EUROPEAN SPALLATION SOURCE

# Neutron Sources (with a heavy bias towards Neutron Scattering Science)

- Introduction and history
- Radioactive and lab sources
- Fusion
- Reactors+Spallation Sources
- Neutron Scattering Beamlines
- The ESS

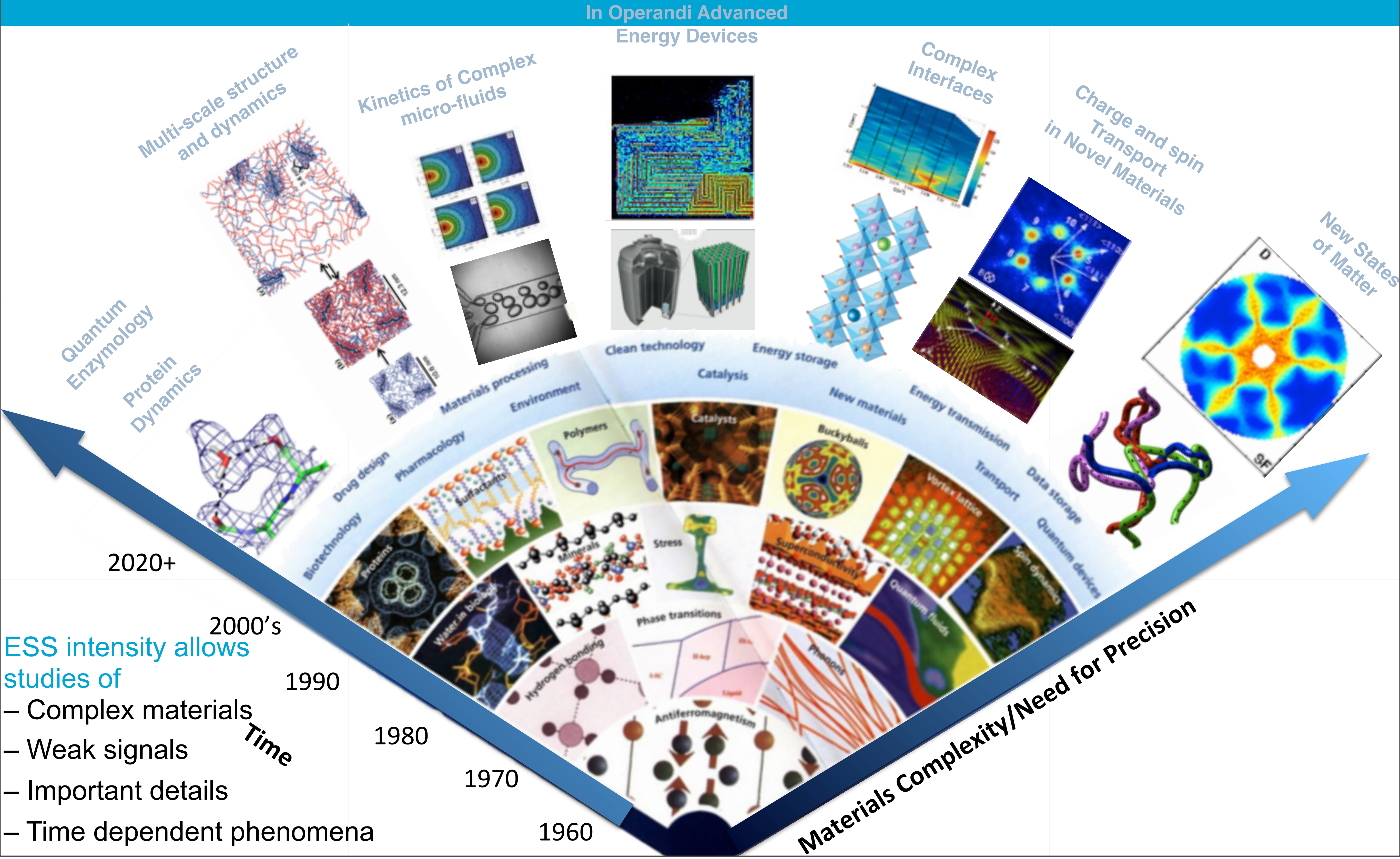
**Richard Hall-Wilton**

**Detector Group Leader**

**NDRA2014**

# Introduction and History

# Neutron Science Pushes the Boundaries



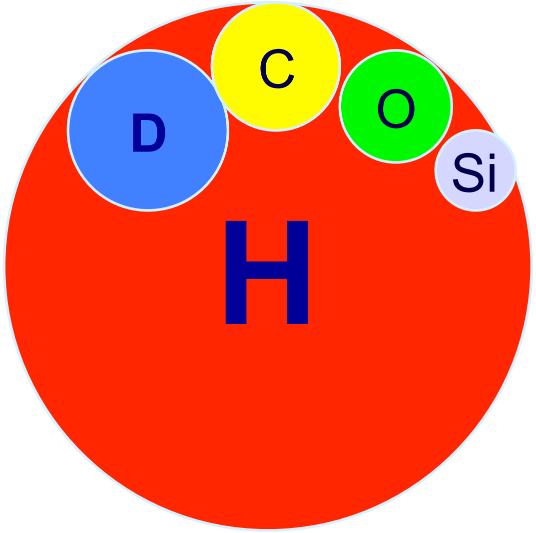
ESS intensity allows studies of

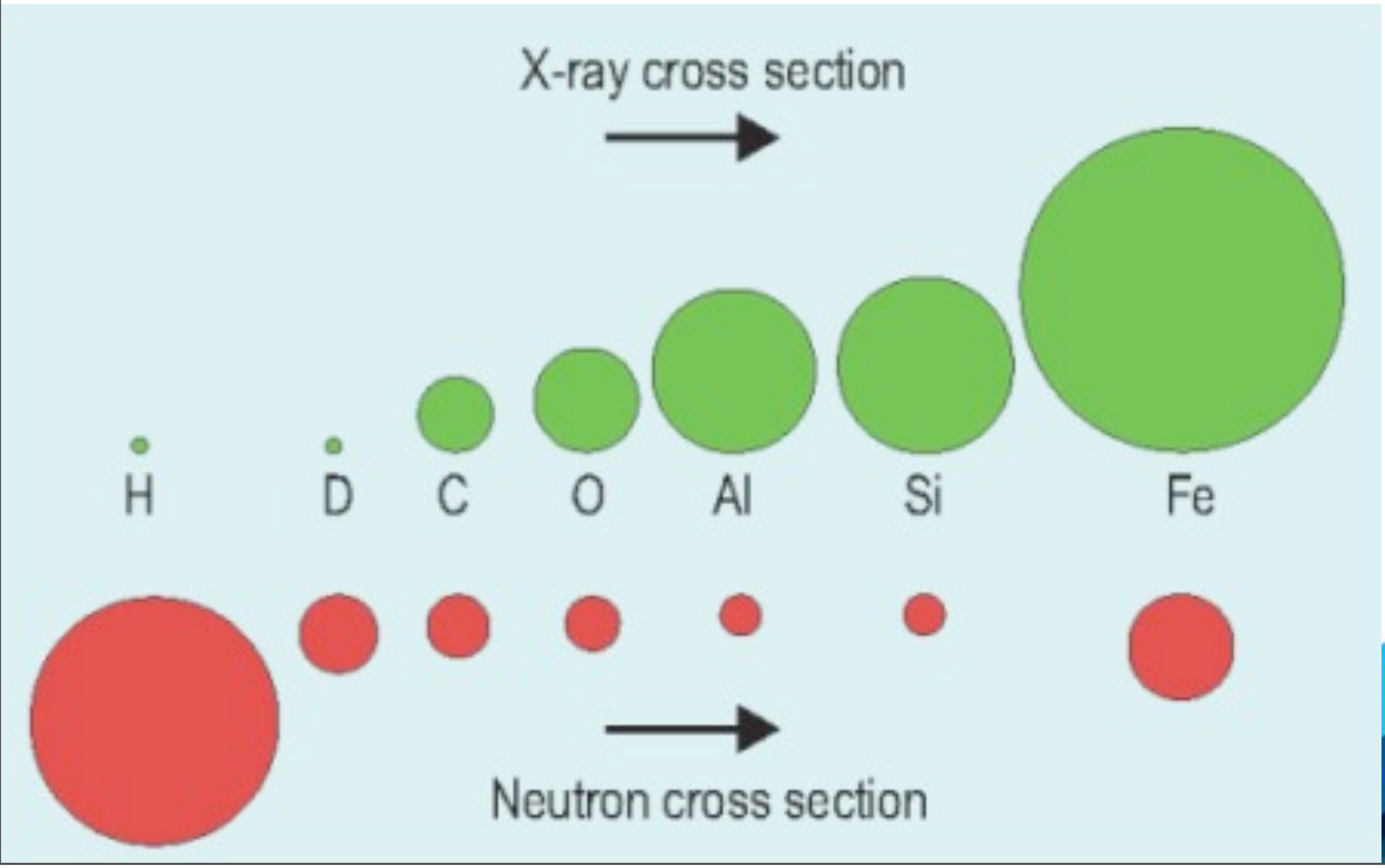
- Complex materials
- Weak signals
- Important details
- Time dependent phenomena

# Why Neutrons?

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

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



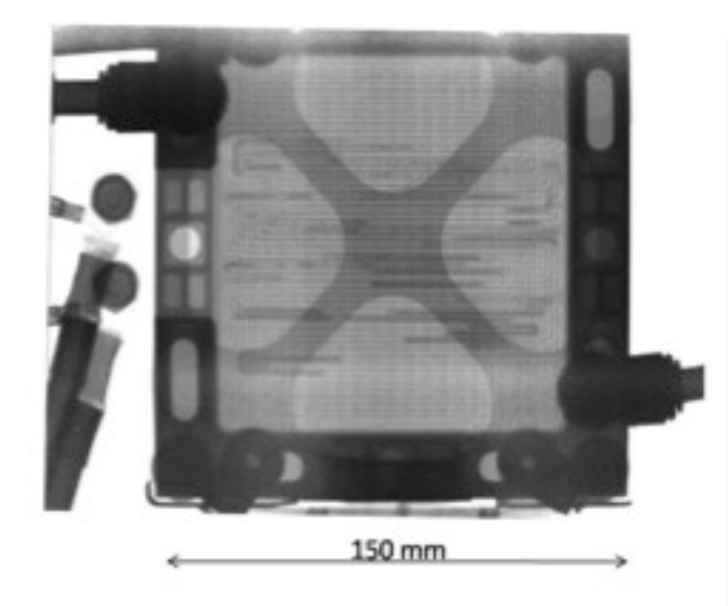


thermal and cold neutrons
meV
"with a small m"
wavelength ca. Å

# Neutrons are special

## Charge neutral

### Deeply penetrating

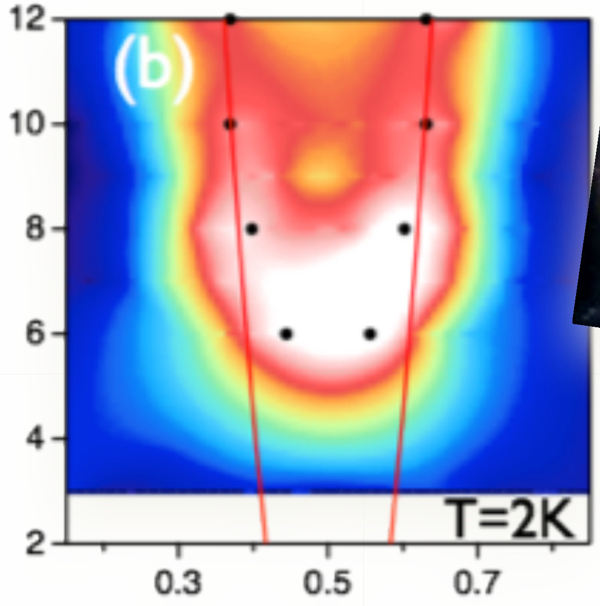


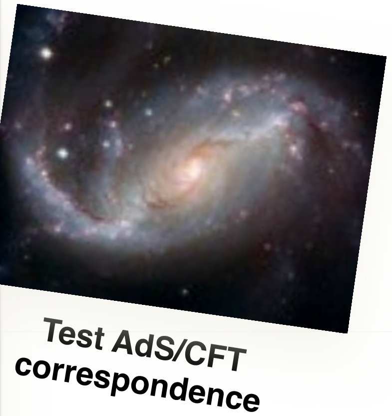
Li motion in fuel cells

Help build electric cars

## S=1/2 spin

### Directly probe magnetism





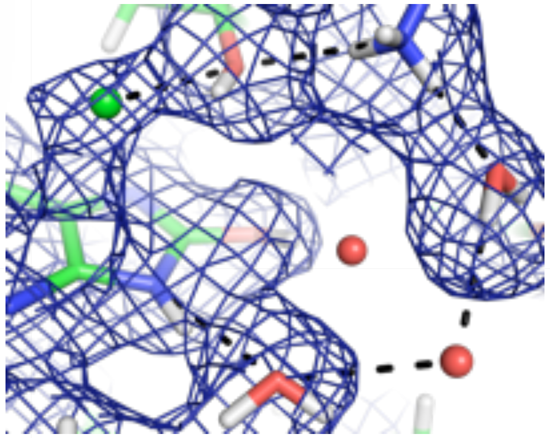
Test AdS/CFT correspondence

Solve the puzzle of High-Tc superconductivity

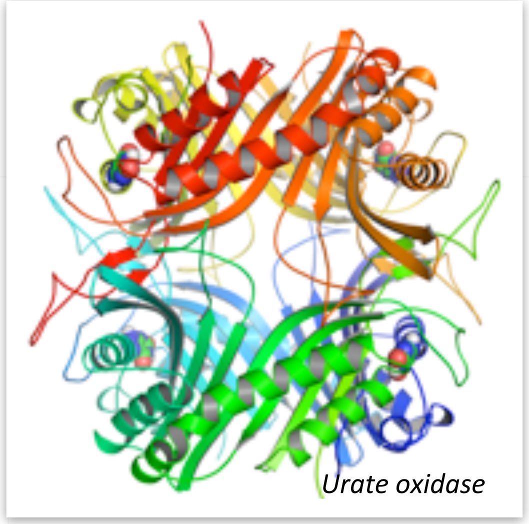
Efficient high speed trains

## Nuclear scattering

### Sensitive to light elements and isotopes



Active sites in proteins



Better drugs

# 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: ~ $1.5\text{x}10^{10}$ (in ~ 2 liter volume)
**(but neutron slowing down efficiency reduced by ~20 times)**

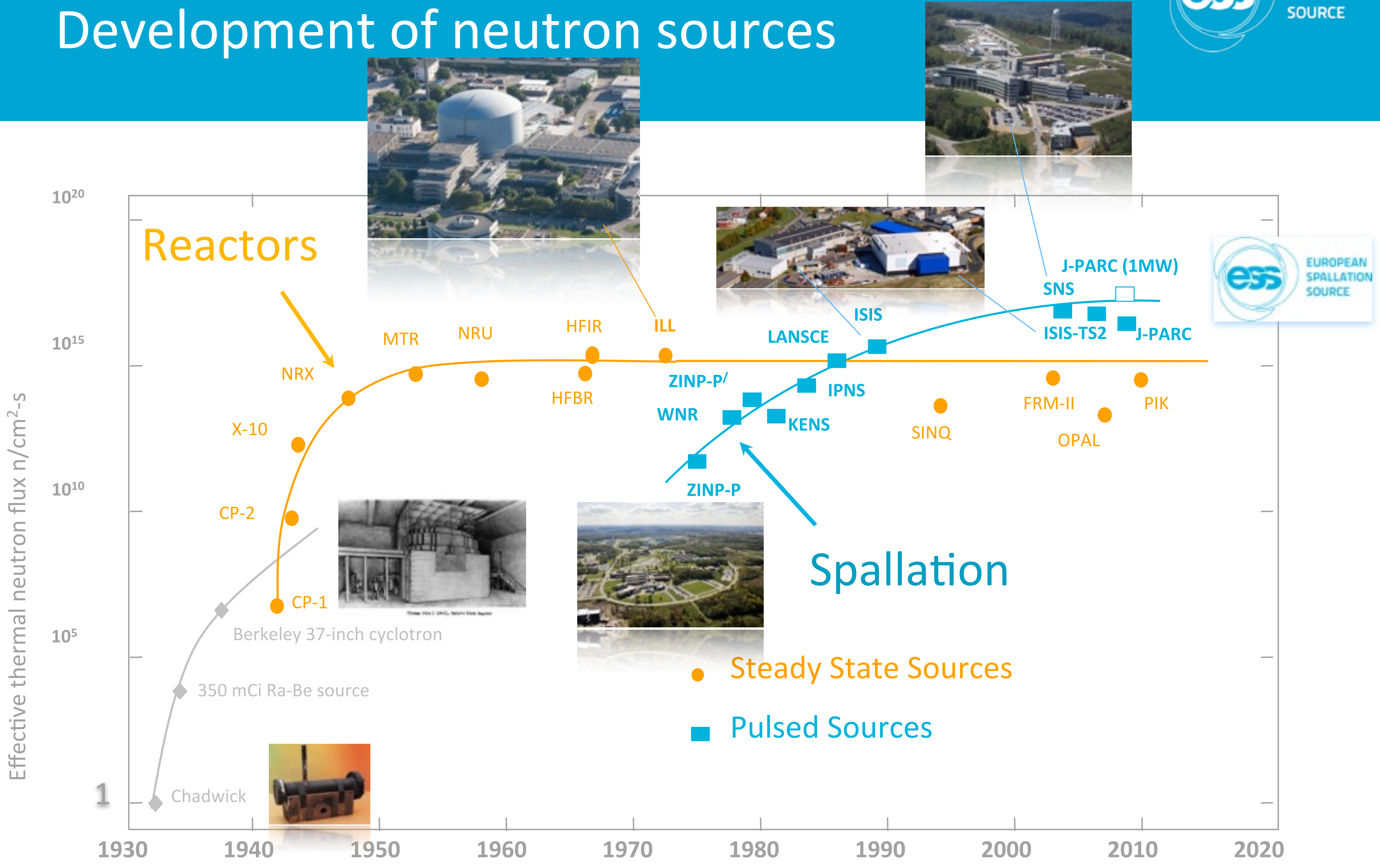
Photo neutrons: ~ $10^9$ (in ~ 0.01 liter volume)

→ 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**

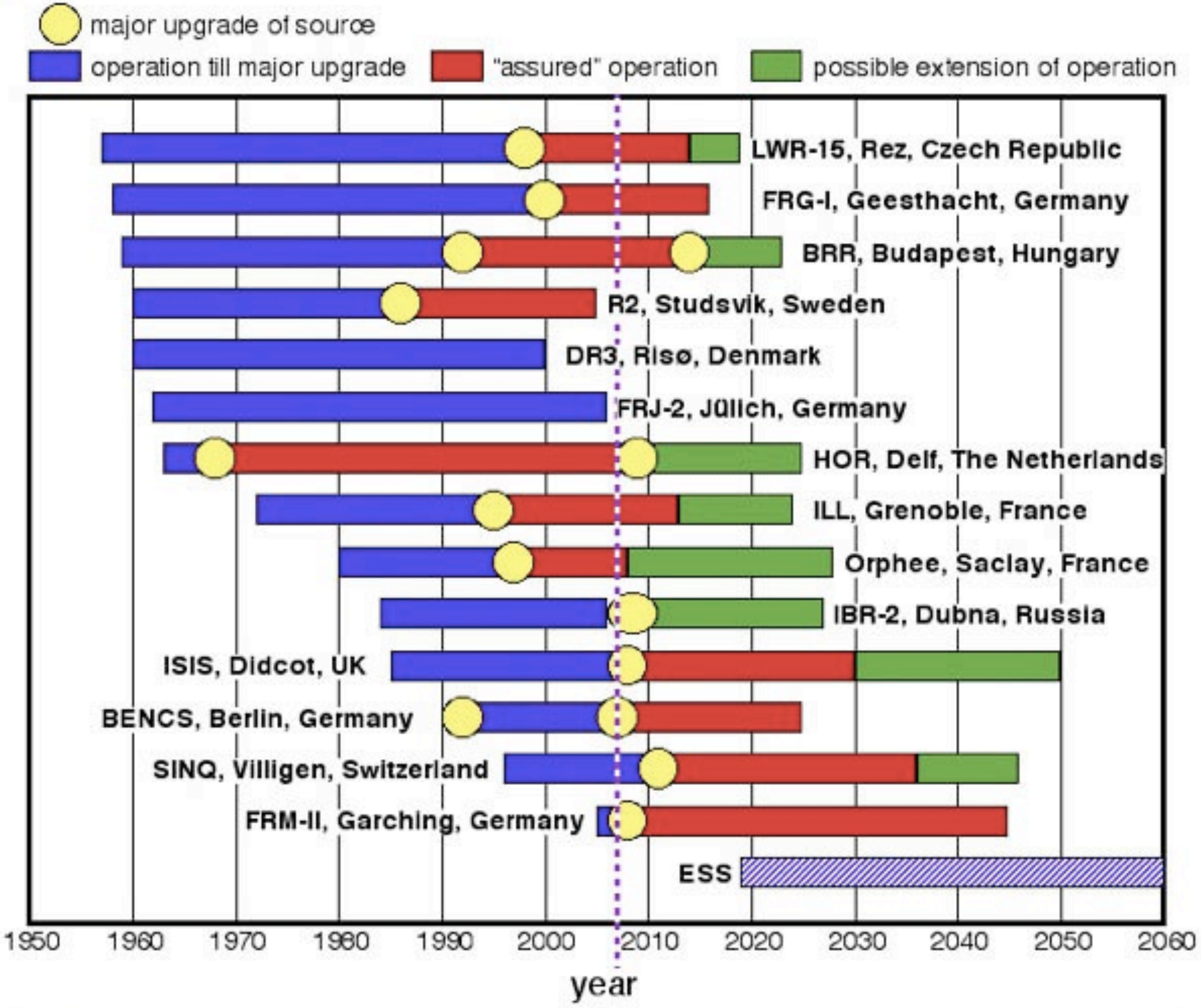
# Development of neutron sources



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

# Neutron research in Europe:

## ~5000 scientists, 11 facilities (and decreasing): ~ 350 M€/a

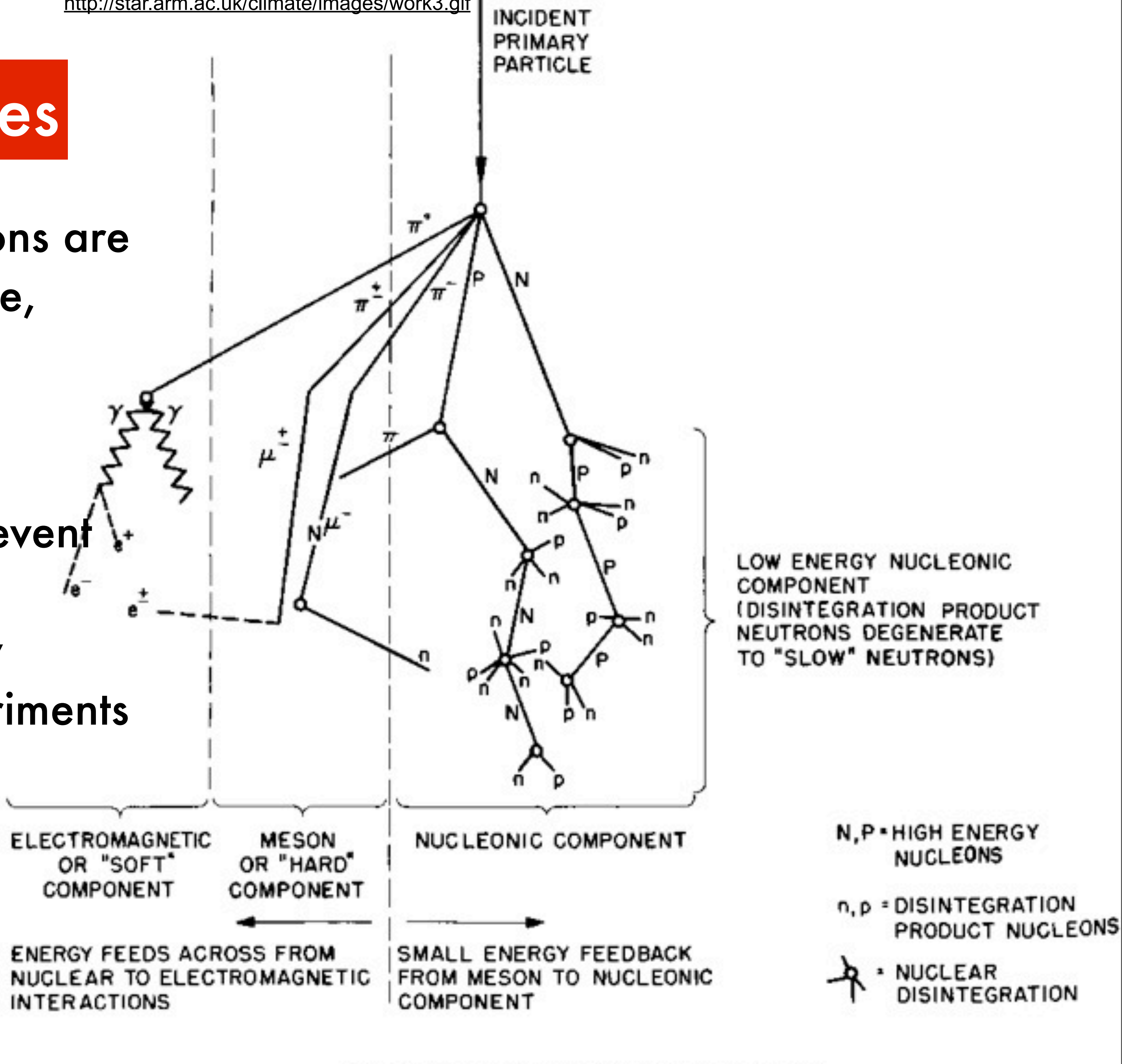


# Natural Sources

# Natural Sources

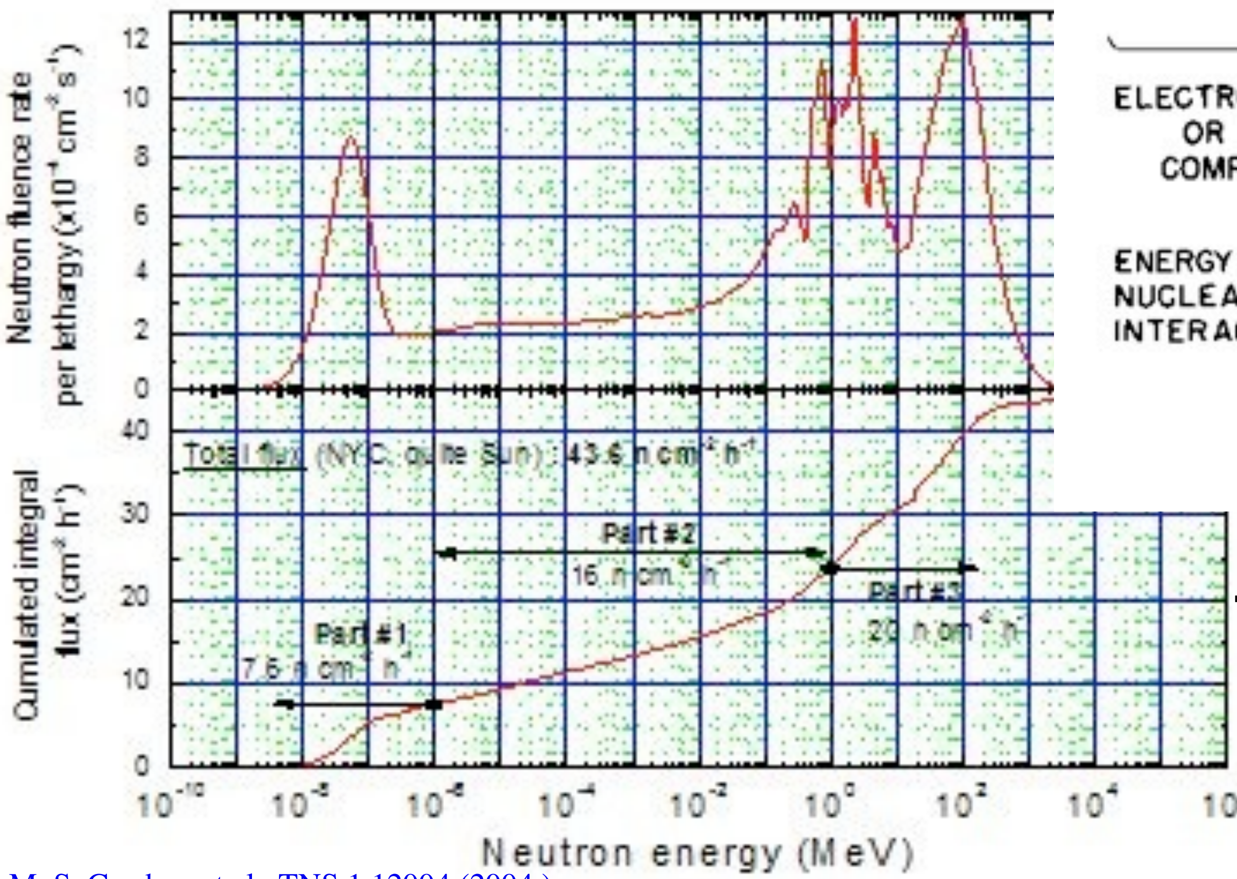
- Natural sources of unbound neutrons are spallation processes in the atmosphere, fusion in stars and natural fission
- Example: cosmic neutrons in the atmosphere
- Of interest for as can cause single event upsets in chips
- Neutrons may be signature for new physics in various underground experiments

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



Schematic Diagram of Cosmic Ray Shower

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

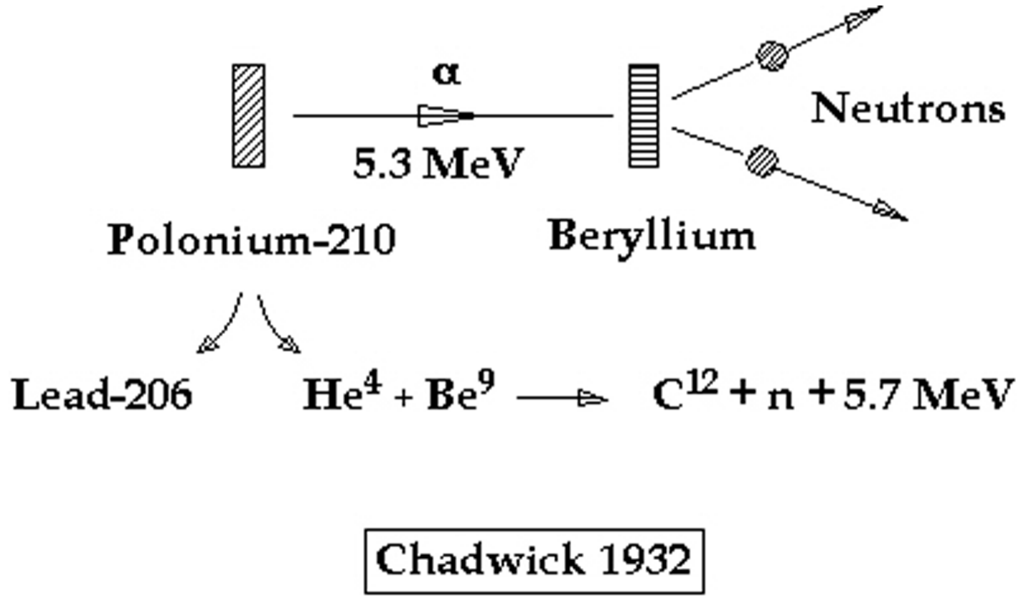


M. S. Gordon, et al., TNS 1 12004 (2004.)

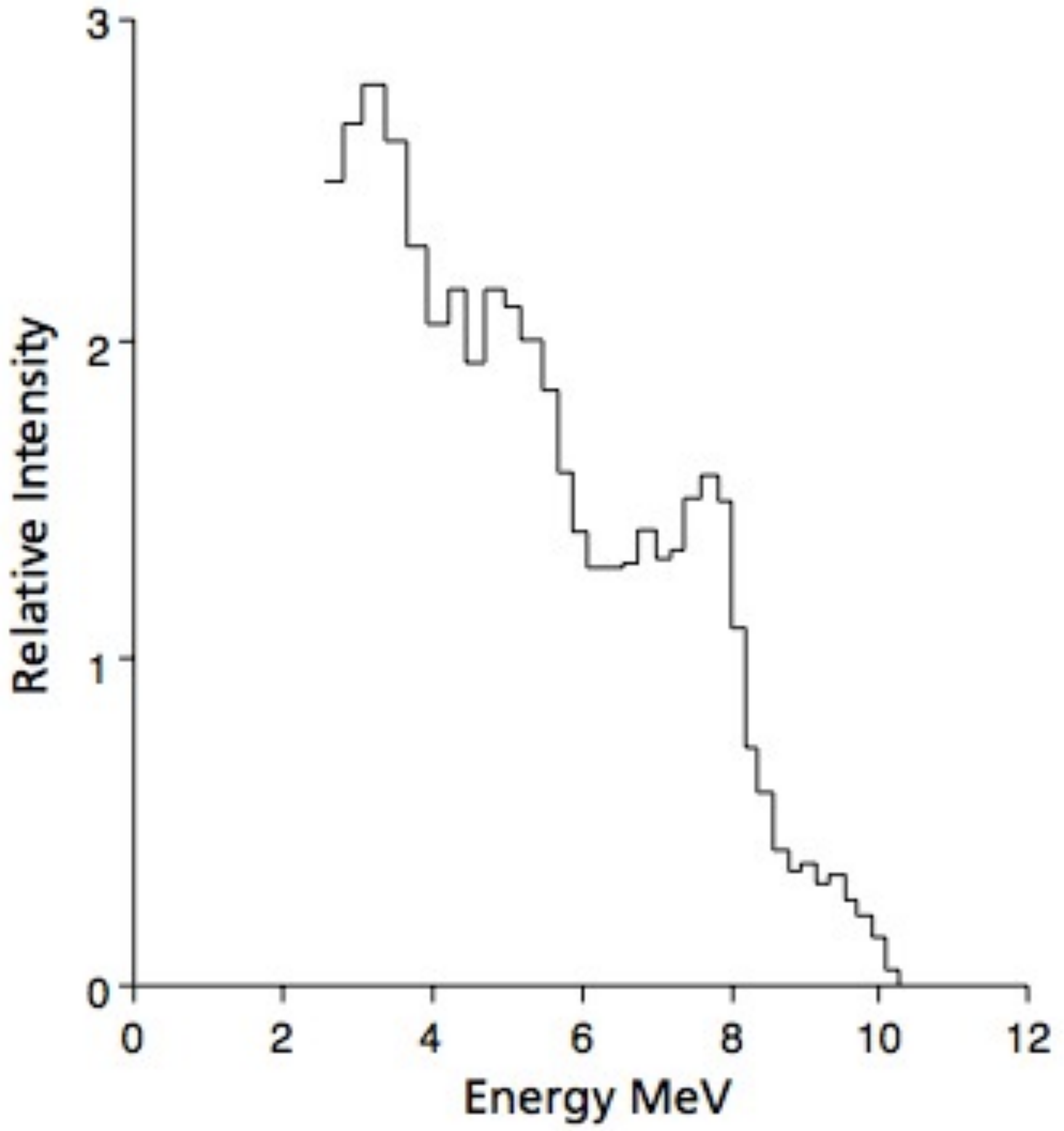
# Radioactive Laboratory Sources

# 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



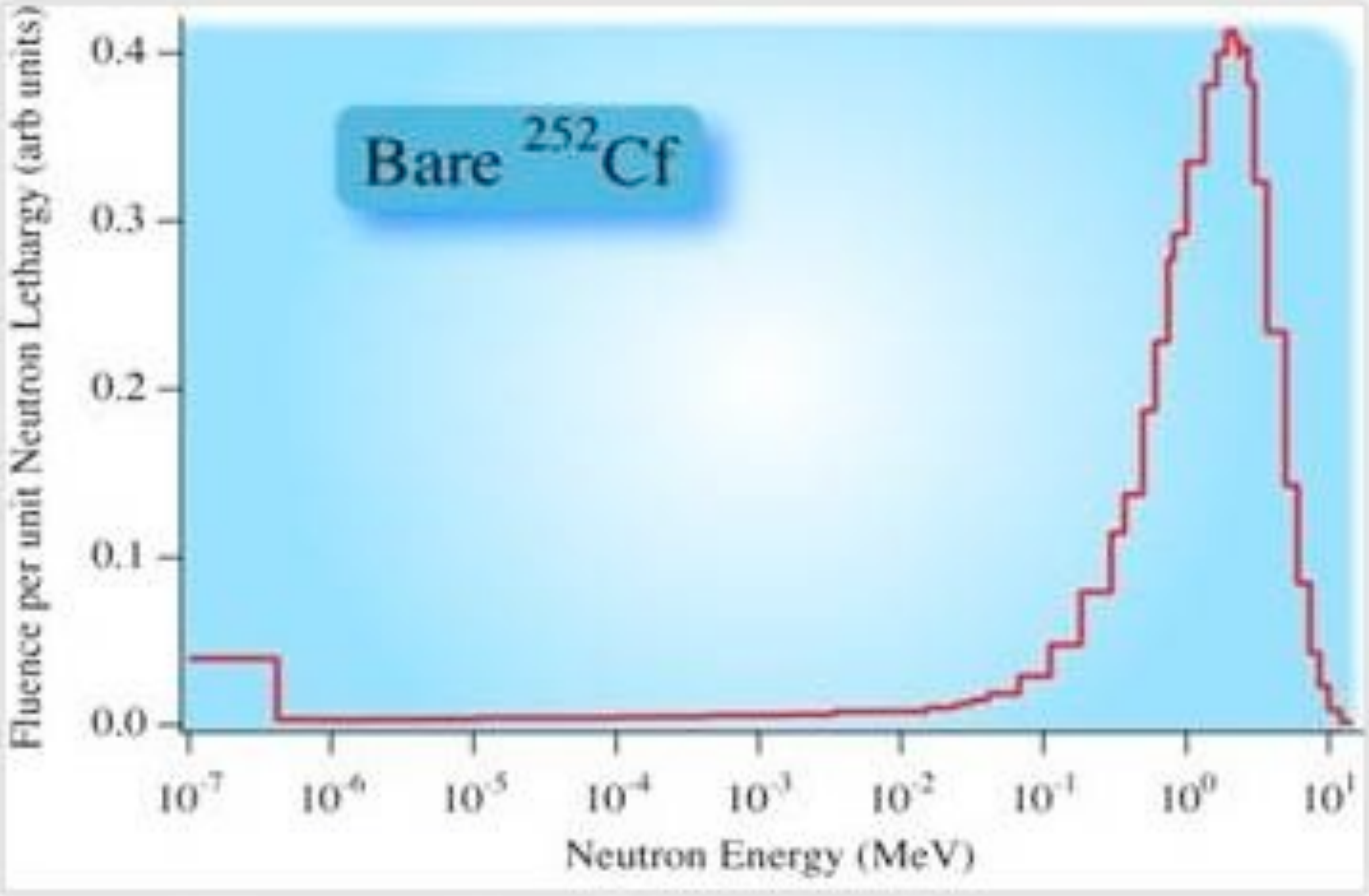
$He^4 + Be^9 \rightarrow C^{12} + n + 5.7 MeV$



- 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
- Neutron production coincident with many photons: possible to “tag” neutron production
- **arXiv:1405.2686**

# Radioactive Sources

- Some isotopes undergo spontaneous fission
- eg Cf-252, 3.1% of decays, average of 3.7 neutrons per fission.
- Californium-252 is not naturally occurring - it must be created by irradiating transuranic elements in a reactor
- Half life is only 2.6 years.



Energy spectrum of a $^{252}$Cf neutron source.

# Fusion

# Neutron Generator

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

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

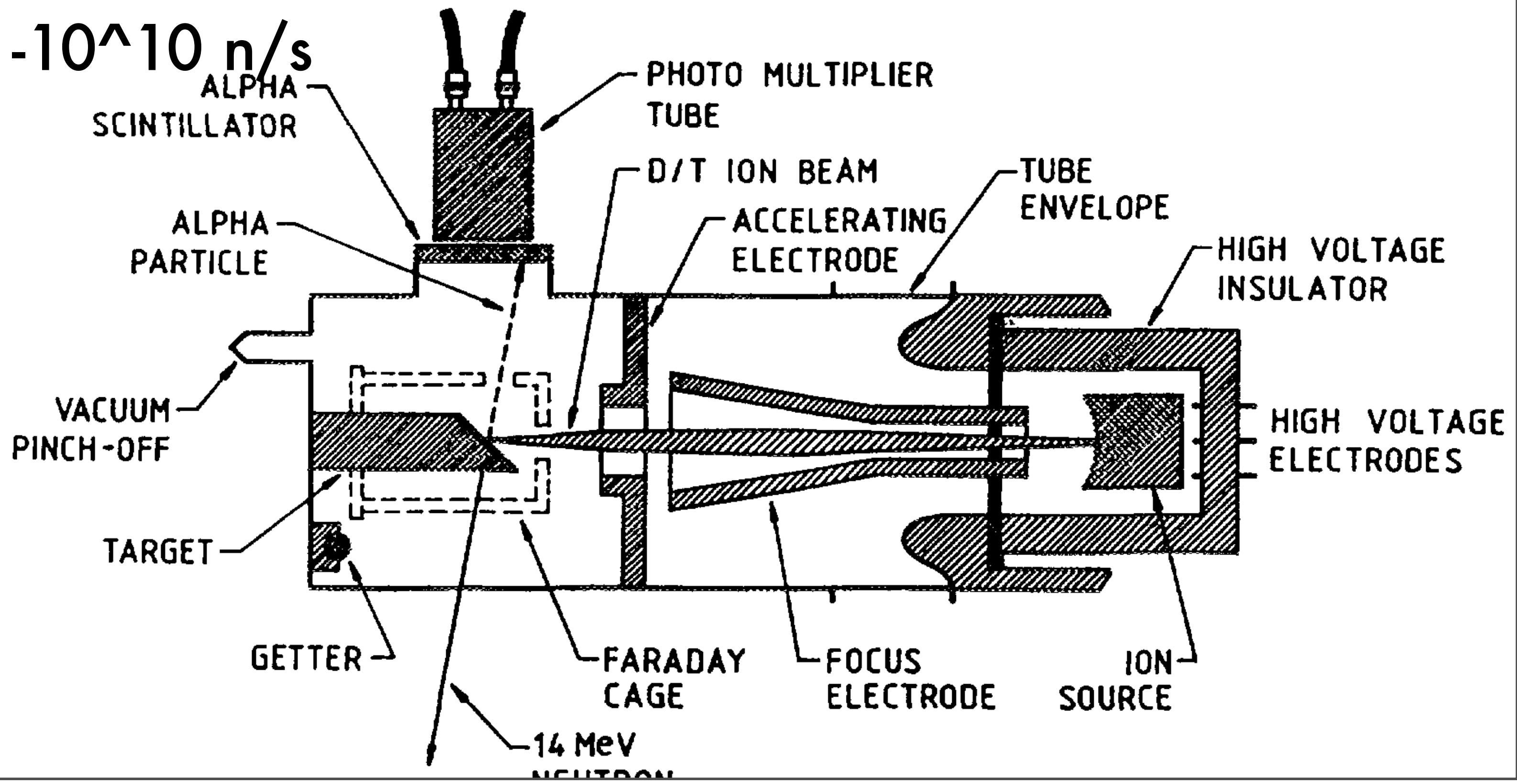
50%: ${}_1D^2 + {}_1D^2 \rightarrow {}_1T^3$ (1.01 MeV)+ ${}_1p^1$(3.02 MeV)

- DD:

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

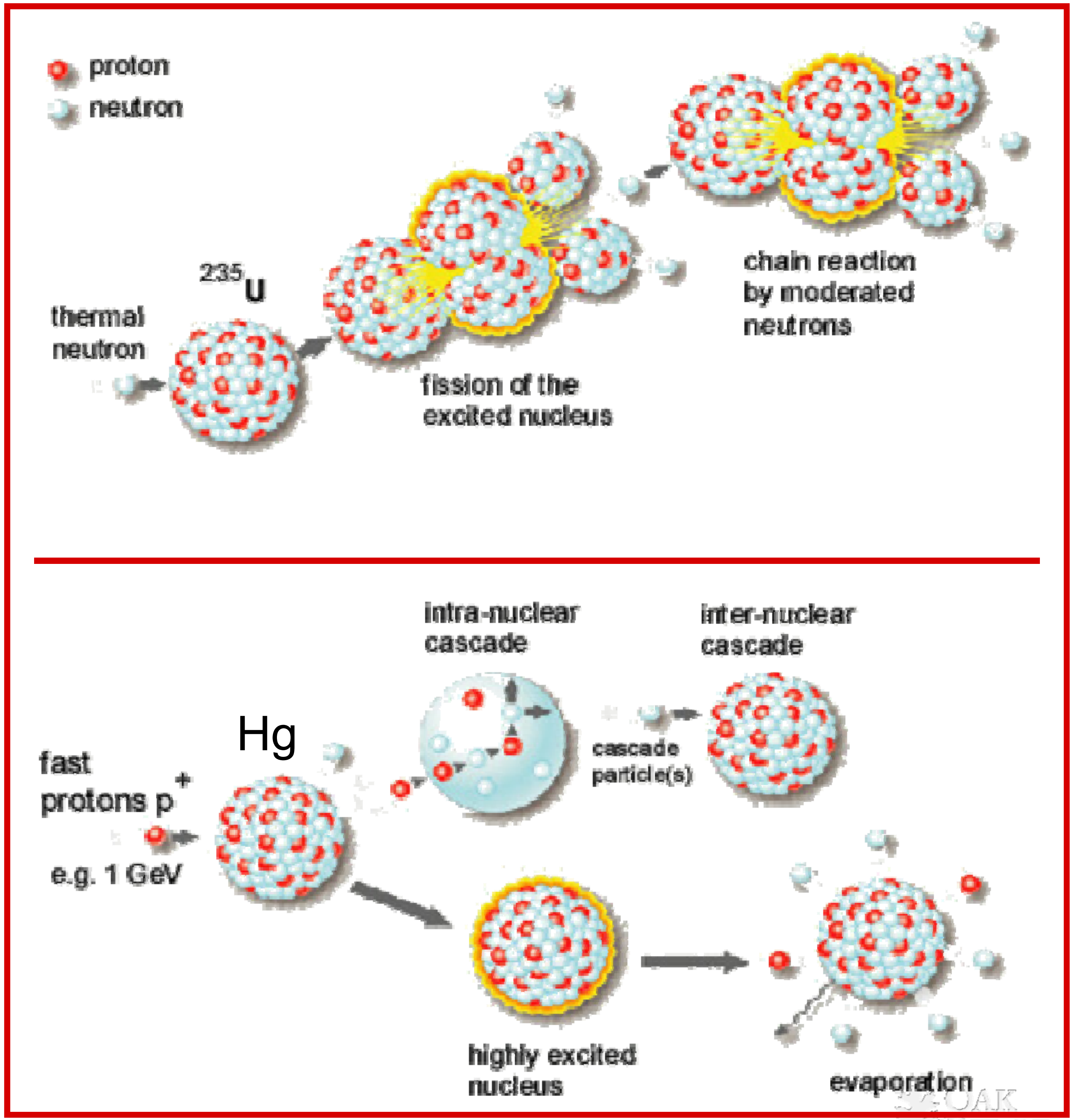
- Many generators available commercially
- eg SODERN, NSD-GRADEL fusion, Thermoscientific

- 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

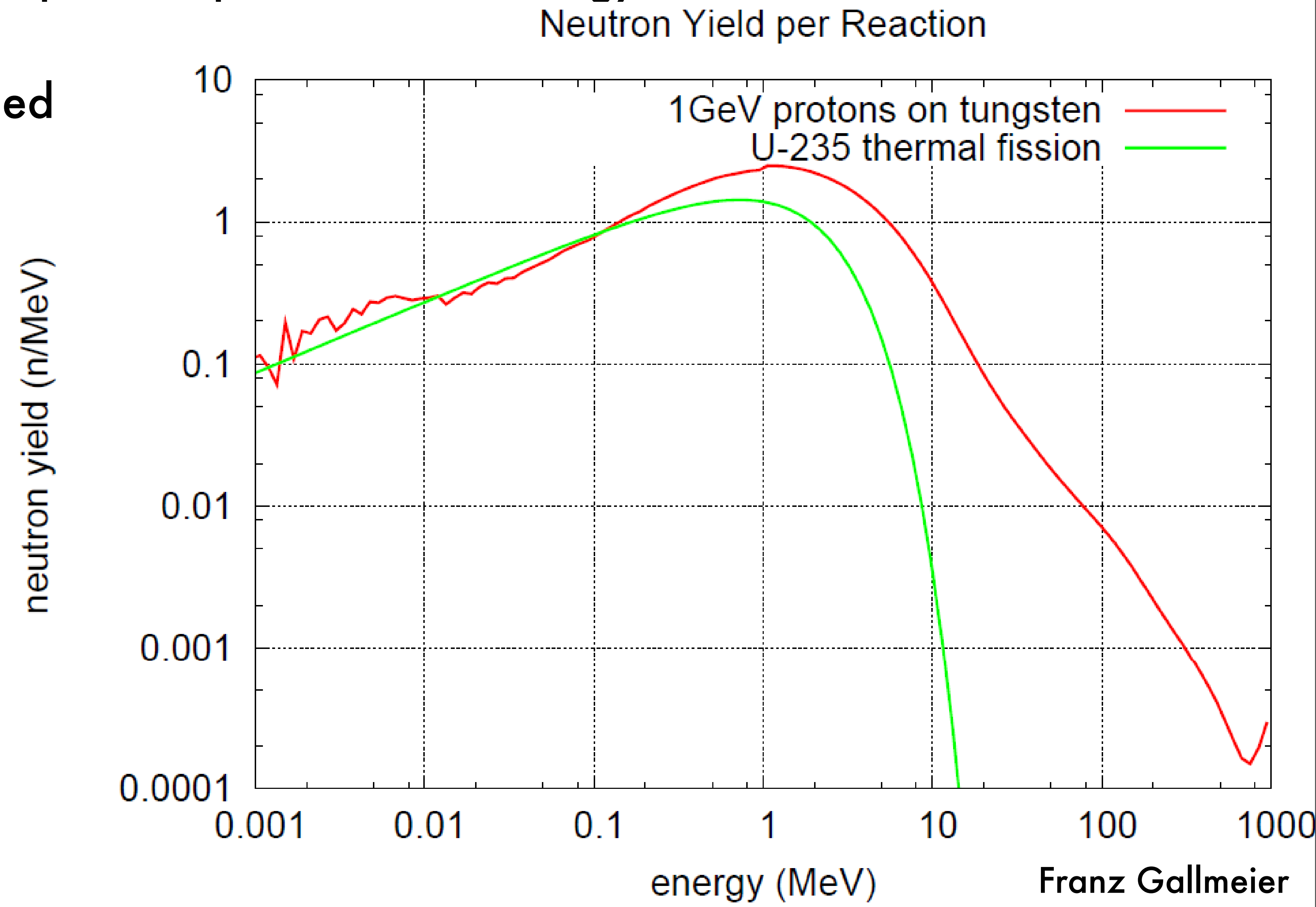


Phil Ferguson

# Fission vs Spallation

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

- Significant shielding needed



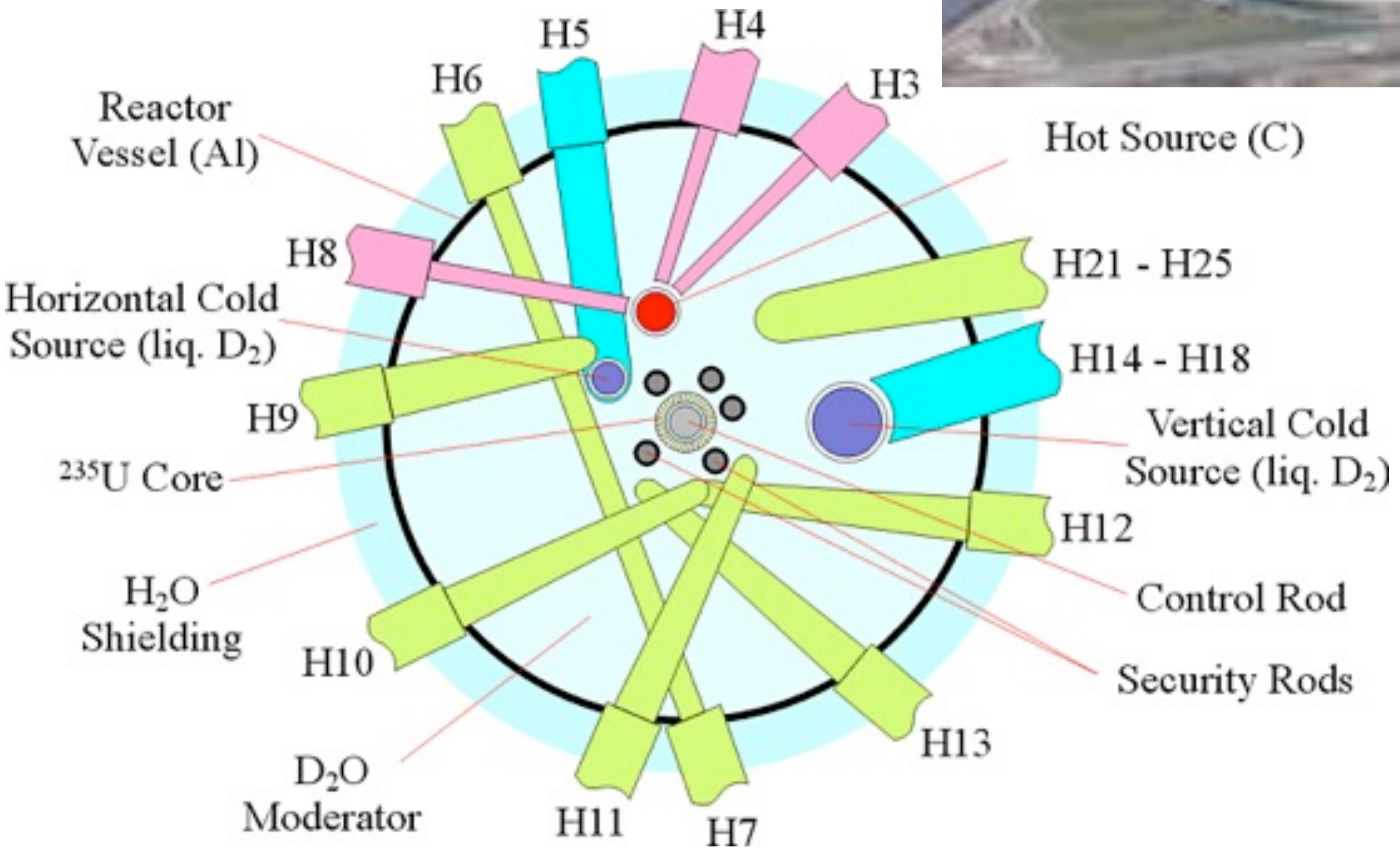
Franz Gallmeier

# Reactors

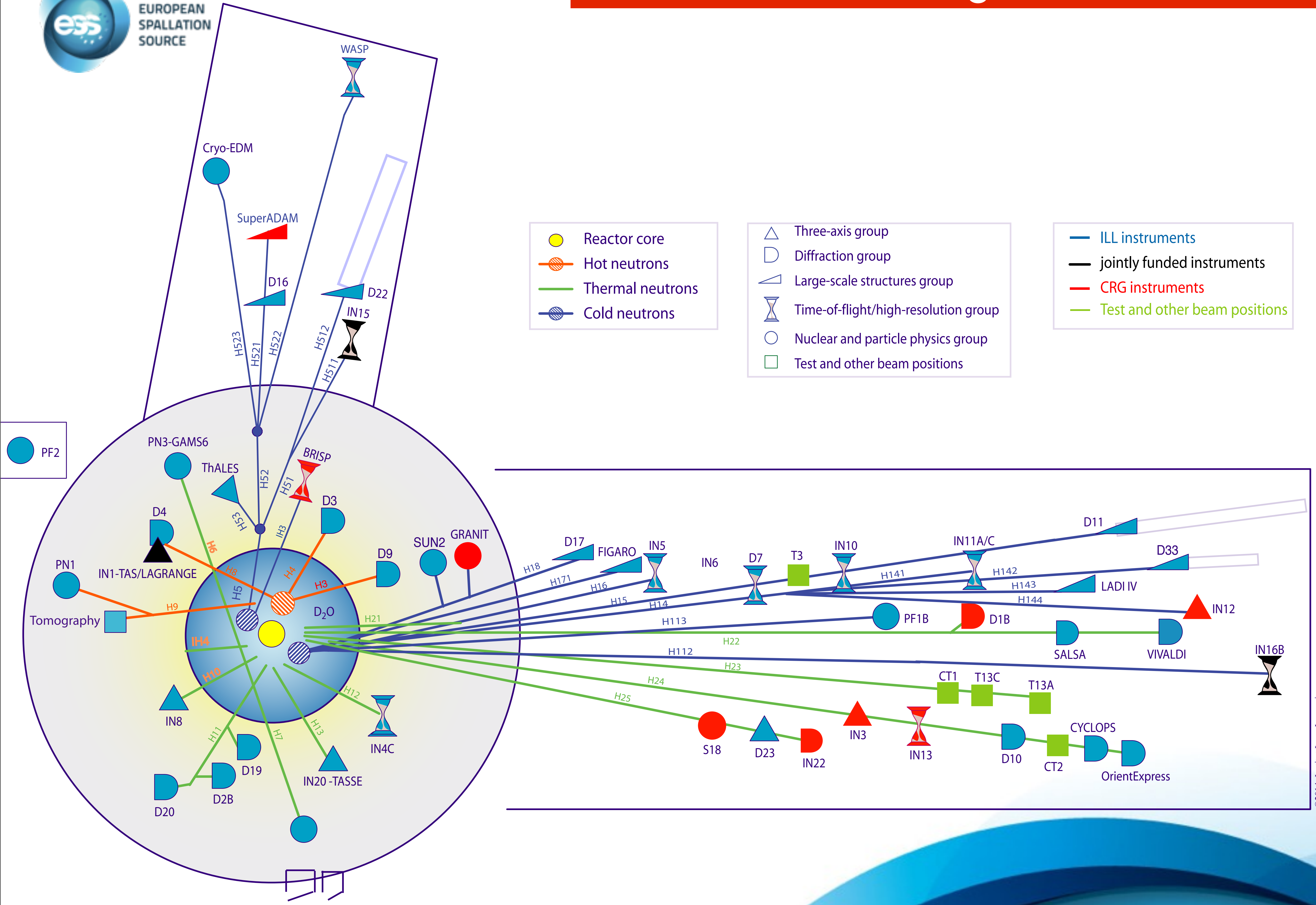
# Institut Laue-Langevin, Grenoble

- 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



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# Spallation Sources

# Current most advanced neutron sources

SNS (Oak Ridge, USA)

J-PARC (Tokai Japan)

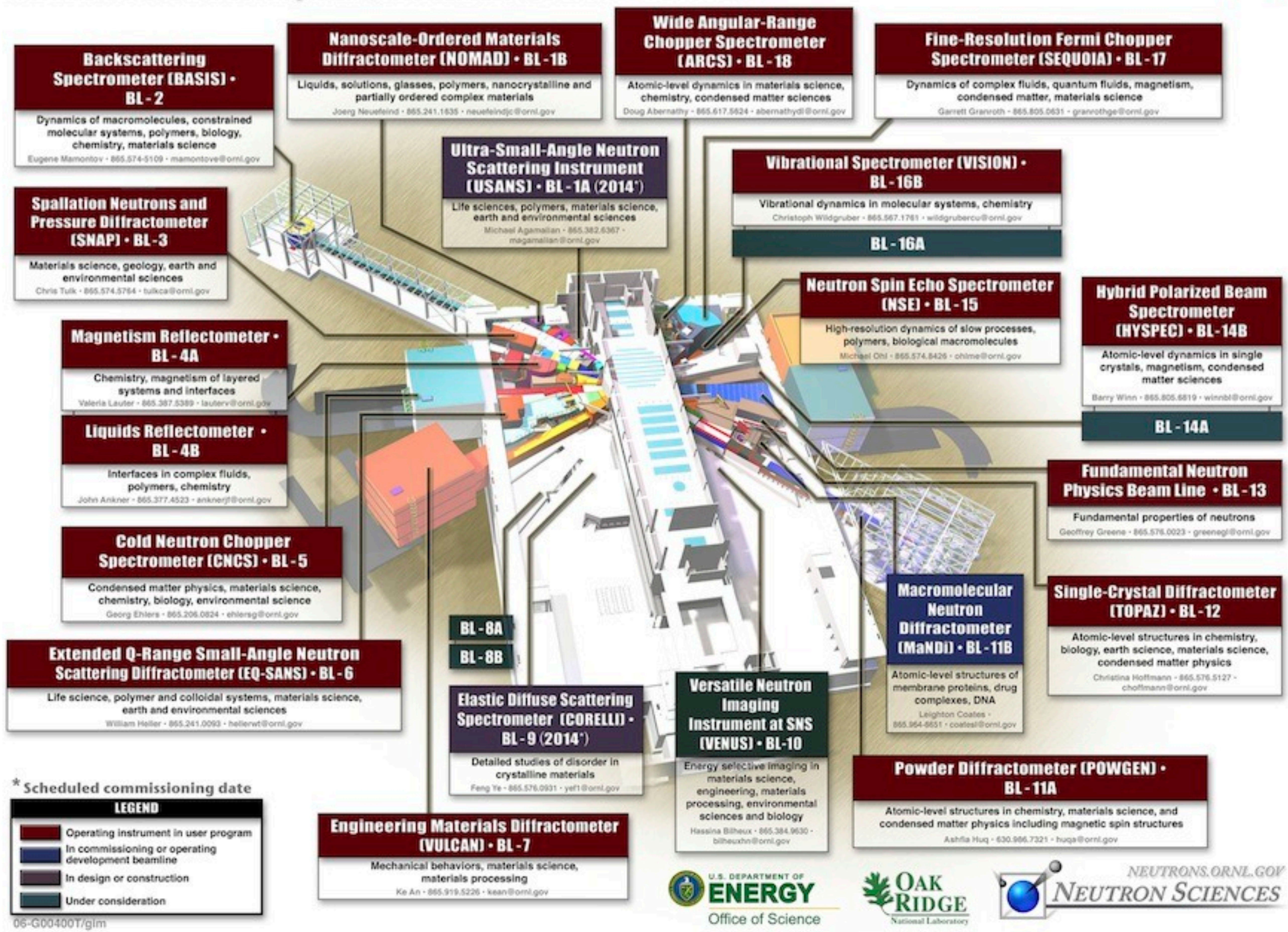
**Instantaneous power on target** (e.g. 1 MW at 60 Hz, i.e. 17 kj in ~1 μs pulses on target): **17 x**

→ **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



**Backscattering Spectrometer (BASIS) • BL - 2**
Dynamics of macromolecules, constrained molecular systems, polymers, biology, chemistry, materials science
Eugene Mamontov • 865.574-5109 • mamontove@ornl.gov

**Nanoscale-Ordered Materials Diffractometer (NOMAD) • BL - 1B**
Liquids, solutions, glasses, polymers, nanocrystalline and partially ordered complex materials
Joerg Neuefeind • 865.241.1635 • neuefeindjc@ornl.gov

**Wide Angular-Range Chopper Spectrometer (ARCS) • BL - 18**
Atomic-level dynamics in materials science, chemistry, condensed matter sciences
Doug Abernathy • 865.617.5824 • abernathydl@ornl.gov

**Fine-Resolution Fermi Chopper Spectrometer (SEQUOIA) • BL - 17**
Dynamics of complex fluids, quantum fluids, magnetism, condensed matter, materials science
Garrett Granroth • 865.805.0631 • granrothge@ornl.gov

**Ultra-Small-Angle Neutron Scattering Instrument (USANS) • BL - 1A (2014*)**
Life sciences, polymers, materials science, earth and environmental sciences
Michael Agamalian • 865.382.6367 • magamalian@ornl.gov

**Vibrational Spectrometer (VISION) • BL - 16B**
Vibrational dynamics in molecular systems, chemistry
Christoph Wildgruber • 865.567.1761 • wildgrubercu@ornl.gov

**BL - 16A**

**Spallation Neutrons and Pressure Diffractometer (SNAP) • BL - 3**
Materials science, geology, earth and environmental sciences
Chris Tulk • 865.574.5764 • tulkca@ornl.gov

**Neutron Spin Echo Spectrometer (NSE) • BL - 15**
High-resolution dynamics of slow processes, polymers, biological macromolecules
Michael Ohl • 865.574.8426 • ohlme@ornl.gov

**Hybrid Polarized Beam Spectrometer (HYSPEC) • BL - 14B**
Atomic-level dynamics in single crystals, magnetism, condensed matter sciences
Barry Winn • 865.805.6819 • winnbl@ornl.gov

**BL - 14A**

**Magnetism Reflectometer • BL - 4A**
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**Liquids Reflectometer • BL - 4B**
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**Fundamental Neutron Physics Beam Line • BL - 13**
Fundamental properties of neutrons
Geoffrey Greene • 865.576.0023 • greenegl@ornl.gov

**Cold Neutron Chopper Spectrometer (CNCS) • BL - 5**
Condensed matter physics, materials science, chemistry, biology, environmental science
Georg Ehlers • 865.206.0824 • ehlersg@ornl.gov

**Macromolecular Neutron Diffractometer (MaNDi) • BL - 11B**
Atomic-level structures of membrane proteins, drug complexes, DNA
Leighton Coates • 865.964-8651 • coatesl@ornl.gov

**Single-Crystal Diffractometer (TOPAZ) • BL - 12**
Atomic-level structures in chemistry, biology, earth science, materials science, condensed matter physics
Christina Hoffmann • 865.576.5127 • choffmann@ornl.gov

**BL - 8A**

**BL - 8B**

**Extended Q-Range Small-Angle Neutron Scattering Diffractometer (EQ-SANS) • BL - 6**
Life science, polymer and colloidal systems, materials science, earth and environmental sciences
William Heller • 865.241.0093 • hellerwt@ornl.gov

**Elastic Diffuse Scattering Spectrometer (CORELLI) • BL - 9 (2014*)**
Detailed studies of disorder in crystalline materials
Feng Ye • 865.576.0931 • yef1@ornl.gov

**Versatile Neutron Imaging Instrument at SNS (VENUS) • BL-10**
Energy selective imaging in materials science, engineering, materials processing, environmental sciences and biology
Hassina Bilheux • 865.384.9630 • bilheuxhn@ornl.gov

**Powder Diffractometer (POWGEN) • BL - 11A**
Atomic-level structures in chemistry, materials science, and condensed matter physics including magnetic spin structures
Ashfia Huq • 630.986.7321 • huqa@ornl.gov

**Engineering Materials Diffractometer (VULCAN) • BL - 7**
Mechanical behaviors, materials science, materials processing
Ke An • 865.919.5226 • kean@ornl.gov

* Scheduled commissioning date

| LEGEND | |
|---|---|
| 🟥 | Operating instrument in user program |
| 🟦 | In commissioning or operating development beamline |
| 🟪 | In design or construction |
| ■ | Under consideration |

06-G00400T/gim

NEUTRONS.ORNL.GOV

# Moderation

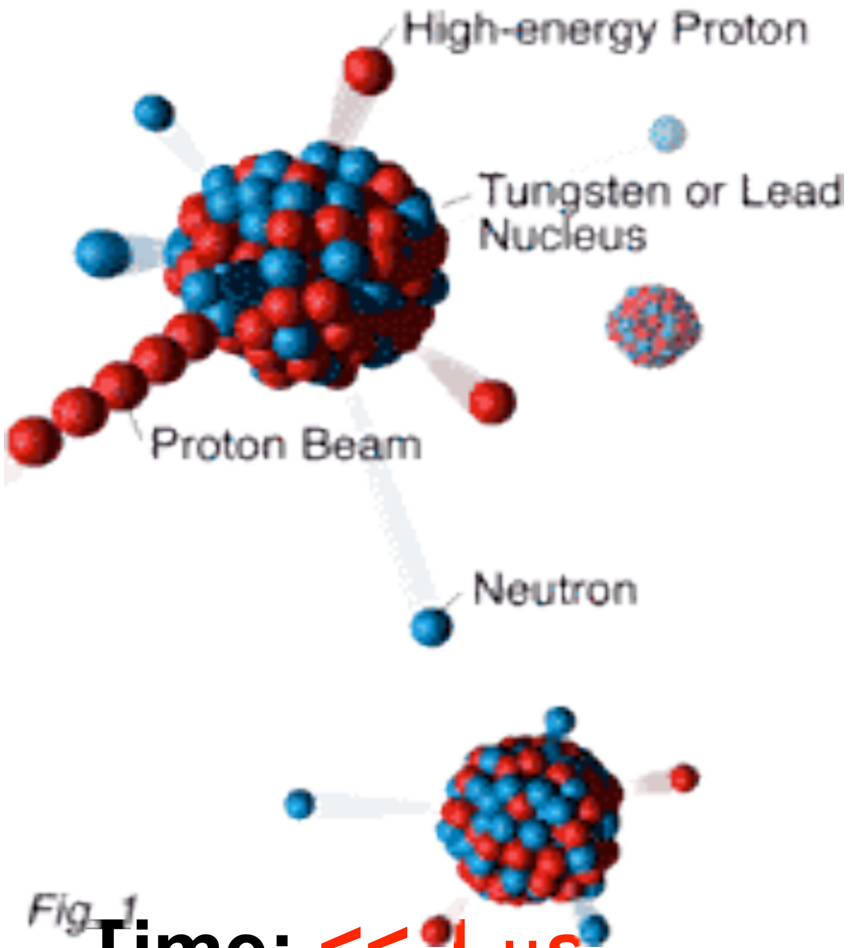
# Slow neutron generation

EUROPEAN SPALLATION SOURCE

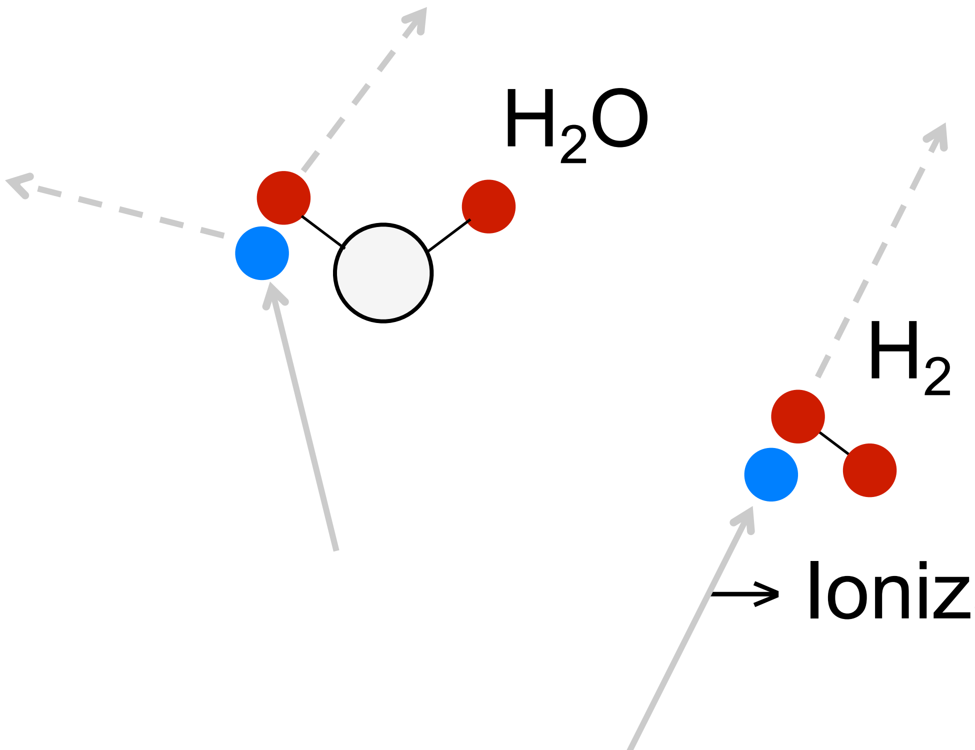
## Two step process in the target station

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



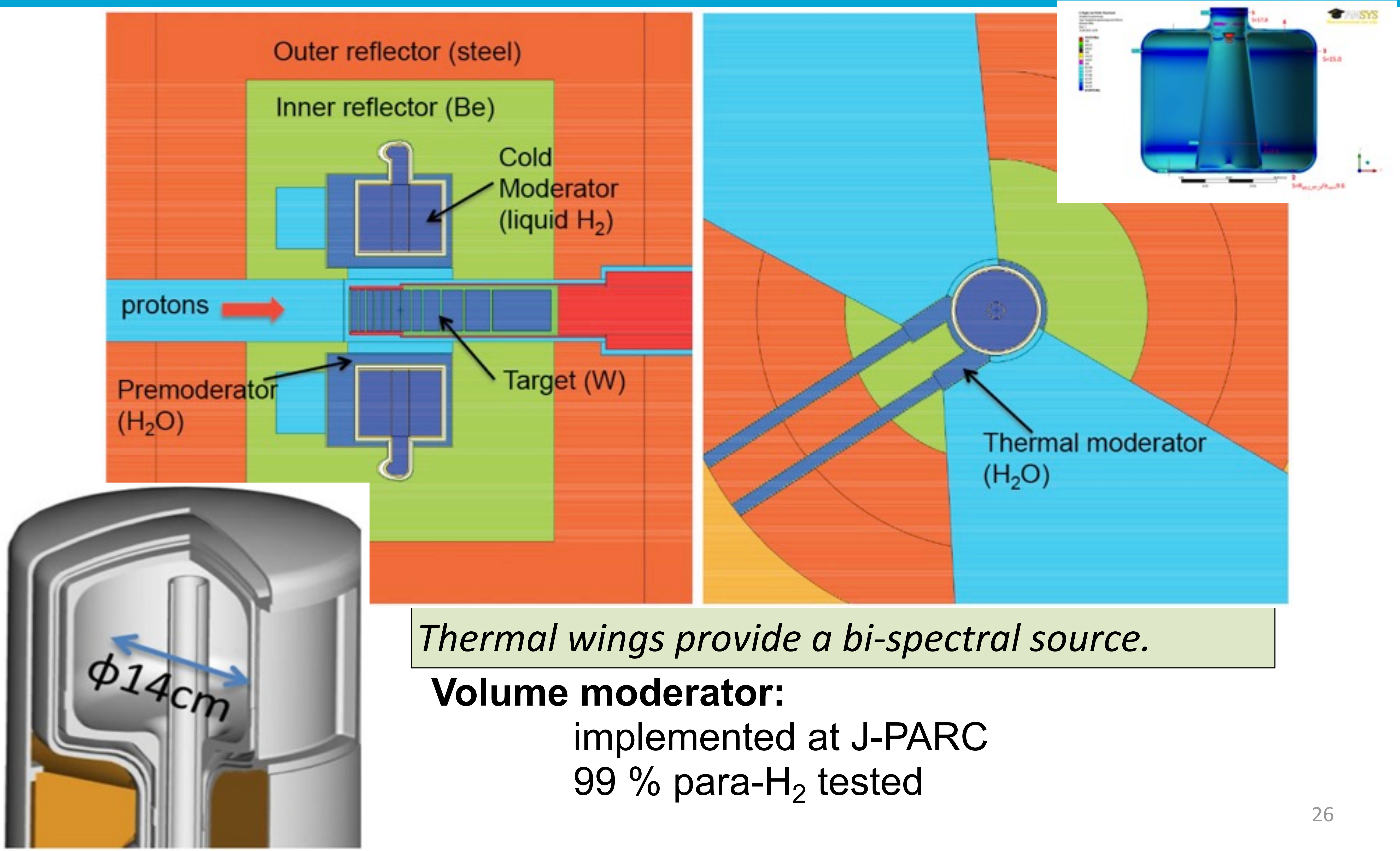
**Time:** **<< 1 µs**



→ Ionization!

**10 – 500 µs**

# TDR configuration: two tall moderators

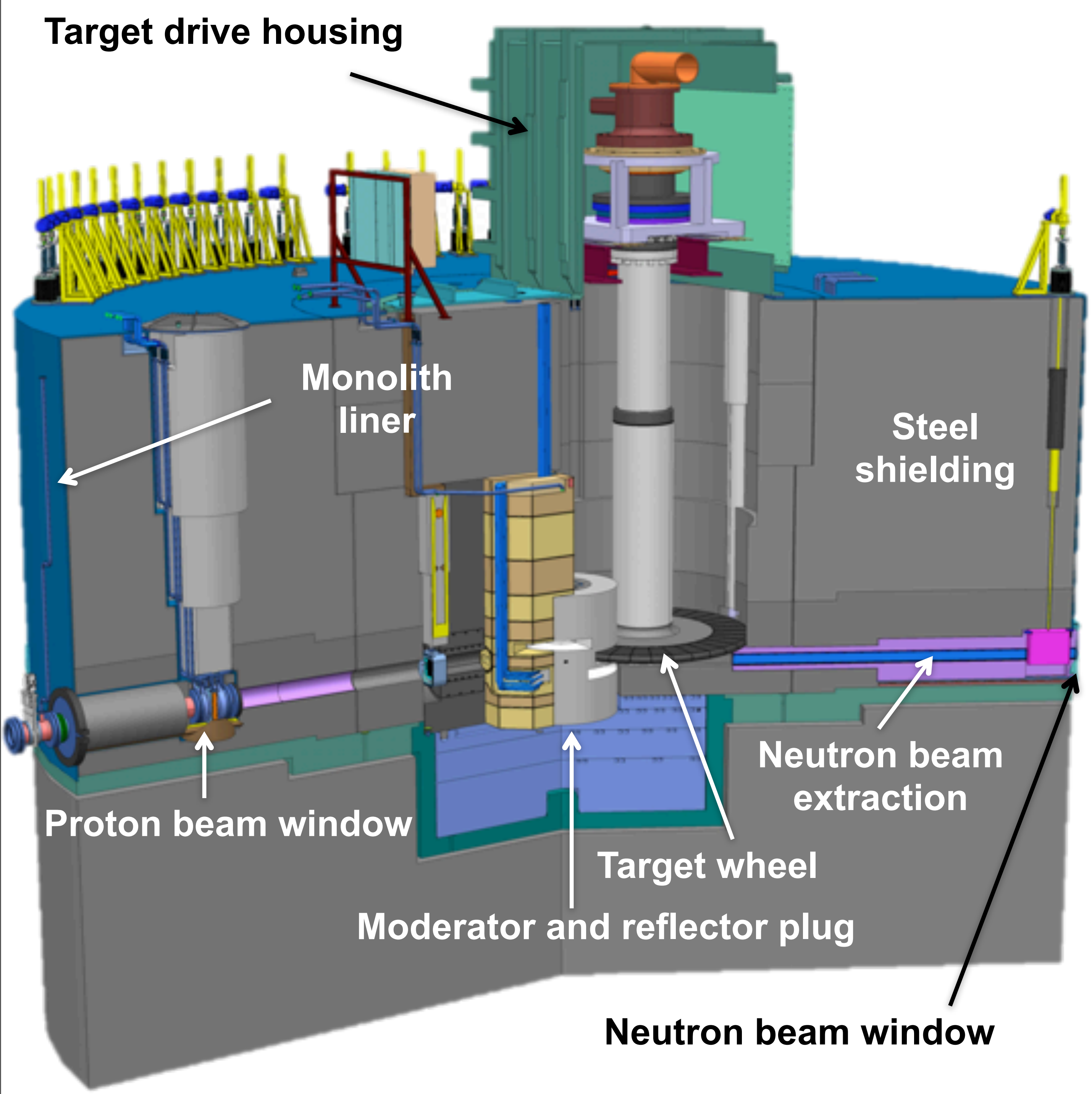


*Thermal wings provide a bi-spectral source.*

**Volume moderator:**

implemented at J-PARC
99 % para-$H_2$ tested

# Slow neutron generation: target monolith



Functions:

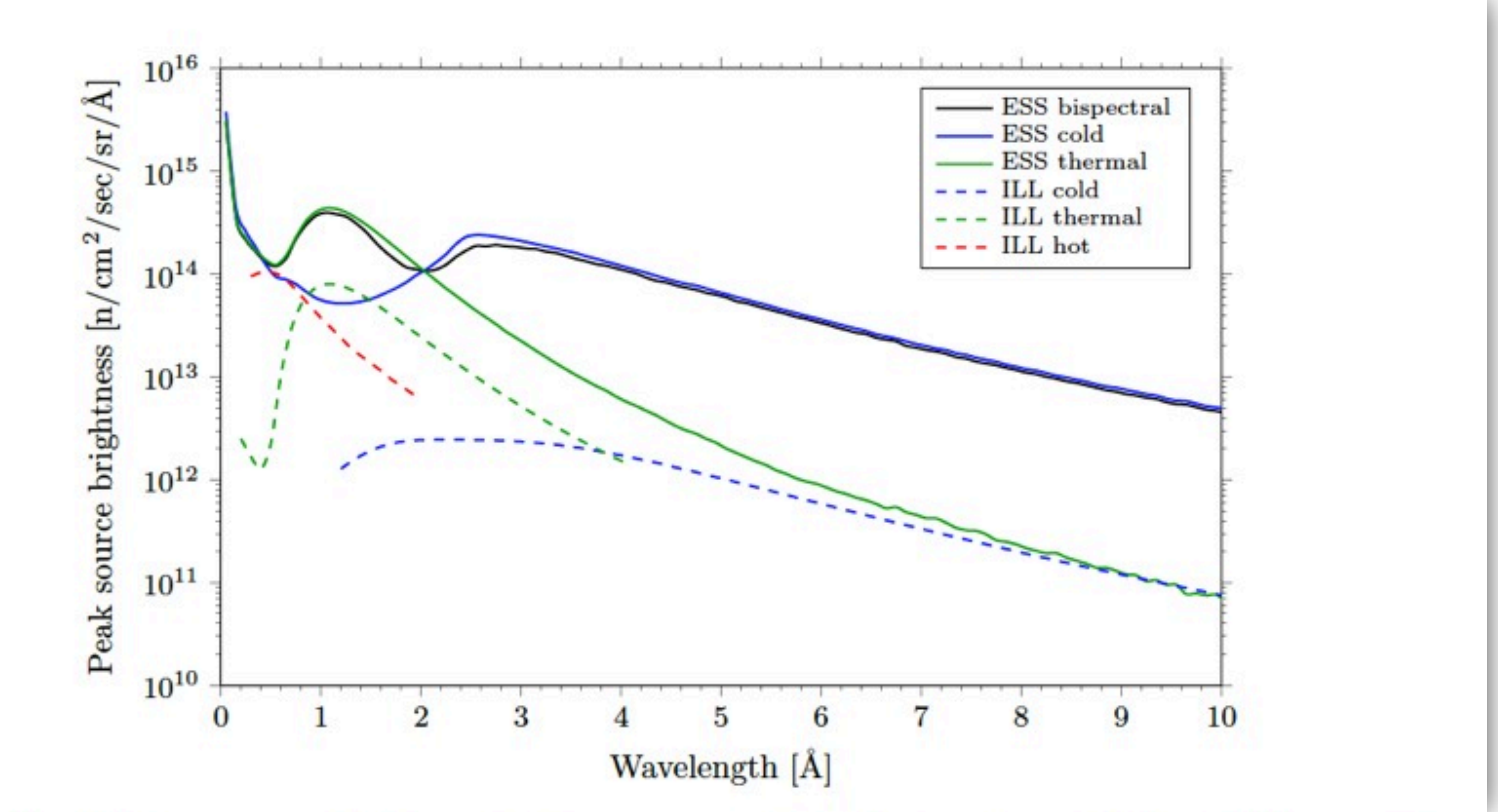
- Convert protons to neutrons
- Heat removal
- Confinement and shielding

Unique features:

- Rotating target
- He-cooled W target

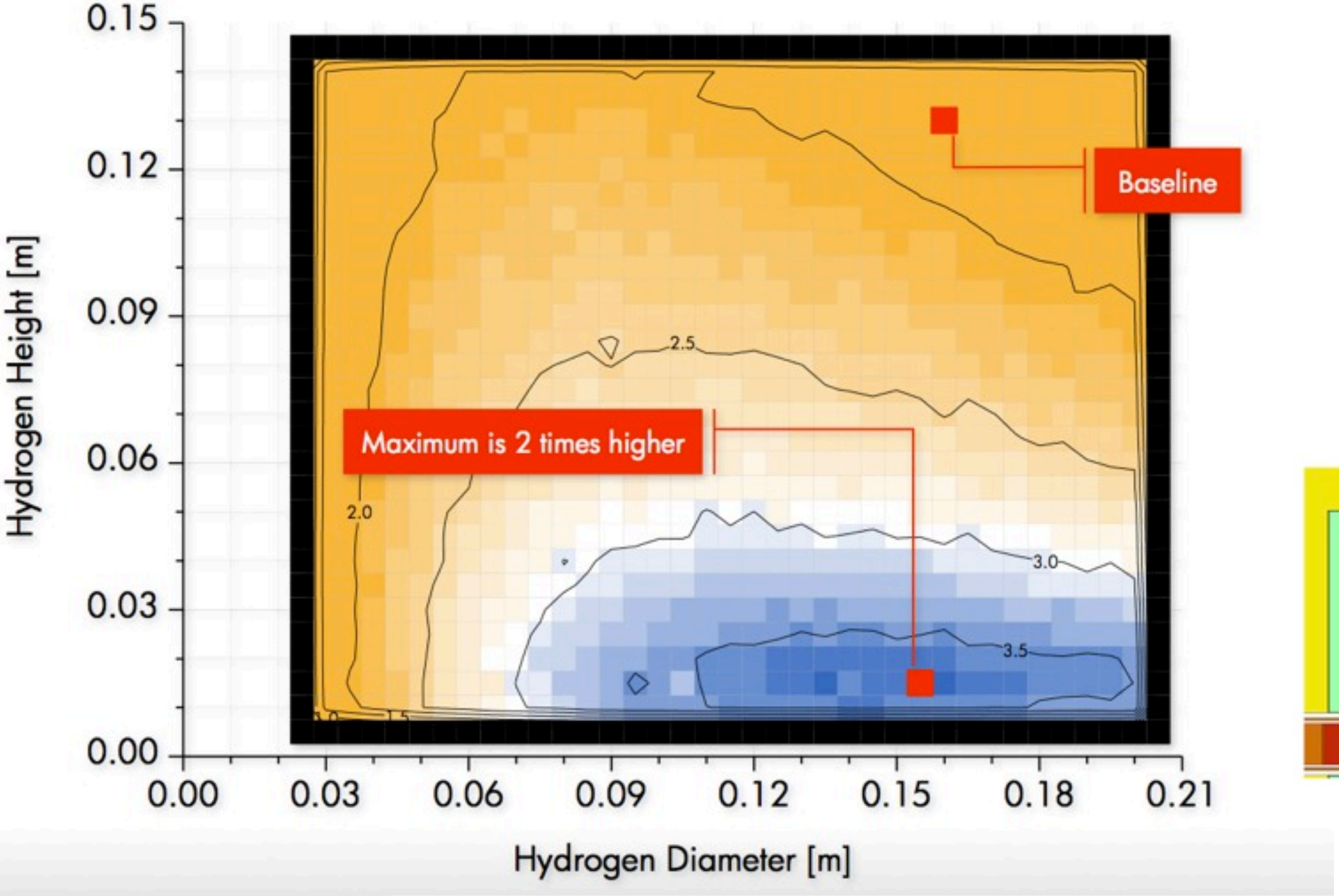
# Excellent performance from the TDR moderators

(ESS Technical Design Report)



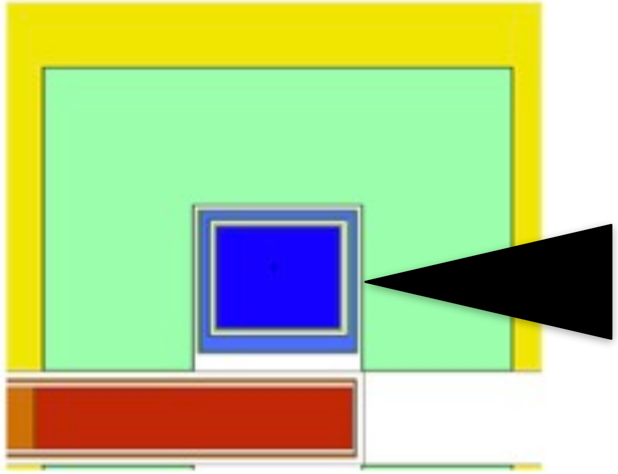
3. ESS Technical Design Report, ESS-doc-274, ISBN 978-91-980173-2-8 (April 23, 2013). URL http://eval.esss.lu.se/DocDB/0002/000274/015/TDR_onli%ne_ver_all.pdf

# We started from the *unperturbed* brightness



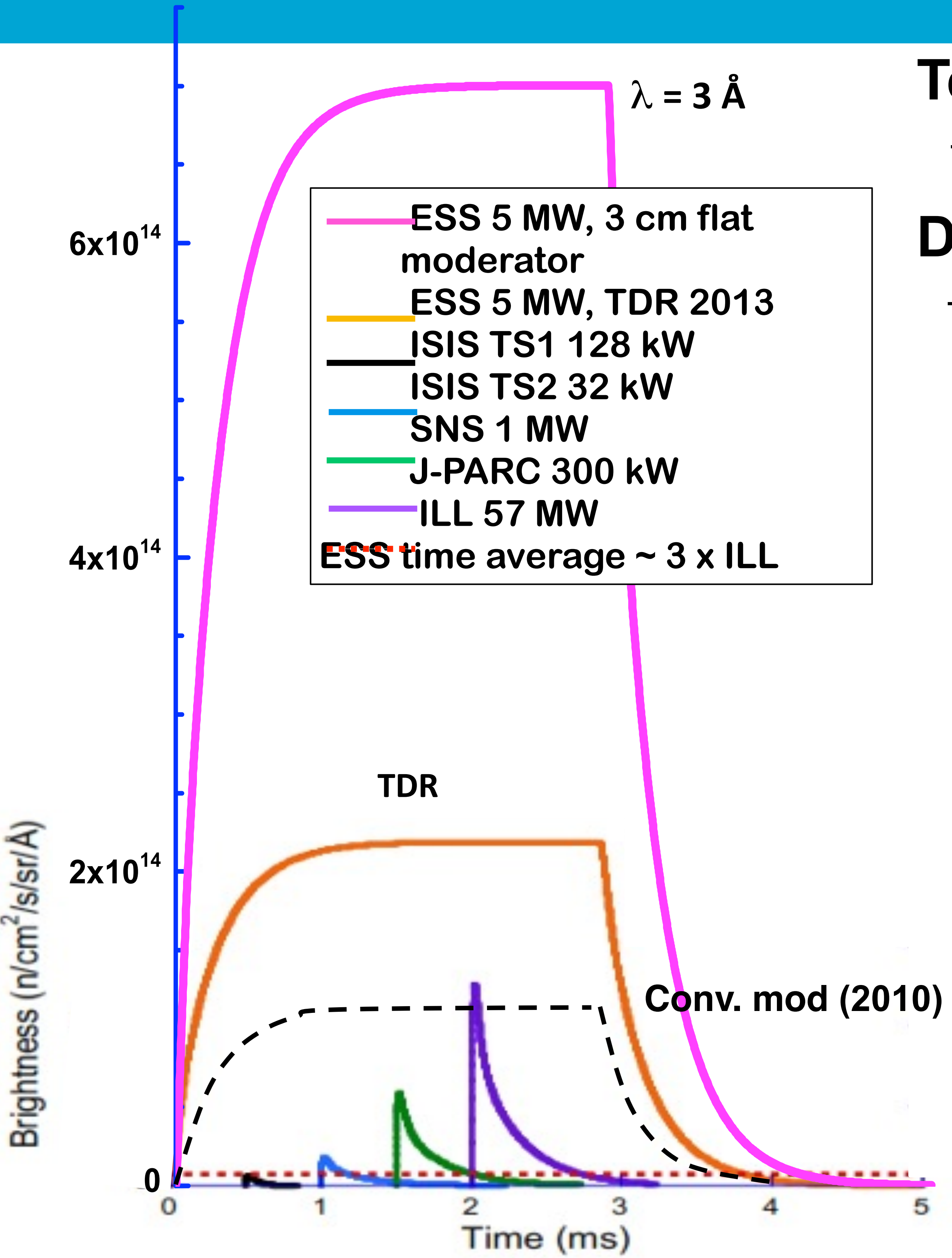
Baseline

Maximum is 2 times higher



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.

# ESS: the next generation



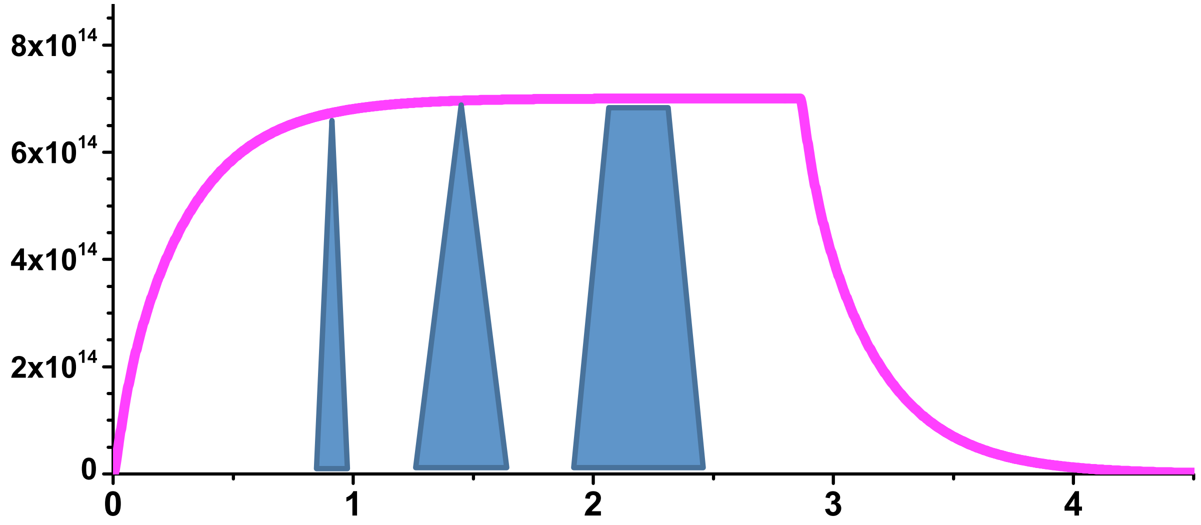
**Technical Design Report 2013 (TDR)**
**→ feasibility, costs**

**Design optimization 2014**
**→ reduce costs, increase performance**

Pulse shaping offers better efficiency of use of peak flux:
- more intensity at same resolution
- variable resolution for optimizing intensity

Flat moderators: higher guide losses for large samples / large beam divergence

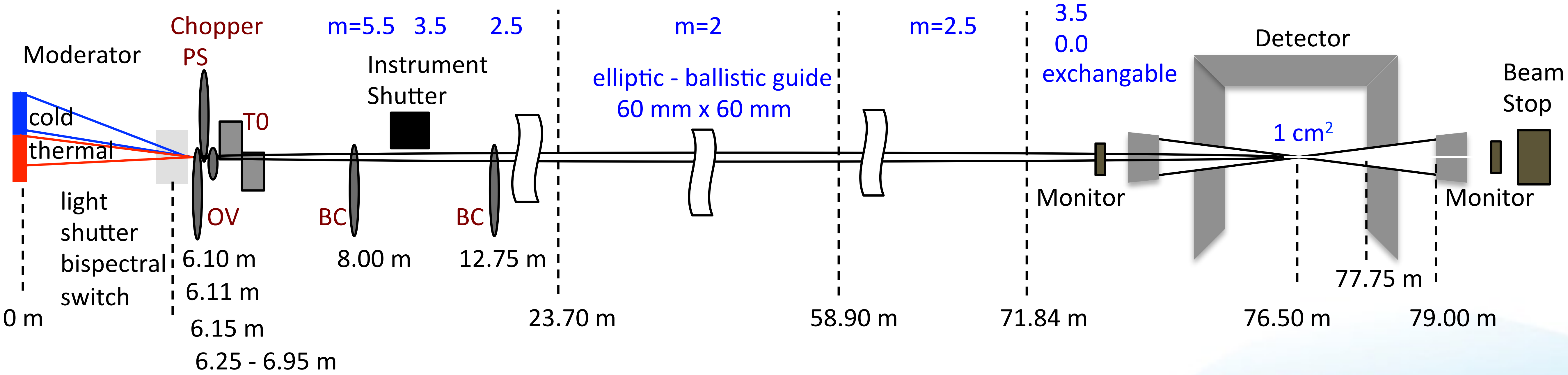
Cumulative effect: another about x 1.5 - 2 in favor of long pulses



# Neutron Beamlines and Instruments

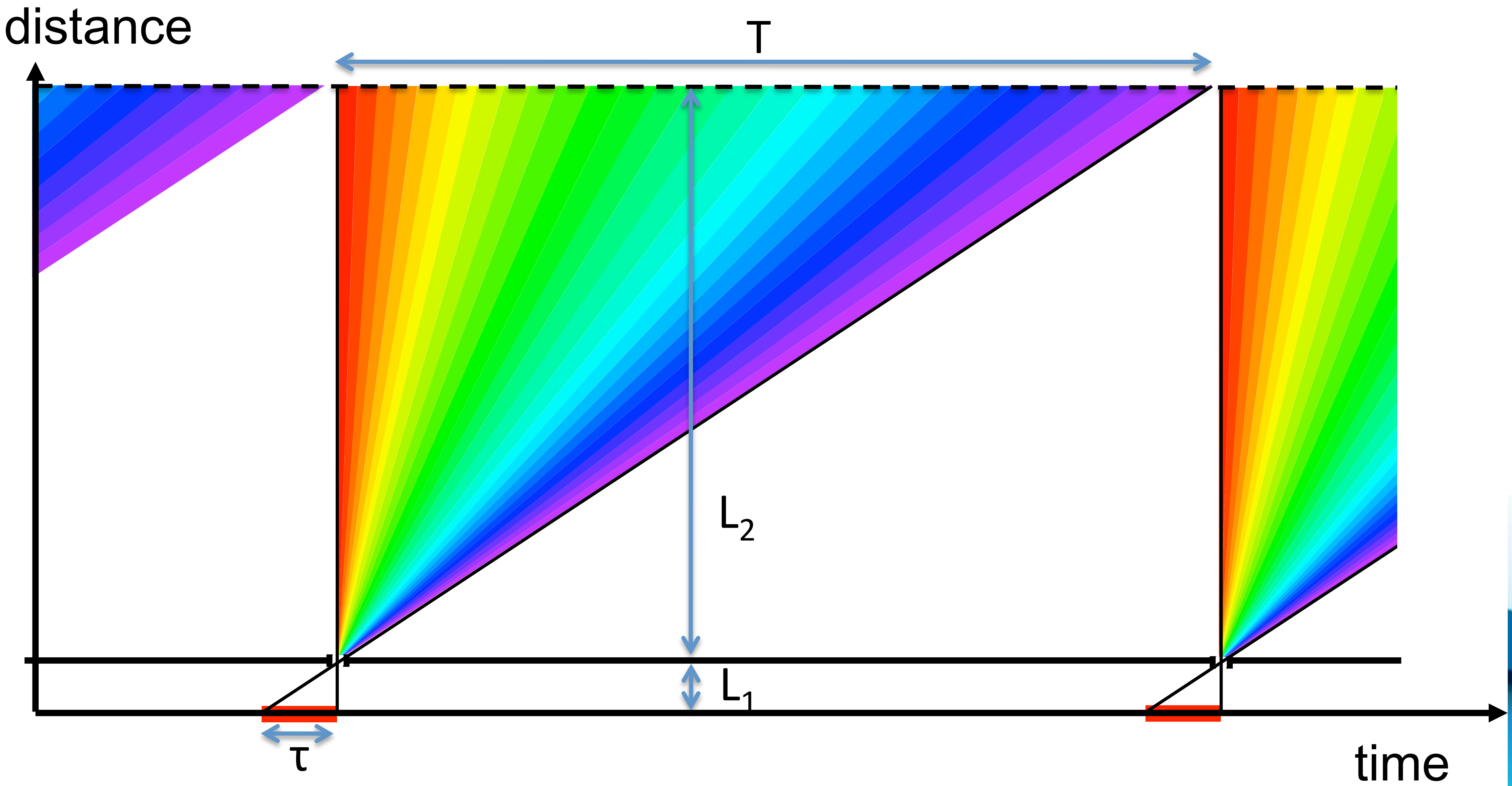
# Instrument Design

- 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



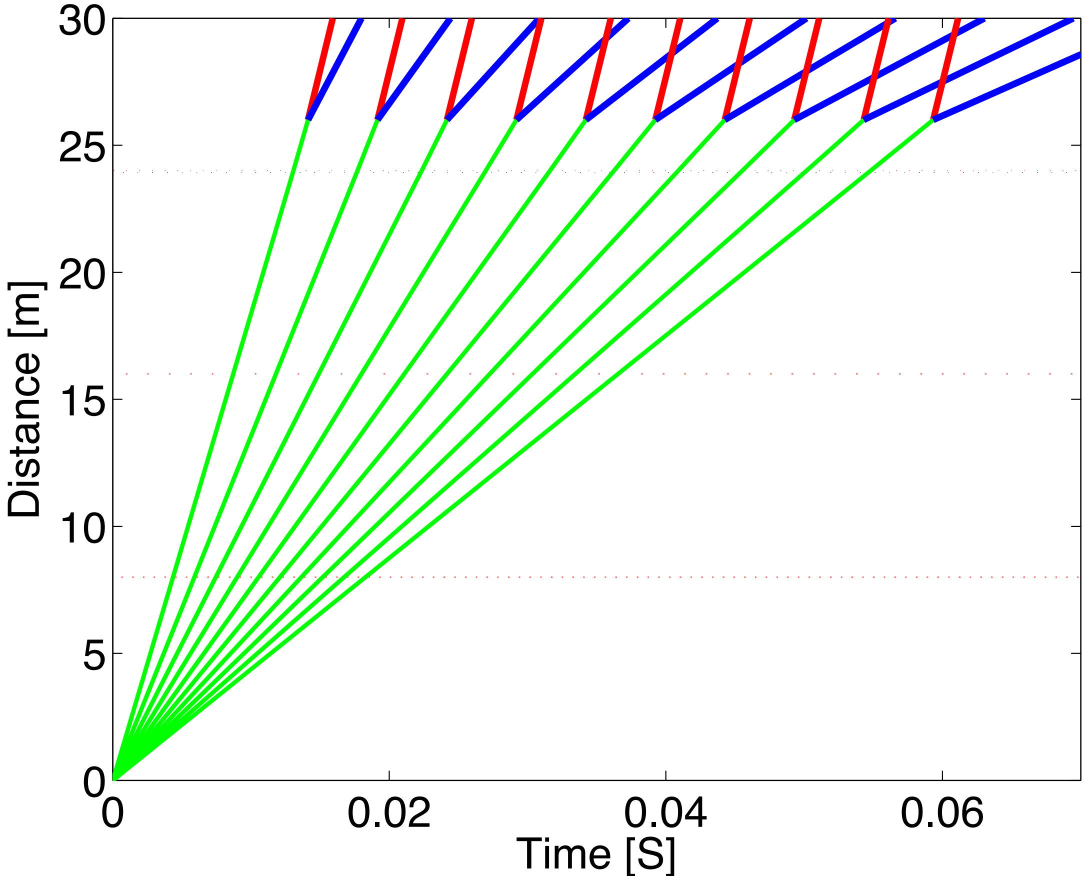
# Time distance diagram

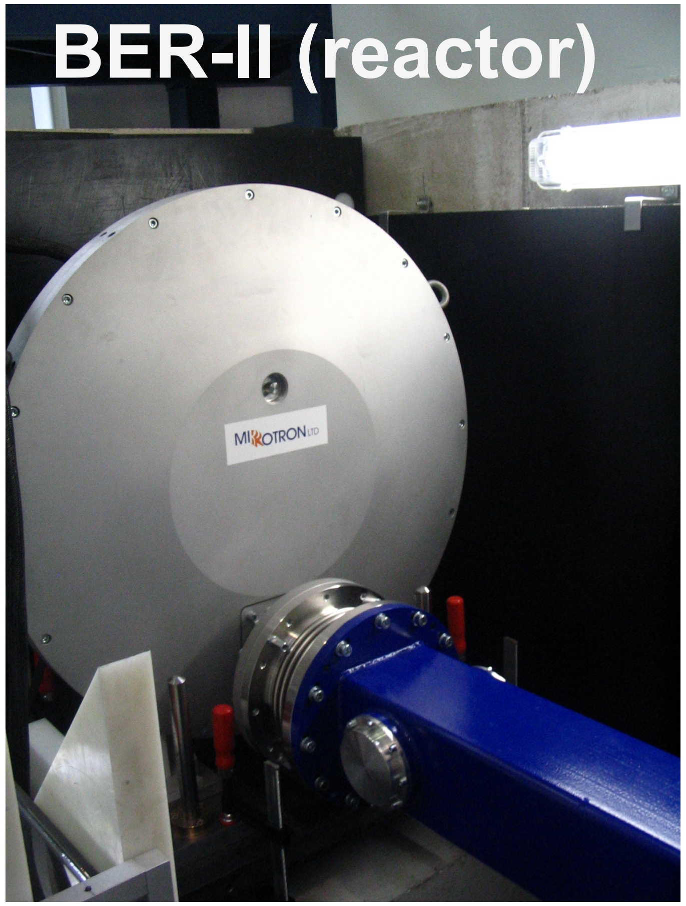
- Time distance diagram of white beam instrument with Pulse shaping chopper .

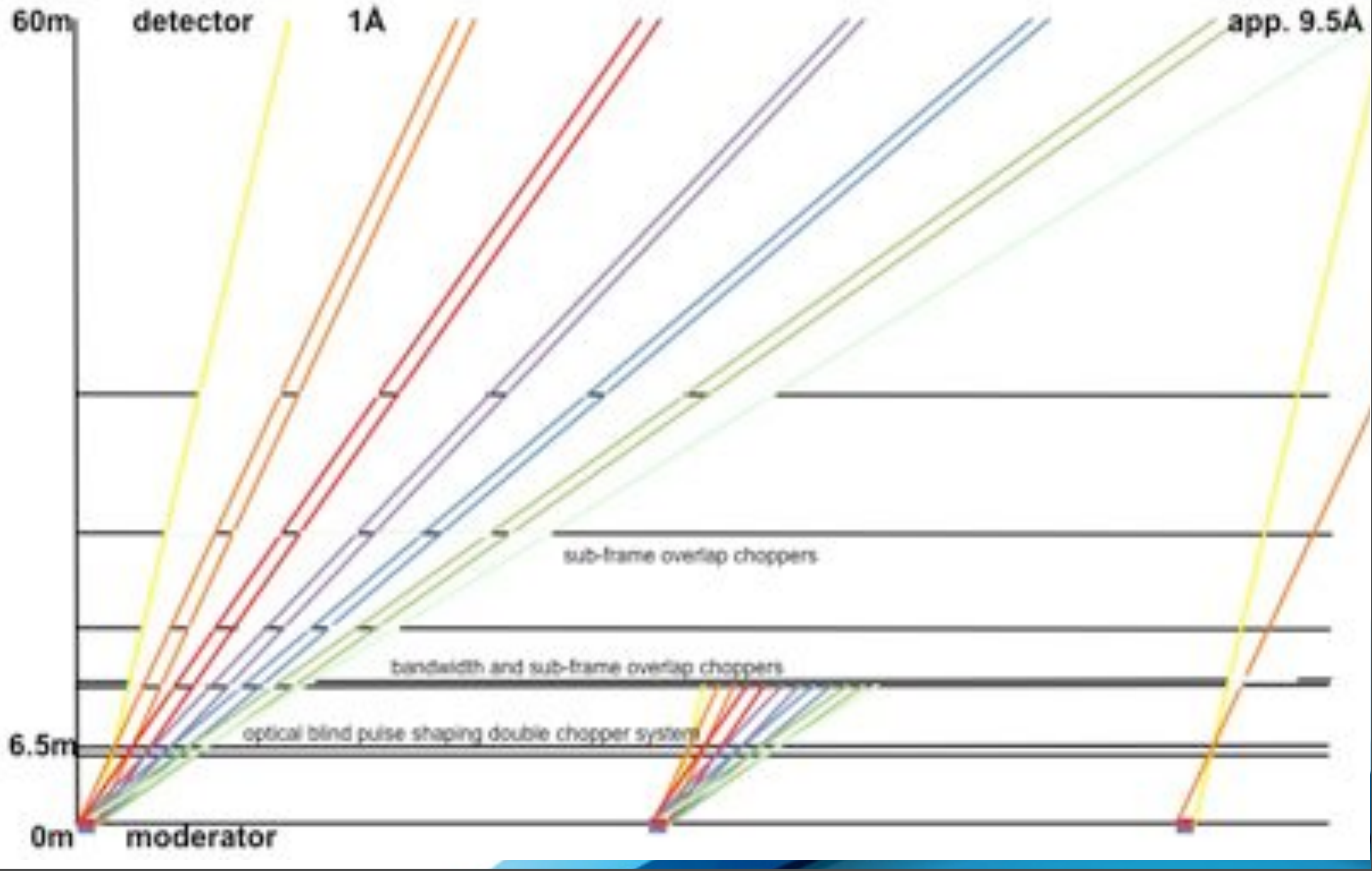


# Neutron Time-of-Flight

- 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

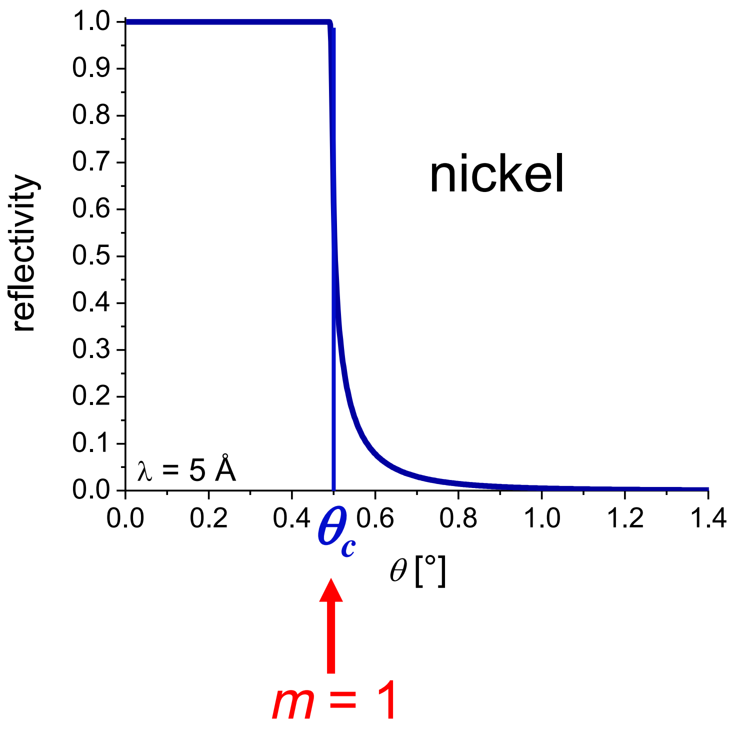


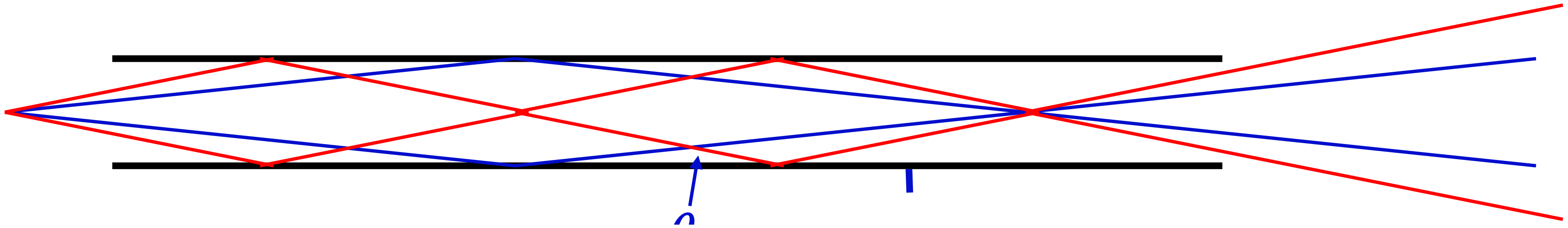




# Neutron Optics

- The phase space density of neutrons cannot be increases
- 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.

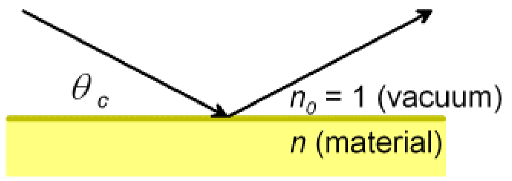




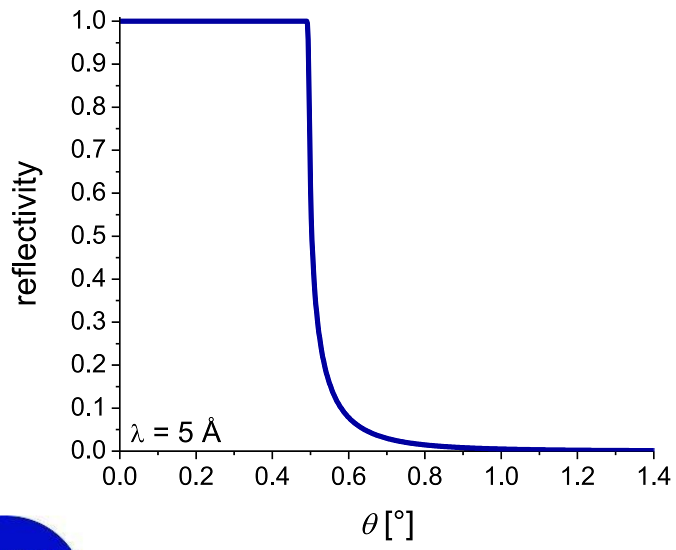
# Invention of Supermirrors

(Turchin 1967, Mezei 1976)

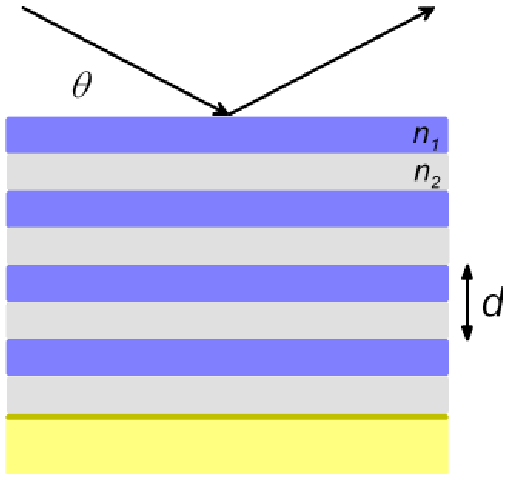
## smooth surfaces



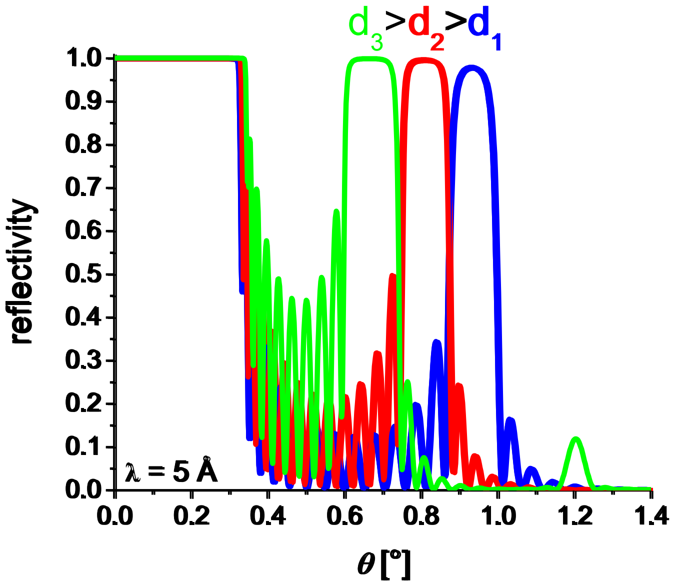
- refractive index $n < 1$
- total external reflection



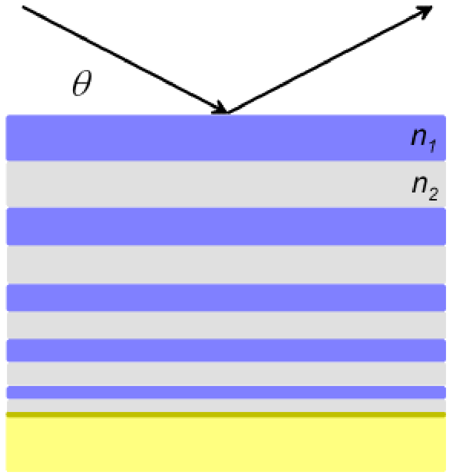
## multilayer

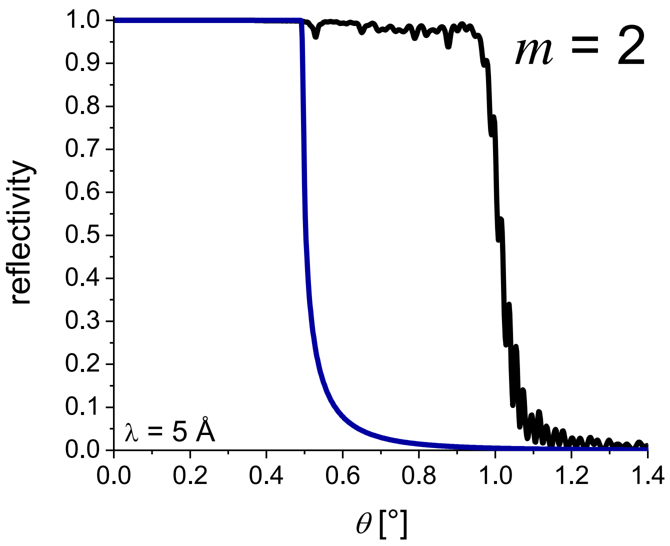


$$\sin\theta = \frac{\lambda}{2d}$$



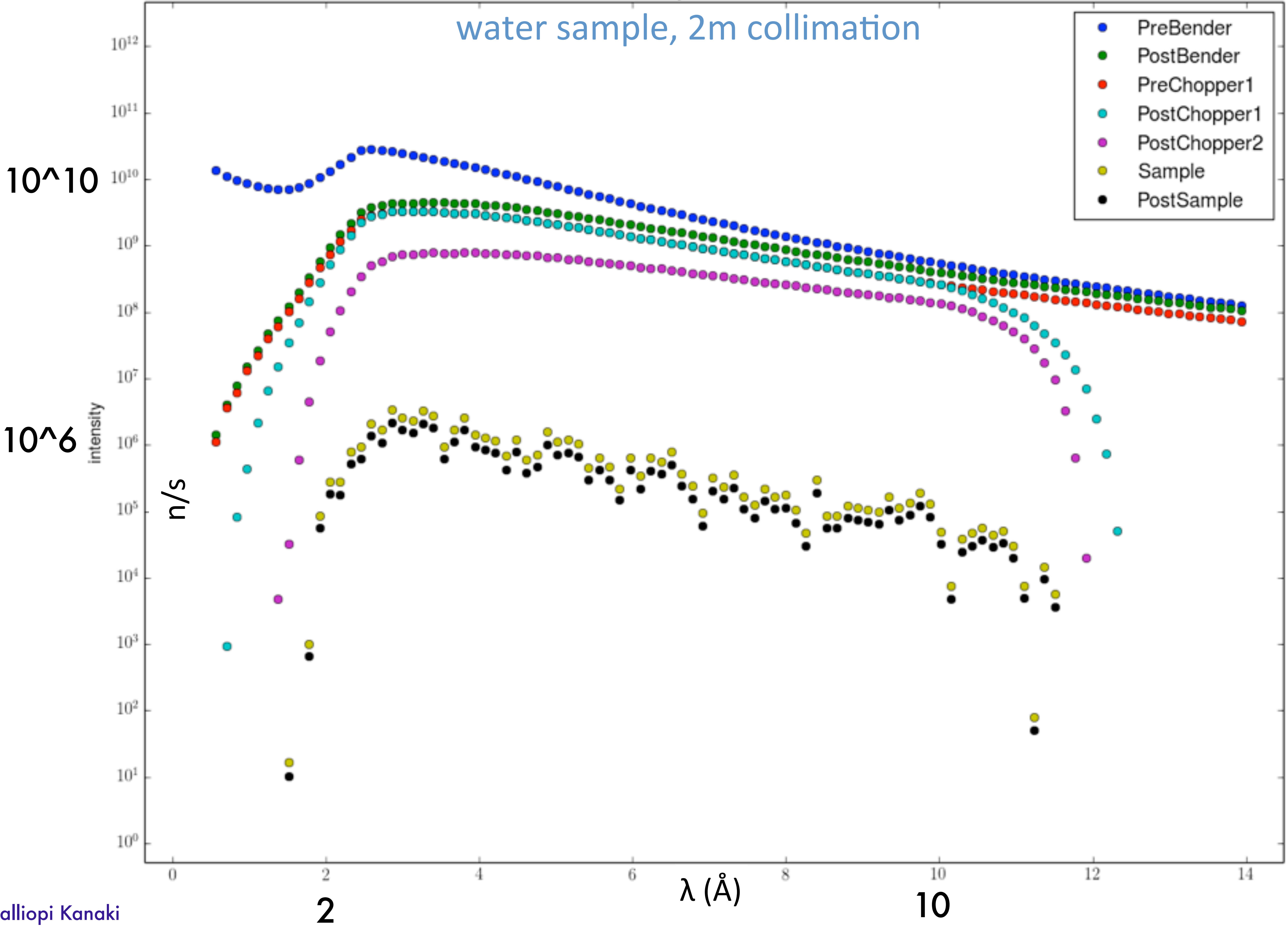
## supermirror





# Selecting phase space ...

## Pre- and post sample λ distribution (McStas)

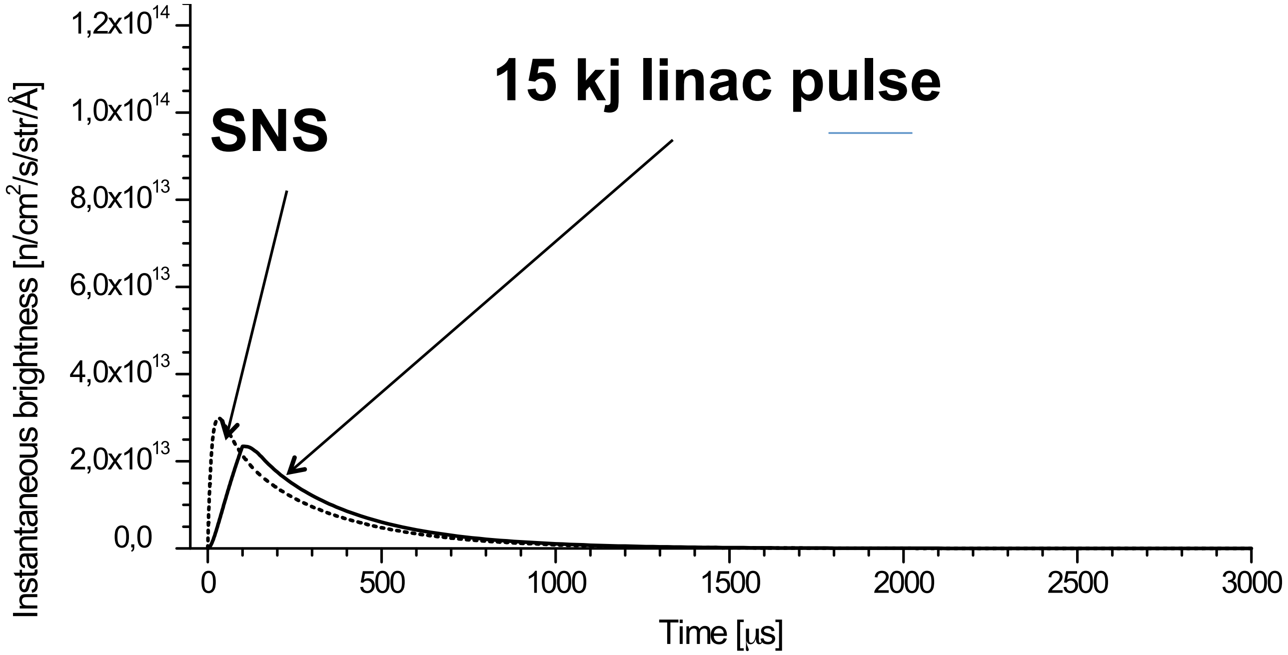


Kalliopi Kanaki

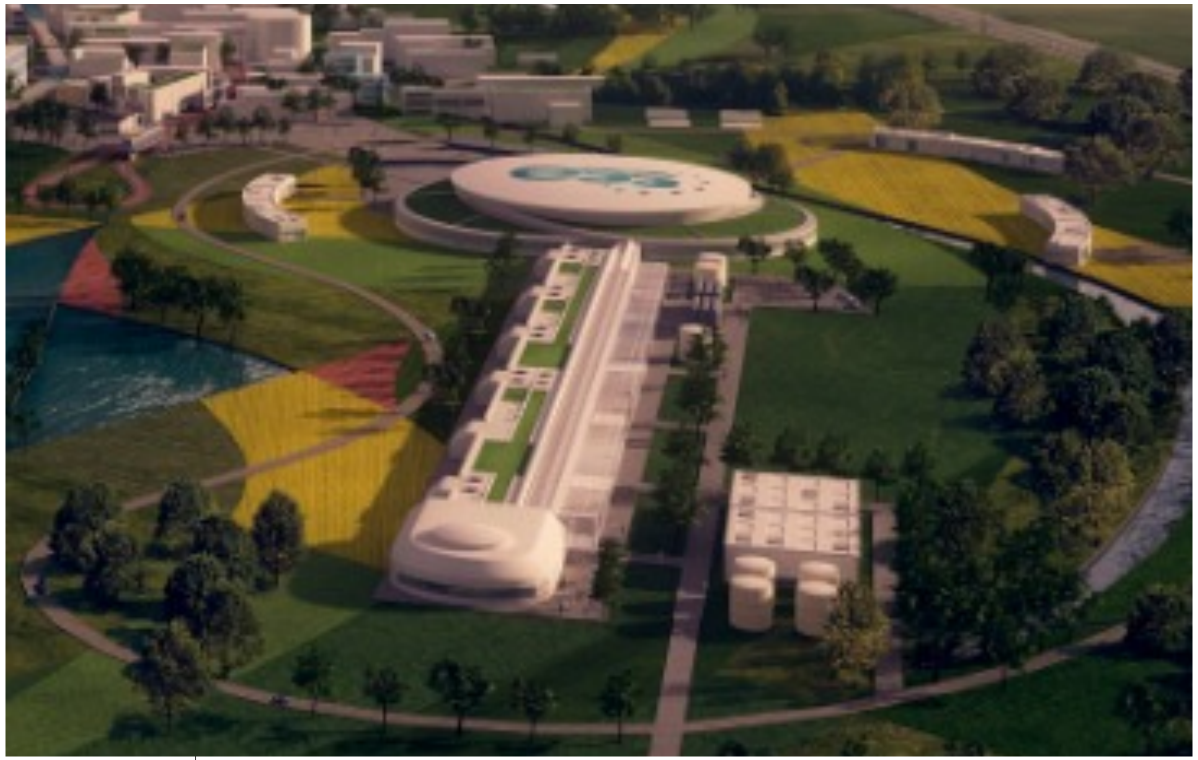
# European Spallation Source

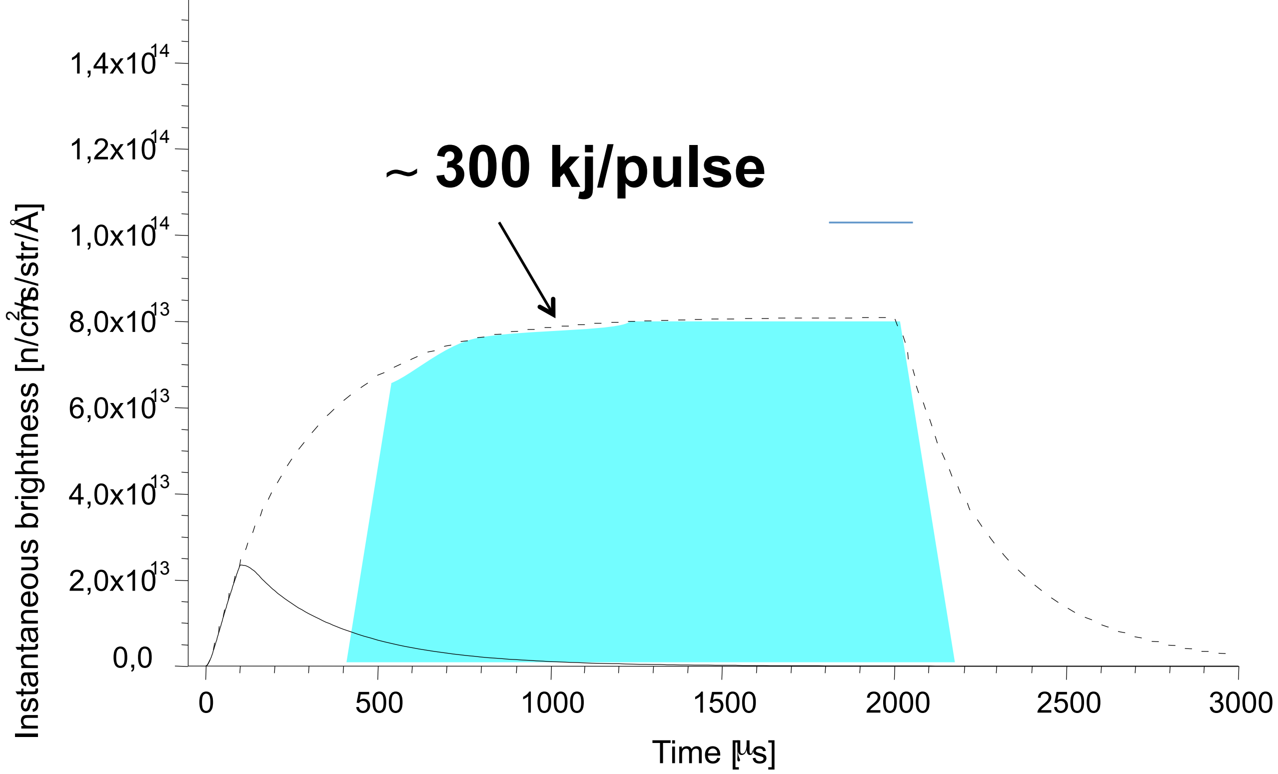
# Current most advanced neutron sources

**But:**
Cost equivalent linear accelerator alone can produce the same **cold neutron pulses by ~100 $\mu$s proton pulses at ~ 0.15 GW instantaneous power: 2 x ILL**



# Next generation: long pulses





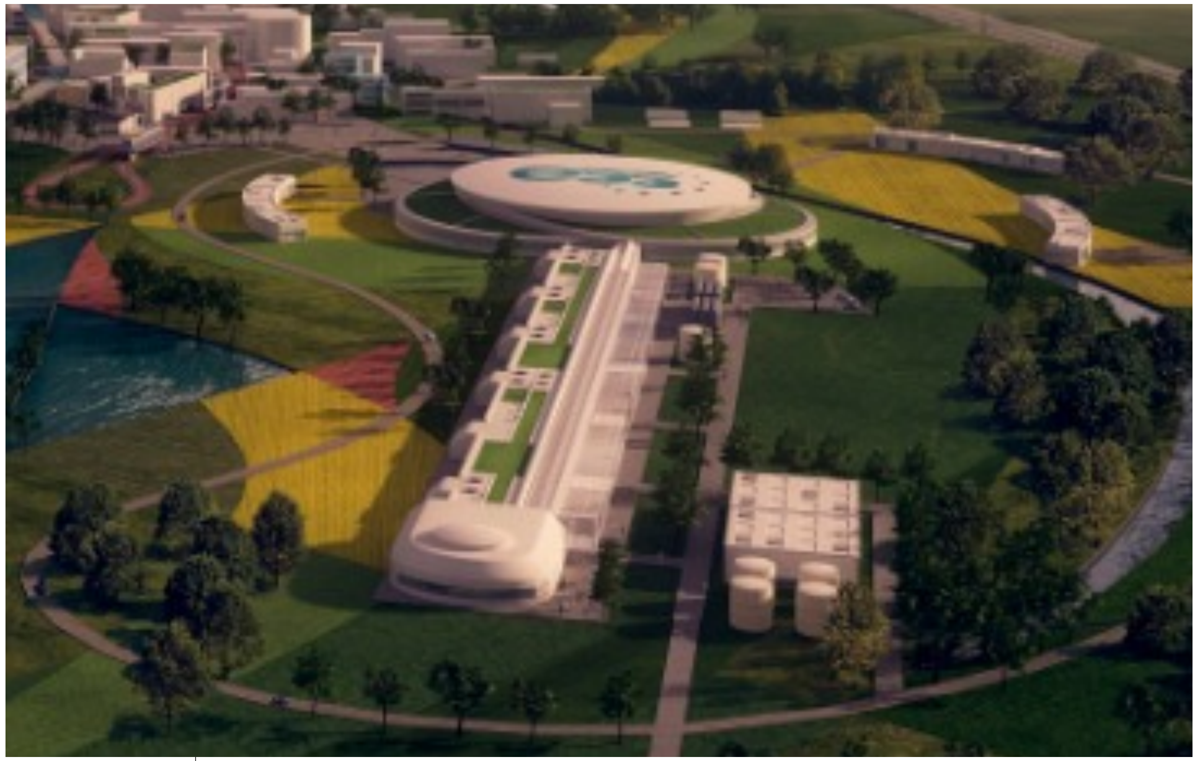
Cost equivalent linear accelerator alone can produce the same cold neutron pulses **by ~100 μs proton pulses at ~ 0.15 GW instantaneous power** → Leave the linac on for **more neutrons per pulse and higher peak brightness…**

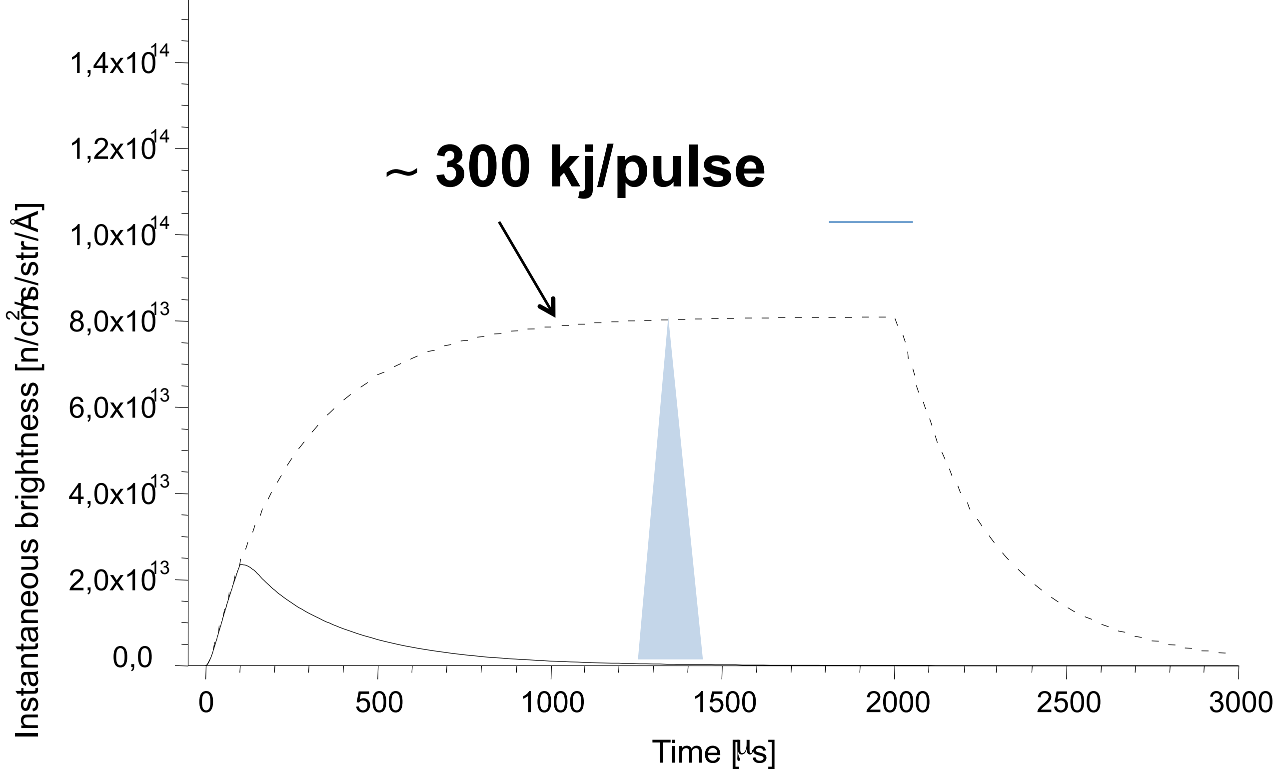
and use mechanical pulse shaping → **Long Pulse source**

**ESS:** 5 MW accelerator power

→ **more neutrons for the same costs and at reduced complexity**

# 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**

# What is the European Spallation Source?

**Europe 2019:** The European Spallation Source (<5 MW)

Lund, Sweden

**Japan 2008:**
JPARC (<1MW)

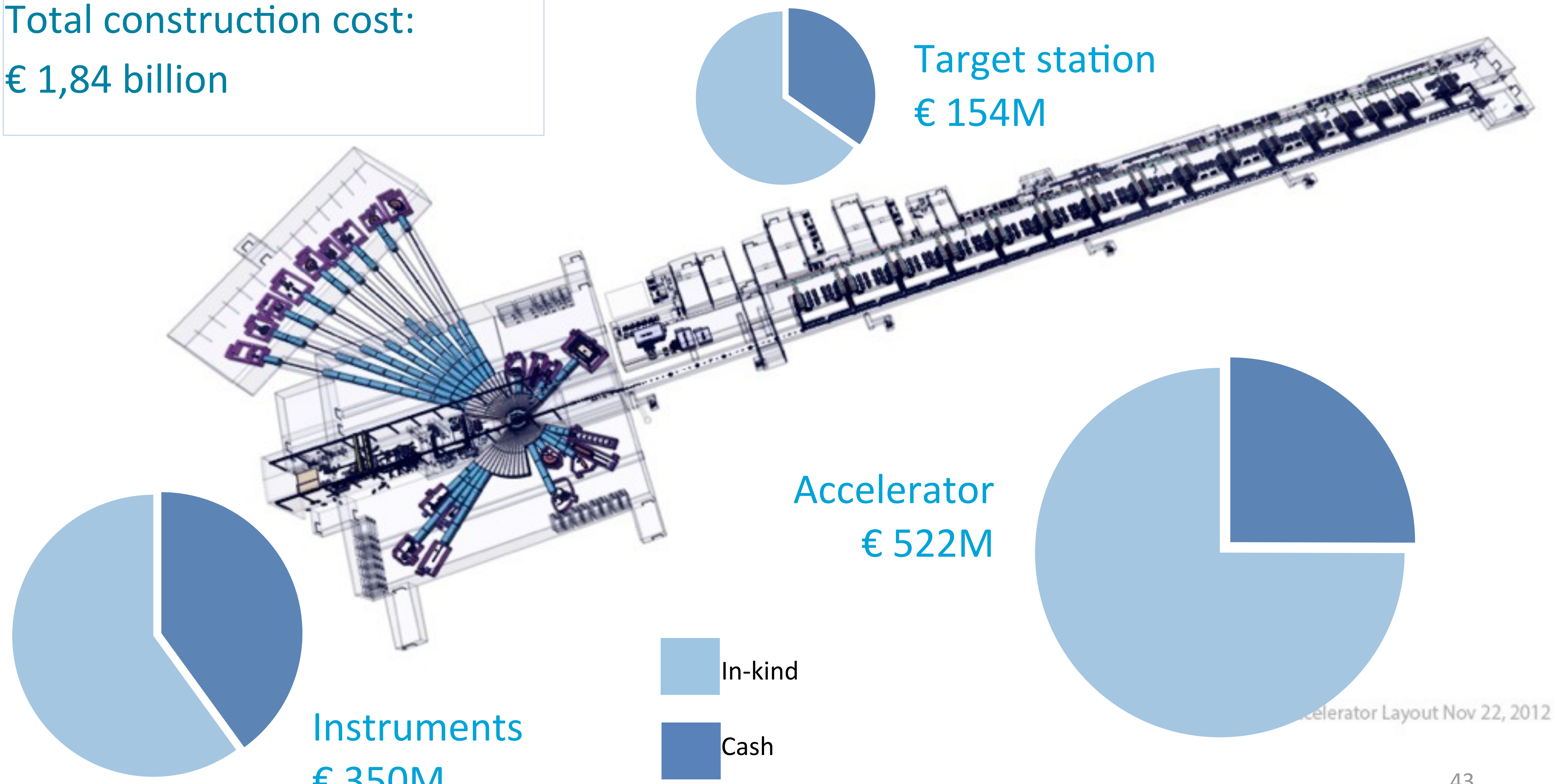
**USA 2006:**
SNS (<1.4 MW)

- One of Europe's largest planned research infrastructures. 1.843 B€.
- For physics, chemistry, life science and more.
- For academia and industry.
- 17 countries plan and build together.
- The world's most powerful linear proton accelerator, and the most powerful source of neutrons for science.
- Ground-break/site preparations June 2014.
- Neutrons & first instruments by the end of the decade.
- ~ 500 employees; ~2500 users/yr.

# Planning & Budget & In-kind potential

Total construction cost:

€ 1,84 billion



Target station

€ 154M

Accelerator

€ 522M

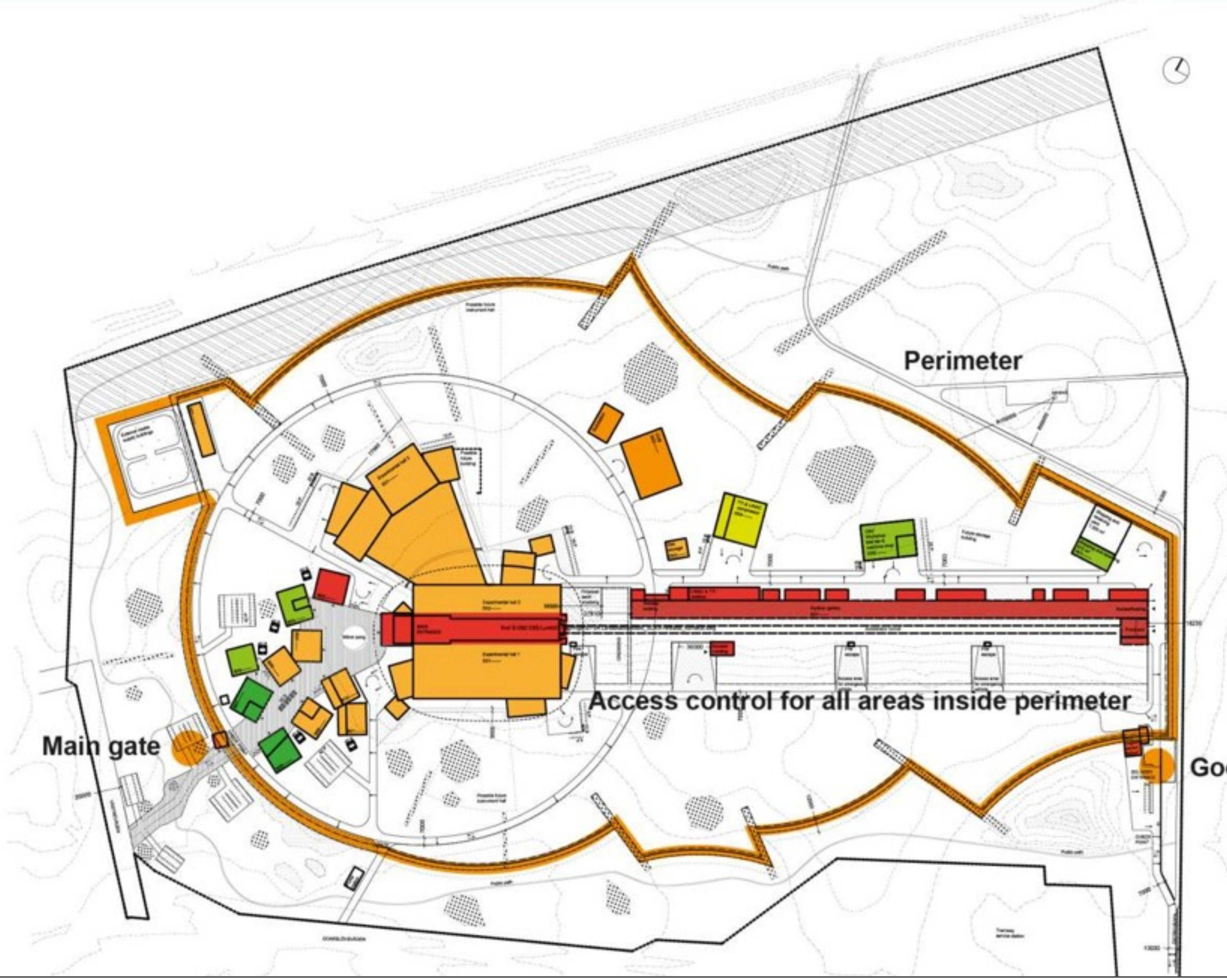
Instruments

€ 350M

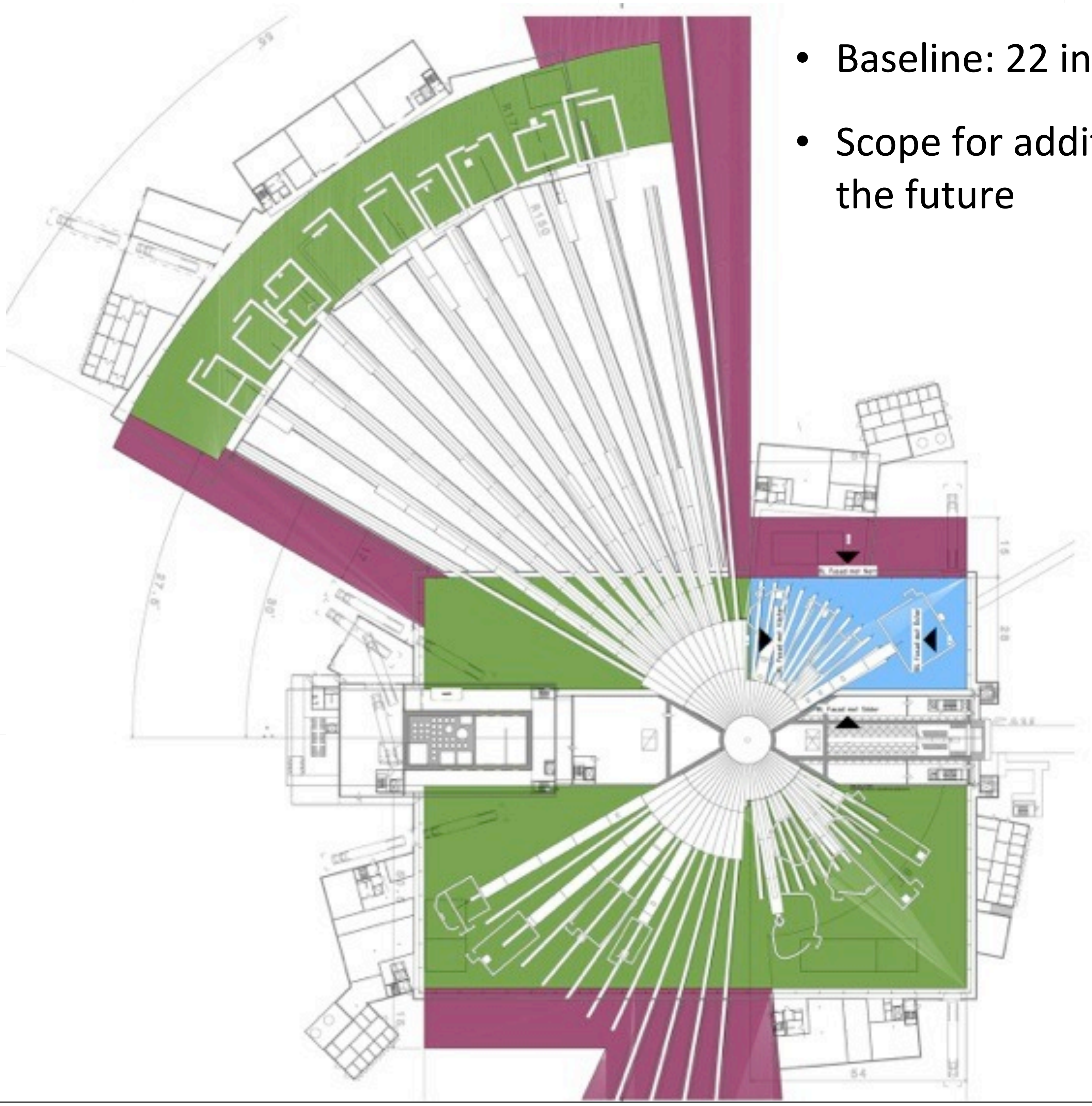
🟦 In-kind

🟦 Cash

# Site Plan

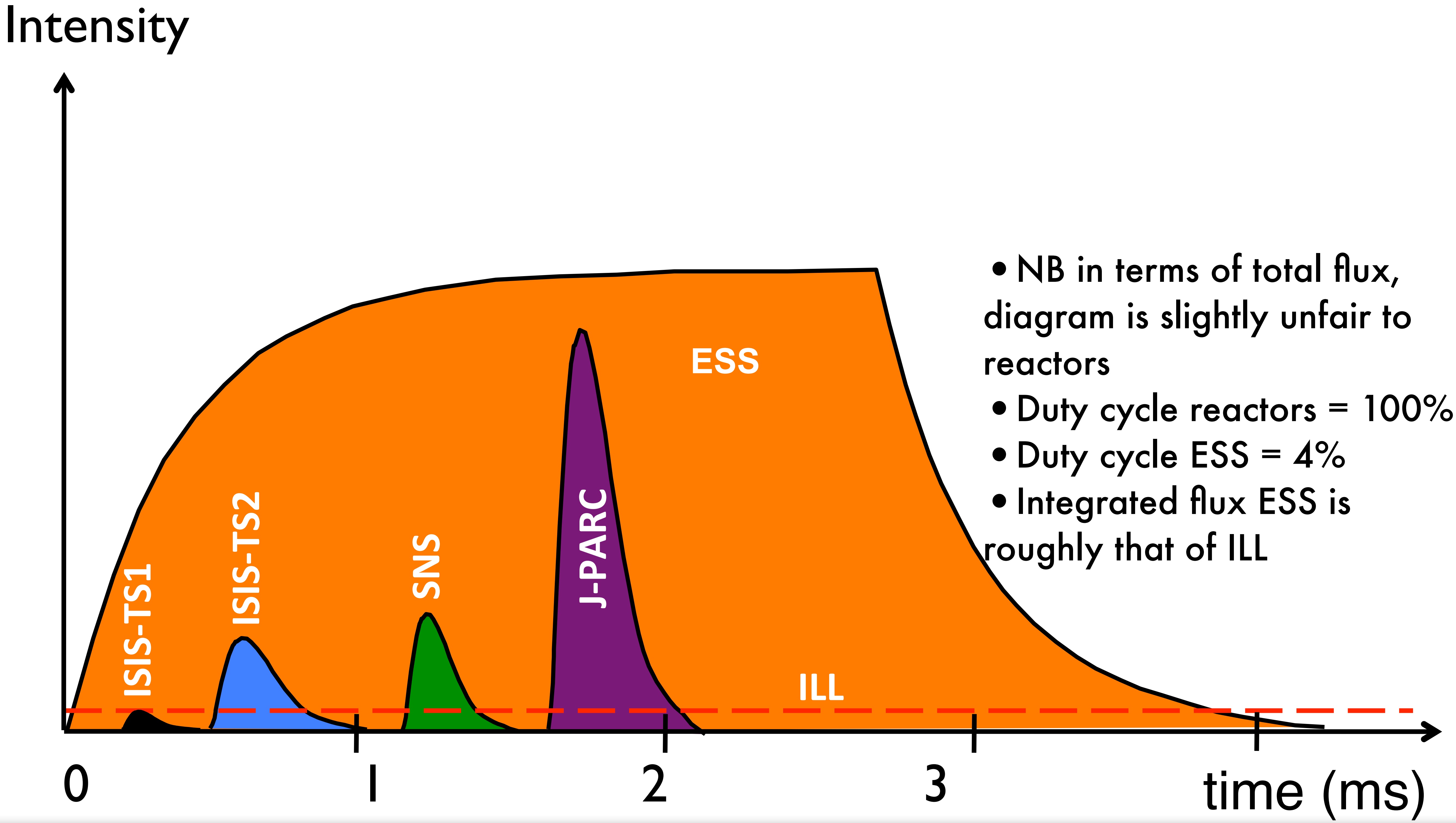

Perimeter
Access control for all areas inside perimeter
Main gate
Goods gate

# Target and Instruments



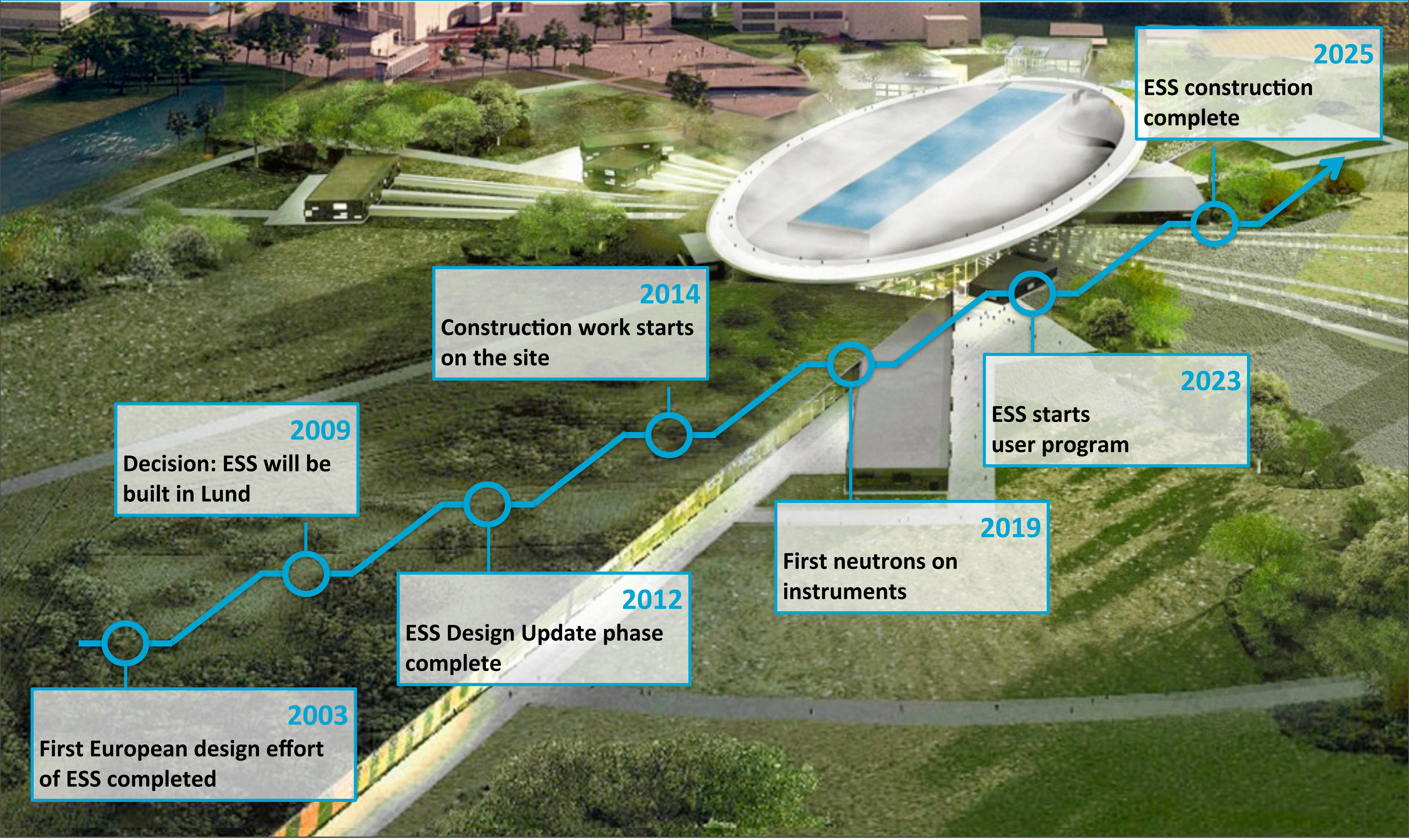
- Baseline: 22 instruments
- Scope for additional instruments in the future

# Relative Neutron Intensity per Pulse



- NB in terms of total flux, diagram is slightly unfair to reactors
- Duty cycle reactors = 100%
- Duty cycle ESS = 4%
- Integrated flux ESS is roughly that of ILL

# The road to realizing the world's leading facility for research using neutrons



**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

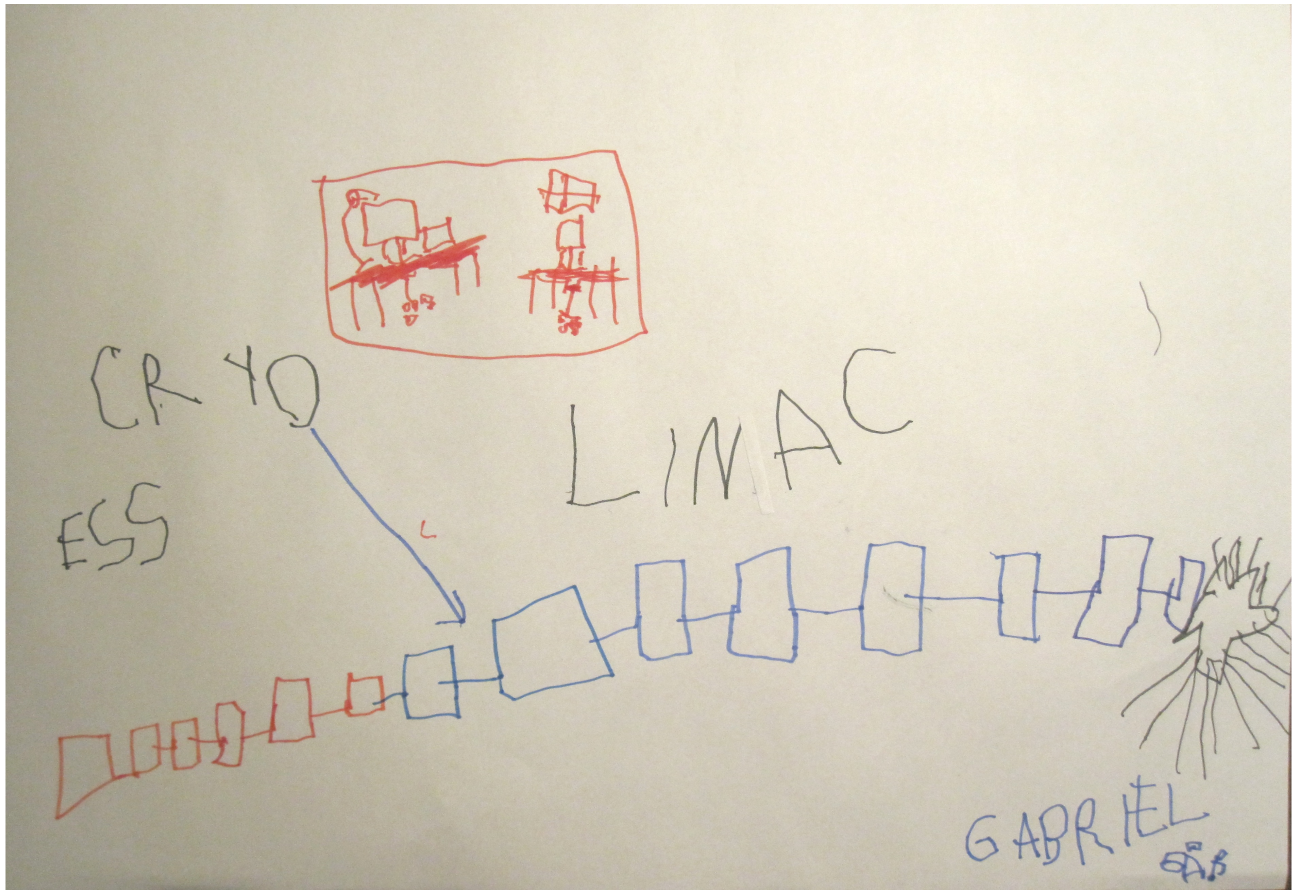
**2025**
ESS construction complete

# ESS Technical Design Report

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

Feb ’12 →

ESS Conceptual Design Report

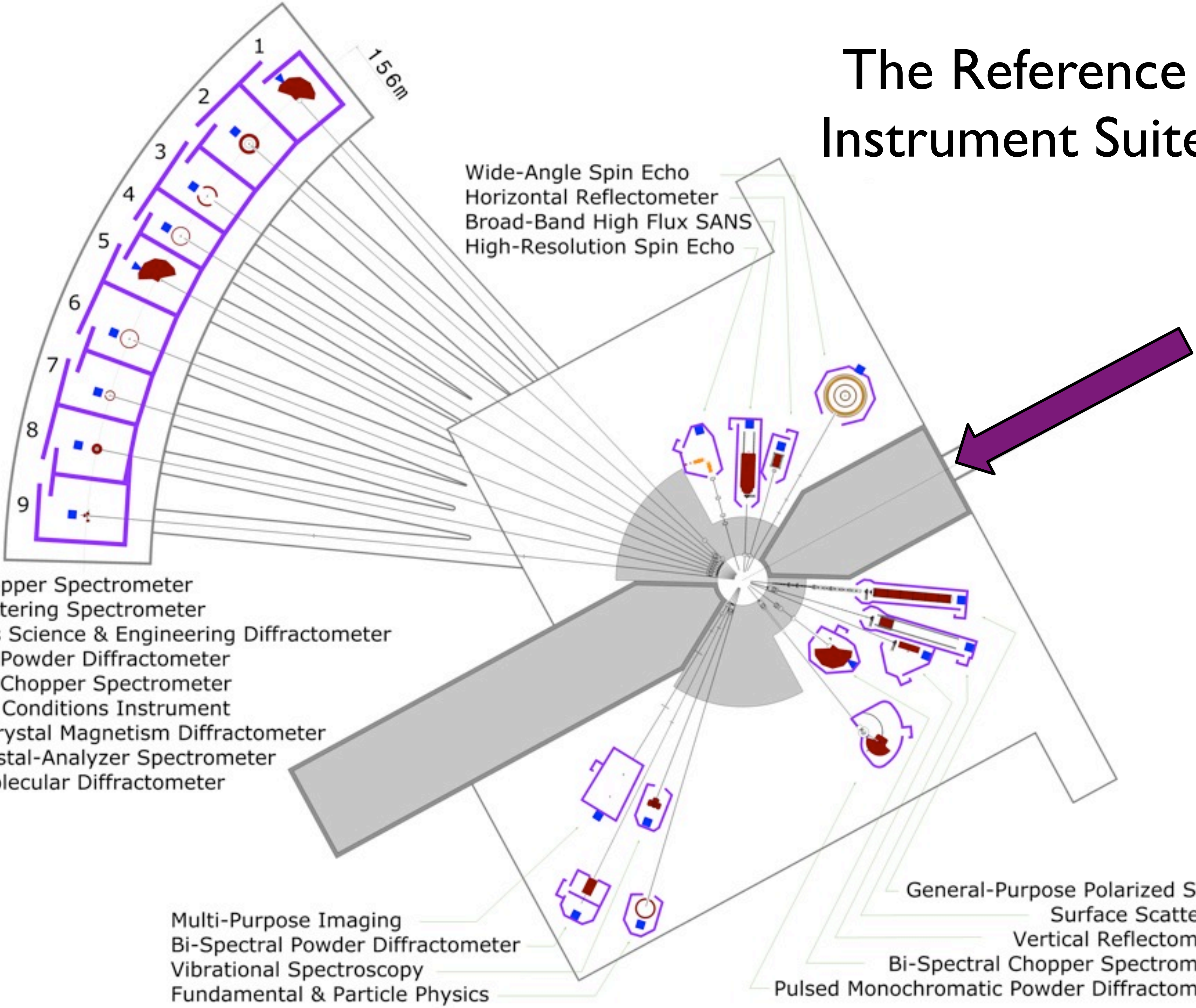


ESS Technical Design Report

Release 2.0

February 5, 2013

# The Reference Instrument Suite



Wide-Angle Spin Echo
Horizontal Reflectometer
Broad-Band High Flux SANS
High-Resolution Spin Echo

1. Cold Chopper Spectrometer
2. Backscattering Spectrometer
3. Materials Science & Engineering Diffractometer
4. Thermal Powder Diffractometer
5. Thermal Chopper Spectrometer
6. Extreme Conditions Instrument
7. Single-Crystal Magnetism Diffractometer
8. Cold Crystal-Analyzer Spectrometer
9. Macromolecular Diffractometer

Multi-Purpose Imaging
Bi-Spectral Powder Diffractometer
Vibrational Spectroscopy
Fundamental & Particle Physics

General-Purpose Polarized SANS
Surface Scattering
Vertical Reflectometer
Bi-Spectral Chopper Spectrometer
Pulsed Monochromatic Powder Diffractometer

# The ESS Site

2011

# The ESS Site

23 October 2012

June 12, 2014

Vision 2020

# Current status

- 3 instrument concepts have entered Construction Phase 1 – preliminary engineering design.
- 16 new instrument concepts have been proposed and reviewed by our independent advisory bodies, the STAPs and the SAC. The SAC will soon be making a recommendation on which ones to build and in what order.
- The construction licensing process is in its end stages.
- National funding negotiations are nearly finished; countries are committed.
- The archaeological survey of the land has been completed, and test piling etc. is on-going.
- Site-preparation has started; contractors on-site
- Official ground breaking end of the summer!

# 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

# Thank you!