EUROPEAN
SPALLATION
SOURCE

ESS towards First Neutron Production

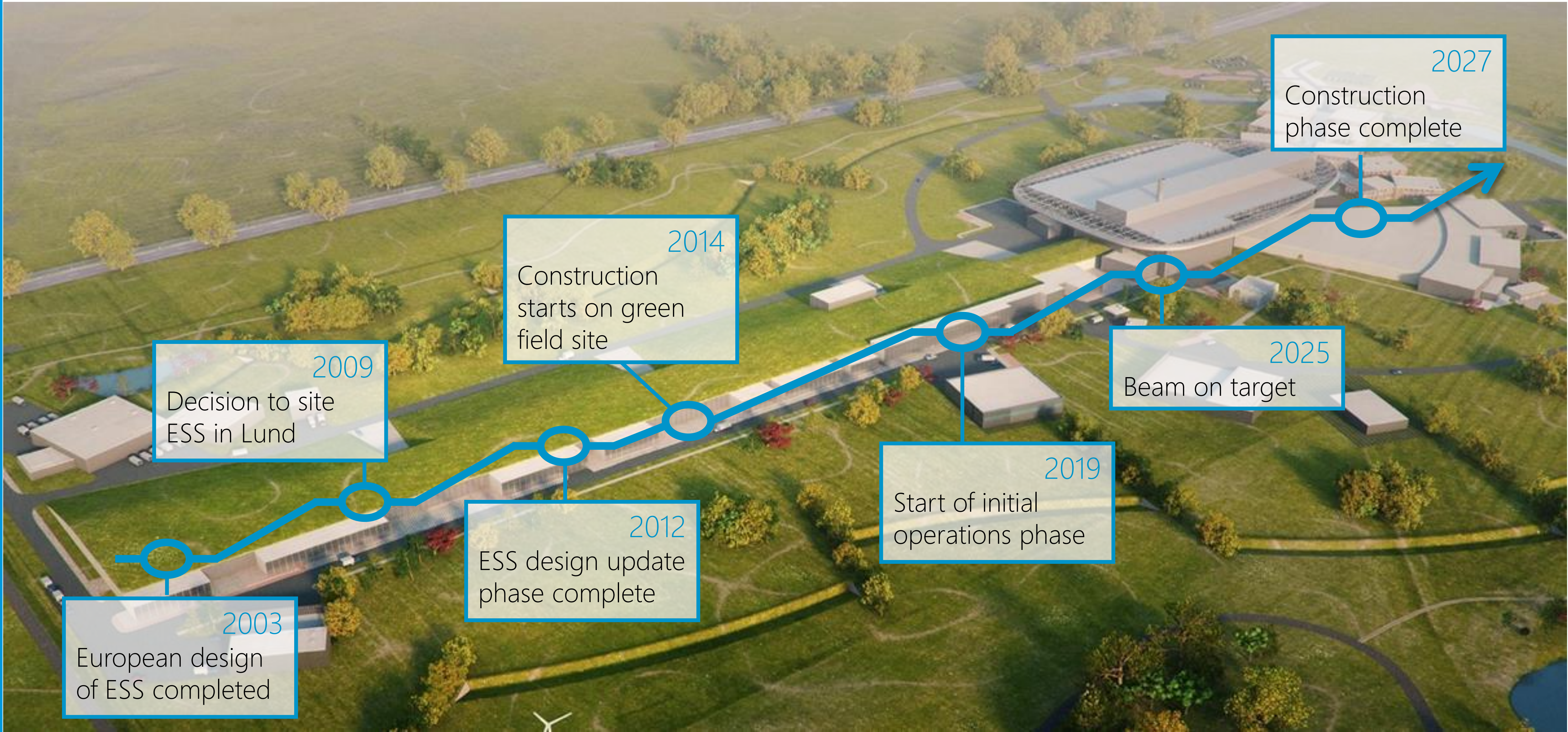
HÅKAN DANARED, FAIR/GSI, 2 JULY 2024

Outline of presentation

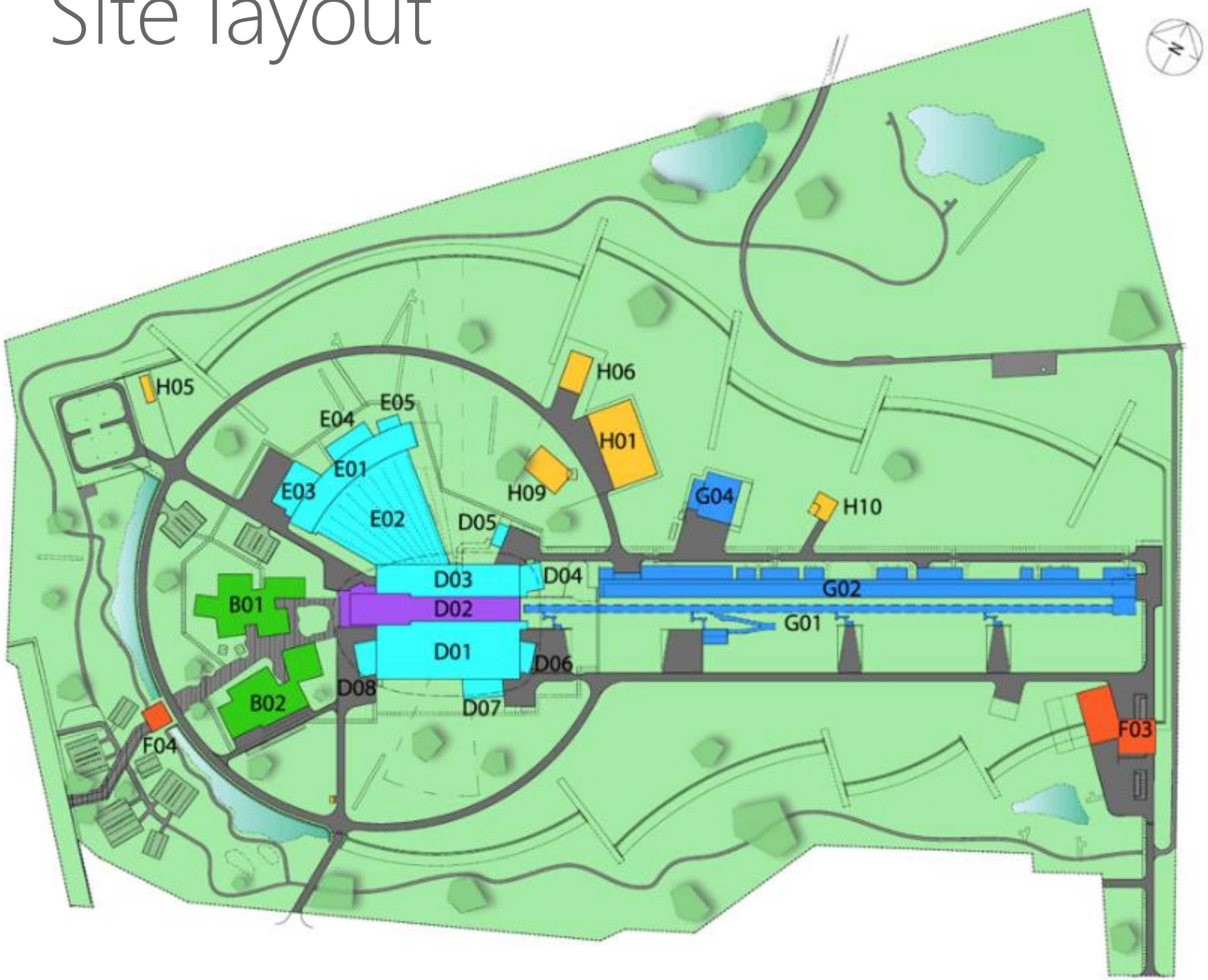
1. Introduction to ESS
2. Why a neutron spallation source
3. Accelerator
4. Target
5. Instruments


Target station:
• Rotating W target
• 36 sectors
• 23 rpm
• Cooled by He gas
• 42 beam ports
Linear proton accelerator:
• Energy: 2 GeV
• Current: 62.5 mA
• Pulse length: 2.86 ms
• Rep. rate: 14 Hz
• Average beam power: 5 MW
• Currently funded: 2 MW
Instruments:
• 5-6 at BOT (beam on target)
• 15 in construction budget
• 22 in total scope
• Plans for programme in fundamental physics
Estimated project cost: 3685 M€
Based on EV close to 80% complete
Contingency on ETC approx. 15%

The ESS journey



Site layout



Accelerator
G01 Accelerator Tunnel
G02 Klystron Gallery
G04 Cryo Compressor Building

Target
D02 Target Building

Experimental Halls
D01 Experimental Hall 1
D03 Experimental Hall 2
D04 Labs, Hall 2
D05 Substation
D06 Substation
D07 Labs, Hall 2
D08 Labs, Hall 2

E01 Experimental Hall 3
E02 Beam Line Gallery
E03 Labs, Hall 3
E04 Labs, Hall 3
E05 Substation

Utilities
H01 Central Utility Building
H05 Substation
H06 Substation
H09 Waste Building
H10 Sprinkler Building

Service
F03 Logistic Center
F04 Entrance Building

Campus
B01 Office Building
B02 Lab/Workshop Building

ERIC with 13 member states

Host countries Sweden and Denmark

Construction 47.5%

Cash investment ~ 97%

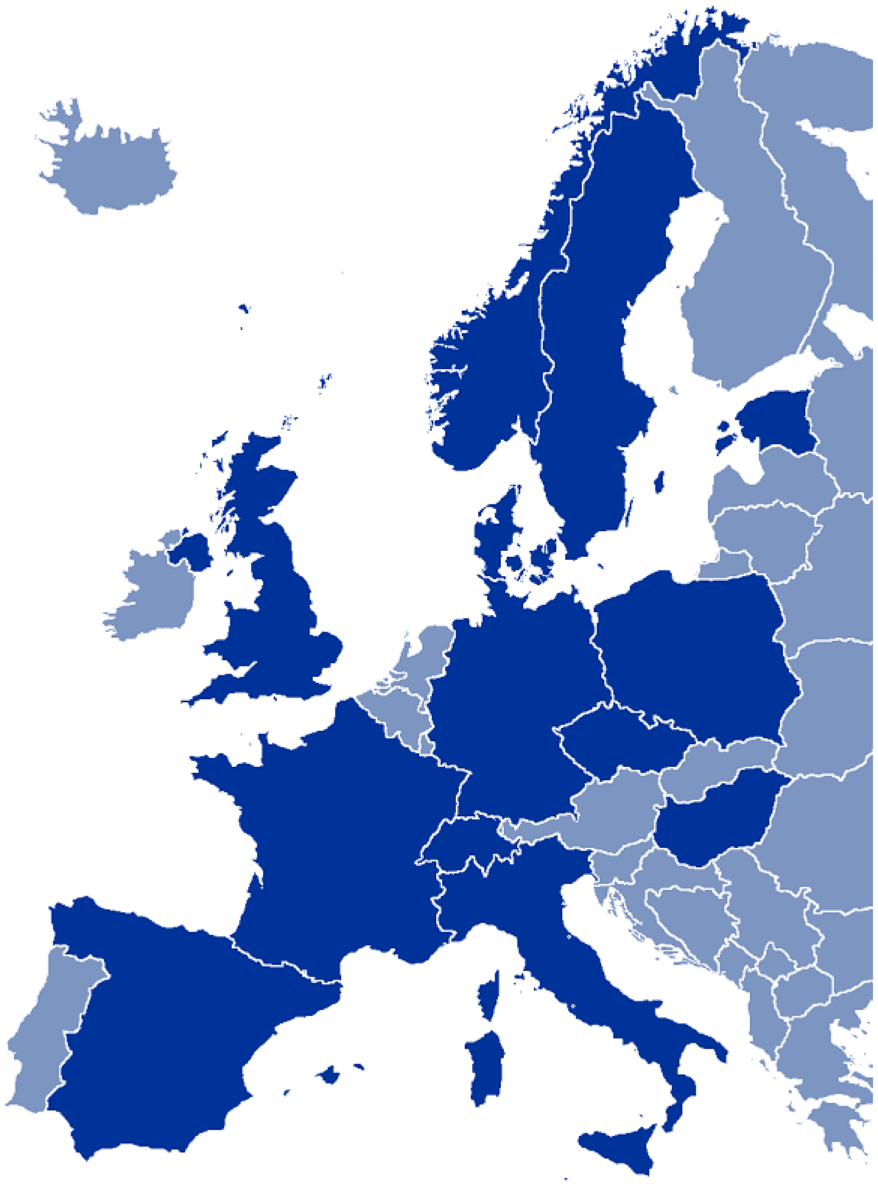
Operations 15%

Non-host member countries

Construction 52.5%

In-kind deliverables ~ 70%

Operations 85%



In-Kind Partners for the Accelerator

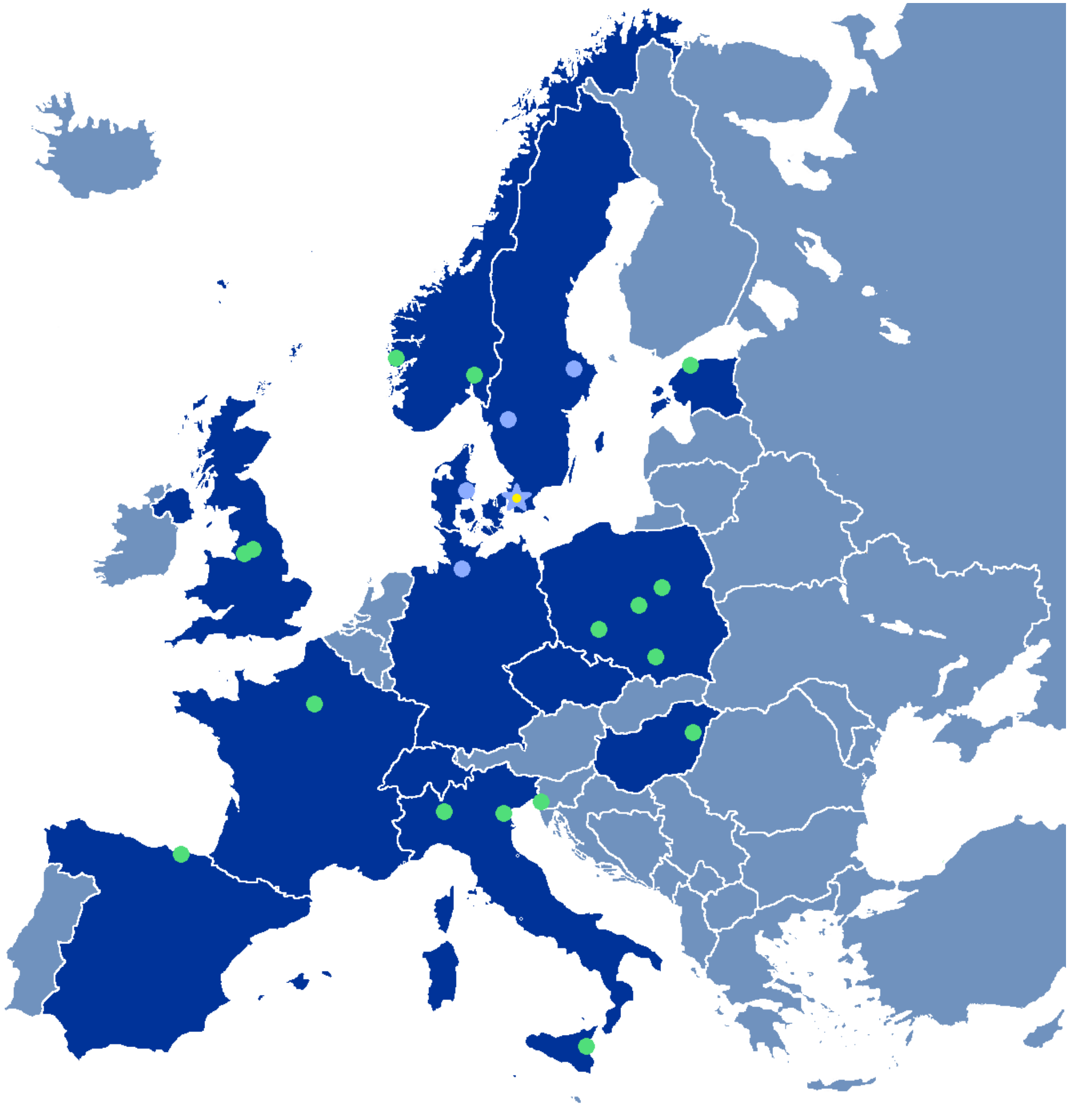
Providing services and components for >50% of the construction budget

In-kind (main contributions)

ATOMKI (RF-Local Protection System)
CEA (RFQ, Elliptical cavities and cryomodules, Diagnostics)
CNRS (Spoke cavities and cryomodules, Cryogenic distribution)
Cockcroft Inst (Diagnostics)
Daresbury Lab (High-beta cavities, Vacuum)
Elettra (Spoke RF, Magnets, Magnet power supplies, Diagnostics)
ESS-Bilbao (Medium-energy beam transport, Warm-linac RF)
Huddersfield Univ (RF distribution system)
IFJ PAN (Installation services)
INFN Catania (Ion source, Low-energy beam transport)
INFN Legnaro (Drift-tube linac)
INFN Milan (Medium-beta cavities)
Lodz UT (Low-level RF)
NCBJ (LLRF, Gamma blockers)
Tallinn UT (Modulator prototype, Diagnostics)
Univ Bergen (Seconded staff)
Univ Oslo (Diagnostics)
Warsaw UT (Low-level RF)
Wroclaw UST (Cryogenic distribution system)

Collaboration contracts

Aarhus Univ (Beam delivery system)
DESY (Diagnostics)
Lund Univ (Low-level RF, RF)
Uppsala Univ (Spoke cryomodule test stand)
Univ West Trollhättan (Diagnostics)



Neutron science

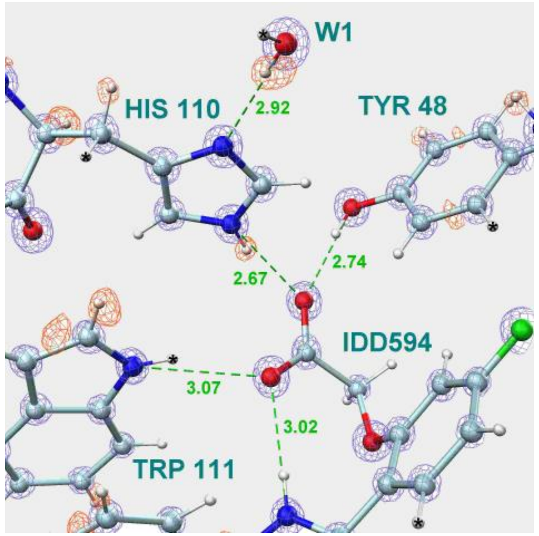
Why neutrons?

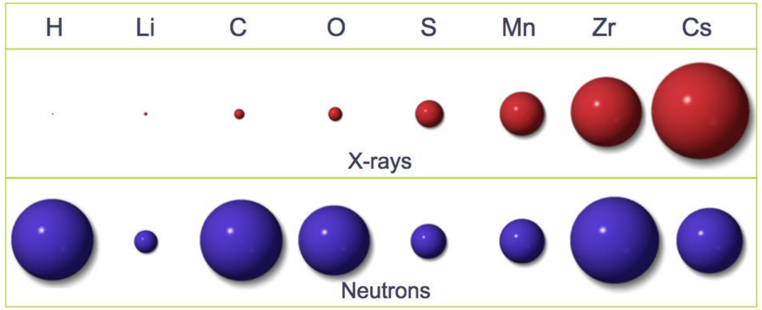
Charge neutral: Deeply penetrating, probe bulk of materials, even inside cryostats, magnets,...

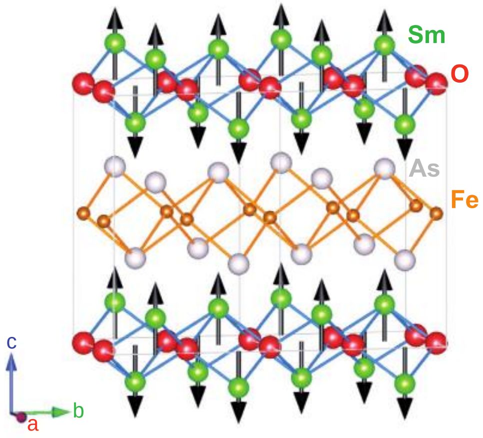
Nuclear interaction: Scattering cross section depends on isotope, not Z, and is high for hydrogen. Sensitivity to light elements.

Mass: Thermal neutrons have wavelengths similar to interatomic distances and energies of elementary excitations of solids.

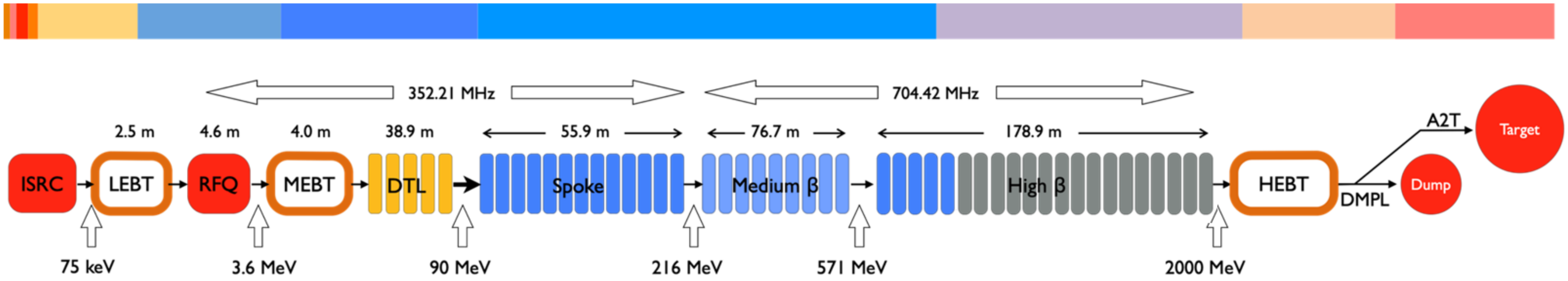
Spin: Makes neutrons a probe for magnetic structure.







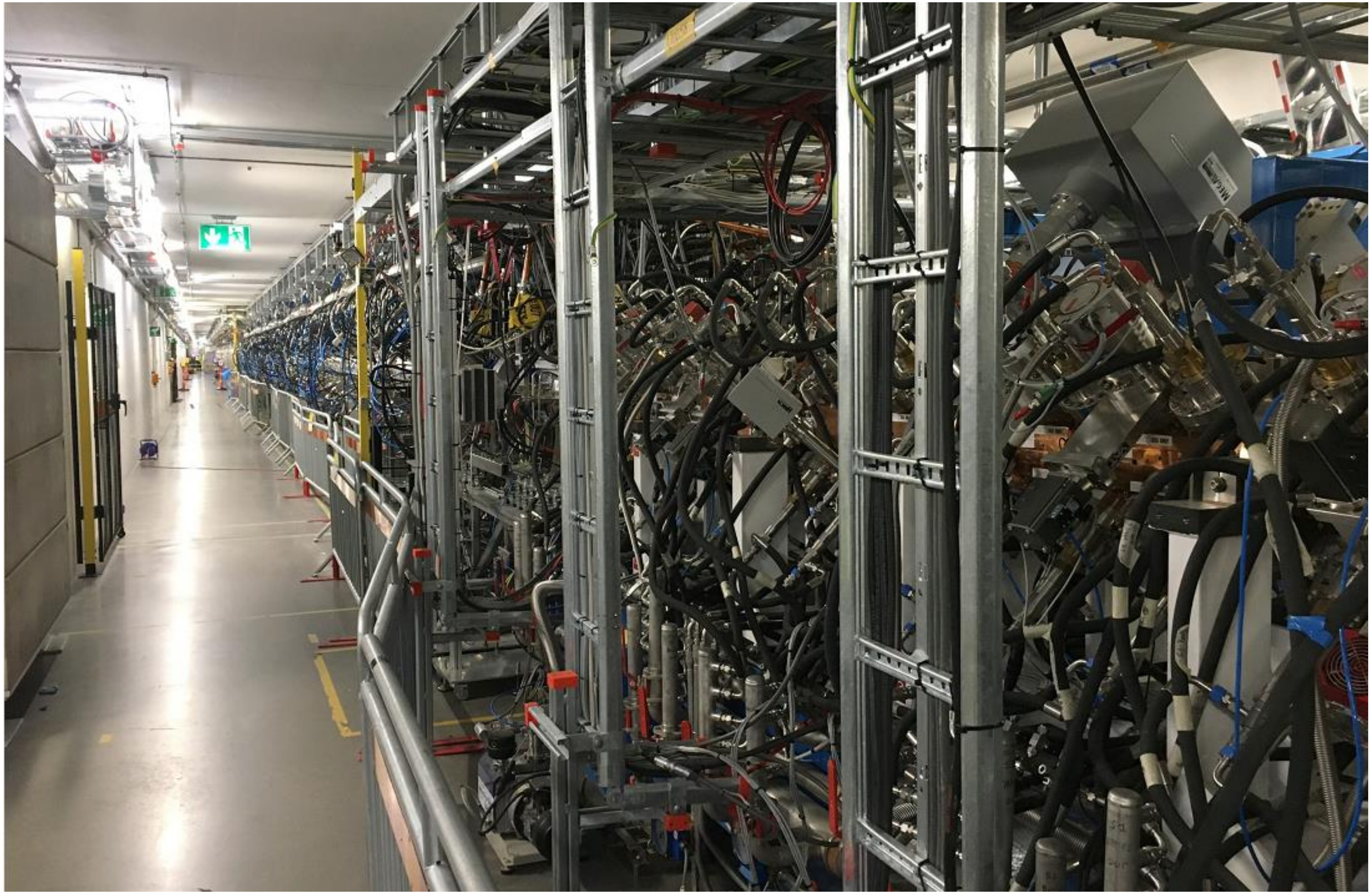
High-power 5 MW proton accelerator



- Designed and built by a collaboration of 23 European institutes and universities
- More than 50% of total accelerator budget delivered as in-kind contributions
- ESS responsibility to install, test, and commission in-kind deliverables
- Beam On Target milestone requires capability for 1.4 MW at 571 MeV with nominal pulse structure
- Start Of User Operation requires capability for 2 MW at 870 MeV with nominal pulse structure*
- Remaining cryomodules will be installed but their RF sources will require additional funding
- Full scope is 5 MW at 2 GeV with 2.86 ms long pulses at 14 Hz

*) Since we are ahead of the plan with the accelerator, we got approval last autumn for installation of additional cryomodules before BOT

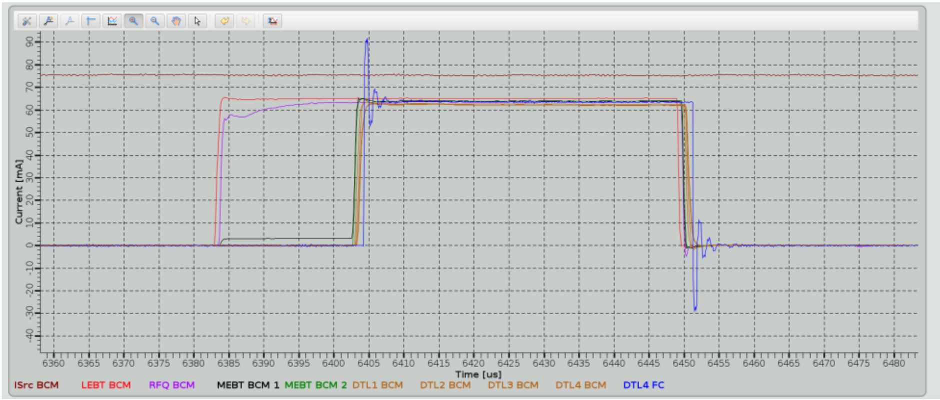
Linac



Ion Source and LEBT

RFQ and DTL


SKANSKA ESS


Current [mA]
Time [us]
6360
6365
6370
6375
6380
6385
6390
6395
6400
6405
6410
6415
6420
6425
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6450
6455
6460
6465
6470
6475
6480
ISrc BCM
LEBT BCM
RFQ BCM
MEBT BCM 1
MEBT BCM 2
DTL1 BCM
DTL2 BCM
DTL3 BCM
DTL4 BCM
DTL4 FC

Superconducting linac, spoke section

Superconducting linac, elliptical section

Klystron gallery: RF sources

Cryoplants and cryogenics

Accelerator installation

- 869 racks to fill
- > 15,000 m cable trays
- > 900,000 m cables
- 49,804 cable terminations
- 17,496 m cooling-water pipes
- 5,000 m waveguides with 450,000 bolts
- Steel and concrete radiation sheilding

All carefully planned and documented, performed with strictest quality control

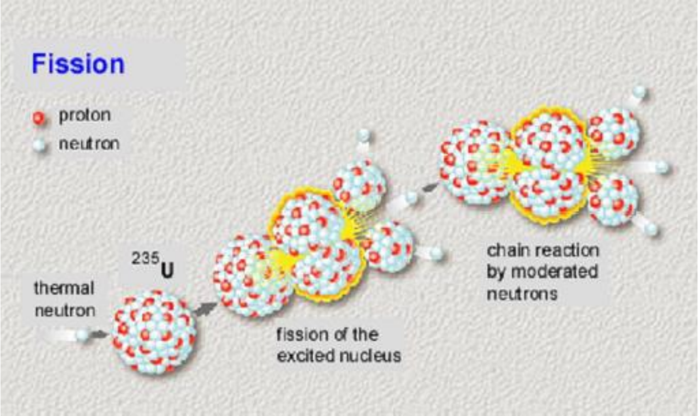
Spallation

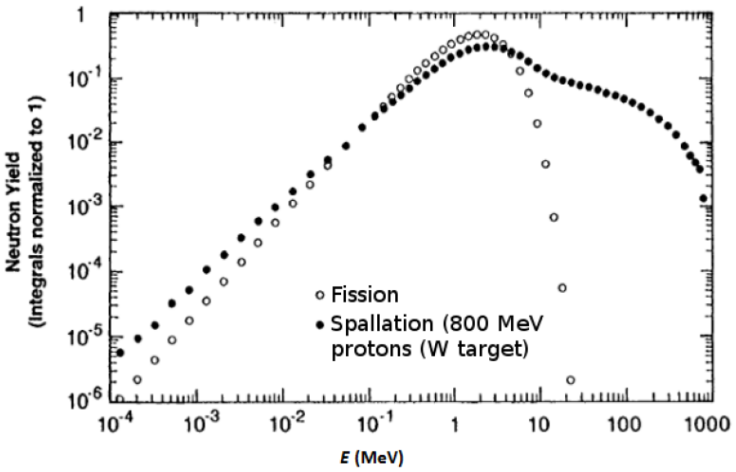
Spall

1. To break into fragments or small pieces
2. To reduce, as irregular blocks of stone, to an approximately level surface by hammering

Fission of uranium in a reactor

2-3 neutrons per event

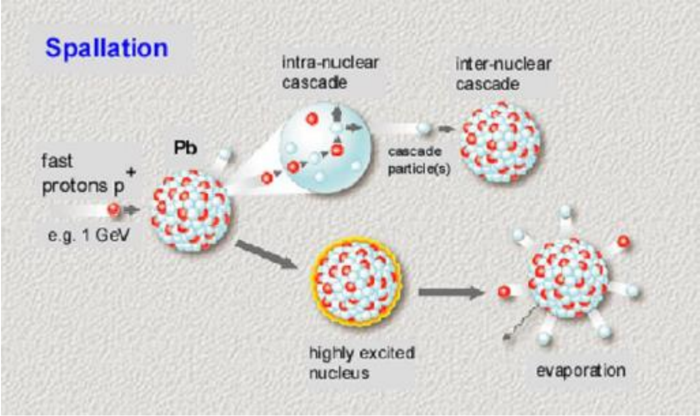




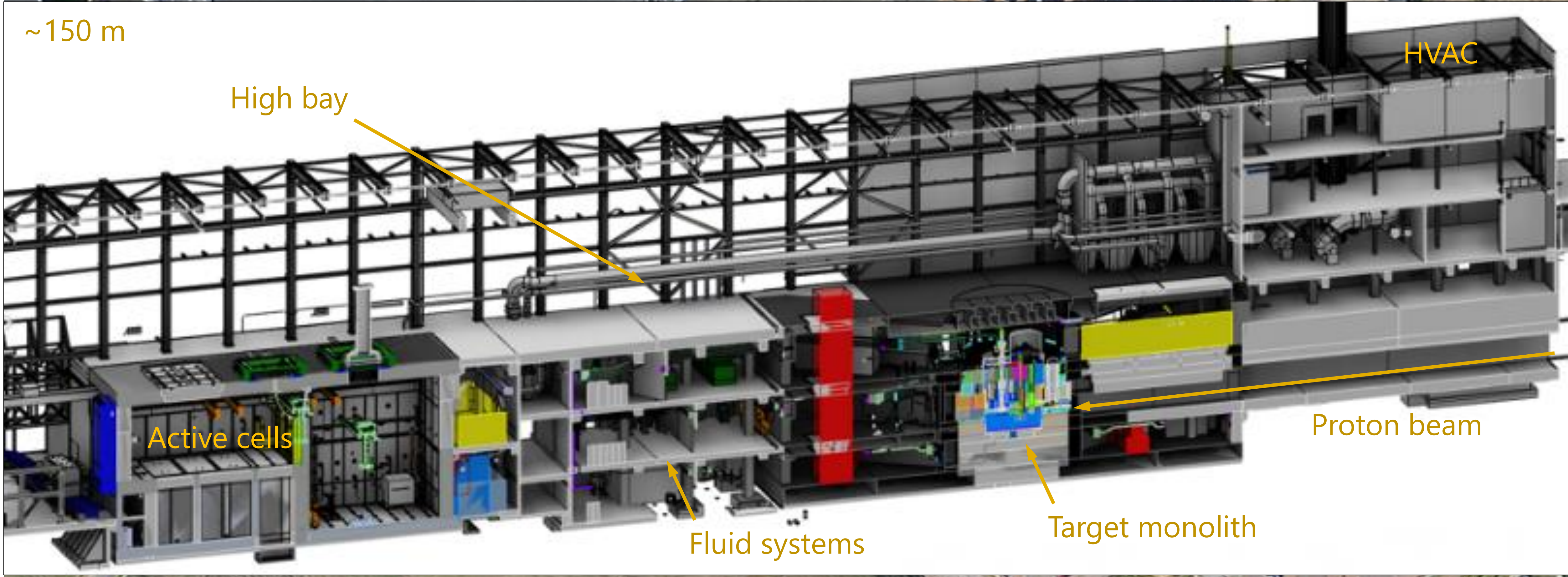
D. Král, Brno

Spallation using proton accelerator

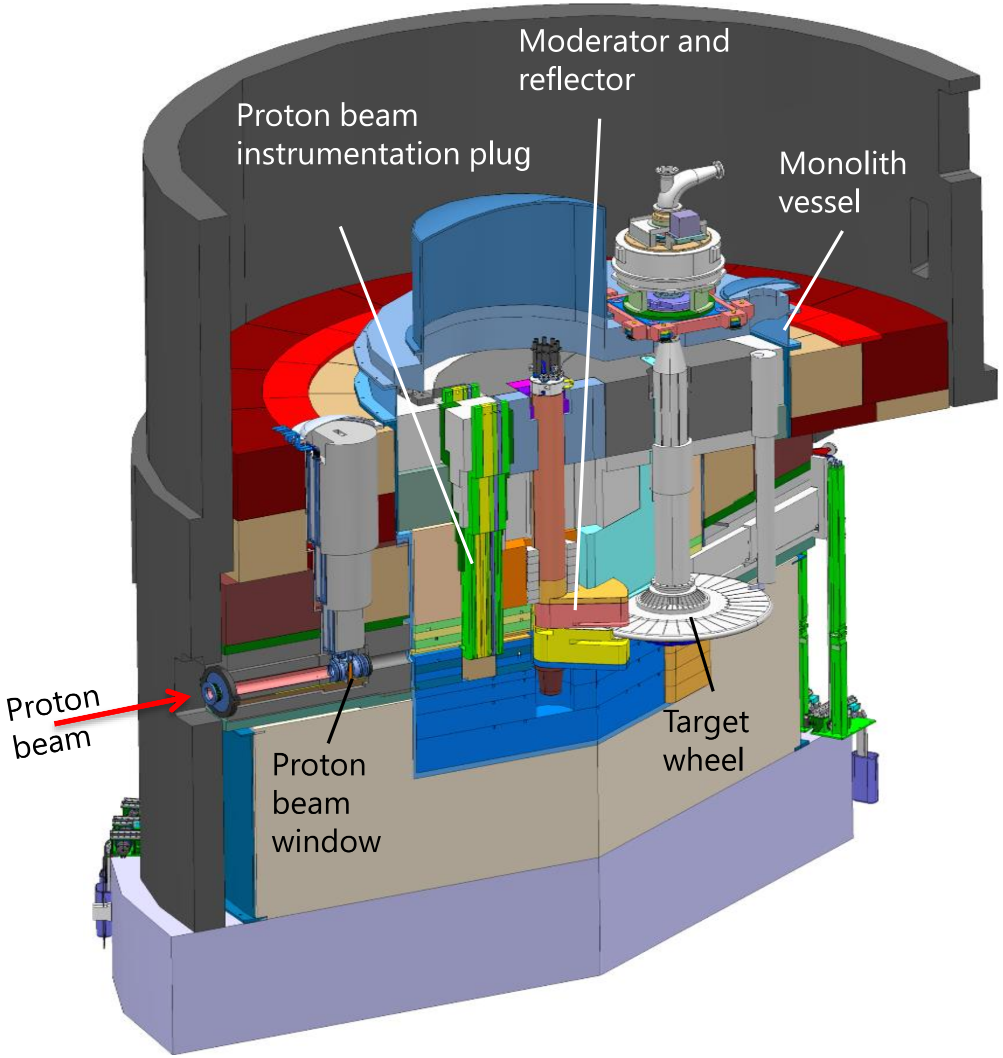
30+ neutrons per event, approx. proportional to beam energy



Target


~150 m
High bay
HVAC
Active cells
Proton beam
Fluid systems
Target monolith

Target monolith



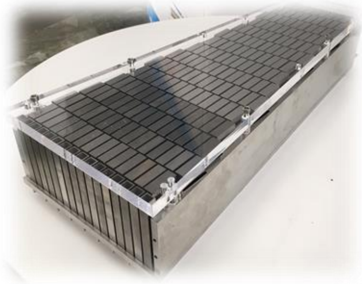
Rotating solid tungsten target

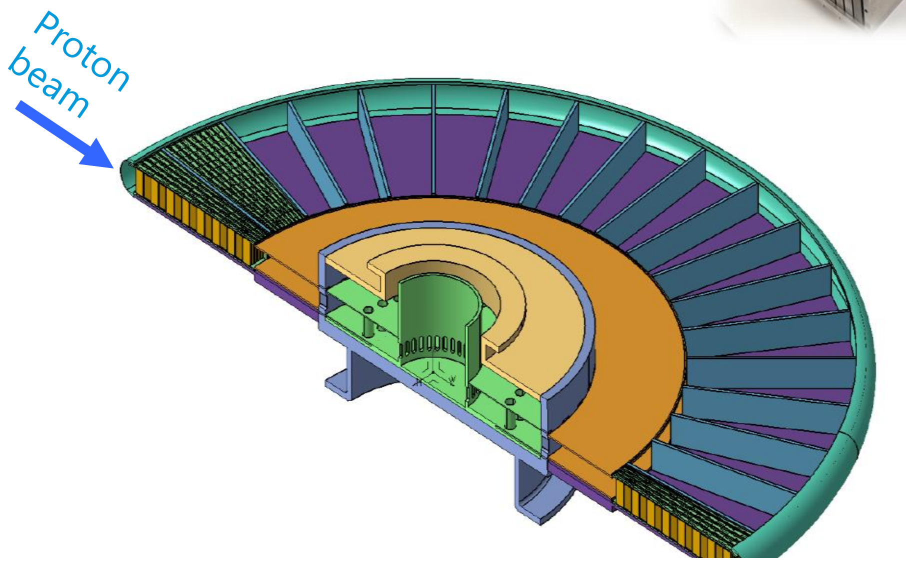
36 sectors

11 tonnes (3 tonnes of tungsten)

3 kg/s gaseous helium at 3 bar

40/240°C inlet/outlet temperature





Energy per pulse at 5 MW: 357 kJ

Target wheel and moderator/reflector

Target vessel, neutron beam ports

Proton beam window plug

Target wheel installed

Target wheel hanging from high-bay crane

Moderator/reflector

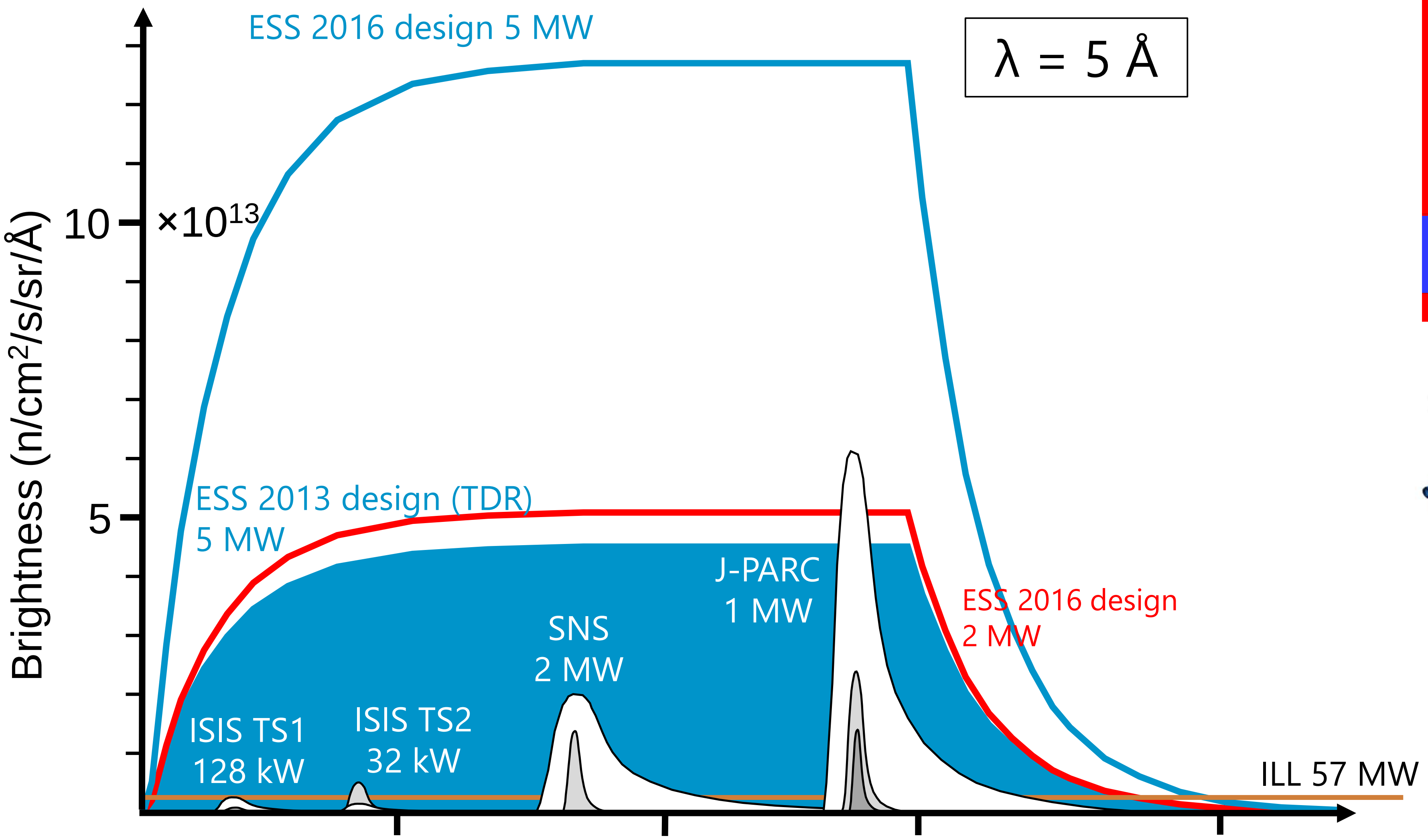
Active cells

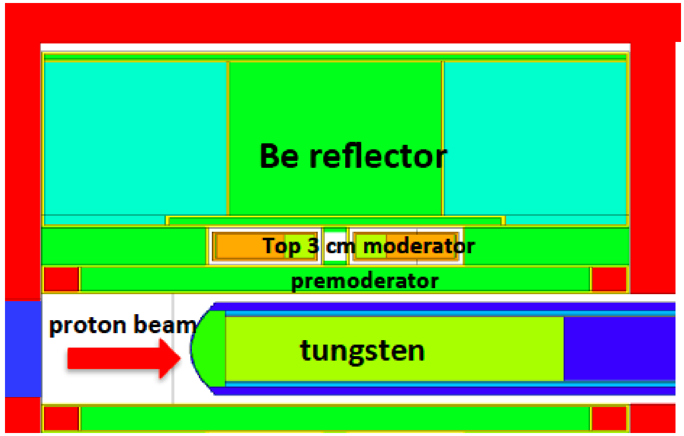
Maintenance cell

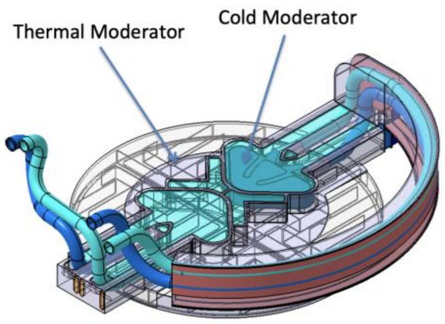
Process cell

Neutron moderators

Long pulse/short pulse



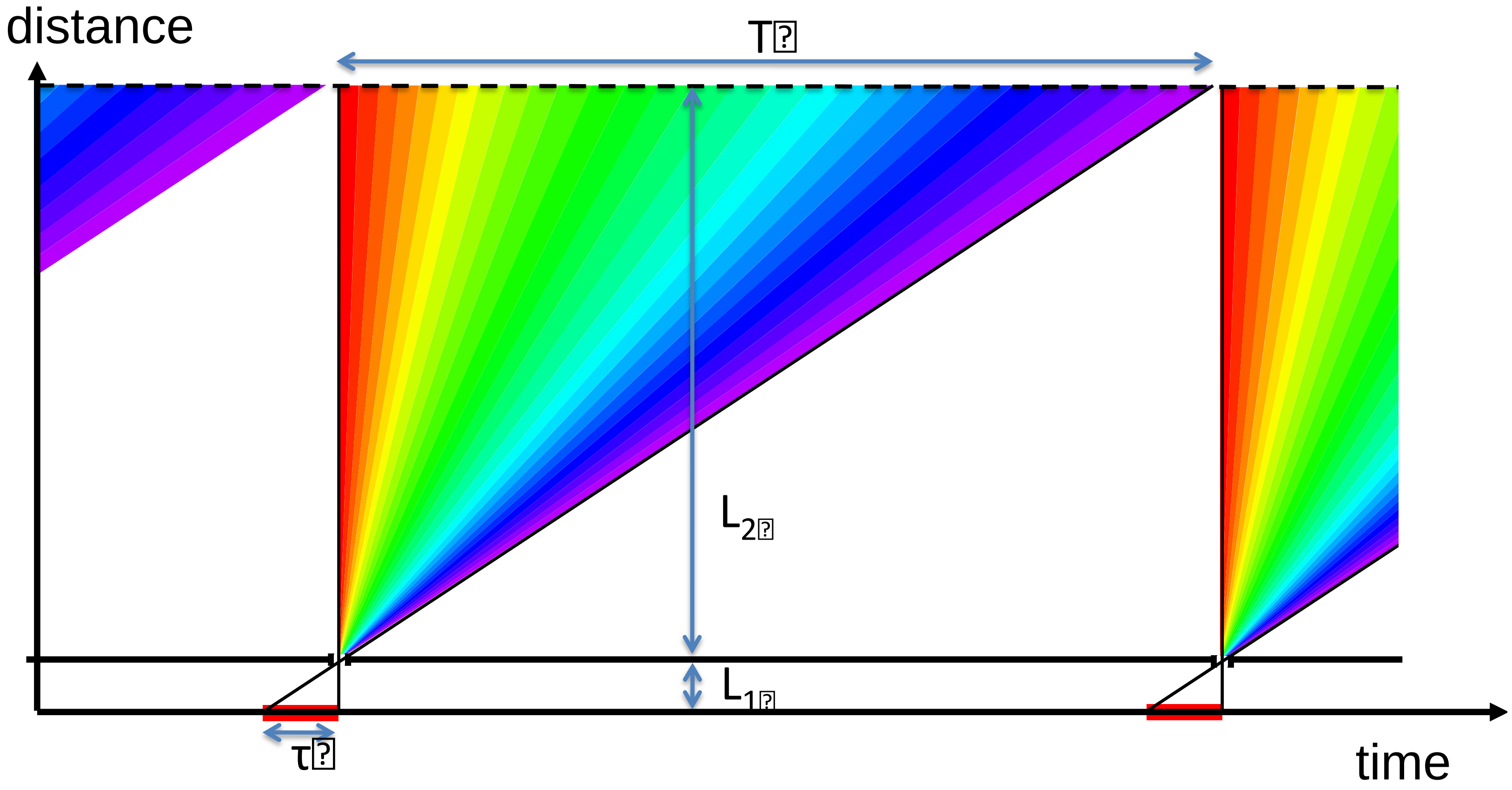




"Butterfly" moderator

Pulse structure/choppers/building layout

$T/\tau = 25 \Rightarrow L_2/L_1 = 25$
$L_1 = 6.3 \text{ m} \Rightarrow L_2 = 157.5 \text{ m}$ $\Rightarrow \Delta\lambda = 1.8$ Å

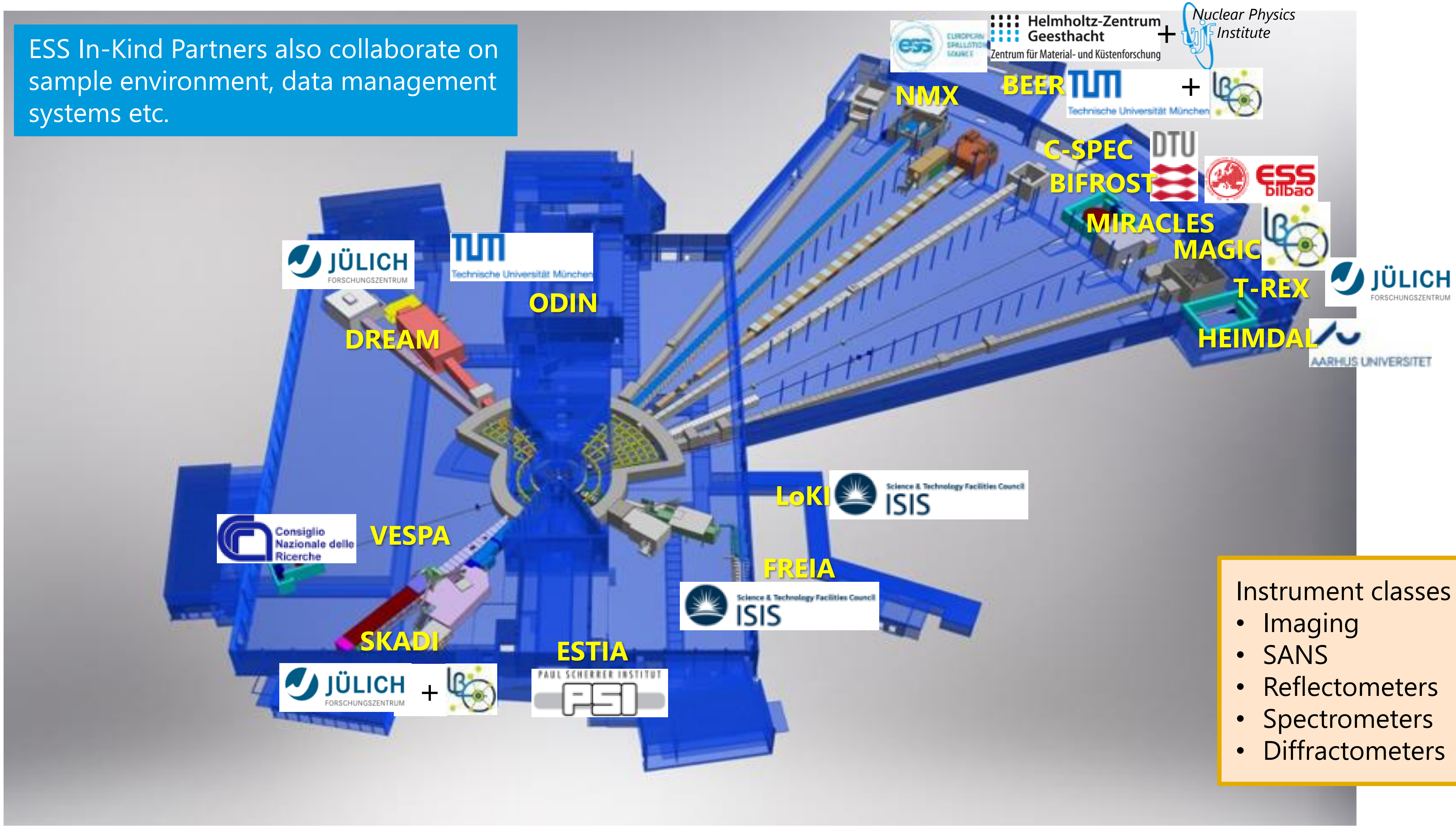



"Generic" chopper

Neutron instruments

With lead partners for construction

ESS In-Kind Partners also collaborate on sample environment, data management systems etc.

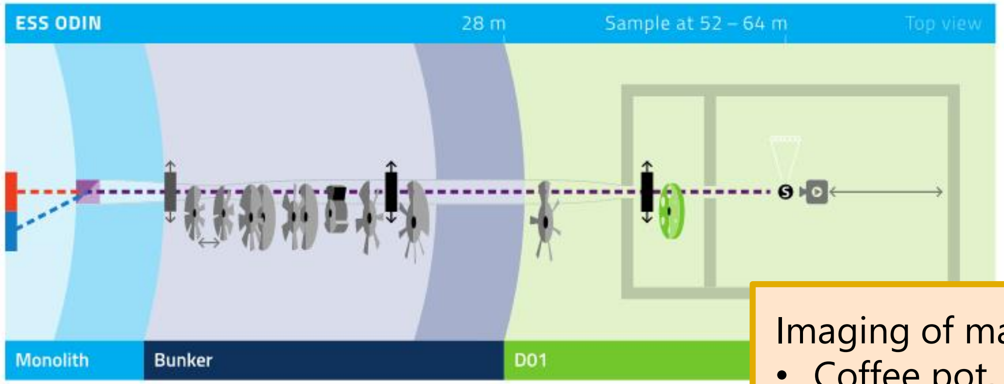


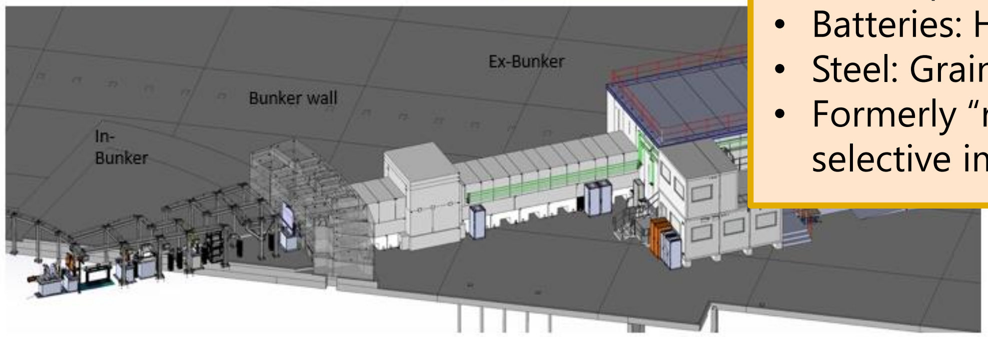
Instrument classes

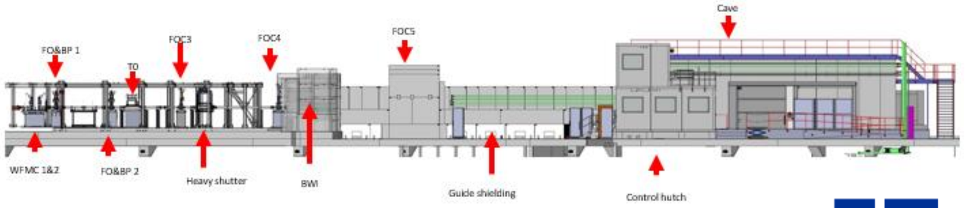
- Imaging
- SANS
- Reflectometers
- Spectrometers
- Diffractometers

ODIN

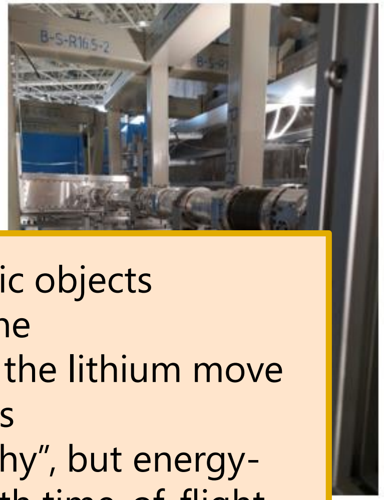
Optical and Diffraction Imaging with Neutrons







Imaging of macroscopic objects
- Coffee pot, car engine
- Batteries: How does the lithium move
- Steel: Grains, stresses
- Formerly "radiography", but energy-selective imaging with time-of-flight



ODIN Quick Facts	
Instrument Class	Imaging
Moderator	Bispectral
Primary Flightpath	50 m (to pinhole)
Secondary Flightpath	2 – 14 m (pinhole to detector)
Wavelength Range	1 – 10 Å
Field of View	20 x 20 cm^2
L/D Ratio	Tunable 300 – 10000
Incident Beam Polarisation	Optional
Polarisation Analysis	Optional
Bandwidth at 14 Hz	4.5 Å
White Beam Mode	
Flux at Sample at 2 MW	1.2 x 10^9 n s^{-1} at 10 m, L/D = 300
Spatial Resolution	< 10 μm
TOF Mode without Pulse-Shaping	
Flux at Sample at 2 MW	9 x 10^8 n s^{-1} at 10 m, L/D = 300
Spatial Resolution	< 10 μm
Wavelength Resolution	$\Delta\lambda/\lambda$ = 10% at λ = 2 Å
TOF Mode width Pulse-Shaping	
Flux at Sample at 2 MW	1 x 10^8 n s^{-1} at 10 m, L/D = 300
Spatial Resolution	< 10 μm
Wavelength Resolution	Adjustable <0.5% - 1% (constant for all λ)

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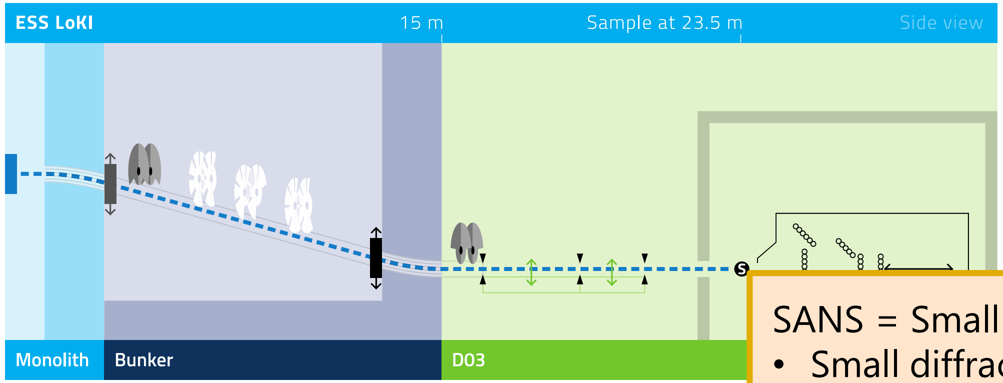
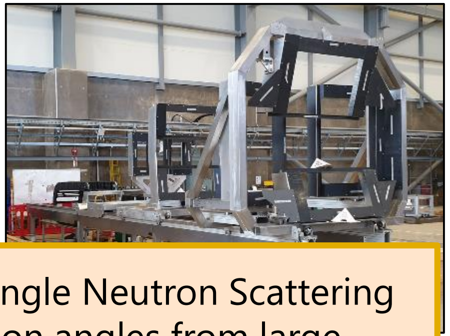
LoKI

SANS for Soft Matter, Materials and Bio-science



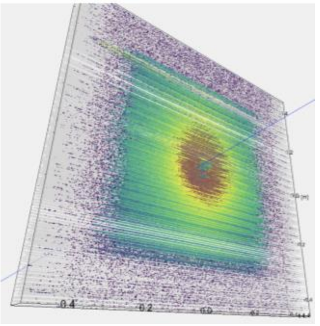


SANS = Small Angle Neutron Scattering
- Small diffraction angles from large objects (Bragg law)
- Biological samples, weak scatterers
- Nanomaterials, polymers
- Compounds in solution – see how clusters form in the liquid

test for hot commissioning.

LoKI Quick Facts	
Instrument Class	SANS
Moderator	Cold
Primary Flightpath	23.5 m, $L_1 = 3, 5, 8$ m
Secondary Flightpath	$L_2 = 1.5$ m, 3 m, 5–10 m
Wavelength Range	2–22 Å
Standard Mode (14 Hz)	
Bandwidth	7.5 Å [$L_2 = 10$ m] 10 Å [$L_2 = 5$ m]
Flux at Sample at 2 MW	4×10^8 n s^{-1} cm^{-2} [$L_1 = 3$ m] 5.6×10^7 n s^{-1} cm^{-2} [$L_1 = 8$ m]
Q-Range	0.01–2 Å^{-1} [$L_1 = 3$ m, $L_2 = 1.5$, 5 m] 0.005–2 Å^{-1} [$L_1 = 8$ m, $L_2 = 1.5$, 10 m]
Pulse Skipping Mode (7 Hz)	
Bandwidth	15 Å [$L_2 = 10$ m] 20 Å [$L_2 = 5$ m]
Flux at Sample at 2 MW	2×10^8 n s^{-1} cm^{-2} [$L_1 = 3$ m] 2.8×10^7 n s^{-1} cm^{-2} [$L_1 = 8$ m]
Q-Range	0.005–2 Å^{-1} [$L_1 = 3$ m, $L_2 = 1.5$, 5 m] 0.002–2 Å^{-1} [$L_1 = 8$ m, $L_2 = 1.5$, 10 m]

Detector tank installed
Shielding walls under installation

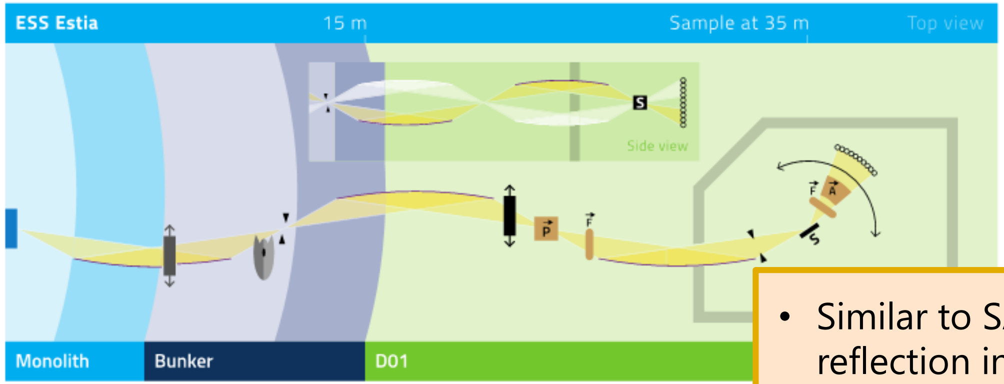


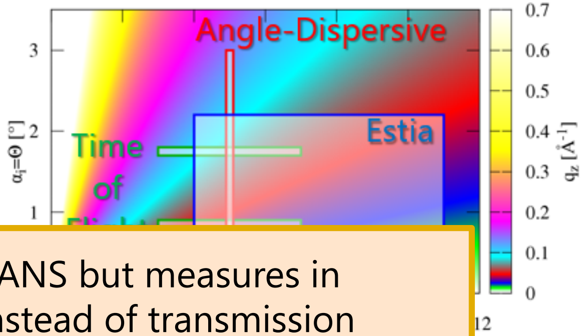
NeXus file displayed in scipp

Science and Technology Facilities Council

Estia

Focussing Polarised Reflectometer for Tiny Samples



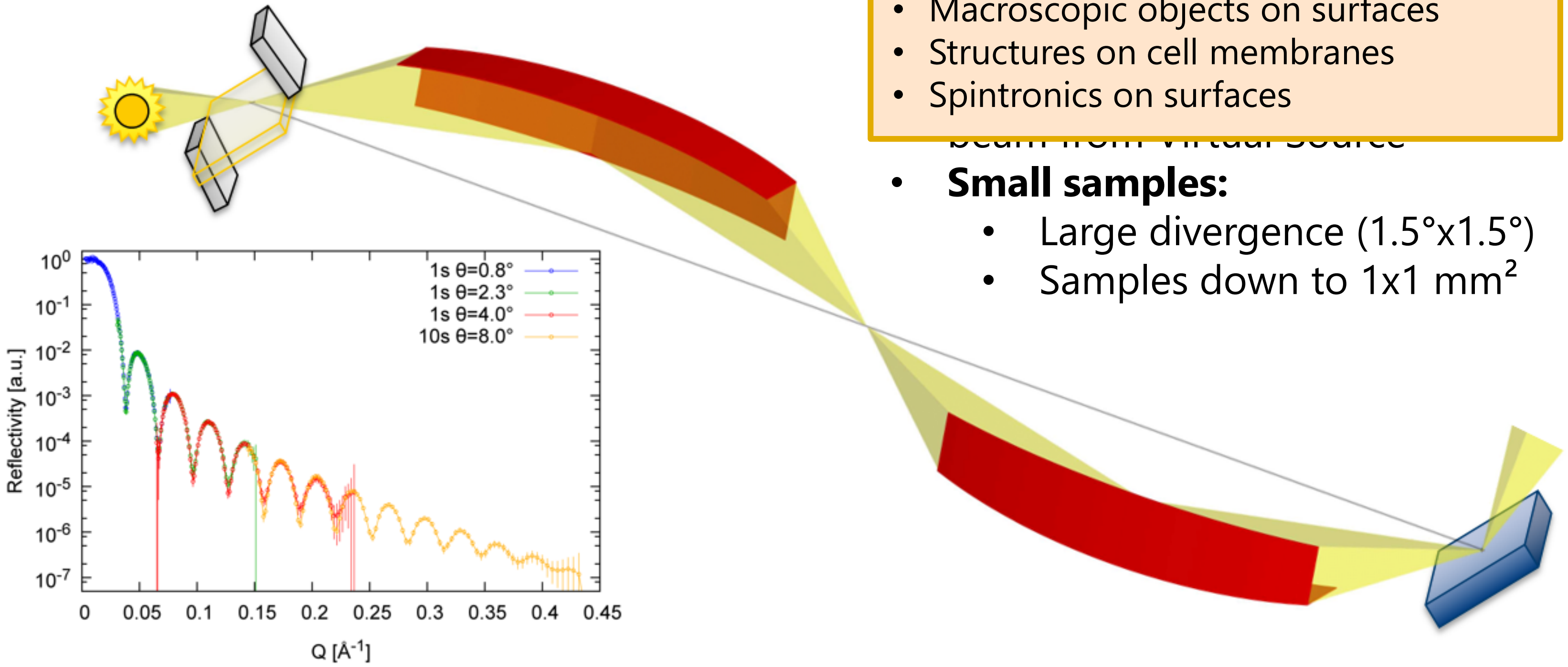


- Similar to SANS but measures in reflection instead of transmission
- Macroscopic objects on surfaces
- Structures on cell membranes
- Spintronics on surfaces

tiny

beam from virtual source

- **Small samples:**
  - Large divergence (1.5°x1.5°)
  - Samples down to 1x1 mm²



Estia Quick Facts.

Estia Quick Facts	
Instrument Class	Reflectometry
Moderator	Cold
Primary Flightpath	35 m
Secondary Flightpath	4 m
Wavelength Range	3.75–28 Å
Polarised Incident Beam	Optional
Polarisation Analysis	Optional
Sample Orientation	Vertical
Total Q-Range	0.001 to 3.15 Å^{-1}/–0.001 to –0.3 Å^{-1}
Standard Mode (14 Hz)	
Bandwidth	7 Å
Flux at Sample at 2 MW[a]	6×10^8 n s^{-1} cm^{-2}
Relative Q-Range	$Q_{max} = 2.85 \times Q_{min}$
Q-Resolution ΔQ/Q	7.8%–3.0% over Q-range
2-Pulse Skipping Mode (4.7 Hz)	
Bandwidth	21 Å
Flux at Sample at 2 MW[a]	2×10^8 n s^{-1} cm^{-2}
Relative Q-Range	$Q_{max} = 6.6 \times Q_{min}$
Q-Resolution ΔQ/Q	7.8%–1.3% over Q-range

[a]Full-divergence beam averaged over 5(H) × 10(V) mm².

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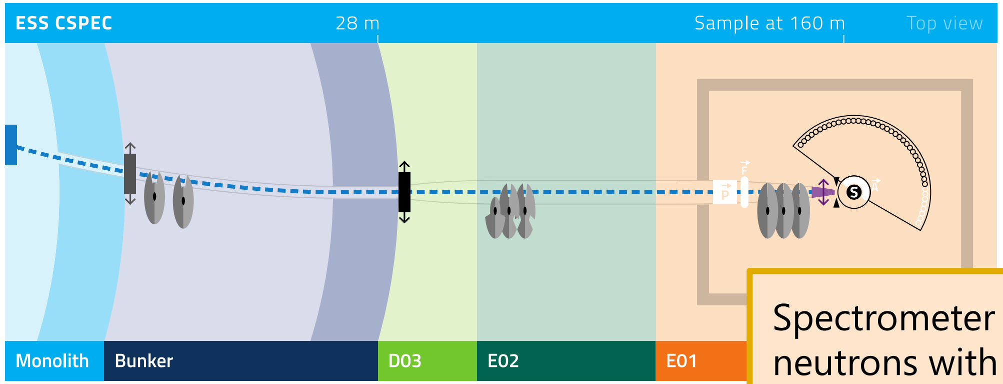
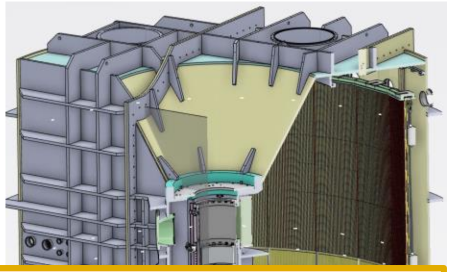
CSPEC

Cold Chopper Spectrometer (not among first 6)



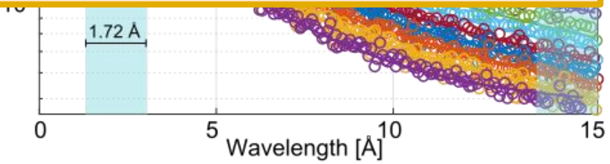


CSPEC quick facts	
Primary flight path	160 m
Secondary flight path	3.5 m
Moderator	Cold
Wavelength range	2-20 Å
Bandwidth	1.72 Å
Flux at sample (2 MW, λ = 5 Å, $\Delta E/E_i$ = 3%, no RRM, with RRM ~ x6)	9 10^5 n s^{-1} cm^{-2} (4 x 2 cm^2 standard beam) 4 10^6 n s^{-1} cm^{-2} (1 x 1 cm^2 focussed beam)
Full detector coverage	5^o – 140^o [H] ± 26^o [V]
Energy resolution	1% - 5% E_i
Polarisation analysis	Foreseen upgrade

Spectrometer measures scattered neutrons with energy resolution

- Direct-geometry instrument
- Neutrons monochromatised with choppers
- Energy analysis by TOF
- Dynamic processes, binding energies
- Phonon energies, magnetisation, temperatures
- Basic physics of materials, materials science

- Collective and quasiparticle excitations in frustrat compounds.
- Low lying excitations of quasiparticles in quantur materials.
- Magnon -phonon hybrid excitations in multiferro materials.
- Time dependence of the rotational and translatio diffusive processes in enzyme catalysis.
- Dynamics of hydration processes and the structu relaxation of the glassy water.
- Time dependent phenomena of hydrogen storage in clathrates.
- Proton diffusion in metal organic frameworks.
- Operando studies of proteins such as those involved in photosynthesis.



Laboratoire Léon Brillouin / Orphée

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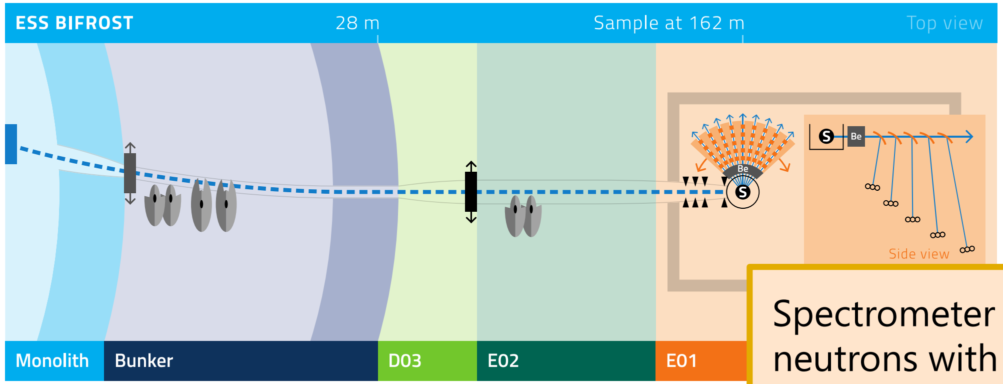
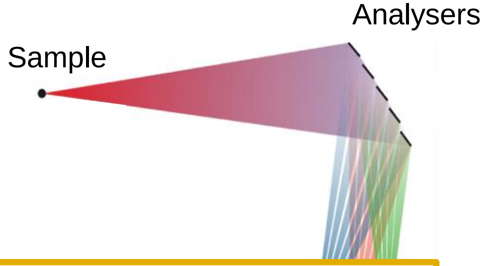
BIFROST

Multiplexing Indirect Spectrometer for Extreme Environments





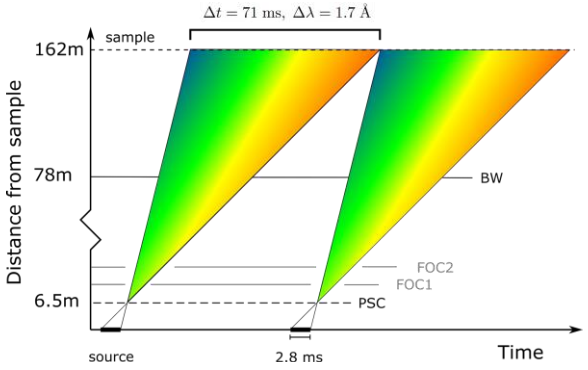
Spectrometer measures scattered neutrons with energy resolution

- Indirect-geometry instrument
- Neutron energy selected by TOF
- Energy analysis by Bragg reflection behind sample

- Low-D magnets
- High-Tc superconductivity
- Functional magnetic materials
- Geoscience
- Parametric studies
- Weak signals & small samples

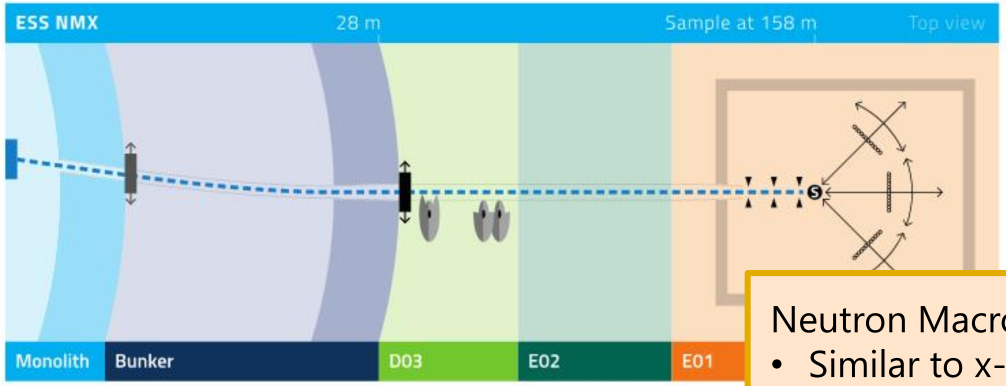
BIFROST Quick Facts.

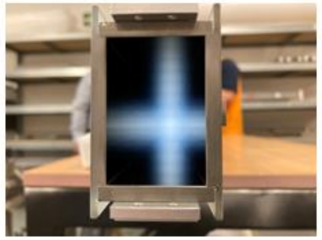
BIFROST Quick Facts	
Instrument Class	Spectroscopy
Moderator	Cold
Primary Flightpath	162 m
Sample-Analyser Flightpath	1.1–1.7 m
Wavelength Range	1.5–6 Å
Bandwidth	1.7 Å
2θ Range	7°–135°
2θ Coverage	90° in 2 settings
2θ Resolution	0.7°–1.2°
Analyser Energies	2.7, 3.2, 3.8, 4.4, 5.0 meV
Energy Transfer Range	−3 to +55 meV
High Flux Mode [2.3–4.0 Å]	
Flux at Sample at 2 MW	6×10^9 n s^{-1} cm^{-2}
Resolution ($E_f = 5$ meV, $\hbar\omega = 0$)	190 μeV
Resolution ($E_f = 5$ meV, $\hbar\omega = 5$ meV)	450 μeV
High Resolution Mode [2.3–4.0 Å]	
Flux at Sample at 2 MW	9×10^8 n s^{-1} cm^{-2}
Resolution ($E_f = 5$ meV, $\hbar\omega = 0$)	50 μeV (prismatic)
Resolution ($E_f = 5$ meV, $\hbar\omega = 5$ meV)	50 μeV (prismatic)



NMX

Macromolecular Diffractometer



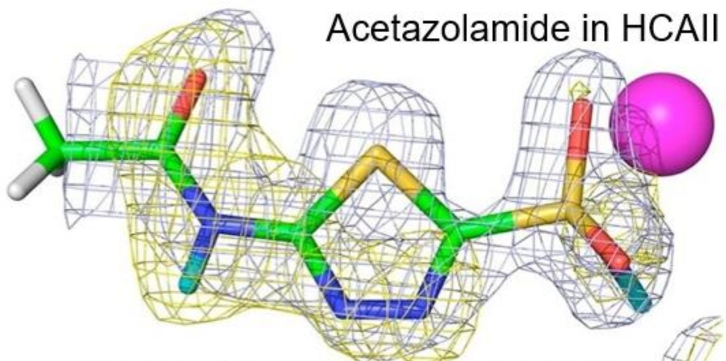


NMX Quick Facts.

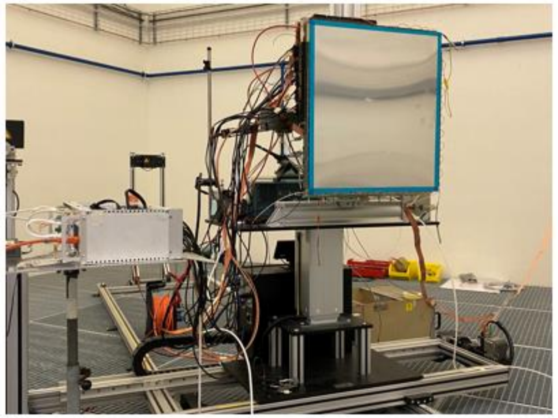
NMX Quick Facts	
Instrument Class	Large-Scale Structures
Moderator	Cold
Primary Flightpath	157 m
Secondary Flightpath	0.2–1.0 m
Wavelength Range	1.8–10 Å
Bandwidth	1.74 Å
t Sample at 2 MW	1×10^9 n s^{-1} cm^{-2} (1.8–3.5 Å)
ength Resolution $\Delta\lambda/\lambda$	2%–4% (over wavelength range)
Divergence	Adjustable up to ±0.2°
Size	0.2–5 mm

Neutron Macromolecular Crystallography
- Similar to x-ray crystallography, but visibility of hydrogens
- Single (large) crystals
- Proteins, minerals
- Protonation, invisible with x rays

- Enzyme mechanisms
- Protein-ligand interactions
- Proton transport across membranes

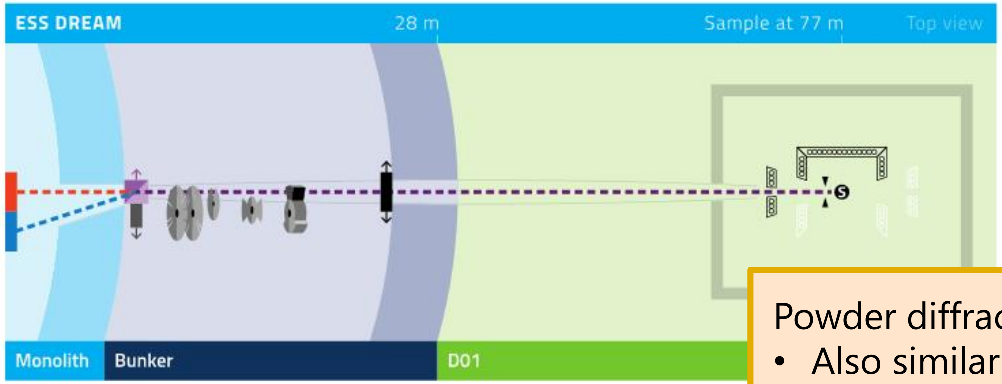


Fisher SZ et al. JACS 2012;134:14726-14729



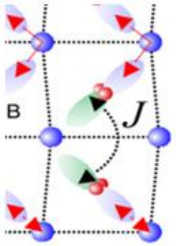
DREAM

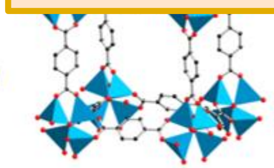
Diffraction Resolved by Energy and Angle Measurements



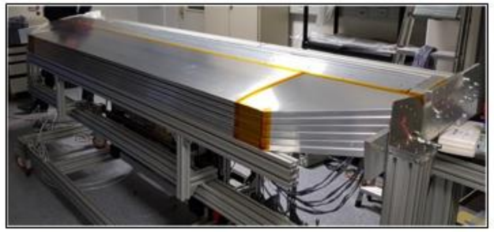
Powder diffractometry
- Also similar to x-ray diffraction
- Hydrogens visible
- Magnetism visible

Sample vessel





Mantle & Endcap detectors



Experimental caves & Control hutches

Magnetism
superconductors
multiferroics
weak moments
orbital ordering
charge ordering

small coin cells

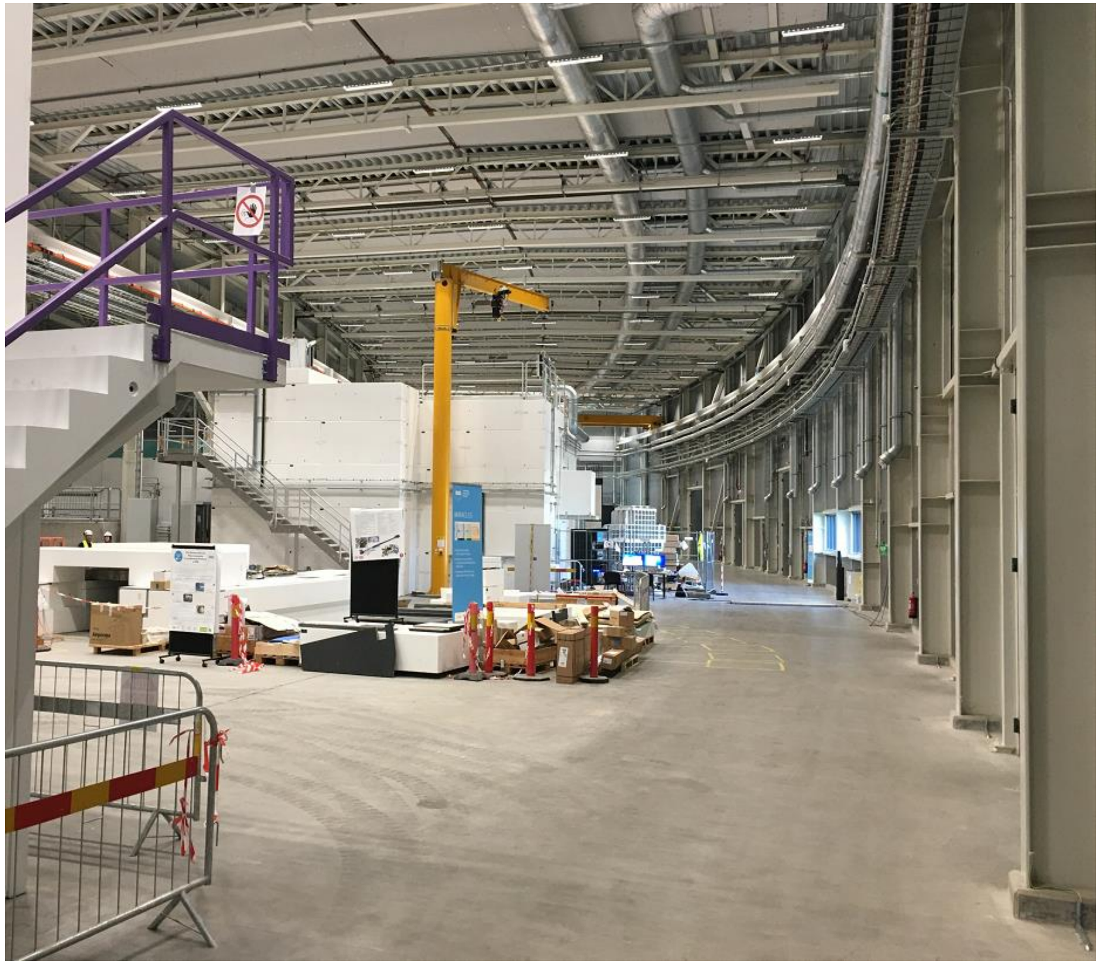
Nanostructures
magnetic nanoparticles
core-shell structures
real-time synthesis

Moderator	Bi-spectral
Primary Flightpath	76.5 m
Secondary Flightpath	1.1 m (end-cap and mantle detectors) 2.5 m (high-resolution and low-angle detectors)
Wavelength Range	0.5–4.1 Å
Flux at sample at 2MW	1.4×10^{7} ns^{-1}cm^{-2} (Δd = 3×10^{-4} Å) 1.0×10^{9} ns^{-1}cm^{-2}(Δd = 2.5×10^{-2} Å)
Q-Range	0.01 – 25 Å^{-1}
Detector Coverage	1.82 sr first day operations 5.12 sr full scope
d-spacing Resolution Δd	Adjustable 3×10^{-4} – 2.5×10^{-2} Å

Instrument hall D01

Instrument hall D03

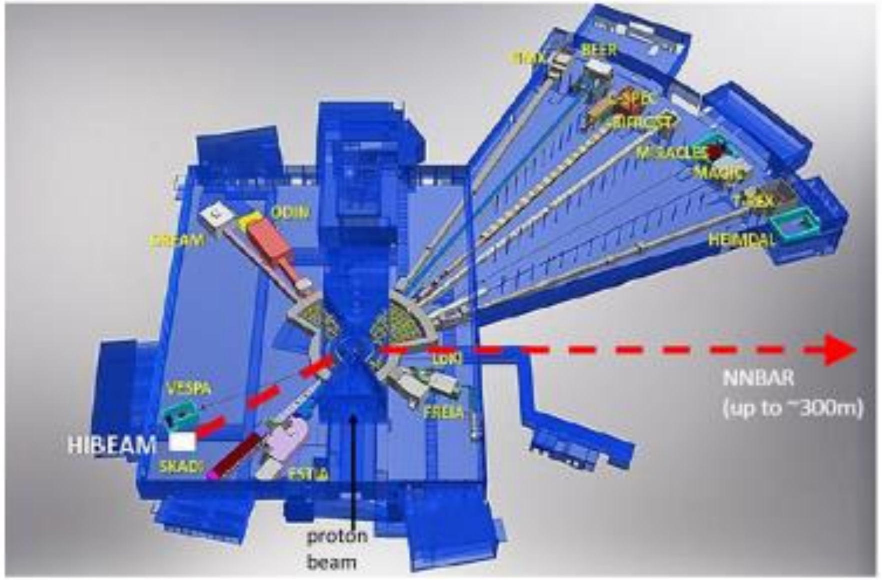
Instrument halls E01/E02

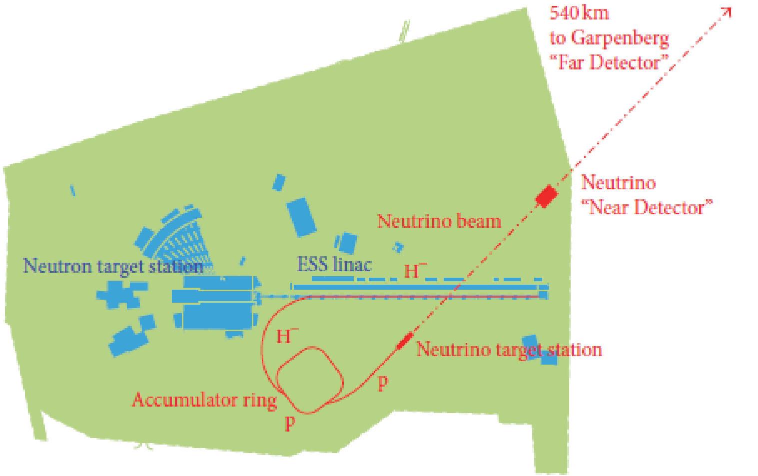


Fundamental physics at ESS

- NNBAR, neutron–antineutron oscillations (HighNess EU-funded study)
- HIBEAM/ANNI, first stage of NNBAR
- ESSnuSB – ESS neutrino Super Beam, neutrino oscilla-tions at 2nd maximum (EU-funded study, completed)
- ESSnuSB+, continuation of ESSnuSB (EU-funded study, in progress)
- Coherent Elastic Neutrino–Nucleus Scattering – CEνNS

Spallation Neutron Source, SNS





The End