ESS

The European Spallation Source: providing neutrons to determine material functionality.

PASCALE DEEN
DIVISION HEAD FOR SPECTROSCOPY
AFFILIATE PROFESSOR: SOLID STATE PHYSICS AND NEUTRON SCATTERING.
NIELS BOHR INSTITUTE, UNIVERSITY OF COPENHAGEN

ESS

The future European flagship in neutron science

Designed to enable scientific breakthroughs in matter and materials research with a particular focus on European technological competitiveness in the areas of energy, health, and the environment.

BREEAM
Renewable energy & waste heat recovery

Creating Impact

We strive to be the world's leading institution for neutron-based research, driving advancements that benefit science, industry, and society. Our impact is built on:

- **Scientific Discovery** – Expanding the frontiers of knowledge to better understand the world.
- **Industrial and Economic Competitiveness** – Enabling industries to innovate responsibly through our research, improving materials and processes.
- **Technological Leadership** – Developing cutting-edge methods and technologies to ensure ESS remains at the forefront of scientific excellence.
- **Sustainability** – Minimising our environmental footprint while addressing global challenges through responsible and innovative practices.

A coalition of 13 European countries

Host countries

Sweden, Denmark

Construction
47.5%

Operations
15%

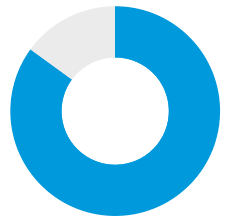
Base budget for construction €1.84 B_{2013}

Estimated annual operating budget €140 M_{2013}

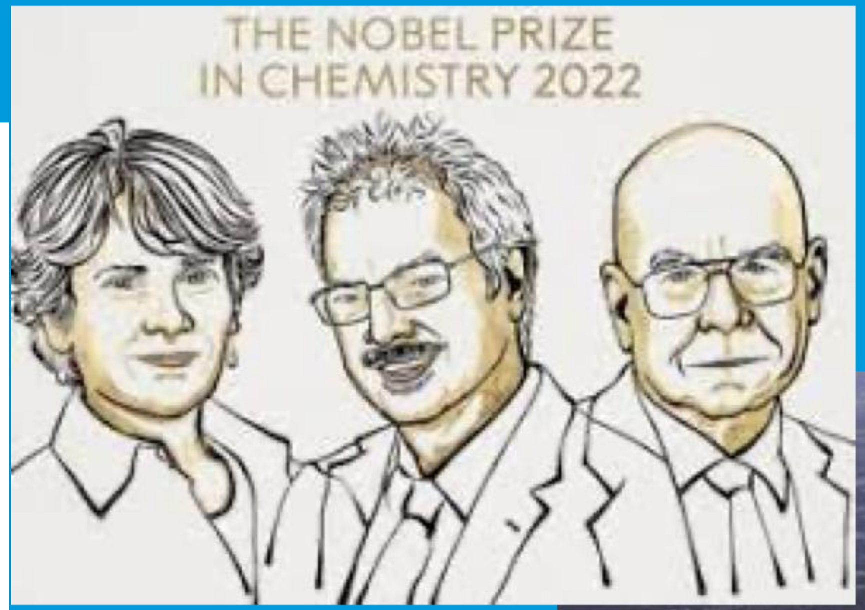
Non host member countries

Czech Republic, Estonia, France, Germany, Hungary, Italy, Norway, Poland, Spain, Switzerland, United Kingdom

Construction
52.5%
(of which 70% is in-kind deliverables)



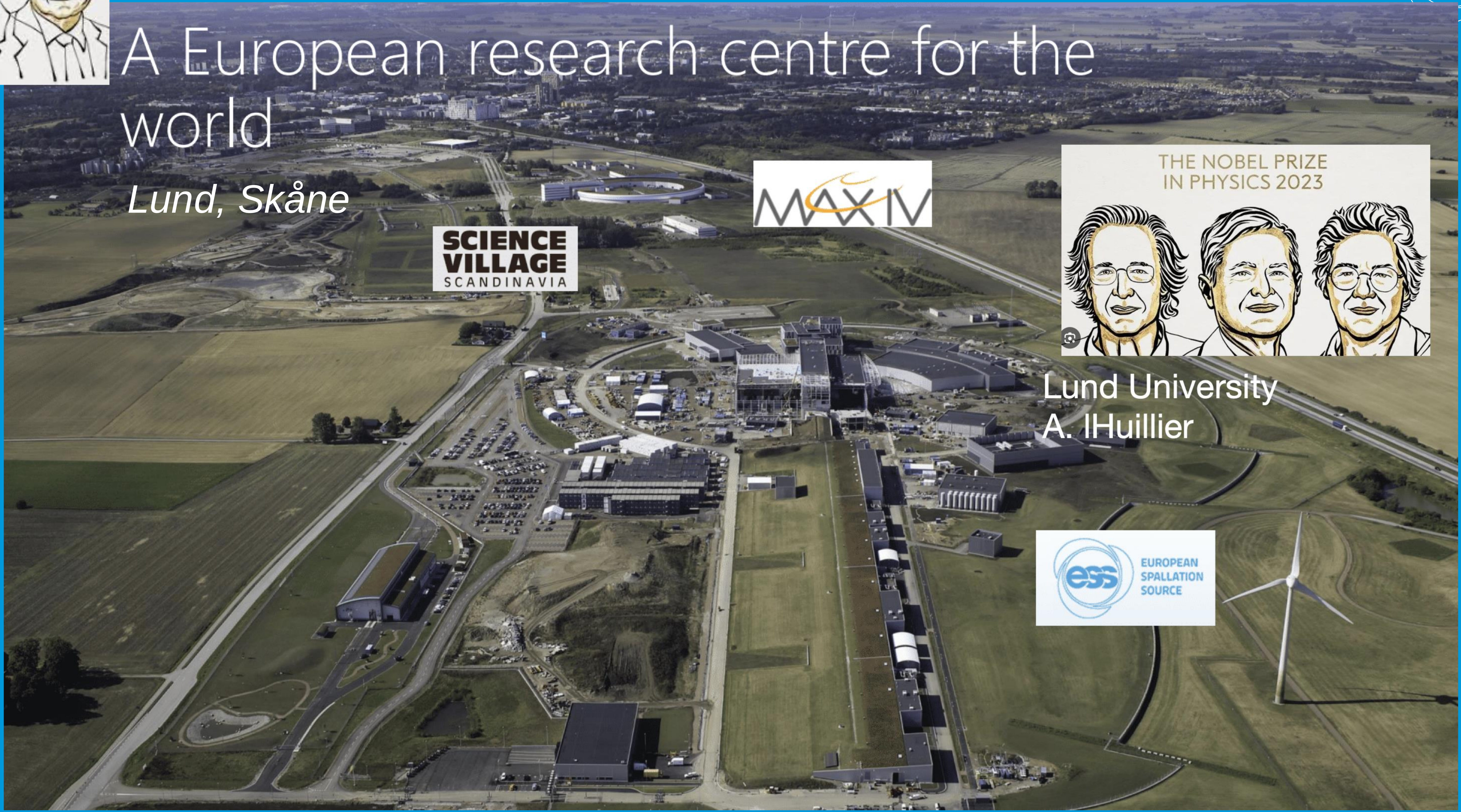
Operations
85%



Copenhagen University
M. Meldal

A European research centre for the world

Lund, Skåne



Lund University
A. lHuillier

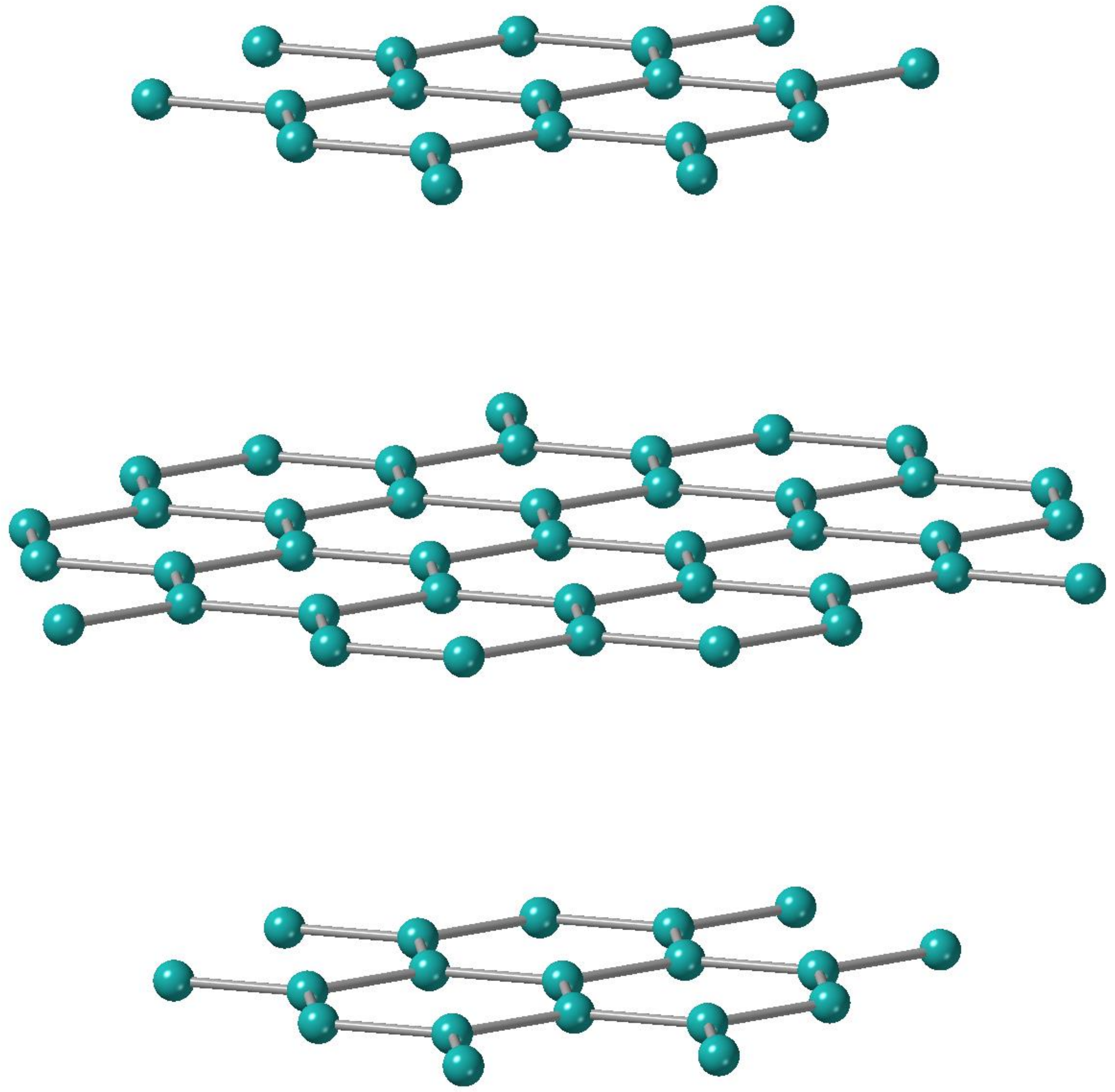
ESS : a vital facility for the study of materials science
Materials: what is the interest?

Carbon : 4 allotropes

Graphite (1600):

Layers of Carbon

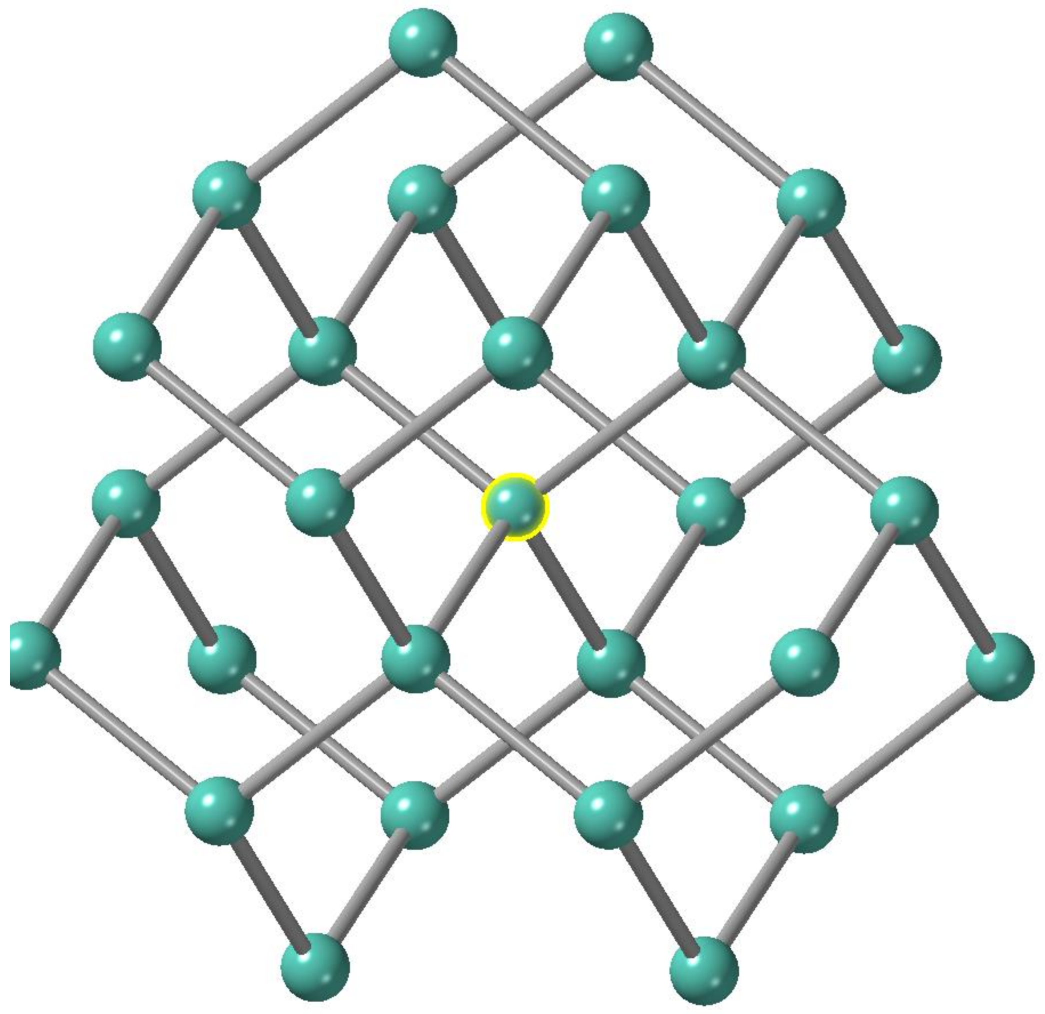
- Pencils
- Nuclear reactor cores



Diamond (4BC):

Tetrahedral Carbon

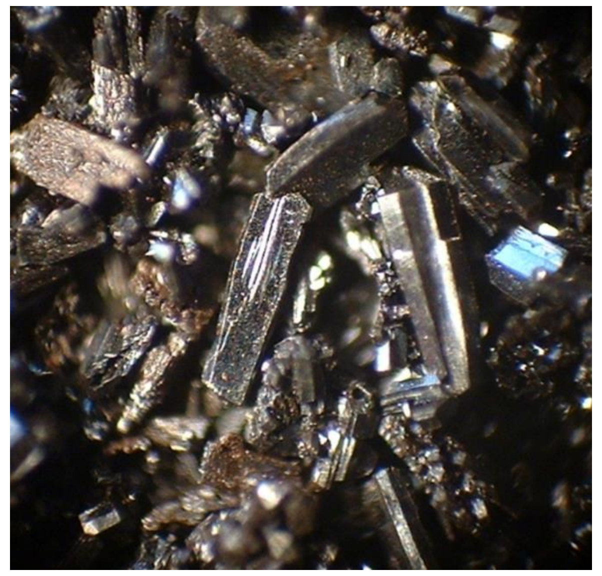
- Drill bits, diamond saws.
- High pressure research.
- Jewellery.

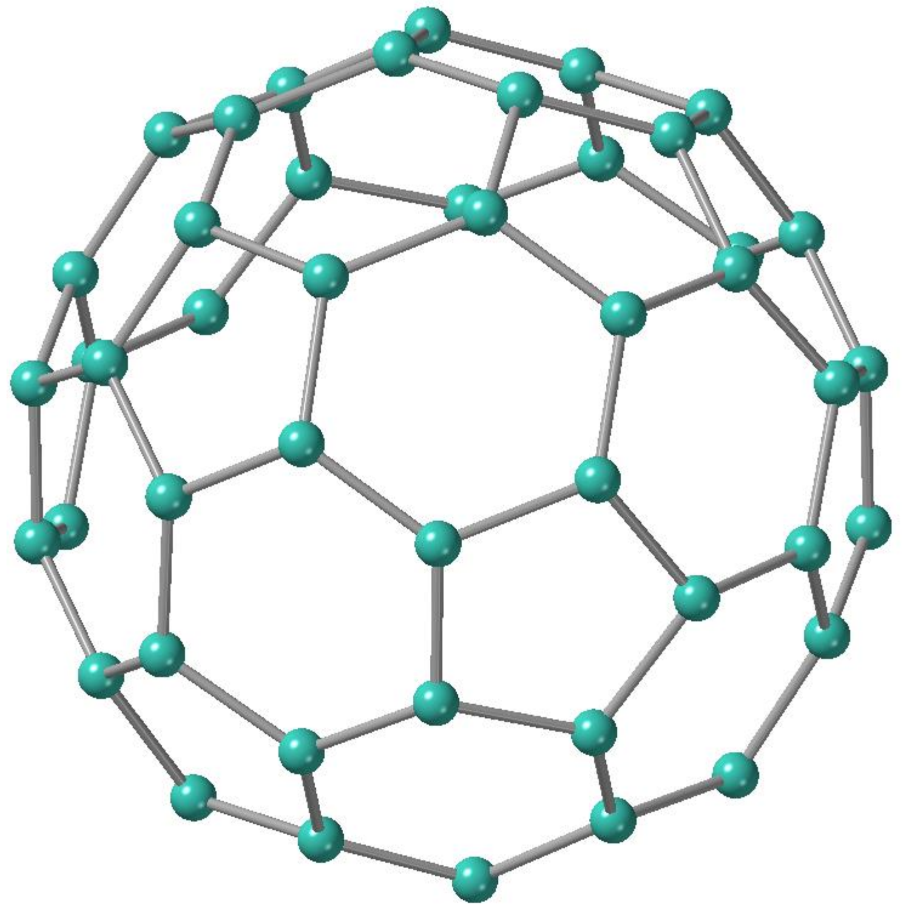


Fullerenes(1985):

Cage of Carbon atoms

- Drug and gene delivery
- Gas absorber
- Biomedical applications

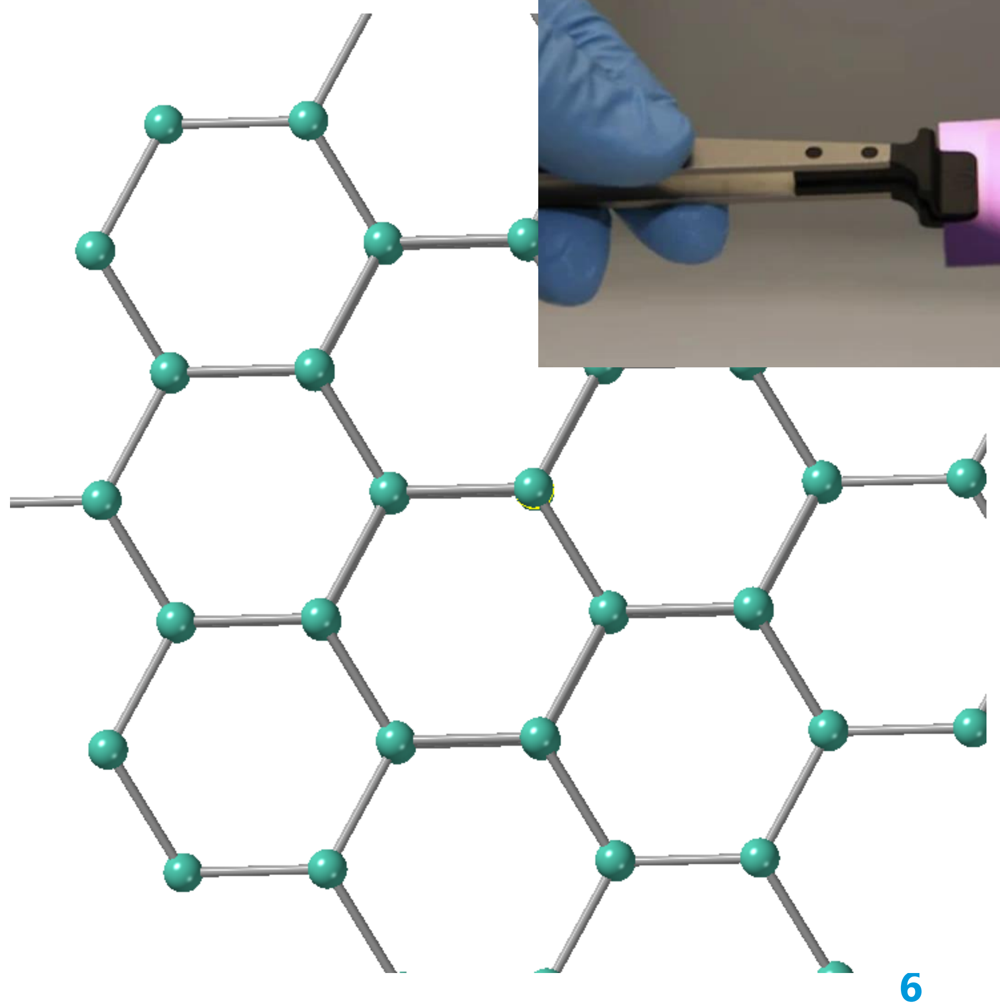


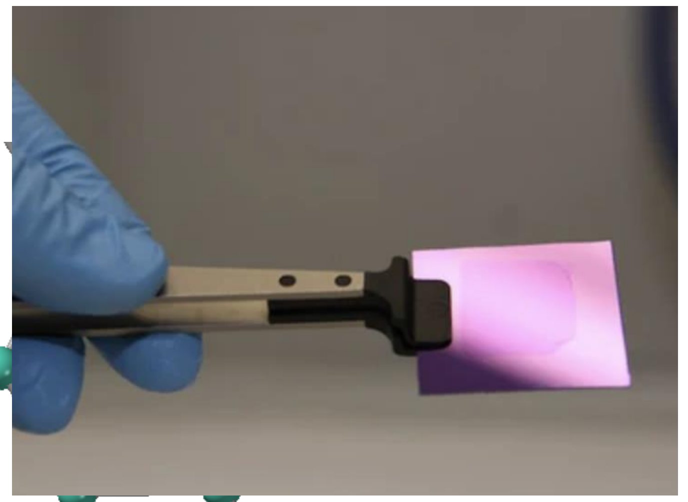


Graphene (2004):

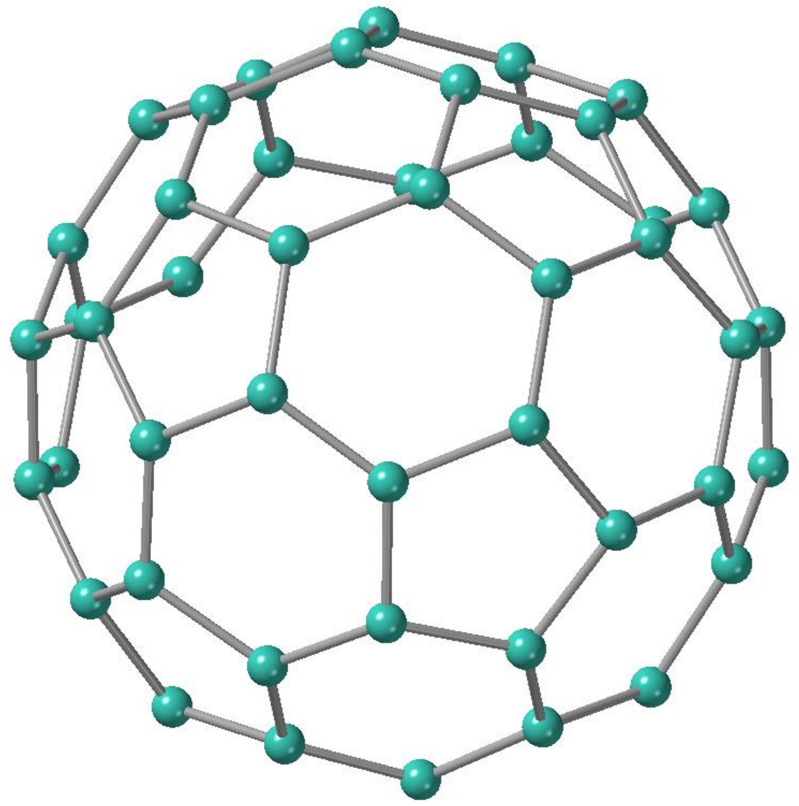
Single hexagonal layer

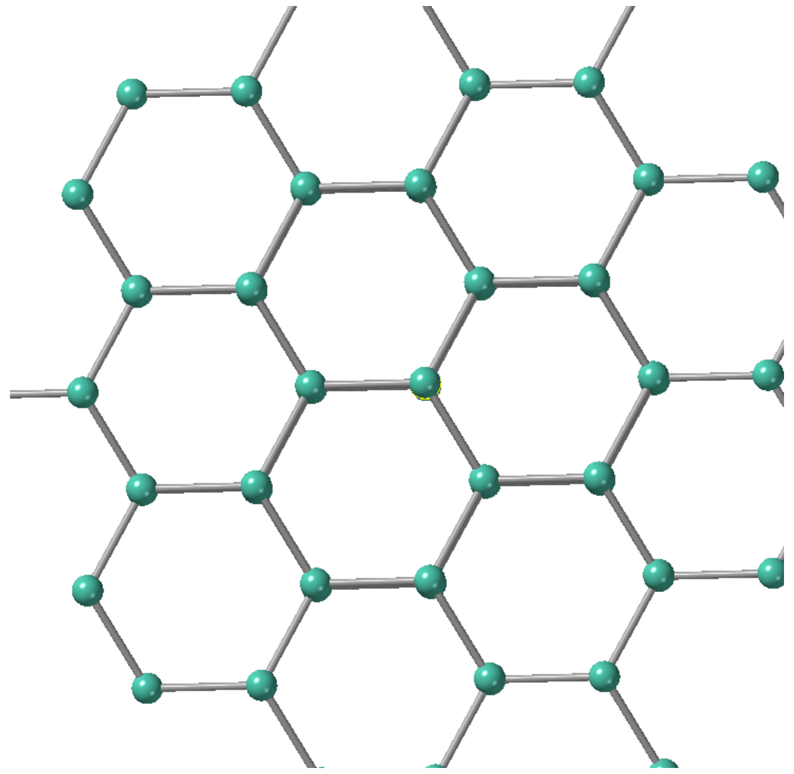
- Electrochemical & Biochemical sensors
- Energy storage, batteries, solar cells
- Graphene composites: enhance material strength and rigidity





Functionality of materials

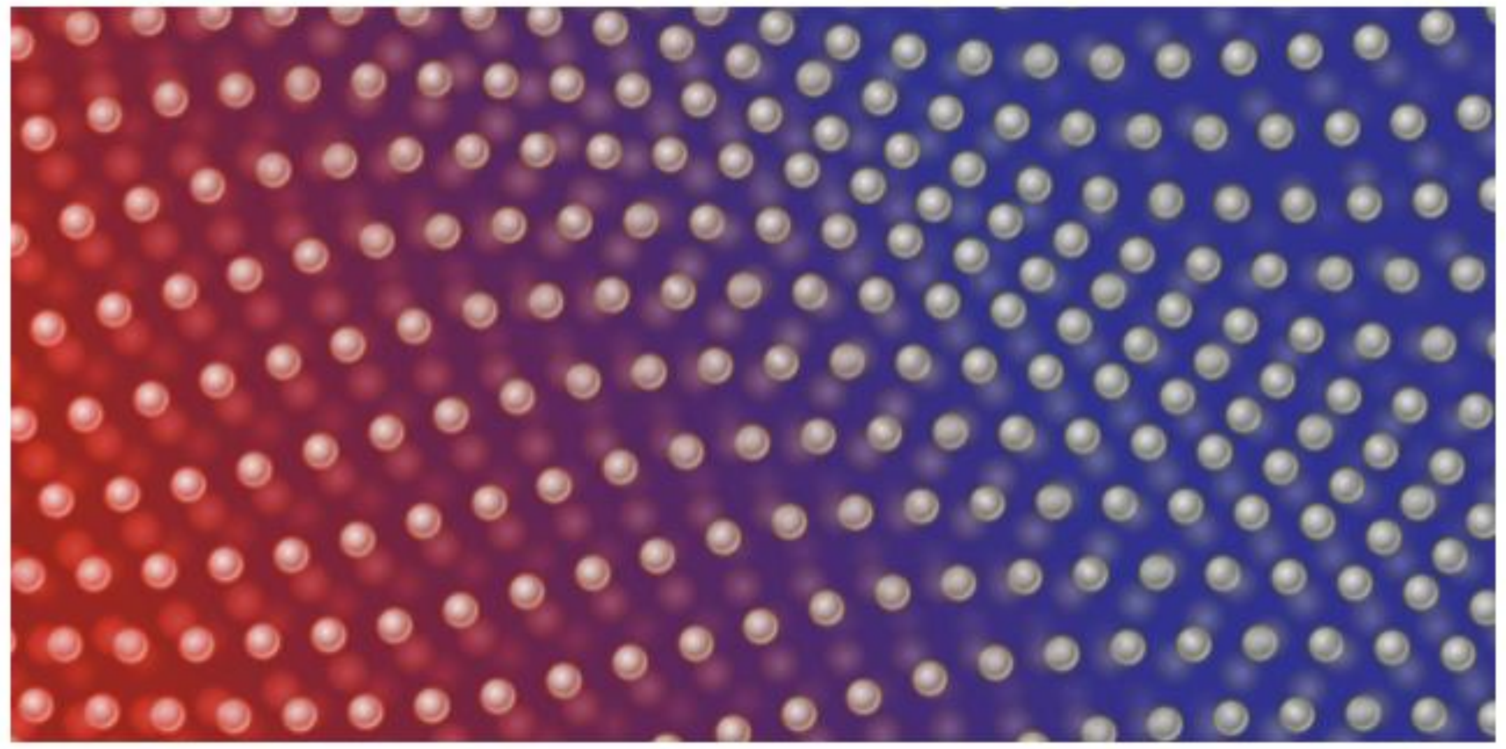




What the atoms are ?

Where the atoms are ?

How do they move ?



How are they bonded ?

Dynamics ?

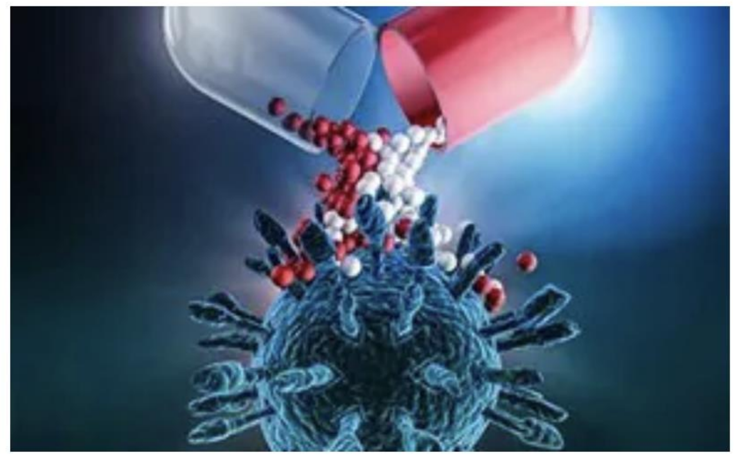
Orbital and spin contributions ?

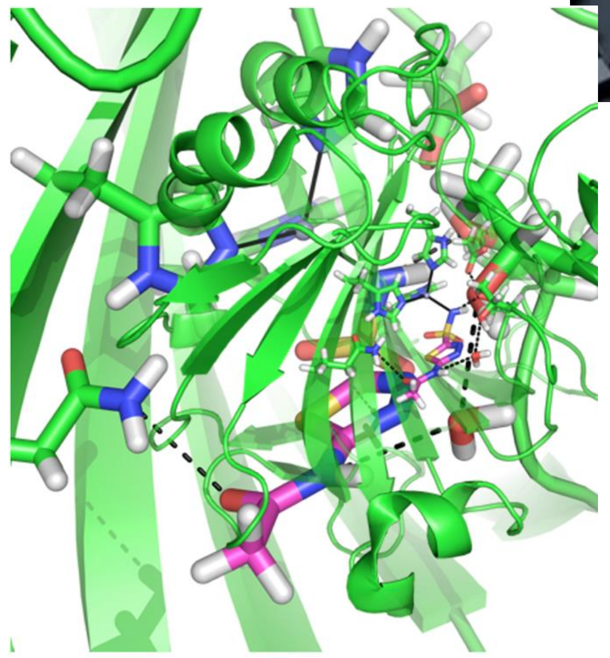
Exchange interactions ?

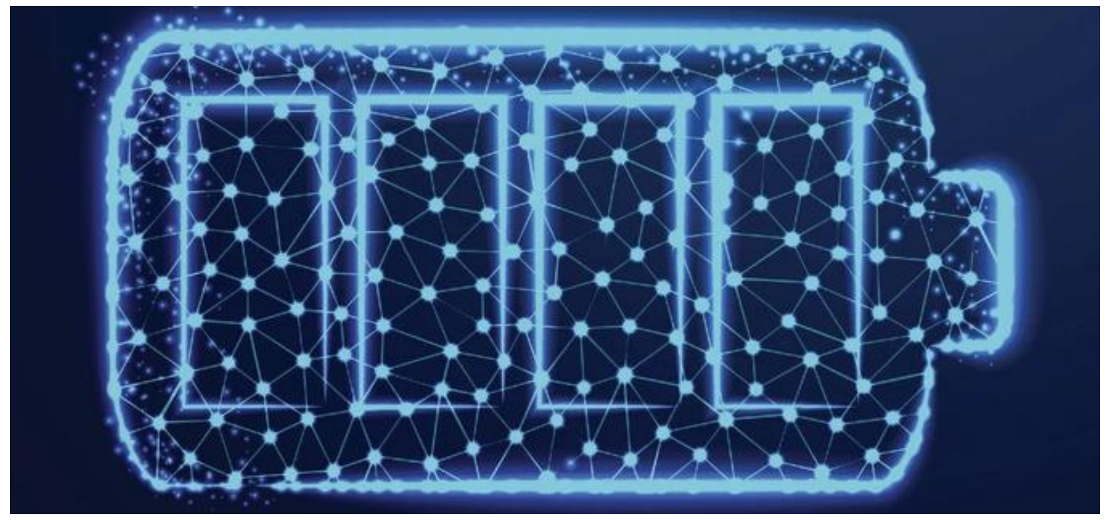
Phononic excitations ?

Diffusional behaviour ?

………………..Probe??

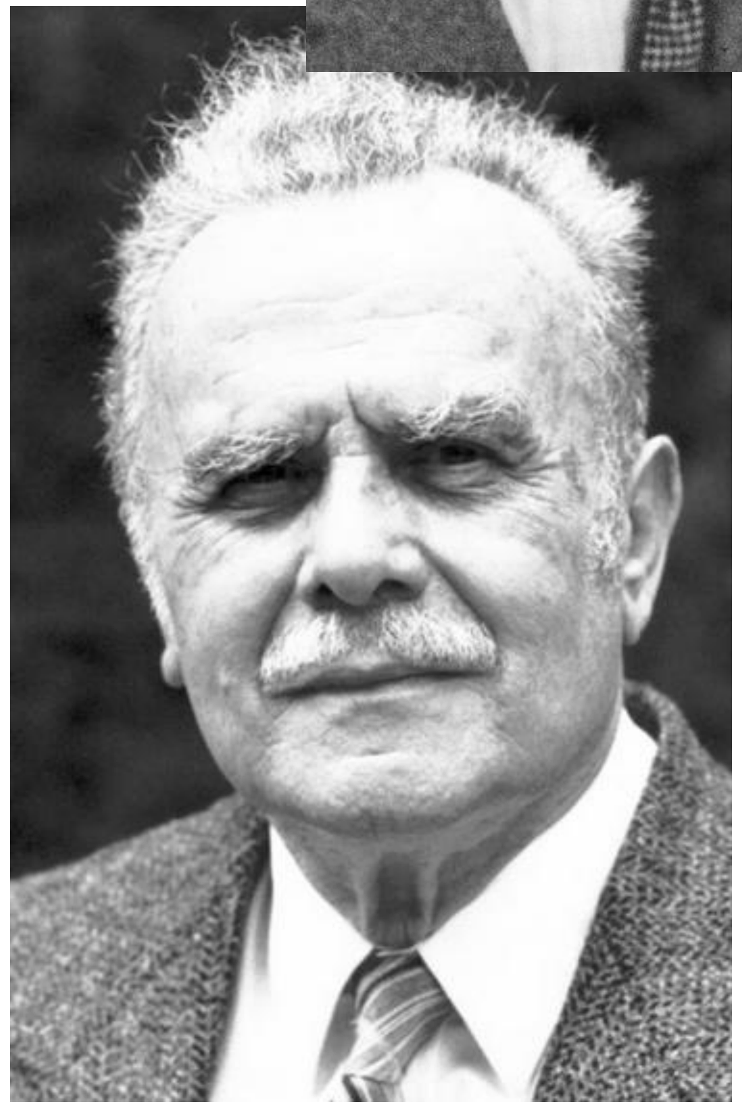






Neutrons for the study of materials

Chadwick
Nobel Laureate



Bert Brockhouse
Nobel Laureate (1994)

The neutron is ideal for the study of condensed matter:

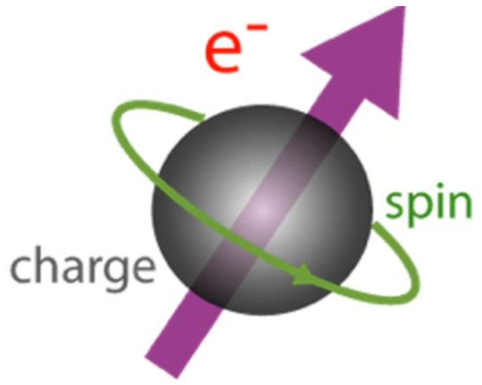
It might be said that, if the neutron did not exist, it would need to be invented.

- **Charge = 0 : NON-DESTRUCTIVE and with high PENETRATION POWER**
- **Interaction with atomic nuclei via the strong force. Sensitivity to LIGHT ELEMENTS and ISOTOPIC VARIATION**
- **Magnetic, S = 1/2 , μ = 1.91 (unpaired electrons : dipole interactions) Sensitive to the microscopic MAGNETIC PROPERTIES**
- **Wavelength ~ atomic length, energy scale of interatomic dynamics: Ideal for probing the STRUCTURE and DYNAMICS of a wide range of materials**

- Mean lifetime = 880 seconds
- Mass = 1.69e-27 kg.

Neutrons to drive our high technology civilisation

Neutrons probes directly **magnetic spins**.



High technology society: magnetic and electronic phenomena.

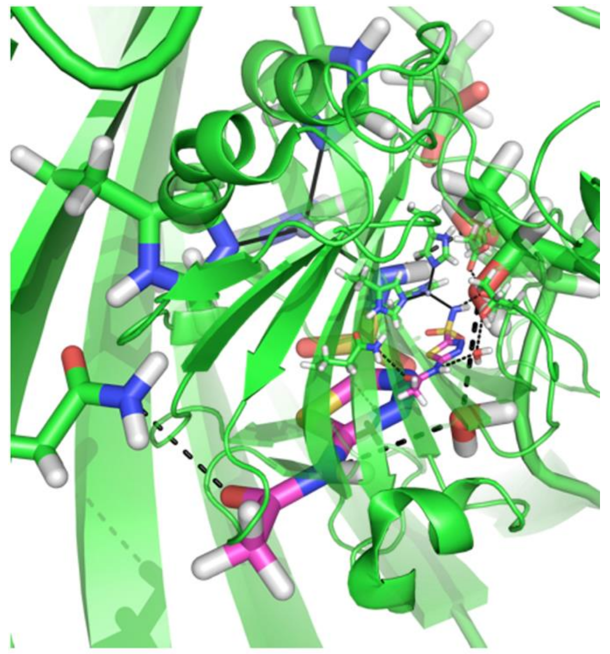
Magnetic spins:

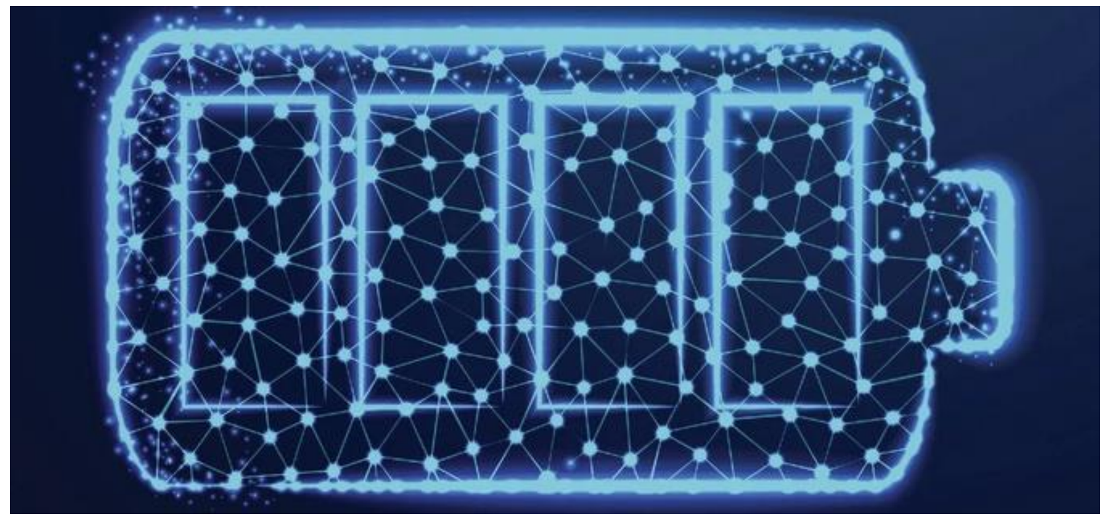
- quantum computing / Classical

  = 200 sec/10 000 years (Google 2021)
- Superconductivity : lossless power transfer
- Magnetocaloric cooling : low carbon technology

Neutrons: Probes directly light elements

(hydrogen, lithium)





- Biological processes: where hydrogen (H) atoms are and how they are transferred between biomacromolecules, solvent molecules, and substrates.
- Optimise diffusion in battery materials.

The Nobel Prize in Physics 2016

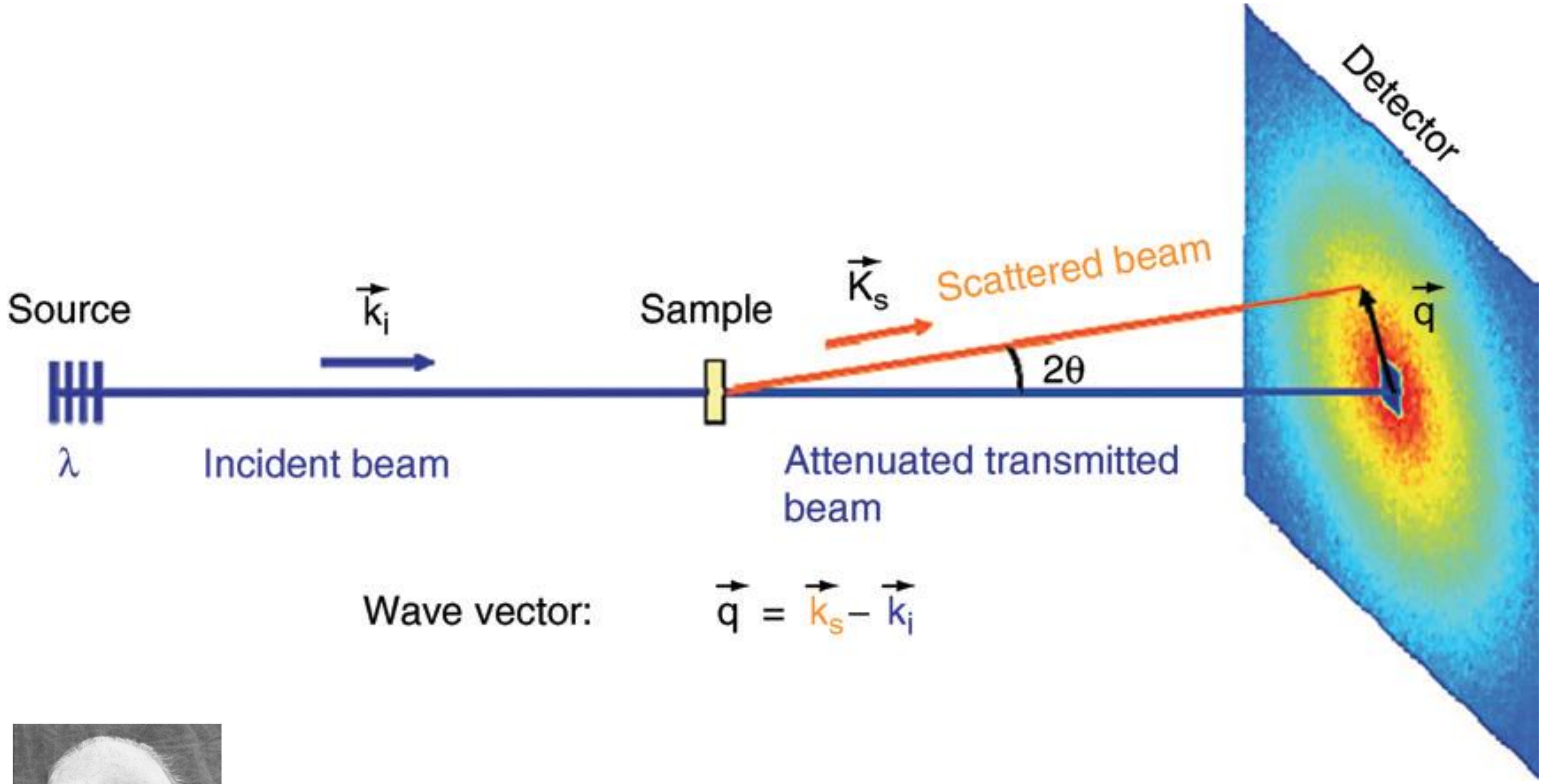
David J. Thouless, F. Duncan M. Haldane and J. Michael Kosterlitz
“for theoretical discoveries of topological phase transitions and topological phases of matter”

The Nobel Prize in Chemistry 2019

John B. Goodenough, M. Stanley Whittingham and Akira Yoshino “for the development of lithium-ion batteries”

How a neutron scattering instrument works.

The energy/wavelength of a neutron = diffraction pattern
Atomic constituents & positions in a material
The energy/wavelength of a neutron = energy lost/gained to material,
How does matter move?



Different instruments for different length scales

- ➢ **Imaging**
- ➢ **Reflectometry**
- ➢ **Small-angle neutron scattering**
- ➢ **Diffraction**

and different energy scales:

- ➢ **Spin Echo spectroscopy**
- ➢ **Backscattering Spectroscopy**
- ➢ **Time of flight**
- ➢ **Vibrational spectroscopy**

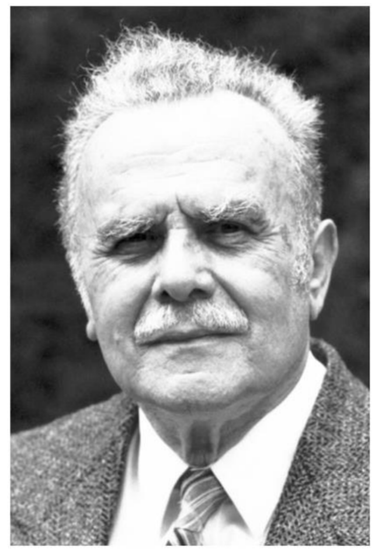


Photo from the Nobel Foundation archive.
Bertram N. Brockhouse
Prize share: 1/2

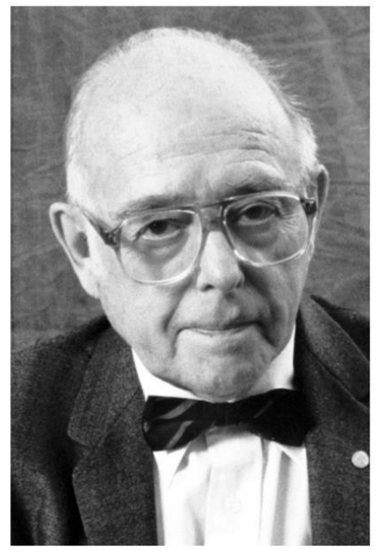


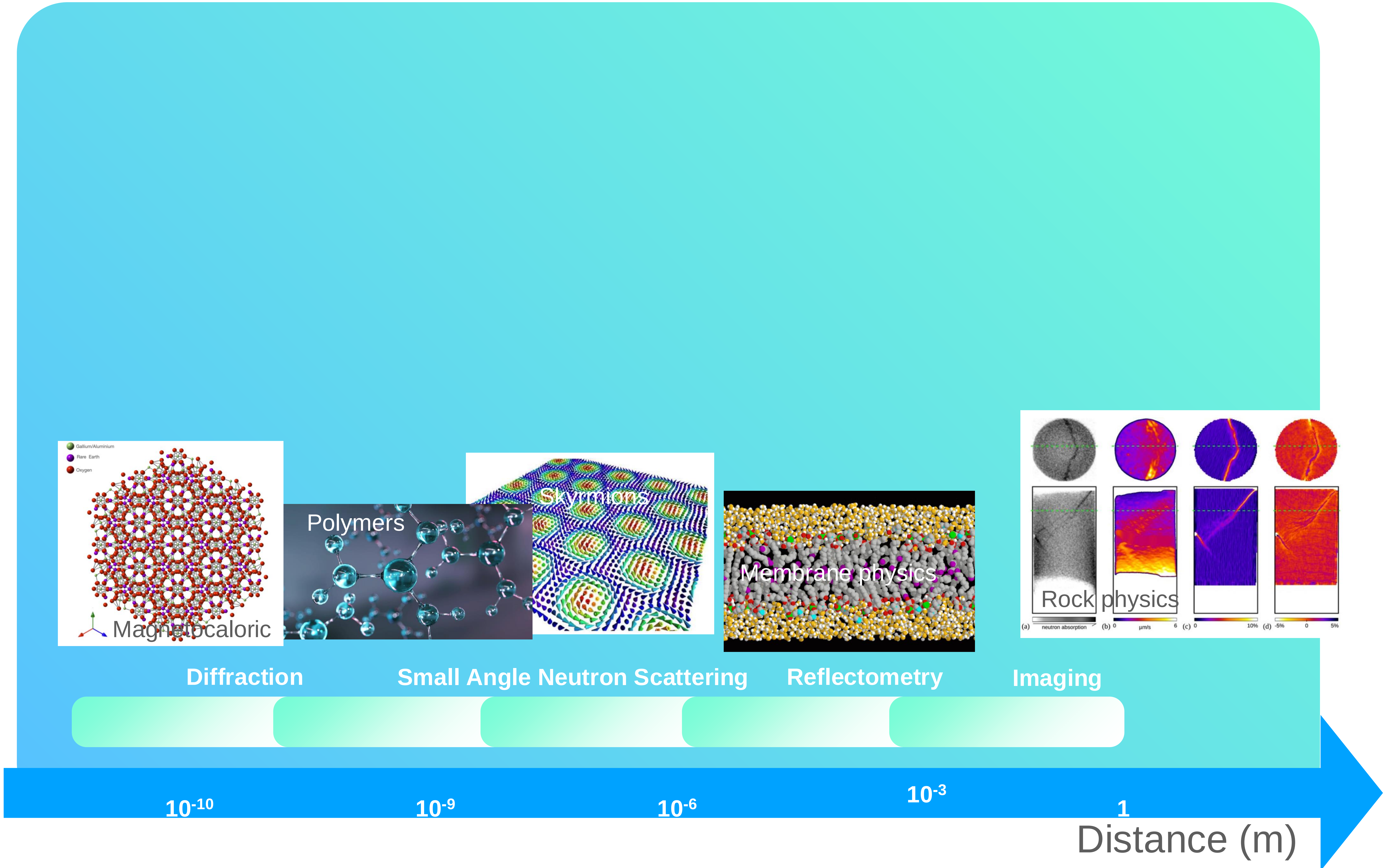
Photo from the Nobel Foundation archive.
Clifford G. Shull
Prize share: 1/2

The Nobel Prize in Physics 1994

“for pioneering contributions to the development of neutron scattering techniques for studies of condensed matter”

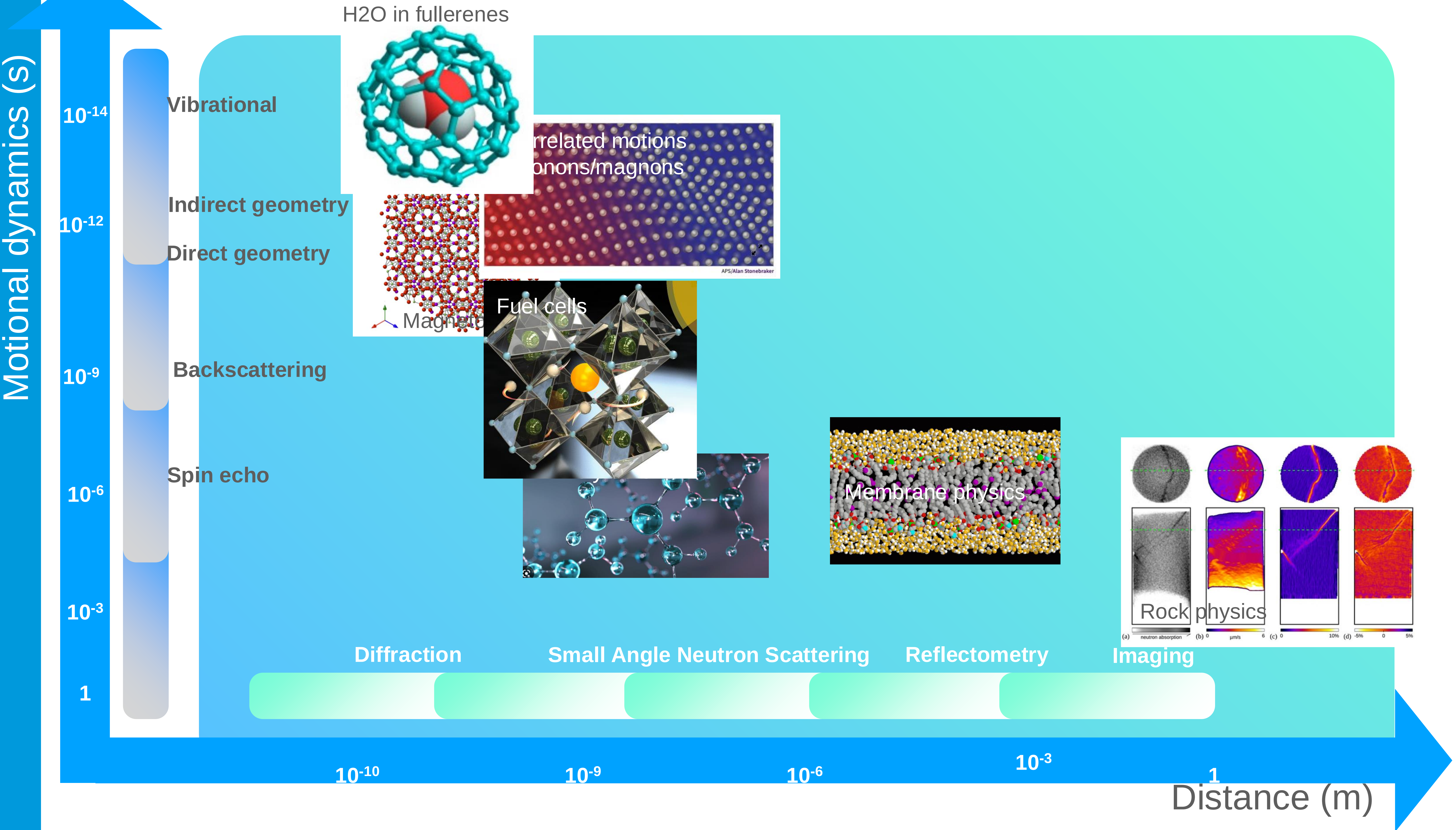
Spatial and time(energy) scale of materials = functionality

What can neutrons probe



Spatial and time(energy) scale of materials = functionality

What can neutrons probe



Some examples of magnetic structures, microstructures and dynamics

Functionality

EUROPEISKA UNIONEN
Europeiska regionala utvecklingsfonden

LUND UNIVERSITY

tillväxt verket

A. Backis, E. Blackburn , Wai Tung (Hal) Lee
3D magnetic polarimetry.
EPJ Web of Conferences 286, 05003 (2023)

Neutron imaging (ODIN)
Polarisation analysis

Science Case

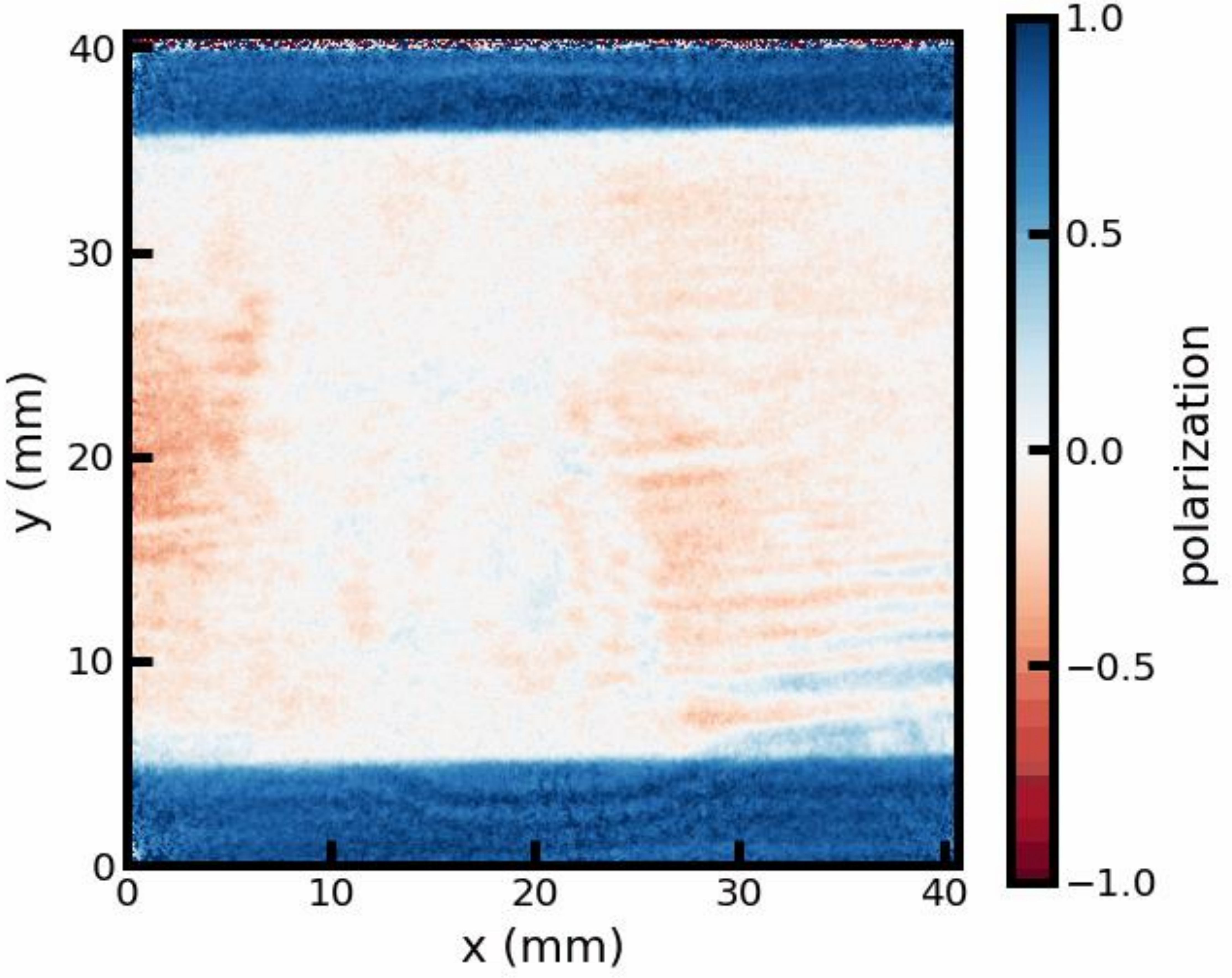
- Magnetic properties of ferromagnetic metal sheets
- Optimising the domain structure, reducing the formation of micro-vortex dots and broadening the size of the domain.

Application

- Magnetic cores of transformers or electric motors

Neutron scattering:

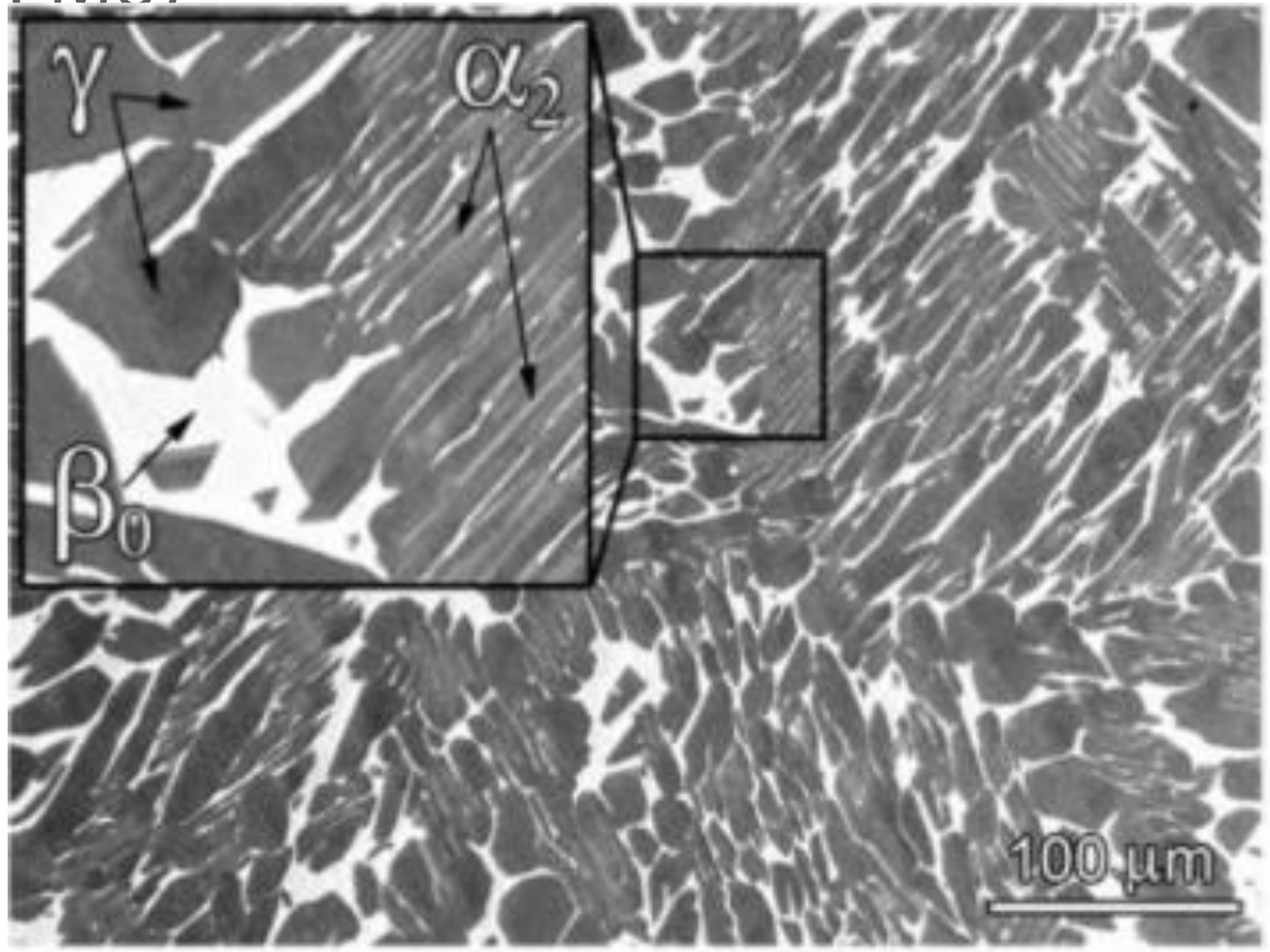
- Directly access large areas
- Depth profile
- Image domains in bulk materials

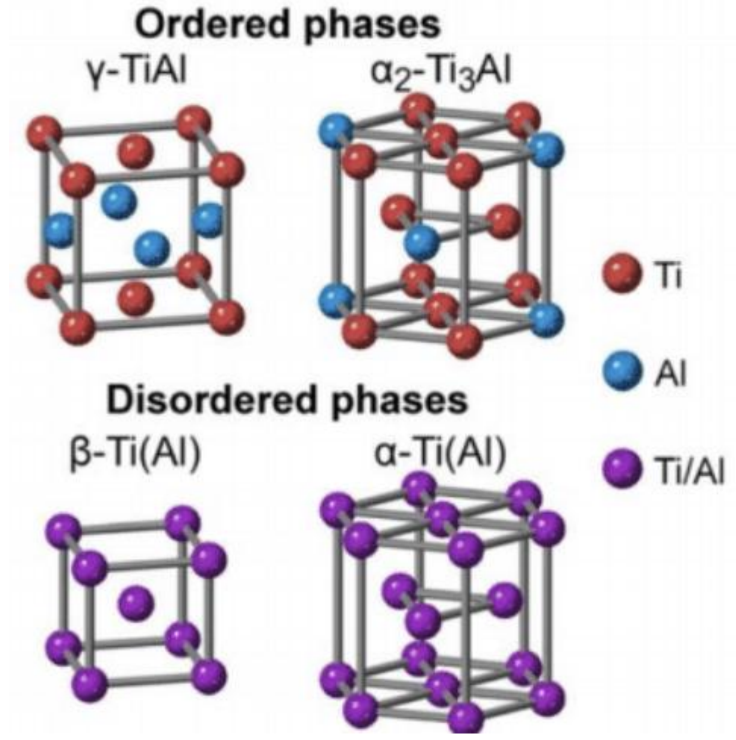


Domain formation in ferromagnetic sheet upon applied field – chemical uniformity or damage?.

Neutron engineering diffraction (BEER)

Sample: $TiAl_7Nb$ with various alloying elements (C, Mo)





UPPSALA UNIVERSITET

Science Case

Smart material: reversible changes in shape in response to a magnetic field. Optimise through alloying

Application

Rapid, controllable, and repeatable movement electromagnetic variables: piezoelectrics, magnetostrictives or magnetic actuators.

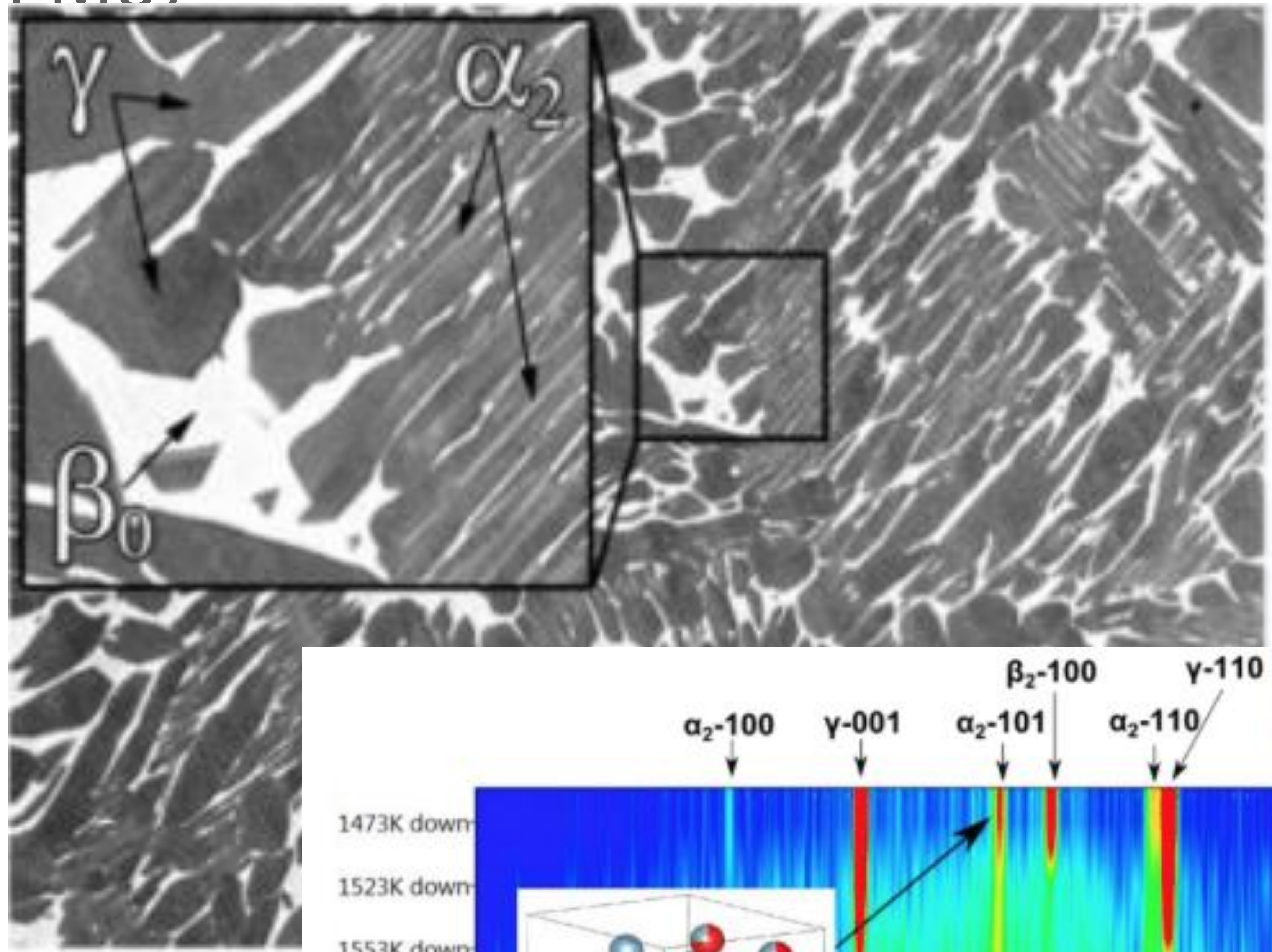
Beran, et al.,Intermetallics , 54 (2014) 28
Beran, et al., J. Mech. Phys. Solids, 95 (2016) 647

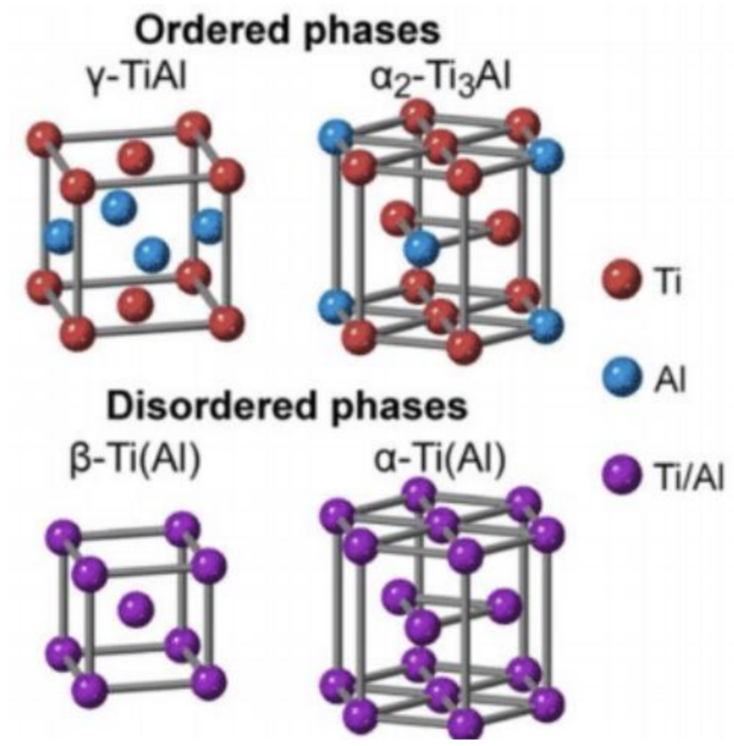
Some examples of magnetic structures, microstructures and dynamics

Neutron engineering diffraction (BEER)

Sample: $TiAl_7Nb$ with various alloying elements (C, Mo)

UPPSALA UNIVERSITET





Science Case

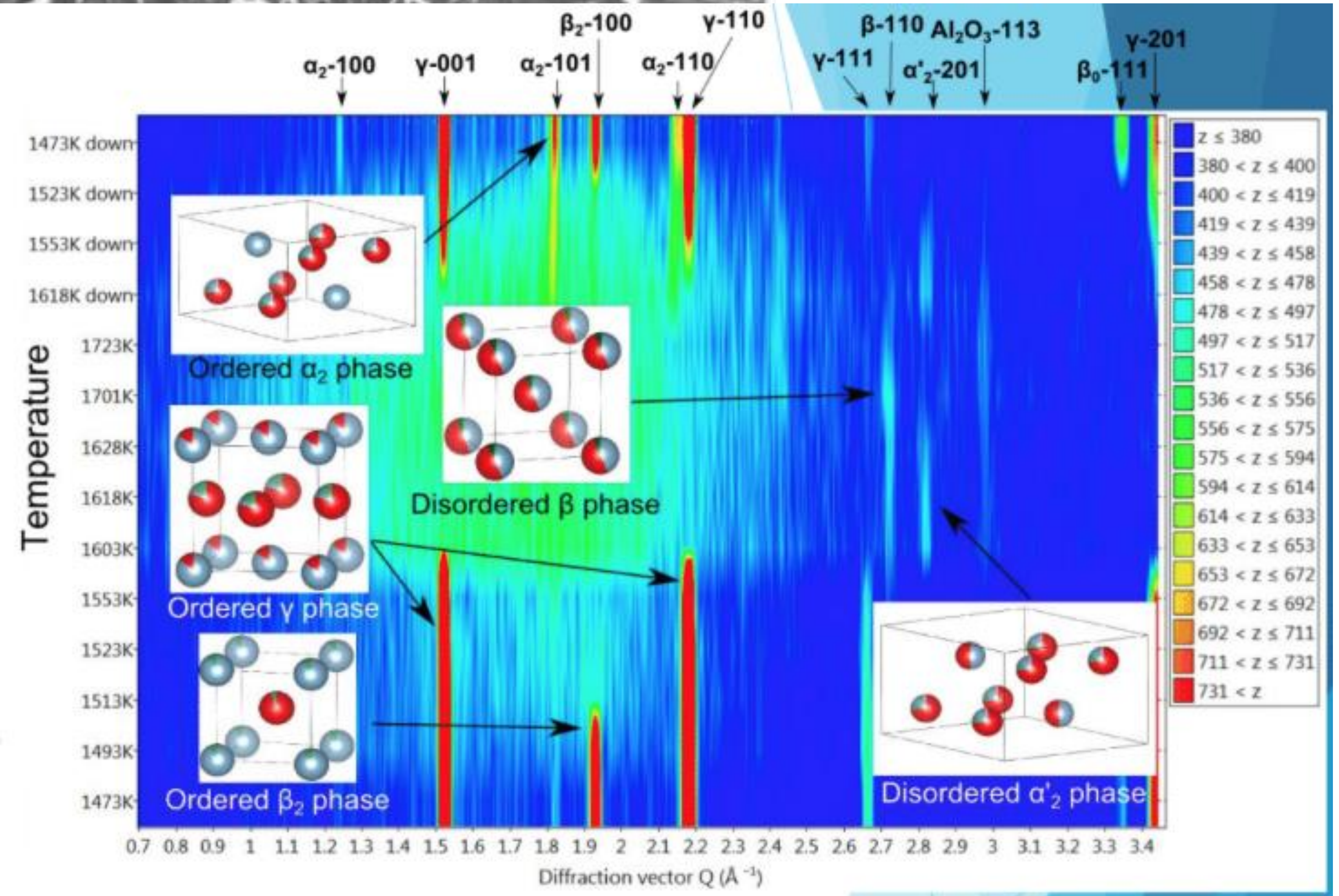
Smart material: reversible changes in shape in response to a magnetic field. Optimise through alloying

Application

Rapid, controllable, and repeatable movement electromagnetic variables: piezoelectrics, magnetostrictives or magnetic actuators.

Neutron scattering

- Structural evaluation of the influence of alloying on the phase diagram
- Radiation depth for large components.



Diffraction pattern colour map of Ti46Al7Nb2Mo
Time for 1 pattern: 20 minutes

Beran, et al.,Intermetallics , 54 (2014) 28
Beran, et al., J. Mech. Phys. Solids, 95 (2016) 647

Some examples of magnetic structures, microstructures and dynamics

Magnetic excitations (Inelastic neutron scattering) (CSPEC, BIFROST, T-REX)

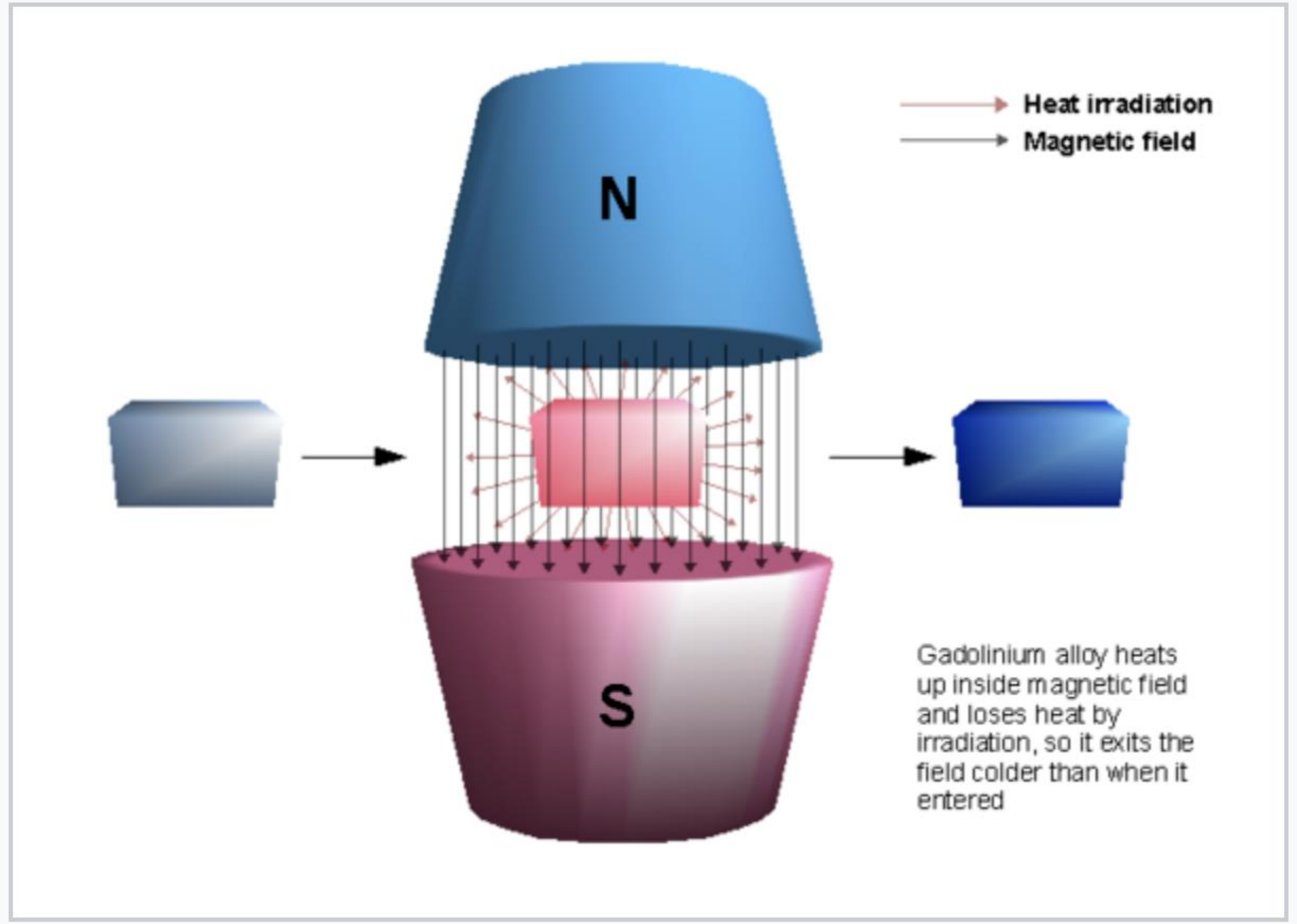
Enhanced magnetocaloric effect in frustrated magnets

M. E. Zhitomirsky
Phys. Rev. B **67**, 104421 – Published 21 March 2003

Garnet lattice $A_3B_5O_{12}$: A = RE^{3+}, B = post-transition metal.

Science Case

Understanding and optimising dynamics of materials optimised for heat transfer



Gadolinium alloy heats up inside the magnetic field and loses thermal energy to the environment, so it exits the field and becomes cooler than when it entered.

Application

Magnetocaloric materials for innovative cooling applications

Some examples of magnetic structures, microstructures and dynamics

Magnetic excitations (Inelastic neutron scattering) (CSPEC, BIFROST, T-REX)

Enhanced magnetocaloric effect in frustrated magnets

M. E. Zhitomirsky
Phys. Rev. B **67**, 104421 – Published 21 March 2003

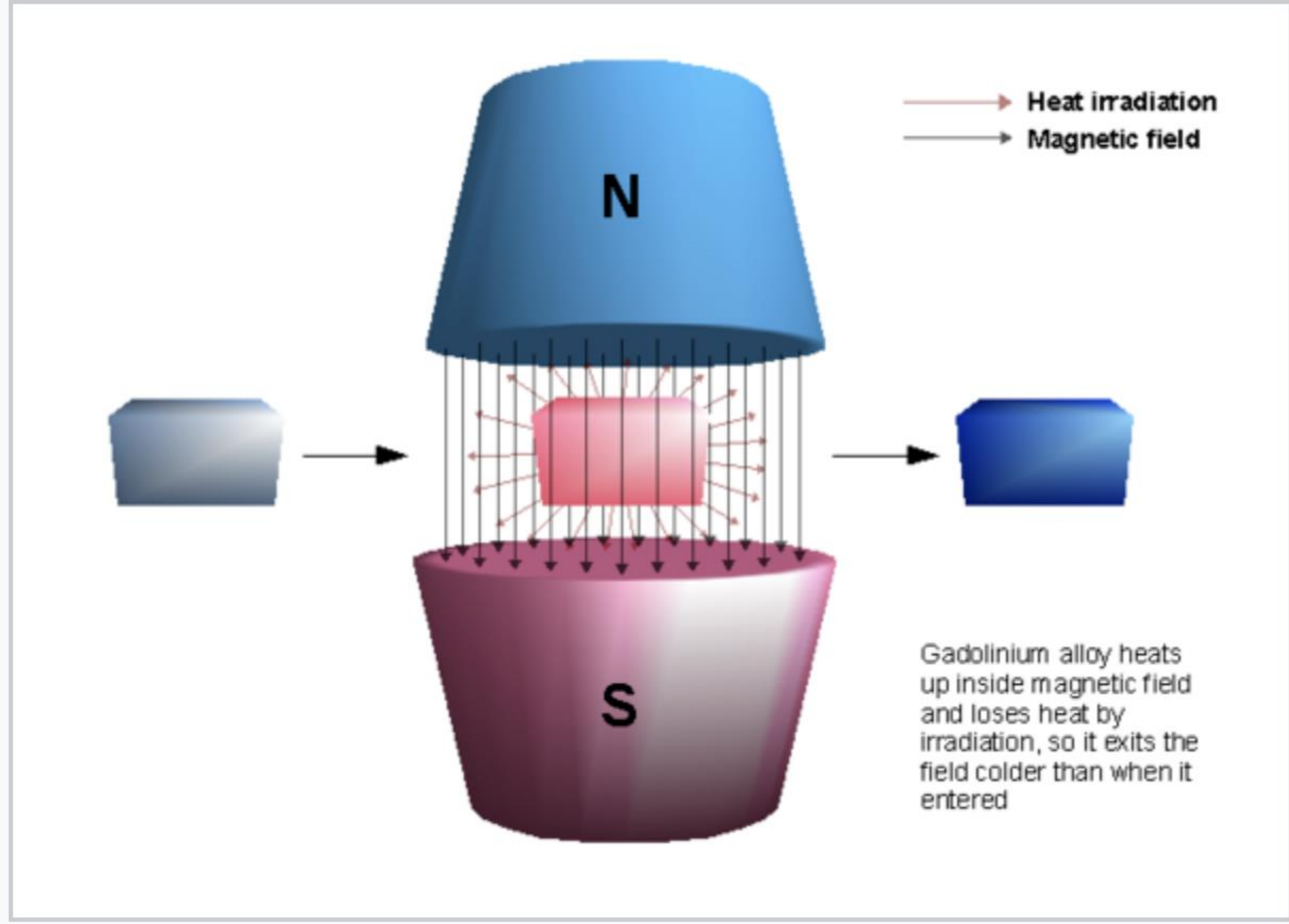
Science Case

Understanding and optimising dynamics of materials optimised for heat transfer

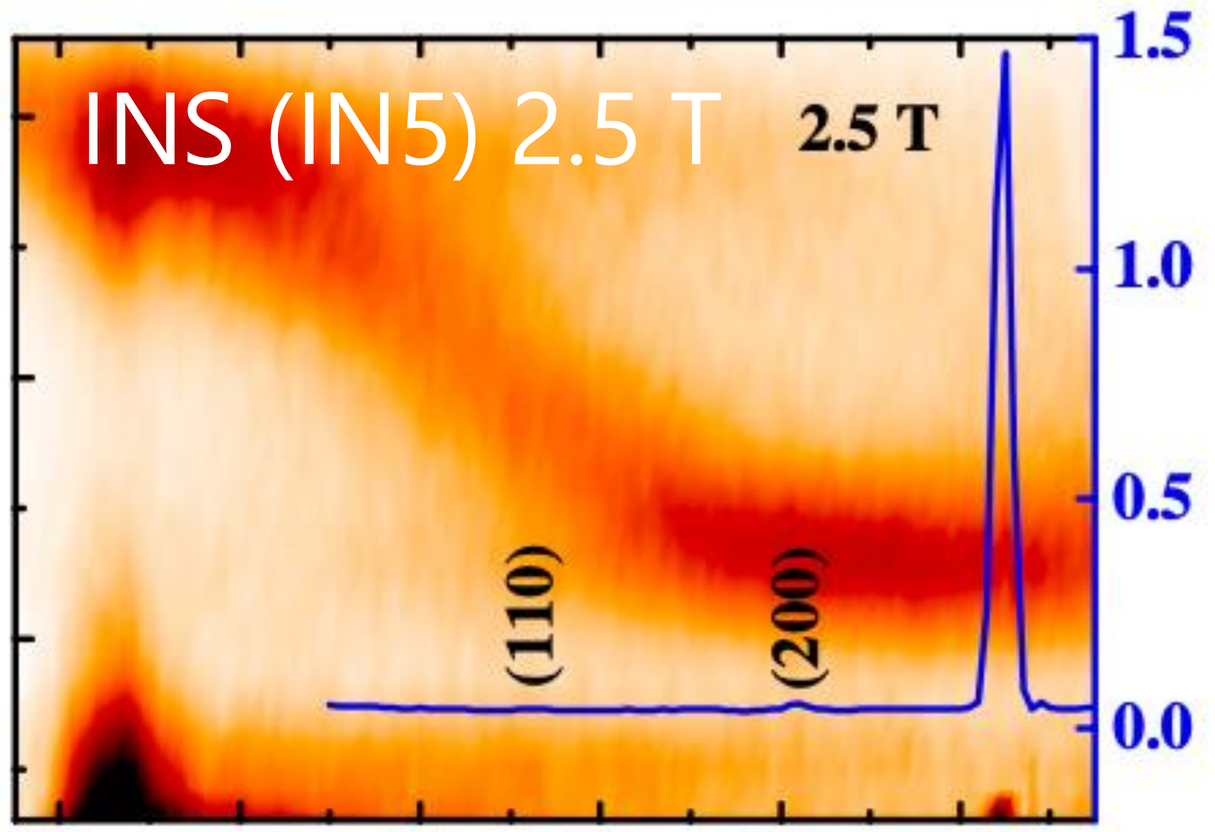
Application

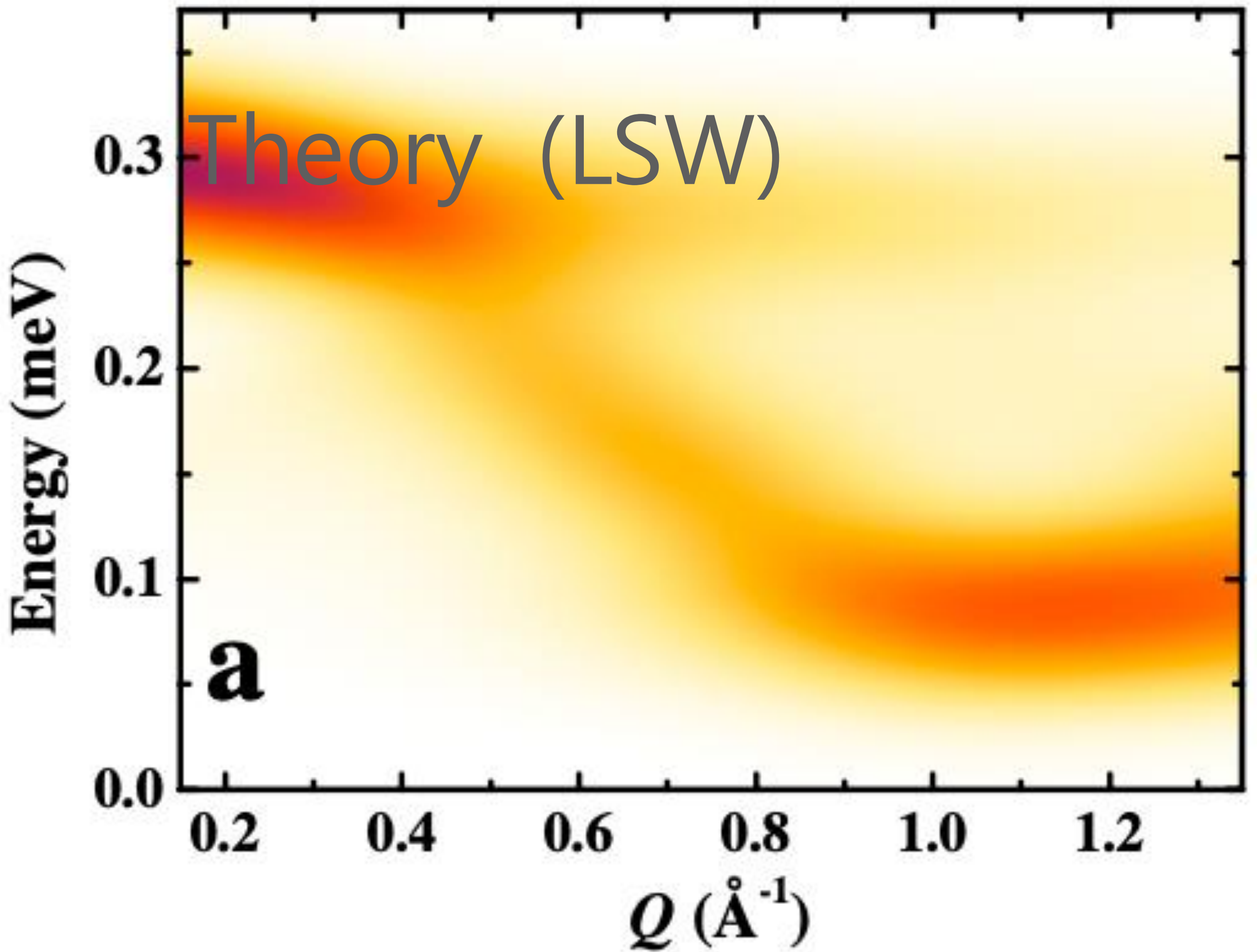
Magnetocaloric materials for innovative cooling applications

Garnet lattice $A_3B_5O_{12}$: A = RE^{3+}, B = post-transition metal.



Gadolinium alloy heats up inside the magnetic field and loses thermal energy to the environment, so it exits the field and becomes cooler than when it entered.





Some examples of magnetic structures, microstructures and dynamics

Magnetic excitations (Inelastic neutron scattering) (CSPEC, BIFROST, T-REX)

Garnet lattice $A_3B_5O_{12}$: A = RE^{3+}, B = post-transition metal.

Enhanced magnetocaloric effect in frustrated ma

M. E. Zhitomirsky
Phys. Rev. B **67**, 104421 – Published 21 March 2003

Dispersionless Spin Waves and Underlying Field-Induced Magnetic Order in Gadolinium Gallium Garnet

N. d'Ambrumenil, O. A. Petrenko, H. Mutka, and P. P. Deen
Phys. Rev. Lett. **114**, 227203 – Published 2 June 2015

Science Case

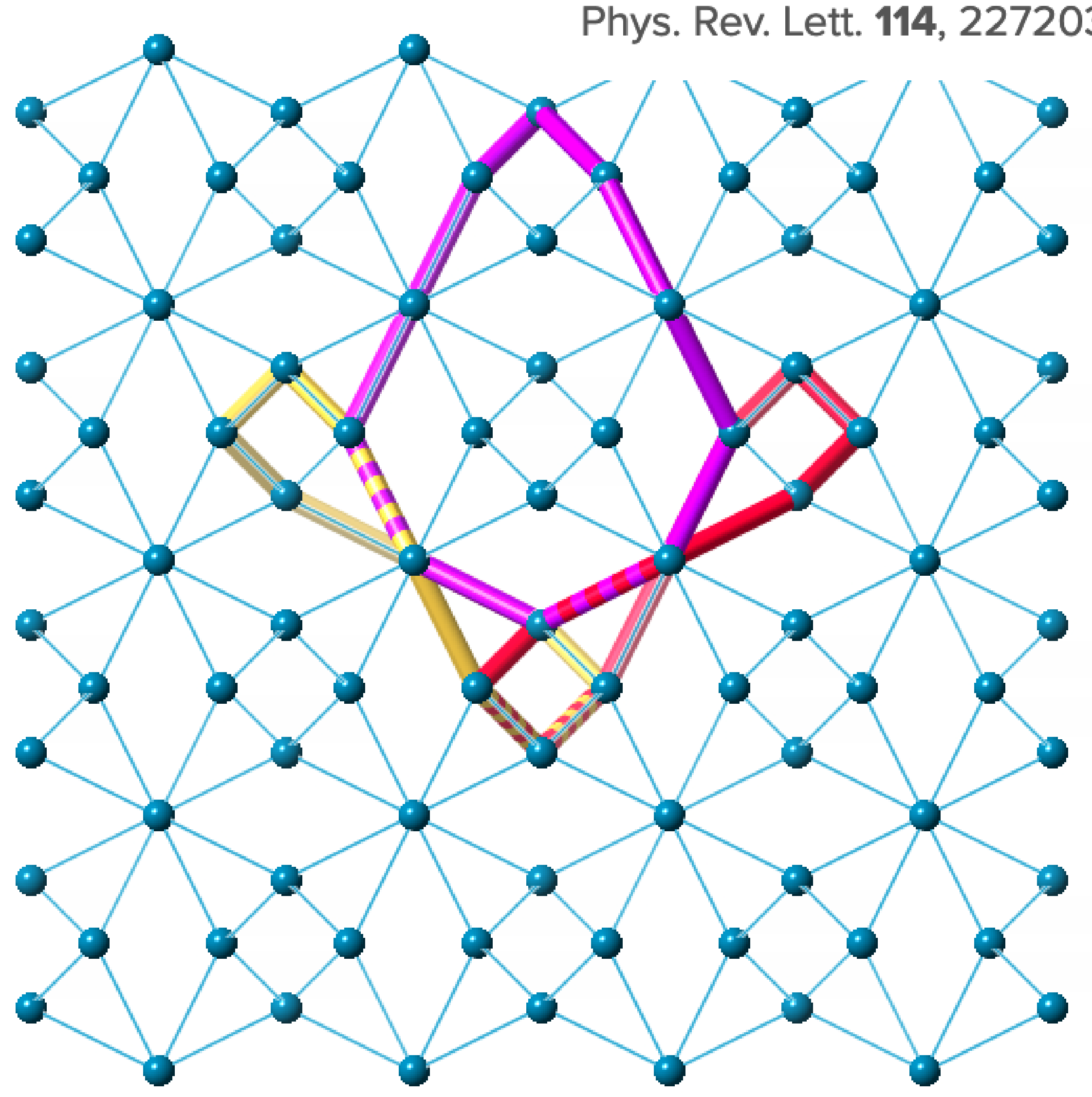
Understanding and optimising dynamics of materials optimised for heat transfer

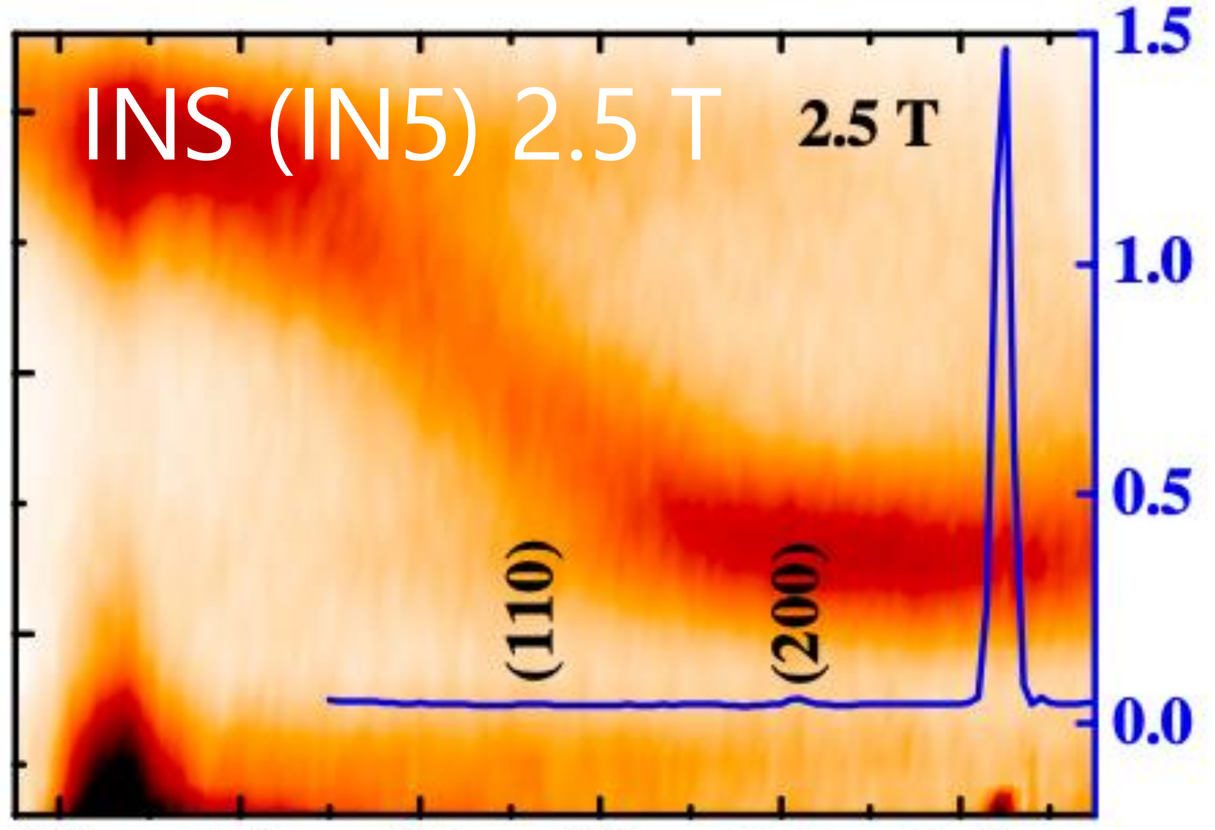
Application

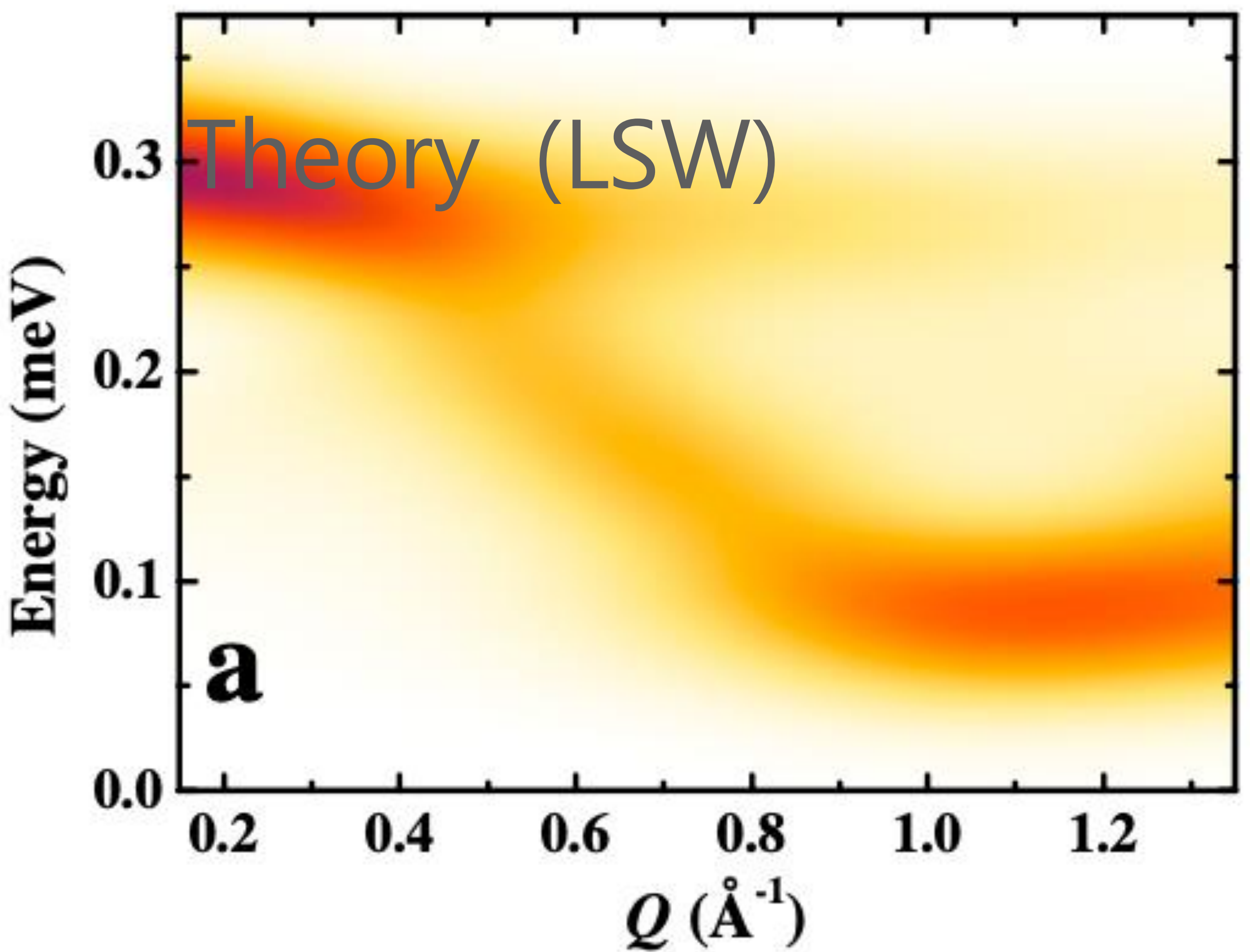
Magnetocaloric materials for innovative cooling applications

Benefit

- High energy resolution of magnetic excitations - dynamics.
- Probe of quasipartile excitations & magnons & phonons.
- Theory and experiment closely aligned.

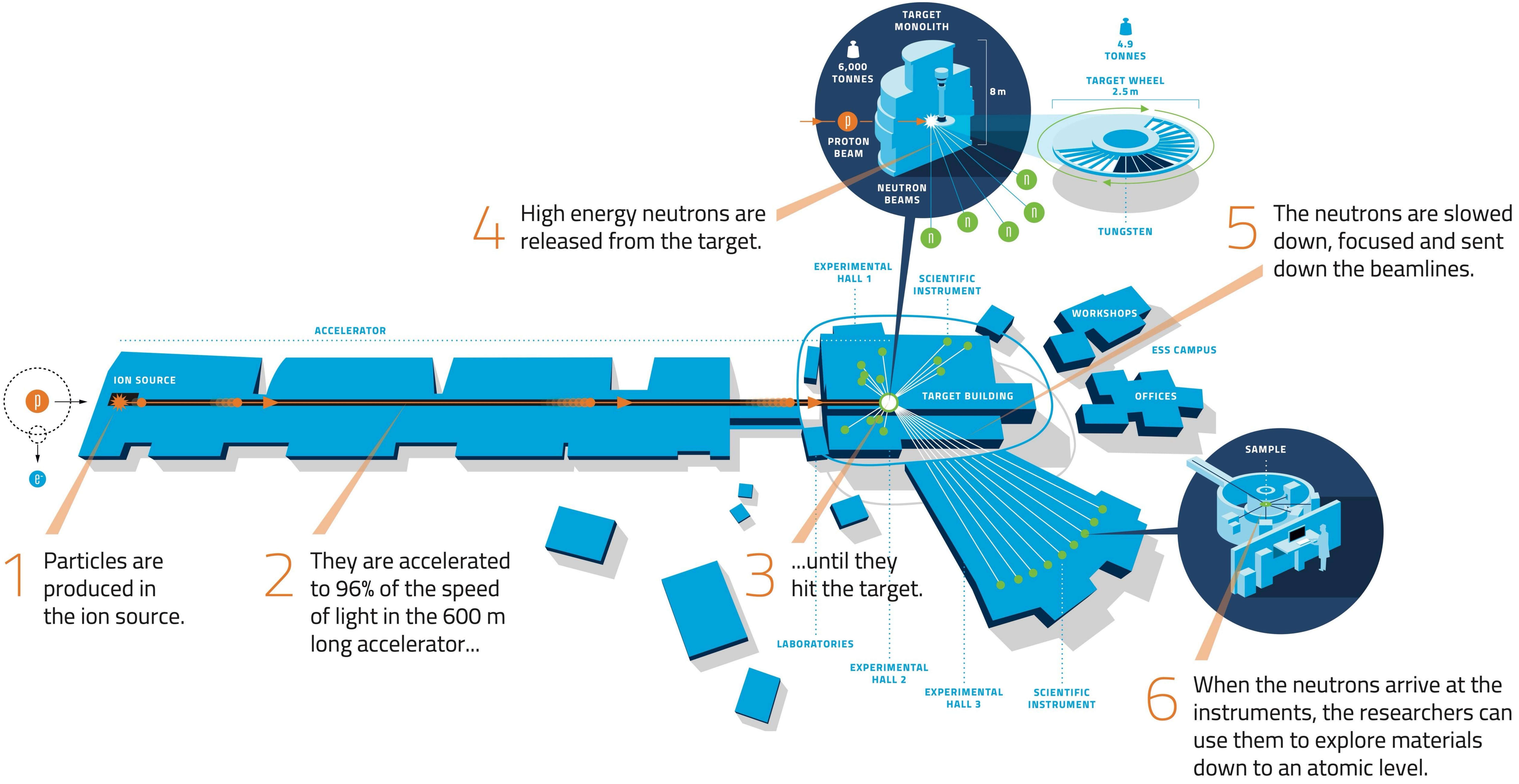






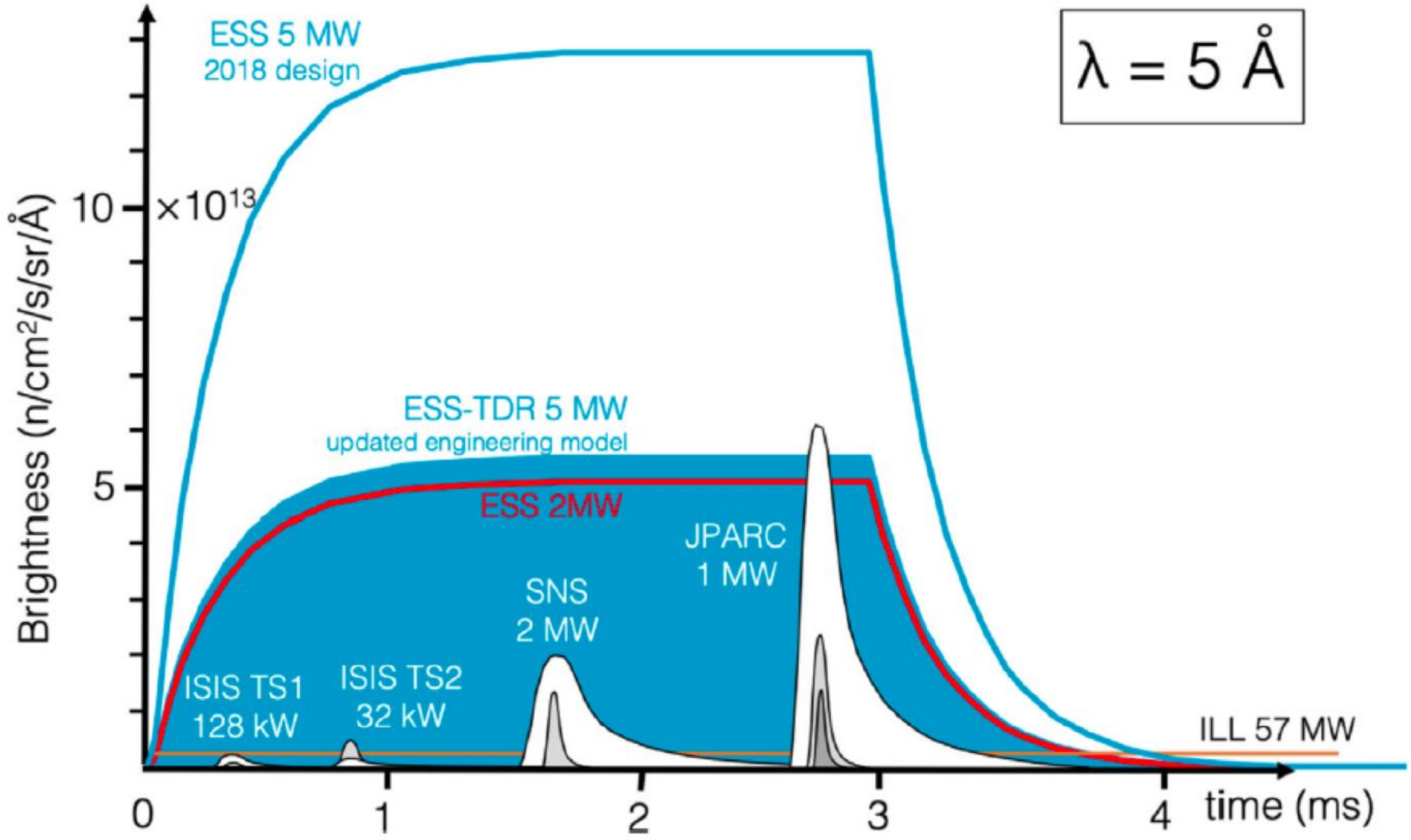
LSW: Spin waves localised on 10 site rings

How ESS works: material information from neutron scattering instruments



European Spallation Source

Long pulse of (mainly) cold neutrons



Overview of ESS instruments

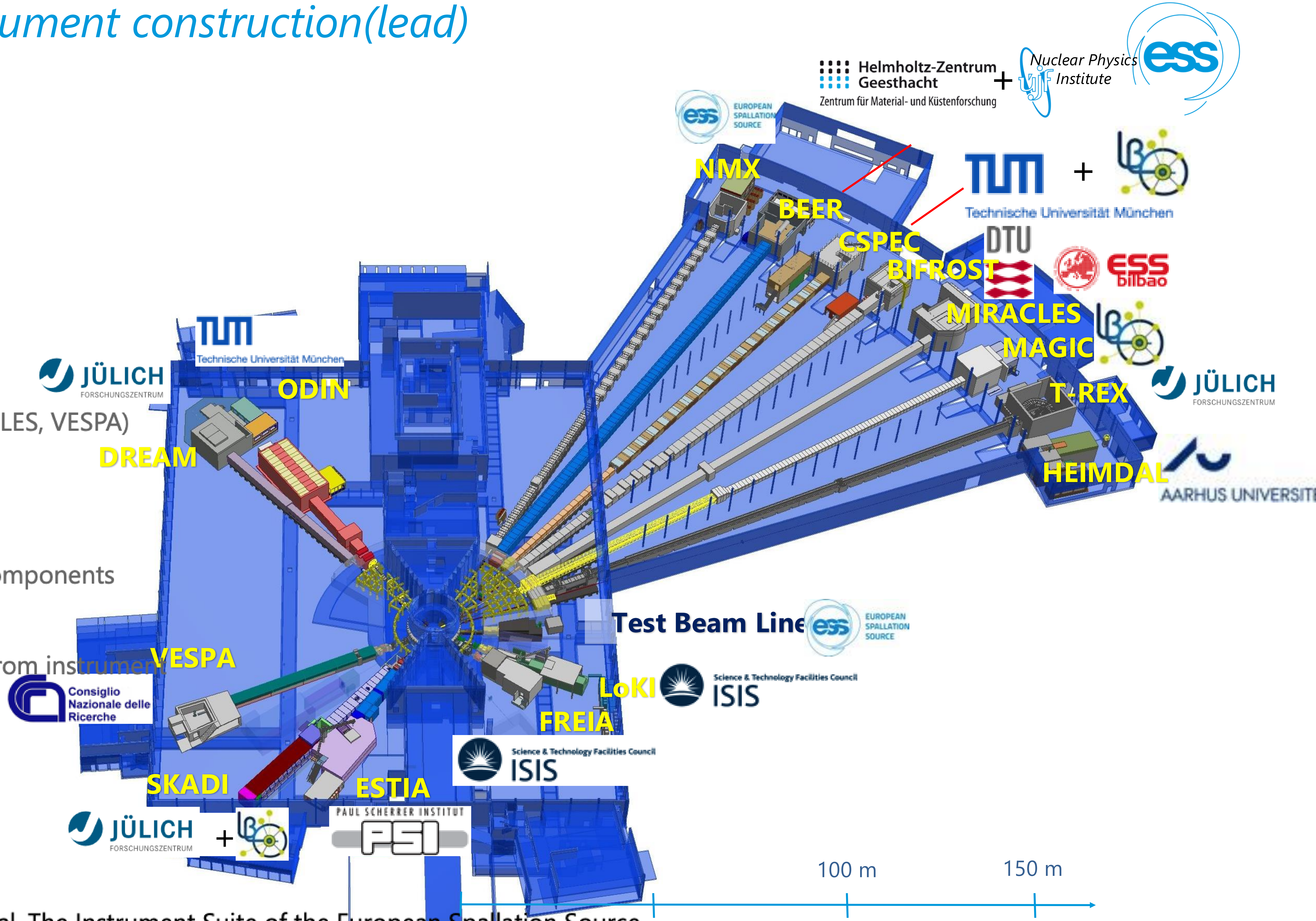
ESS partners for instrument construction(lead)

15 instruments + Test Beamline

Diffractometers (DREAM, MAGiC, HEIMDAL)
SANS (LoKI, SKADI)
Reflectometers (Estia, FREIA)
Imaging (ODIN)
Engineering Diffraction (BEER)
Macromolecular Crystallography (NMX)
Spectrometers (CSPEC, T-REX, BIFROST, MIRACLES, VESPA)

Novel detector technologies and geometries
Complex pulse-shaping

Shared neutron bunker – common space for components
Common timing system for facility
Single controls infrastructure (EPICS)
Control and data recording running remotely from instrument



Andersen, K. H.; Argyriou, D. N.; Jackson, A. J. et al. The Instrument Suite of the European Spallation Source. *Nuclear Instruments and Methods in Physics Research Section A:* **2020**, *957*, 163402. https://doi.org/10.1016/j.nima.2020.163402.

ESS

General Overview

Neutrons – a quick background

ESS: **Ion source**

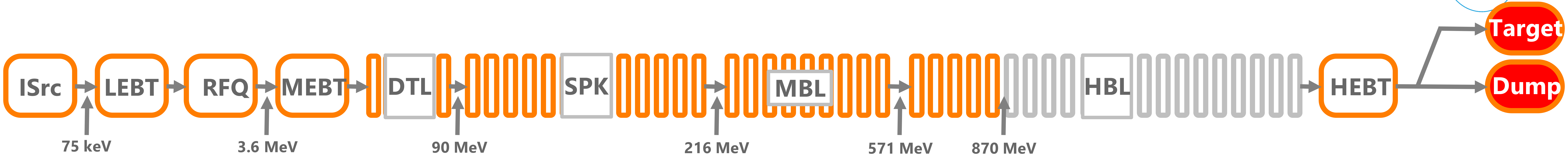
Accelerator

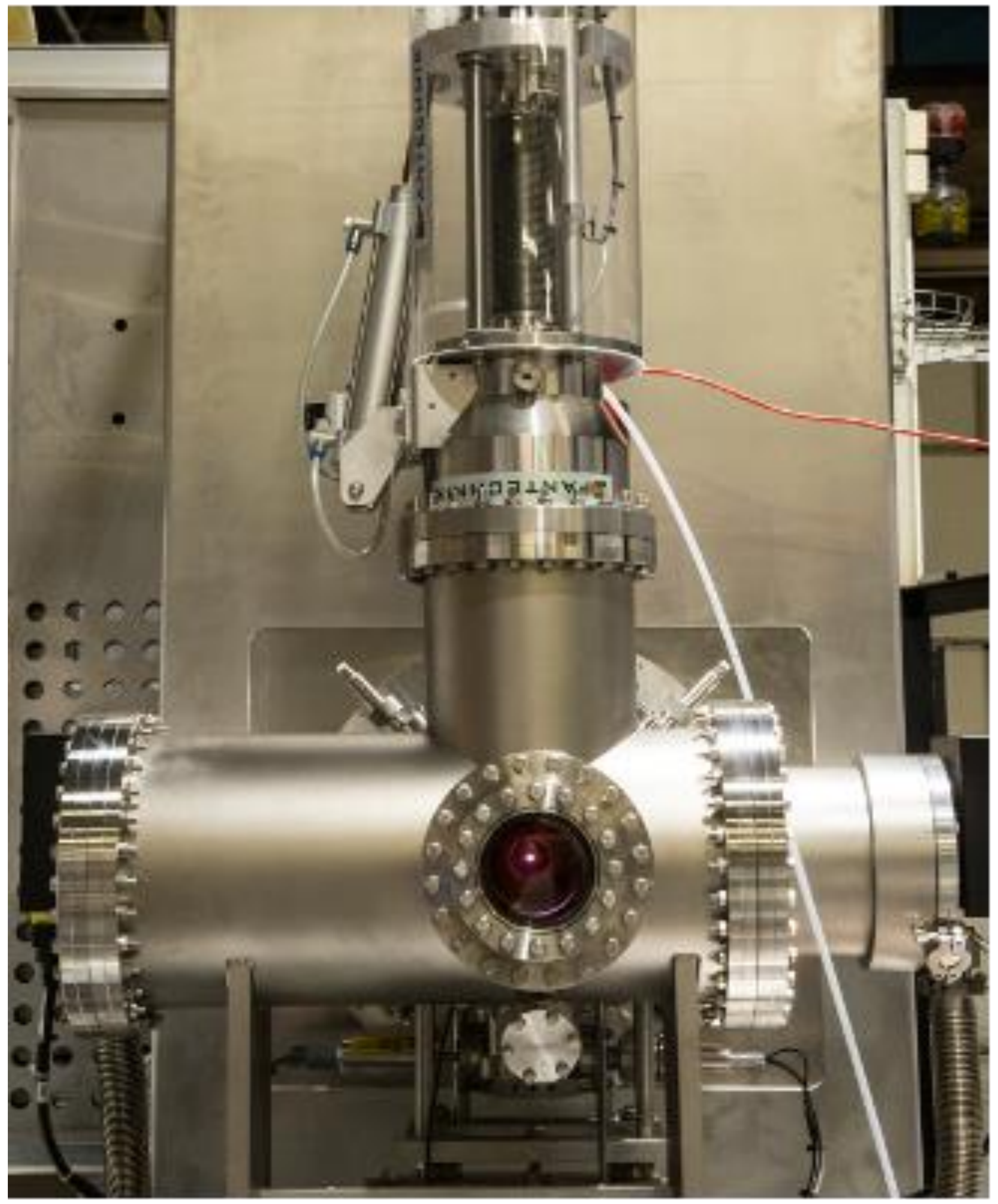
Target

Moderator

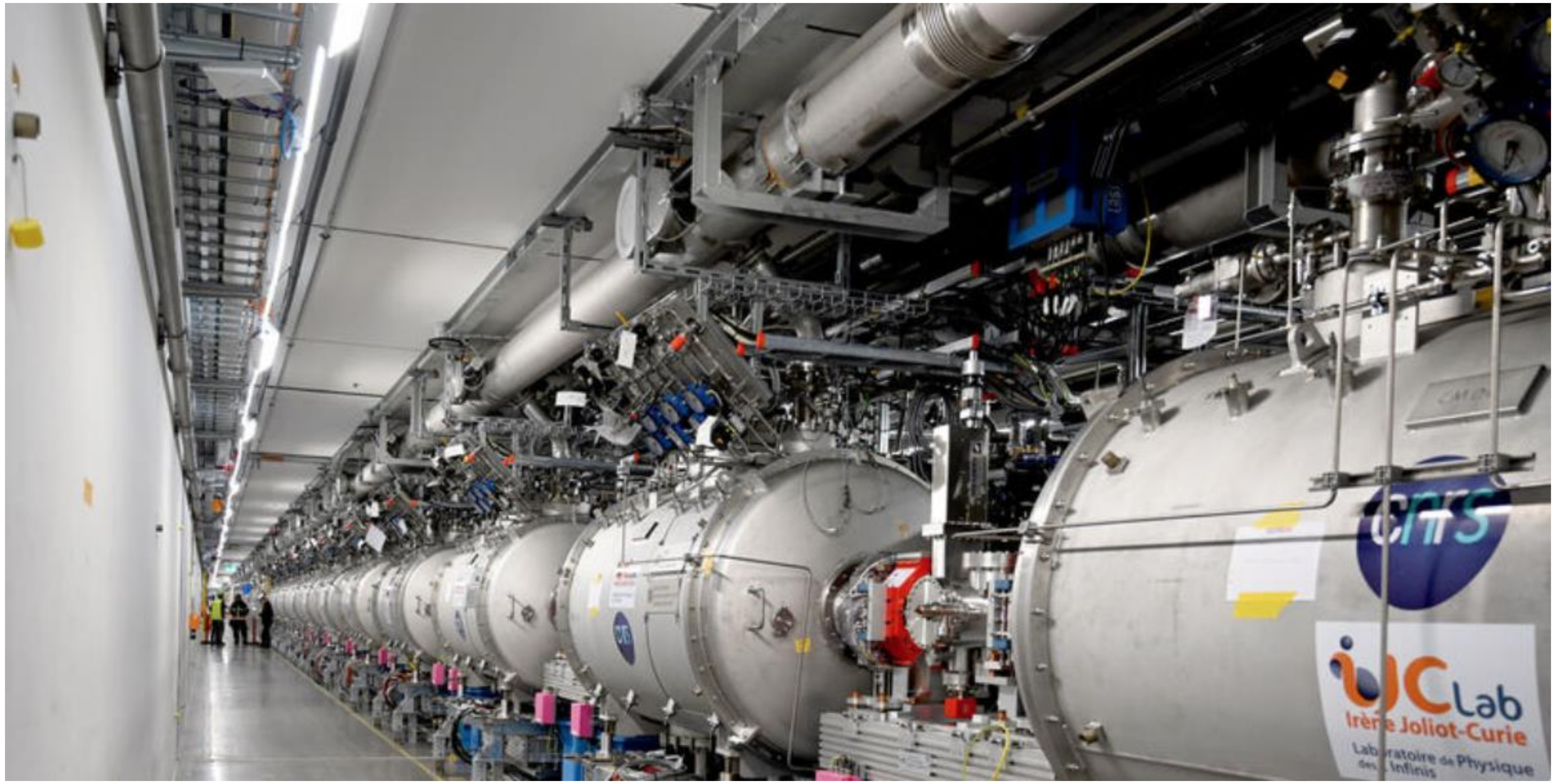
Some Instruments

Ion source (2017) & Accelerator (2025)





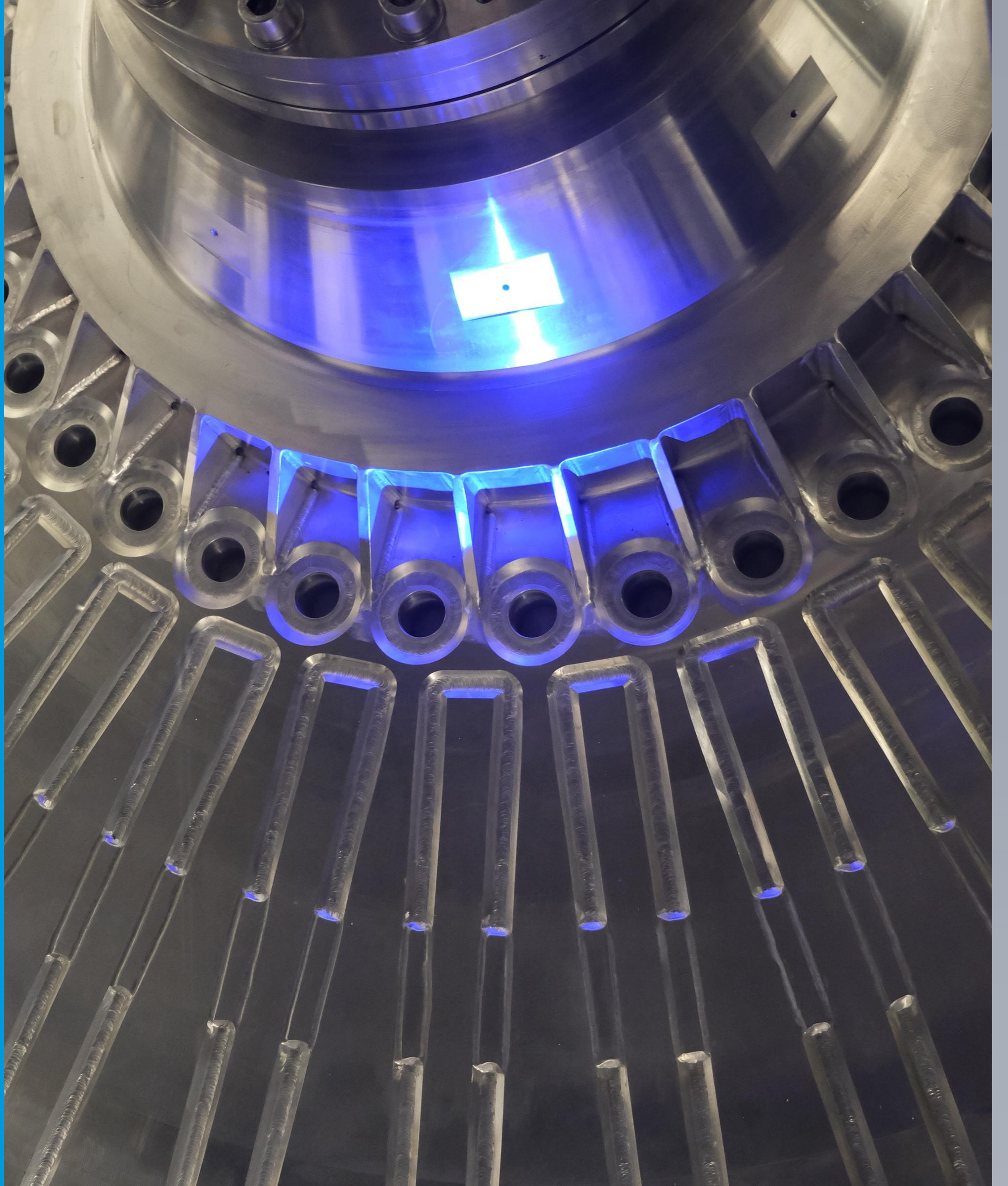
View of white, glowing ball of proton plasma in the Ion Source.



Cryo Systems for superconducting linac components
Spoke Cavities installed

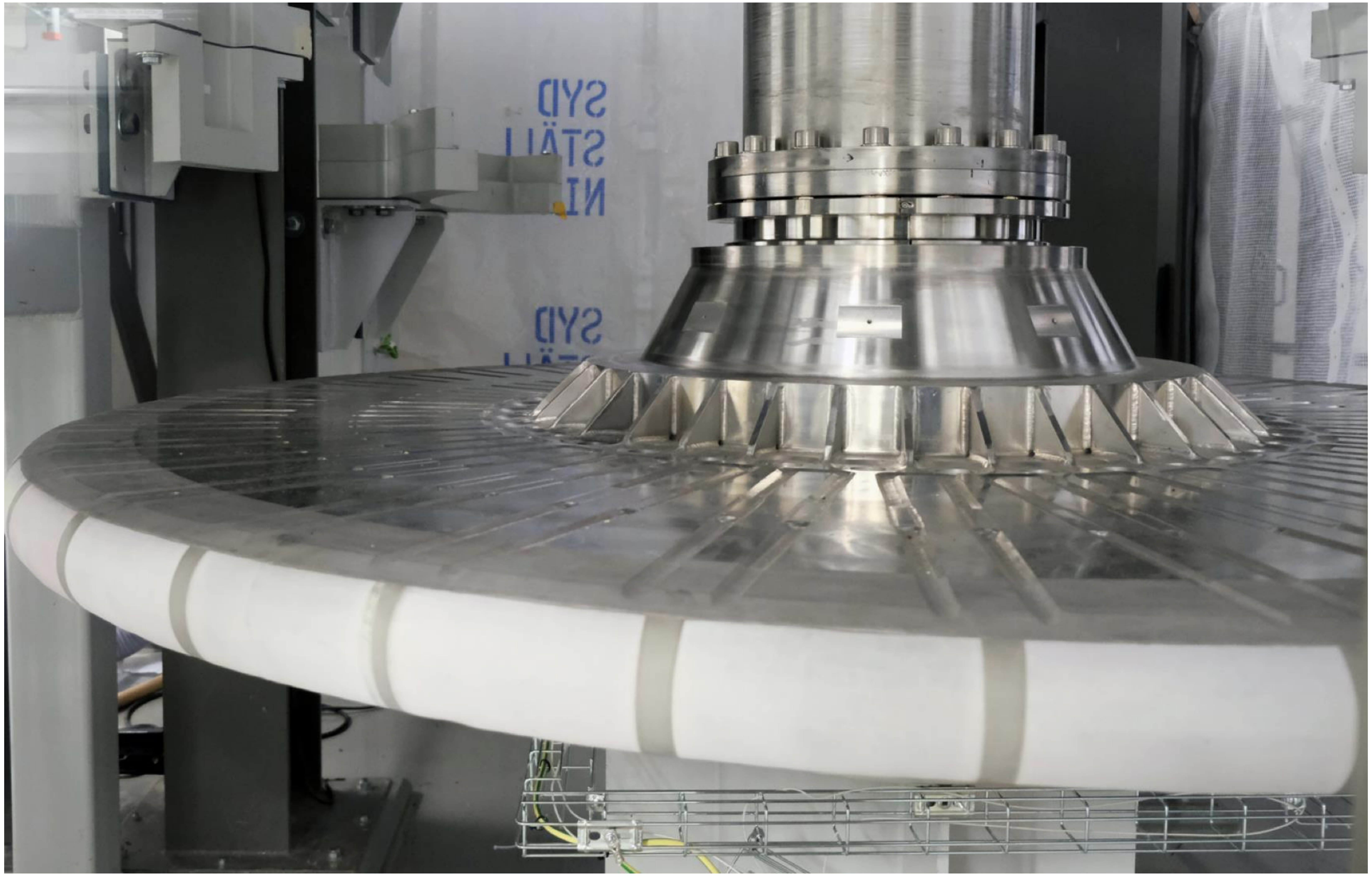
ESS

General Overview
Neutrons – a quick background
ESS: Ion source
- Accelerator
- **Target & moderator**
- Some Instruments



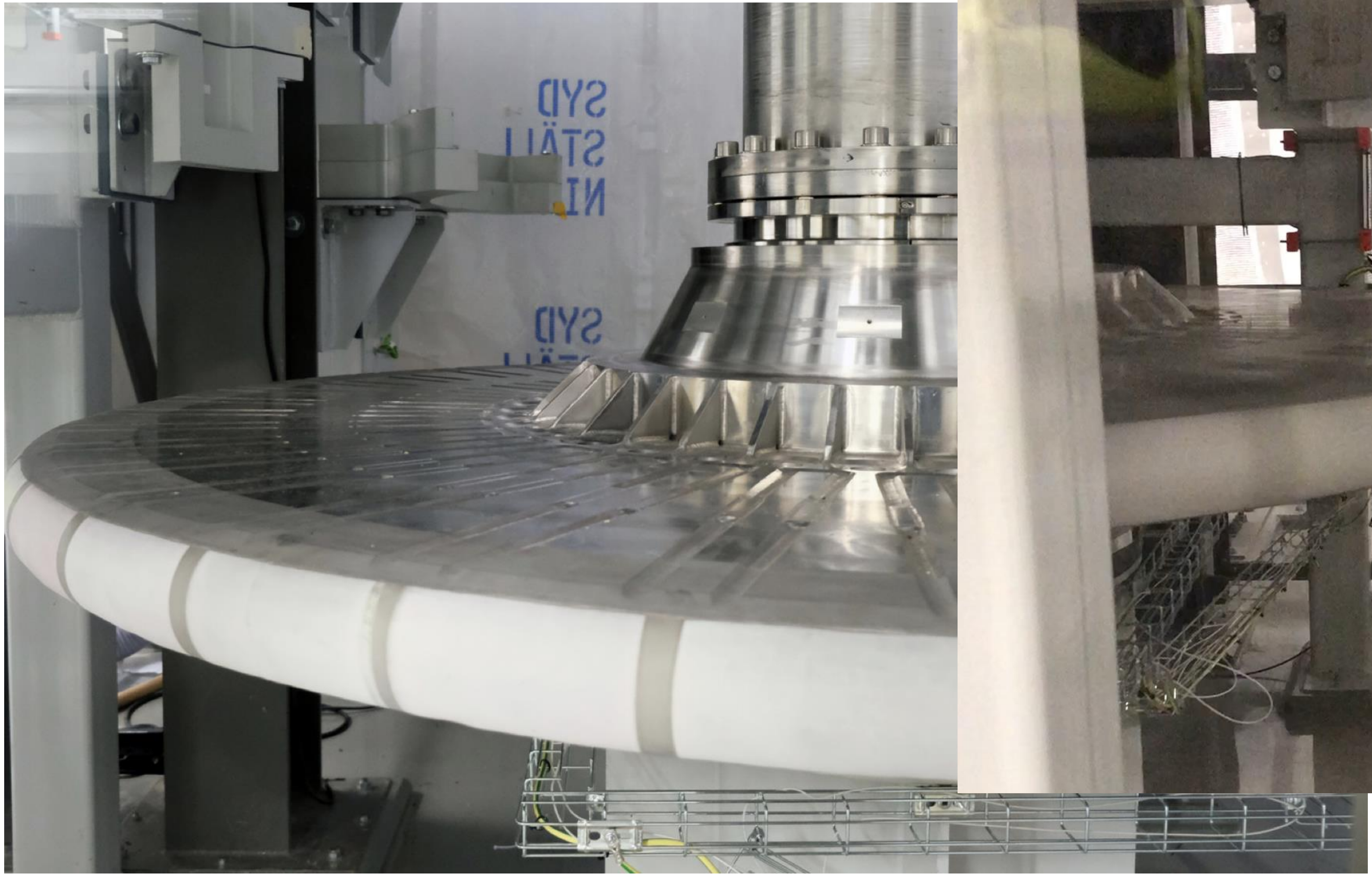
Target

Tungsten rotating target (23 RPM)



Target

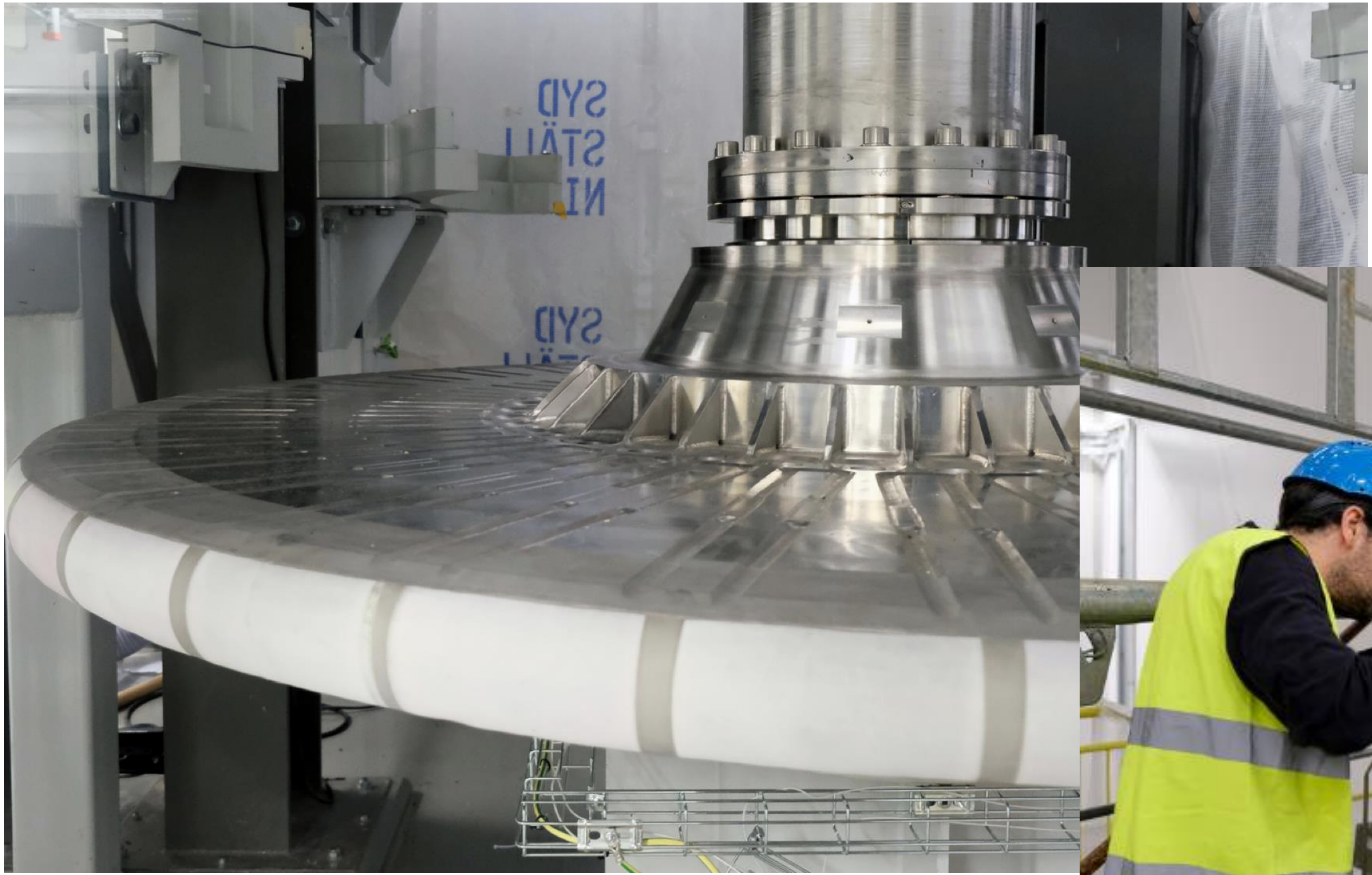
Tungsten rotating target (23 RPM)
1000 hours of testing



Target

Tungsten rotating target (23 RPM)

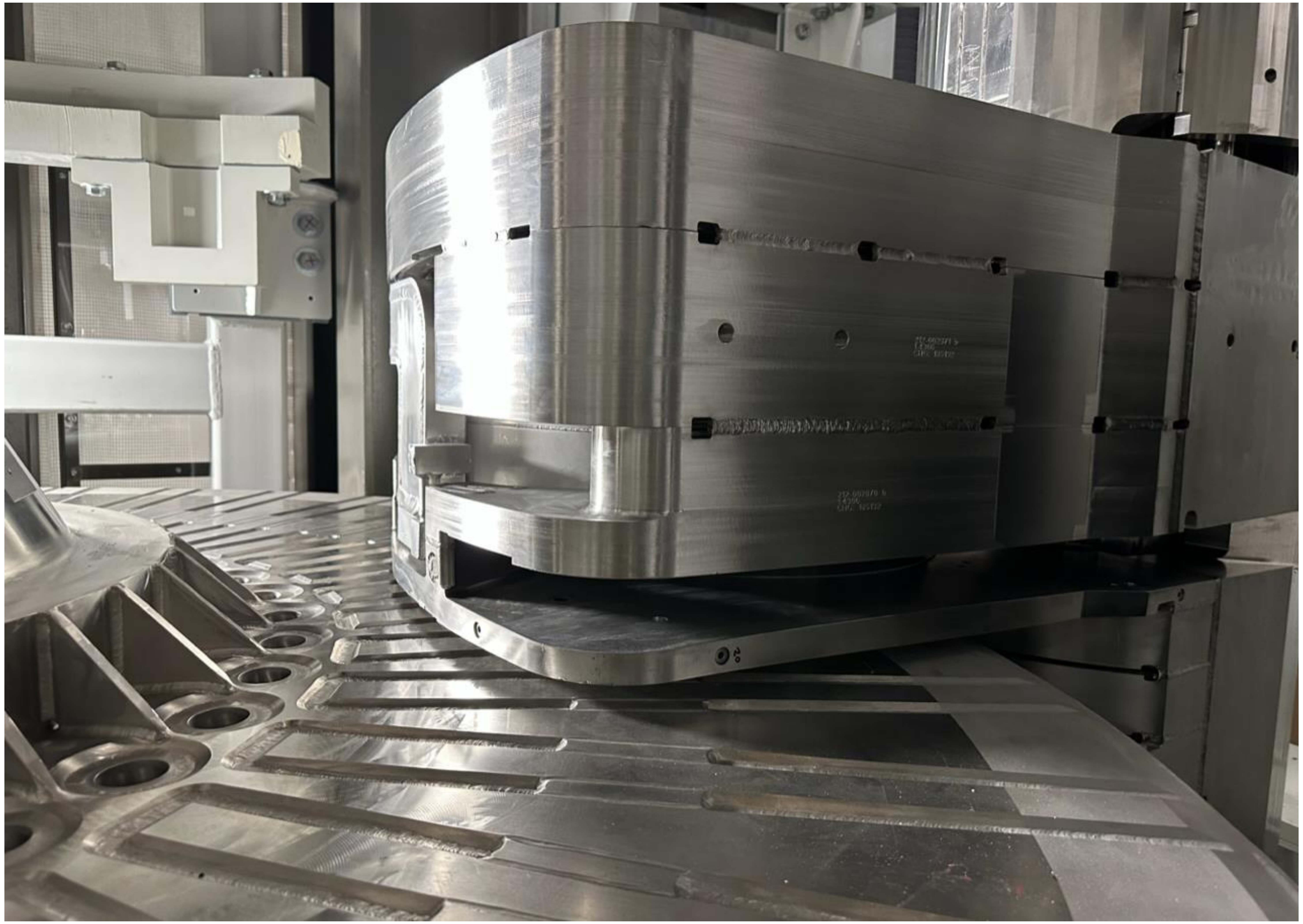
Target cooling (Helium 3kg/s), in = 20 - 55^{o}C, out = 180 - 273^{o}C



Target in place

Building up the target and Beam extraction

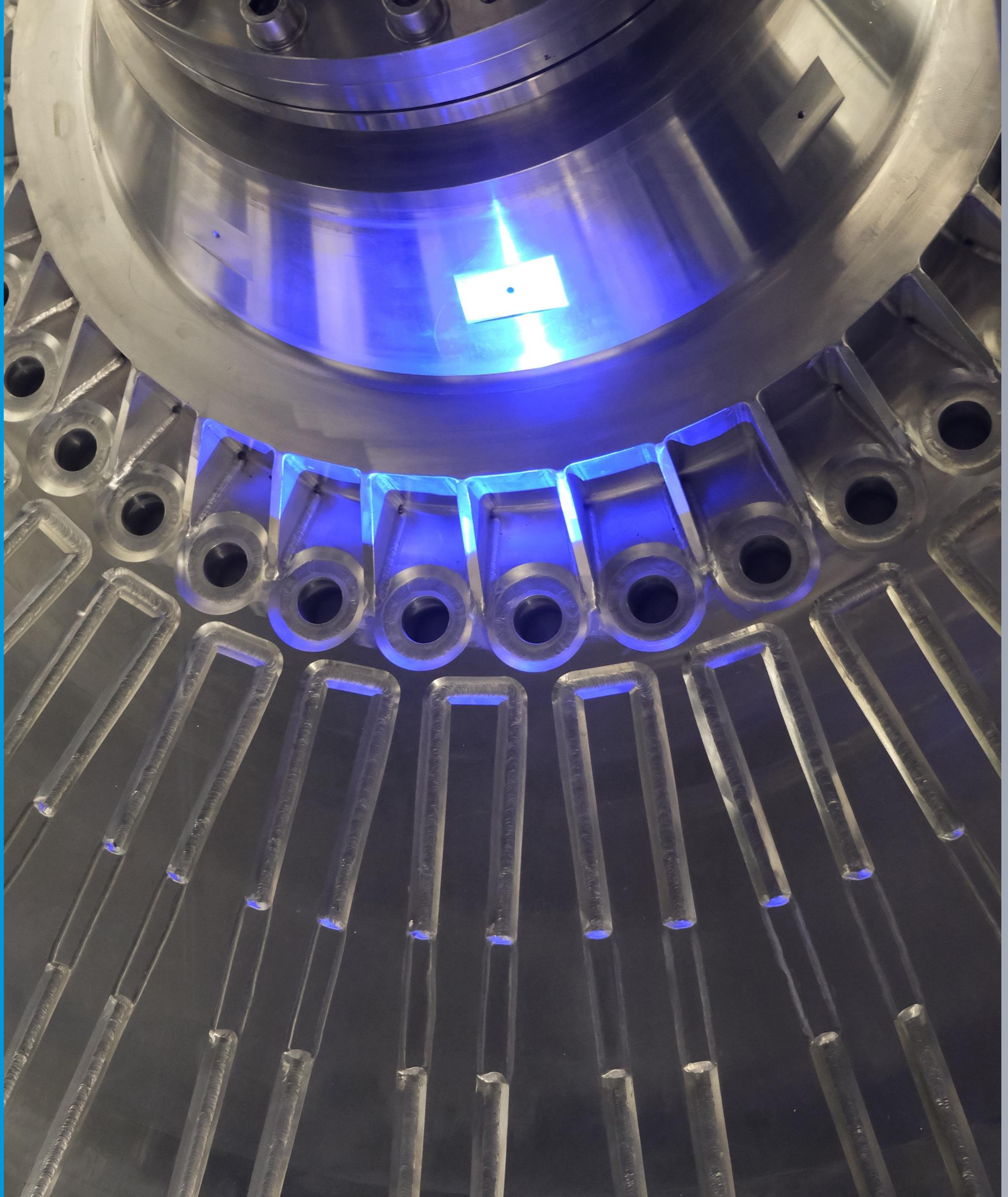
Moderator/reflector plug



Shielding completed

ESS

General Overview
Neutrons – a quick background
ESS: Ion source
    Accelerator
    Target & moderator
    Some Instruments



ODIN: Imaging instrument : ready 2025

Technische Universität München

PAUL SCHERRER INSTITUT

Instrument cave

ODIN: Imaging instrument : ready 2025

Experimental cave

DREAM: Bi-spectral general purpose powder diffractometer : ready 2025

View inside cave
Detectors and detector support

BIFROST: Extreme environment cold spectrometer; ready 2025

Neutron guide support and beam optimisation (choppers)

BIFROST: Extreme environment cold spectrometer; ready 2025

Inside in strument cave with some sample environment.

2026/2027, ESS will be a user facility

- Researchers who need neutron beams for their experiments.
- From universities, institutes, industry. 2026: Industrial liaison scientist
- We provide tools & support (+Data analysis + modelling); they bring their projects and perform the experiments.
- 2000-3000 visiting users/year. A stay can be days or weeks.
- Many different disciplines: materials research, physics, chemistry, life science…

2003
Concept design of ESS presented

2009
Decision to site ESS in Lund

2012
ESS design update phase complete

2014
Start of construction

2019
Start of initial operations phase

2025
Today

2026/27
First science

2027
Construction phase completed

BREEAM
Renewable energy & waste heat recovery

Beam on Dump: March 2025
Beam on Target: November 2025: Neutrons on instruments
First Science: April 2026
Start of user program: November 2026
14th instrument commissioned: November 2027

Hope to see you soon

EUROPEAN
SPALLATION
SOURCE

PASCALE.DEEN@ESS.EU