# Neutron Sources

## (Complement to “Proton Accelerators”)

Christine Darve and Zoe Fisher

ASP2018 – Windhoek
July 13, 2018

African School of Fundamental Physics and Applications

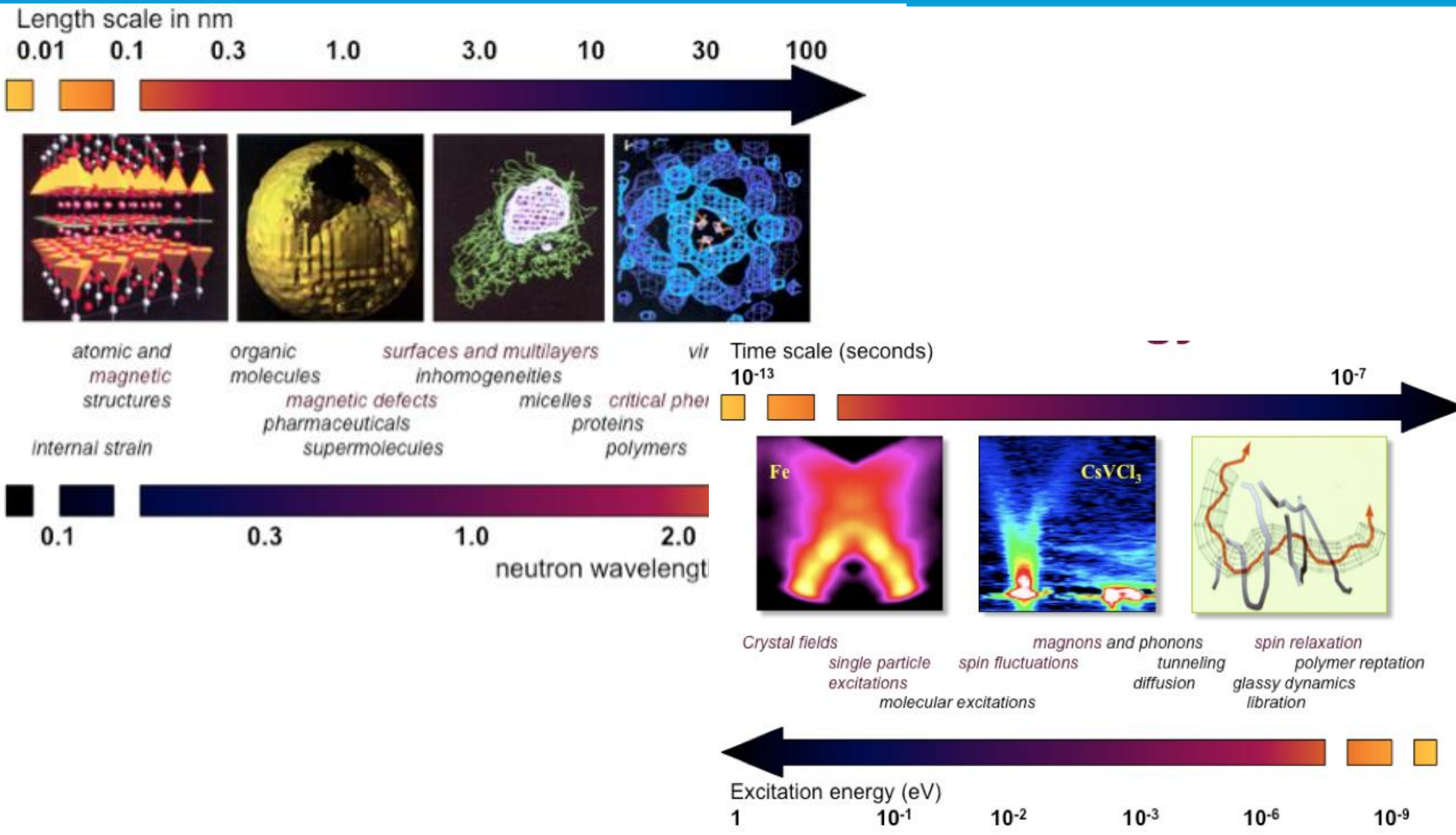
# Outline

- Neutron as a tool for discovery
- What do we see and measure using neutron beam ?
- *How to generate intense neutron beams using high power proton linear accelerator: The ESS*

*for further reading: Applications using Neutrons*

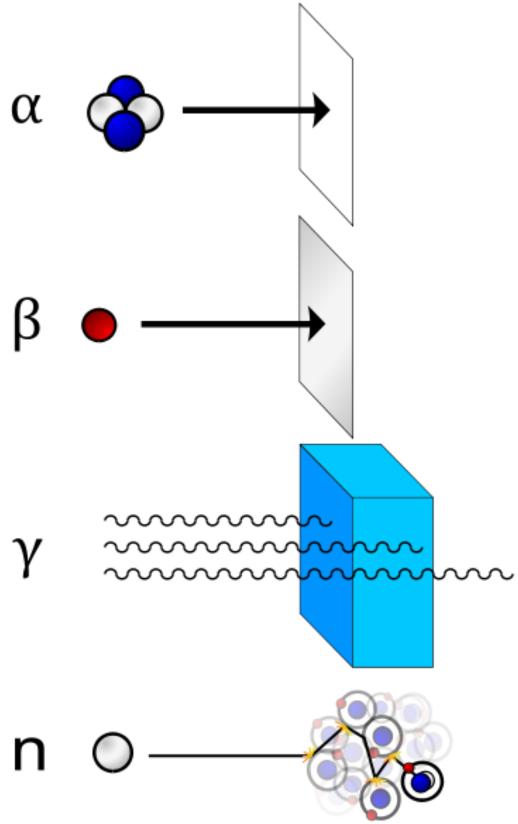
# Neutron Microscope – Length, Time & energy scales

EUROPEAN SPALLATION SOURCE



# Ionizing Radiation

Ionizing radiation is radiation composed of particles that individually carry enough energy to liberate an electron from an atom or molecule without raising the bulk material to ionization temperature.




When ionizing radiation is emitted by or absorbed by an atom, it can liberate a particle. Such an event can alter chemical bonds and produce ions, usually in ion-pairs, that are especially chemically reactive.

Note: Neutrons, having zero electrical charge, do not interact electromagnetically with electrons, and so they cannot *directly* cause ionization by this mechanism.

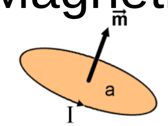
➔ **High precision non-destructive probe … why ?**

# Fields of interest

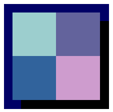
Wave

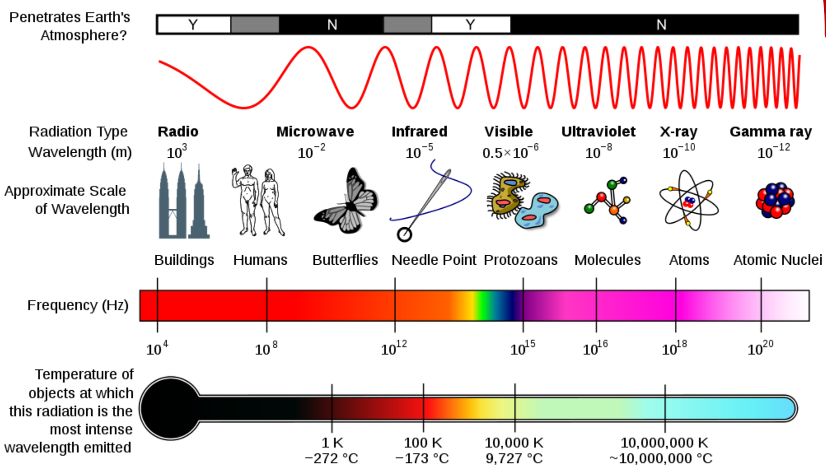
Particle

Magnetic moment

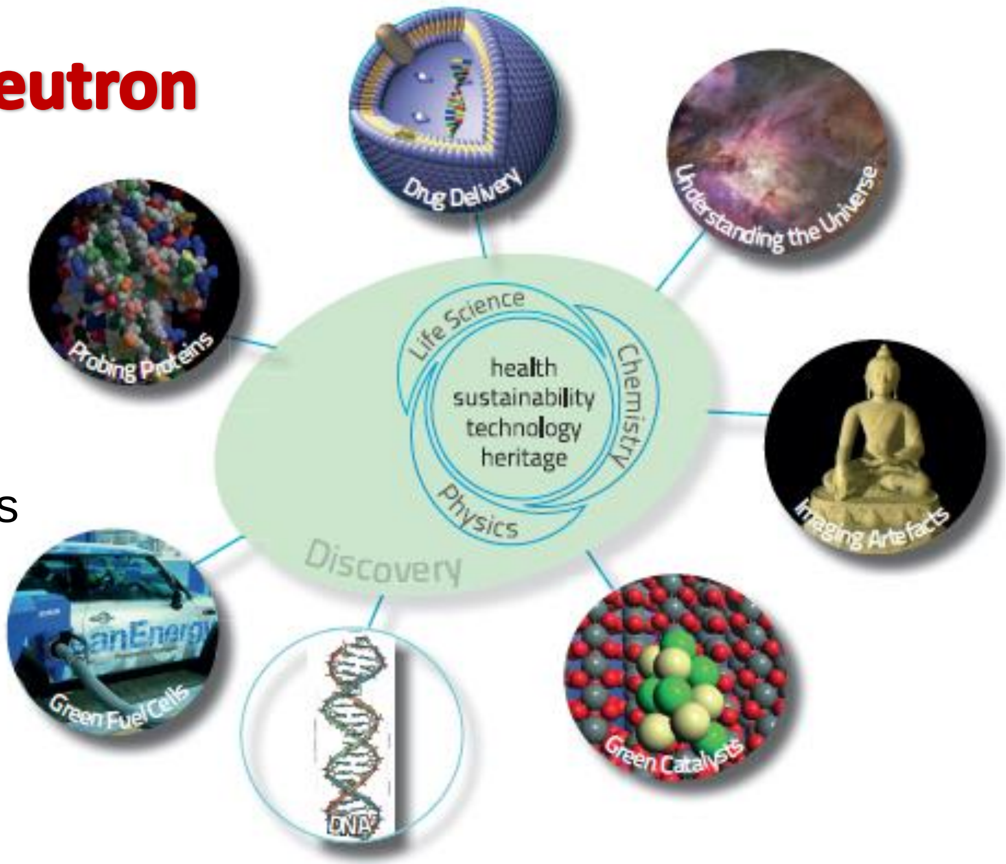



Neutral



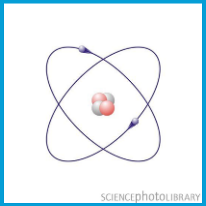



**Neutron**

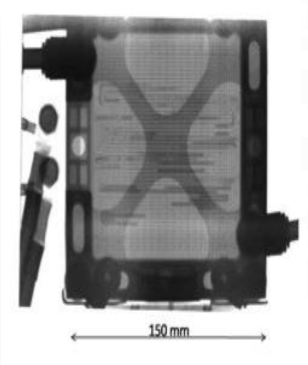



- A wide range of length and timescales
- High sensitivity and selectivity
- Deep penetration
- A probe of fundamental properties
- A precise tool
- An ideal probe for magnetism

# Multi-science with neutrons



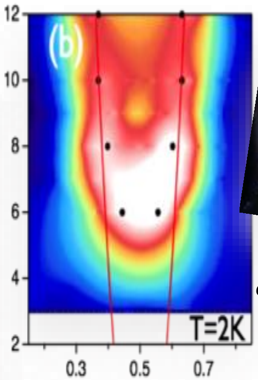

Charge neutral
**Deeply penetrating**




Li motion in fuel cells

Improve electric cars

Magnetic moment
**Probe of magnetism**

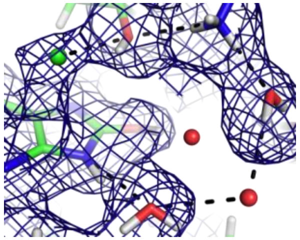



**Test AdS/CFT correspondence**

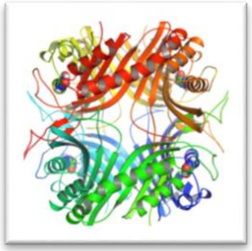
Solve the HTS puzzle

Efficient high-speed trains

Nuclear scattering
**Sensitive to light element and isotopes**



Active sites in proteins



*Urate oxidase*

Better drugs

- They have wavelengths appropriate to inter-atomic distances
- They have energies comparable to molecular motions
- They interact weakly with materials, and can penetrate into the bulk
- They are non-destructive
- Most important: *they see a completely different* ***contrast*** *compared to x-rays* (with appropriate isotope labelling).

# Why neutrons?

Electrically Neutral – neutrons are non-destructive and can penetrate deep into matter. This makes them an ideal probe for biological materials and samples under extreme conditions of pressure, temperature, magnetic field or within chemical reaction vessels.

Microscopically Magnetic – they possess a magnetic dipole moment which makes them sensitive to magnetic fields generated by unpaired electrons in materials. Precise information on the magnetic behavior of materials at atomic level can be collected. In addition, the scattering power of a neutron off an atomic nucleus depends on the orientation of the neutron and the spin of the atomic nuclei in a sample. This makes the neutron a powerful instrument for detecting the nuclear spin order.

Ångstrom wavelengths – neutron wavelengths range from 0.1 Å to 1000 Å, making them an ideal probe of atomic and molecular structures, be they single atomic species or complex biopolymers.

# Why neutrons?

Energies of millielectronvolts – their energies are of the same magnitude as the diffusive motion in solids and liquids, the coherent waves in single crystals (phonons and magnons), and the vibrational modes in molecules.  It is easy to detect any exchange of energy between a sample of between 1microeV (even 1 neV with spin-echo) and 1eV and an incoming neutron.

Randomly sensitive – with neutrons the variation in scattering power from one nucleus to another within a sample varies in a quasi-random manner.  This means that lighter atoms are visible despite the presence of heavier atoms, and neighboring atoms may be distinguished from each other.  In addition, contrast can be varied in certain samples using isotopic substitution (for example D for H, or one nickel isotope for another); specific structural features can thus be highlighted.  The neutron is particularly sensitive to hydrogen atoms; it is therefore a powerful probe of hydrogen storage materials, organic molecular materials, and biomolecular samples or polymers.

# Scientific challenges

## Solid State Physics
*Dynamics of superlattices, wires and dots, molecular magnets, quantum phase transitions*

## Liquids and Glasses
*Solvent structures, influence of molecular structures on protein folding*

## Fundamental Physics
*Left and right handedness of the universe, neutron decay, ultracold neutrons*

## Soft Condensed Matter
*Time resolution, molecular rheology, structures and dynamics*

## Biology and Biotechnology
*Hydrogen and water , membranes, biosensors, functions*

## Materials Science and Engineering
*Real time investigations with realistic dimensions under real conditions*

## Chemical Structure, Kinetics and Dynamics
*Thin films, pharmaceuticals, supramolecules - structures and functionality*

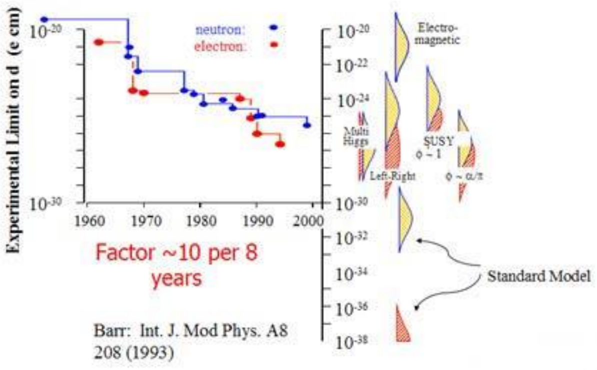
## Earth and Environmental Science, Cultural Heritage
*Extreme temperatures and pressures simulating the mantle*

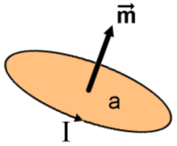
# The visions

- Room Temperature Super Conductors
- Sterile neutrinos
- Hydrogen storage substrate
- Neutron electric dipole moment
- Efficient membrane for fuel cells
- Flexible and highly efficient solar cells
- Carbone nano-tubes for controlled drug release
- Self healing materials – smart materials
- Spin-state as a storage of data ($10^{23}$ gain in capacity)
- $CO_2$ sequestration
- Graphene !

Unobtainium

Avatar



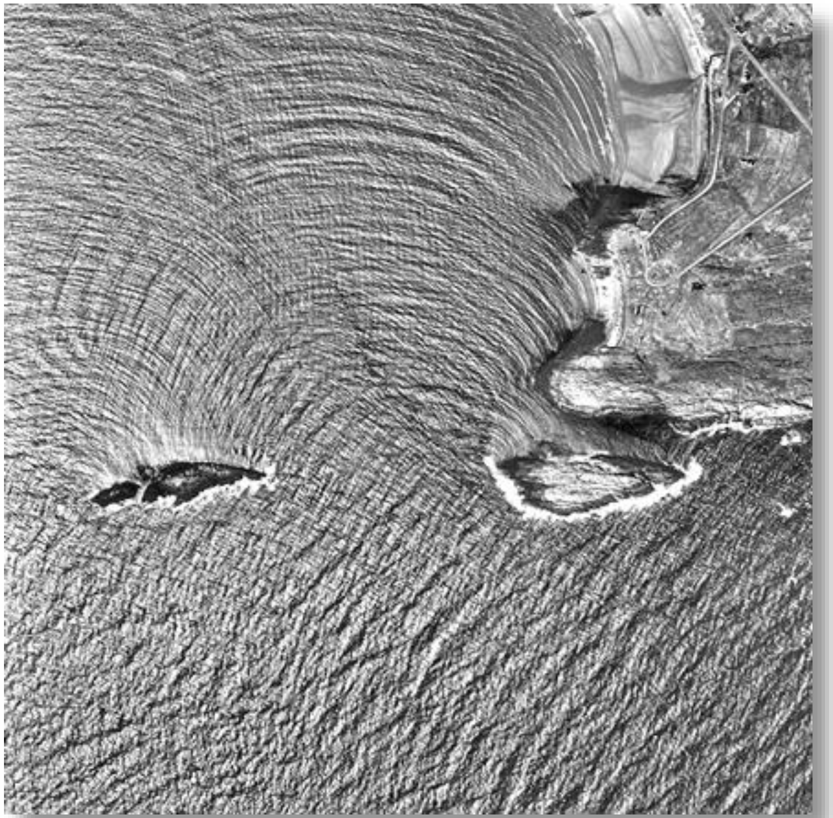



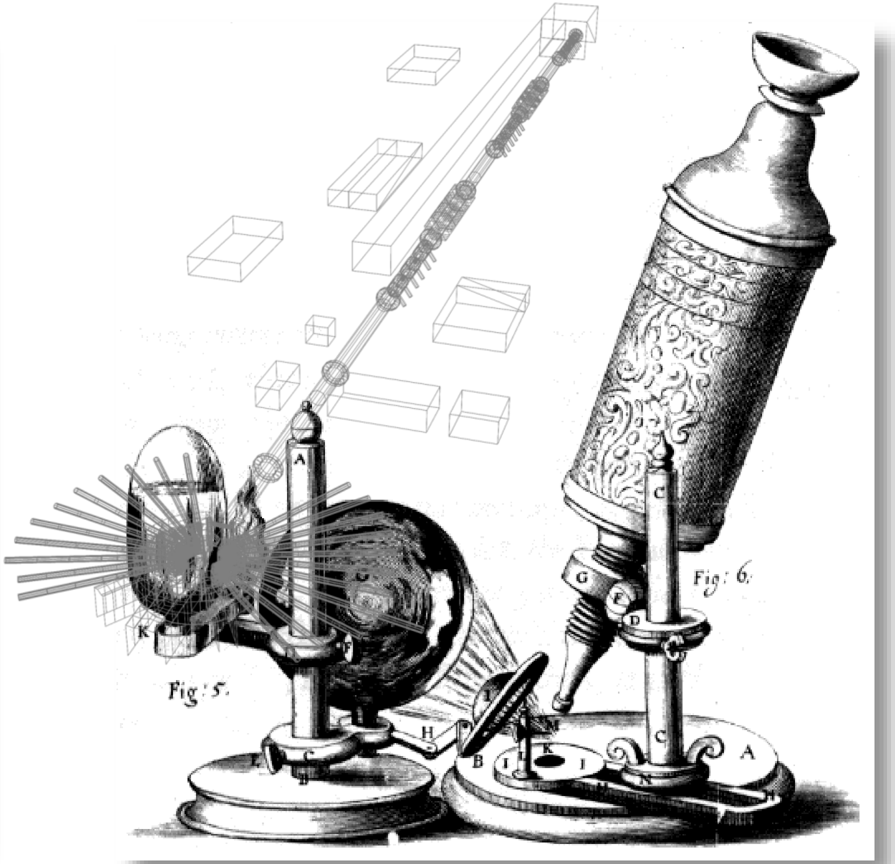
# Outline

- Neutron as a tool for discovery
- What do we see and measure using neutron beam ?
- *How to generate intense neutron beams using high power proton linear accelerator: The ESS*

*for further reading: Applications using Neutrons*

# Complementarity between X-rays and Neutrons






Consider ESS/MaxIV equal in terms of functionality

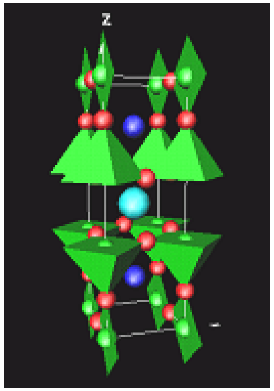
# Why neutrons?

EUROPEAN SPALLATION SOURCE

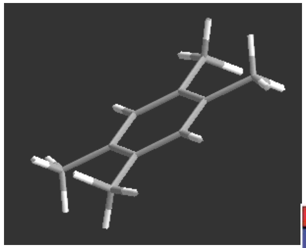
In half a century we have developed neutron scattering science with an effective gain in source performance of only a factor of 4 !

- Diffractometers - Measure structures
  - Where atoms and molecules are

1 - 10 Ångström

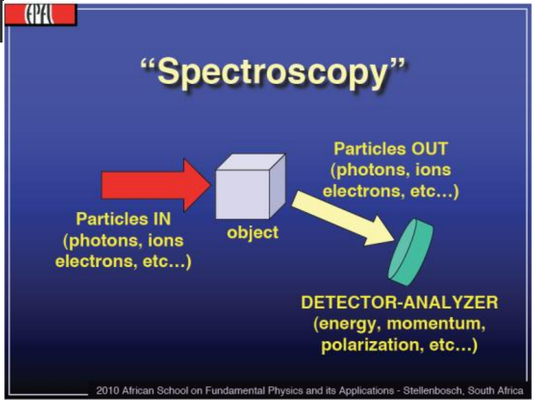


→ To analyze the structure of a material from the scattering pattern produced when a beam of radiation or particles (such as X-rays or neutrons) interacts with it



- Spectrometers - Measure dynamics
  - What atoms and molecules do

1 - 80 meV




→ To measure properties of light over a specific portion of the electromagnetic spectrum

# Neutron Energy

$$E = k_B T$$

$$E = k_B T = \tfrac{1}{2} m v^2 = \frac{h}{2m\lambda^2}$$

$$\lambda = \frac{h}{mv}$$

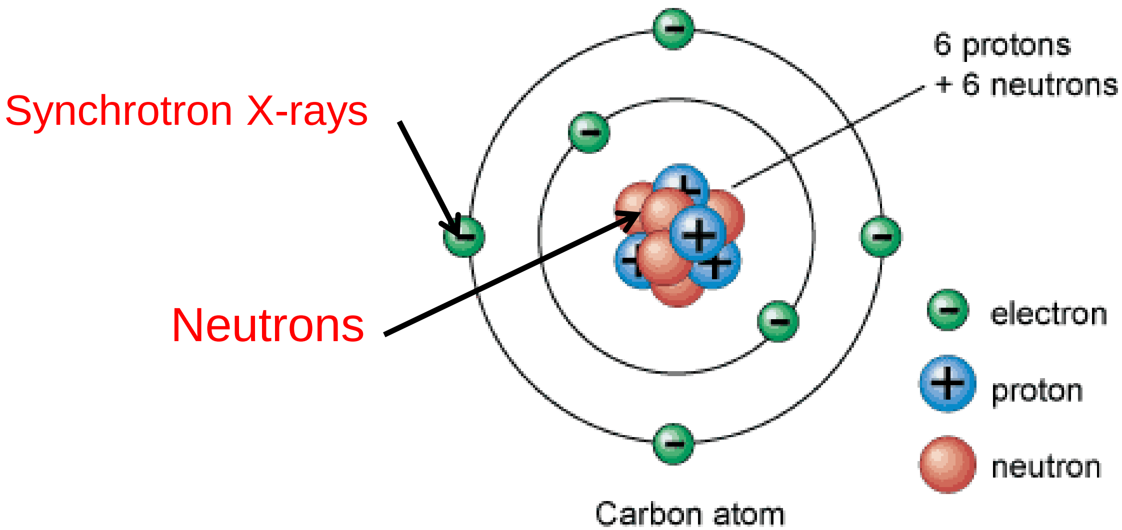
Boltzmann distribution

De Broglie

$$E\,[meV] = 0.0862\ T\,[K] = 5.22\ v^2\,[km/s] = 81.81\frac{1}{\lambda^2}\,[A]$$

| Source | Energy | Temperature | Wavelength |
|---|---|---|---|
| cold | 0.1-10 | 1-120 | 30-3 |
| thermal | 5-100 | 60-1000 | 4-1 |
| hot | 100-500 | 1000-6000 | 1-0.4 |

# Neutrons Properties



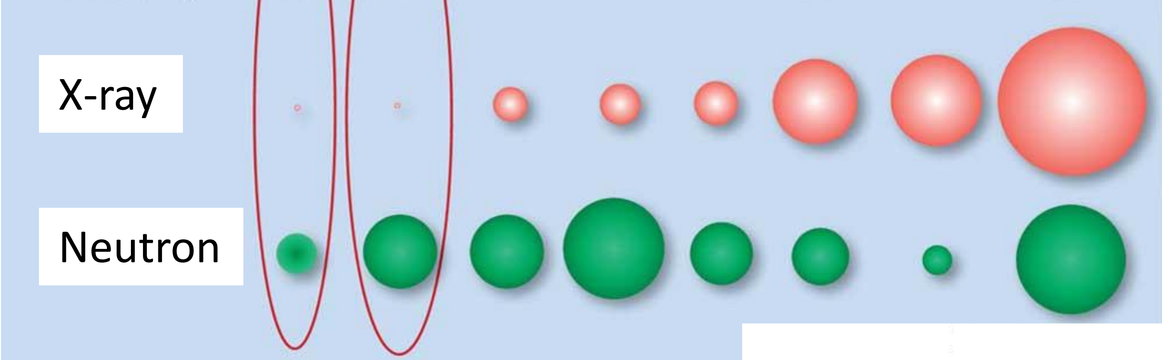

Note: X-rays are emitted by electrons outside the nucleus, while gamma rays are emitted by the nucleus.

| | | |
|---|---|---|
| $1.675\times10^{-27}$ kg Mass | 939.57 MeV | $m_n \approx m_p + 2.5 m_e$ |
| Mean lifetime | 15 min | $n \longrightarrow p + e^- + \bar{\nu}_e$ |
| Composition | udd | hadron |
| Electric charge | 0 | high penetration |
| Magnetic moment | $-1.04\,\mu_B$ | feels the nucleus |

# Complementarity between X-rays & Neutrons

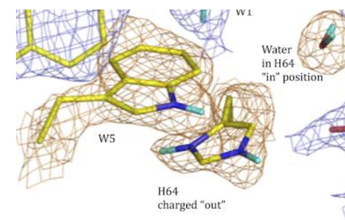
## Neutron scattering lengths for different atom types found in biological materials:

| Atom | H | D($^2$H) | C | N | O | P | S | Fe |
|---|---|---|---|---|---|---|---|---|
| No. of electrons | 1 | 1 | 6 | 7 | 8 | 15 | 16 | 26 |
| Coherent scattering | -3.74 | +6.67 | +6.65 | +9.37 | +5.81 | +5.13 | +2.80 | +10.1 |

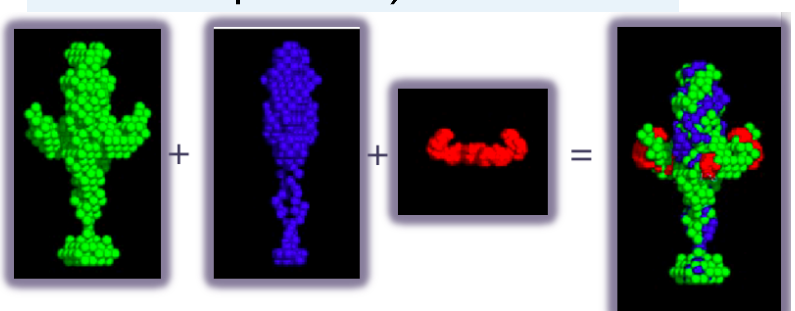



H atoms make up *~50% of atoms of biological macromolecules* (lipids, proteins, nucleic acids, carbohydrates).

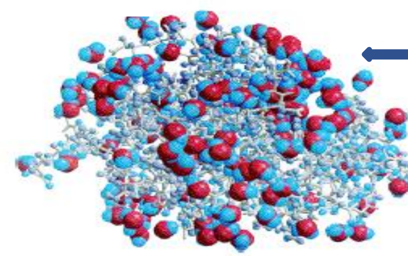
Localization of Hydrogen atoms




Appropriate isotope labeling is very important (replace H with D wherever possible)




X-rays



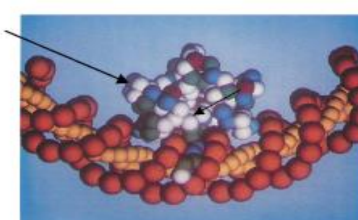
Neutrons

Water molecules Observed with neutrons

N. Niimura, et al.

Protein

From structure to function




A proten molecule moving along the DNA chain

# Complementarity between X-rays & Neutrons

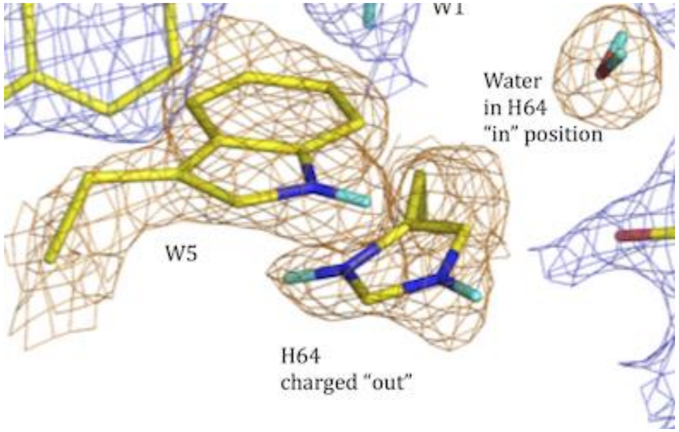
| Neutrons | Synchrotron radiation |
|---|---|
| • Particle beam (neutral subatomic particle)<br>• Interactions with the nuclei and the magnetic moment of unpaired electrons (in the sample)<br>• Scattered by all elements, also the light ones like the hydrogen isotopes<br>• Deep penetration depth (bulk studies of samples)<br>• Less intense beam measuring larger samples | • Light beam (electromagnetic wave)<br>• Interactions with the electrons surrounding the nuclei (in the sample)<br>• Mainly scattered by heavy elements<br>• Small penetration depth (surface studies of samples)<br>• Very intense beam measuring small or ultra-dilute samples |

# Complementarity between X-rays & Neutrons

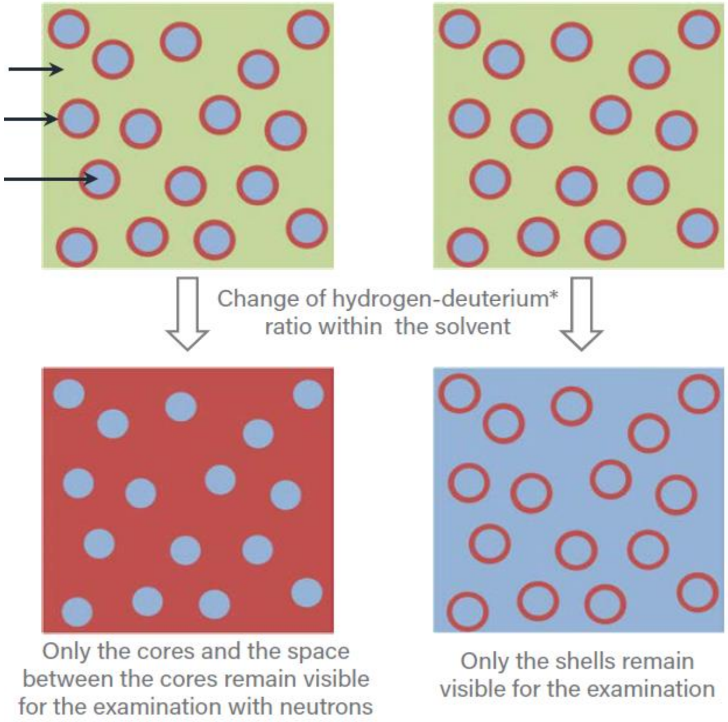
| Neutrons Applications | SR Applications |
|---|---|
| • Magnetic structures & excitations<br>• Organic structures using the H-D isotope effect<br>• Bulk studies (strains, excitations)<br>• Low-energy spectroscopy e.g. molecular vibrations | • Protein-crystal structures<br>• Fast chemical reactions<br>• Surface studies (defects, corrosion)<br>• High-energy spectroscopy e.g. measurements of electron energy-levels |

# Purpose of deuteration depends on technique

Localization of hydrogen atoms in macromolecular structures




Neutrons enable contrast variation through selective deuteration of materials (SANS, NR):

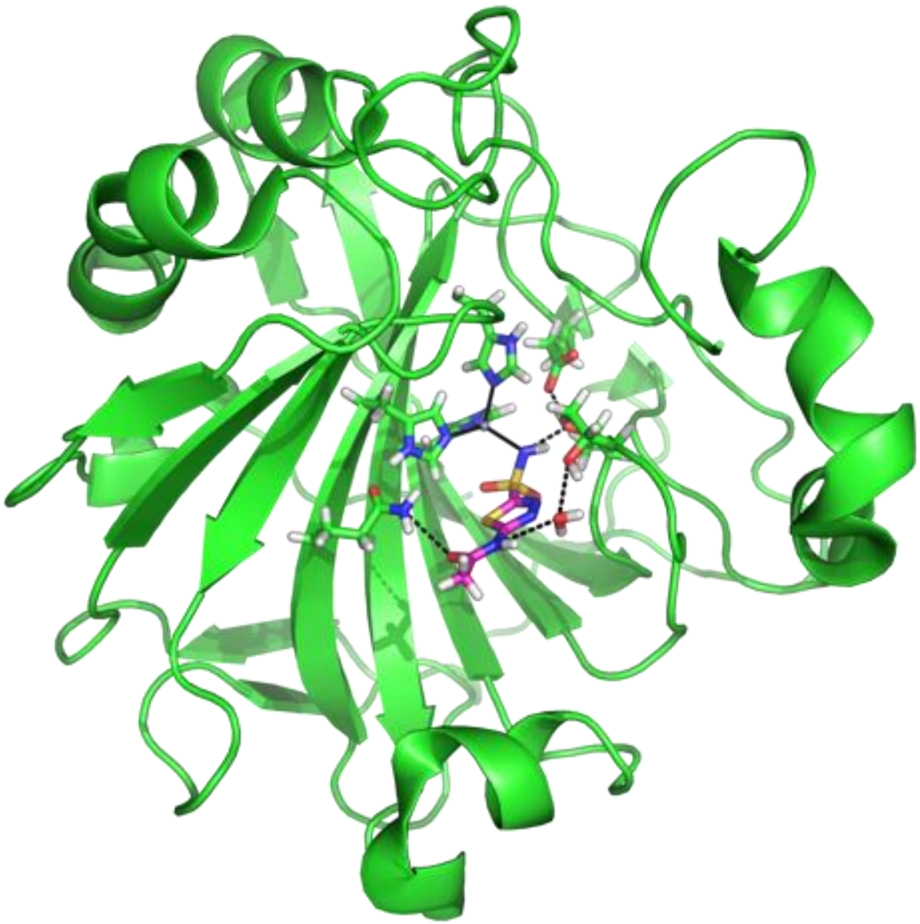


# Life science using neutrons as a tool

Several areas where neutrons are a very good – and complementary - tool:

- To determine the 3-D atomic (crystal) structures of macromolecule (eg. protein or DNA): the structure of the molecule is related to its function. Enzymes are bio-catalysts and “seeing” their insides allows us to understand how they work .
- Sometimes biological systems are large, complex, and dynamic (i.e. not well-ordered enough to form a crystal) – then we need small angle scattering to see larger “shapes” but at lower resolution. Dynamic data!
- For layers – like lipid bilayers (eg. cell membranes) – we can use reflectometry, to tell us about the thickness and behaviour of the membranes under a variety of conditions (temperature, pH, salt concentration etc.)
- Imaging can be done in the same way as taking a photo of an object– but with neutrons we get interesting contrast that lets us “see” special features that are not possible with optical or X-ray techniques.

# Neutrons reveal how drugs interact with disease targets



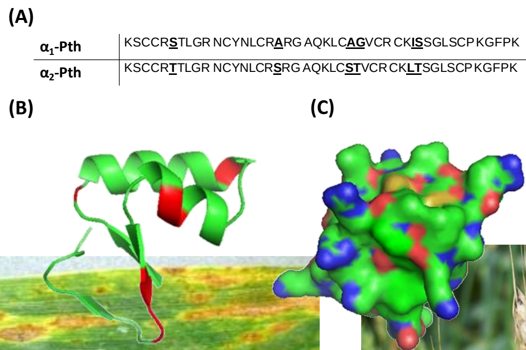
The enzyme carbonic anhydrase transports $CO_2$ and regulates blood acidity. It is a major player in some cancers, glaucoma, obesity and high blood pressure

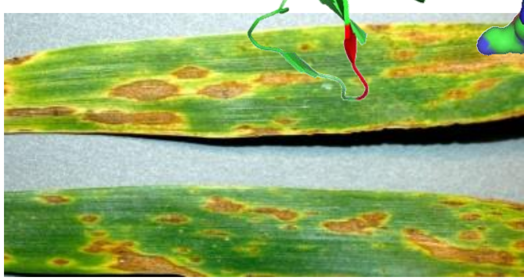
Neutron crystallography pinpoints protons and waters in the active site, showing how the drug Acetazolamide binds

Image: Fisher, S. Z. *et al*. 2012 JACS

# Plant antimicrobial & antifungal proteins

## α-purothionins



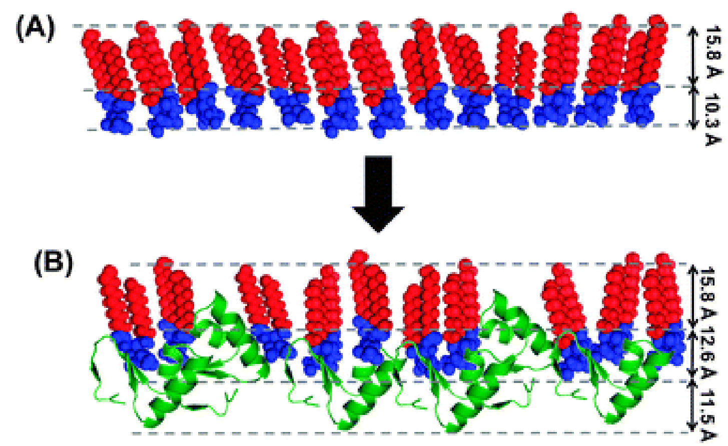
Tan spot (*Pyrenophora tritici-repentis)*

Glumbe Blotch (*Stagonospora nodorum)*


Common Smudge (*Cochliobolus sativus)*

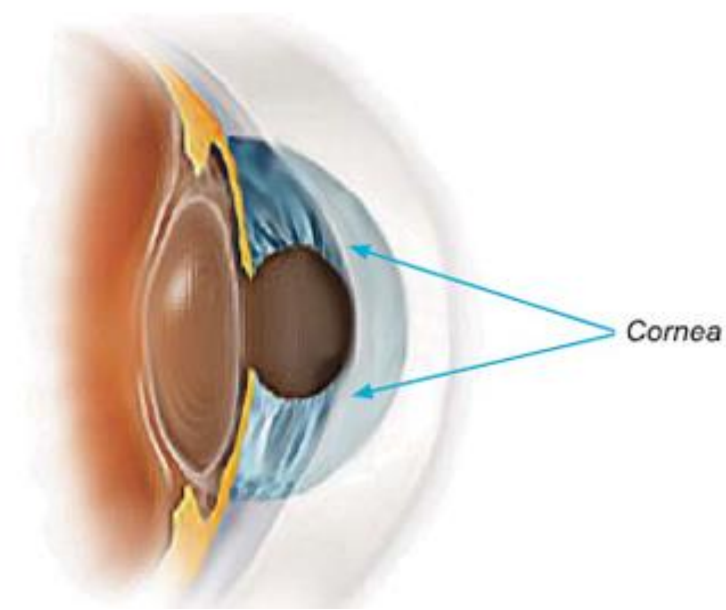
Stripe blight (*Pseudomonas syringie)*

Neutron reflectometry used to determine how plant defence proteins from common wheat interact with cell membranes.




Clifton et al. *Phys. Chem. Chem. Phys.*, 2012, 14, 13569-13579

# Advanced Materials for Health

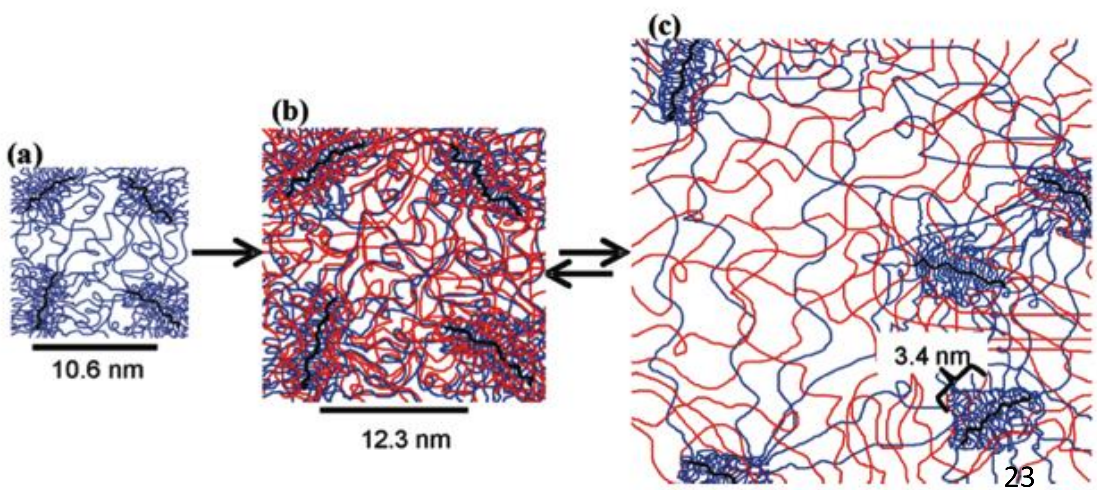



**Double network hydrogels** provide strength and resilience together with high water content.

Gel structure forms over **multiple length scales.**

Kinetics of gelation can be rapid needing **sub-second** time resolution.

Neutrons provide the structure of each component in the presence of the other.




Swelling of a double network hydrogel designed for use as a cornea replacement.
(Frank Group, Stanford)

# Adding Value and Stability to Fermented Milk Drinks

Fermented milk products are a consumer success, but their low-pH level is inherently unstable. This can be remedied by adding natural biopolymers as stabilizers.

Neutrons can describe how two different pectin stabilizers affect the milk protein particles in very small scales. Food companies can use the results to further understand the mechanistic aspects of their stabilizers.

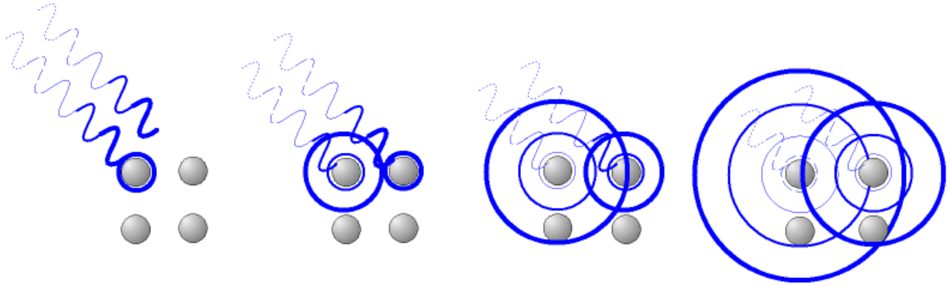
Case: University of Copenhagen, Denmark

Next set of slides:

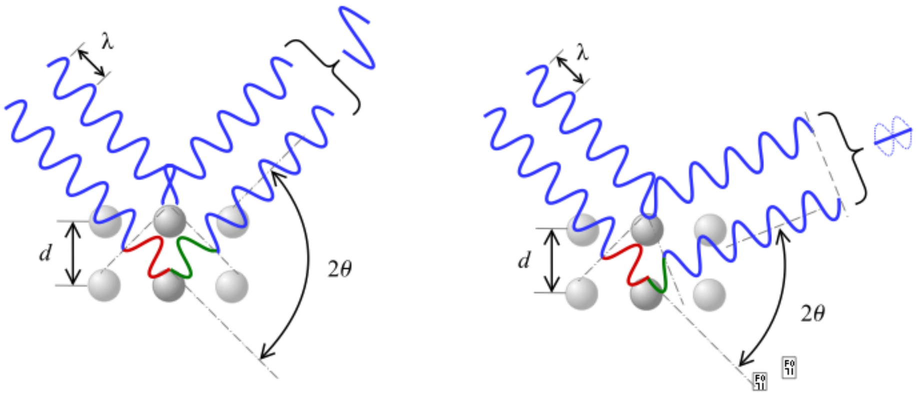
Slightly more technical description of different neutron techniques used in life science/soft matter

# Diffraction - Bragg

Diffraction of X-rays or neutrons by polycrystalline samples is one of the most important, powerful and widely used analytical techniques available to materials scientists. For most crystalline substances of technological importance, the bulk properties of a powder
or a polycrystalline solid, averaged throughout the sample, are required; in general a single-crystal data, even if they can be obtained, are usually of little interest except for determination of the crystal structure or for studying some other fundamental physical property.  By *J Ian Langford and Daniel Louer*

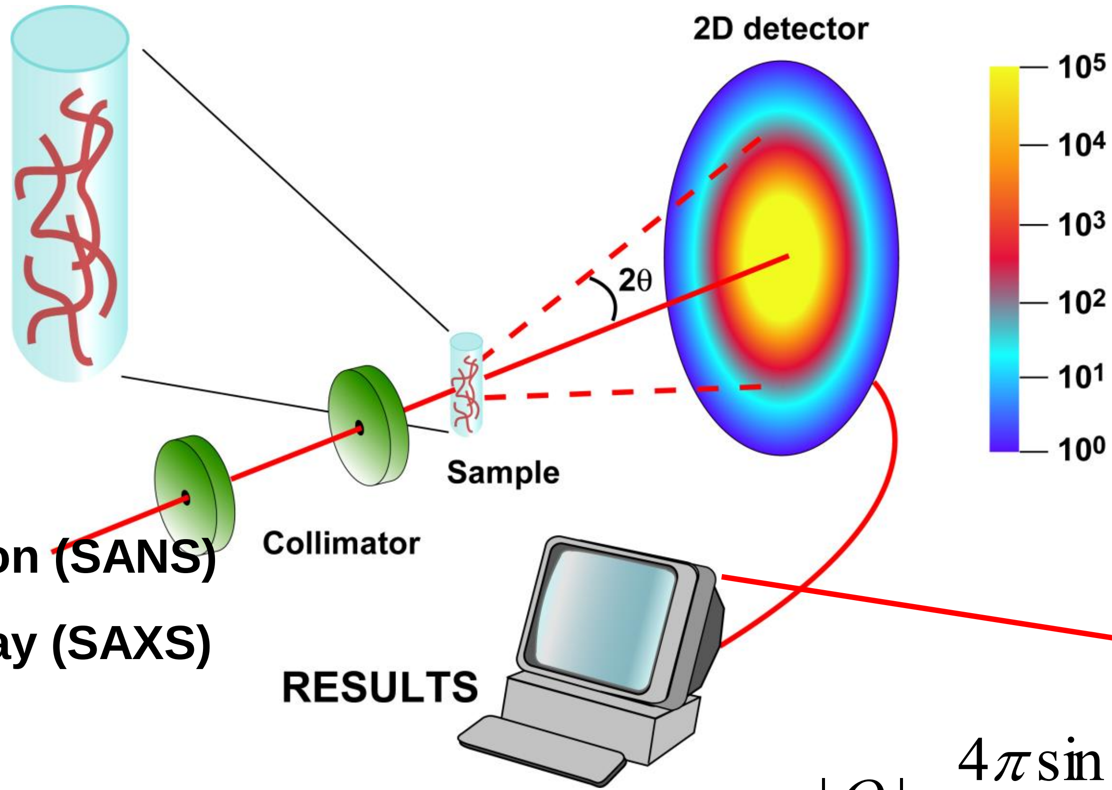


X-rays interact with the atoms in a crystal.




According to the 2θ deviation, the phase shift causes constructive (left figure) or destructive (right figure) interferences.

# SANS: Experimental Setup

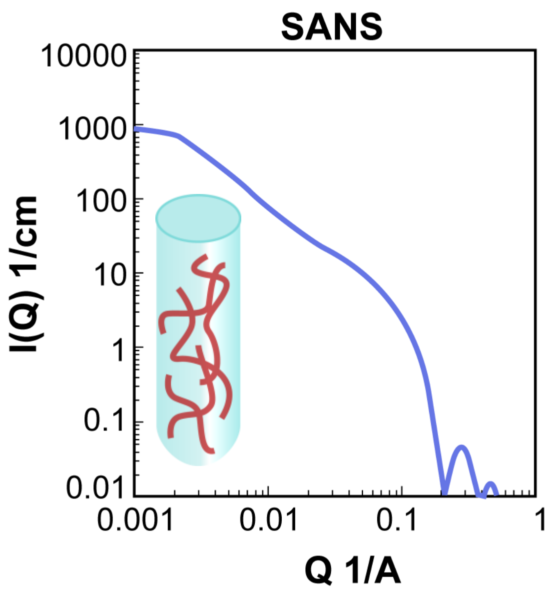



**Beam:**

**Neutron (SANS)**

**or X-ray (SAXS)**

Measures structures at length scales from 1 nm to 100 nm



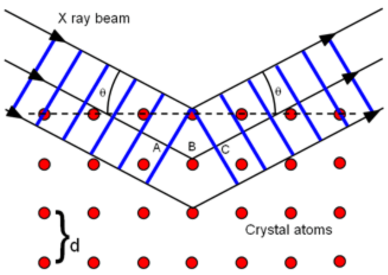

$$|Q| = \frac{4\pi \sin\theta}{\lambda}$$

$\boxed{Q_{min} \approx 0.03° \quad , \quad Q_{max} \approx 3°}$

In a standard crystallography experiment, theta_max is typically 45 degrees

# Diffraction - Bragg

Using the grains as internal strain gauges

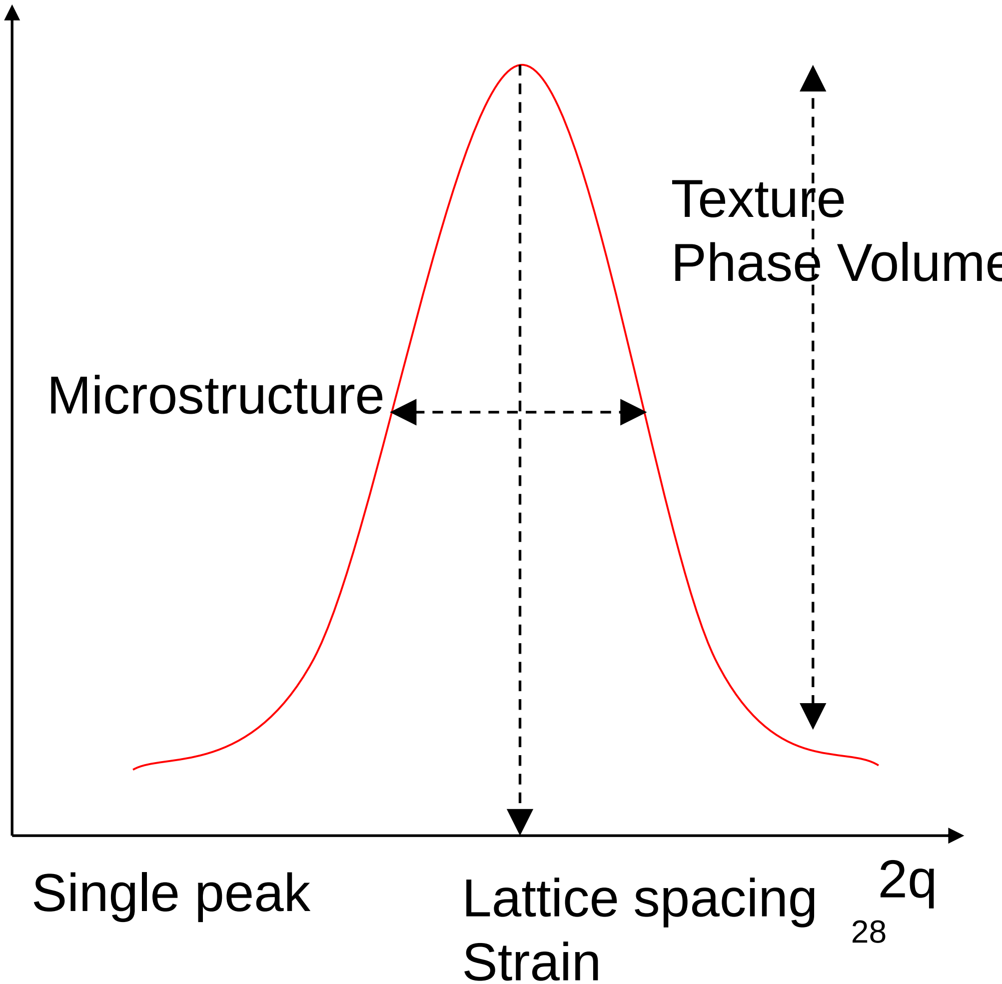



$$\lambda = 2d \sin\theta$$

$$\varepsilon = -\cot(\theta)\,(\theta - \theta_0)$$

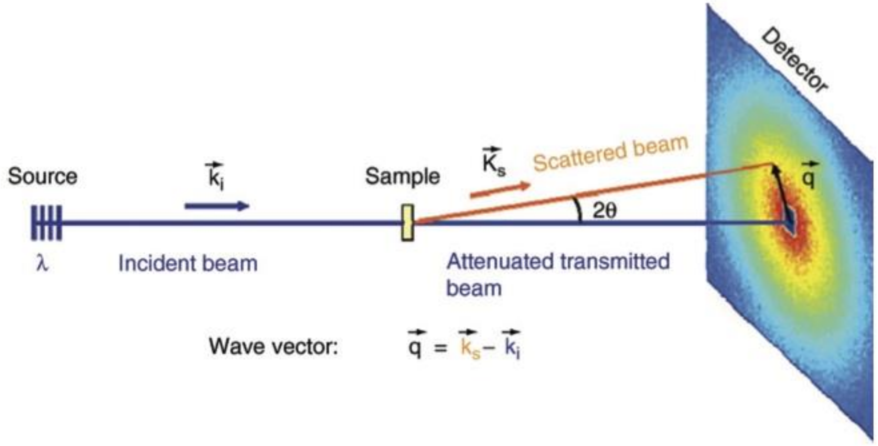
Two ways to measure d:
-keep λ fixed and measure θ
constant wavelength
-keep θ fixed and measure λ
time-of-flight

Braggs law gives information about position of a diffraction peak from a type of lattice planes. Rietveld approach calculated height, position and width of diffraction peaks from first principles, I.e. Temperature, composition, vacancies, etc.

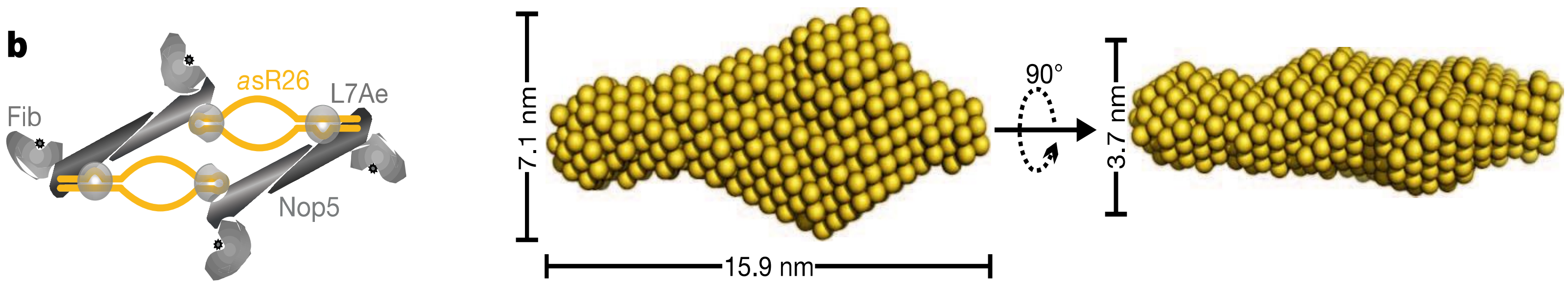


# Small angle neutron scattering (SANS)

- SANS used to study materials in 1 - 1000 nm length scale (can be done on solids, solutions, powders, crystals).
- Large, complex biological systems that are dynamic and inherently flexible are very well suited to SANS.
- Contrast matching: selective perdeuteration strategies of macromolecules in combination with SANS measurements in different ratios of $D_2O/H_2O$.
- Mask parts of a large complex while highlighting molecules/areas of interest.
- Information: size, structure, and dynamic behavior of molecules in a complex while being able to change the environment.



# Small angle neutron scattering (SANS)

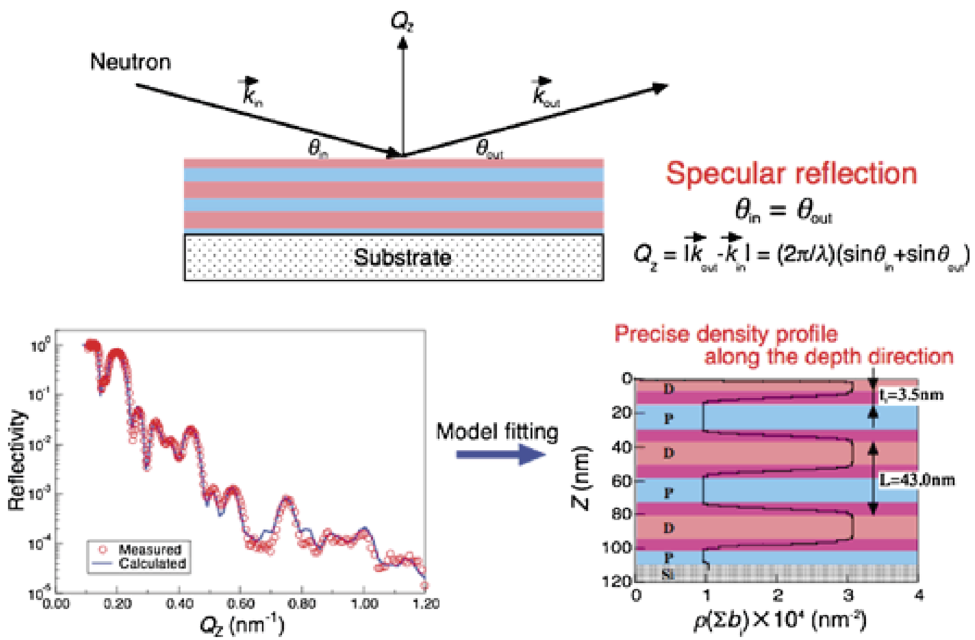



*Scheme of a RNA:protein complex explaining the concept of contrast matching in SANS. The data were collected on perdeuterated RNA (yellow) and unlabeled protein (gray). Measurement were done in a mix of $D_2O/H_2O$ that masked the (gray) unlabeled protein. The deuterated RNA scattering dominates the curve. Researchers were able to derive a model of RNA (yellow space-filled model) in the context of the complex from SANS data.*

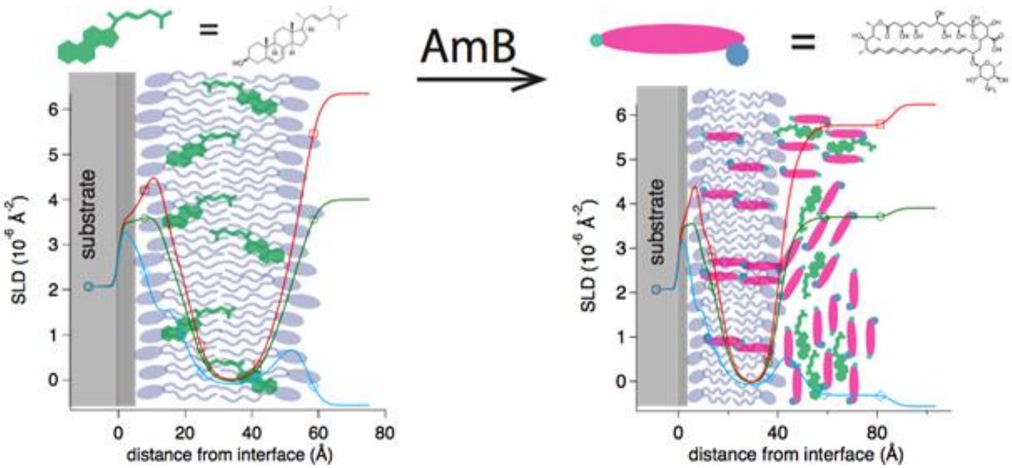
(From Lapinaite et al. (2013) *Nature* **502**, p.519)

# Neutron reflectometry (NR)

- NR is used to study thin films and interfaces on 0.2 to 100 nm scale.
- Similar to SANS, selective isotope labeling is very powerful, especially for biological samples.
- Measure nuclear scattering length density profiles perpendicular to the membrane surface.
- Gives information about the internal organization of the membrane/interface under different conditions
- Well suited to the study of lipids and biological membranes.



# Neutron reflectometry (NR)

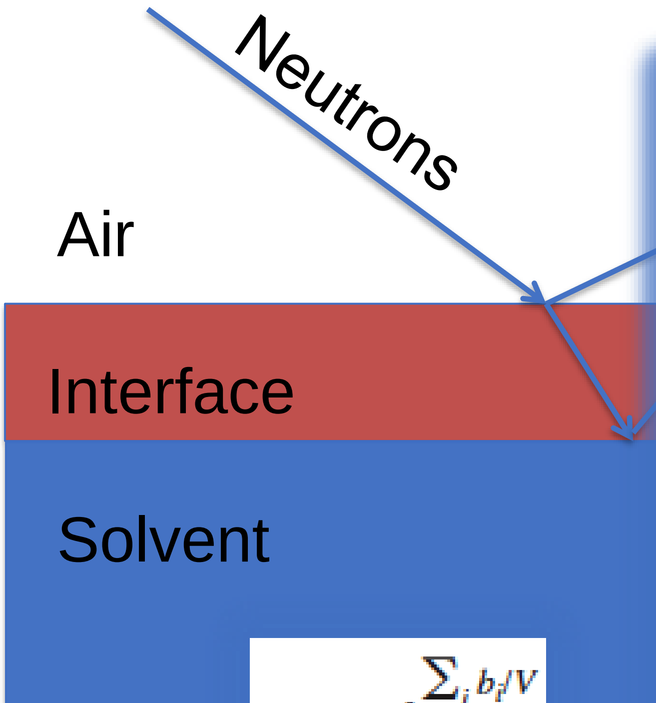


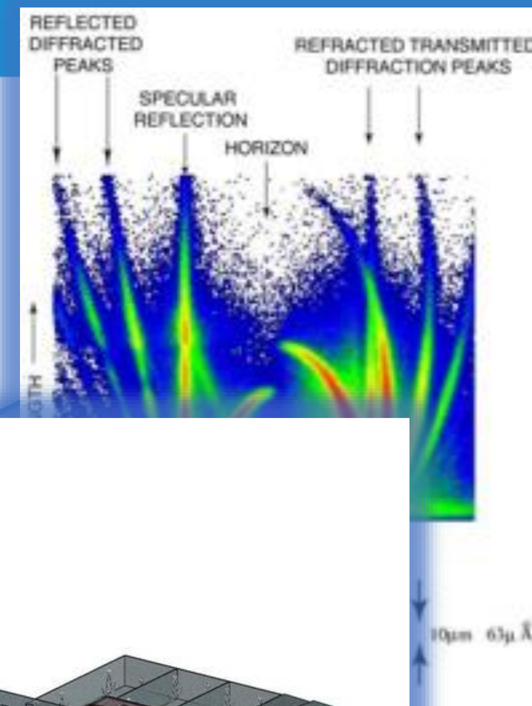

*A diagram showing the orientation of potent antifungal drug AmB in relation to the layer thickness in a lipid membrane. The experiments using NR were done on membranes with different lipid components and showed that the efficacy of the drug was strongly dependent on the lipid composition. This could help explain why AmB causes toxic side effects in human but also how it works to disrupts fungal membranes.*

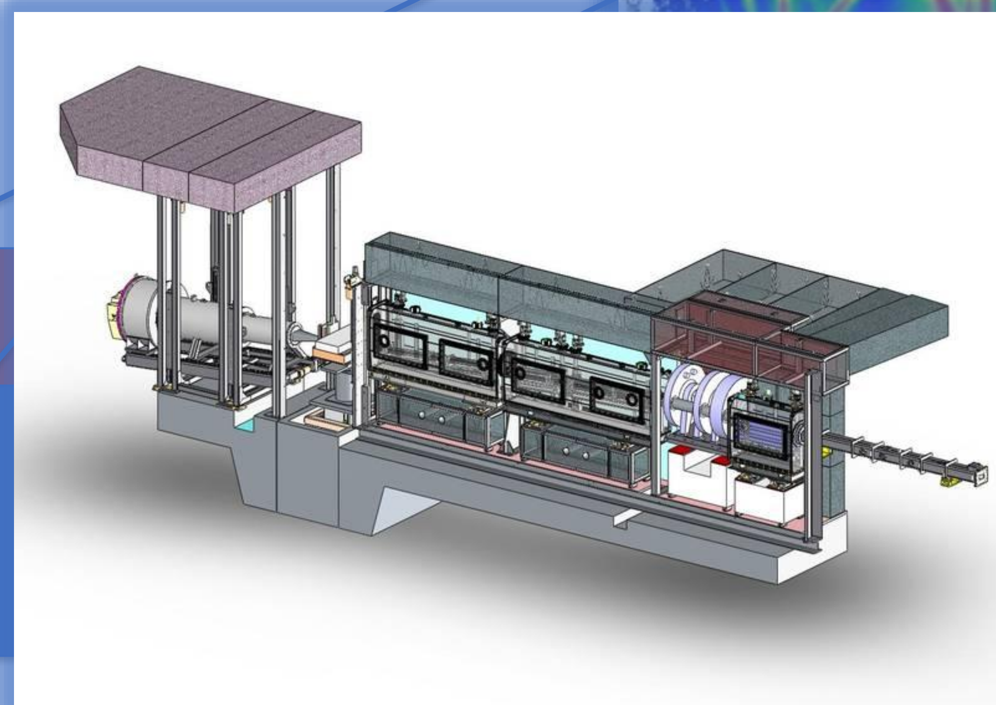
(From de Ghellinck et al. (2015) *BBA Biomembranes* **1848**, p. 2317.)

# Neutron Reflectivity

- Basic principle



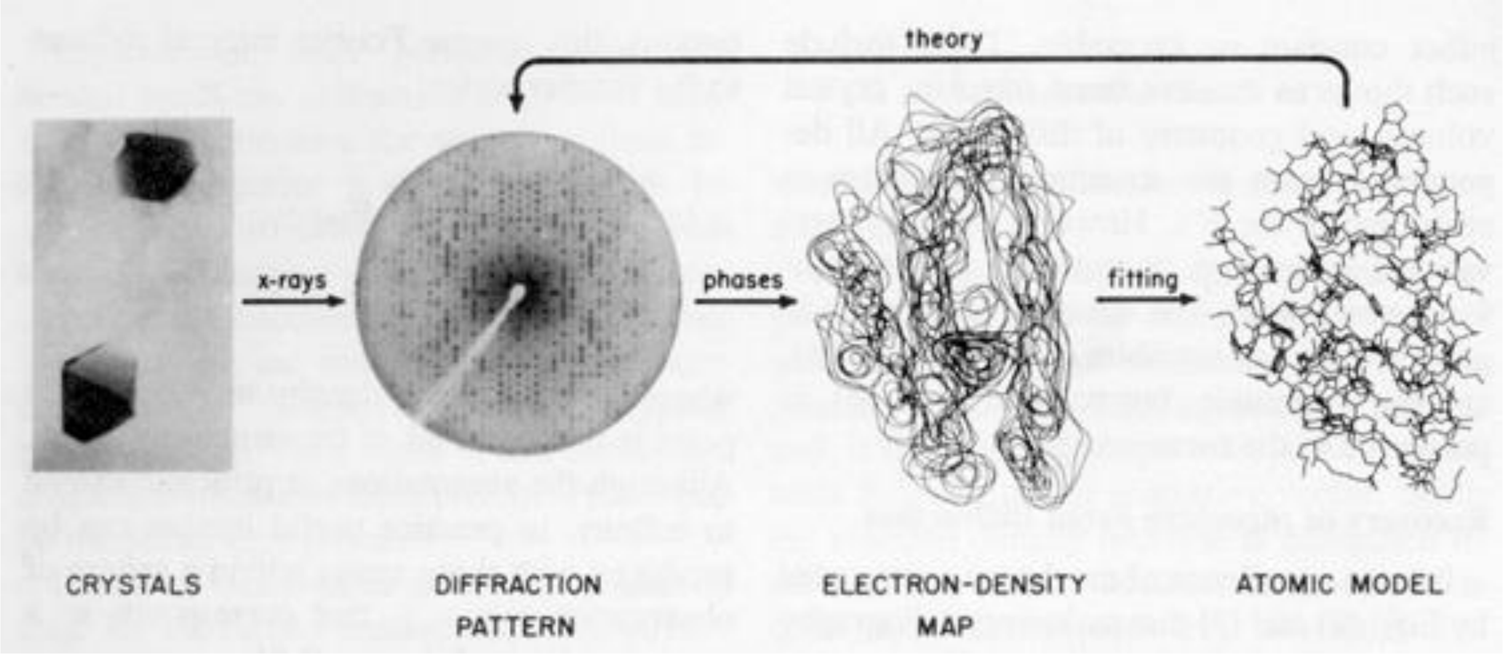



$$n = 1 - \lambda^2 \frac{\sum_i b_i/V}{2\pi},$$

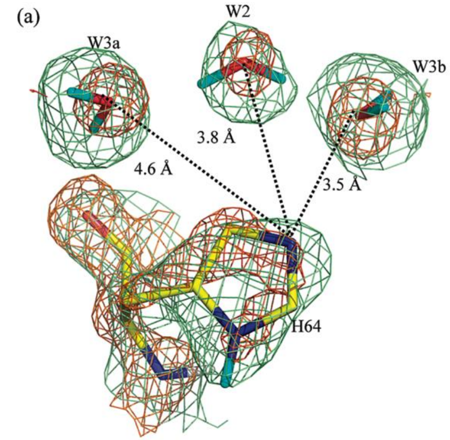
# Neutron protein crystallography (NPX)

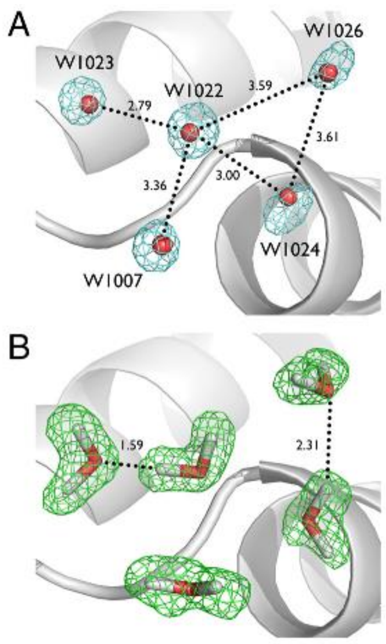
- NPX is used to determine the atomic crystal structure of protein molecules. Uses neutrons in the wavelength range ~ 0.7 to 7 Å
- Single crystal Bragg diffraction (can be monochromatic or Laue) – same as X-ray diffraction theory.
- Data quality is significantly weaker and takes longer to collect. Quality, speed enhanced in *labeled samples*, still requires large crystals.

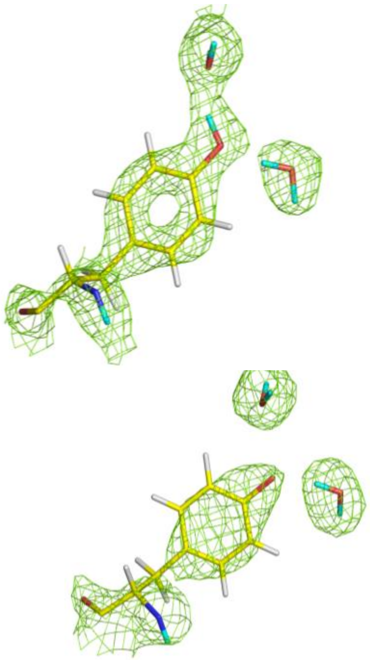


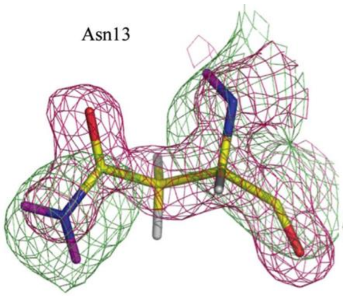
# NPX gives the ability to “see” Hydrogen atoms

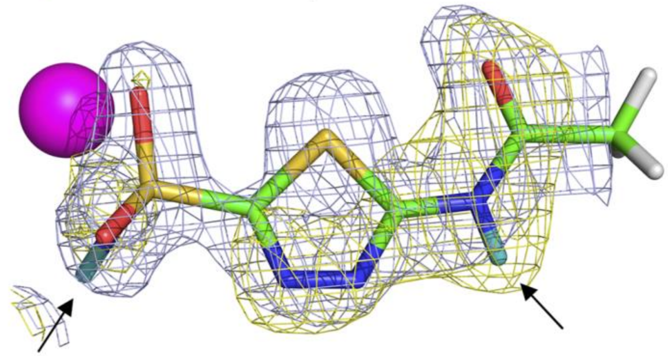
**Elucidate enzyme mechanism and function**
Protonation states, orientation of amino acid residues
Observe water structures/H-bonded networks
Discerning solvent species ($D_2O$ vs $OD^-$ vs $D_3O^+$)





It can also: tell us about H/D exchange kinetics, minimal protein folding domains and solvent accessibility, ***drug/inhibitor/substrate binding interactions.***

# Sample needs

- All of these neutron techniques in life sciences/soft matter require large amounts of either fully deuterated or partially deuterated samples.
- In the case of NPX these samples also have to be crystallized, and the crystals have to be large (added layer of complexity).
- These materials are expensive or time consuming to make and often require specialized knowledge and equipment.
- ESS aims to establish *support labs* so that users can get *advice and support* to prepare enough of the proper sample, characterize their sample.
- The helps ensure the *best possible use* of their allocated beam time.

# Outline

- Neutron as a tool for discovery

- What do we see and measure using neutron beam ?

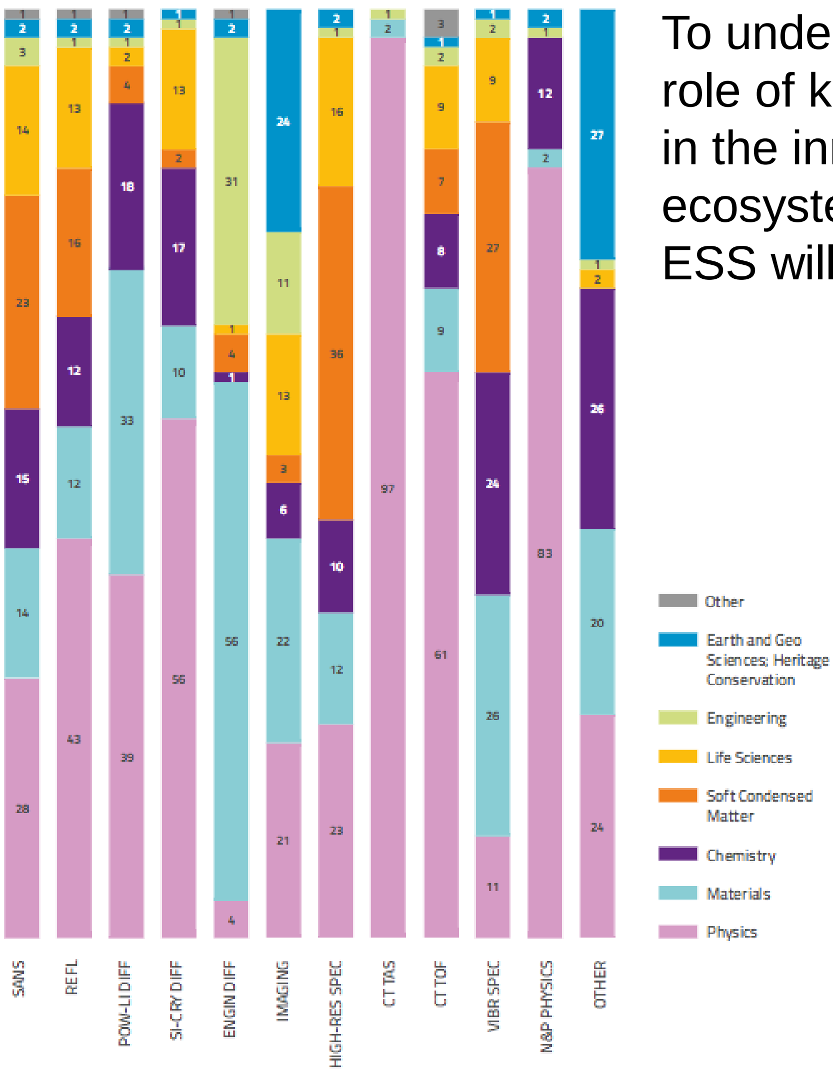
- *How to generate intense neutron beams using high power proton linear accelerator: The ESS*

*for further reading: Applications using Neutrons*

# BrightnESS survey

EUROPEAN SPALLATION SOURCE

Fig 3.15 Europe: Science fields per method expressed as a percentage of experiments




To understand the role of key players in the innovation ecosystem that ESS will foster !

Fig 3.14 Europe: Horizon 2020 topics and challenges expressed as a percentage of research, averaged over all participating neutron sources

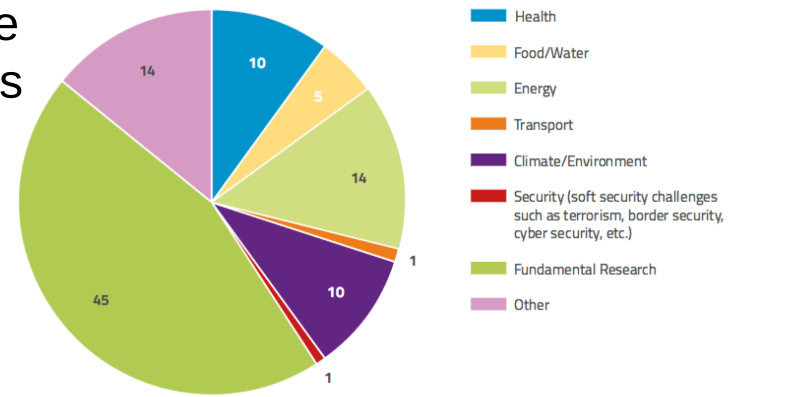



Fig 3.16 Europe: Science fields expressed as a percentage of experiments

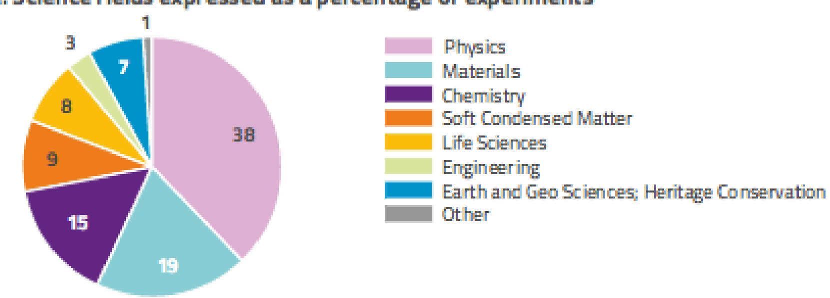
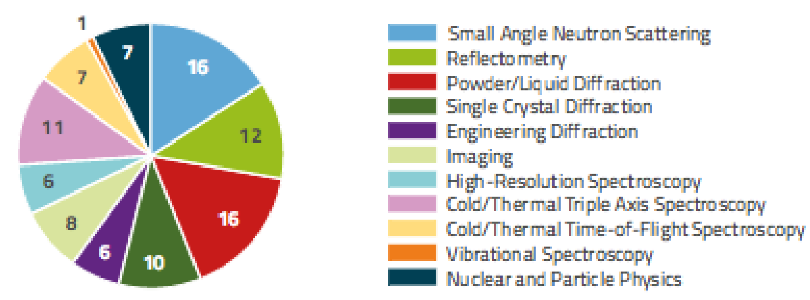
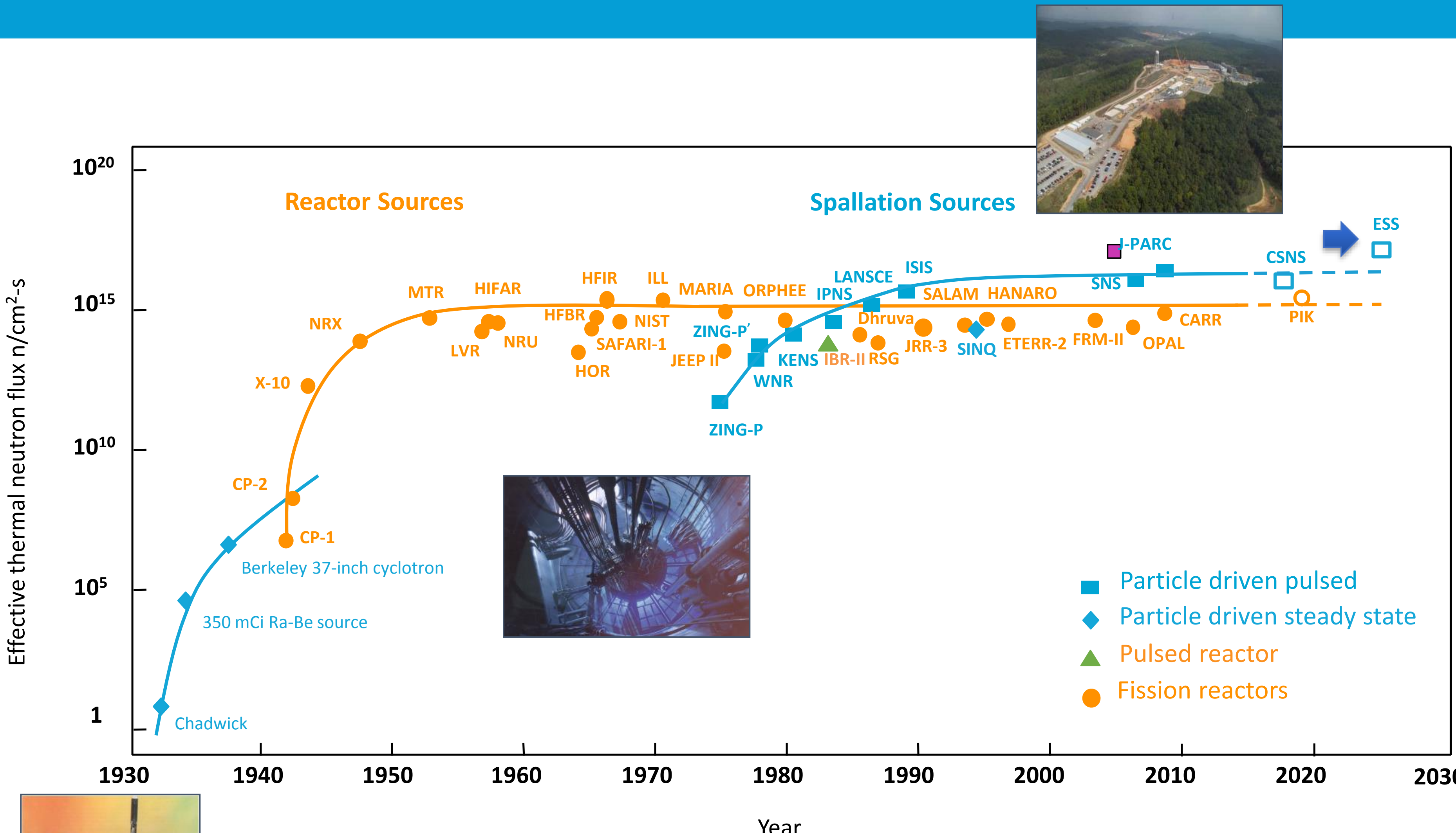



Fig 3.17 Europe: Use of methods expressed as a percentage of beam days



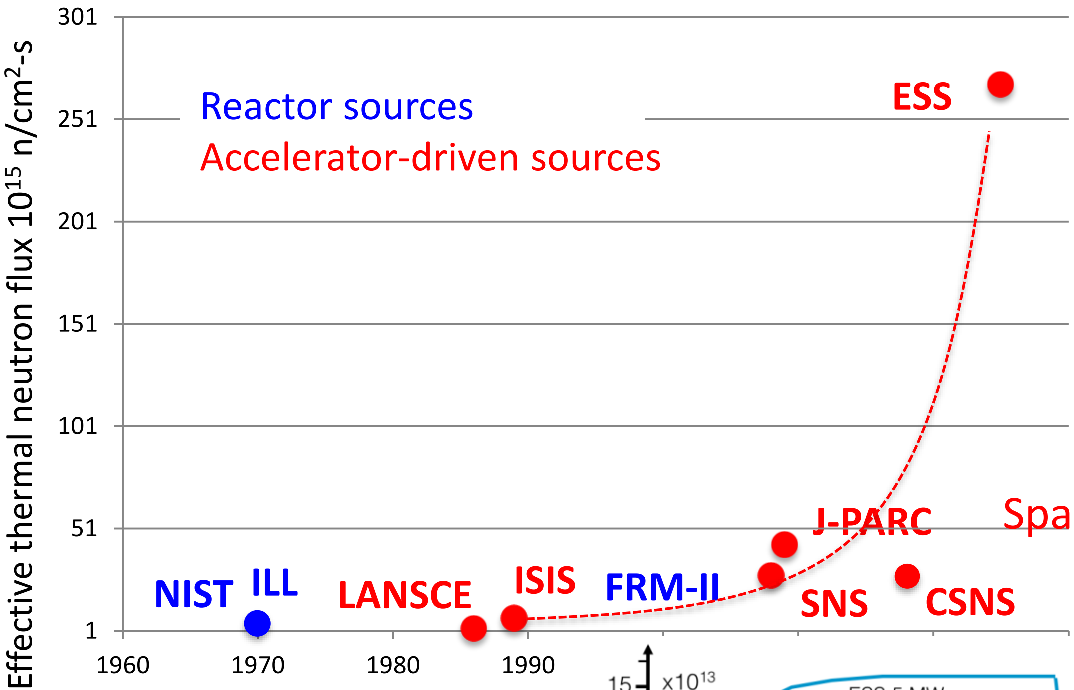
# High time average and peak flux



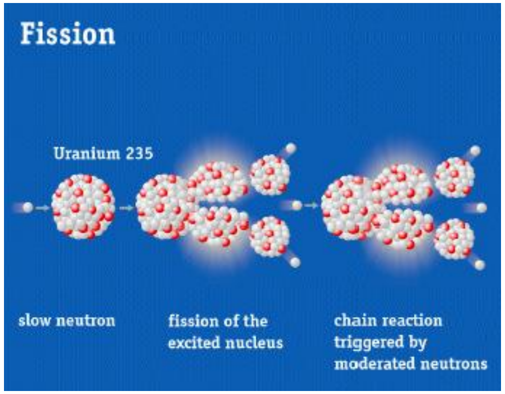

(Updated from *Neutron Scattering*, K. Skold and D. L. Price, eds., Academic Press, 1986)

# ESS Vision: Build and operate the world’s most powerful neutron source

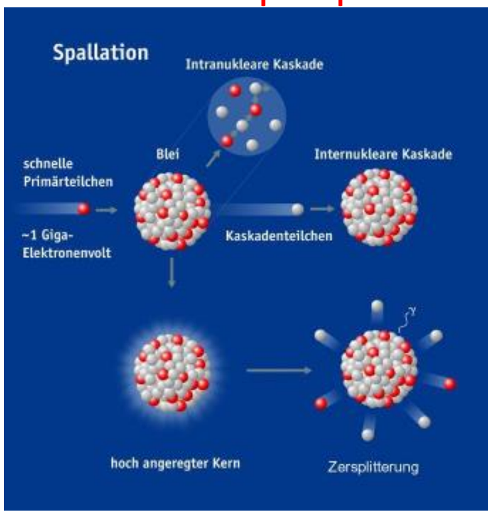
EUROPEAN SPALLATION SOURCE

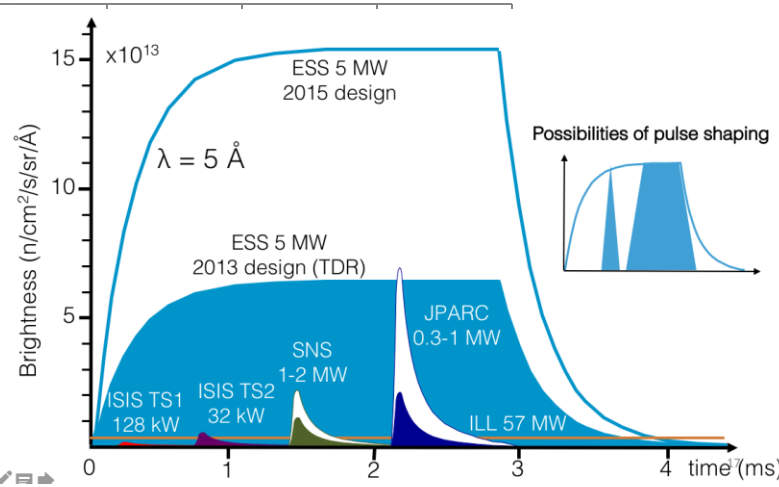



Fission of uranium in nuclear reactor
2-3 neutrons per process




Spallation on target using proton accelerator
30+ neutrons per process



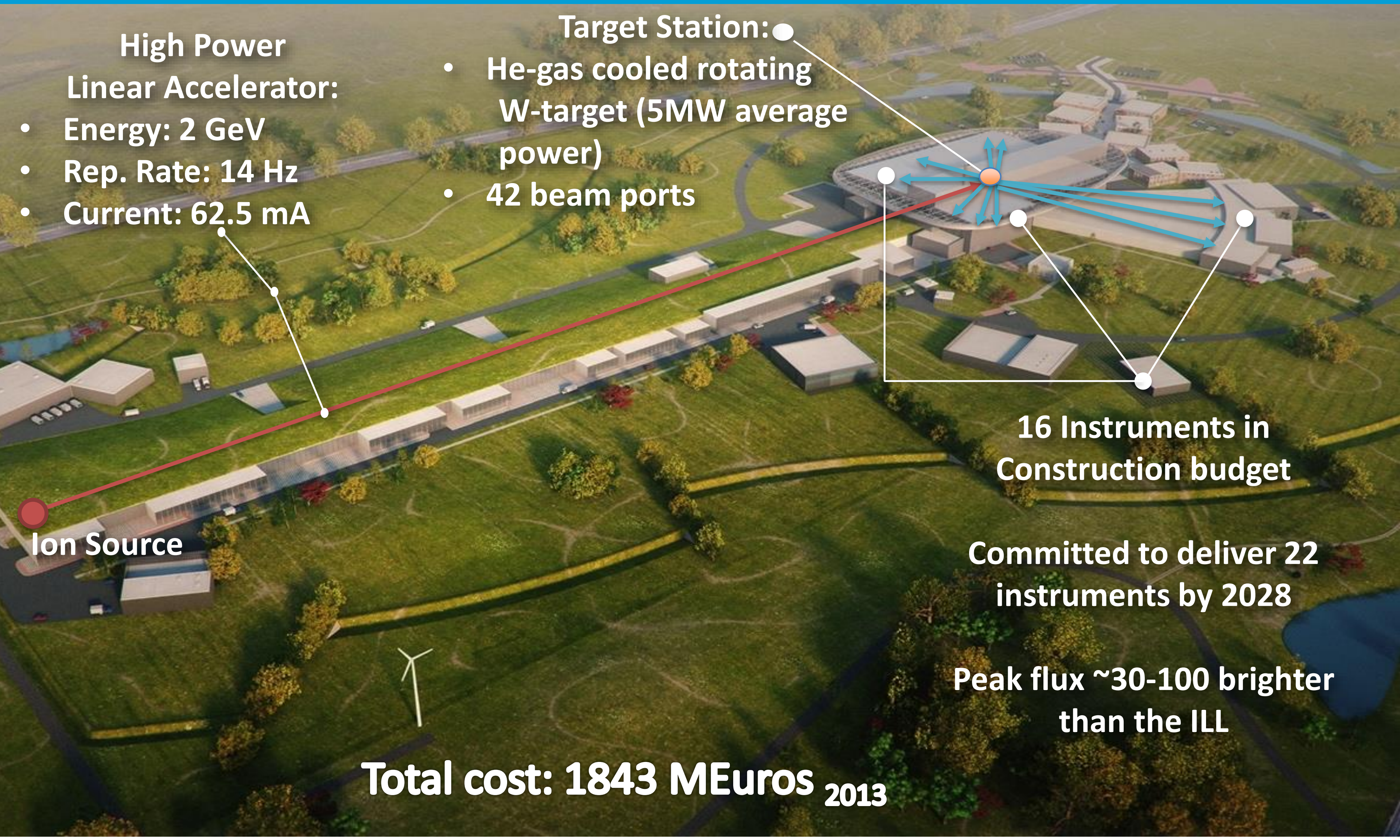




Many research reactors in Eu
Urgent need for a new high flu

- The vast majority of users will
- A large fraction of the users are (approx 2 ms, 20 Hz)
- Existing short pulse sources (I and imminent future need of sh

EUROPEAN SPALLATION SOURCE

# Basic design principle



# ESS employees (as of March 2018)

EUROPEAN SPALLATION SOURCE

COMMUNICATIONS AND EXTERNAL RELATIONS DIVISION (4070)
A. Weeks
HEAD OF DIVISION

M-L. Ainalem
M. Armstrong
C. Bocchetta
A-C. Joubert
D. Stric
J. Tierney
J. Öberg

C. Holgersson
PERSONAL ASSISTANT

**EUROPEAN SPALLATION SOURCE**
**EUROPEAN RESEARCH INFRASTRUCTURE CONSORTIUM** (1000)

| | |
|---|---|
| L. Börjesson | Council Chair |
| B. Vierkorn-Rudolph | Council Vice Chair |

J. Womersley
Director General

| | |
|---|---|
| SENIOR EXECUTIVE ASSISTANT | K. Hélène |
| HEAD OF HOST STATES RELATIONS | P. Kinhult |
| PROJECT MANAGER | J. Haines |
| TECHNICAL COORDINATORS | M. Arai, F. Mezei (C), S. Kennedy |

ADMINISTRATION & FINANCE COMMITTEE
B. Dormy, Chair
N. Pratt, Vice-Chair

SCIENCE ADVISORY COMMITTEE
A. Meyer, Chair
S. McClain, Co-Chair

TECHNICAL ADVISORY COMMITTEE
P. Lebrun, Chair
P. Ferguson, Co-Chair
J. Galambos, Co-Chair

IN-KIND REVIEW COMMITTEE
M. Marazzi, Chair

COMMITTEE ON EMPLOYMENT CONDITIONS
L. Börjesson, Chair

ES&H ADVISORY COMMITTEE
P. Berkvens, Chair

CONVENTIONAL FACILITIES ADVISORY COMMITTEE
M. Fallier, Chair

ANNUAL REVIEW
M. Nessi, Chair

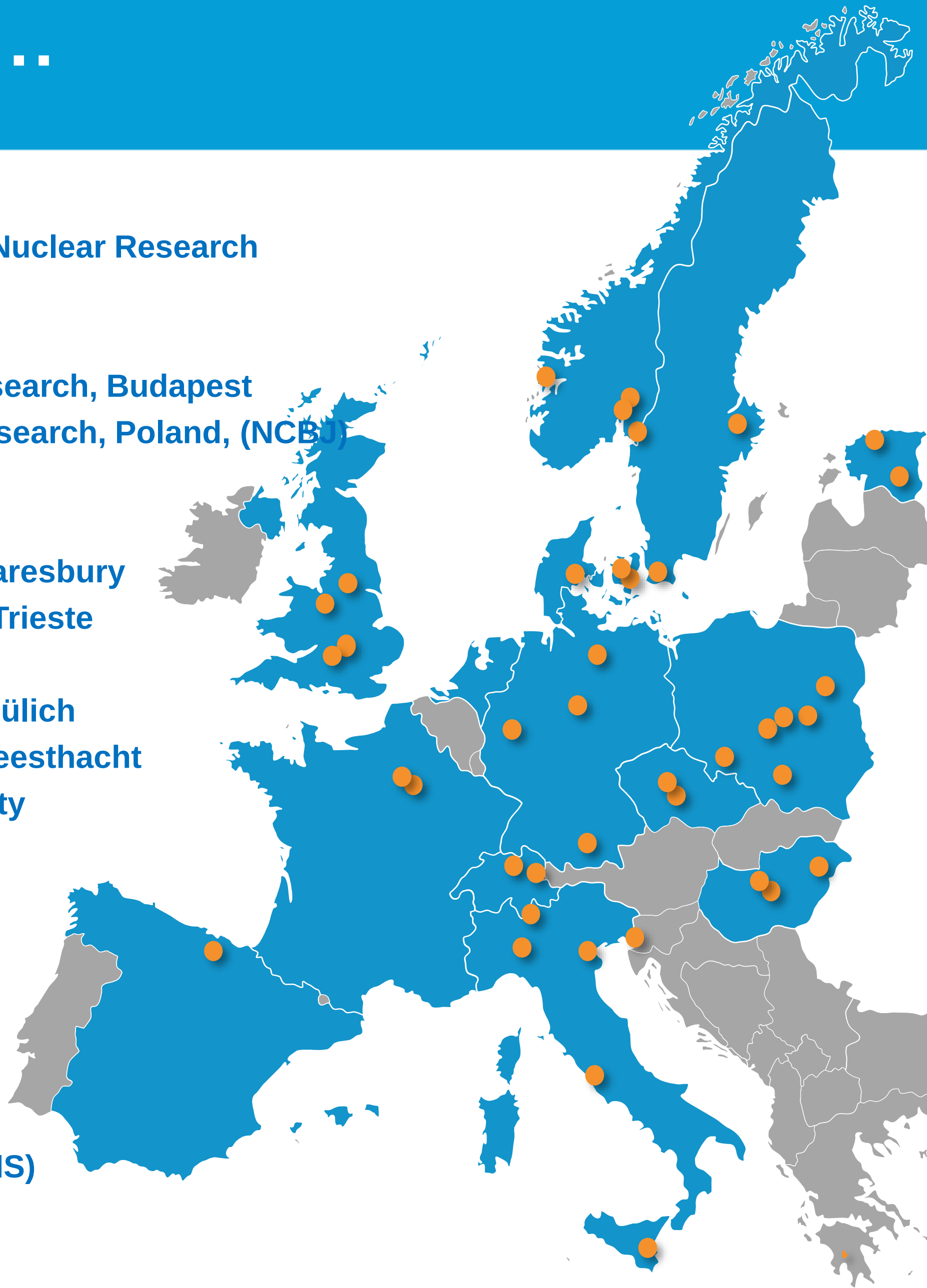
**434**
Employees

**50**
Nationalities

**> 40**
Collaborating Institutions

# ESS in-kind partners make ESS possible…

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 Laboratory, Oxford(ISIS)



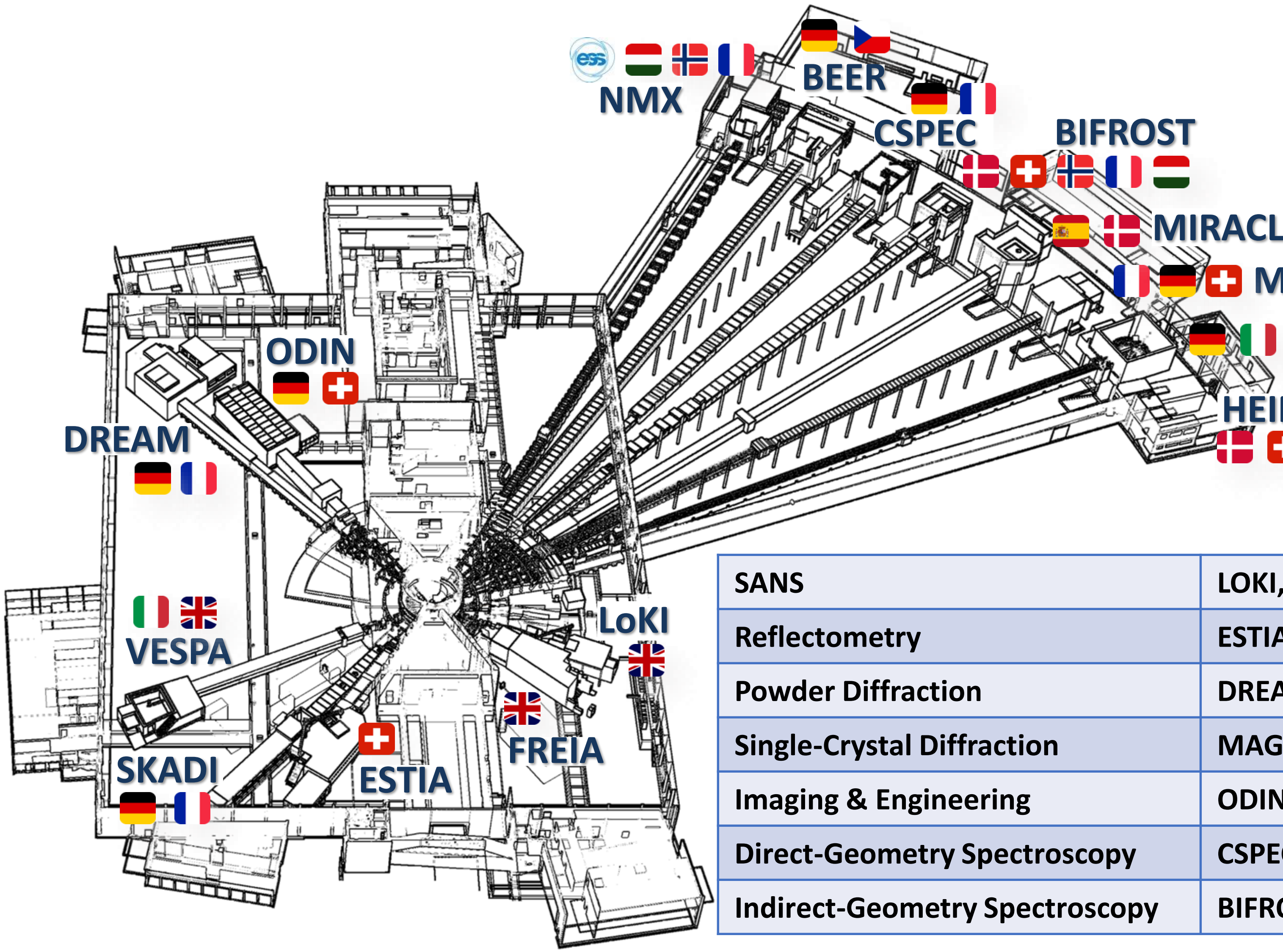
Kopenhagen University
Laboratoire Léon Brilouin (CEA – CNRS – LLB)
Lund University
Nuclear Physics Institute of the ASCR
Oslo University
Paul Scherrer Institute (PSI)
Polska Grupa Energetyczna - PGE
Roskilde University
Tallinn Technical University
Technical University of Denmark
Technical University 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)

# Current Status

🡐 From September 2014, green field

To June 2018, concrete blocks 🡒

# Instrument Suite




| | |
|---|---|
| **SANS** | **LOKI**, *SKADI* |
| **Reflectometry** | **ESTIA**, FREIA |
| **Powder Diffraction** | **DREAM**, HEIMDAL |
| **Single-Crystal Diffraction** | **MAGIC**, *NMX* |
| **Imaging & Engineering** | **ODIN**, **BEER** |
| **Direct-Geometry Spectroscopy** | **CSPEC**, *T-REX* |
| **Indirect-Geometry Spectroscopy** | **BIFROST**, MIRACLES, VESPA |

# Science Drivers for the Reference Instrument Suite

EUROPEAN SPALLATION SOURCE

## Large-Scale Structures

| Instrument | Science areas |
|---|---|
| **Multi-Purpose Imaging ODIN** | life sciences, soft condensed matter, magnetism & superconductivity, engineering & geo-sciences, archeology & heritage conservation |
| **General-Purpose SANS SKADI** | chemistry of materials, soft condensed matter, magnetism & superconductivity, energy research |
| **Broadband SANS LOKI** | life sciences, soft condensed matter |
| Surface Scattering | life sciences, soft condensed matter, chemistry of materials, magnetism & superconductivity |
| **Horizontal Reflectometer FREIA** | life sciences, soft condensed matter, chemistry of materials |
| **Vertical Reflectometer ESTIA** | magnetism & superconductivity, chemistry of materials, energy research, soft condensed matter |

## Diffraction

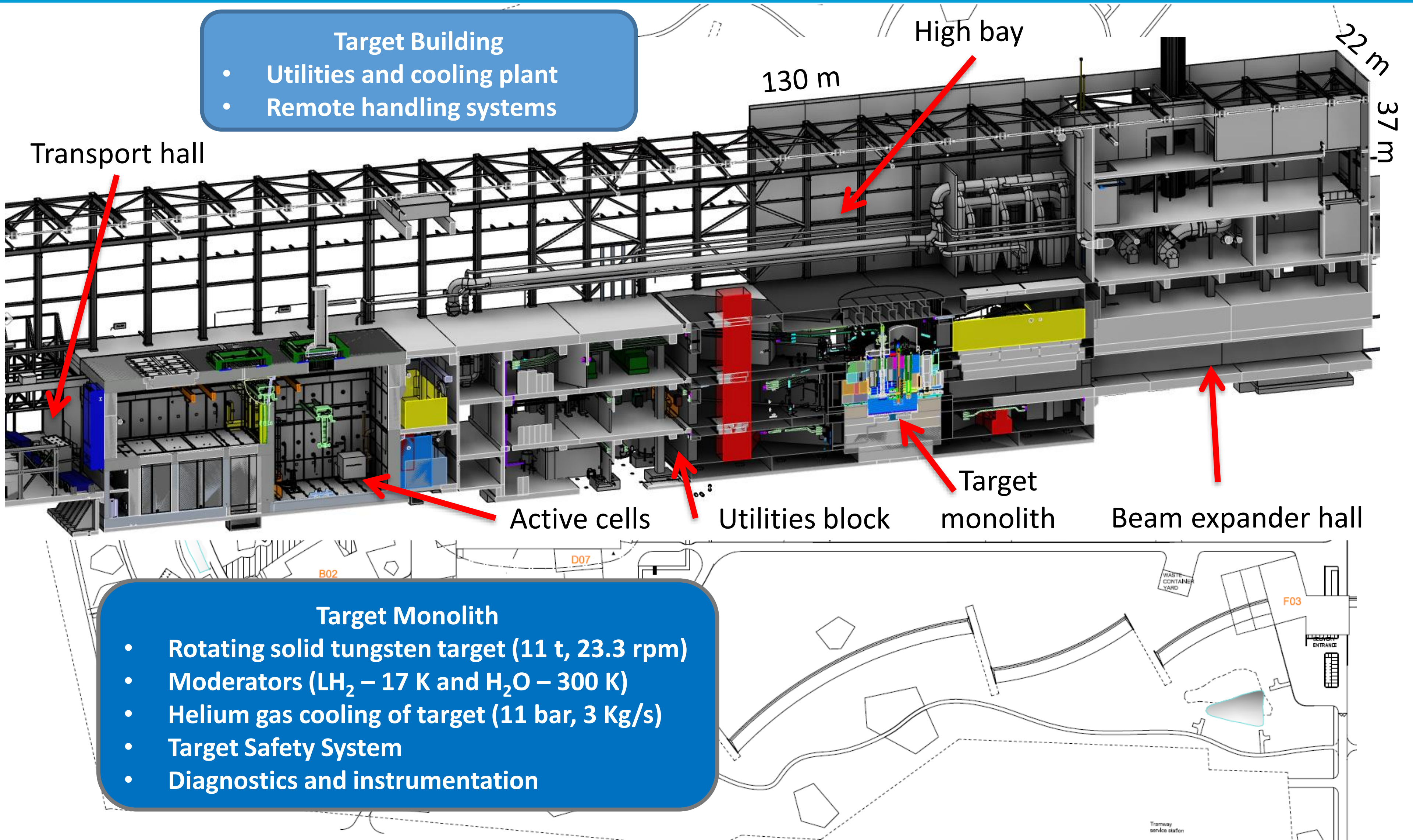
| Instrument | Science areas |
|---|---|
| **Thermal Powder Diffractometer HEIMDAL** | chemistry of materials, energy research, engineering & geo-sciences, magnetism & superconductivity |
| **Bispectral Powder Diffractometer DREAM** | magnetism & superconductivity, chemistry of materials, energy research, engineering & geo-sciences |
| Monochromatic Powder Diffractometer | chemistry of materials, energy research, magnetism & superconductivity |
| **Materials Science Diffractometer BEER** | engineering & geo-sciences, chemistry of materials |
| Extreme Conditions Diffractometer | energy research, magnetism & superconductivity, chemistry of materials |
| **Single-Crystal Magnetism Diffractometer MAGICS** | magnetism & superconductivity, chemistry of materials |
| **Macromolecular Diffractometer NMX** | life sciences, magnetism & superconductivity |

## Spectroscopy

| Instrument | Science areas |
|---|---|
| **Cold Direct Geometry Spectrometer C-SPEC** | life sciences, chemistry of materials, magnetism & superconductivity |
| Wide Bandwidth Direct Geom. Spectrometer VOR | life sciences, soft condensed matter, chemistry of materials, magnetism & superconductivity |
| **Bispectral Direct Geometry Spectrometer TREX** | magnetism & superconductivity, chemistry of materials, energy research |
| **Cold Crystal-Analyser Spectrometer BIFROST** | magnetism & superconductivity, chemistry of materials, energy research, engineering & geo-sciences |
| **Vibrational Spectrometer VESPA** | magnetism & superconductivity, chemistry of materials, energy research |
| **Backscattering Spectrometer MIRACLES** | life sciences, soft condensed matter, chemistry of materials |
| High-Resolution Spin-Echo | life sciences, soft condensed matter, chemistry of materials, energy research |
| Wide-Angle Spin-Echo | life sciences, soft condensed matter, magnetism & superconductivity, energy research |
| Fundamental & Particle Physics | fundamental & particle physics |

- life sciences
- soft condensed matter
- chemistry of materials
- energy research
- magnetism & superconductivity
- engineering & geo-sciences
- archeology & heritage conservation
- fundamental & particle physics

# ESS Target and Target building

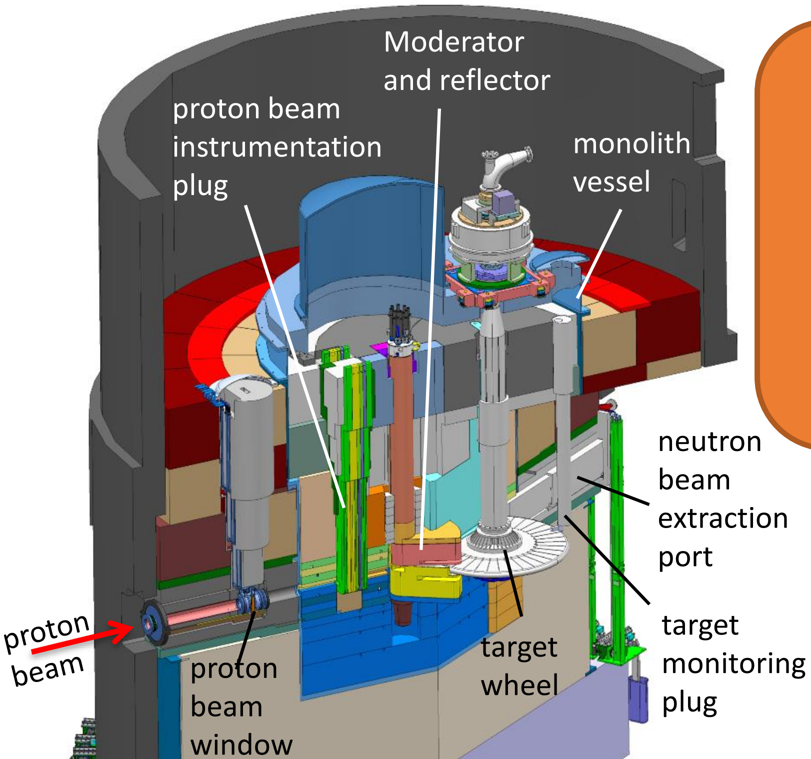



**Target Building**
- Utilities and cooling plant
- Remote handling systems

**Target Monolith**
- Rotating solid tungsten target (11 t, 23.3 rpm)
- Moderators ($LH_2$ – 17 K and $H_2O$ – 300 K)
- Helium gas cooling of target (11 bar, 3 Kg/s)
- Target Safety System
- Diagnostics and instrumentation

# Key features of the ESS Target Station

EUROPEAN SPALLATION SOURCE




## Target Safety System

- Monitors target coolant flow, pressure and temperature, monolith pressure, & target wheel rotation
- Prohibit beam on target if parameters are outside specified limits

## Helium cooling of target material

- Mass flow 3 kg/s
- Pressure 11 bar
- Temperature inlet/outlet 40 °C/240 °C

## Rotating solid tungsten target

- 36 sectors
- Mass, total 11 tonnes, whereof 3 tonnes of W
- Rotates 23.3 rpm, synchronized with pulsed proton beam 14 Hz

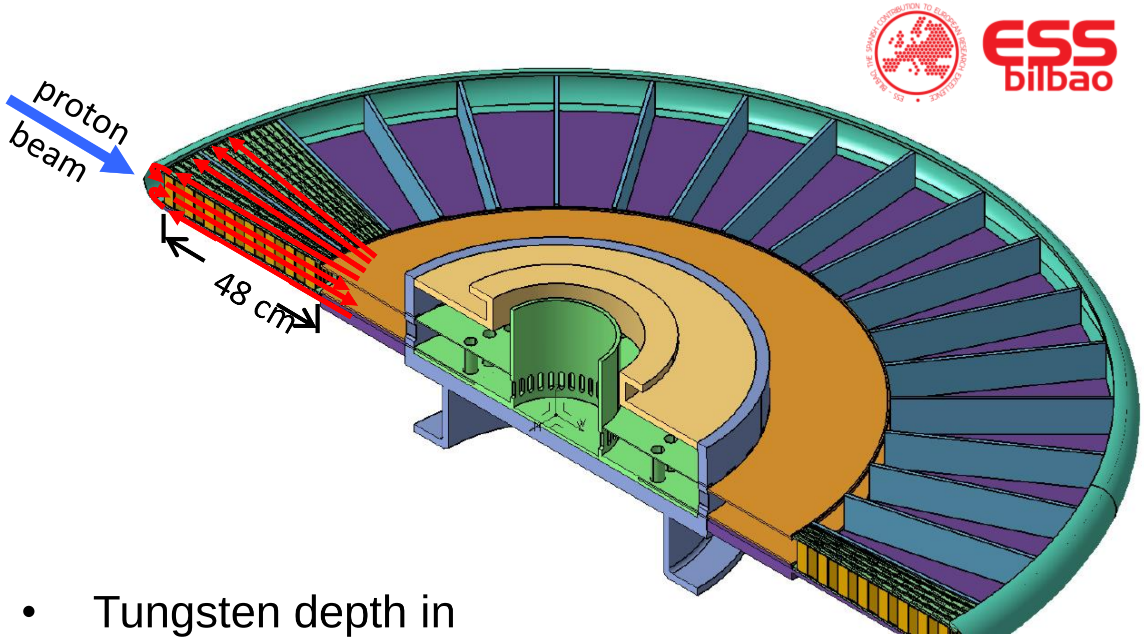
## Moderators

- Provisional locations of moderators above and beneath the target wheel, i.e. monolith centre
- 1st MR plug exploits the upper space, offering:
  - ✓ Cold, 30 mm high, liquid $H_2$ moderators, 17 K
  - ✓ Thermal, 30 mm high, $H_2O$ moderator, 300 K

## Diagnostics and instrumentation

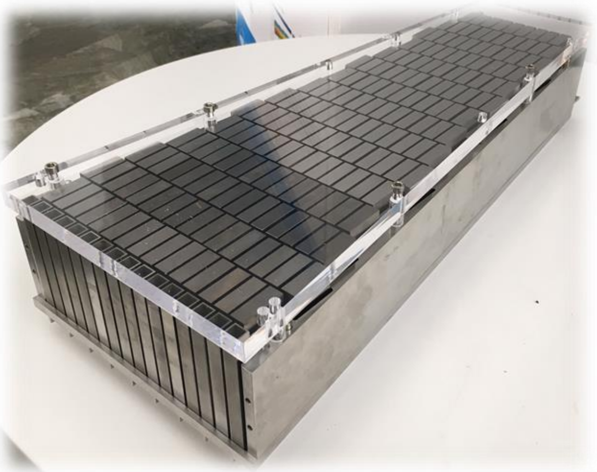
- Controlled and integrated commissioning and operation of the accelerator and target
- Fluorescent coating of PBW and target front face
- Optical paths, grid profile monitor, aperture monitor
- Wheel monitoring including position, temperature, vibration, as well as internal structure

# The Target disk has 36 sectors of tungsten-filled cassettes




*Tungsten bricks*

- Tungsten depth in
  the proton beam direction is 45 cm
- The range of a 2-GeV proton in tungsten is 74 cm
- Brick dimensions: 10 W x 30 D x 80 H mm$^3$
- 190 bricks per sector, 6840 bricks in total
- Helium flows
  - radially outward above and below the cassette,
  - reverses direction at the wheel rim,
  - and returns through the tungsten



*Cassette*

# Thank you for your interest!

- Questions?
- Life sciences @ ESS : Zoë Fisher zoe.fisher@esss.se
- Protein crystallography: Esko Oksanen esko.oksanen@esss.se
- Neutron reflectometry: Hanna Wacklin hanna.wacklin@esss.se
- Small angle scattering: Andrew Jackson andrew.jackson@esss.se
- Imaging: Robin Woracek robin.woracek@esss.se
- Web information on soft matter, life sciences at ESS:
- https://europeanspallationsource.se/page/soft-condensed-matter-life-science