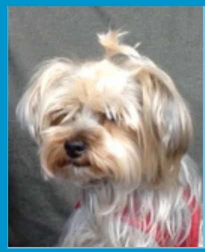
Neutron Sources

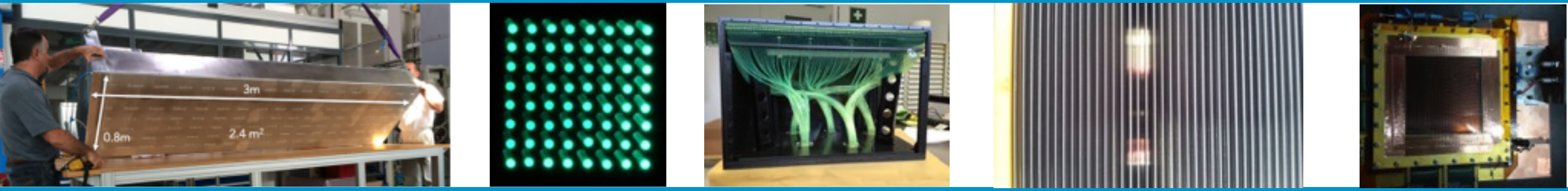
Richard Hall-Wilton

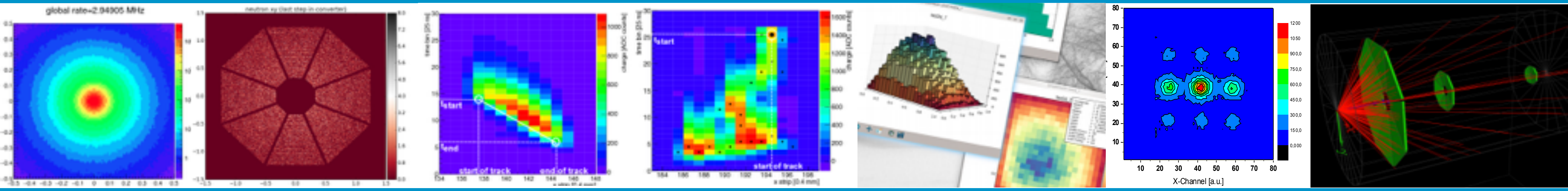
Leader of Detector Group
Deputy Division Head of Instrument Technologies



www.europeanspallationsource.se

NDRA2016



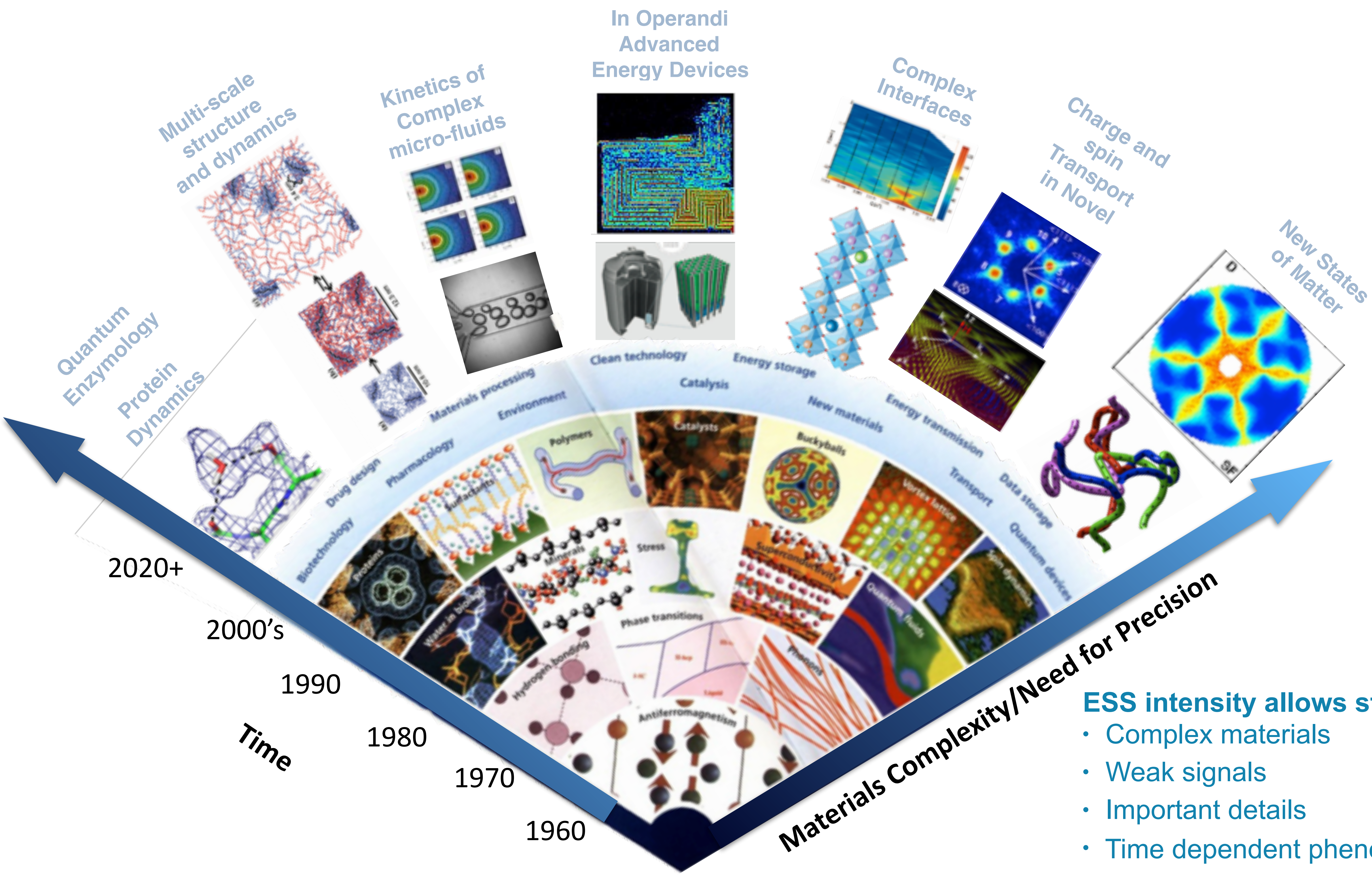


Today:

- Introduction and History
- What is Neutron Scattering Science?
- Radioactive and lab sources
- Fusion
- Reactors and Spallation Sources
- Neutron Scattering Beamlines
- The European Spallation Source


Lighting
New materials
Solar energy
Food
Medicine
Tailor made materials
Pacemakers
Mobile phones
Cosmetics
Bio fuels
Implants
Transportation
Geo science
ESS

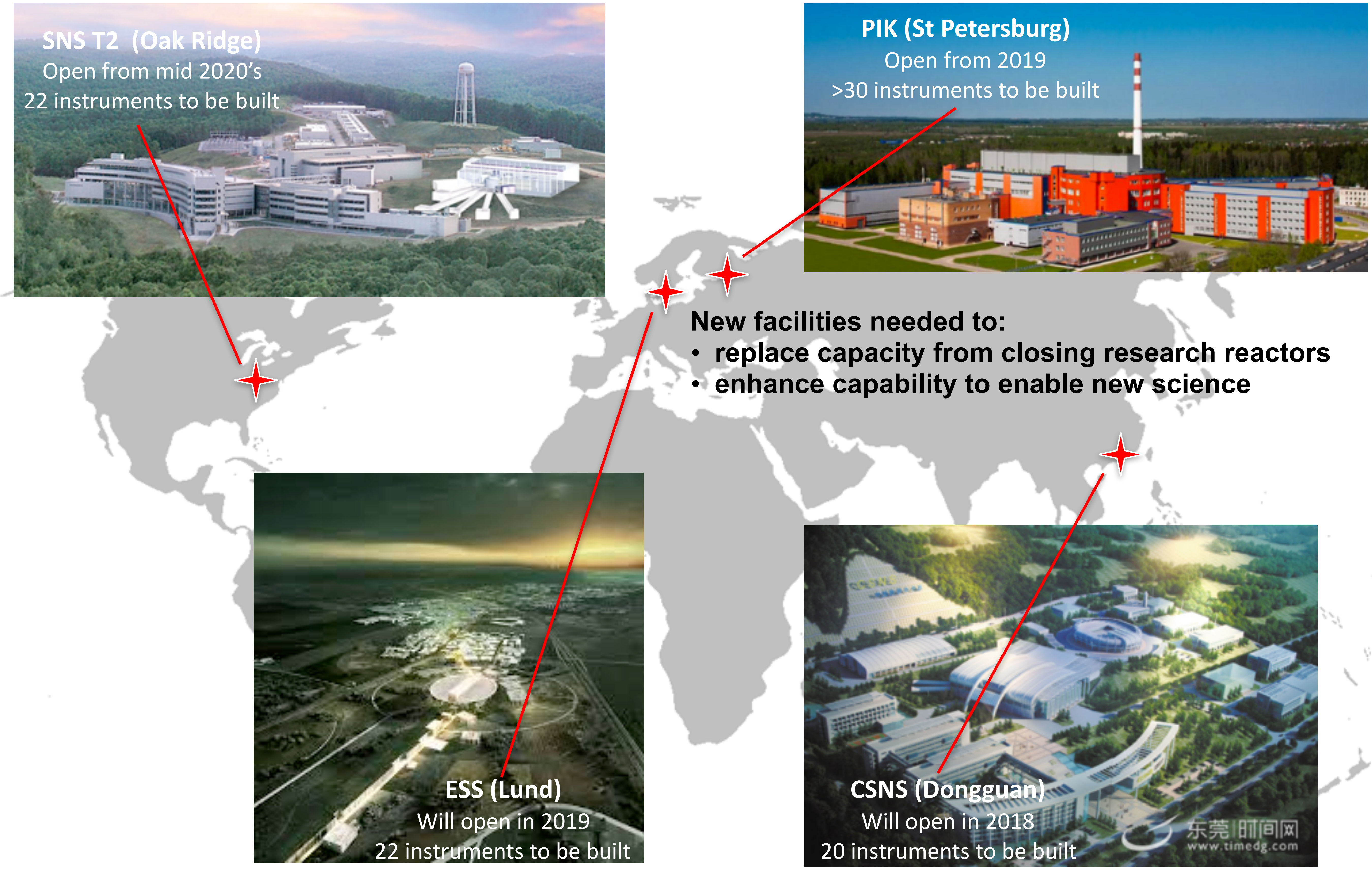
Neutron Science Pushes the Boundaries



ESS intensity allows studies of:

- Complex materials
- Weak signals
- Important details
- Time dependent phenomena

Upcoming Research Facilities



New facilities needed to:

- **replace capacity from closing research reactors**
- **enhance capability to enable new science**

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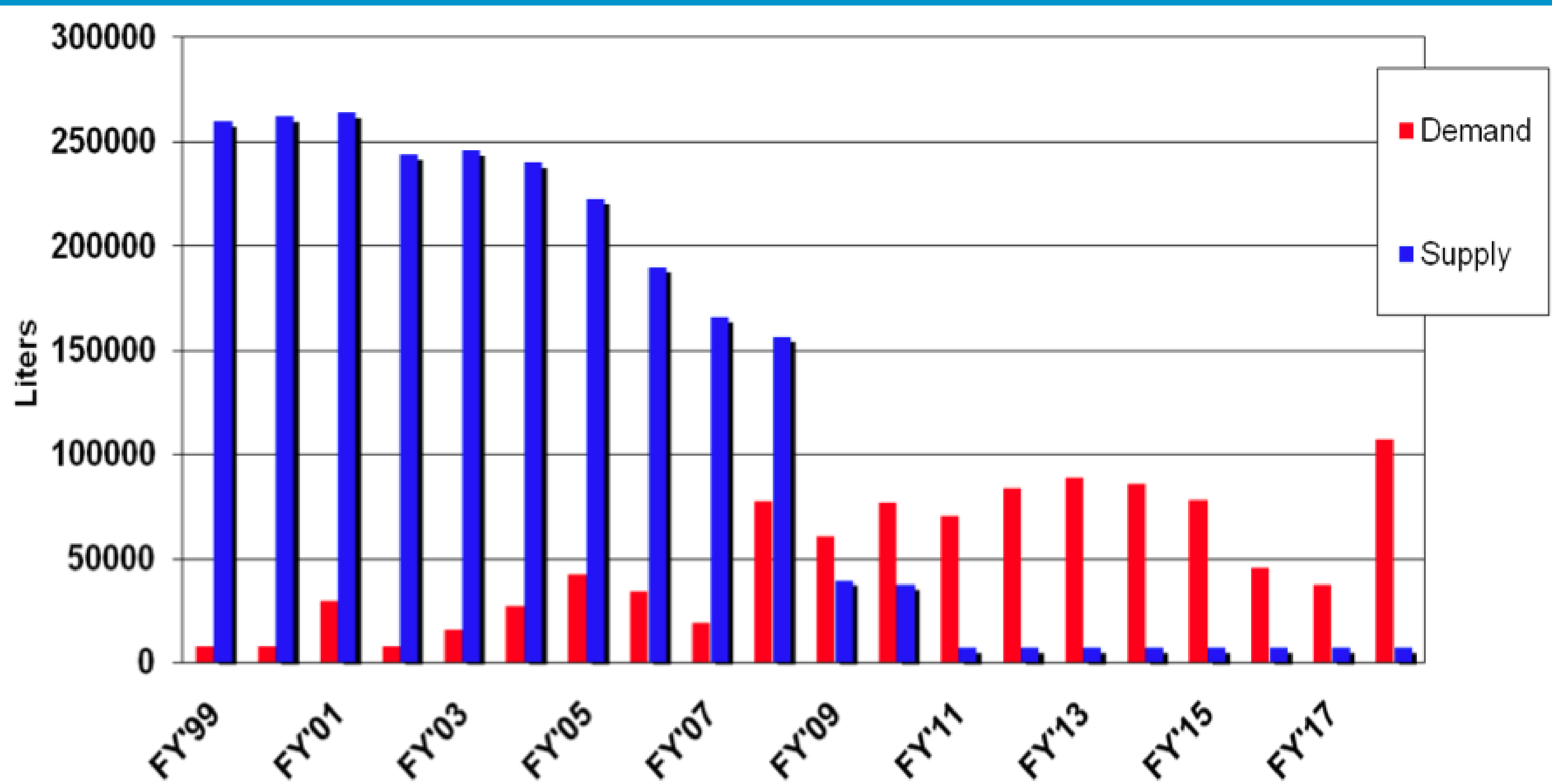
Helium-3 Crisis

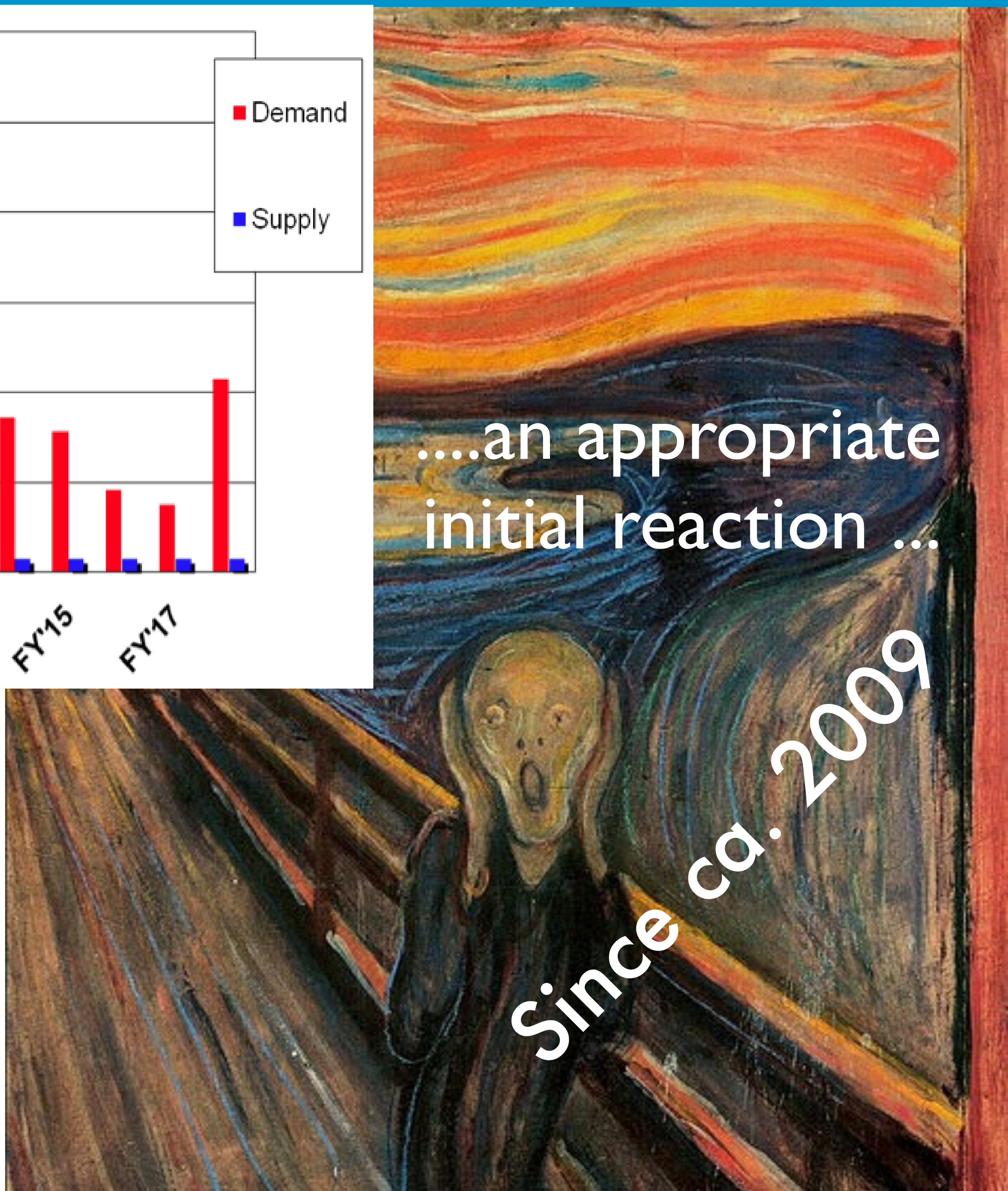
EUROPEAN SPALLATION SOURCE



Comment: seems to be some naivety at the moment as stocks are being emptied rapidly

Aside … maybe He-3 detectors are anyway not what is needed for ESS? eg rate, resolution reaching the limit …

Crisis or opportunity … ?



What is Neutron Scattering Science?

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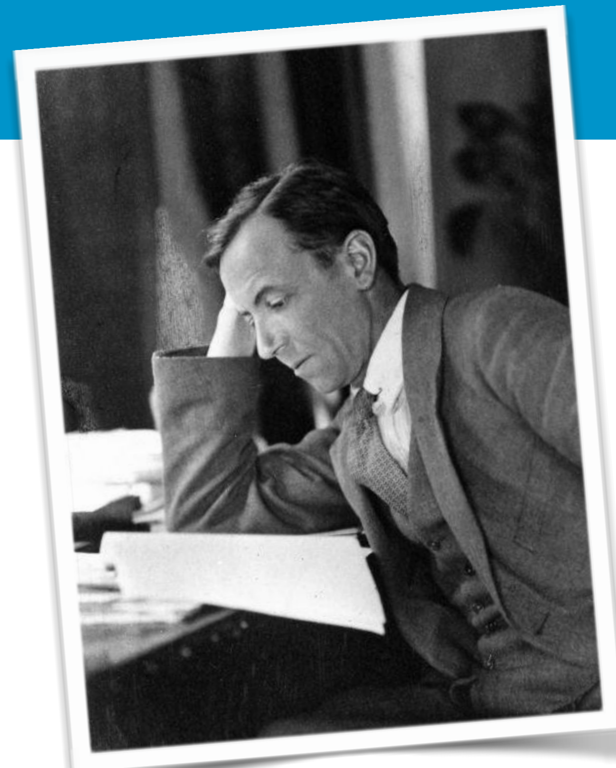
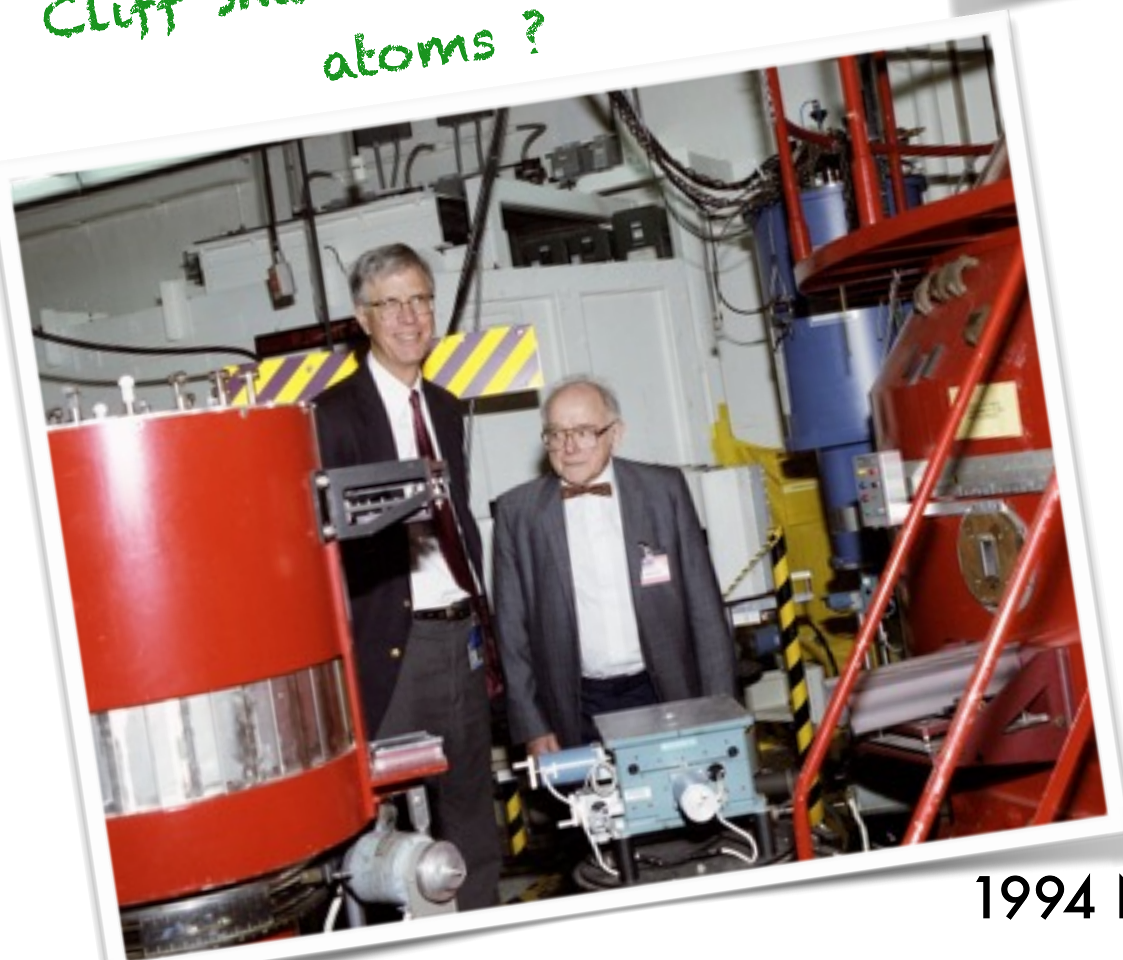
Neutrons

EUROPEAN SPALLATION SOURCE



1932: Chadwick discovers "a radiation with the more peculiar properties", the neutron.

Cliff Shull: where are the atoms ?

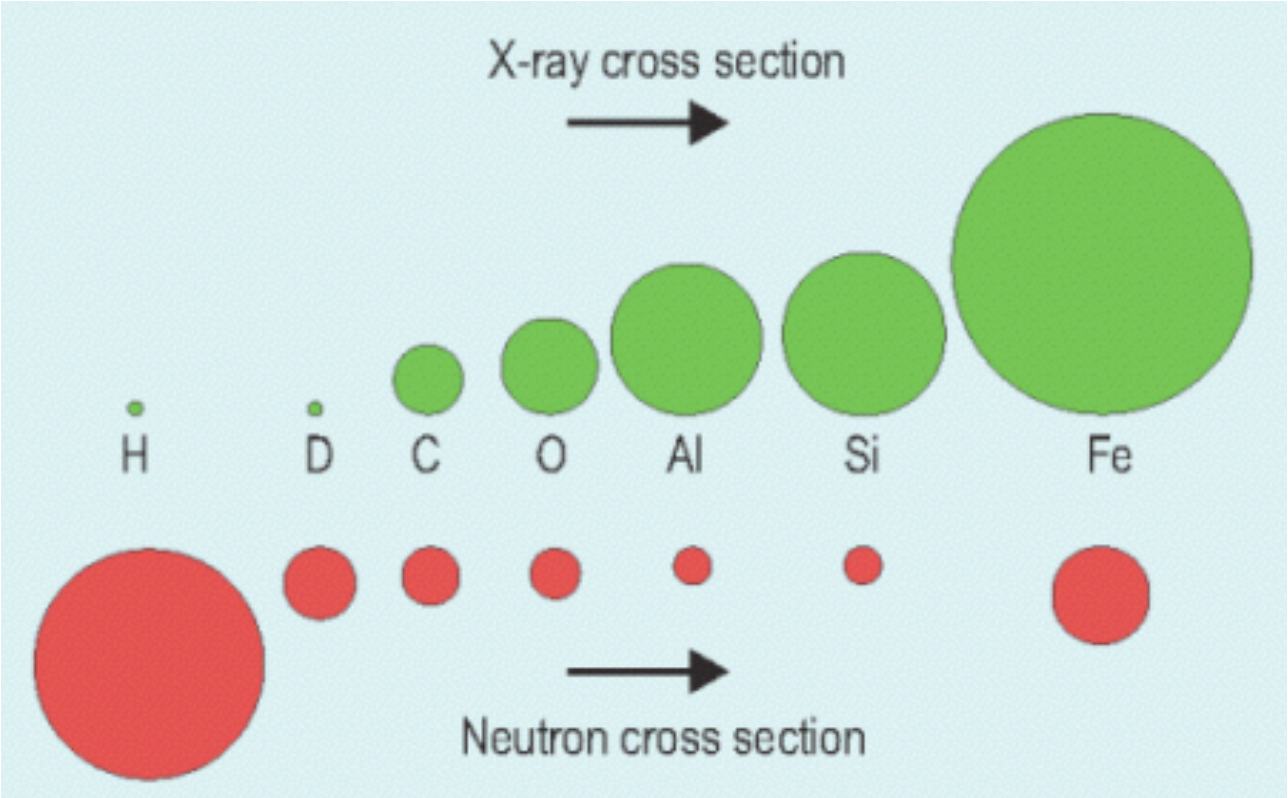


Bert Brockhouse: what do they do ?

1994 Nobel Prize in Physics

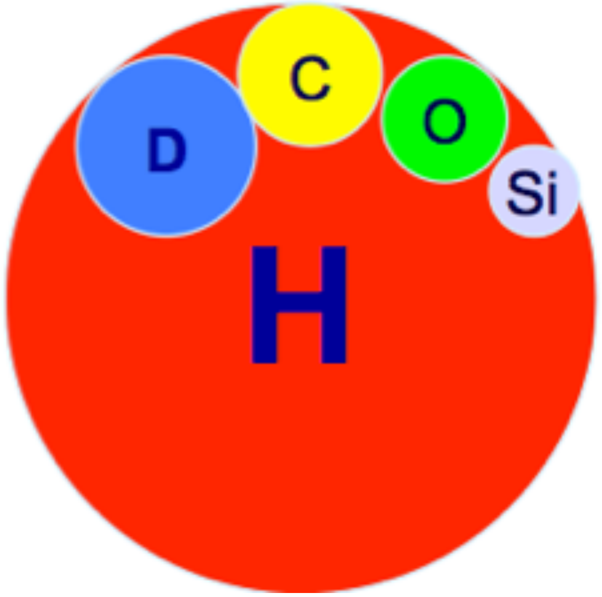
Why Neutrons?

Neutrons are:
- **low energy**
- **non-damaging**
- **penetrating**
- **broad wavelength range**

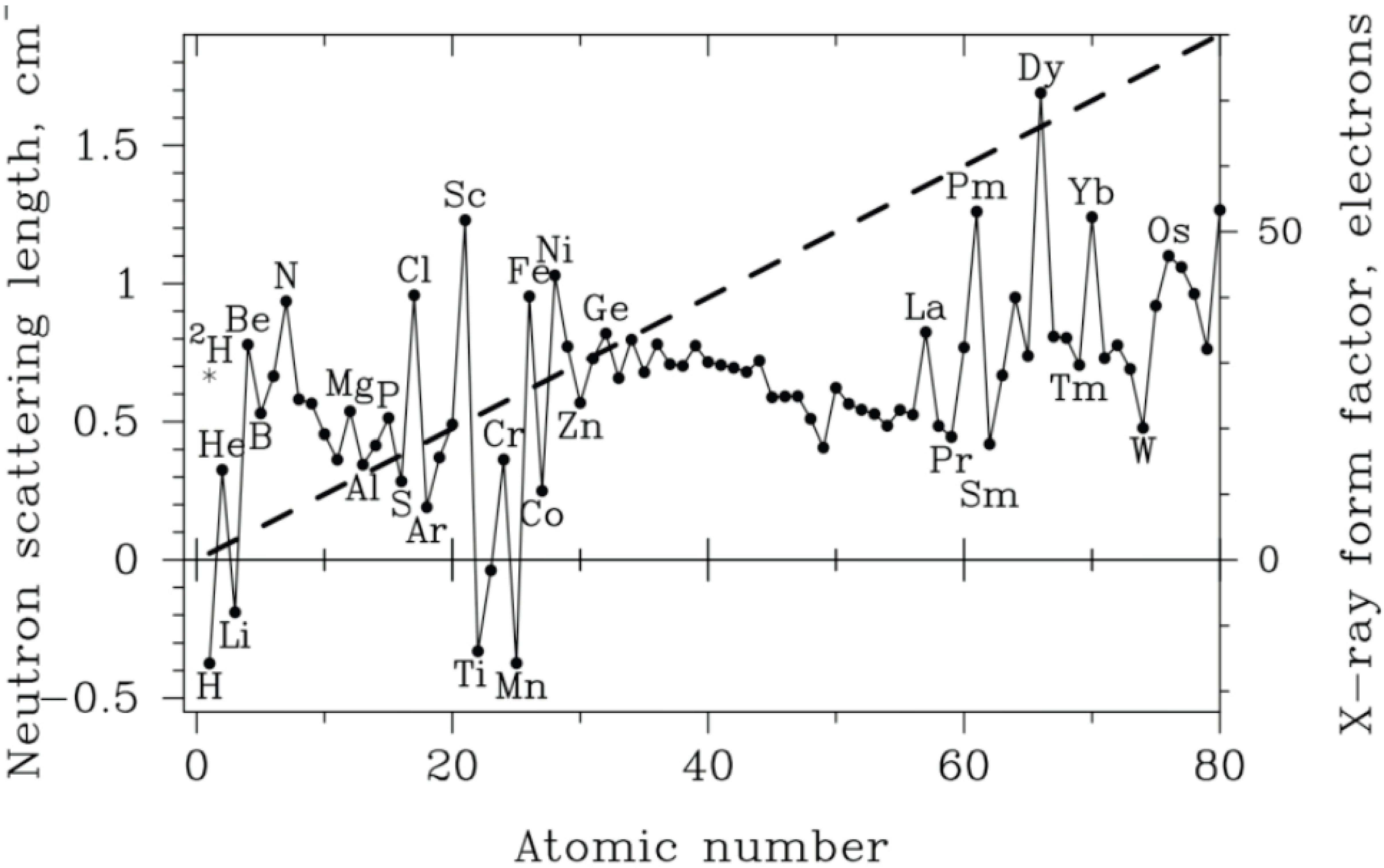


thermal and cold neutrons
meV
"with a small m"
wavelength ca. Å

1) Ability to measure both energy and momentum transfer
   Geometry of motion
2) Neutrons scatter by a nuclear interaction => different isotopes scatter differently
   H and D scatter very differently
3) Simplicity of the interaction allows easy interpretation of intensities
   Easy to compare with theory and models
4) Neutrons have a magnetic moment



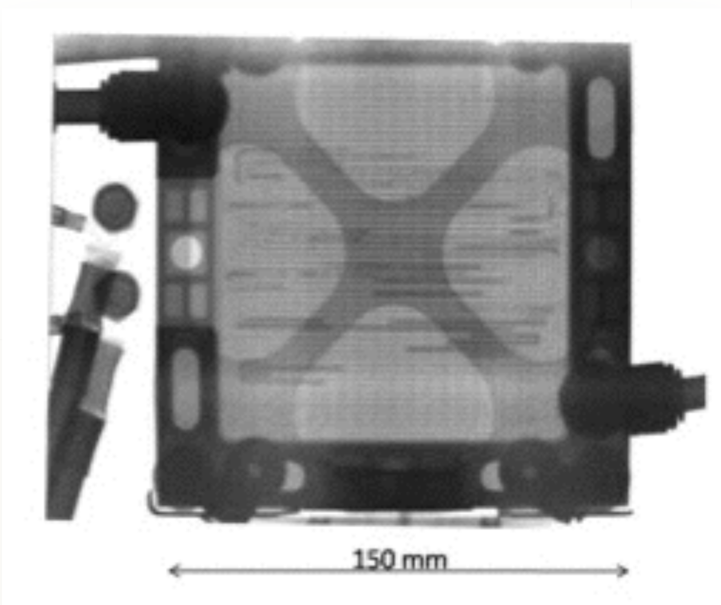
Why Neutrons?



Neutrons are special

Charge neutral

Deeply penetrating

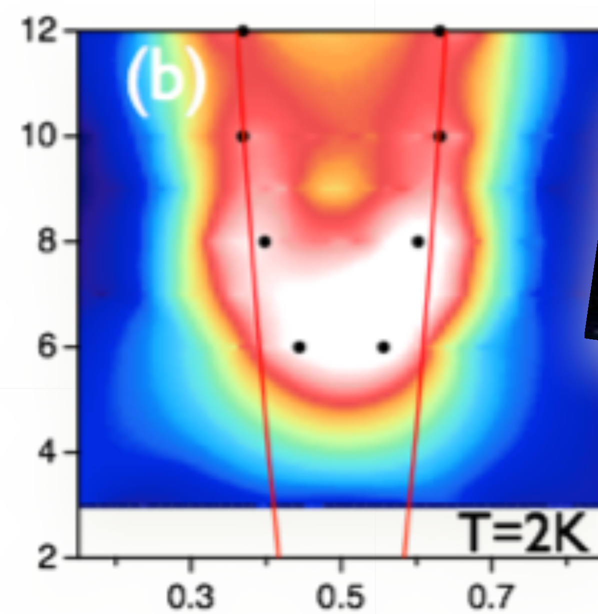


Li motion in fuel cells

Help build electric cars

S=1/2 spin

Directly probe magnetism



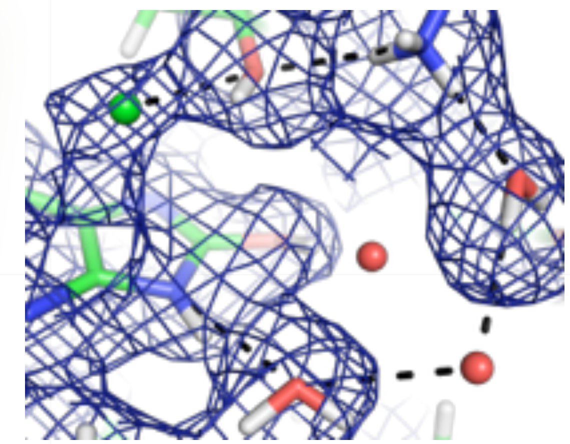
Test AdS/CFT correspondence

Solve the puzzle of High-Tc superconductivity

Efficient high speed trains

Nuclear scattering

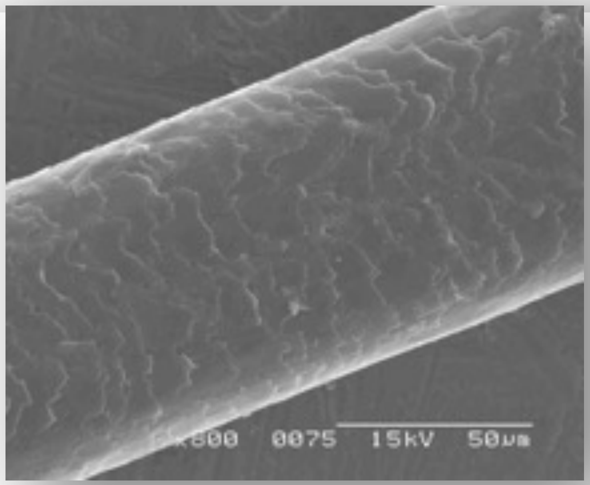
Sensitive to light elements and isotopes



Active sites in proteins

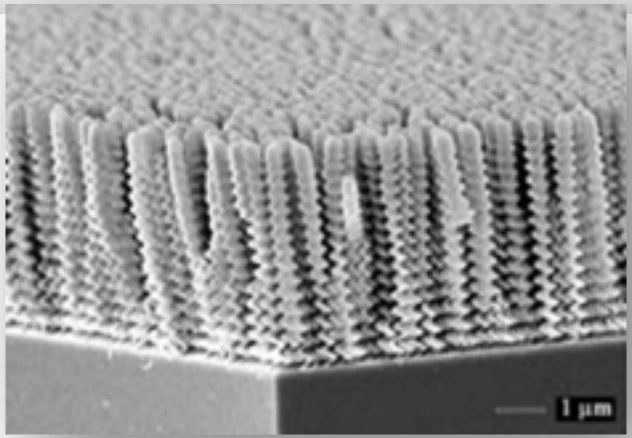
Better drugs

Probing length scales and dynamics



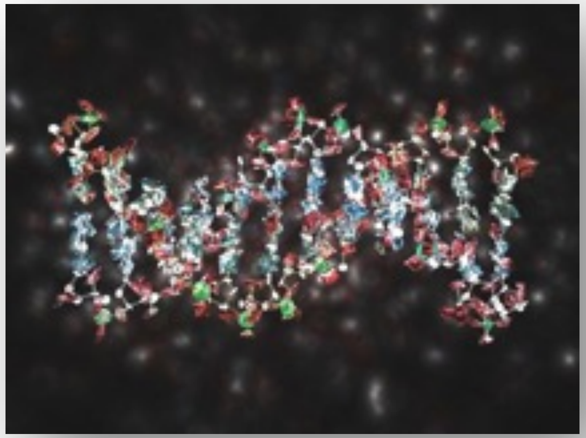
Human Hair
~100,000 nm

Red Blood Cells
~7000 nm

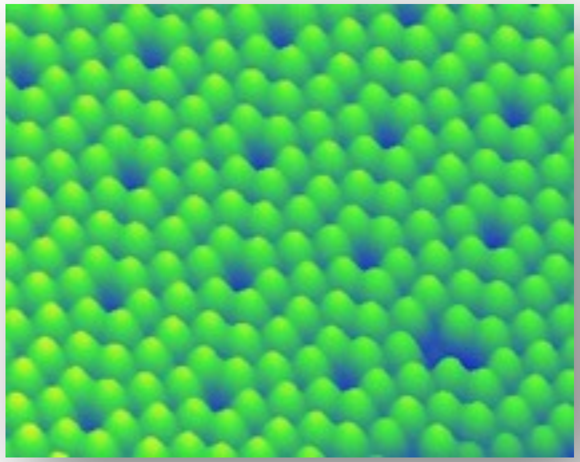


Deposited Nanostructures
~500 nm

Influenza Virus ~100 nm

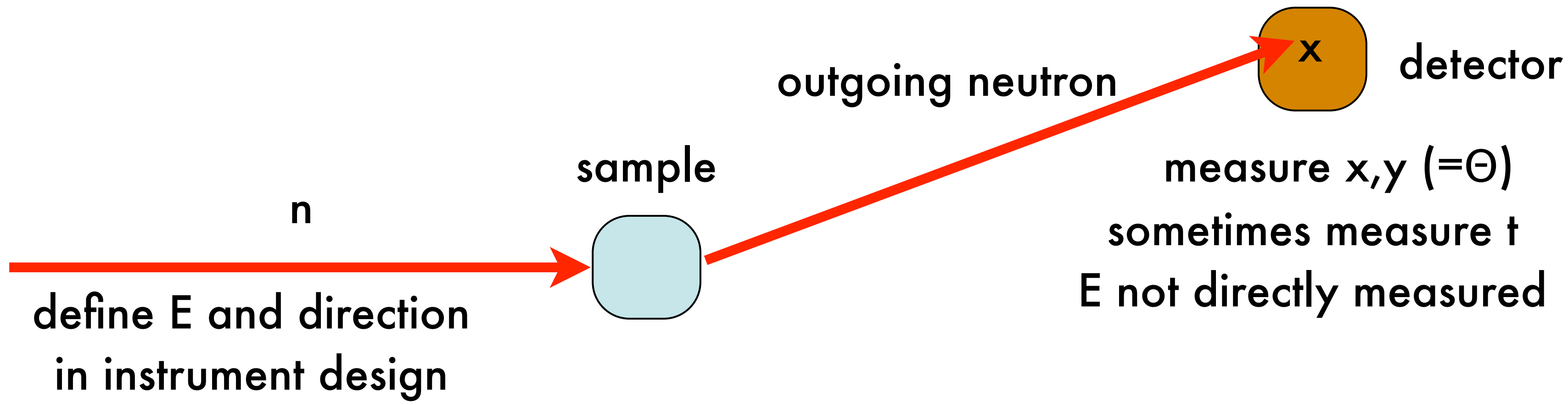


DNA ~2 nm



Si Atoms ~0.2 nm

Neutron Scattering - what information do you get?

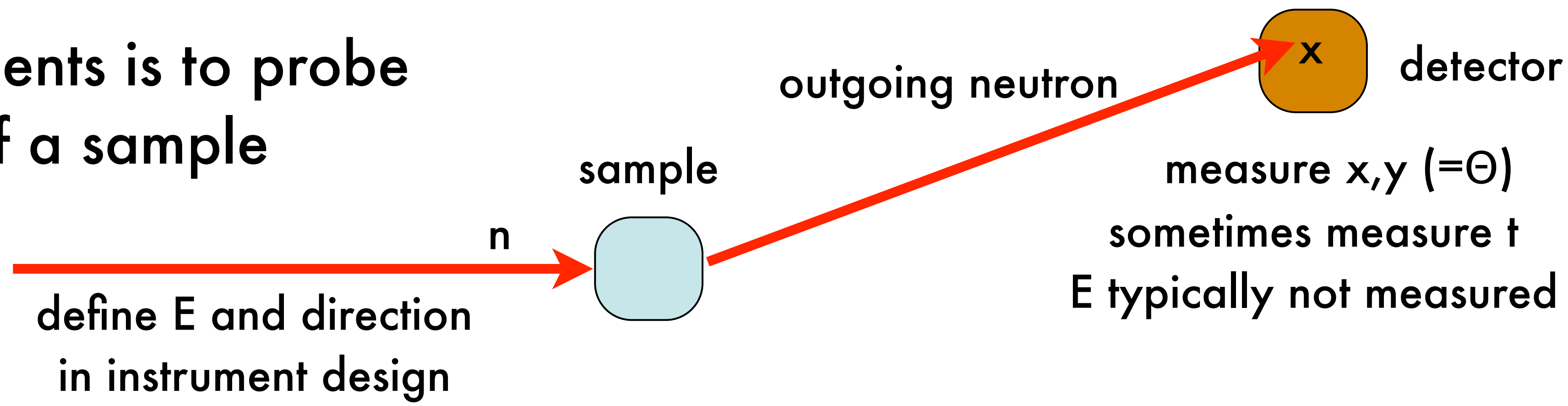


- Scattering angle measured through x,y position of the neutron detected
- Time of detection often used
  - It is vital to have good time resolution for instruments at spallation sources
- Energy typically not measured
  - In some ways, the holy grail to have a good energy measurement of the neutron?
- Design needs to be adapted to the expectations for that instrument
  - Not one design fits all

Cost is always a limiting factor in the design of detectors
Schedule will determine what you can do about it

Neutrons as a Probe

- The purpose of the instruments is to probe with neutrons some aspect of a sample



- Very generically, this can be divided into elastic and inelastic categories
  - elastic: gives information on where atoms are
  - inelastic: gives information on what atoms do (ie move)
- This is measuring the cross sections:

elastic

$$\frac{d\sigma}{d\Omega}(\lambda,2\theta,\psi)$$

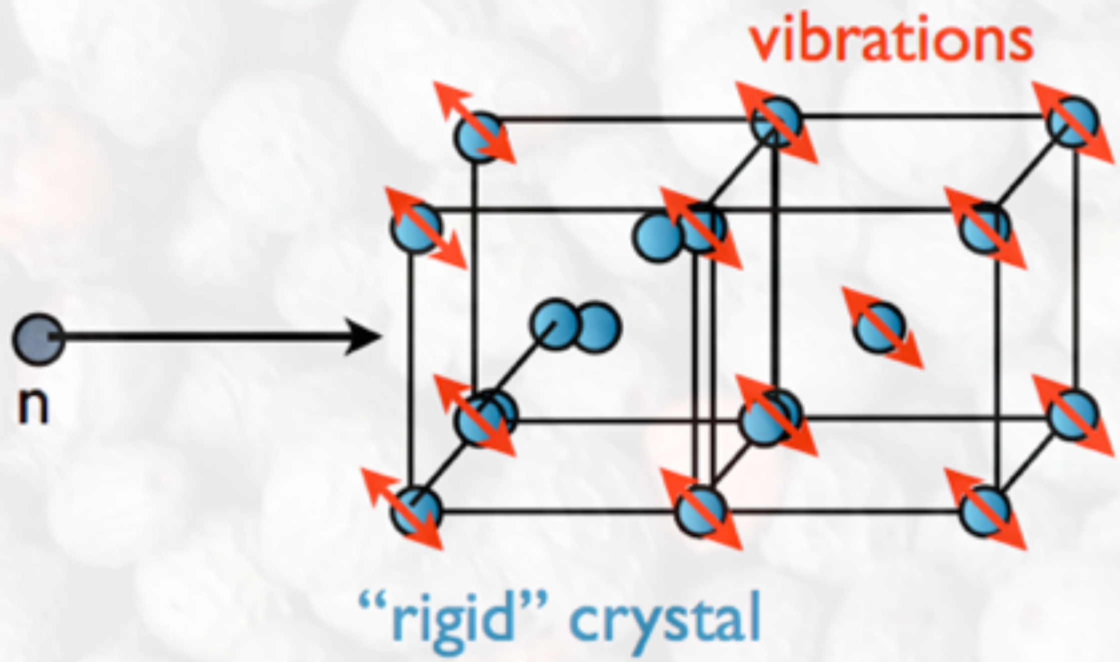
- cross section / scattering probability into a solid angle, as a function of wavelength, scattering angle and aximuthal angle

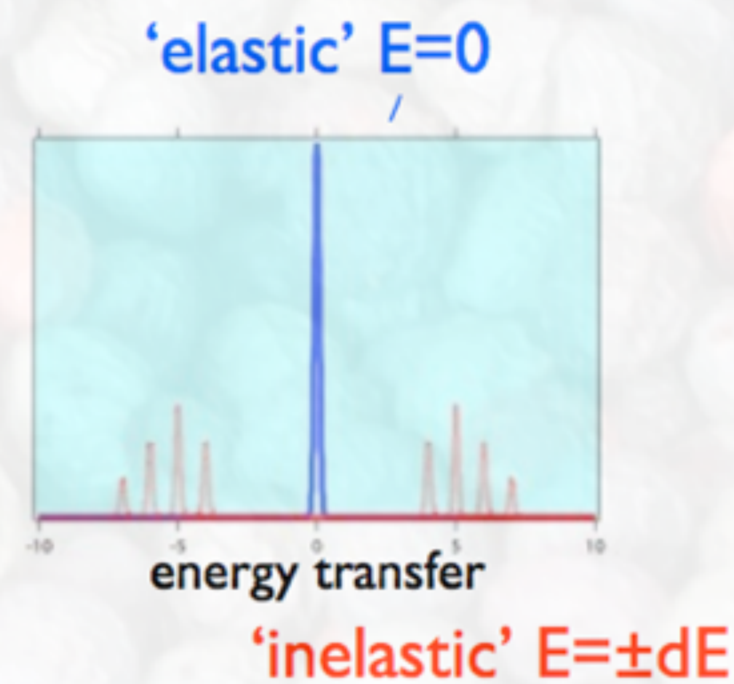
inelastic

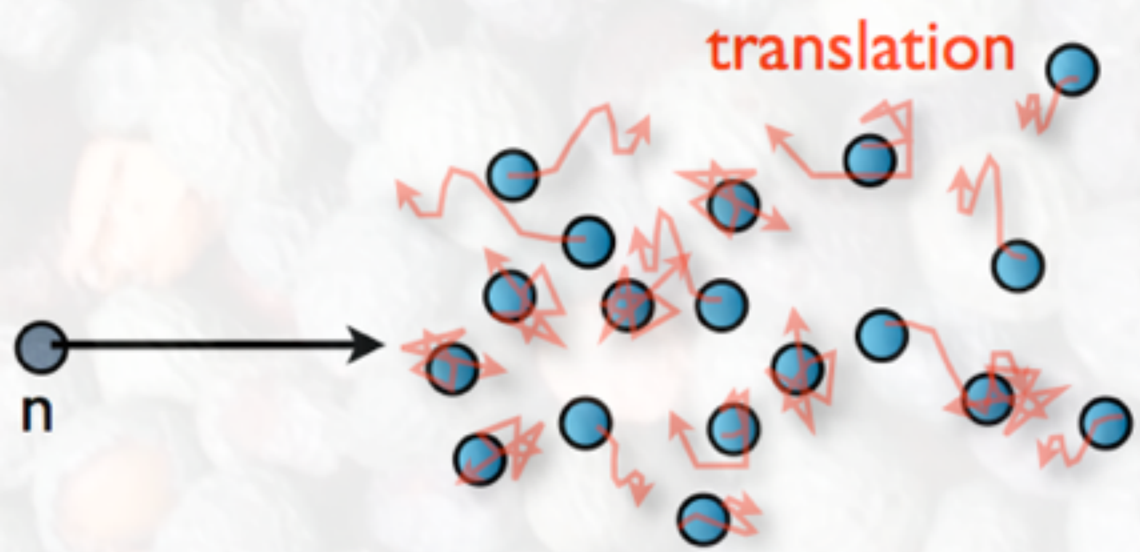
$$\frac{d^2\sigma}{d\Omega dE}(\lambda_{in},\lambda_{sc},2\theta,\psi)$$

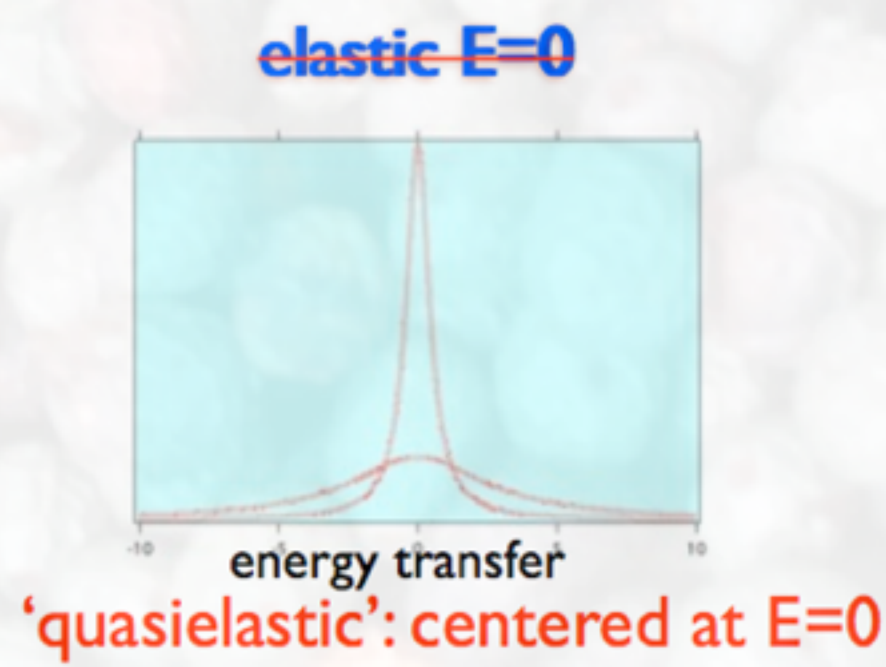
- double differential cross section / scattering probability into a solid angle, as a function of wavelength, scattered wavelength scattering angle and aximuthal angle

Elastic vs Inelastic





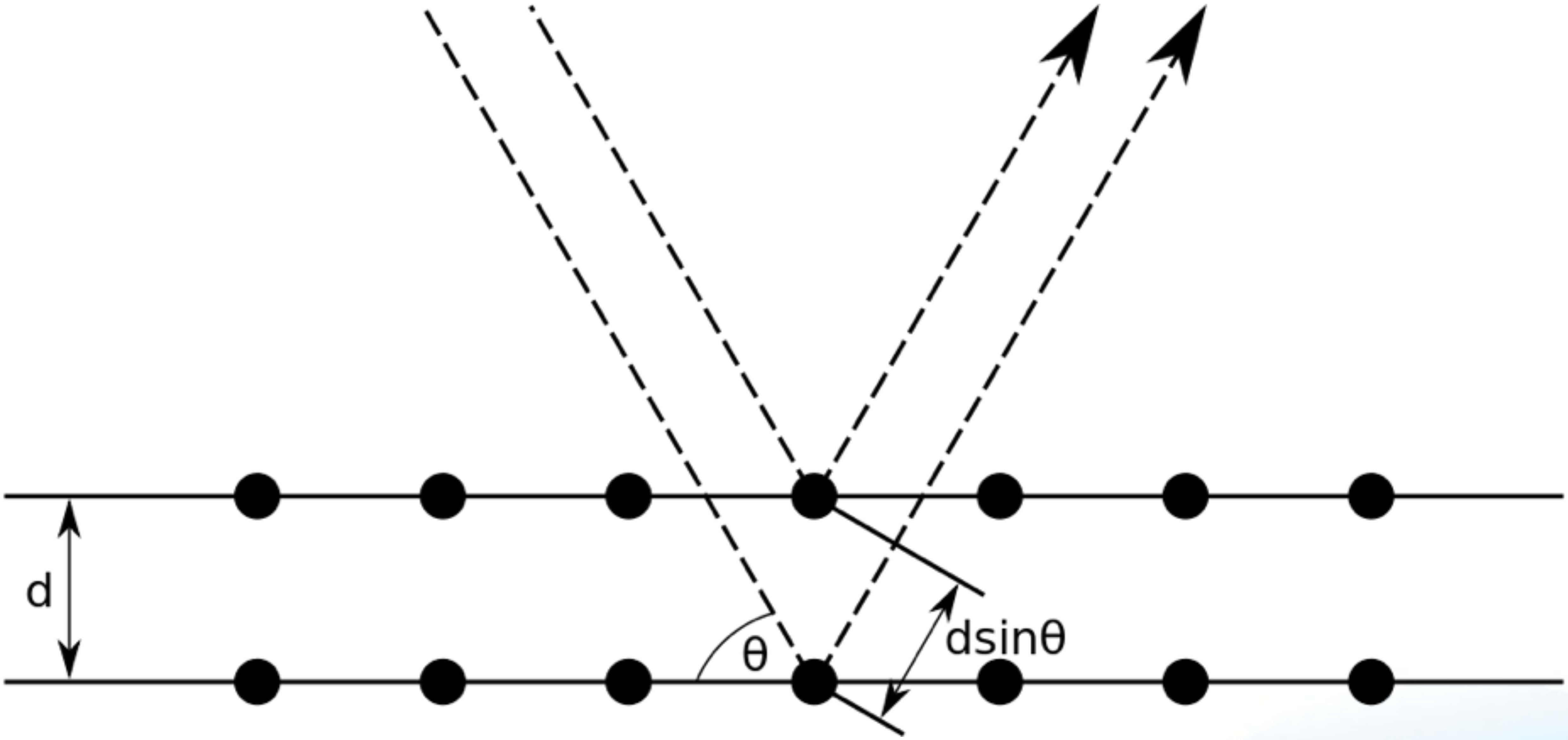




Andrew Jackson

Diffraction

Sizes probed = “atomic structures” = 0.1 nm - 10 nm

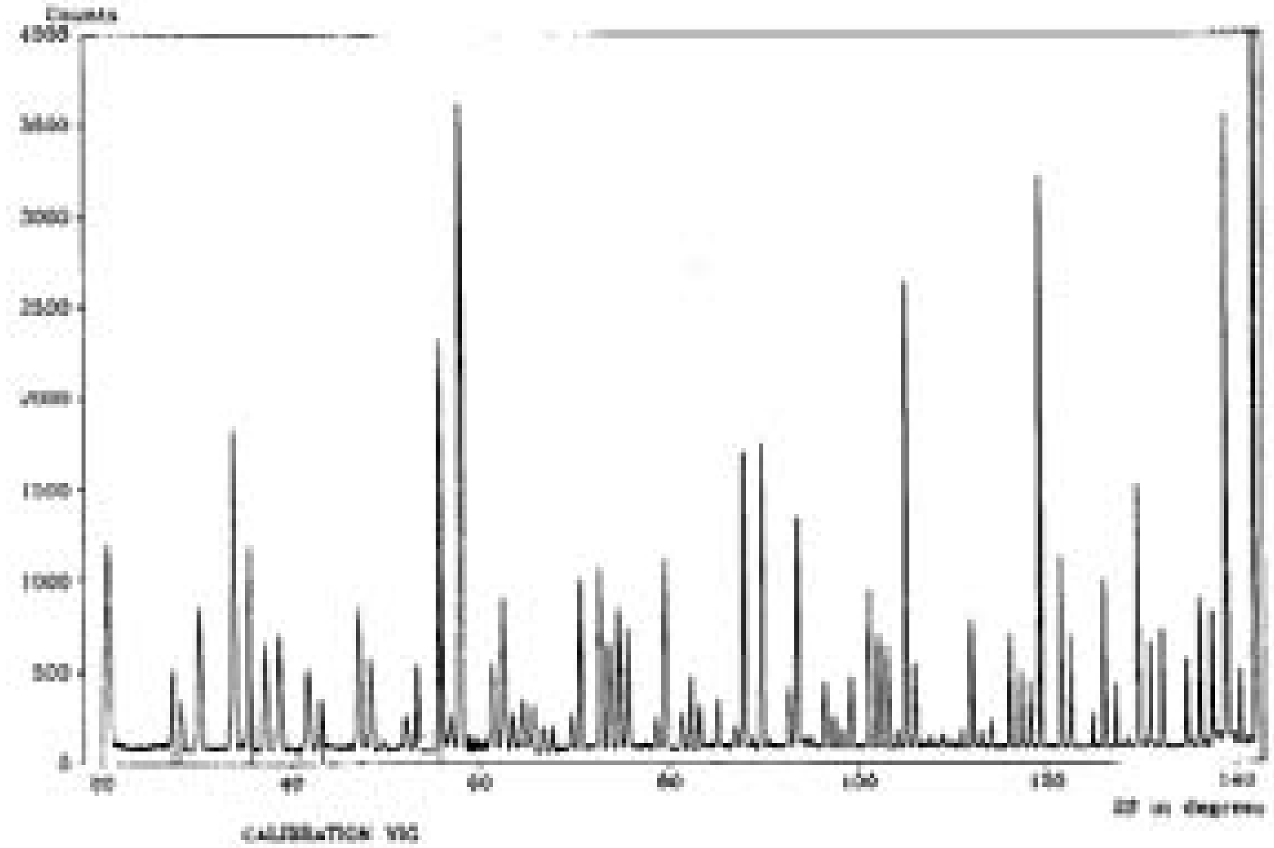


Position and intensity of diffraction peaks gives atomic positions

Purpose of the Instrument

Basically, in some form,
you want to measure
Bragg's equation

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



Define the neutron wavelength with your instrument design

Detectors allow you to measure theta

It means that you can calculate "d"

Therefore the instrument should be designed to give you the most appropriate measurement of scattering angle for a instrument class

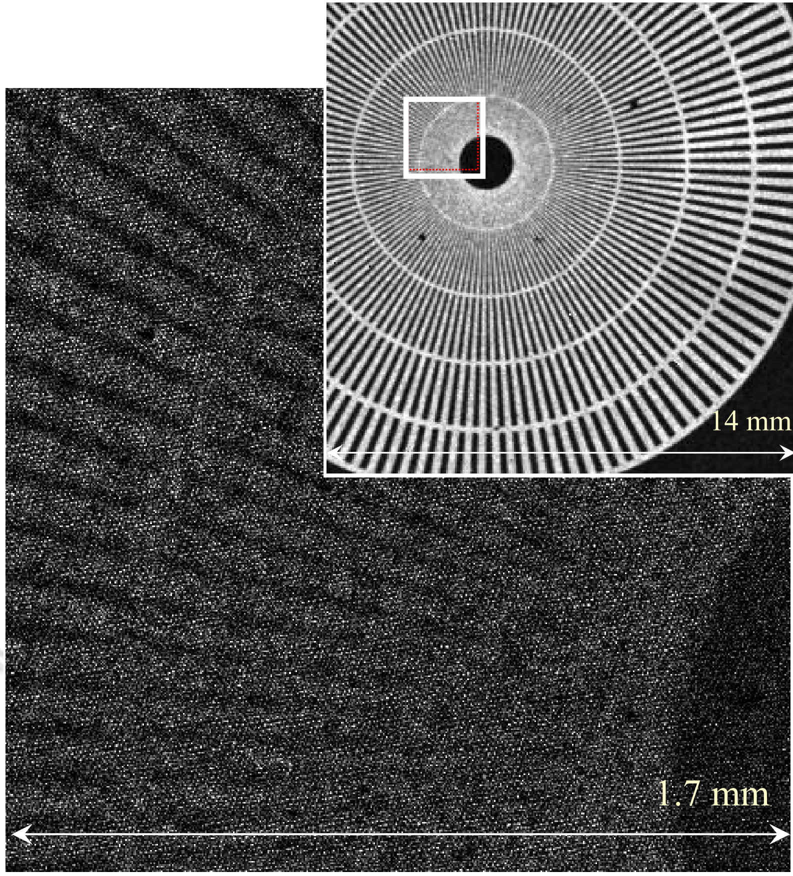
"horses for courses "

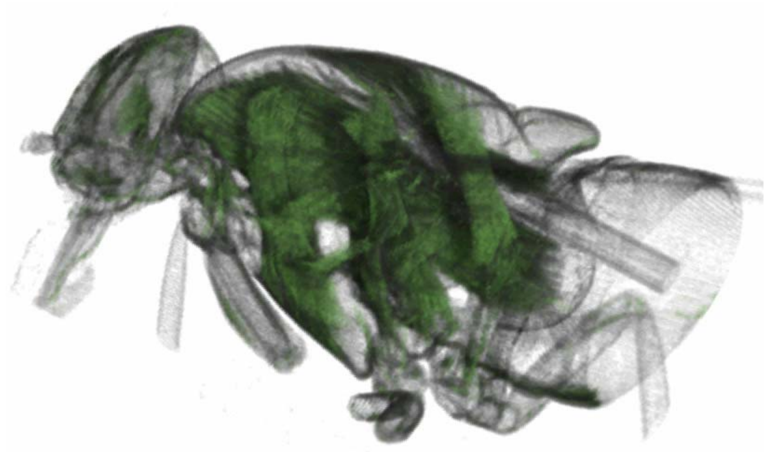
Examples of neutron instruments

- Neutron Scattering for materials science comprise a great variety of instruments as tools for studying materials
- Each has its own “figure of merit”

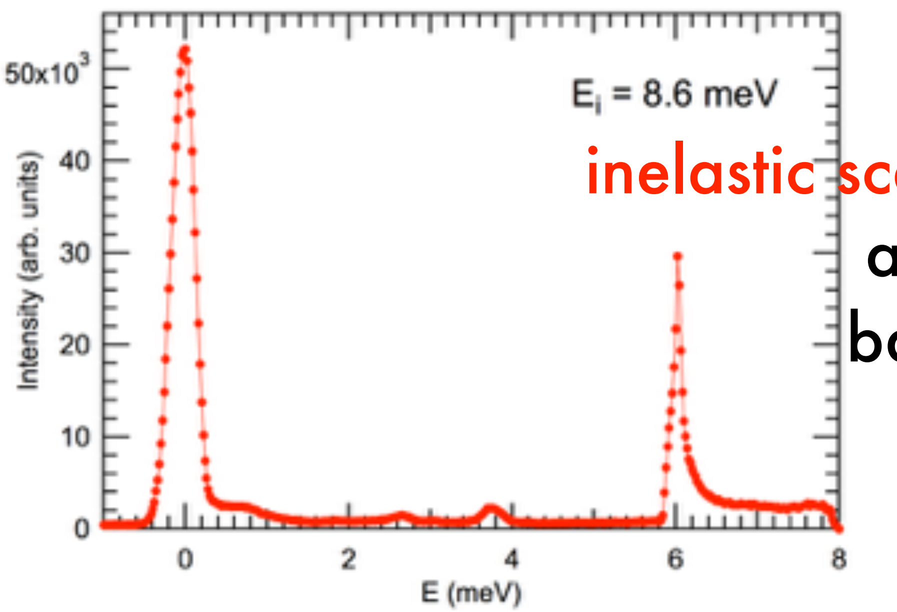
imaging

resolution (<100um), rate



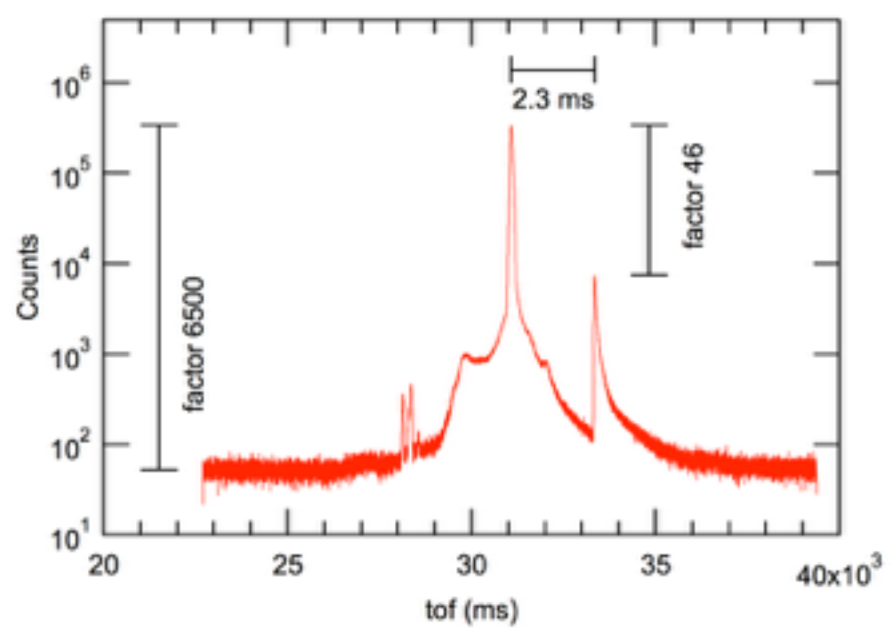


“horses for courses ”



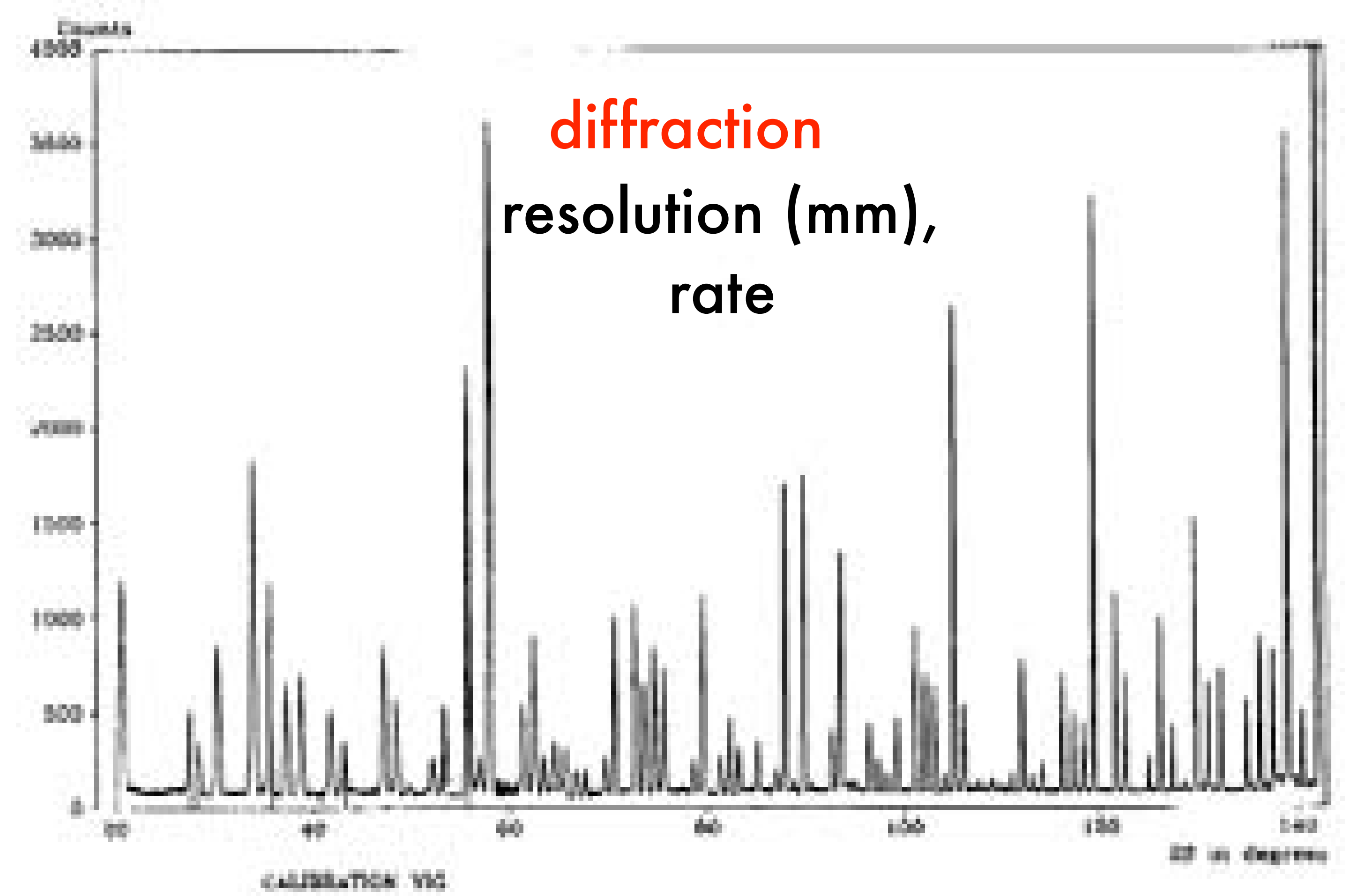
inelastic scattering

area, cost, background



diffraction

resolution (mm), rate



Neutron Generation

Neutron generation:
energy → atomic nuclei

Fast neutrons produced / joule heat deposited:

Fission reactors:	~ 10^9	(in ~ 50 liter volume)
→ Spallation:	~ 10^{10}	(in ~ 2 liter volume)
Fusion:	~ 1.5×10^{10}	(in ~ 2 liter volume)
	(but neutron slowing down efficiency reduced by ~20 times)	
Photo neutrons:	~ 10^9	(in ~ 0.01 liter volume)
→ Nuclear reaction (p, Be):	~ 10^8	(in ~ 0.001 liter volume)
Laser induced fusion:	~ 10^4	(in ~ 10^{-9} liter volume)

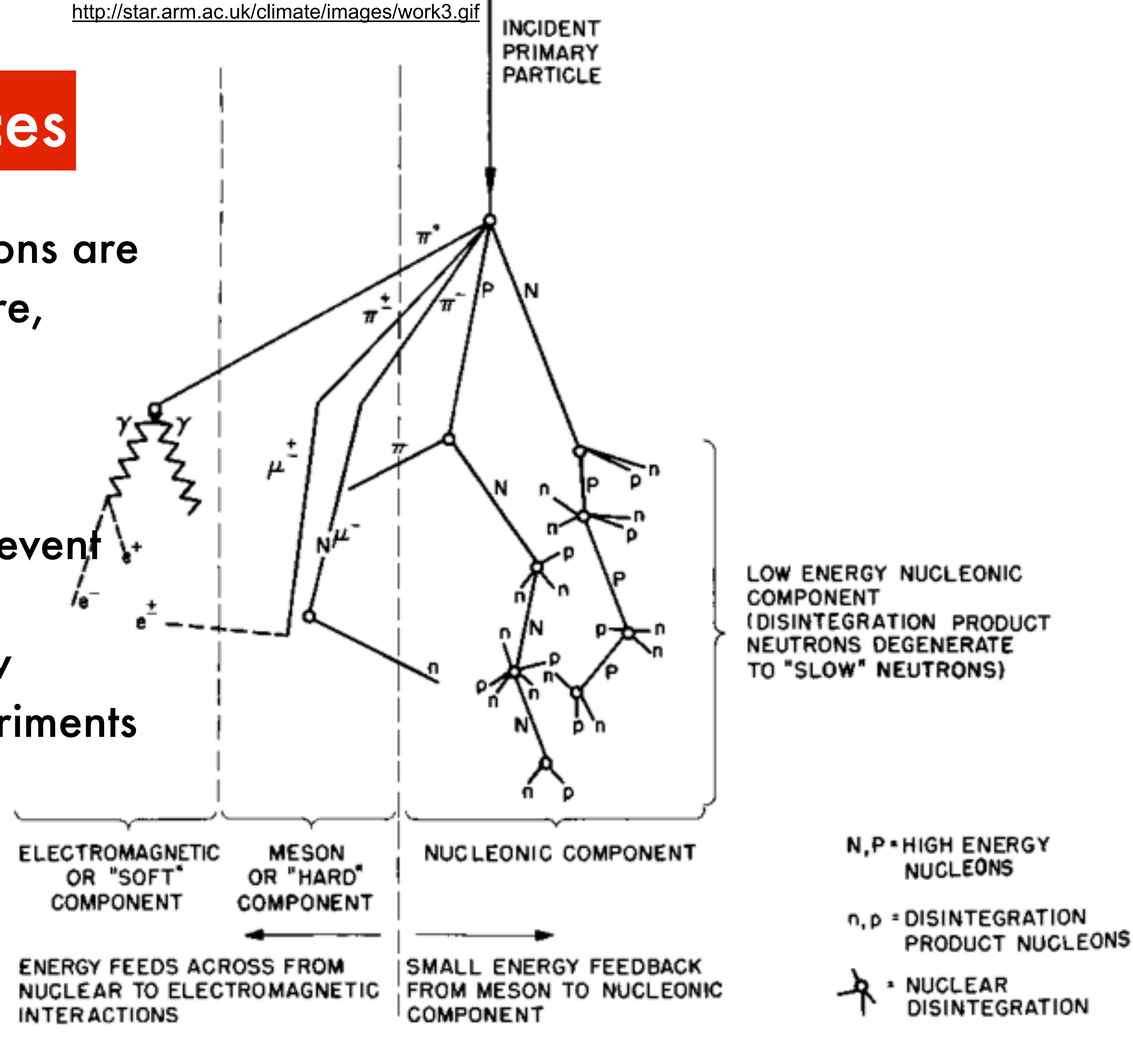
Spallation: most favorable for the foreseeable future (neutrons/€)
Compact source: lowest cost / facility

Natural Sources

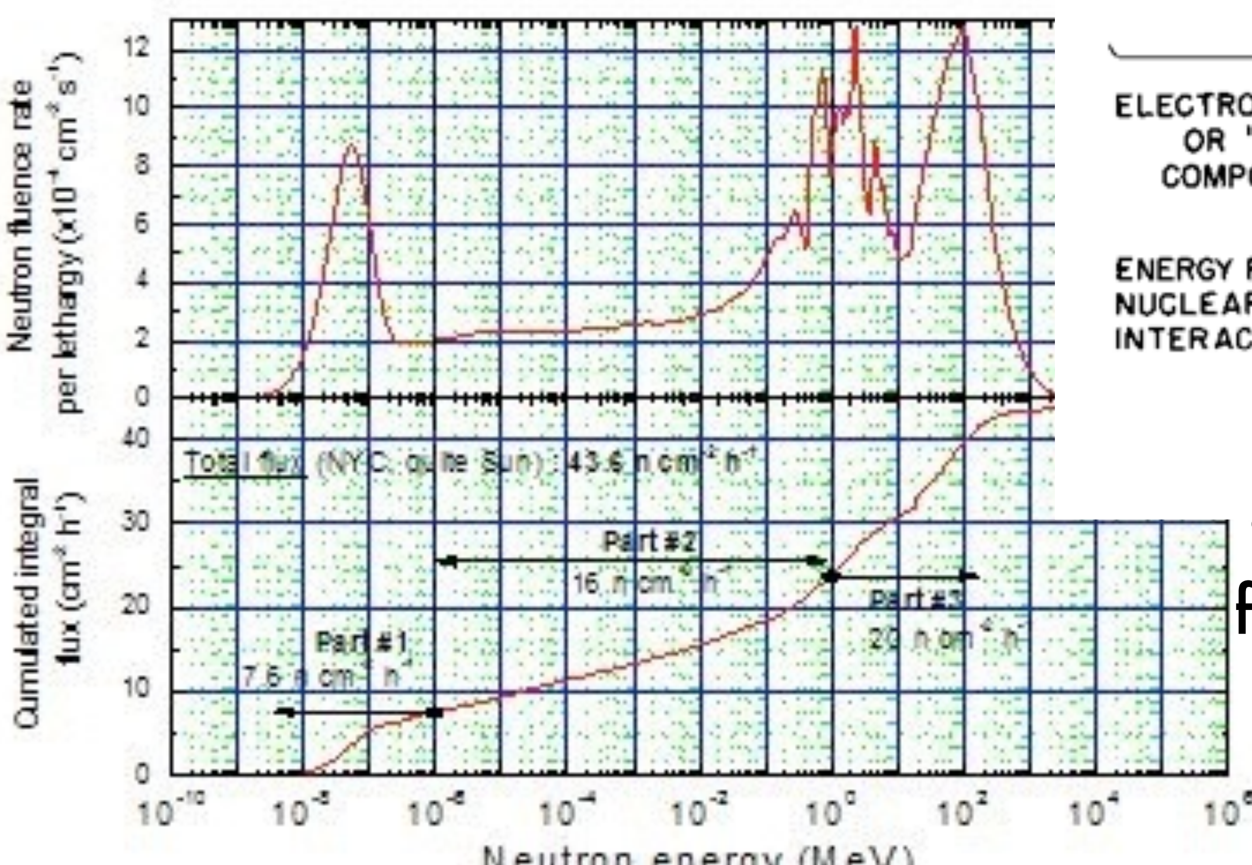
http://star.arm.ac.uk/climate/images/work3.gif

Natural Sources

- Natural sources of unbound neutrons are spallation processes in the atmosphere, fusion in stars and natural fission
- Example: cosmic neutrons in the atmosphere
- Of interest for as can cause single event upsets in chips
- Neutrons may be signature for new physics in various underground experiments



Schematic Diagram of Cosmic Ray Shower



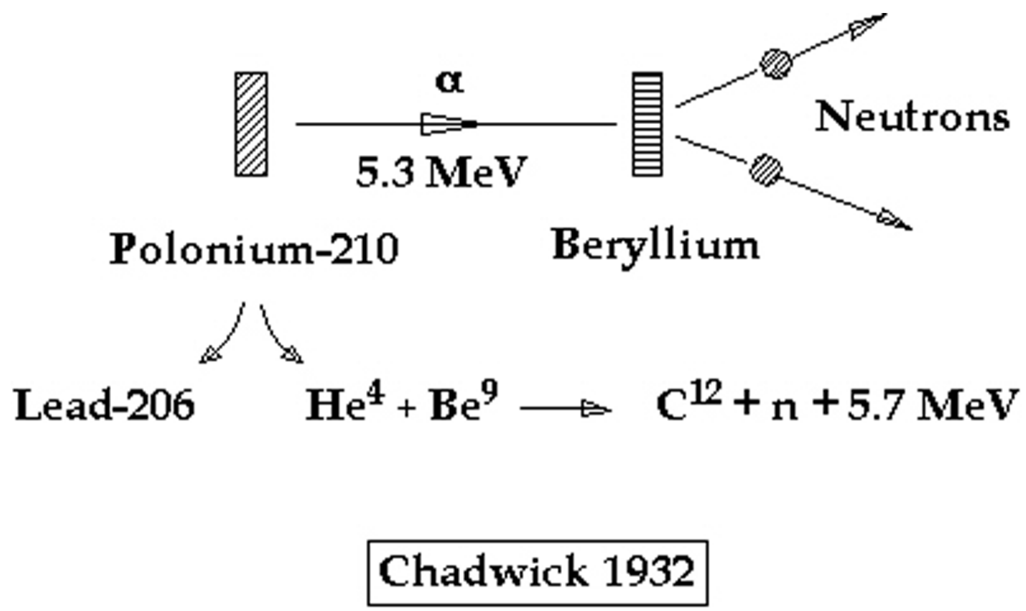
M. S. Gordon, et al., TNS 1 12004 (2004.)

- Whilst of interest in themselves, none of them are frequent enough to be used a probe

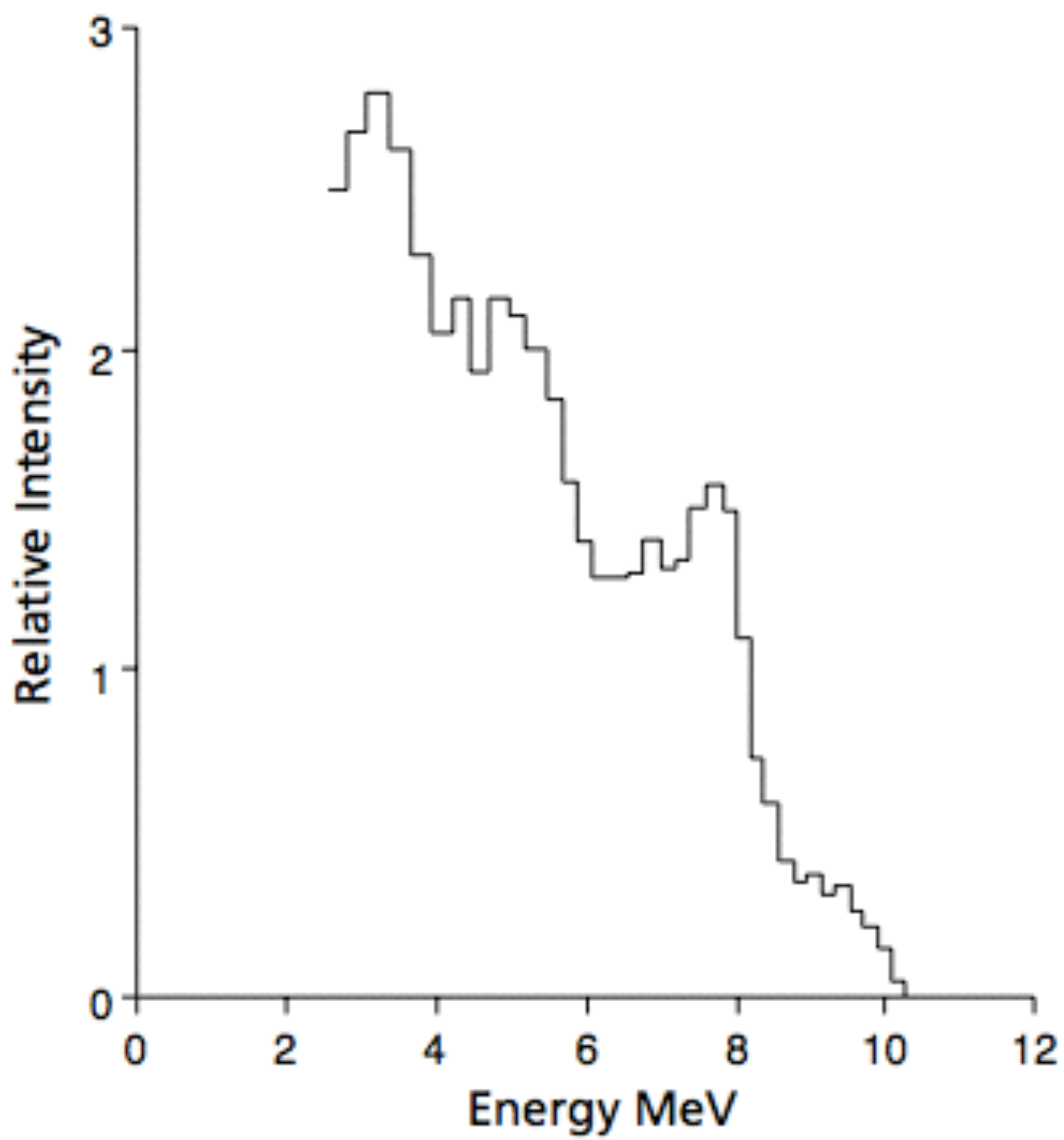
Radioactive Laboratory Sources

Radioactive Sources

- Neutron was discovered by the (alpha, n) reaction, where in some lighter elements the last neutron is weakly bound, and released when alpha particle is incident



$He^4 + Be^9 \rightarrow C^{12} + n + 5.7 MeV$



- Americium-241 commonly used
- typical number 6. 10^7 n/s for 1 TBq
- Details of neutron production depend upon geometry of sources
- ca. 40% of neutrons below 1 MeV

- Some isotopes undergo spontaneous fission
- eg Cf-252, 3.1% of decays, average of 3.7 neutrons per fission.
- Cf-252 not naturally occurring

Fusion

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Neutron Generator

- Use Deuterium-Deuterium or Deuterium-Tritium fusion
- Small accelerator arrangement of few 100 keV
- DD:

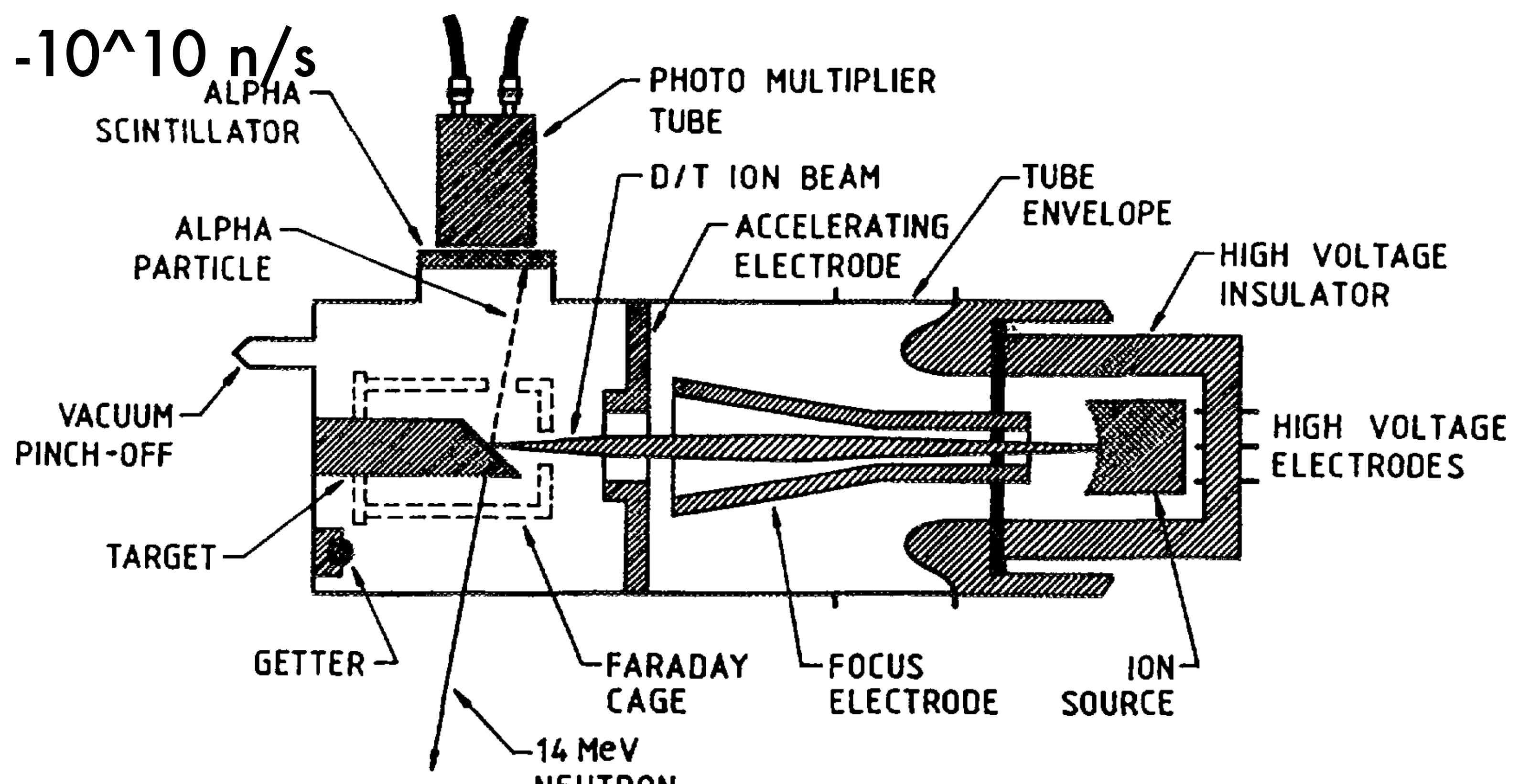
50%: $_1D^2 + {}_1D^2 \dashrightarrow {}_2He^3$ (0.82 MeV) + $_0n^1$ (2.45 MeV)

50%: $_1D^2 + {}_1D^2 \dashrightarrow {}_1T^3$ (1.01 MeV)+ $_1p^1$(3.02 MeV)

- DD:

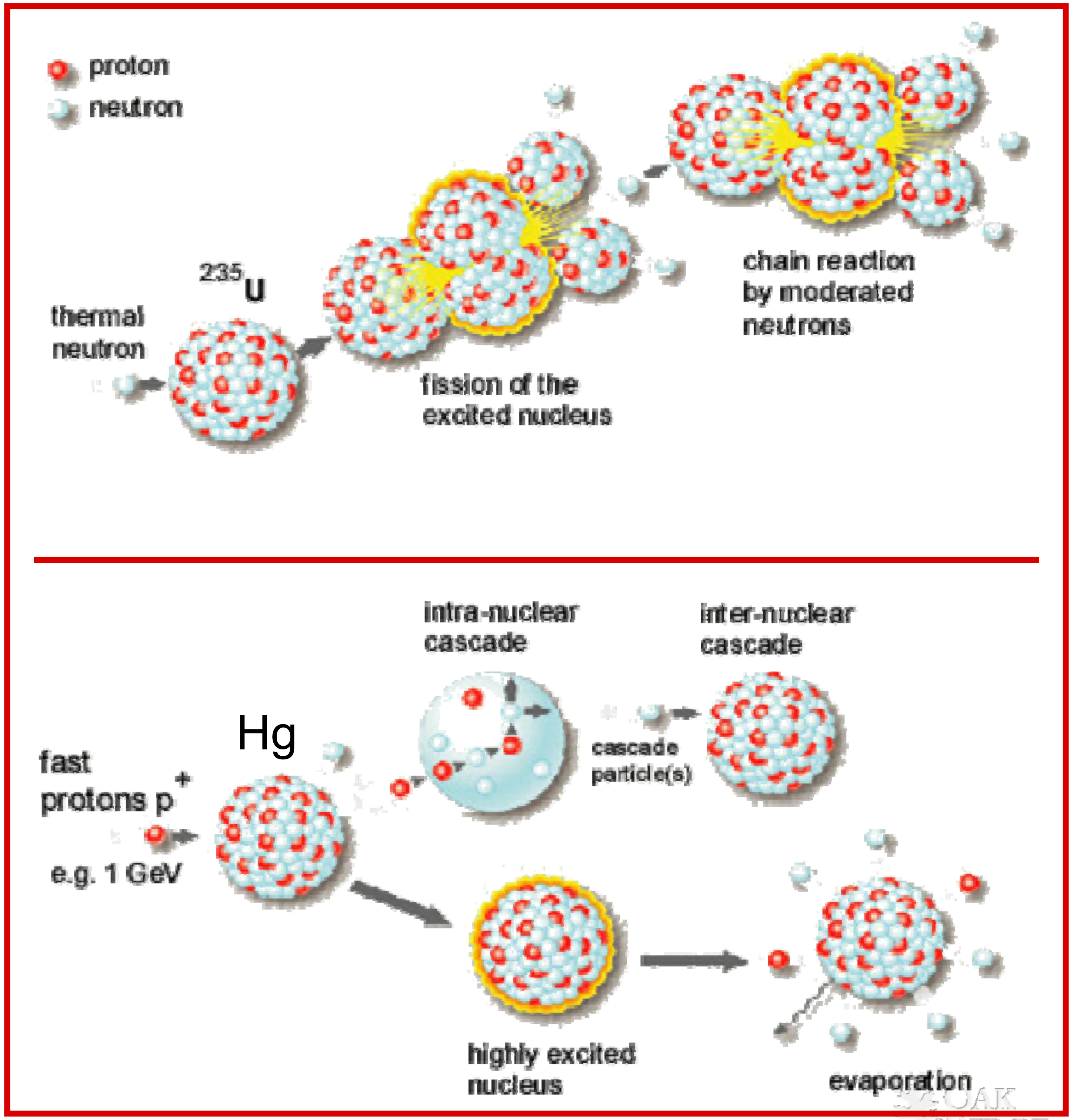
$_1D^2 + {}_1T^3 \dashrightarrow {}_2He^4$ (3.5 MeV) + $_0n^1$ (14.1 MeV)

- Many generators available commercially
- eg SODERN, NSD-GRADEL fusion, Thermoscientific
- fluxes typically in the range 10^6 -10^10 n/s



Fission vs Spallation

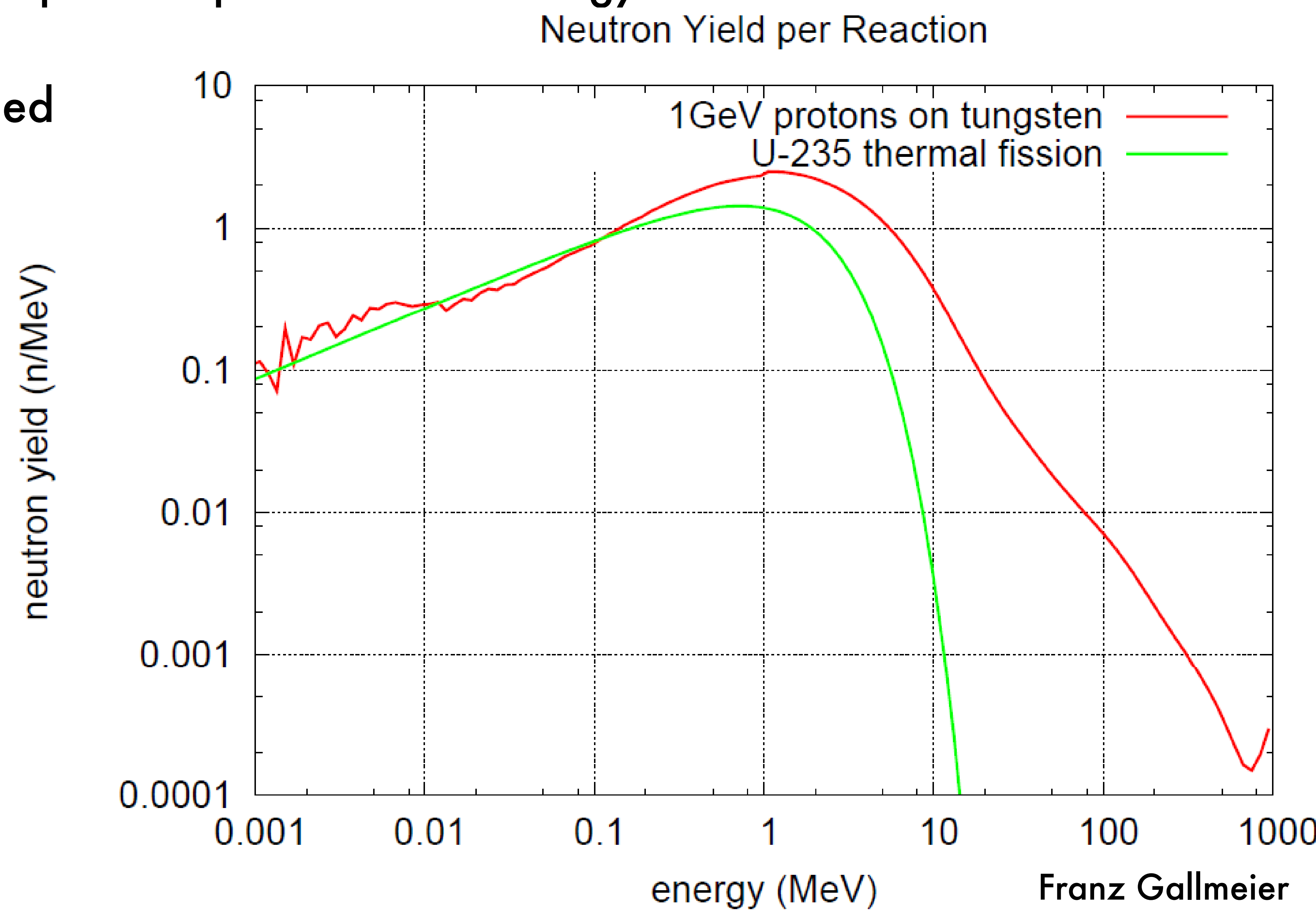
- Processes very different
- Fission results in light and heavy debris
- Spallation results in debris close to that of target
- Neutron yield:
  - Fission: 2.5n / fission. 1 needed to substain criticality
  - Spallation: very energy dependent. Typically ca. 10.
- Heat:
  - Fission: ca. 160 MeV/neutron
  - Spallation: ca. 25 MeV/neutron



Phil Ferguson

Fission vs Spallation

- Energy spectrum very different
- Spallation yields neutrons up to the proton beam energy
- Significant shielding needed



Franz Gallmeier

Present and Future of Neutron Research Facilities

Neutron facilities – reactors and particle driven

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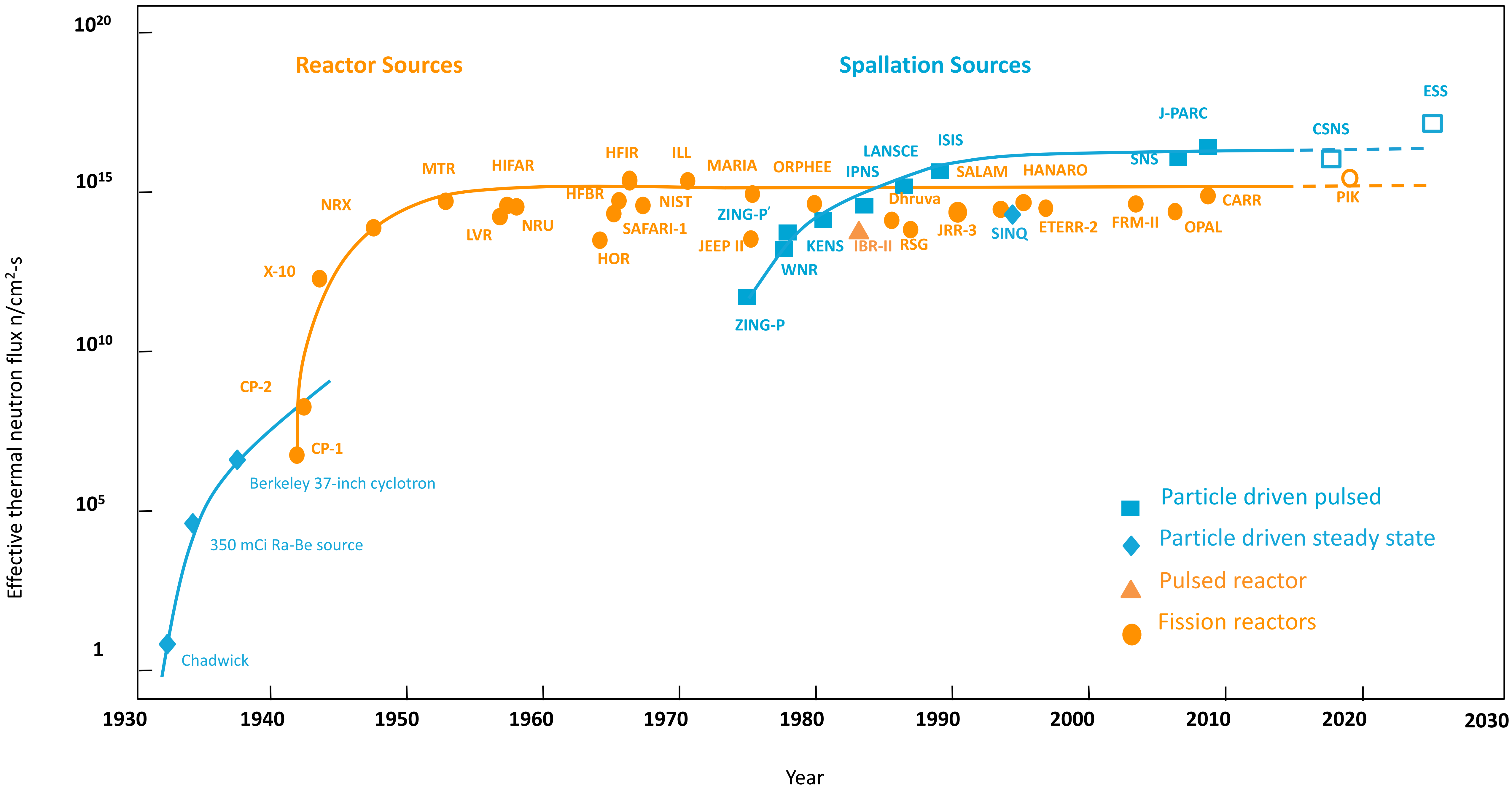
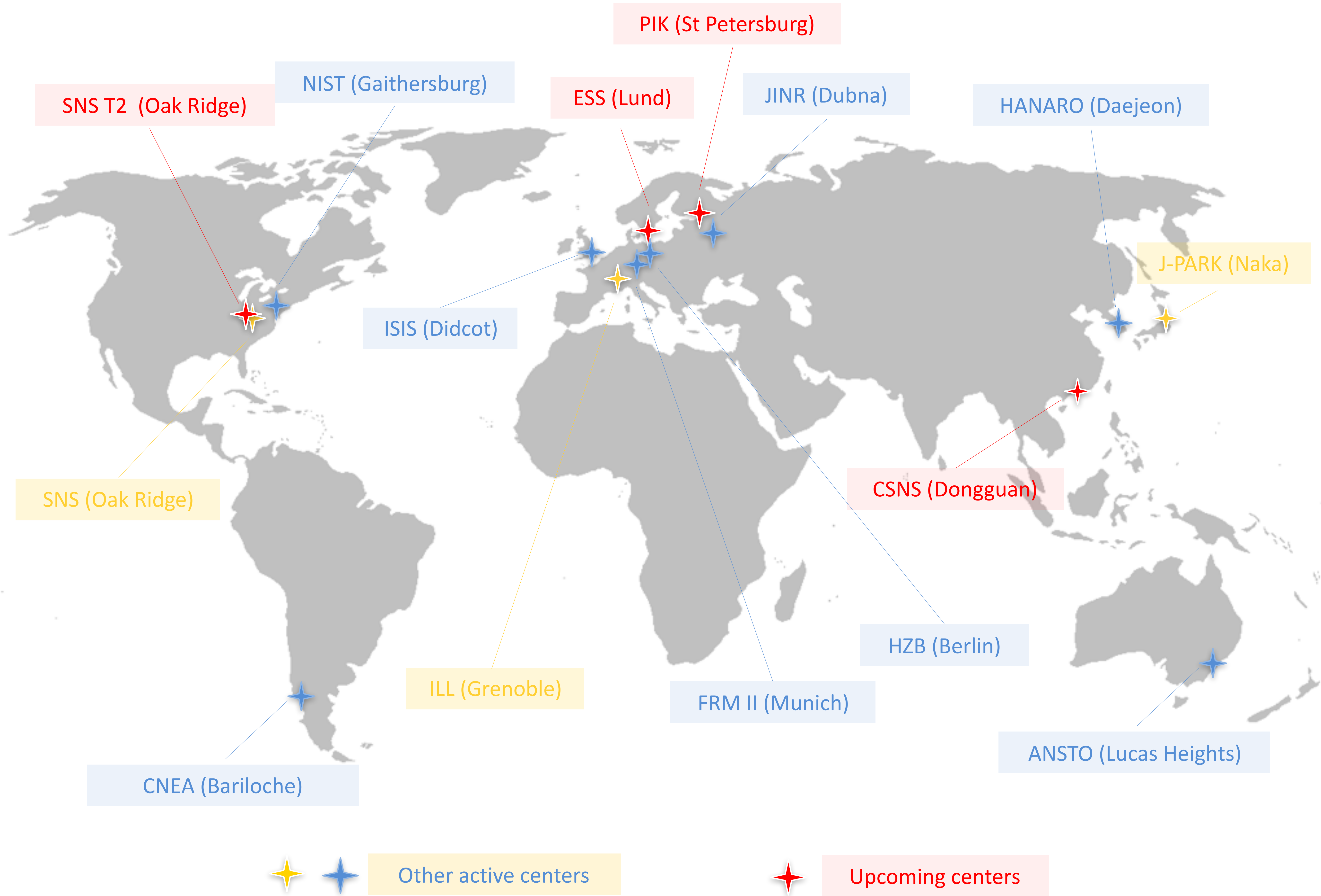
EUROPEAN SPALLATION SOURCE



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



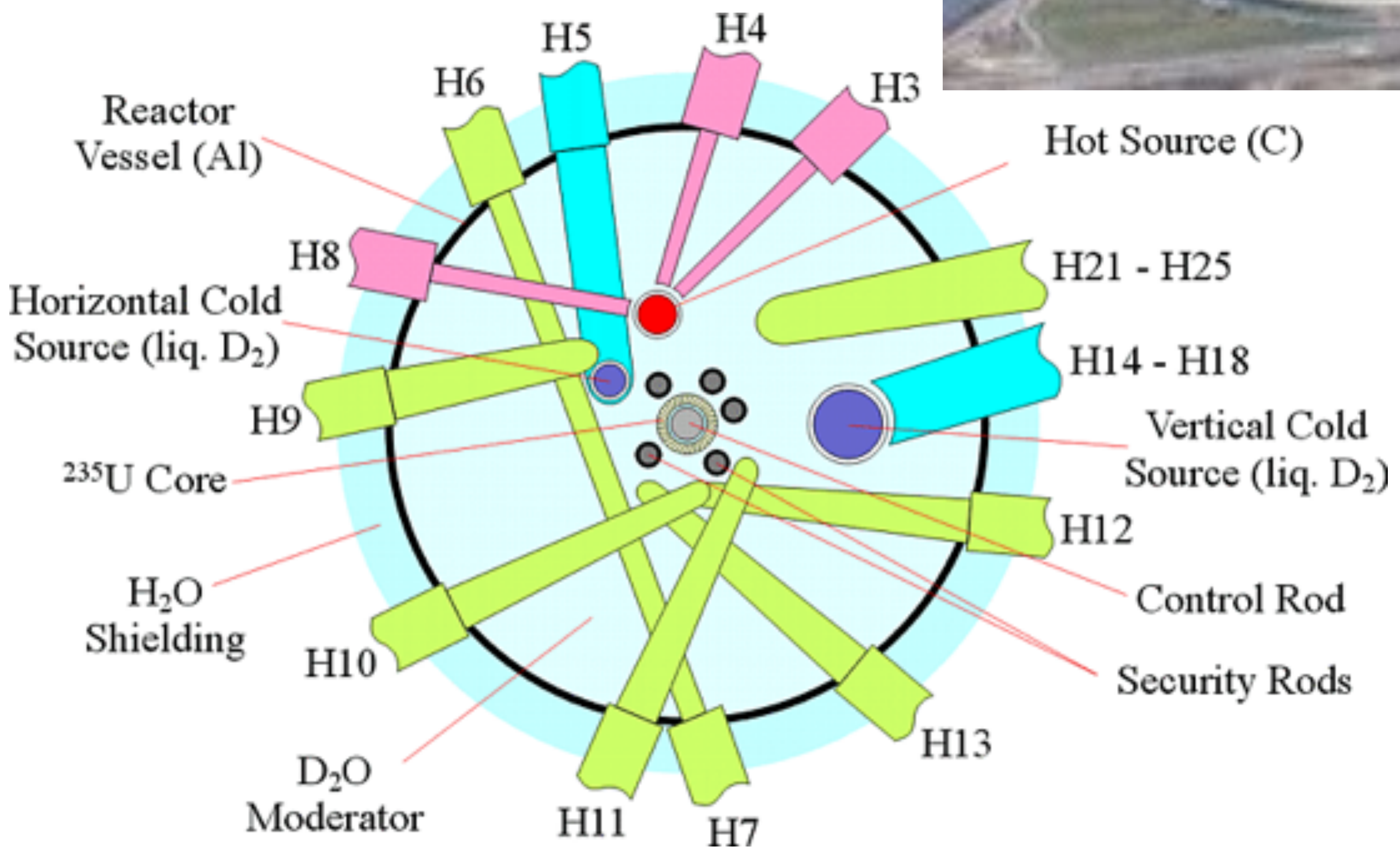
... AND THESE ARE ONLY 14 OF THE ALMOST 50 NEUTRON RESEARCH FACILITIES WORLDWIDE

Reactors

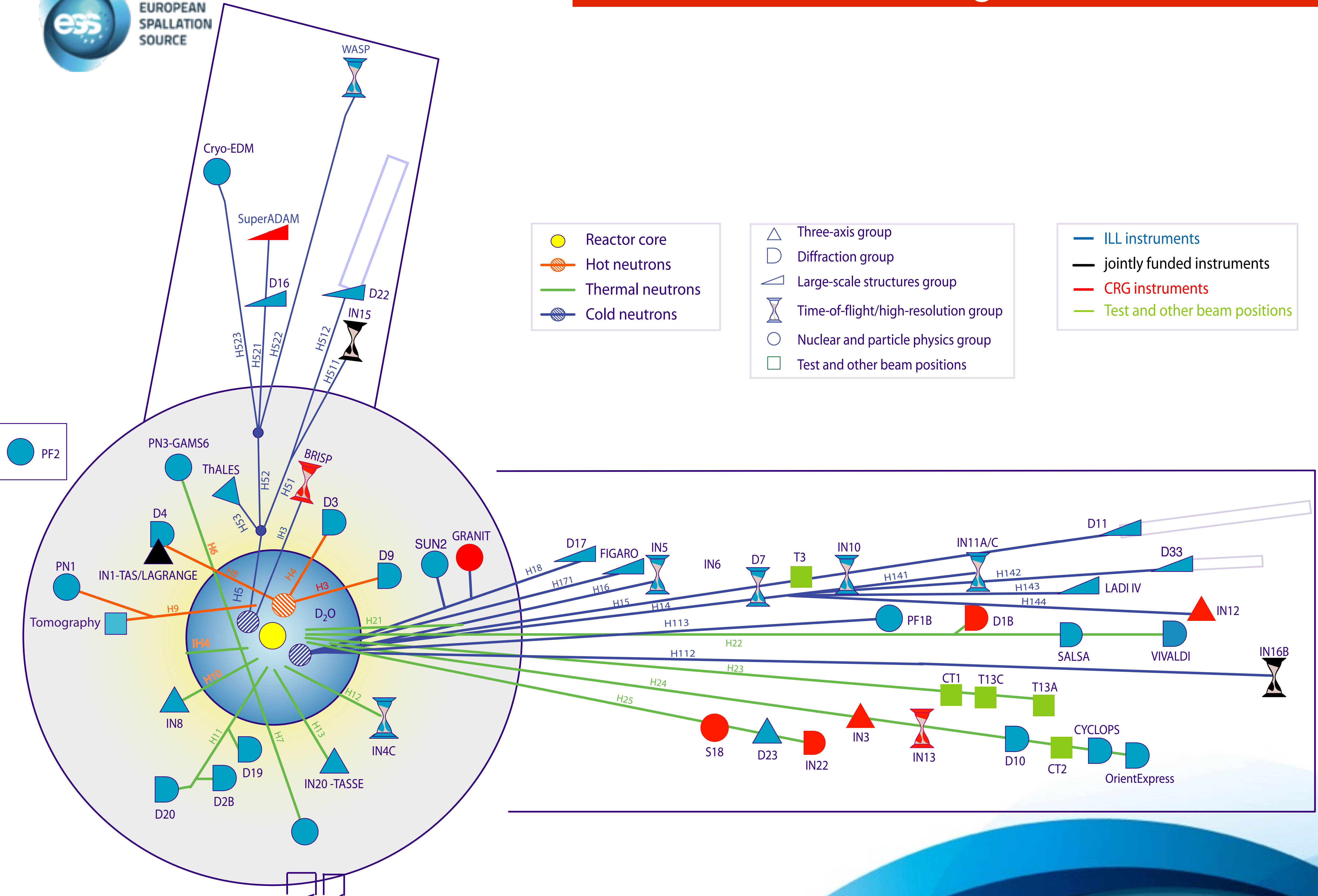
Institut Laue-Langevin, Grenoble

- World's leading research reactor
- Came into operation in 1971
- 58 MW thermal power
- Most intense continuous neutron flux in the moderator region:
- 1.5 . 10^15 n/cm^2/s

- ca. 600 papers/year



Institut Laue-Langevin, Grenoble



Spallation Sources

Current most advanced neutron sources

SNS (Oak Ridge, USA)

J-PARC (Tokai Japan)

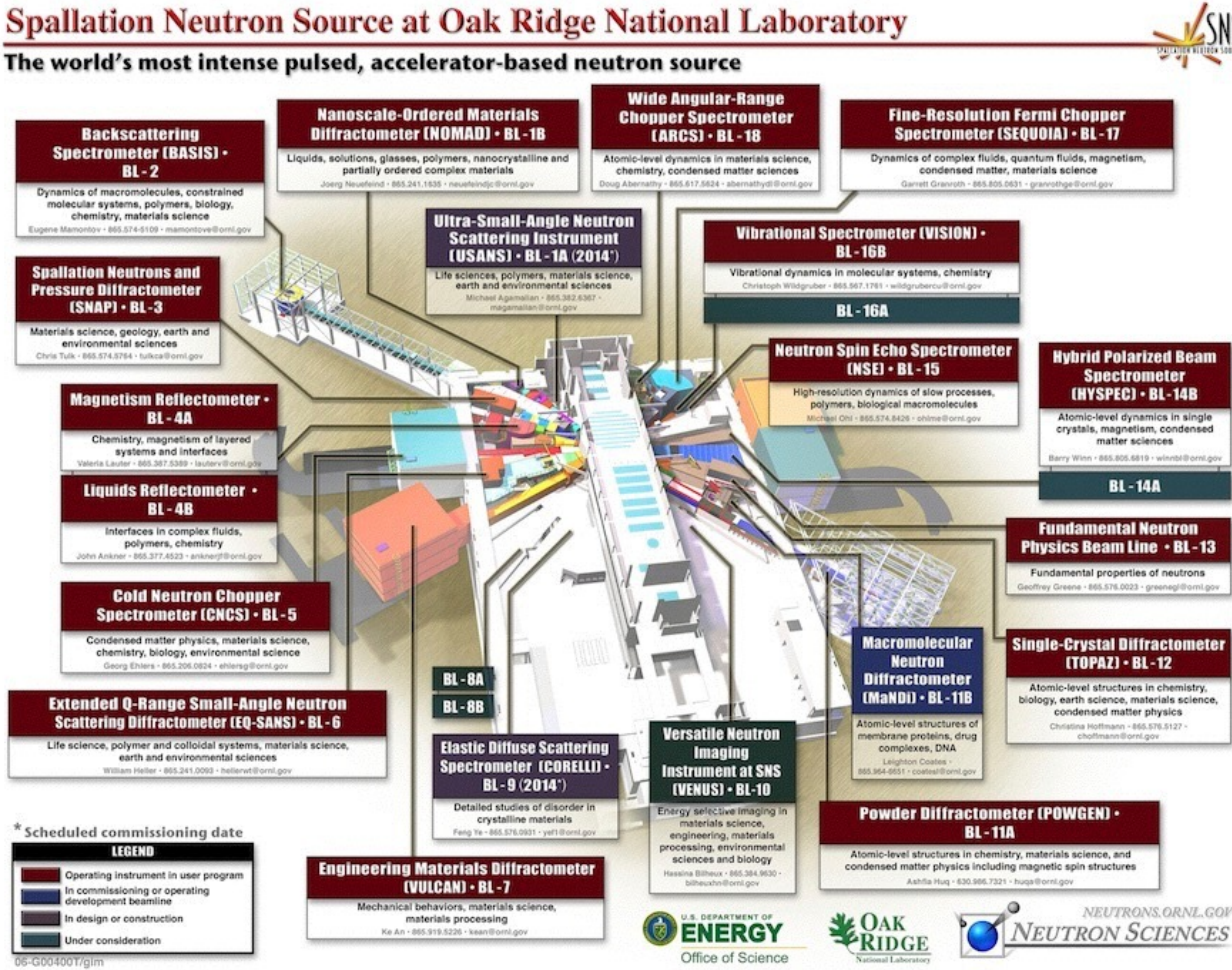
Instantaneous power on target (e.g. 1 MW at 60 Hz, i.e. 17 kj in ~1 μs pulses on target): **17 x**

→ **Pressure wave: 300 bar**

Reaches limits of technology

Spallation Neutron Source at Oak Ridge National Laboratory

The world's most intense pulsed, accelerator-based neutron source



What does a neutron facility look like?

Advanced Spallation Sources require high power accelerators

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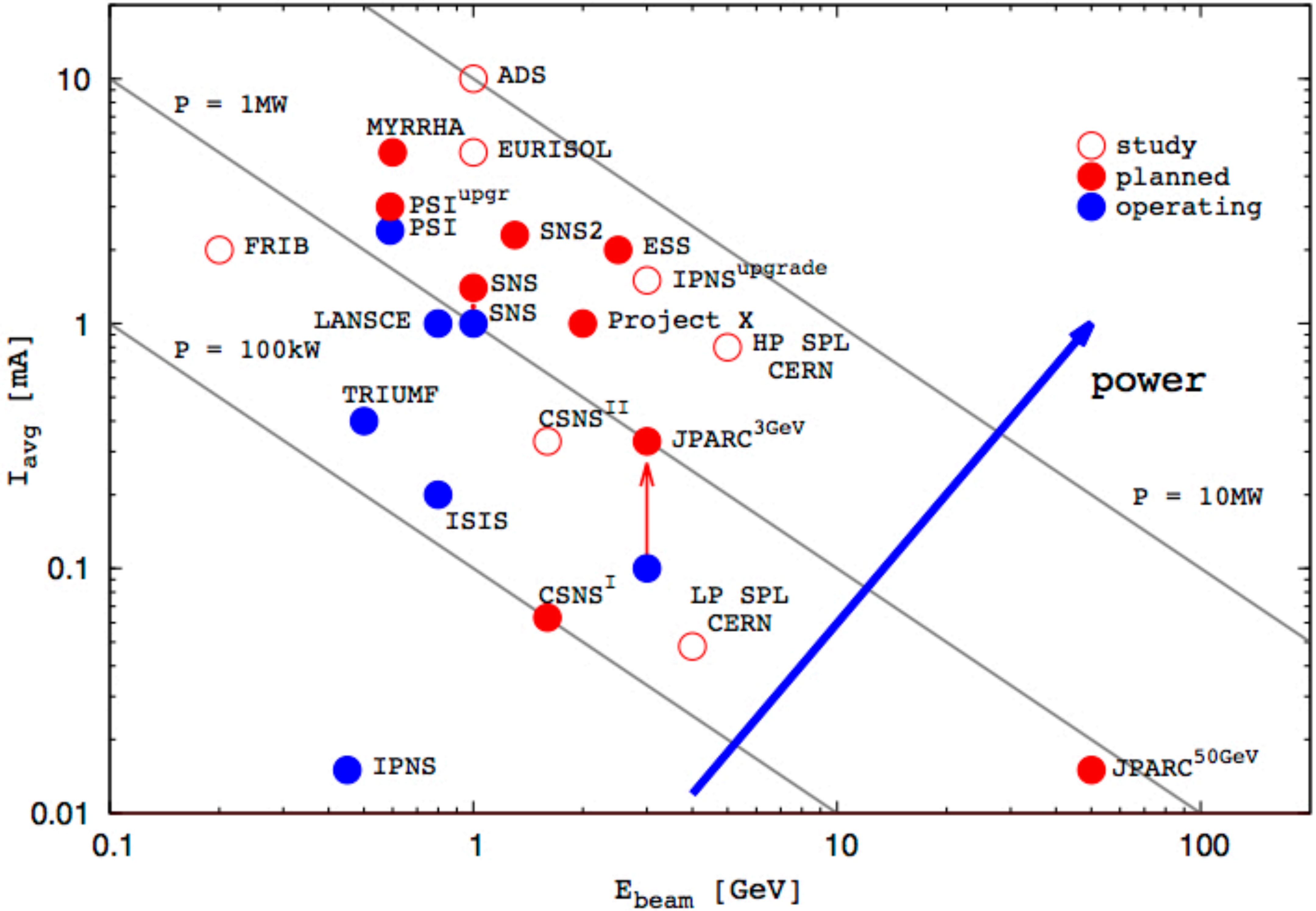

Moderation

Slow neutron generation

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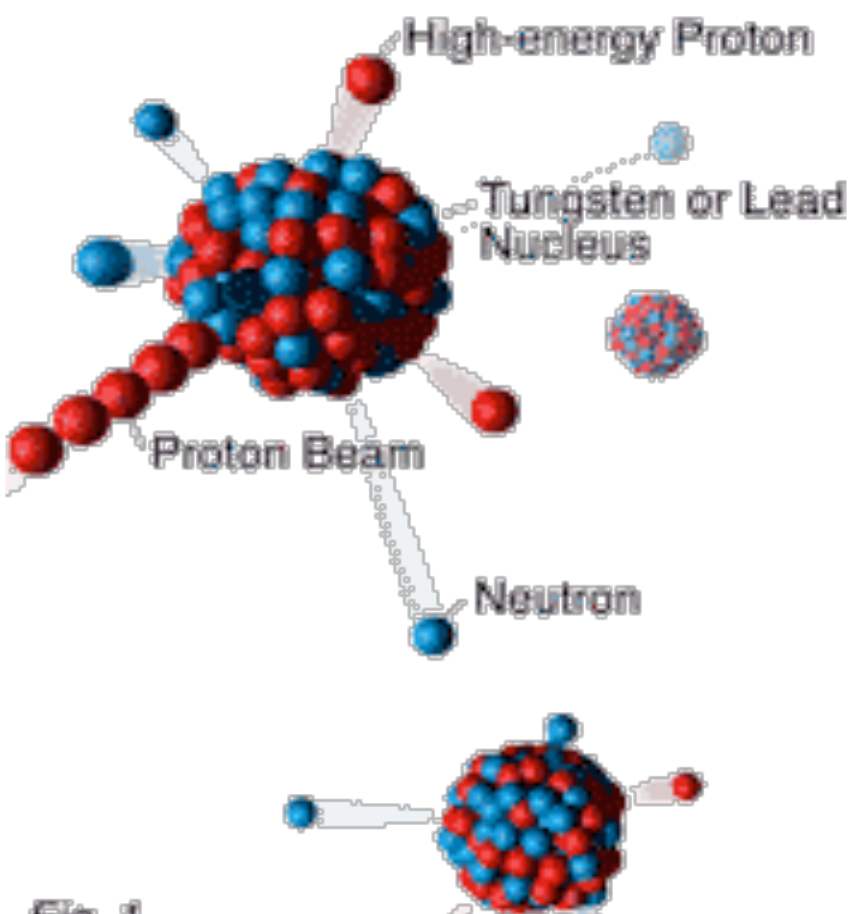
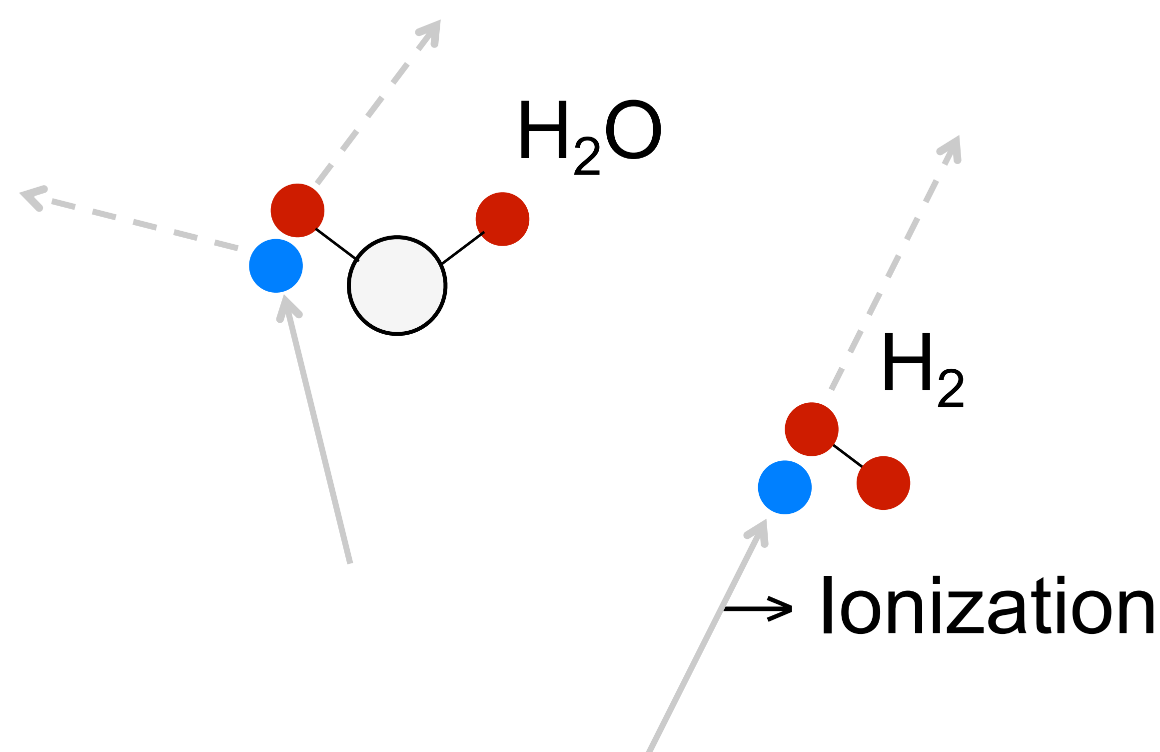
Two step process in the target station

A) Series of nuclear reactions:
spallation → fast neutrons
~100 billion °C

B) Collisions with H atoms:
moderation → slow neutrons
"Thermal": ~ 20 °C
"Cold": ~ -220 °C ≈ 50 K

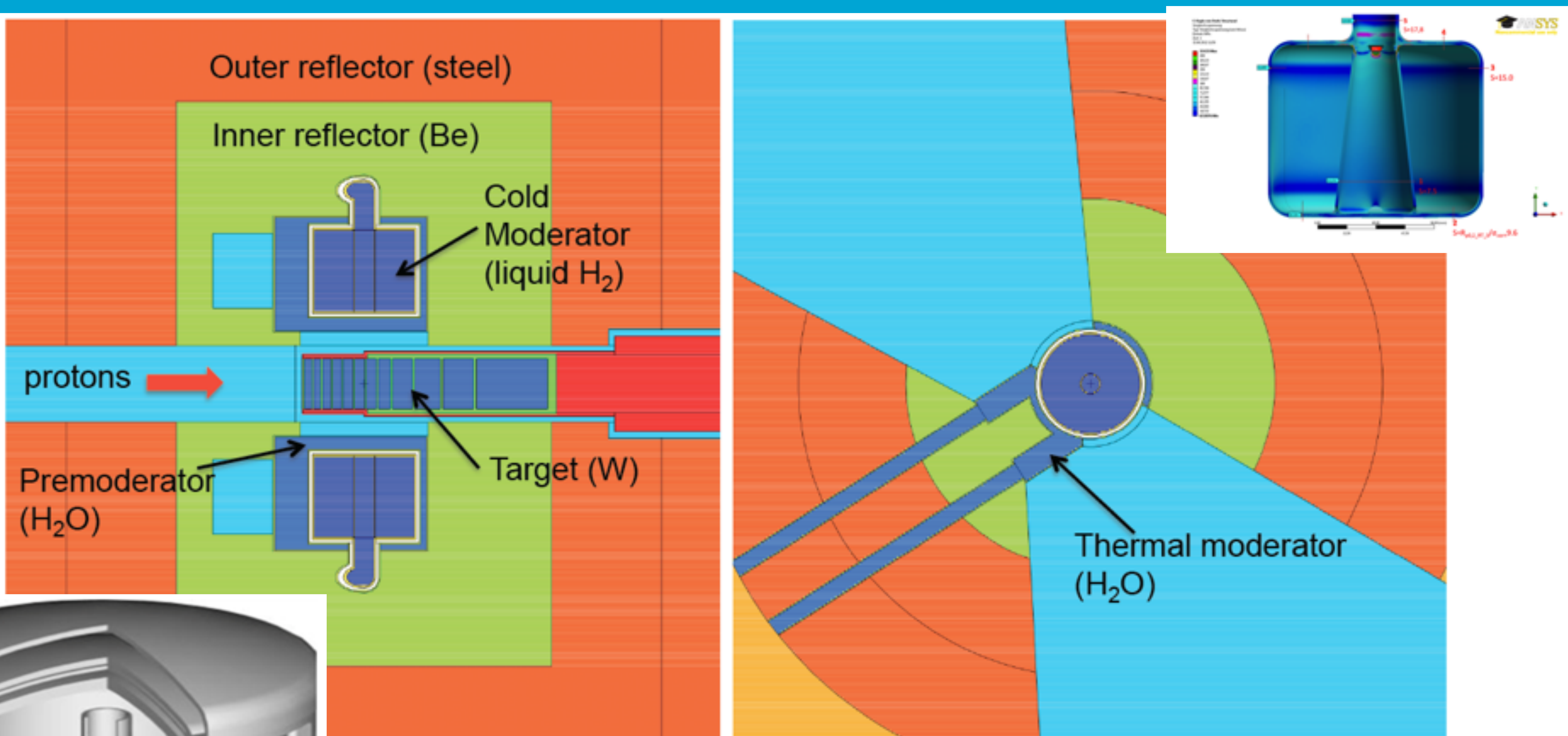


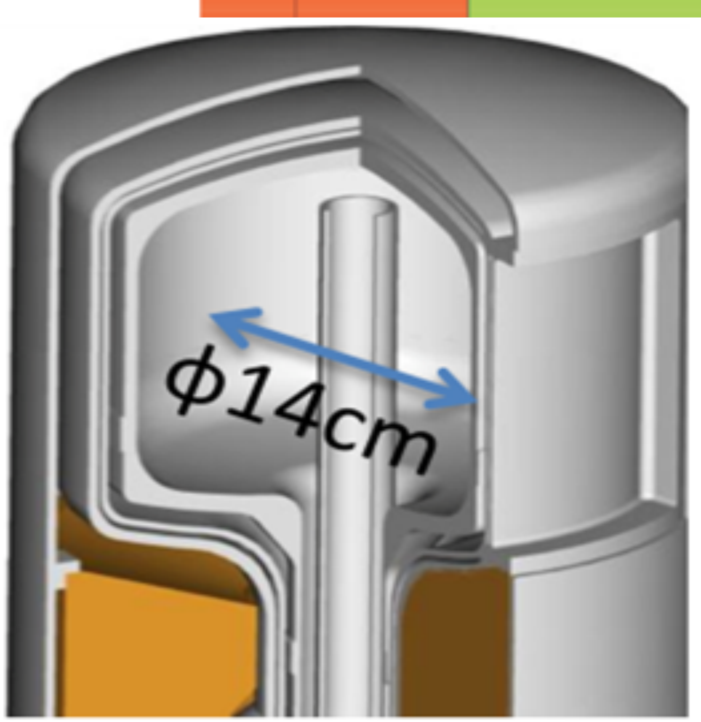


Time: << 1 μs

10 – 500 μs

TDR configuration: two tall moderators





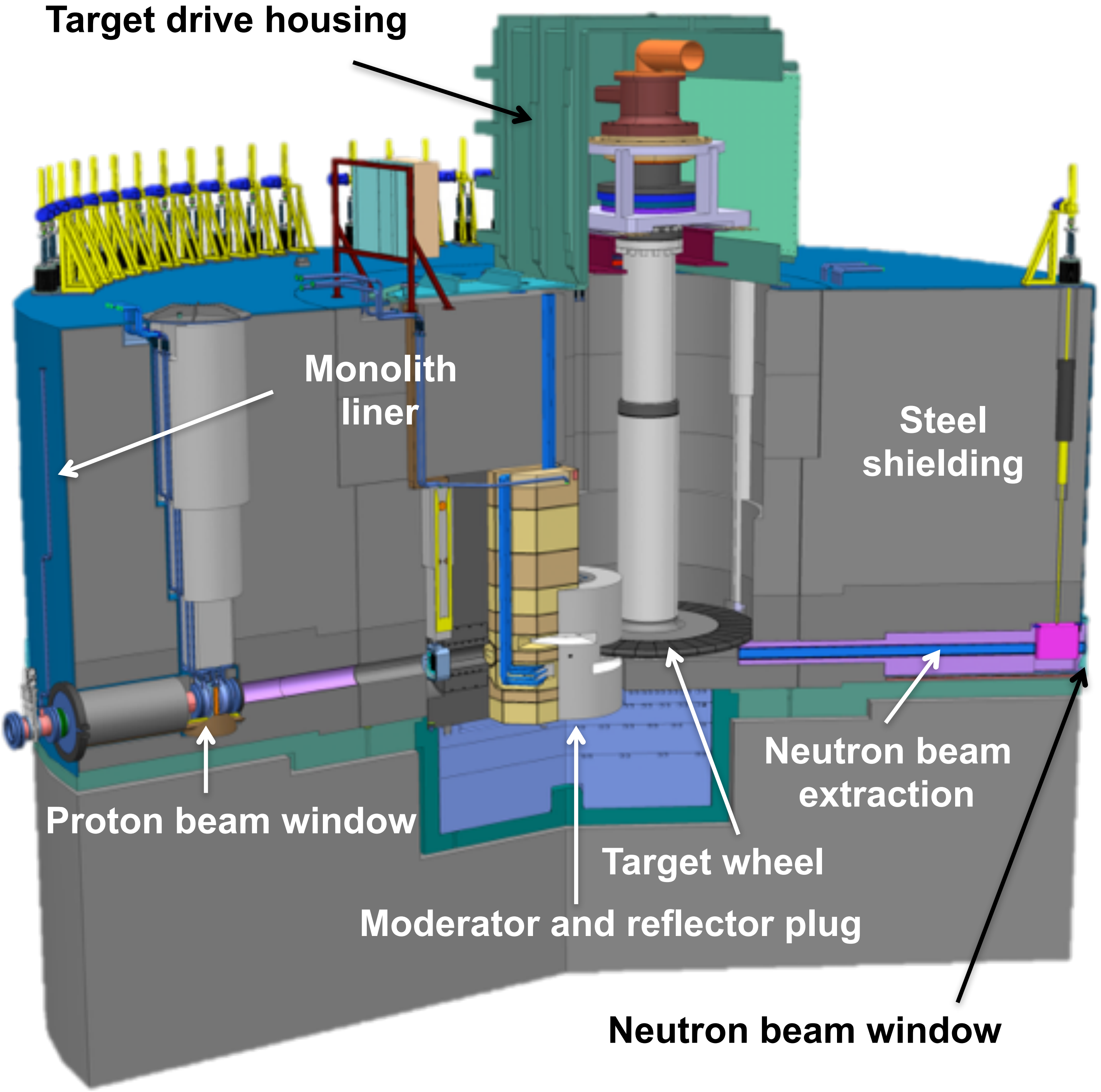
Thermal wings provide a bi-spectral source.

Volume moderator:

implemented at J-PARC

99 % para-H_2 tested

Slow neutron generation: target monolith



Functions:

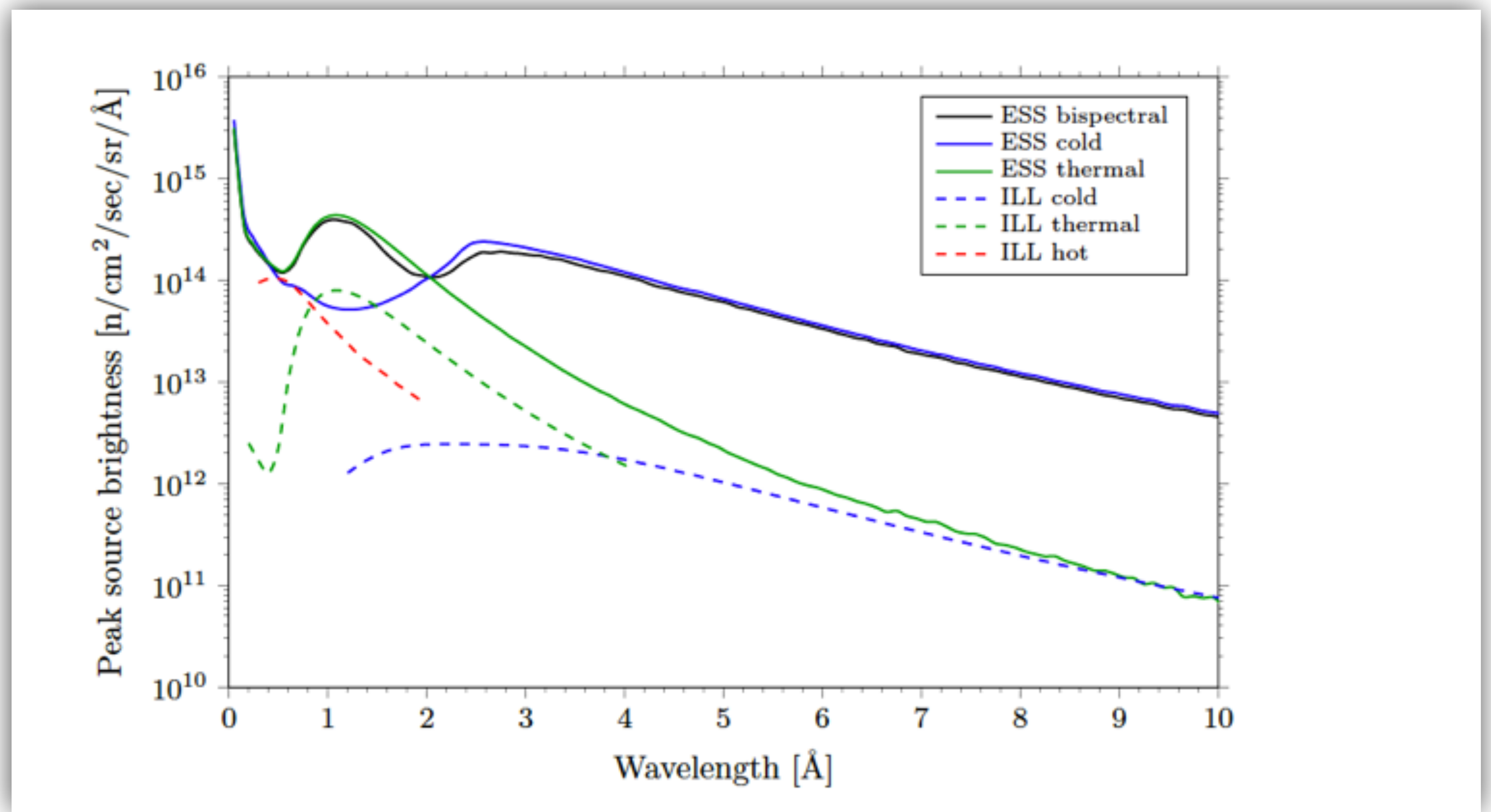
- Convert protons to neutrons
- Heat removal
- Confinement and shielding

Unique features:

- Rotating target
- He-cooled W target

Excellent performance from the TDR moderators

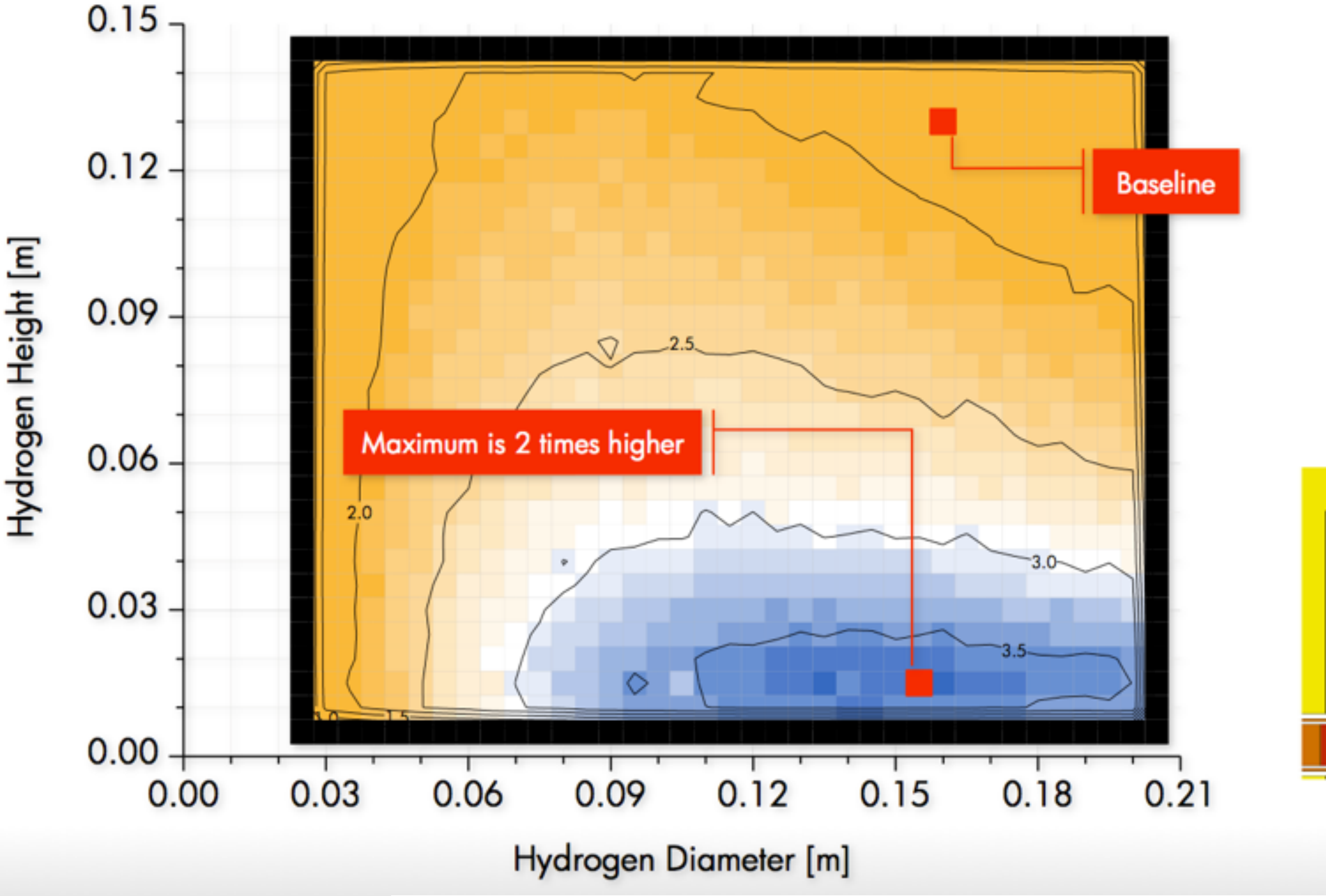
(ESS Technical Design Report)

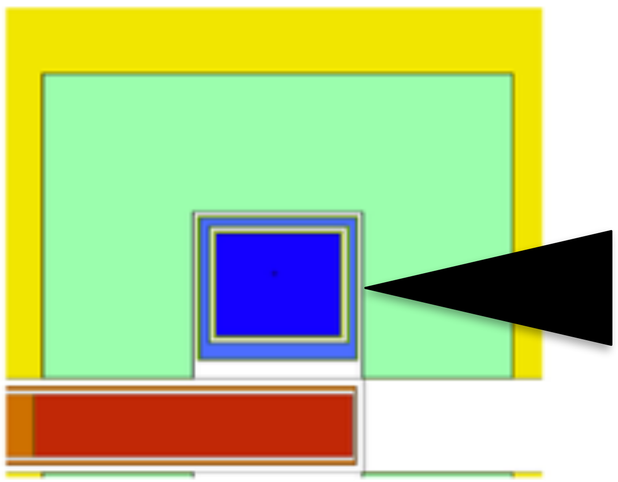


3. ESS Technical Design Report, ESS-doc-274, ISBN 978-91-980173-2-8 (April 23, 2013). URL http://eval.esss.lu.se/DocDB/0002/000274/015/TDR_onli%ne_ver_all.pdf

We started from the *unperturbed* brightness

EUROPEAN SPALLATION SOURCE





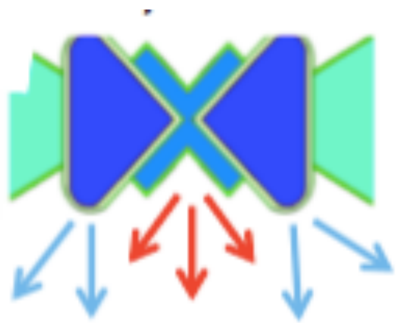
4. K. Batkov, A. Takibayev, L. Zanini and F. Mezei, *Unperturbed moderator brightness in pulsed neutron sources*, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 729 (2013) 500 - 505.

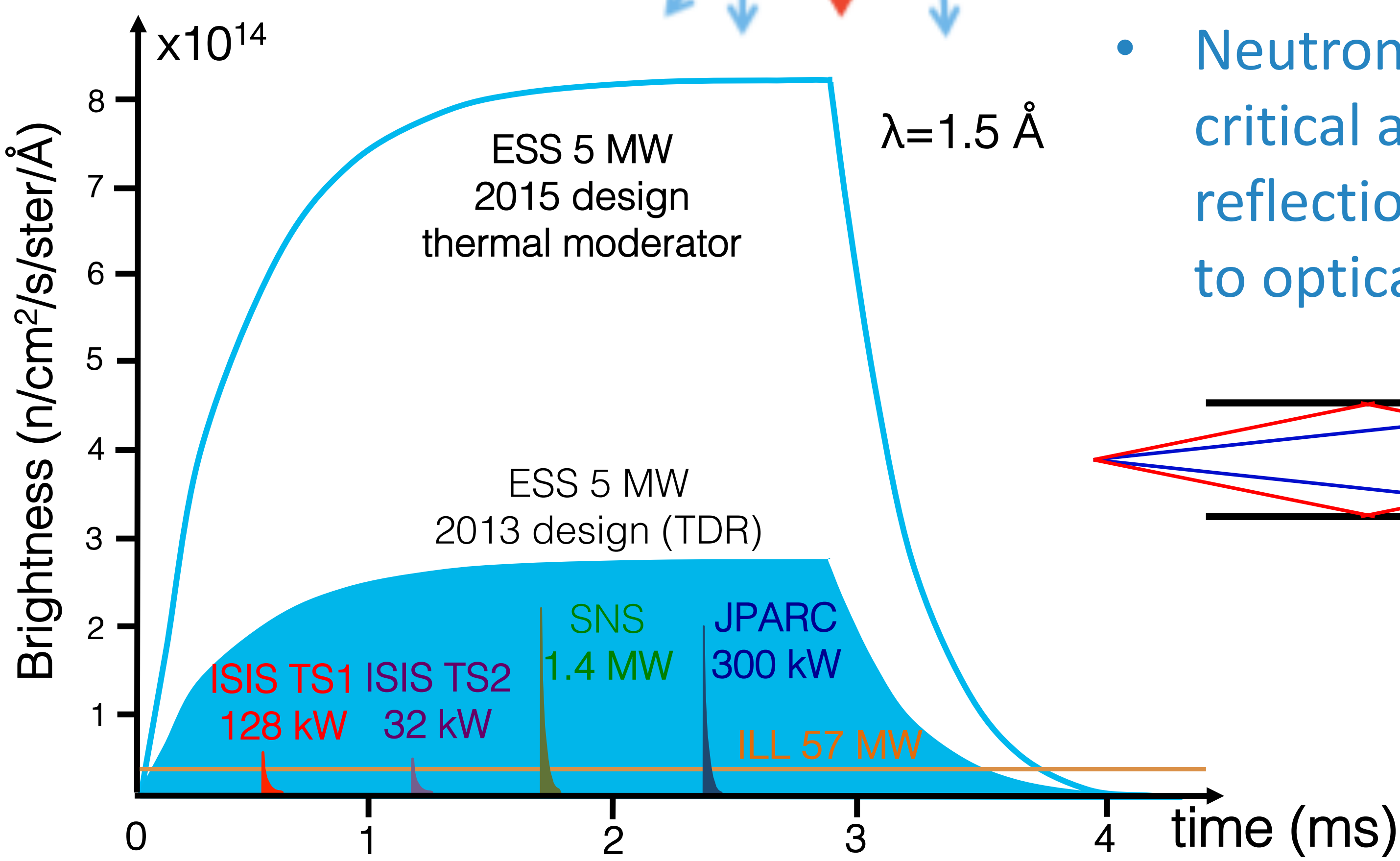
Neutron Beamlines and Instruments

Neutron Instrumentation Technology

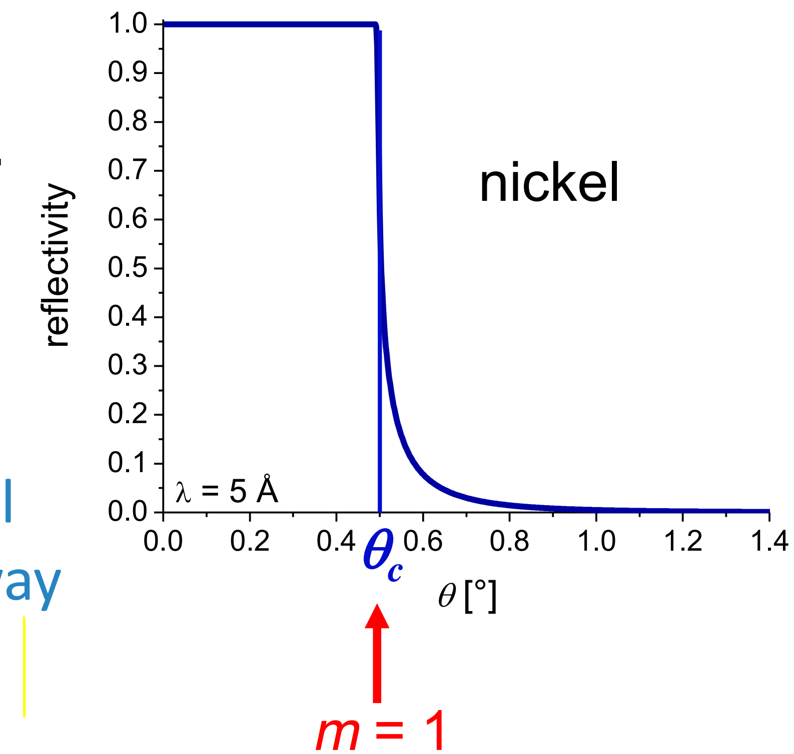
- ESS will be more powerful and several times brighter than existing facilities.
- However, over the past decades the major order of magnitude gains have been in the instrumentation design

eg neutron moderators

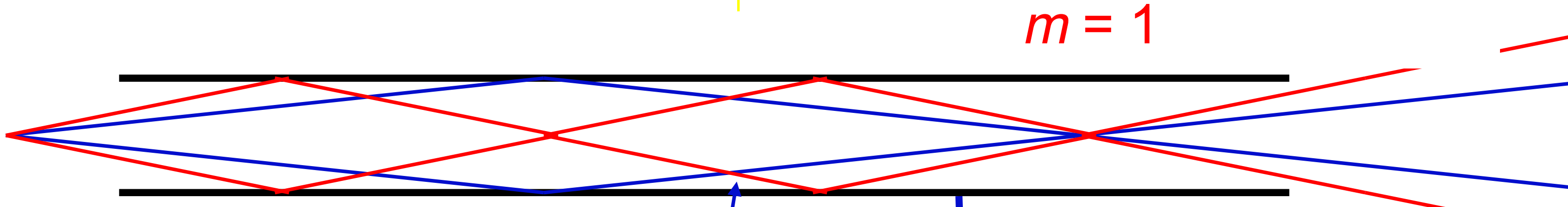


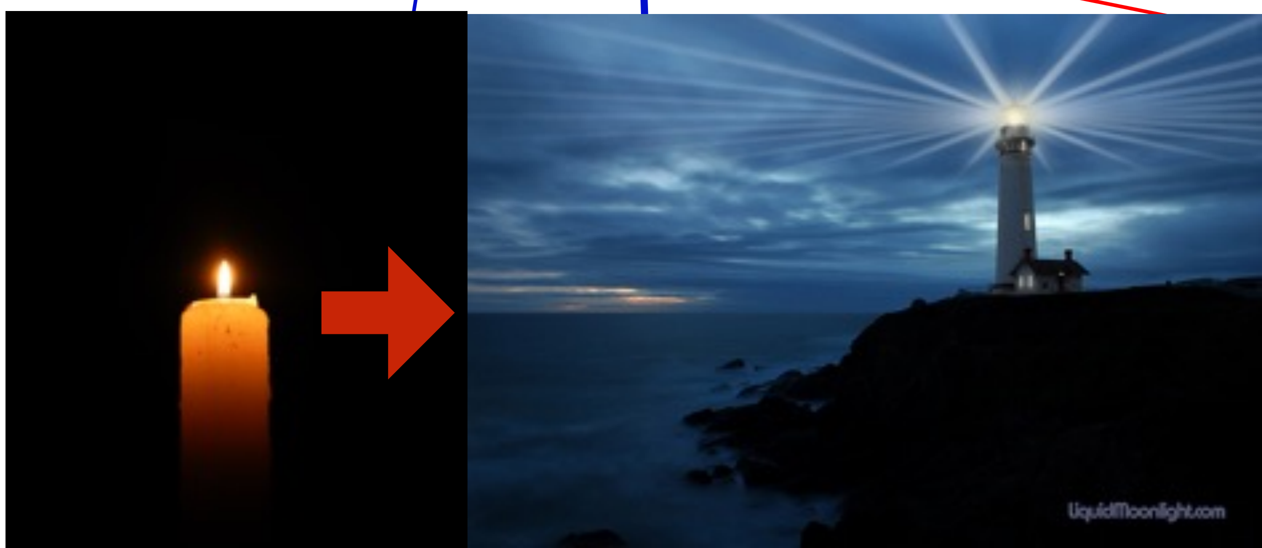


eg neutron transport "neutron optics"



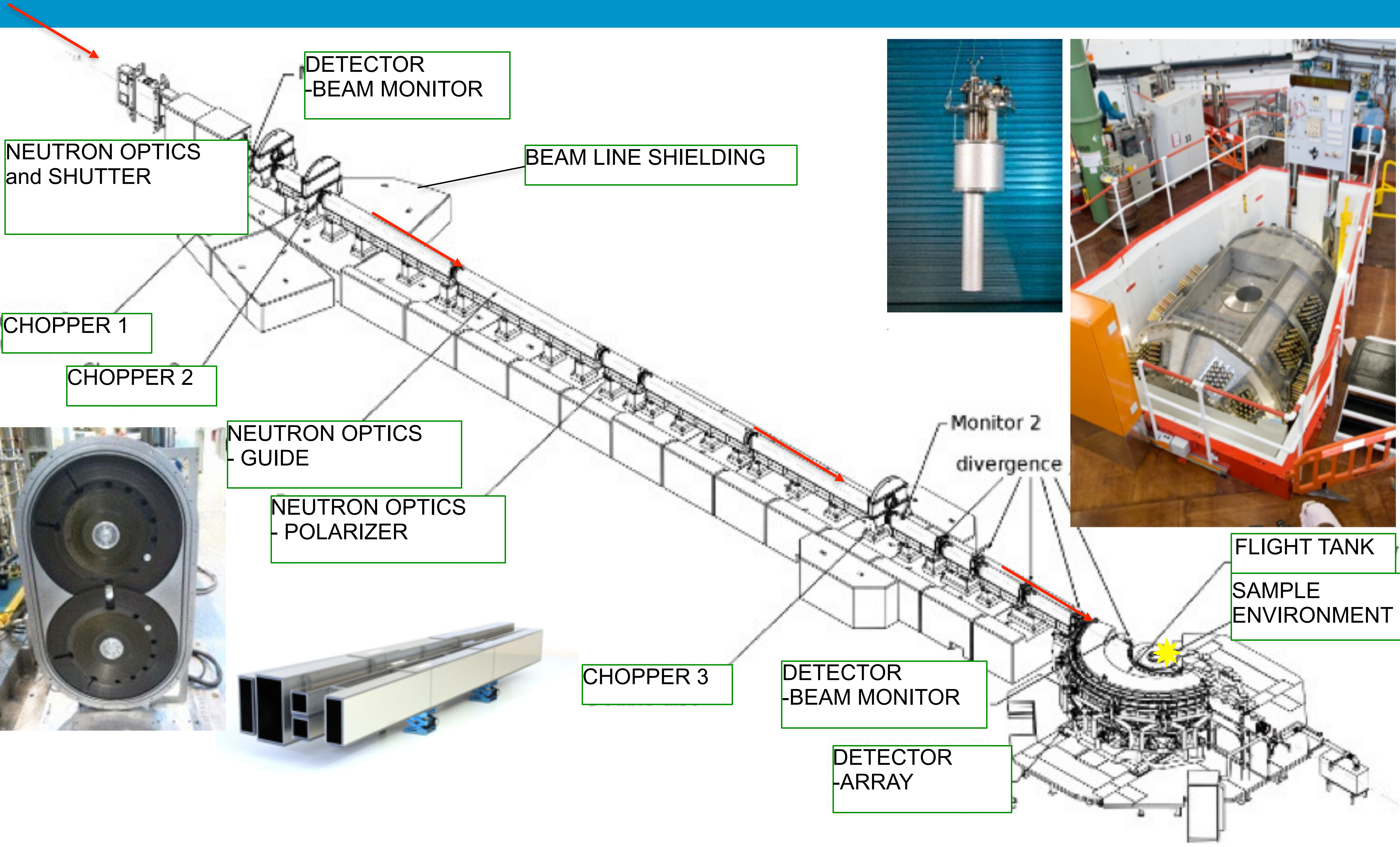
- Neutron guides use this critical angle for internal reflection, in a similar way to optical fibres





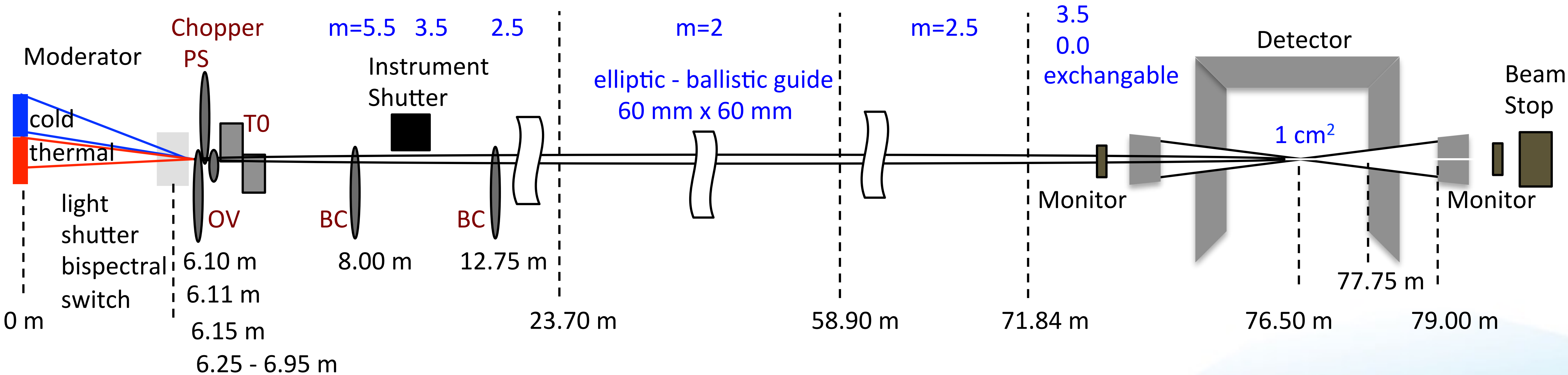
- The advances in neutron detection have been more modest, until recently …

Layout of a Neutron Instrument



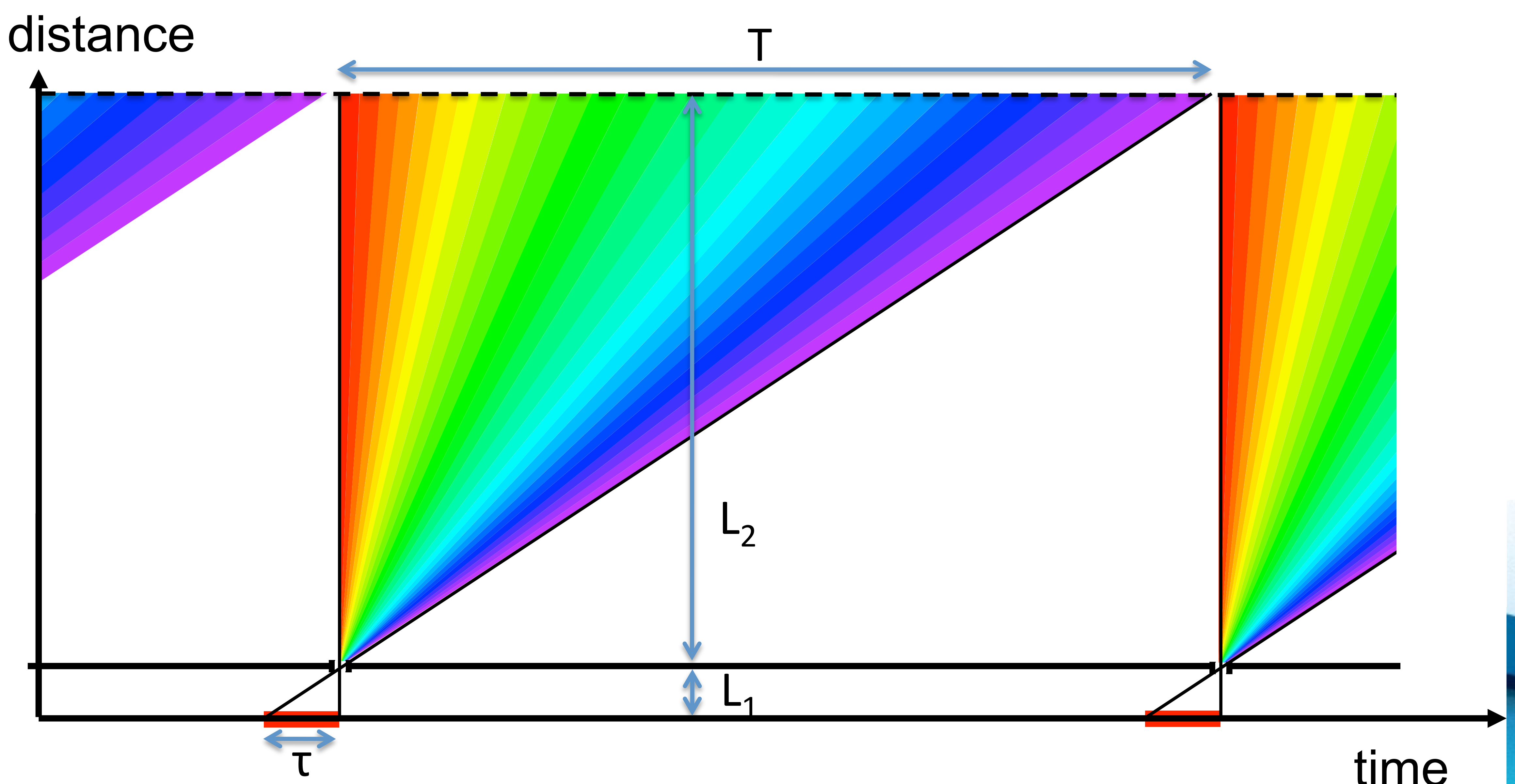
Instrument Design

- Instrument Design is about selecting the phase space of interest and maximising that
- Phase space here primarily means flux (6D: position, divergance) and neutron energy/ wavelength
- Remember that as the neutron energy is not measurable, need to use time-of-flight or diffractive scattering to determine neutron energy
- Remember Liouville's theorem:
    - Phase space density is constant for conservative force fields
- It implies that high resolution measurements are low flux and vice-versa



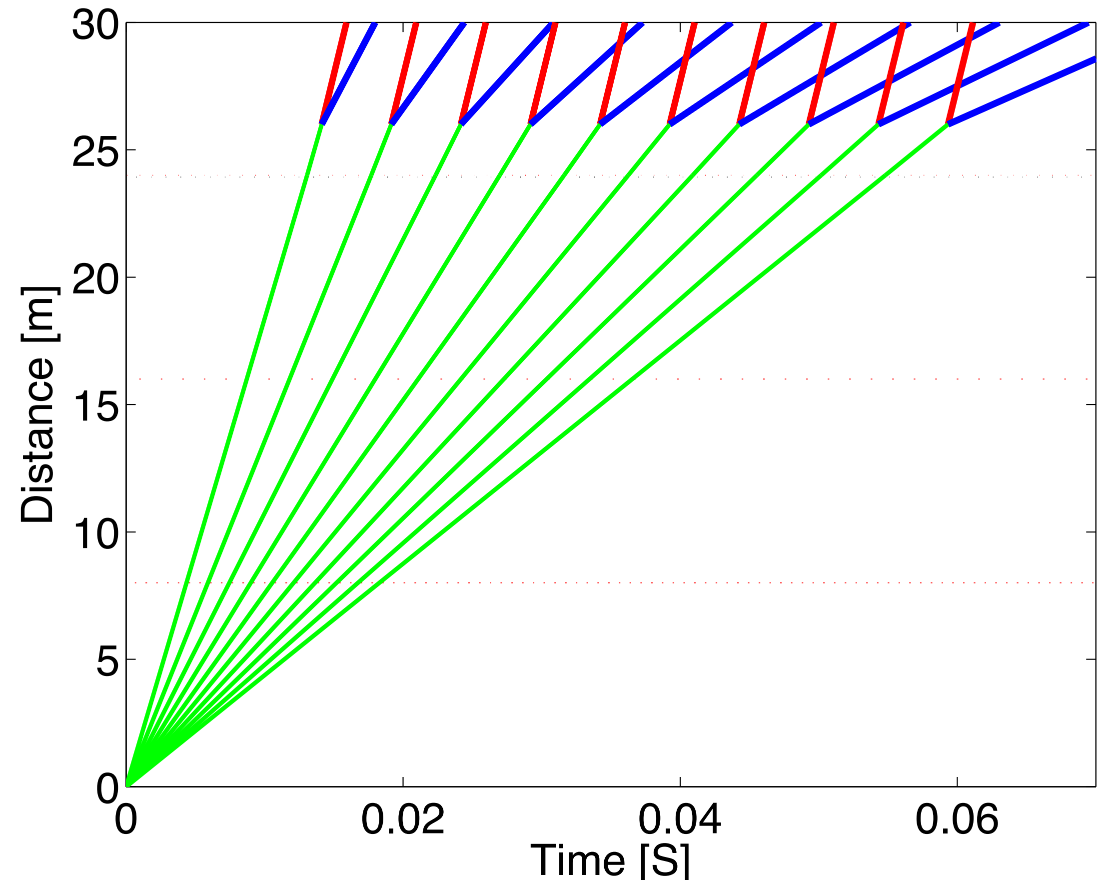
Time distance diagram

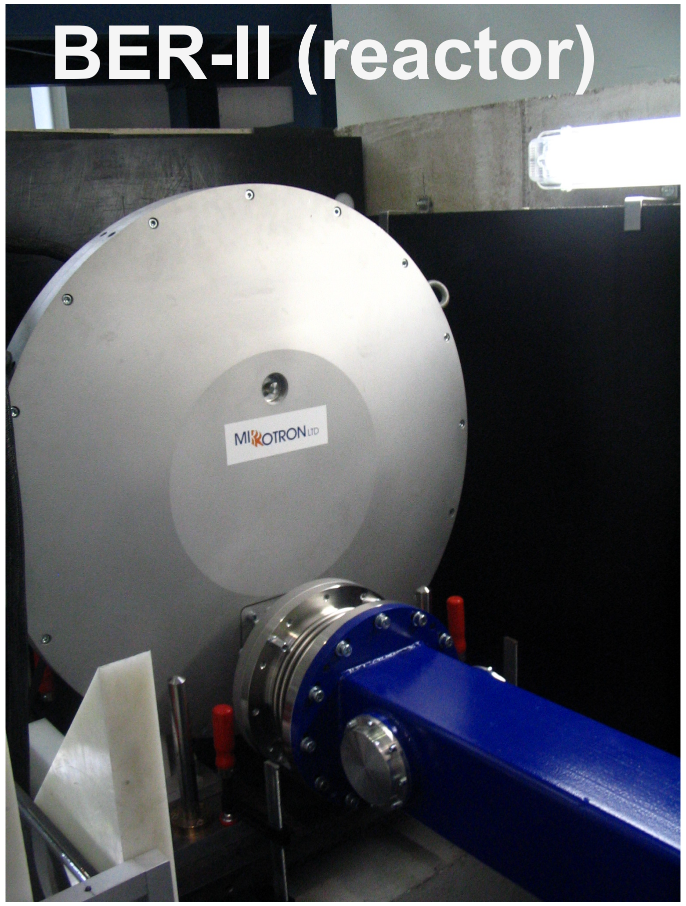
- Time distance diagram of white beam instrument with Pulse shaping chopper .

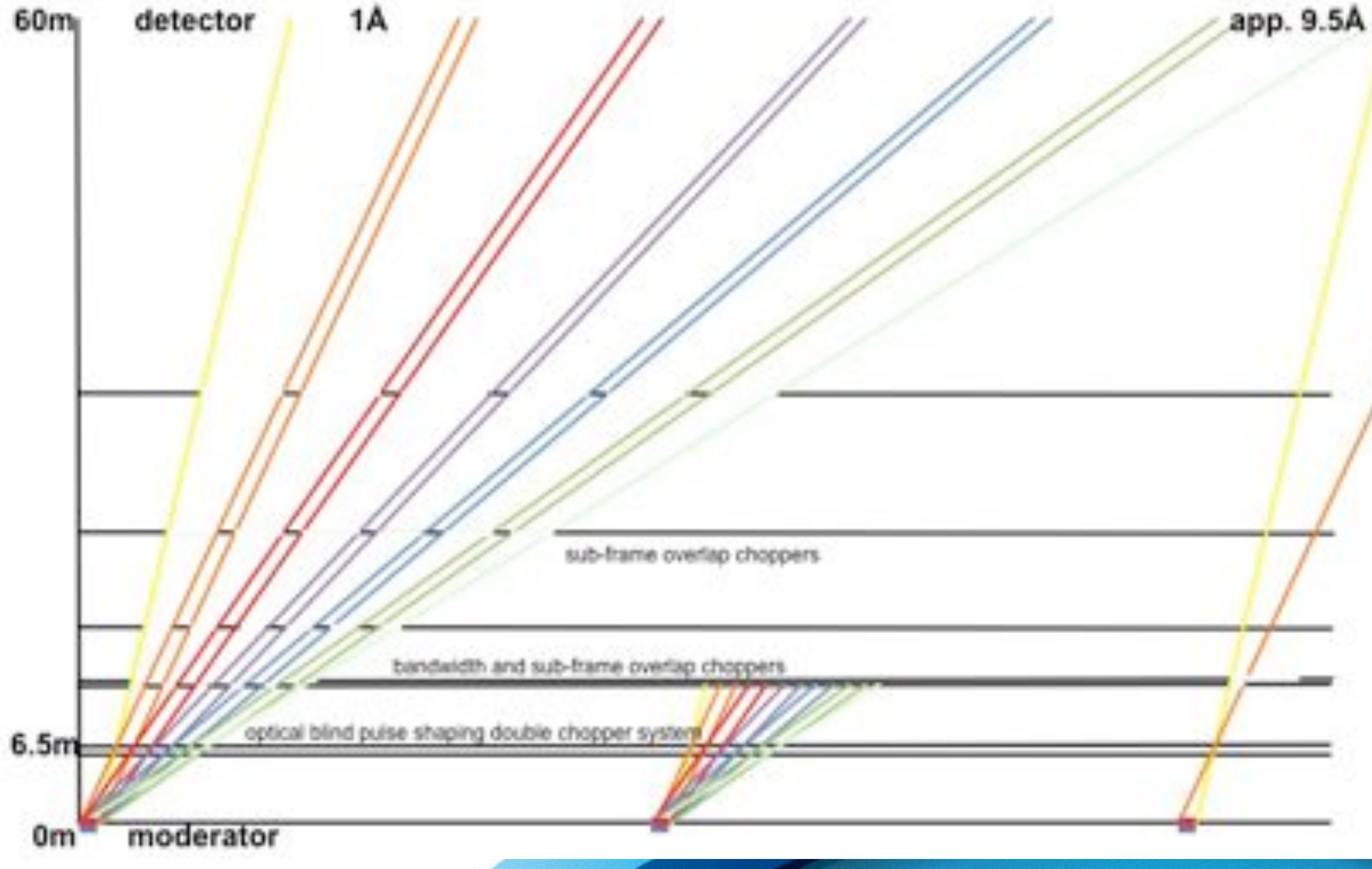


Neutron Time-of-Flight

- Use time of flight to separate neutrons of different energies
- Thermal neutrons 1.8A: v = 2200 m/s
- Rotating Mechanical “choppers”, made of neutron absorbing material can select neutrons of interest

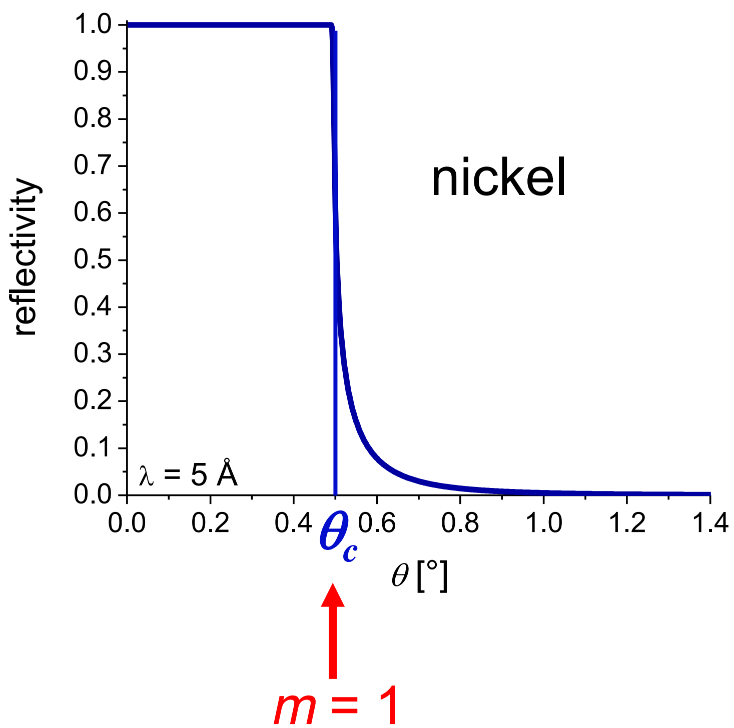


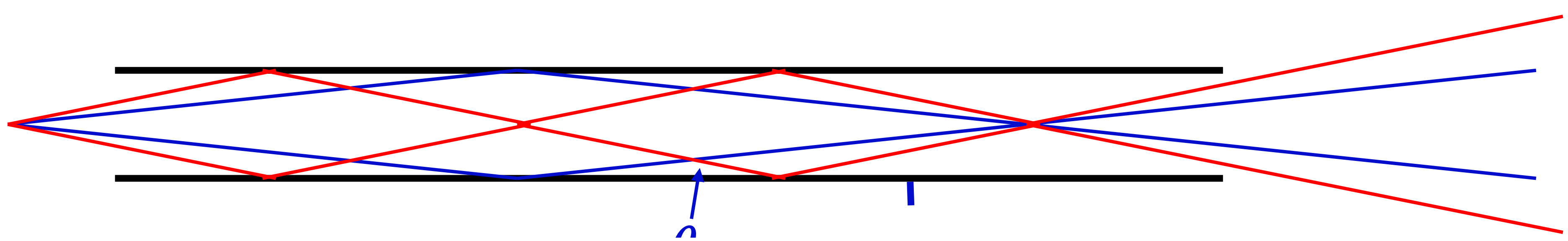




Neutron Optics

- The phase space density of neutrons cannot be increased
- Absorption and finite efficiency of optical components means that phase space density decreases
- Neutron optics designed to transport phase space density as well as possible
    - Focus decreases size of beams, but increases divergance
    - Collimation decreases divergance but reduces flux
- Neutron mirrors and guides can be constructed by using the critical angle
- In particular neutron guides use internal reflection in a similar fashion to that of optical fibres.



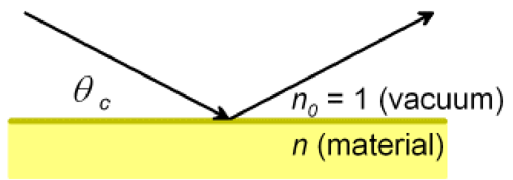


Supermirrors

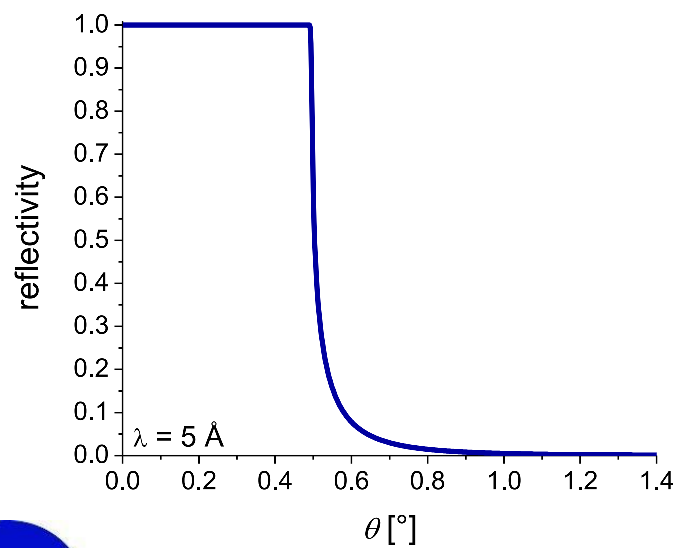
Invention of Supermirrors

(Turchin 1967, Mezei 1976)

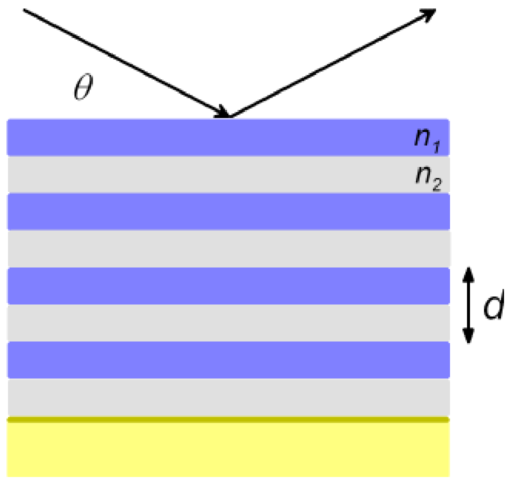
smooth surfaces



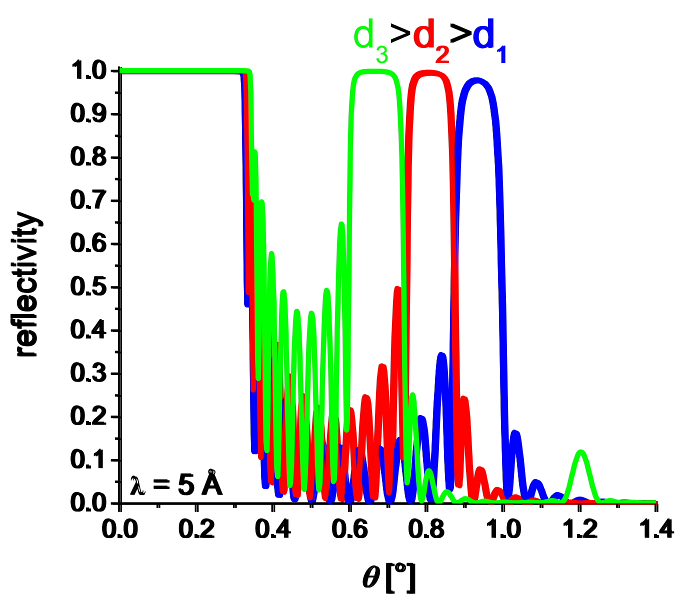
- refractive index $n < 1$
- total external reflection



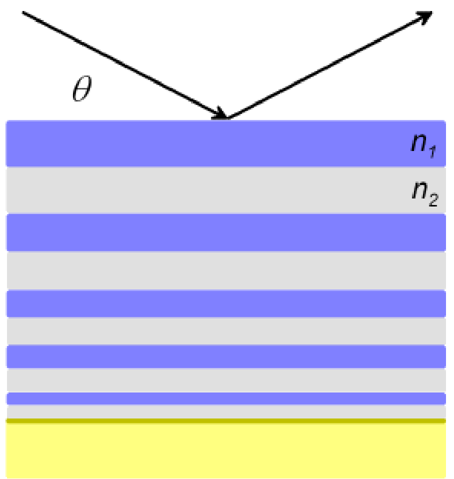
multilayer

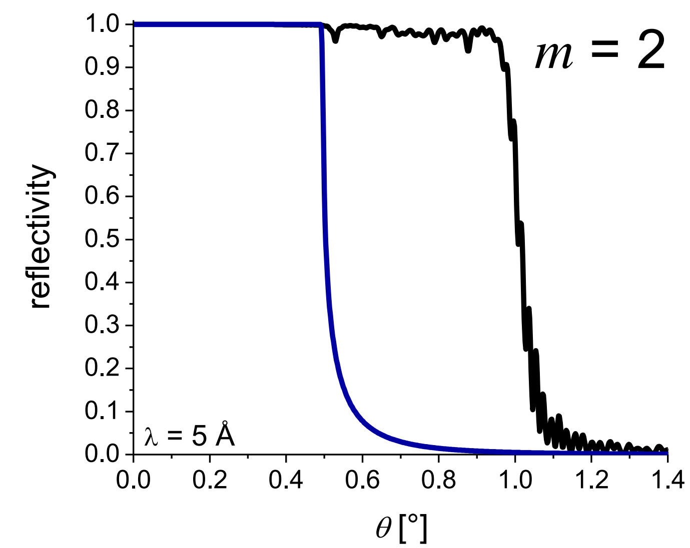


$$\sin\theta = \frac{\lambda}{2d}$$



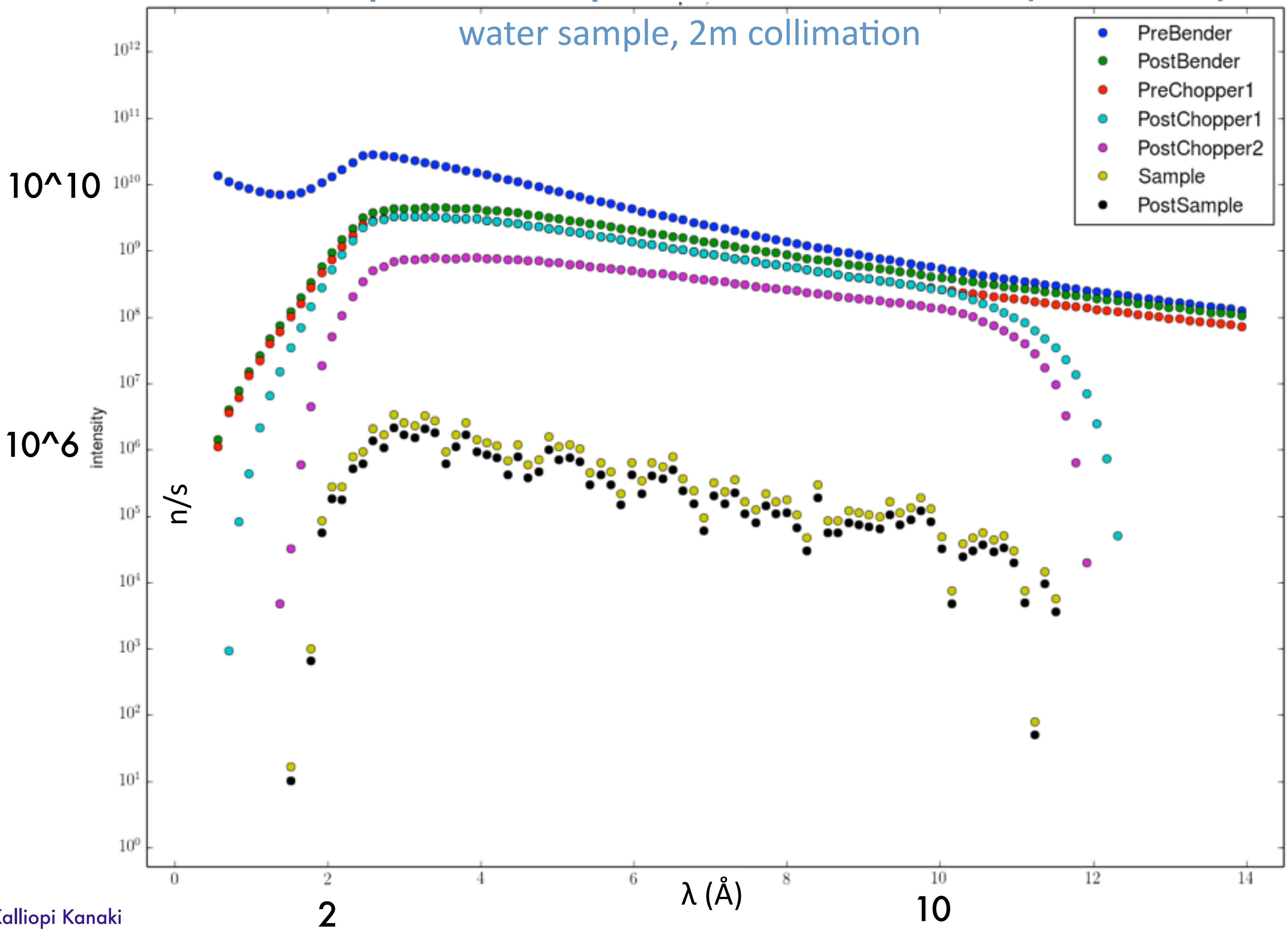
supermirror





Selecting phase space ...

Pre- and post sample λ distribution (McStas)



European Spallation Source

The European Spallation Source: view to the Southwest in 2025

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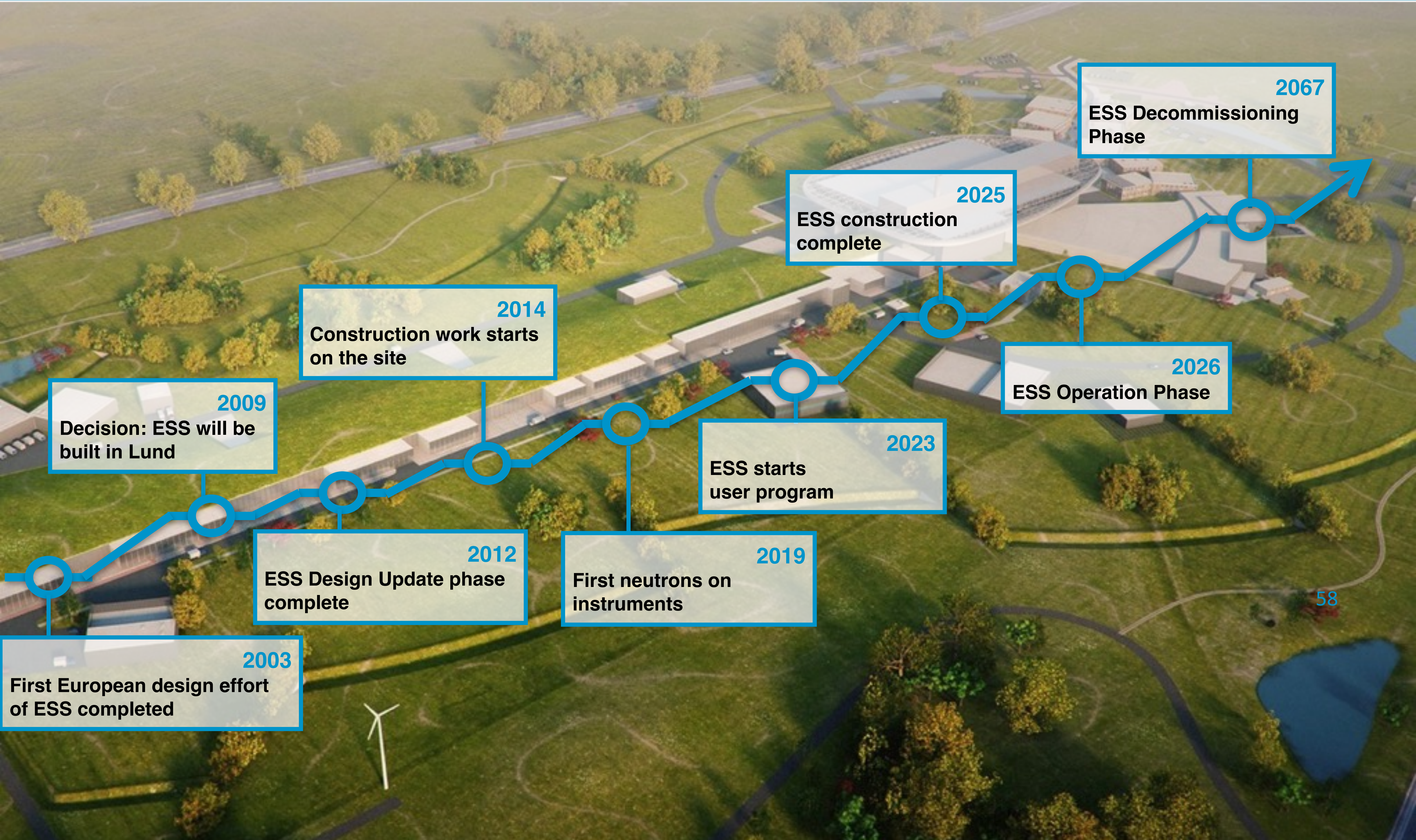
EUROPEAN SPALLATION SOURCE

ESS: Project commitments

- ☑ 5 MW accelerator capability,
  30 times brighter than exisiting facilities
- ☑ 22 Public Instruments, state-of-the-art technologies
- ☑ Construction cost of 1,843 B€
- ☑ Steady-State Ops at 140 M€/year

Time plan


2003
First European design effort of ESS completed
2009
Decision: ESS will be built in Lund
2012
ESS Design Update phase complete
2014
Construction work starts on the site
2019
First neutrons on instruments
2023
ESS starts user program
2025
ESS construction complete
2026
ESS Operation Phase
2067
ESS Decommissioning Phase

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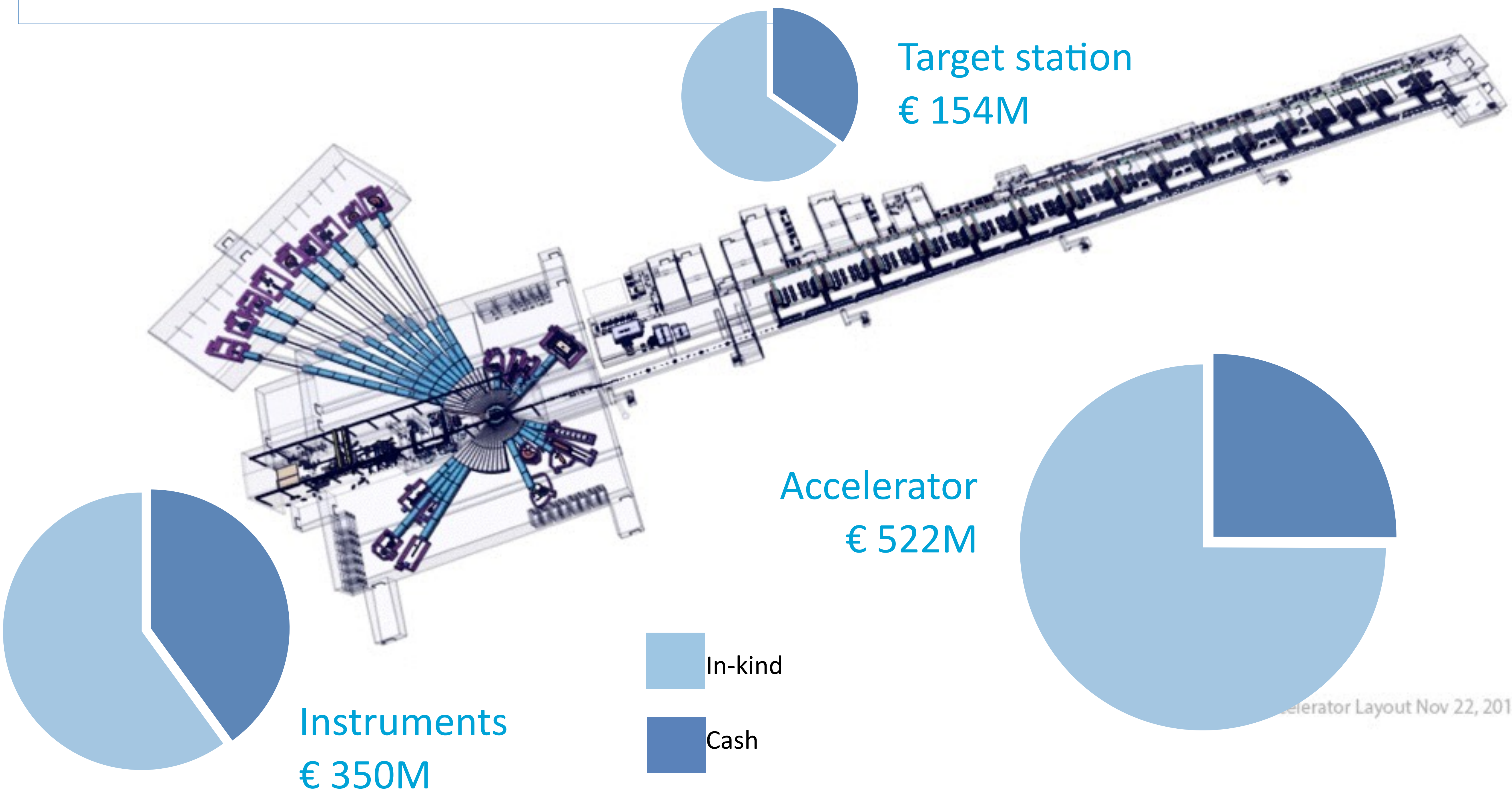
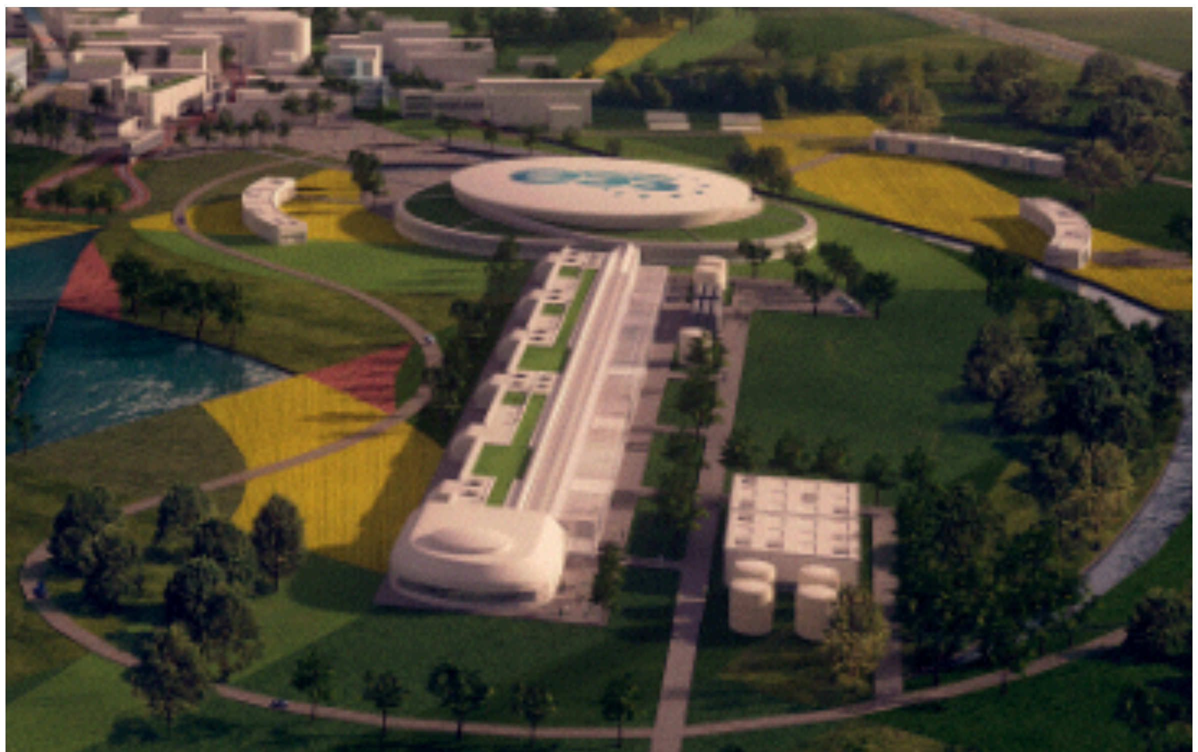
Planning , Budget and In-Kind potential

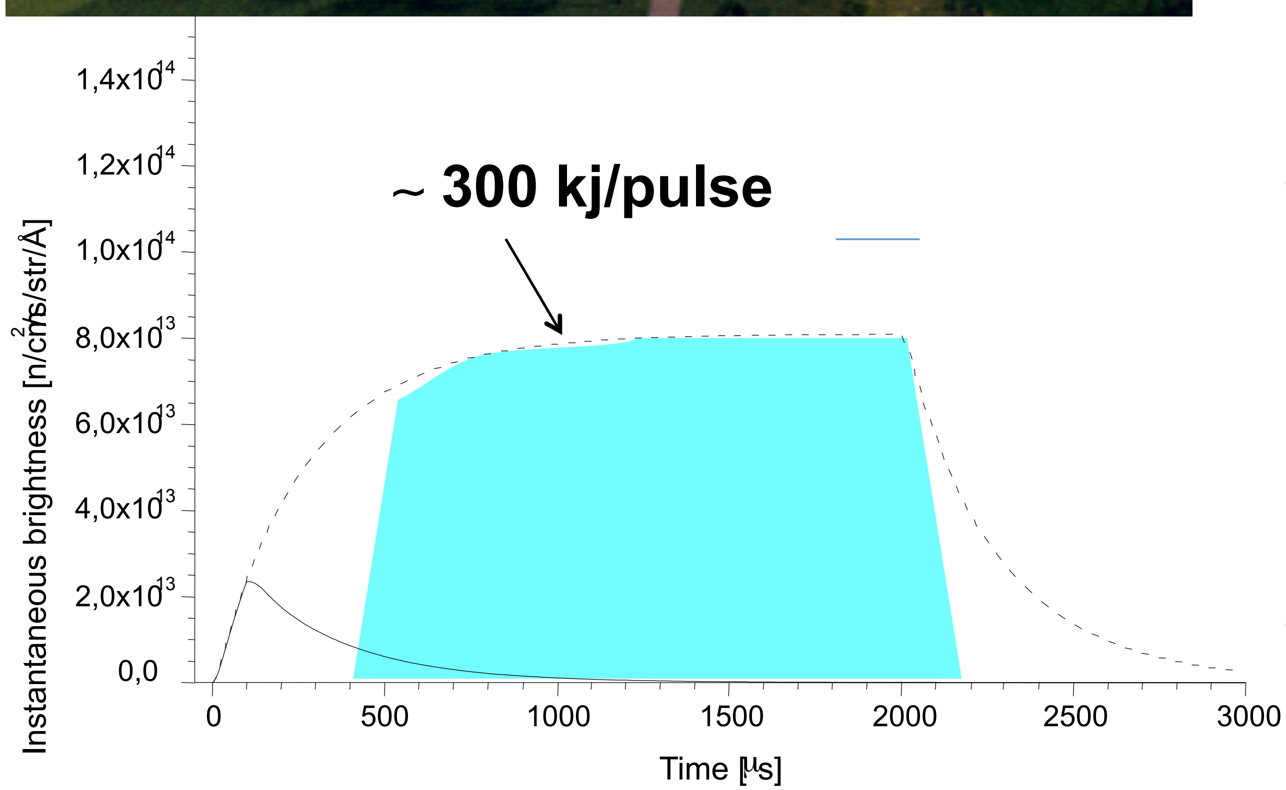
EUROPEAN SPALLATION SOURCE

Total construction cost: € 1,84 billion



Next generation: long pulses





Cost equivalent linear accelerator alone can produce the same cold neutron pulses **by ~100 μs proton pulses at ~ 0.15 GW instantaneous power** → Leave the linac on for **more neutrons per pulse and higher peak brightness…**
and use mechanical pulse shaping →
Long Pulse source

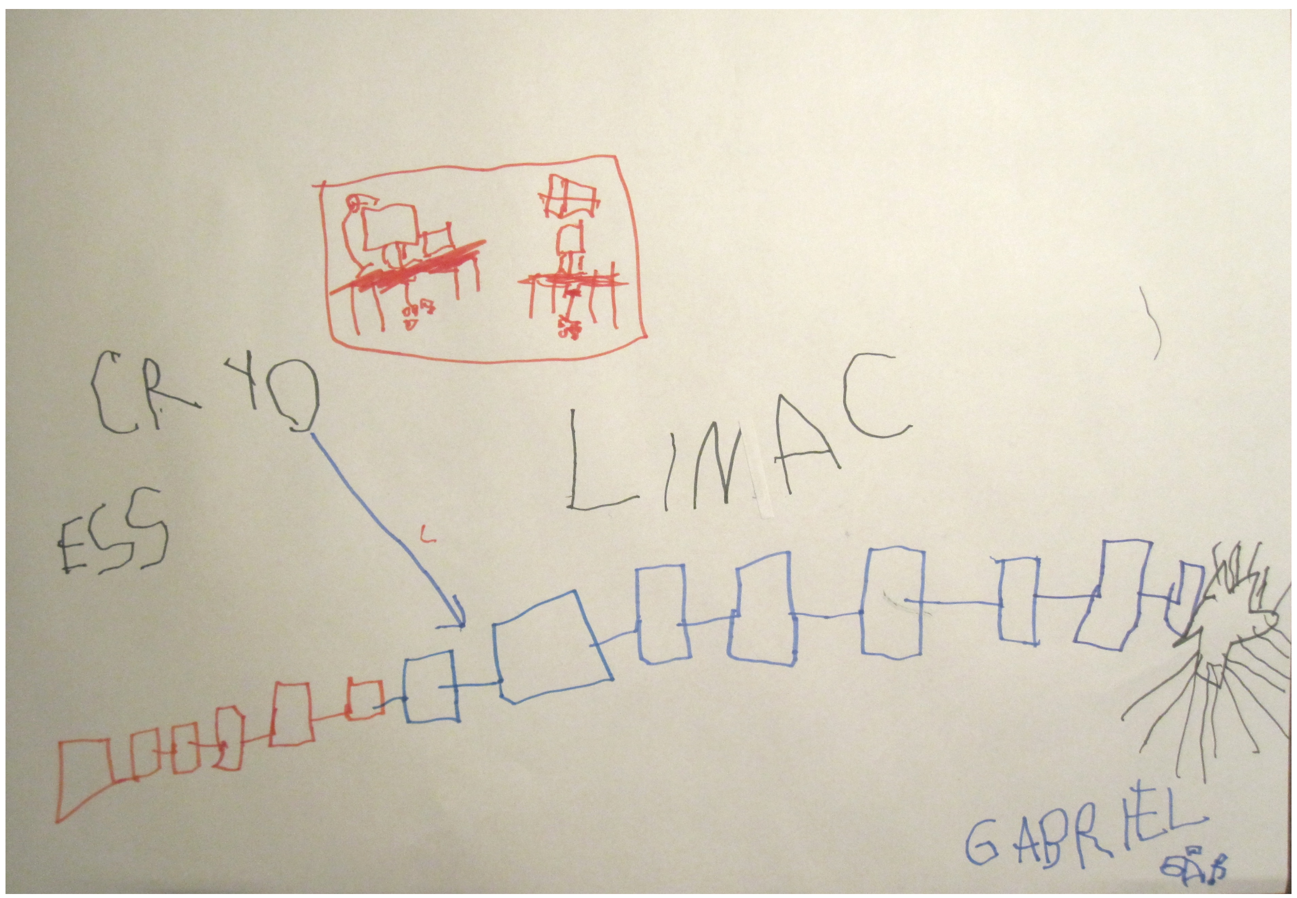
ESS: 5 MW accelerator power
→ **more neutrons for the same costs and at reduced complexity**

ESS Technical Design Report

- ESS TDR released: available on ESS website
- Will serve as a baseline for construction

Feb '12

ESS Conceptual Design Report

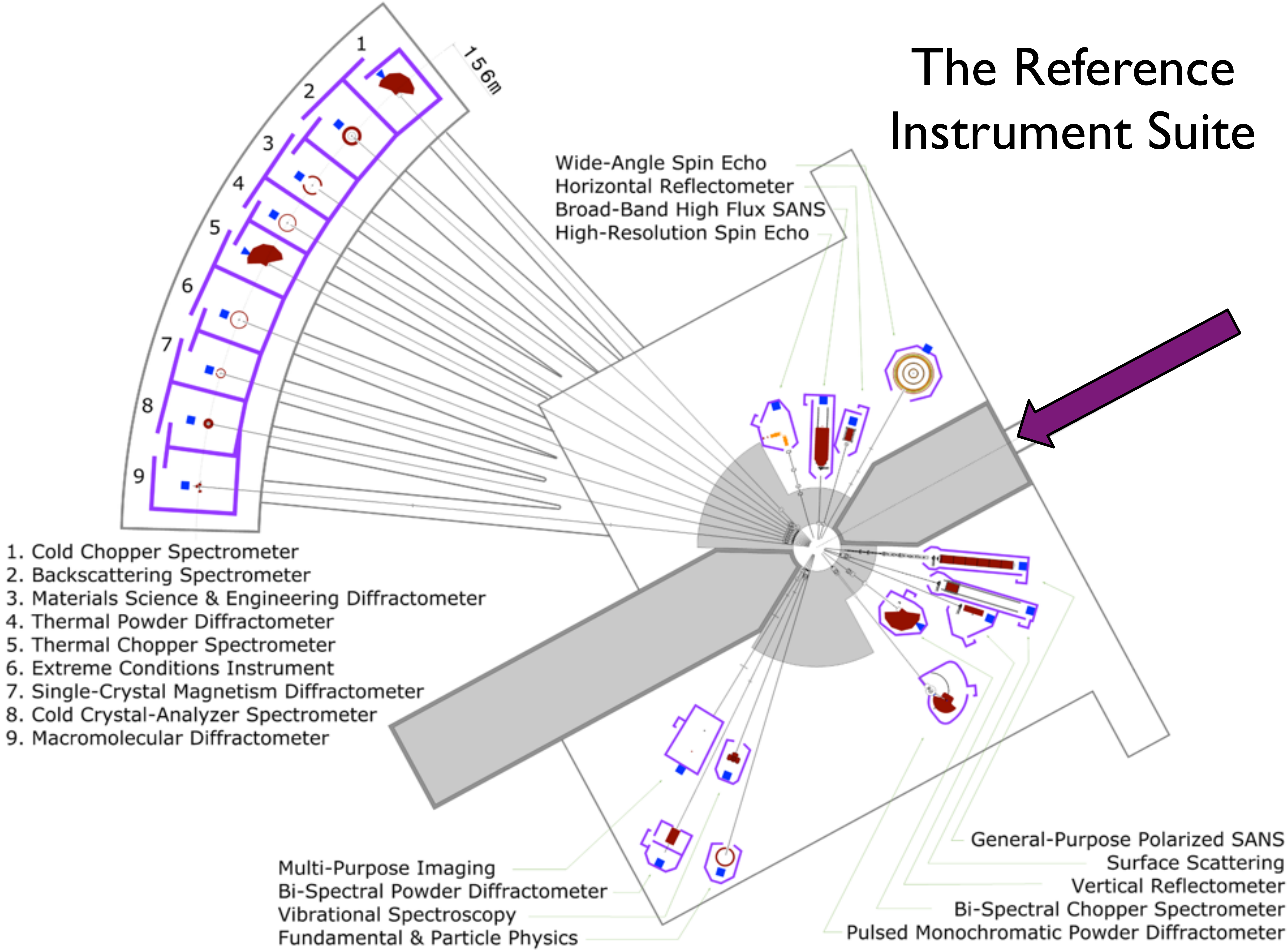


ESS Technical Design Report

Release 2.0

February 5, 2013

The Reference Instrument Suite




webbkameror.se
ess
EUROPEAN SPALLATION SOURCE
The ESS site
2011

The ESS Site

23 October 2012


June 12, 2014


Vision 2020
Arriving at ESS from the tram

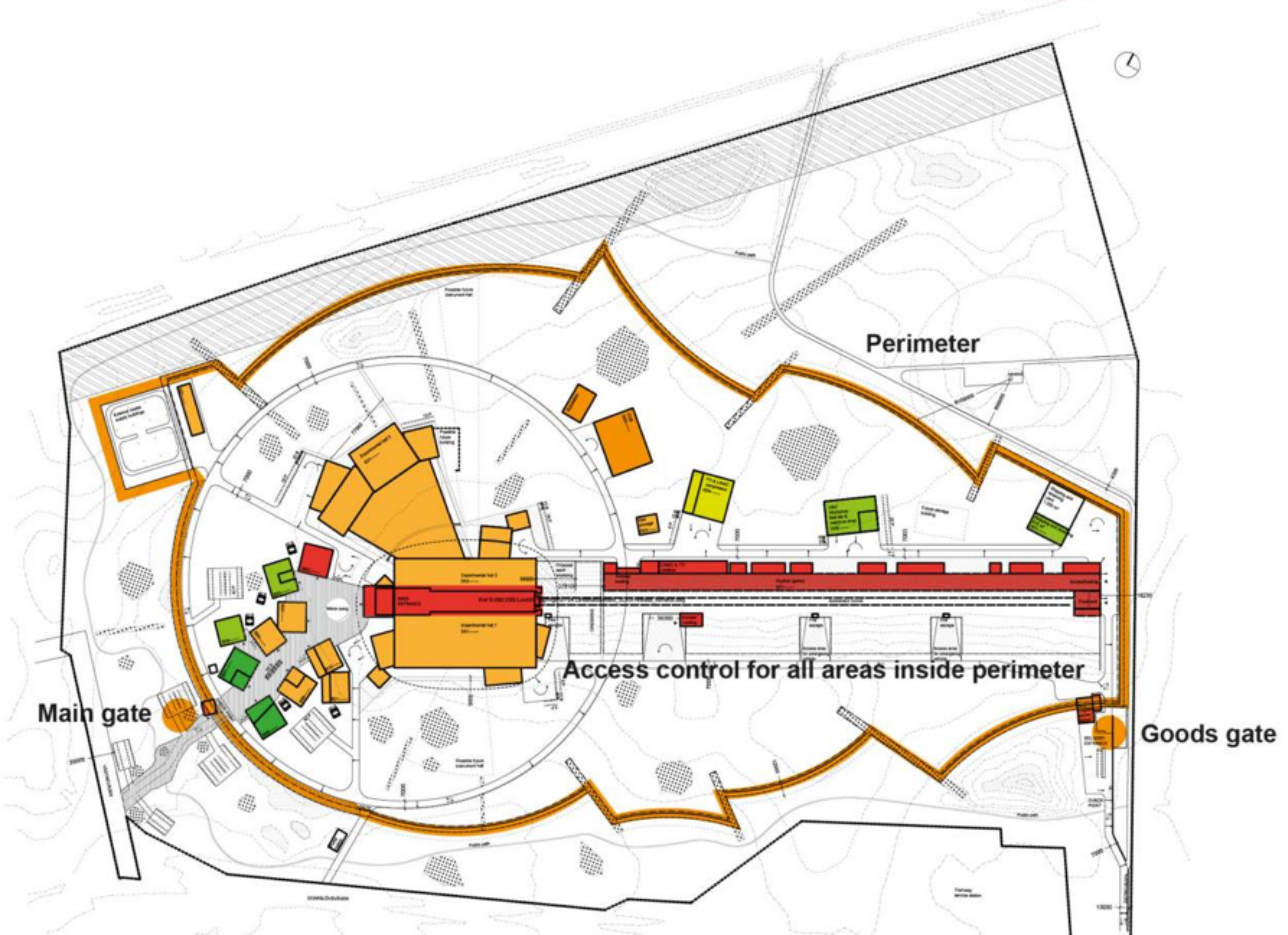

Preliminary Design – For Review
Preliminary Design – For Review
Preliminary Design – For Review
Preliminary Design – For Review

July 2014

2014: Construction begins …

- Environmental court approval received.
- Successful project review.
- Conventional Facilities Preliminary Design under review.
- Ground break took place Sept. 2.
- Foundation Stone Ceremony and Science Symposium Oct. 9.

Site Plan



Perimeter
Access control for all areas inside perimeter
Main gate
Goods gate


5 Feb 2015


5 May 2015

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ESS construction

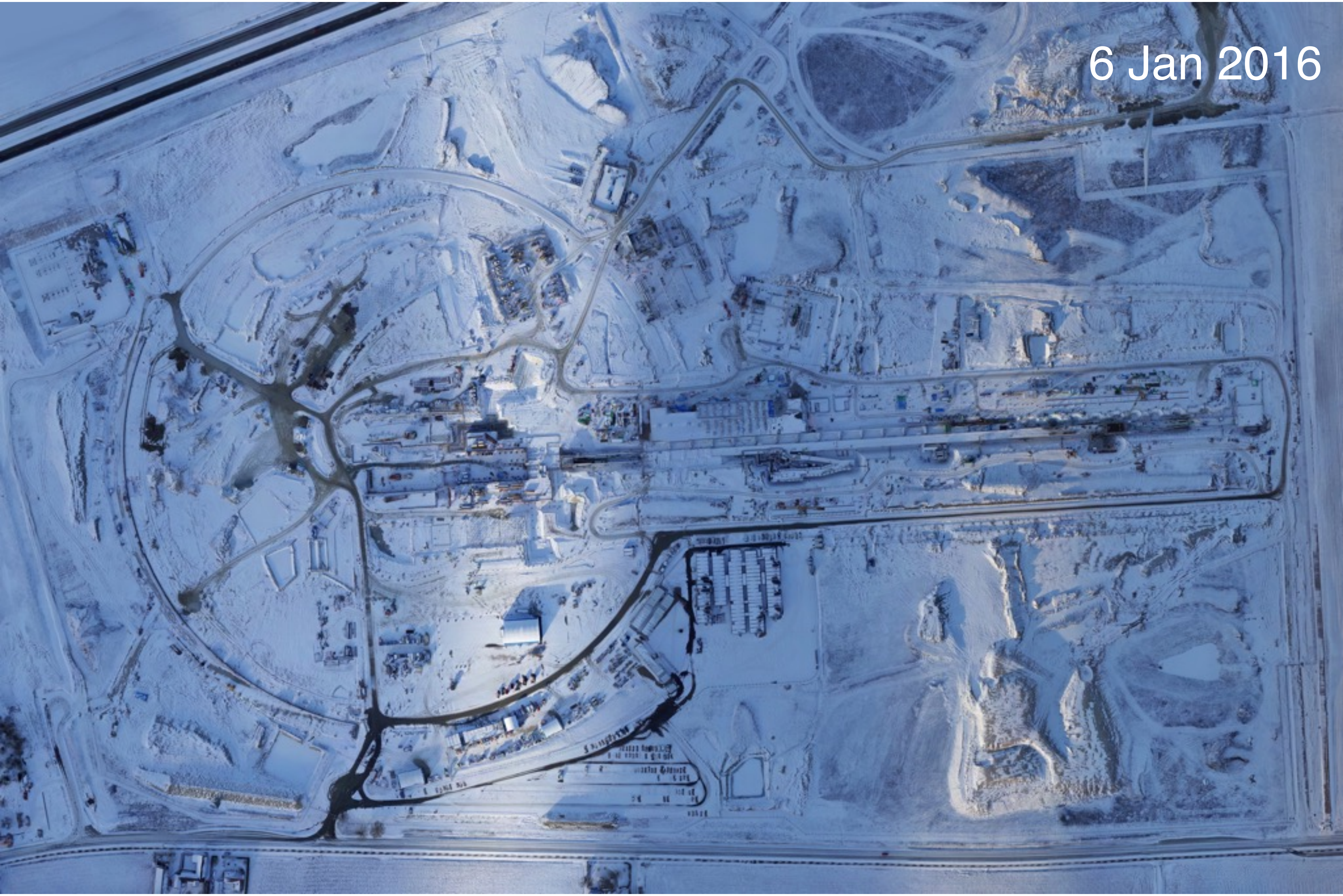
EUROPEAN
SPALLATION
SOURCE

The roof installation for the HEBT Loading Bay on the north side of the Accelerator tunnel.

Preparations for the monolith foundation piles, which will be bored into the concrete rings.

Pilons for constructing the target.

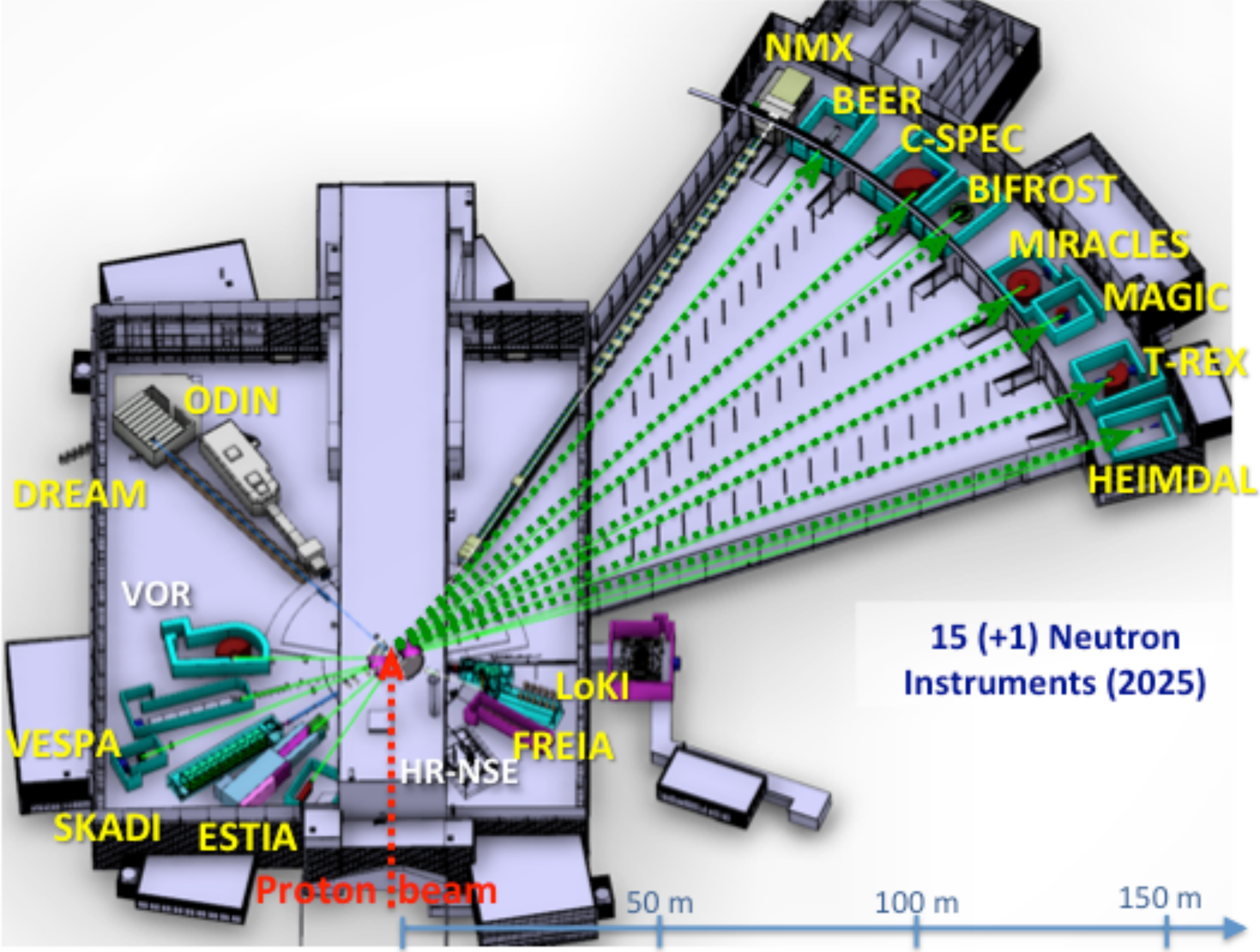
Accelerator tunnel.
Installation of components will begin in 2017.


6 Jan 2016

Target Station and Service Tunnels

Electrical Substation Building

Basement work for Experimental Halls Lab 3B (E04). Background: village of concrete piles for the Experimental Hall 3, where the instruments with the longest beam guides, up to 156 meters, will be housed.


NMX
BEER
C-SPEC
BIFROST
MIRACLES
MAGIC
T-REX
HEIMDAL
ODIN
DREAM
VOR
LoKI
FREIA
VESPA
HR-NSE
SKADI
ESTIA
Proton beam
15 (+1) Neutron
Instruments (2025)
50 m
100 m
150 m

Further Reading

- Neutron Scattering:
  - B. Willis + C. Carlile, Experimental Neutron Scattering, 2009
  - R. Pym, The Neutron Primer. http://totalscattering.lanl.gov/docs/nprimer.pdf
  - G. Squires, Thermal Neutron Scattering. (1978)
  - http://neutronsources.org/

- ESS Technical Design Report available from esss.se
- ILL Blue book, available at ill.eu

Summary

- An overview neutron scattering
- A tool for many detailed studies of materials using neutrons

- Overview of Neutron Sources
- In particular Reactor and Spallation Sources
- An overview status of construction of the European Spallation Source

BrightnESS