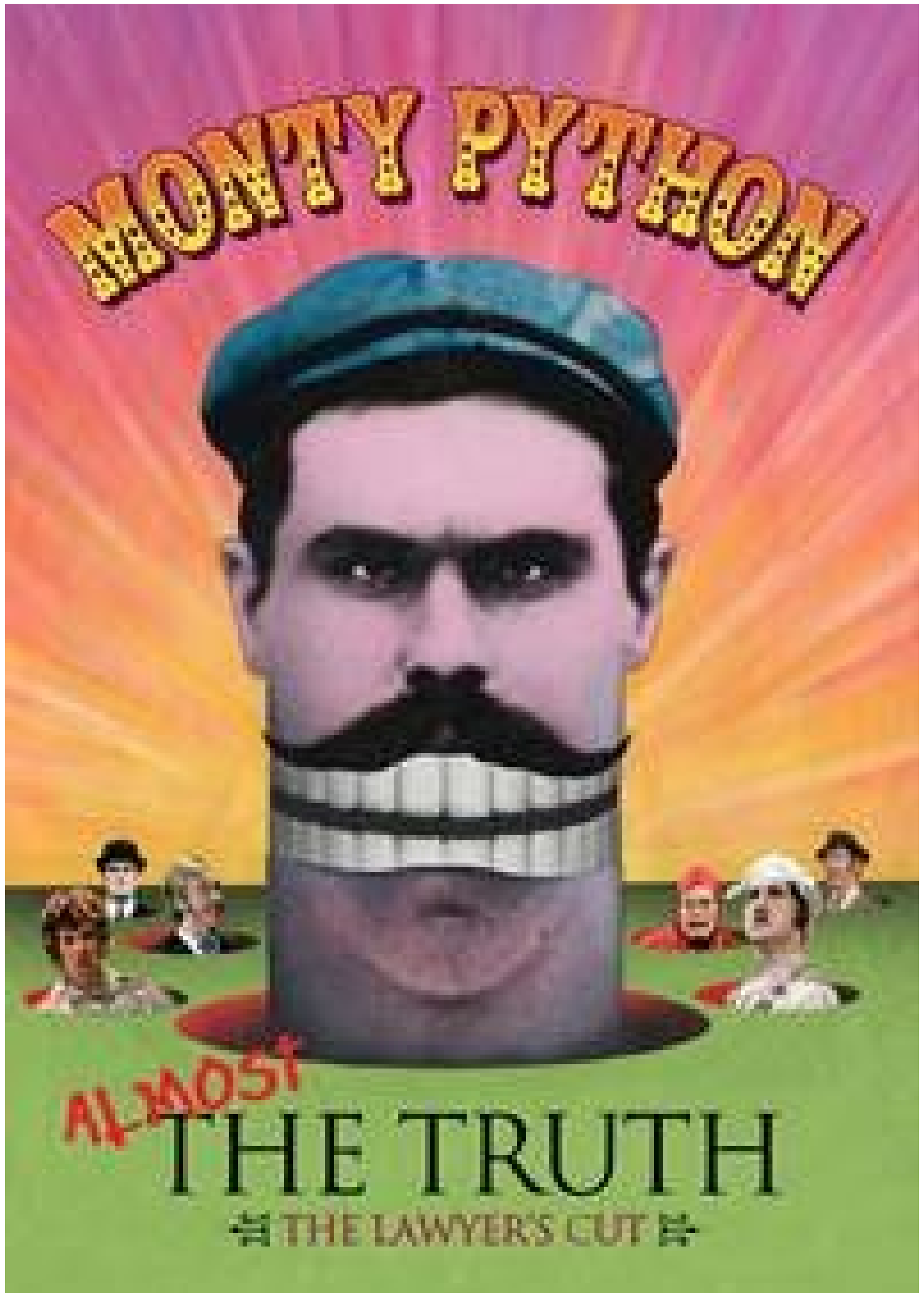
And now for something completely different.....?



neutron imaging

EUROPEAN SPALLATION SOURCE

Markus Strobl

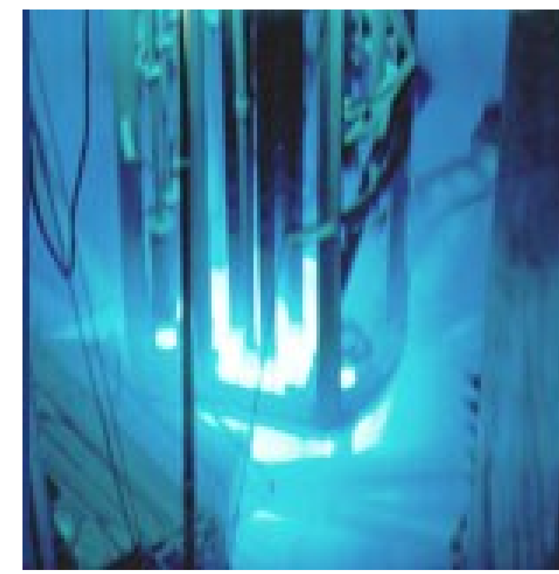
Instrumentation Division@ ESS

Vienna

ATOMINSTITUT

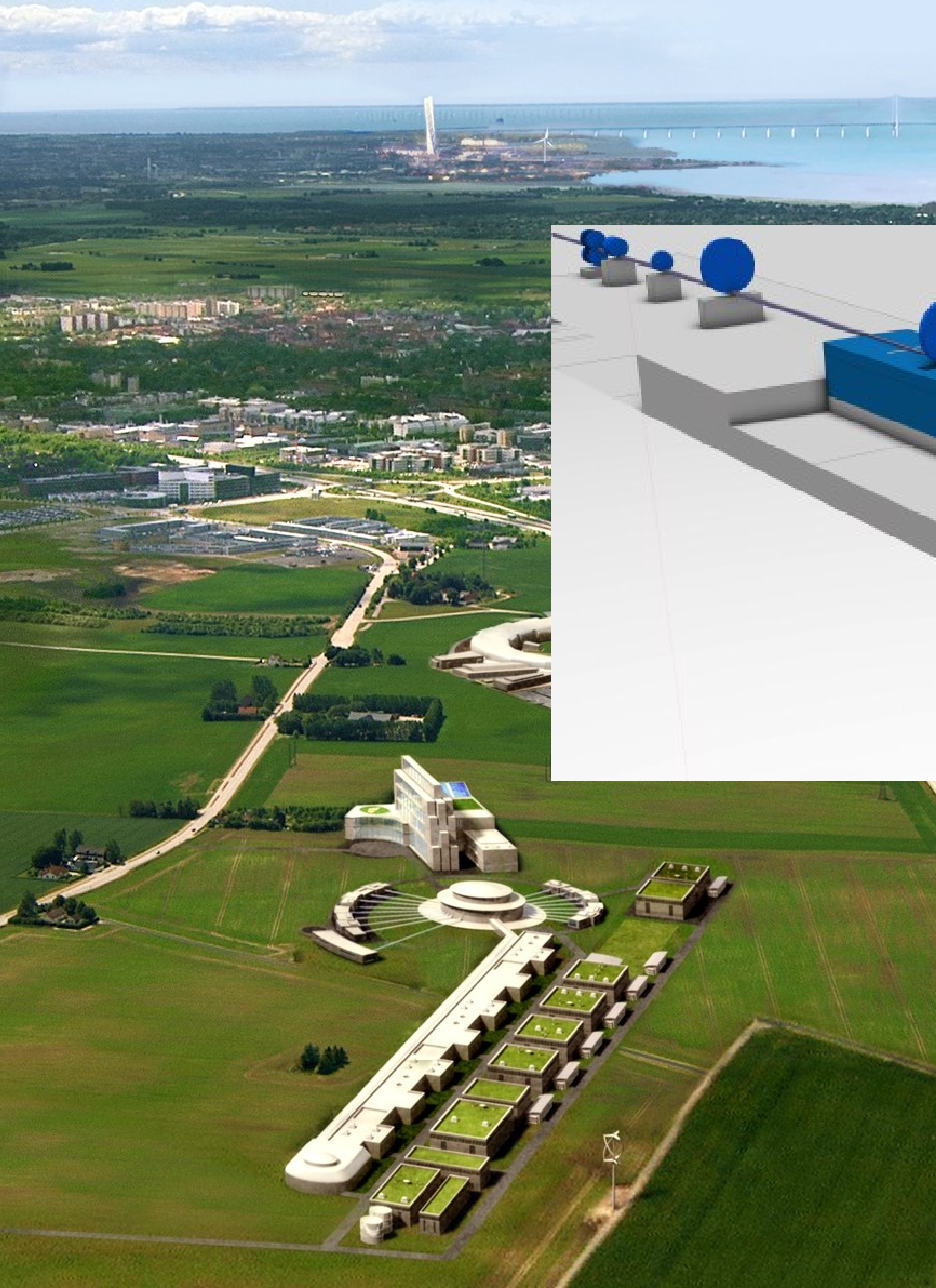
Berlin

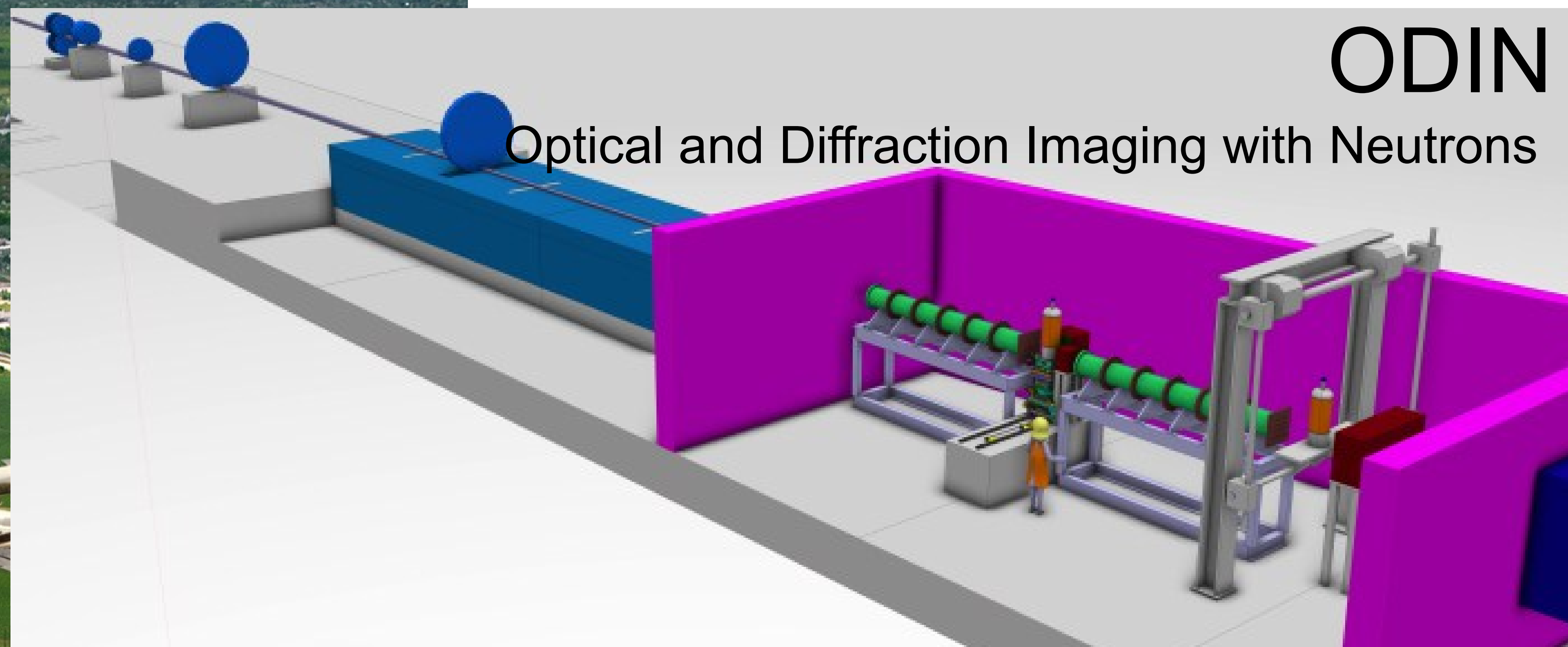
Helmholtz Zentrum



Lund
Copenhagen

ESS – future for neutron scattering in Europe





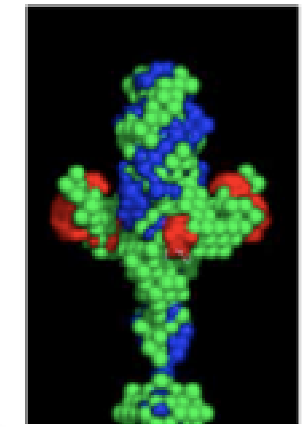
One out of the two first instruments endorsed by the ESS SAC for a build decision!

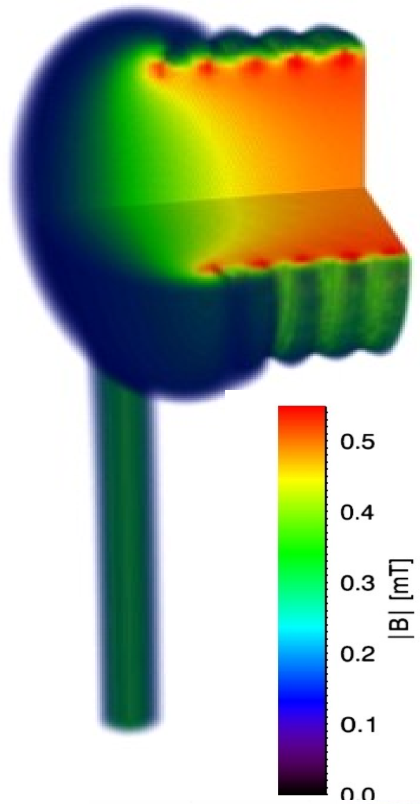
Is neutron imaging in fact just another scattering technique?

When do we talk about an image?

When about imaging?

images





0.5
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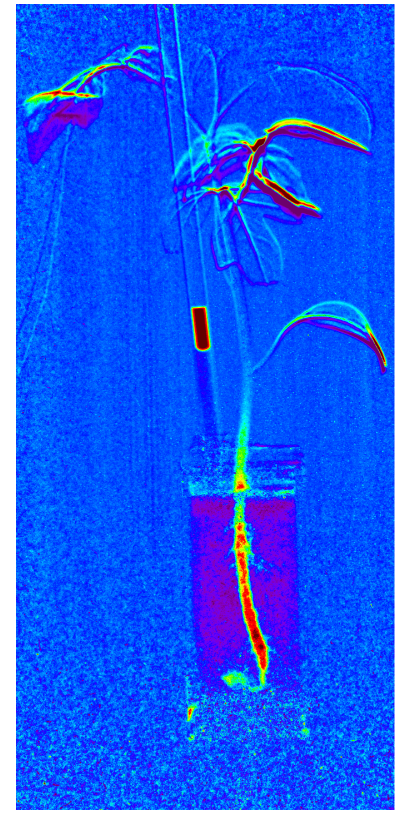
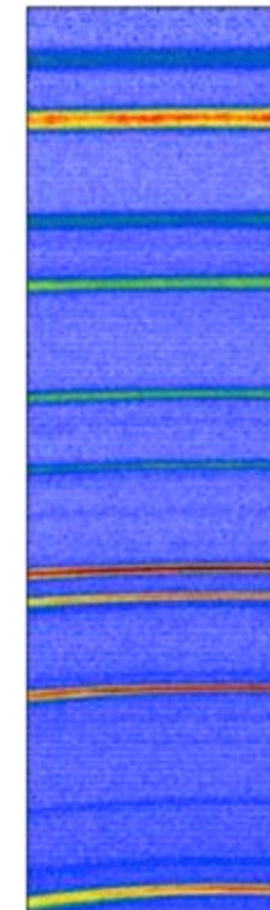
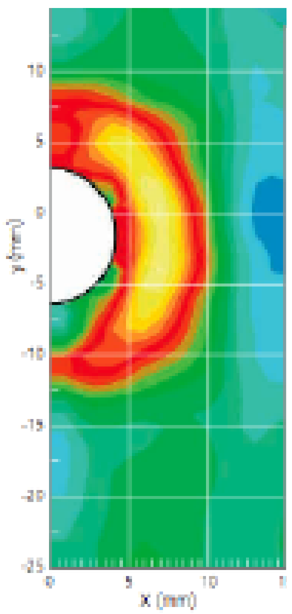
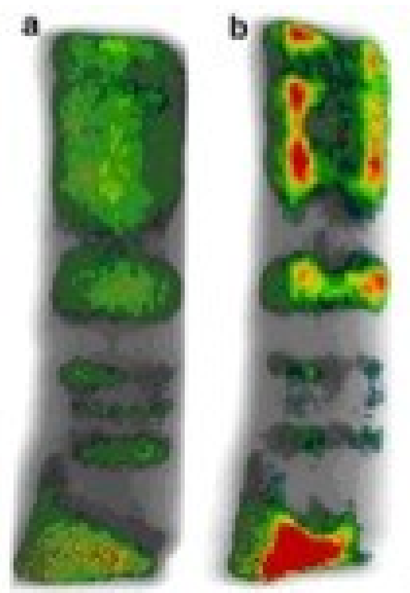
|B| [mT]

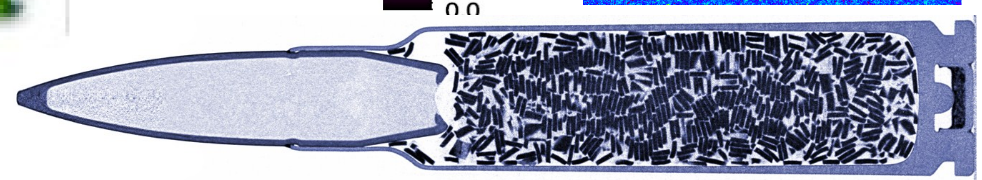


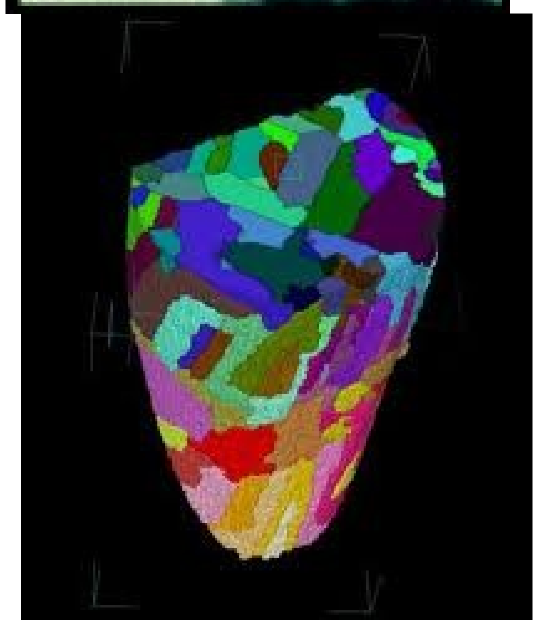




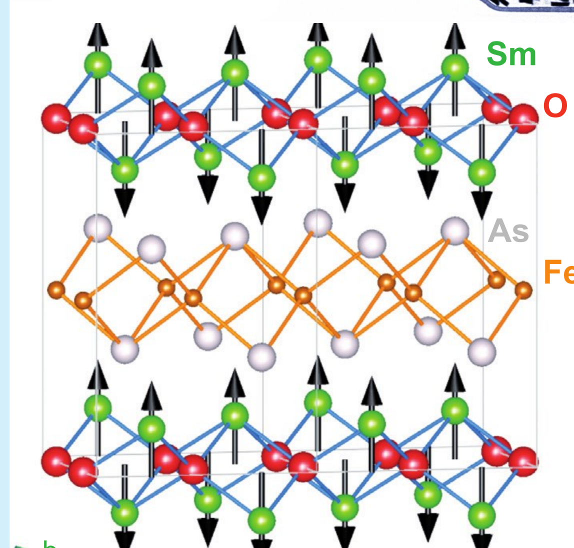


a
b

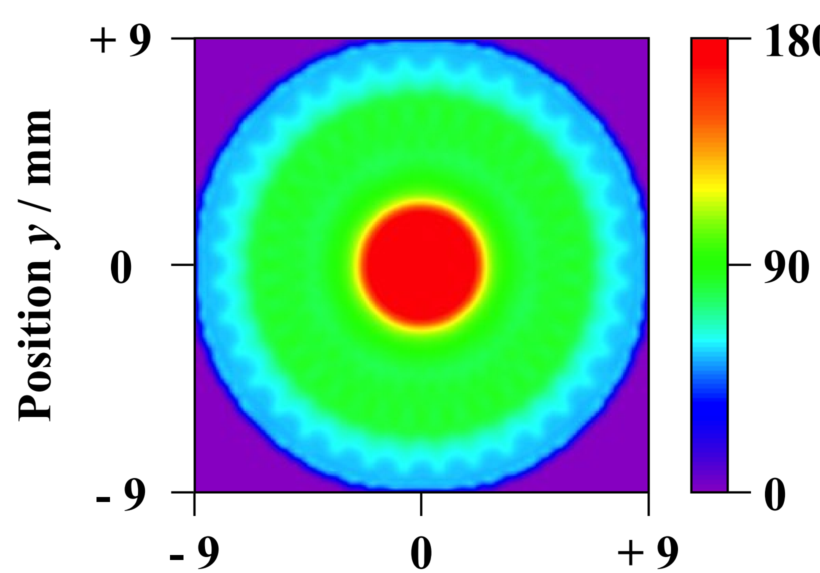




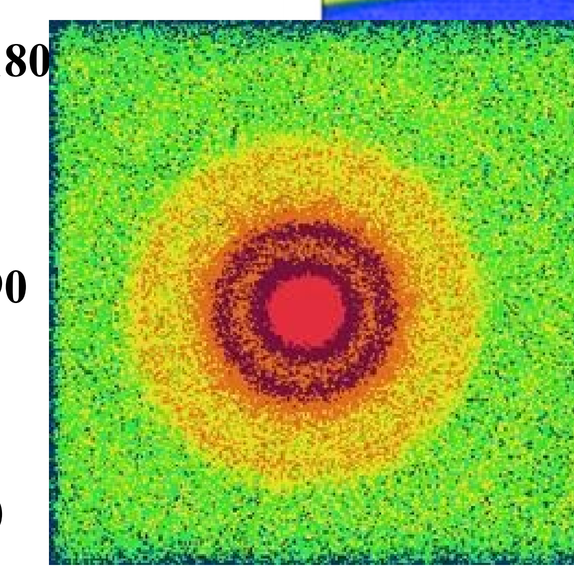
100 μm



Sm
O
As
Fe
b



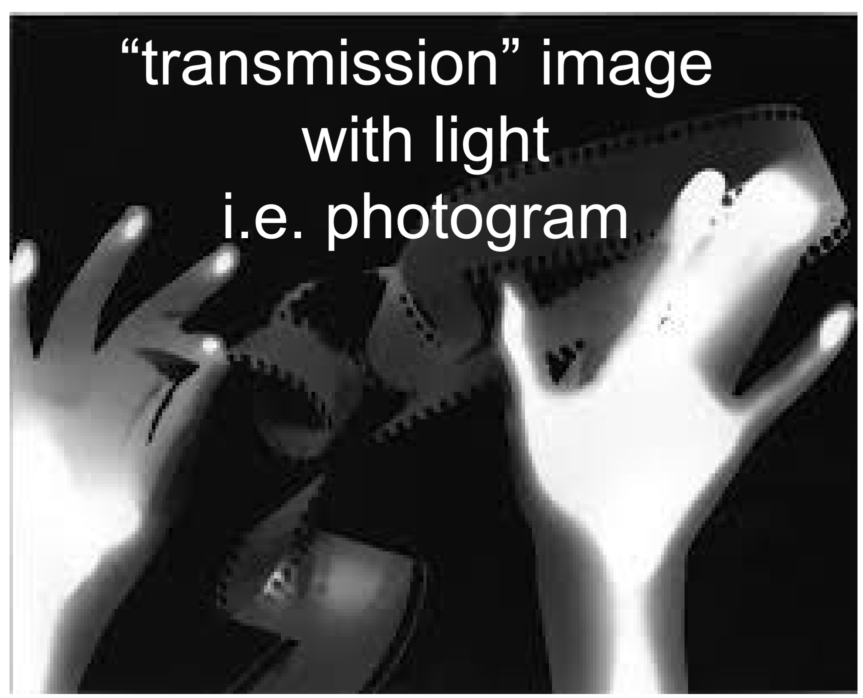
+ 9
0
- 9
Position y / mm
- 9
0
+ 9
180
90
0



images

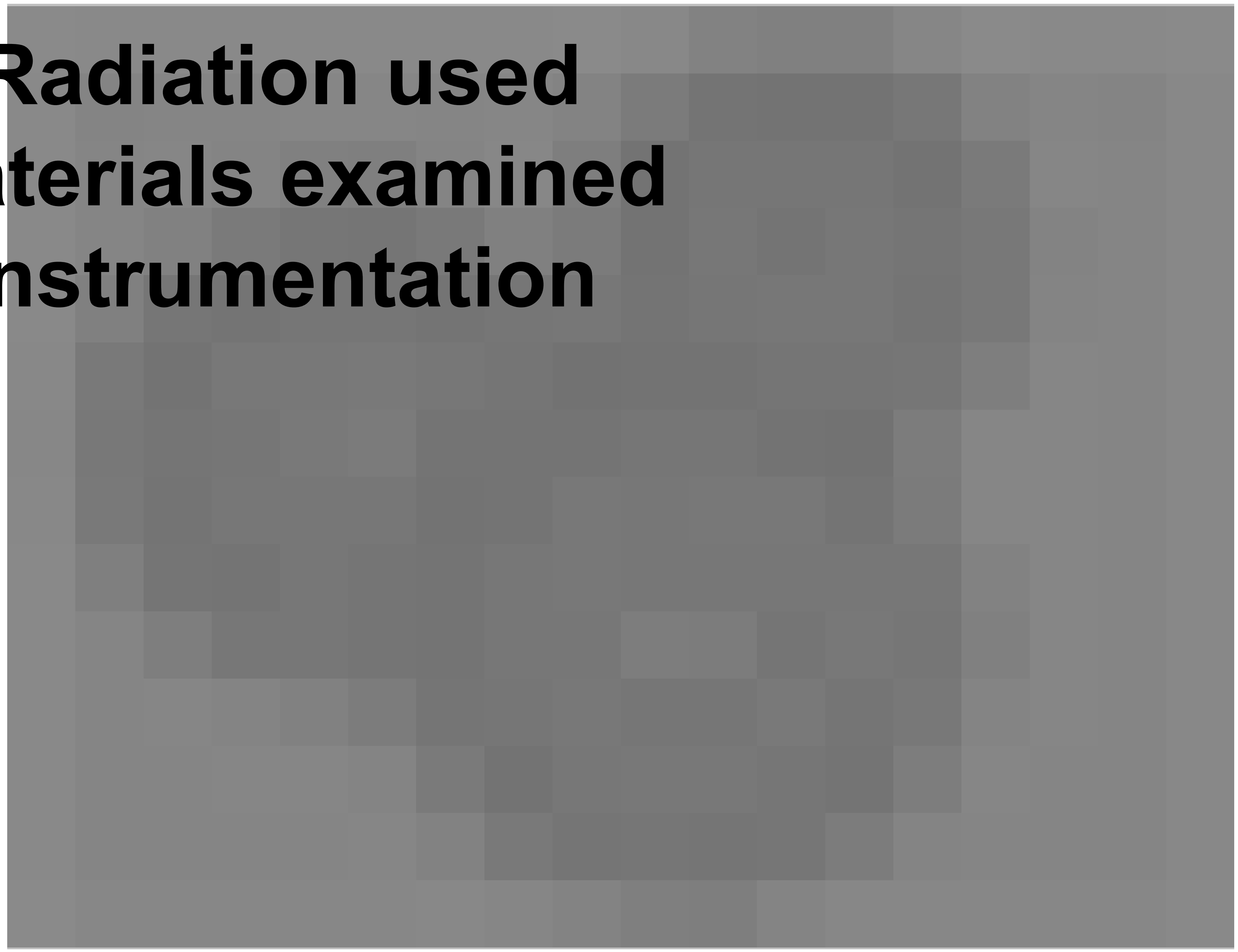
transmission

reflection



Contrast

- Radiation used
- Materials examined
- Instrumentation



Contrast

Transmission

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

- Cross sections:

Microscopic cross section: σ

$$\frac{d\sigma}{d\Omega} = \frac{\text{number of interacting particles / unit time} \cdot \text{unit cone } d\Omega}{\text{number of incident particles / unit time x unit area} \cdot \text{unit cone } d\Omega} = [\text{area}]$$

Unit of σ : 1 barn $= 10^{-24}$ cm^2

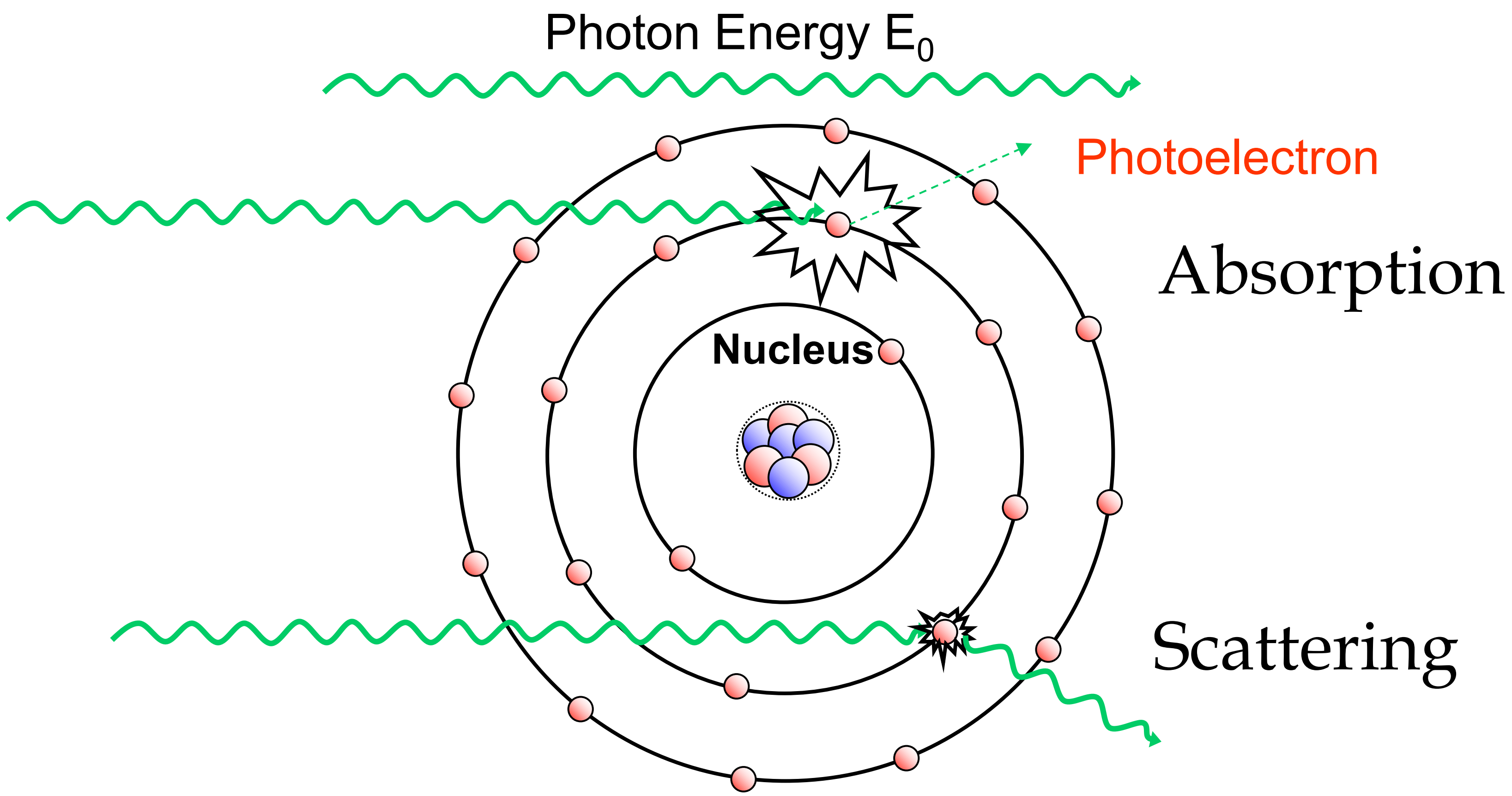
Macroscopic cross section : Σ (i.e. μ linear attenuation coefficient)

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

Unit of Σ is [cm^{-1}].

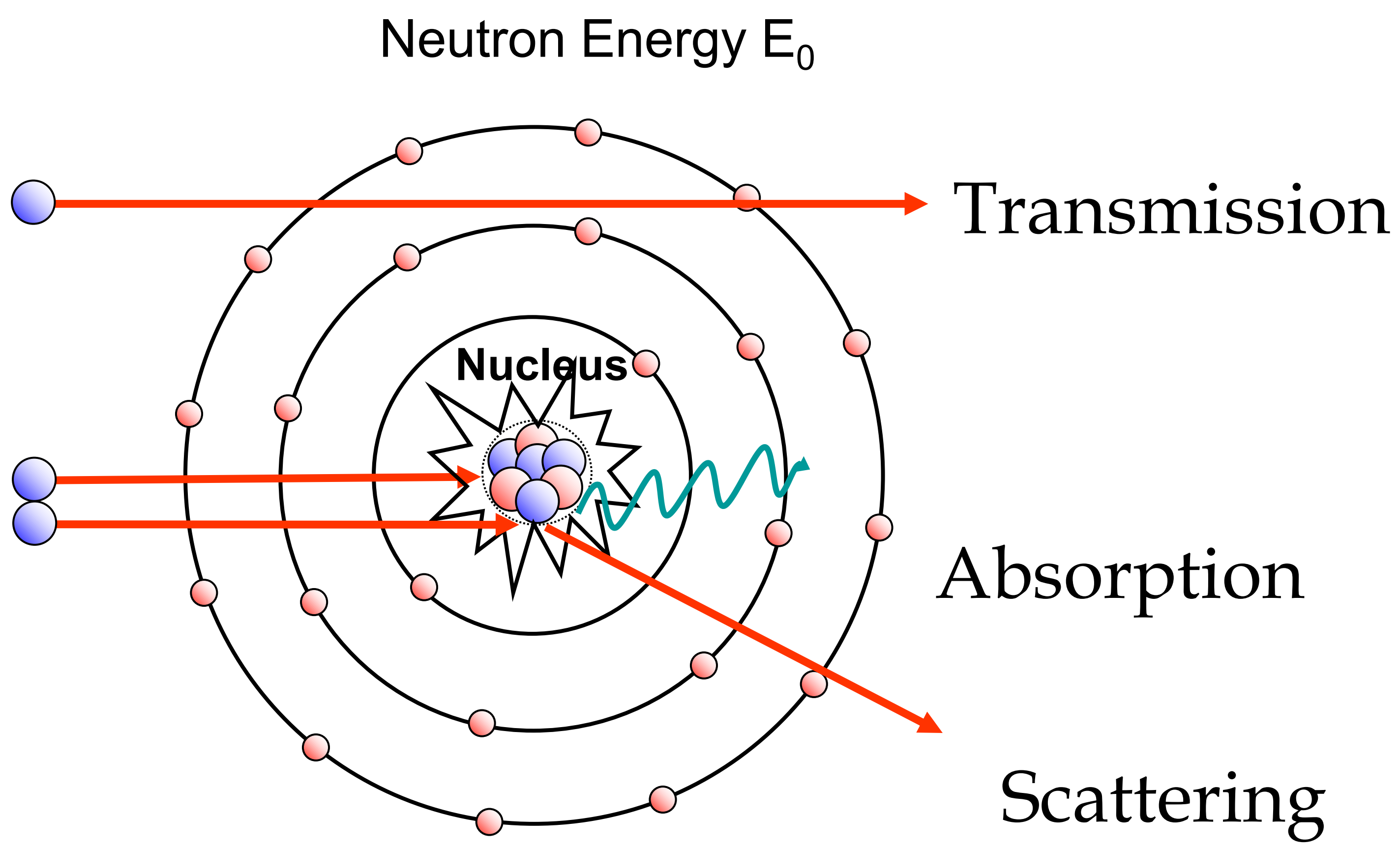
Contrast

X-ray interaction with matter

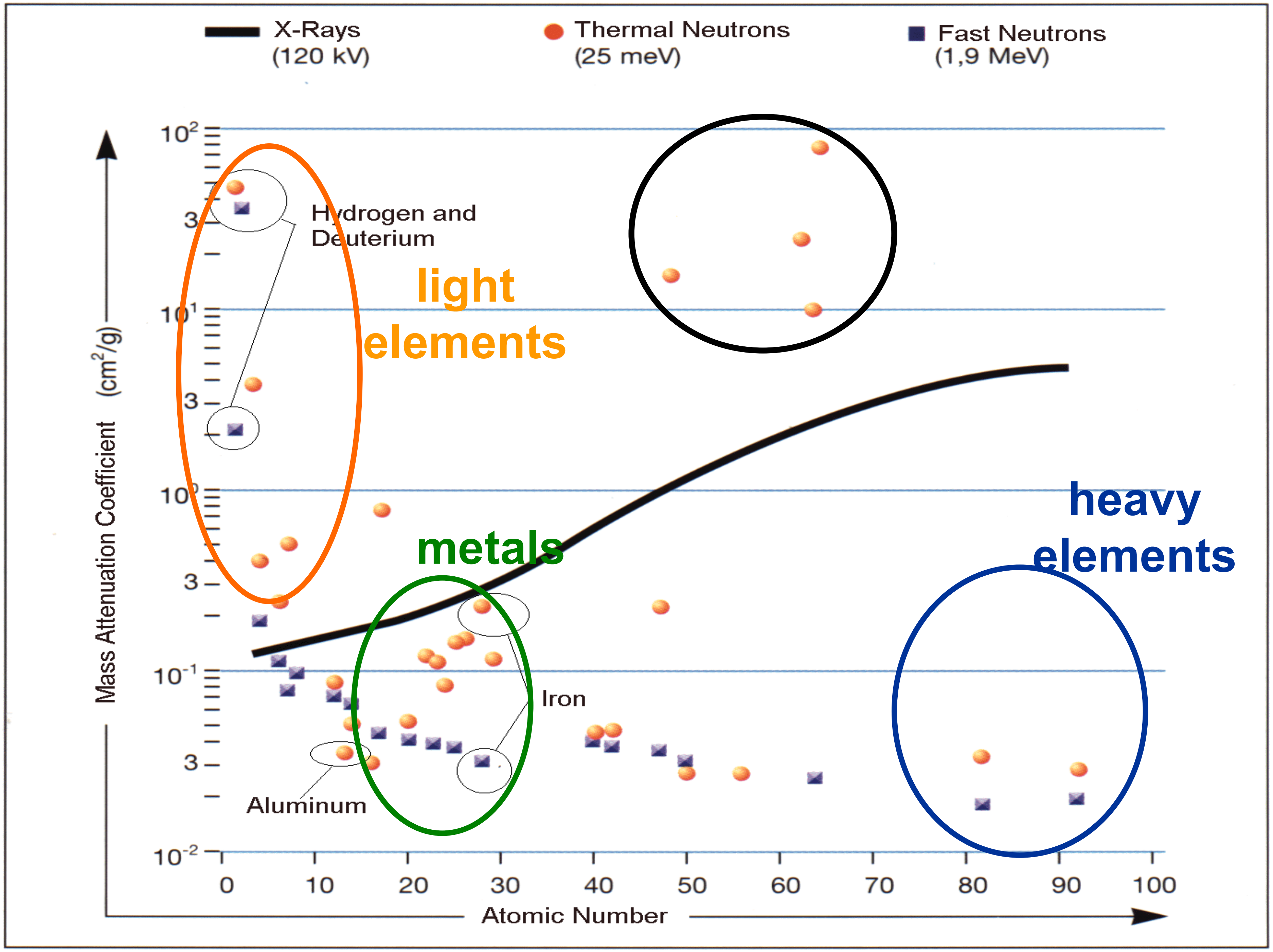


Contrast

neutron interaction with matter



Contrast

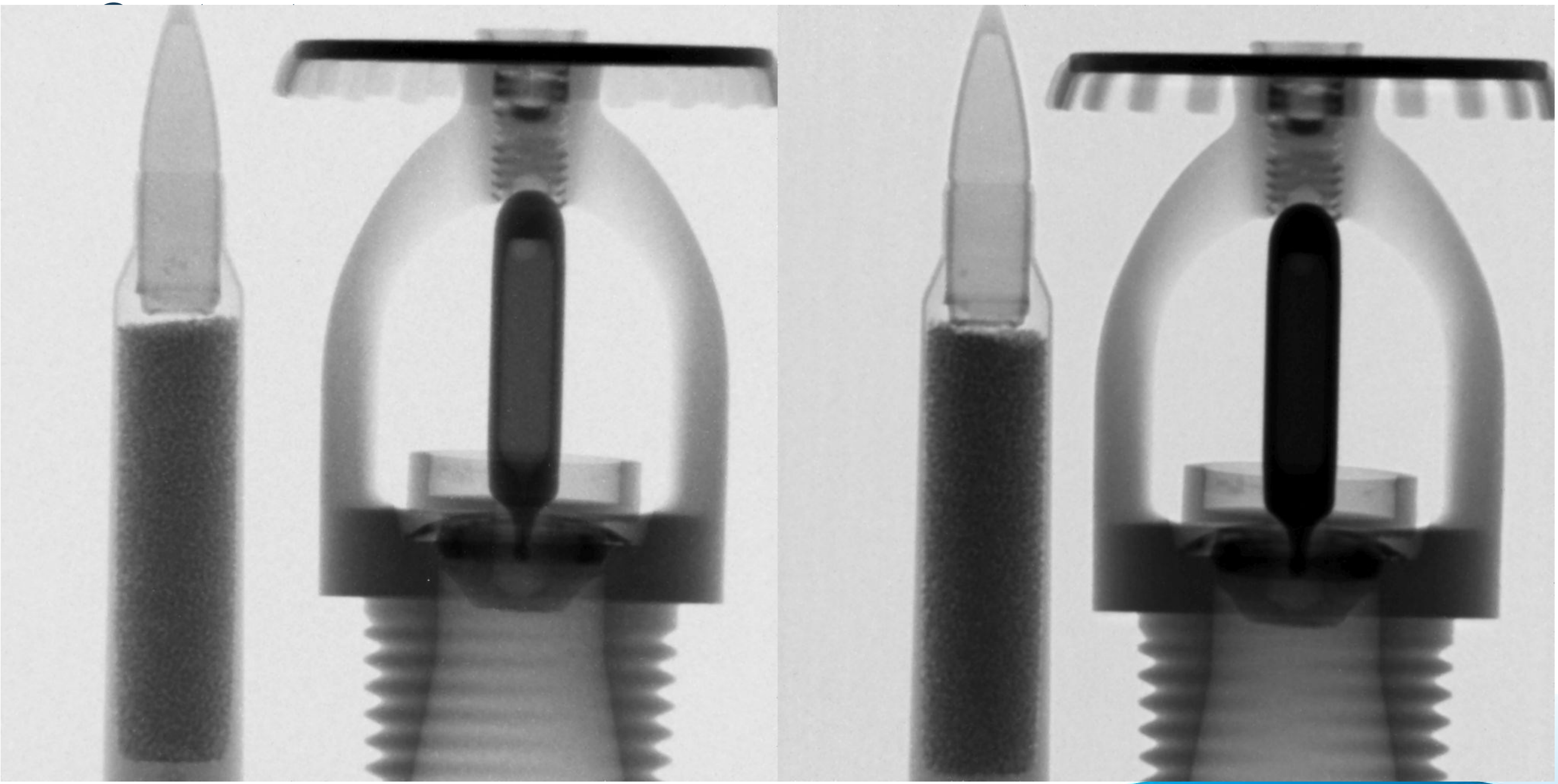


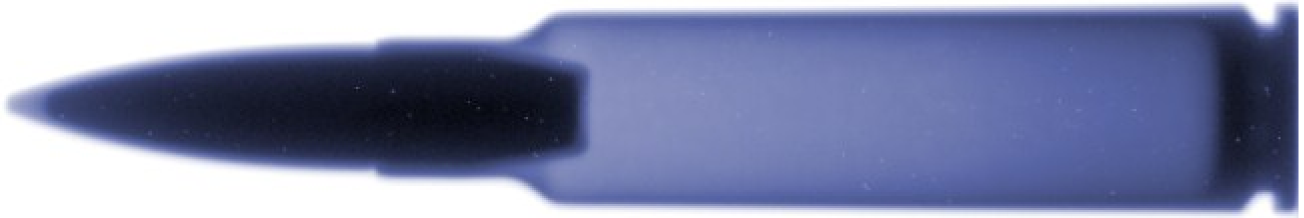
X-Rays (120 kV)
Thermal Neutrons (25 meV)
Fast Neutrons (1,9 MeV)
Mass Attenuation Coefficient (cm²/g)
Atomic Number
Hydrogen and Deuterium
Aluminum
Iron
light elements
metals
heavy elements

Contrast

Thermal neutrons

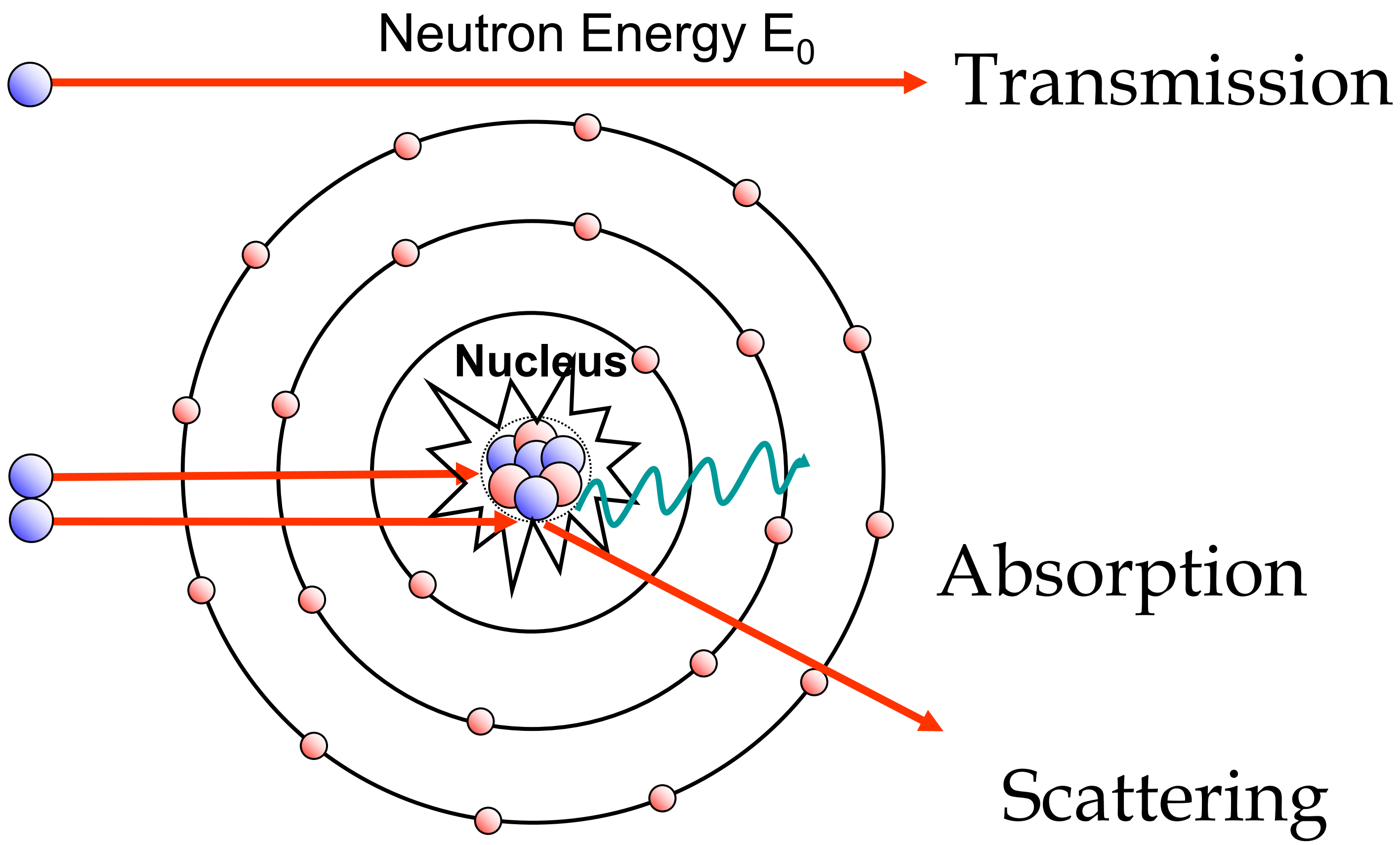
Cold neutrons

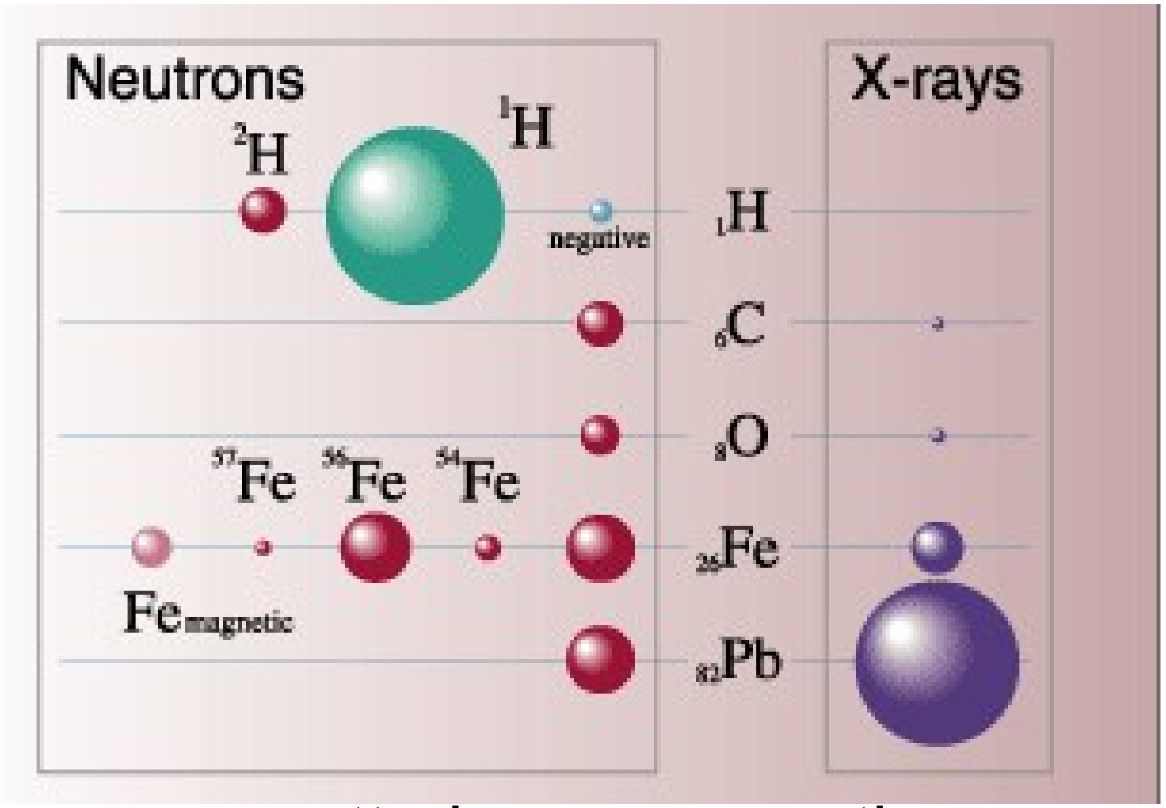




X-ray

Contrast

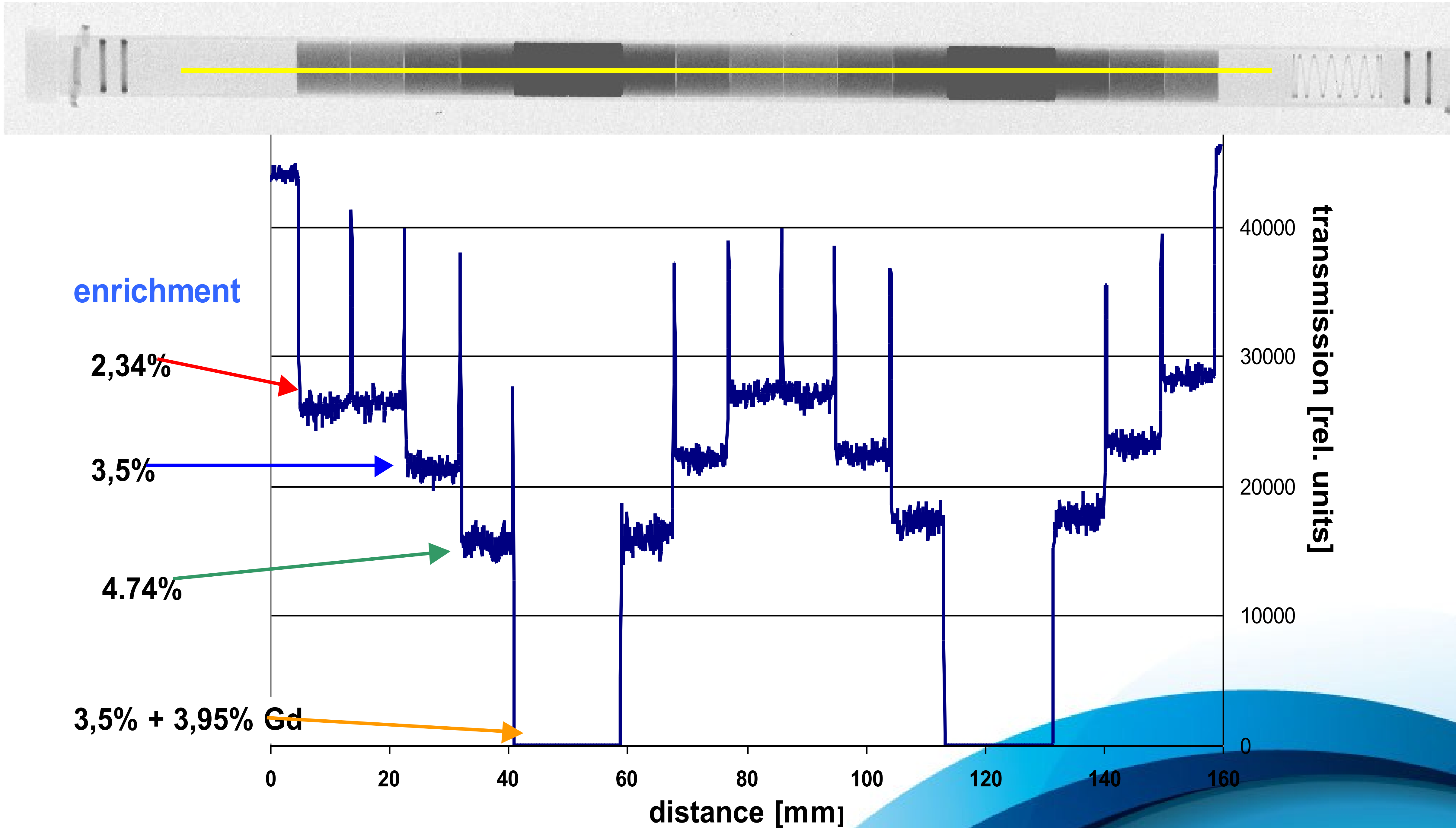




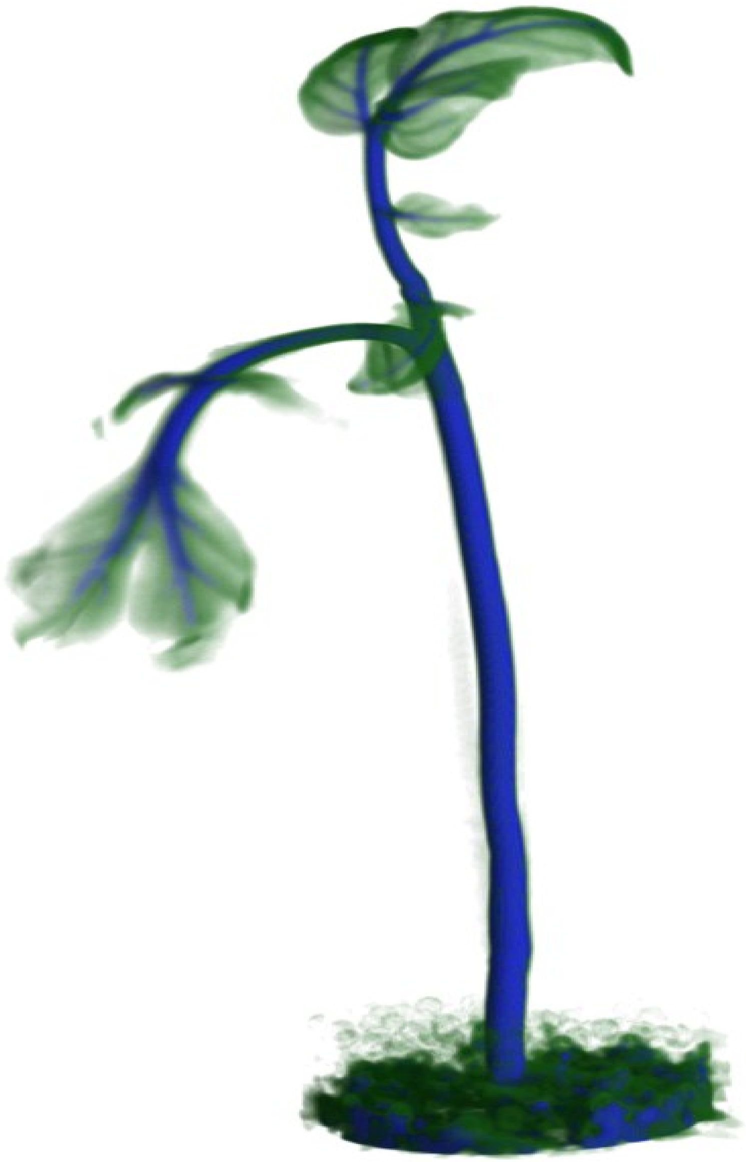
scattering cross sections

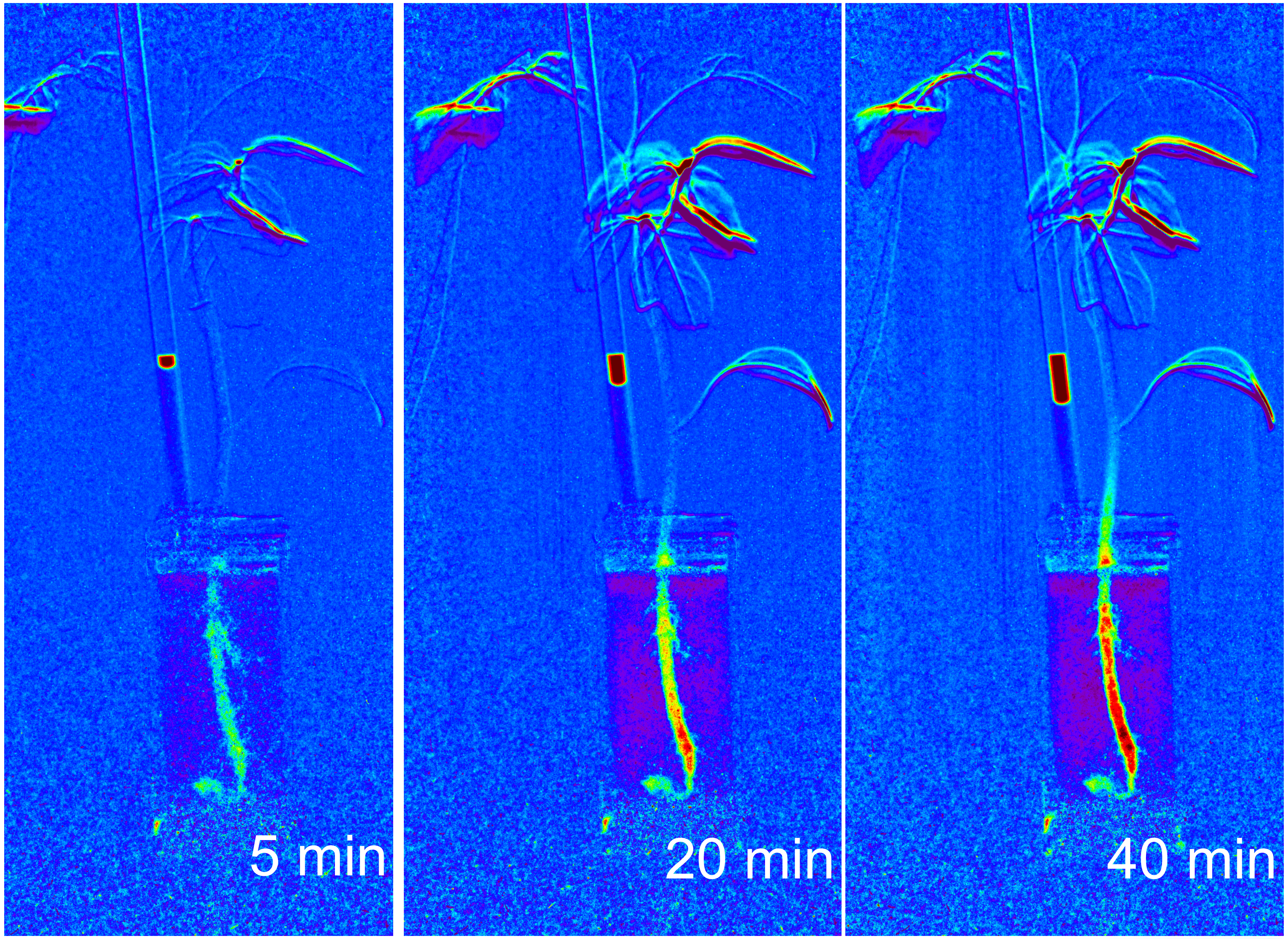
Contrast

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



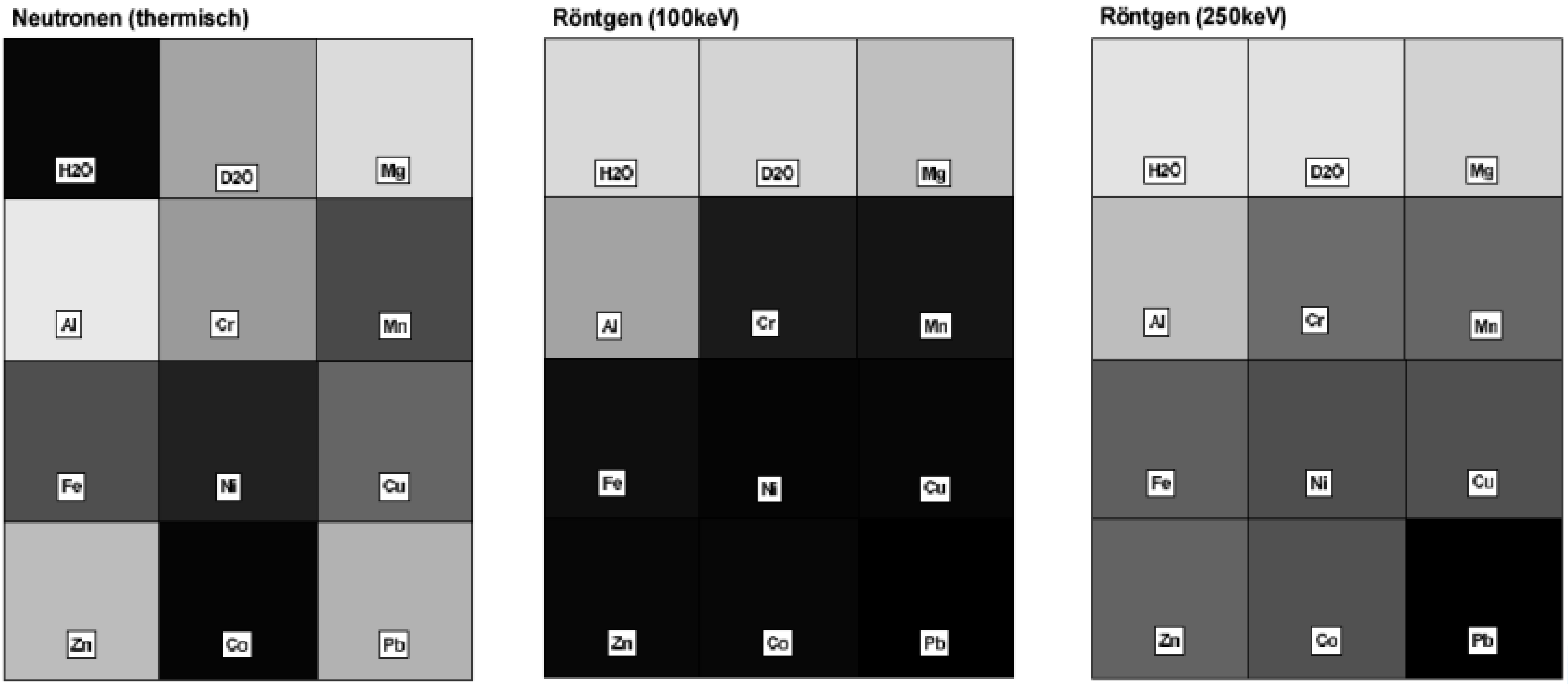
Contrast





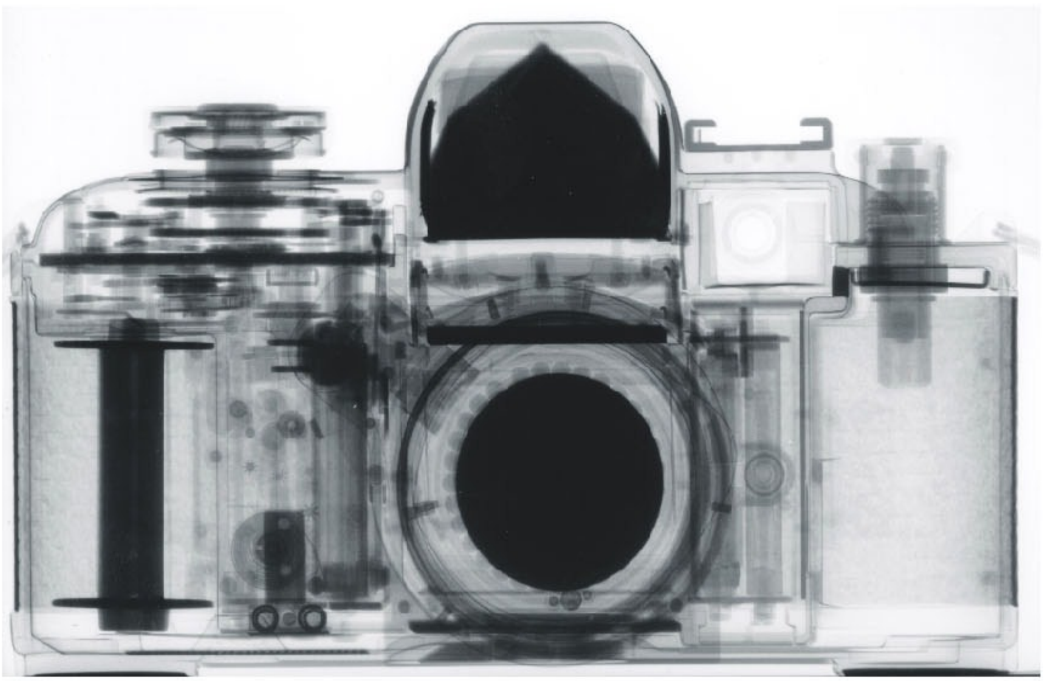
H_2O / D_2O

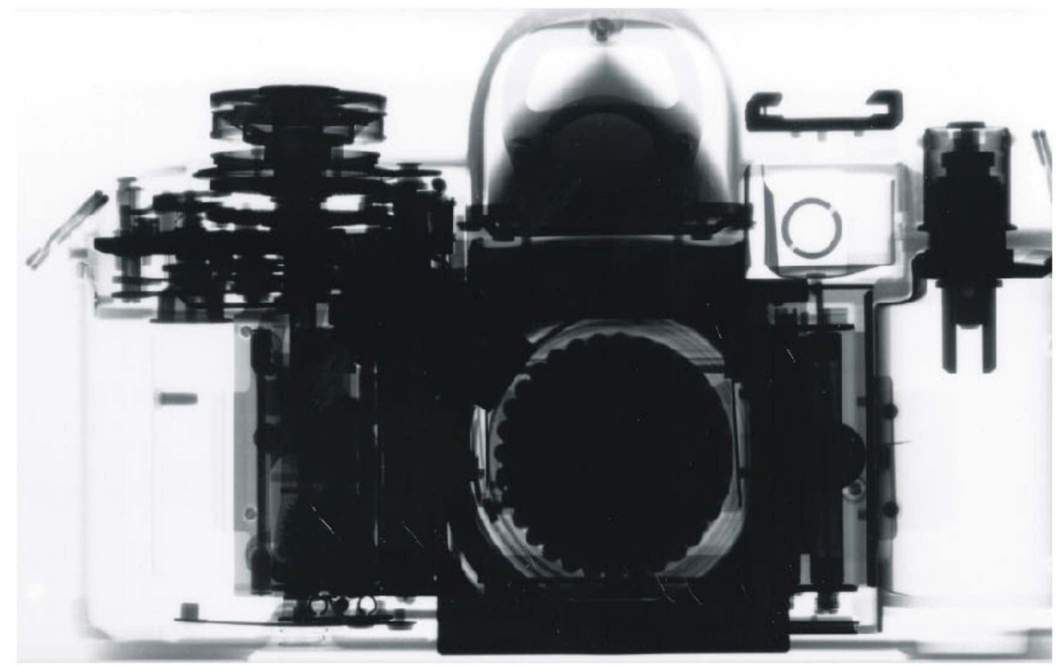
Contrast



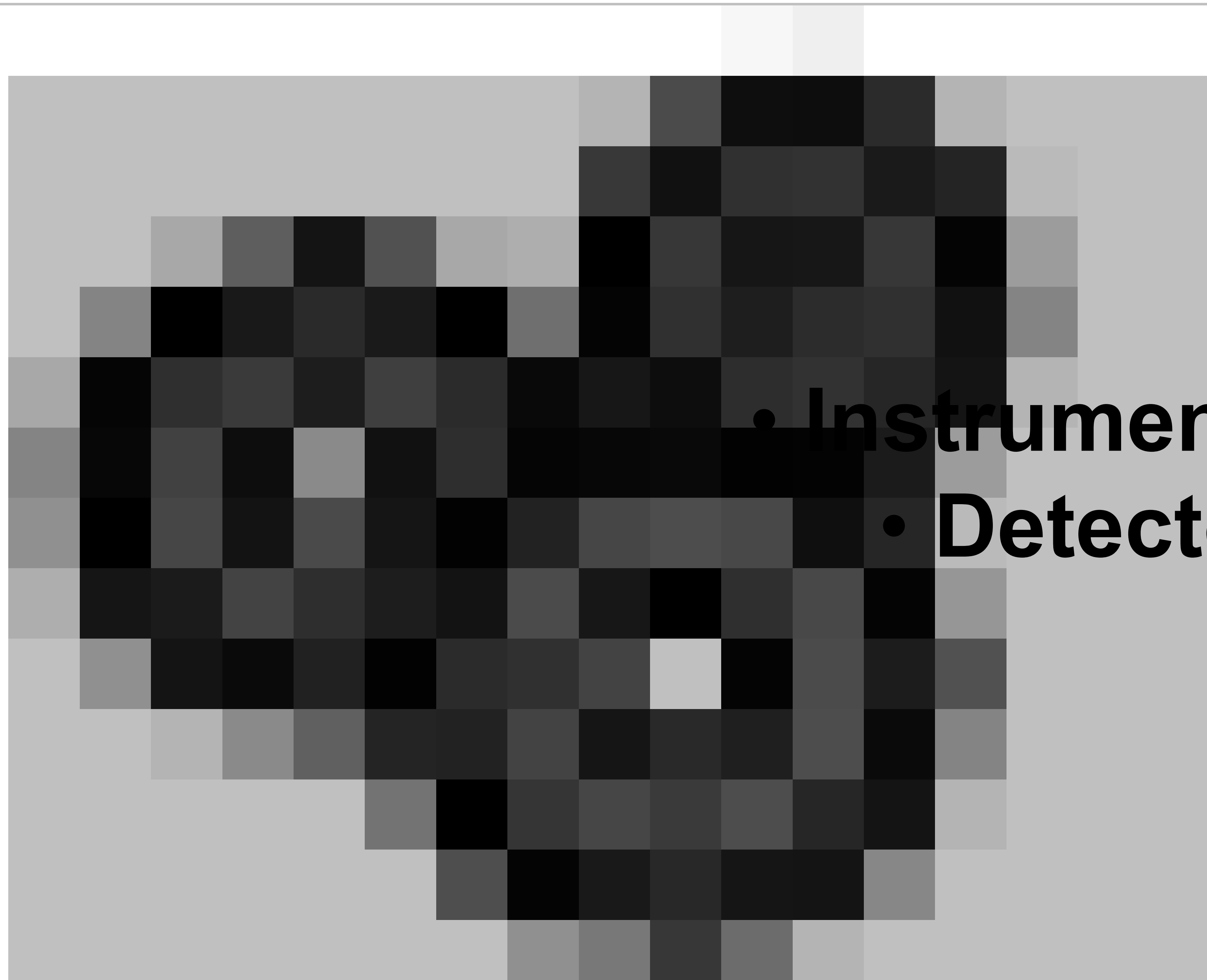
Neutronen (thermisch)
H2O
D2O
Mg
Al
Cr
Mn
Fe
Ni
Cu
Zn
Co
Pb
Röntgen (100keV)
H2O
D2O
Mg
Al
Cr
Mn
Fe
Ni
Cu
Zn
Co
Pb
Röntgen (250keV)
H2O
D2O
Mg
Al
Cr
Mn
Fe
Ni
Cu
Zn
Co
Pb

Contrast





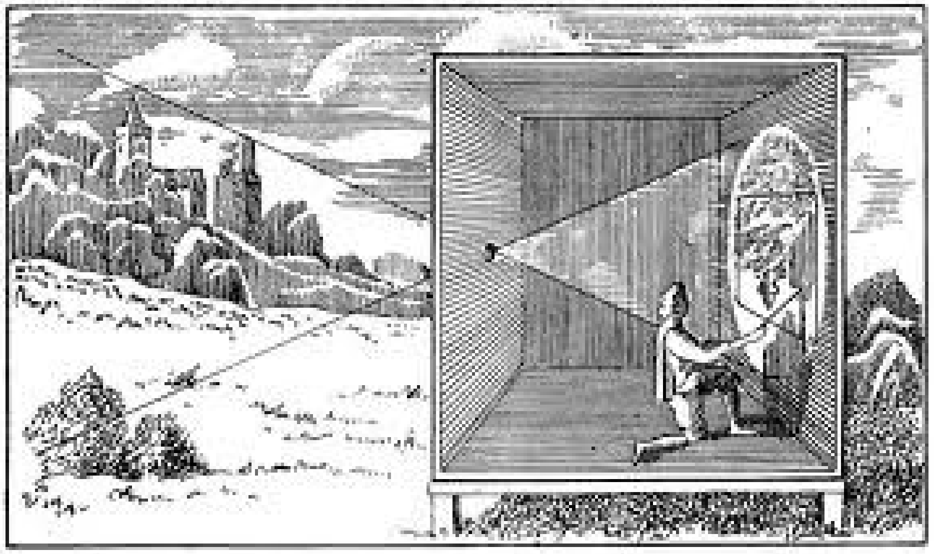
Contrast Resolution



- Instrumentation
  - Detectors

images

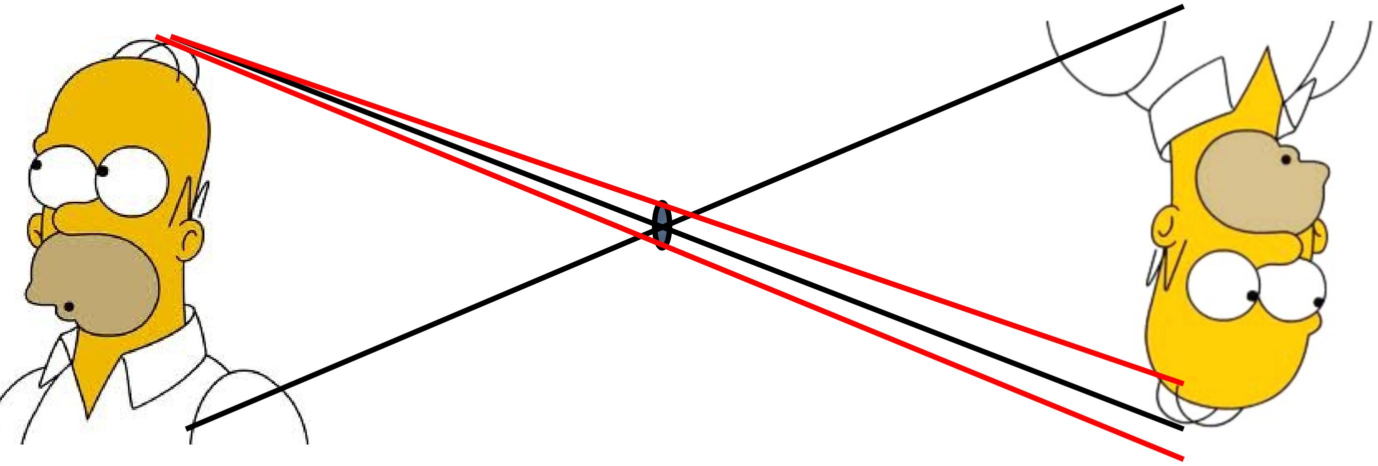
No optics

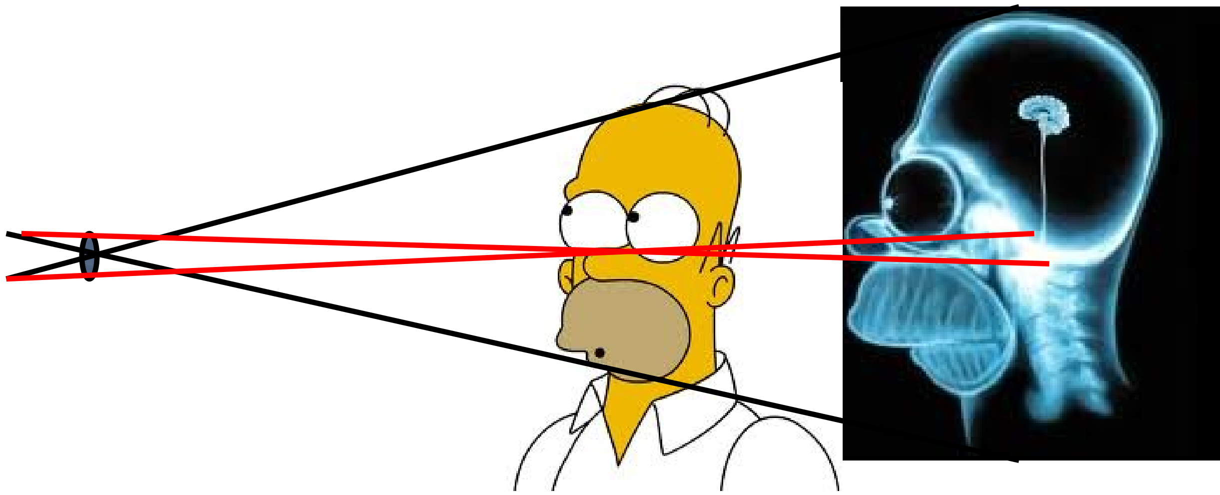


Camera obscura

images

No optics

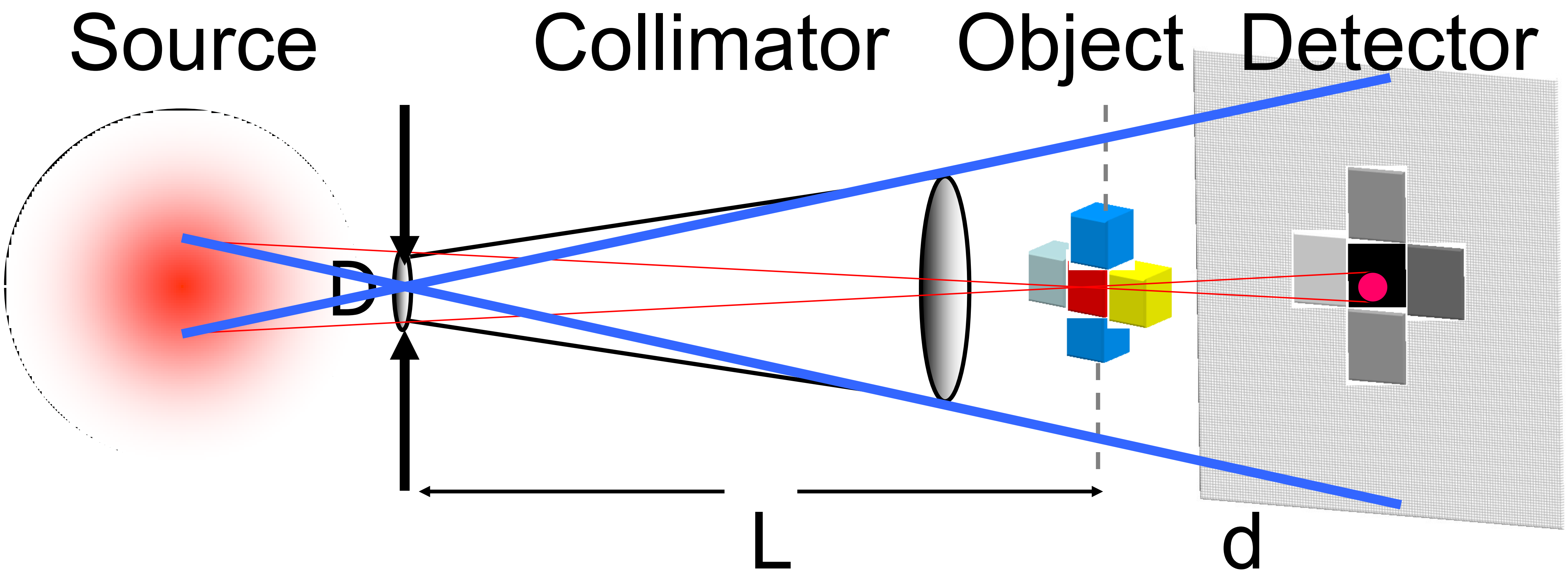




But spatial resolution!

Clearly a condition for imaging!

Resolution



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

collimation ratio L/D typical: several 100

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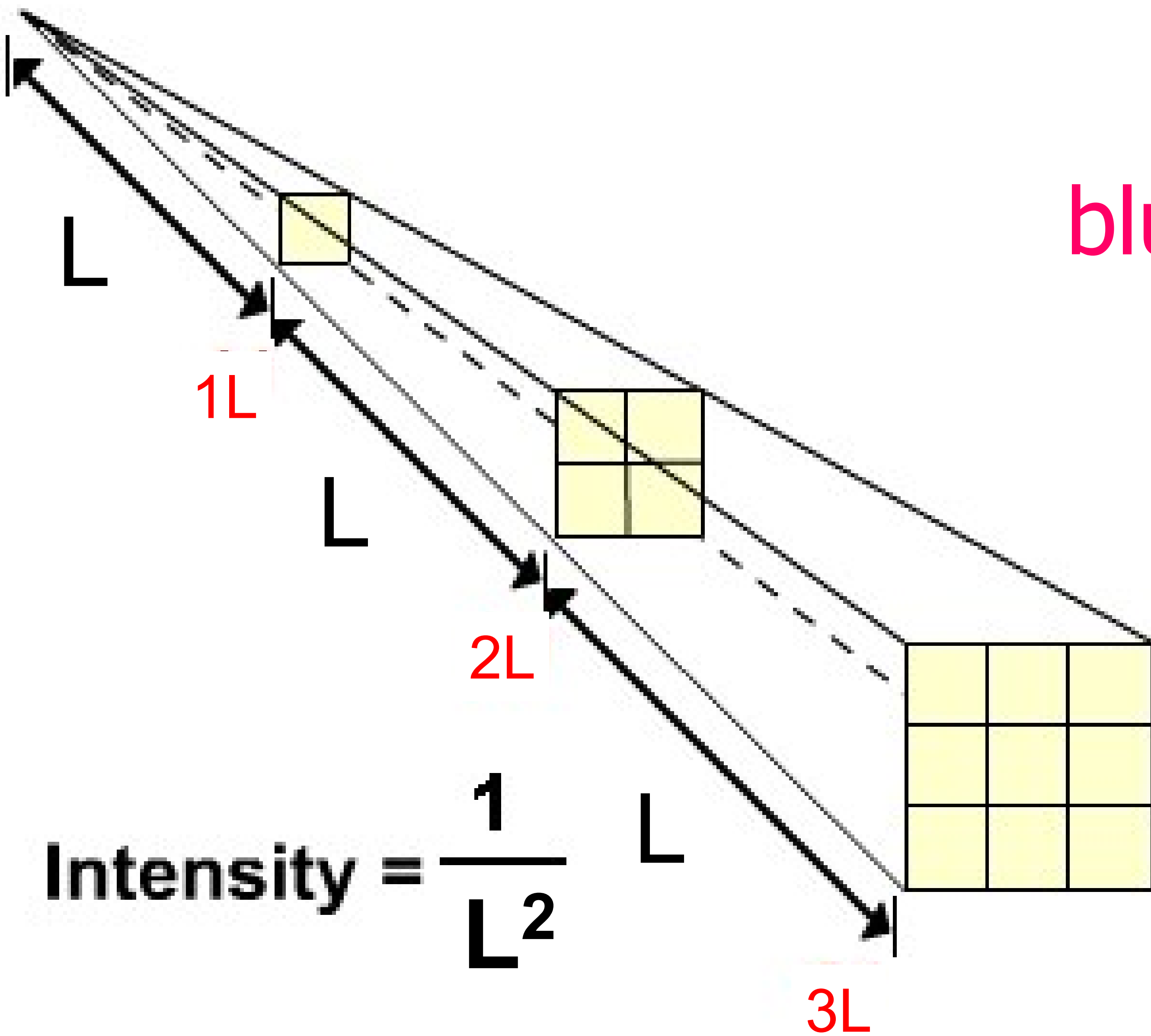
Resolution

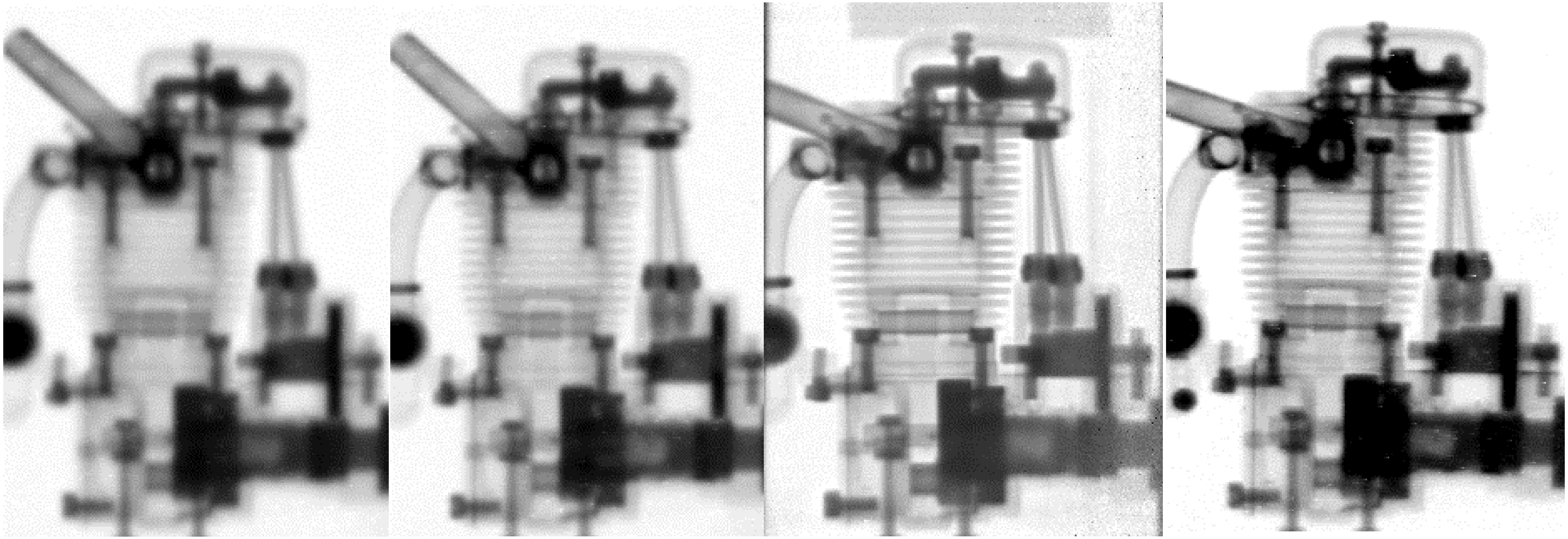
flux limitations $10^9\ cm^{-2}s^{-1}$

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



$$\text{Intensity} = \frac{1}{L^2}$$

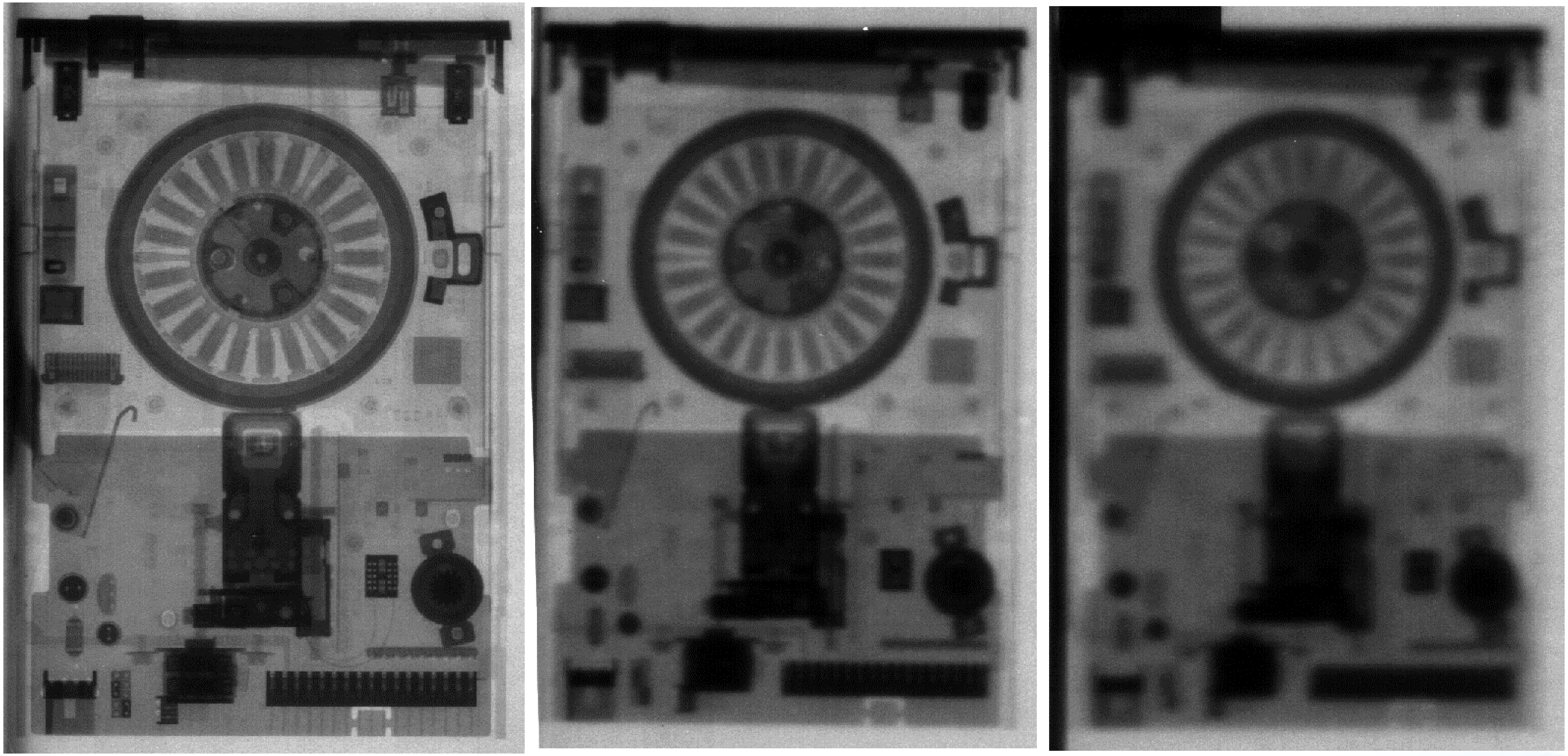
Resolution



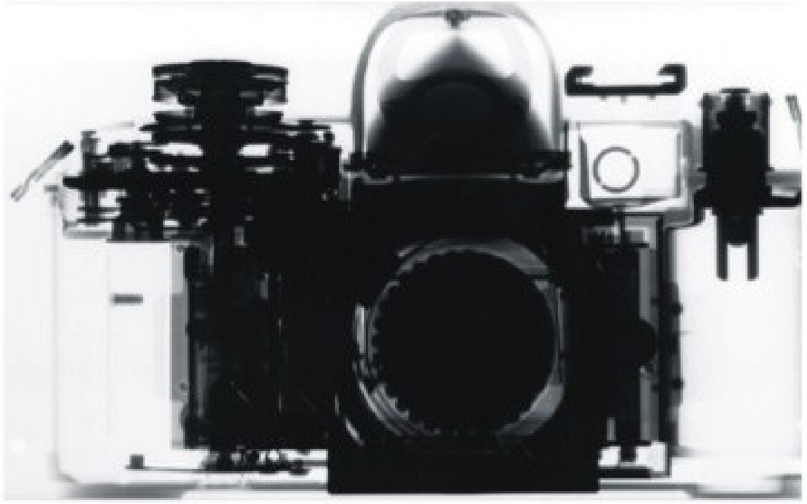
L/D=71 L/D=115 L/D=320 L/D>500.

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

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.

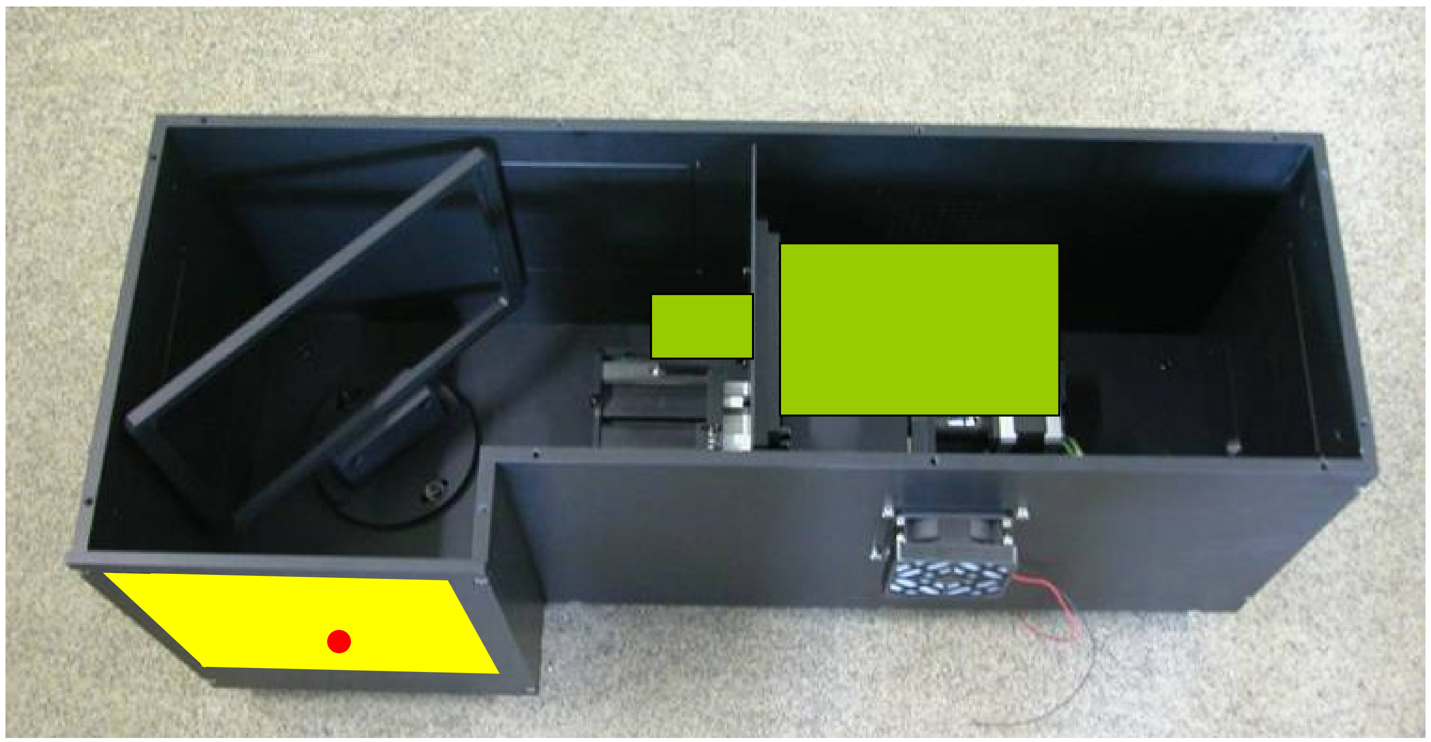


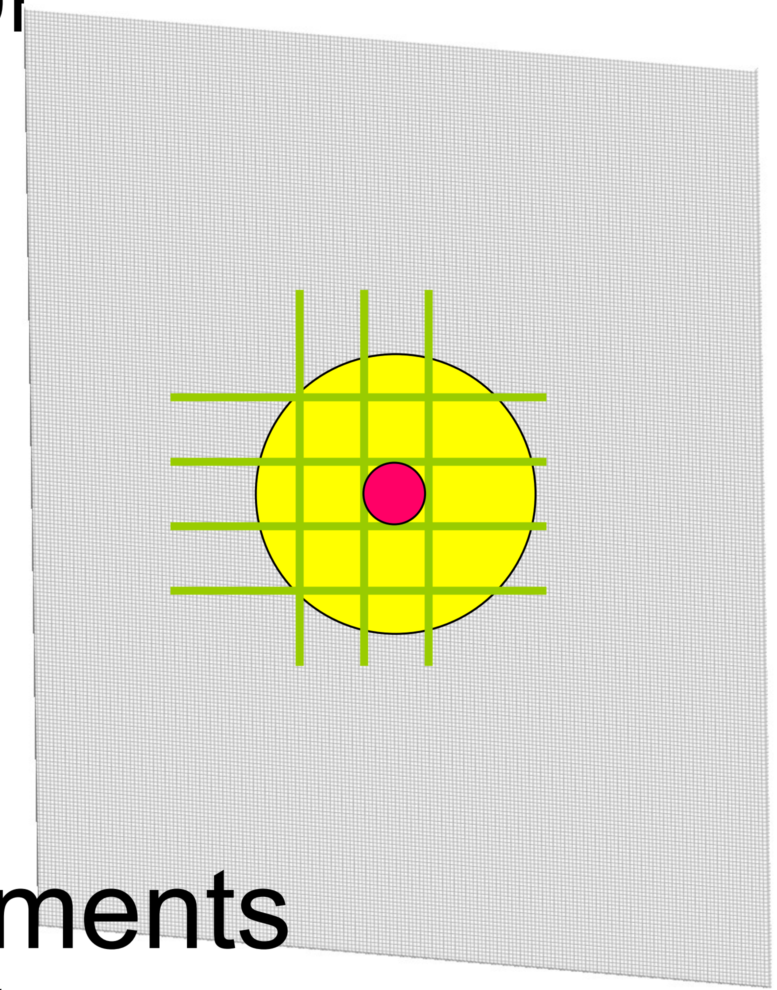
images

Detection?
No optics

Resolution

Detector





recent developments

LiF-ZnS/Ag

PSI: development of advanced scintillators → ≅ 30 µm

HZB: adapting X-ray scintillators (GADOX) → ≅15 µm

GADOX

NIST (UCLA, Nova Scientific Inc.): MCP-detectors → ≅ 13 µm

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

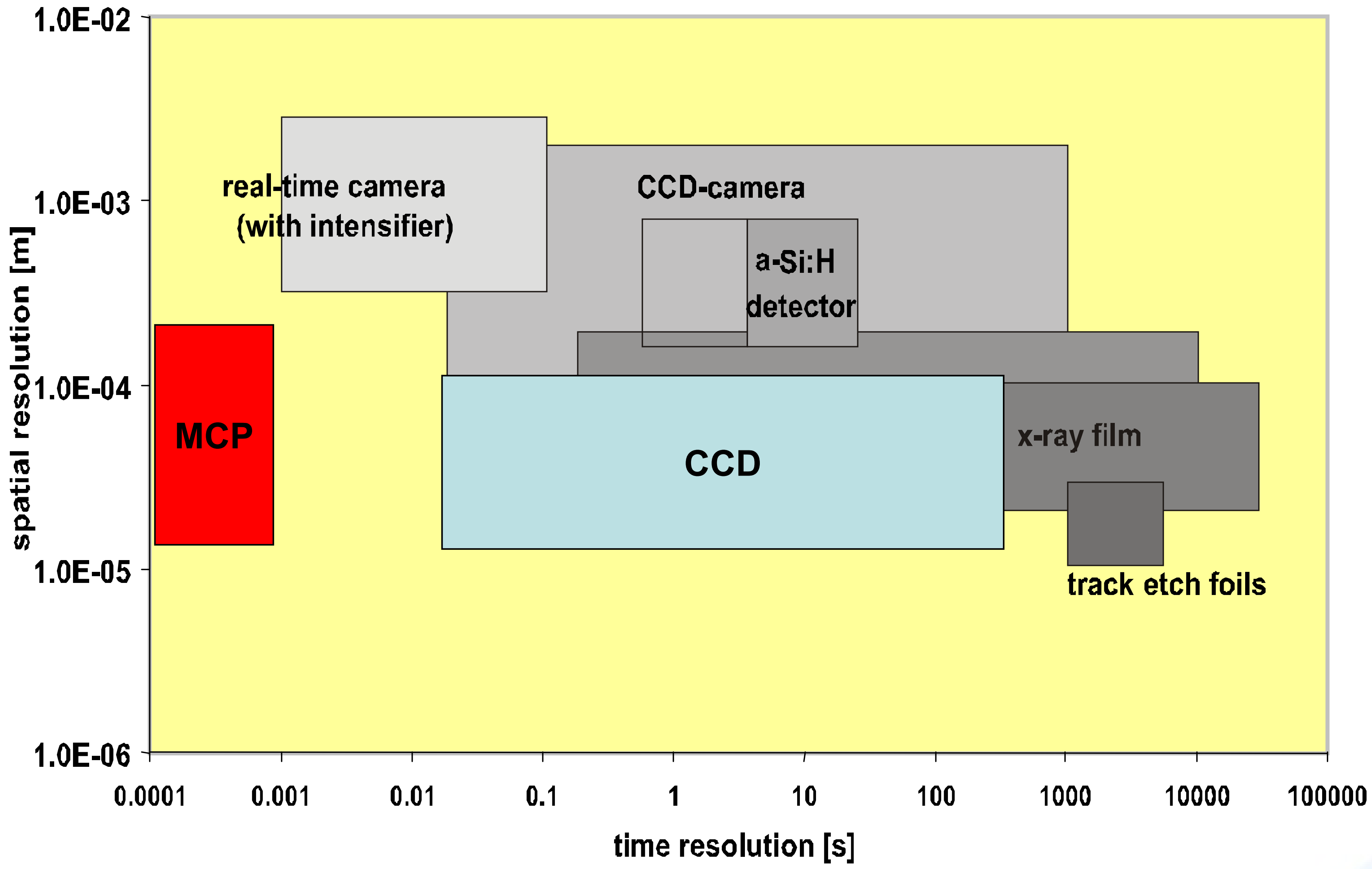
$^{155}Gd + {}^{1}n \Rightarrow {}^{156}Gd + \gamma$'s + CE's (7.9 MeV)

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

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

Resolution

Imaging Detectors



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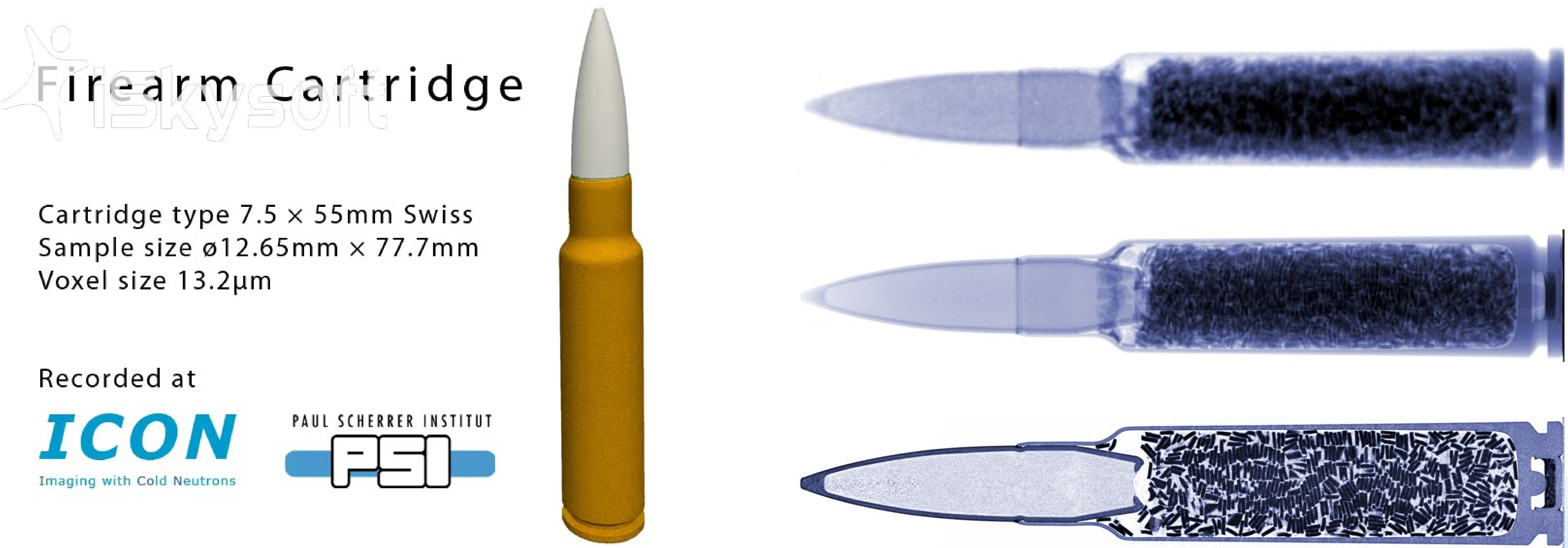
Resolution of DIGITAL detectors

Routine resolution today 50 µm

Best today **<15µm**

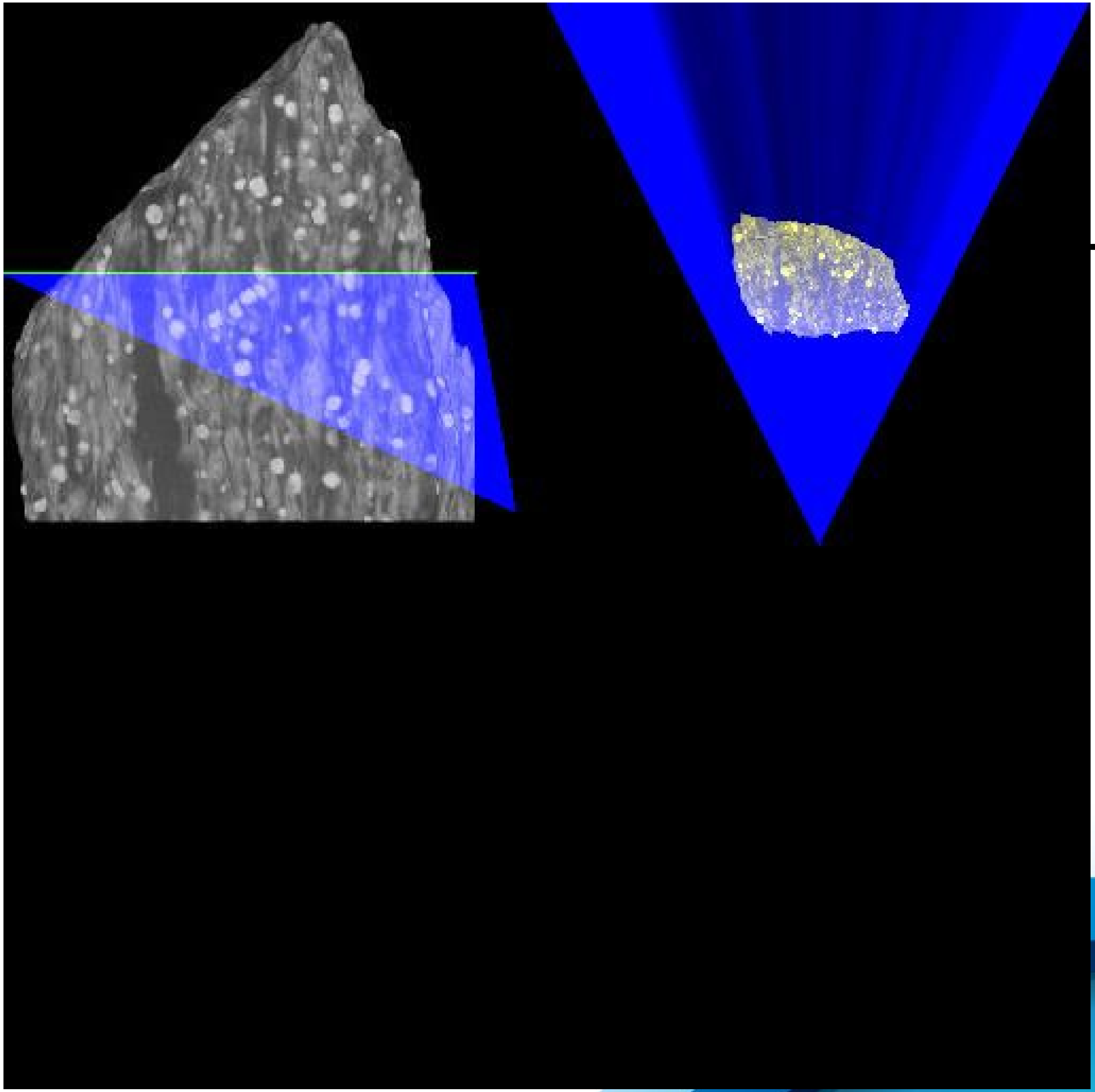
Aiming at 1µm



Transmission also enables tomography: 3D imaging!

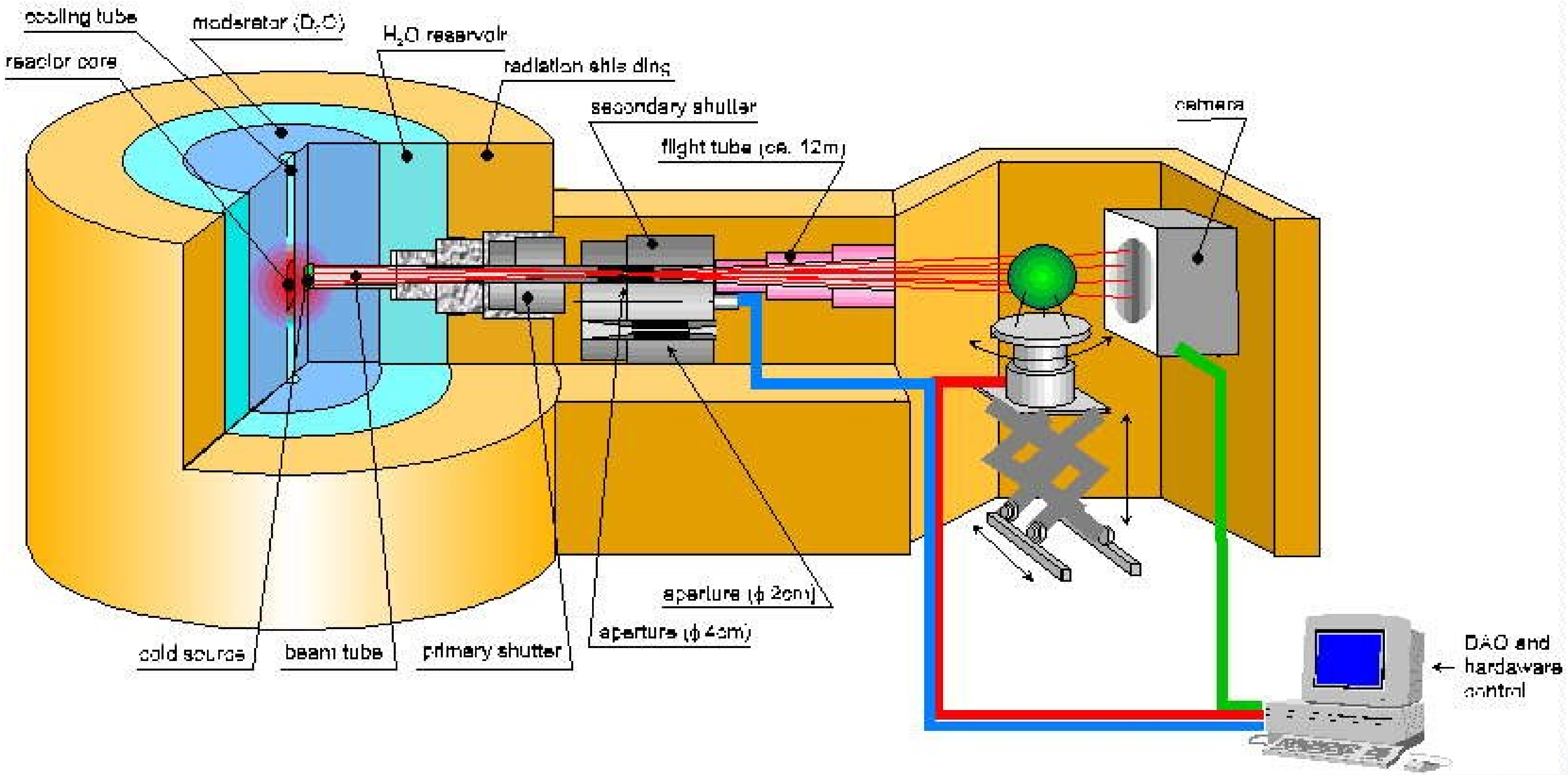
reconstruction

Radon Transform



Fourier Slice Theorem

So now we have it all…



…do we really?

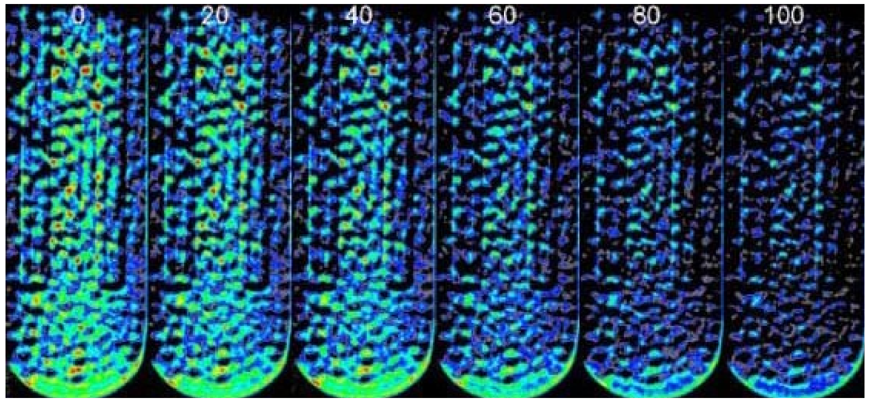
Neutron imaging

Some advantages:

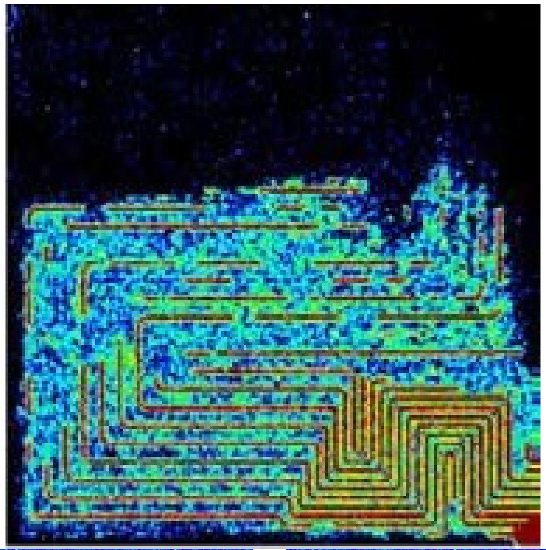
High penetration power

High sensitivity to Hydrogen

Low radiation damage



Neutron imaging



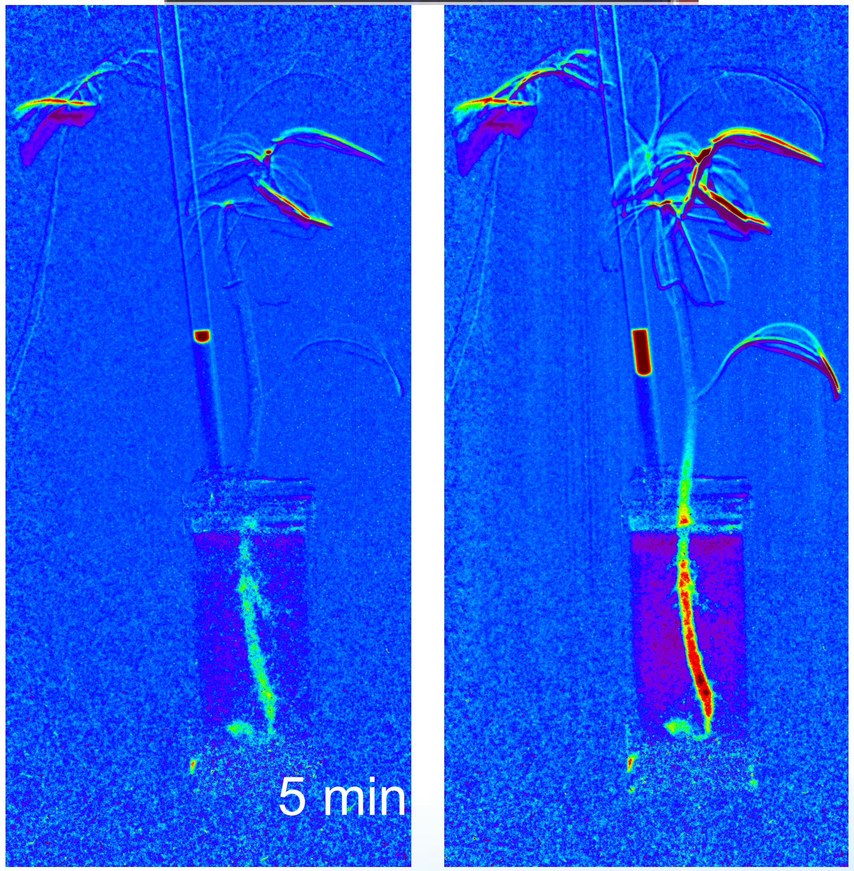
Some advantages:

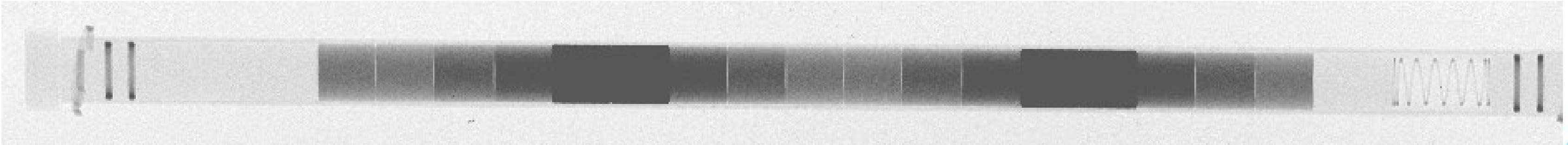
High penetration power

High sensitivity to Hydrogen

Low radiation damage

Isotope sensitive





Enrichmet of fuel element

Neutron imaging

…also some disadvantages

Low phase space density – slow

☹

Low spatial resolution

☹

Expensive

Neutron imaging

Some advantages:

High penetration power

High sensitivity to Hydrogen

Low radiation damage

Isotope sensitive

Neutron imaging

Some advantages:

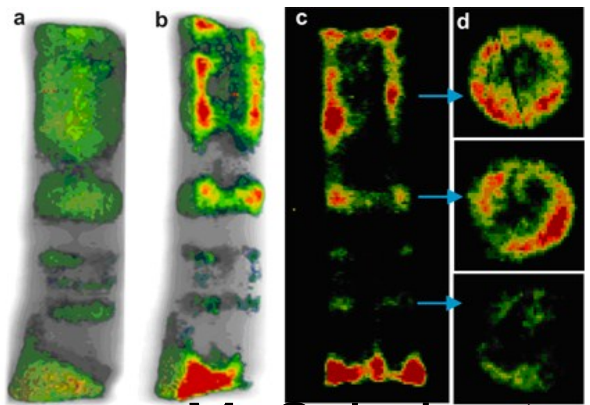
High penetration powe

High sensitivity to Hydrogen

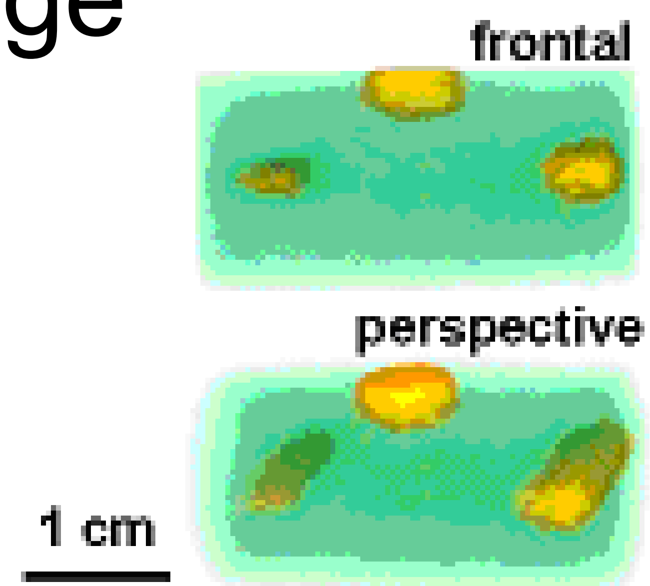
Low radiation damage

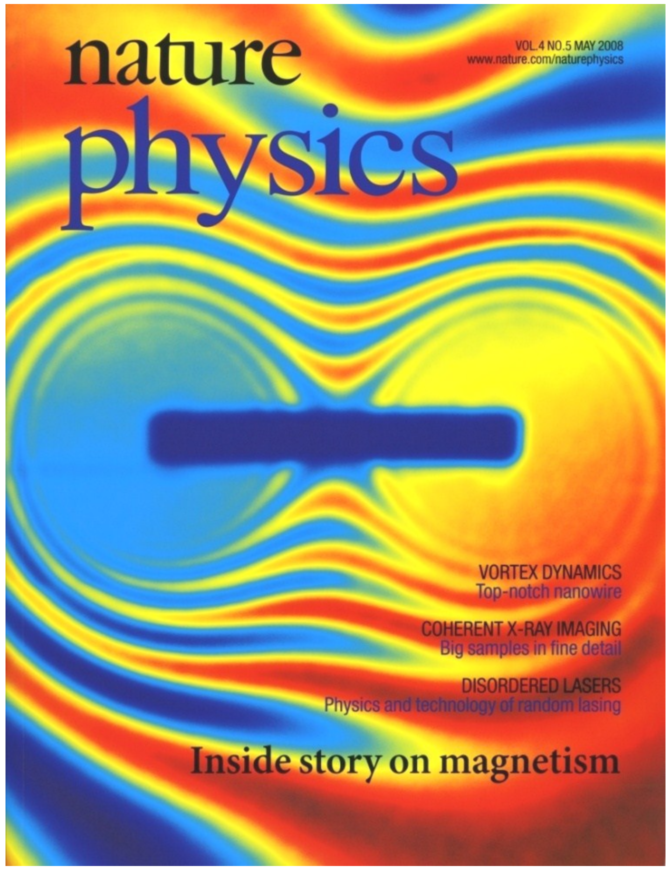
Isotope sensitive

Magnetic moment

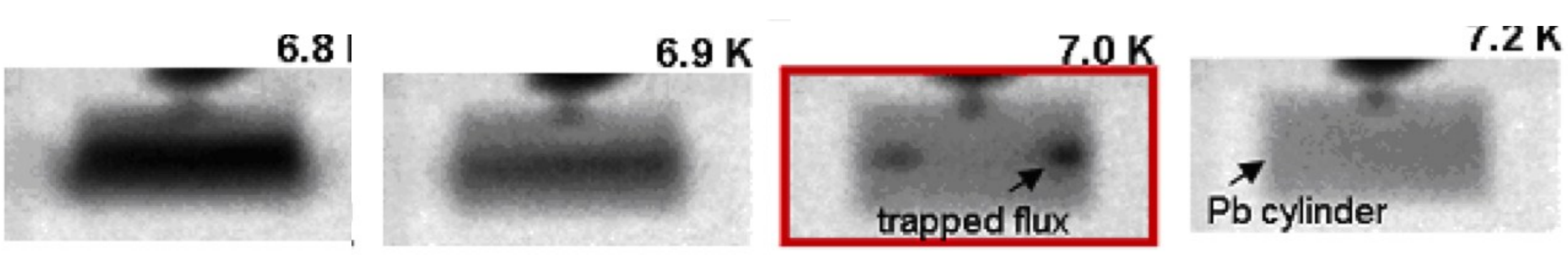


M. Schulz et al.

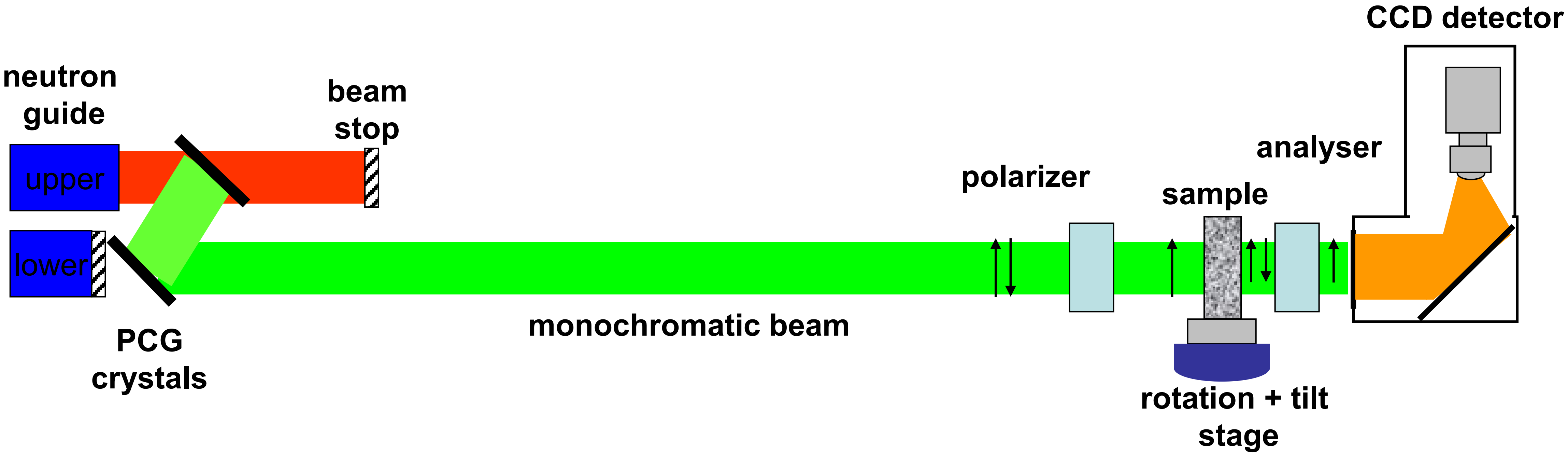




N. Kardjilov, I. Manke, M. Strobl, A. Hilger et al. Nat. Phys. 4 (2008)

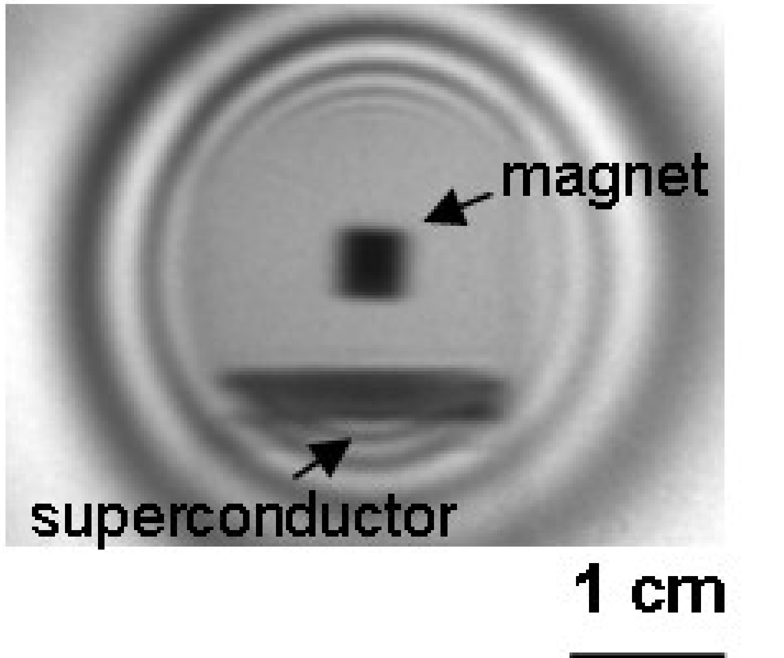


Polarised neutron imaging



$$I(x,y) = I_0(x,y) \cdot \exp\left(-\int_{path} \sigma \cdot ds\right) \cdot \frac{1}{2}\left(1 + \cos \varphi(x,y)\right)$$

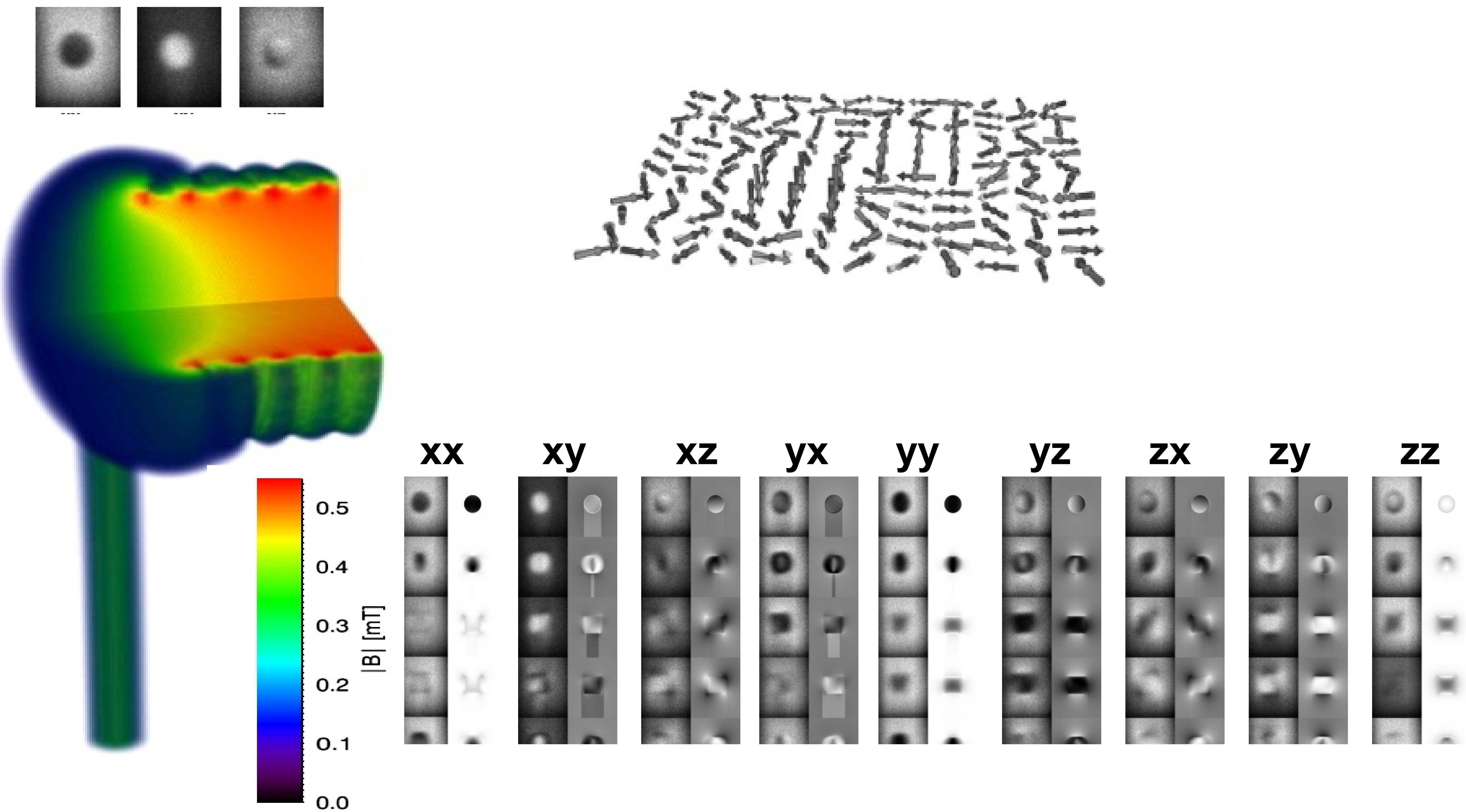
$$\varphi = \int_{path} \frac{\lambda m_n \gamma_n B}{h} ds$$



N. Kardjilov, I. Manke, M. Strobl, A. Hilger et al. Nature Phys. 4 (2008)

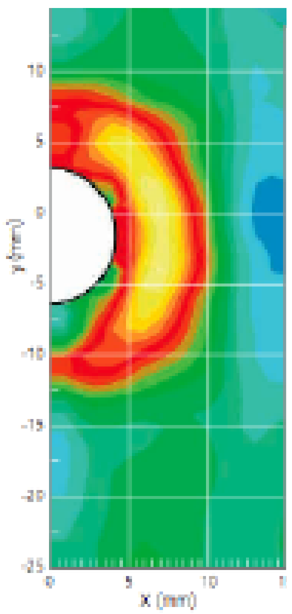
Polarized neutron imaging

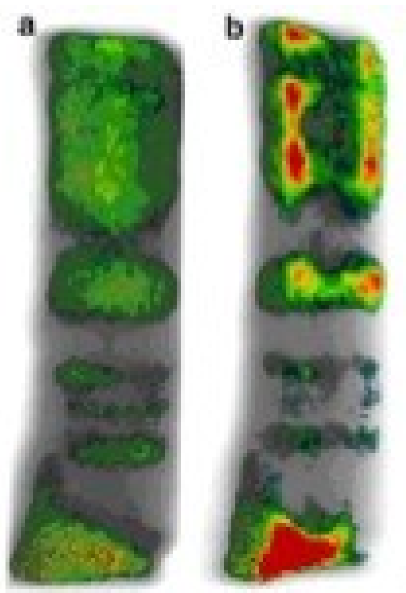
3D vector quantification through polarimetric imaging

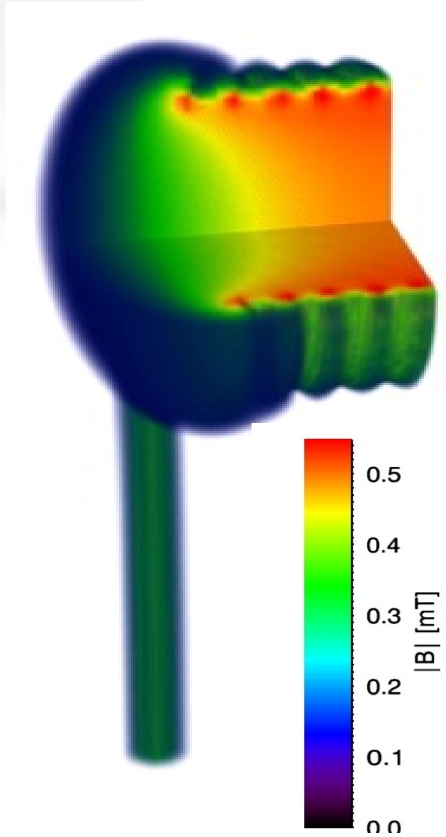


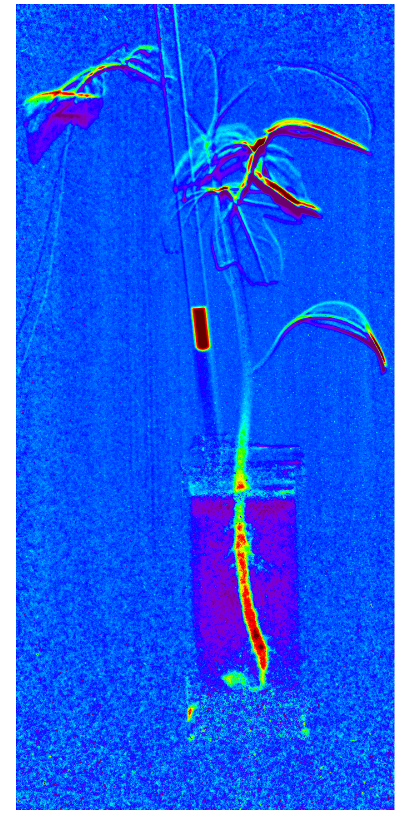
images

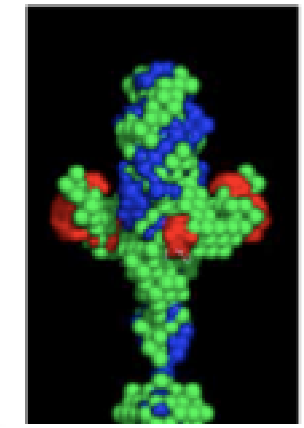

Nikon
SONY
α
EOS
5D

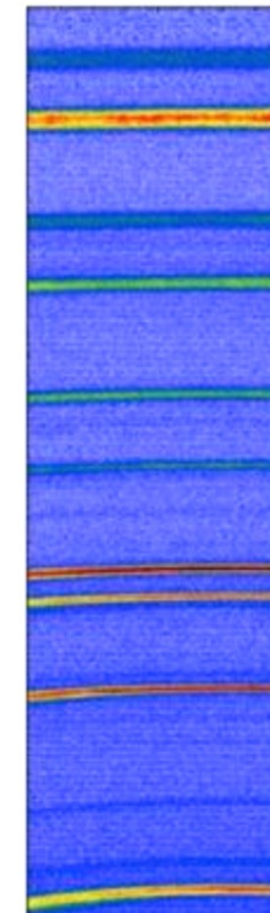


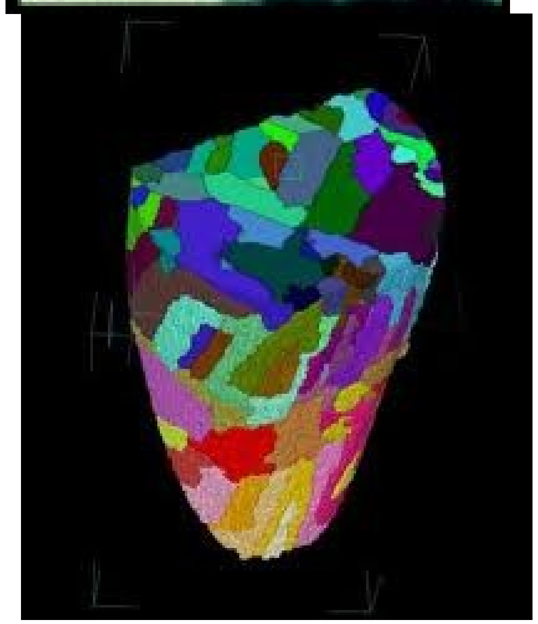

a
b

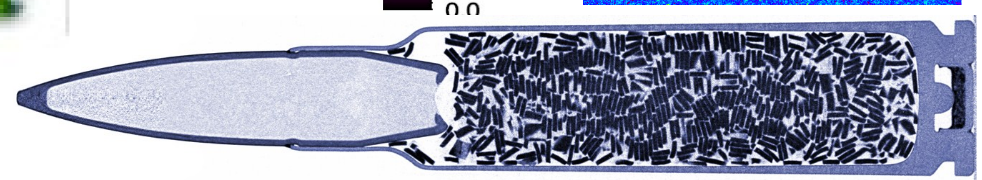

0.5
0.4
0.3
0.2
0.1
0.0
|B| [mT]



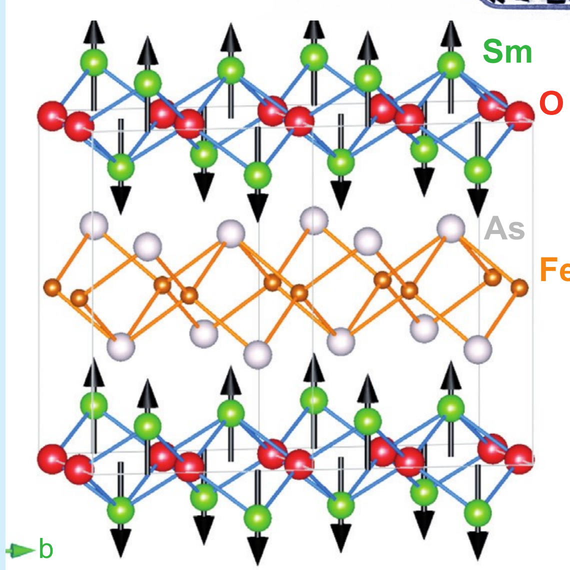


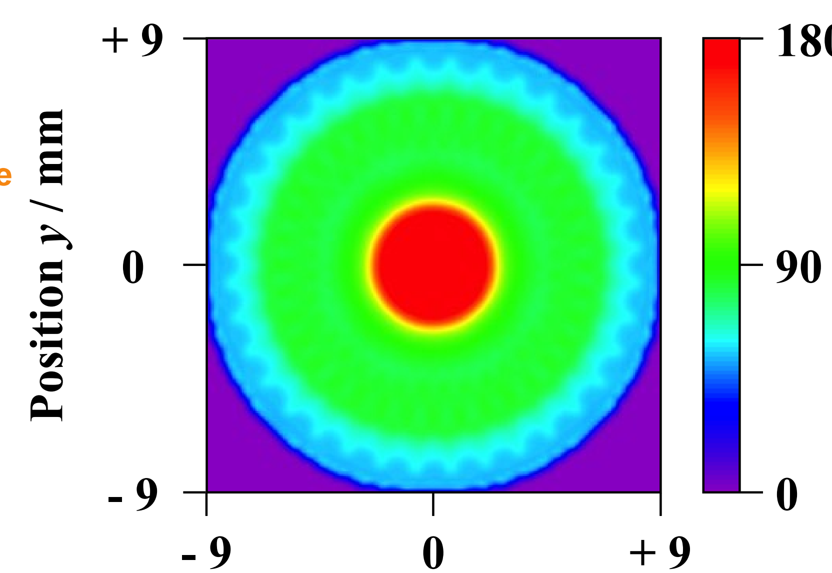


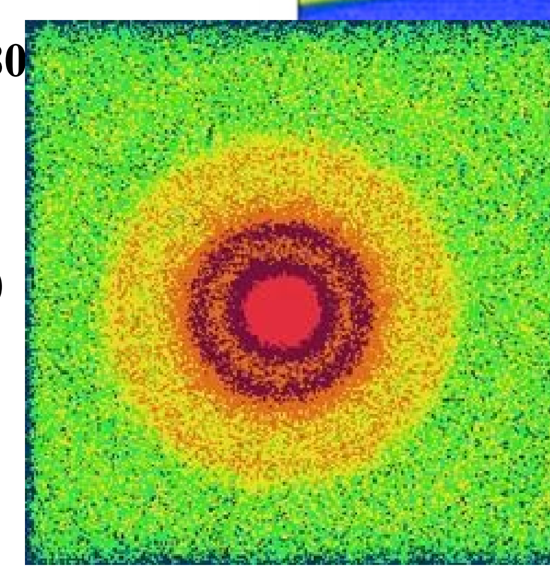


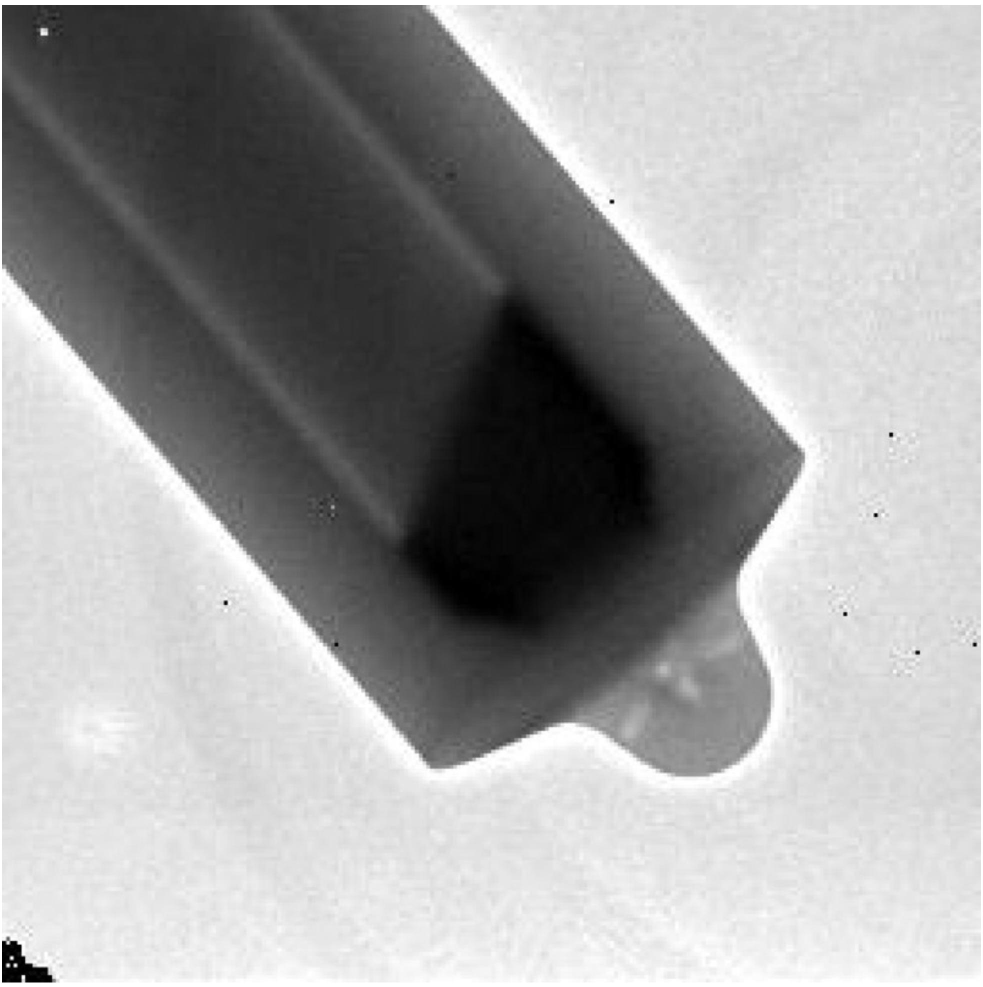



100 µm


Sm
O
As
Fe
b

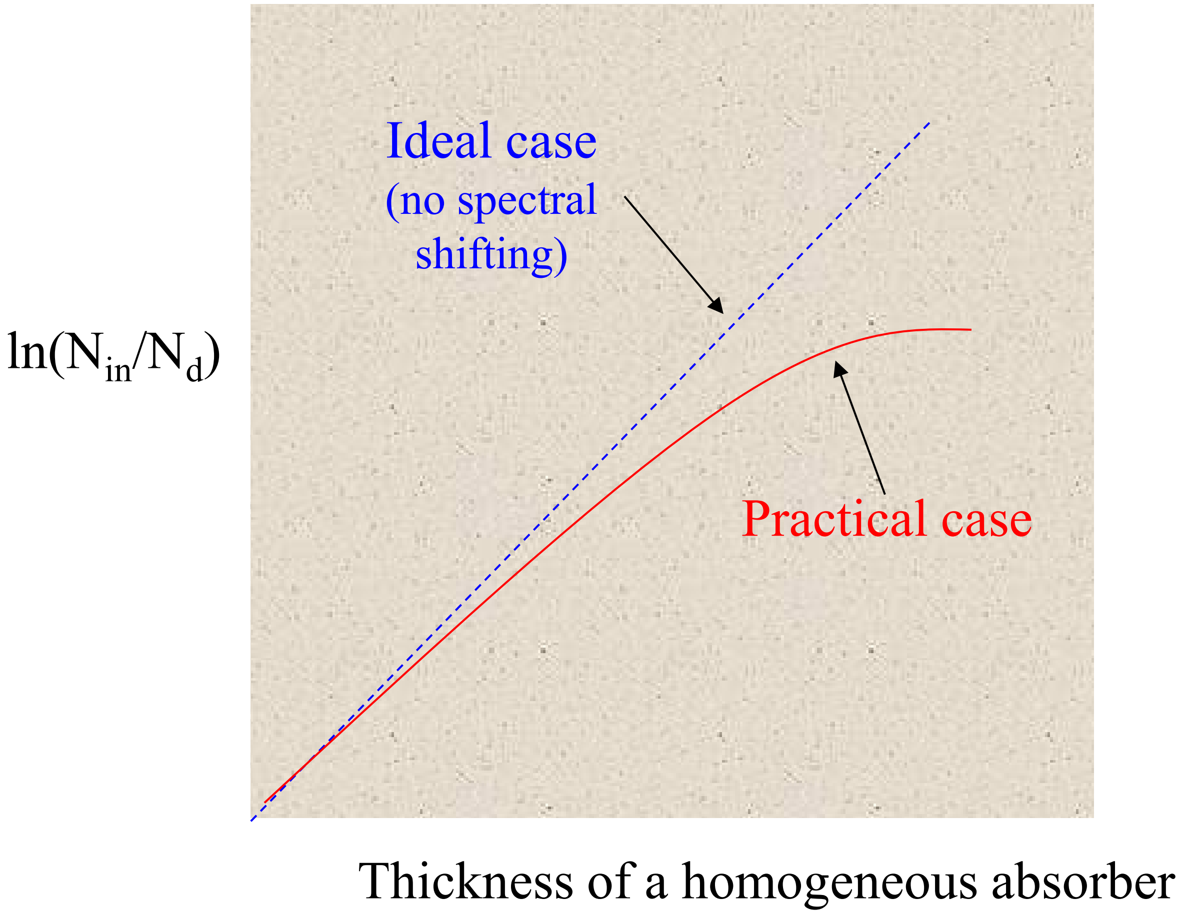

+ 9
0
- 9
Position y / mm
- 9
0
+ 9
180
90
0

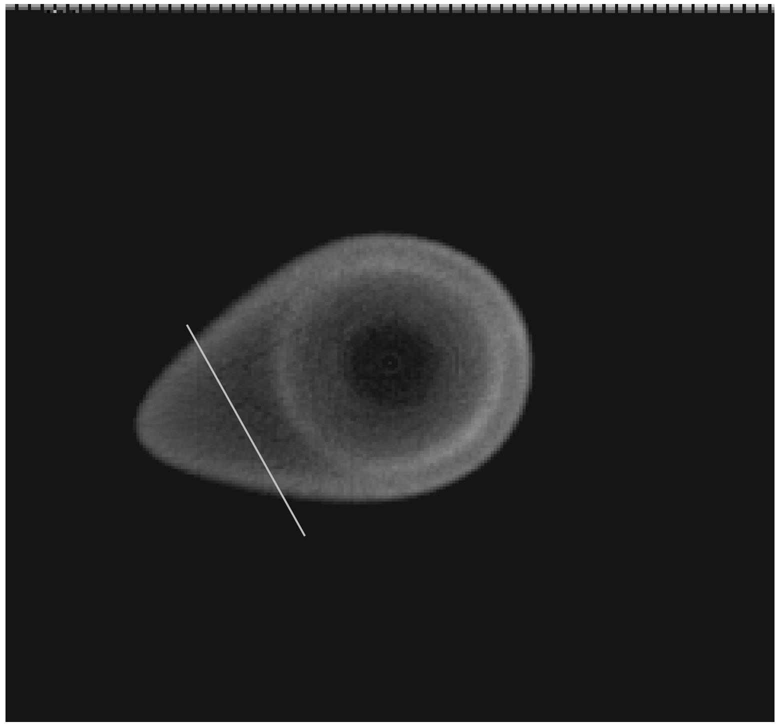


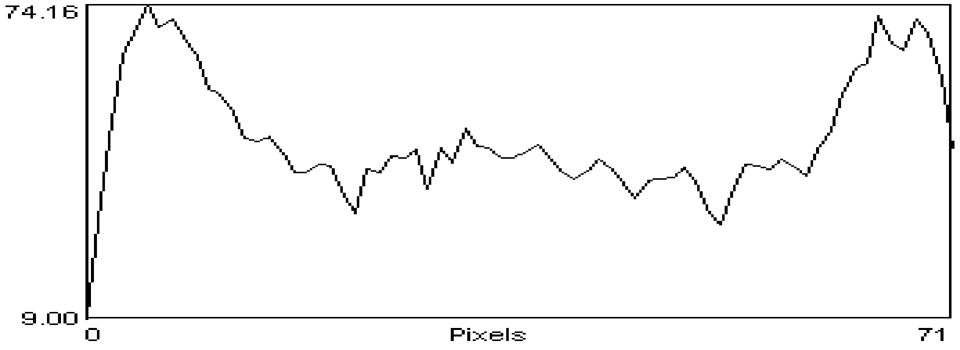


What about scattering now?

Artifacts!







Contrast

Interaction of neutrons with matter:

Scattering & Absorption

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

Cross sections:

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

$$\frac{d\sigma}{d\Omega} = \frac{\text{number of interacting particles / unit time} \cdot \text{unit cone } d\Omega}{\text{number of incident particles / unit time x unit area} \cdot \text{unit cone } d\Omega} = [\text{area}]$$

Unit of σ : 1 barn $= 10^{-24}$ cm^2

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

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

Unit of Σ is [cm^{-1}].

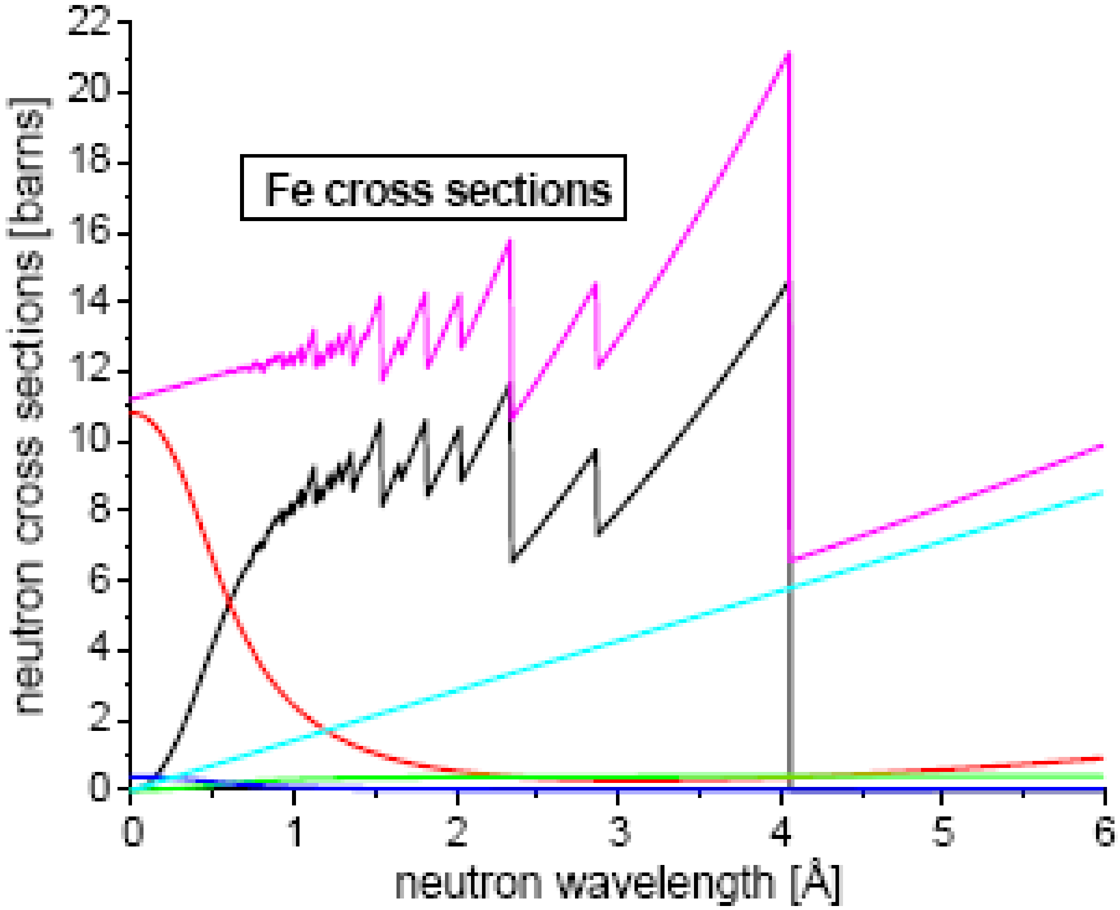
Total neutron cross section

Total neutron cross section

Most significant

Defines the Bragg edge position

$$\sigma_{coh}^{el}(\lambda) = \frac{\lambda^2}{2V_0} \sum_{d_{hkl}=0}^{2d_{hkl}<\lambda} |F_{hkl}|^2 d_{hkl}$$



$$\sigma_{inc}^{el}(\lambda) = \overline{\sigma}_{inc} \sum_n \frac{\lambda^2}{2B_{iso,n}}(1 - e^{(-\frac{2B_{iso,n}}{\lambda^2})})$$

$$\sigma_{total}^{inel}(\lambda) = (\overline{\sigma}_{coh} + \overline{\sigma}_{inc})(\frac{M/m}{M/m+1})^2 \sum_n (1 + \frac{9\varphi_3(\theta)\varphi_3(\theta)\lambda^2}{2M^2/m^2 B_{iso}}) - \cdots$$

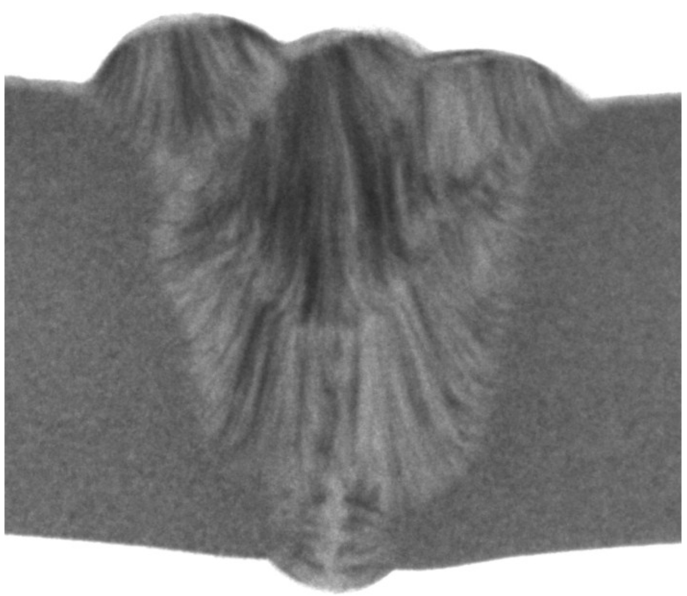
$$\sigma_{abs}(\lambda) = B \cdot \frac{m\lambda}{h} = \frac{\sigma_{abs}^{2200m/s}}{1.798\text{Å}} \cdot \lambda$$

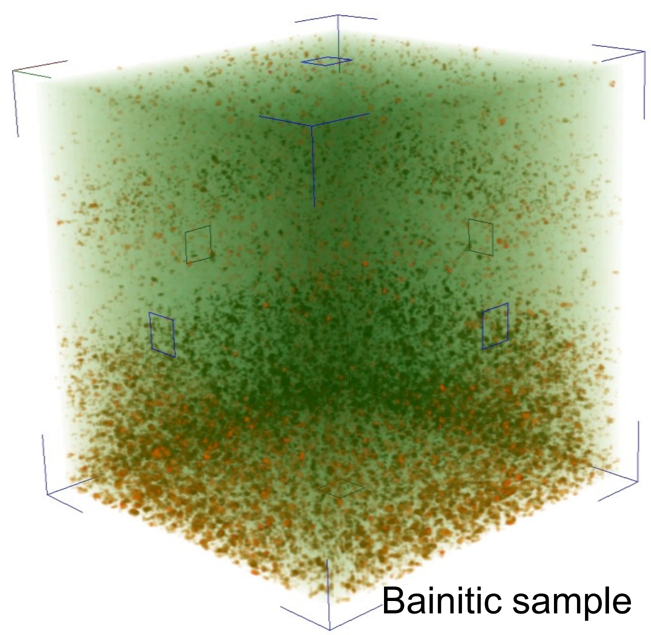
$$\sigma_{total}(\lambda)$$

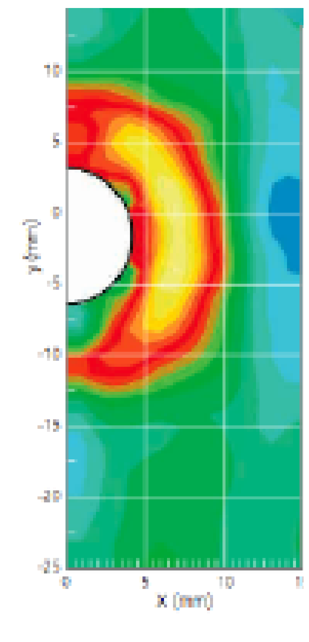
Energy resolved

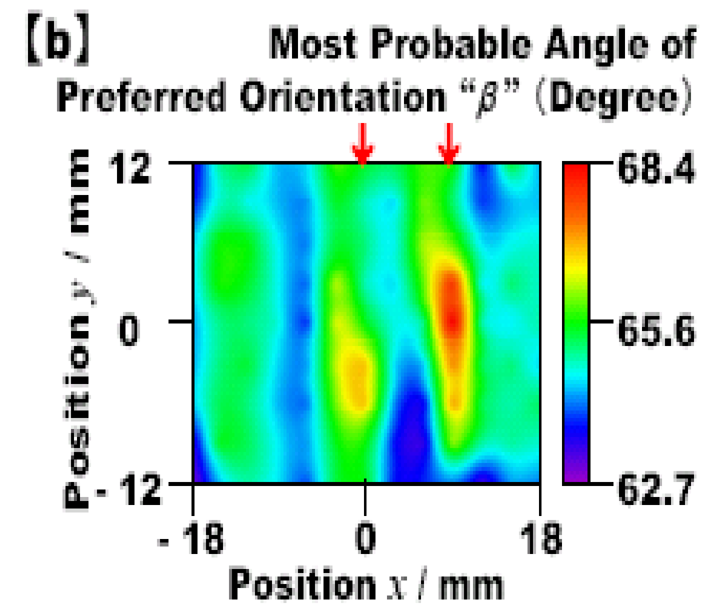
Examples

cryst. inhom. / phase distribution /strain / grain structu

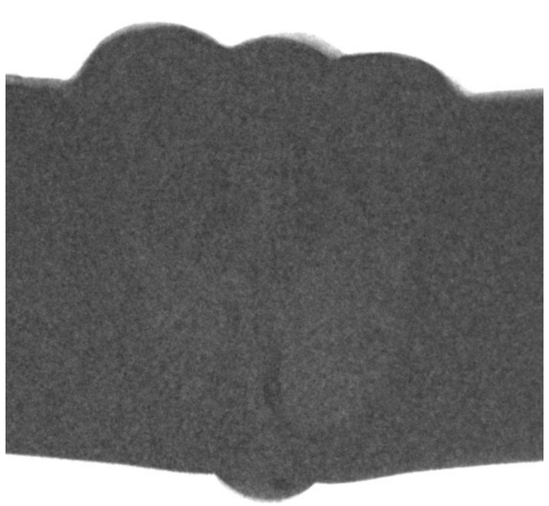


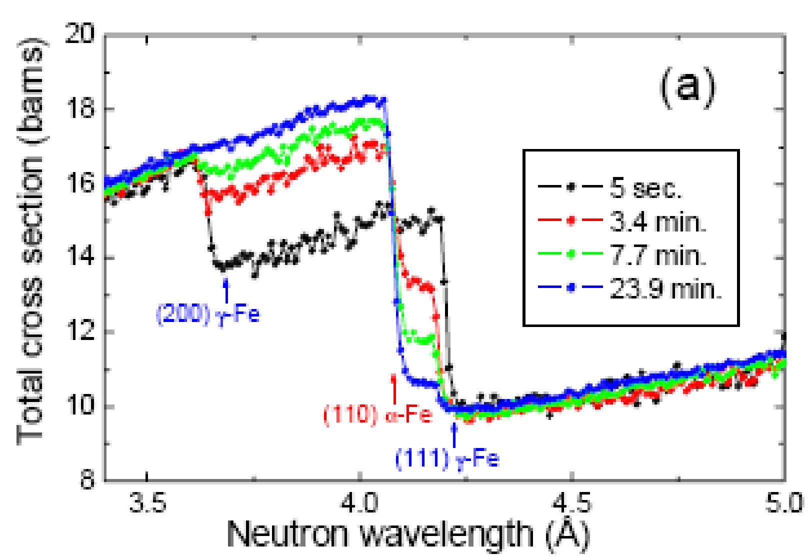


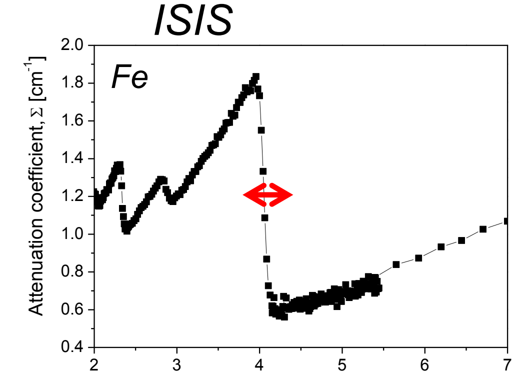


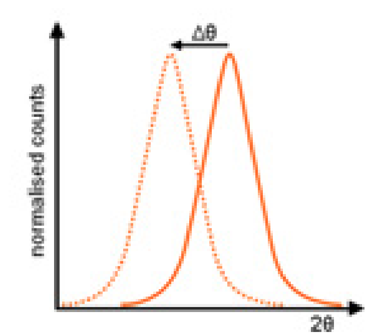


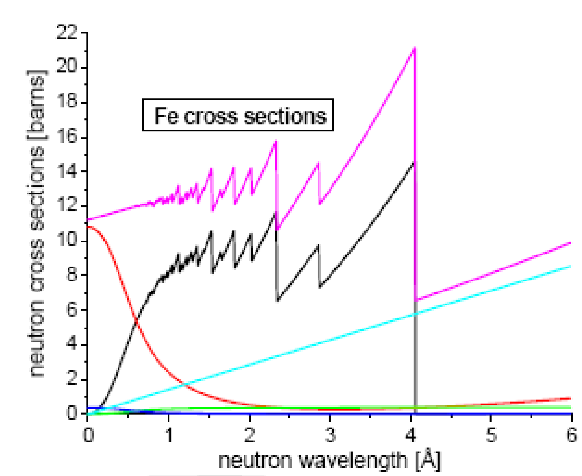
PSI/HZB *HZB* *ISIS* *JPARC*



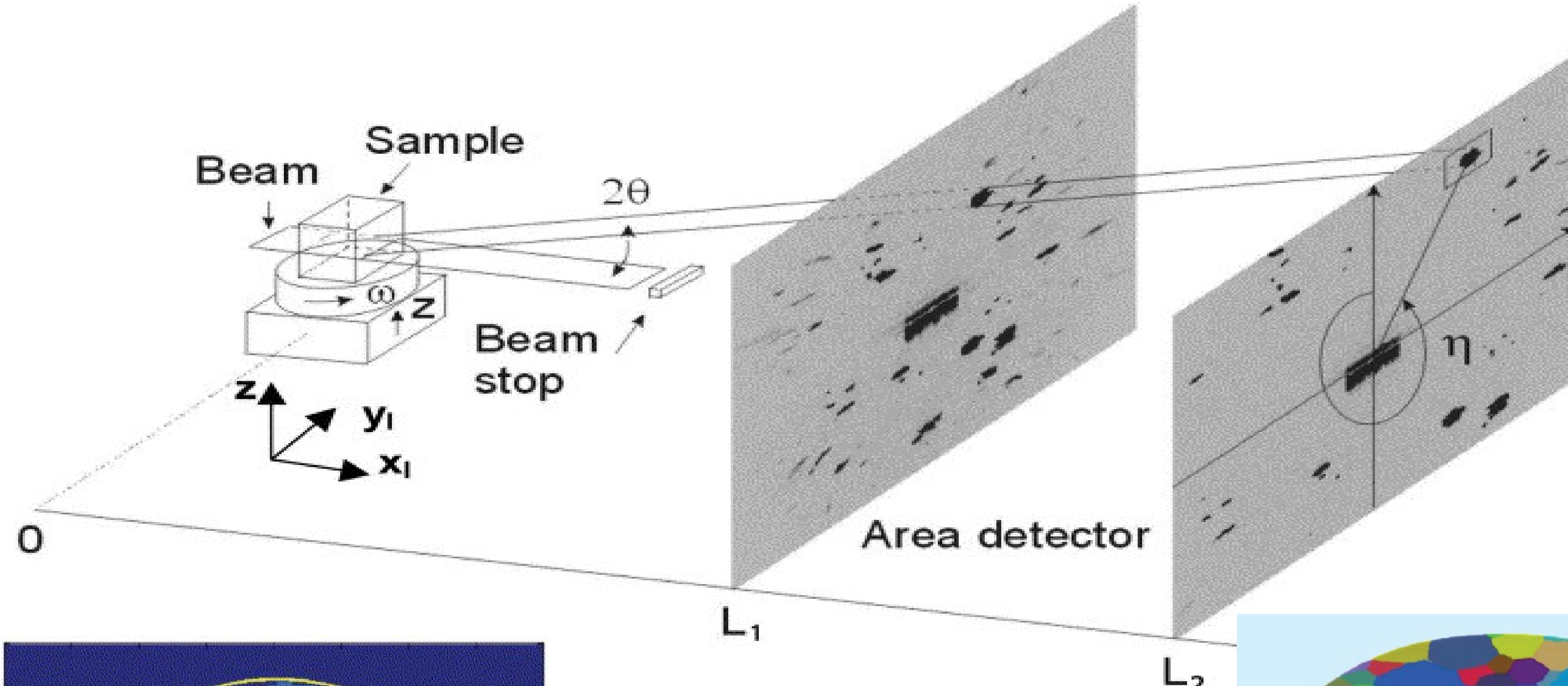


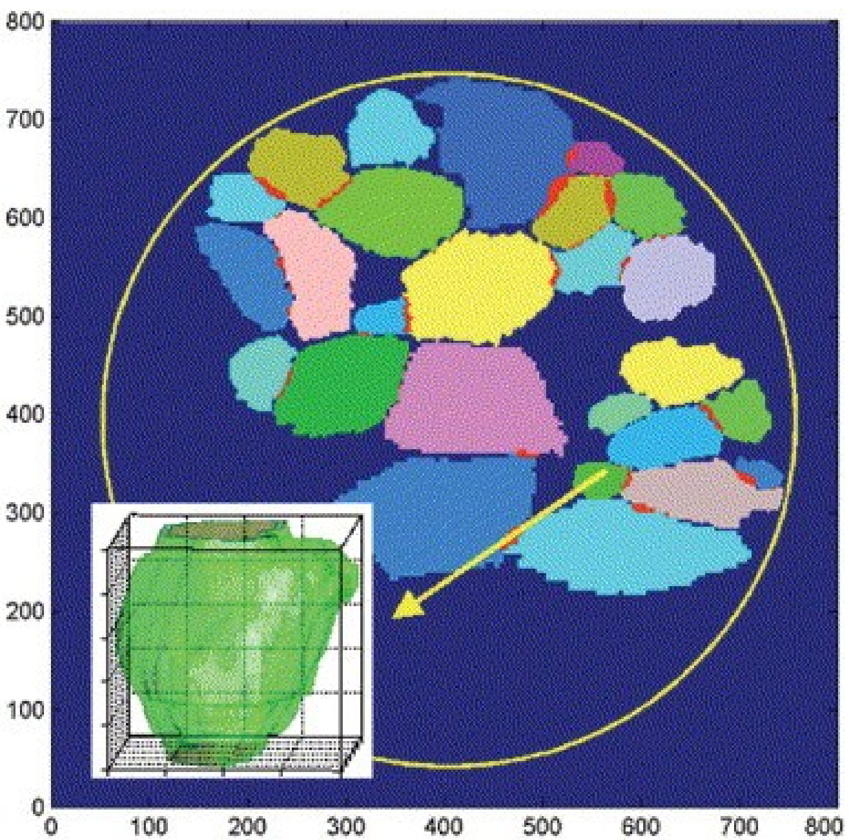


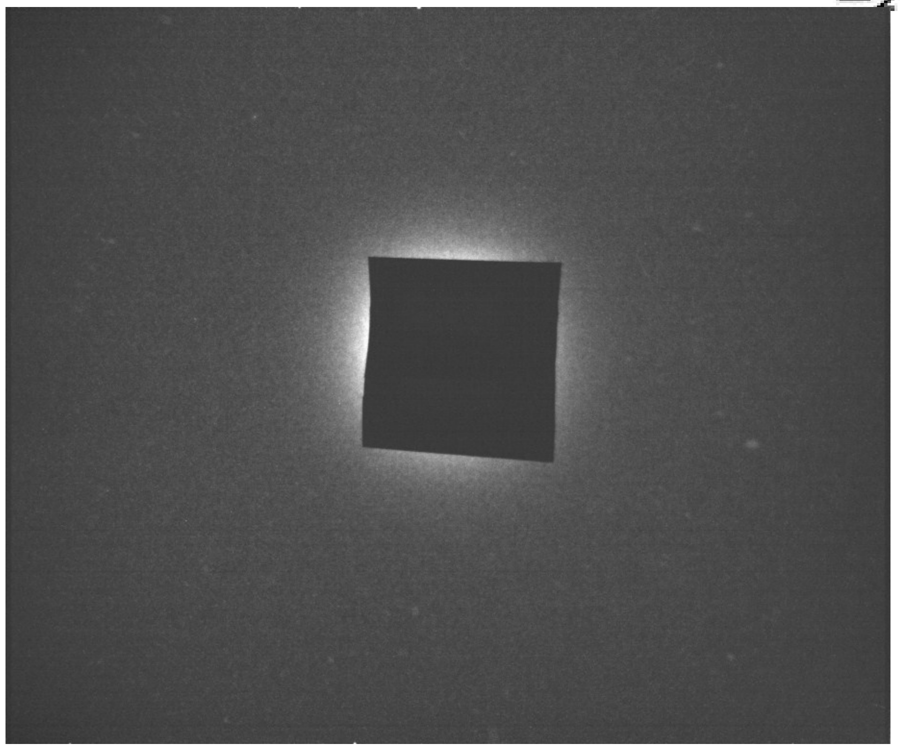


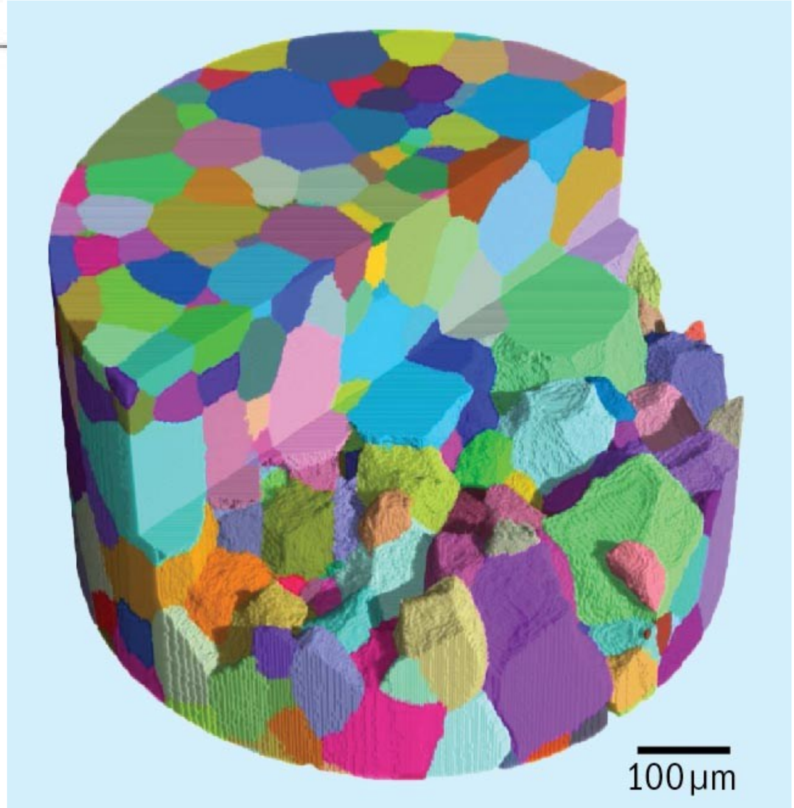


3D-XRD, diffraction imaging









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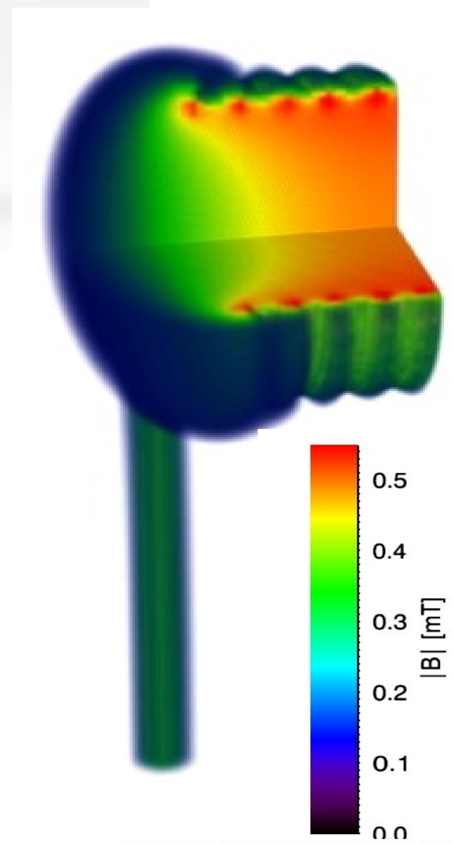
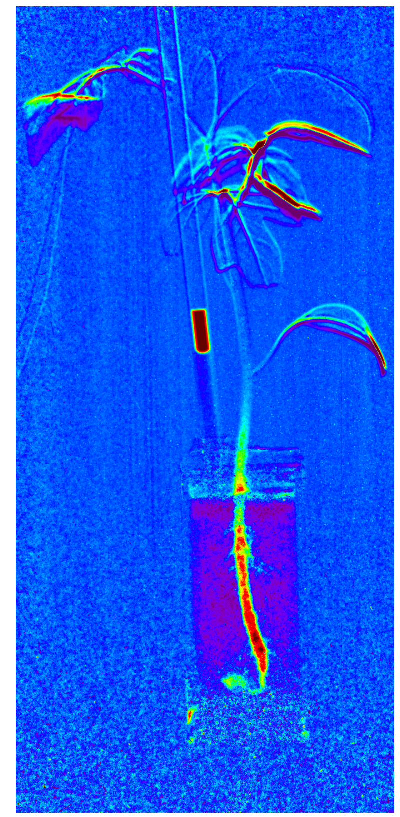
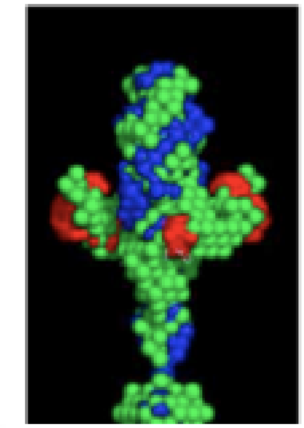
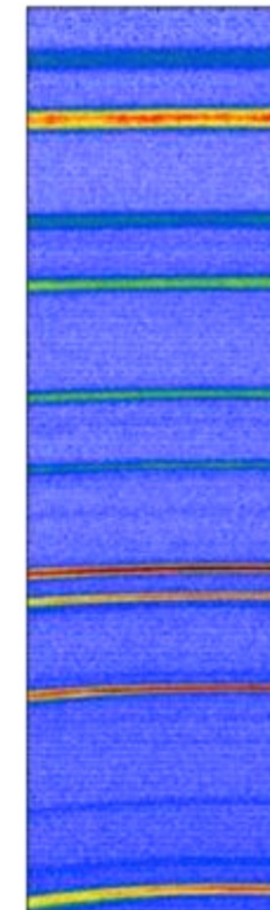
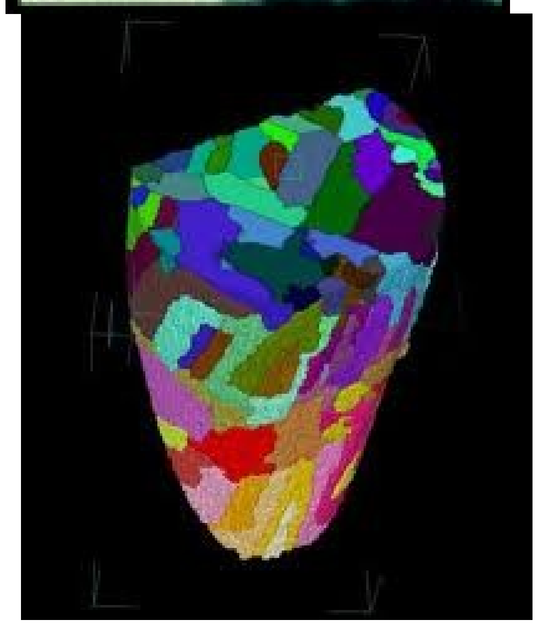
Nikon
SONY
α
EOS
5D

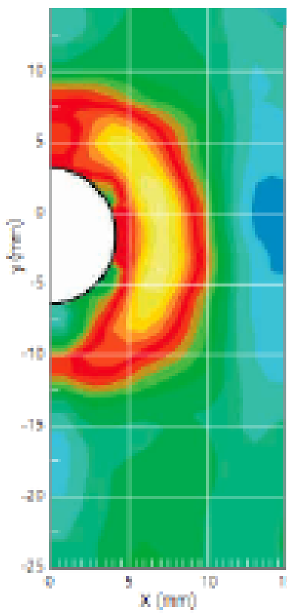

0.5
0.4
0.3
0.2
0.1
0.0
|B| [mT]

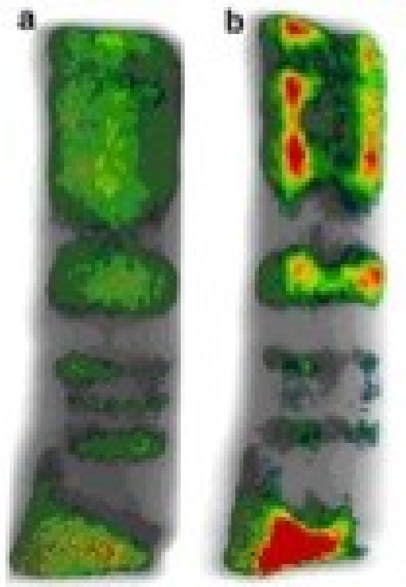


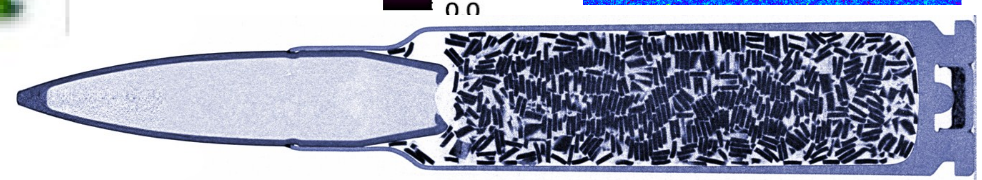




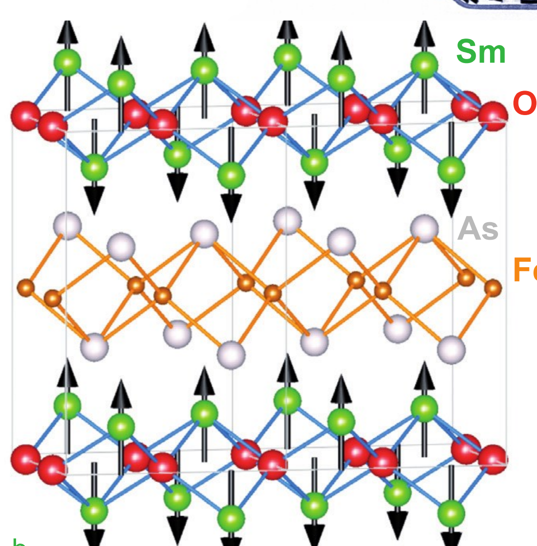


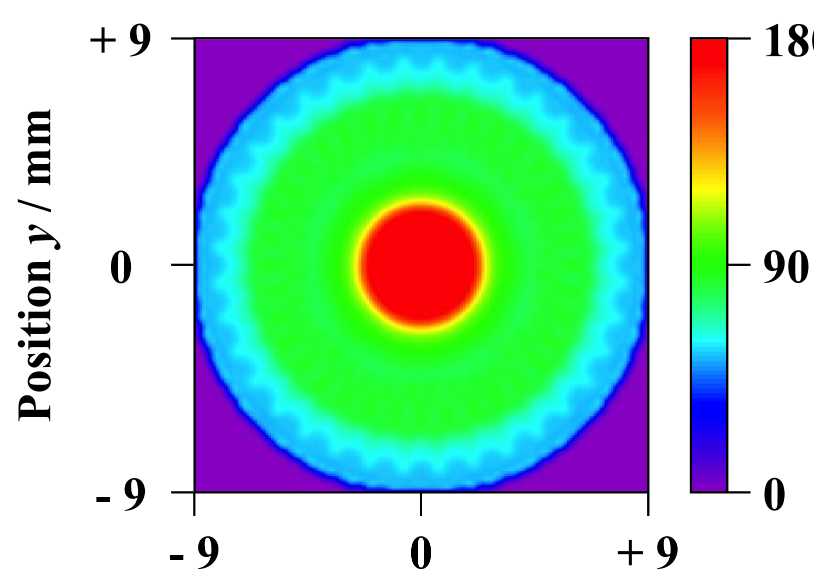

y (mm)
x (mm)

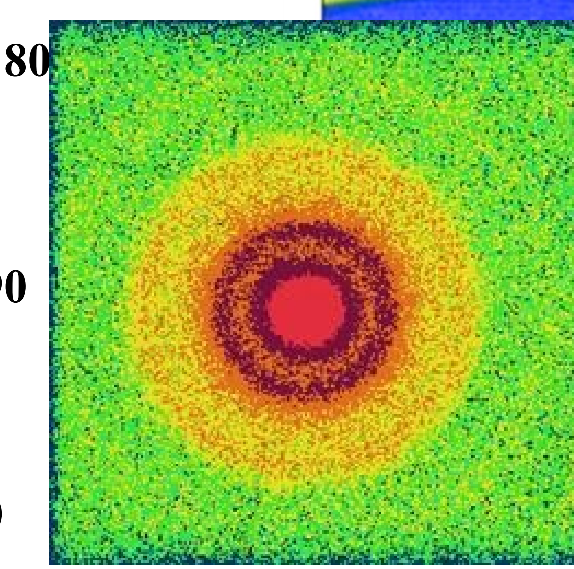

a
b




100 μm


Sm
O
As
Fe
b


+ 9
0
- 9
Position y / mm
- 9
0
+ 9
180
90
0



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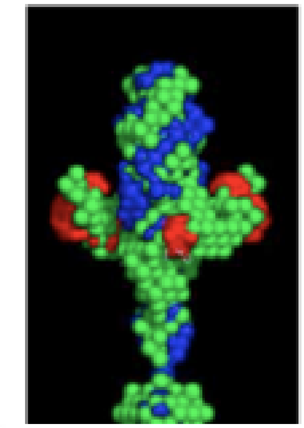

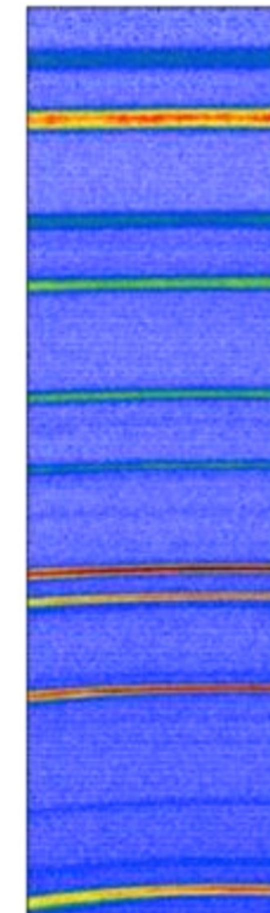

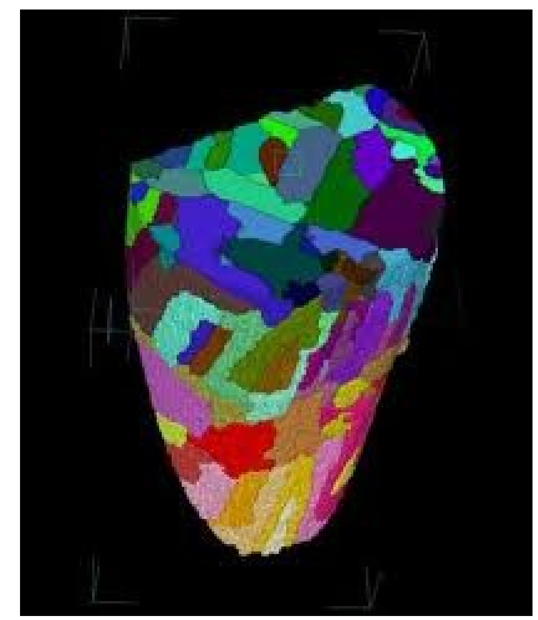

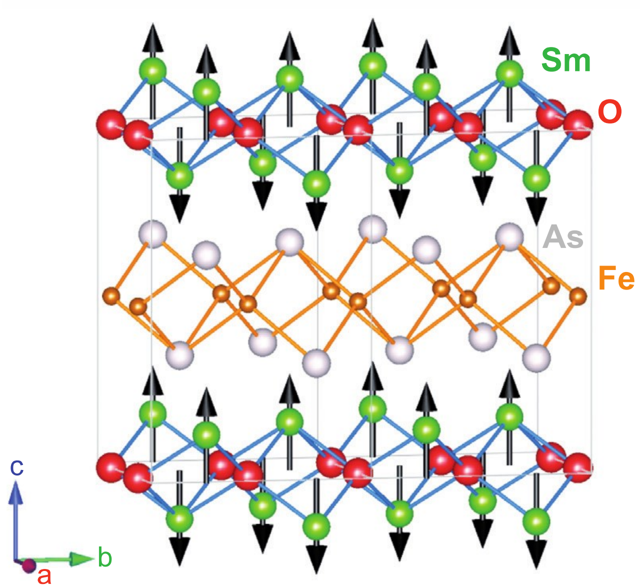

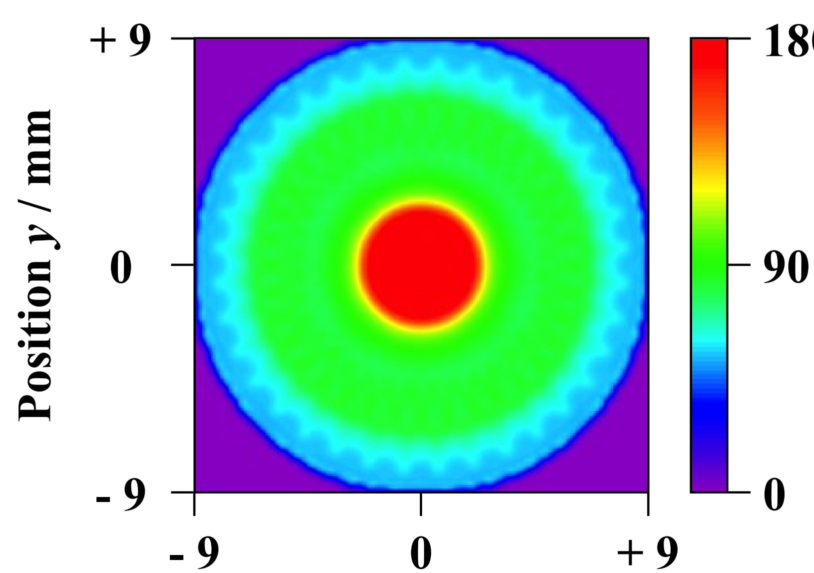

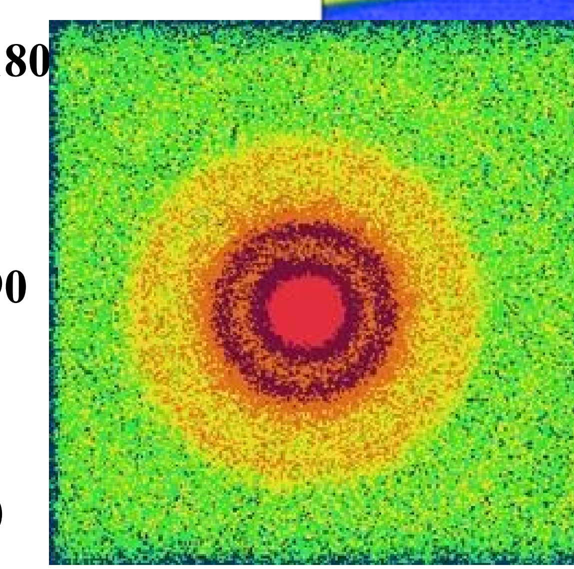

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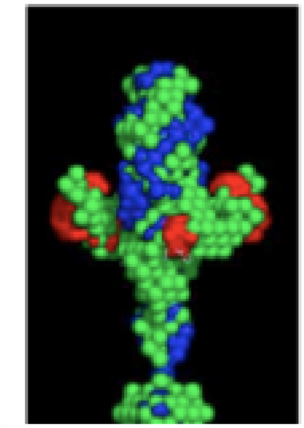
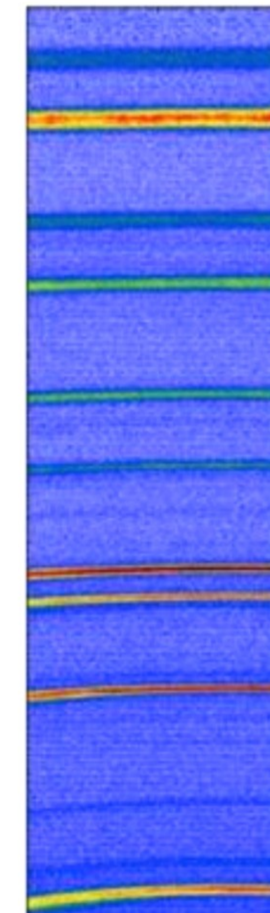
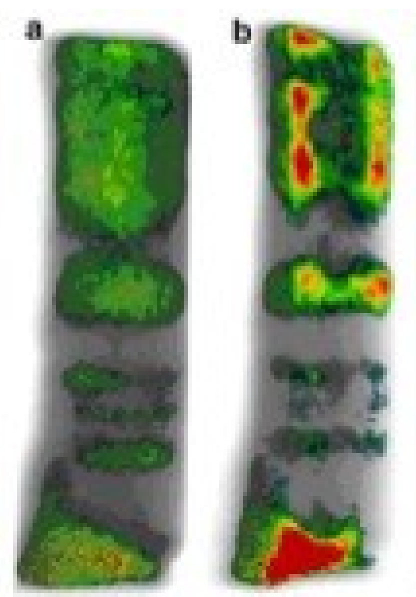
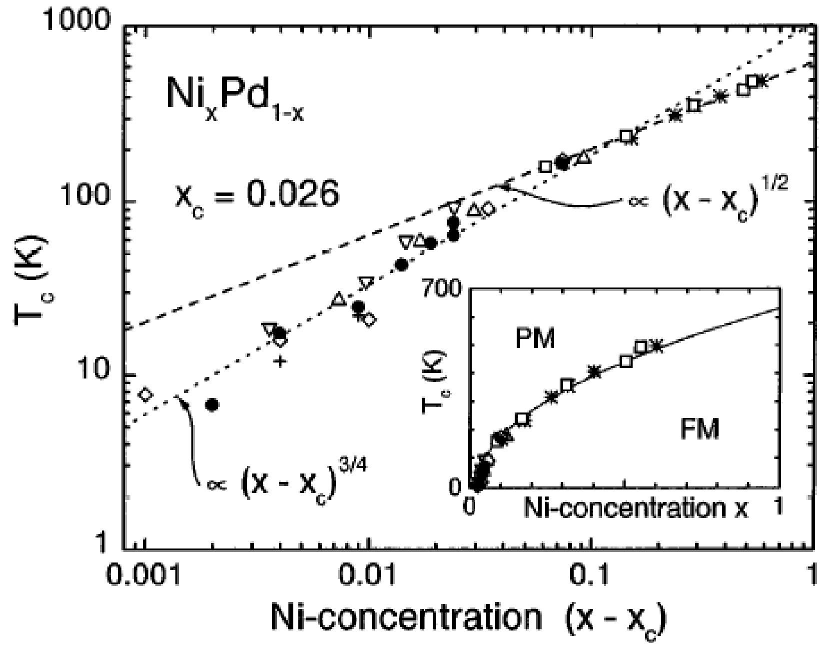
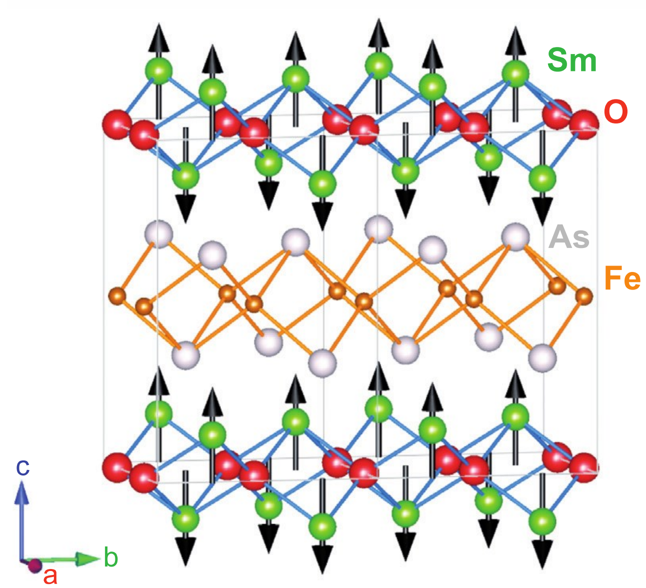





a
b


Ni_xPd_{1-x}
$x_c = 0.026$
$\propto (x - x_c)^{1/2}$
$\propto (x - x_c)^{3/4}$
T_c (K)
1000
100
10
1
0.001
0.01
0.1
1
Ni-concentration $(x - x_c)$
700
PM
FM
0
0
1
Ni-concentration x


Sm
O
As
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c
a
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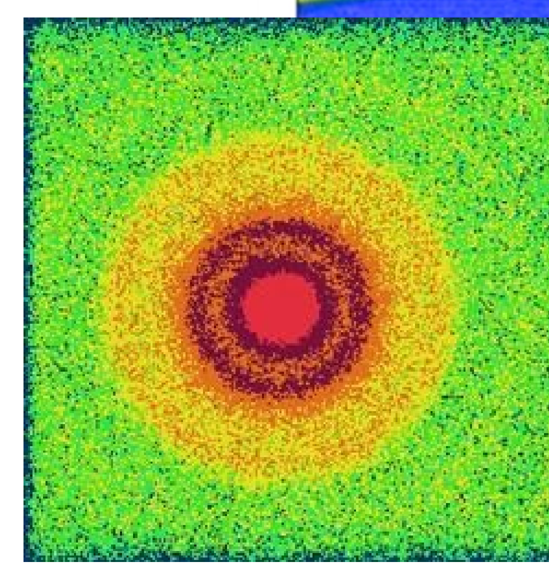

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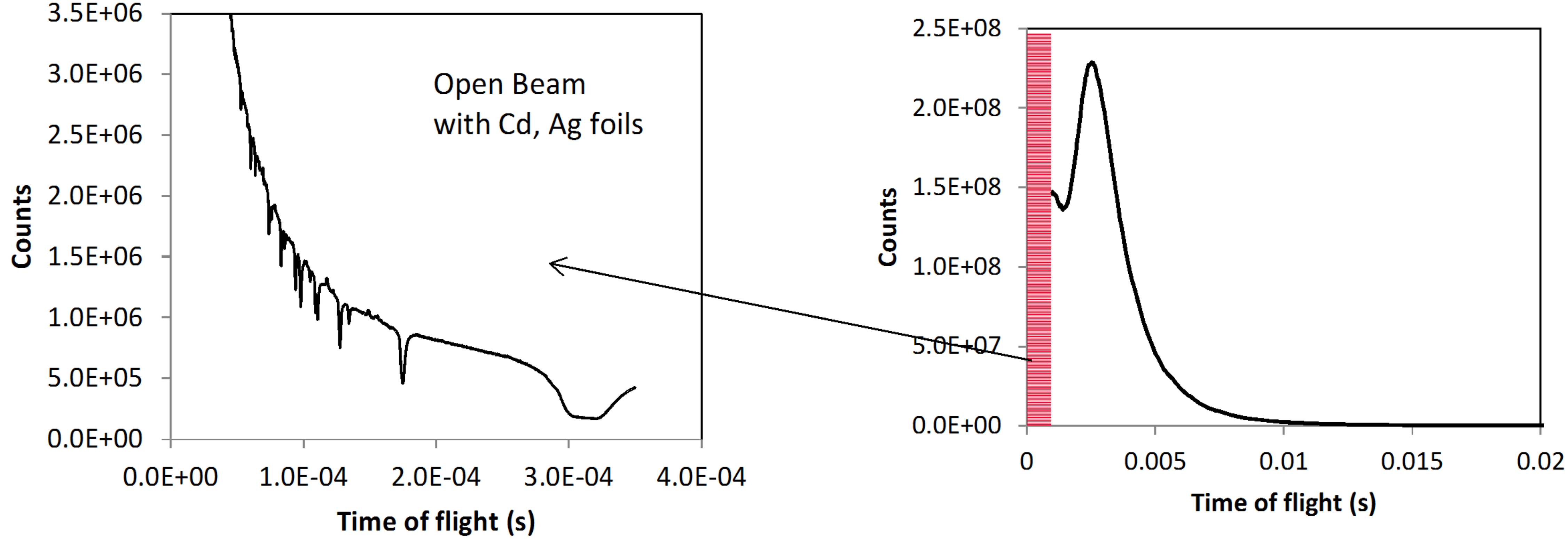
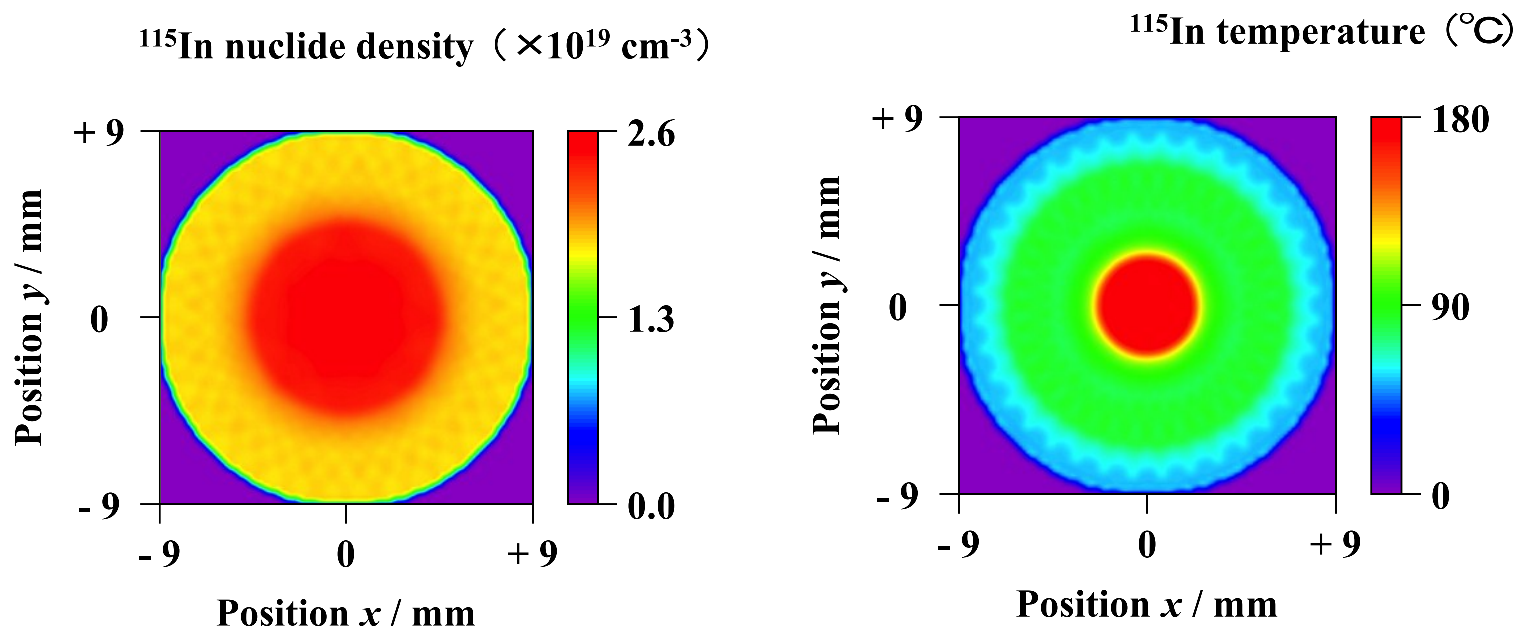
Entire neutron spectrum can be measured in one experiment with event counting detector providing XYT





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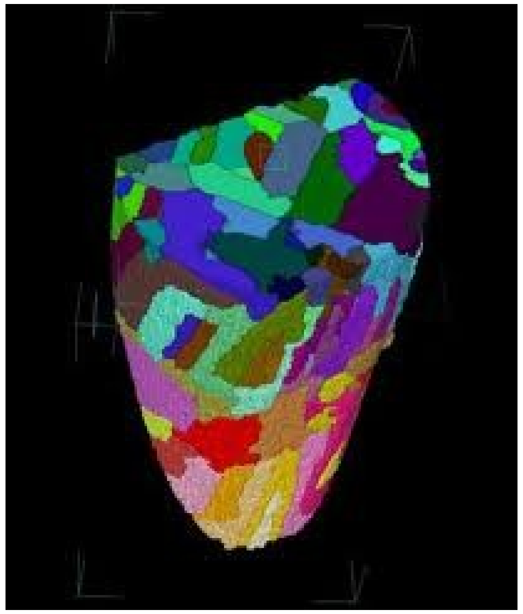
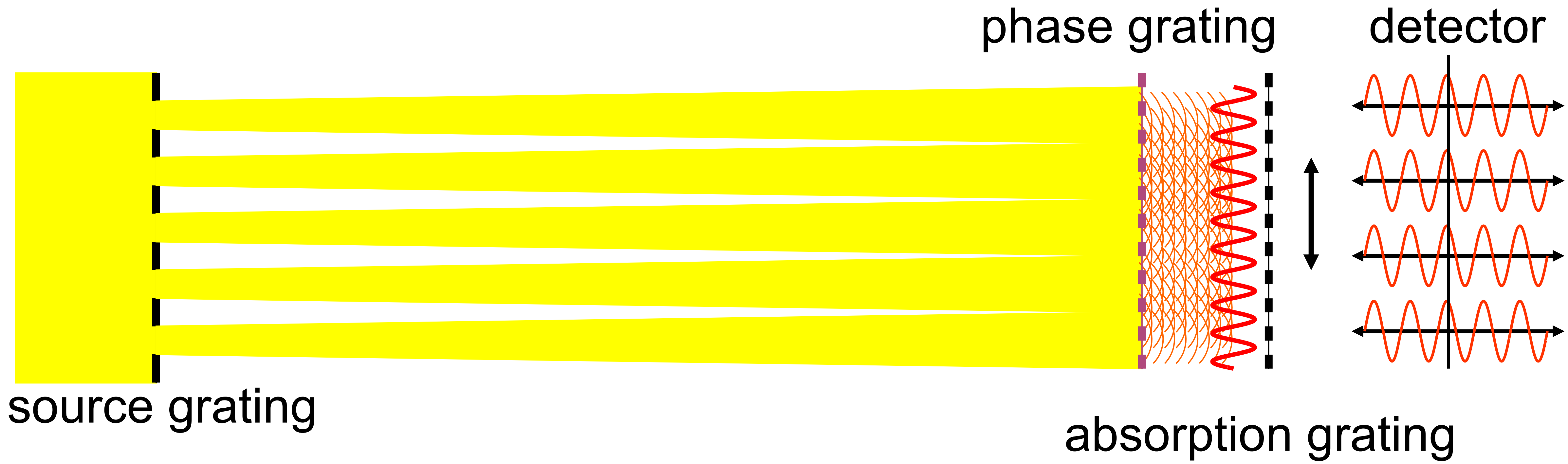


modulated imaging beam?

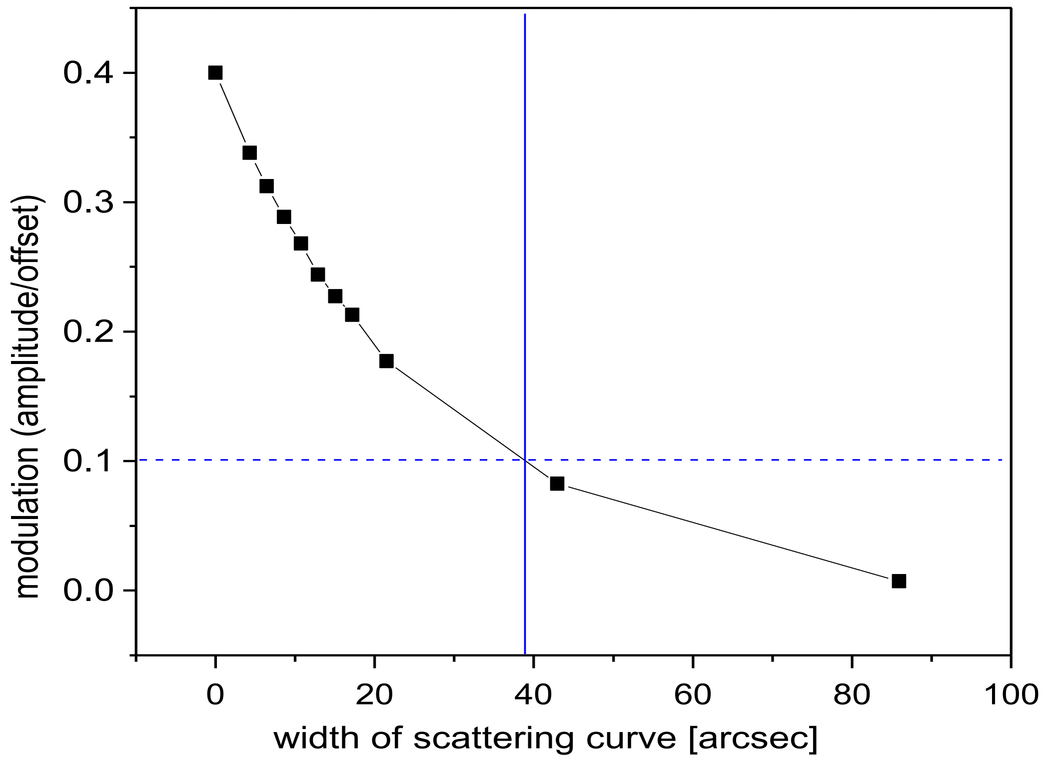
Grating Interferometer

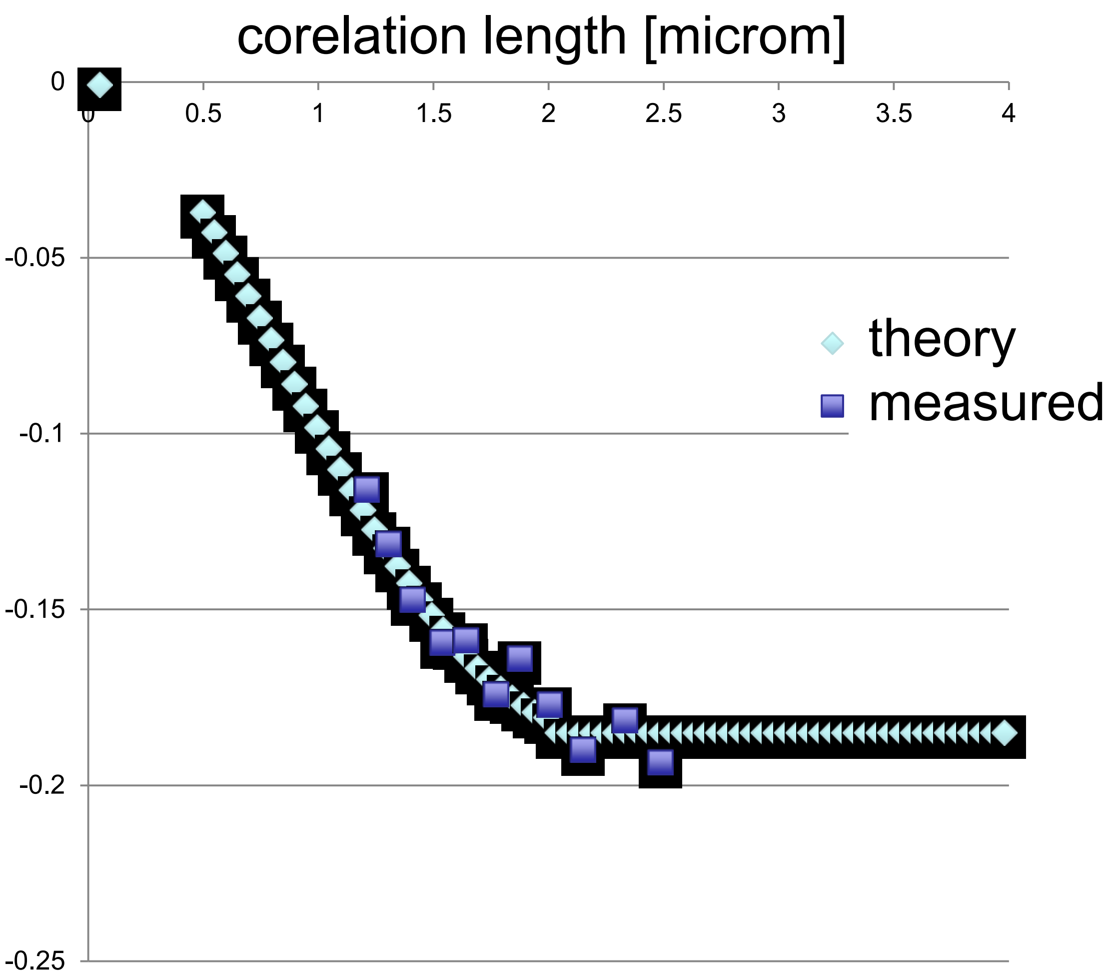


F. Pfeiffer et al. Phys. Rev.Lett. 96, 215505 (2006)

modulated imaging beam?

Dark field contrast

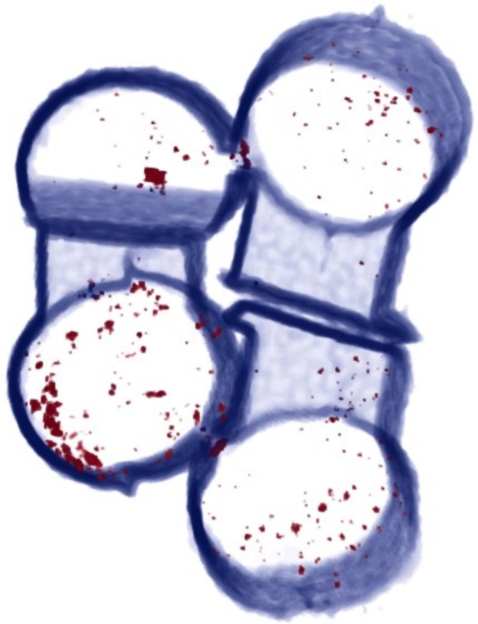


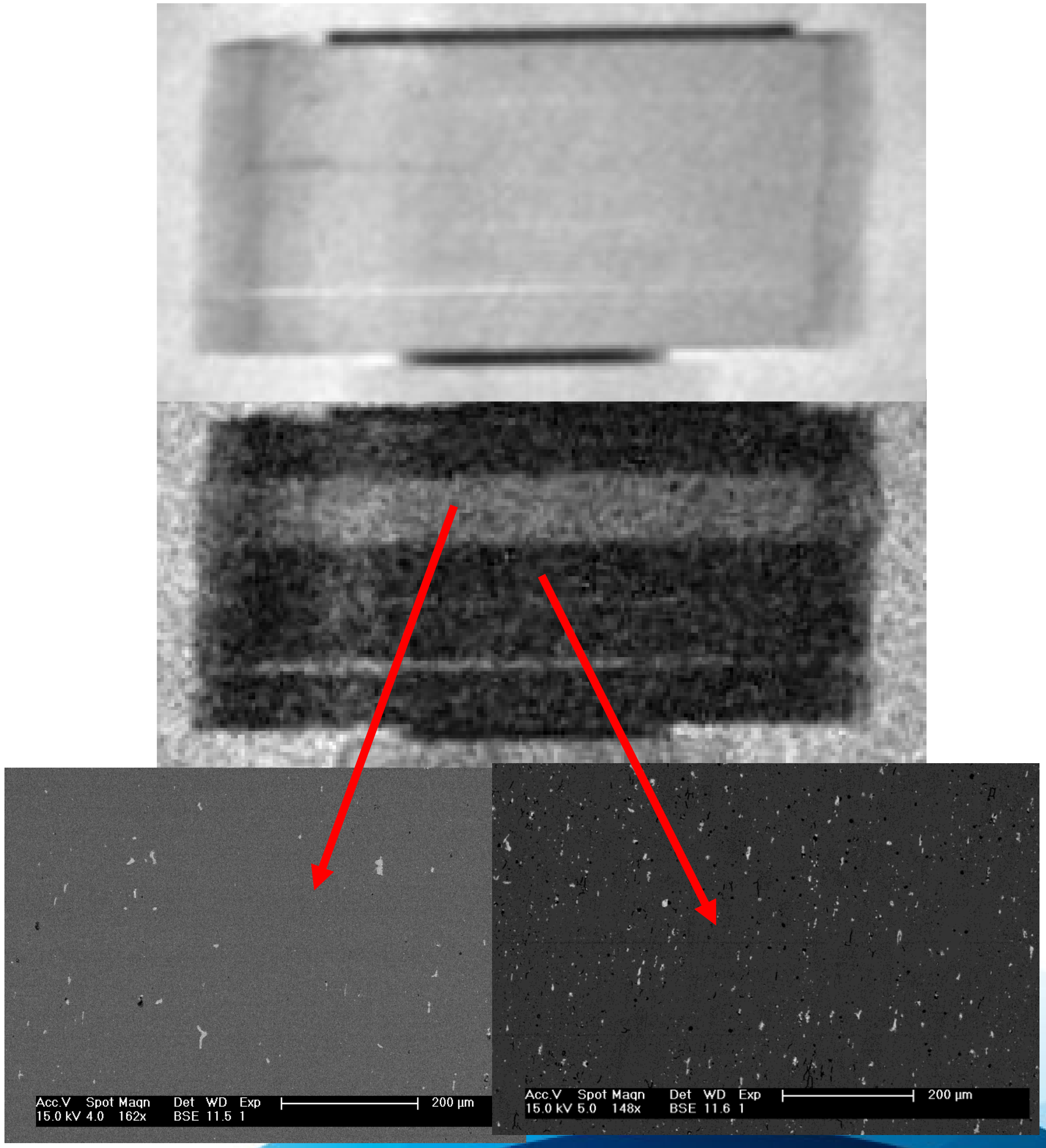


$$P_{\theta}(t) = w(\theta, t)^2 = \int_{path} \frac{\sigma(x,y)N(x,y)}{R^2(x,y)} \cdot ds$$

M. Strobl et al. PRL (2008)

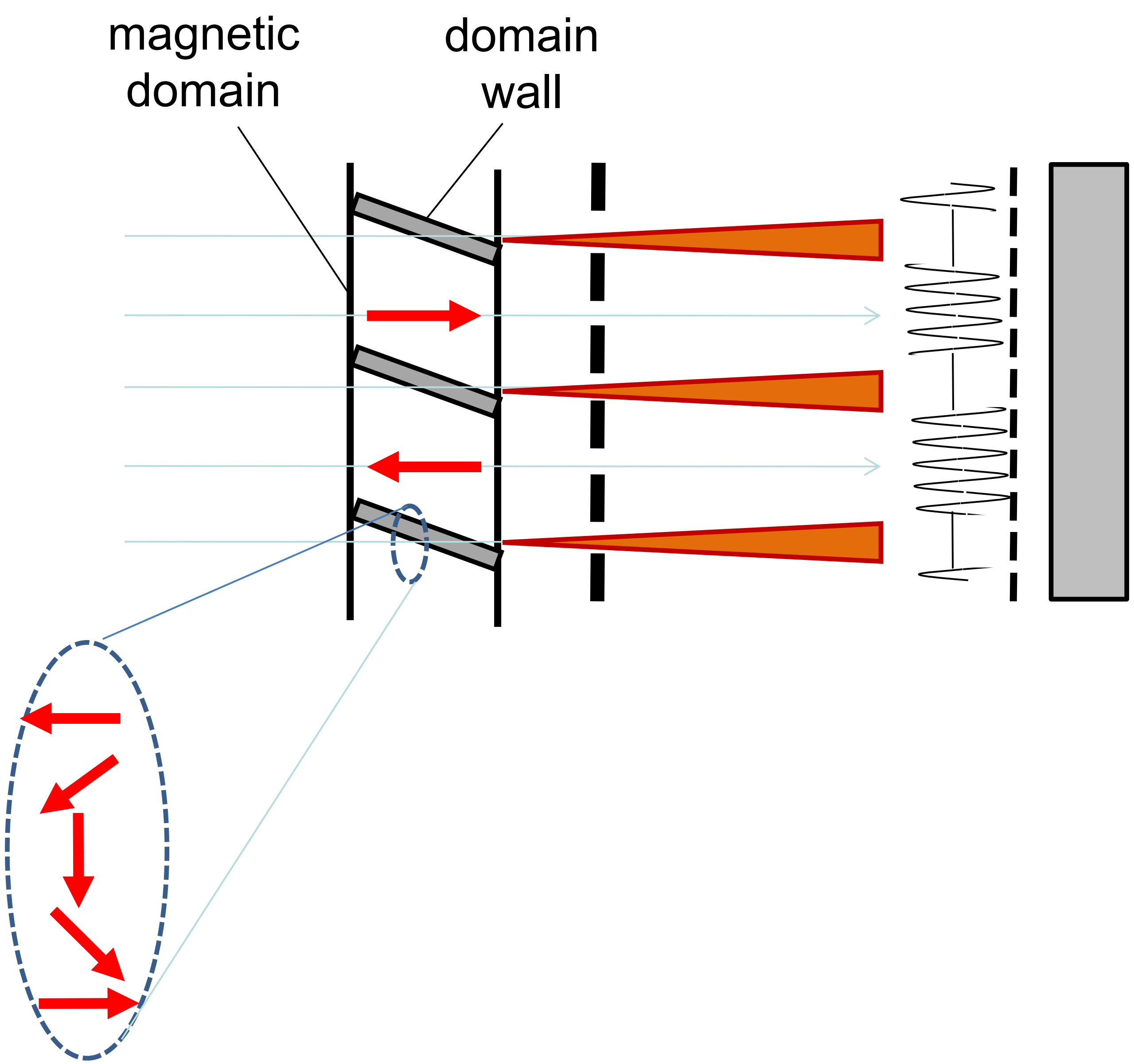
Dark field contrast

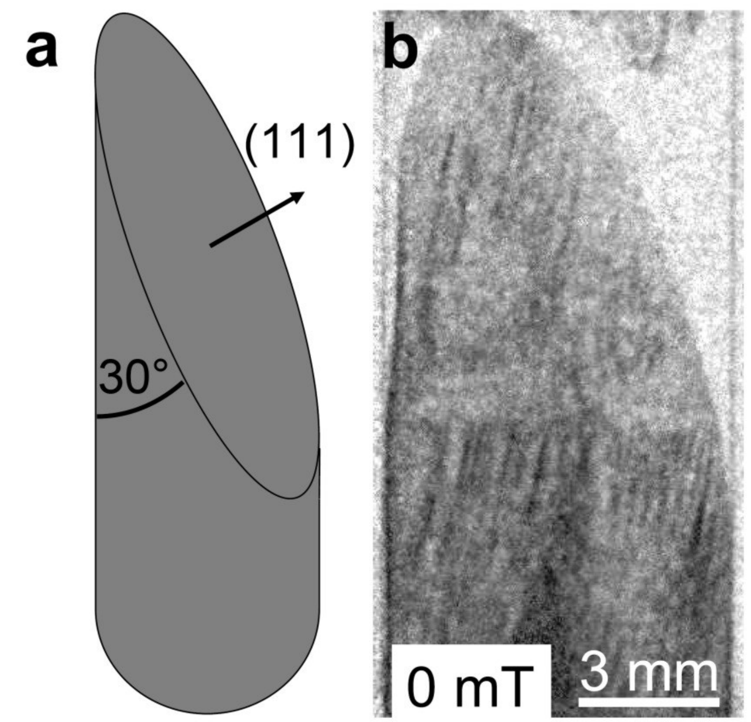




A. Hilger et al. JAP (2010)

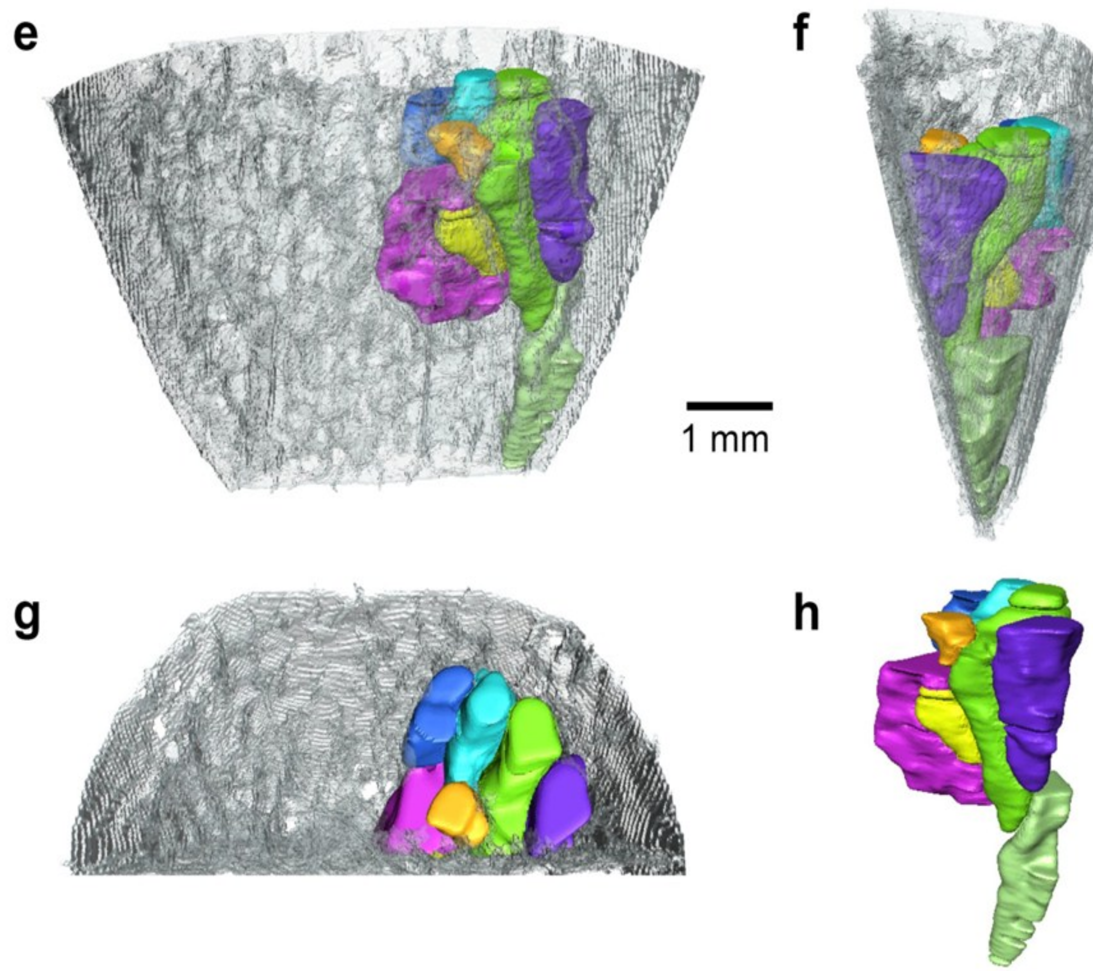
Dark-field NI

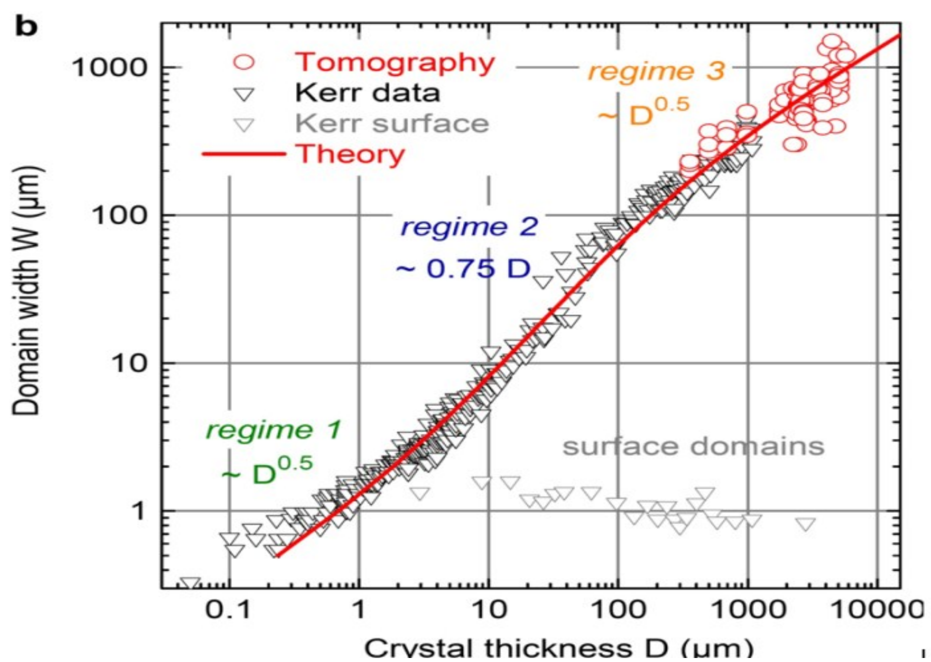


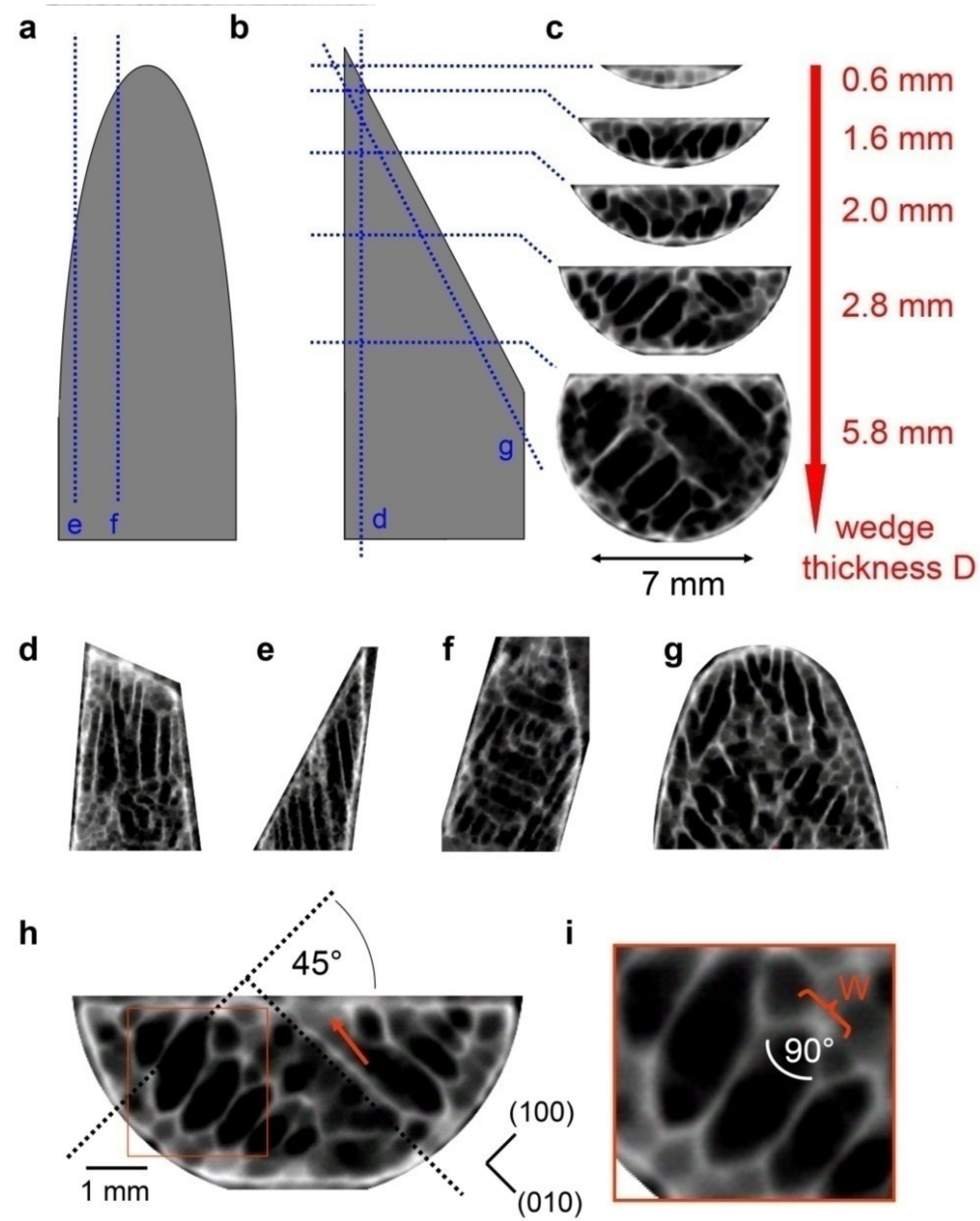


K. M. Podurets et al. Phys. B 1989
M. Strobl et al. APL 2007
Ch. Grünzweig et al. APL 2009

Dark field contrast







I. Manke et al., Nature comm. 2010

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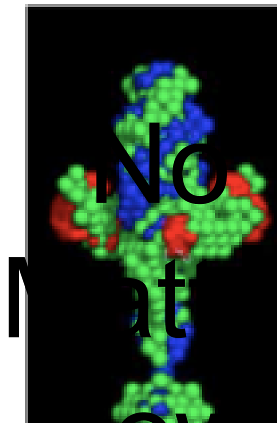
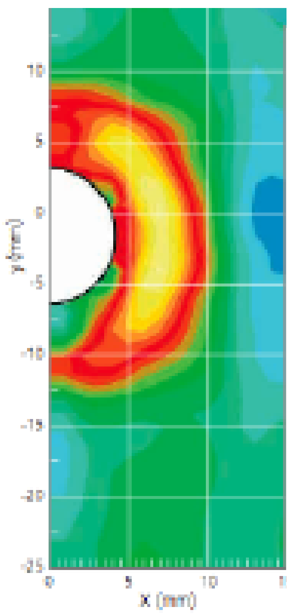
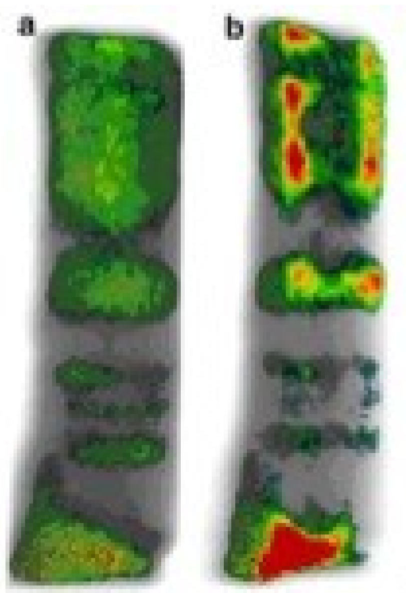
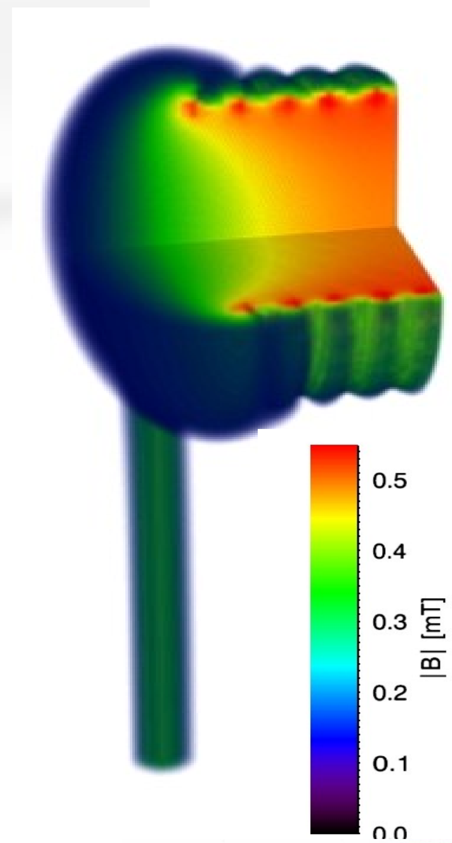
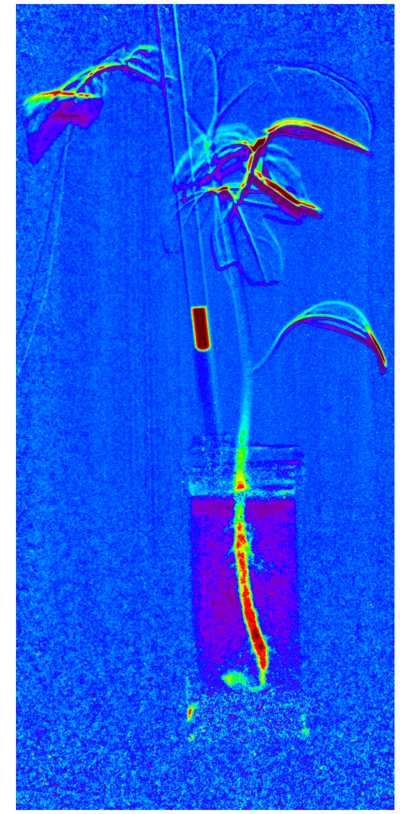
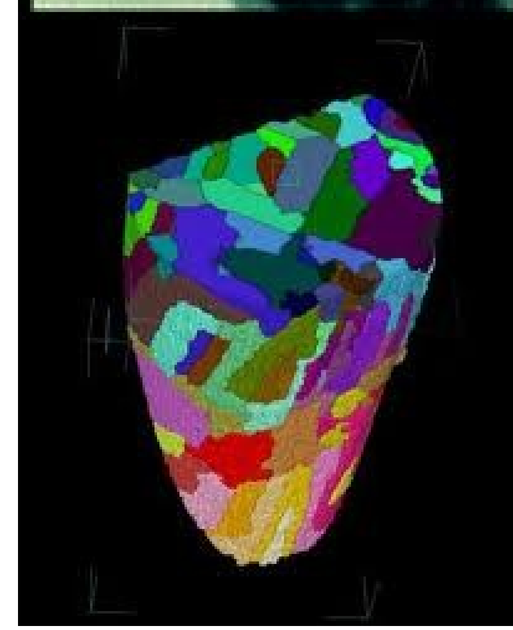
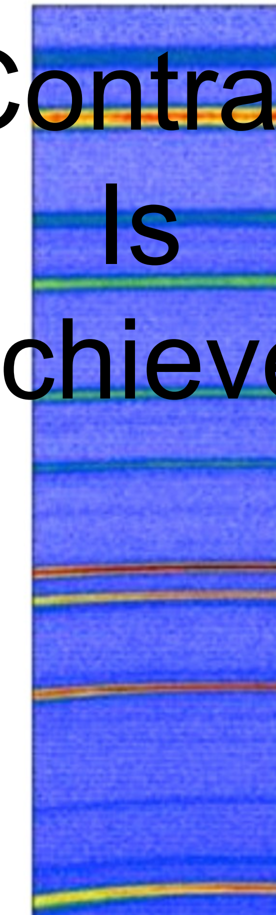
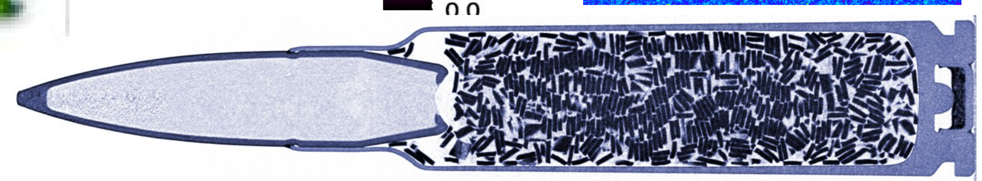
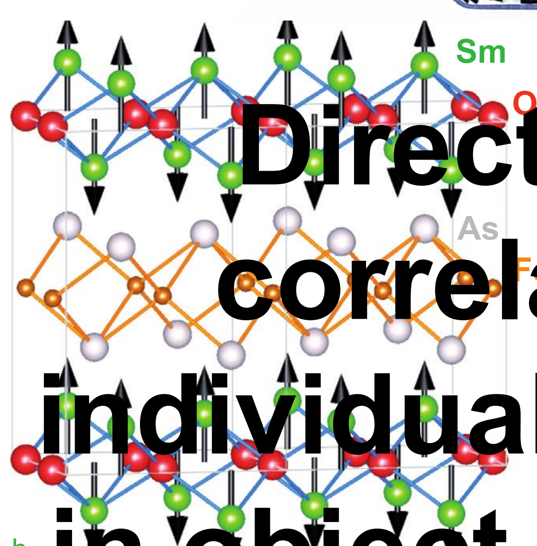


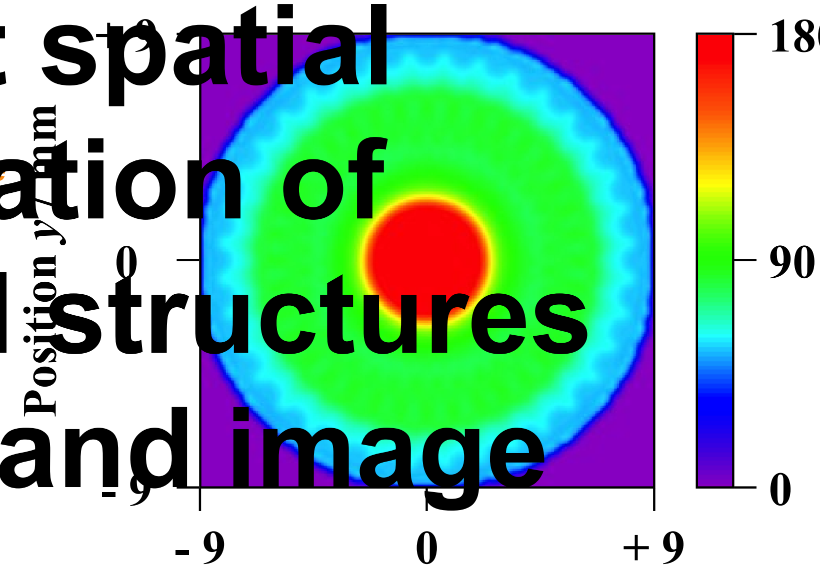
No Matter How Contrast Is Achieved

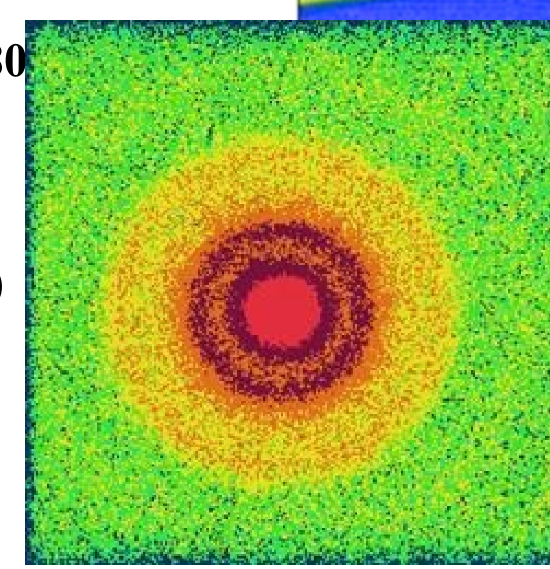









Direct spatial correlation of individual structures in object and image

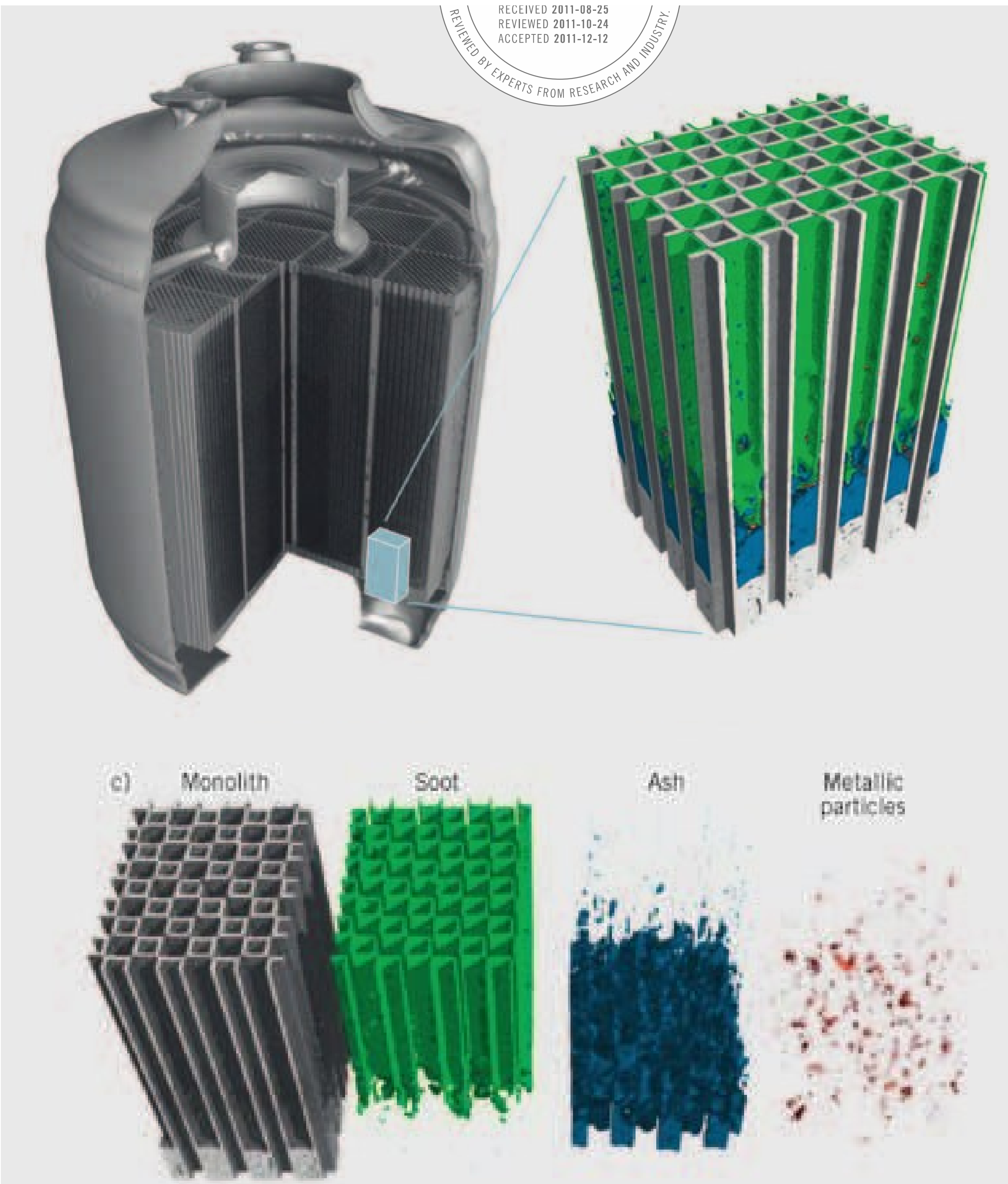
Courtesy E. Lehmann, PSI

EUROPEAN
SPALLATION
SOURCE

Markus Strobl

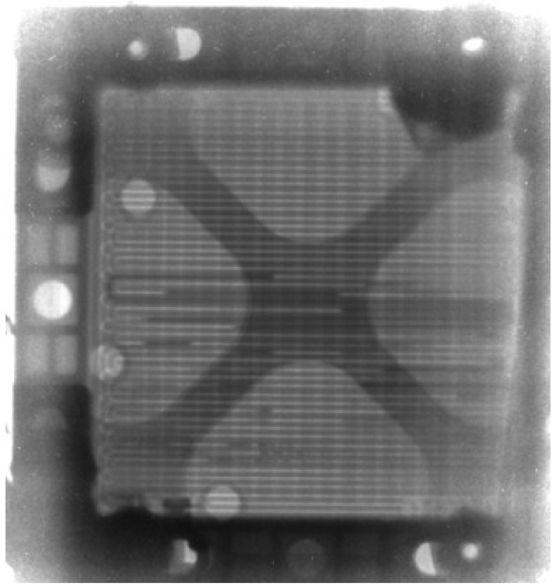
Instrumentation Division@ ESS

Neutron imaging applications

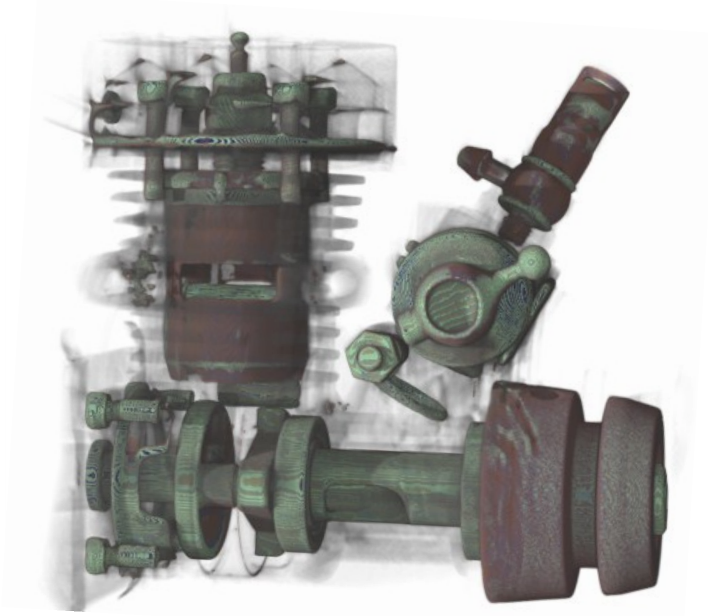


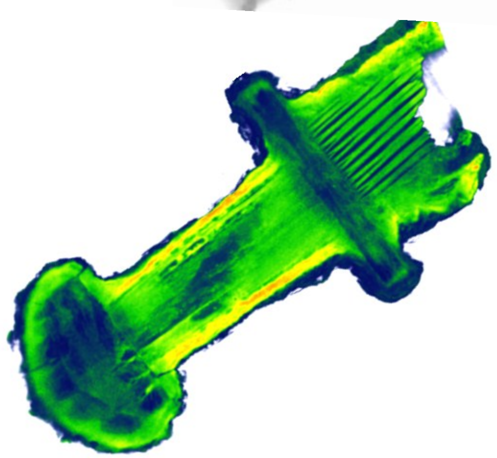
Introduction Neutron imaging

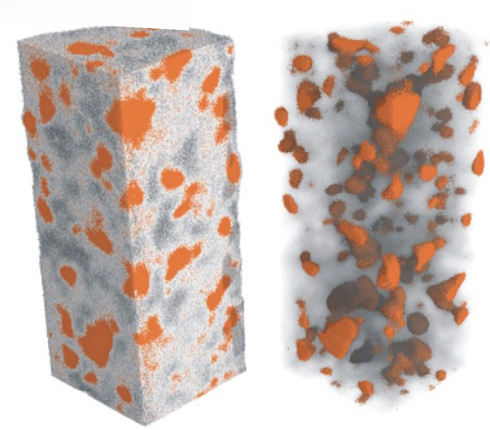
Imaging Applications

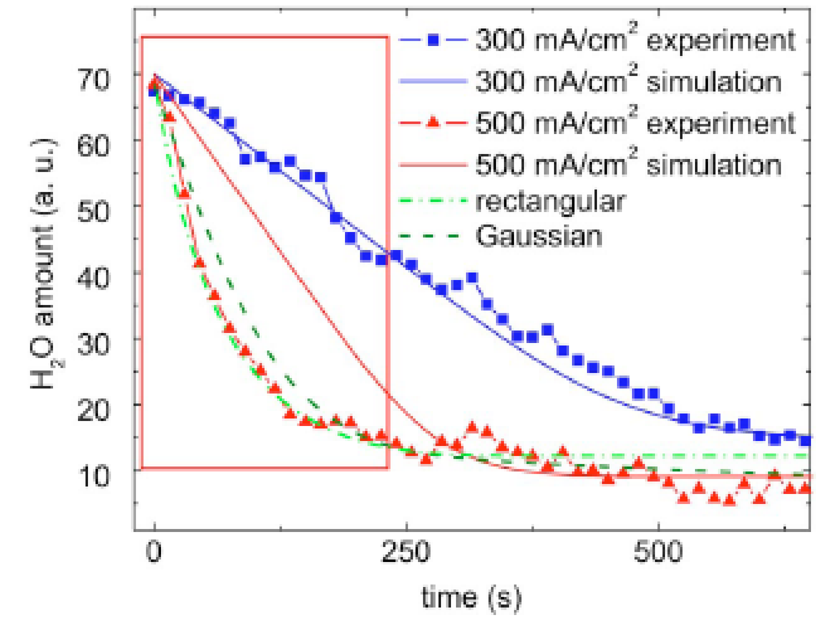


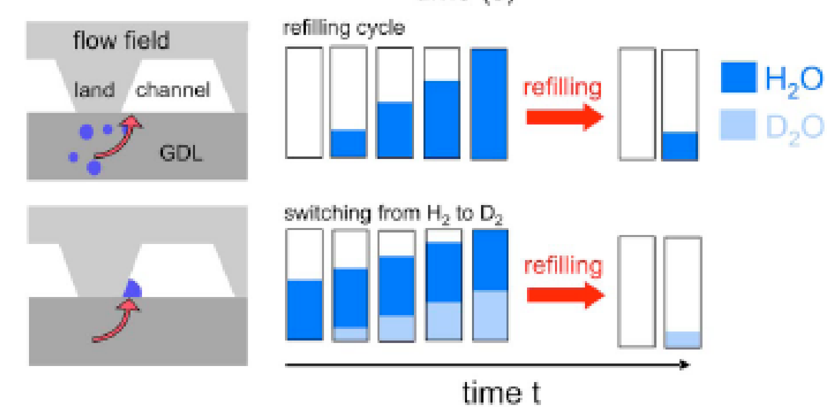
R&D
Biology
& Agriculture
Geology
Archeology
Paleontology
Art History
Material science
& Engineering
Industry
etc.











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