ANTARES
NEUTRON IMAGING

Neutron Imaging Instruments

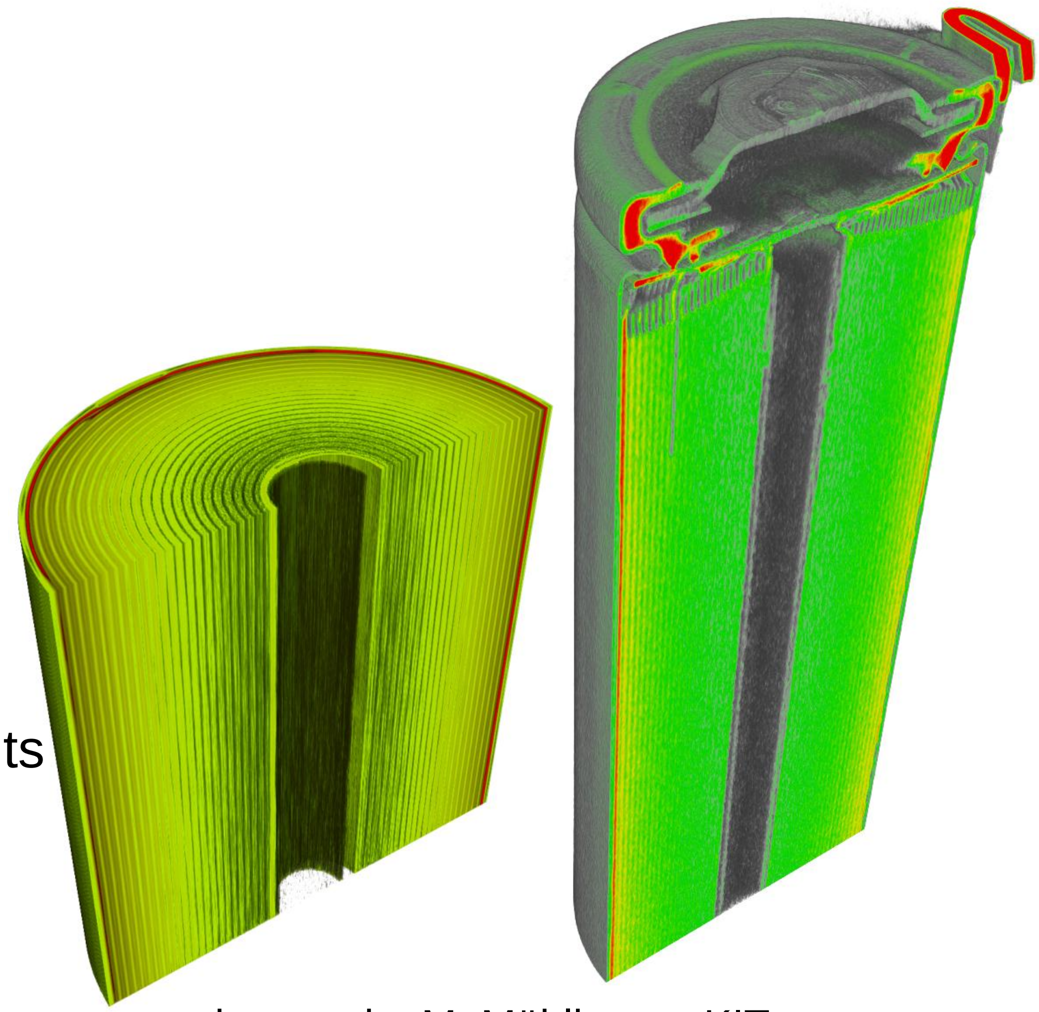
Applications and Principles of Instrumentation

Michael Schulz

T. Reimann, B. Schillinger, P. Schmakat, D. Bausenwein, P. Böni

Outline

- Neutron Interaction
- The principle of neutron imaging
- Motivation: Examples
- Pinhole camera geometry: details
- Instrumentation / Main Components

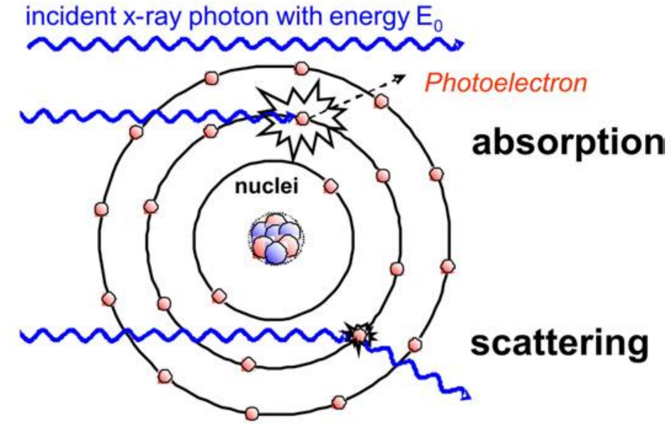


images by M. Mühlbauer, KIT

Comparison neutrons & x-rays

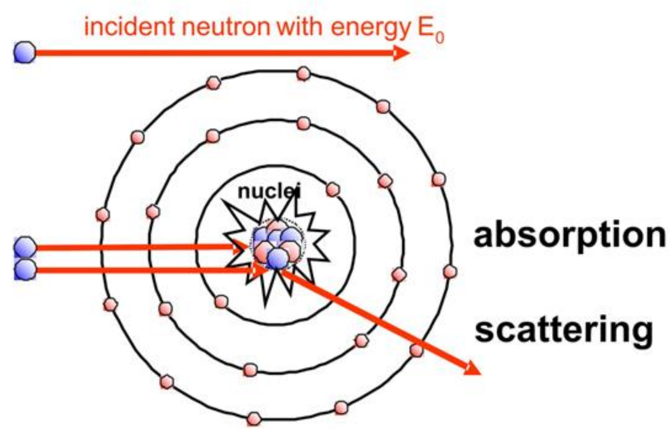
Period \ Group	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	H 0.02																	He 0.02
2	Li 0.06	Be 0.22											B 0.28	C 0.27	N 0.11	O 0.16	F 0.14	Ne 0.17
3	Na 0.13	Mg 0.24											Al 0.38	Si 0.33	P 0.25	S 0.30	Cl 0.23	Ar 0.20
4	K 0.14	Ca 0.26	Sc 0.48	Ti 0.73	V 1.04	Cr 1.29	Mn 1.32	Fe 1.57	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
5	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
6	Cs 1.47	Ba 2.73		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
7	Fr -	Ra 11.80		Rf -	Db -	Sg -	Bh -	Hs -	Mt -	Ds -	Rg -	Uub -	Uut -	Uuq -	Uup -	Uuh -	Uus -	Uuo -
Lanthanides				La 5.04	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 10.17	Er 11.70	Tm 12.49	Yb 9.32	Lu 14.07
Actinides				Ac 24.47	Th 28.95	Pa 39.65	U 49.08	Np -	Pu -	Am -	Cm -	Bk -	Cf -	Es -	Fm -	Md -	No -	Lr -

x-rays



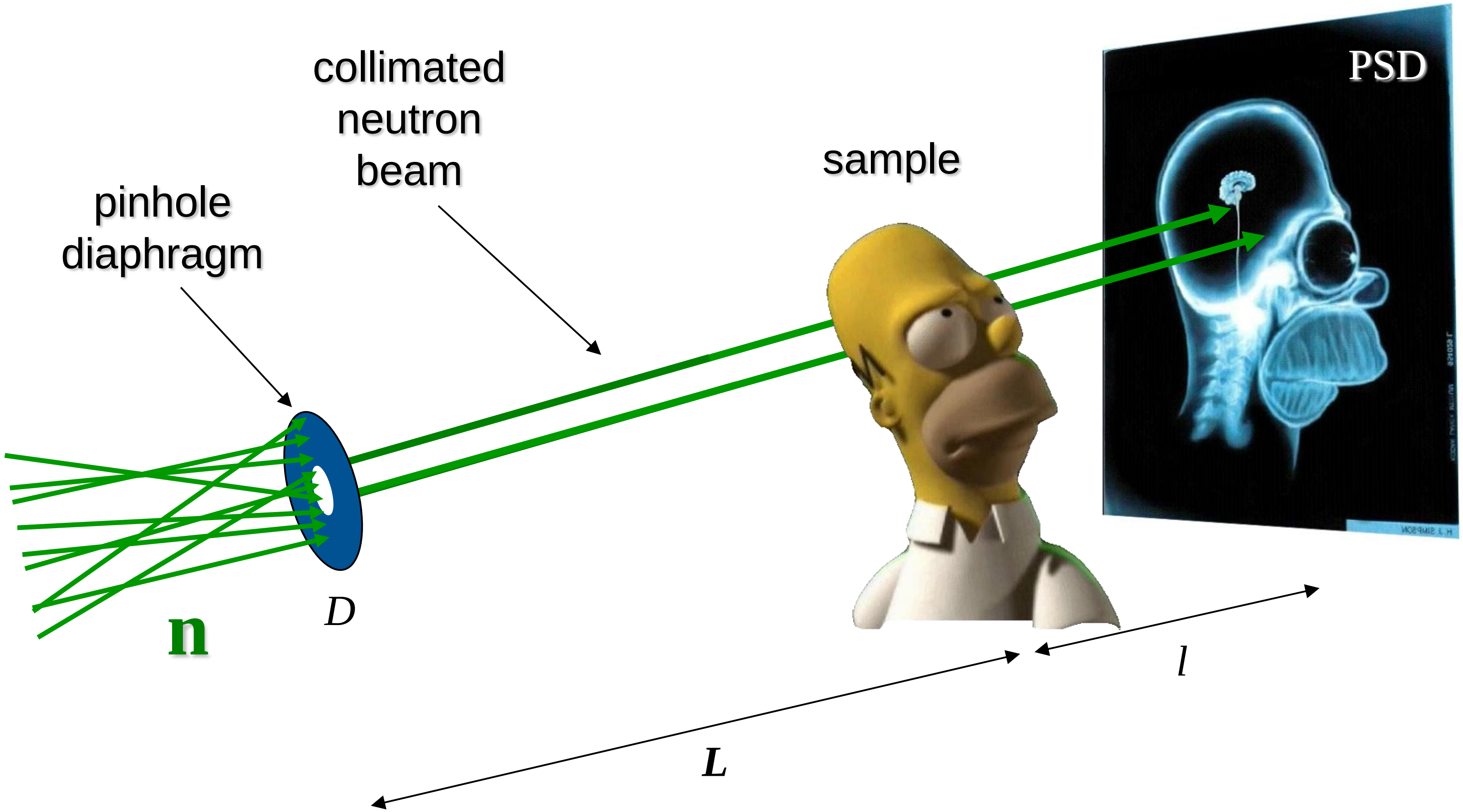
Period \ Group	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	H 3.44																	He 0.02
2	Li 3.30	Be 0.79											B 101.6	C 0.56	N 0.43	O 0.17	F 0.20	Ne 0.10
3	Na 0.09	Mg 0.15											Al 0.1	Si 0.11	P 0.12	S 0.06	Cl 1.33	Ar 0.03
4	K 0.06	Ca 0.08	Sc 2.00	Ti 0.60	V 0.72	Cr 0.54	Mn 1.21	Fe 1.19	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
5	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 115.1	In 7.58	Sn 0.21	Sb 0.30	Te 0.25	I 0.23	Xe 0.43
6	Cs 0.29	Ba 0.07		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 -
7	Fr -	Ra 0.34		Rf -	Db -	Sg -	Bh -	Hs -	Mt -	Ds -	Rg -	Uub -	Uut -	Uuq -	Uup -	Uuh -	Uus -	Uuo -
Lanthanides				La 0.52	Ce 0.14	Pr 0.41	Nd 1.87	Pm 5.72	Sm 171.47	Eu 94.58	Gd 1479.0	Tb 0.93	Dy 32.42	Ho 2.25	Er 5.48	Tm 3.53	Yb 1.40	Lu 2.75
Actinides				Ac -	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 -

neutrons

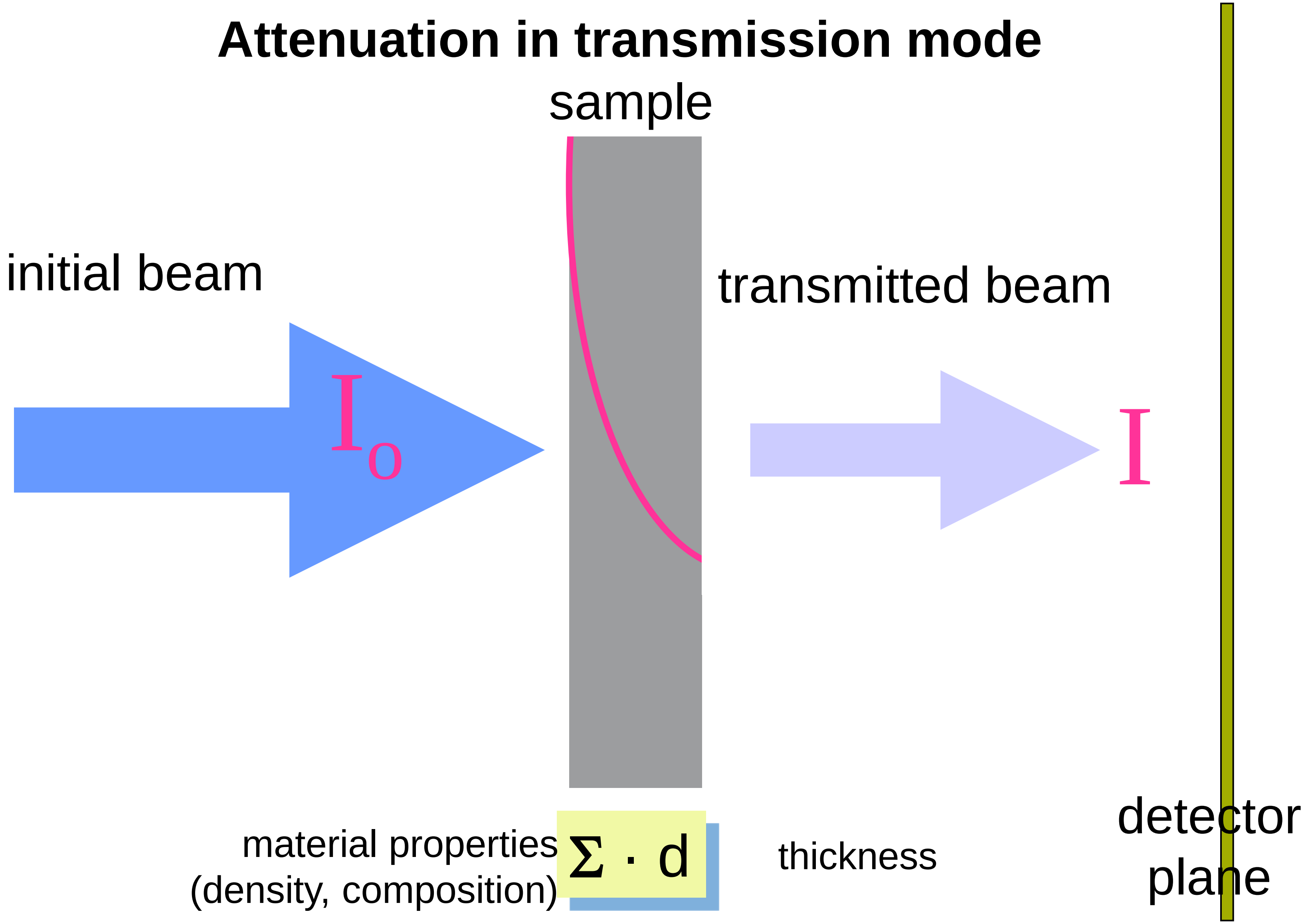


Top: www.psi.ch
Right: M.Strobl, J. Phys. D, **42,** 243001 (2009)

The Principle of Neutron Imaging



Attenuation in transmission mode



from E. Lehmann, PSI

Analytical description of the transmission process

Transmission **Beer-Lambert law**

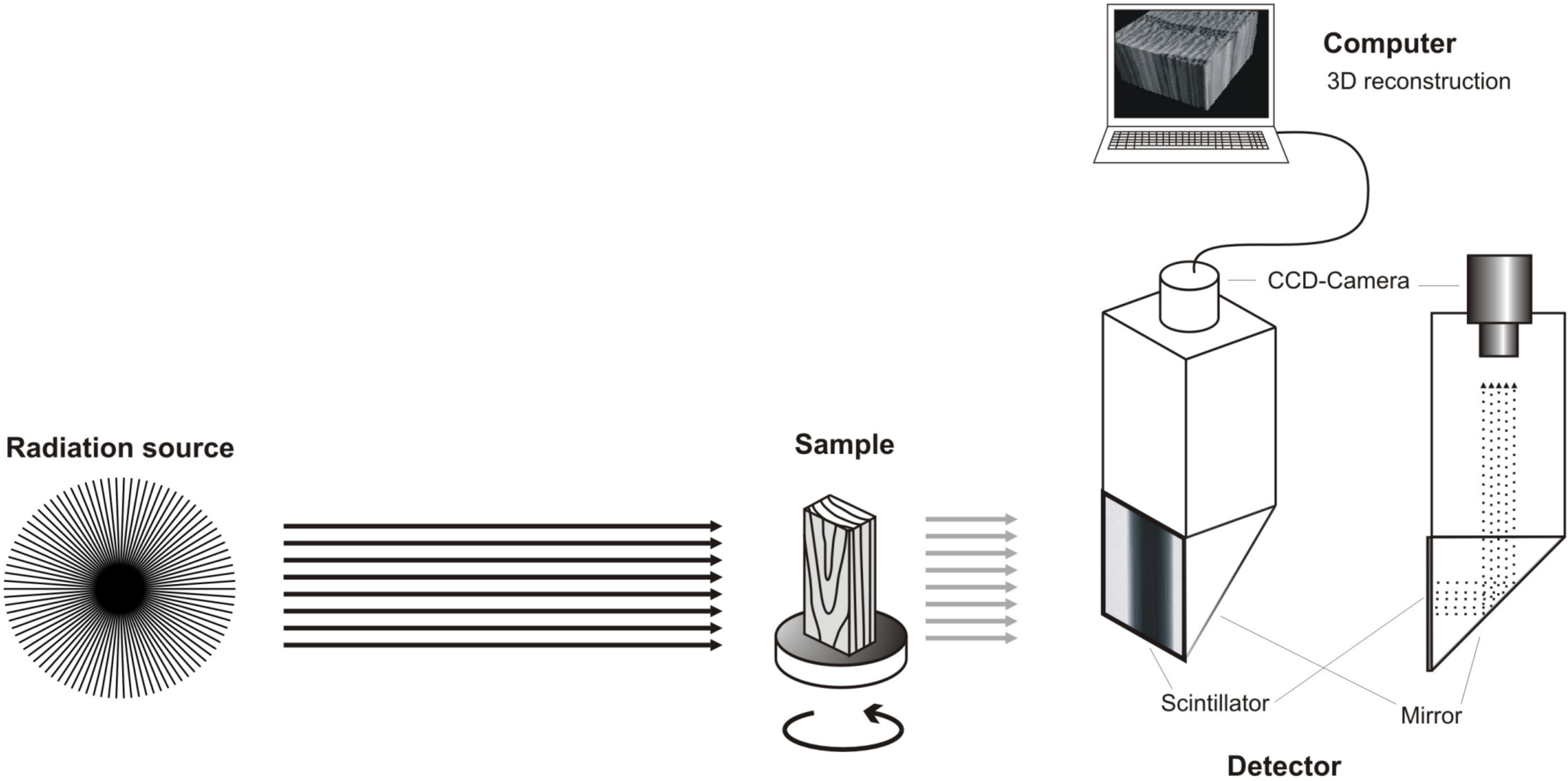
$$T = \frac{I}{I_0} = e^{-\Sigma \cdot d} = e^{-\sigma \cdot N \cdot d}$$

and inverted …

$$\Sigma \cdot d = \ln\left(\frac{I_0}{I}\right)$$

from E. Lehmann, PSI

Neutron tomography →3D information



- Several hundred single projections are required
- A reconstruction algorithm delivers the 3D structural data
- A visualization tool delivers slices and views at arbitrary positions

from E. Lehmann, PSI

Tomography Result: Virtual Reality

5 mm

Micro-Tomography
with cold neutrons

from E. Lehmann, PSI

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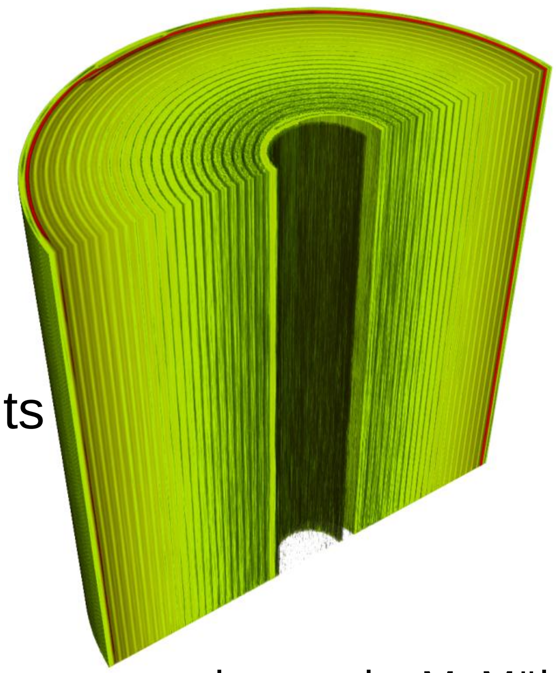
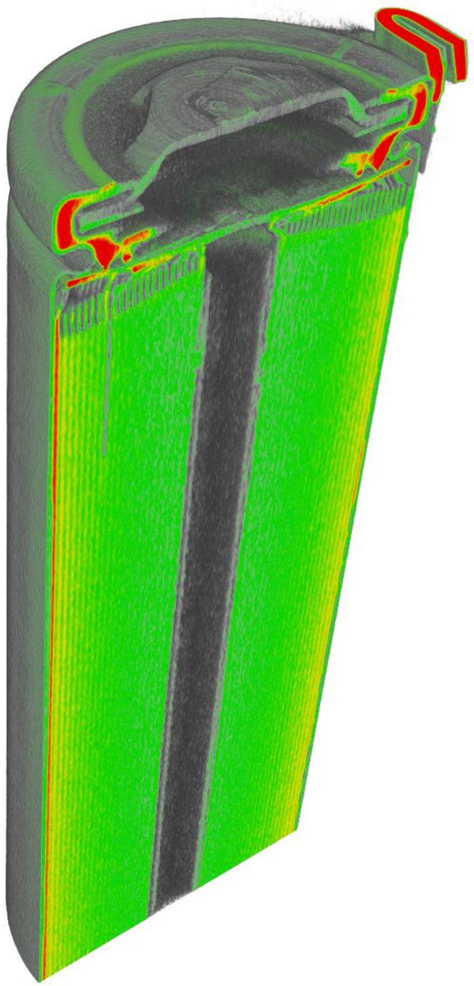
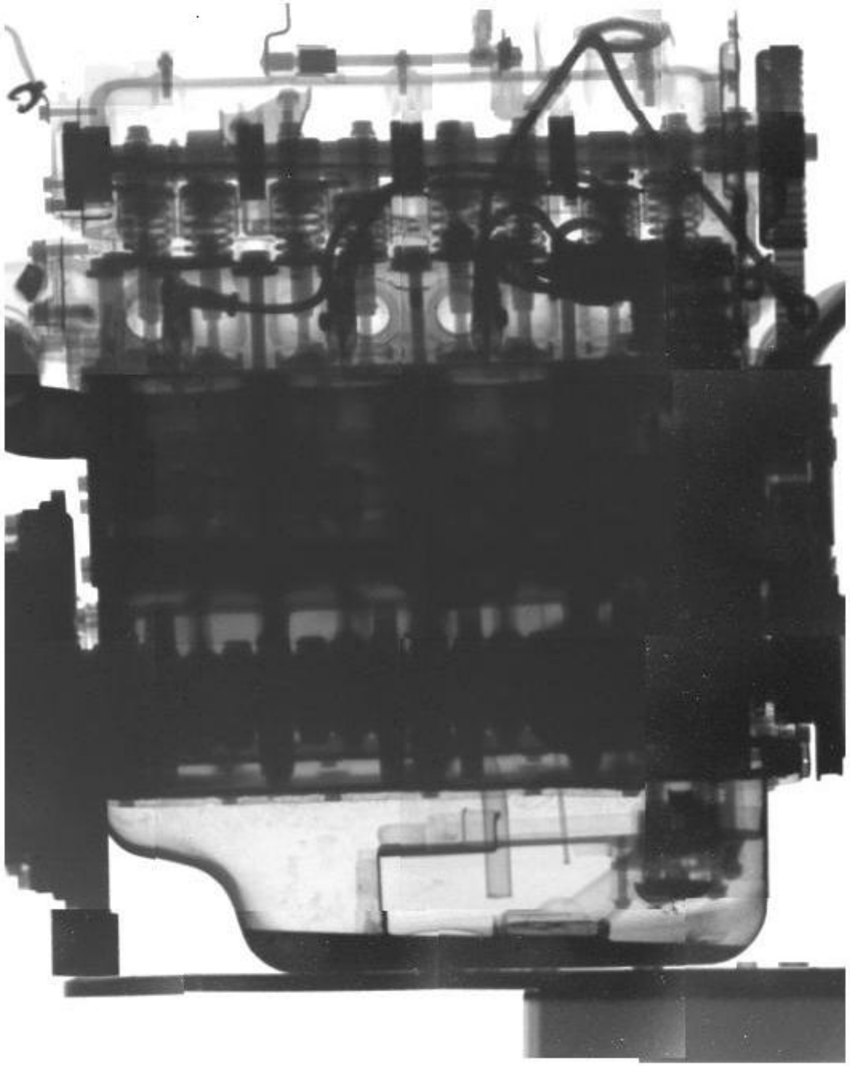




images by M. Mühlbauer, KIT

Stroboscopic imaging



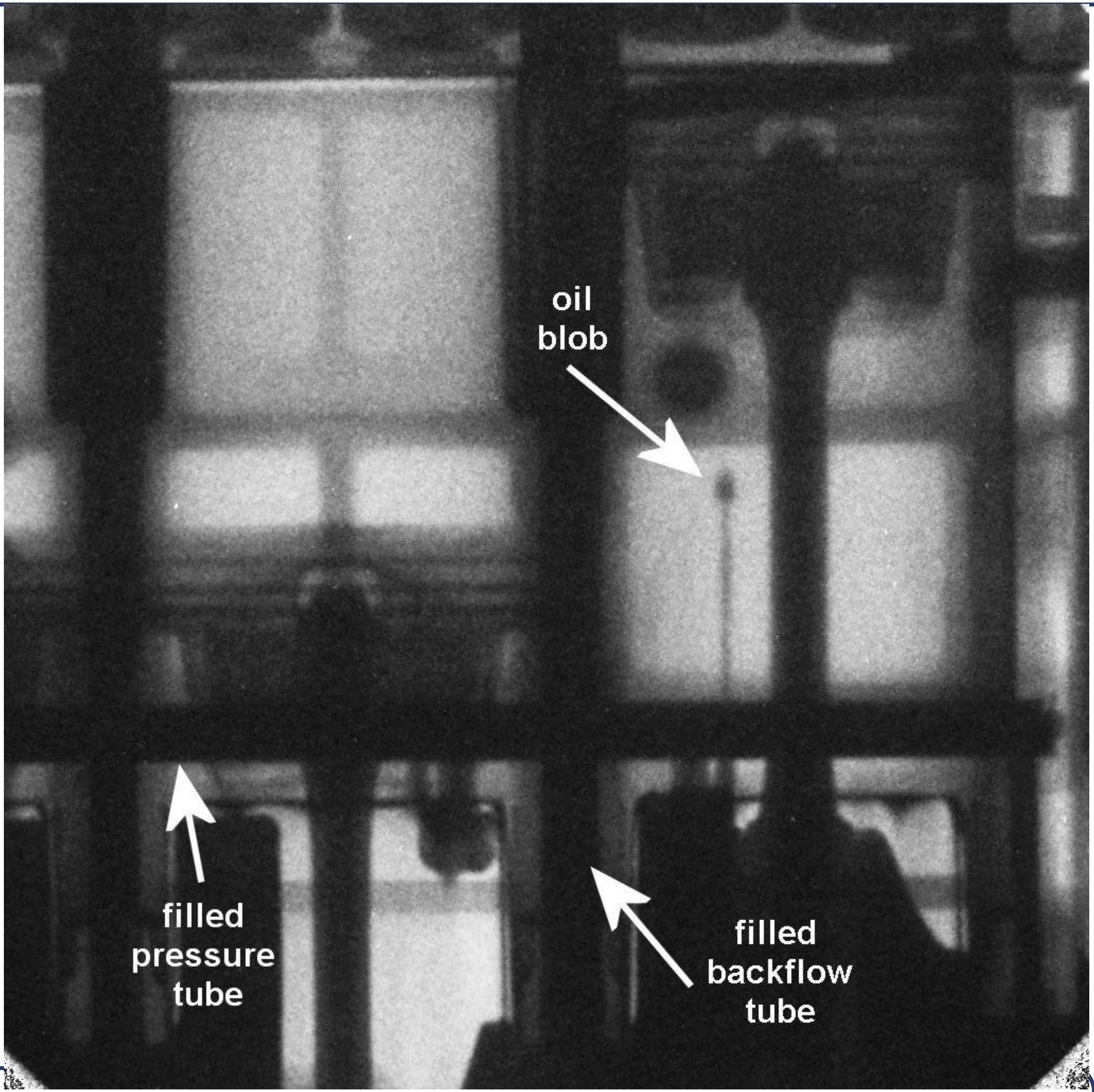
- Electrically driven engine at 600rpm
- Time window 1ms
- Observation area could be varied by displacement of the full set-up.


t= 0 ms

Dynamic radiography of the engine,

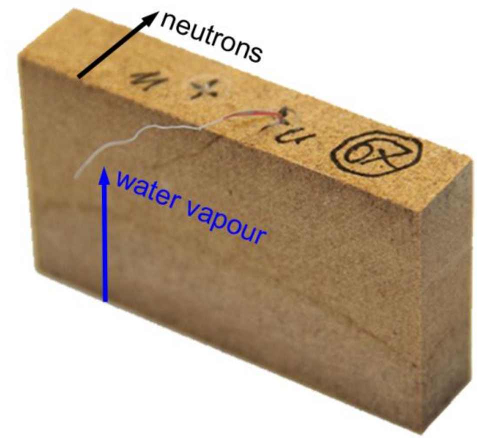
with oil filled horizontal pressure tubes and vertical backflow tubes,

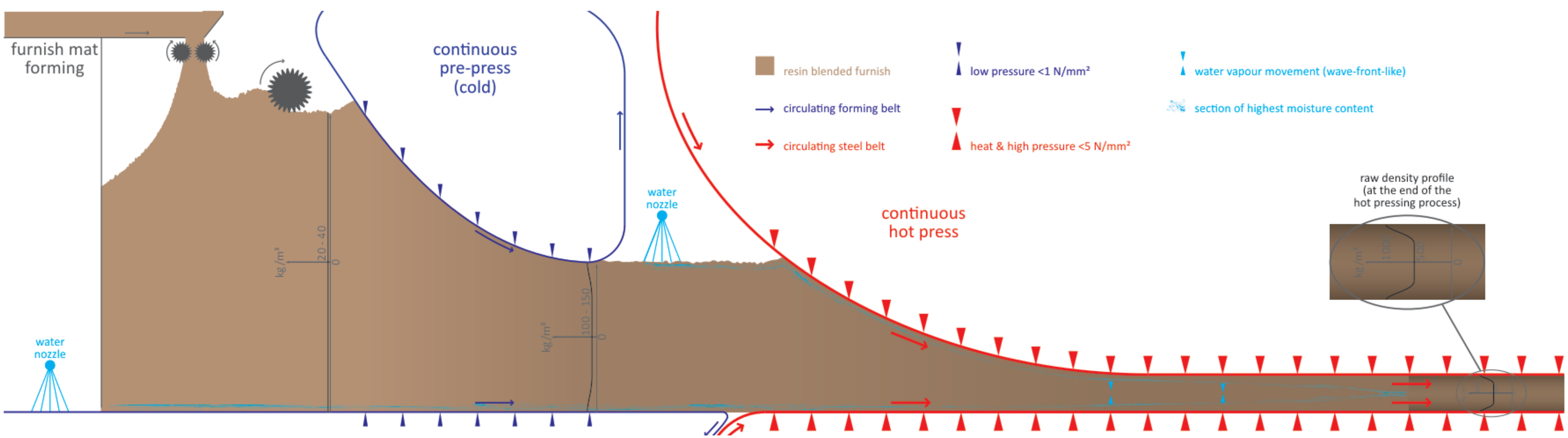
and oil blob within the oil jet to the piston bottom

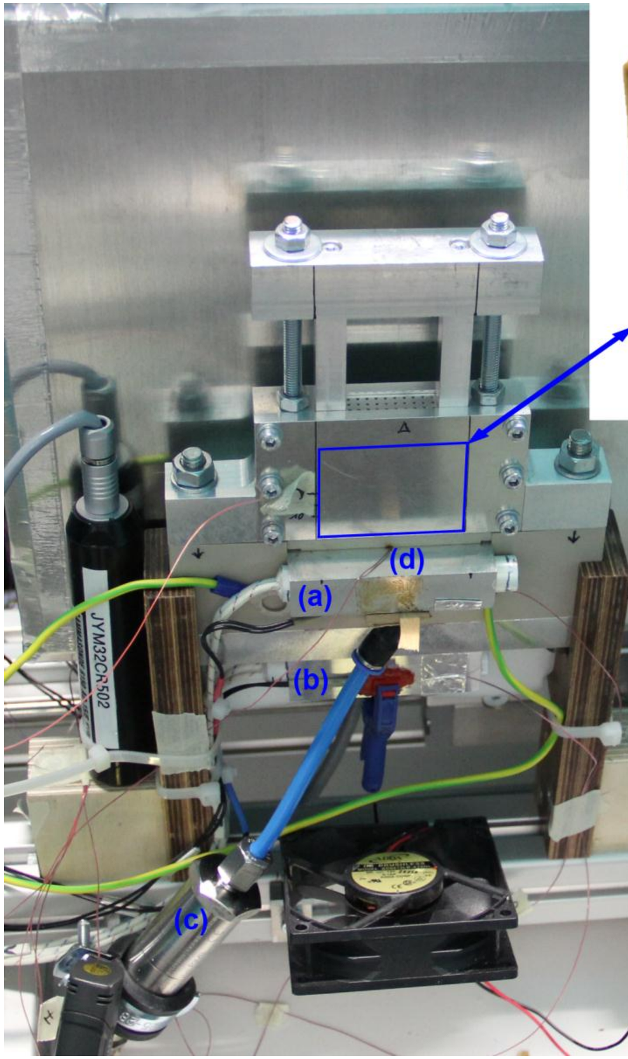


Vapour transport in Wood Based Composites

- Mixture of fibres & resin
- Fabrication of panels by cold & hot pressing
- How does vapour move during hot pressing?
- Theories predict wavefront-like movement

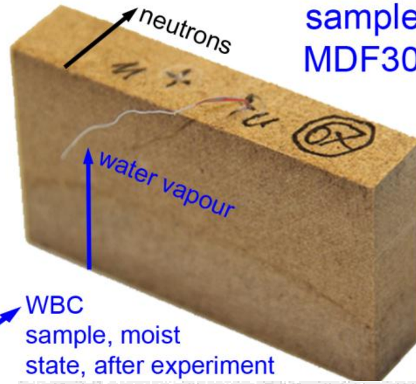




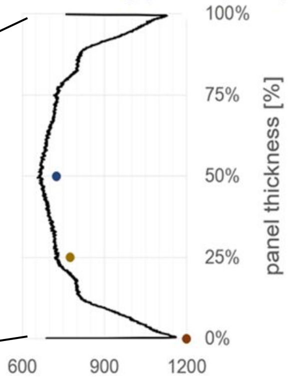


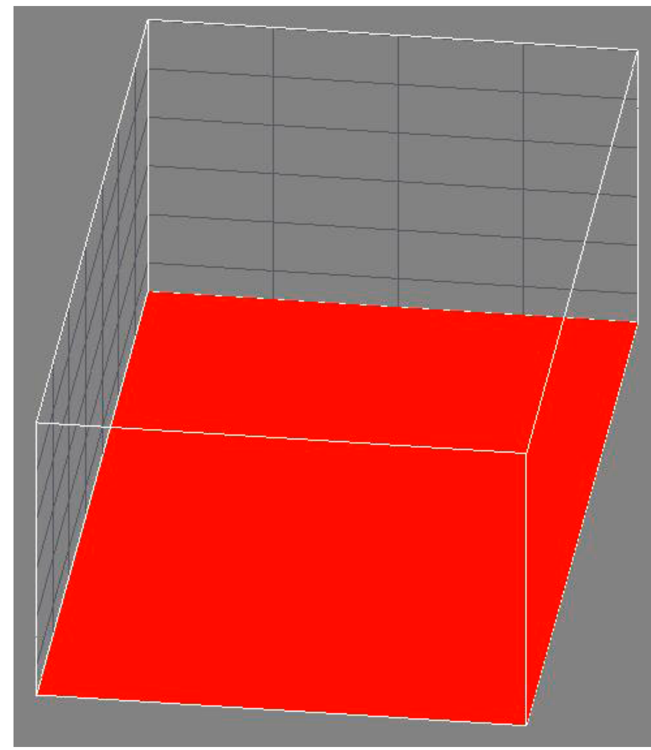
WBC
sample, moist
state, after experiment

sample
MDF30



raw density profile (RDP)



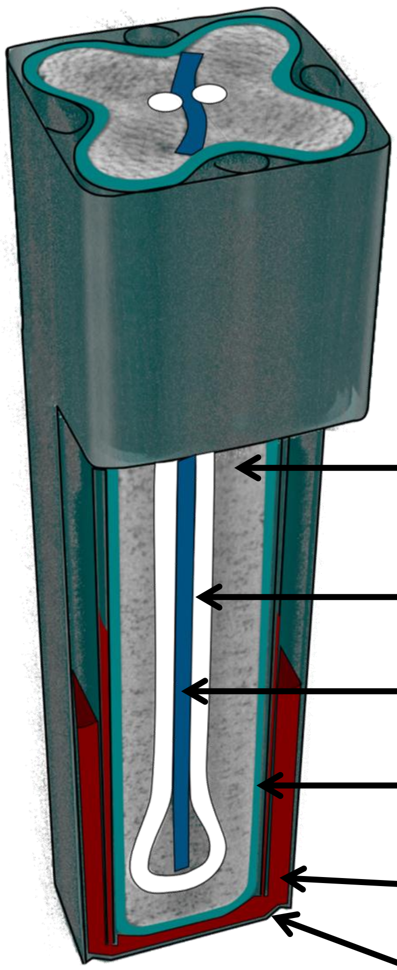


Sodium metal halide battery

2 NaCl + M → MCl_2 + 2 Na [M = Fe, Ni]

Operating temperature: 270 ºC – 350 ºC

(special Al furnace for neutron measurements)



Cell setup:

Cathode: Fe,Ni/ $Ni_{1-x}Fe_xCl_2$/ NaCl

$NaAlCl_4$ (liquid electrolyte)

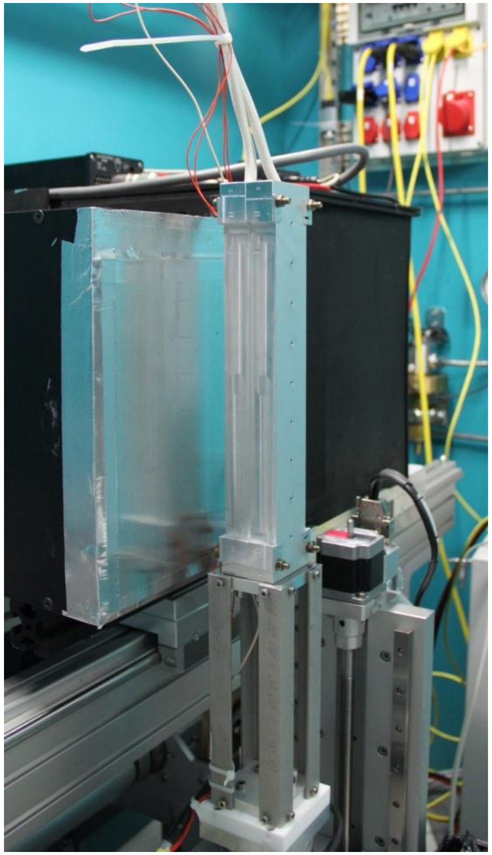
Cathode current collector

Electrolyte reservoir (porous graphite)

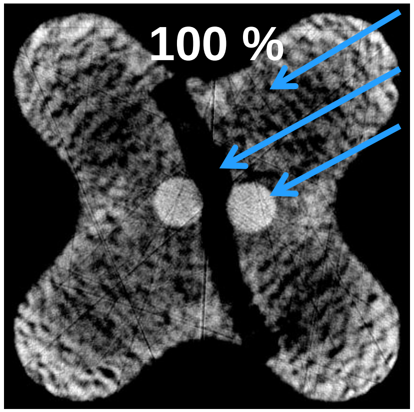
β''-alumina (separator, conducts Na^+)

Anode: liquid sodium

Steel case (anode current collector)



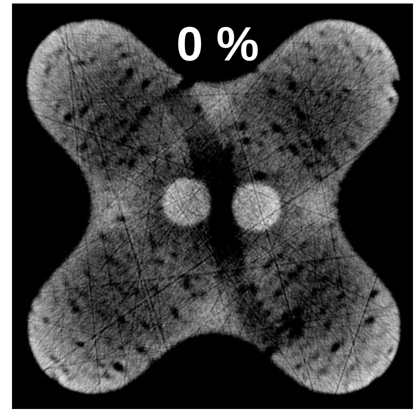
Tomography



cathode
electrolyte reservoir
current collector

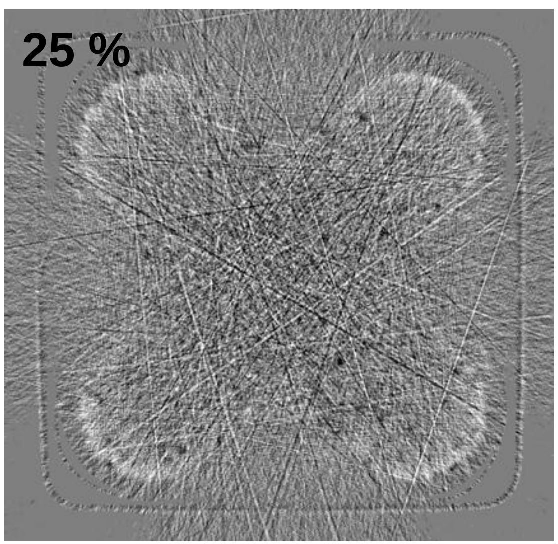
charged

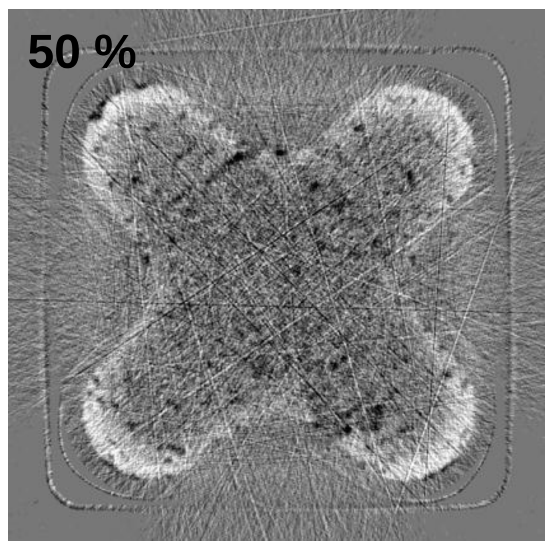
−

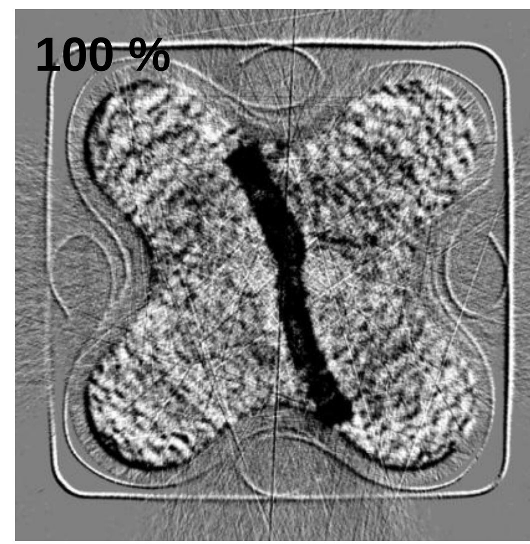


discharged

=

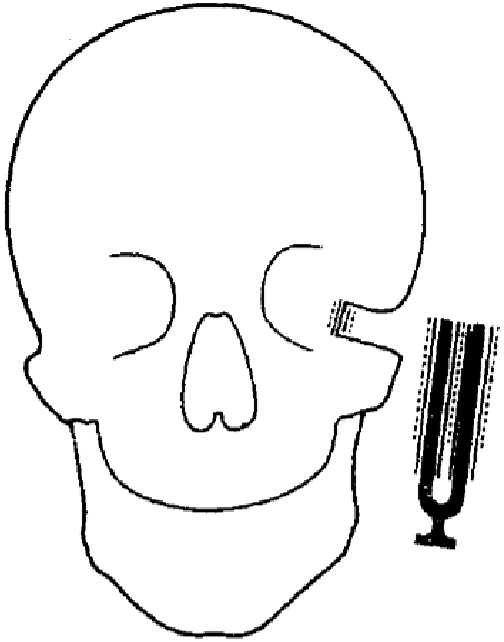






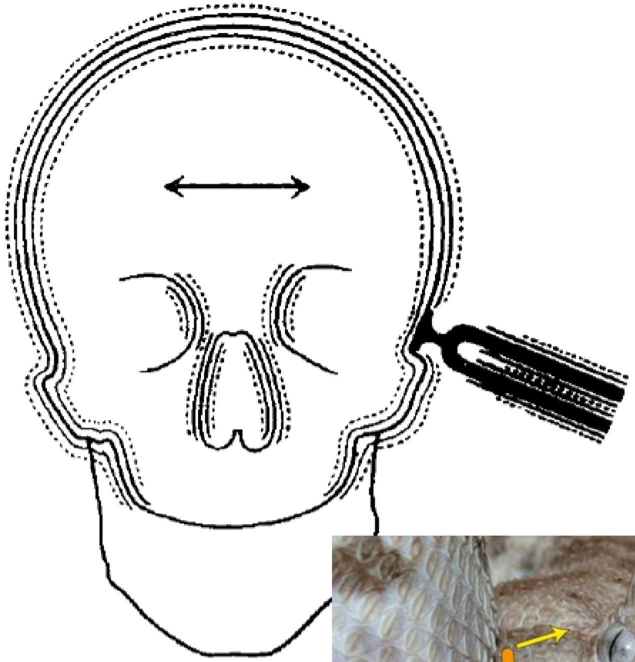
Tympanic Hearing and bone-conduction hearing

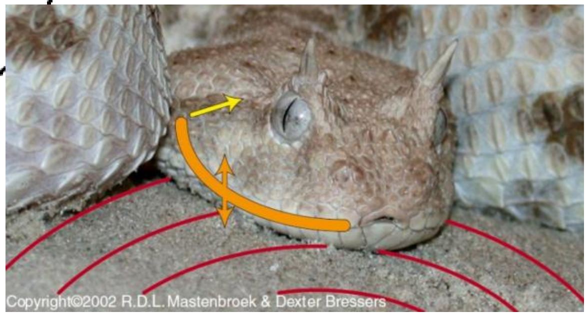
Hearing with tympanic membrane and middle ear bones



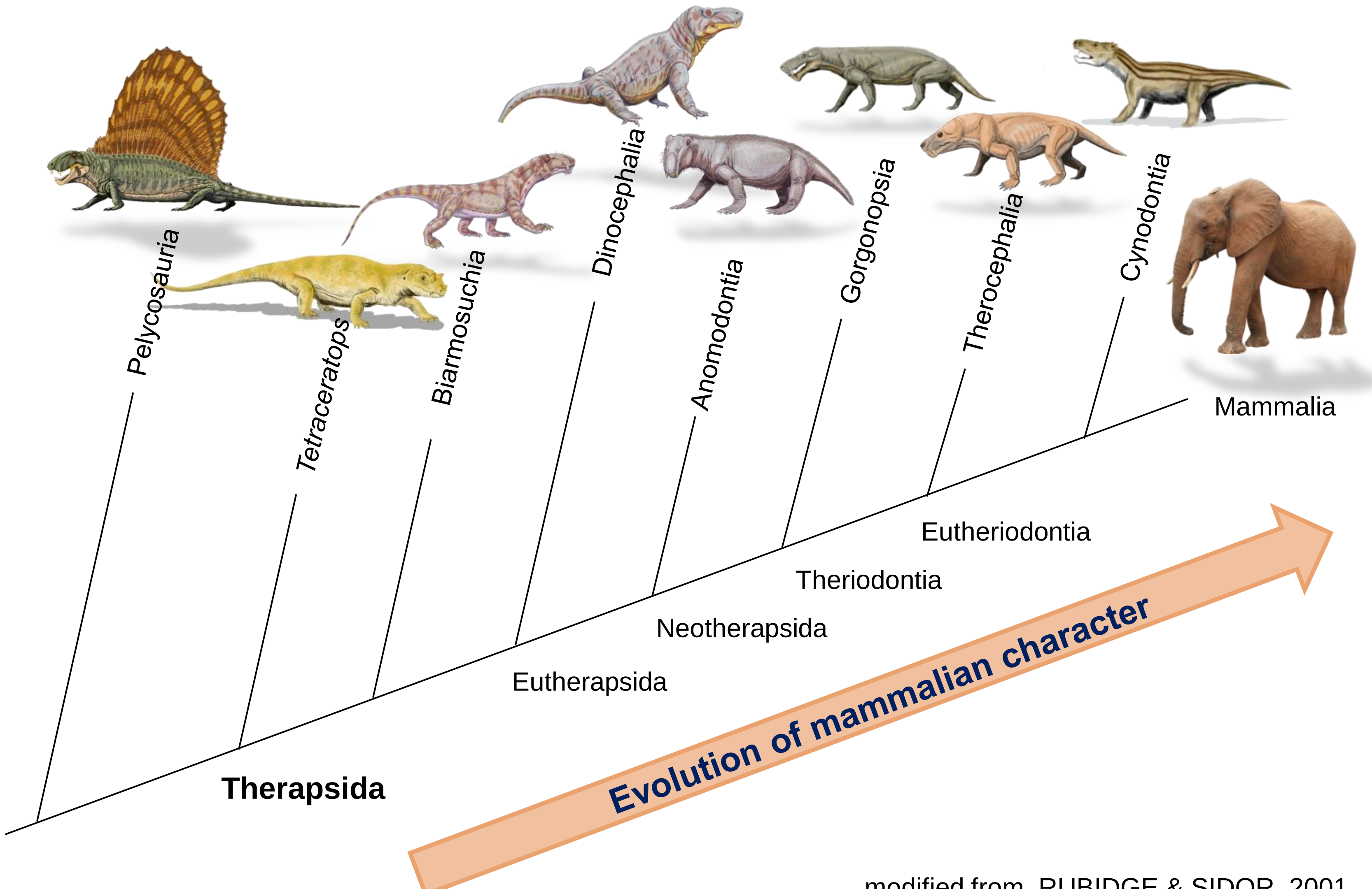
from Tumarkin 1968

Hearing by bone conduction



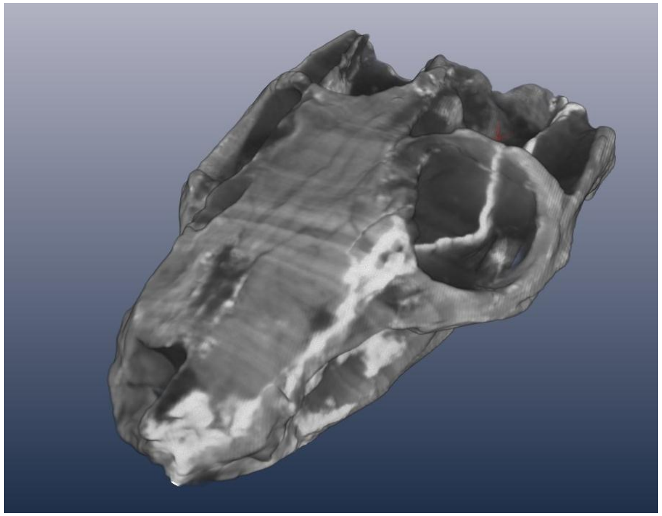


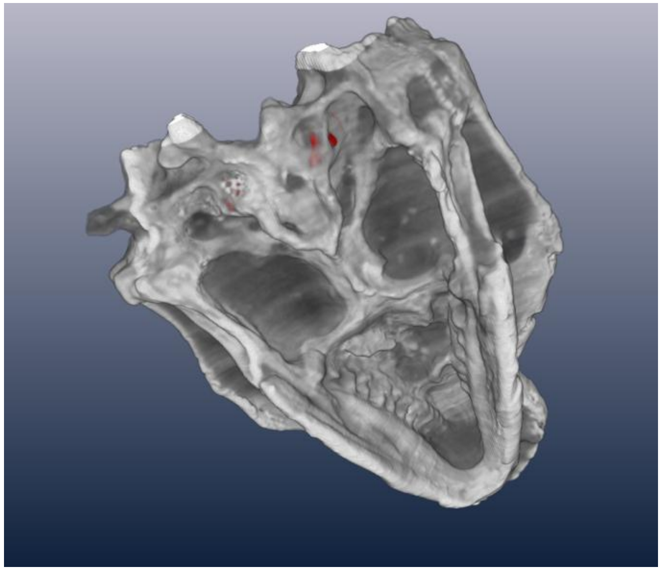
Synapsid evolution



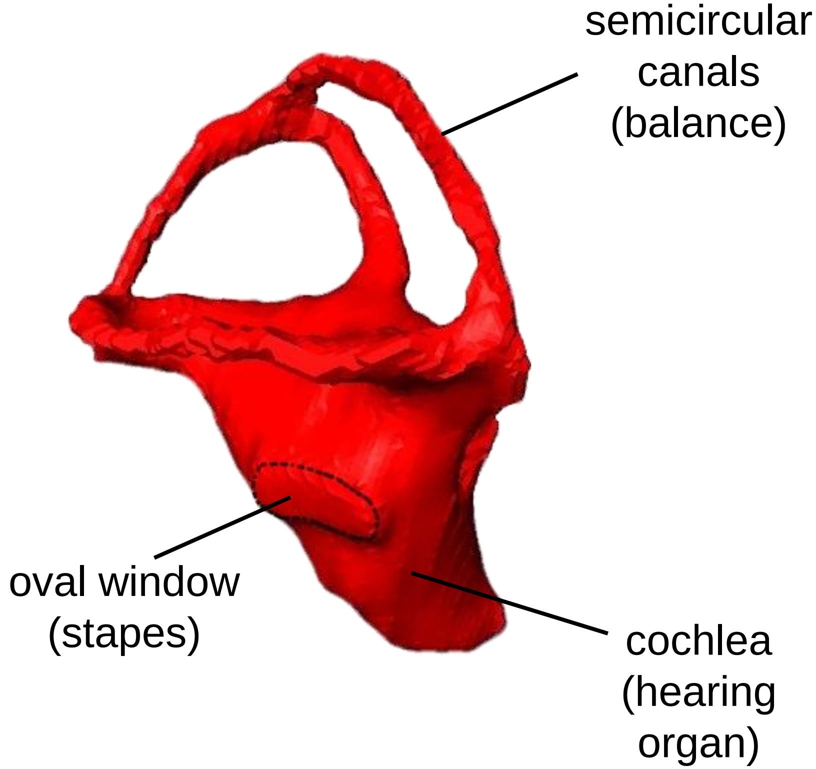
modified from RUBIDGE & SIDOR, 2001

The origin of tympanic hearing





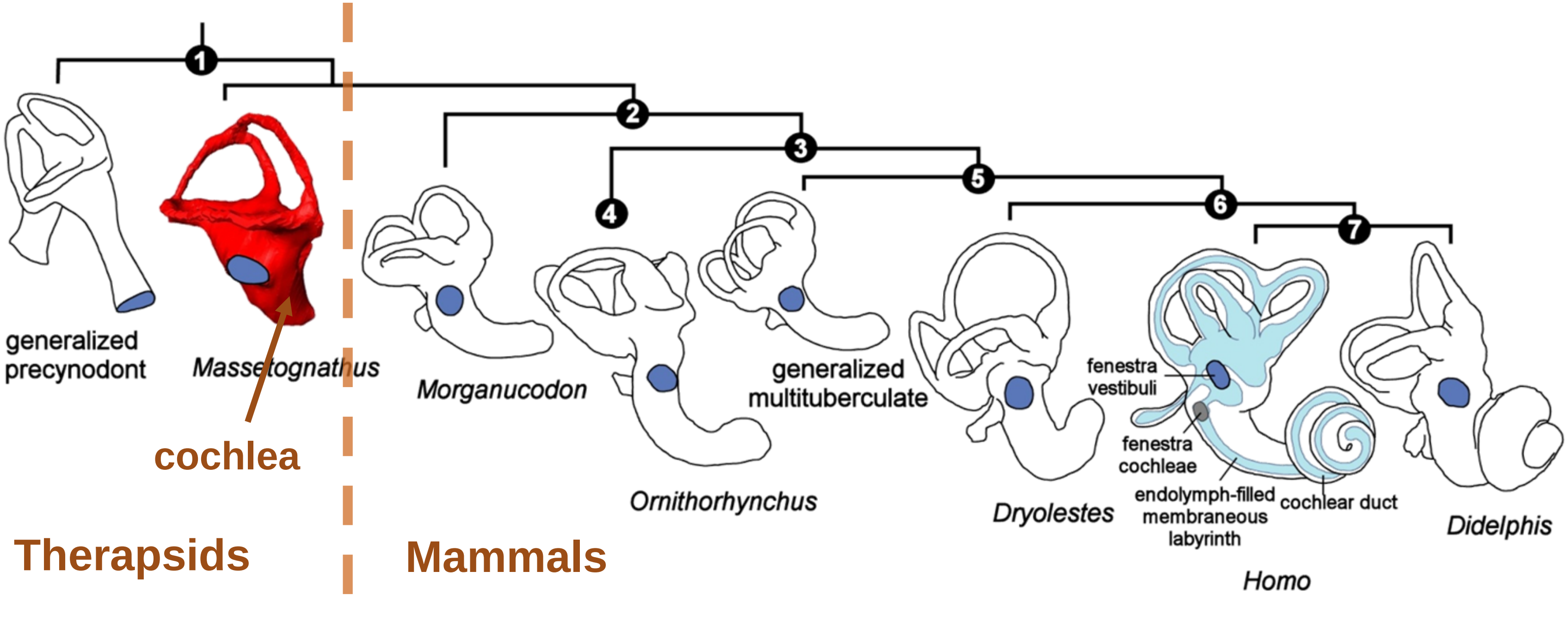
Massetognathus (Cynodontia), approx. 230 million years old



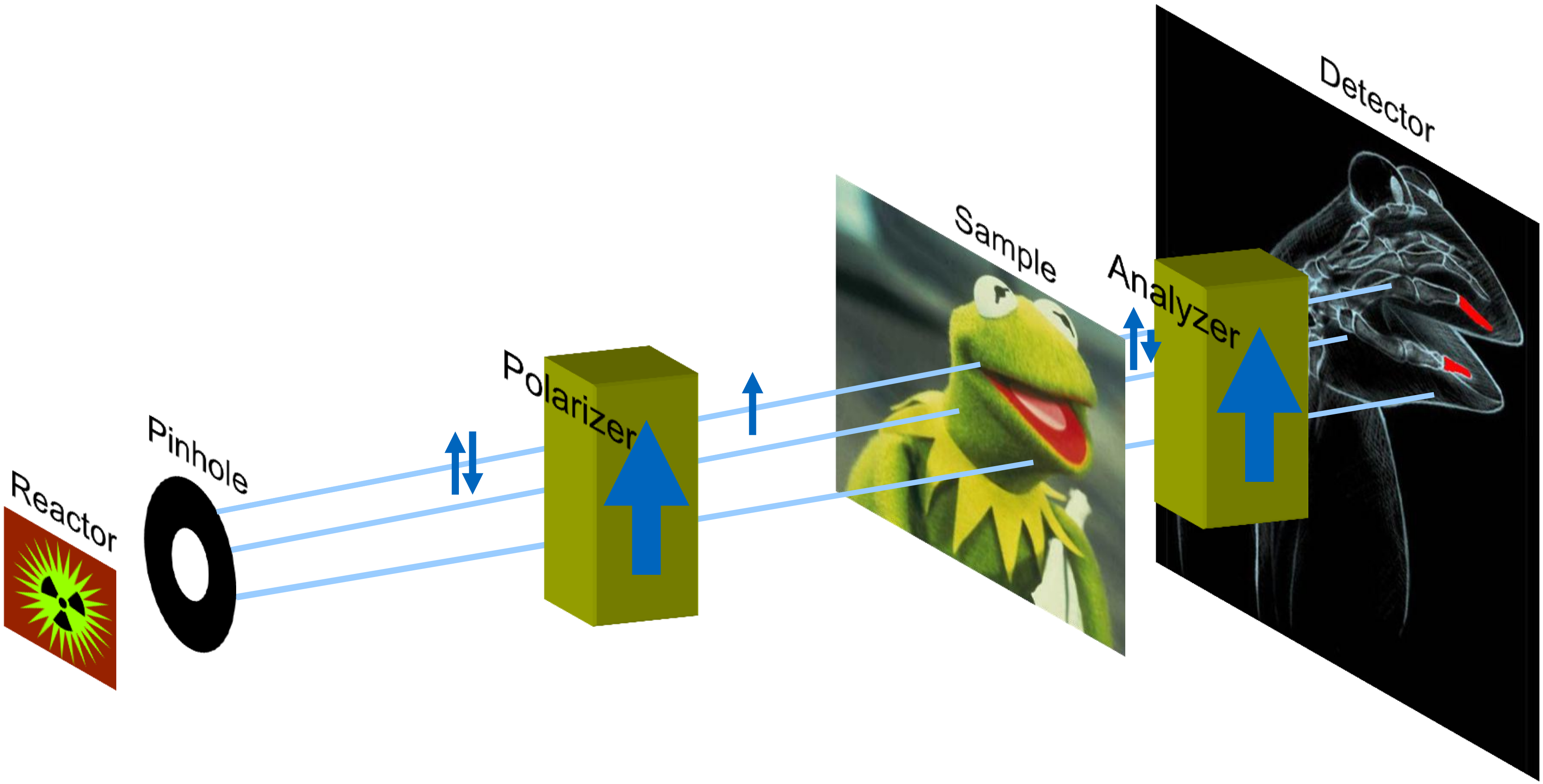
inner ear of *Massetognathus*

The origin of tympanic hearing

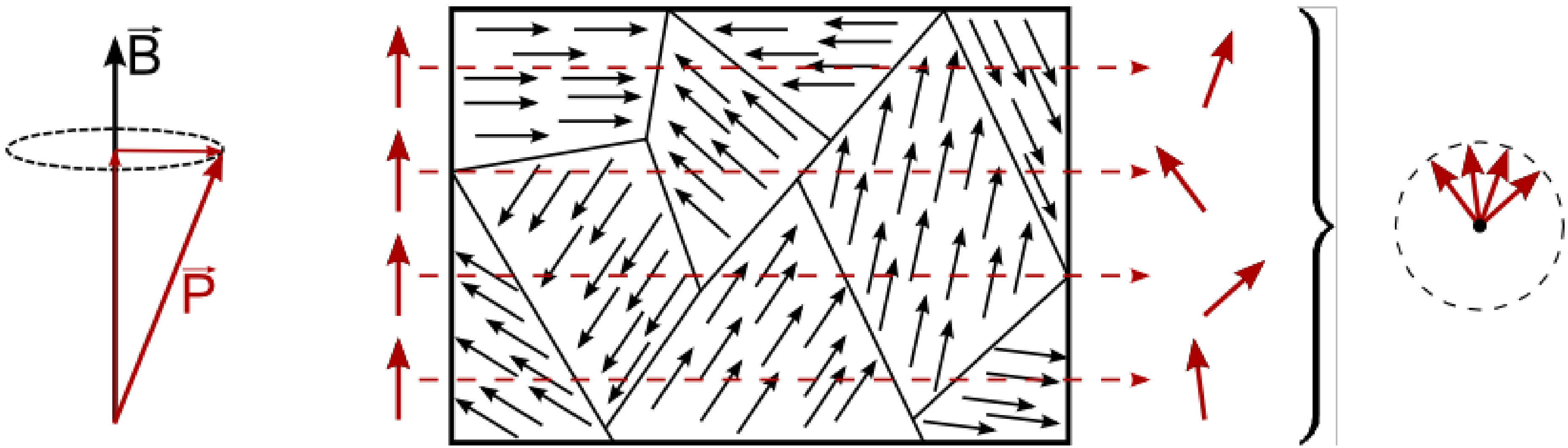
- short, tube-like cochlea in the cynodont therapsid *Massetognathus*
- 3,9 mm long
- enhanced sensitivity to high-frequency air-borne sound
- small stapedial footplate area (1,69 mm²)



More complex: Polarized Neutron Imaging

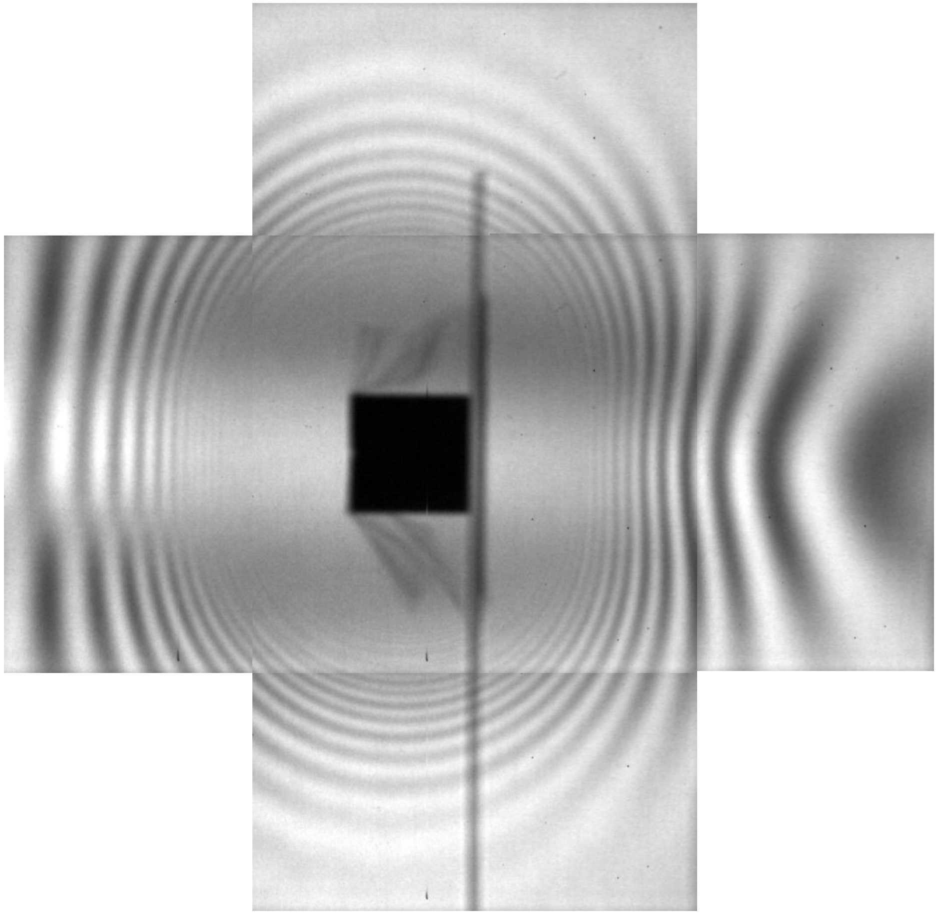


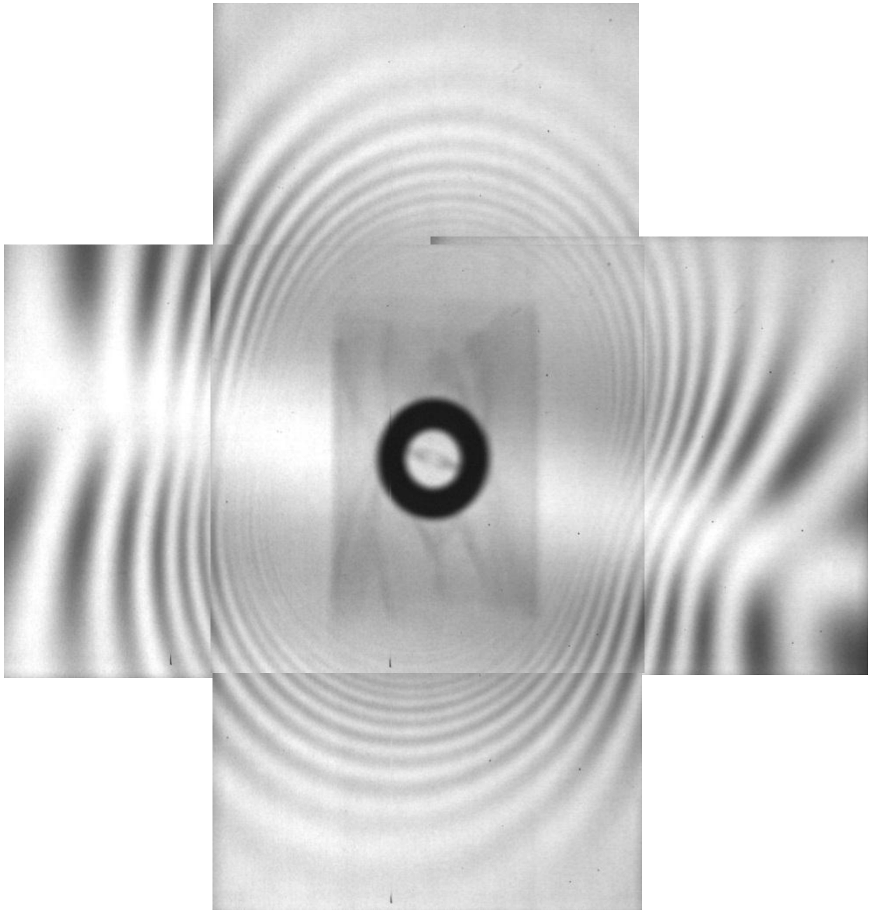
Neutron Depolarisation



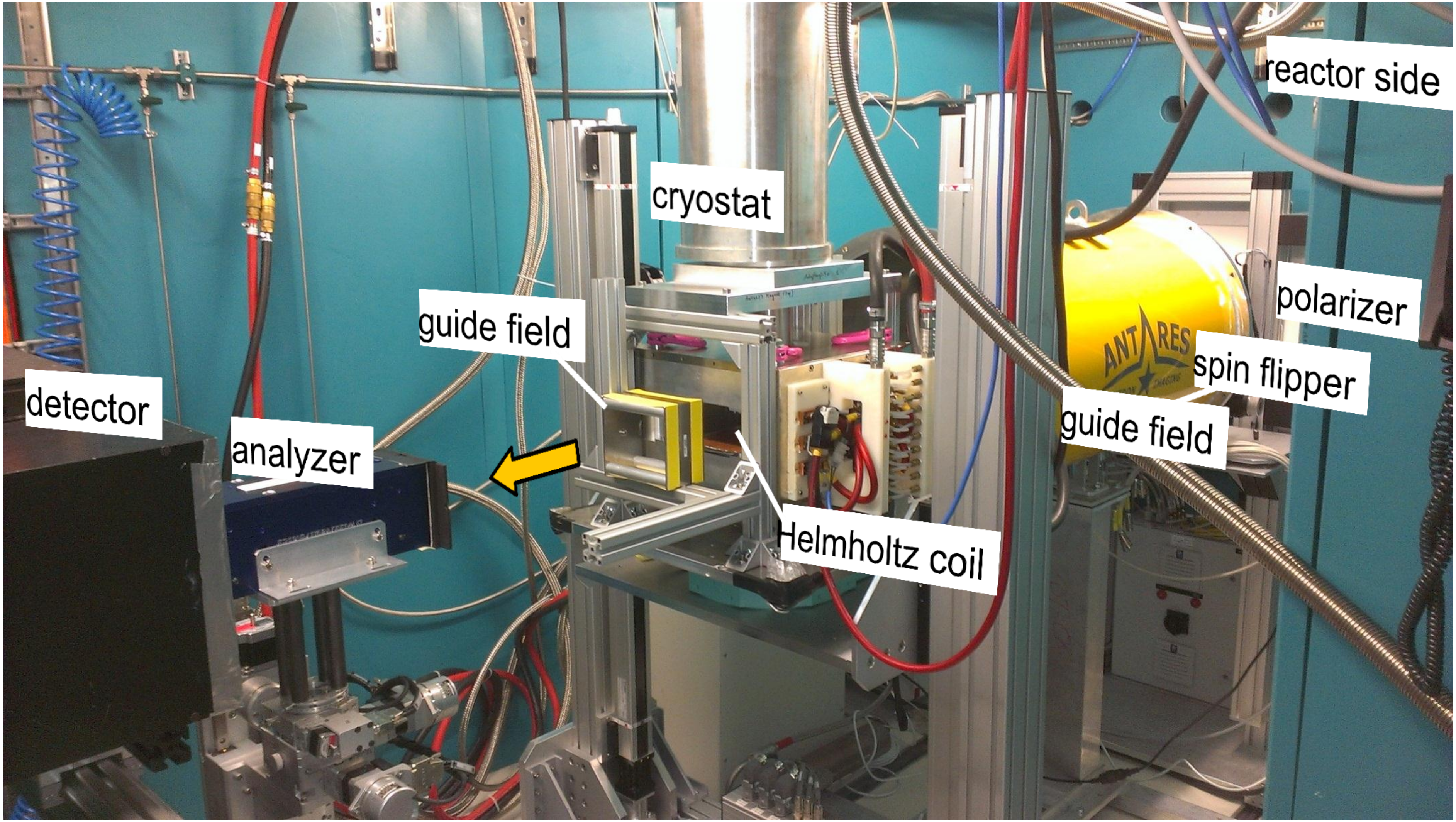
$$P = P_0 \exp\left(-\frac{1}{3}\gamma^2\mu_0^2 M^2 \frac{d\delta}{v^2}\right)$$

Stray Field of Ring Magnet

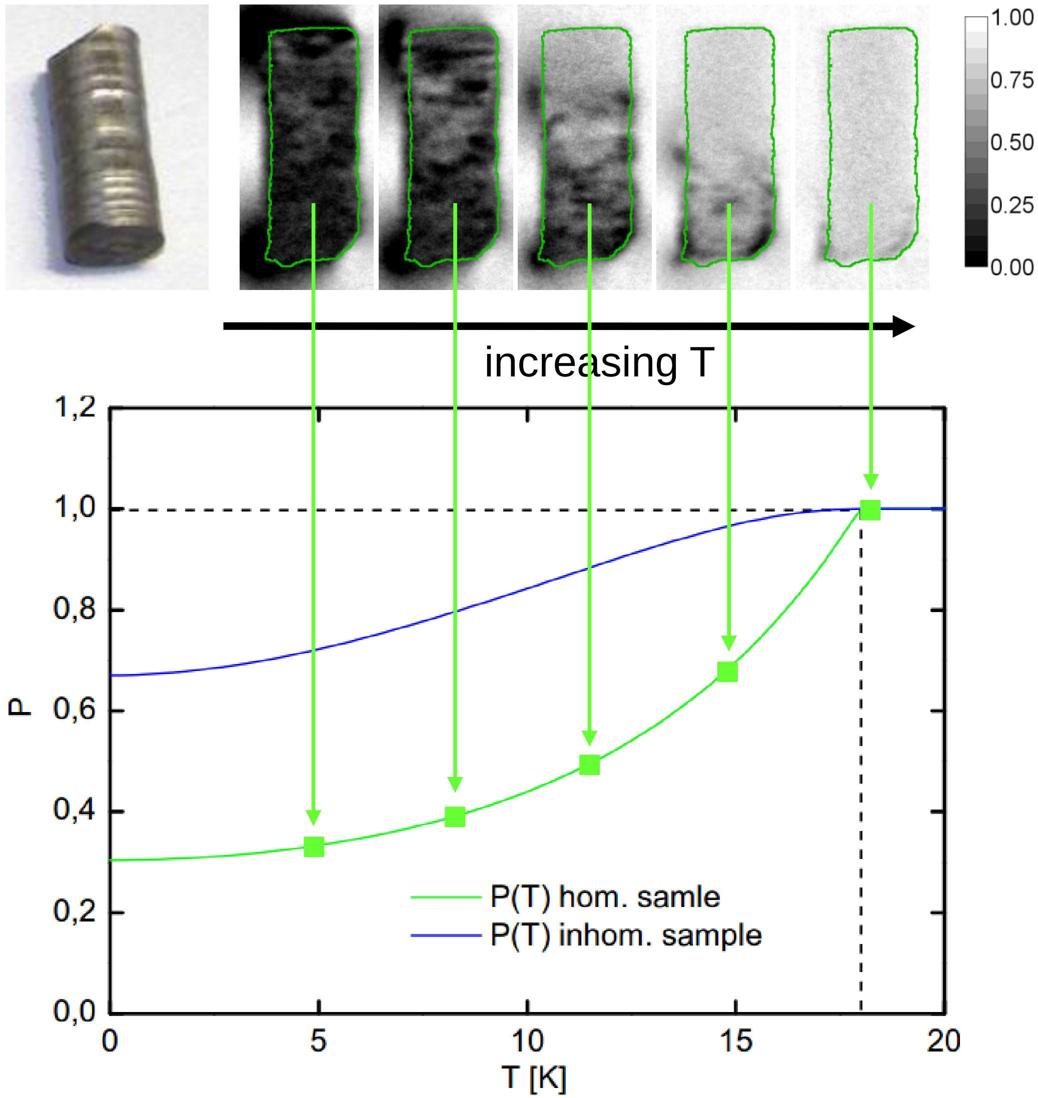


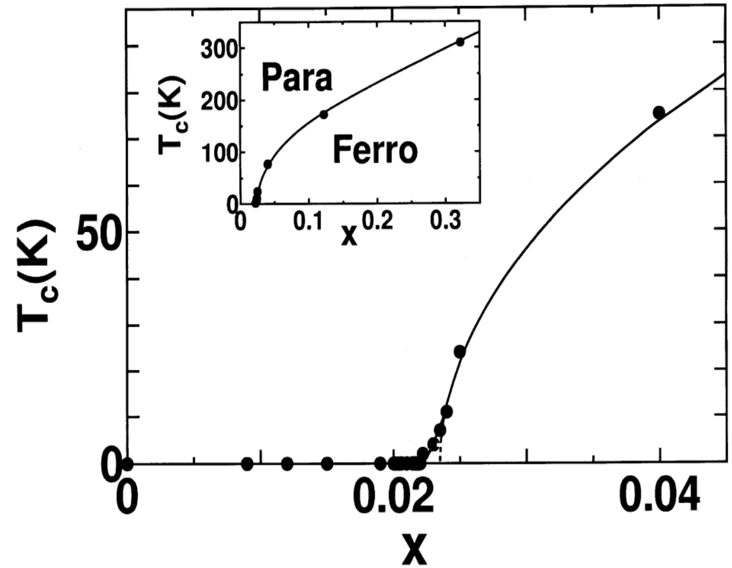


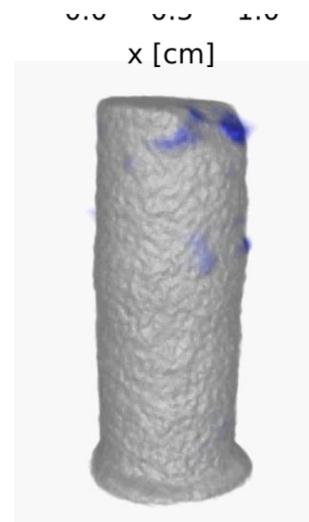
Setup for Depolarisation Imaging



$Pd_{1-x}Ni_x$ depolarization







T = 8K

M. Schulz, *et.al.*
J.Phys. Conf., **211** (2010) 012025

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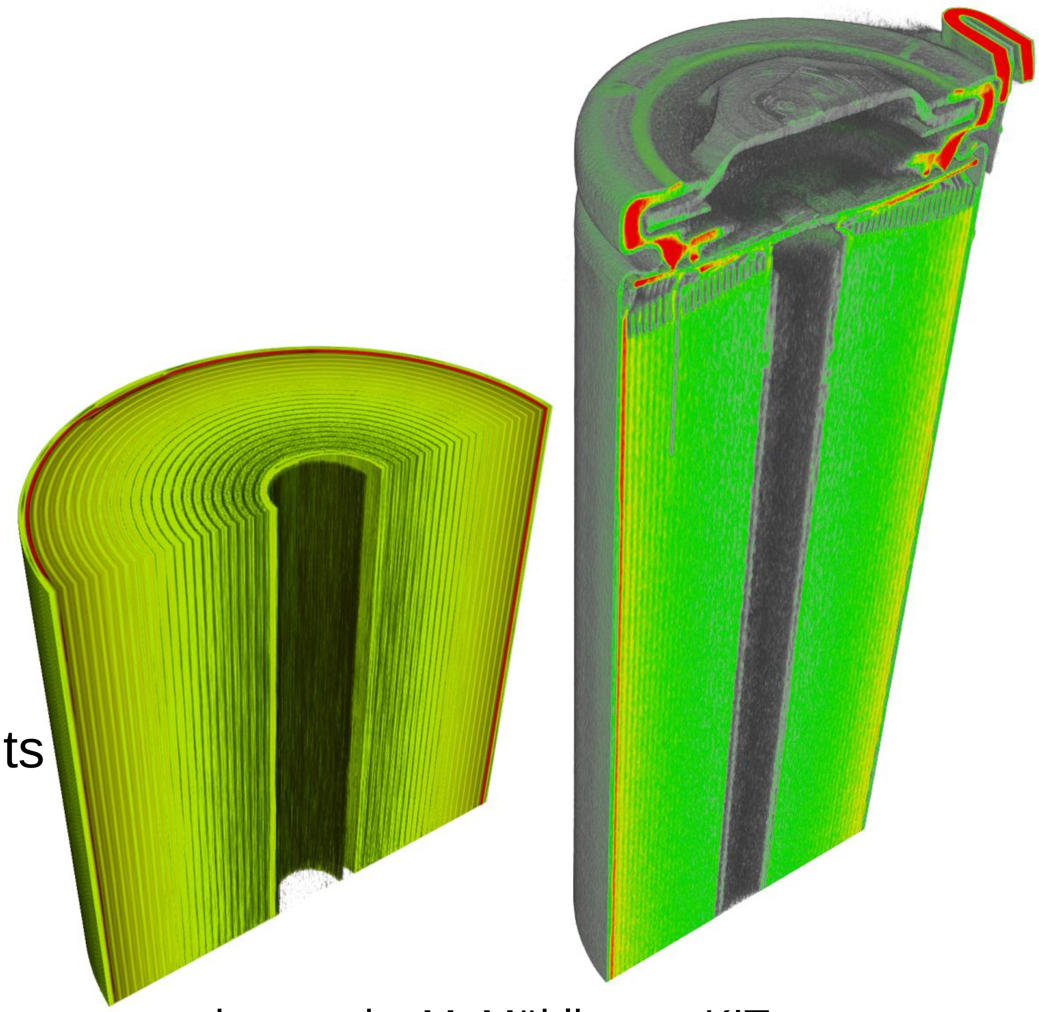
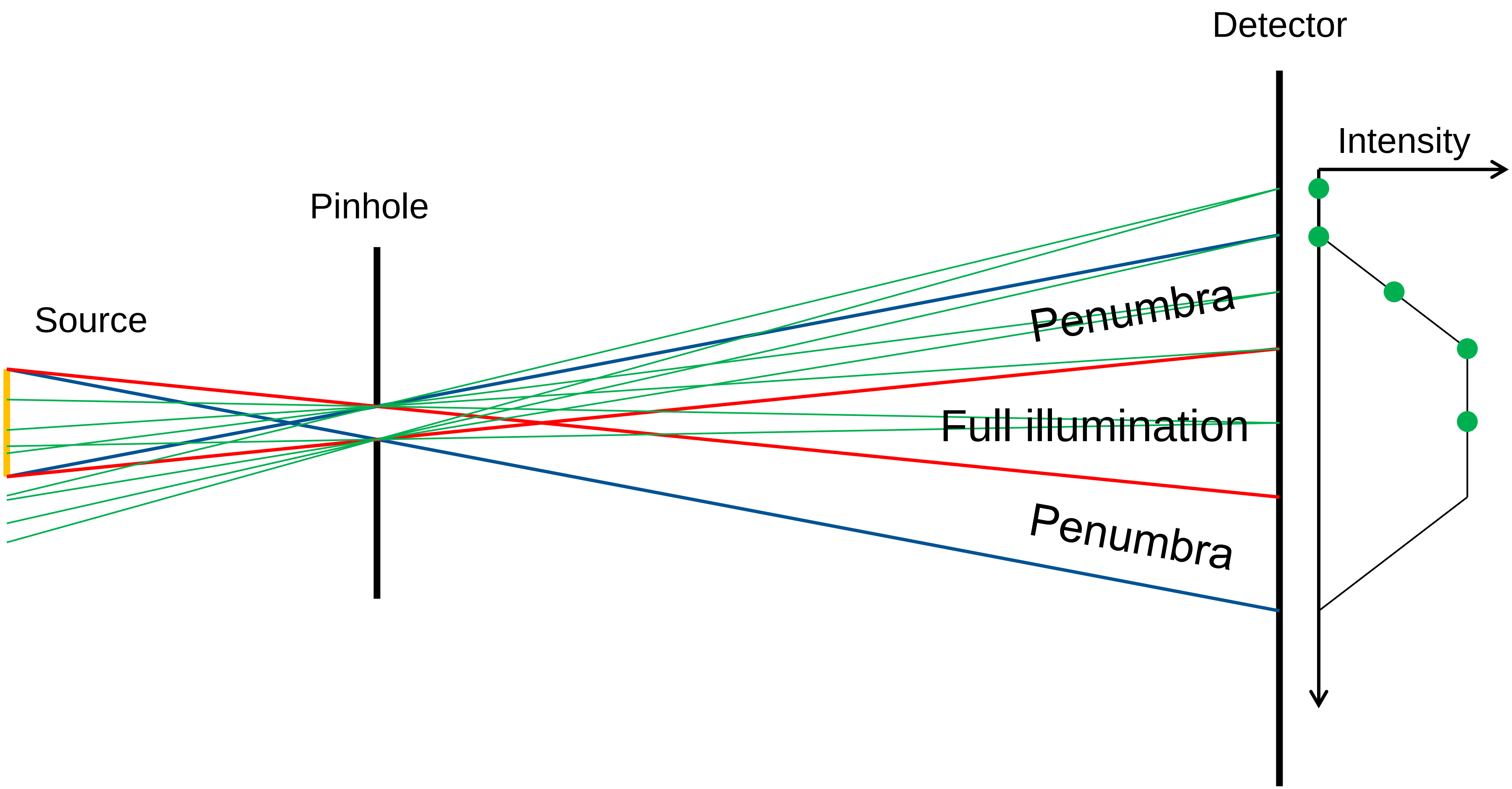


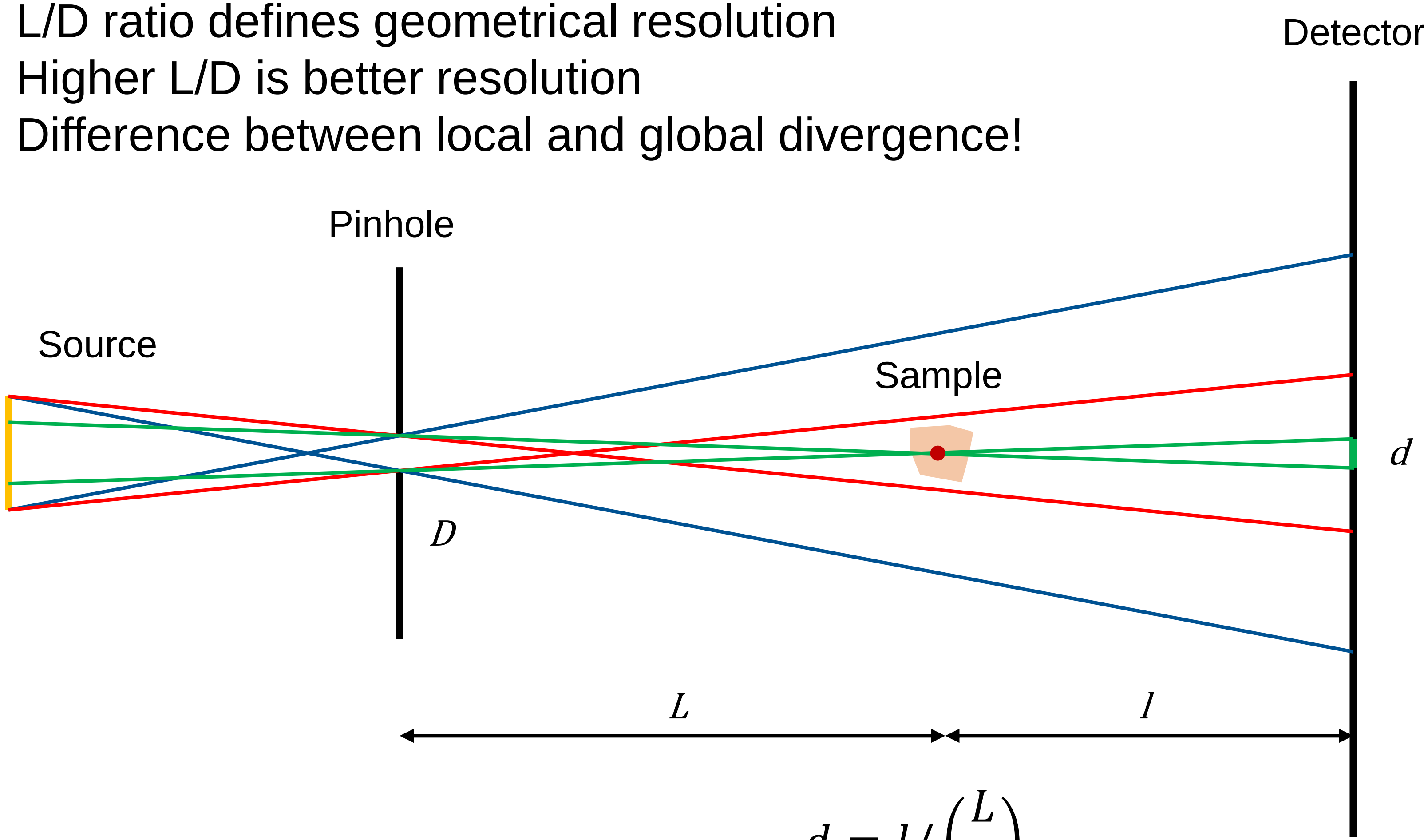
images by M. Mühlbauer, KIT

Pinhole camera geometry in detail



Resolution

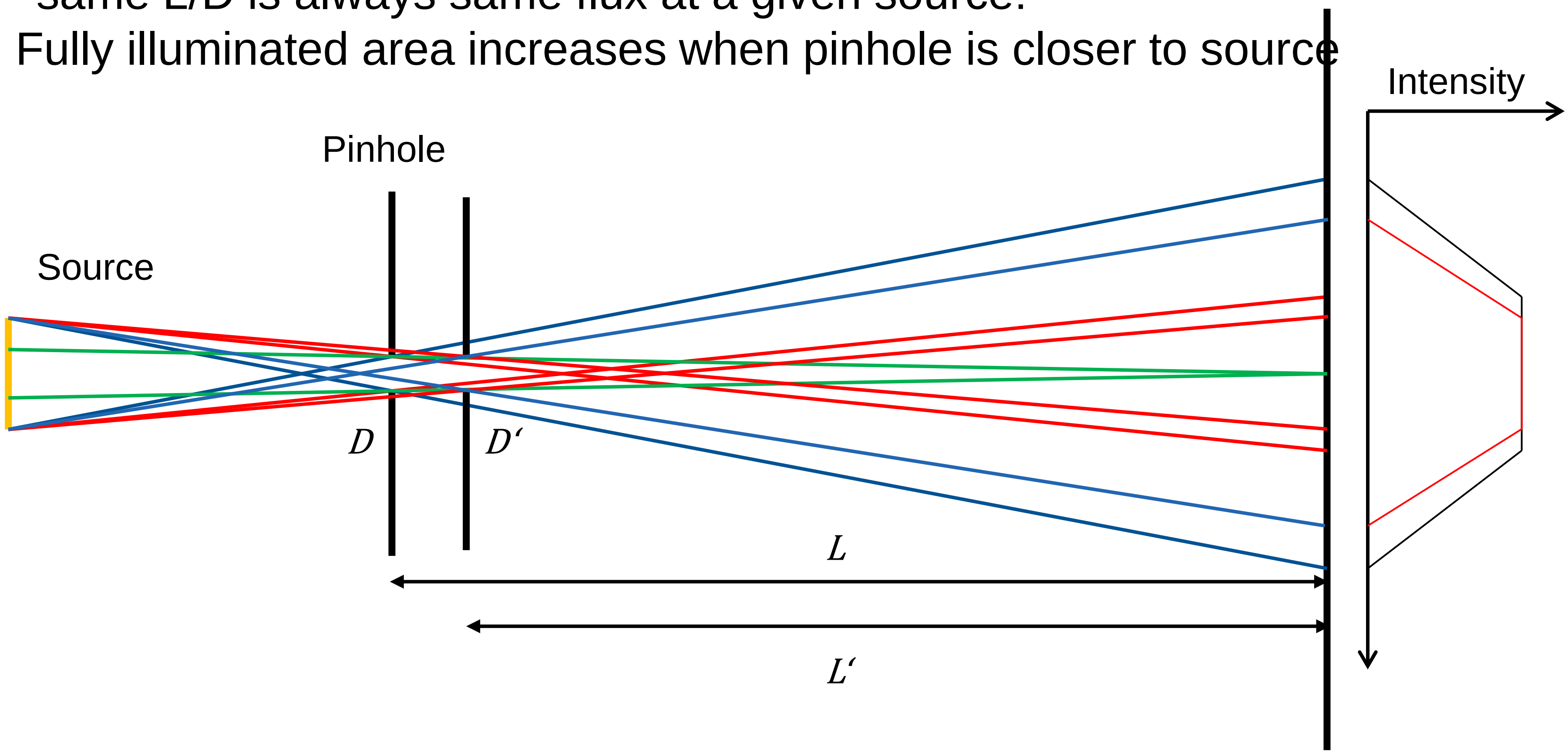
- L/D ratio defines geometrical resolution
- Higher L/D is better resolution
- Difference between local and global divergence!



$$d = l / \left(\frac{L}{D}\right)$$

Distance source-pinhole

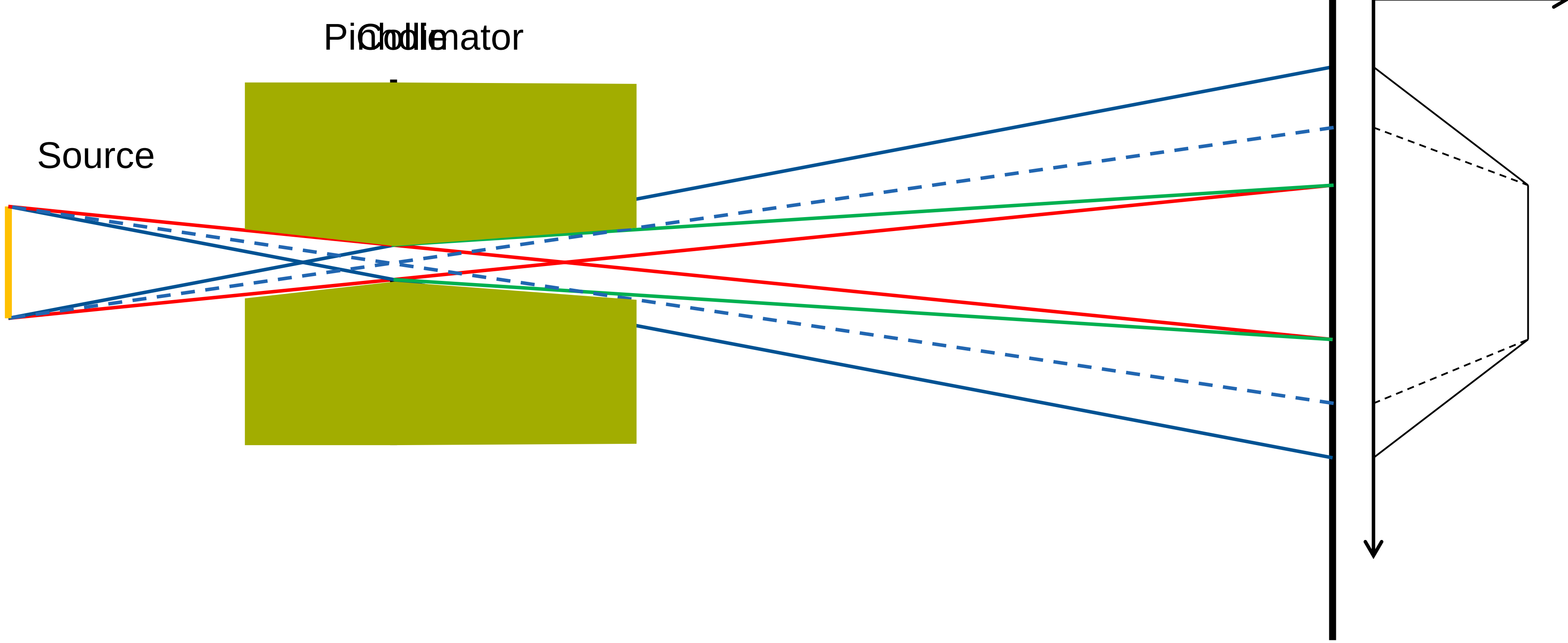
- Flux only depends on source brilliance and collimation
  same L/D is always same flux at a given source!
- Fully illuminated area increases when pinhole is closer to source



$$L'/D' = L/D = const$$

Collimator instead of pinhole

- Massive collimator to reduce penumbra
- Reduction of background
- 3D shape of collimator is complicated to machine



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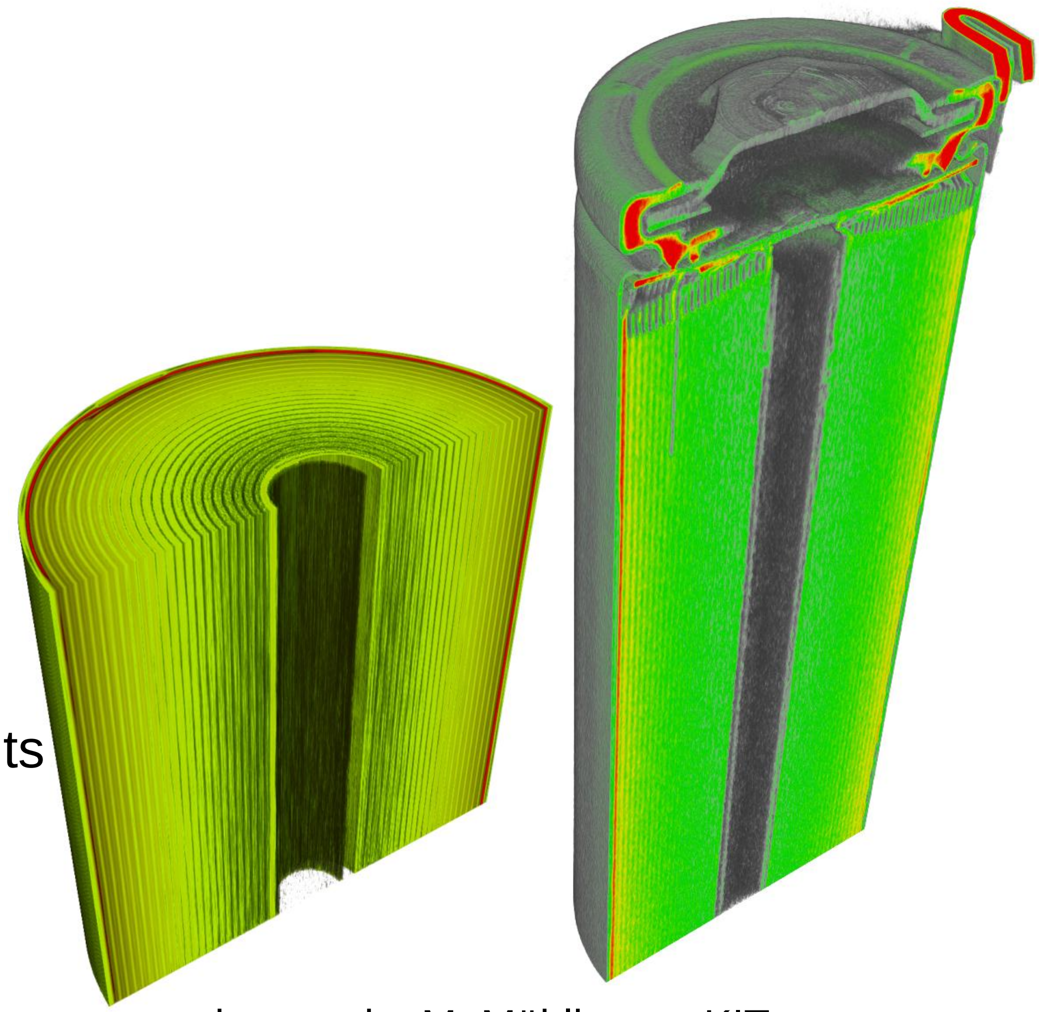
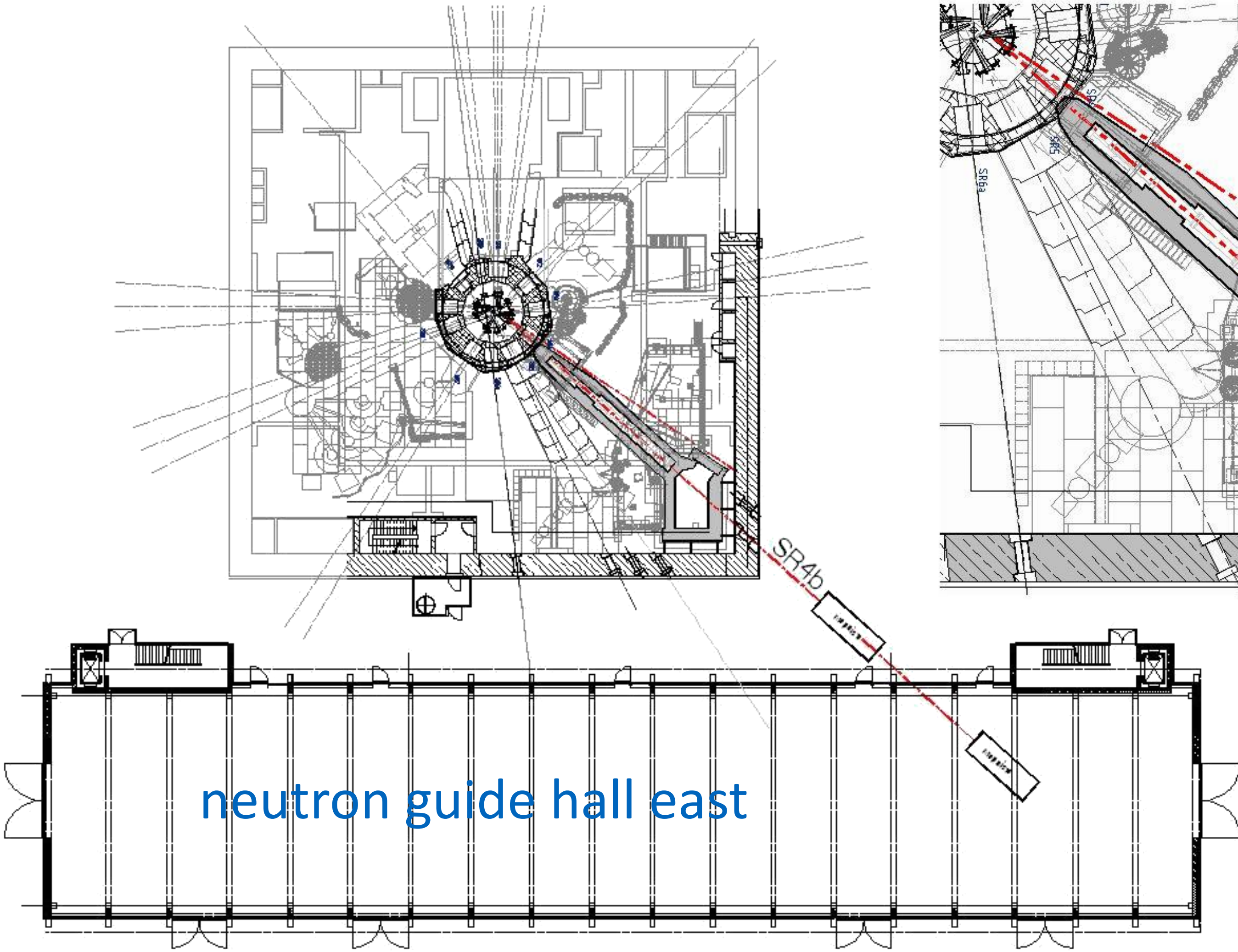
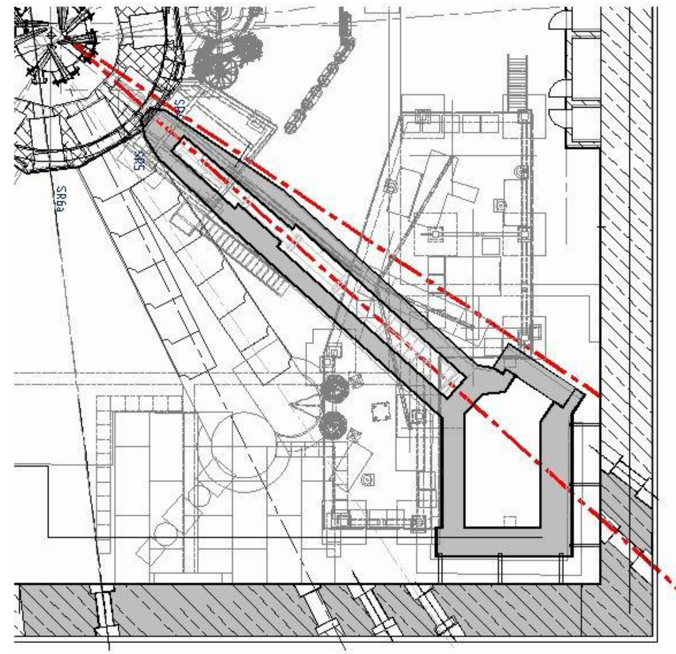


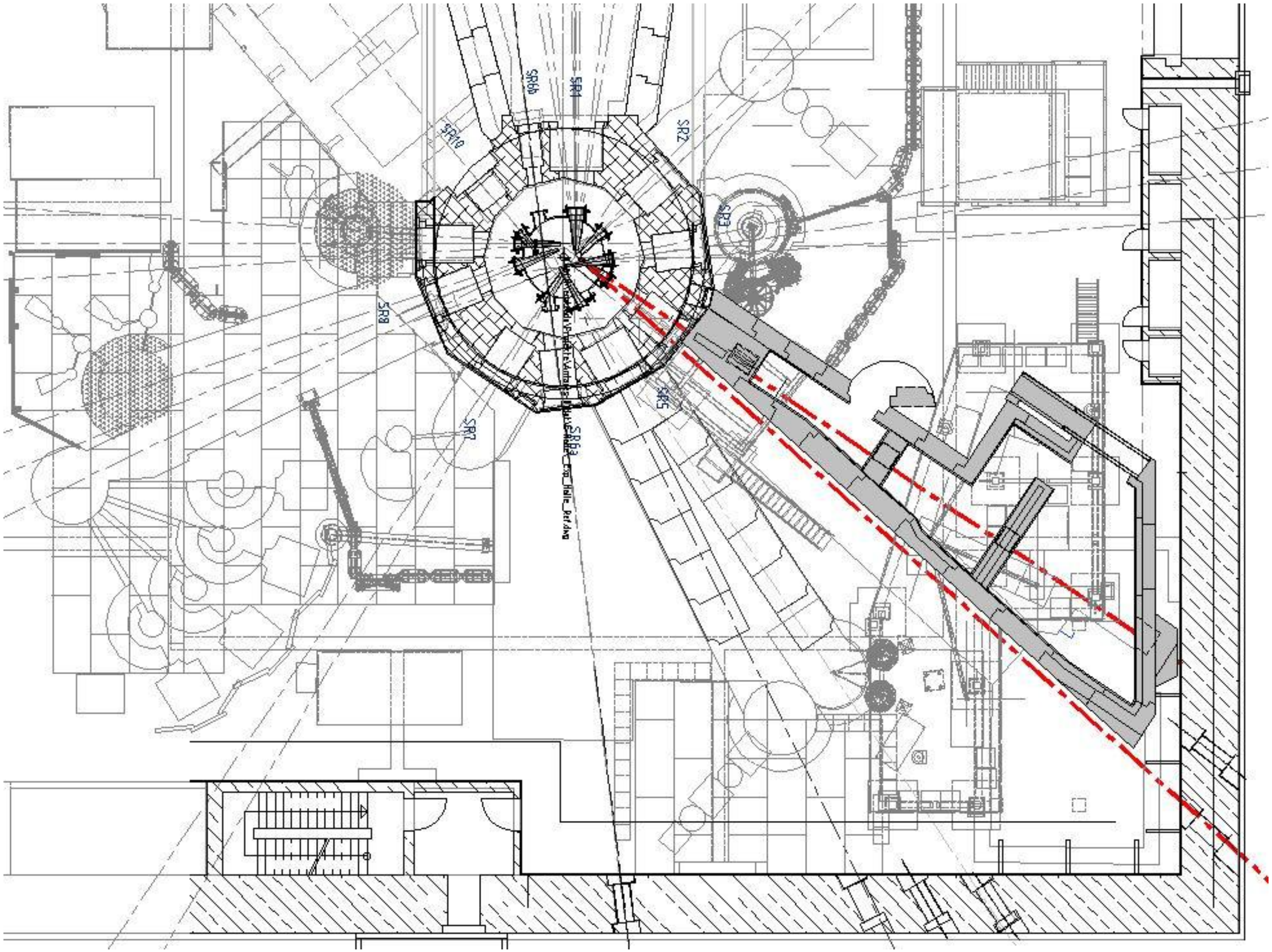
images by M. Mühlbauer, KIT

Why was ANTARES rebuilt?





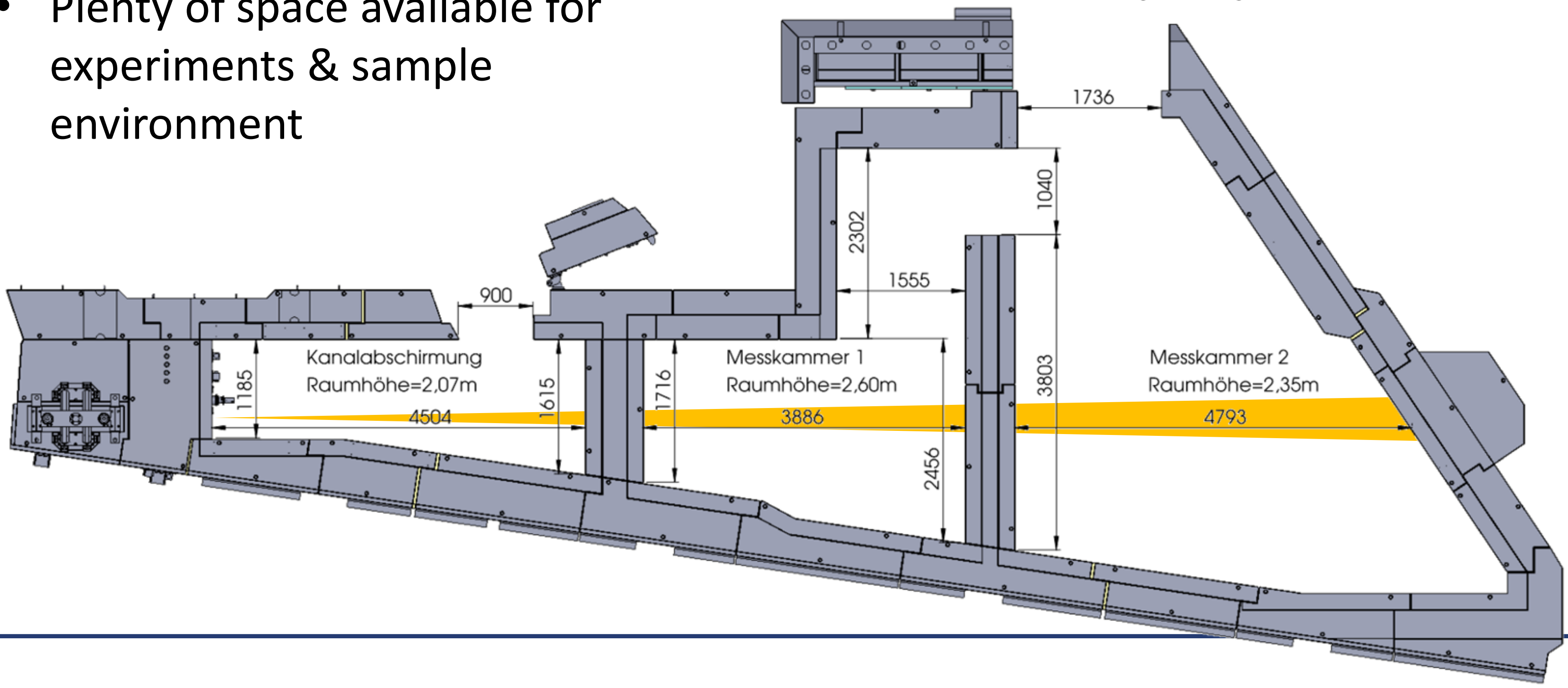
The new ANTARES beamline



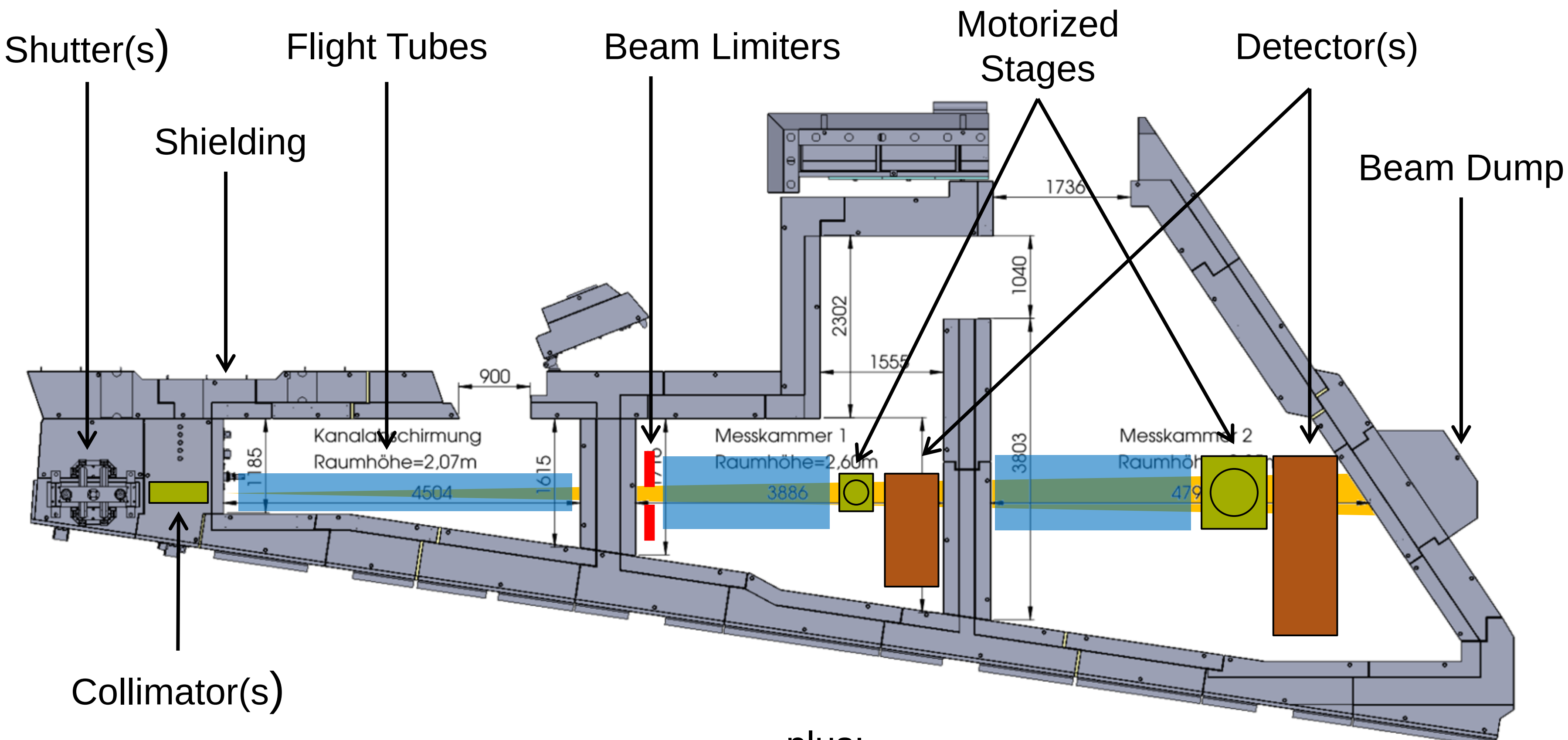
ANTARES Beam Line Concept

- 3 chambers
- Beam accessible along flight path
- High flexibility
- New & light shielding material (only 500t)
- Plenty of space available for experiments & sample environment

ANTARES
NEUTRON IMAGING



Main Components of a NI beamline



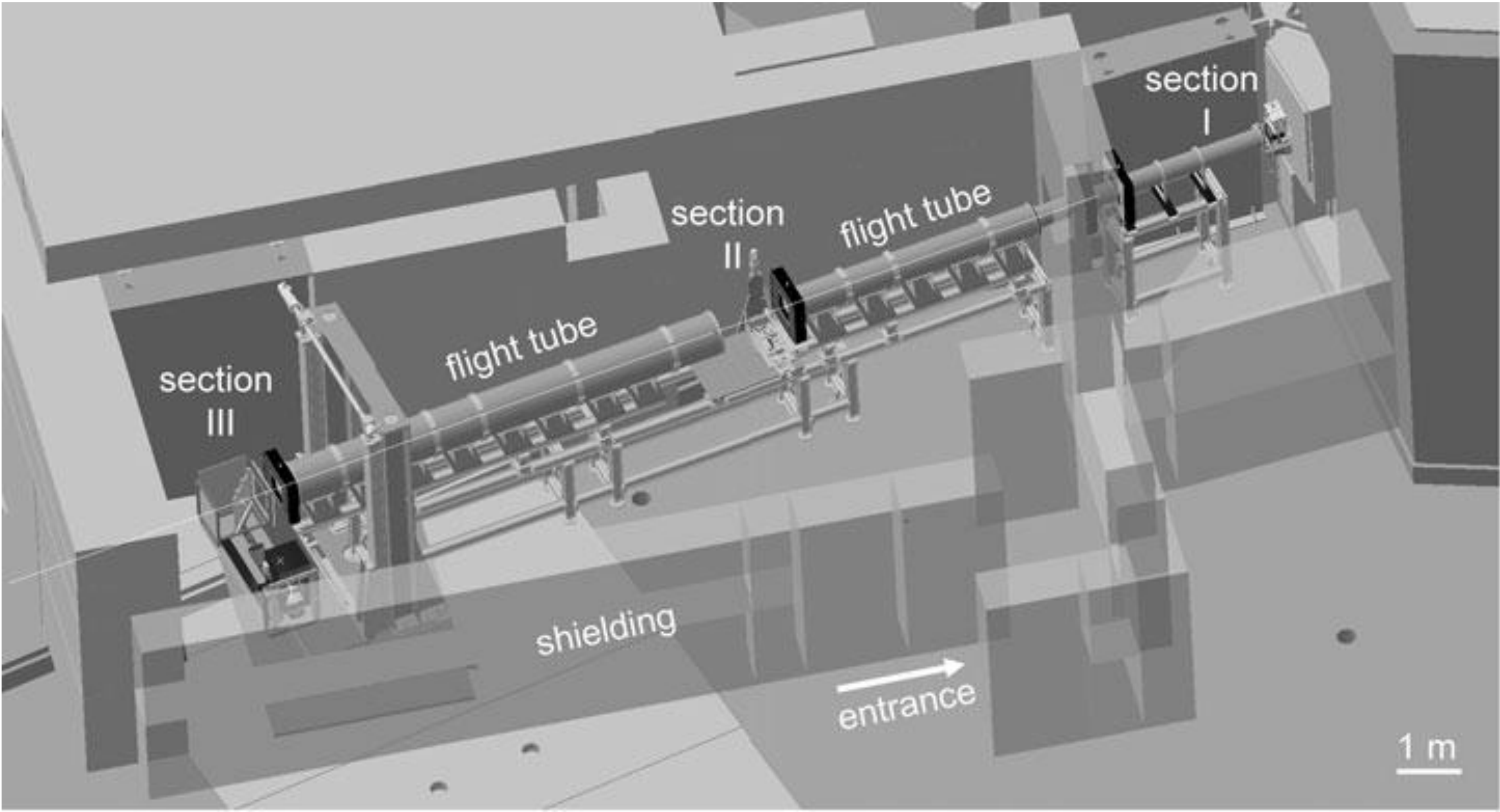
optional:

- Beam Filters
- Monochromator / Selector

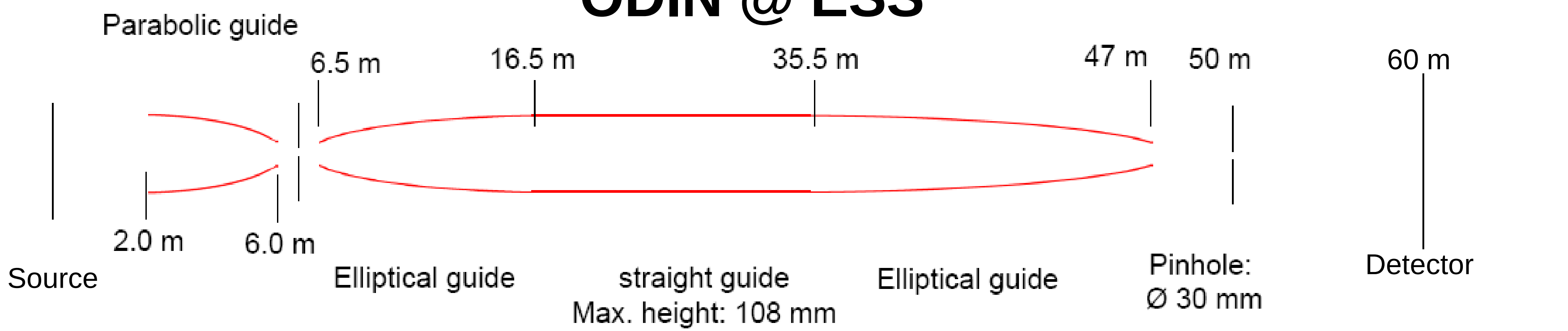
plus:

- Access Control
- Media Supply (electricity, gas, water, …)
- IT (network, storage, servers, software, …)

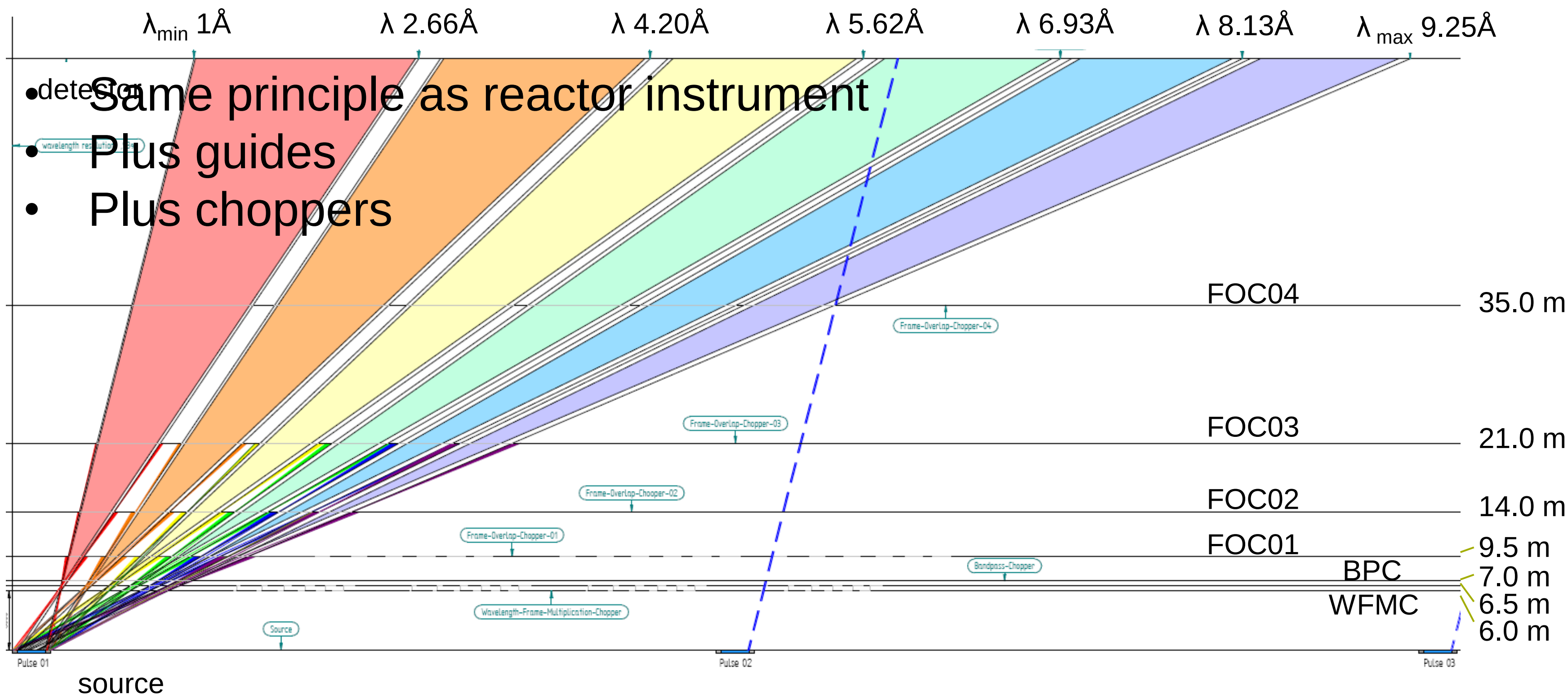
ICON @ PSI


section
I
section
II
flight tube
flight tube
section
III
shielding
entrance
1 m

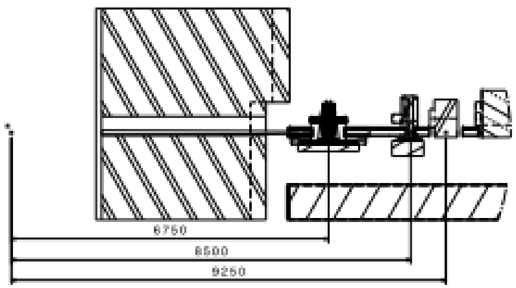
ODIN @ ESS



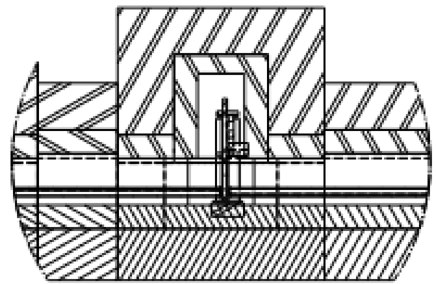
- Same principle as reactor instrument
- Plus guides
- Plus choppers



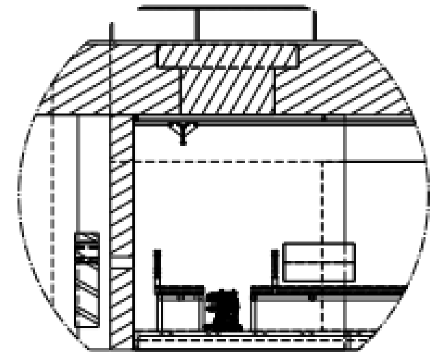
ODIN CAD drawings



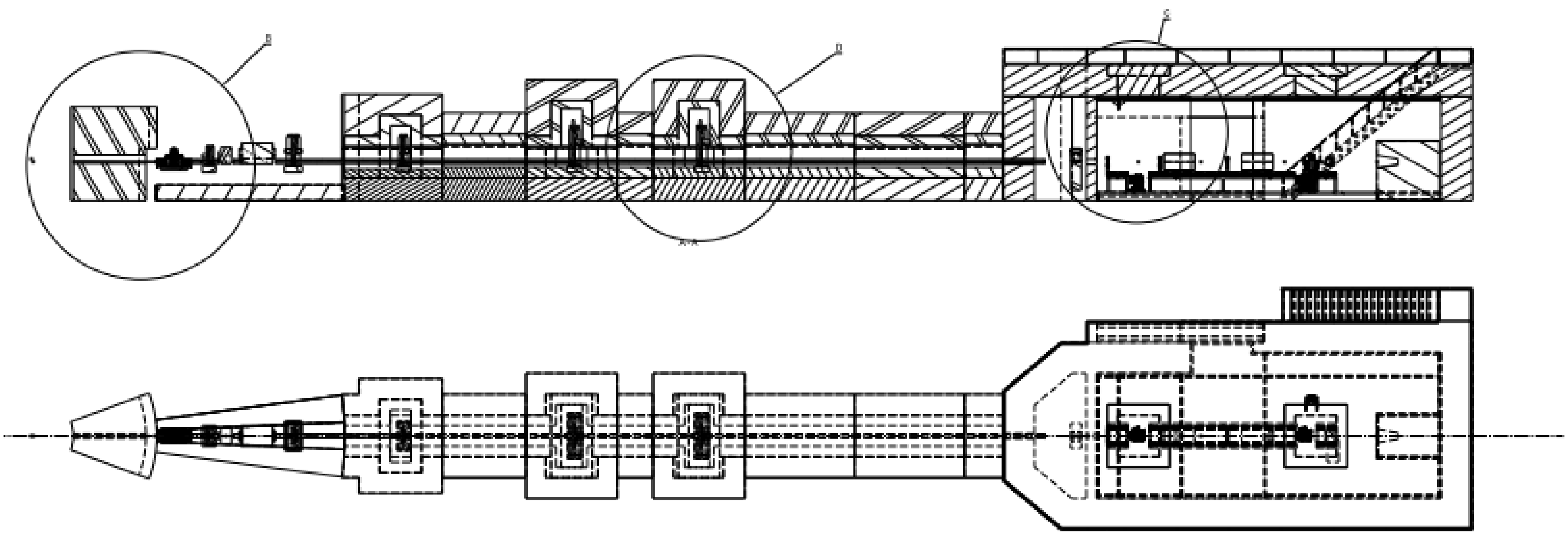
B (1:50)

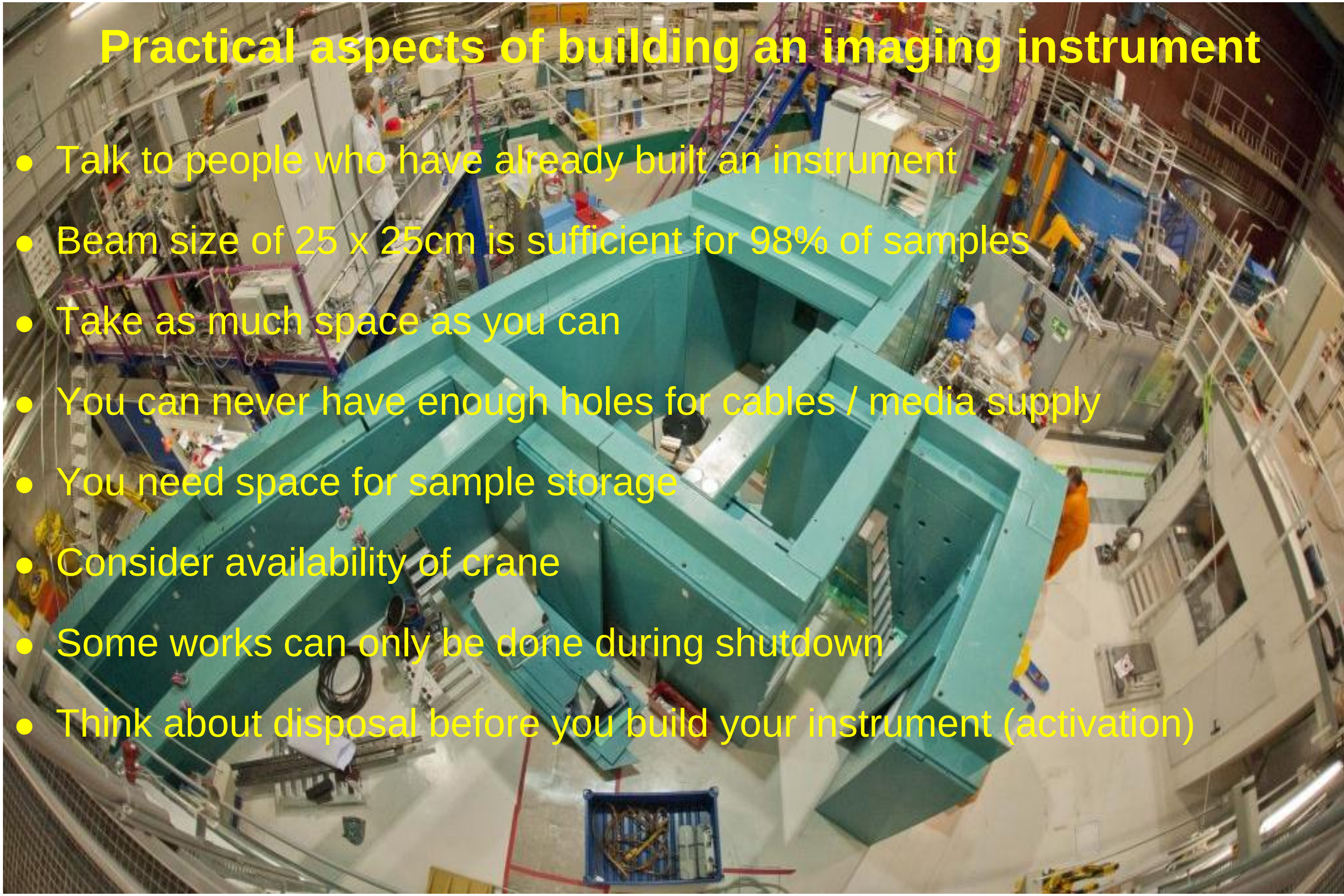


D (1:50)



C (1:50)

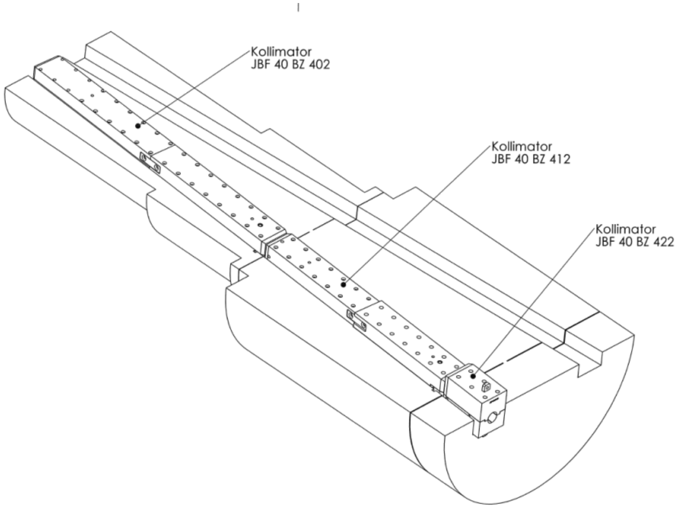




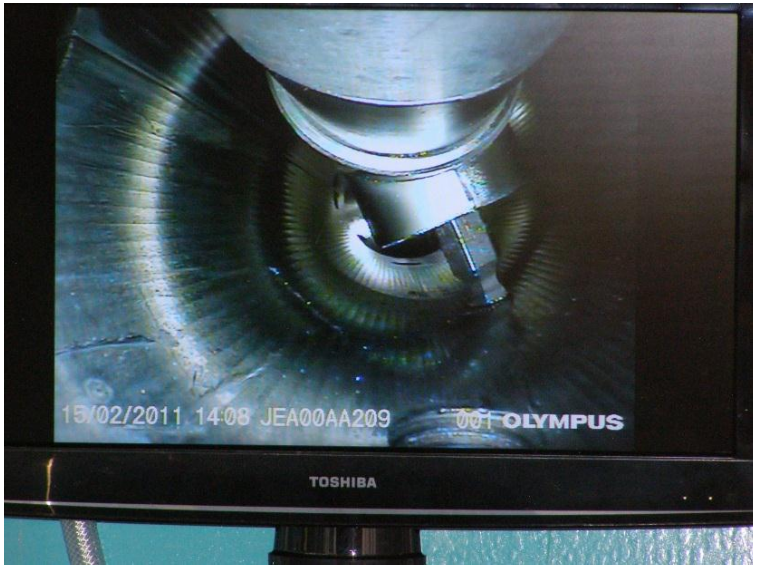
Practical aspects of building an imaging instrument

- Talk to people who have already built an instrument
- Beam size of 25 x 25cm is sufficient for 98% of samples
- Take as much space as you can
- You can never have enough holes for cables / media supply
- You need space for sample storage
- Consider availability of crane
- Some works can only be done during shutdown
- Think about disposal before you build your instrument (activation)

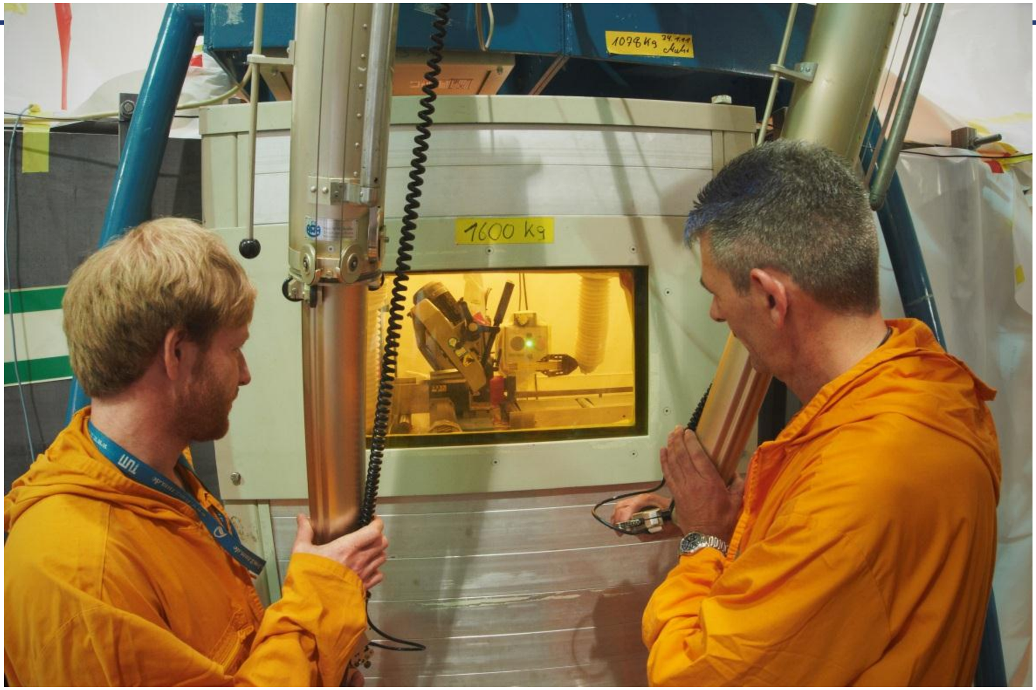
Removal of old ANTARES collimators

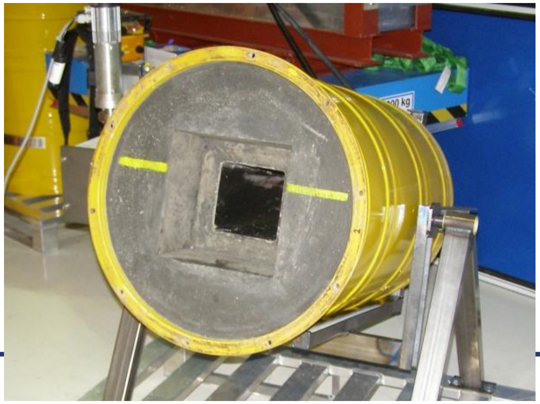


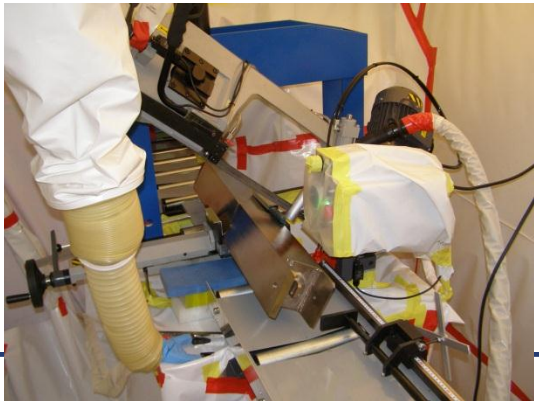
- Very close to reactor core (flux: 10^{12}n/cm²s)
- Highly activated (~1Sv/h)
- Remote controlled removal through massive shielding



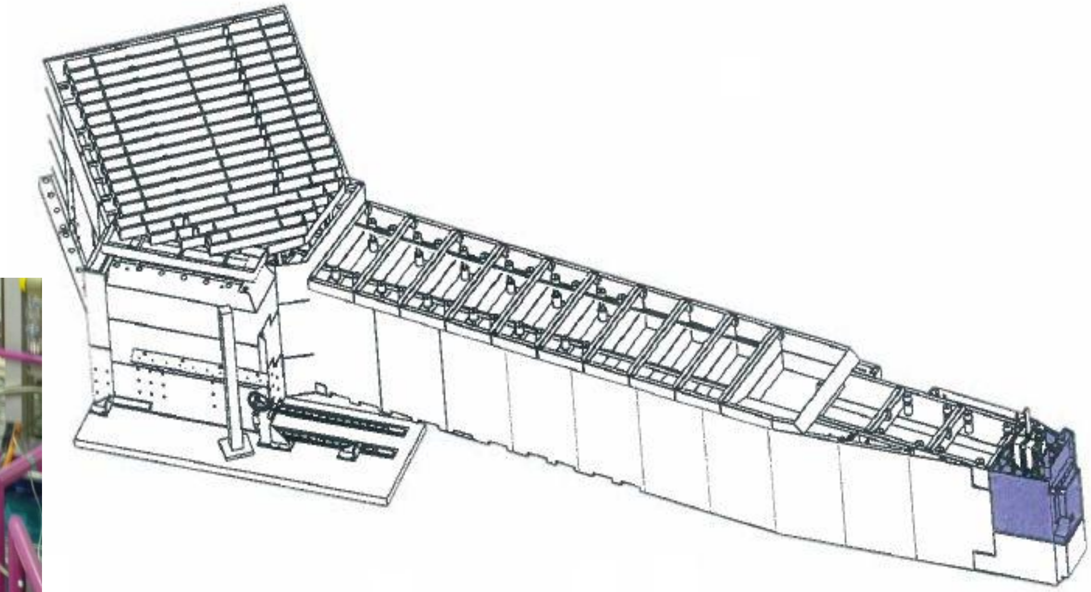
Packaging of old collimators

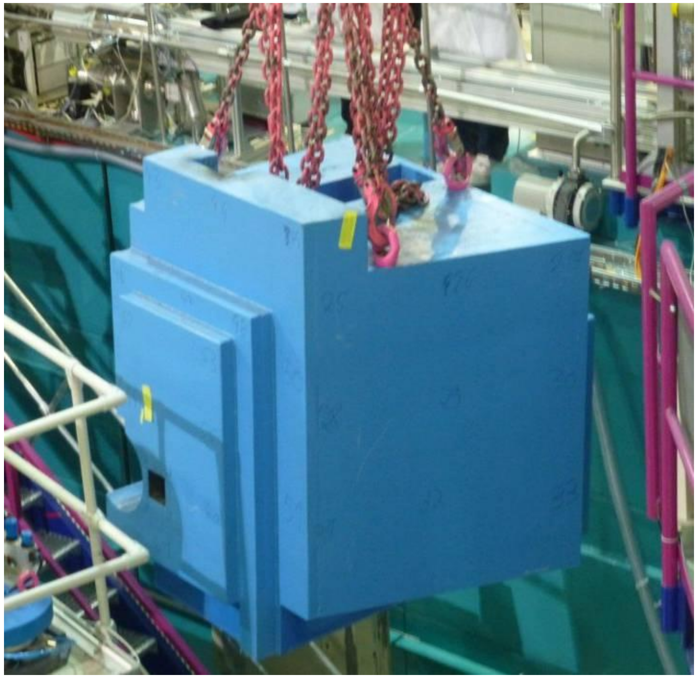






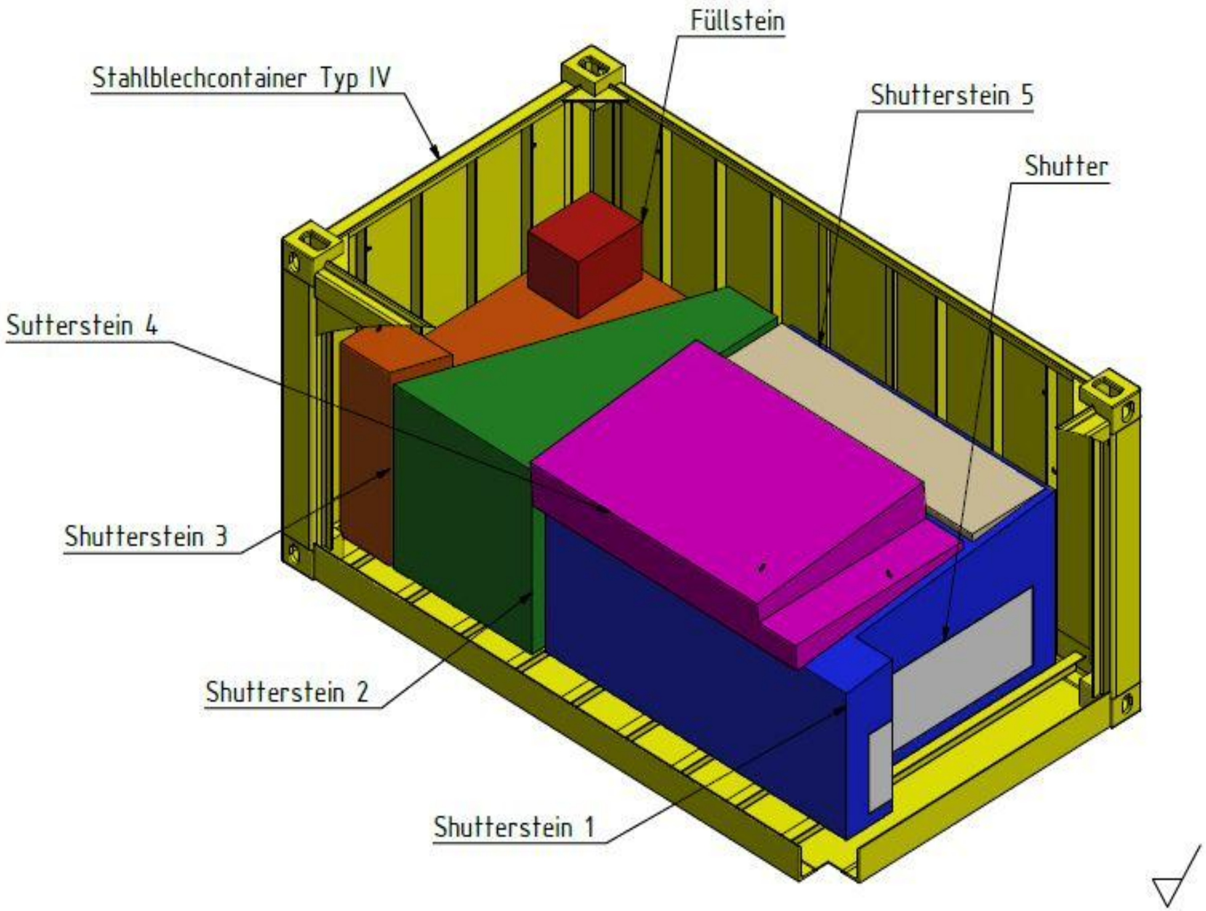
Old ANTARES shutter block

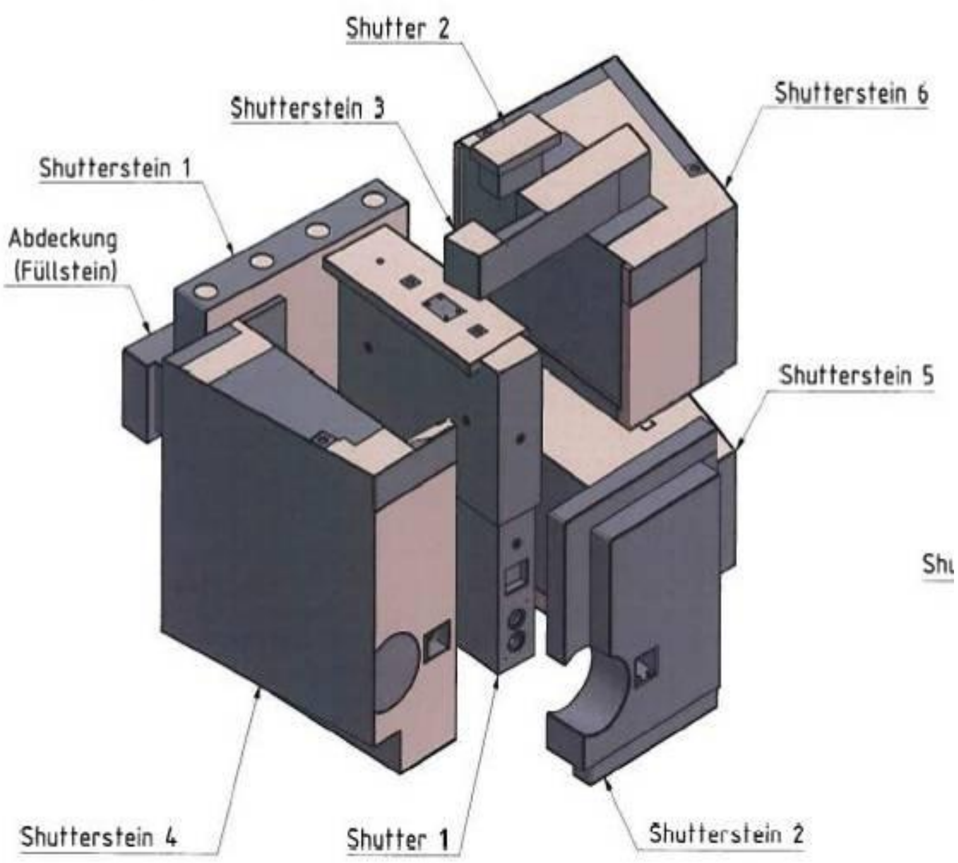


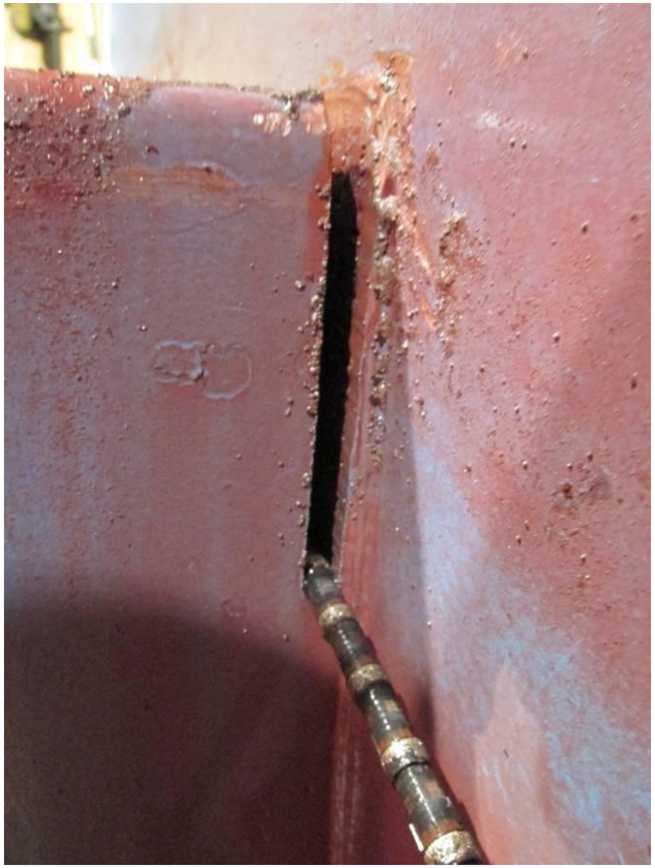


- Activation to ~100µSv/h along beam channel
- Disposal as radioactive waste

Packaging for ultimate storage

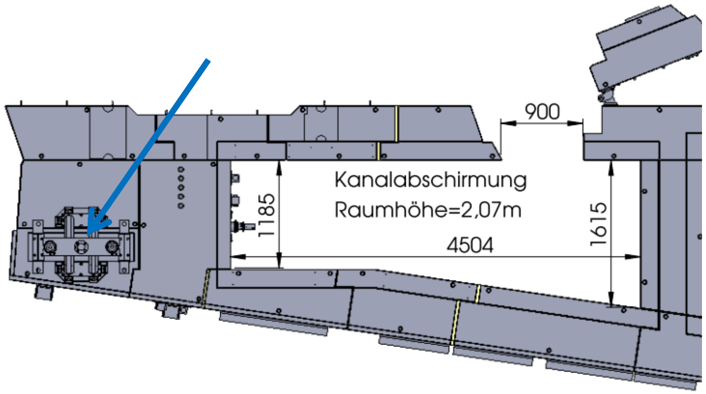



Shutter 2
Shutterstein 3
Shutterstein 6
Shutterstein 1
Abdeckung
(Füllstein)
Shutterstein 5
Shutterstein 4
Shutter 1
Shutterstein 2

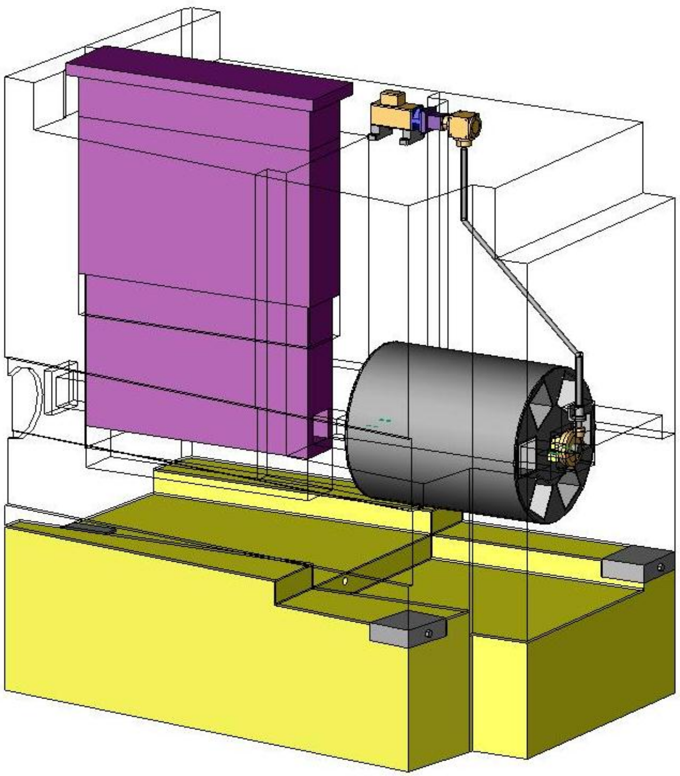


- Cutting time: several days!
- Price: ~150k€

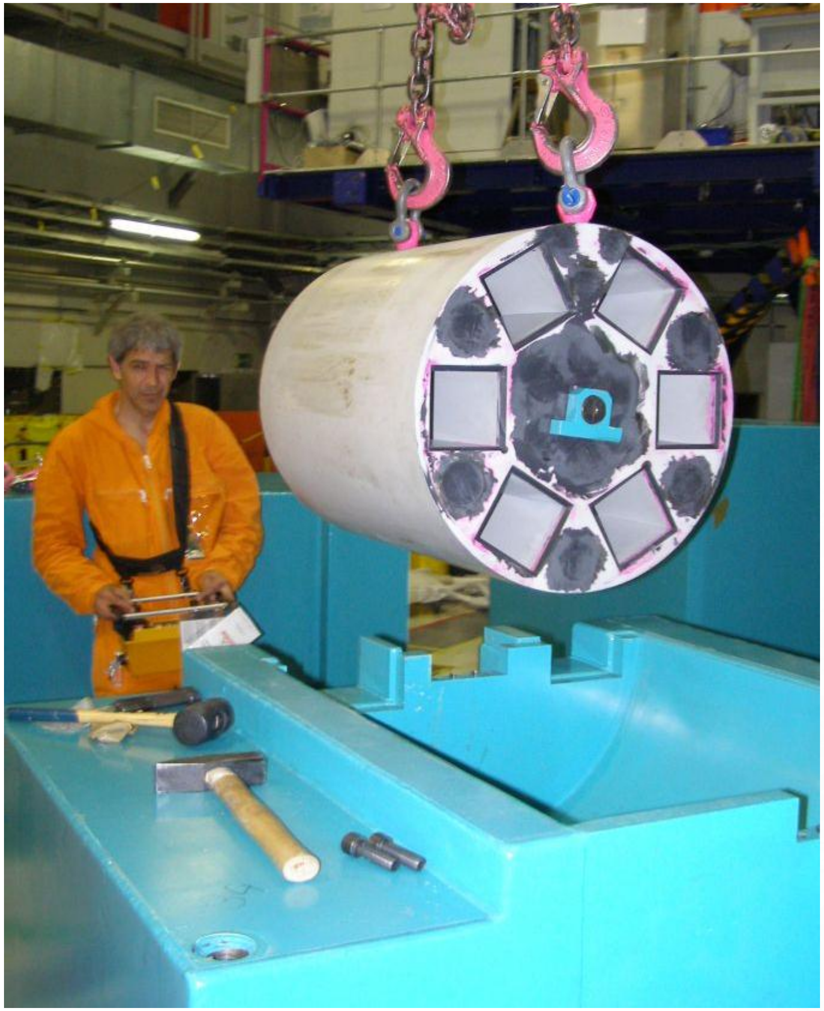
Shutters



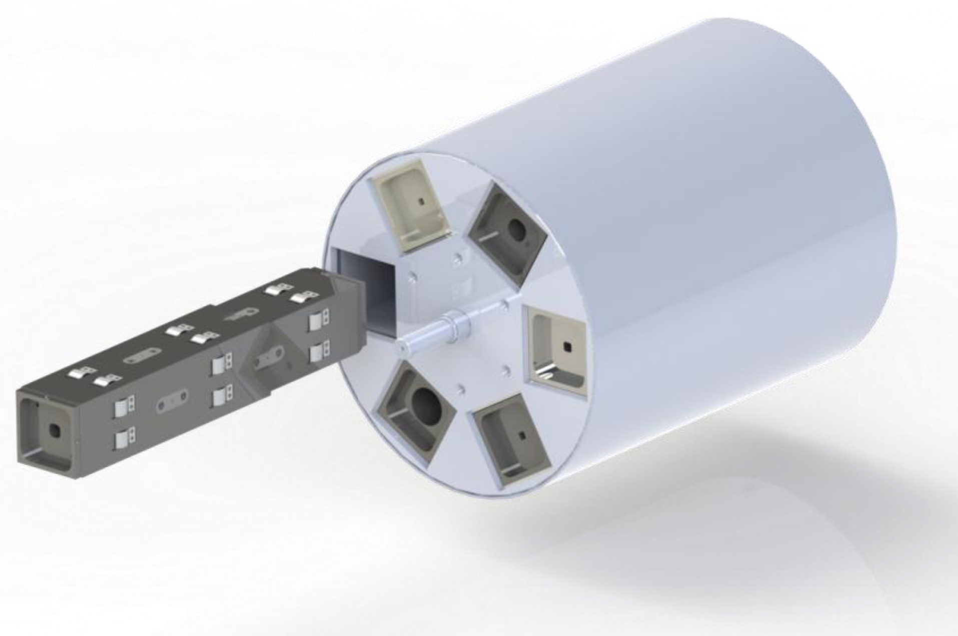
- Stop full beam for access of cave
- Must be fail-safe
- Additional fast shutter (B_4C) to reduce sample activation (closed after each image)



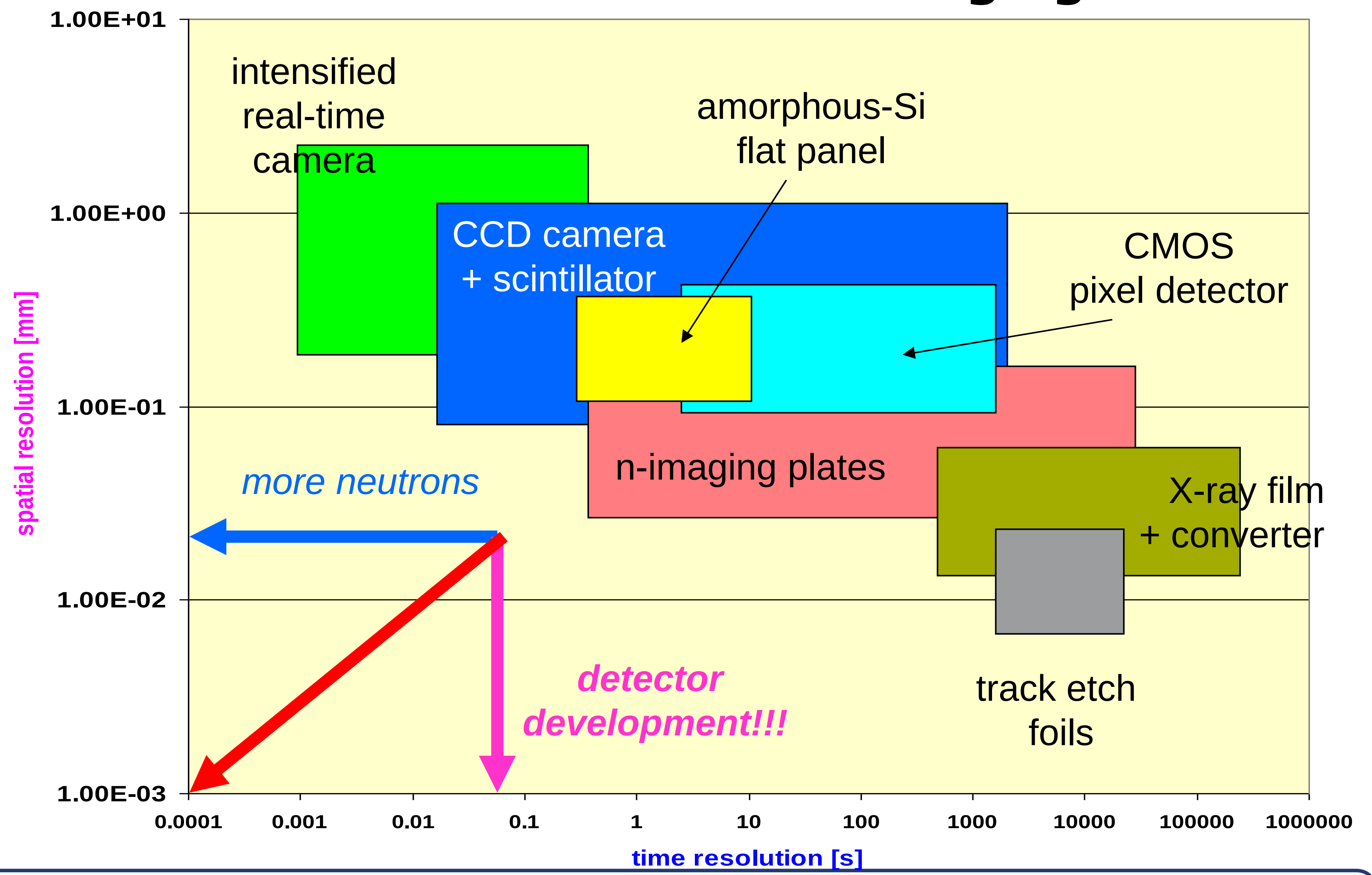
Collimators



- Massive for beam tube instruments to stop background
- Different pinhole sizes selectable
- Material with low activation (i.e. borated steel)
- Machined by spark erosion

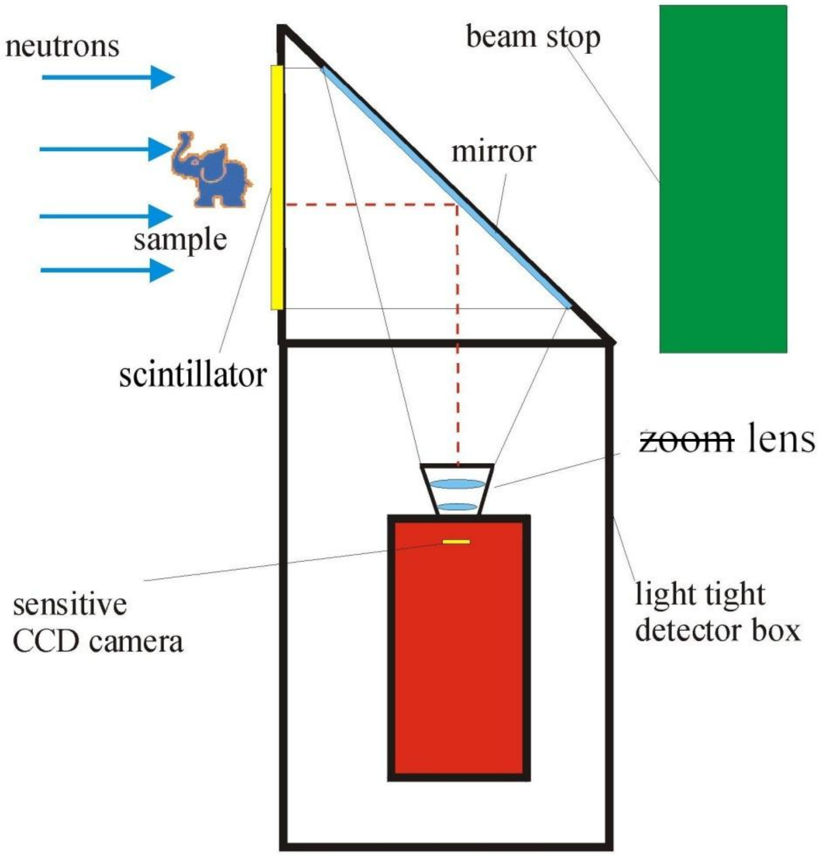


detectors for neutron imaging



from E. Lehmann, PSI

Detectors – Camera Based Systems



- General principle: scintillator – camera – mirror
- Cooled scientific CCD / CMOS for reduced / negligible dark current
- Surface mirror with > 99% reflectivity
- High end optics: SLR or custom made

Detectors - Scintillators

LiF:ZnS:Ag

1. Neutron capture

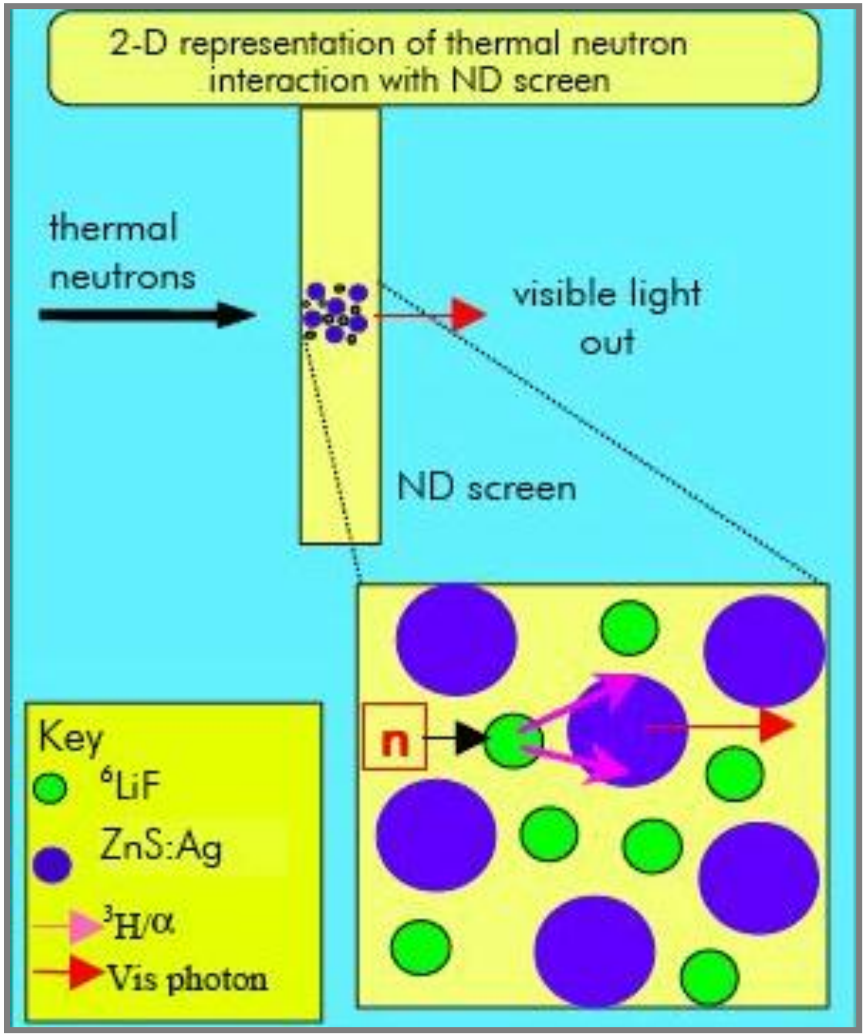
(alpha particle) (Tritium)

$$^{6}_{3}Li + {}^{1}n \rightarrow {}^{4}_{2}He + {}^{3}_{1}H + \gamma + 4.8\ \text{MeV}$$

2. Phosphorescence

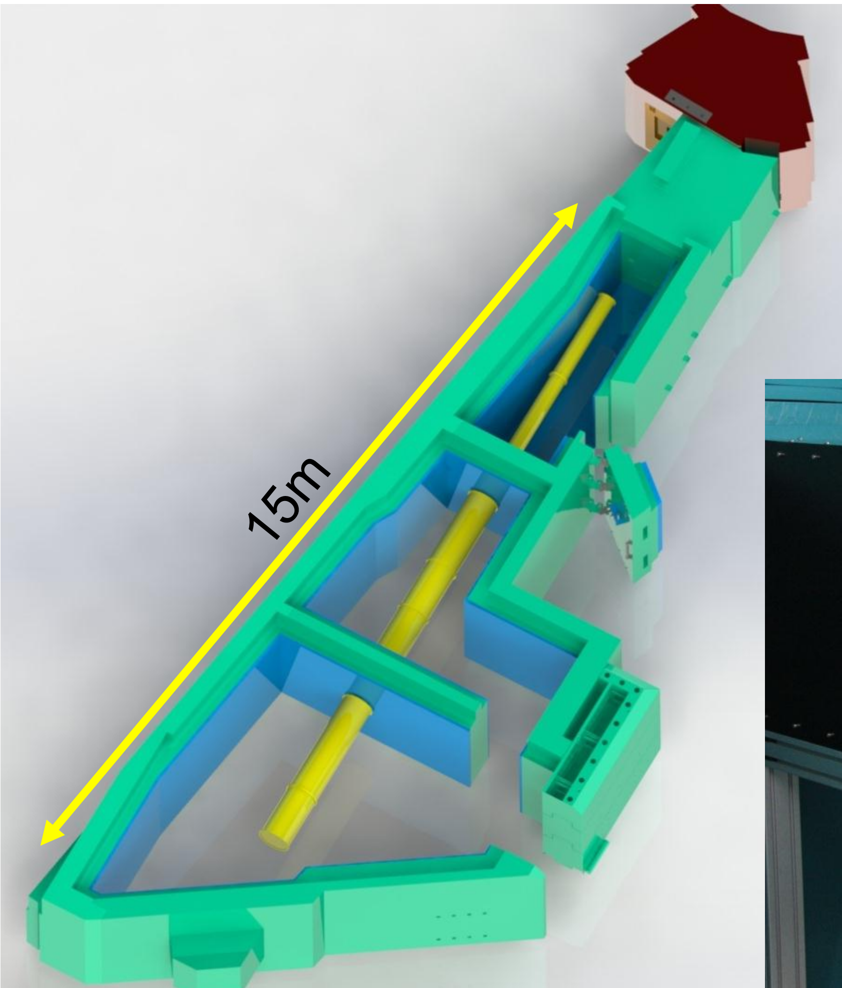
Limitations:

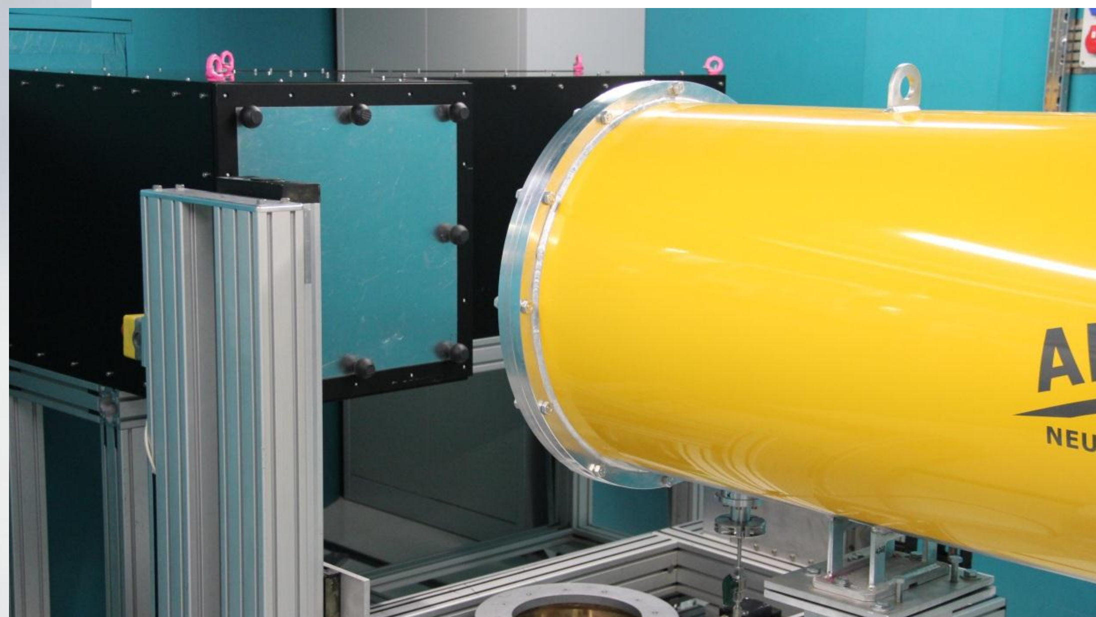
- Smearing ~ proportional to thickness
- Detection efficiency for 100µm ~20%
  σ_{abs} (^{6}Li)=940barn
- Use Gd as neutron absorber: Gd_2O_2S,
  σ_{abs} (Gd)=49700barn



Flight Tubes

- Intensity loss in air ~8% per m
- Flight Tubes with thin Al windows
- Penumbra must not touch the tubes
- He filled or evacuated (danger!)
- Flexible arrangement



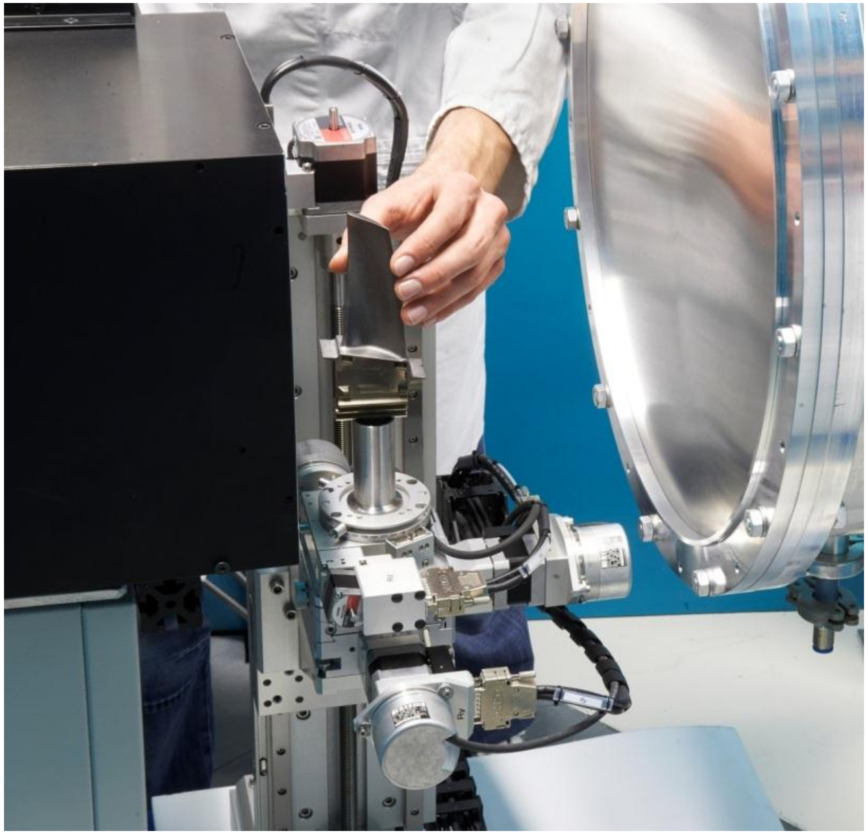


Beam Limiters

- Absorb most of the unused beam area before the sample position
- Reduced background at sample position
- Neutron absorber: BN or B_4C (low gamma energy ~500keV)

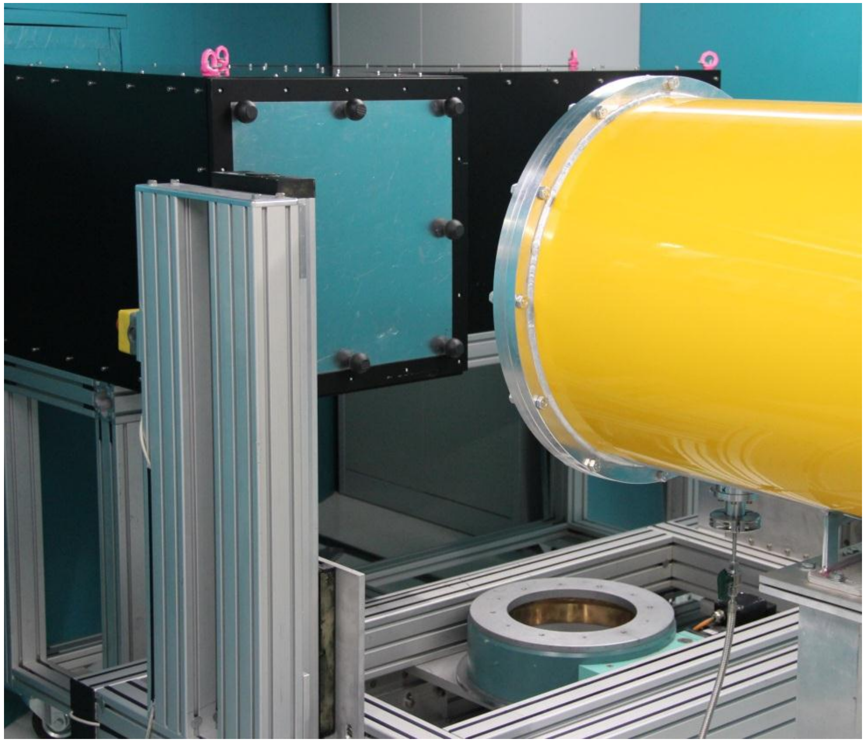
Motorized Stages

- High precision / high load capacity
- X,y,phi, (+ optional goniometers)



10kg

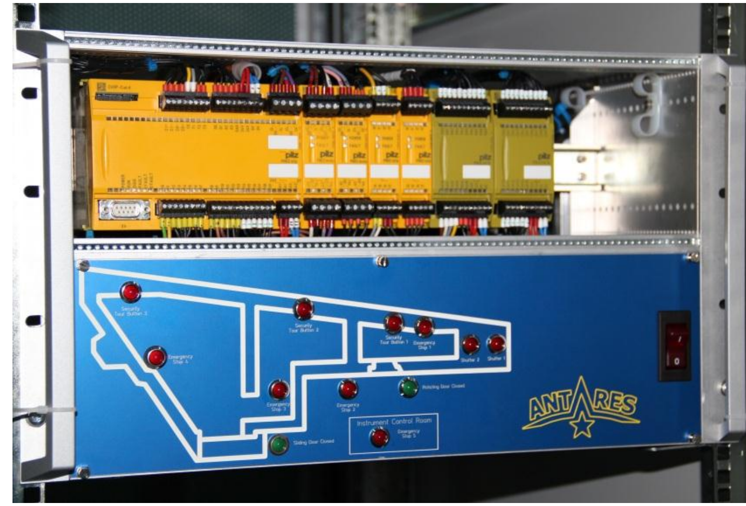
500kg



Additional things…

- A place to work

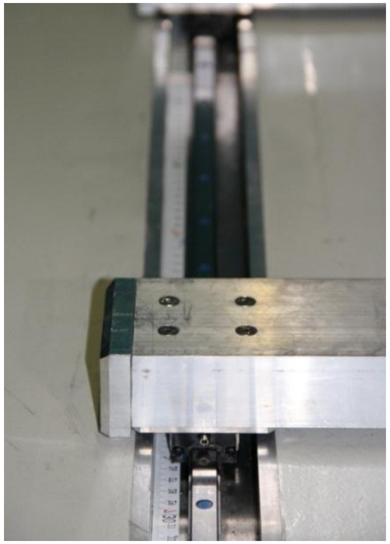
Additional things…



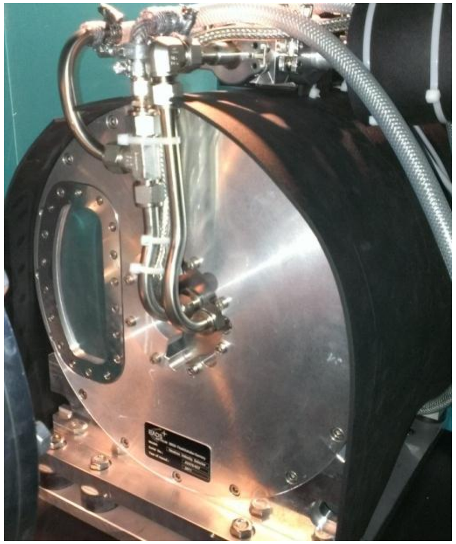
- Racks for electronics
- Safety access control
- IT: (File server, Computers for reconstruction / visualization / Instrument control)

Additional things…

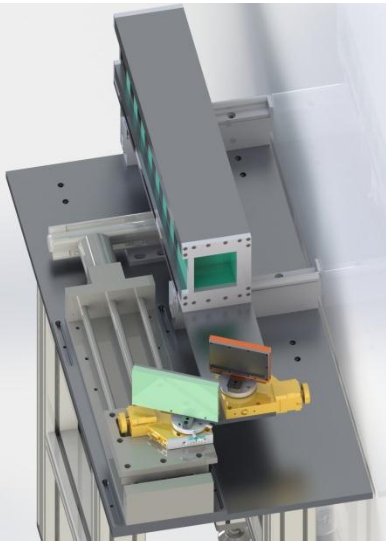
IP camera in bunker



Rail system



Neutron velocity selector



Monochromator

What you should remember

- Neutron imaging is a valuable method for nondestructive testing
- The principle is simple but you can still make many mistakes when building an instrument
- Talk to people who have already made these mistakes
- Think about activation and disposal of the components when you design them