Helmholtz Zentrum Berlin

SoNS 2014

Neutron imaging I

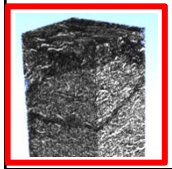
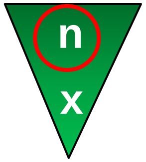
Nikolay Kardjilov

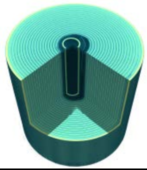
Introduction

Introduction

Institute of Applied Materials

Neutron ***Imaging*** *Micro CT* *Synchrotron*

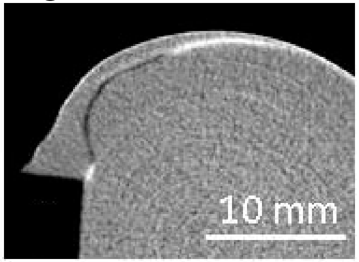





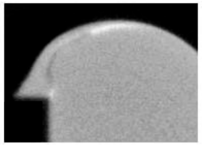

CONRAD at HZB
in operation since 2005

Method development

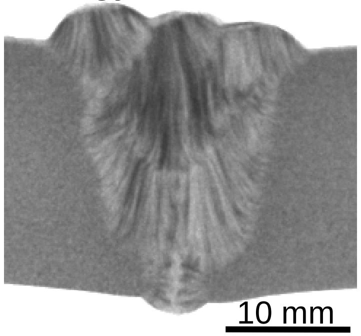
high resolution



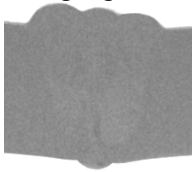
conventional detector



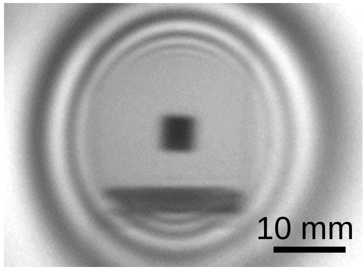
energy-selective imaging



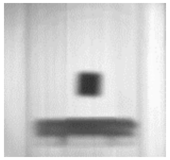
white-beam imaging



magnetic imaging

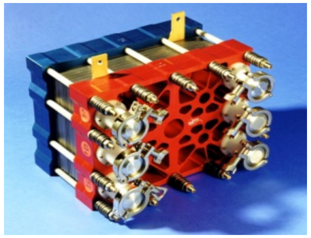


absorption contrast



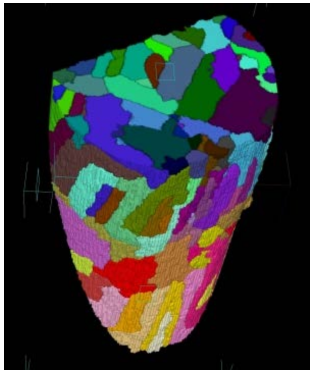
Applications

Energy sources



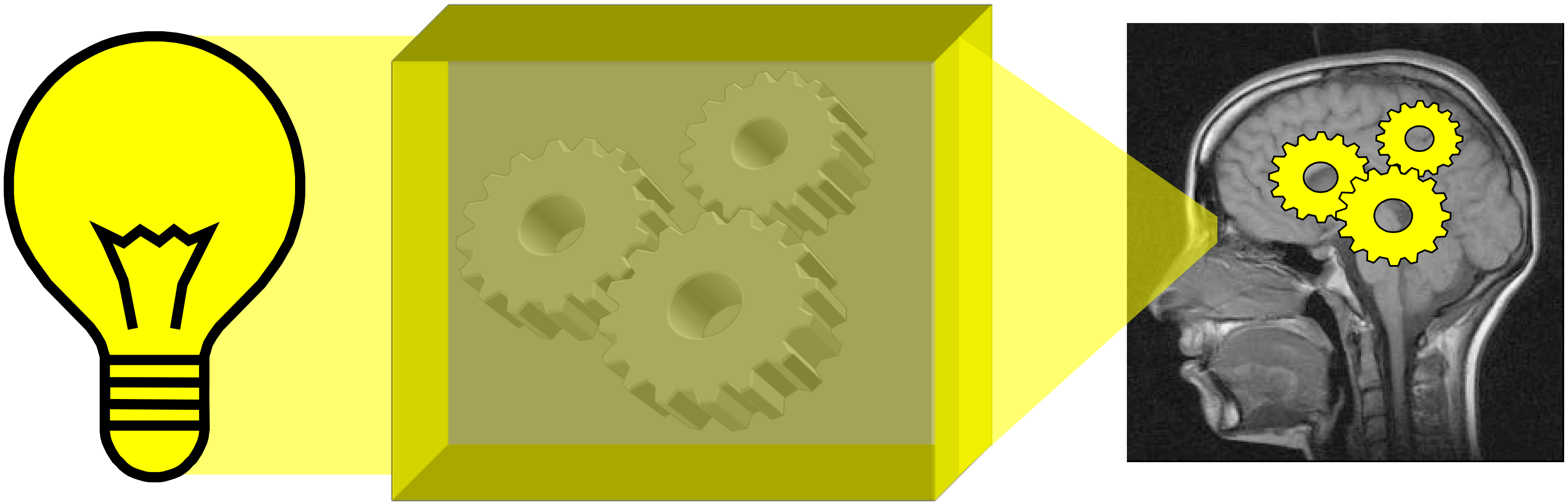
Energy storage

Materials research

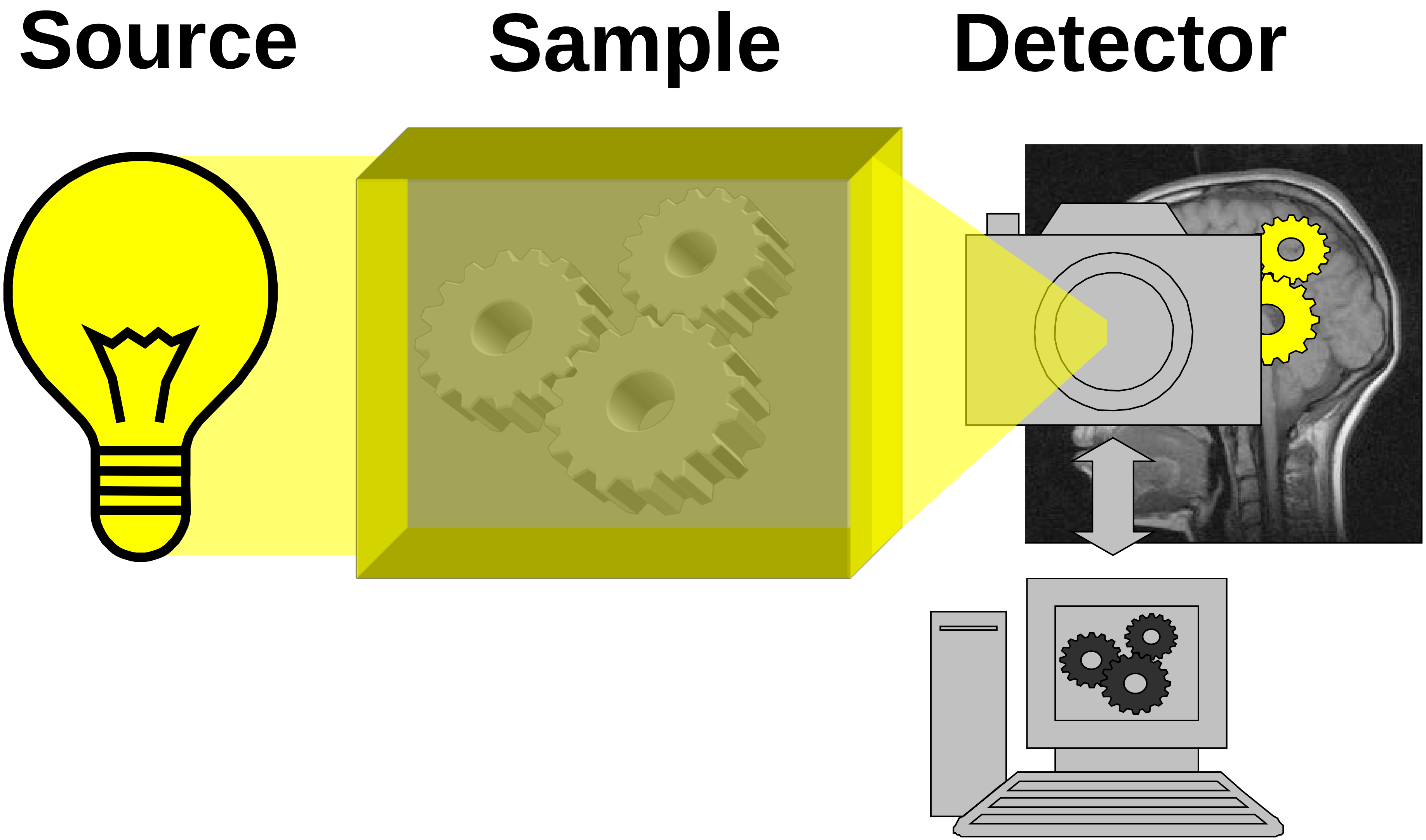


Neutron imaging

Neutron imaging



Neutron imaging



Introduction

X-ray

First experiments with a new kind of radiation were performed by Konrad Röntgen in 1895 during investigations with cathode-ray tubes.

He found the new ray could pass through most substances casting shadows of solid objects.

In conjunction with a photographic plate, a picture of interior body parts can be obtained when human tissue will be investigated.

Introduction

One of the first experiments late in 1895 was a film of a hand of his wife.

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

Neutron imaging

Introduction

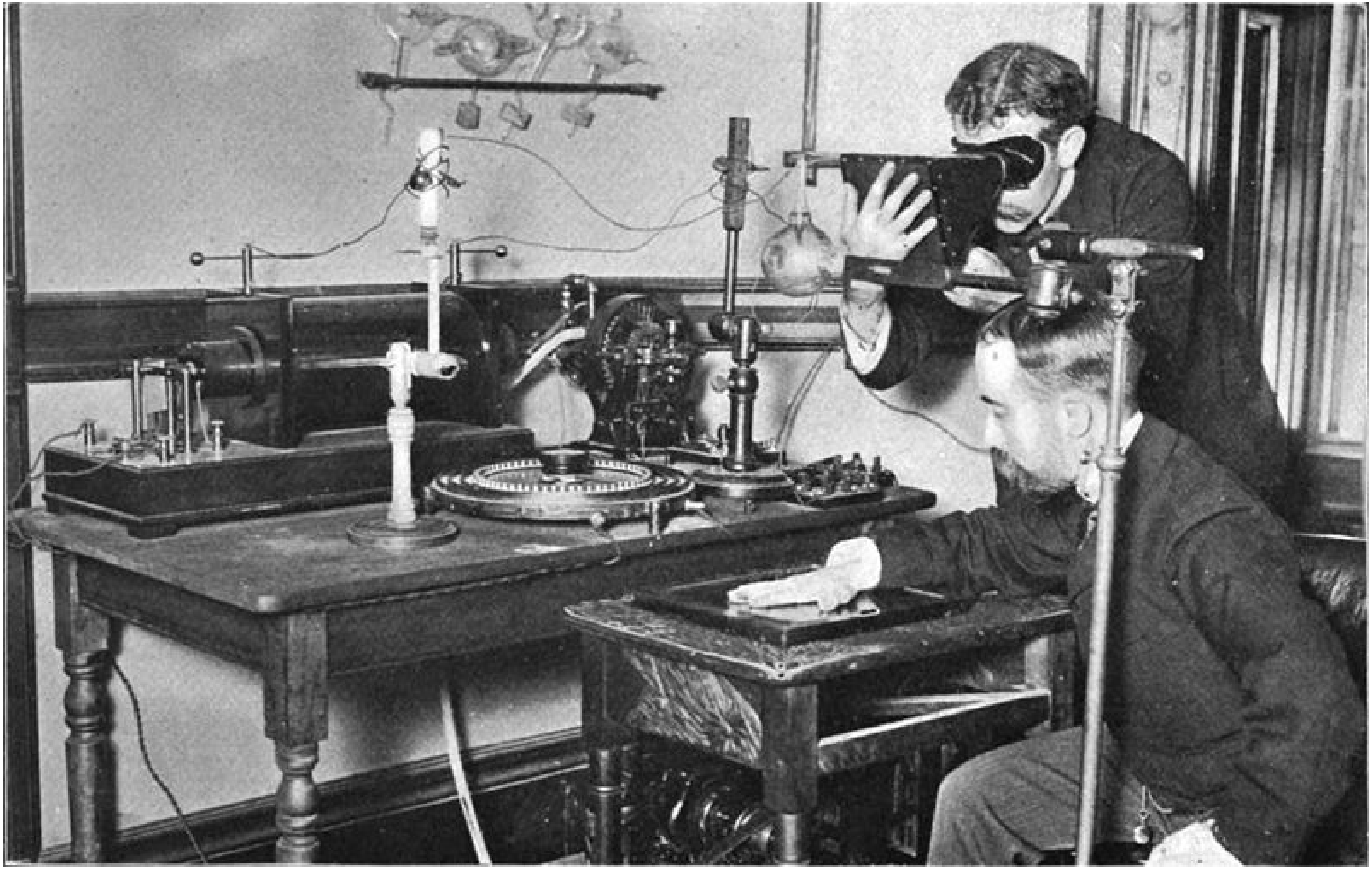
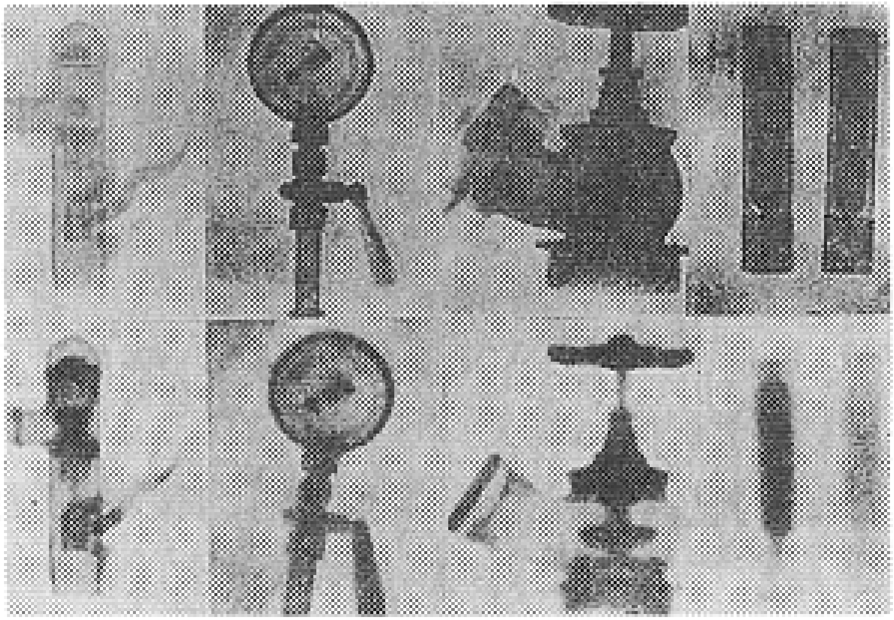


Photo of experimenters taking an X-ray with an early Crookes tube apparatus, from the late 1800s.

Neutron imaging

Roots of neutron radiography

Comparison between x-ray
and neutron images



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

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

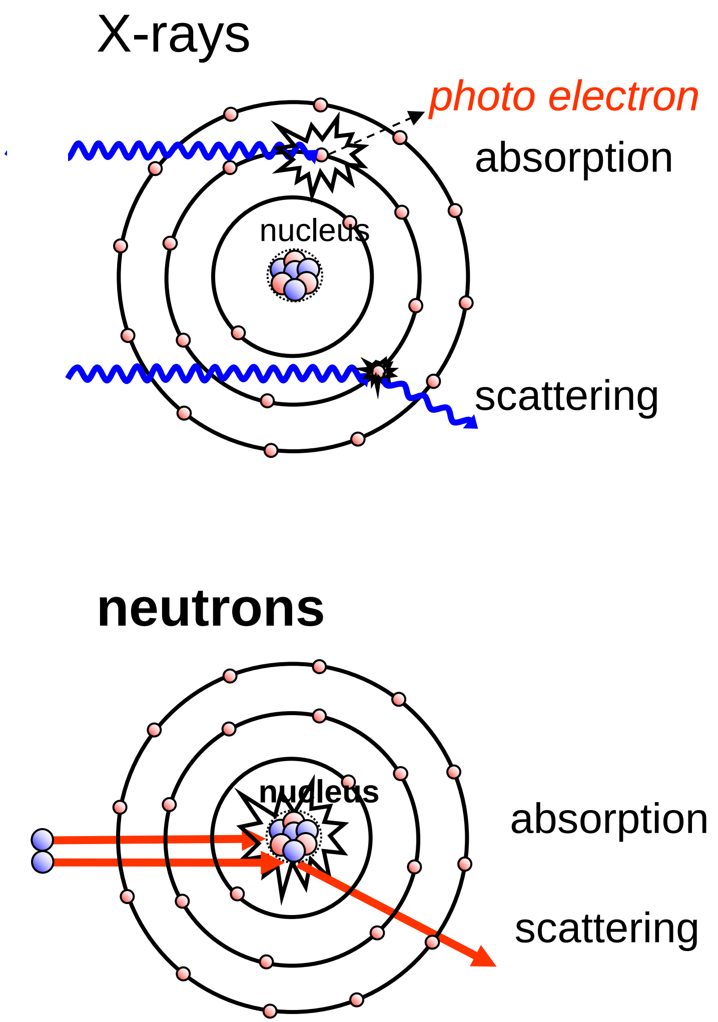
But the real programs with neutrons started after World War II at research reactors

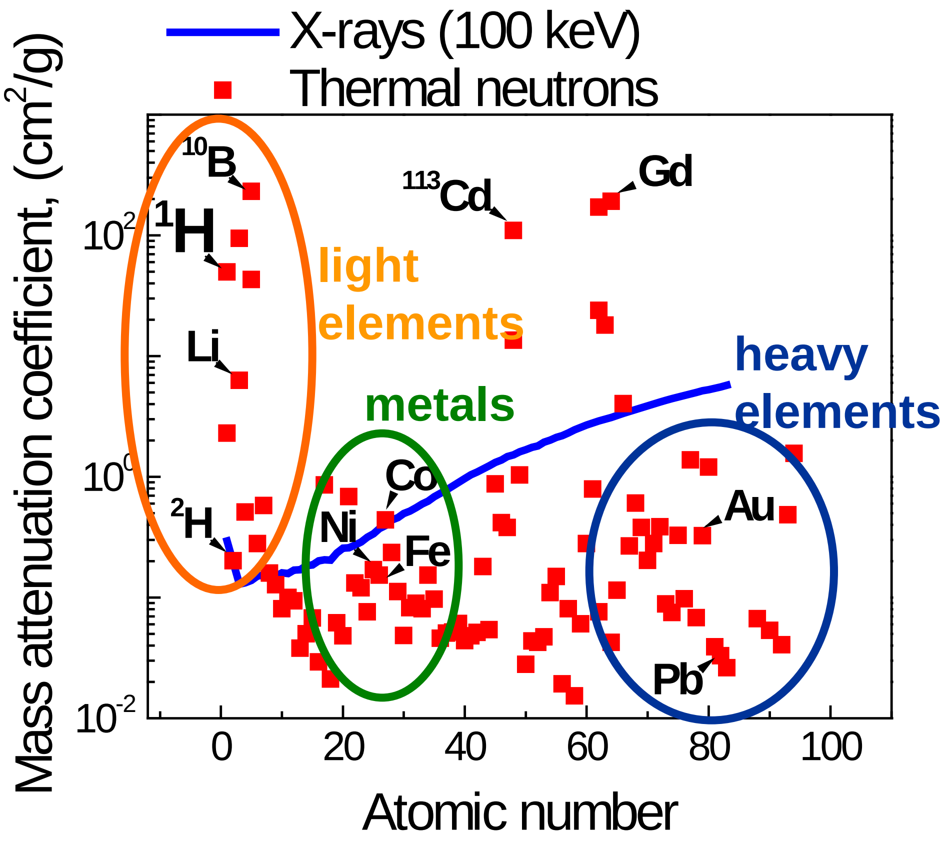
Introduction

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

Neutron imaging

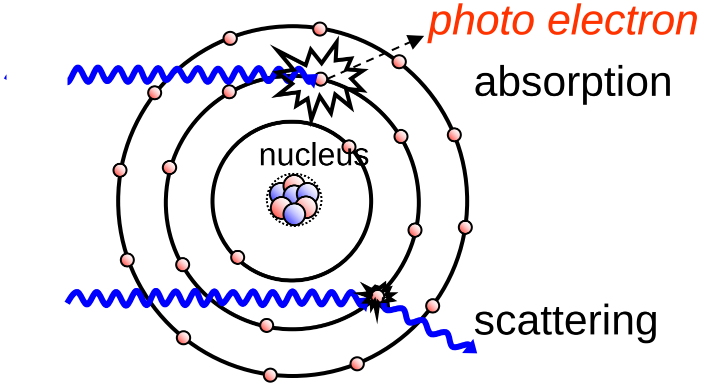
Neutron interaction with matter





Neutron interaction with matter

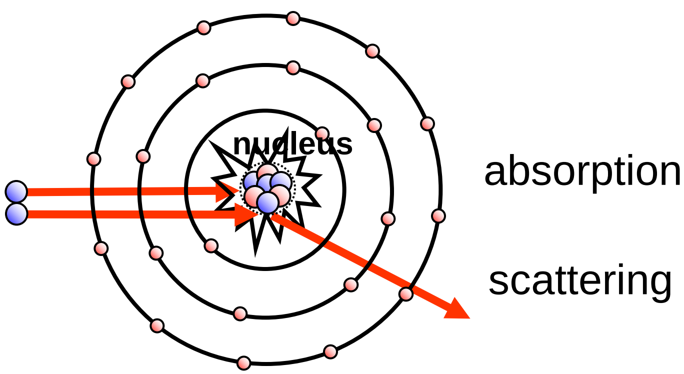
X-rays



Attenuation coefficients with X-ray [cm?[1]]

1a	2a	3b	4b	5b	6b	7b	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			

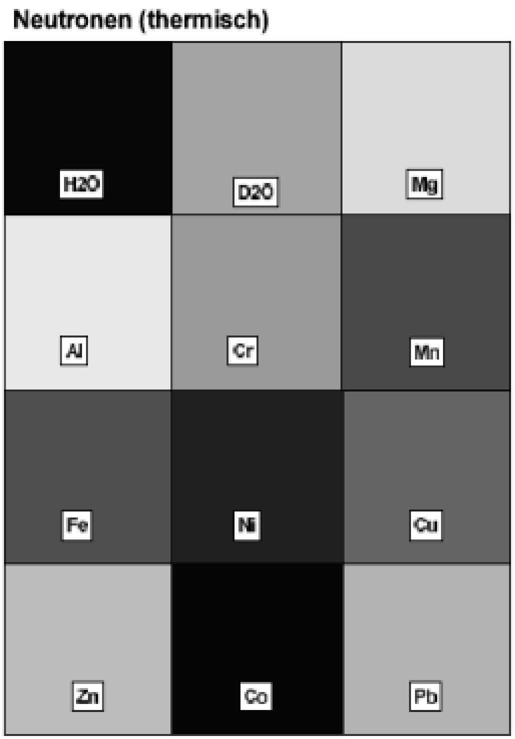
neutrons

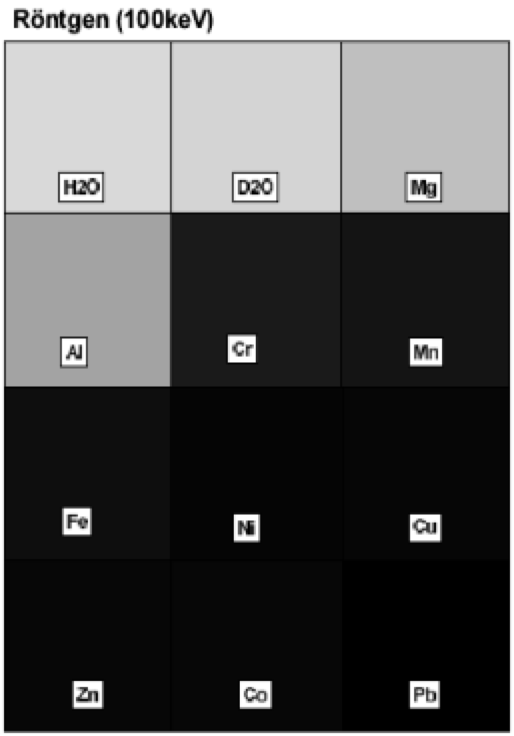


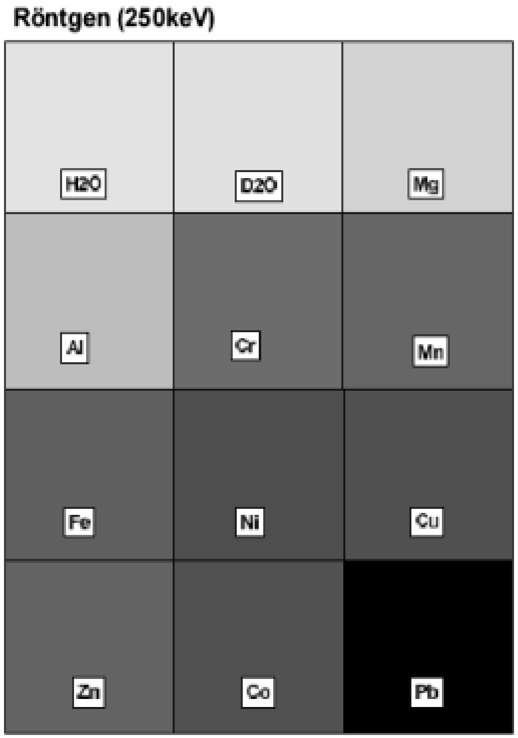
Attenuation coefficients with neutrons [cm?[1]]

1a	2a	3b	4b	5b	6b	7b	8			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 - contrast

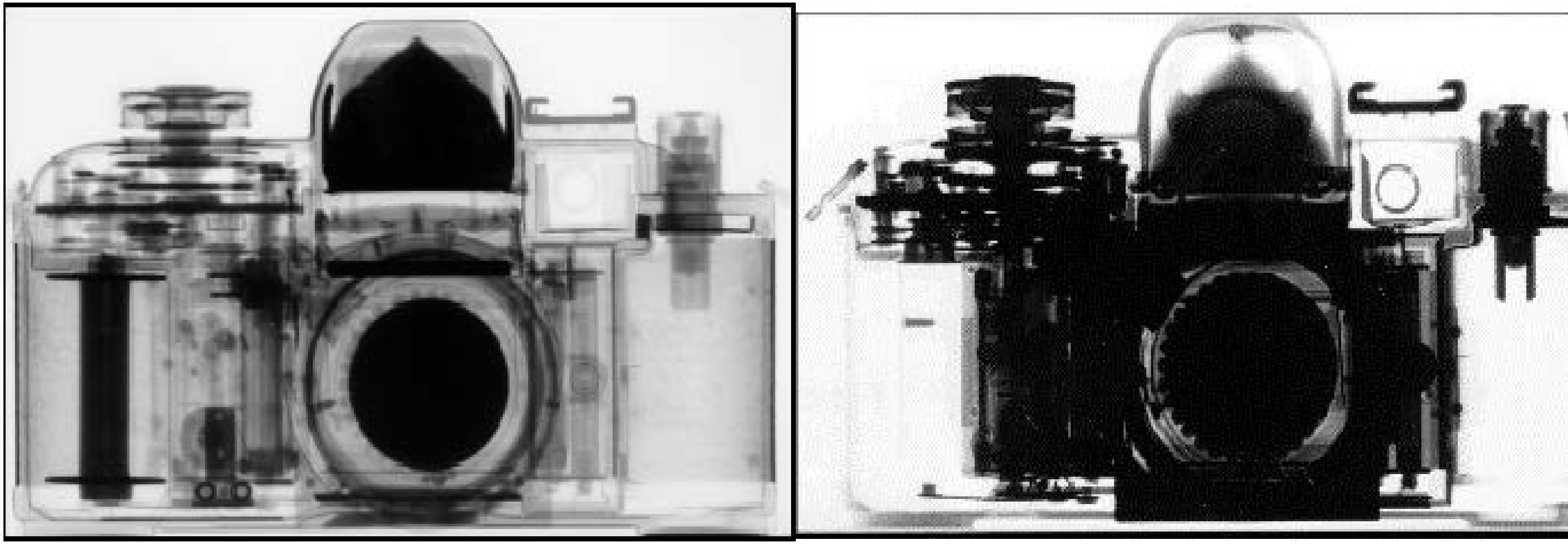






Images courtesy: Dr. Eberhard Lehmann (Paul-Scherrer-Institute, Switzerland)

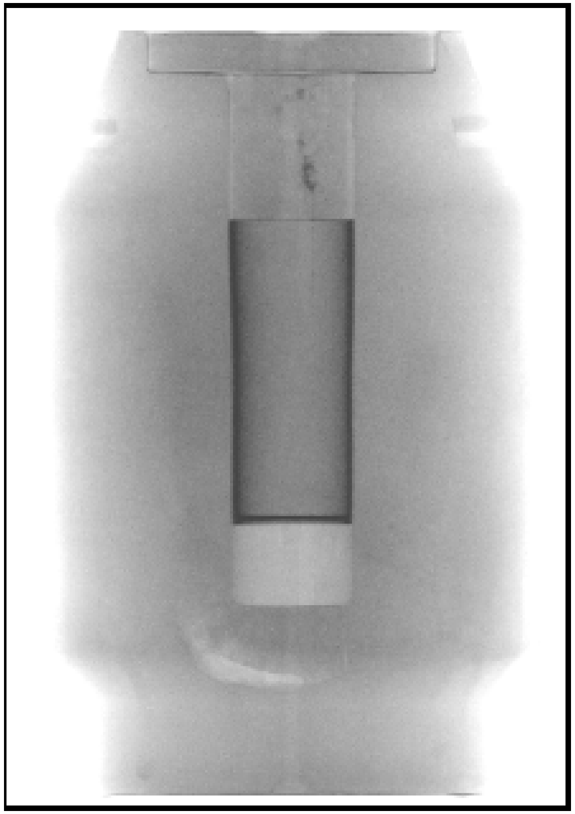
Neutron radiography - examples

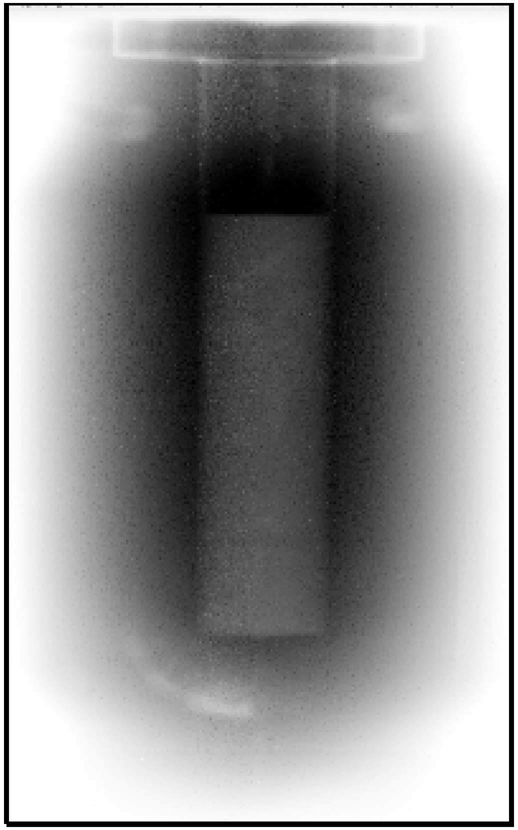


The example for a camera helps to explain differences in neutron (left) and X-ray (right) radiography. Whereas the hydrogen containing parts can be visualised with neutron even at thin layers, thicker metallic components are hard to penetrate with X-rays.

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

Neutron imaging

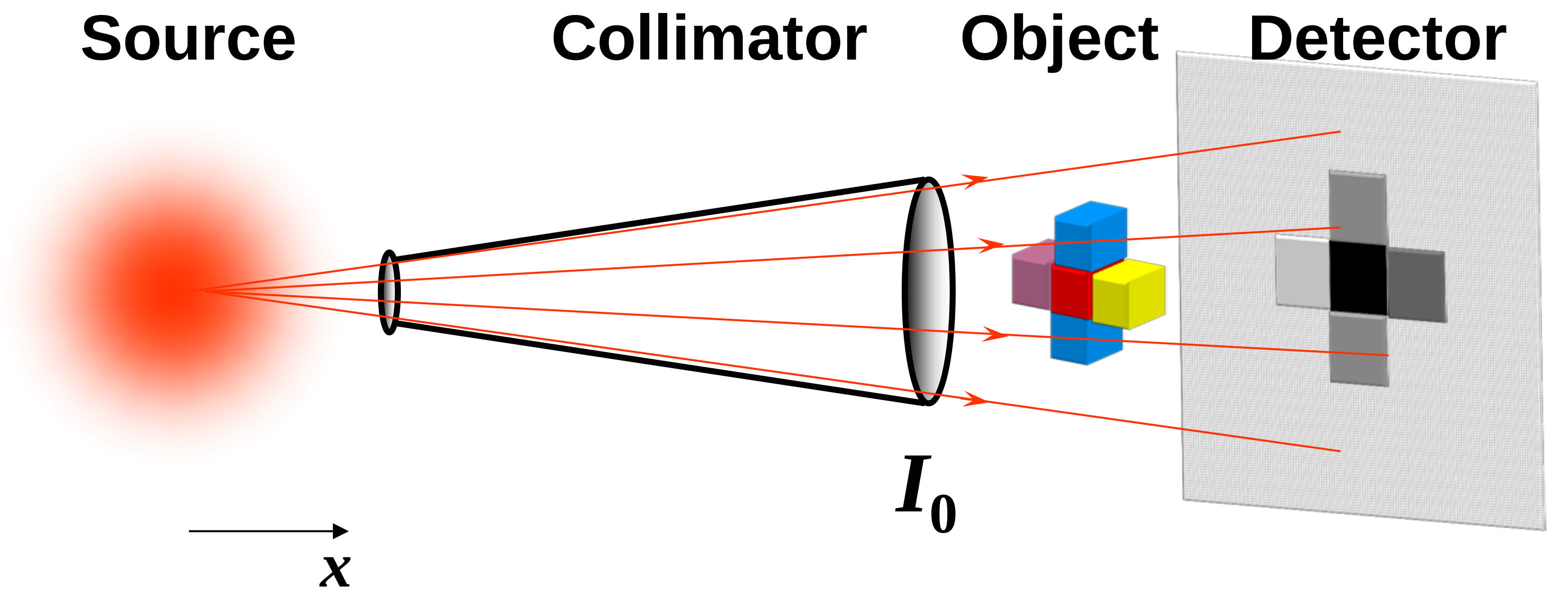




Observation of a lead container. The neutron image on the left was obtained after 20 s. On the right, the gamma radiography with Co-60 (1100 keV) needed 120 minutes of exposure.

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

Beam optimisation



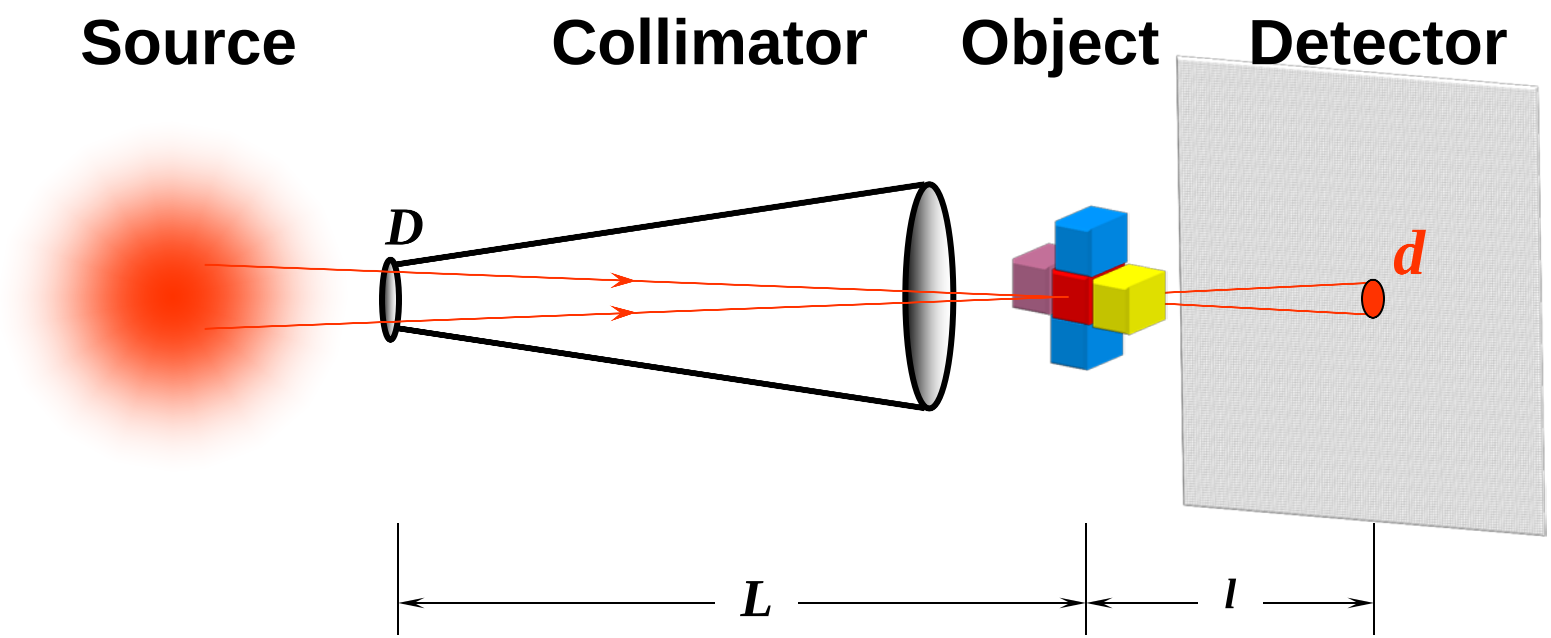
$$\sim I_0 e^{-\int \Sigma(x)dx}$$

x – propagation direction

I_0 – primary beam

$\Sigma(x)$ – attenuation coefficient

Beam optimisation



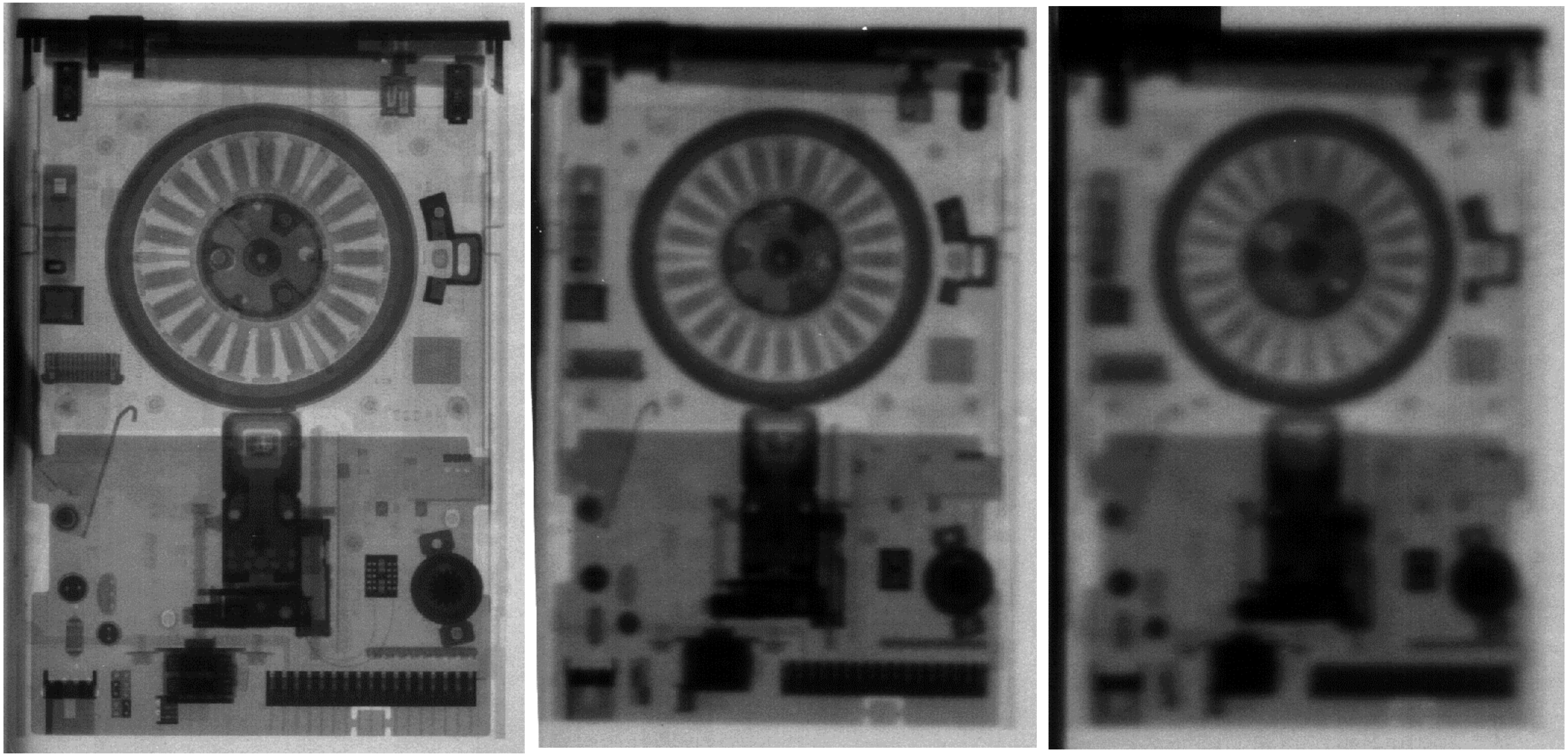
D – Collimator aperture

L – Distance Collimator-Object

l – Distance Object-Detector

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

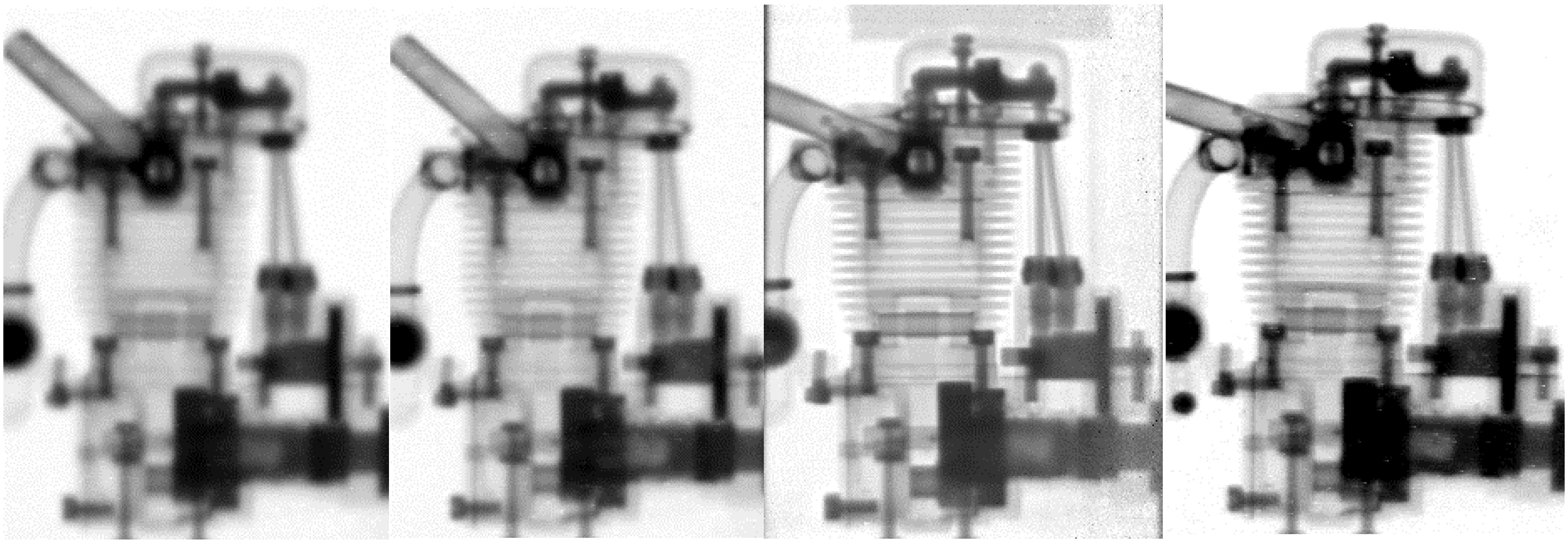
Neutron imaging



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

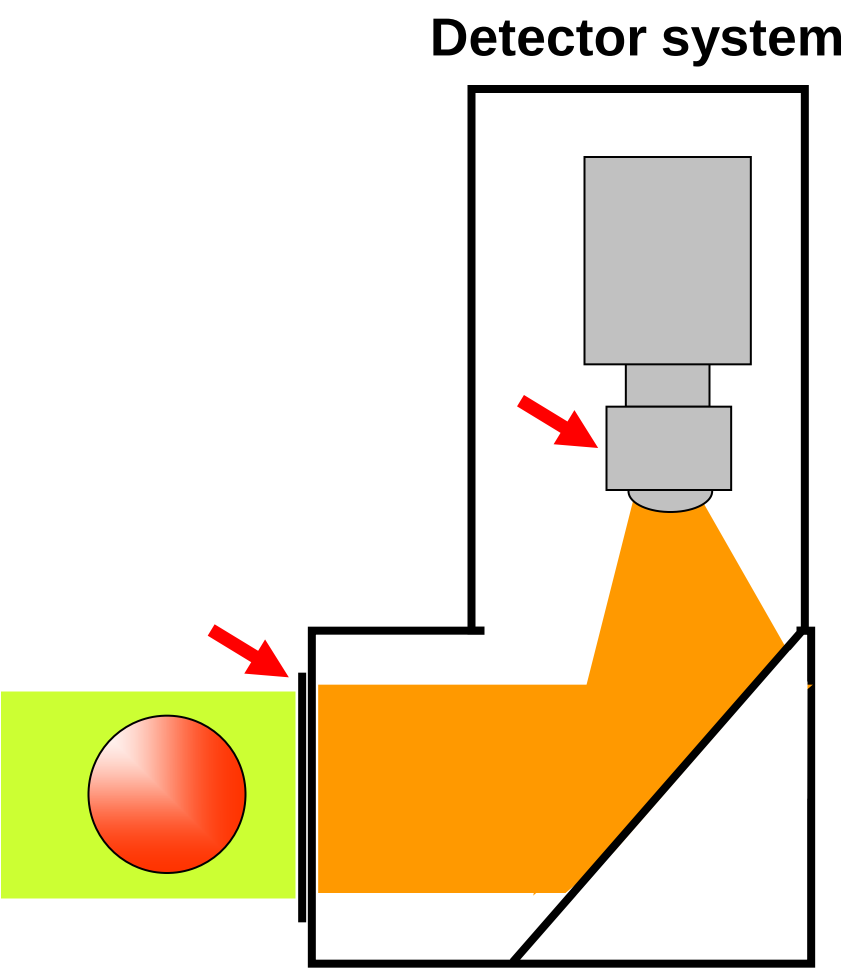


L/D=71 L/D=115 L/D=320 L/D>500.

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

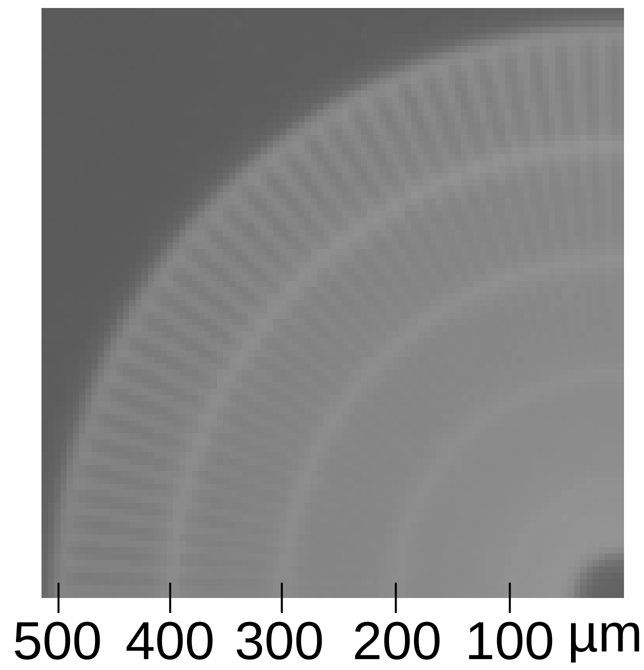
B. Schillinger, Estimation and measurement of L/D on a cold and thermal neutron guide, in: Nondestructive Testing and Evaluation, World Conference on Neutron Radiography, vol. 16, Osaka, 1999, pp. 141–150

Detector development



Standard setup

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



Neutron imaging

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%)

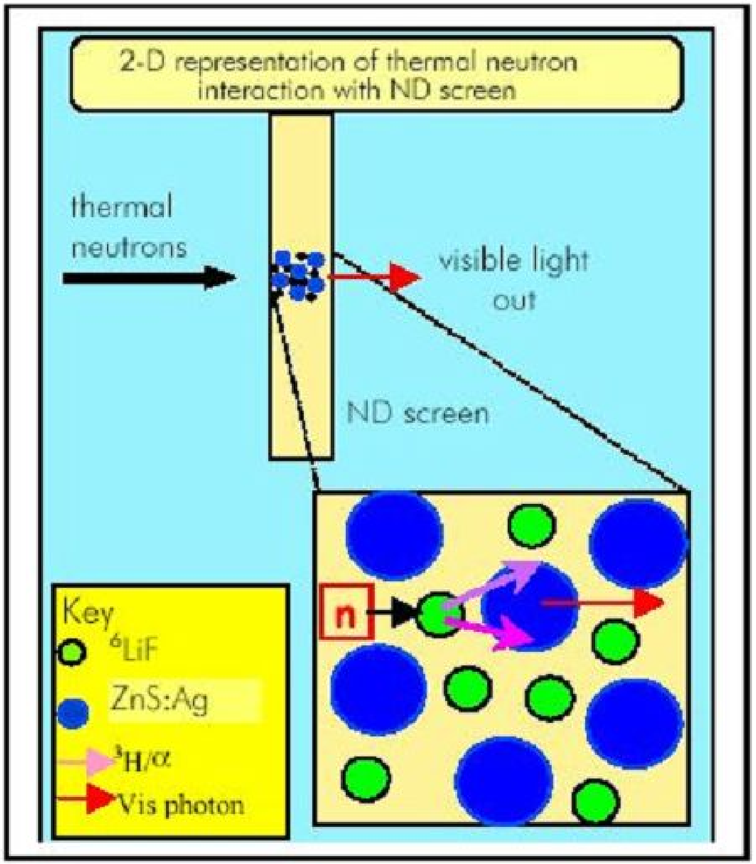
$^{155}Gd + {}^{1}n \Rightarrow {}^{156}Gd + \gamma´s + CE´s\ (7.9\ MeV)$

→

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

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

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



The reaction products of

$^{6}Li(n,\alpha)^{3}H$ + 4.7 MeV

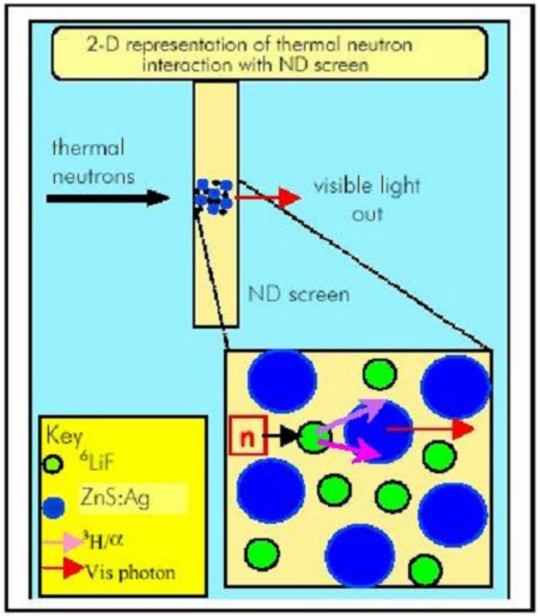
have to be stopped in the ZnS scintillation screen.
Their average range is in the order of 50-80 μm.

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)

The ZnS+^{6}LiF scintillation screen



- One detected neutron produces about 177,000 photons, roughly into 4 Pi space
- The material is opaque for its own light
  - →thickness beyond 0.3 mm makes no sense, produces less light
  - →Due to exponential attenuation, more neutrons are absorbed in the beginning of the screen
    - →less light output to the back
  - →No fixed amount of light per neutron emitted towards the back
  - →Absolute counting is not possible
- Best thickness: 0.1 mm
  Resolution about 0.08 mm
- 0.2 mm thickness producs only 1.5 times as much light

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

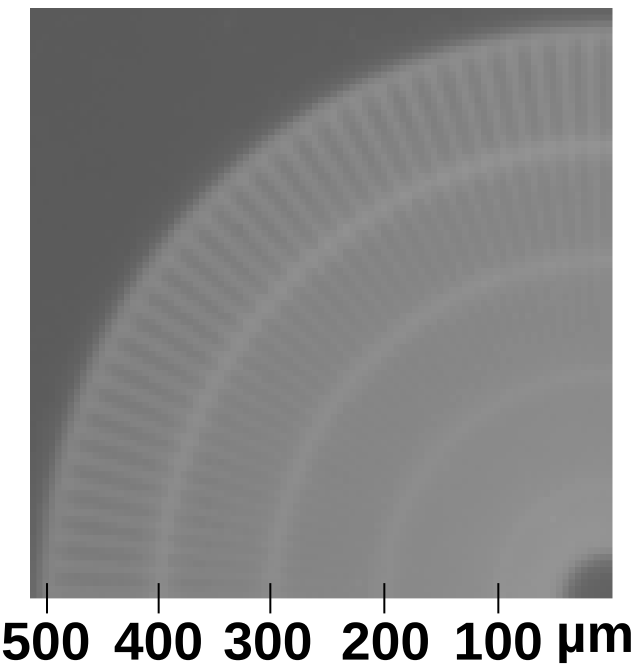
Nikon Micro Nikkor 200mm f/4 D (IF) ED

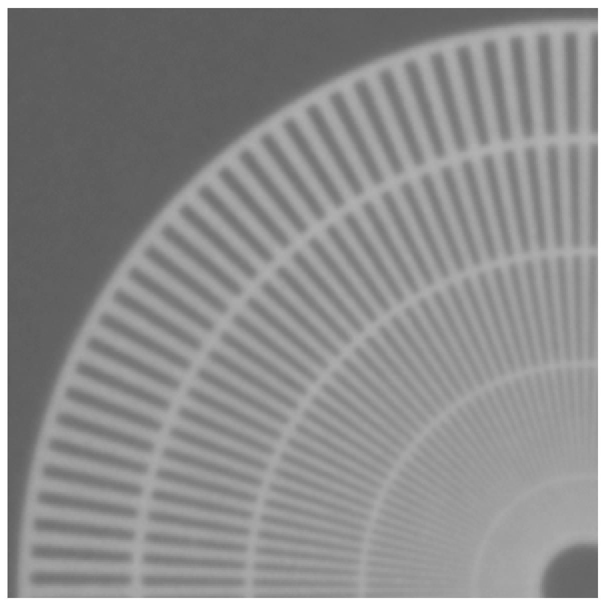
1:1 imaging
FOV_{max}: 2.8 cm x 2.8 cm, pixel size: 13.5 µm

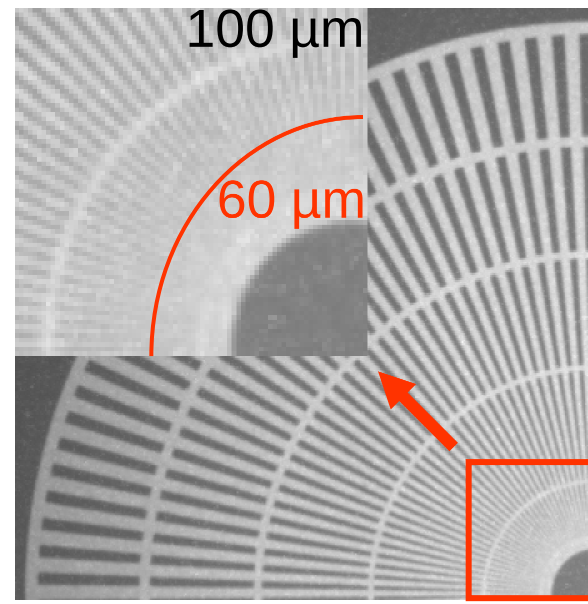
Neutron imaging

Detector development

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

The signal chain

Now let's do it backwards:

- We have a sample that attenuates the neutron beam by 50%.
- We want to detect a 2% variation in the sample.
  (Say, a crack or bubble within the sample.)
- This means 1% of the full neutron fluence (without sample) on one pixel.
- The poisson noise in any particle distribution is sqrt(N), and our signal must be above the noise.
- sqrt(100) =10, sqrt(1,000)= 31.6 , sqrt(10,000)=100
- so we must DETECT at least 10,000 neutrons per pixel to be equal to noise level !
- The detection efficiency of the screen is in the order of 20-30%, say 25%.
- This means we need 40,000 incoming neutrons on one pixel !

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

The signal chain

Now let's do it backwards:

• Let's say the lens system projects an area of 0.1 mm x 0.1 mm of the screen onto one pixel of 12 um x 12 um size, we detect several photons per neutron (remember: 177,000 photons are generated in the screen per detected neutron).

• So we need 40,000 neutrons per 0.1 mm x 0.1 mm, which is 40,000 x 10,000 neutrons per 1 cm^2, a total fluence of 4x 10^8n/ cm^2.

• In a beam with a neutron flux of 1 x 10^6/ cm^2s, we need 400 seconds or 6 minutes 40 seconds exposure time.

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

The signal chain

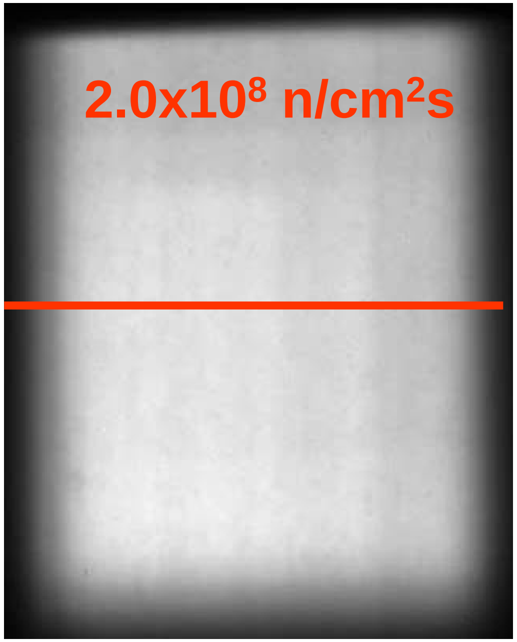
Now let's do it backwards:

- This means the dynamic resolution of neutron imaging depends on the NEUTRON statistics, and NOT on the PHOTON statistics!
- It makes no sense to employ a super light collecting lens that transmits dozens of photons per neutron – and makes the camera overflow before the required neutron statistics is reached!
- BUT the lens should collect several photons per detected neutron so that the photon statistics does not influence the neutron statistics.

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

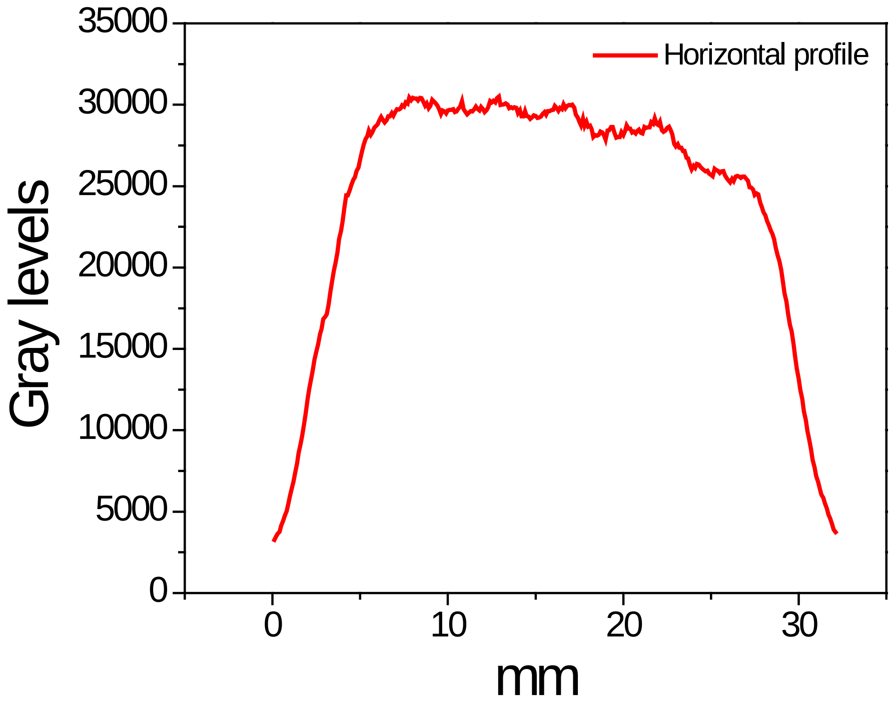
Real-time imaging

Open beam image



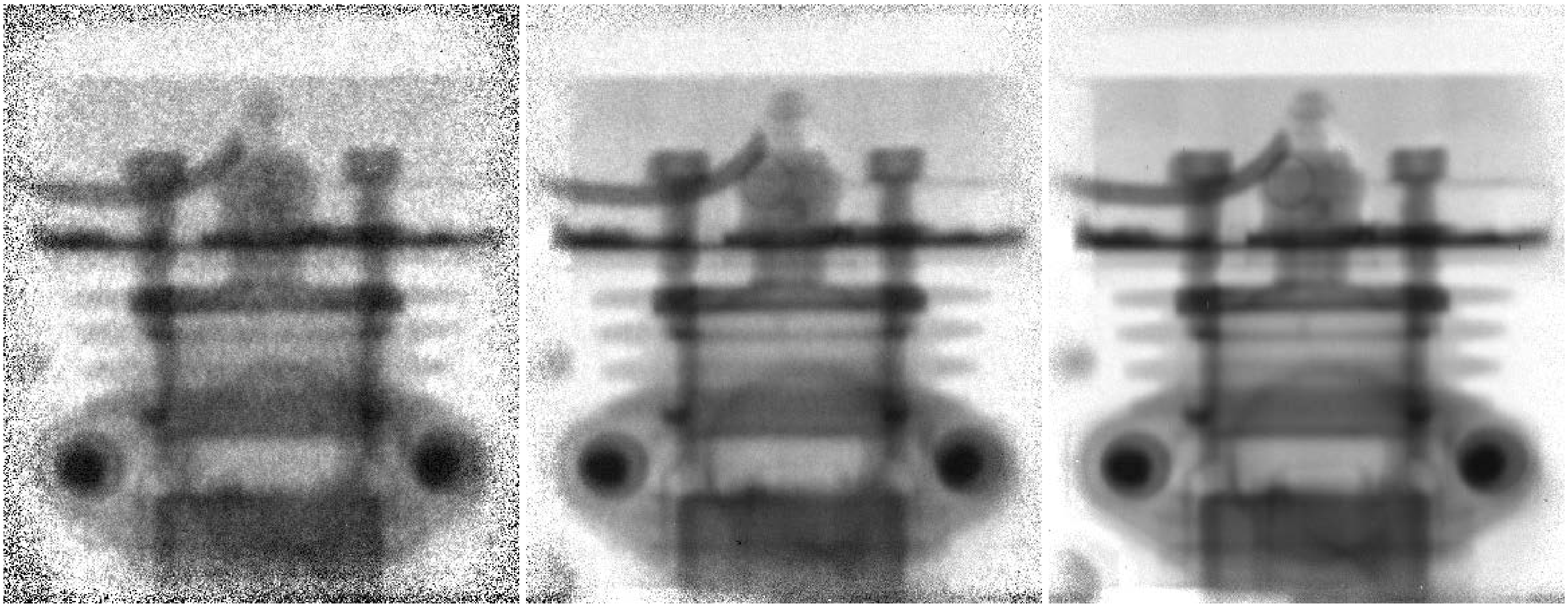
5 cm

3 cm



Exposure time: 0.4 s
SensiCam PCO (1280 x 1024) – 12 bit

Exposure times: 4 ms 40 ms 400 ms



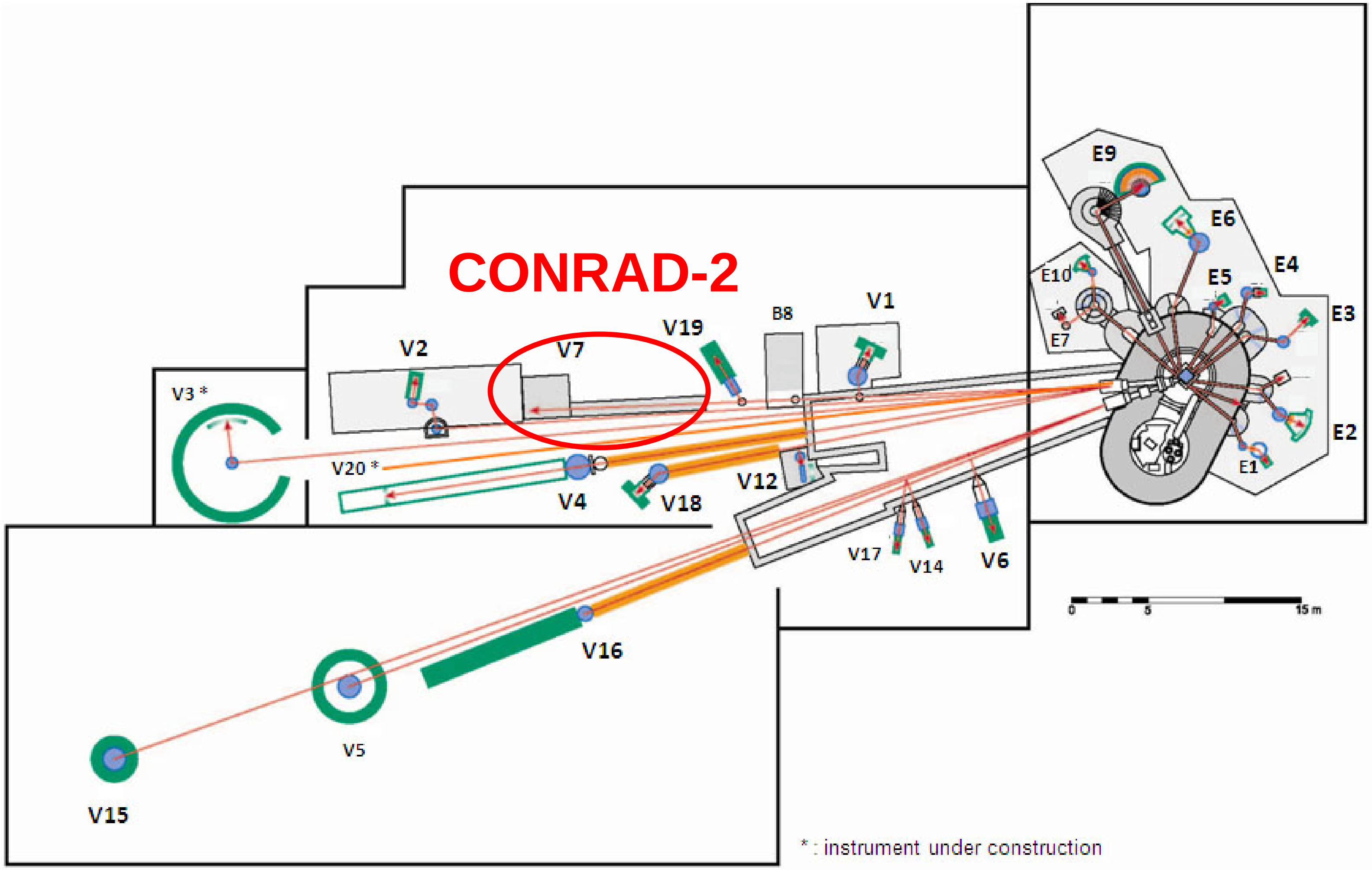
binning 2x2

1 cm

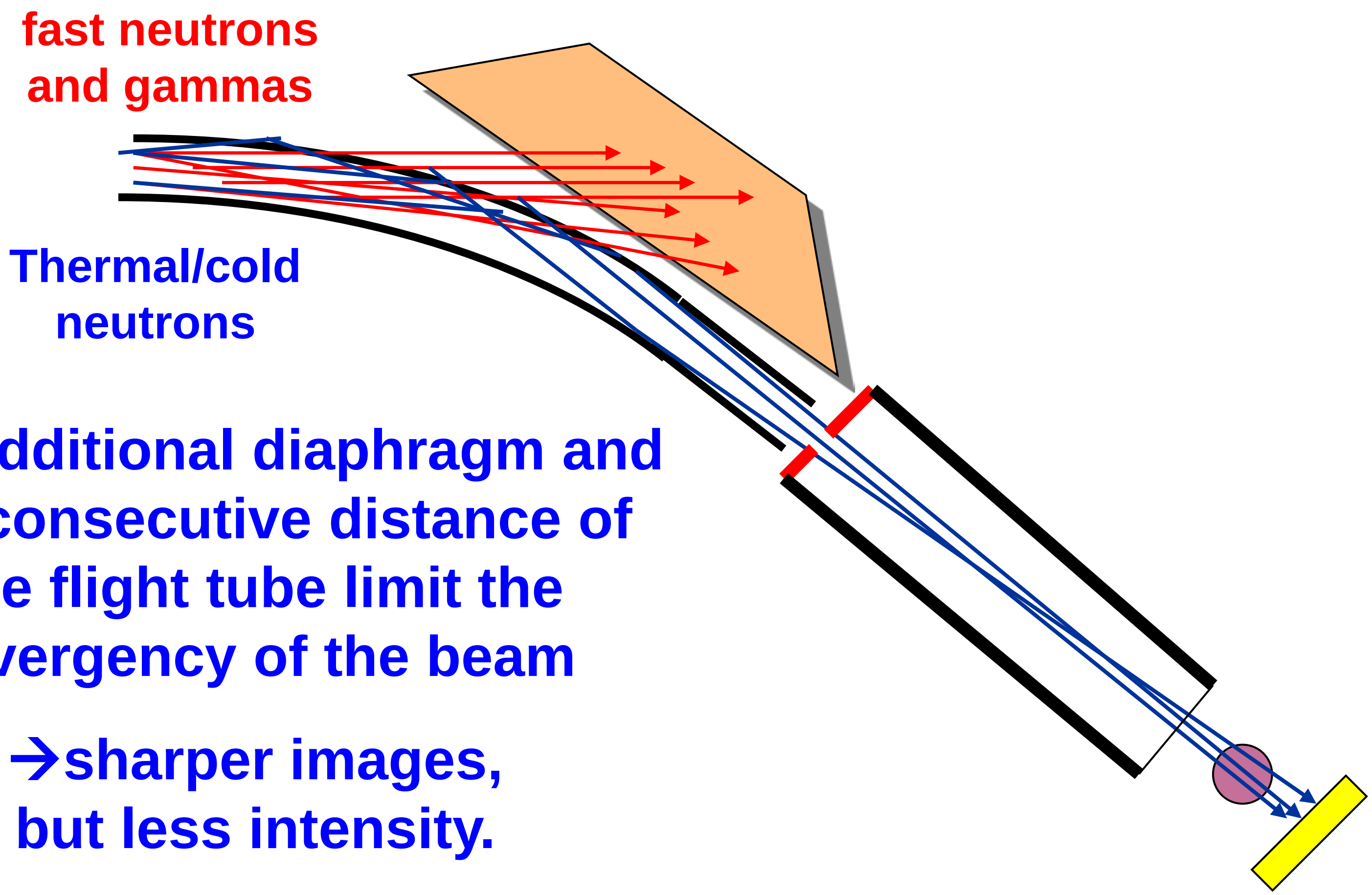
SensiCam PCO (1280 x 1024) – 12 bit

Neutron imaging

Beam optimisation



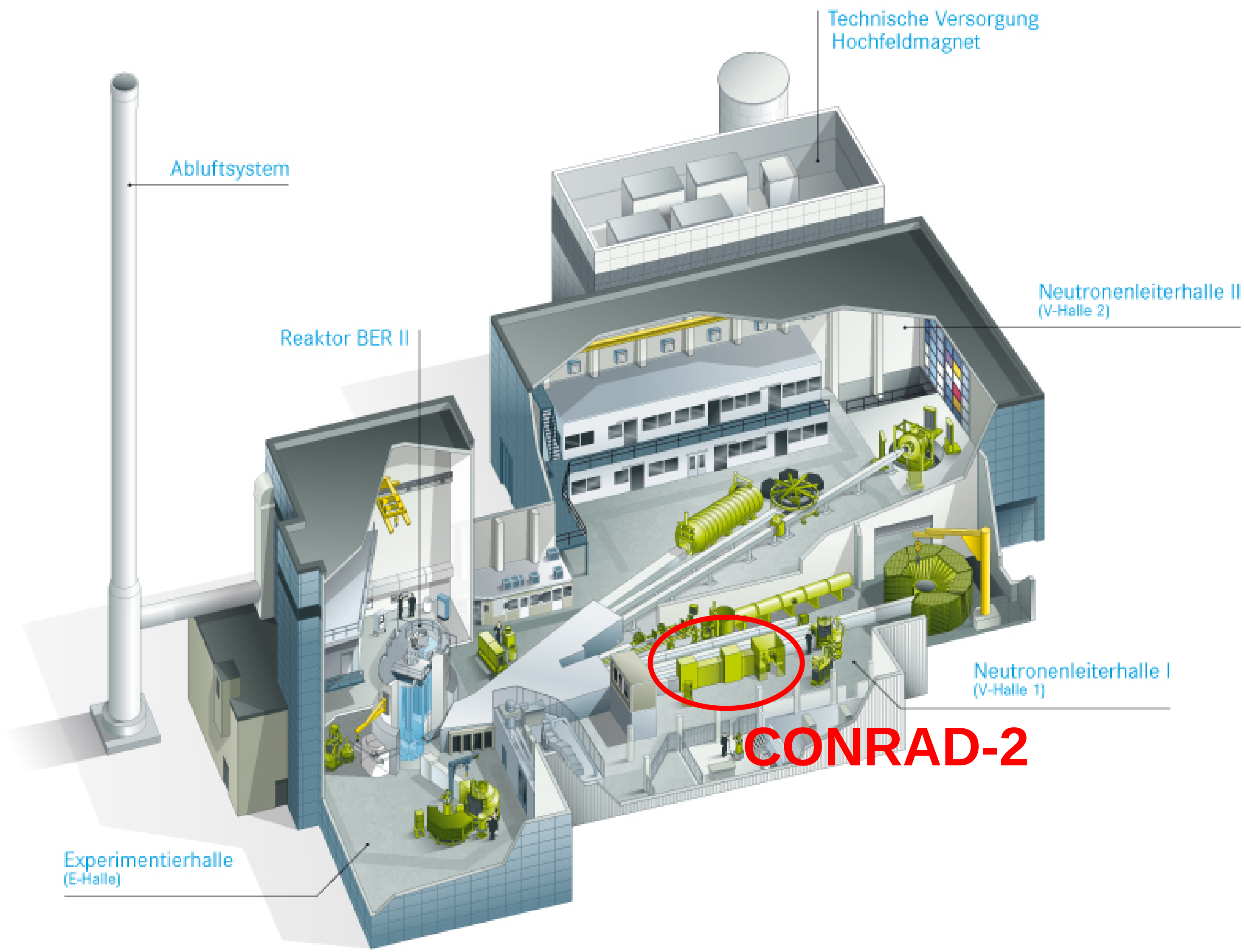
Principle setup with neutron guide plus diaphragma and flight tube for imaging with thermal neutrons (e.g. CONRAD)



The additional diaphragm and the consecutive distance of the flight tube limit the divergency of the beam

**→sharper images,
but less intensity.**

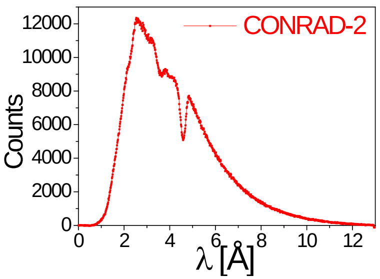
Neutron imaging

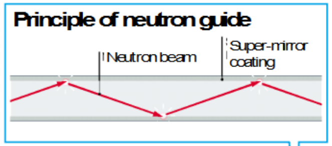


CONRAD-2

Cold neutrons

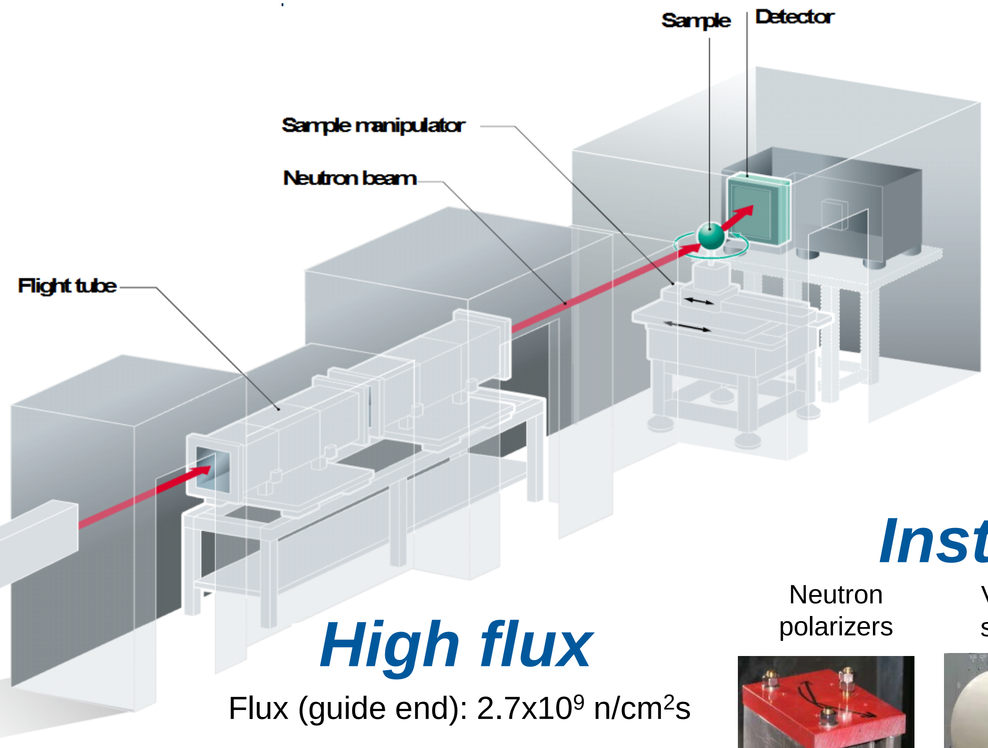
Wavelength range: 1.5 Å – 10 Å





Labs

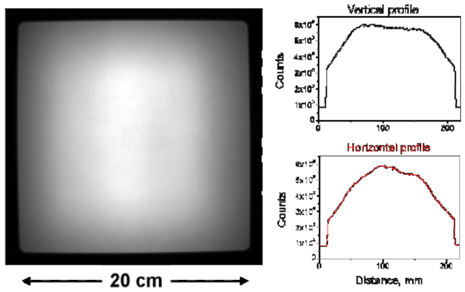
Micro-CT Lab
3D Data Analytics Lab



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.

Large beam

Beam size: 20 cm x 20 cm

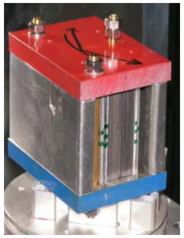


High flux

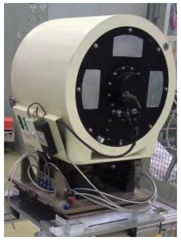
Flux (guide end): 2.7×10^9 n/cm^{2}s

Instrumentation

Neutron polarizers

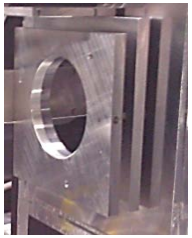


Velocity selector

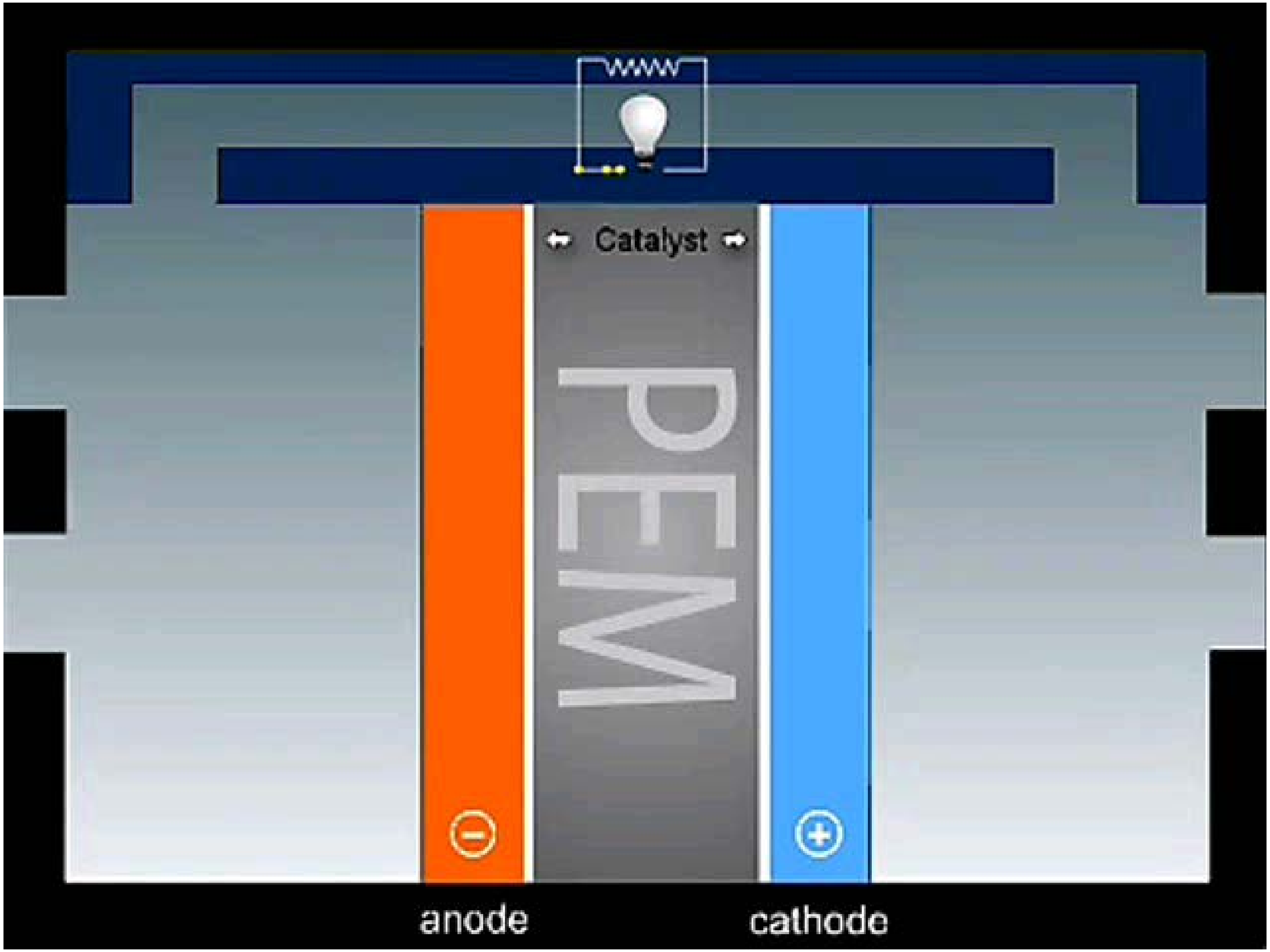


Double-crystal monochromator

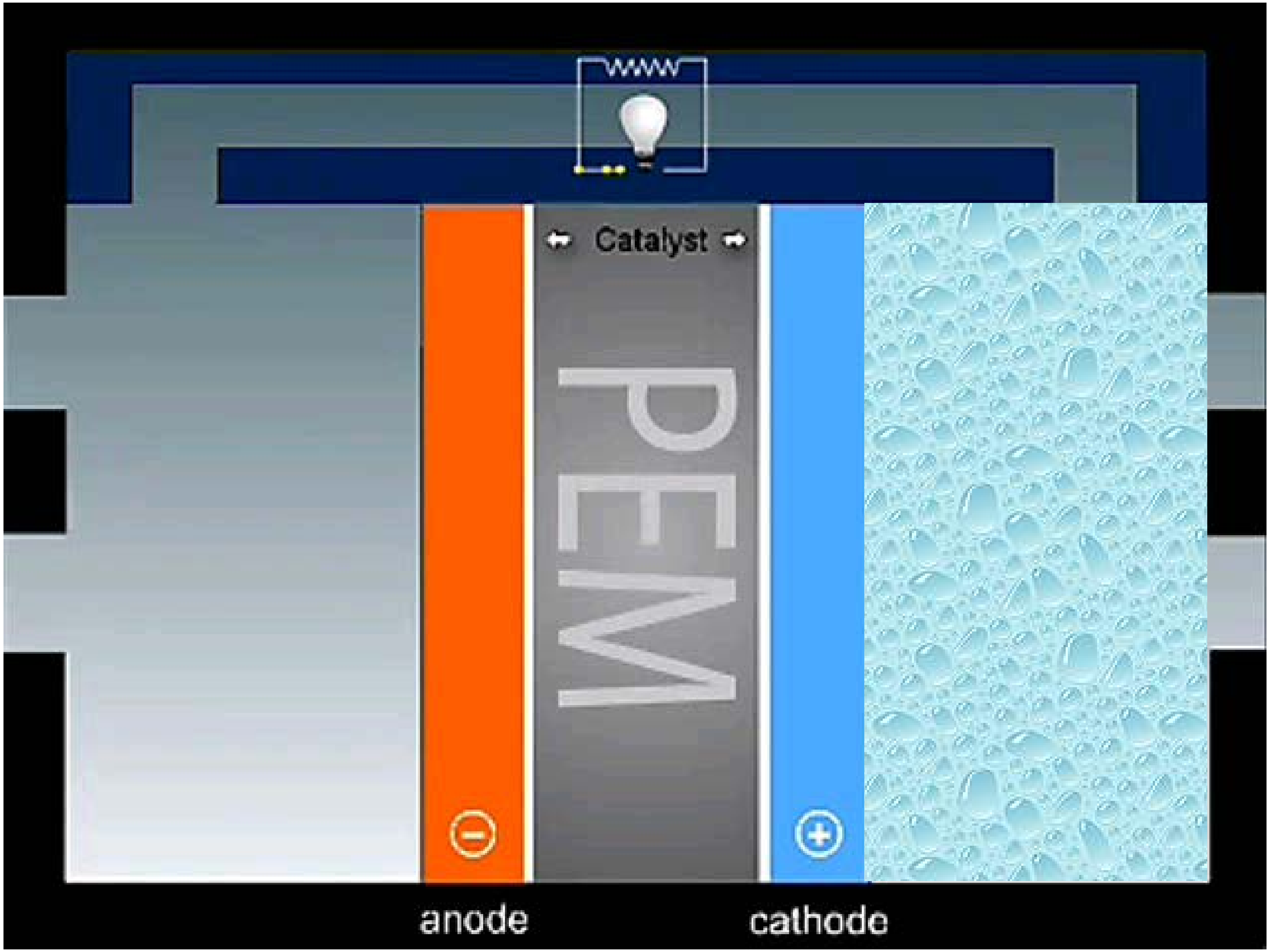
Grating interferometry



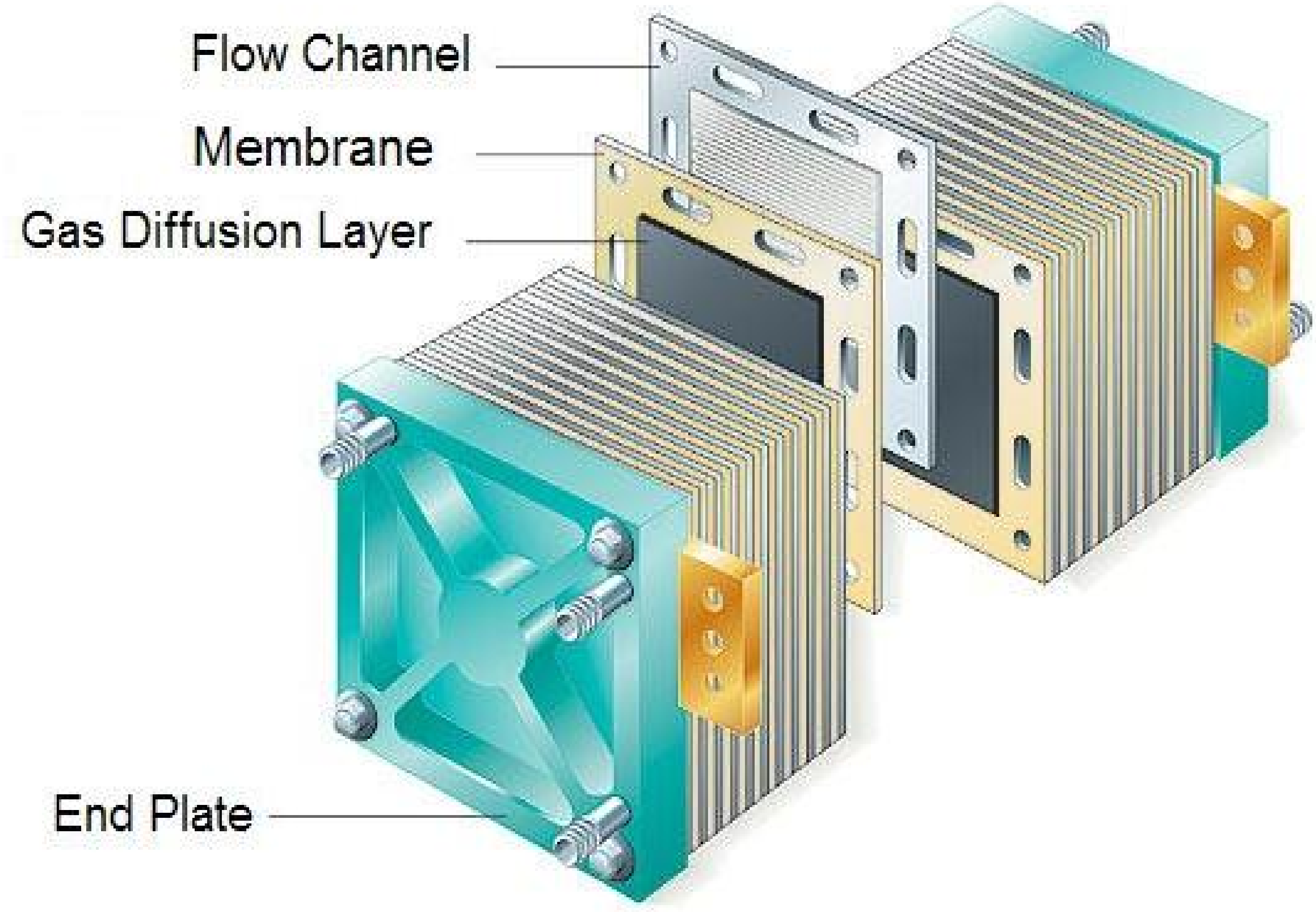
Application – fuel cells



Application – fuel cells

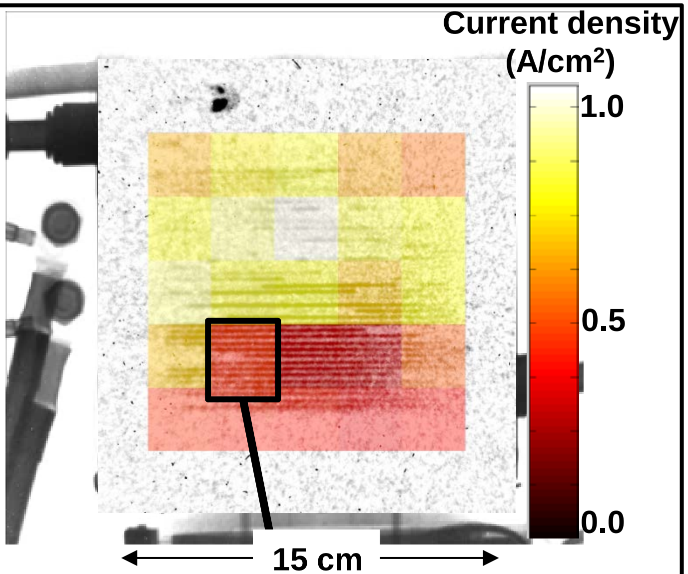


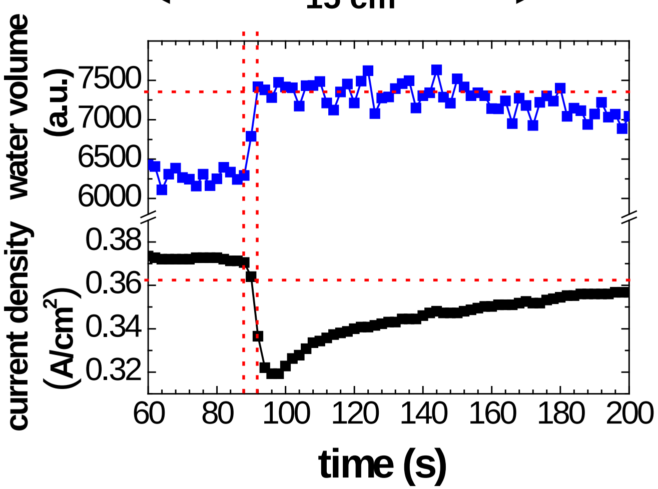
Application – fuel cells



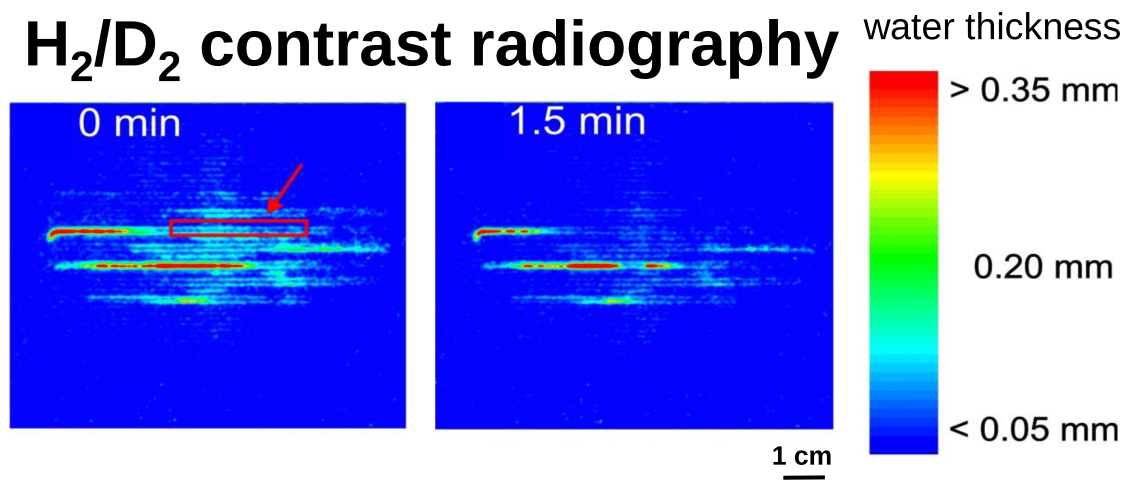
Attenuation Contrast

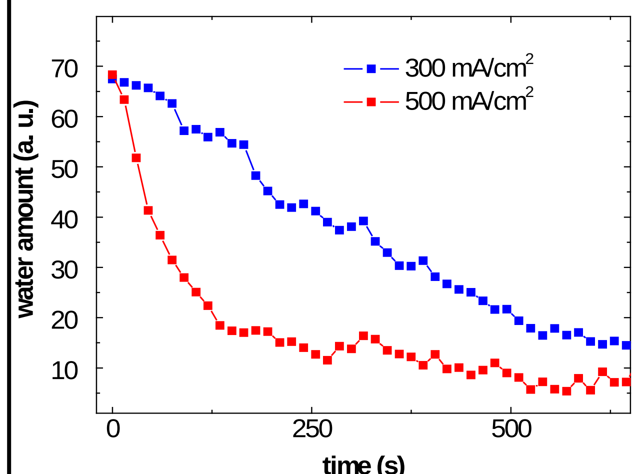
Fuel cells





H_2/D_2 contrast radiography





I. Manke et al, **APL** 92, (**2008**)

A.Schröder et al, **Electrochem Commun** (**2009**)

A. Schröder et al, **J Power Sources** 195 (**2010**)

C. Tötzke et al, **J Power Sources** 196 (**2011**),

A. Lange et al, **J Power Sources** 196 (**2011**)

R. Kuhn et al, **Int J Hydrogen Energy** 37 (**2012**)

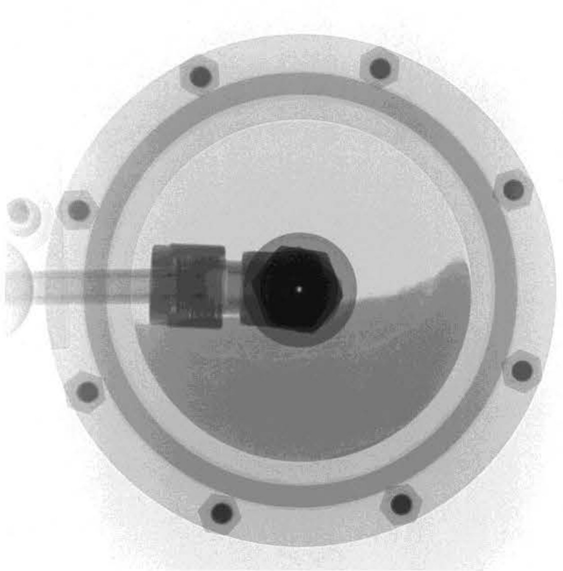
H. Markötter et al, **J Power Sources** 219 (**2012**)

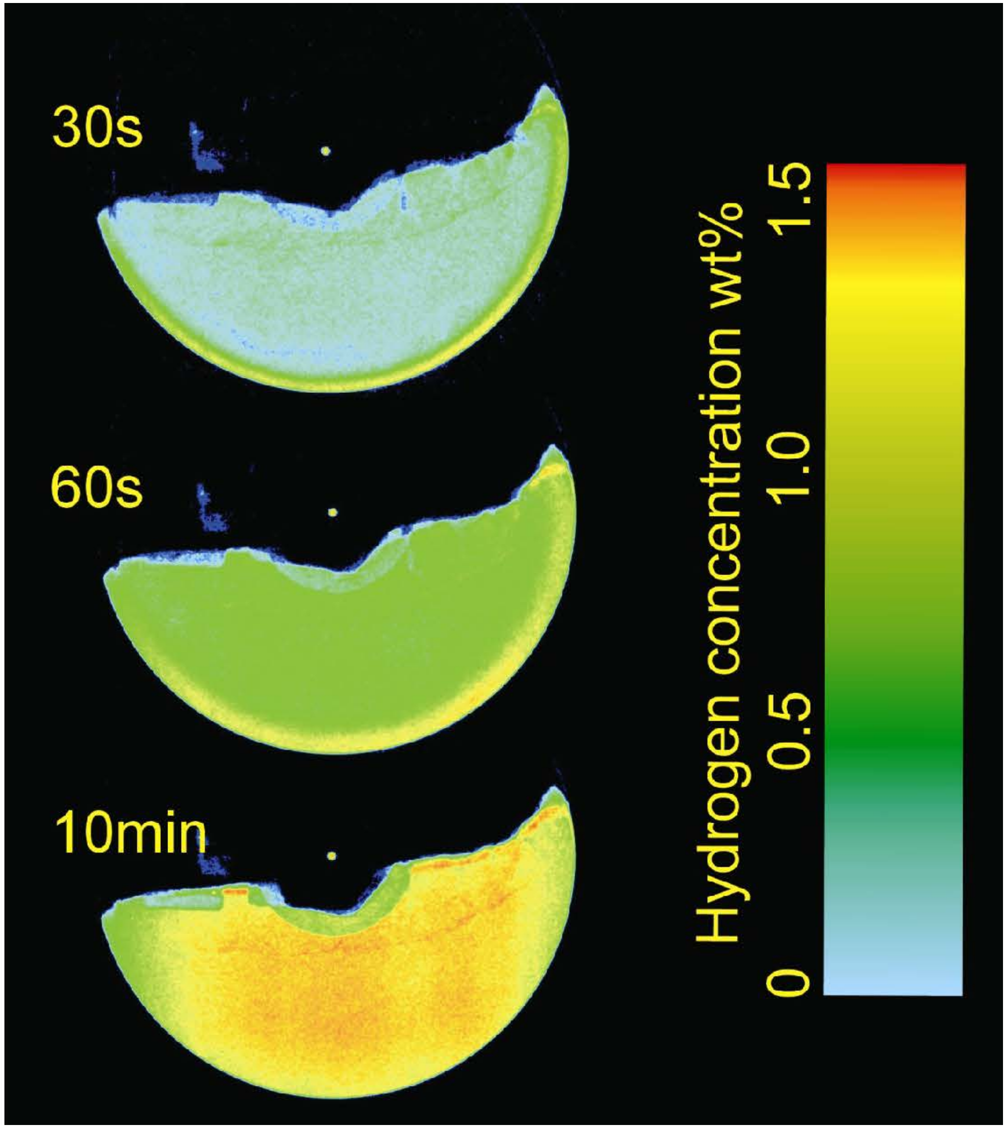
Highlights – Applications

Hydrogen storage ($LaNi_{4.8}Al_{0.2}$)

AGH Fraunhofer IFAM

11 bar of H_2



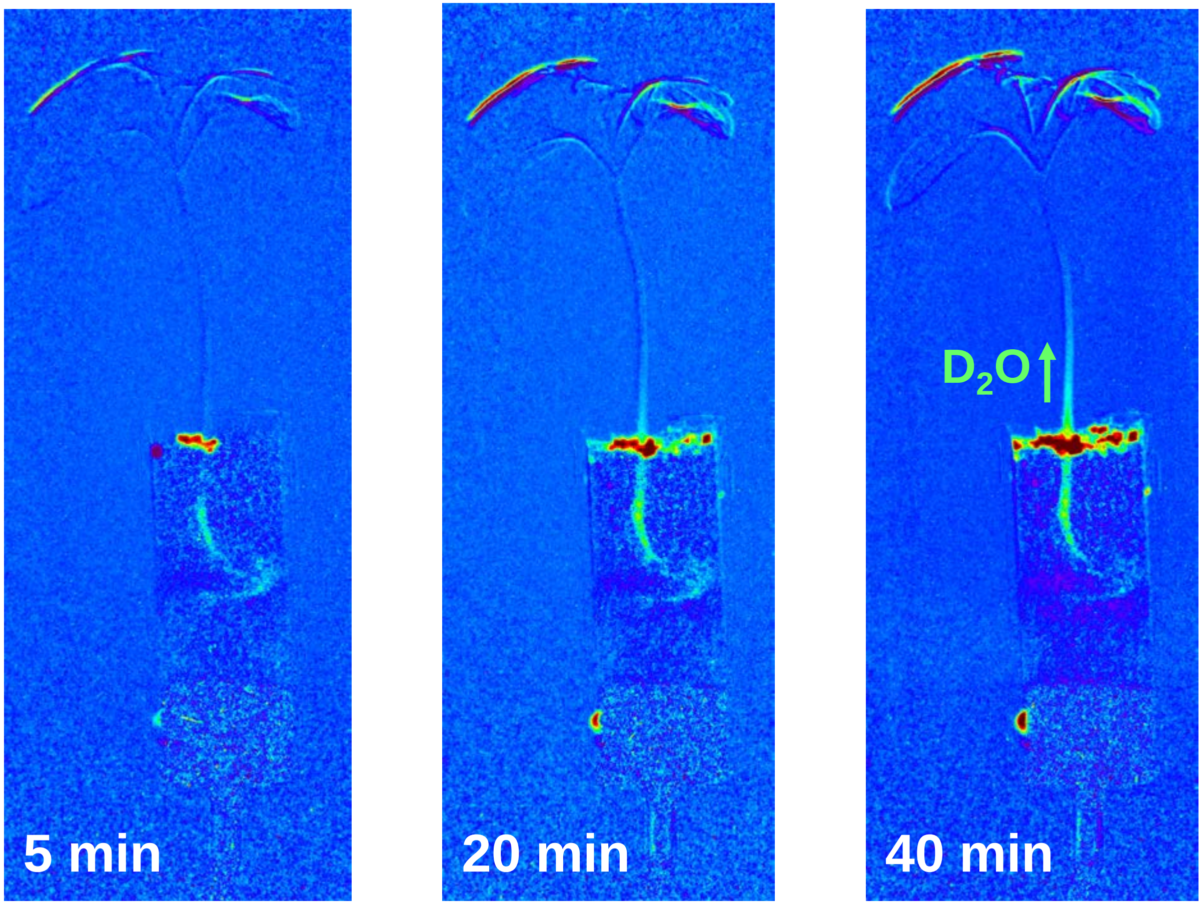


L. Gondek et al.,**International Journal of Hydrogen Energy** 36 (2011)

Neutron imaging

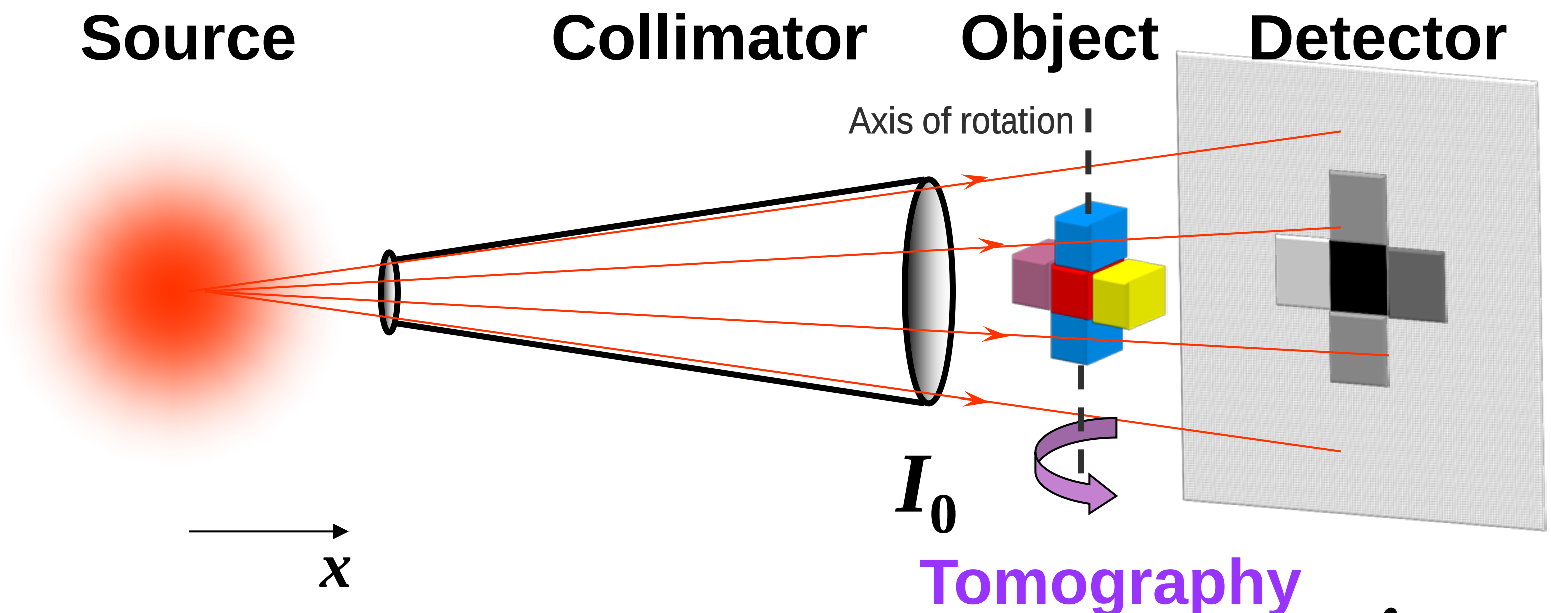
Application - plants

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.

Absorption tomography

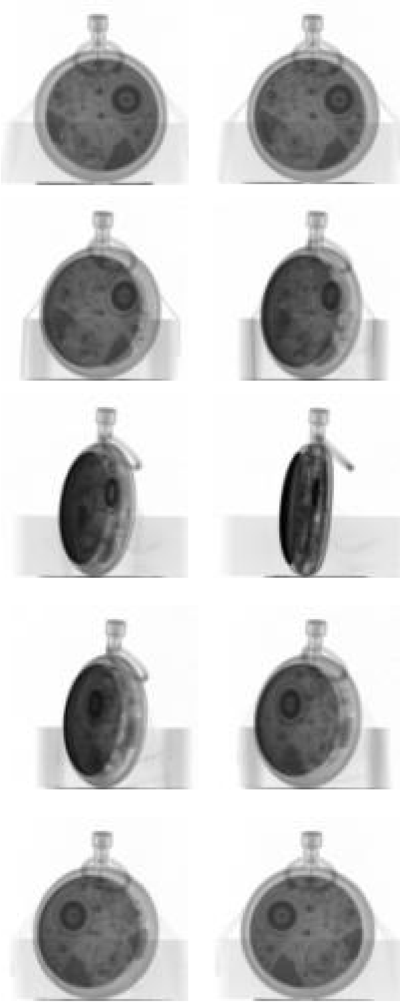


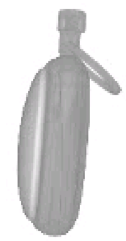
$$\sim I_0 e^{-\int \Sigma(x)dx}$$

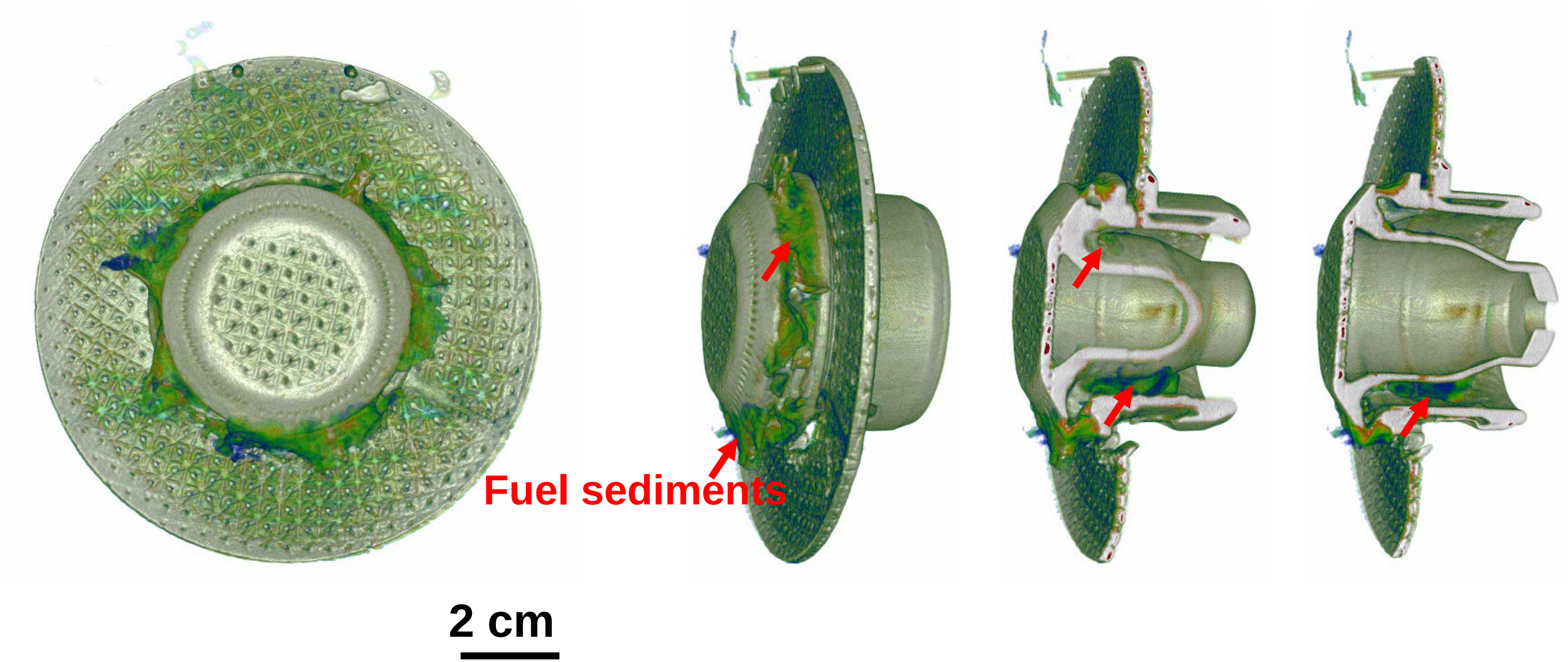
x **– propagation direction**

I_0 **– primary beam**

$\Sigma(x)$ **– attenuation coefficient**






Fuel sediments
2 cm

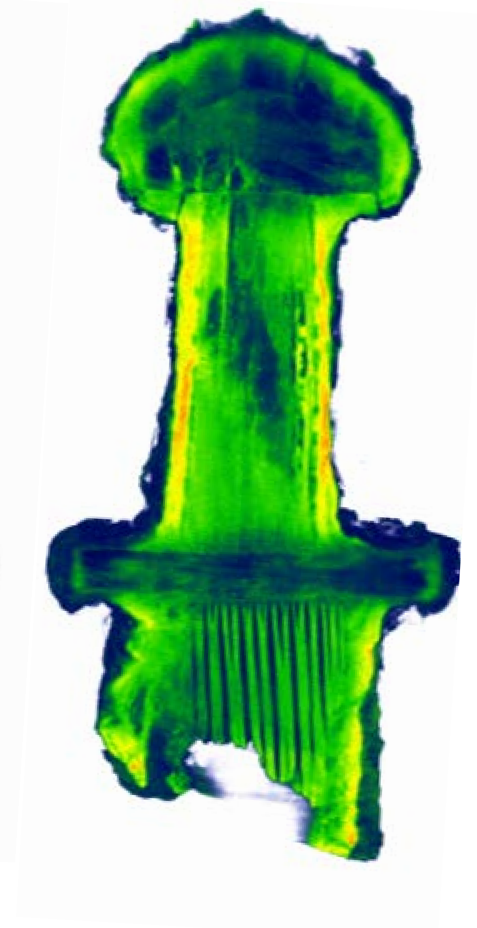
Neutron imaging

Absorption tomography - example

Late Roman sword (IV-V century A.D.) from ship wrecks near Sicily (Scoglio della Bottazza)

radiogram

tomographic slice

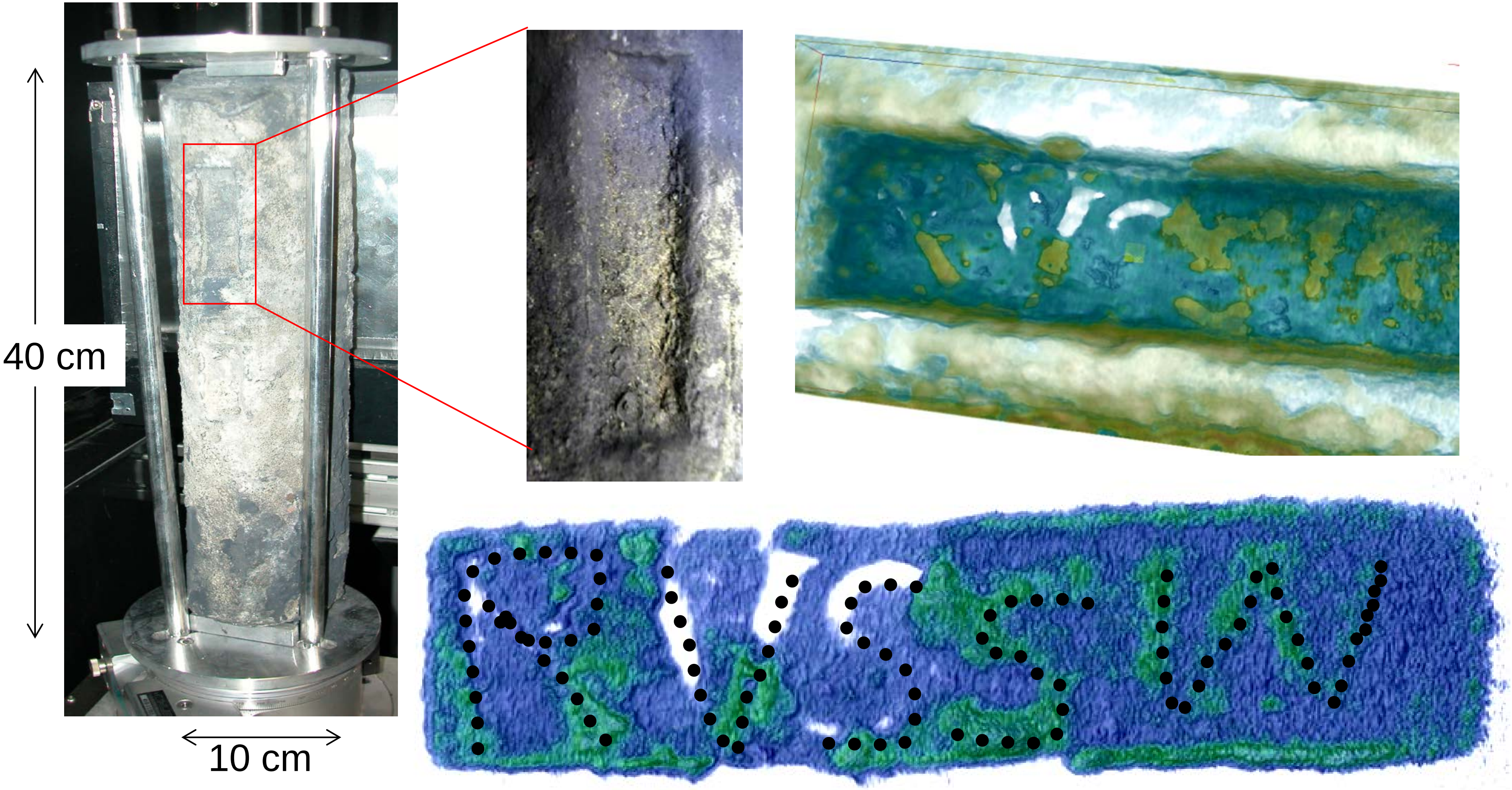


The corrosion process fully removed the metal part leaving only the calcareous matrix around the objects.

Kardjilov, Nikolay, et al. "Neutron tomography for archaeological investigations." *Journal of Neutron Research* 14.1 (2006): 29-36.

Extreme samples

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



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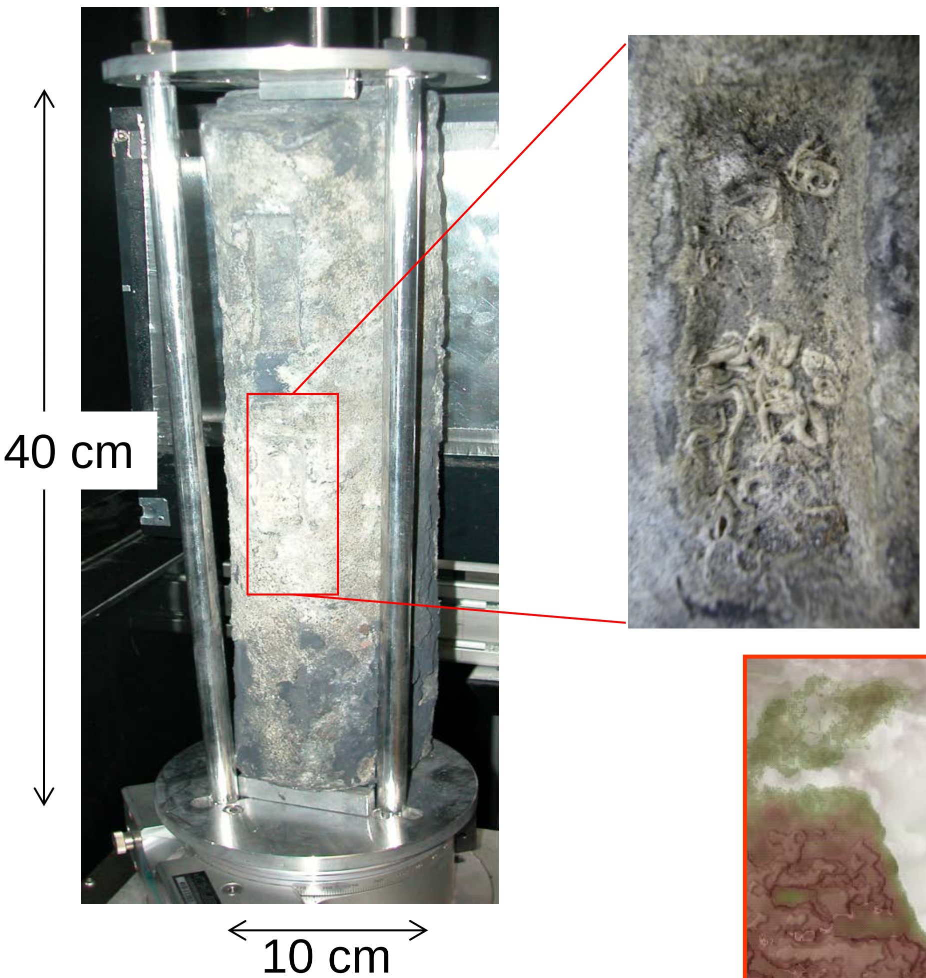
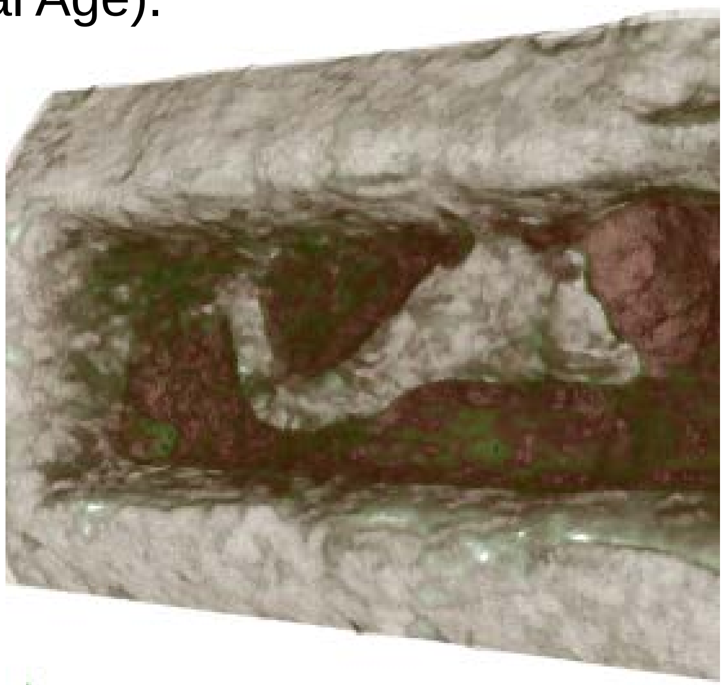
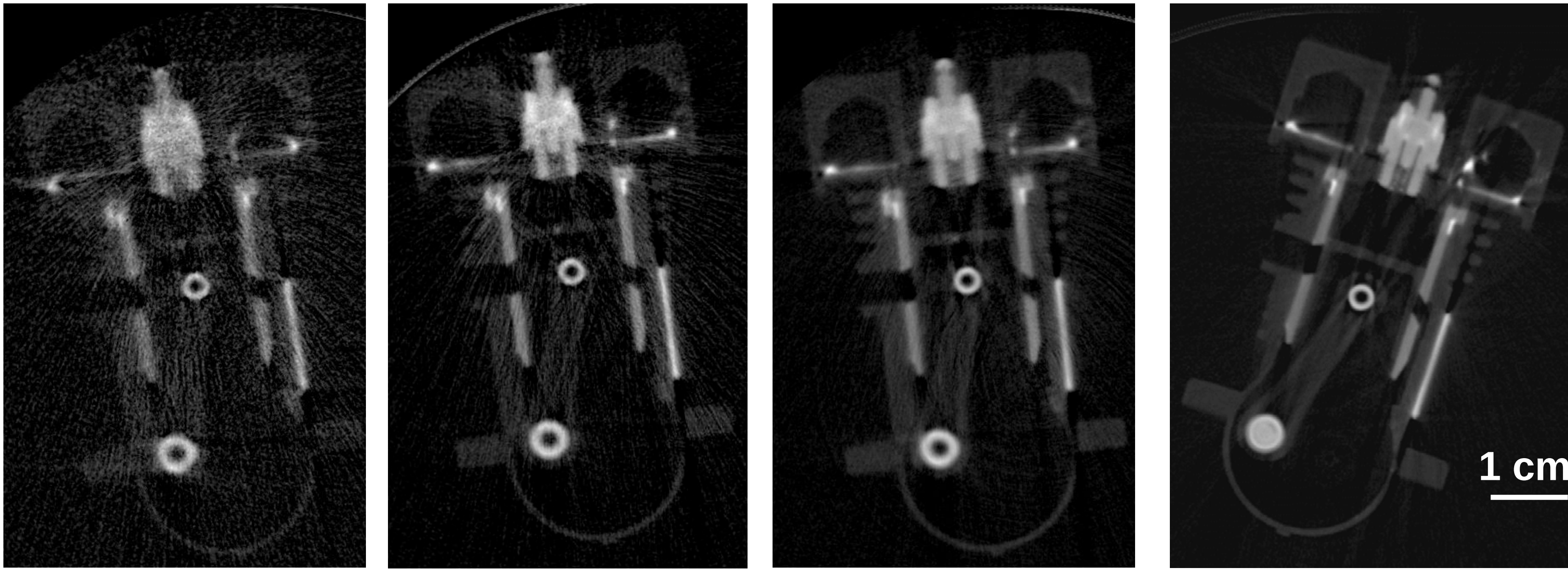




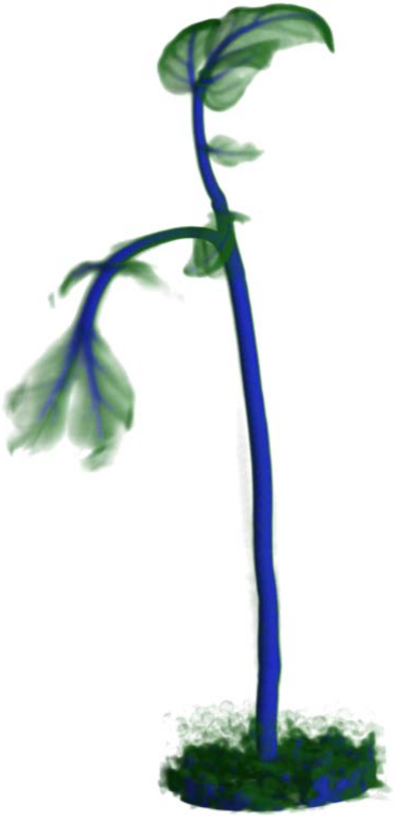
High speed tomography

CMOS PCO 1200hs	CMOS PCO 1200hs	CMOS PCO 1200hs	CCD ANDOR DW436N-BV



0.10s / 1 proj. 200 proj. / 20s	0.25s / 1 proj. 200 proj. / 50s	1.00s / 1 proj. 200 proj. / 200s	1.00s / 1 proj. 400 proj. / 7800s

Experiments performed at ANTARES (FRM-2): L/D 400; $1x10^8$ n/cm^{2}s



Thank you !