Neutron imaging @ESS, principles and applications.

PRESENTED BY MANUEL MORGANO

2023-04-18

Agenda

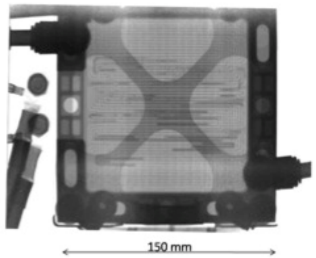
1. Why neutrons?
2. Applications of neutron imaging
3. What is ESS (in brief)
4. ODIN @ESS
5. Advanced Neutron Imaging (just a taste)

Why neutrons?

Why Neutrons?

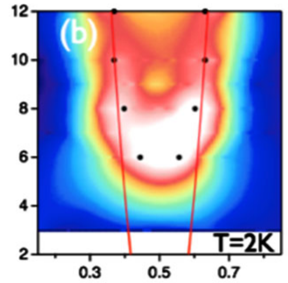
Neutrons have special properties …

Charge neutral
Deeply penetrating



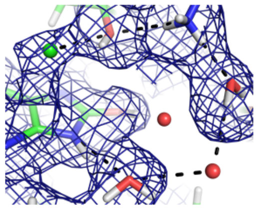
Hydrogen and water distribution in fuel cells

Magnetic moment (spin)
Probe of magnetism



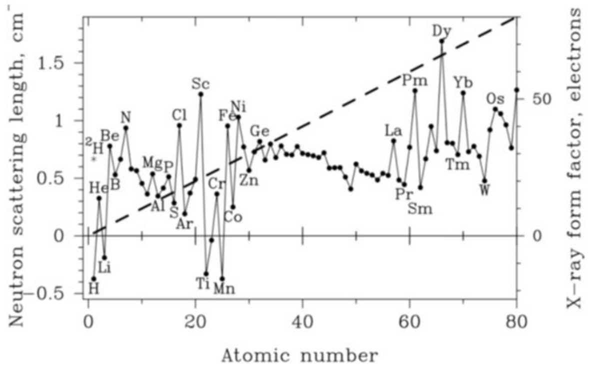
Understanding supercondutors

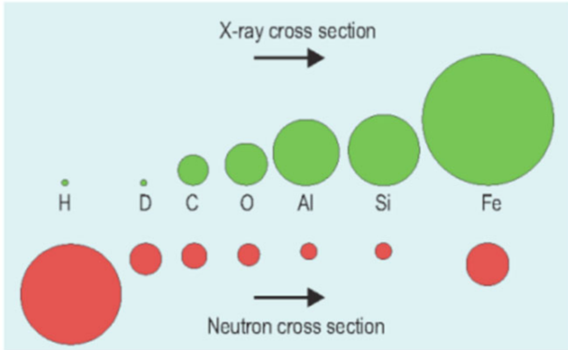
Nuclear scattering
Sensitive to light elements and isotopes



Understanding drug binding and enzyme action

X-Rays and Neutrons



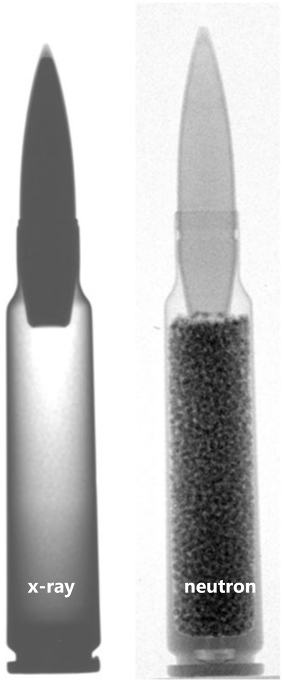


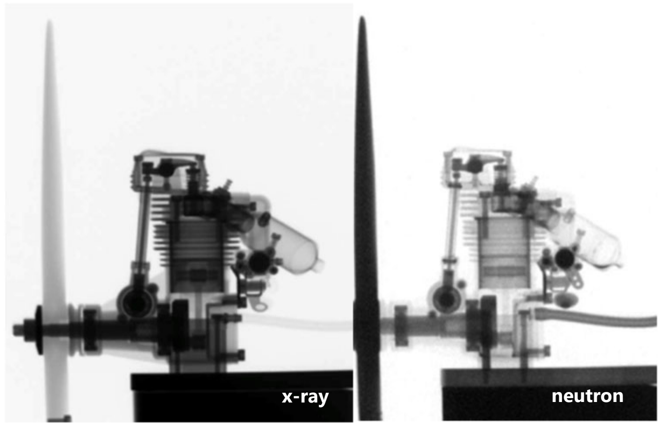
	X-Ray	Neutron
Mass	None	1.674928 x 10^{-27} kg (1839 electrons)
Speed	Fixed	Energy dependent
Spin	1	1/2
Magnetic Moment	None	-1.9130427 μ_n
Energy	10 eV – 100 keV	0.1 meV – 0.5 eV
Wavelength	0.01 nm to 100 nm	0.01 nm to 3 nm
Source brightness	10^6 – 10^{20} (photons/mm^2/s/mrad/0.1% bandwidth)	10^{10} – 10^{14} (neutrons/cm2/s/sr/Å)
Type of radiation	Ionizing	Non (directly) ionizing
Source	“point-like”	Macroscopic

X-Rays and Neutrons

Different views of the same thing

Courtesy of the NIAG group, PSI, Switzerland.





Due to the different interaction and cross sections, neutrons and x-rays provide complementary information

X-Rays and Neutrons

TOMCAT beamline at PSI

$$Flux = {10^{16}}/{ph \cdot s \cdot cm^2}$$

ANTARES beamline at TUM

$$Flux = {10^{8}}/{n \cdot s \cdot cm^2}$$

That's one of the main differences between x-ray and neutron imaging

X-Rays and Neutrons

TOMCAT beamline at PSI

$$Flux = {10^{16}}/{ph \cdot s \cdot cm^2}$$

ANTARES beamline at TUM

$$Flux = {10^{8}}/{n \cdot s \cdot cm^2}$$

That's one of the main practical differences between x-ray and neutron imaging

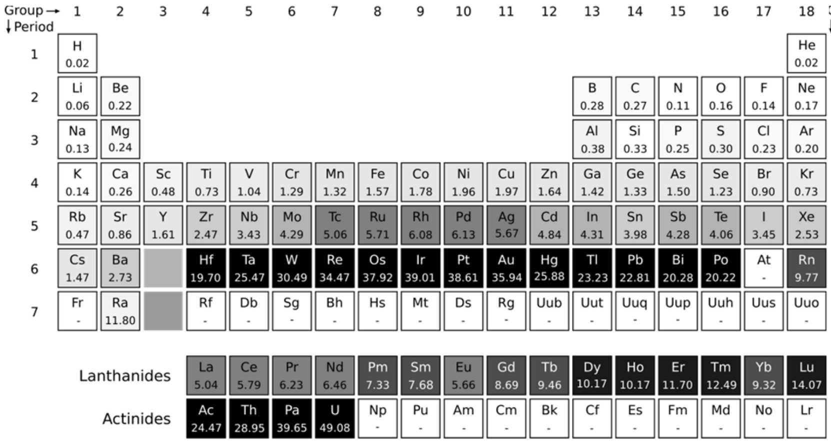
X-Rays and Neutrons

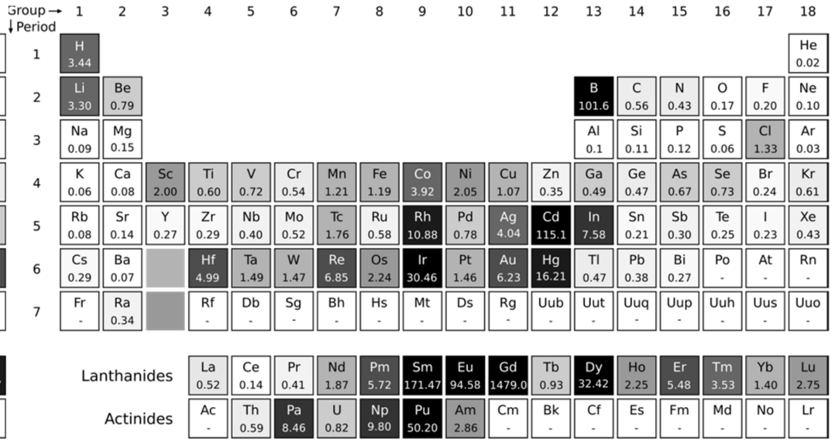
X-rays:

- Interacting with the electron shell

Neutrons:

- Interacting with the nucleus





X-Rays and Neutrons

X-rays:
- Interacting with the electron shell

Group → / ↓ Period	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 -

Neutrons:
- Interacting with the nucleus

Group → / ↓ Period	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 -

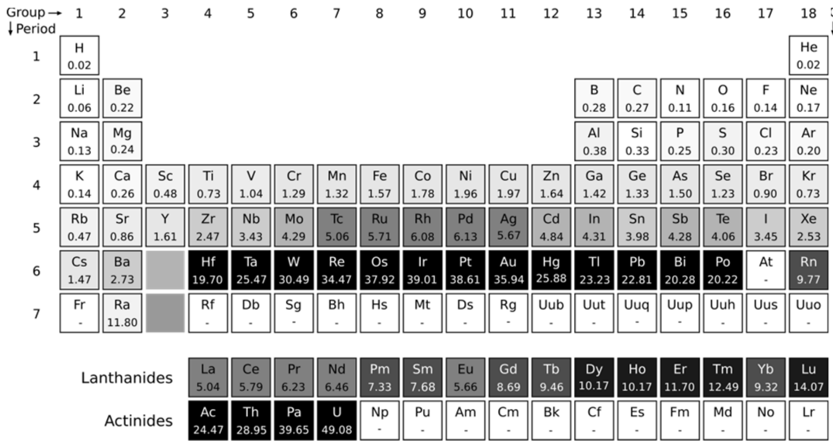
X-Rays and Neutrons

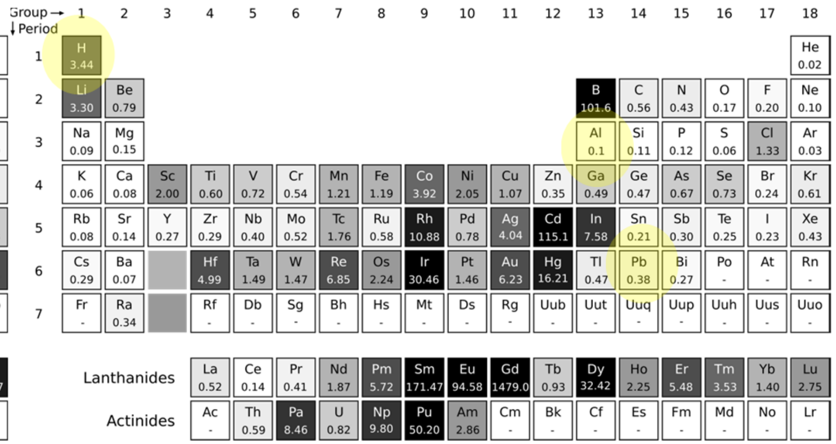
X-rays:

- Interacting with the electron shell

Neutrons:

- Interacting with the nucleus





Already this creates a clear domain for neutron imaging!

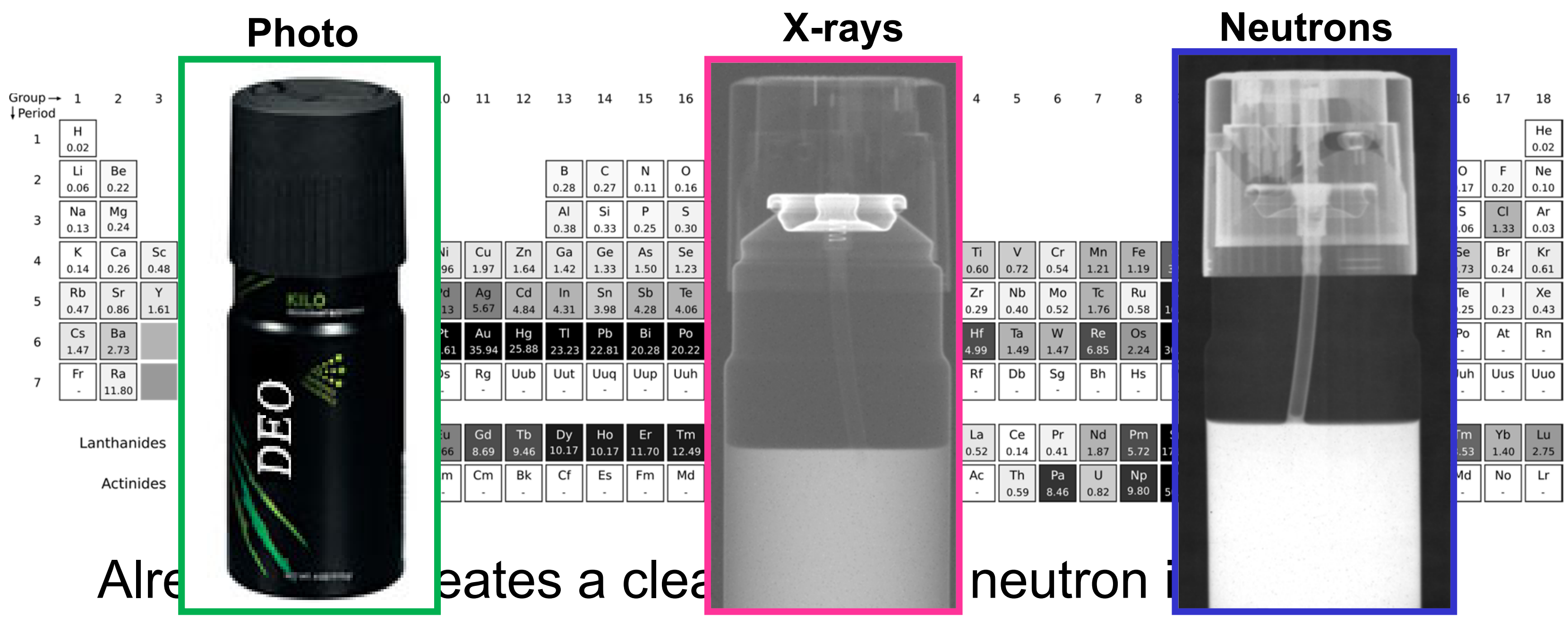
X-Rays and Neutrons

X-rays:

- Interacting with the electron shell

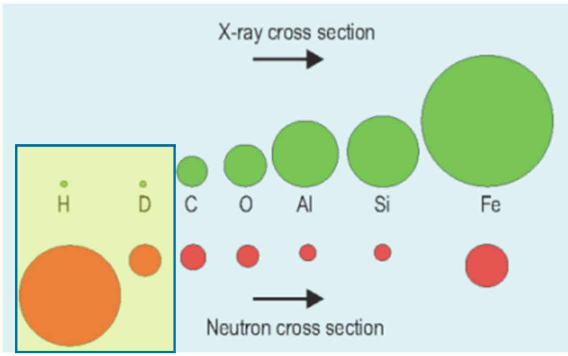
Neutrons:

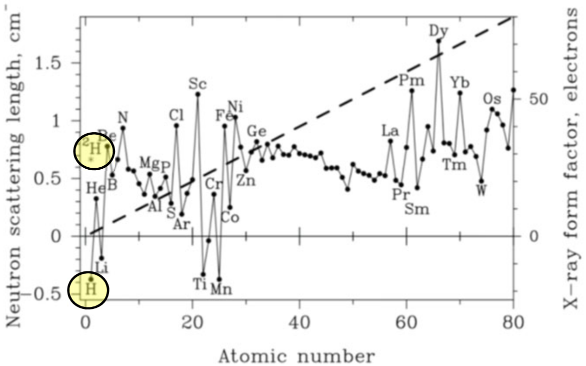
- Interacting with the nucleus

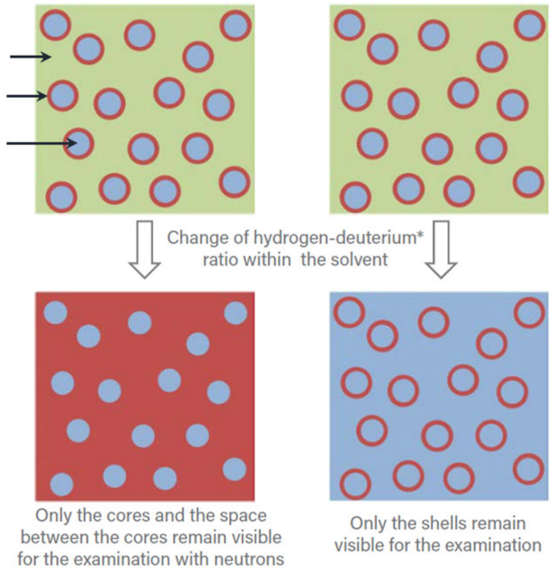


Alre… eates a clea… neutron i…

Contrast Variation







I. Grillo, ILL

The most valuable contrast variation mechanism makes use of H vs D contrast – primarily H_2O vs D_2O and mixtures.

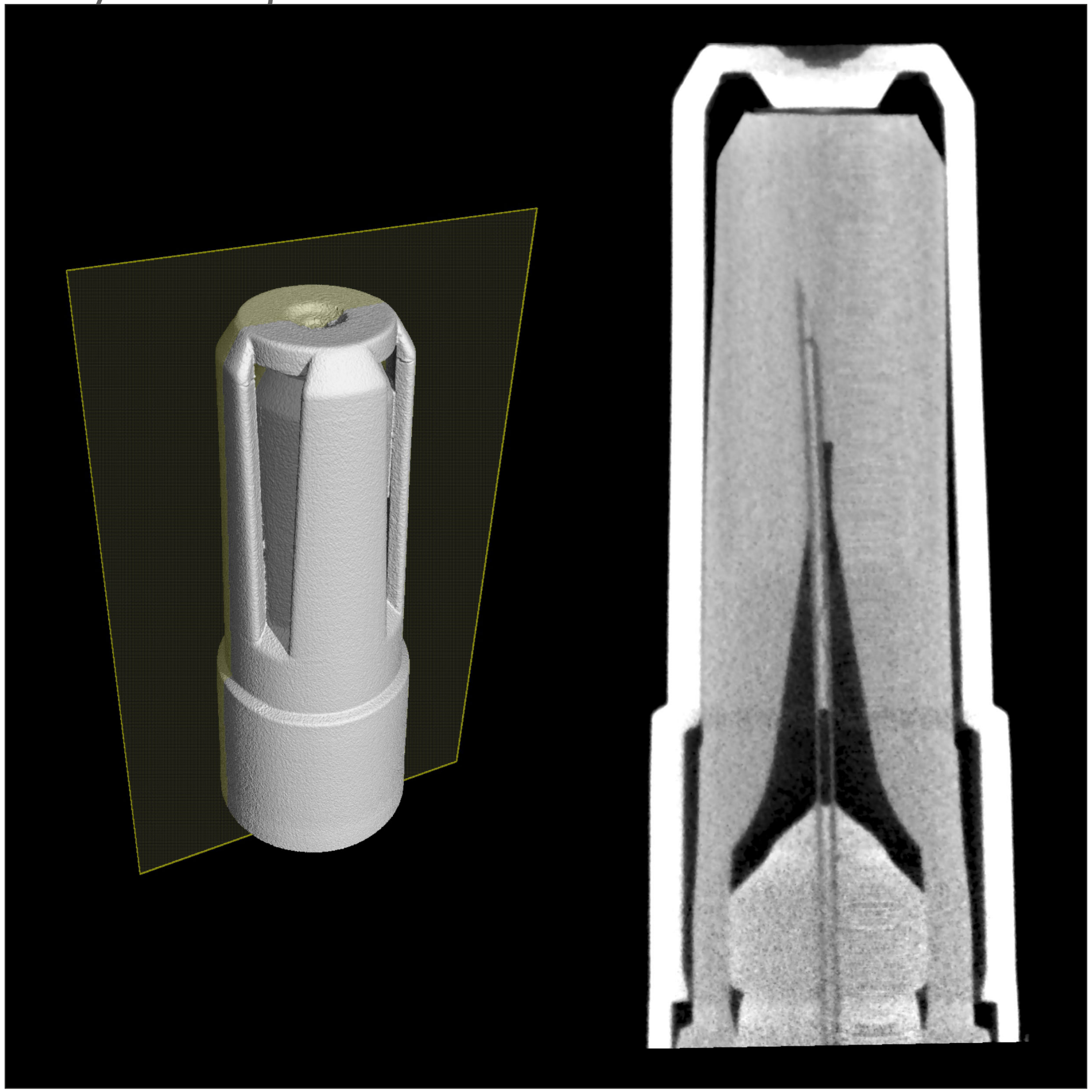
Selective deuteration in combination with neutrons lets us investigate selected parts of complex assemblies.

Combining X-Ray and Neutron measurements provides more information

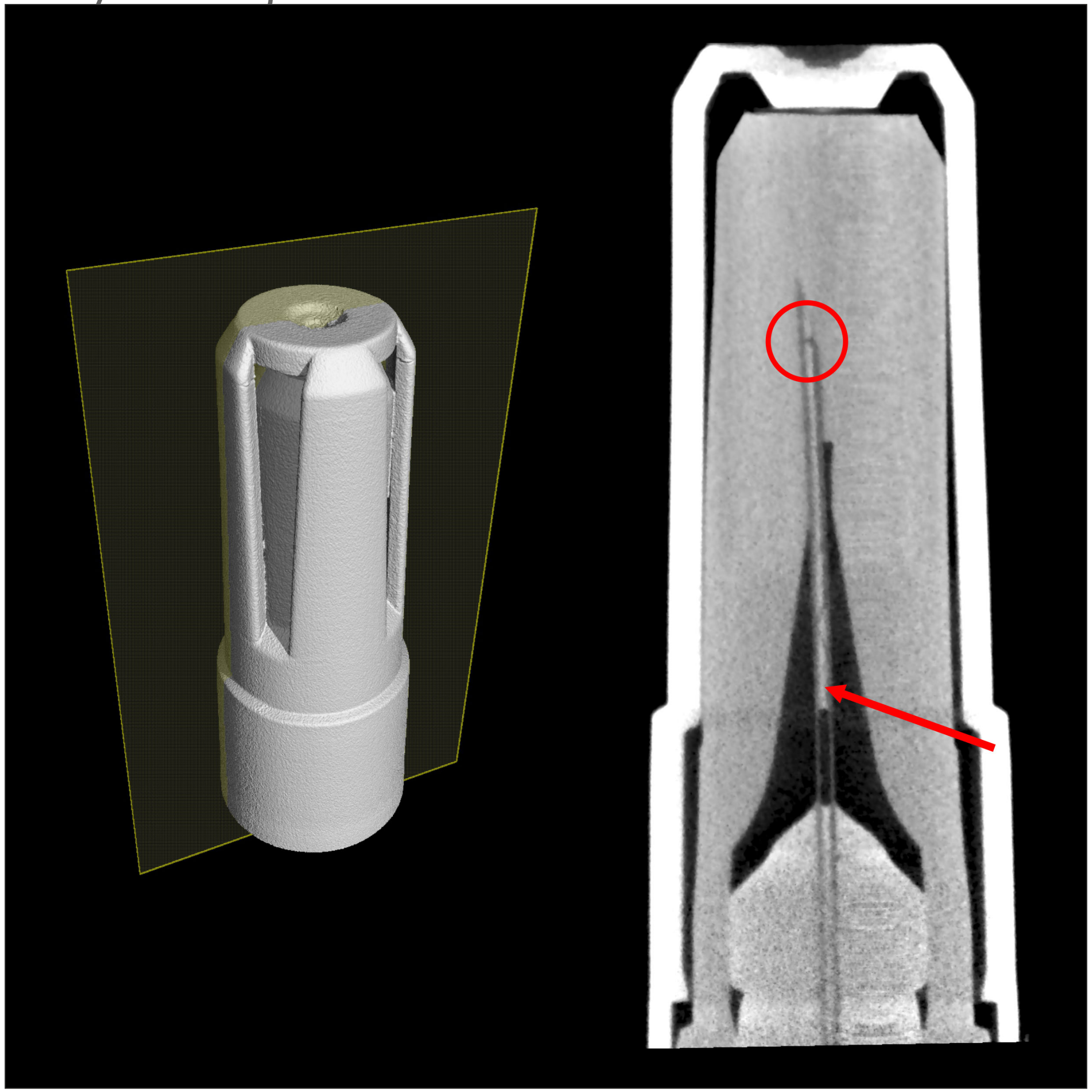
Applications of Neutron Imaging

Fly

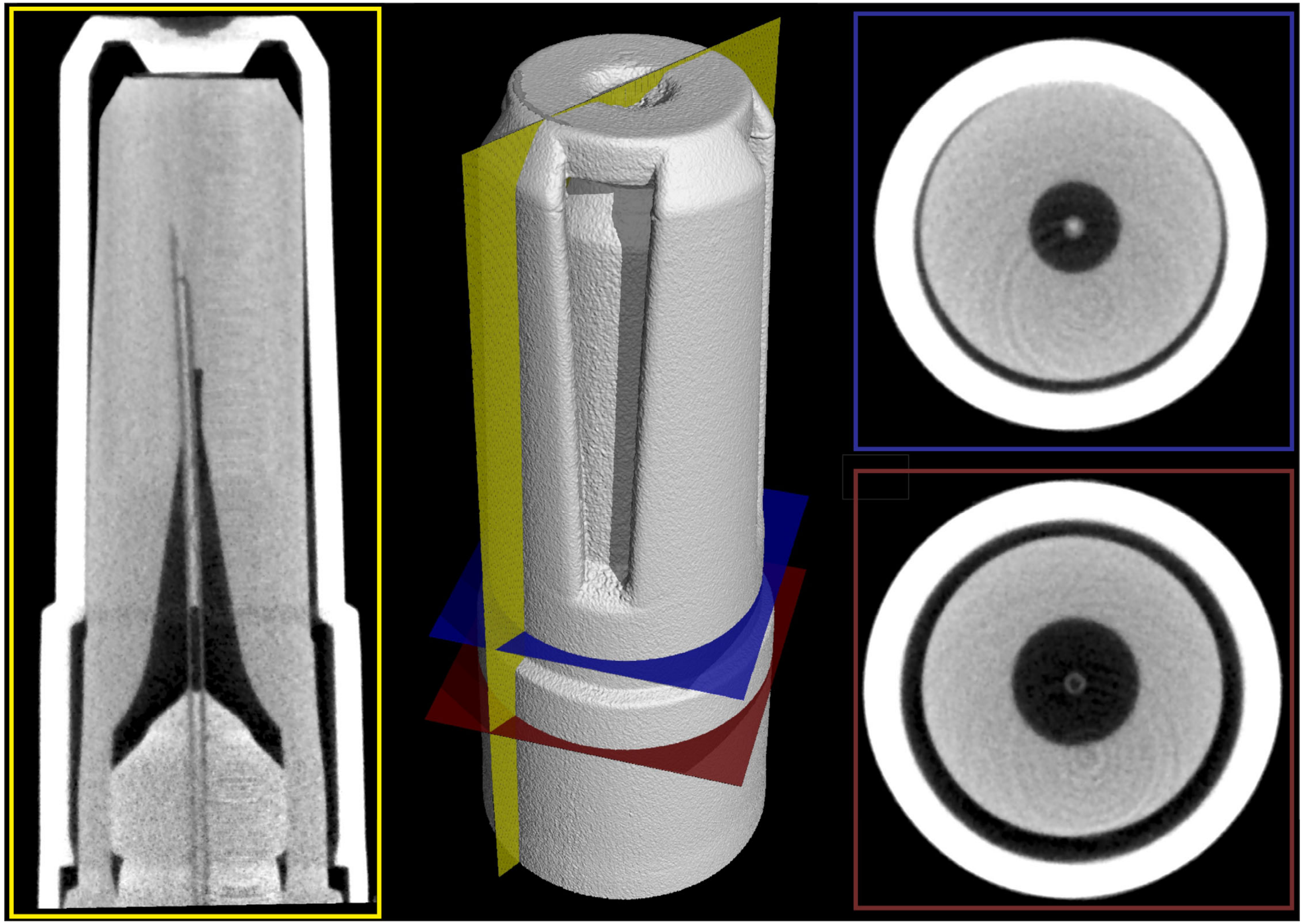
Drugs in syringes



Drugs in syringes



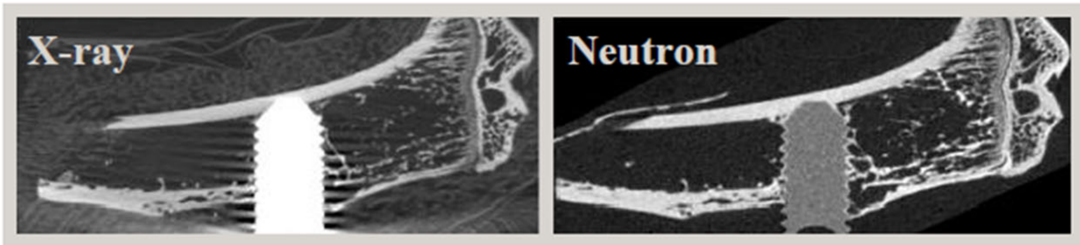
Drugs in syringes

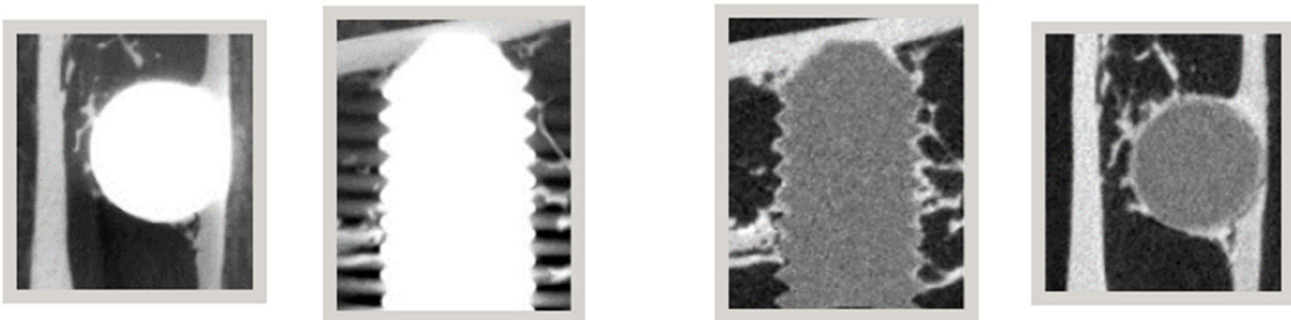


Examples: dual mode imaging

From: Elin TÖRNQUIST, Biomedical Engineering, Lund University

Study III – Dual-modality tomography





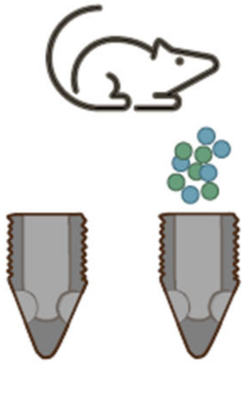
Isaksson et al. (2010)
Isaksson et al. (2017)
H. Isaksson et al. (2017) Bone

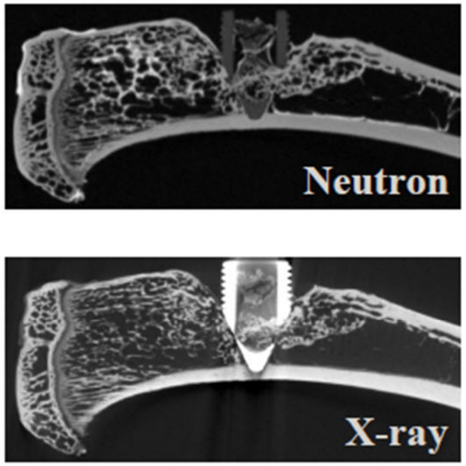
Examples: dual mode imaging

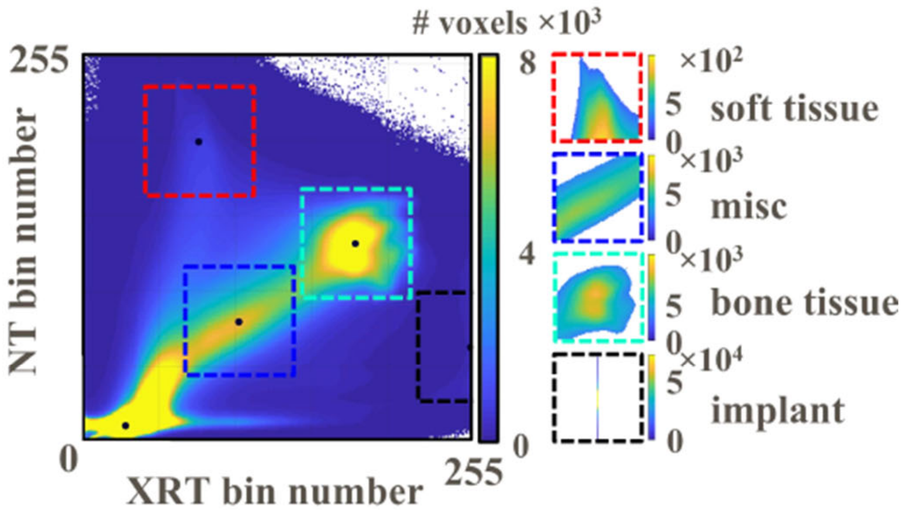
From: Elin TÖRNQUIST, Biomedical Engineering, Lund University

Study III – Dual-modality tomography

NEUTRONS FOR SOCIETY





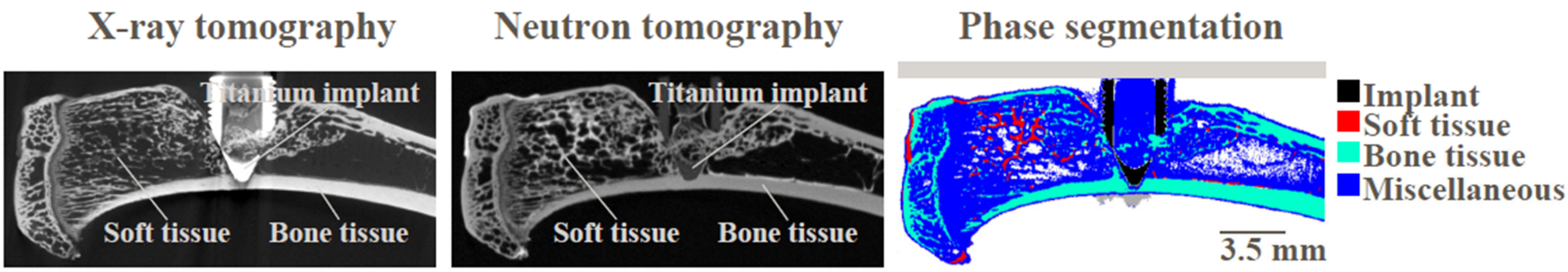


Isaksson et al. (2010)
D. B. Raina et al. (2019) Acta Biomater
E. Roubin et al. (2019) Cem Concr Compos

NT – neutron tomography
XRT – x-ray tomography

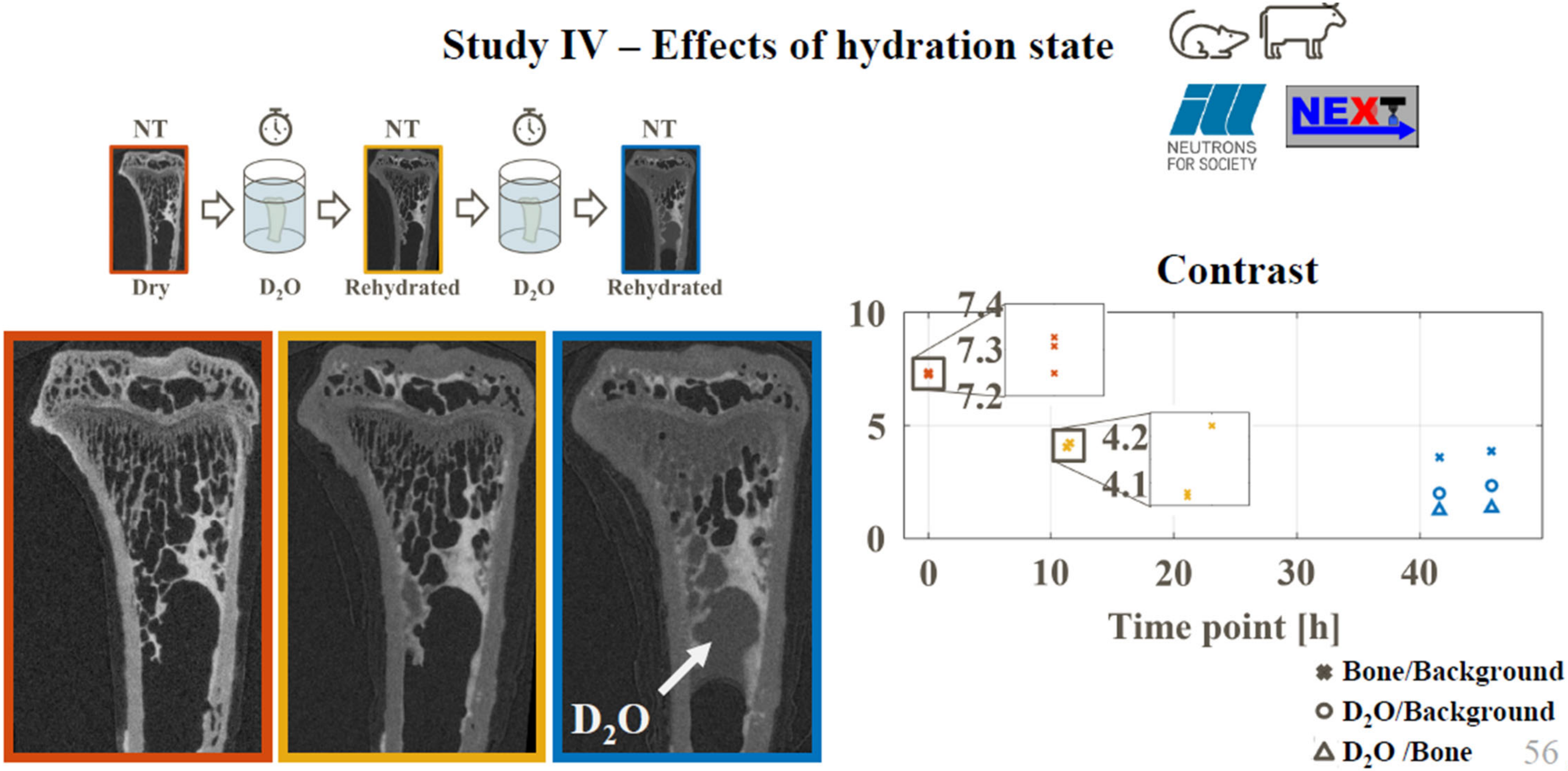
Examples: dual mode imaging

From: Elin TÖRNQUIST, Biomedical Engineering, Lund University



Examples: contrast matching

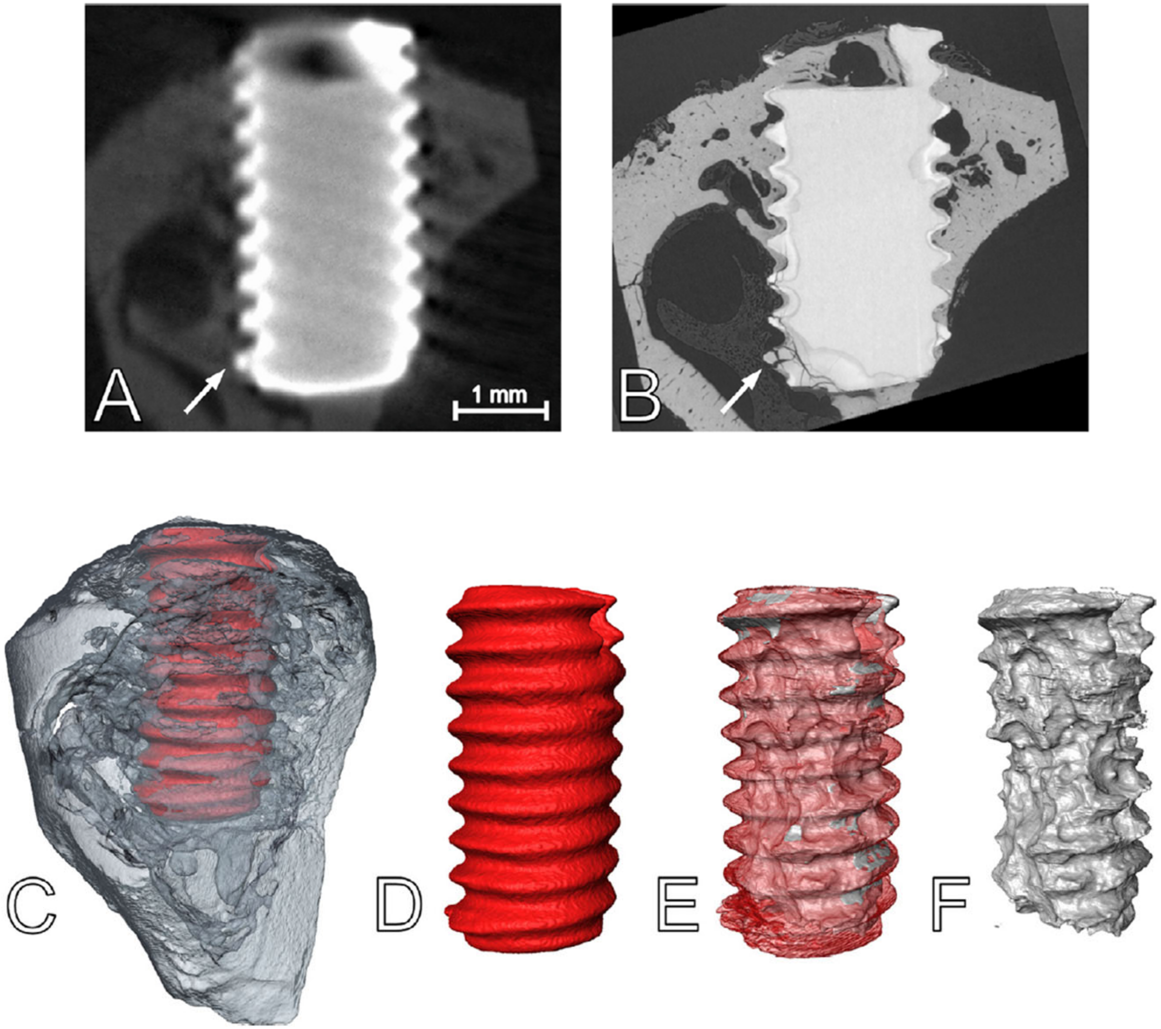
From: Elin TÖRNQUIST, Biomedical Engineering, Lund University



Examples: Mg-Gd screw corrosion

N. Peruzzi, S. Galli, H. Helmholz et al.

Acta Biomaterialia 136 (2021) 582–591



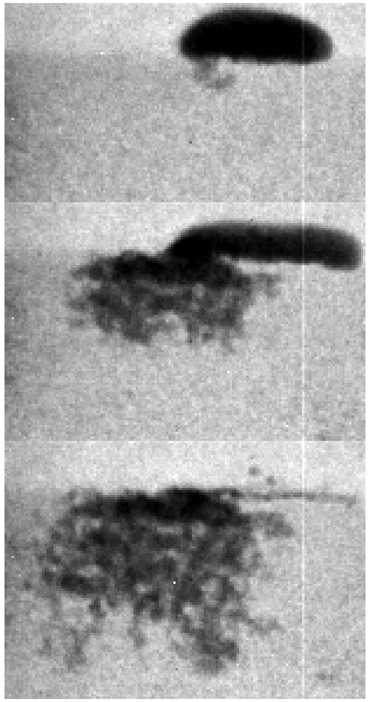
Neutron imaging investigations

Neutron imaging offers different types of investigations:

- Radiography → 2D
- Tomography → 3D
- Dynamic neutron imaging
  - Realtime

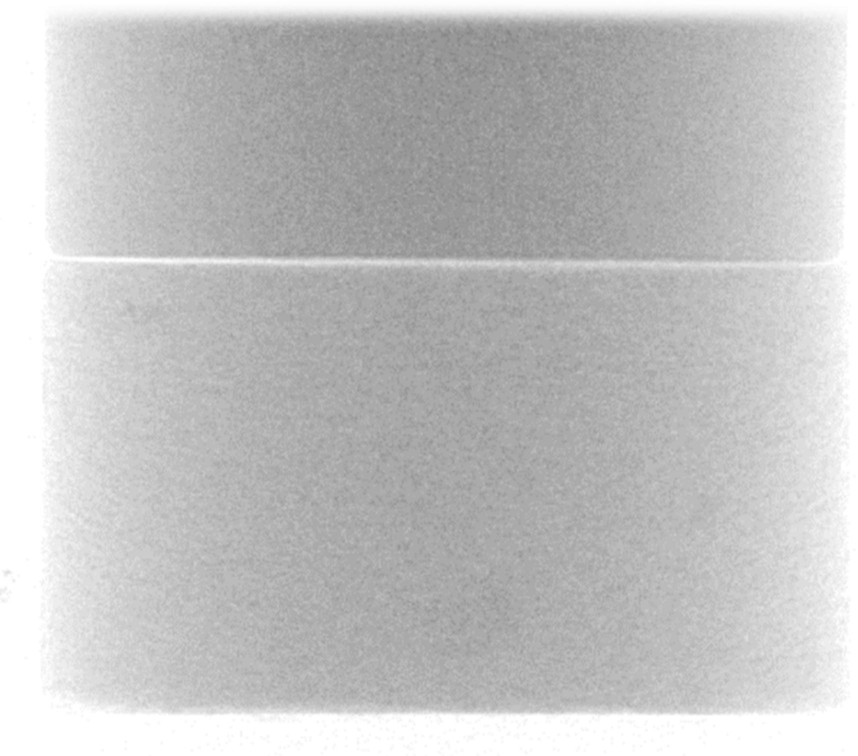
Soil science

Water droplet on sand;
sequence taken with 4 fps;
time difference between first and last image 2.75s



Slide courtesy of D. Mannes

•in-situ neutron imaging of metal hydride composites swelling upon hydrogenation



What is ESS (in brief)

What is ESS

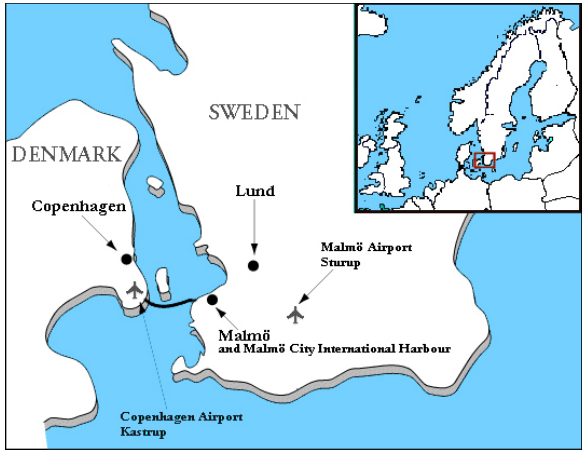
ESS will be the next generation spallation source

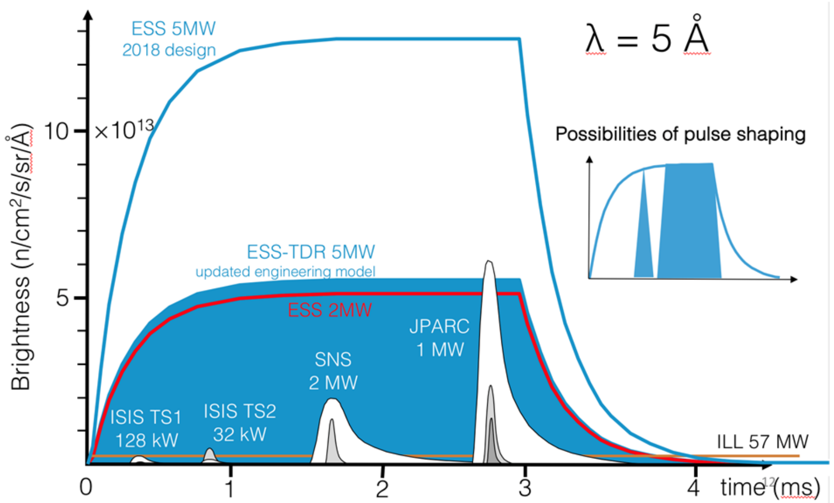
Located in Lund (Sweden)

~2.5 B€ total budget

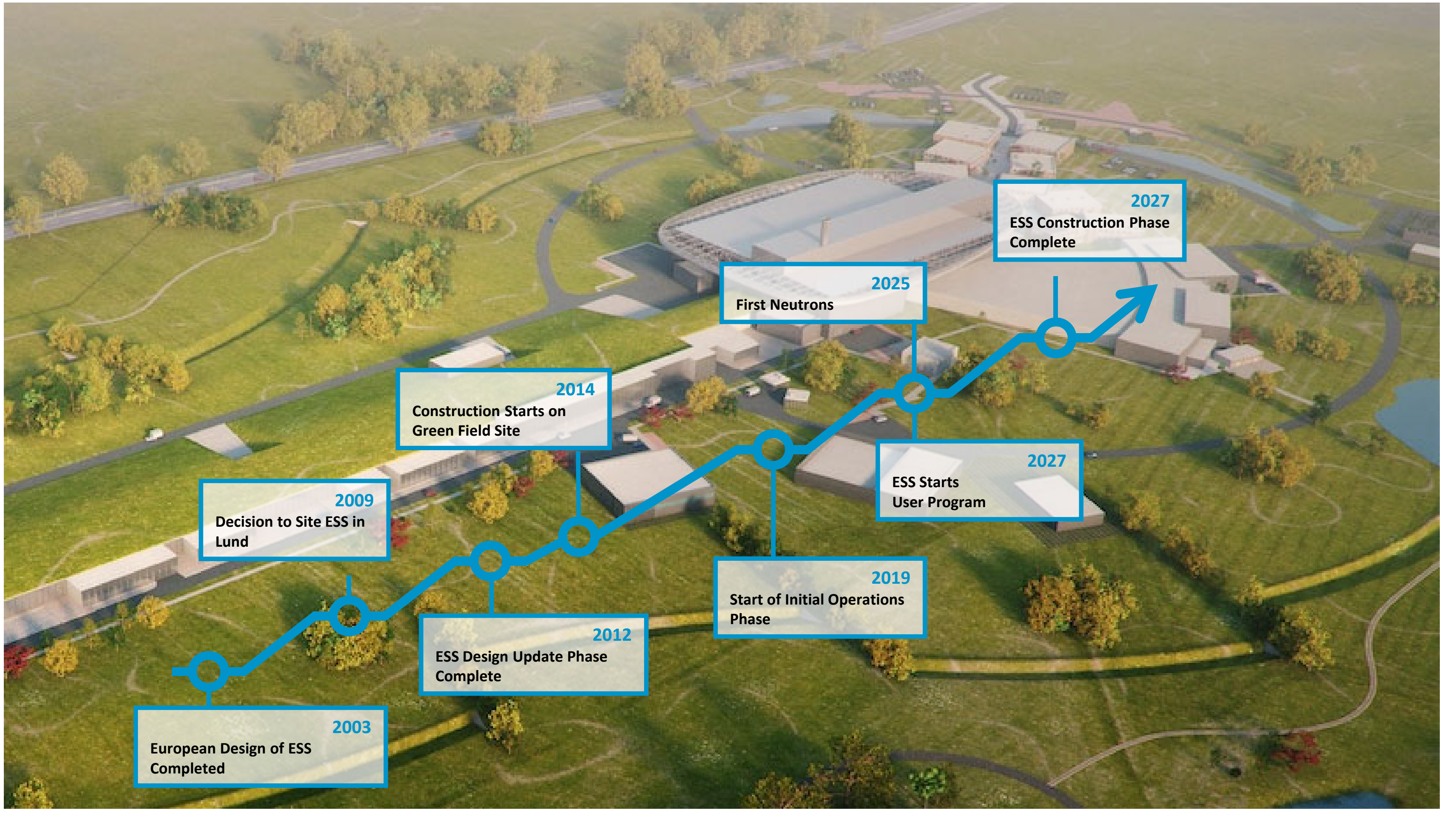
2 GeV linear proton accelerator, up to 5 MW power

14 Hz repetition rate with 2.86 ms pulse duration (~4% duty cycle)





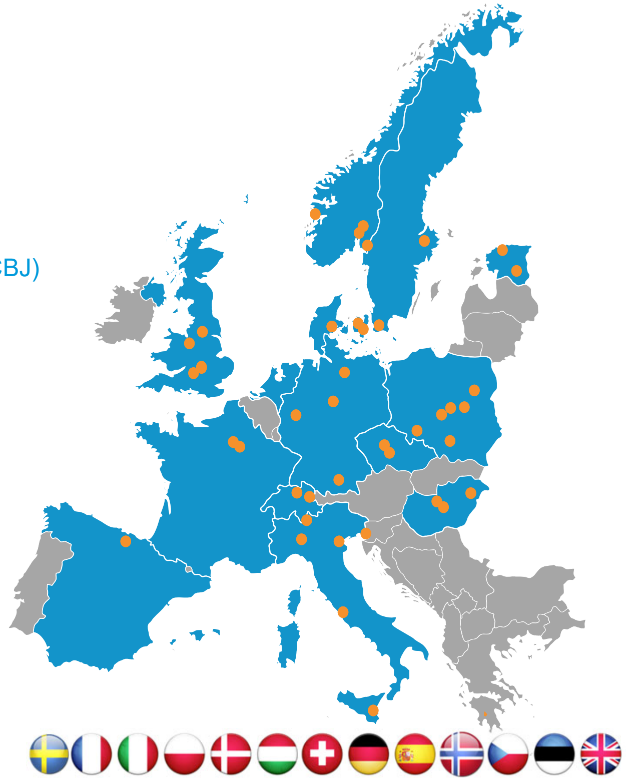
The Road to ESS



A European Project …

… built by teams across Europe

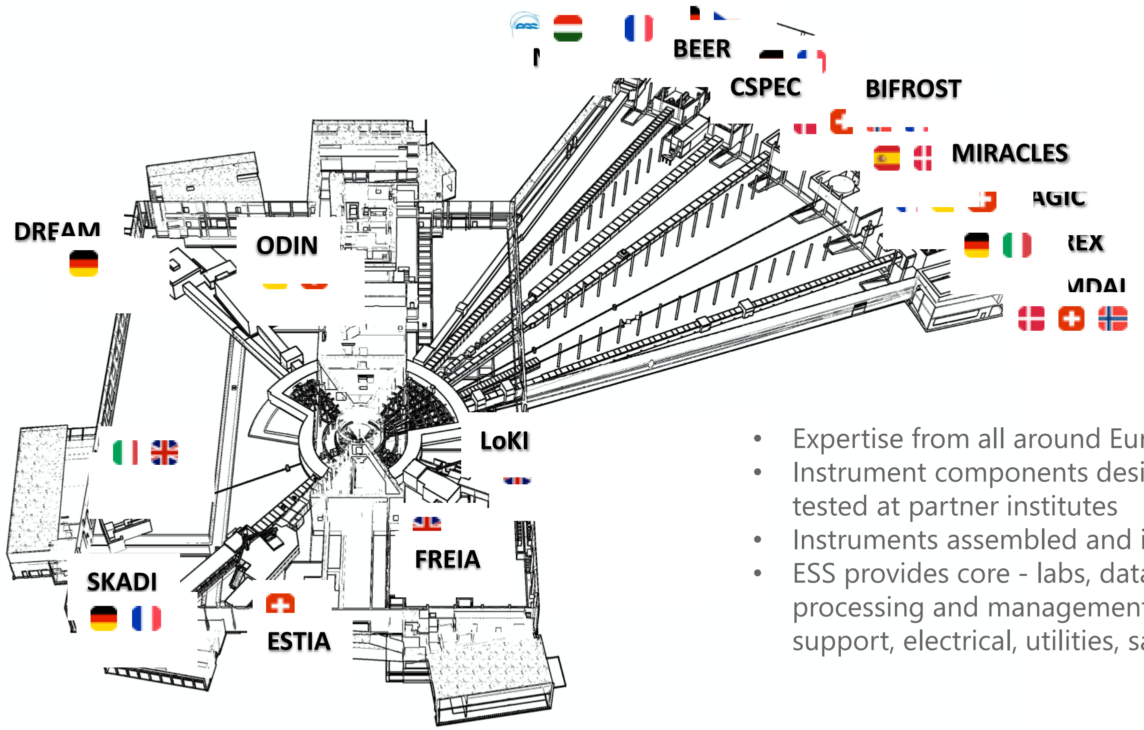
Aarhus University
Atomki - Institute for Nuclear Research
Bergen University
CEA Saclay, Paris
Centre for Energy Research, Budapest
Centre for Nuclear Research, Poland, (NCBJ)
CNR, Rome
CNRS Orsay, Paris
Cockcroft Institute, Daresbury
Elettra – Sincrotrone Trieste
ESS Bilbao
Forschungszentrum Jülich
Helmholtz-Zentrum Geesthacht
Huddersfield University
IFJ PAN, Krakow
INFN, Catania
INFN, Legnaro
INFN, Milan
Institute for Energy Research (IFE)
Rutherford-Appleton
04-19



Laboratory, Oxford(ISIS)
Kopenhagen University
Laboratoire Léon Brilouin (CEA/CNRS/LLB)
Lund University
Nuclear Physics Institute of the ASCR
Oslo University
Paul Scherrer Institute (PSI)
Polish Electronic Group (PEG)
Roskilde University
Tallinn Technical University
Technical University of Denmark
Technical University Munich
Science and Technology Facilities Council
UKAEA Culham
University of Tartu
Uppsala University
WIGNER Research Centre for Physics
Wroclaw University of Technology
Warsaw University of Technology
Zurich University of Applied Sciences (ZHAW)

Neutron Science Instruments at ESS

1 Imaging, 2 SANS, 2 Reflectometers, 5 Spectrometers, 5 Diffractometers, 1 Test Beamline



- Expertise from all around Europe
- Instrument components designed, built, and tested at partner institutes
- Instruments assembled and integrated at ESS
- ESS provides core - labs, data acquisition, processing and management, engineering support, electrical, utilities, safety systems,

ODIN @ESS

ODIN beamline in brief

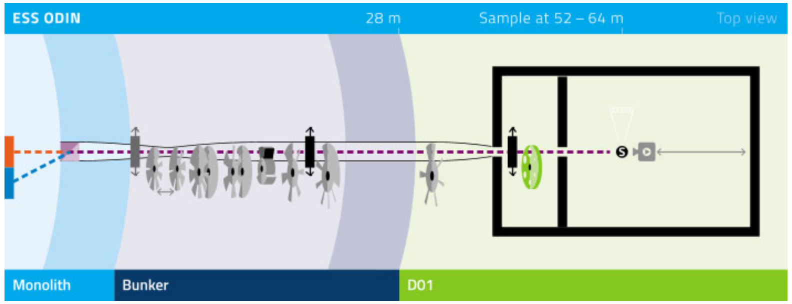
ODIN will be the only imaging instrument installed at ESS initially

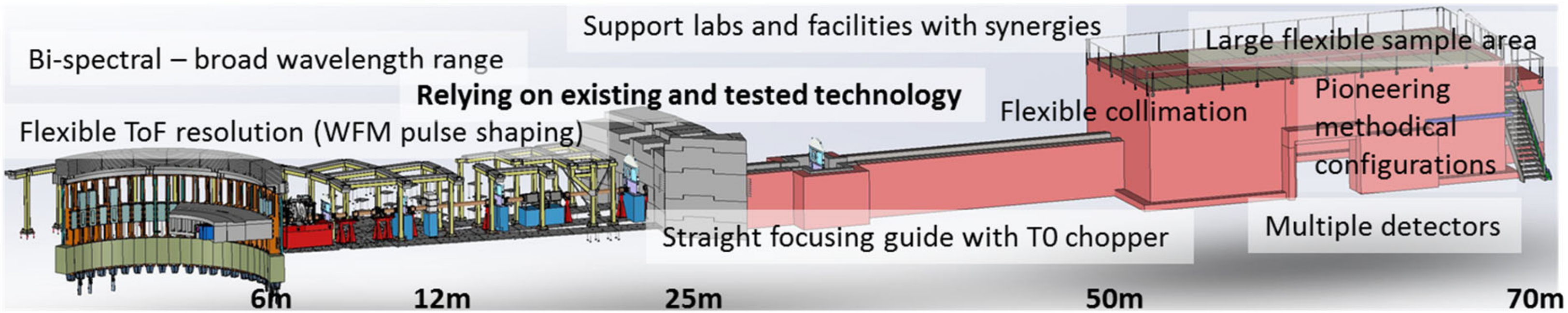
Planned to receive first neutrons in 2025 (day-1 instrument)

Optical and **D**iffraction **I**maging with **N**eutrons: ToF imaging with variable wavelength resolution

Joint project between TUM (A. Tartaglione and E. Calzada, ~65%) and PSI (M. Strobl and M. Morgano, ~35%)

Budget of 11.6M€.





ODIN team

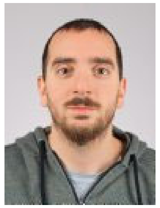
ODIN construction core team

Aureliano Tartaglione

ODIN Scientist

Manuel Morgano

ODIN Scientist

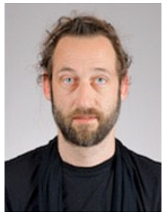


Elbio Calzada

ODIN Lead Engineer

Markus Strobl

Head of Imaging group



Virginia Martinez Monge

ODIN Installation Engineer

Jan Hovind

Technician of Imaging Group

Michael Schulz

Head of Imaging group

Robin Woracek

Instrument Class Coordinator

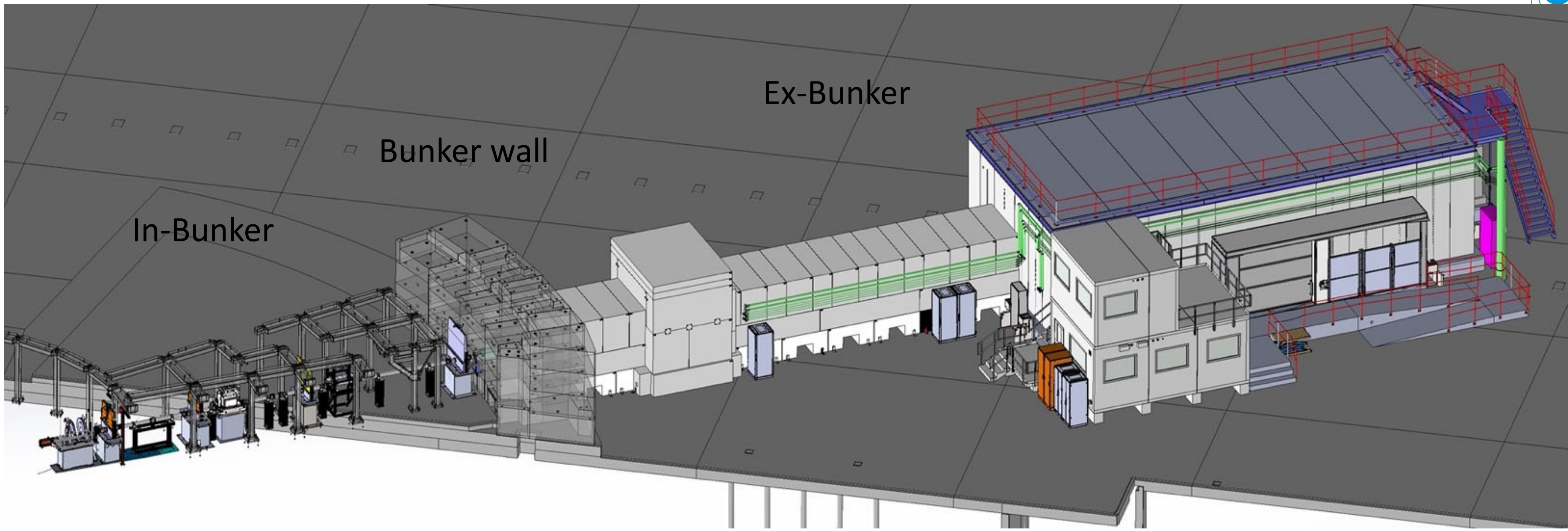
Søren Schmidt

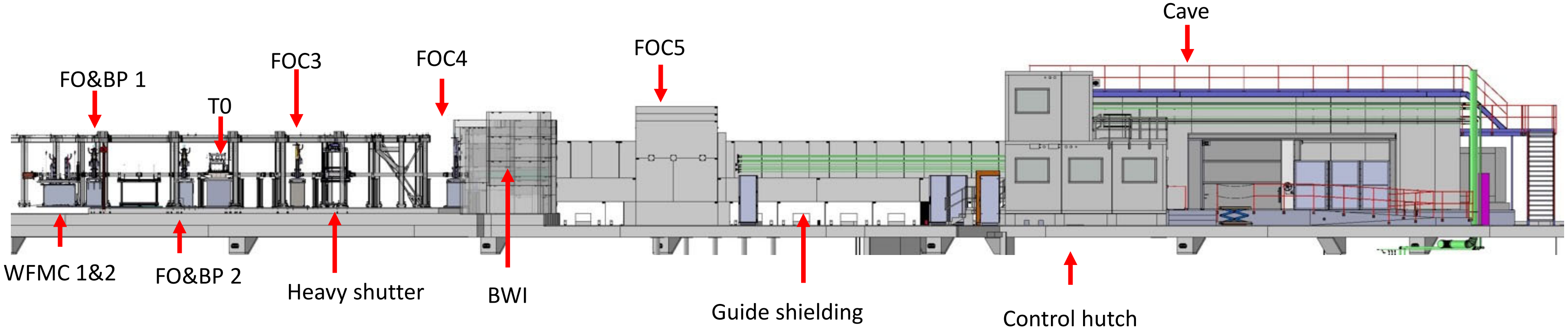
Instrument Data Scientist for ODIN, BEER & TBL

Alexandre Gonçalves Gerk

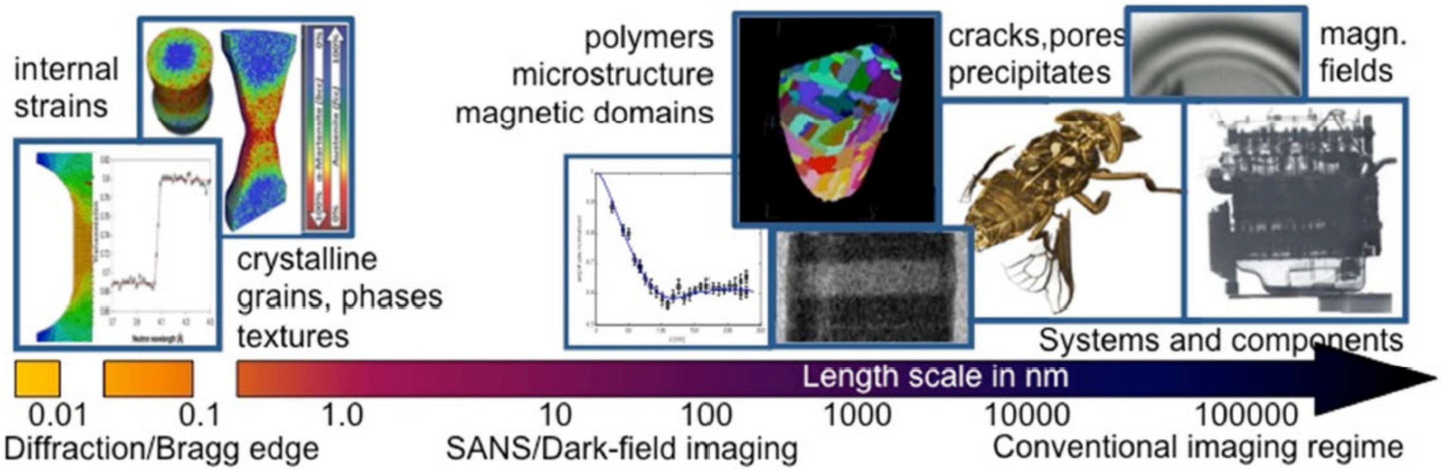
MCA Engineer for ODIN

ODIN overview





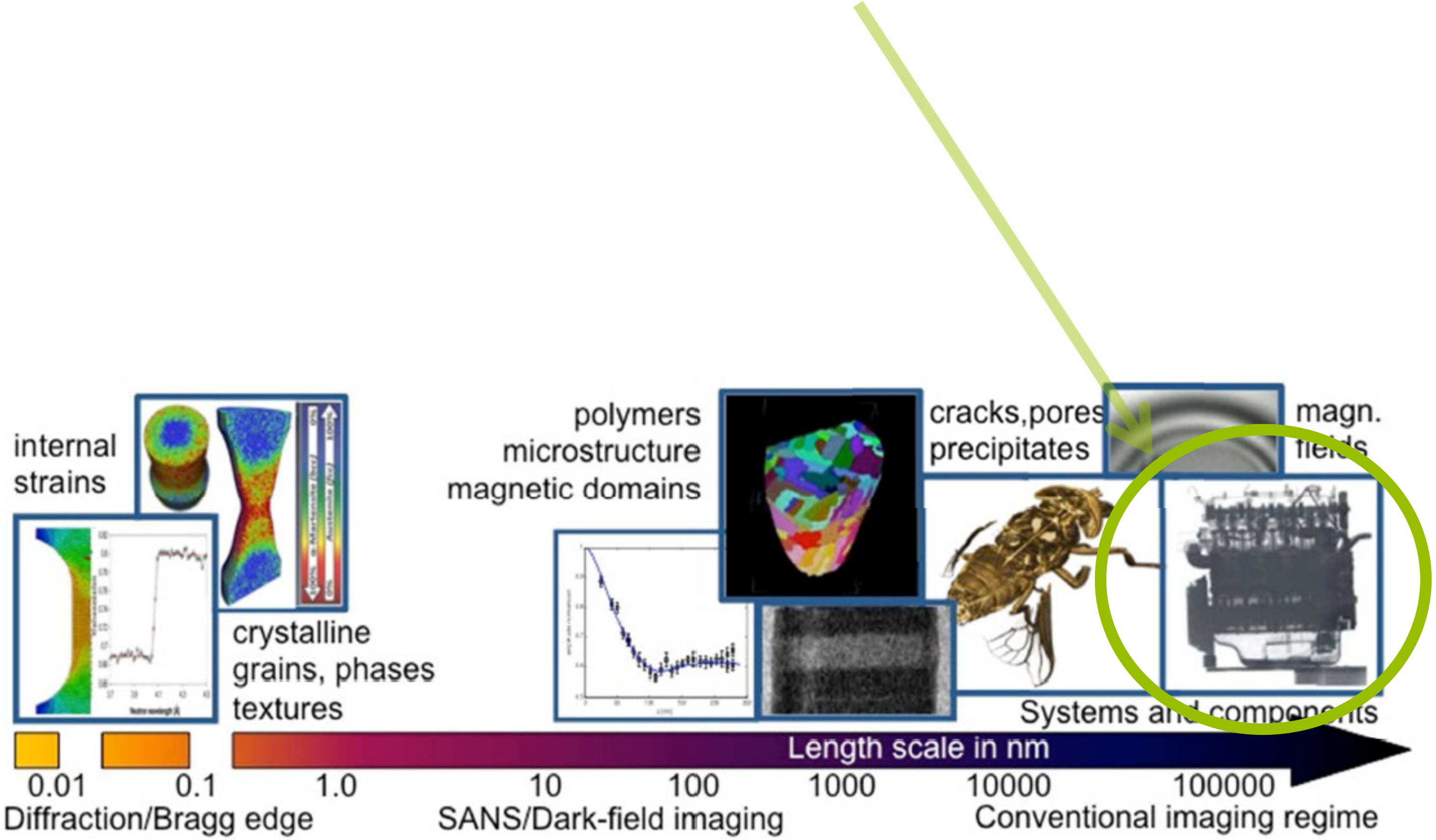
Full scope of ODIN



M. Strobl, Physics Procedia, 69 (2015) 18-26

Full scope of ODIN

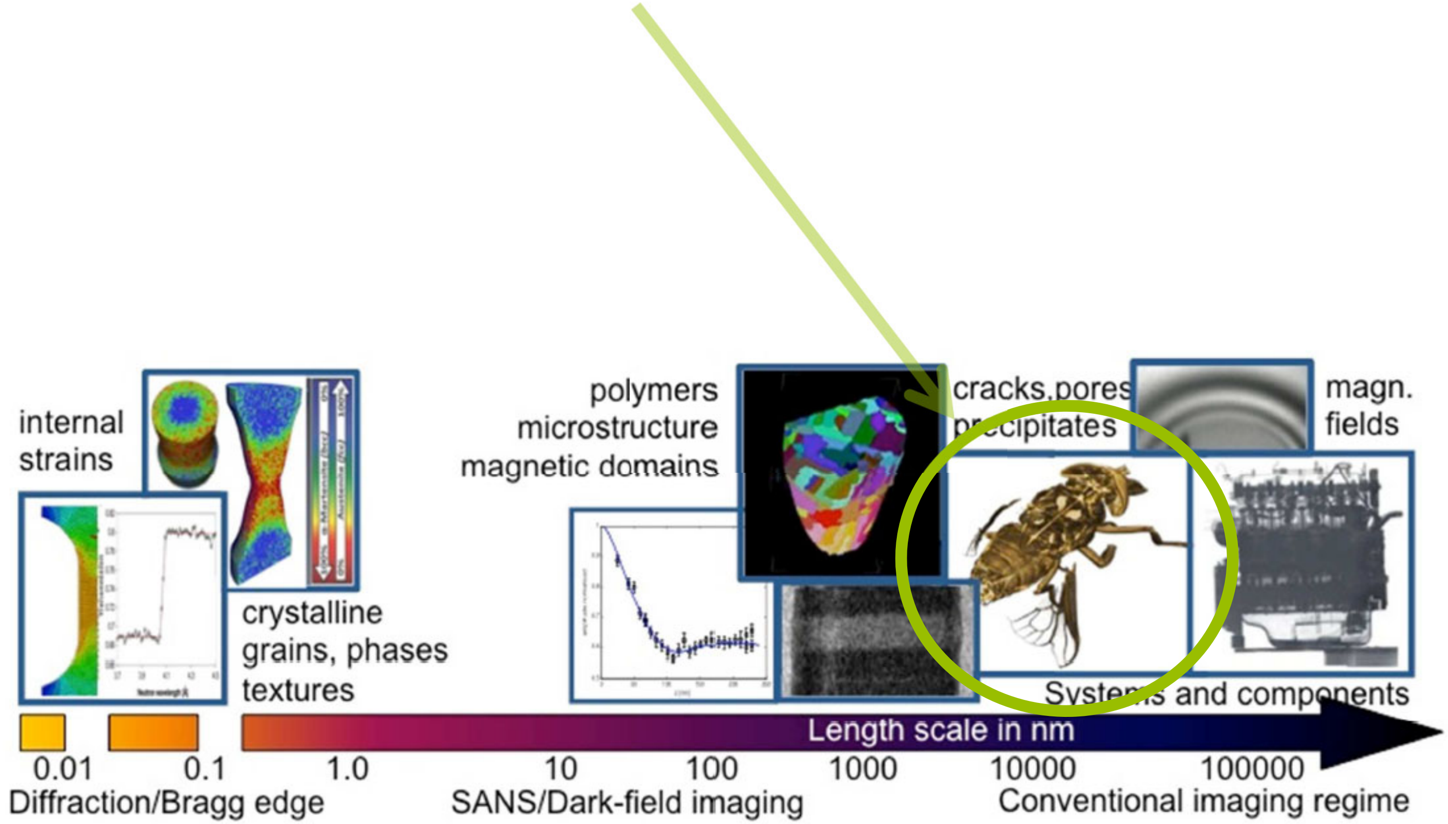
- White beam imaging with best spatial resolution and variable FoV:
  - Of big objects thanks to the 25 x 25 cm^2 FoV and thermal spectrum…



M. Strobl, Physics Procedia, 69 (2015) 18-26

Full scope of ODIN

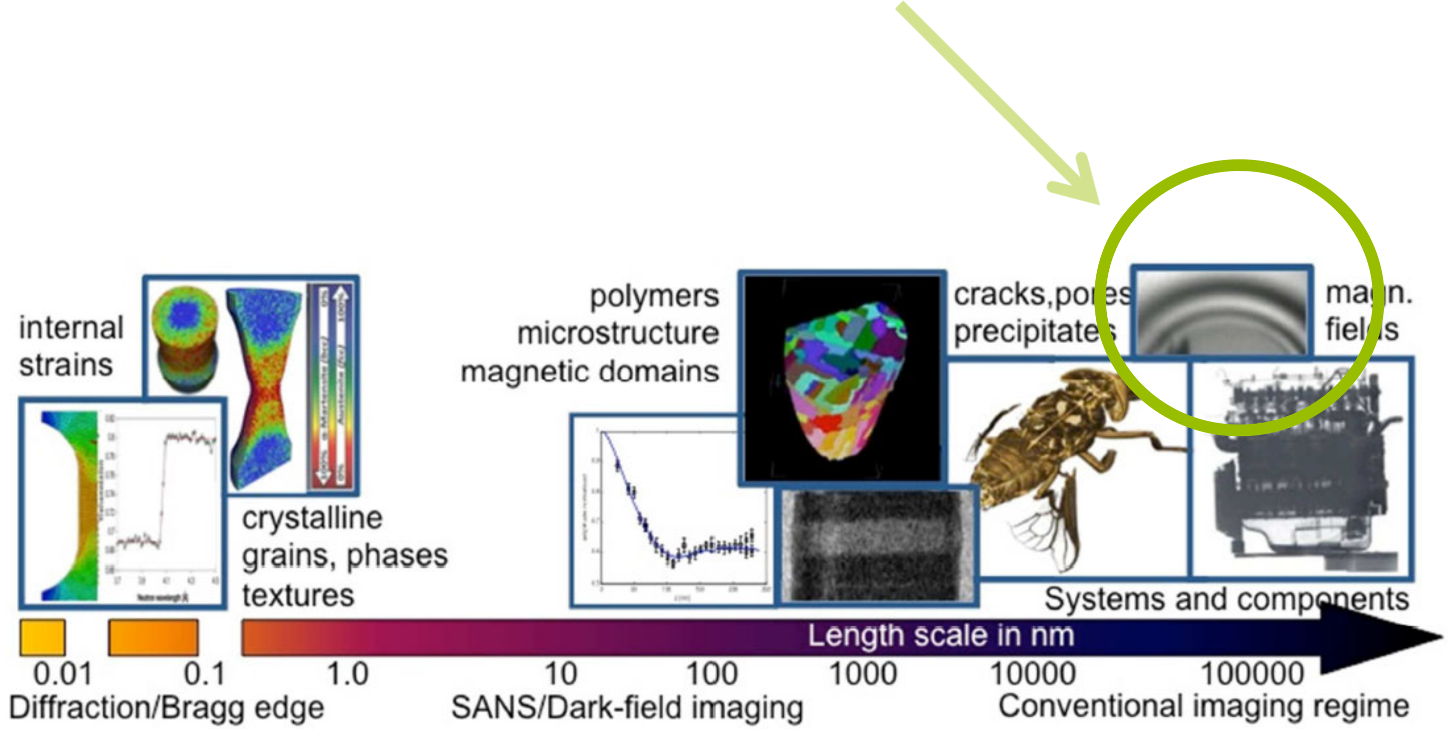
- White beam imaging with best spatial resolution and variable FoV:
  - Of big objects thanks to the 25 x 25 cm^2 FoV and thermal spectrum
  - And small objects thanks to the high flux and cold spectrum



M. Strobl, Physics Procedia, 69 (2015) 18-26

Full scope of ODIN

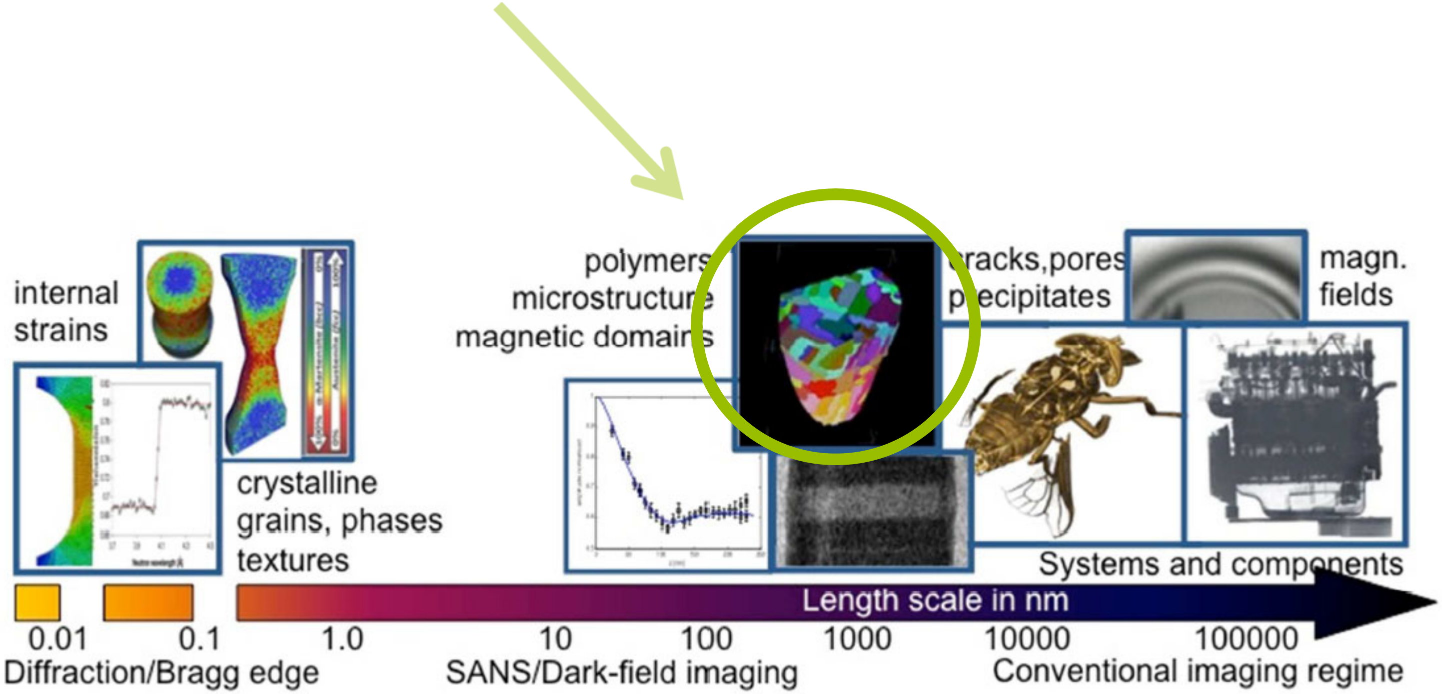
- White beam imaging with best spatial resolution and variable FoV
- Polarized neutron imaging
  - To visualize (and quantify thanks to ToF information) magnetization in bulk samples and magnetic field outside



M. Strobl, Physics Procedia, 69 (2015) 18-26

Full scope of ODIN

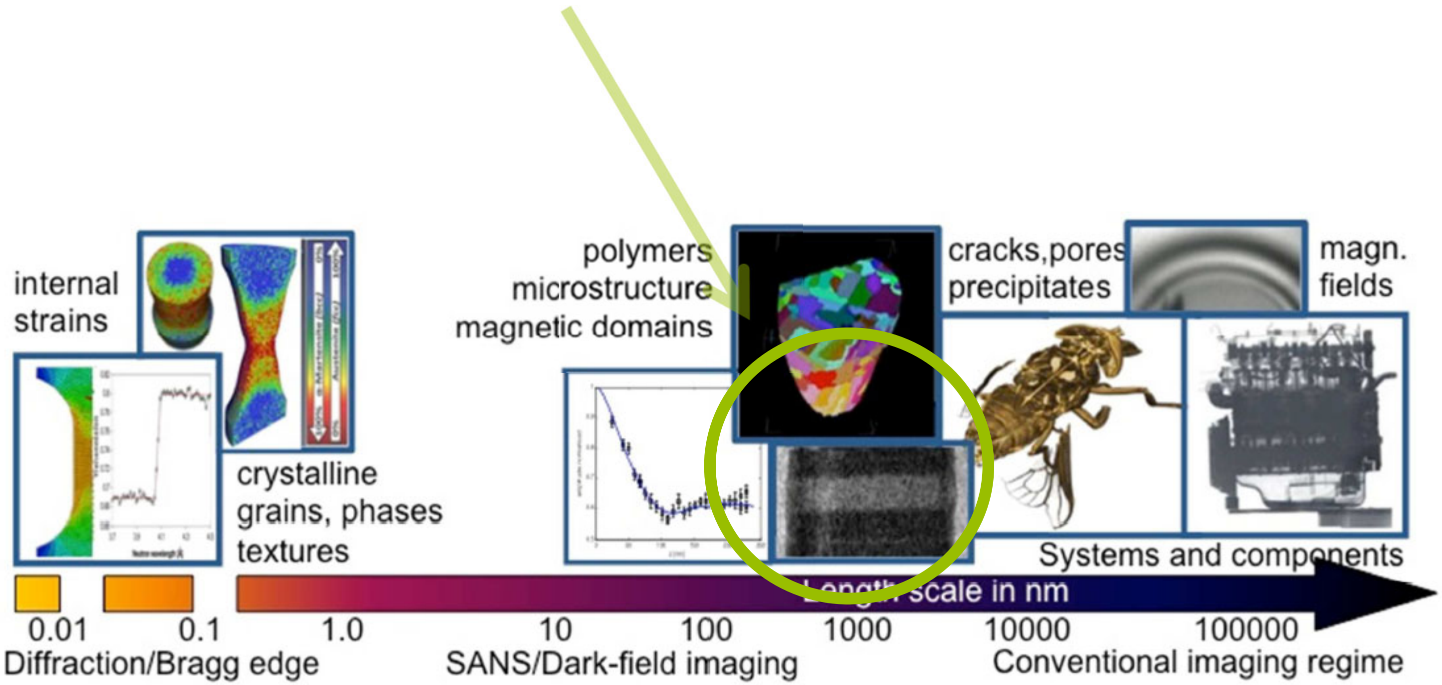
- White beam imaging with best spatial resolution and variable FoV
- Polarized neutron imaging
- Dark field imaging
  - To visualize magnetic domains



M. Strobl, Physics Procedia, 69 (2015) 18-26

Full scope of ODIN

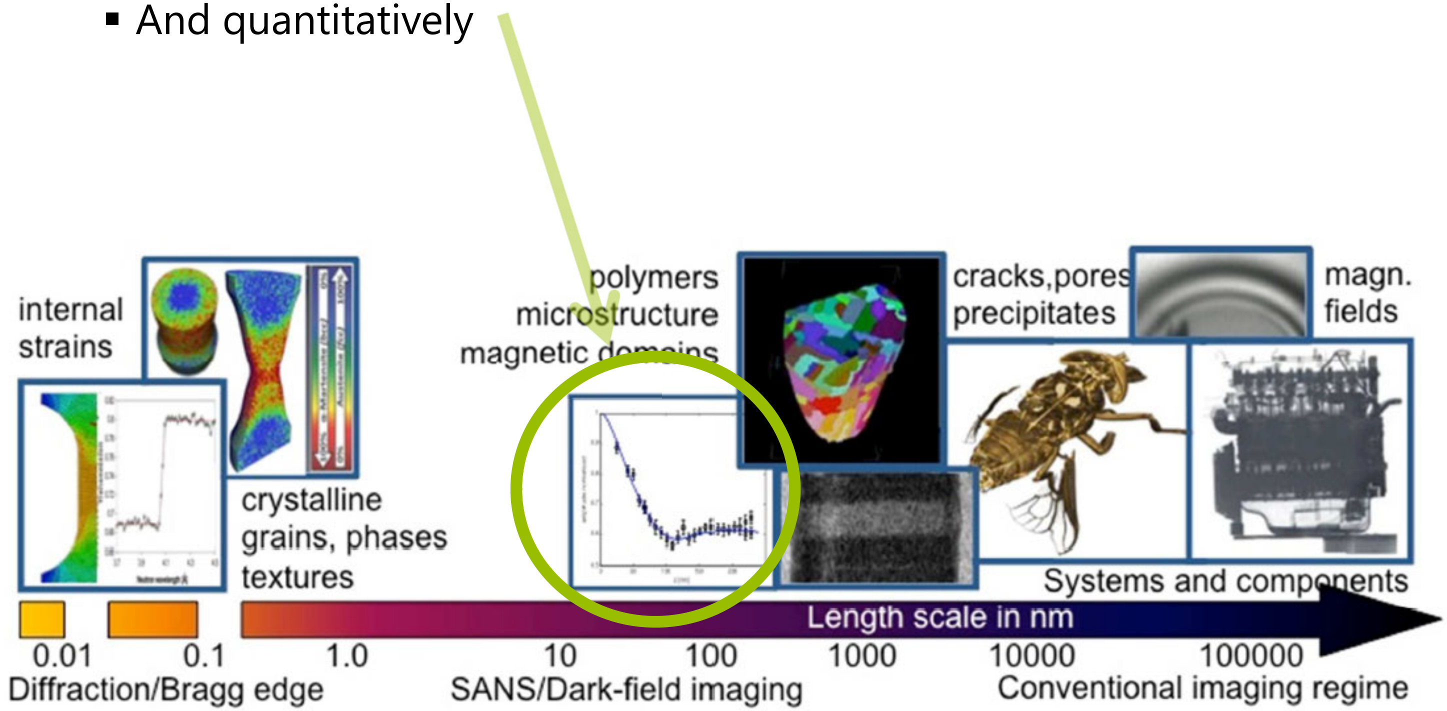
- White beam imaging with best spatial resolution and variable FoV
- Polarized neutron imaging
- Dark field imaging
  - To visualize magnetic domains
  - Microstructures beyond the image resolution qualitatively



M. Strobl, Physics Procedia, 69 (2015) 18-26

Full scope of ODIN

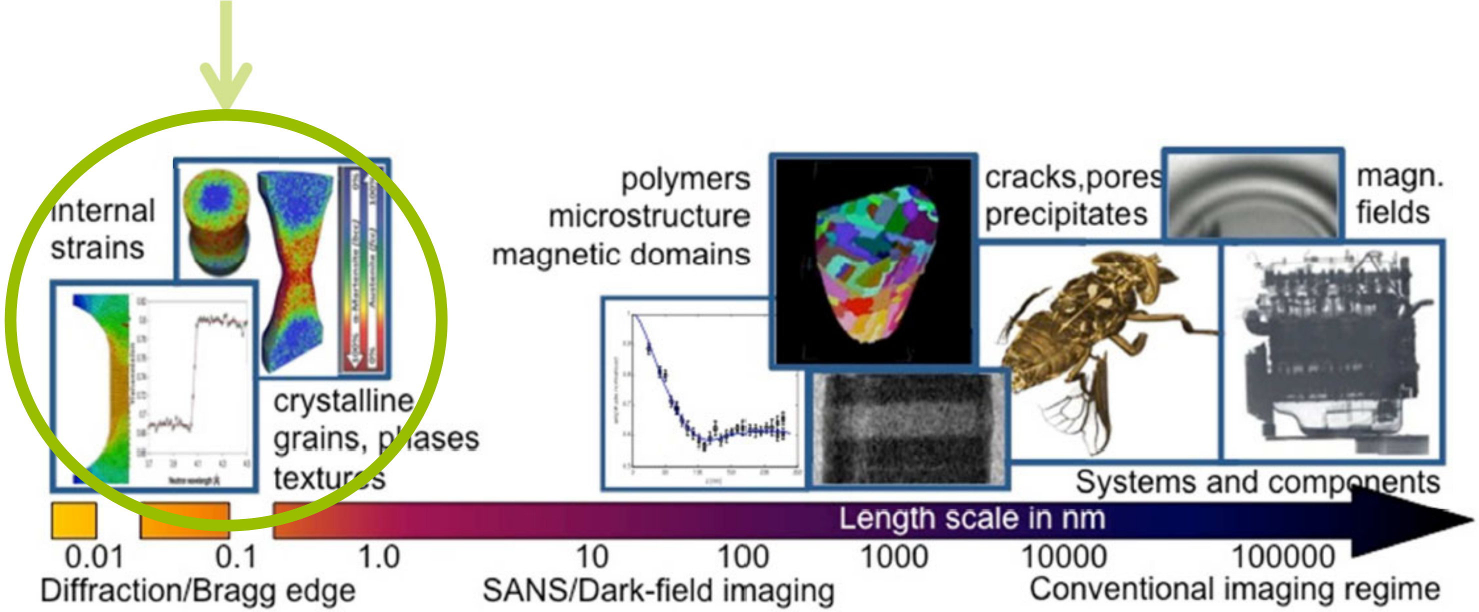
- White beam imaging with best spatial resolution and variable FoV
- Polarized neutron imaging
- Dark field imaging
  - To visualize magnetic domains
  - Microstructures beyond the image resolution qualitatively
  - And quantitatively



M. Strobl, Physics Procedia, 69 (2015) 18-26

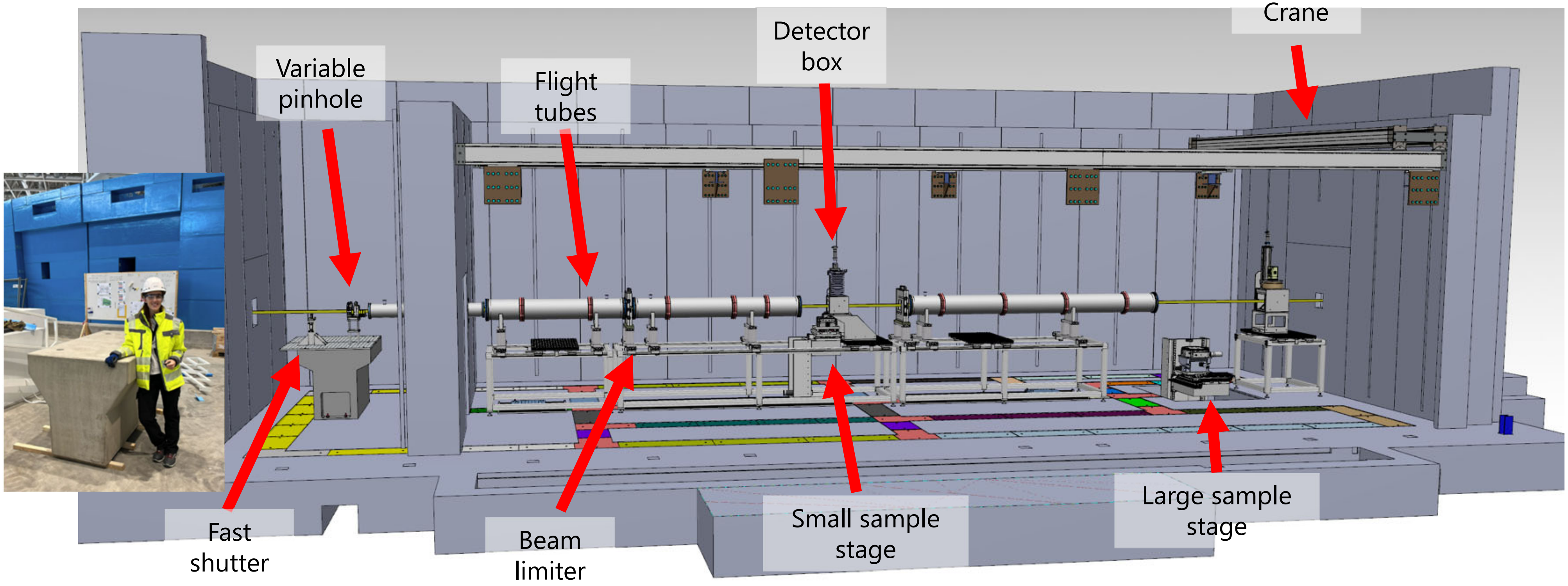
Full scope of ODIN

- White beam imaging with best spatial resolution and variable FoV
- Polarized neutron imaging
- Dark field imaging
- Wavelength resolved Bragg edge imaging
  - To visualize grains, phases, strains and texture

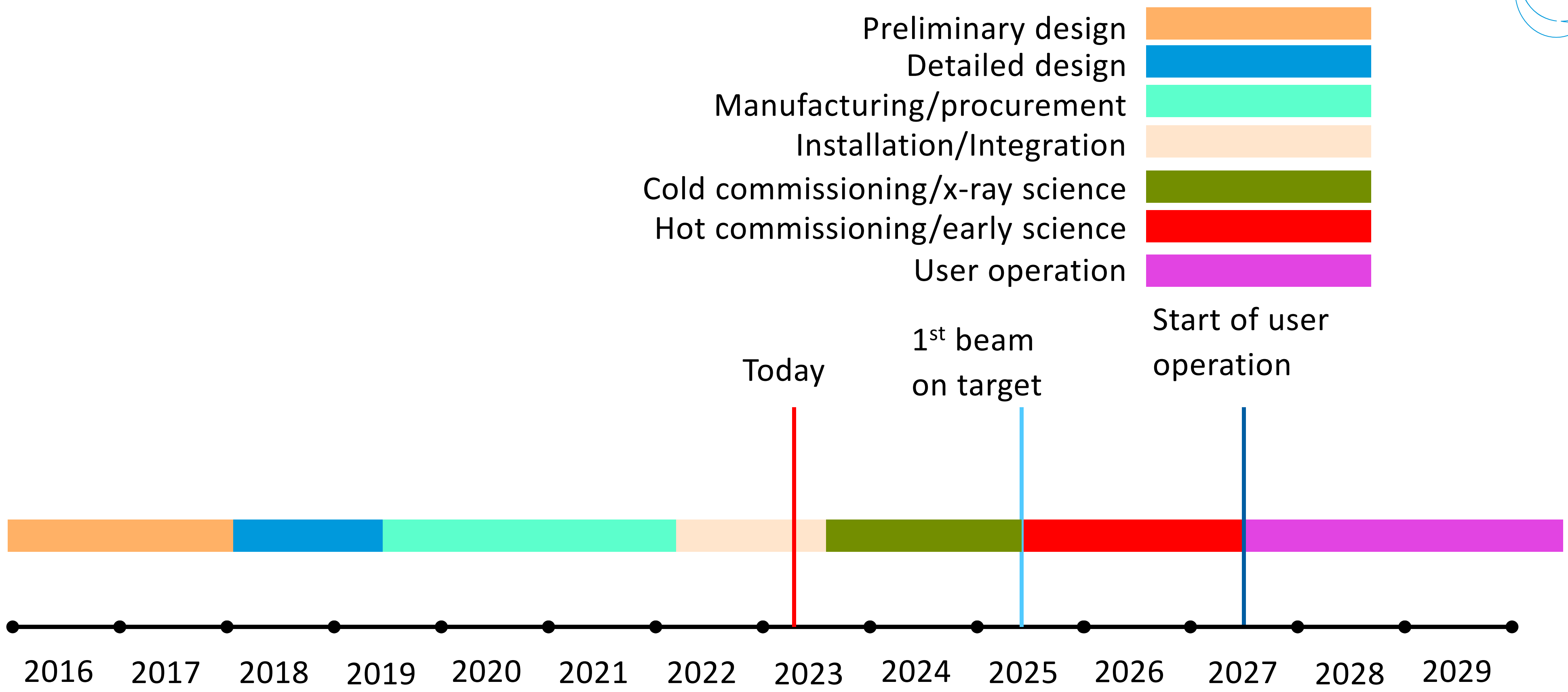


M. Strobl, Physics Procedia, 69 (2015) 18-26

Cave interior

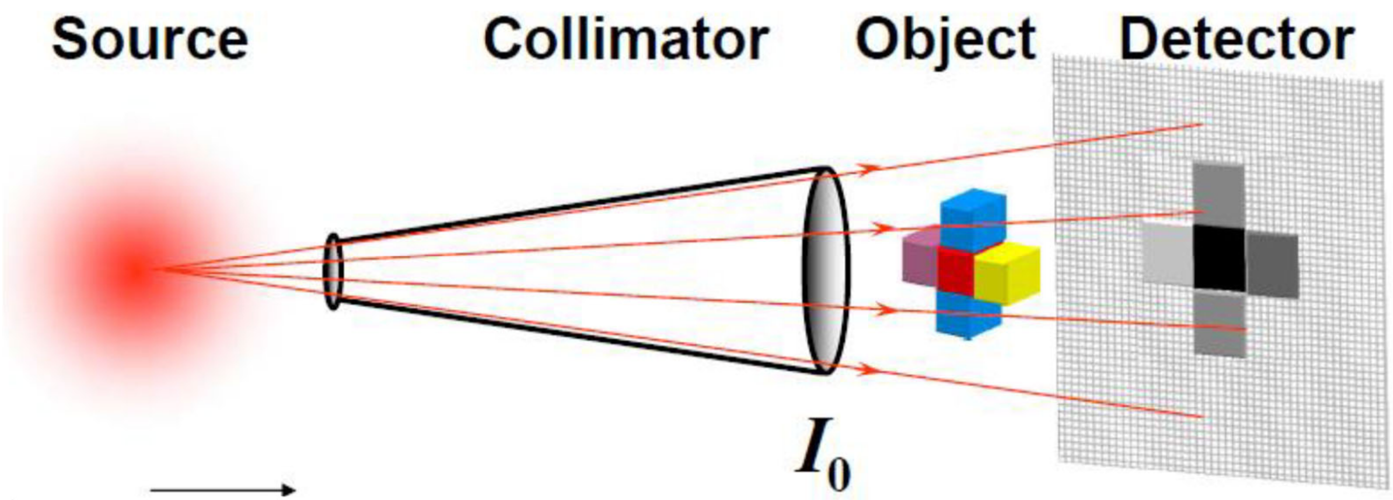


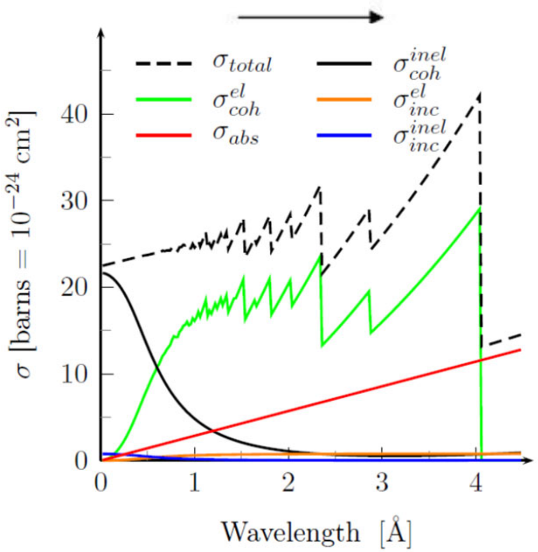
ODIN Timeline



Advanced Neutron Imaging (just a taste)

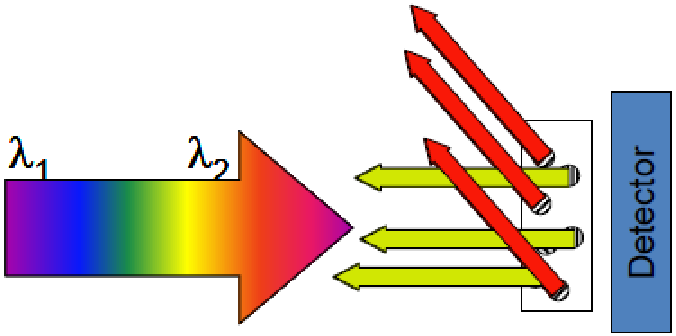
Neutron imaging with energy resolution



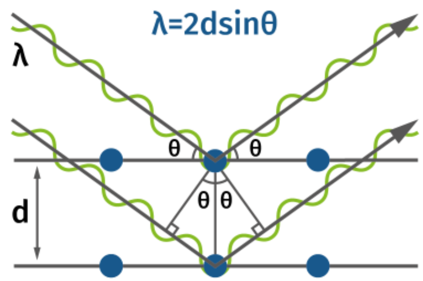


$$\sigma_{total} = \sigma_{coh}^{inel} + \sigma_{incoh}^{inel} + \sigma_{coh}^{el} + \sigma_{incoh}^{el} + \sigma_{abs}$$

Bragg Edges



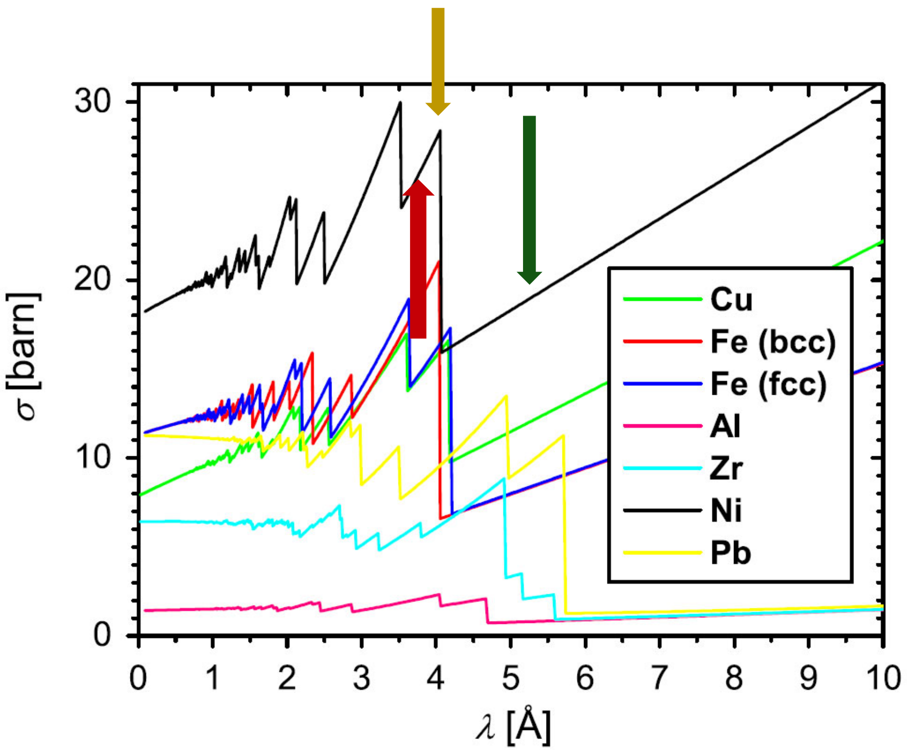
Bragg's law:



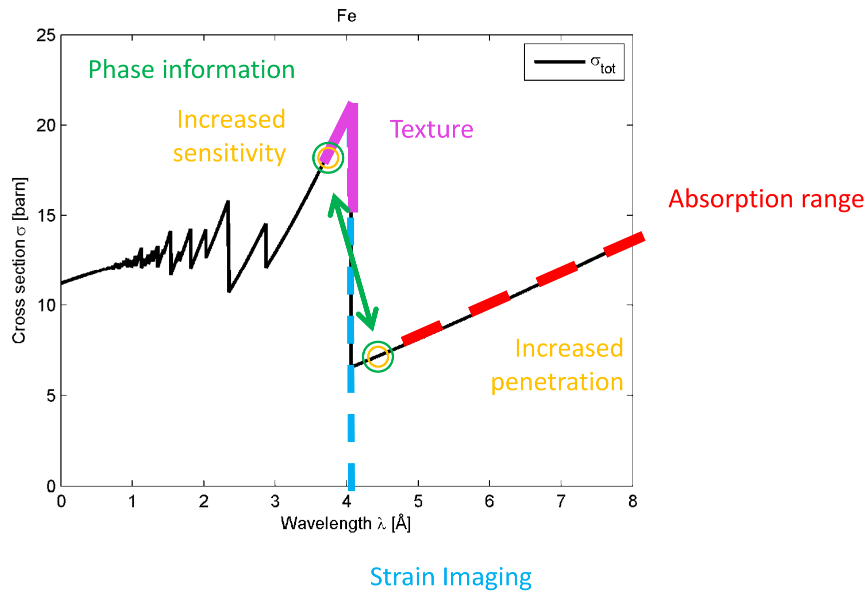
$2d_{hkl}\sin\theta=\lambda$

$2d_{hkl}\sin 90°=\lambda$

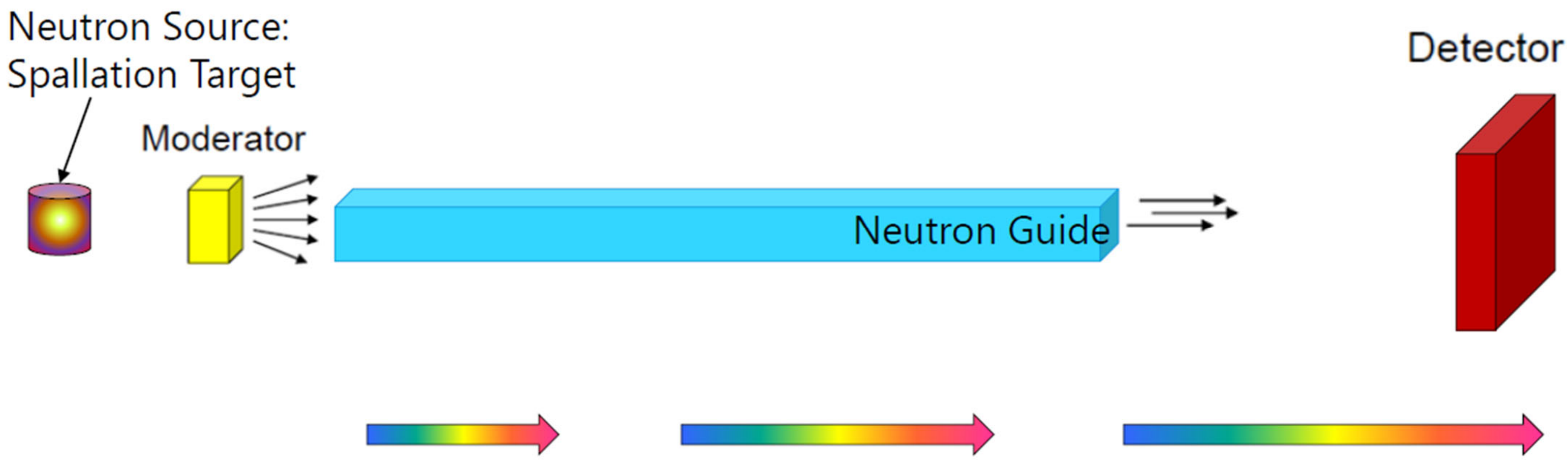
$2d_{hkl}\sin\theta<\lambda$



Neutron imaging to map phases: principles of Bragg Edge imaging



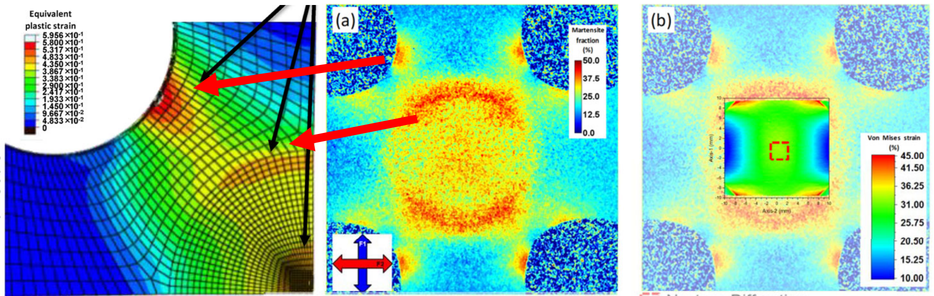
Concept of ToF imaging (in brief)



Wavelength	Speed (m/s)	ToF @10 m (ms)
1 Å	3956	2.5
2 Å	1978	5.1
5 Å	791	12.6
10 Å	395	25.3

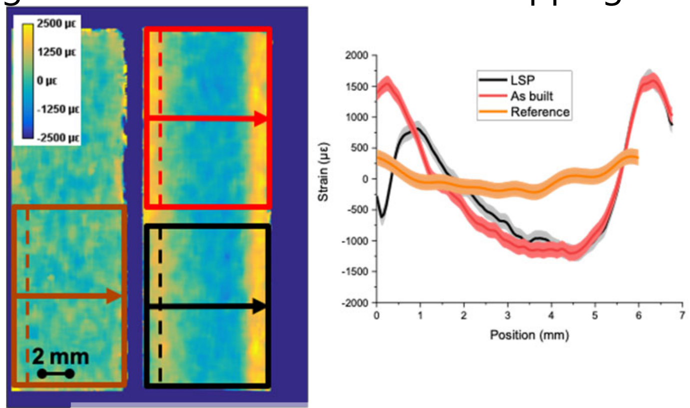
Use of ToF neutron imaging: an example

Medium resolution: phase fraction mapping of steel



Polatidis et al. (2020) Materials

High resolution: residual strain mapping in AM steel



Morgano et al. (2020) Additive Manufacturing

Thanks for your attention!