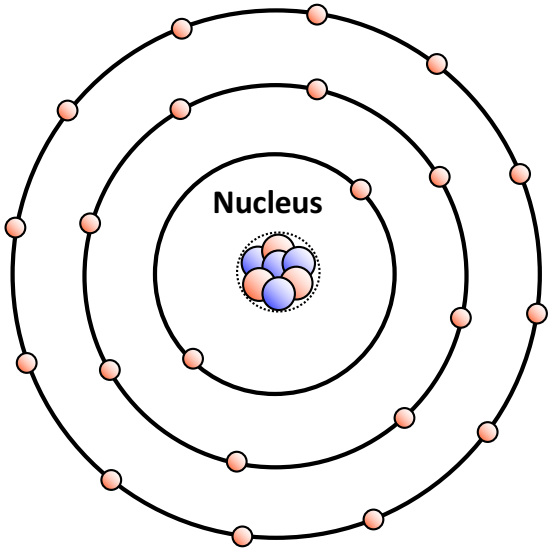
Why neutrons?



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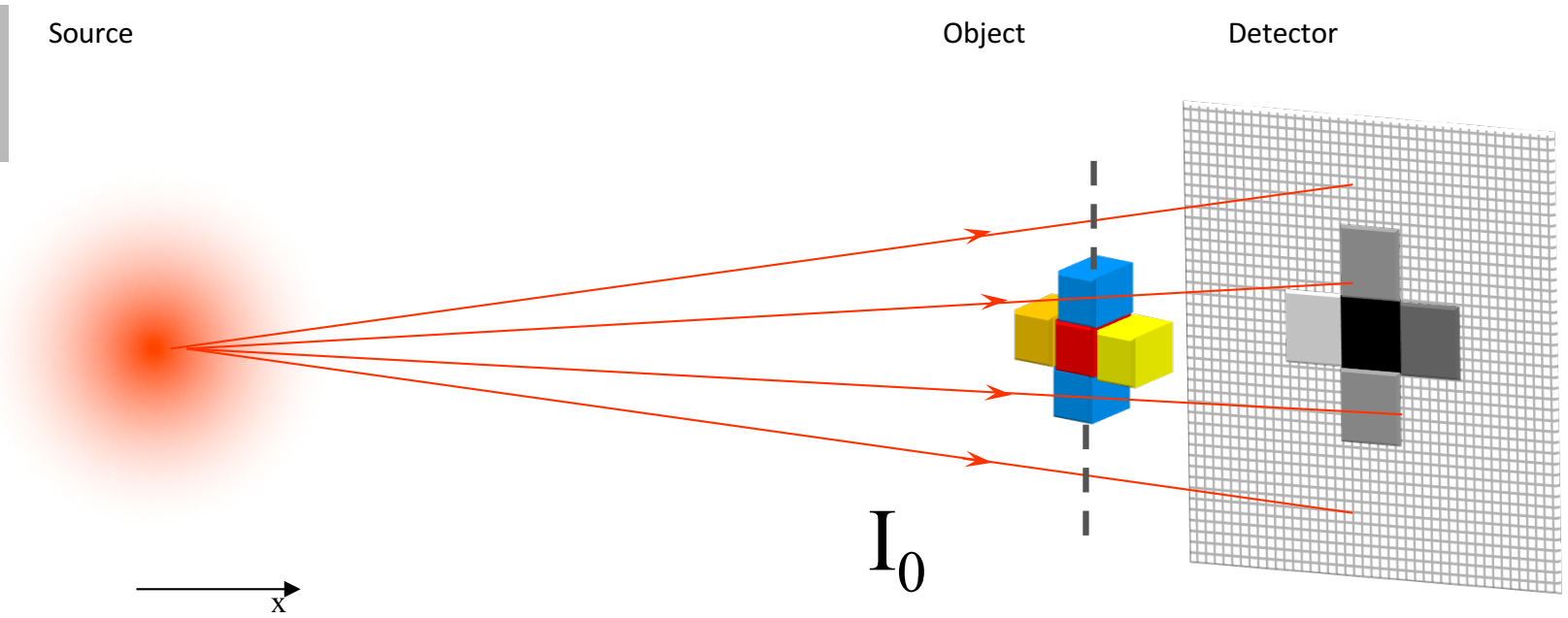
Contrast



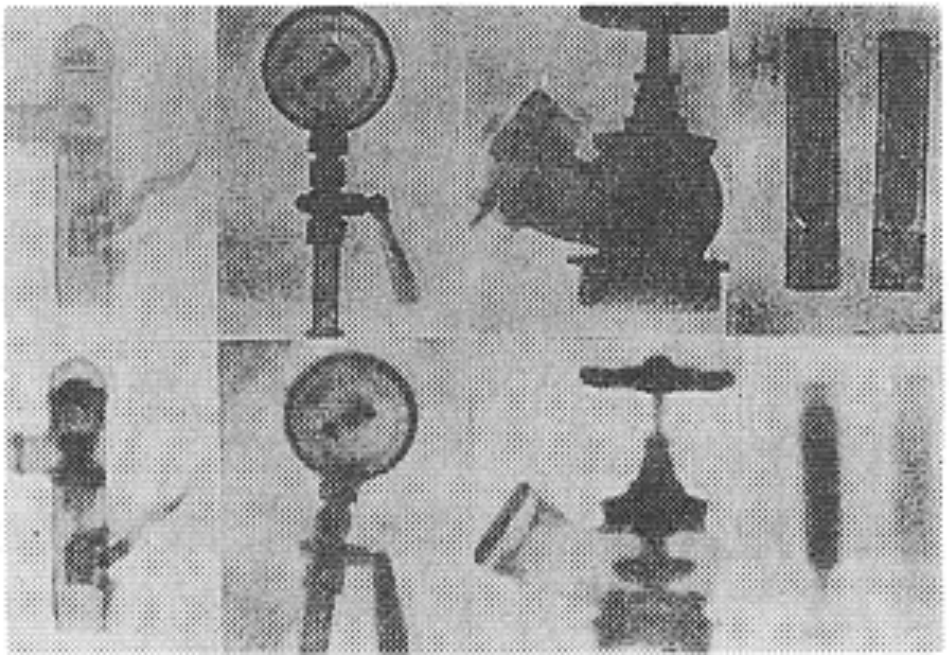
$$\sim I_0 e^{-\int \Sigma(x)dx}$$

I_0 – primary beam

$\Sigma(x)$ – attenuation coefficient

x – propagation direction

Contrast



As typical: valves, manometers, injectors

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Contrast

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

Interaction of neutrons with matter: Scattering

& Absorption

- Cross sections:

  Microscopic cross sections : $\sigma = \sigma_a + \sigma_s$

Unit of σ : 1 barn $= 10^{-24}$ cm^2

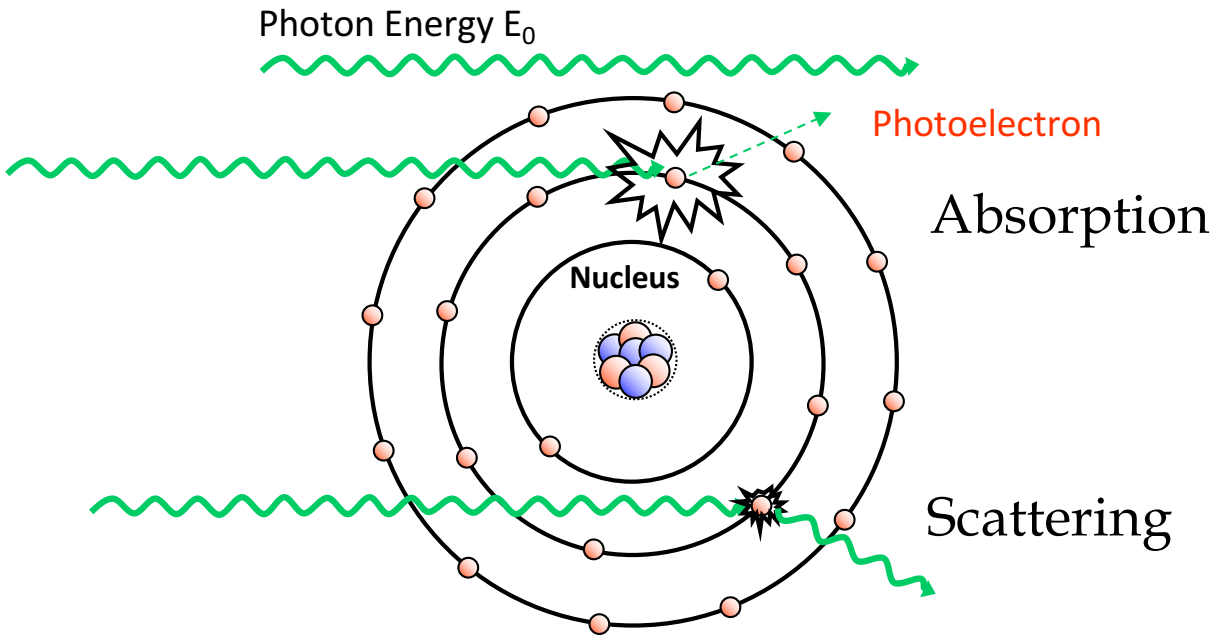
Macroscopic cross section : Σ (i.e. μ linear attenuation coefficient)

$\Sigma = N \cdot \sigma$, N = number of nuclei per cm^3 .

Unit of Σ is [cm^{-1}].

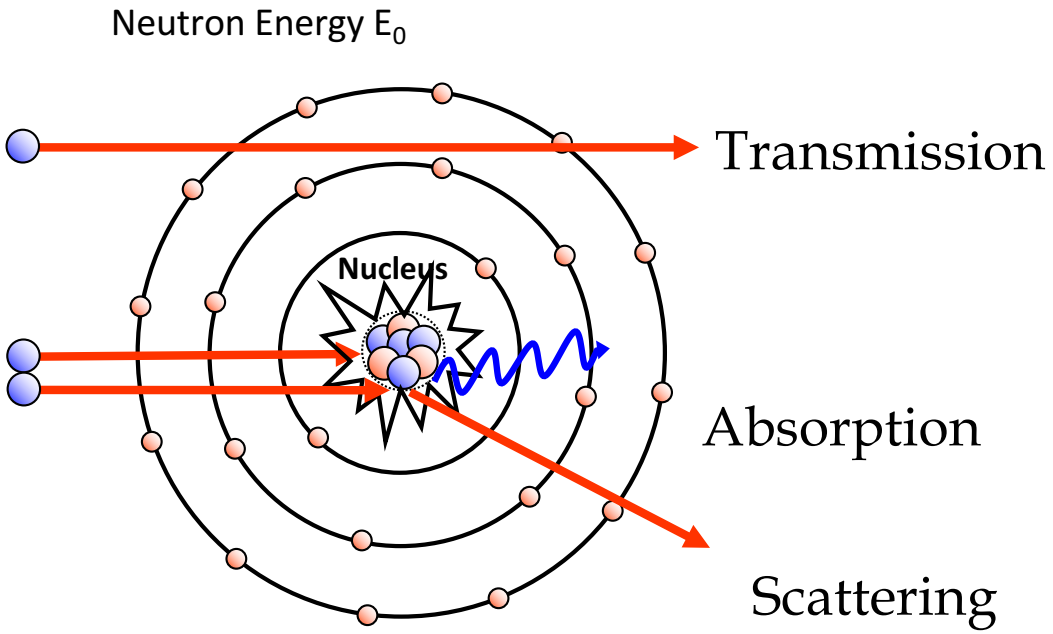
Contrast

X-ray interaction with matter



Contrast

neutron interaction with matter



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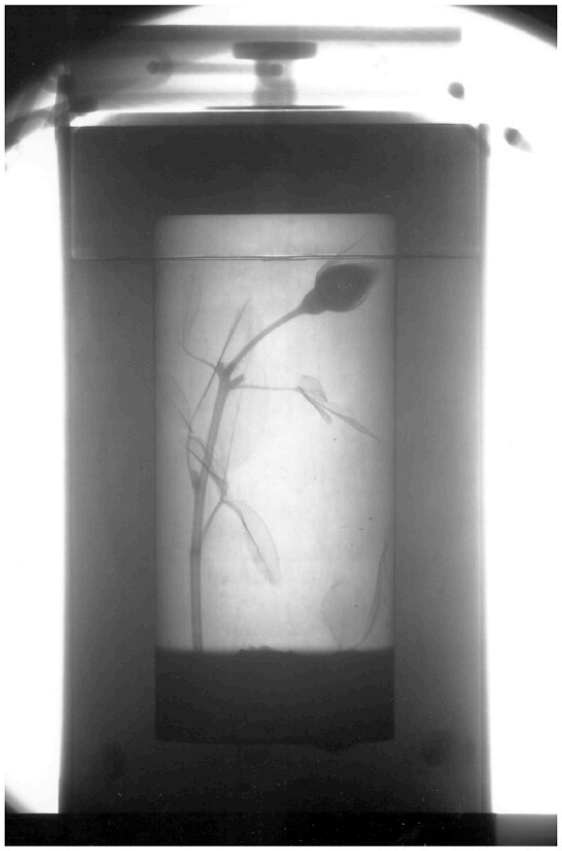
Introduction Neutron imaging

Some advantages:

High penetration power



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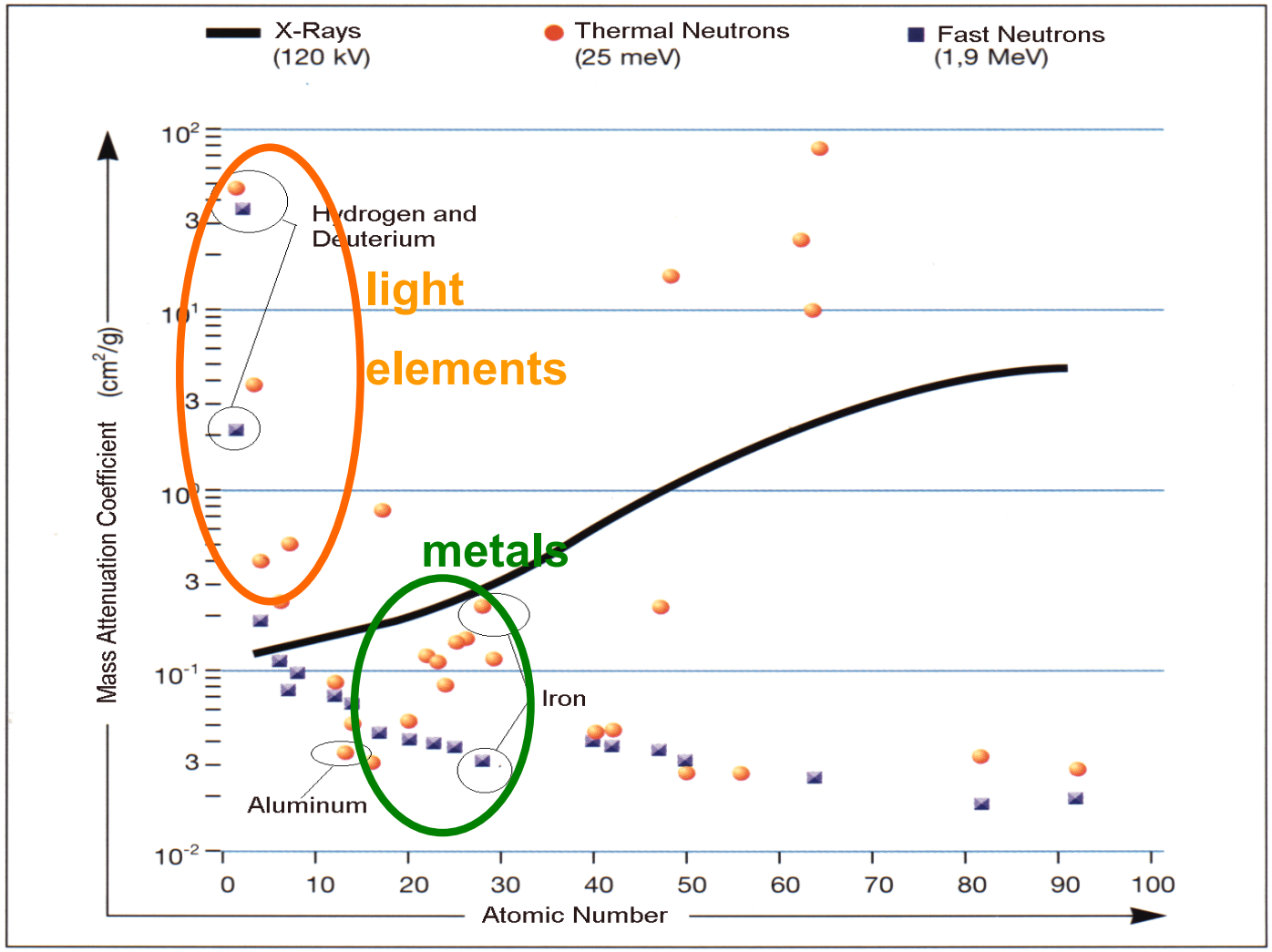
Contrast



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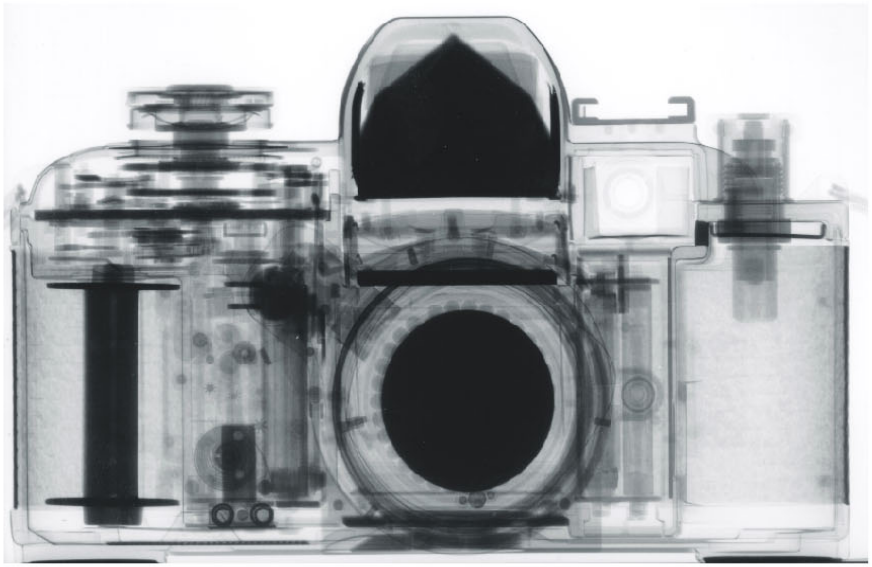
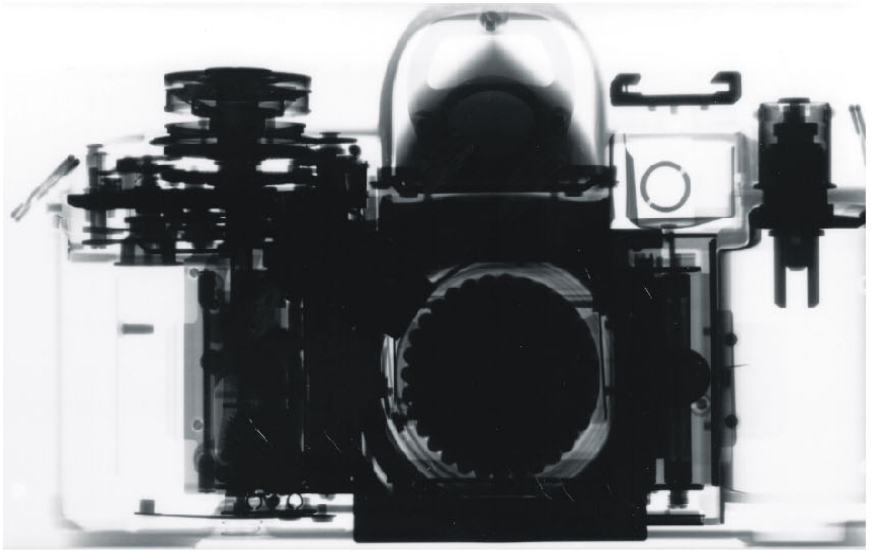
Contrast

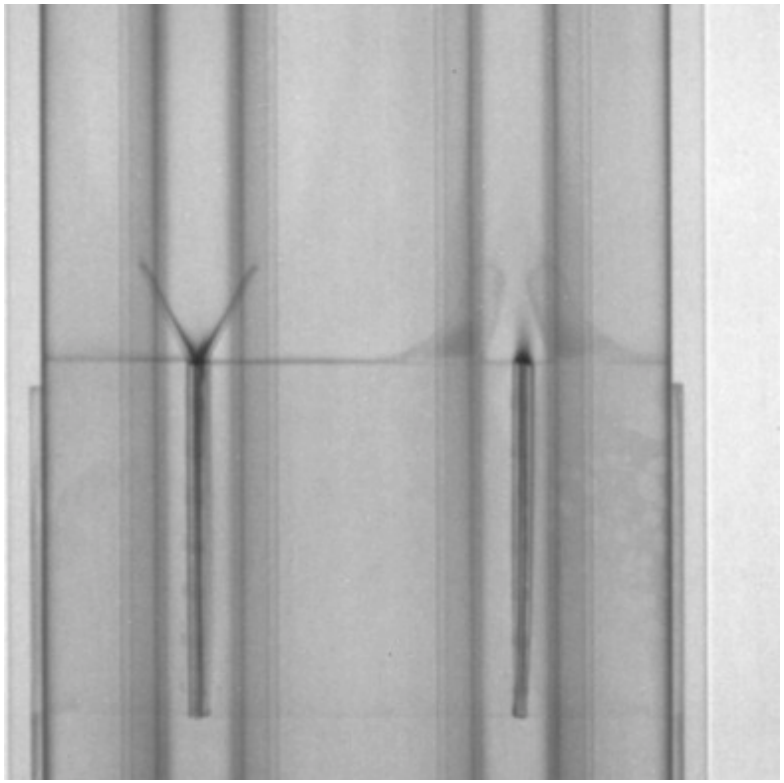




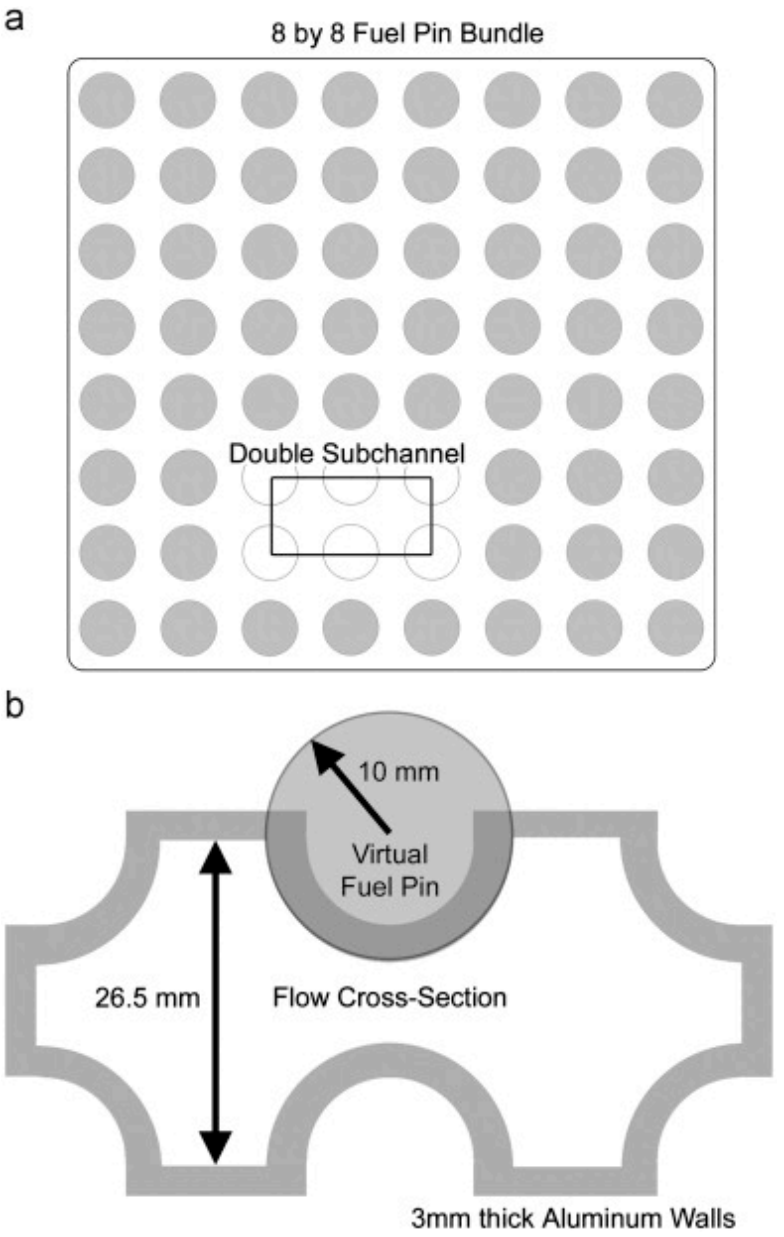
Contrast

Penetrates metal – sensitive to hydrogen (water)

Application: coolant flow in reactor core

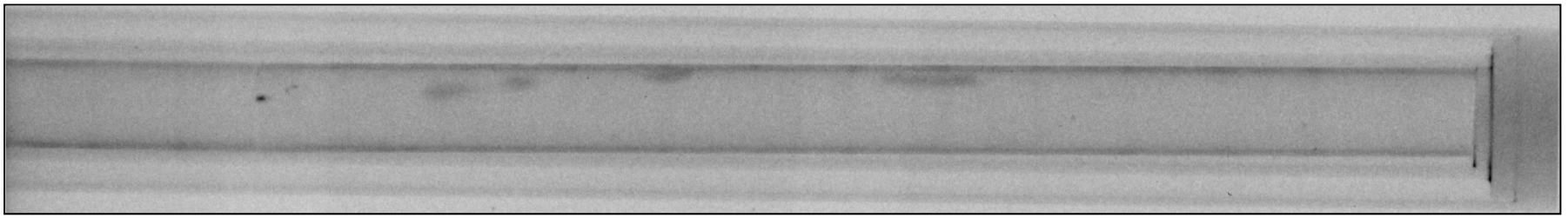


J.L. Kickhofel NIMA 2011



Application: nuclear energy / safety

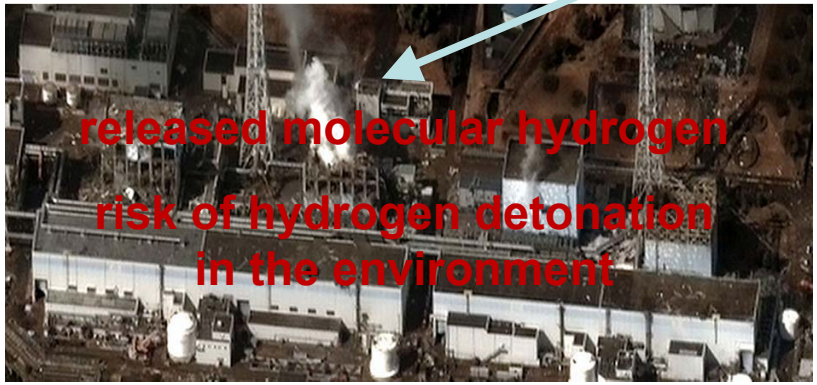
Zircaloy cladding only: ZrH_2 blisters



Emerging cooling of the overheated reactor core results in steam oxidation of the zirconium alloys used as fuel rod cladding material:

$2\ H_2O + Zr \rightarrow ZrO_2 + 4\ H$ (very simplified)

$4\ H \rightarrow 2H_2\uparrow\ /\ 4\ H_{absorbed}$



Application: fuel cells

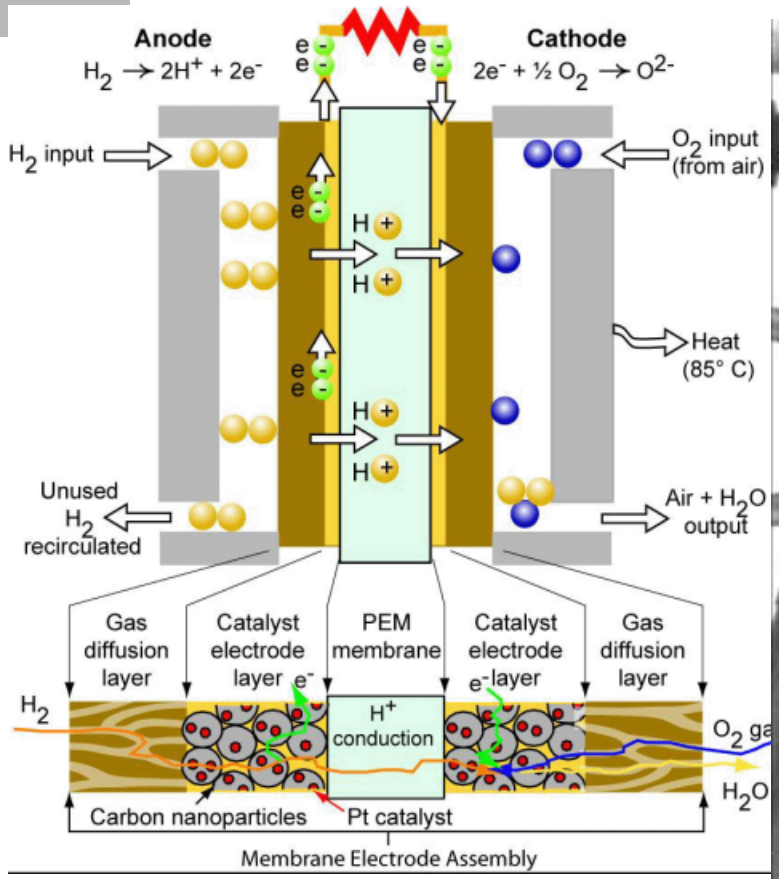


Figure 1. Schematic of a PEM Fuel Cell

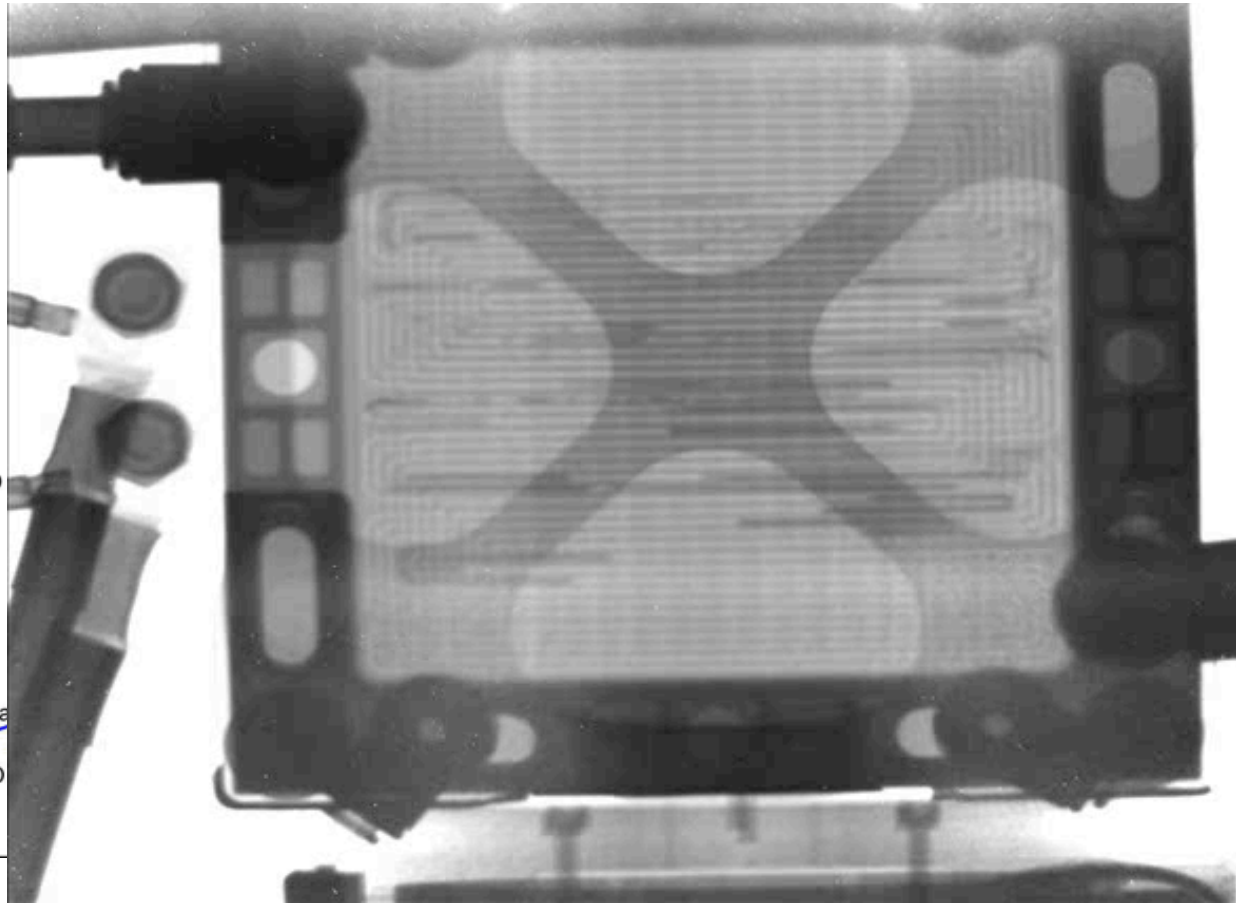
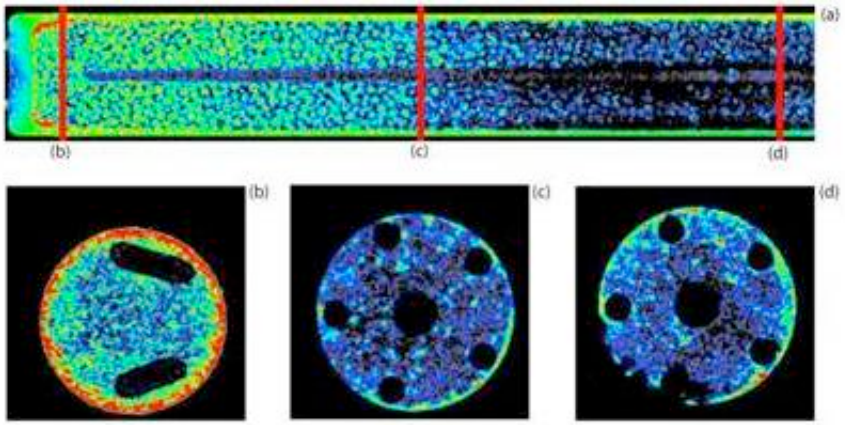


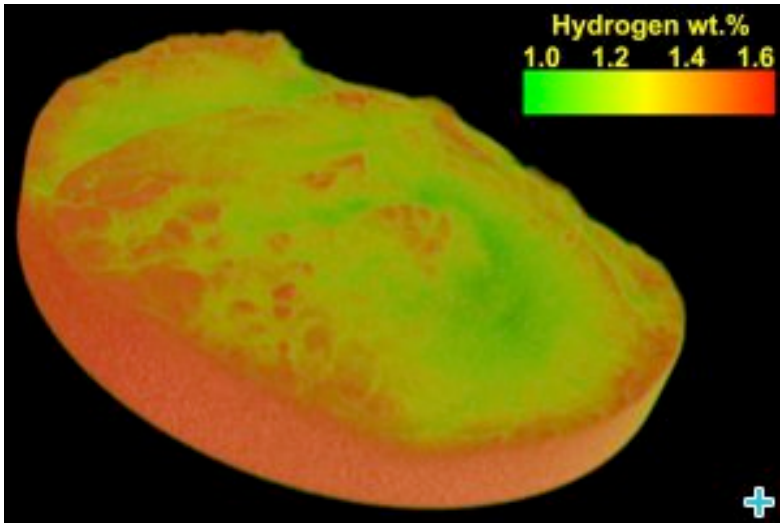
Figure 4. Image of Nearly Uniformly Hydrated Flow Fields and Membrane Assembly

Application: hydrogen storage

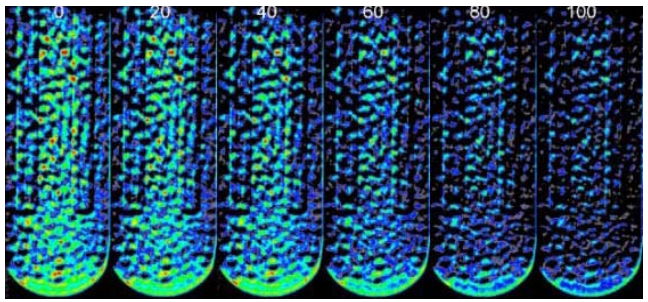


(a) Slice along the length of the storage bed, *(b)-(d)* axial slices from the locations denoted in *(a)*.

p://www.nist.gov/pml/div682/grp03/neutron-tomgraphy.cfm



Ł. Gondek, N. B. Selvaraj, J. Czub, H. Figiel, D. Chapelle, N. Kardjilov, A. Hilger, I. Manke, Int. J. Hyd. Energy 36 (2011) 9751-9757



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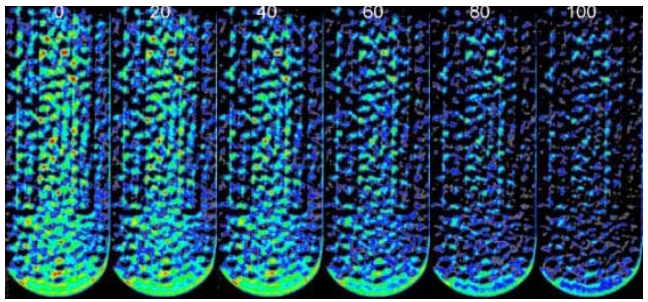
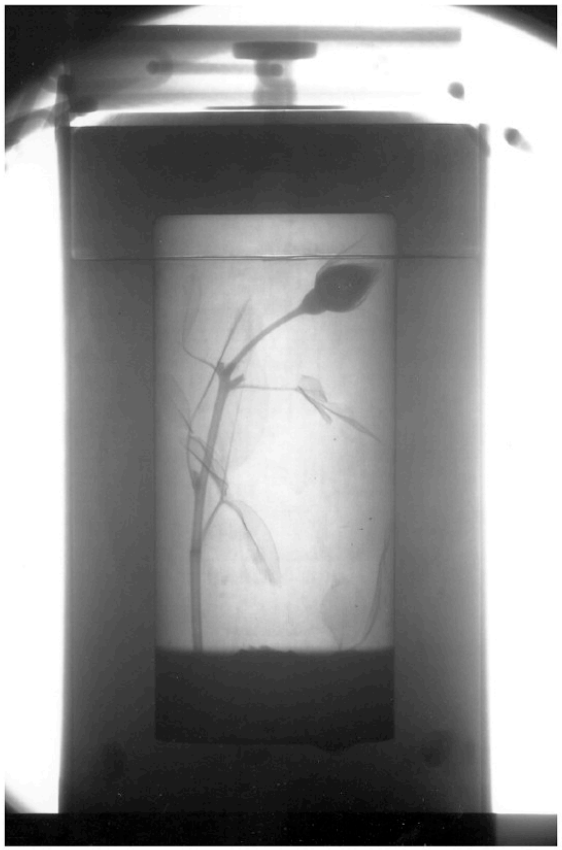
Introduction Neutron imaging

Some advantages:

High penetration power

High sensitivity to Hydrogen





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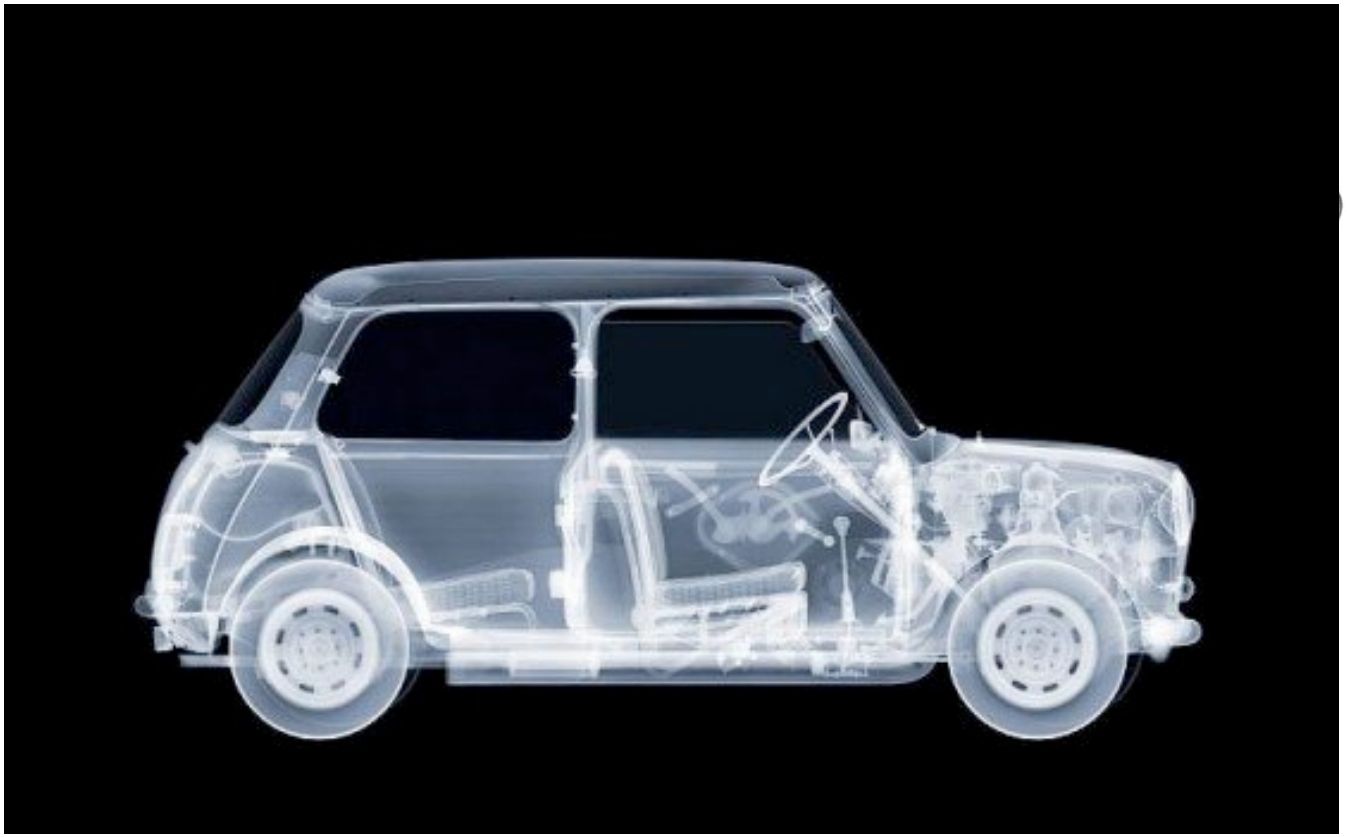
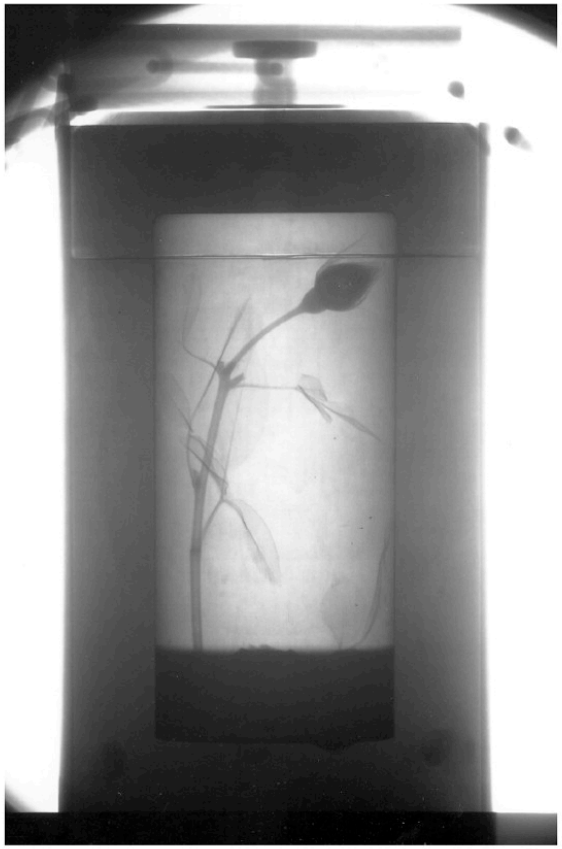
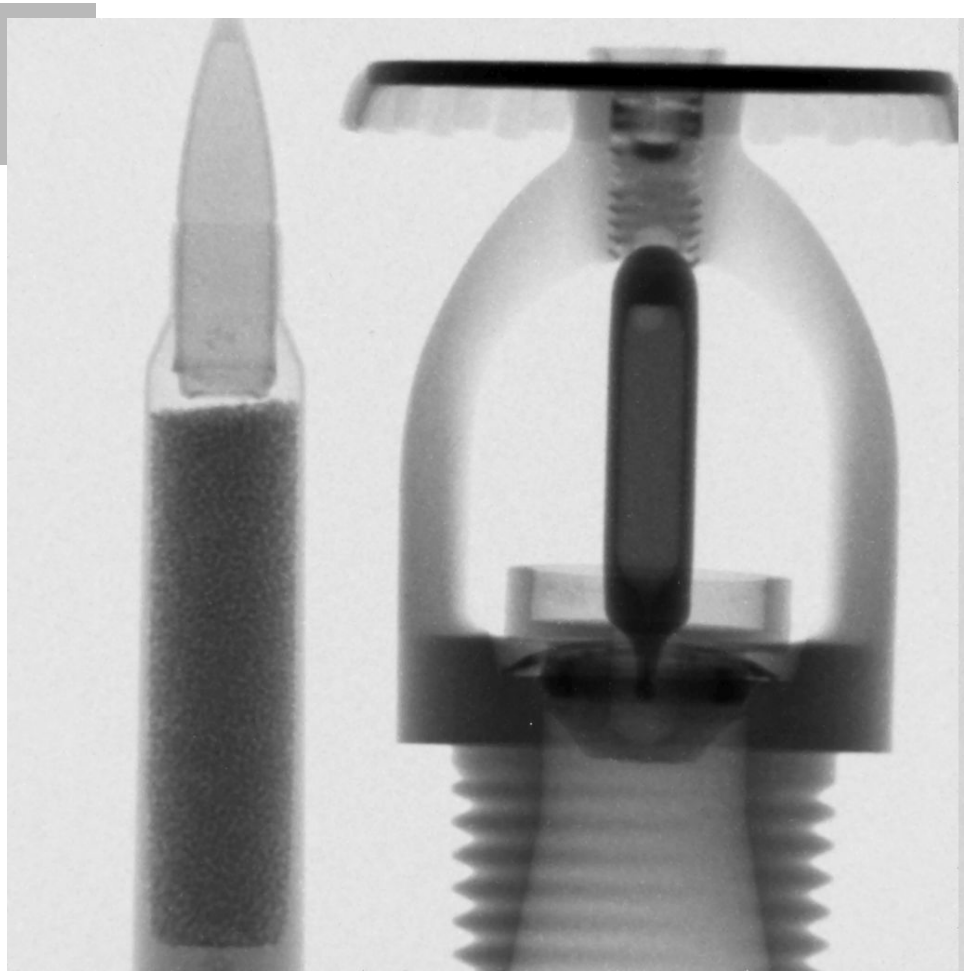


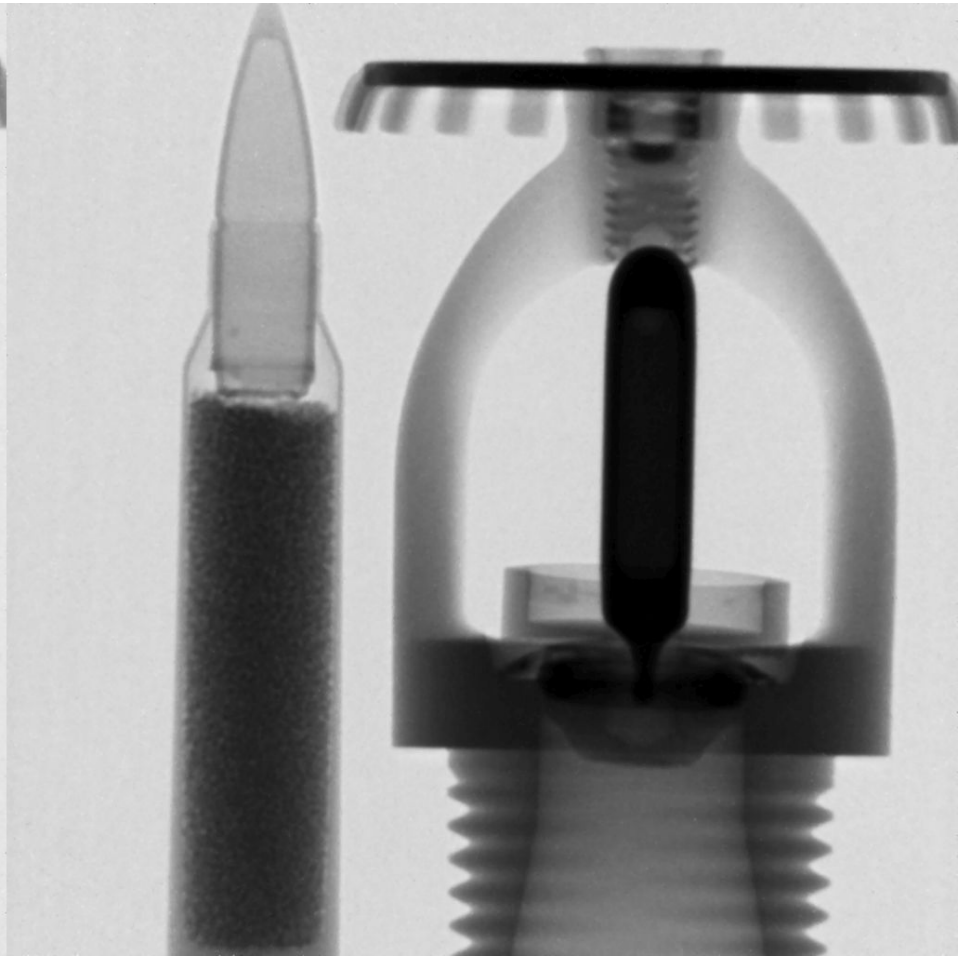


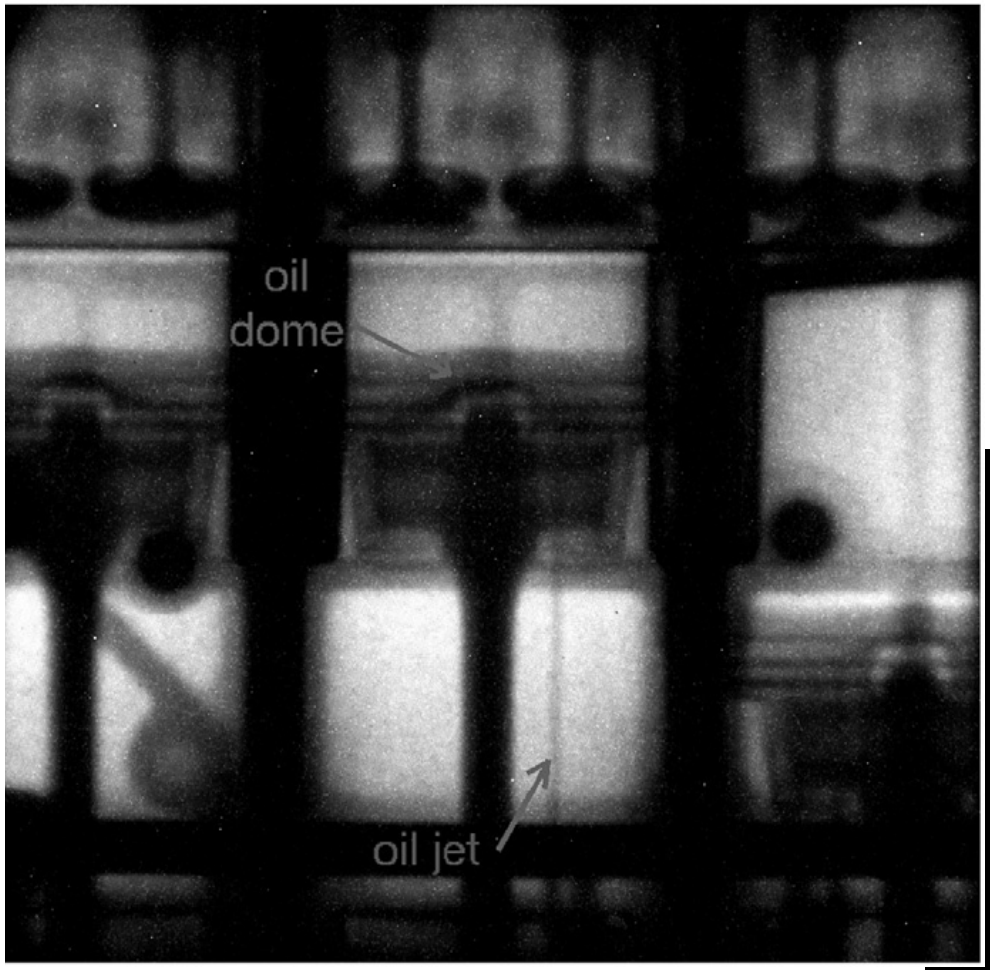
Contrast – effect of energy change

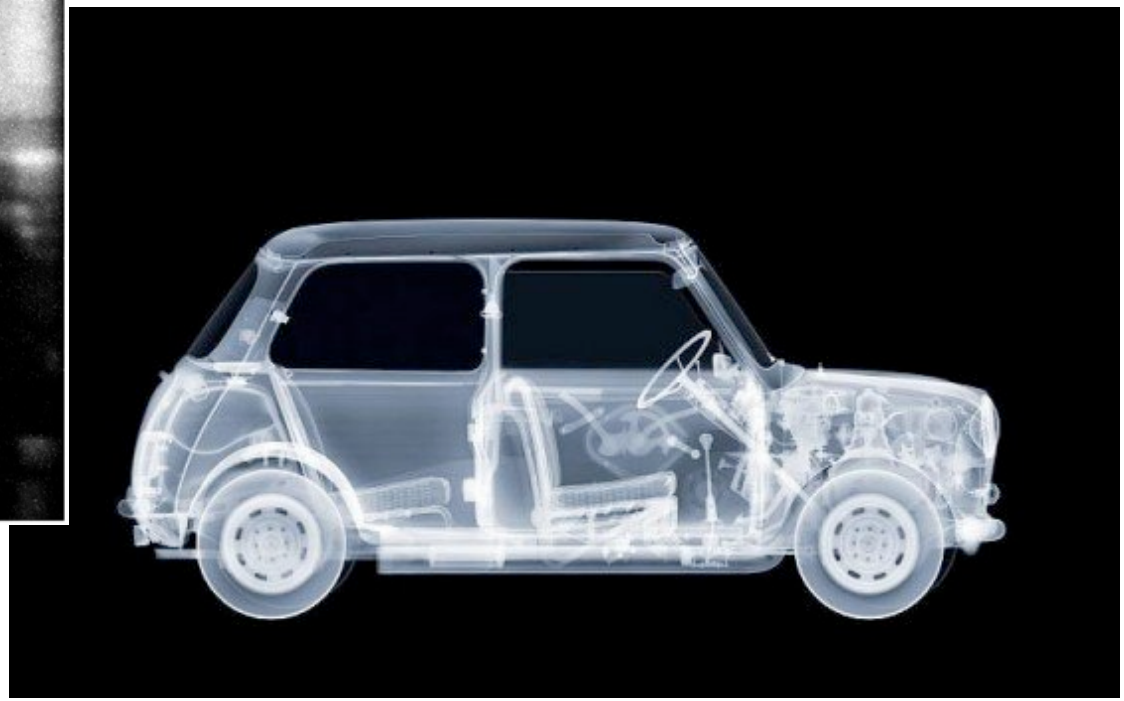
Thermal neutrons



Cold neutrons







B. Schillinger et al. Physica B (2006)

(200 microsec time resolution)

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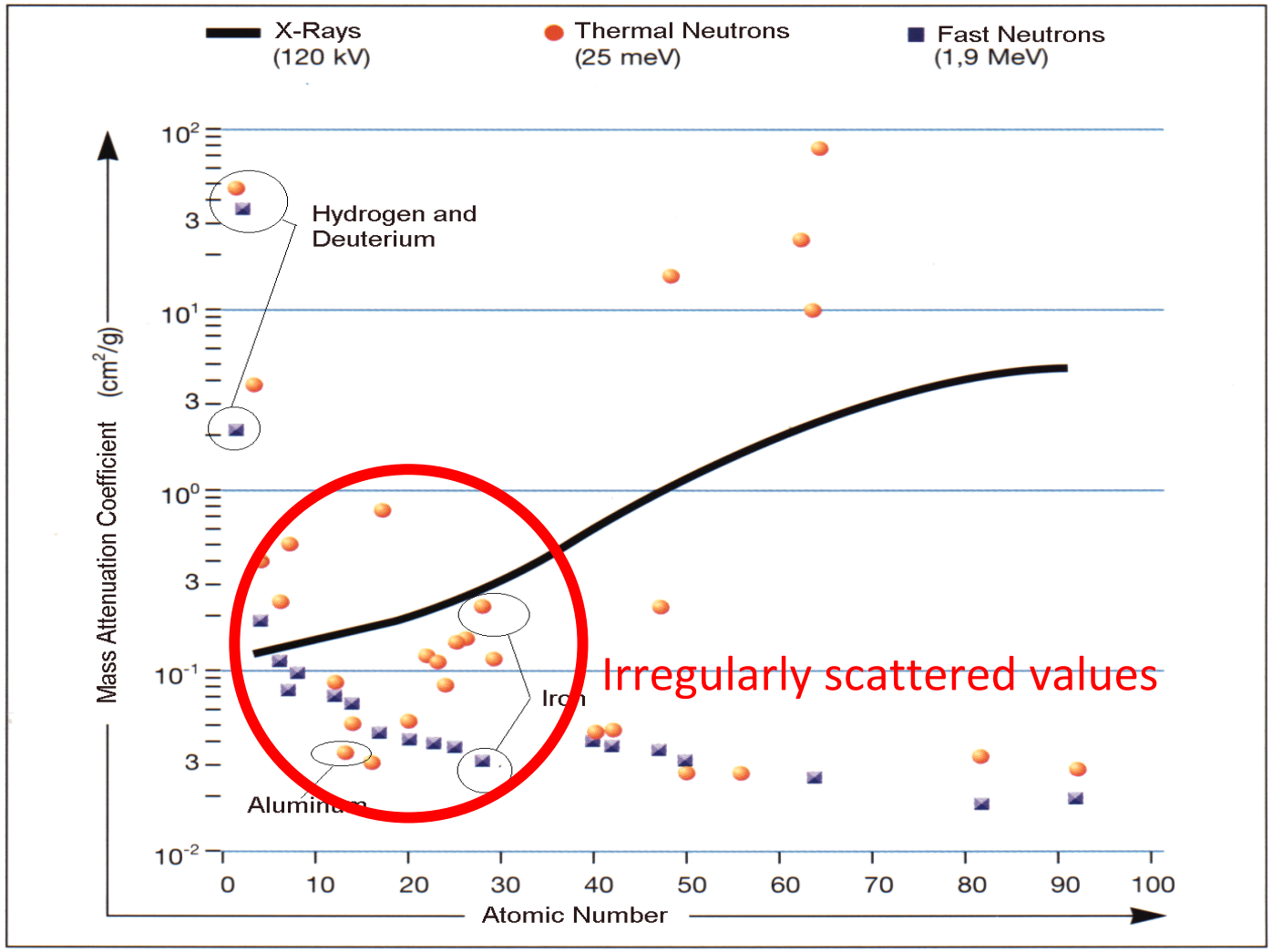
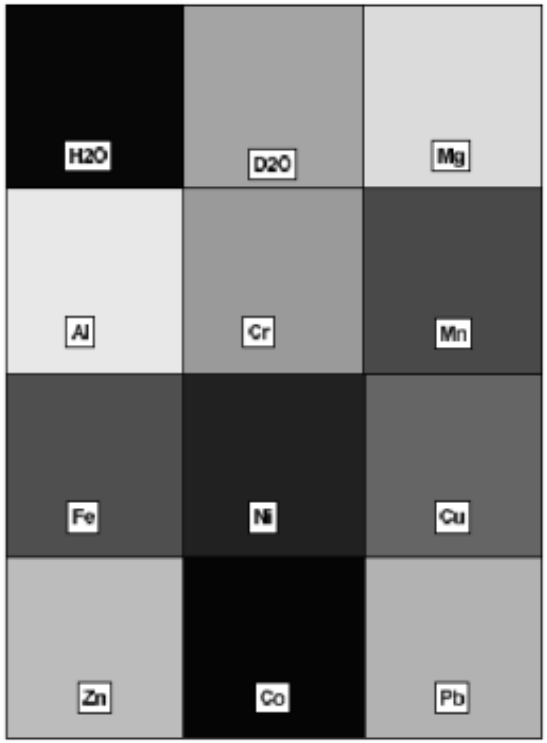
Contrast

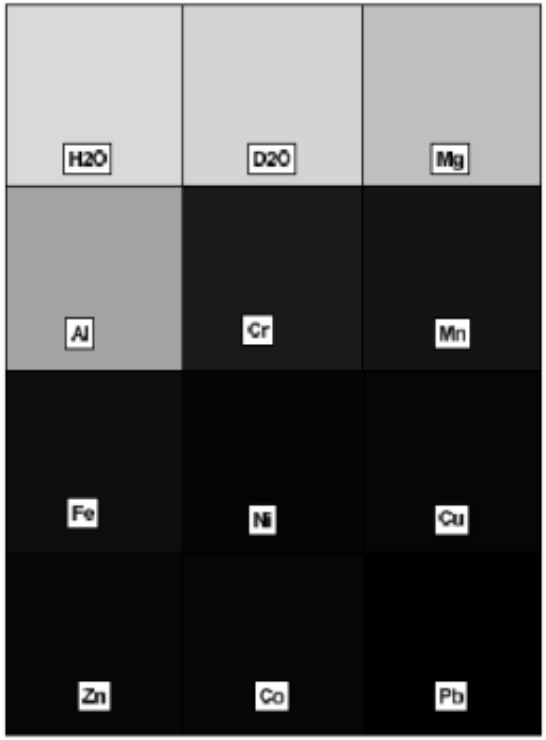


Contrast

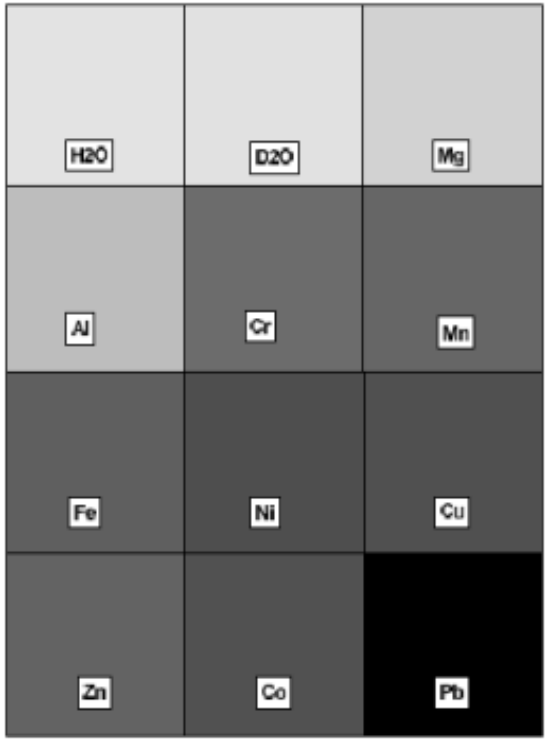
Neutronen (thermisch)



Röntgen (100keV)



Röntgen (250keV)



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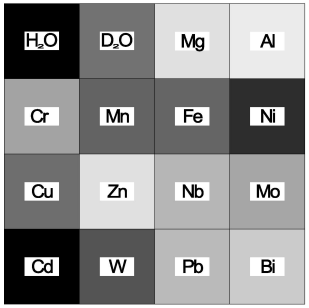
PSI

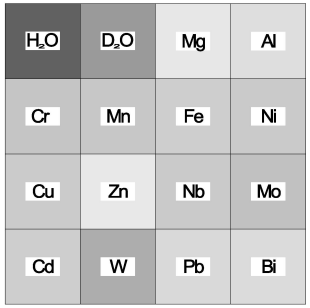
Thickness of materials: 1 cm

Neutrons

thermal neutrons (E = 25 meV)

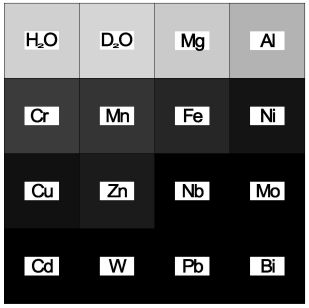


fast (fission) neutrons (E = 1.7 MeV)

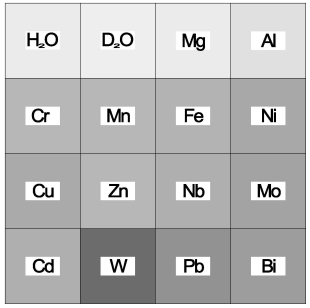


X-rays and gamma-rays

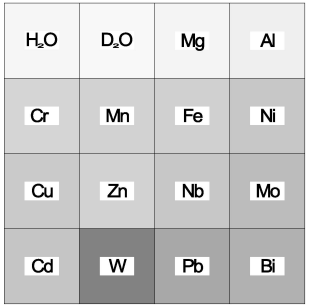
X-rays (E = 120 keV)

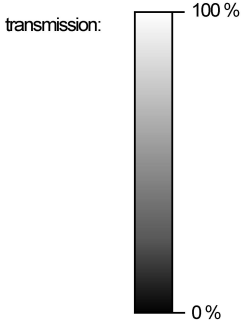


gamma-rays (E = 1.25 MeV)



gamma-rays (E = 6 MeV)

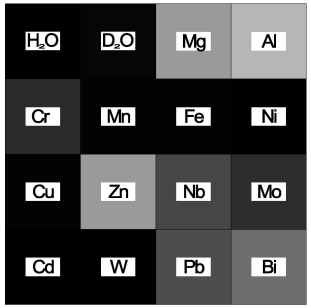




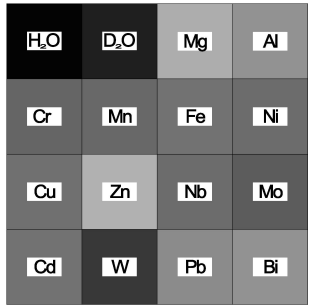
Thickness of materials: 4 cm

Neutrons

thermal neutrons (E = 25 meV)

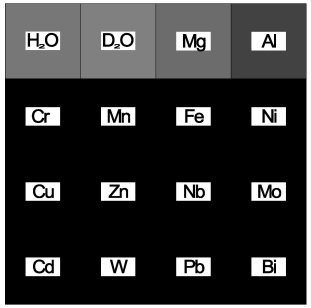


fast (fission) neutrons (E = 1.7 MeV)

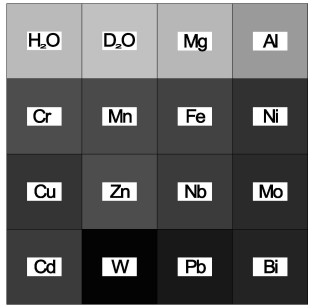


X-rays and gamma-rays

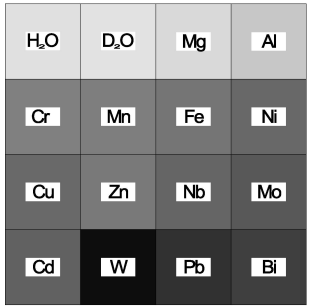
X-rays (E = 120 keV)

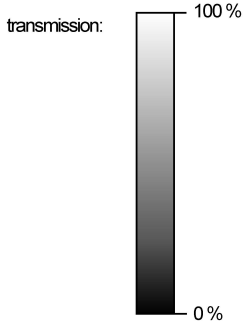


gamma-rays (E = 1.25 MeV)



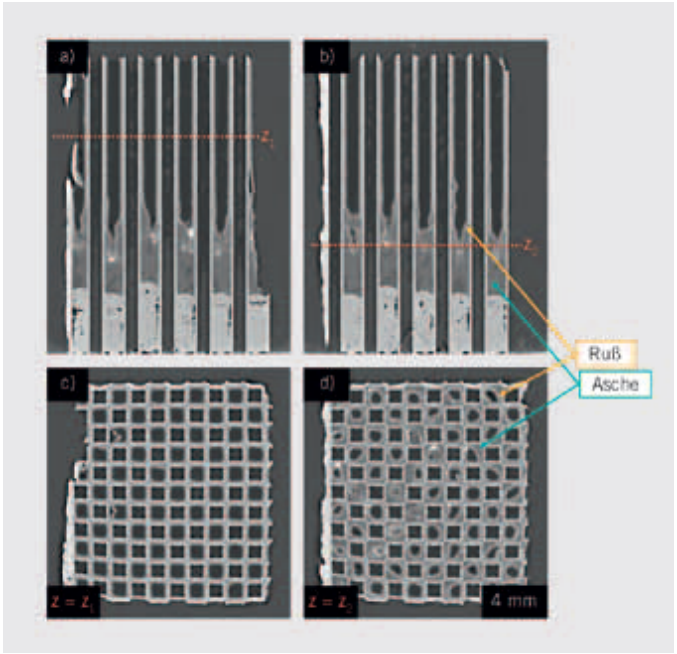
gamma-rays (E = 6 MeV)

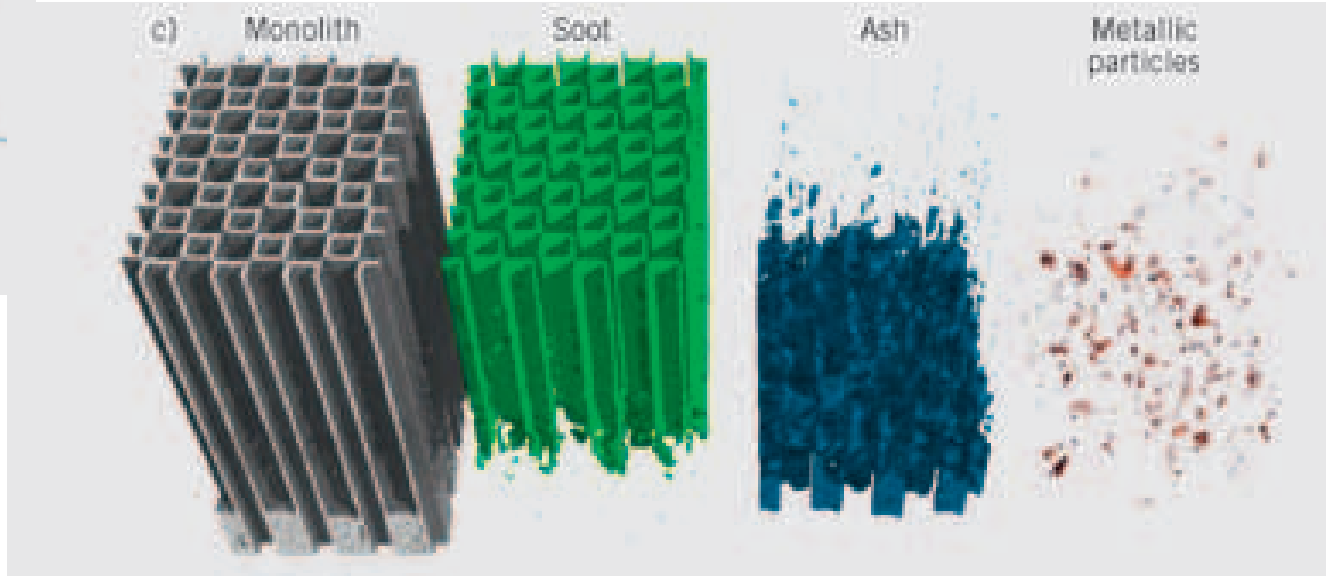




Application: diesel particulate filters

C. Gruenzweig et al. MTZ 2011





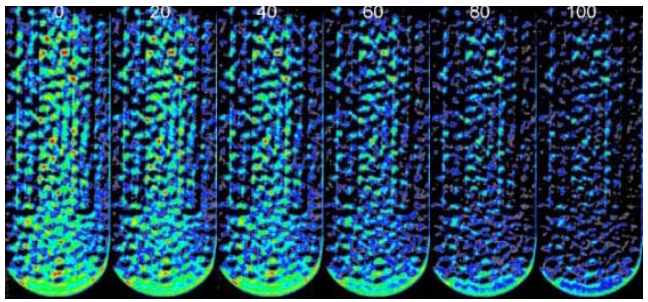
Neutron imaging

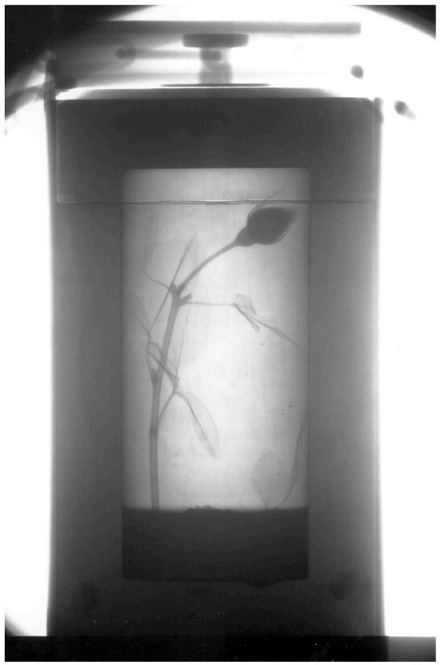
Some advantages:

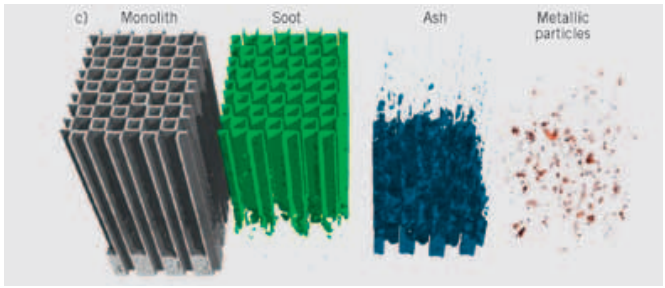
High penetration power

High sensitivity to Hydrogen

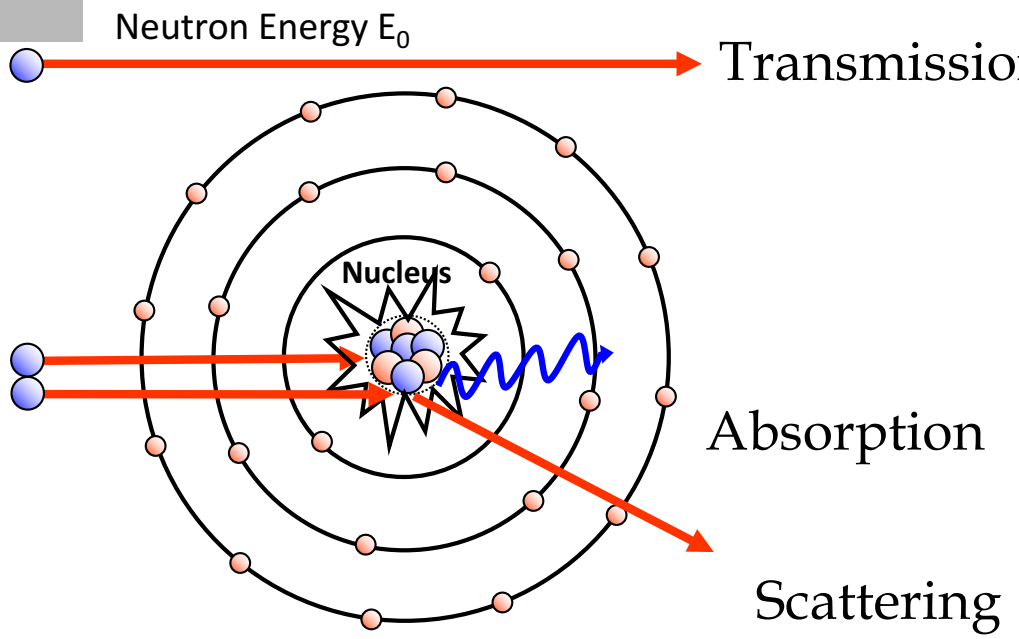
Scattered contrast

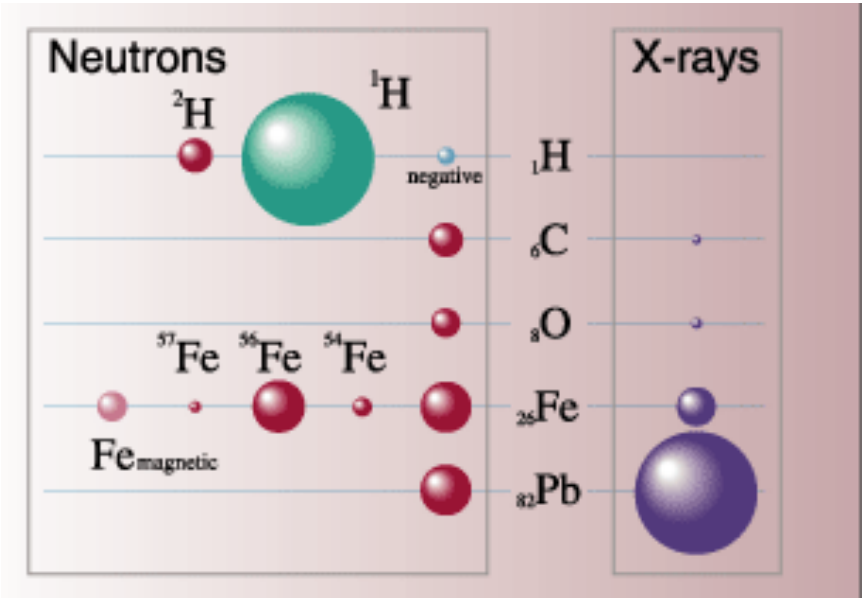






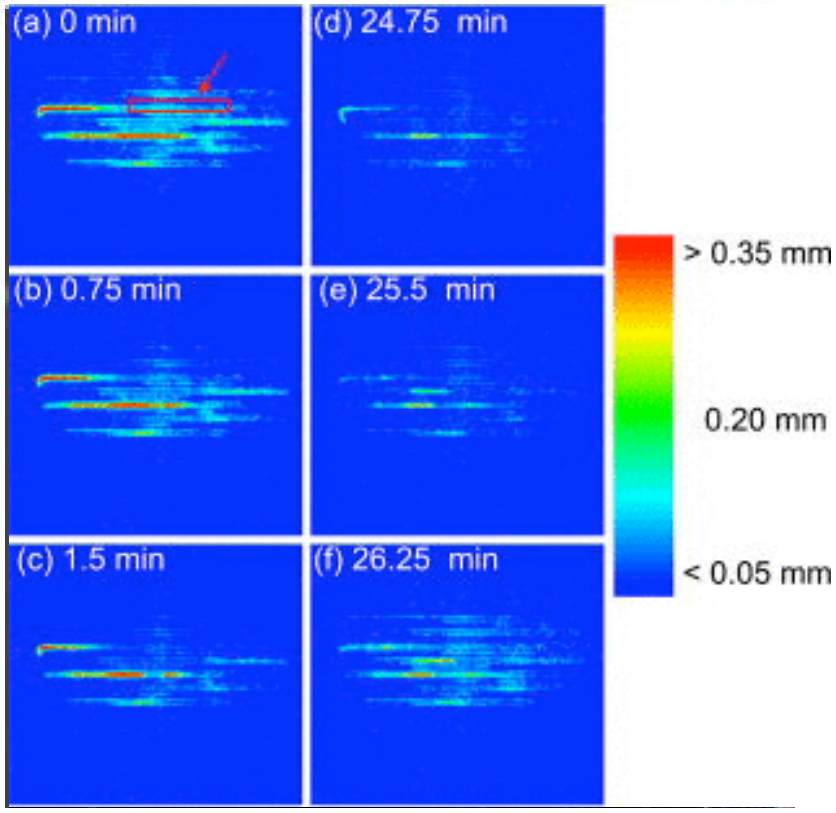
Contrast

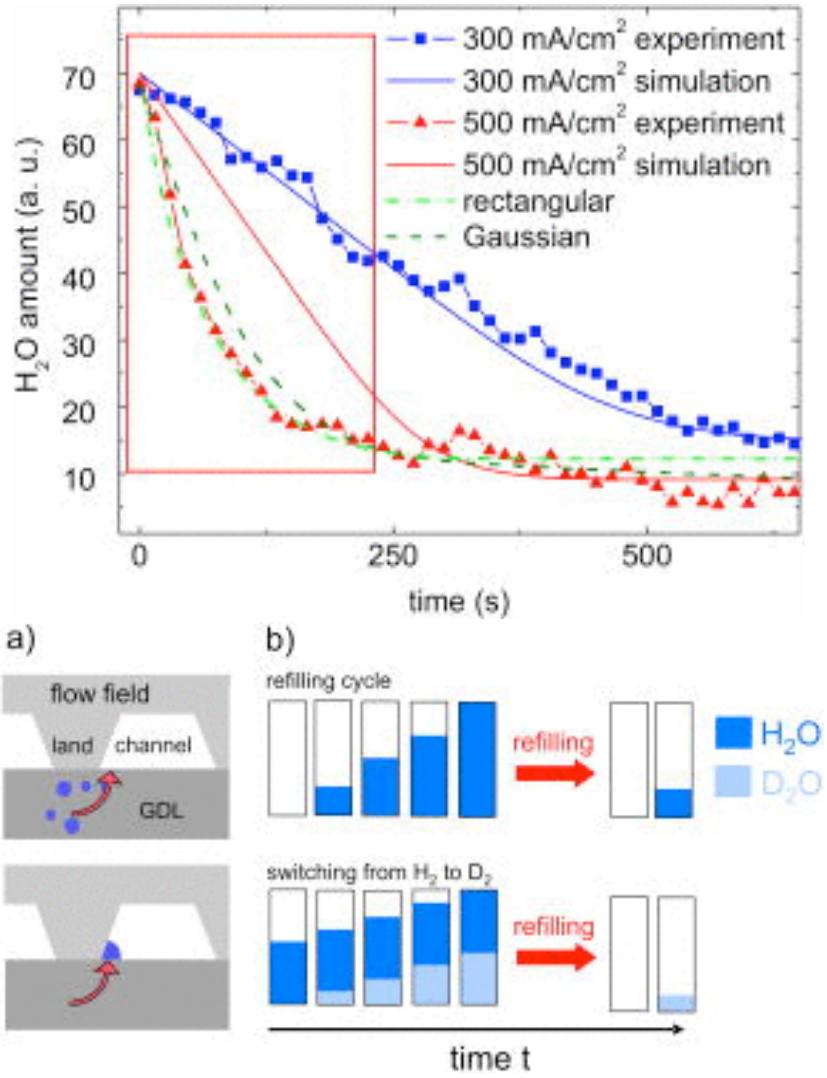




scattering cross sections

Application: fuel cells

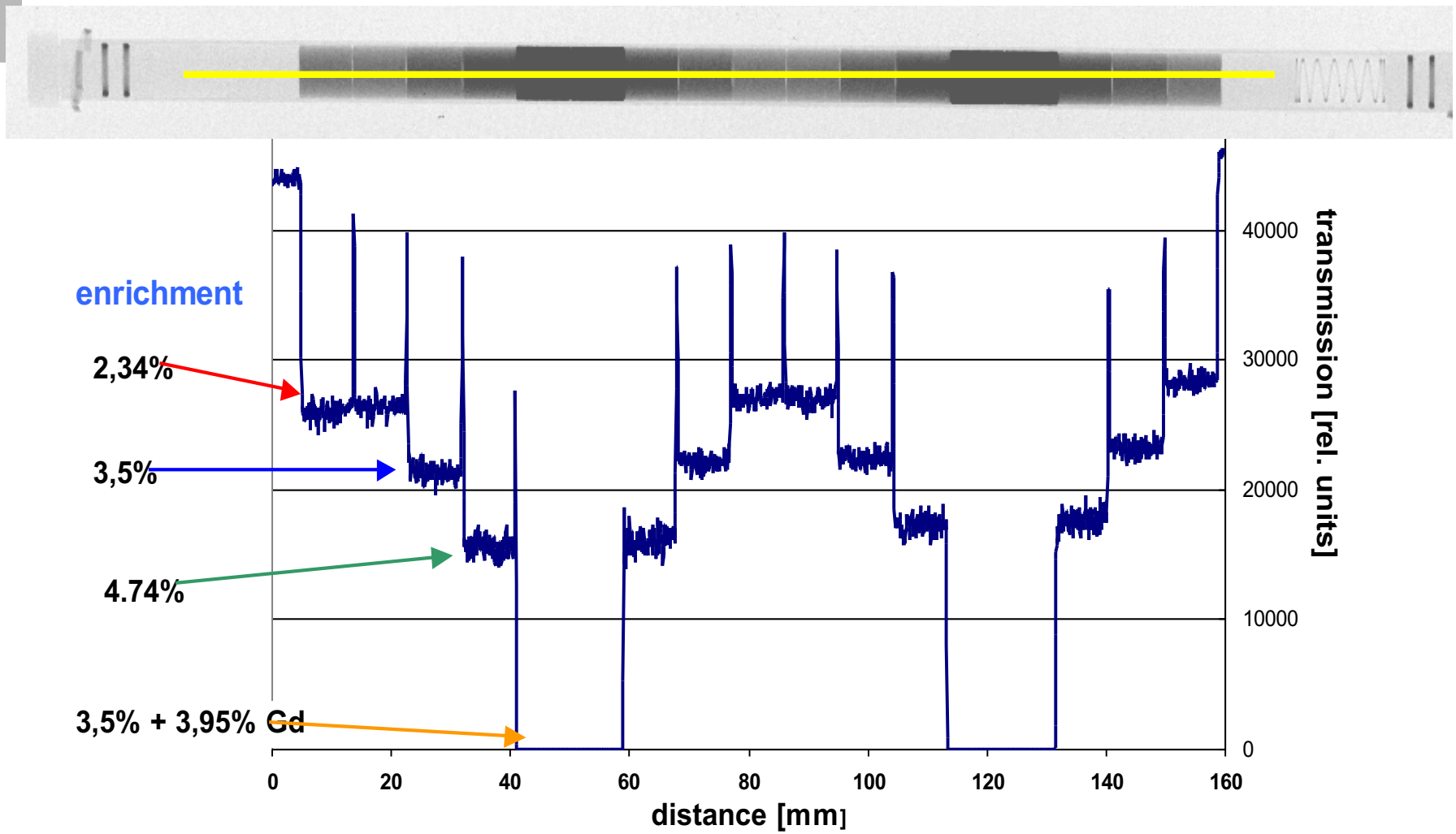




I. Manke et al. Appl. Phys. Lett. 92, 244101 (2008)

Application: nuclear energy

Determination of the U-235 content (enrichment) in nuclear fuel elements



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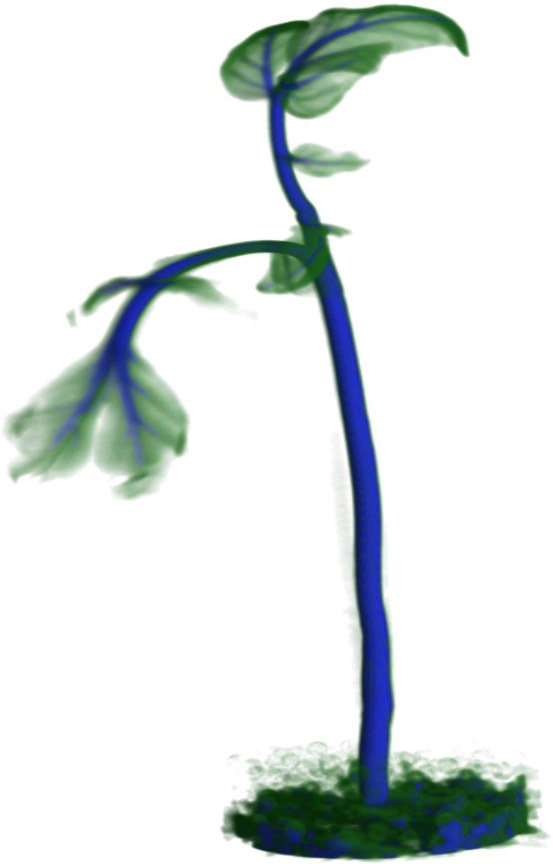
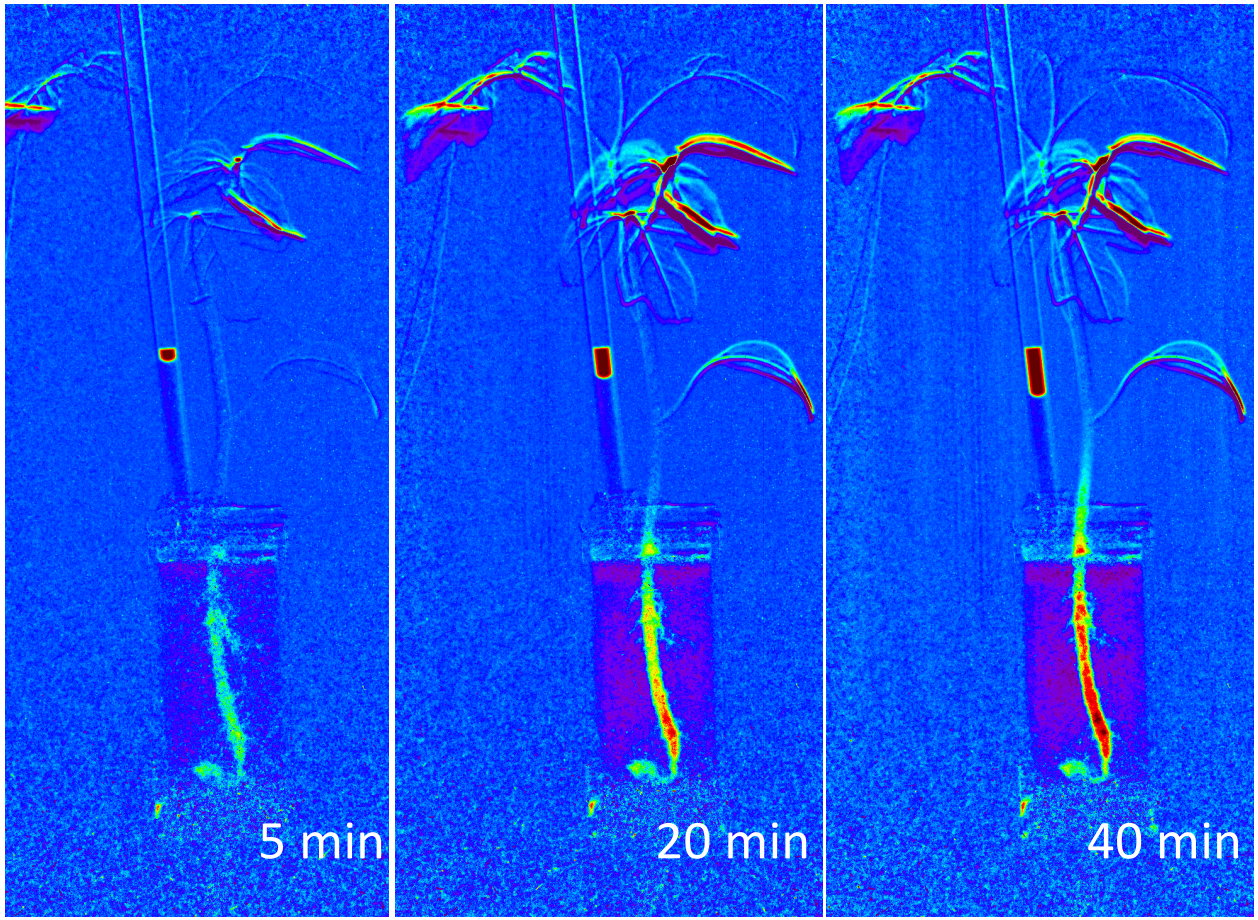
Application: biology



H_2O D_2O



…and no stress!!

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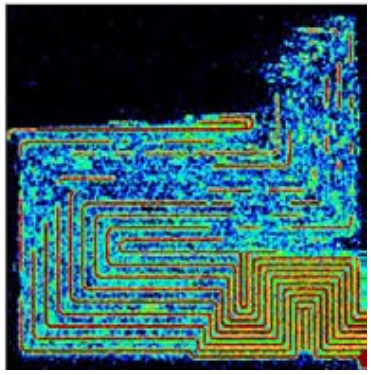
Introduction Neutron imaging



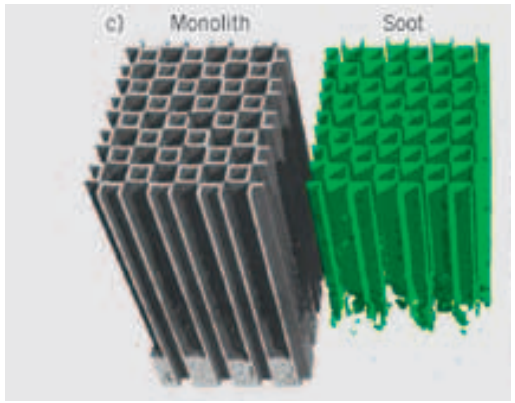
Some advantages:

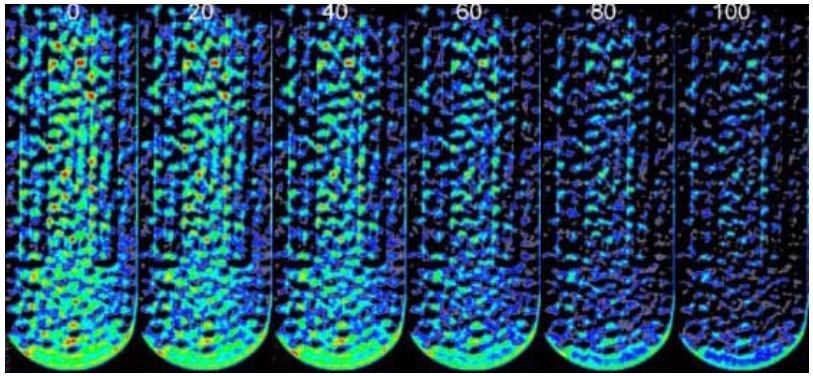
High penetration power

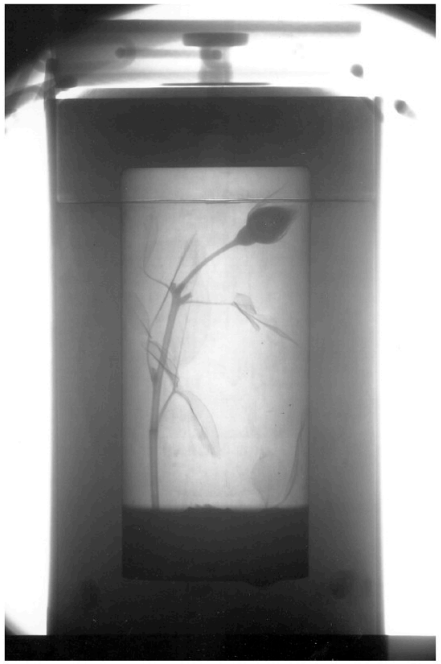
High sensitivity to Hydrogen

Scattered contrast

Isotope sensitivity

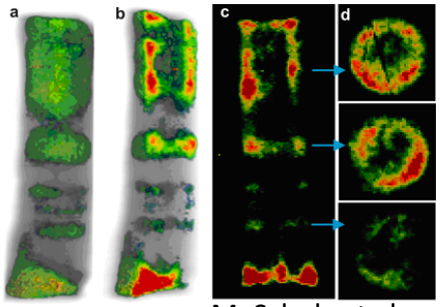




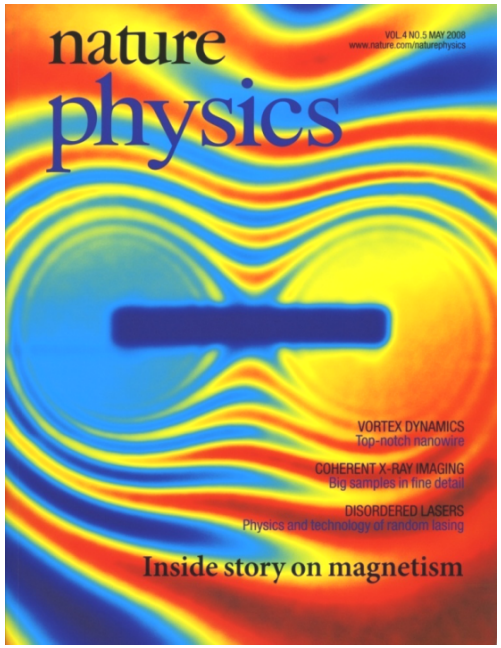


Neutron imaging

Some advantages:



M. Schulz et al.

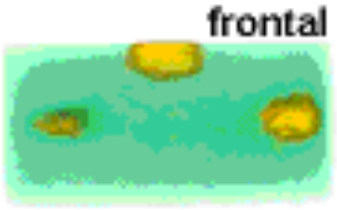


High penetration power

High sensitivity to Hydrogen

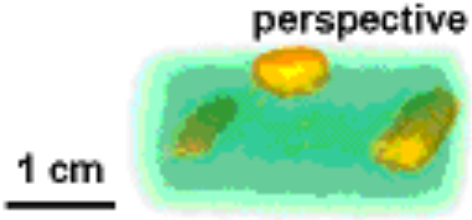
Scattered contrast

Isotope sensitivity

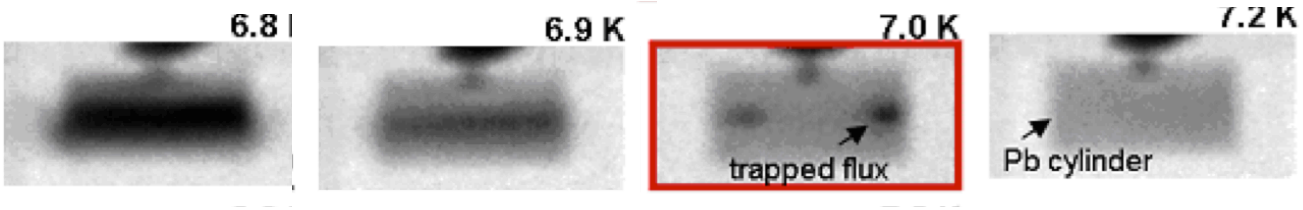


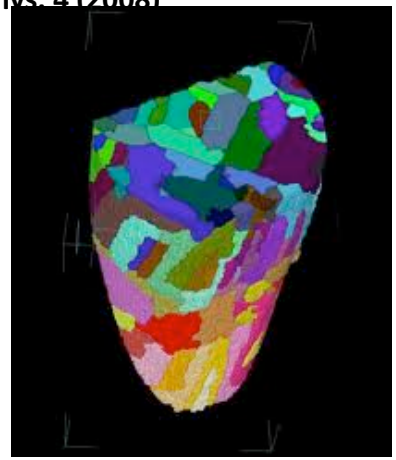
N. Kardjilov et al.

Nat. Phys. 4 (2008)



Magnetic moment





I. Manke et al.

Nat. Comm.

(2011)

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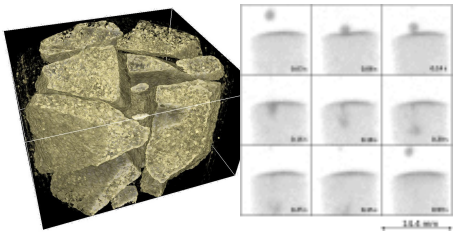
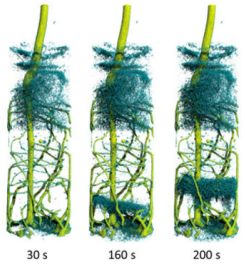
Neutron Imaging

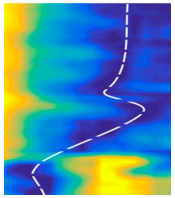
Imaging **2D** **3D** **4D+**

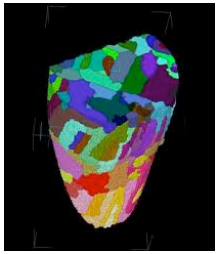
- attenuation

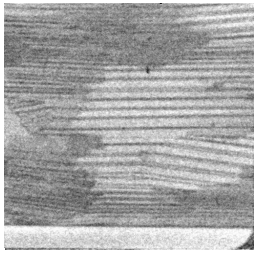




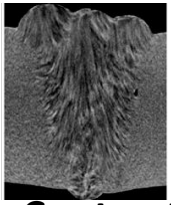
-Phase & Dark-field

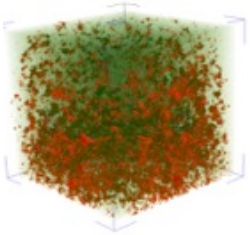


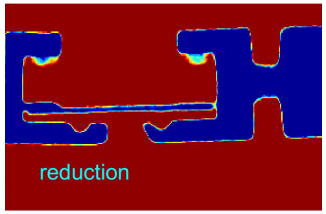


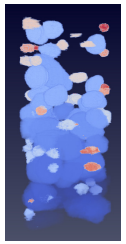


-Diffraction Contrast

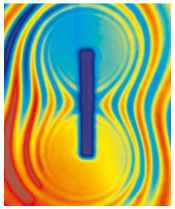


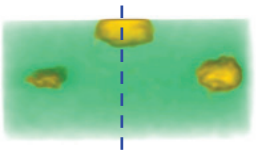


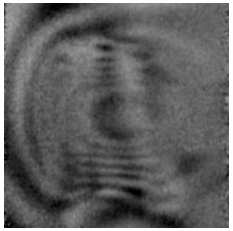


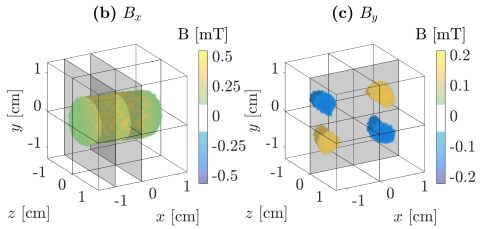


-Polarisation Contrast

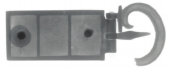


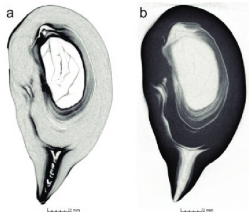


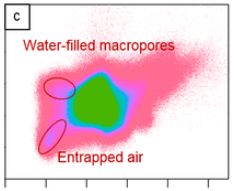


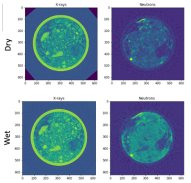


-Bi-modal









Thank you!

- Questions?