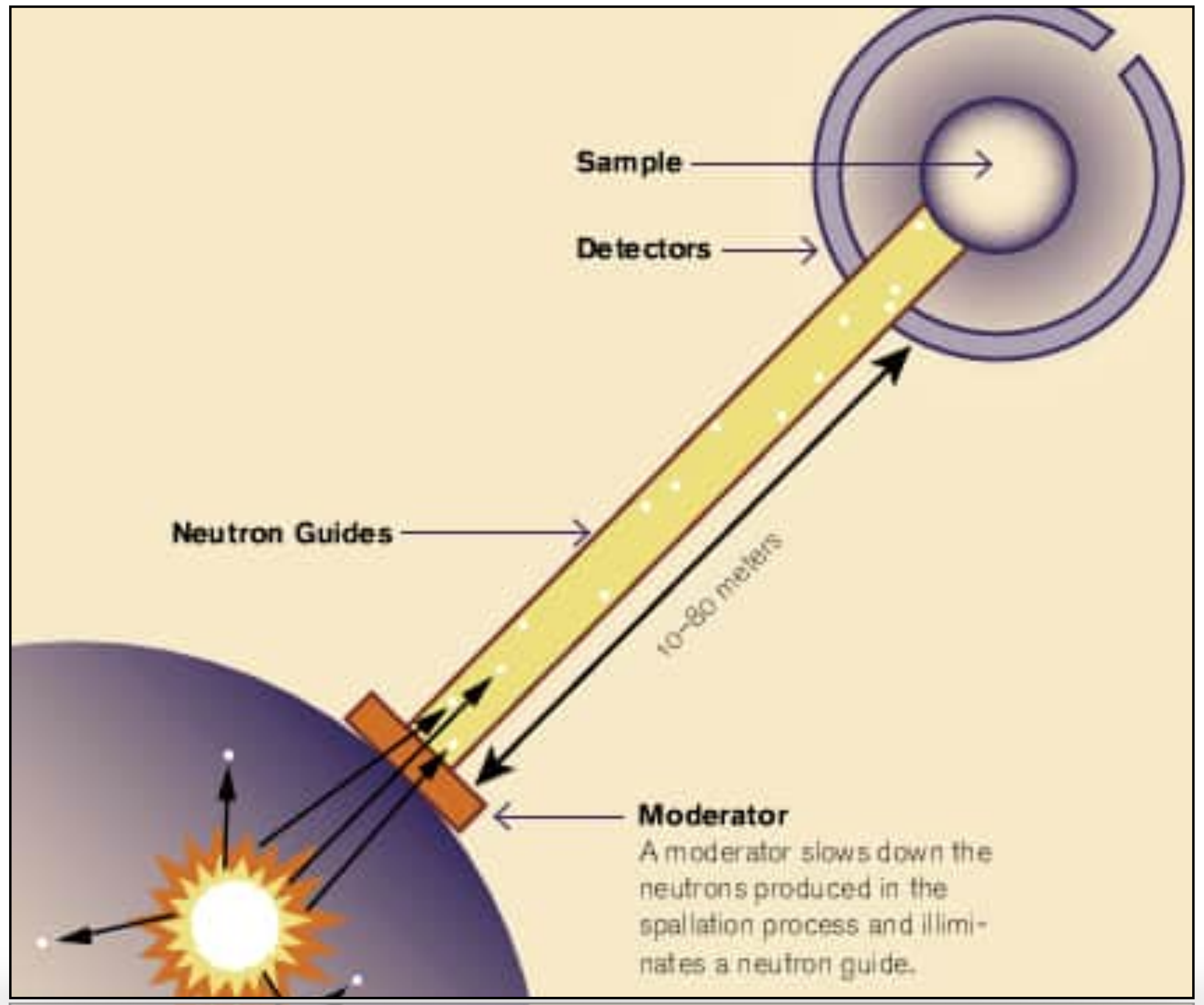
18th Oxford School on Neutron Scattering

Science and Technology Facilities Council

ISIS Neutron and Muon Source




# Neutron Sources

## With Focus on Neutron Scattering Facilities

Dr Lina Quintieri

*11th October 2024 , St Anne's College, Oxford*

# RAL at Harwell Campus- Oxford

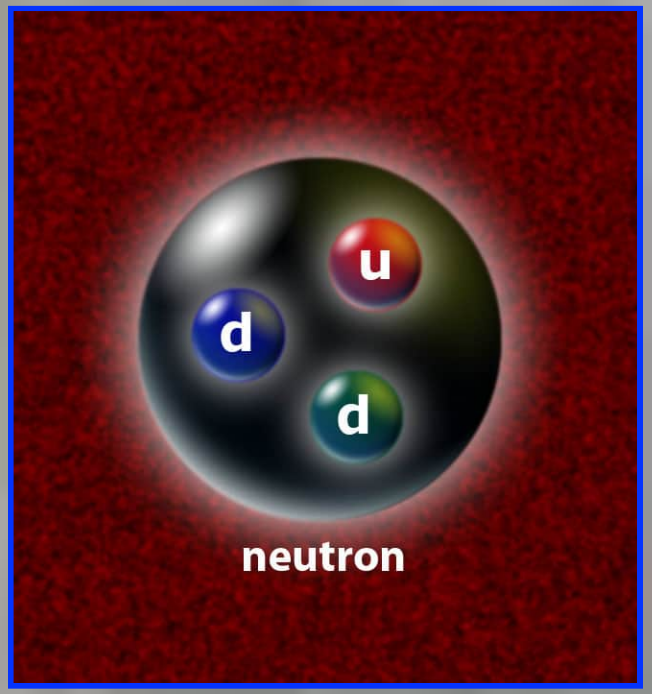

- ISIS
- DIAMOND
- CLFC
- QUANTUM Comp. Center
- Historical remark of Harwell campus: the construction of the first nuclear reactors in Western Europe (PLUTO and DIDO)

# Overview

- Brief introduction to the neutron and its importance in applied and fundamental research
- Neutron production: overview of main mechanisms
- Spallation vs Fission process —> Accelerator driven sources vs research nuclear reactors
- Large Neutron Facilities for neutron scattering around the world: a few examples
- The spallation "core" : Target/Moderator/Reflector assembly
- The research reactor core vs NPP
- Moderators in pulsed neutron sources and in research reactors
- Neutron Spectrometry: a few elements of time of flight technique—> how reactors compare and contrast to Spallation sources
- short description of main instrument components of beam line of a Large scale scattering facility

# ID of a Neutron

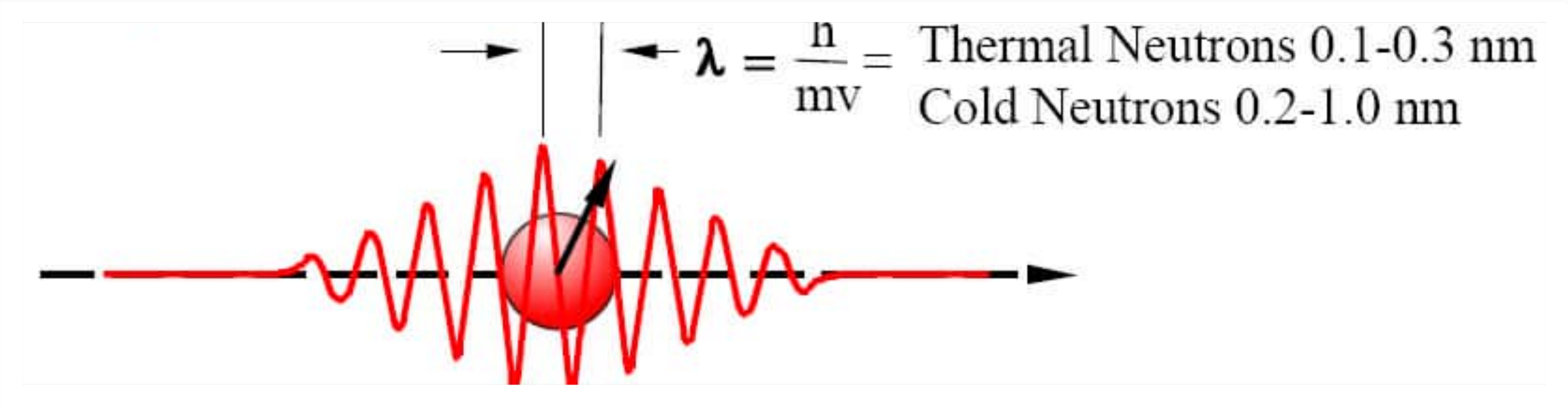
***Neutron mass:*** $1.674927471 \cdot 10^{-27}$ kg
***Proton mass:*** $1.672621898 \cdot 10^{-27}$ kg
***Electron mass:*** $9.10938356 \cdot 10^{-31}$ kg




*This mean that it is energetically possible for the neutron can decay via:*

$$n \rightarrow p + e + \overline{\upsilon}_e$$

**Long life times (almost15 min)** $\Rightarrow$ before decaying possibility to interact$\Rightarrow$ n physics ...




Although neutral, neutron is made of quarks that are electrically charged particles.

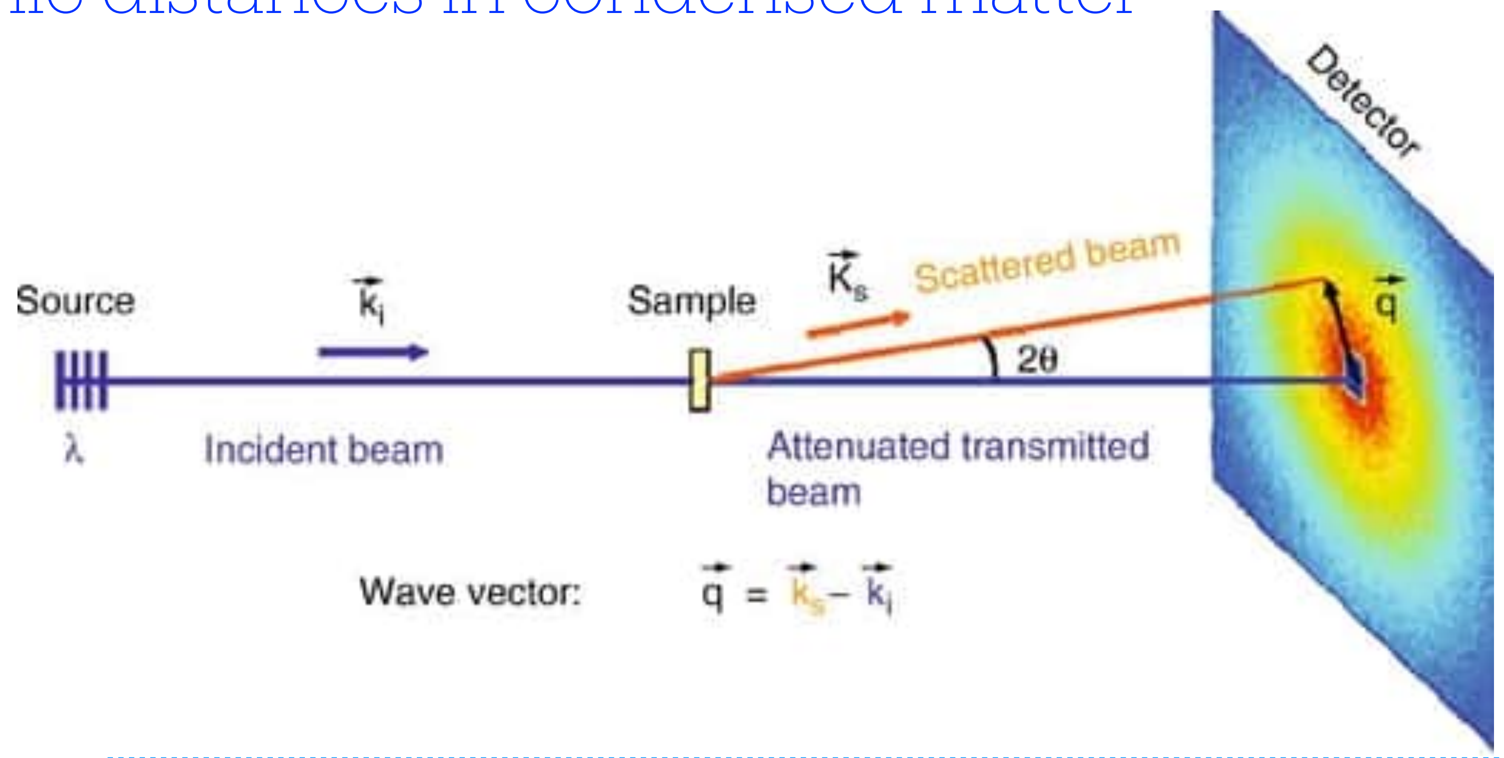
The neutron is composed of three quarks, and the magnetic moments of these elementary particles combine to give the neutron its magnetic moment.


The neutron interacts with matter primarily through the nuclear force and through its magnetic moment.

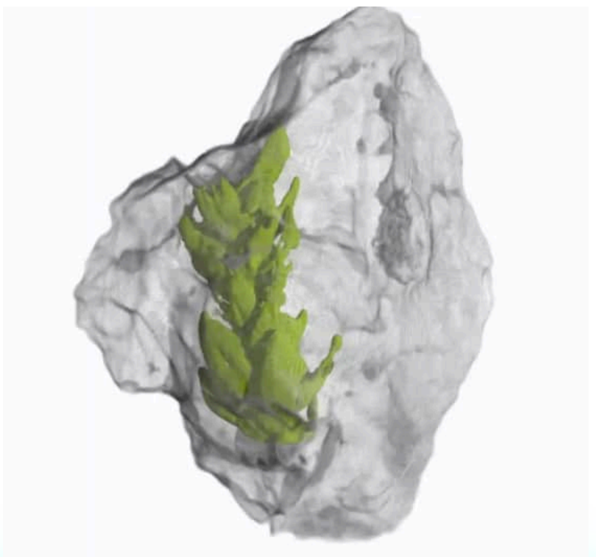
# Why Neutrons Are So Attractive?

The importance of neutrons is rooted in their unique properties; penetrating, uncharged (weakly interacting with matter), they have a magnetic moment and wavelengths that can be similar to inter-atomic distances in condensed matter

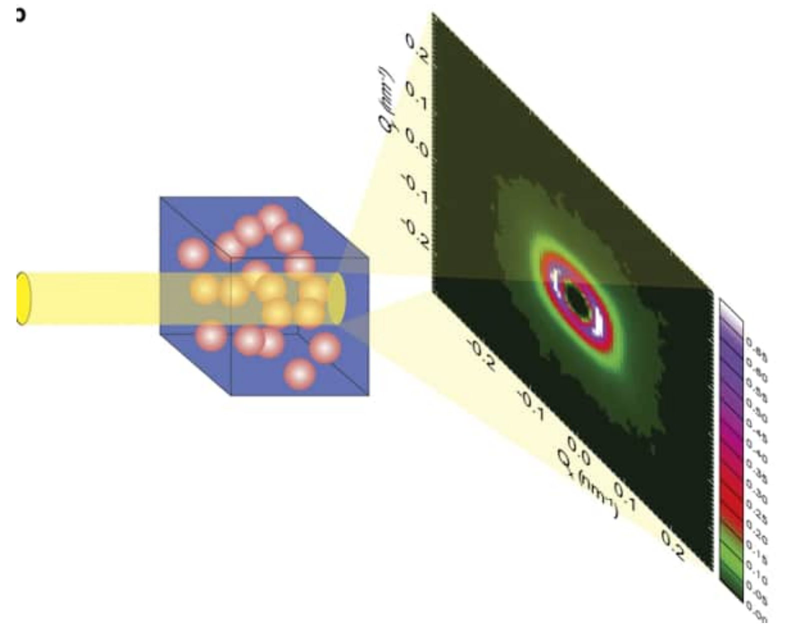
- See the nuclei.
- Interact weakly / penetrate deep into matter
- Have isotopic sensitivity (especially H and D differentiation)
- Thermal neutron have wavelengths similar to inter-atomic distances and energies comparable to lattice vibrations
- Interact via a simple point-like potential amplitudes are straightforward to interpret
- See a completely different contrast to x-rays
- See elementary magnets.



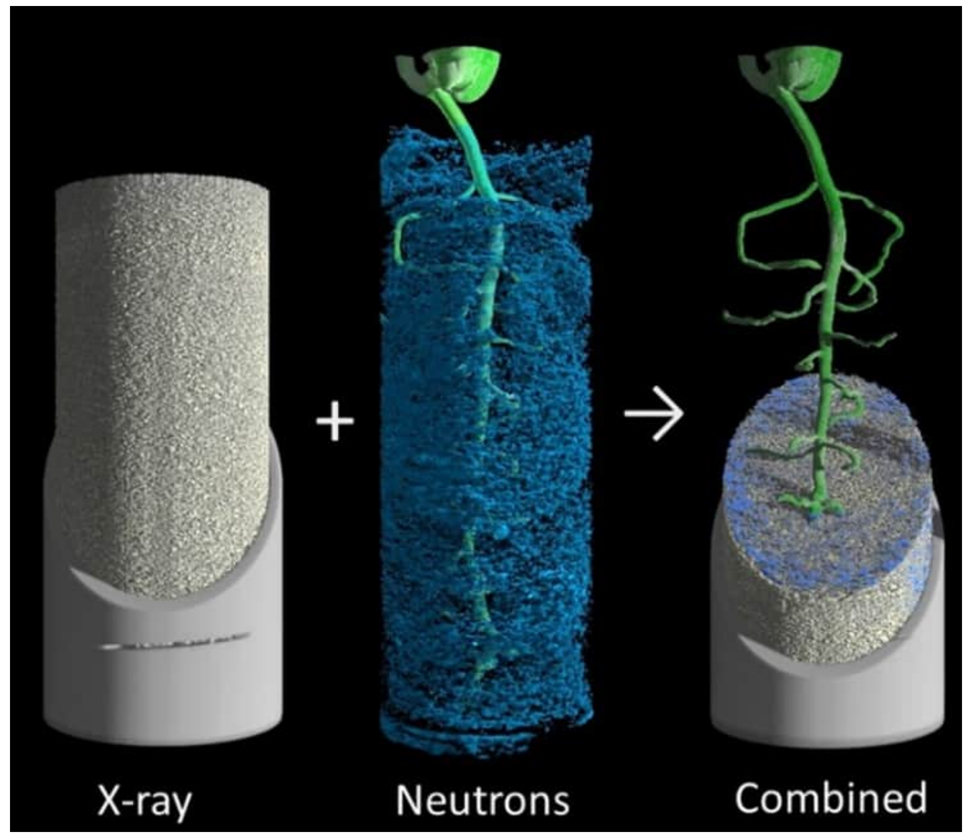

By observing the patterns in space of the scattered neutrons, it is possible to establish where the atoms are positioned with exceptional precision. They can provide structural information from Angstrom to microns



Neutrons are highly penetrating and can be used as non-destructive probes, also to study samples in extreme environments (ex. high pressure/ high magnetic field).



Neutron is also sensitive to the magnetic properties of the sample, and can therefore resolve complex magnetic structures.

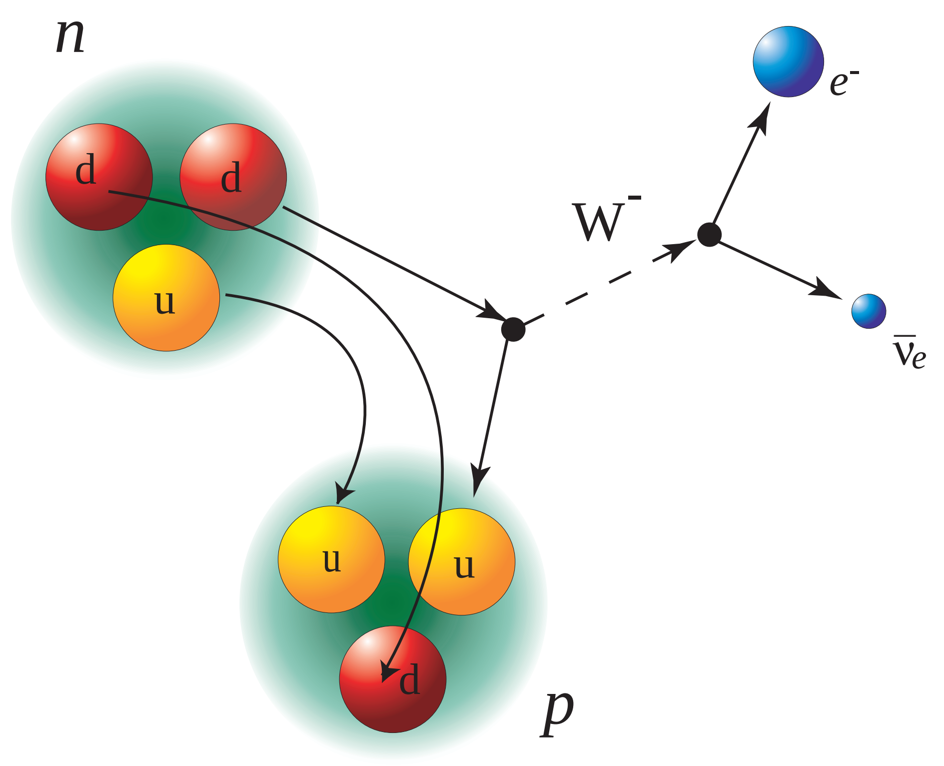



Neutrons can see light nuclei next to heavy ones

# Neutrons and Fundamental Physics Research

## Cold (meV) and ultra cold neutrons (neV) in nuclear experiments: the "enigma" of neutron half-life

### Neutron Decay

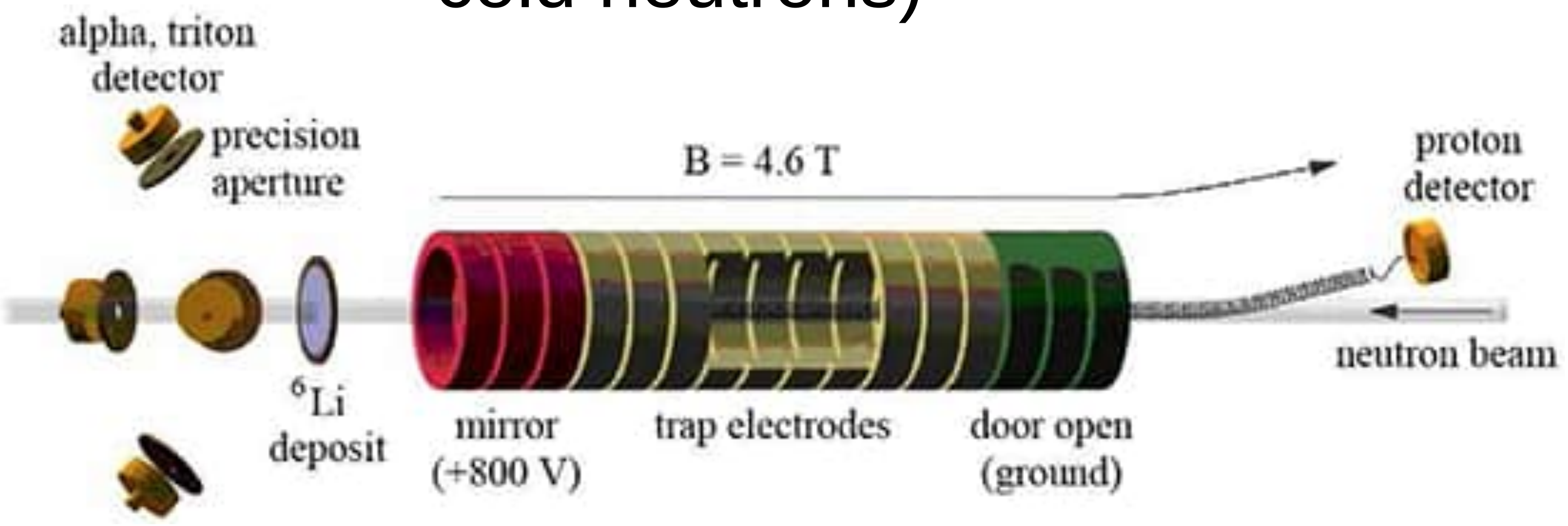



$$n \rightarrow p^+ + e^- + \bar{\nu}_e + 782 \text{ keV}$$

The importance of the neutron lifetime knowledge: The accurate assessment of the lifetime of neutrons is the key to understanding the formation of elements after the Big Bang 13.8 billion years ago.

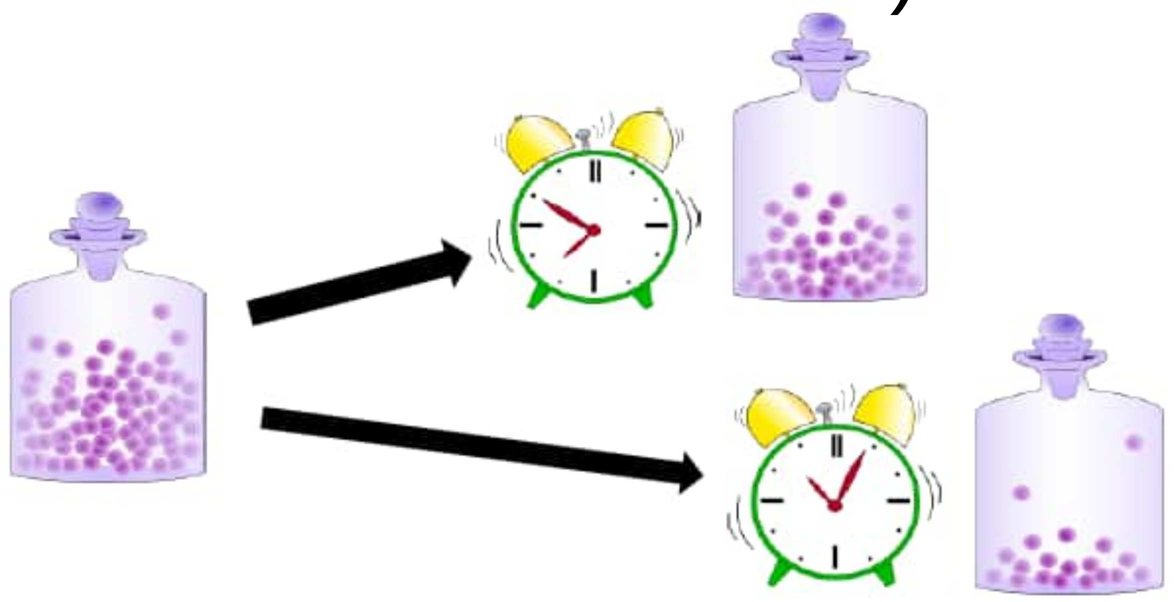
It could influence the standard model of physics that governs our understanding of the formation of the universe.Neutron lifetime is the easiest and most direct way of measuring the weak force, one of four fundamental forces in nature.

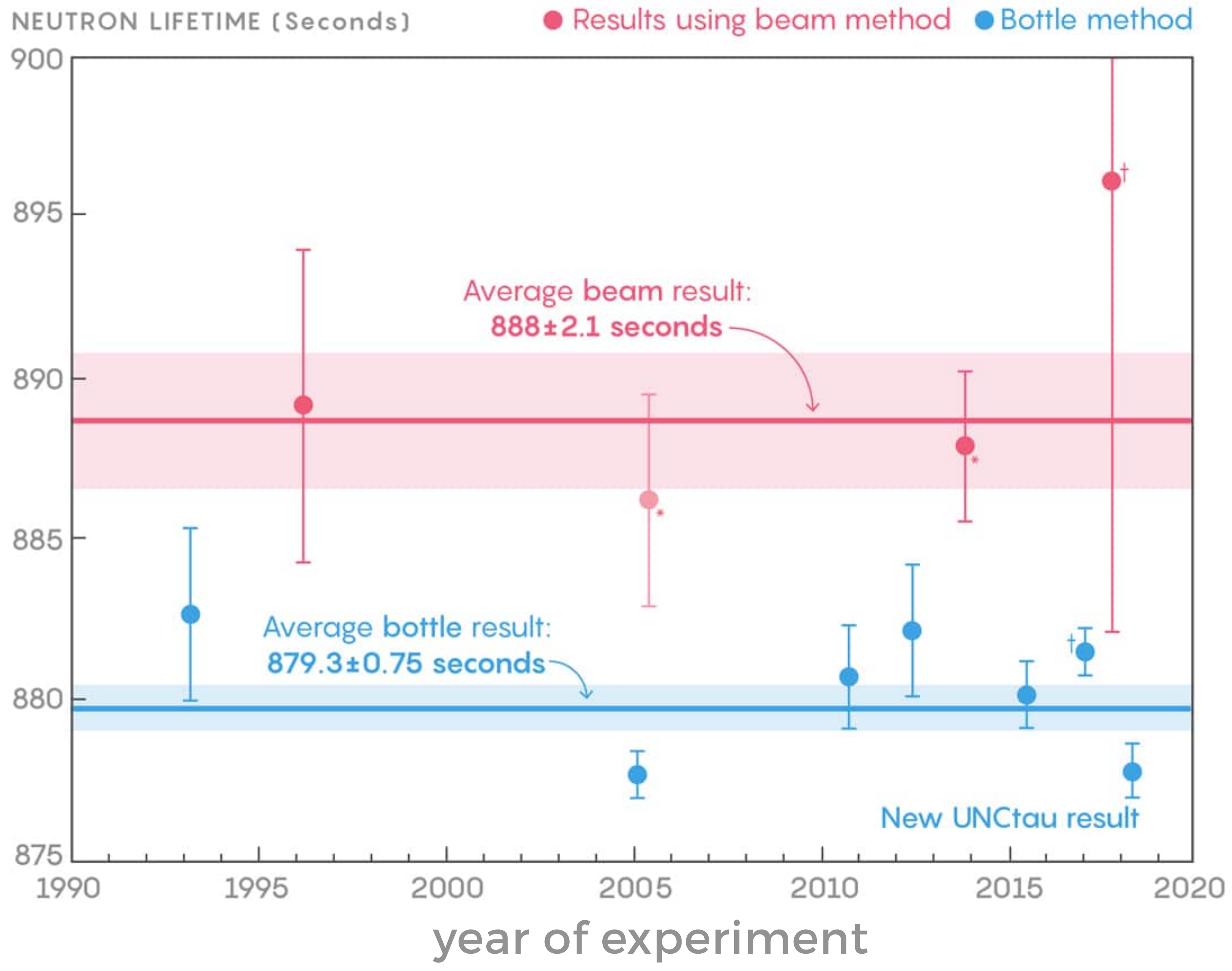
**Beam** experiment
(2 absolute measurement
cold neutrons)




https://www.nist.gov/programs-projects/neutron-lifetime-measurement-using-cold-neutron-beam

« **Bottle** » experiment
(2 relative measurement
ultra cold neutrons)





# Timeline of 92 Years of Neutrons

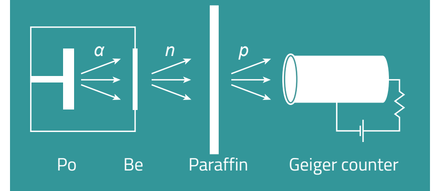
## The discovery of neutron has marked the beginning of modern nuclear physics

## TIMELINE OF KEY EVENTS FOR NEUTRON SCIENCE

**neutron discovery**

### 1932

James Chadwick demonstrates the existence of the neutron and is awarded the 1935 Nobel Prize in Physics for the discovery.




**work on scattering cross sections of thermal neutrons**

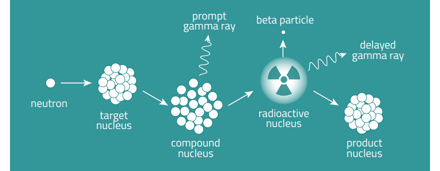
### 1938

Enrico Fermi is awarded the Nobel Prize in Physics for work on the atomic absorption and scattering cross-sections of slow and thermal neutrons, and for the discovery of transuranium elements.

**development of activation method based on neutron bombardment**

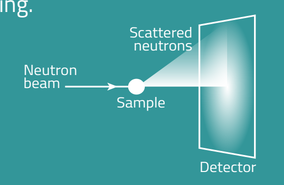
### 1943

George de Hevesy, who developed a method of activation analysis based on neutron bombardment, is awarded the Nobel Prize in Chemistry for work on radiotracers.




### 1974

Paul J Flory is awarded the Nobel Prize in Chemistry for fundamental achievements in the physical chemistry of macromolecules. His prediction that polymer chains adopt self-avoiding random walks was confirmed by small angle neutron scattering.



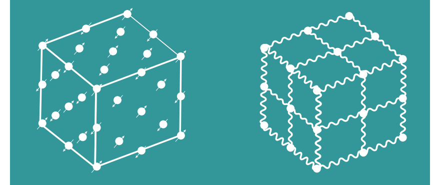

### 1991

Pierre-Gilles de Gennes is awarded the Nobel Prize in Physics for his work on liquid crystals and polymers. His models of polymer dynamics were validated using the neutron spin echo technique.

**Pioneering of neutron scattering techniques: where atoms are and what they do**

### 1994

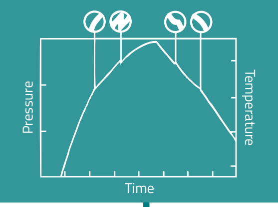
Clifford Shull and Bertram Brockhouse are awarded the Nobel Prize in Physics for pioneering contributions to the development of neutron scattering techniques that show where atoms 'are' and what they 'do'.



**Discovery of He3 superfluidity, with important information on liquid and phase transition provided by neutrons**

### 1996

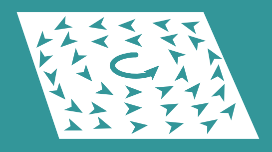
David Lee, Douglas Osheroff and Robert Richardson are awarded the Nobel Prize in Physics for discovering superfluidity in $^3$He. Neutron scattering experiments provided important information on the liquid and solid phases of $^3$He and $^4$He.




**Topological phase transitions validated by neutron scattering**

### 2016

David Thouless, Duncan Haldane and Michael Kosterlitz are awarded the Nobel Prize in Physics for theoretical discoveries of topological phase transitions and topological phases of matter, which were validated by neutron scattering experiments.



### 2018

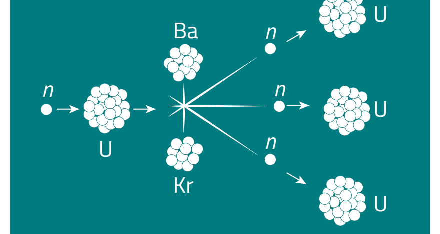
The League of advanced European Neutron Sources is established.

LENS

1930 1940 1950 1960 1970 1980 1990 2000 2010 2020

### 1942

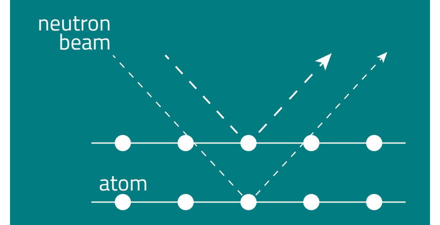
Chicago Pile-1 (USA), the world's first nuclear reactor, goes critical, initiating the first controlled and self-sustaining nuclear chain reaction, providing an intense source of neutrons suitable for scientific experiments.




**First controlled chain reaction in Chicago**

### 1946

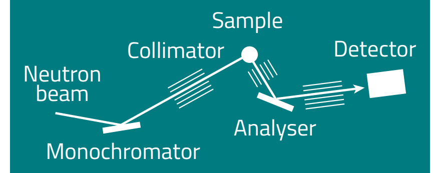
First neutron diffraction using a reactor neutron source developed at Oak Ridge National Laboratory (USA).




**First neutron diffraction using neutron source at OAK RiDGE**

### 1955

The triple axis spectrometer is developed at Chalk River (Canada), enabling the study of the motions of atoms in crystals.




### 1967

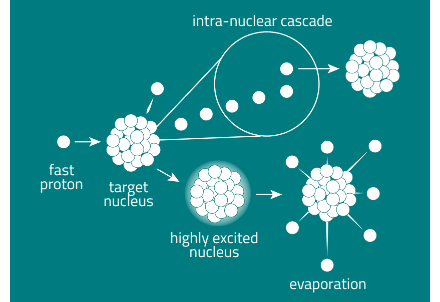
The ILL is launched as the international flagship centre for neutron science. The first neutrons are produced in 1971.

NEUTRONS FOR SOCIETY

**ILL flagship for neutron science has started**

### 1972

Jack Carpenter demonstrates pulsed spallation neutron source concepts at Argonne National Laboratory (USA).




**Pulsed SNS feasibility demonstrated in ARGONNE National Laboratories**

### 1984

ISIS Neutron and Muon Source begins operation as the first spallation neutron source in Europe.

ISIS

**First spallation neutron source for scattering experiments**

### 1994

The European Neutron Scattering Association (ENSA) is formed.

ENSA

### 1996

Inauguration of the Swiss Spallation Neutron Source (SINQ) at the Paul Scherrer Institut.

PAUL SCHERRER INSTITUT
PSI

**Accelerator driven continuous source**

### 2004

Forschungs-Neutronenquelle Heinz Maier-Leibnitz (FRM II) goes into operation.

FRM II
Forschungs-Neutronenquelle
Heinz Maier-Leibnitz

### 2014

Construction begins on the European Spallation Source.

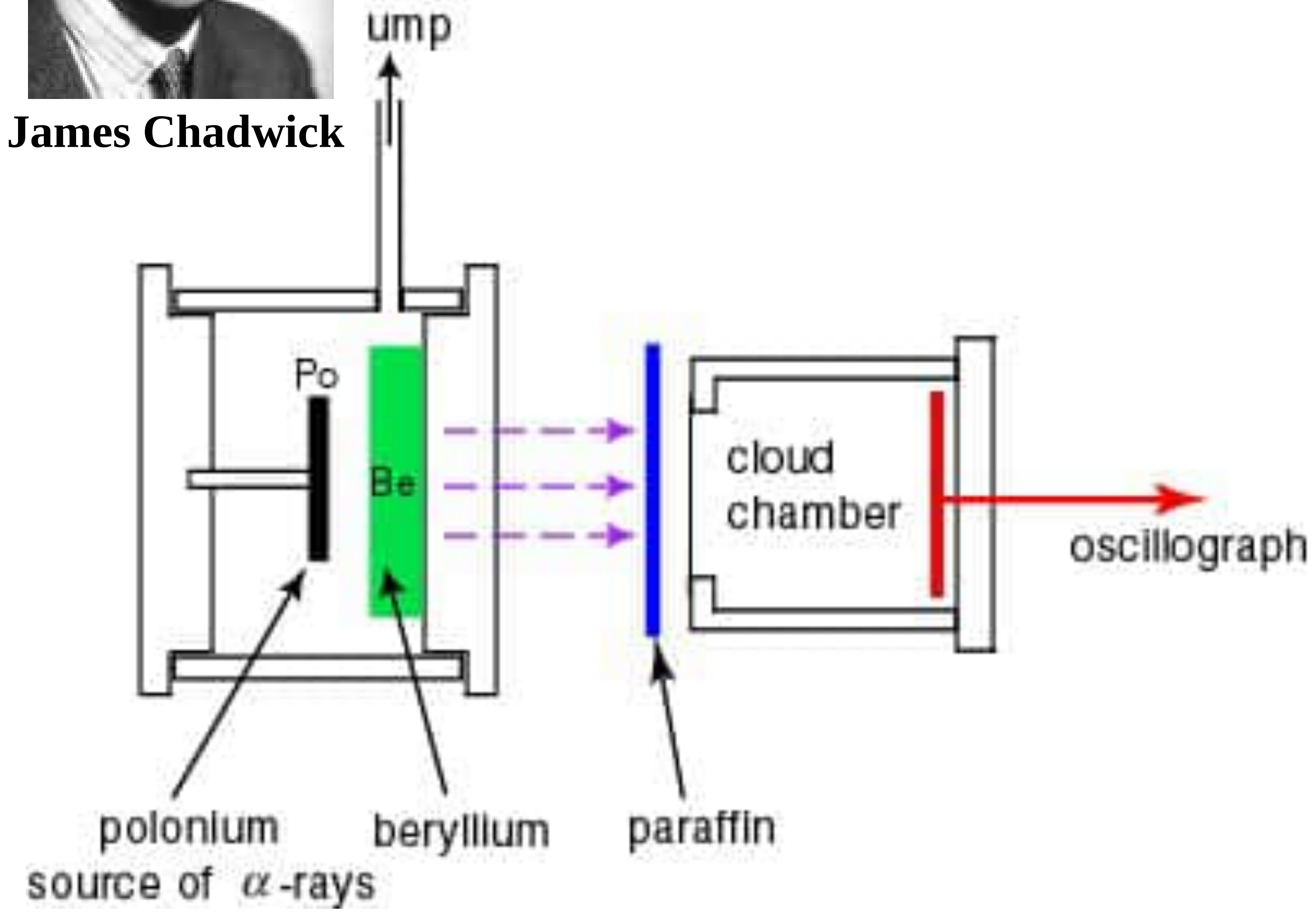
ess

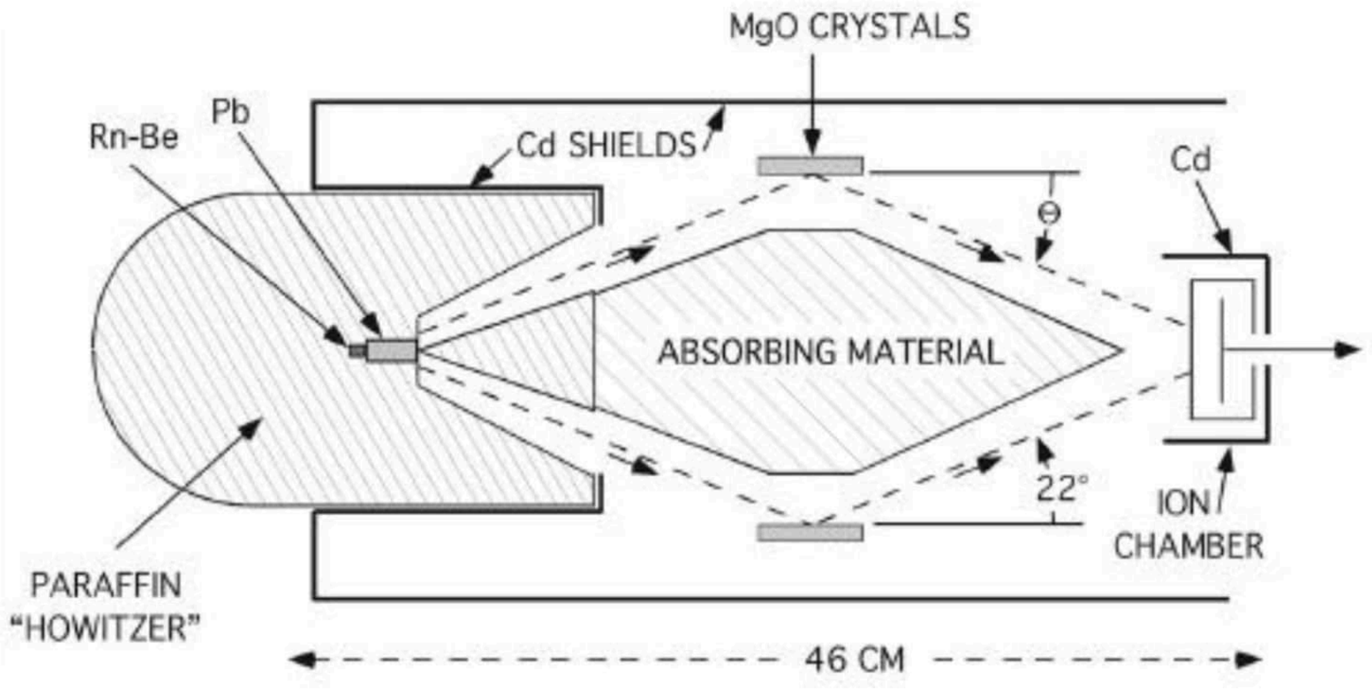
# Important Milestones: a Little Bit of History

- 1932: Chadwick discovers the neutron
- 1936: Mitchell and Powers see neutron diffraction (demonstrations of coherent neutron diffraction (Bragg scattering by crystal lattice planes)
- 1947: Zinn measures the first neutron Bragg peak rocking curve

Discovery of the neutron
1932

James Chadwick




Apparatus of Mitchell and Powers (1936)

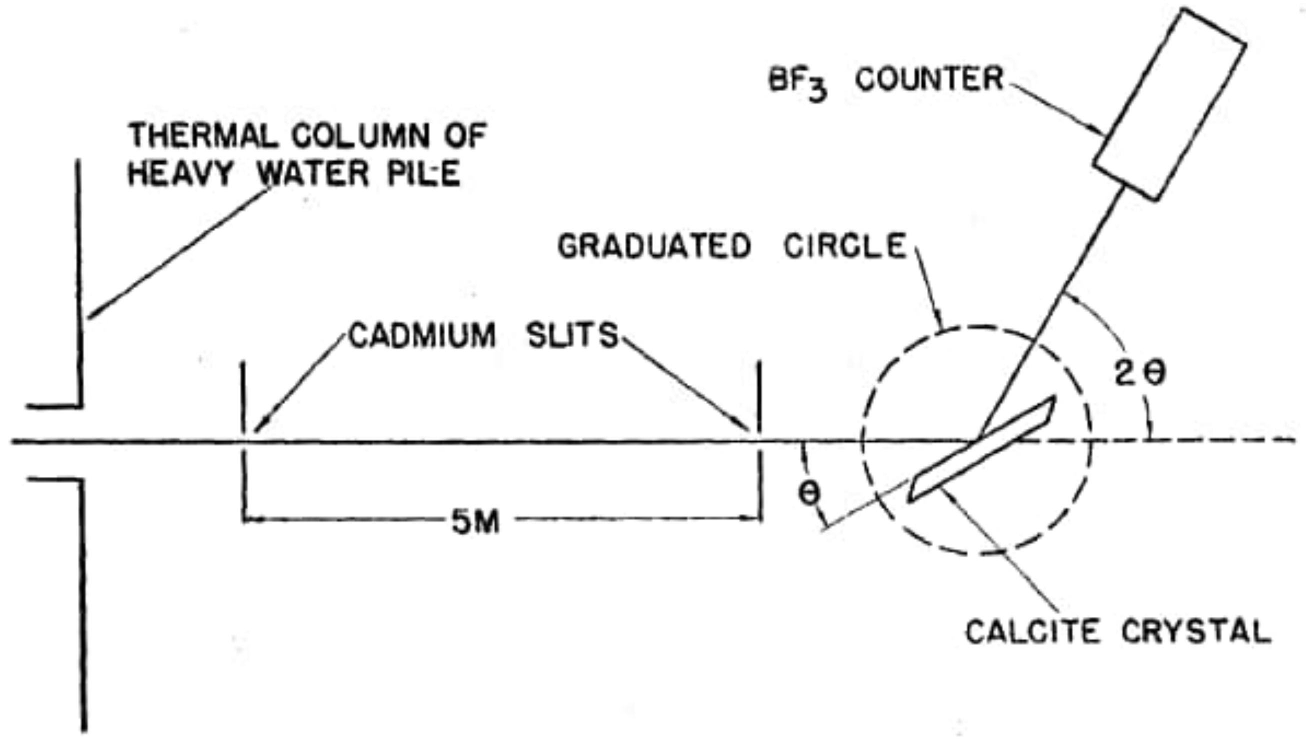
TABLE I. OBSERVED NUMBERS

| Run | Bragg Counts $\times 10^{-3}$ | Bragg Rate $N_B$/min. | Crossed Counts $\times 10^{-3}$ | Crossed Rate $N_X$/min. | Background Counts $\times 10^{-3}$ | Background Rate $N_{Cd}$/min. |
|---|---|---|---|---|---|---|
| 1st | 23 | $60{\cdot}5\pm{\cdot}4$ <br> $N_B-N_X=4{\cdot}9\pm{\cdot}6$ | [illegible] | [illegible] | $3{\cdot}8$ | $43{\cdot}3\pm{\cdot}7$ |
| 2nd | 11 | $28{\cdot}8\pm{\cdot}3$ <br> $N_B-N_X=2{\cdot}3\pm{\cdot}4$ | [illegible] | [illegible] | 3 | $20{\cdot}9\pm{\cdot}4$ |
| 3rd | 12 | $37{\cdot}6\pm{\cdot}3$ <br> $N_B-N_X=\ {\cdot}1\pm{\cdot}4$ | 12 | $37{\cdot}7\pm{\cdot}3$ | 6 | $28{\cdot}0\pm{\cdot}4$ |

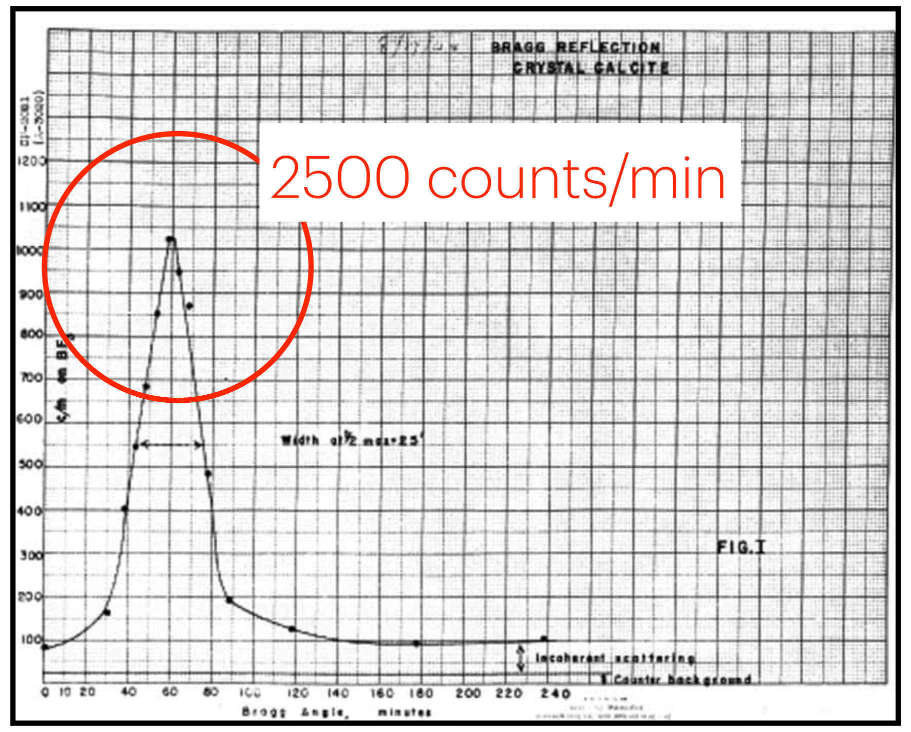
5 counts/min

Low Intensity

High Intensity




First experimental setup at CP-3
[W. H. Zinn, *Phys. Rev.* **71,** 752–757 (1946)]




Laboratory source PoBe, RaBe

CP-3 reactor

# Intensity Matters

## Scattering experiments need of intense neutron beam

- Neutron scattering measures a neutron count rate
- The count rate is the number of counts, N, divided by the measurement time, t.
- The statistical uncertainty is given by the square root of the counts, $\sqrt{N}$, i.e. 10 000 counts have an uncertainty of 100, or 1%
- Neutron scattering is generally weak

Scattering experiments need good statistics for significant results

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NEUTRON DIFFRACTION BY CRYSTALS*

By Dr. KATHLEEN LONSDALE, F.R.S.

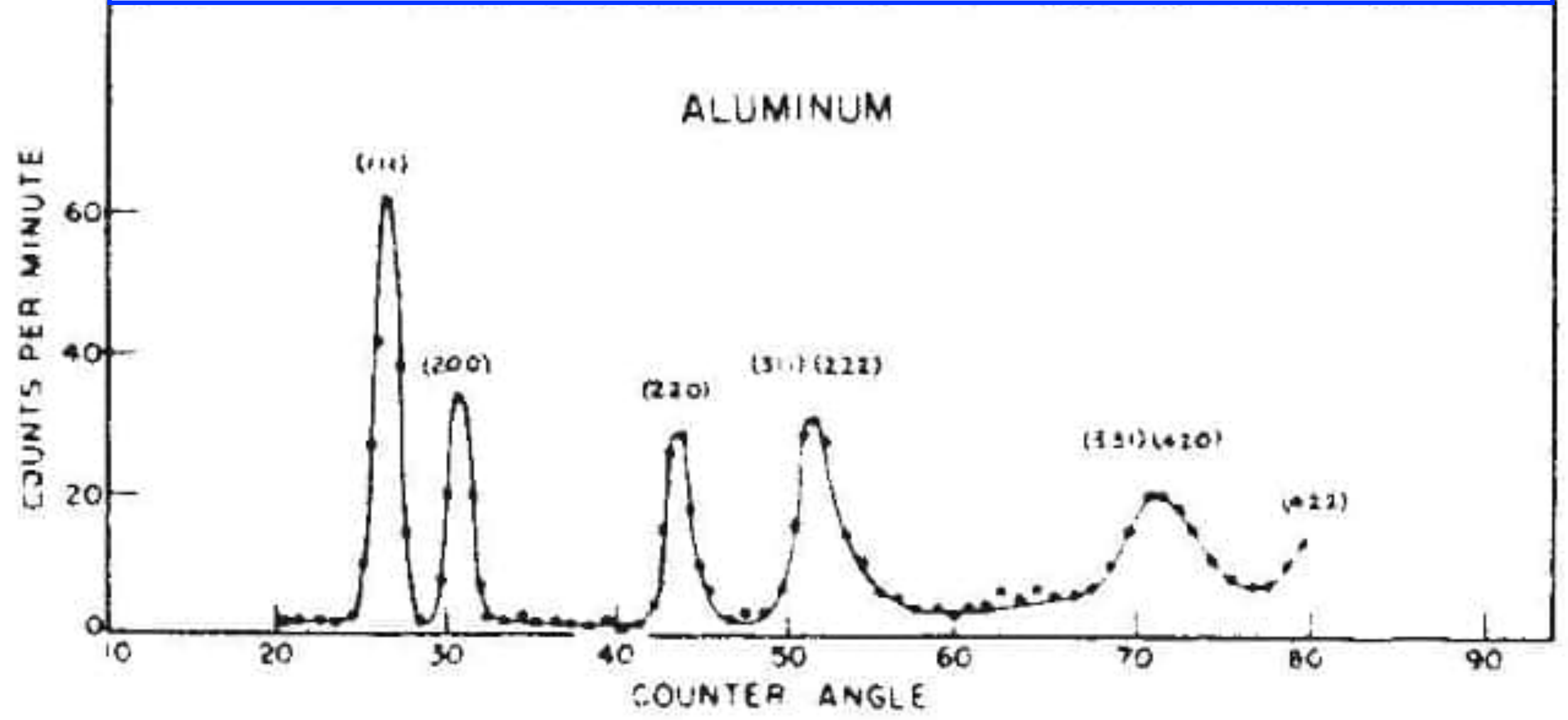



**Fig. 1.** Diffraction pattern for powdered aluminium in counts per minute versus counter angle (2θ) (E. O. Wollan and C. G. Shull, Oak Ridge)

Wollan's group at Oak Ridge in 1946 laid the foundations for widespread application of neutron diffraction as an important research tool.

# Neutrons Born Fast

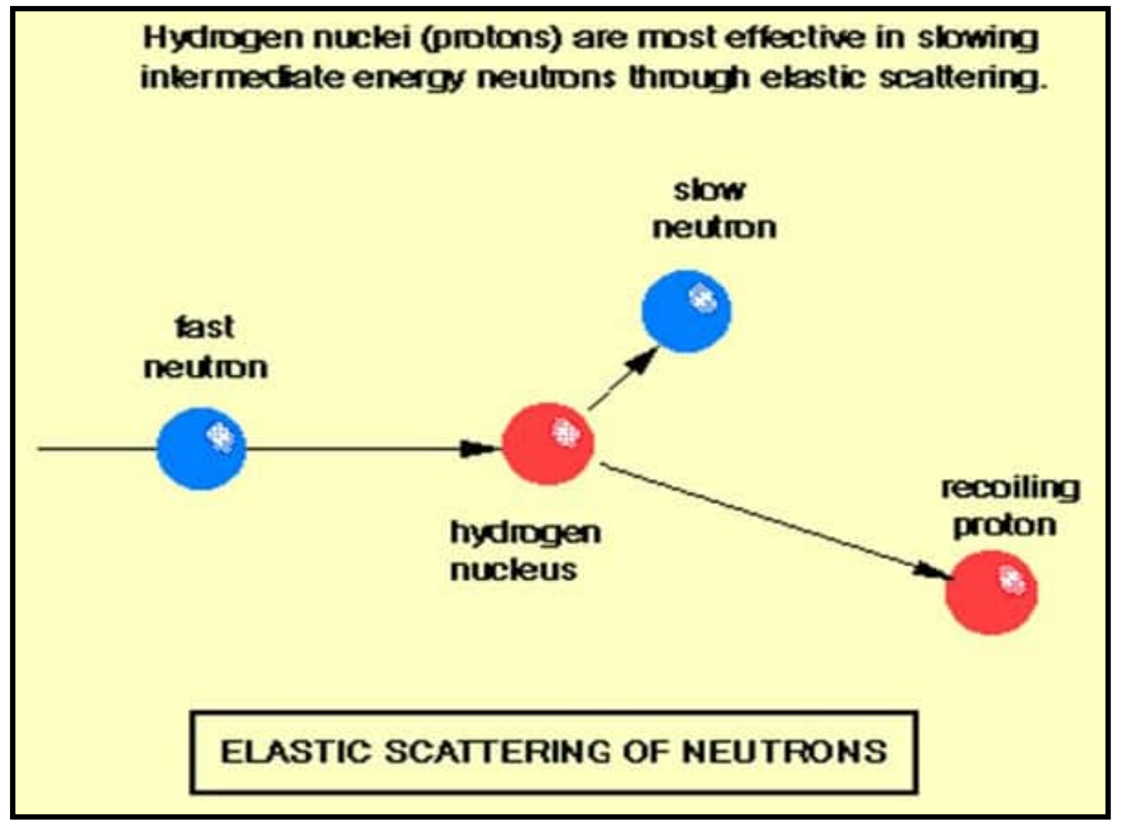
(High Energy Physics Jargon)

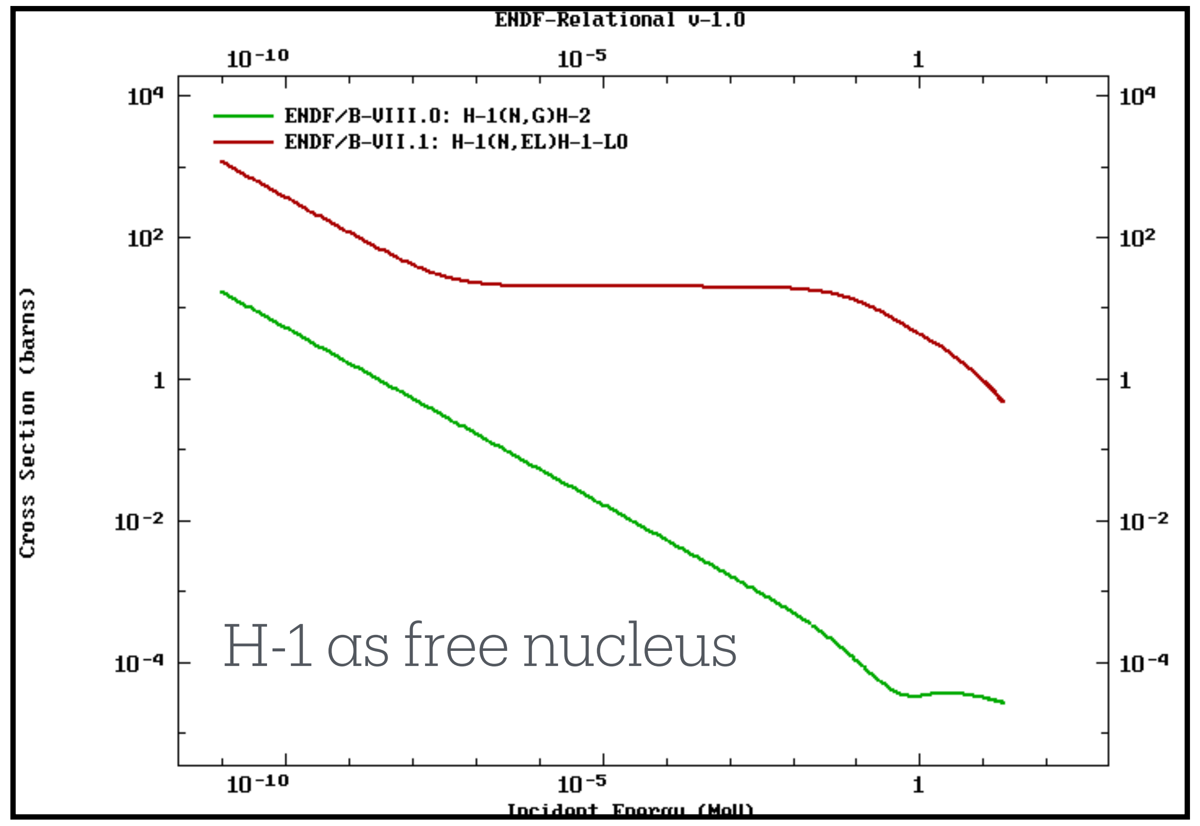
# NEUTRONICS: Neutron Transport and Interaction with Matter

- Wide range of energy —-> wide range of mechanism of interactions —> different scientific jargon

Elastic collision: conservation of KE and momentum

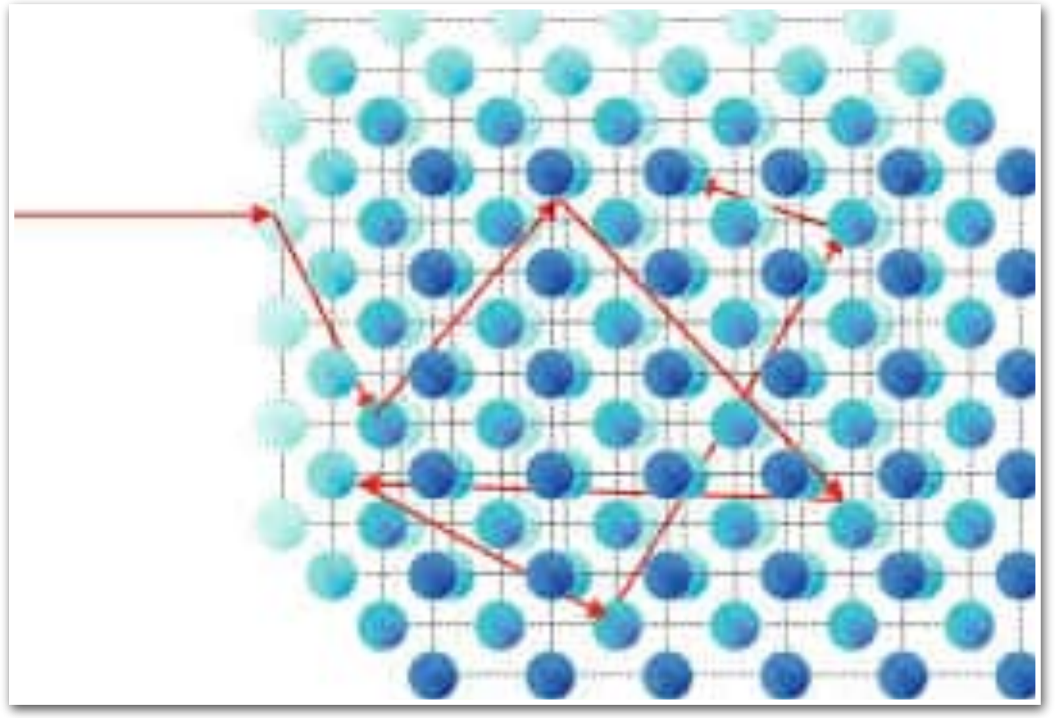
**Fast neutron down to thermal:**
Elastic collisions are the preferred and more efficient way to reduce the neutron energy .
In an elastic collision neutron-nucleus behave as billiard balls —> no excitation of the compound nucleus. The total kinetic energy before and after the collision is preserved

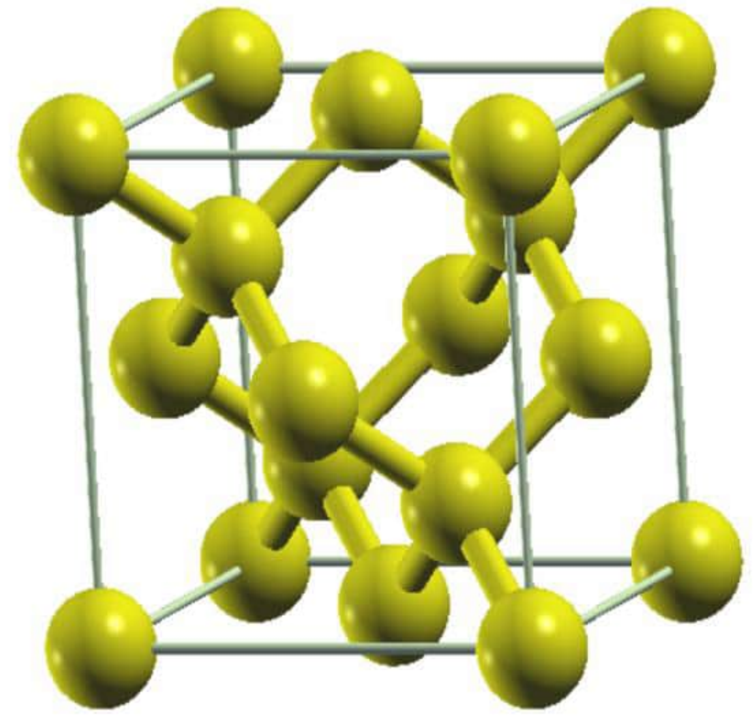



High Energy Range

**In the eV range and below:**
Neutrons see nuclei as bound in molecule
several vibrational modes can be activate as a mechanism to lose energy.
the scattering nucleus is considered at rest (KE=0)
neutron scattering elastically only changes direction





Energy range < few eV

# Energy Dependent Interaction with Matter

Designing a neutron source for scattering experiment means optimise the leakage from the source to the instruments.

- Diffraction
- Magnetitc scattering

- Elastic Scattering

with secondaries

- Nuclear Reactions:
  - Radiative Capture: A (n,$\gamma$)
  - Other Captures (n,p) or (n,**α**): A( n,x)
  - Inelastic Scattering A(n,n')A*
  - Nuclear Fission (n,f)

total microspcic cross section

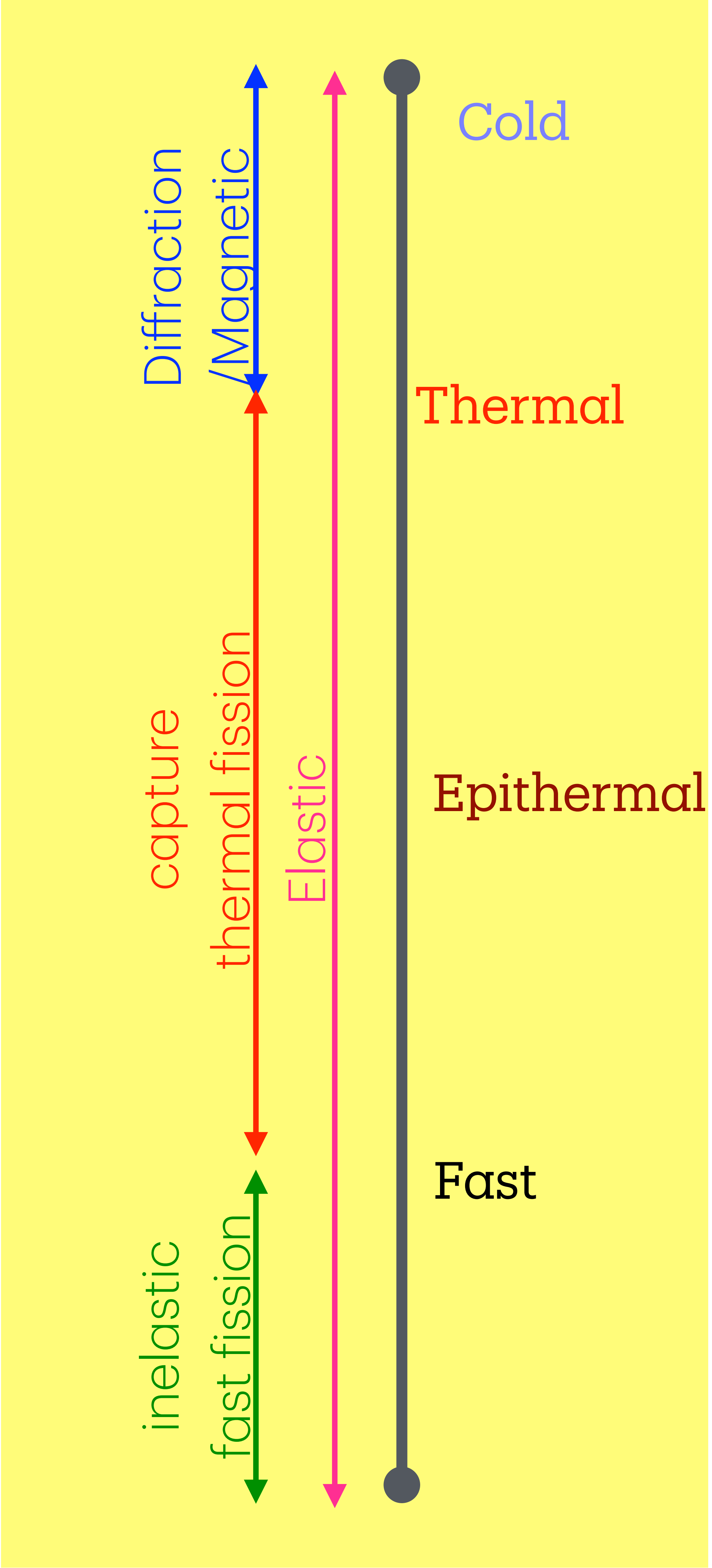
$$\sigma_T = \sigma_{el} + \sigma_{inl} + \sigma_\gamma + \sigma_p + \sigma_\alpha + \sigma_f + \ldots$$

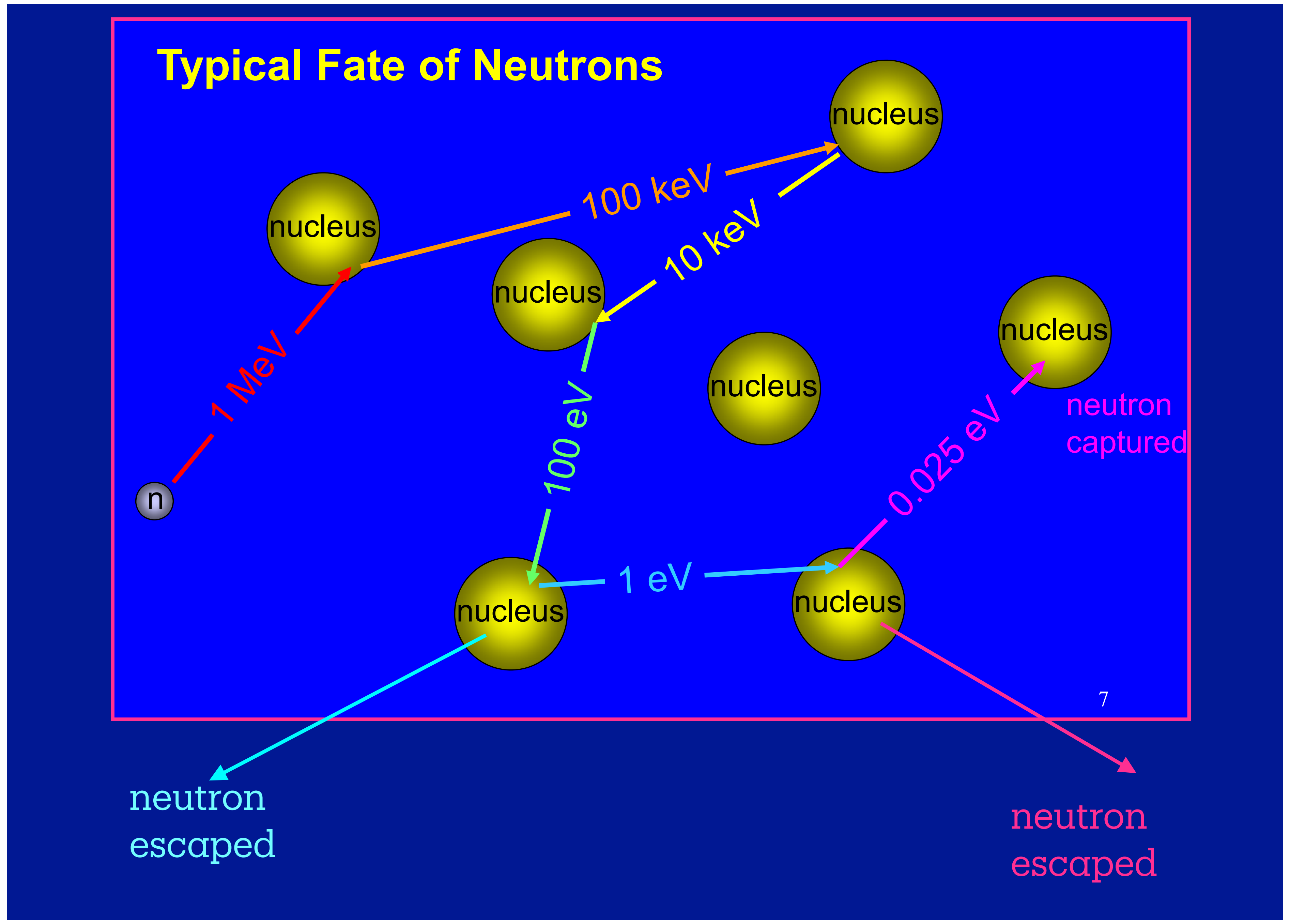
total macroscopic cross section

$$\Sigma_T = N\sigma_T$$

Reaction rate:

$$RR(E) = N\sigma_i(E)\Phi(E) = \Sigma_i(E)\Phi(E)$$

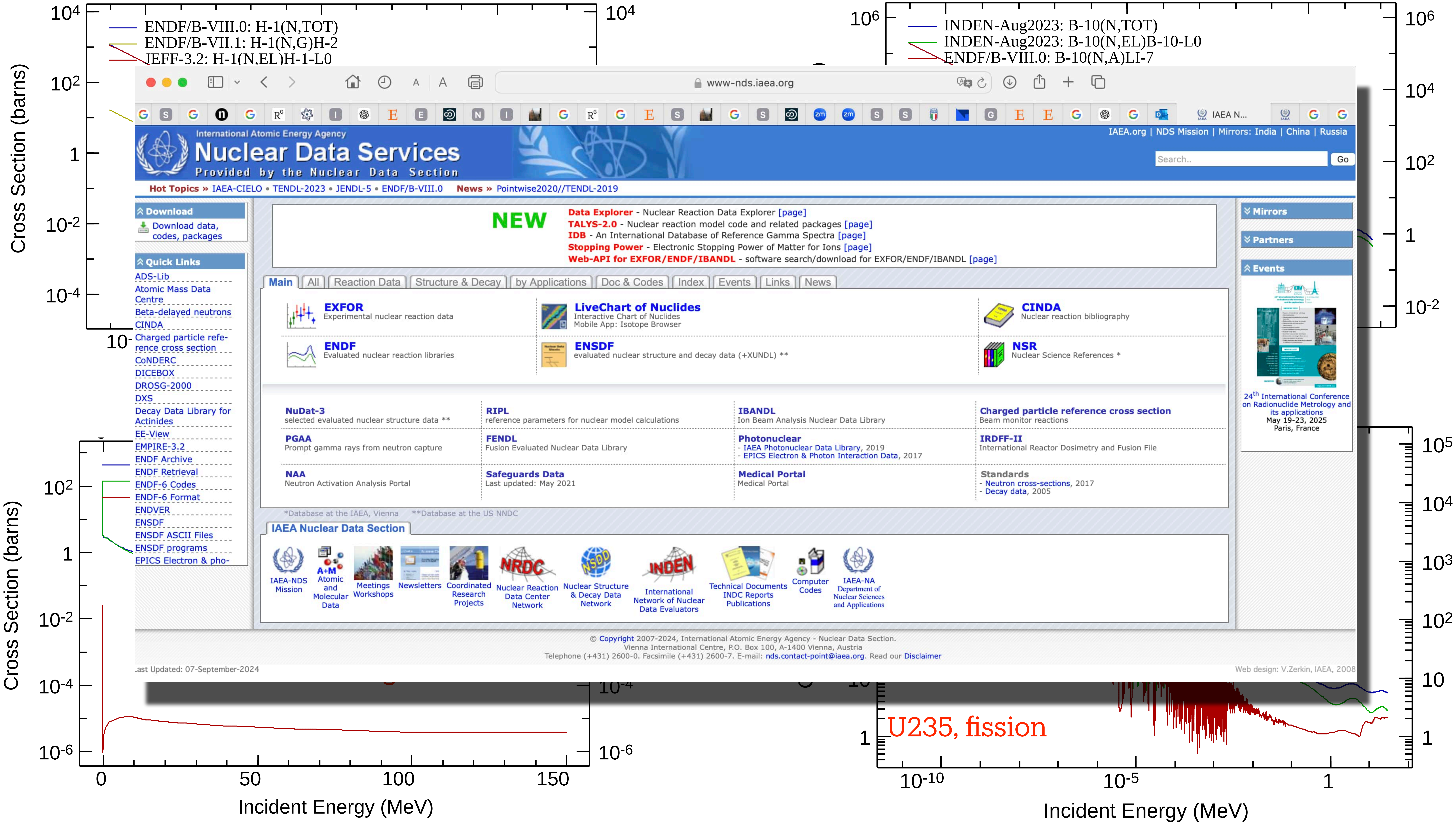



| definition | energy range* |
|---|---|
| ultra cold | < 0.3 μeV* |
| cold | 0.3 μeV to 0.01eV* |
| thermal | 0.01 eV to 0.3 eV* |
| epithermal | 0.3 eV to 10 keV |
| fast | 10 keV to 20 MeV |
| Ultra fast | >20 MeV |

* slow neutrons

# Moderators, Absorbers, Fissile Nuclei



# Neutron Sources

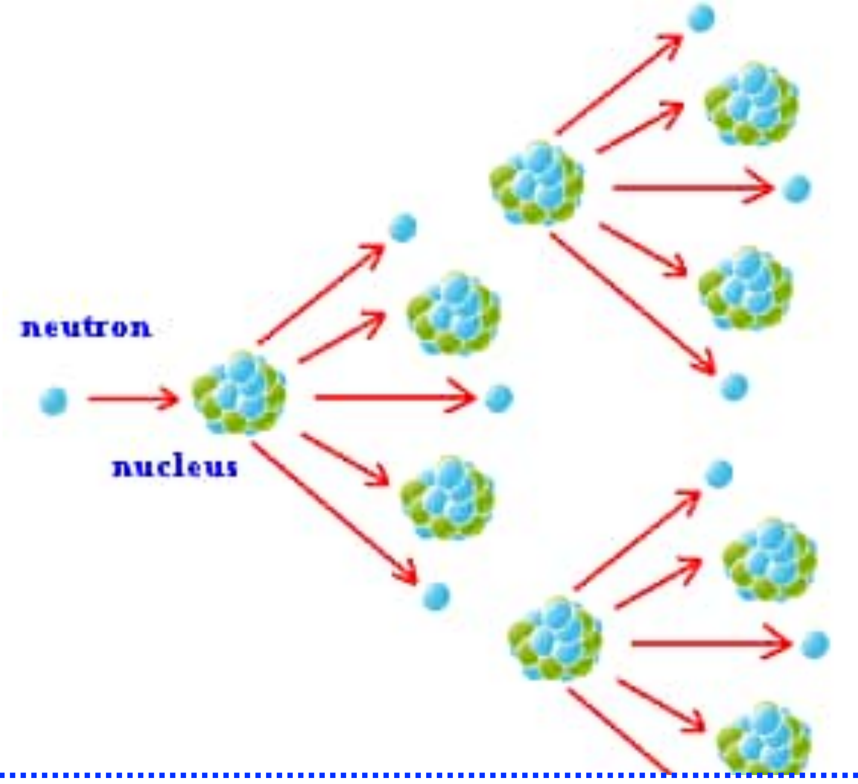
(the Physics: Phenomenological Description)

# How To Free Neutrons?

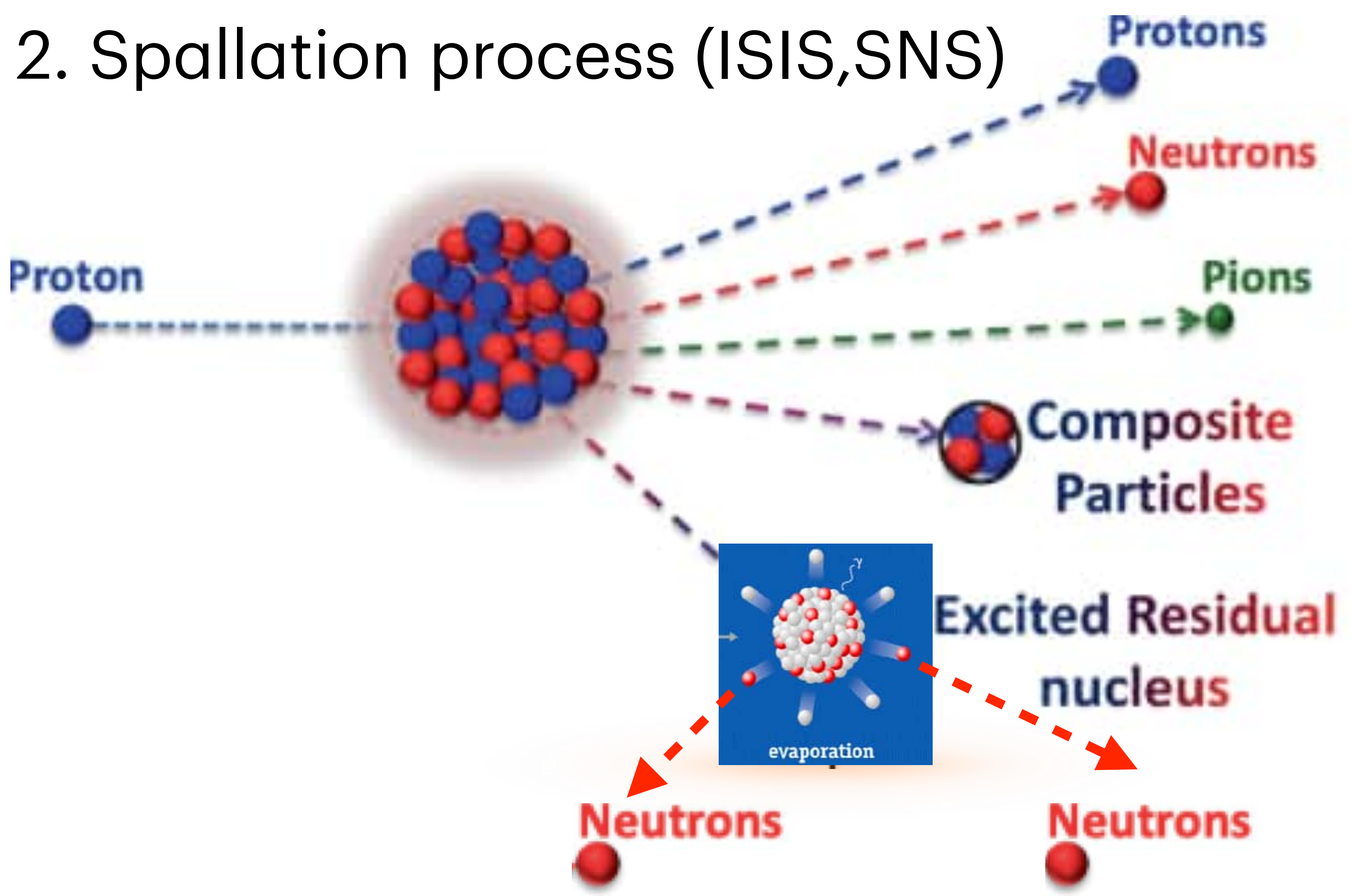
## A general overview of the main physics processes

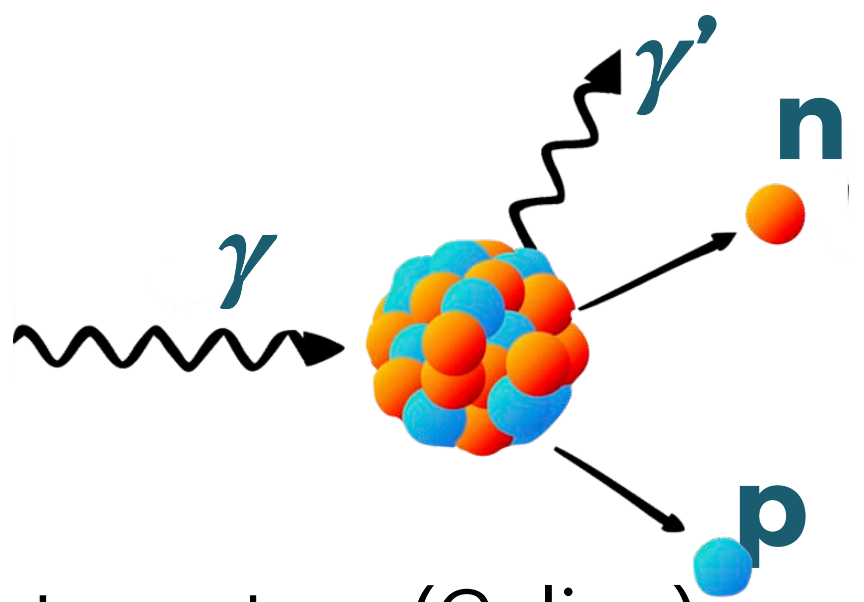
| Process | Source Scale |
|---|---|
| Fission | Reactor |
| Spallation | Large acc. complex |
| Photonuclear/ photofission | Large acc. complex |
| Fusion | intermediate |
| Laser p acceleration + nuclear reaction | Compact Source (still under study and development) |
| Radioactive decay + nuclear interaction | Small laboratory Source |
| Direct radioactive decay | Rare uncontrolled events in large scale facilities (noise source) |

1. Fission (ILL)



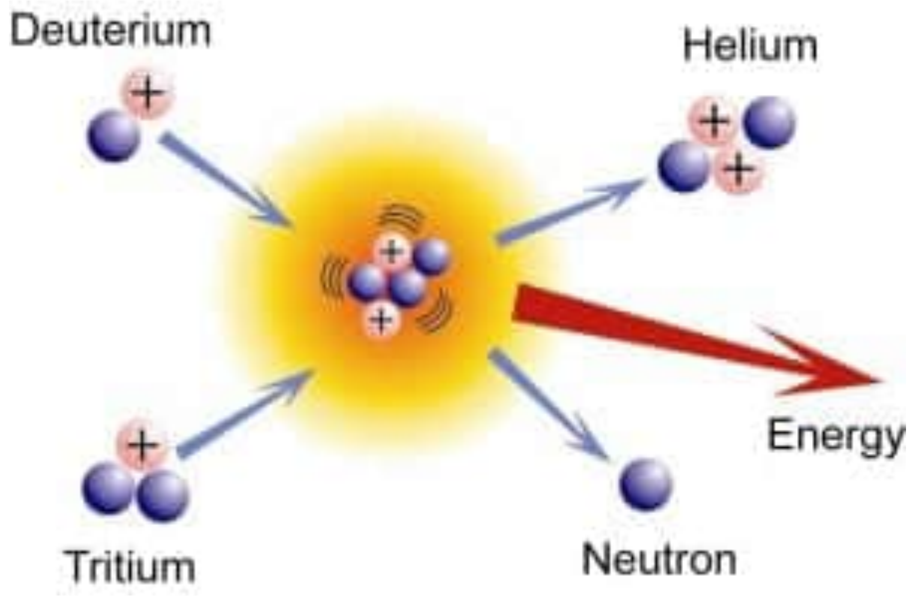

2. Spallation process (ISIS,SNS)



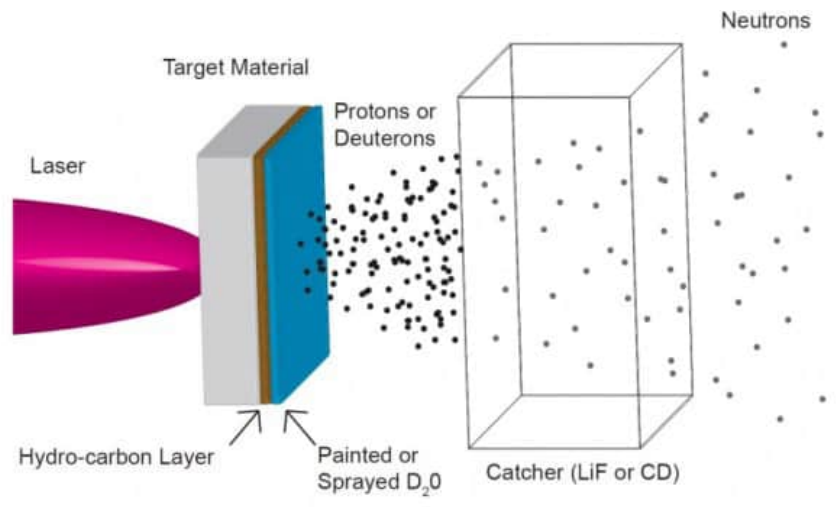



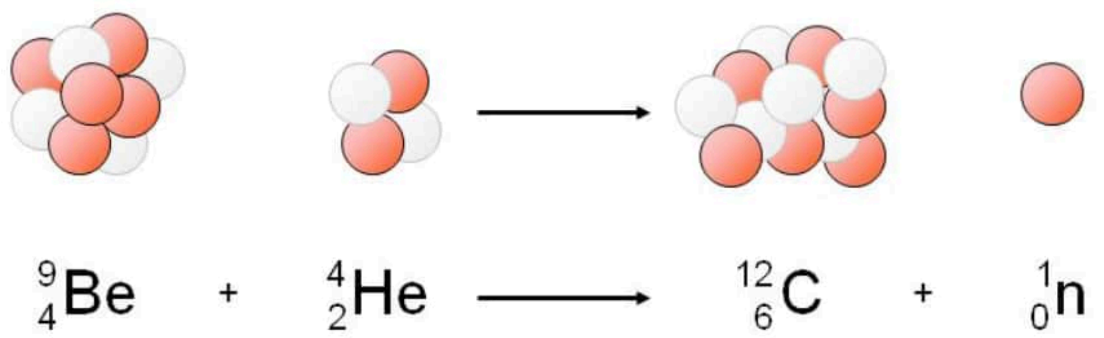

3. photoneutron (Gelina)

4. Fusion

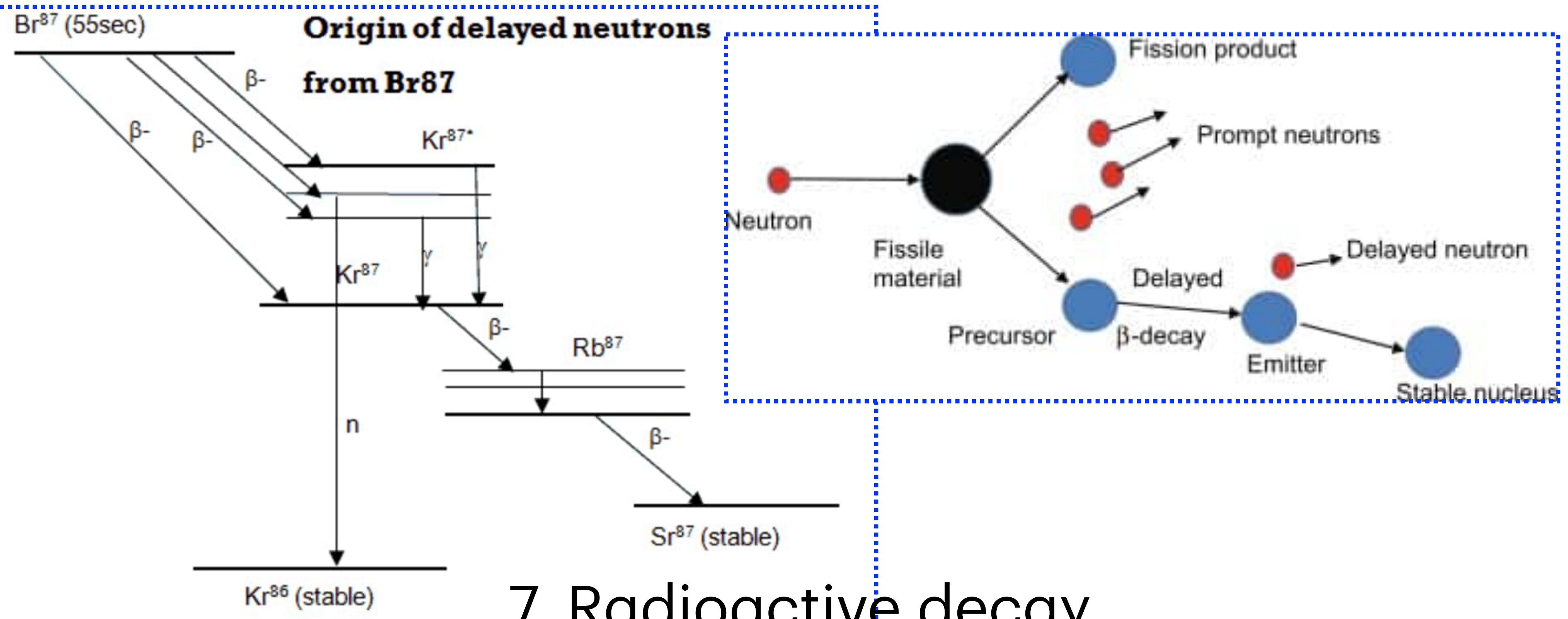



5 Laser



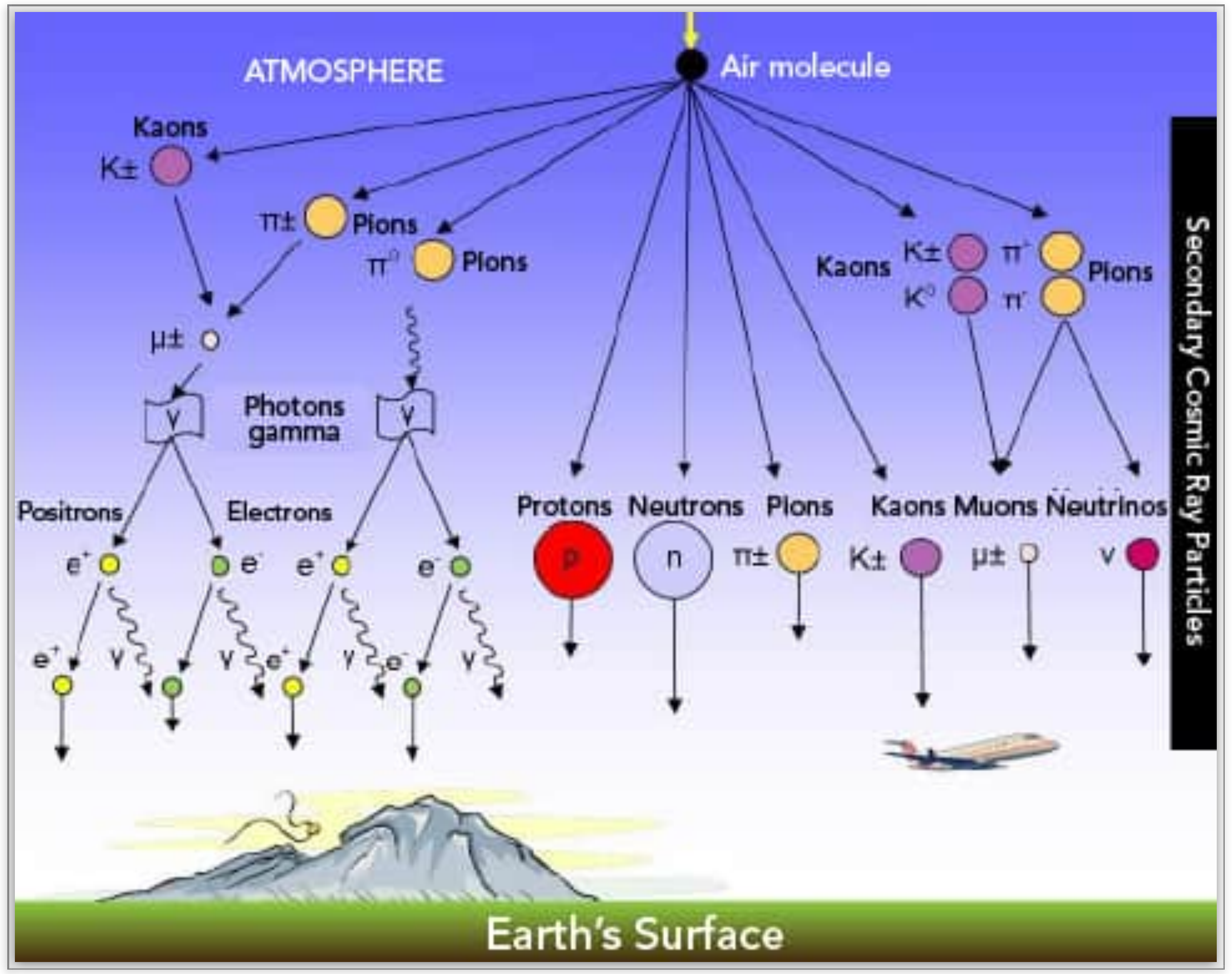

6. nuclear reaction




7. Radioactive decay

# Neutrons from Cosmic Rays

## The “oldest” neutron spallation source on earth is provided by Nature




~1 m²

$$10^{-4} \sim 10^{-3}\ neutron/cm^2 \cdot s$$


Neutron background around us is coming mainly from spallation of high energy protons on Oxygen and Nitrogen nuclei in the atmosphere....

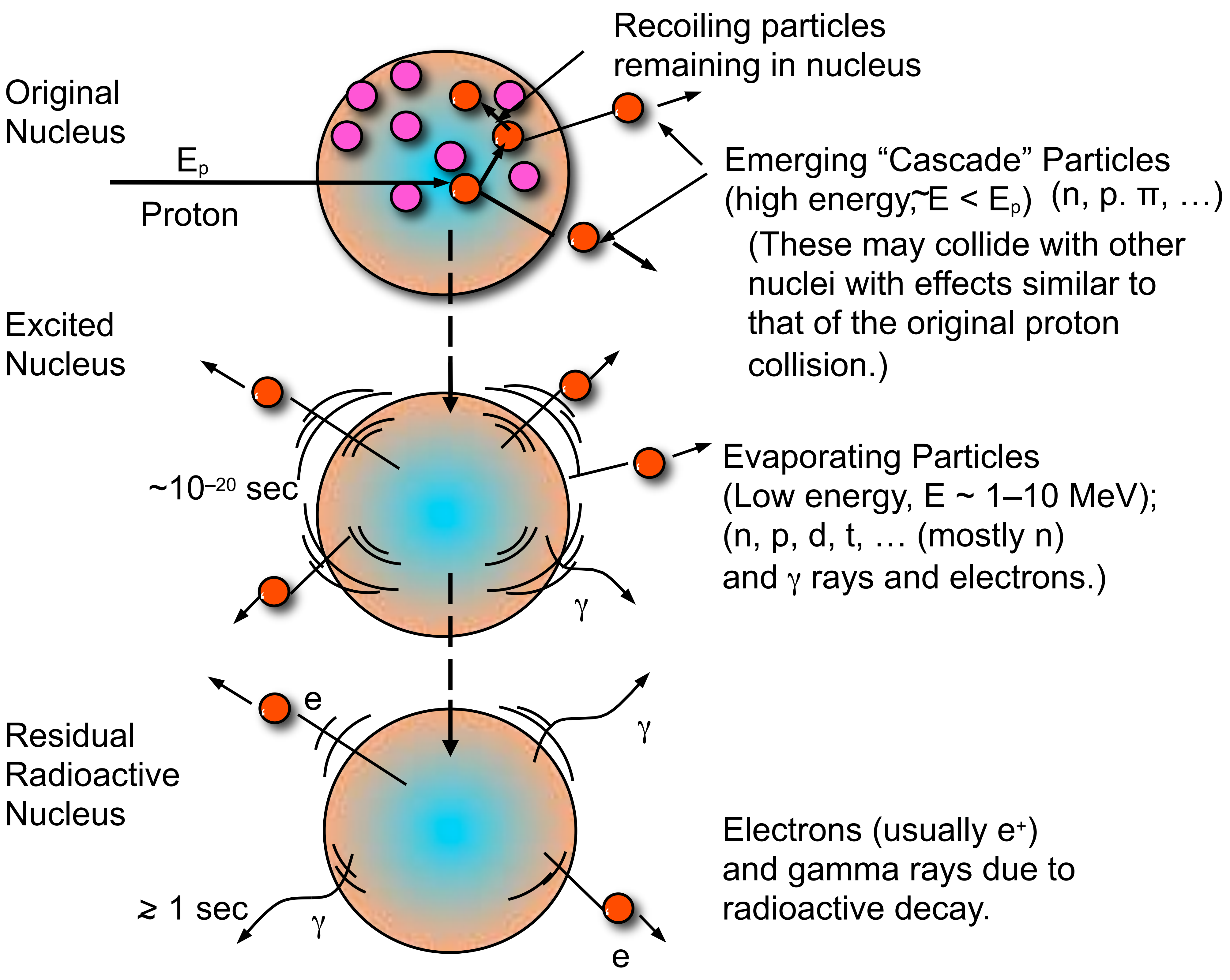
The thermal neutron flux at the Earth’s surface is ~ $10^{-4}$—$10^{-3}$ n/cm2/s, varying with atmospheric pressure (i.e., weather)

# Spallation vs Fission

(… and Photo-Production)

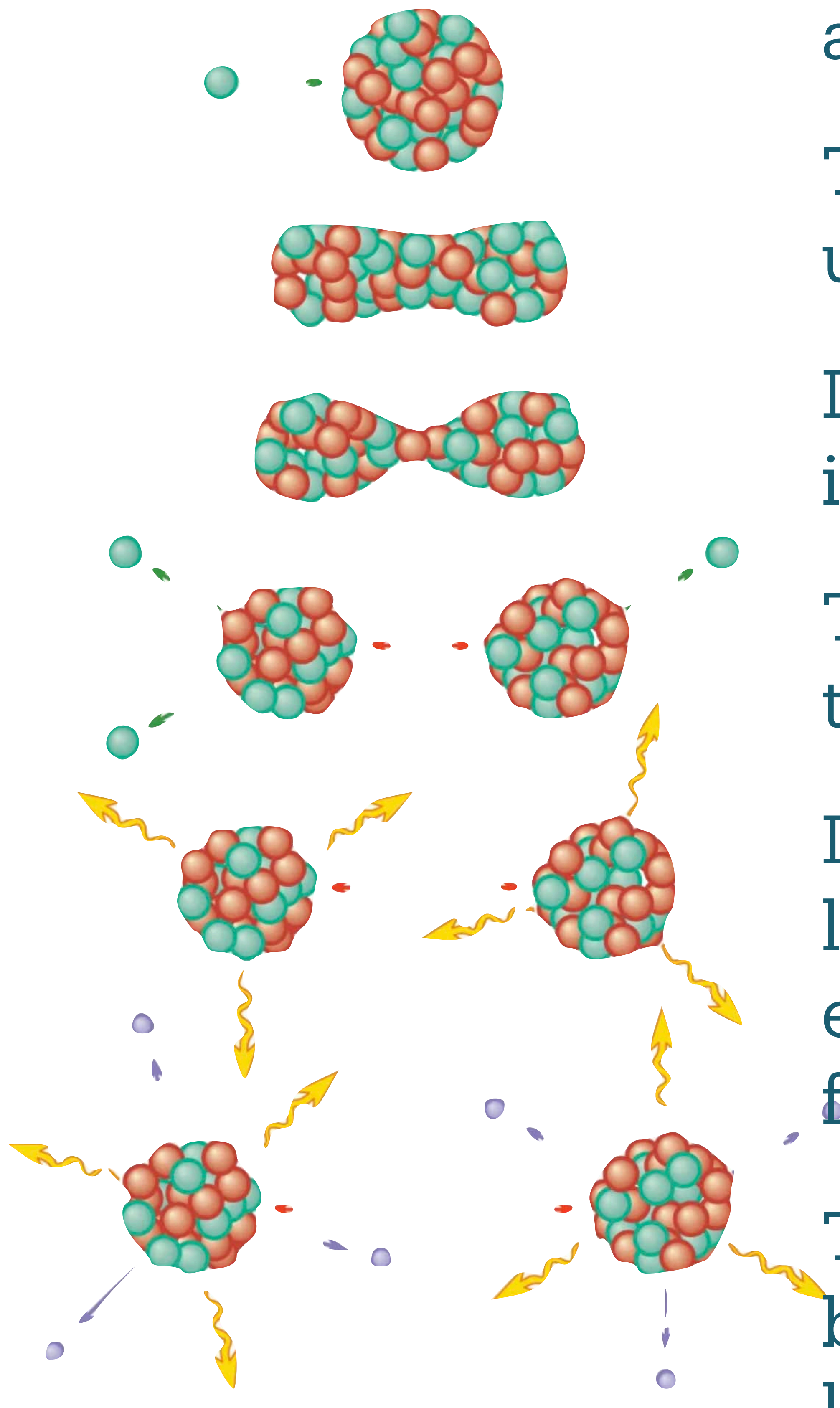
# Mechanisms of Neutron Production

## Spallation




*Spallation is an efficient process for releasing neutrons from nuclei . It is an endothermic process and can be in principle triggered in any nucleus but the neutron yield increases with the atomic mass of nucleus*

## Fission



The neutron strikes the nucleus and is absorbed.

The absorbed neutron causes the nucleus to undergo deformation.

In about $10^{-14}$ second, one of the deformations is so drastic that the nucleus cannot recover.

The nucleus fissions, releasing an average of two to three neutrons.

In about $10^{-12}$ second, the fission fragments loose their kinetic energy and come to rest, emitting a number of gamma rays. Now the fragments are called fission products.

The fission products loose their excess energy by radioactive decay, emitting particles over a lengthy time period (seconds to years).

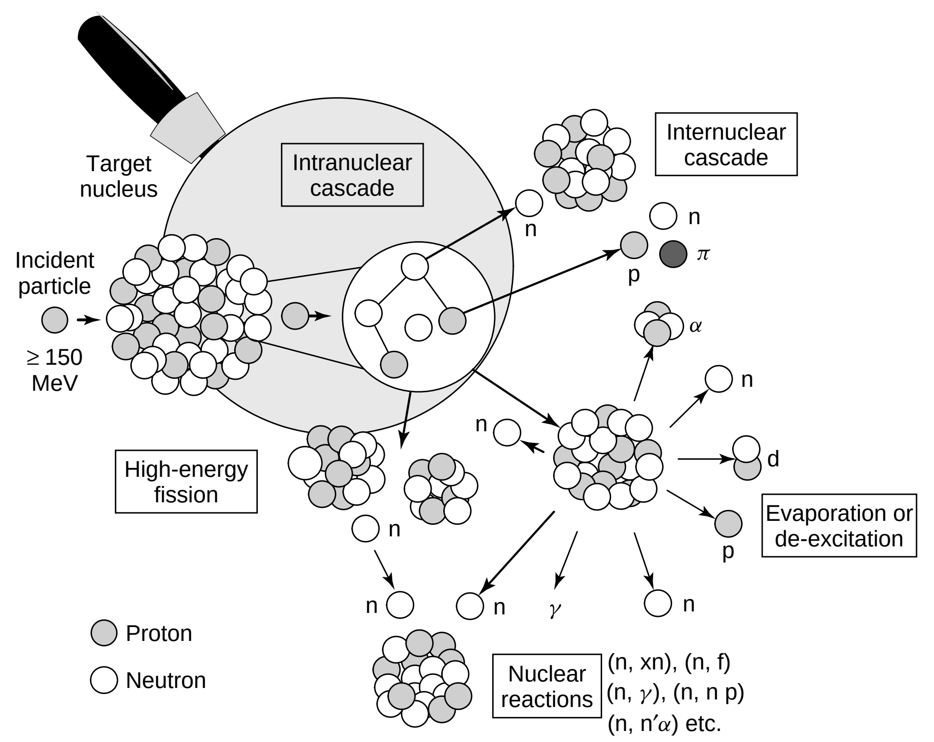
*Fission reactor technology is intrinsically neutrons poor: only few excess neutrons can be made available*

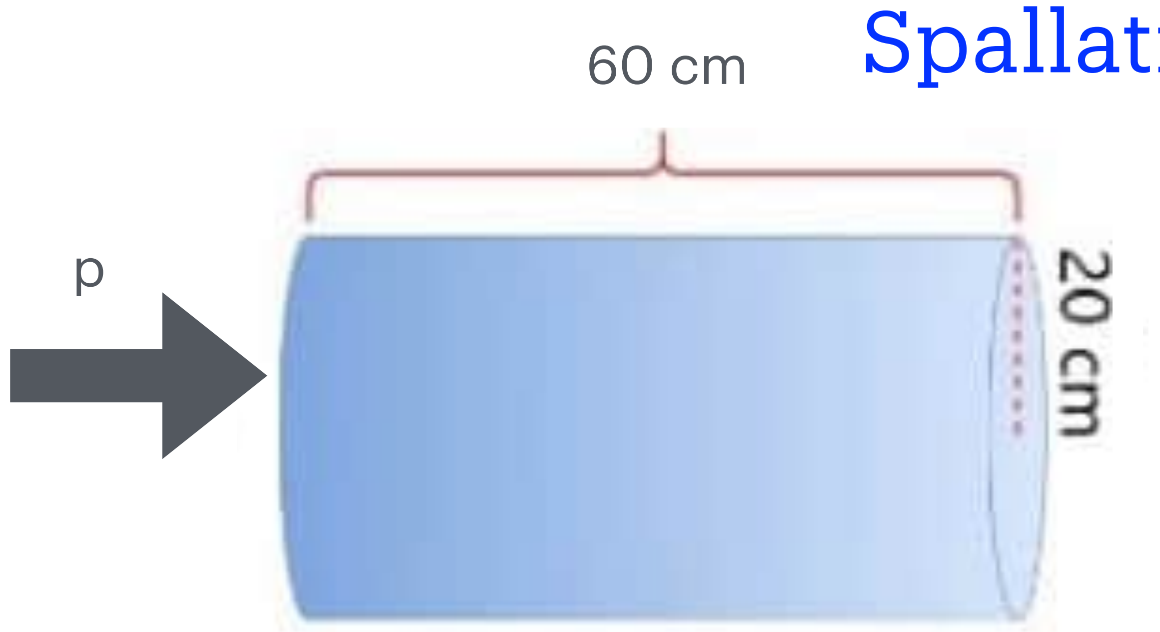
Neutrons · Protons · Beta particles · Gamma rays

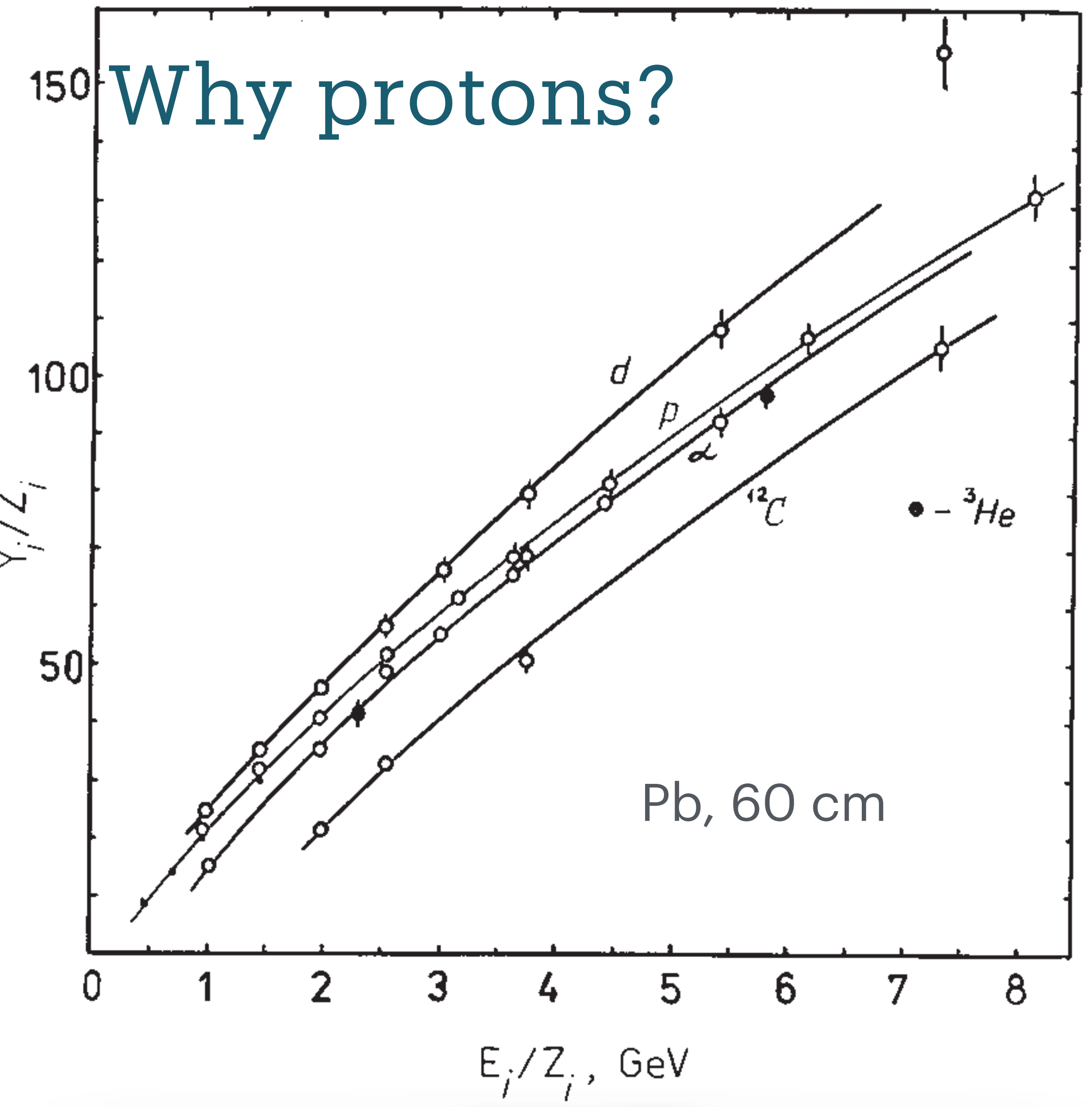
| | | |
|---|---|---|
| Fissile | U233<br>U235 | Pu239<br>Pu241 |

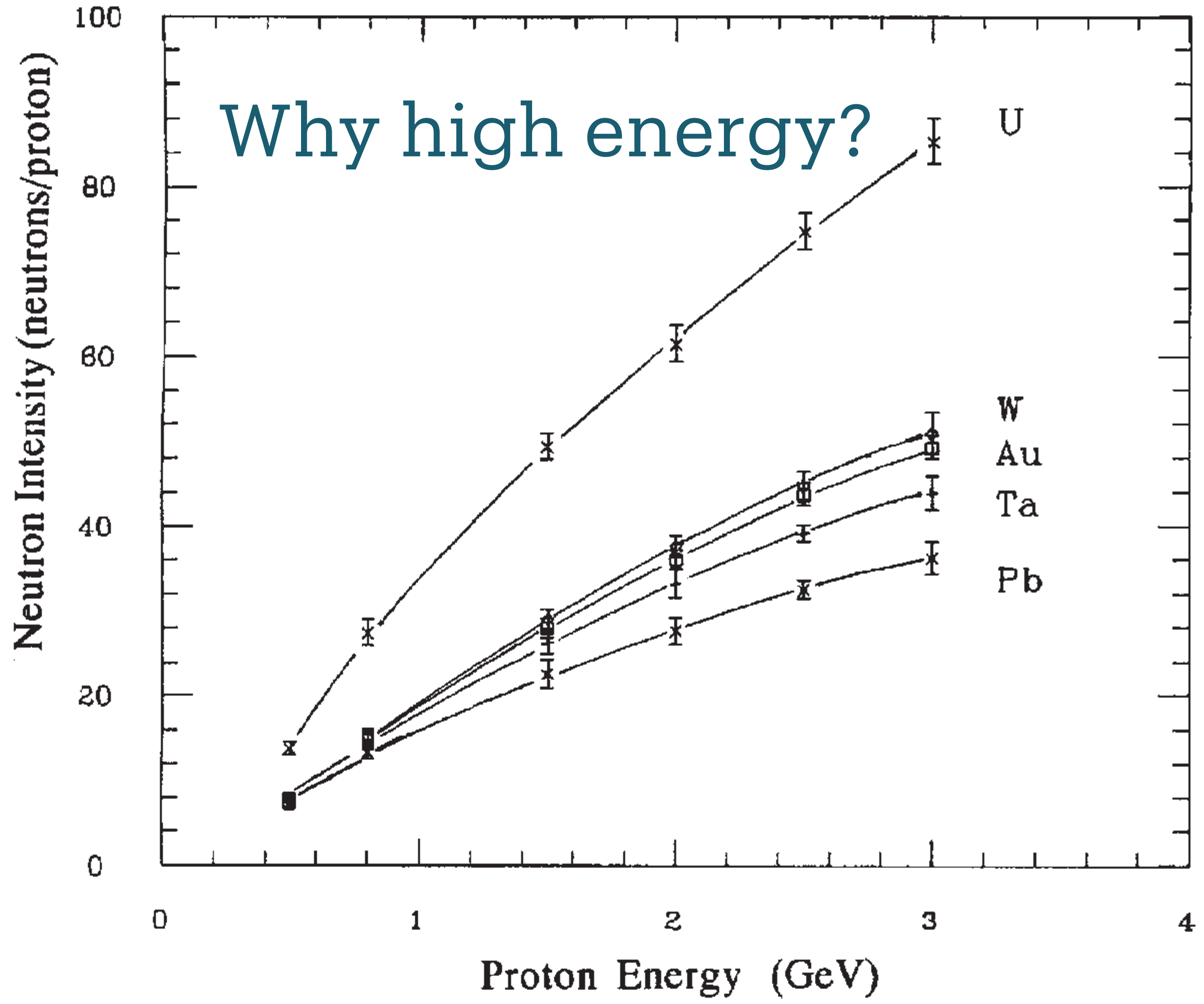
# Neutron Yield and Leakage

## Spallation



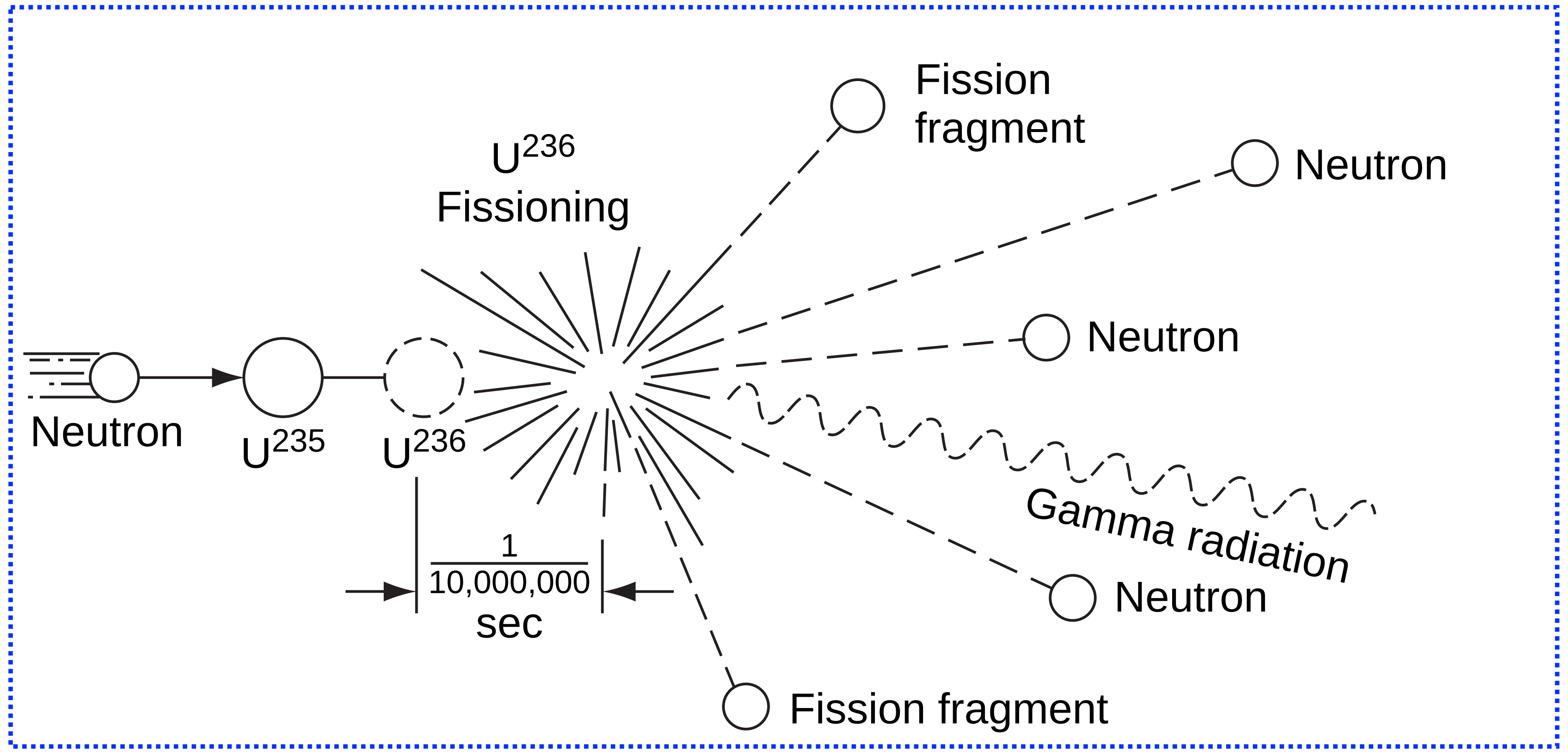

$$Y(E, A) = \{E\ (\mathrm{GeV}) - 0.12\} \times \{A + 20\} \times 0.1\ (\mathrm{n/p}).$$

Yield for W target @ 800 MeV: $Y(0.8GeV,183) = 14\,\dfrac{n}{p}$

Y= Leakage (neutron absorption inside the target is negligible)

$$ISIS(200\mu A) - - > 1.25 \cdot 10^{15}\frac{p}{s} - - > Leakage(ISIS) \simeq 2 \cdot 10^{16}\frac{n}{s}$$

## • Fission




Production: an average of 2.5 neutrons/fission

$$^{1}_{0}\mathrm{n} + {}^{235}_{92}\mathrm{U} \rightarrow {}^{236}_{92}\mathrm{U} \rightarrow {}^{141}_{56}\mathrm{Ba} + {}^{92}_{36}\mathrm{Kr} + 3\,{}^{1}_{0}\mathrm{n}$$

$$^{1}_{0}\mathrm{n} + {}^{235}_{92}\mathrm{U} \rightarrow {}^{236}_{92}\mathrm{U} \rightarrow {}^{140}_{54}\mathrm{Xe} + {}^{94}_{38}\mathrm{Sr} + 2\,{}^{1}_{0}\mathrm{n}$$

Leakage: 1 n is needed to sustain chain reaction—->

1 neutron/fission available for scattering

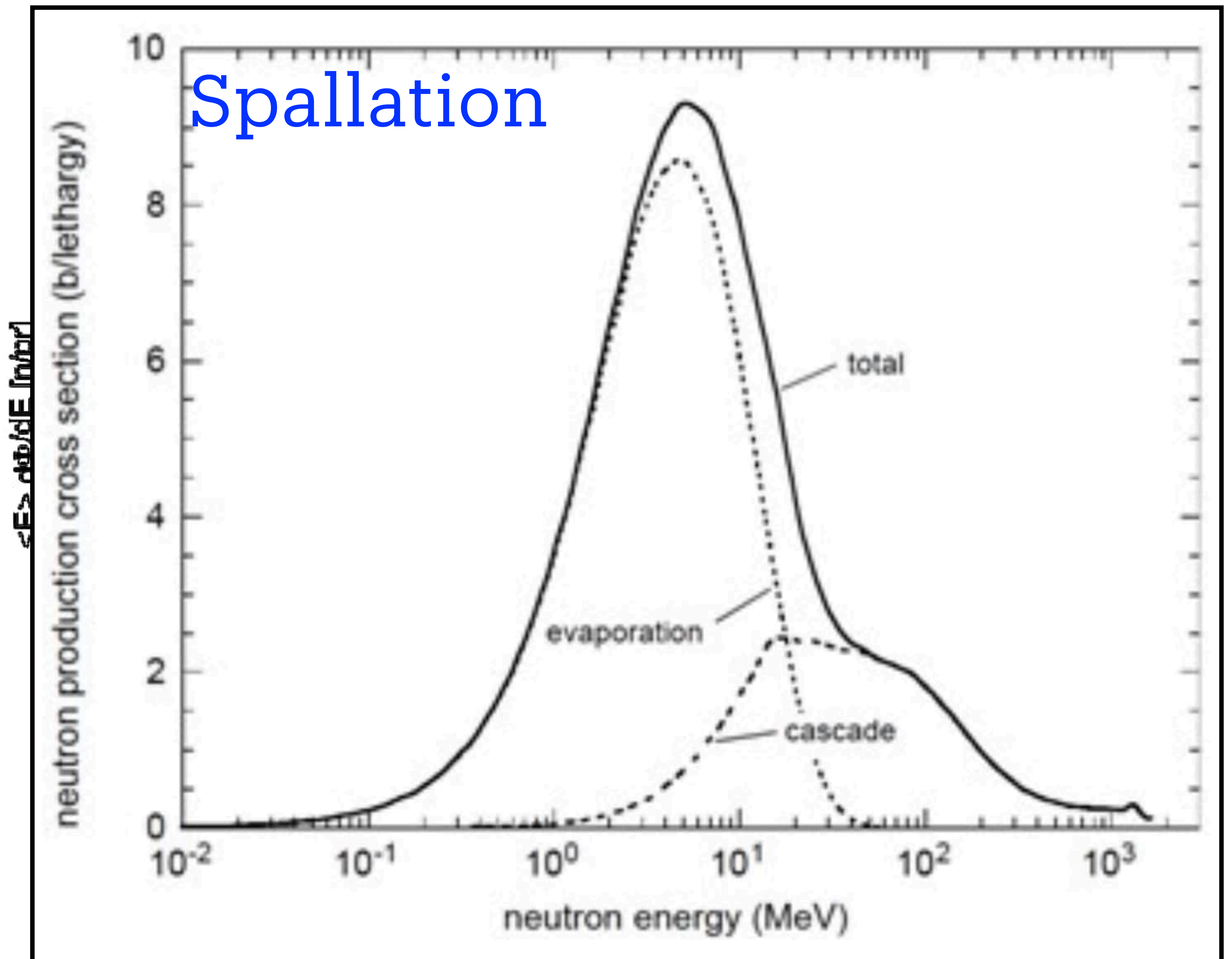
$$Rate\ of\ Fissions(ILL) = \frac{Power}{energy\ from\ one\ fission}$$

$$Leakage(ILL) = \frac{58 \cdot 10^{+6}}{200 \cdot 10^{+6} \cdot 1.6 \cdot 10^{-19}} \simeq 2 \cdot 10^{18}\,\frac{n}{s}$$

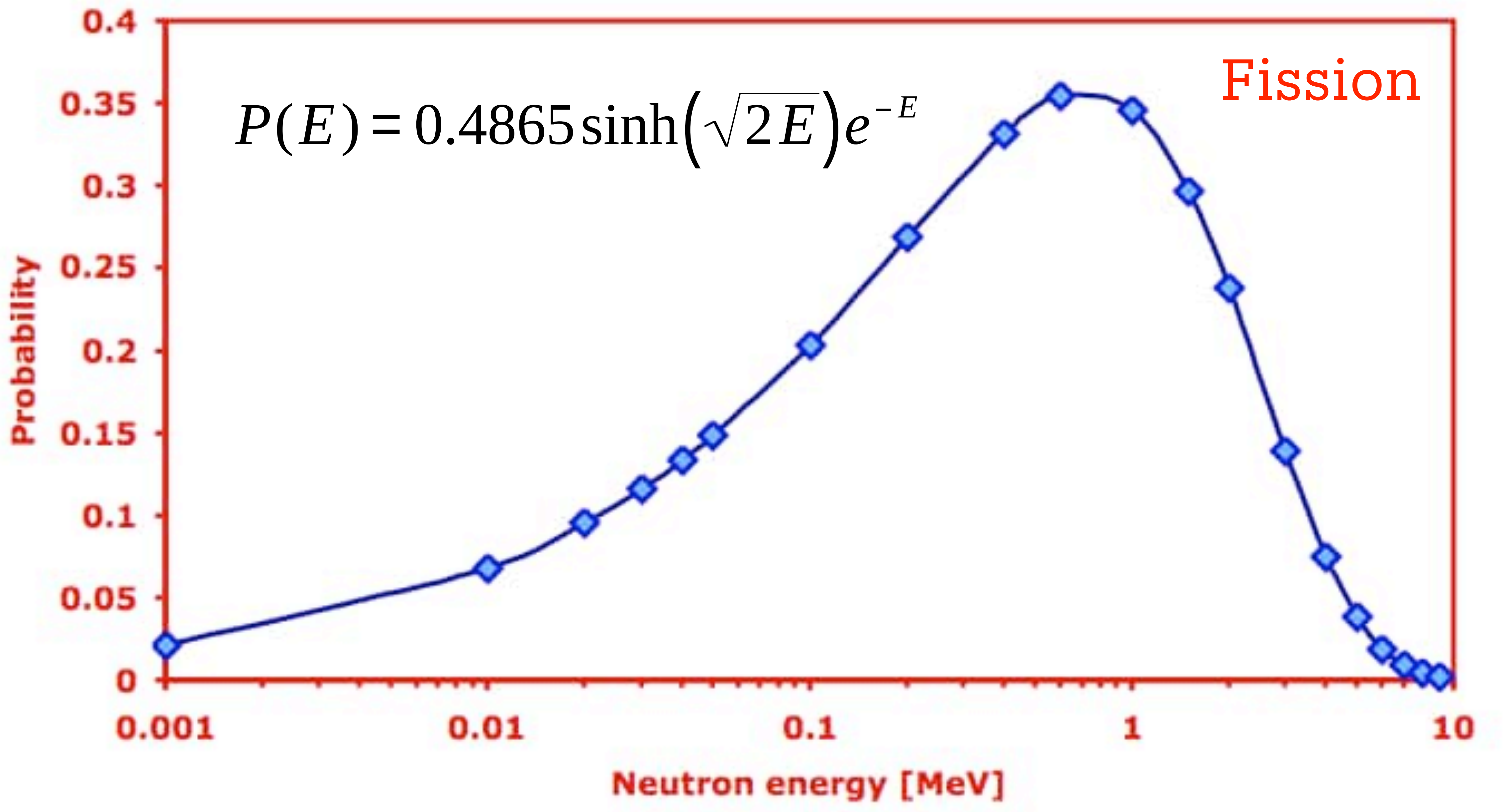
# Neutron Energy Spectrum

## Difference in the energy distribution of the emitted neutrons

**Figure 11: Energy spectrum of neutron escaping from the *bare* target**




*Energy distribution of neutrons produced via spallation by 1.7-GeV protons on tungsten*




Spallation neutrons extend to higher energies than fission neutrons:

In a spallation source, high-energy cascade neutrons approach the energy of the incident proton (i.e 800 MeV at ISIS).

Neutrons from evaporation OF HIGH Z NUCLEI are around 1 MeV and are emitted isotropically

Fission spectrum is peaked around 1 MeV and extends up to 10 MeV

Very few neutrons are in the eV range

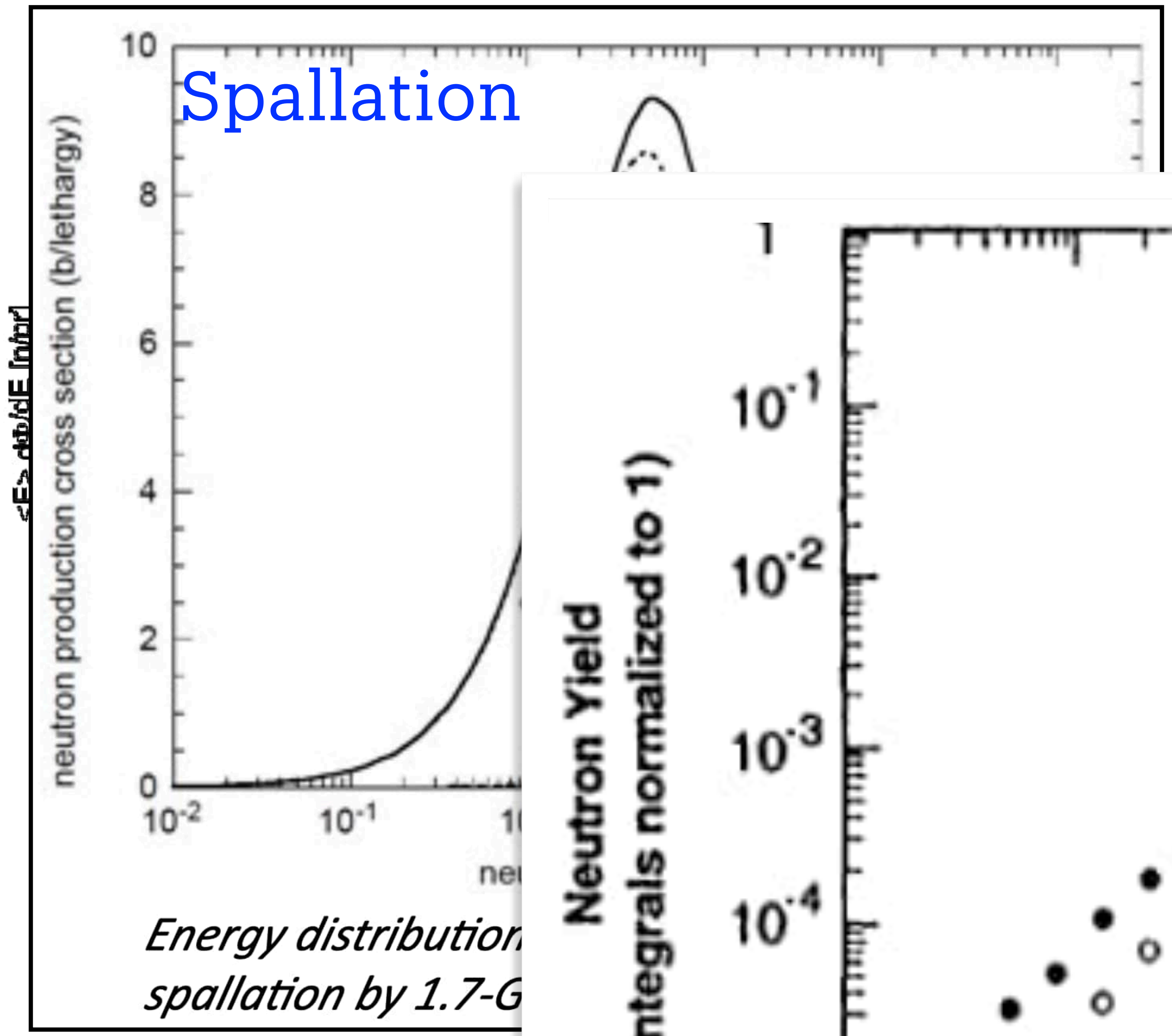
The Watt function is an empirical formula to fit the experimental data

The shape is pretty the same for thermal fissions of different fissile nuclei

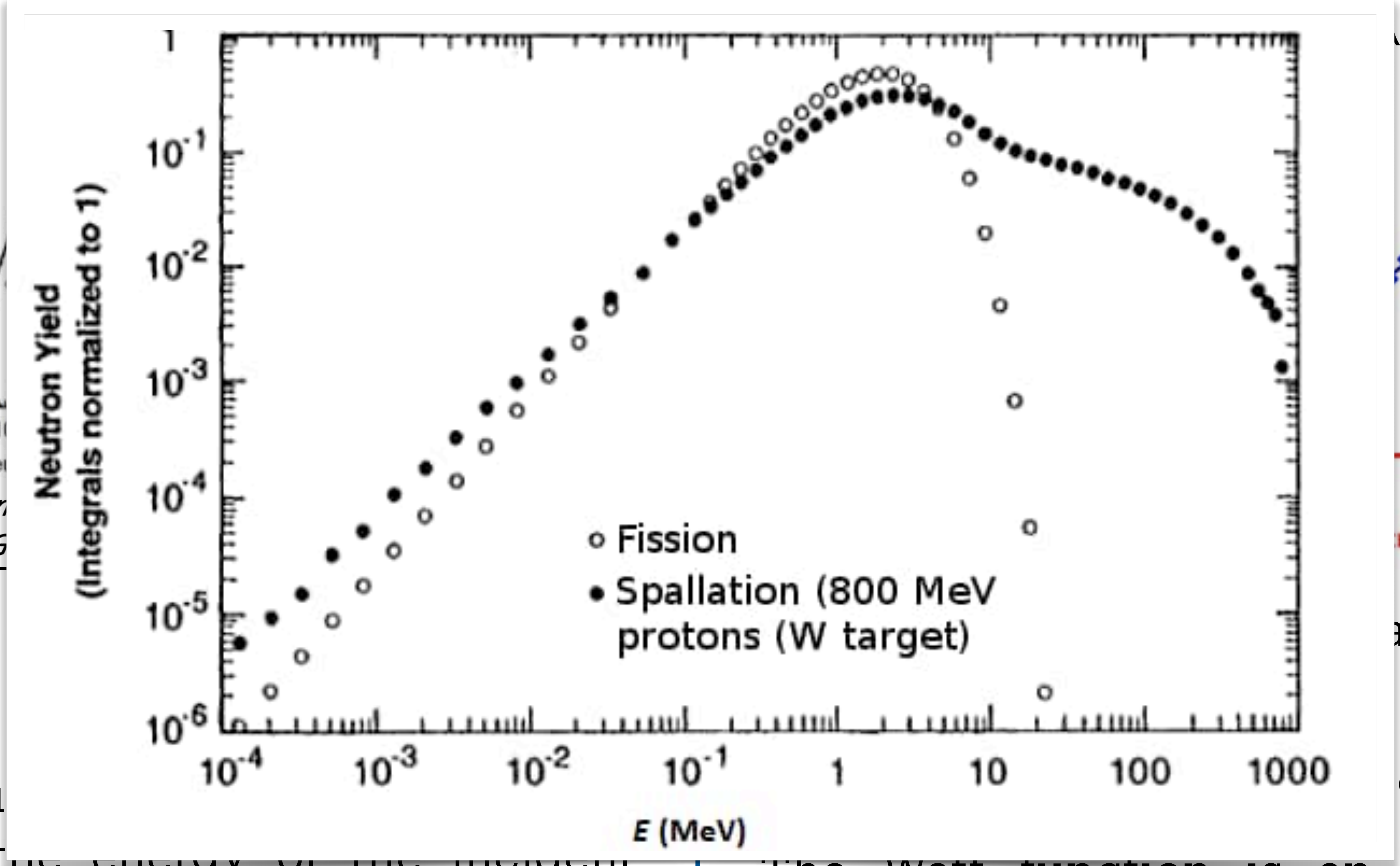
# Neutron Energy Spectrum

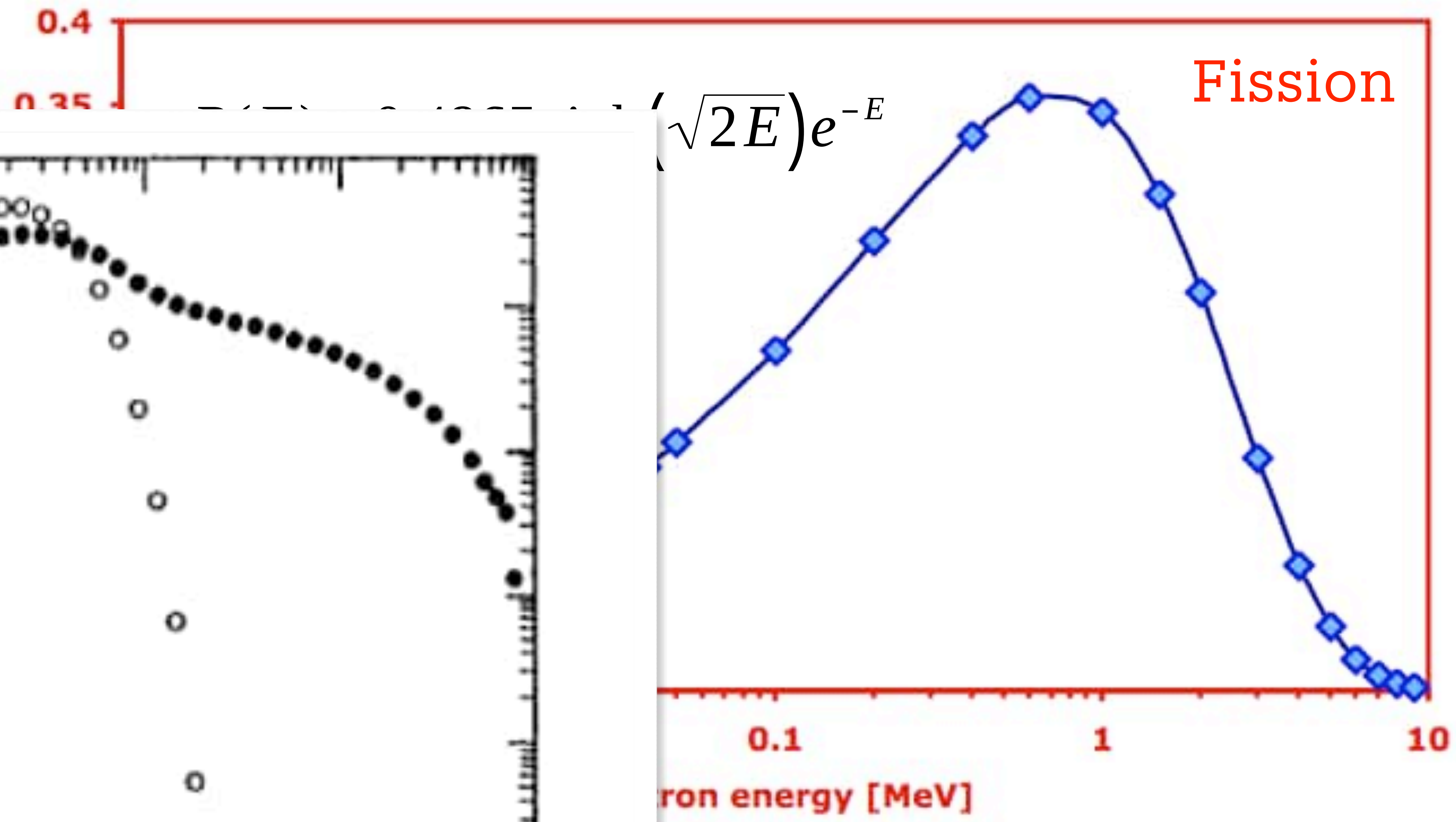
## Difference in the energy distribution of the emitted neutrons

**Figure 11: Energy spectrum of neutron escaping from the *bare* target**




*Energy distribution*
*spallation by 1.7-G*




Spallation neutrons
than fission neutrons:

In a spallation sou
neutrons approach t
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Neutrons from evaporation OF HIGH Z NUCLEI are around 1 MeV and are emitted isotropically

around 1 MeV and extends up to

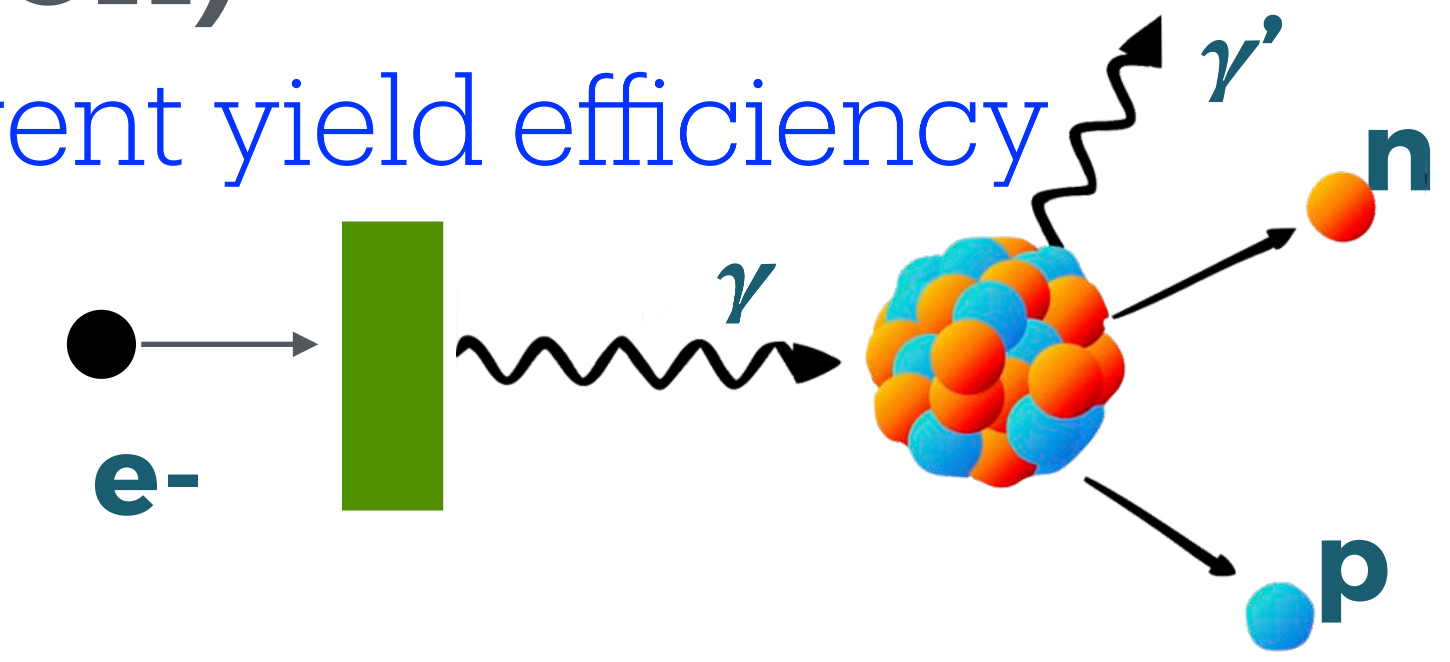
eV range

The Watt function is an empirical formula to fit the experimental data

The shape is pretty the same for thermal fissions of different fissile nuclei

# Photonuclear (vs Spallation)

## Same spectrum shape but different yield efficiency



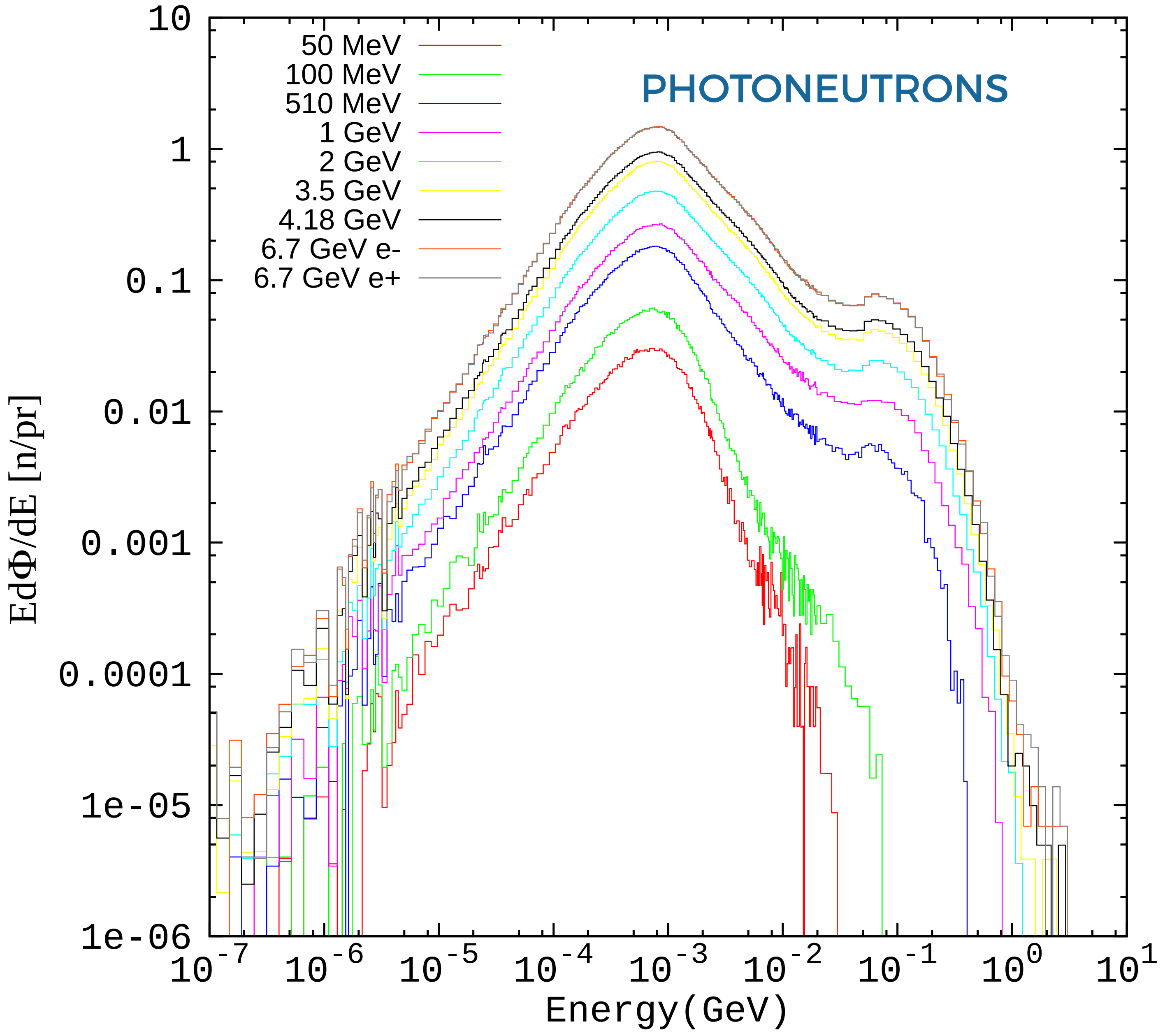

Bremsstrahlung Photons interact with nuclei causing the emission of nucleons (neutron, protons, pion, etc)

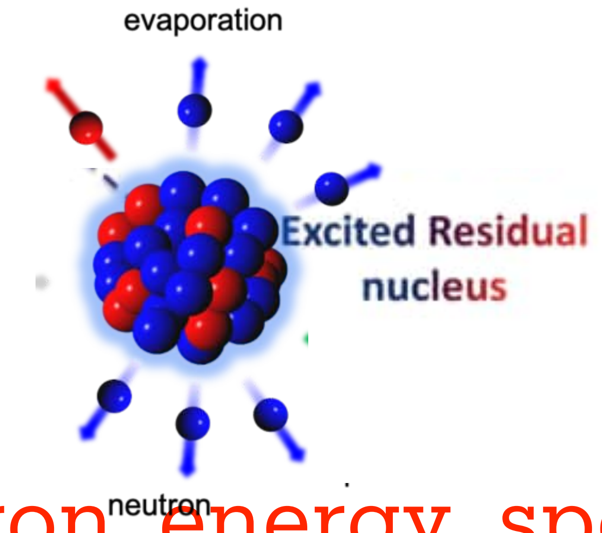
Photon energy levels above the nuclei binding energy (5-15 MeV) are necessary. Photo-nuclear interactions are threshold reactions: threshold is lower for heavy nuclei

**electrons—>gammas—>neutrons**


Main mechanism of neutron production: Giant dipole resonance

Neutron flux from the giant resonance process is distributed according to a Maxwellian




$$\frac{d\phi_n}{dE} \alpha \frac{E}{T^2} \cdot e^{-\frac{E}{T}}$$

$T = 0.7$ MeV for W

Neutron energy spectra from spallation and photonuclear production are pretty simular : they both extend up to the primary E and 90% of the neutrons are around 1 MeV (W)....
but the efficiency of production of neutron is quite different (photo nuclear yield is almost 2 orders of magnitude less than spallation)

Spallation:

**1 GeV p on W target → 14 n/p**

Photonuclear:

**1 GeV e- on W target → 0.7 n/e-**

# Delayed Neutrons

1.Delayed neutrons are emitted by neutron-rich (fission or spallation) fragments that are called delayed neutron precursors.
2.These precursors usually undergo beta decay, but a small fraction of them are excited enough to undergo neutron emission.
3.The emission of neutrons happens orders of magnitude later compared to the emission of the prompt neutrons.

## Relevance in Nuclear reactors

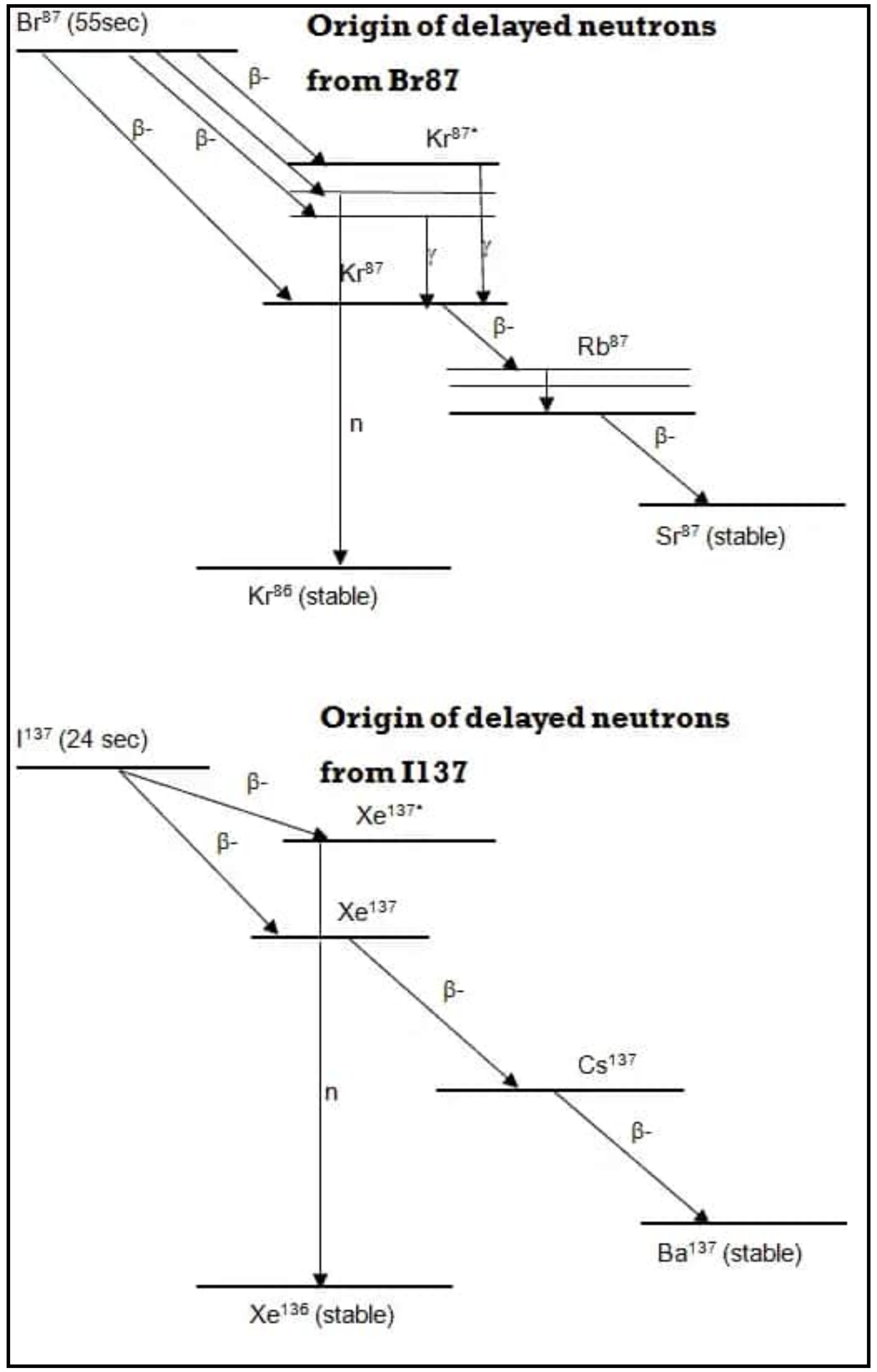
Most of the neutrons produced in fission are prompt neutrons,

"Delayed" neutrons are emitted with half-lives ranging from few milliseconds up to 55 s for the longest-lived precursor (87Br)

The presence of delayed neutrons is perhaps the most important aspect of the fission process from reactor control:

Neutron balance for CANDU reactors

| Neutrons | Contribution |
|---|---|
| Prompt Neutrons | 99,470,000,000,000 |
| Delayed Neutrons | 500,000,000,000 |
| Photoneutrons | 30,000,000,000 |
| Spontaneous Fission | 1 |
| Total ($10^{14}$ n $cm^{-2}$ $s^{-1}$) | 100,000,000,000,000 |




## Neutronic background in Spallation Facilities

Delayed neutrons from Bromine and Rubidium are produced as a results of spallation process.

Neutrons coming from (alpha, n) reactions with high energy alpha ( > 4 MeV) coming from short life alpha decay radionuclides

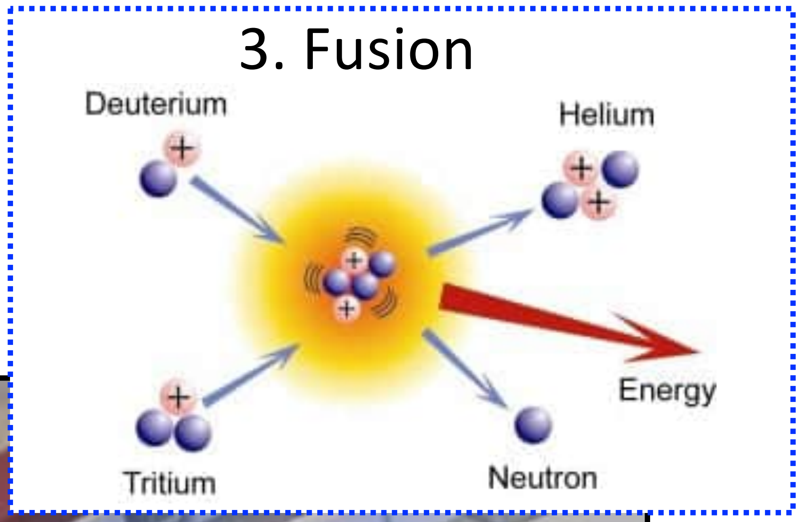
Photoneutron produced in coolant or Be when the target is not irradiated by proton but still kept in loco for cool down purposes

**Delayed neutron precursor's activity at EOI @ ISIS**

| Z | A | RN | Activity [Bq] | T1/2 |
|---|---|---|---|---|
| 35 | 86 | Br86 | 5.06E+09 | 54-sec |
| 35 | 87 | Br87 | 1.27E+09 | 55-sec |
| 35 | 88 | Br88 | 4.43E+09 | 15.5 sec |

# A Few Words on the Other Production Mechanisms of Neutron….

# Intermediate Flux Sources (Fusion Sources)

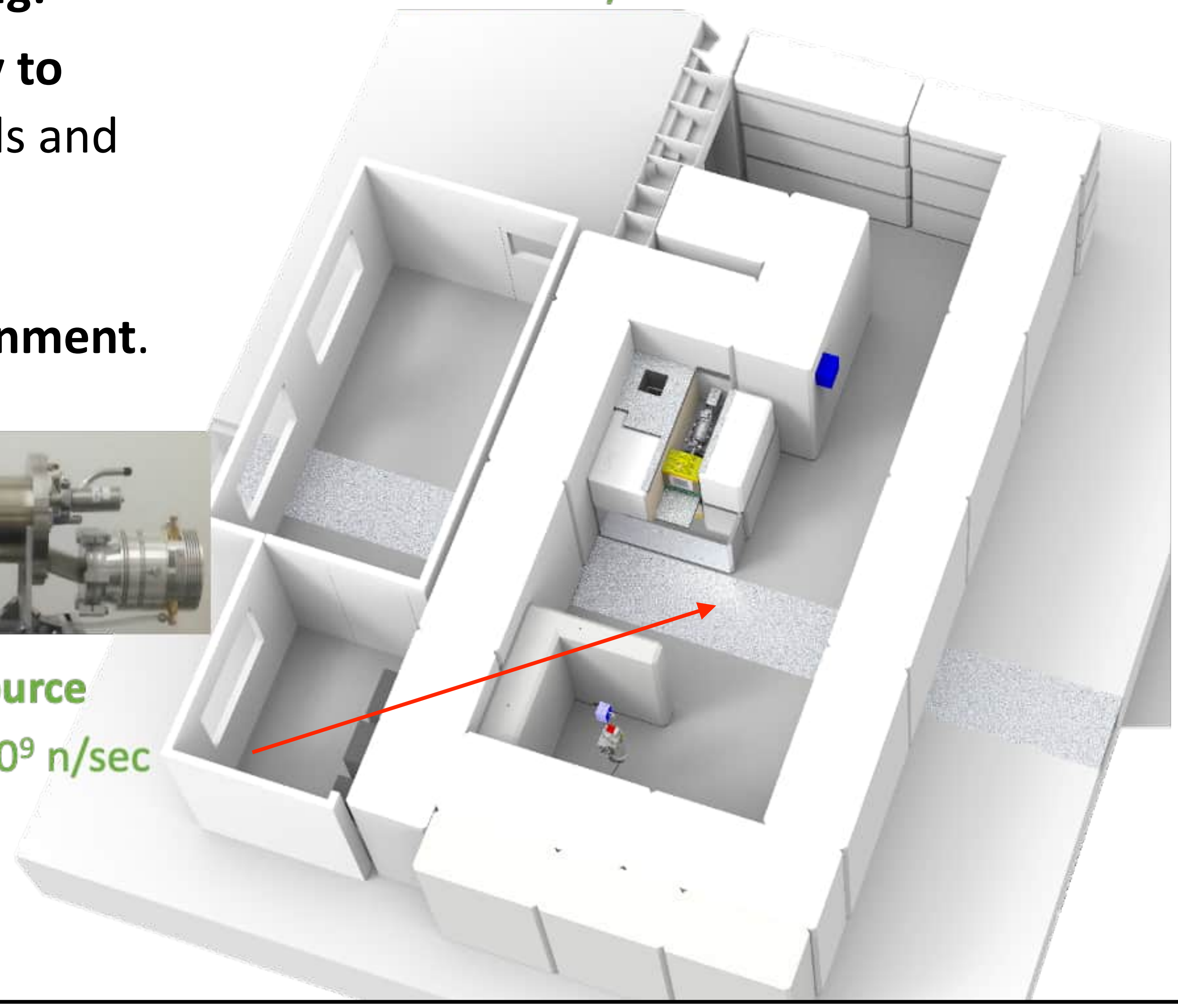



**Motivation**

**Electronics testing:**

- **Complementary to ChipIr** → methods and test setups.
- **Training**.
- **Reactors environment**.

**NILE-RAL**





Fast-neutrons fields at 14MeV (with a total flux of $10^{10}$ neutrons/sec) and 2.5MeV (with a total flux of $10^{9}$ neutrons/sec).

Neutron D-T & D-D generator(fusion neutrons @ 14 MeV and 2.5 MeV respectively ) up $10^{11}$ -$10^{8}$ n/s

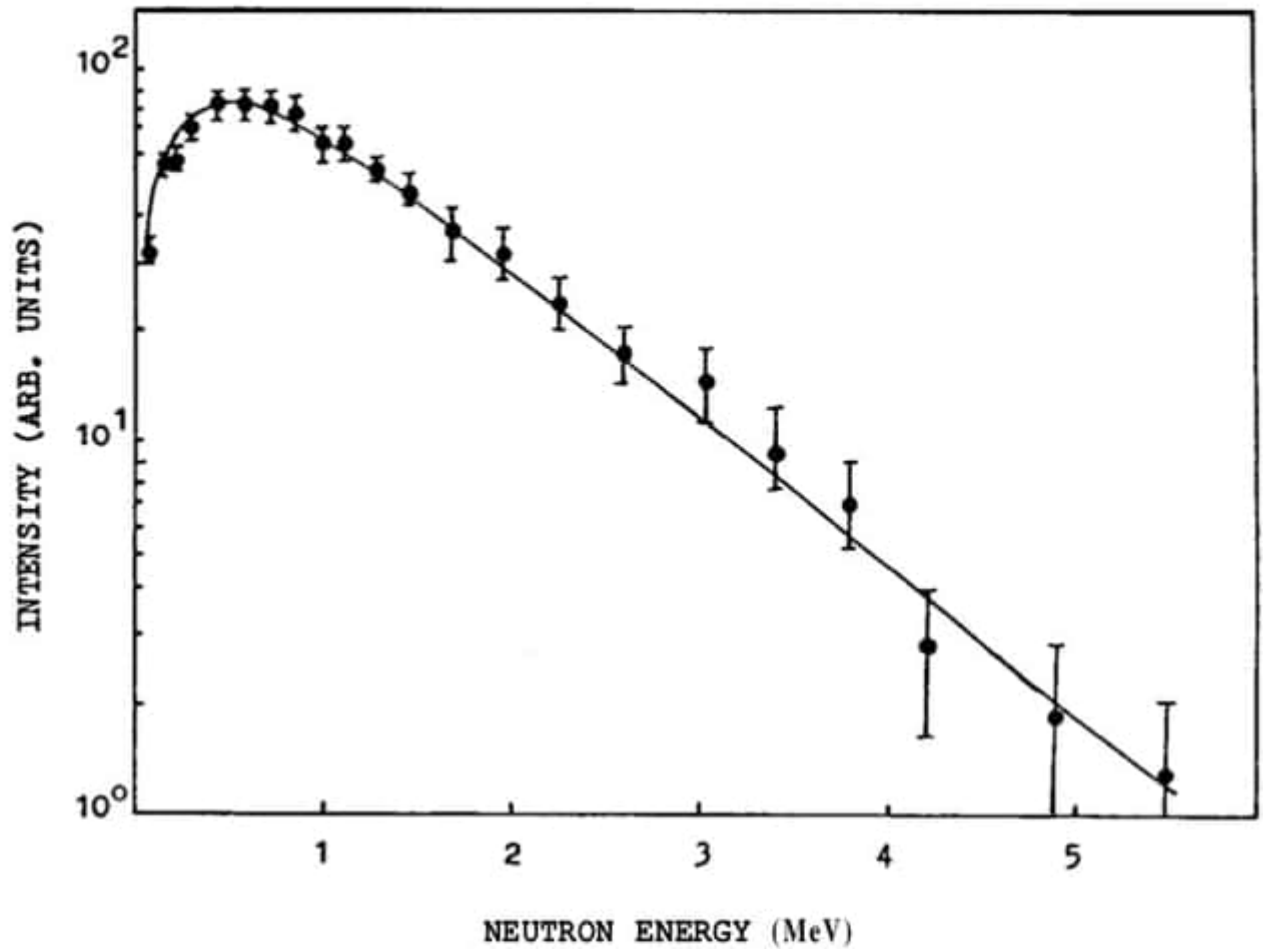
$$D + T \rightarrow n + {}^{4}He \quad E_n = 14.1\ MeV$$
$$D + D \rightarrow n + {}^{3}He \quad E_n = 2.5\ MeV$$

# Low Flux Sources: Laboratory Neutron Sources

- **Transuranic nuclide in low Z matrix**: AmBe 1 Ci —> 10^6 n/s
- **Photo-neutron source: Sb-Be** Be bombarded by photon with E above the binding energy of nucleons ( E>1.7 MeV) (short half life) emits neutrons: (1 Ci —> 5 * 10^6 n/s)
- **Spontaneous fission source:** Cf-252

$$\alpha + {}^{9}Be \rightarrow {}^{13}C^{*} \rightarrow \begin{cases} {}^{12}C^{*} + n \rightarrow \gamma = 4.4\ \text{MeV} \\ {}^{8}Be + \alpha + n \\ 3\alpha + n \end{cases}$$

from ${}^{241}Am$, ${}^{238}Pu$, ${}^{242}Cm$, ${}^{226}Ra$, ${}^{227}Ac$...

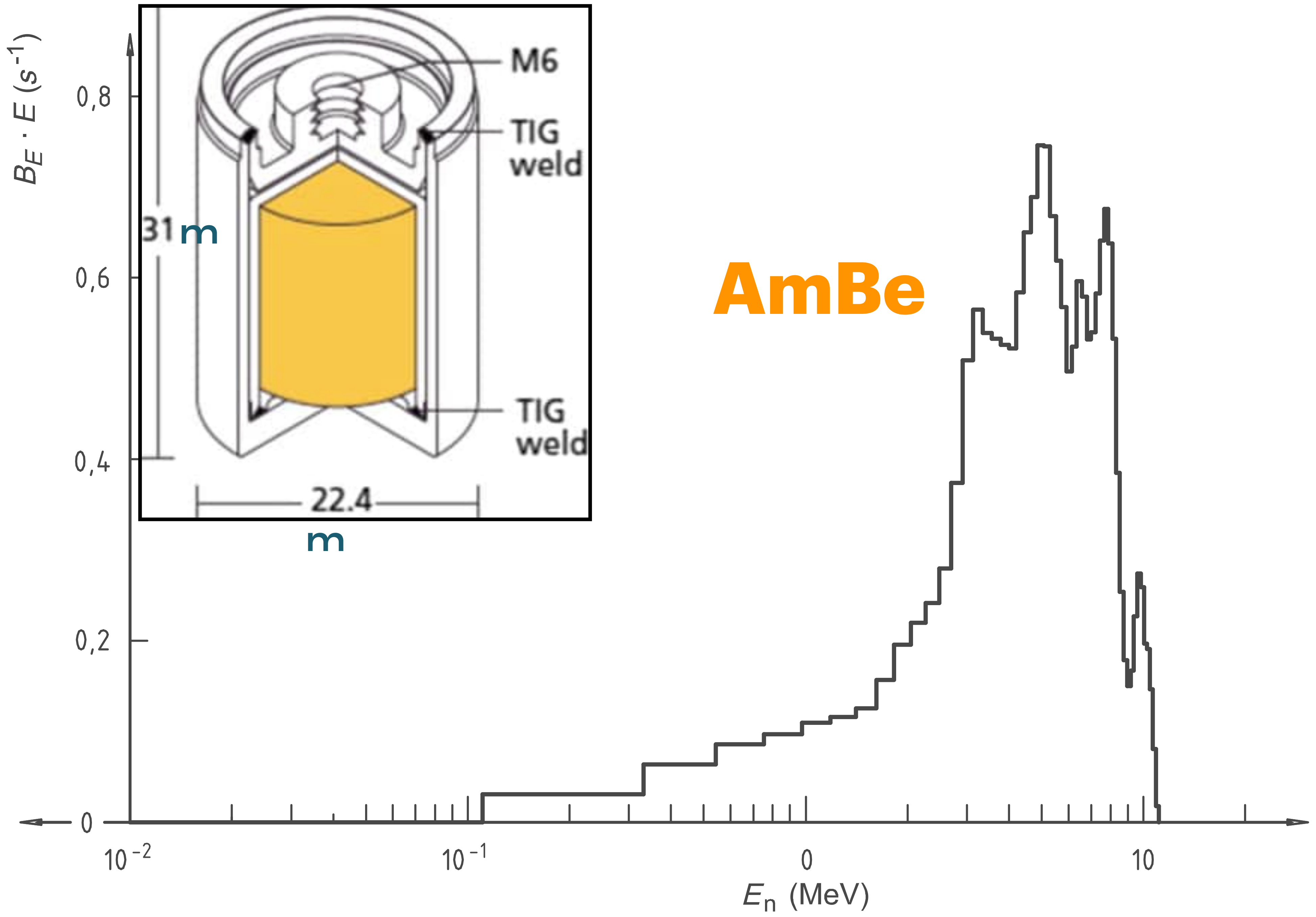



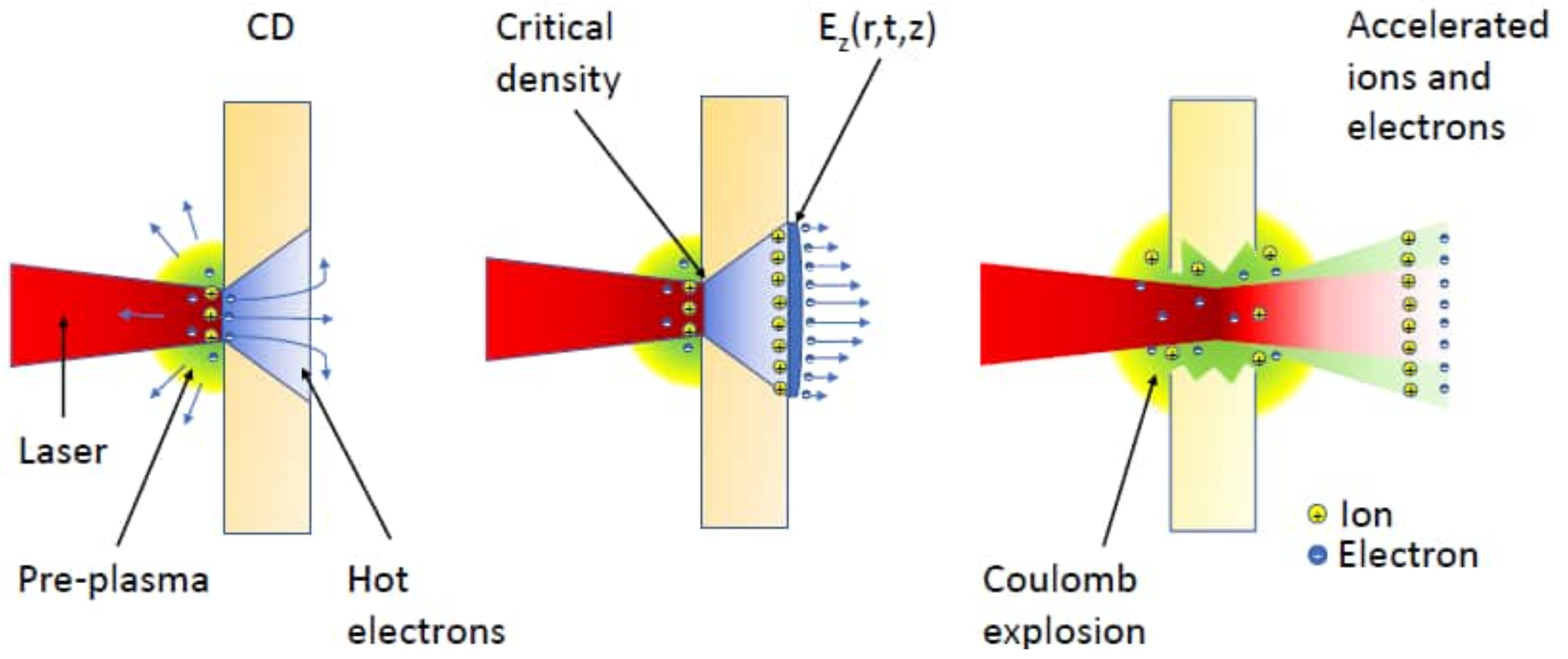

**Figure A.4 — Neutron spectrum from a ${}^{241}$Am-Be(α,n) source**

Used in metrology for calibration of neutron dose rate meters

${}^{252}$Cf (Californium)—> 10^7-10^8 n/s
– 2.6 year half life; mainly alpha decay but also fission(SF branch ratio about 3.1 percent)
– 1 mg emits $2.3\times10^{11}$ n/s with average energy 2.1 MeV
– 3.8 n/fission + 9.7 γ

# Innovative Neutron Sources: Laser Driven Sources

## Laser driven neutron sources are undergoing rapid development at big laboratories




Neutron beams with multi-MeV energies can be produced using laser based acceleration mechanisms.

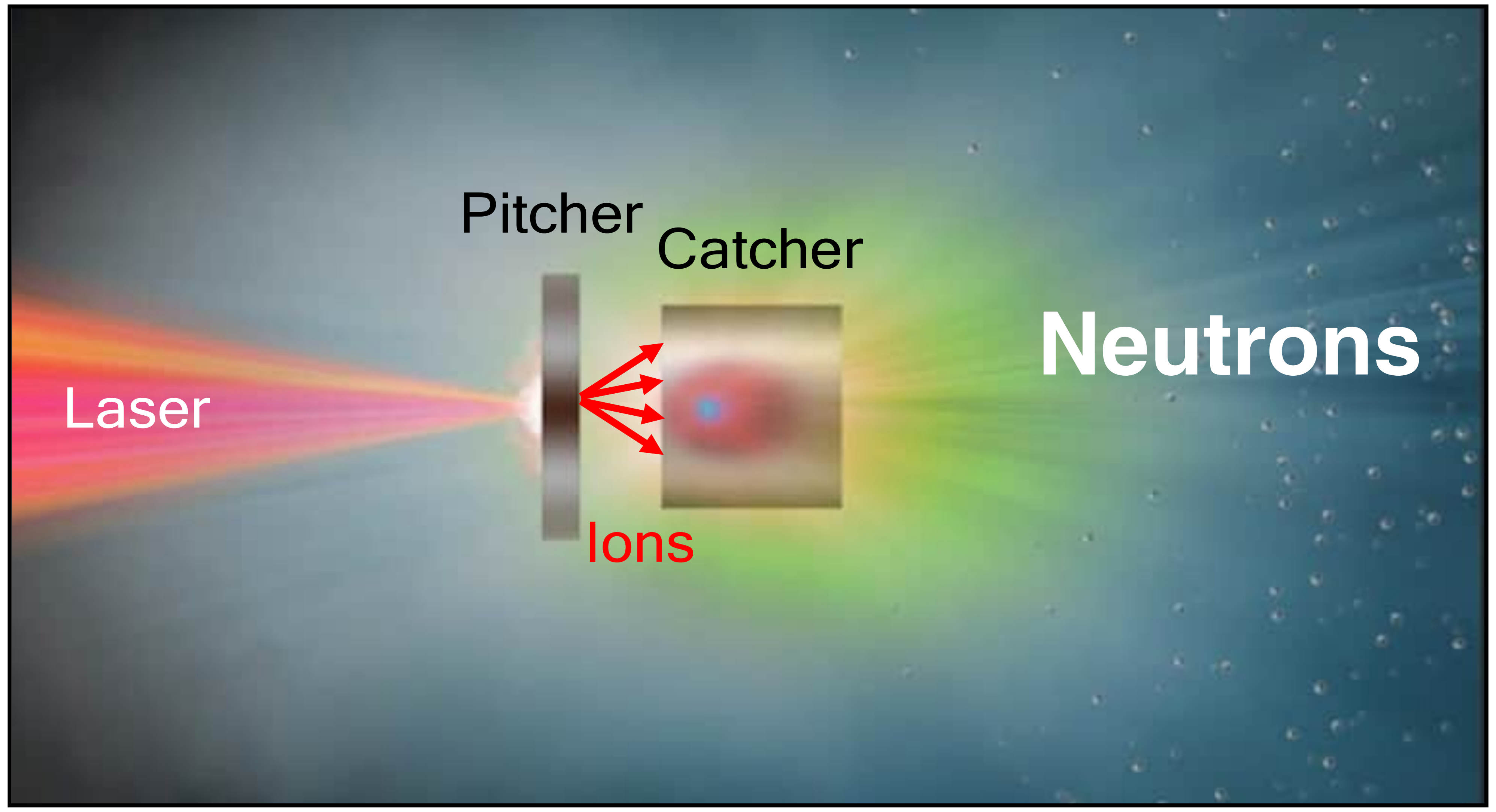
Within plasma intense electric fields are generated

Two stage process:1) ions produced in the Pitcher are accelerated and 2) converted into neutrons through nuclear reactions in the Catcher: such as 2d(d, n)3He and 7Li(p, n)7Be

Spallation and laser-driven sources are pulsed owing to the short duration of the driving ion beam,: t is in orders of μs for spallation and ps for laser driven source respectively.

Compared to conventional accelerators, laser based techniques offer the advantage of:

- reduced charged particle acceleration distances, from the meter scale to the millimeter scale due to the high electrical fields supported by plasmas
- high instantaneous neutron production rates, due to the short pulse duration of the laser and the corresponding short acceleration time.



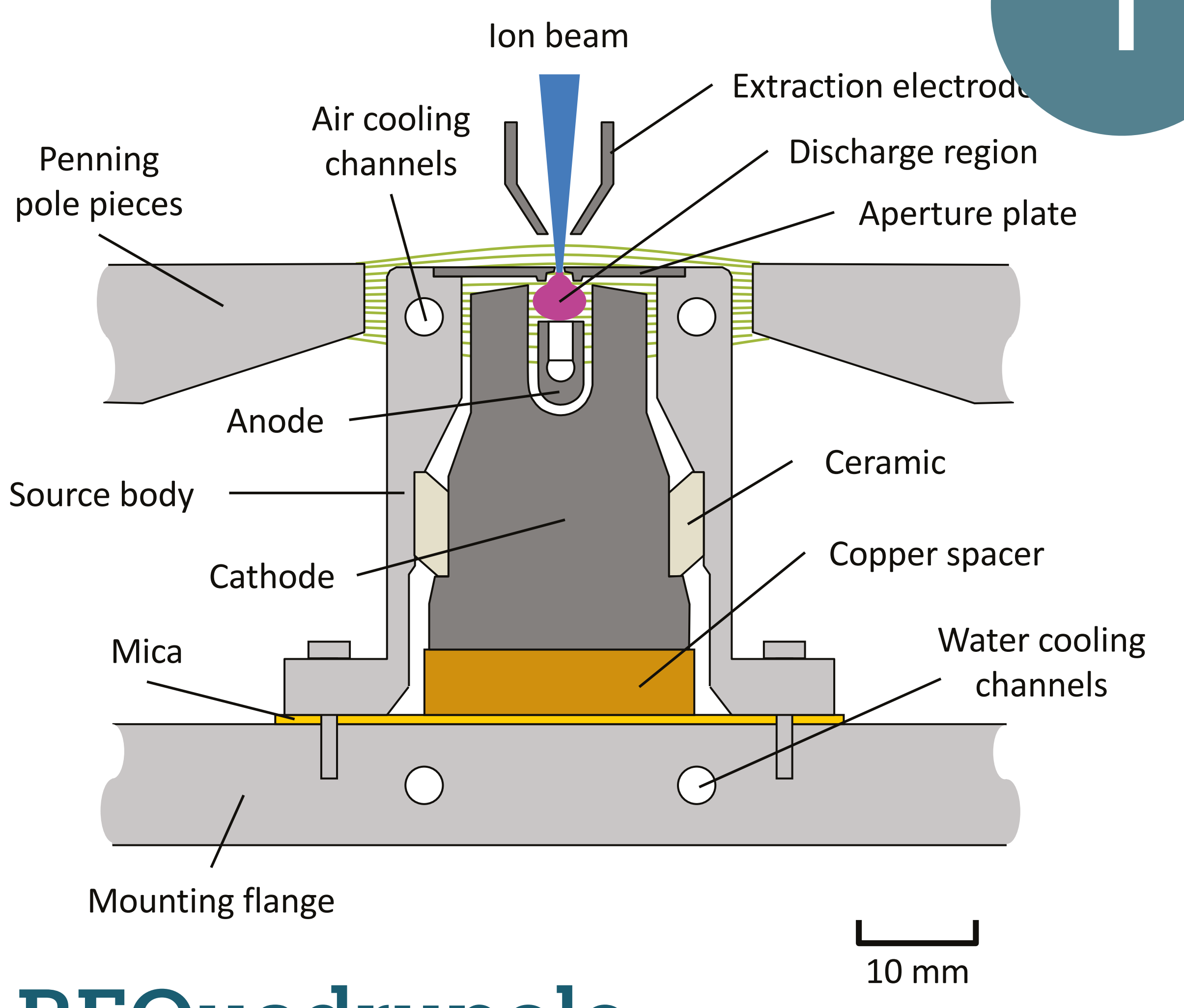
# Proton Accelerator &
# Design of the TARGET for Spallation Sources

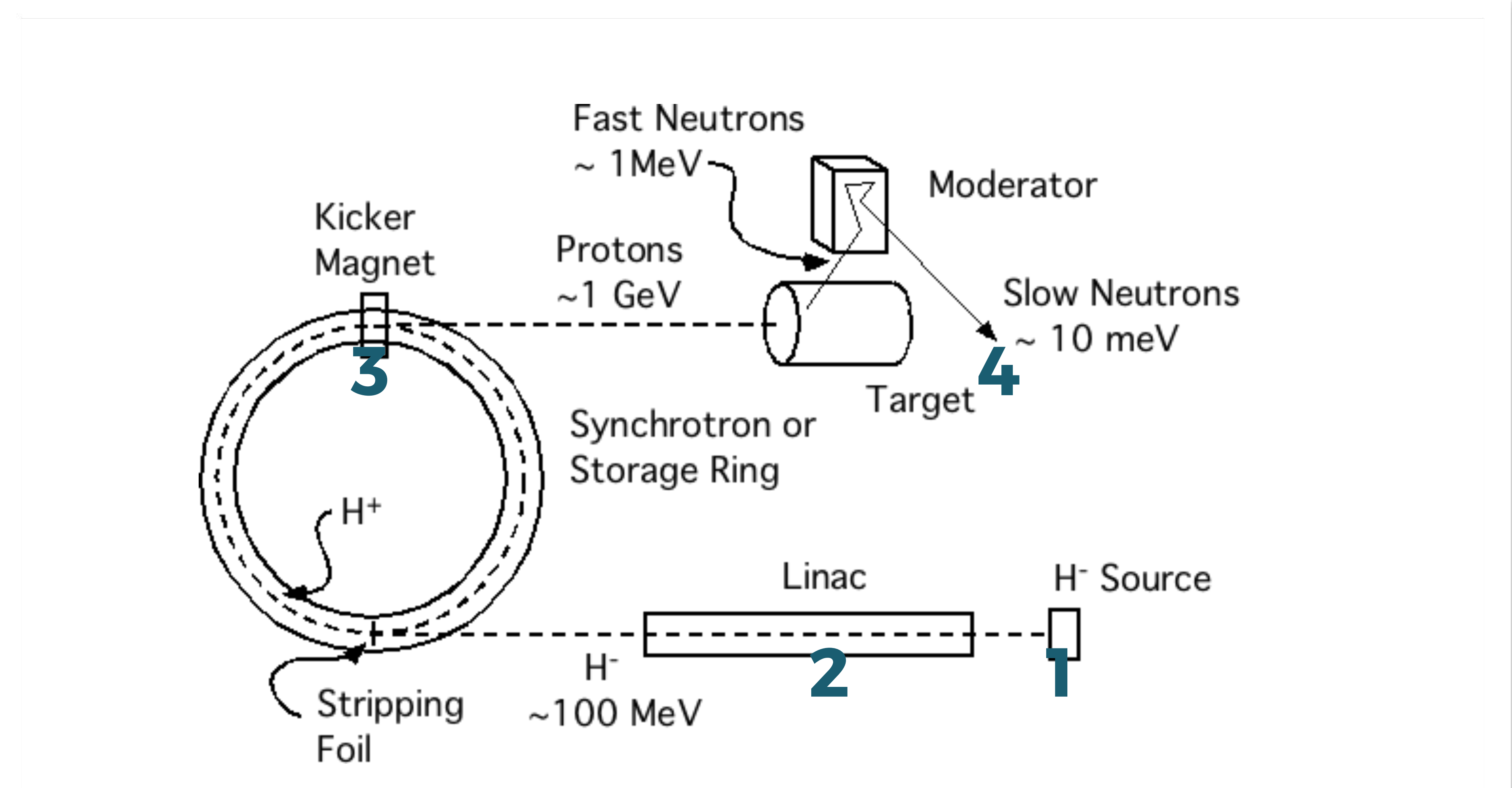
(Where Primary Protons and Spallation Neutrons Are Produced)

# Anatomy of a Pulsed Spallation Source (ISIS)

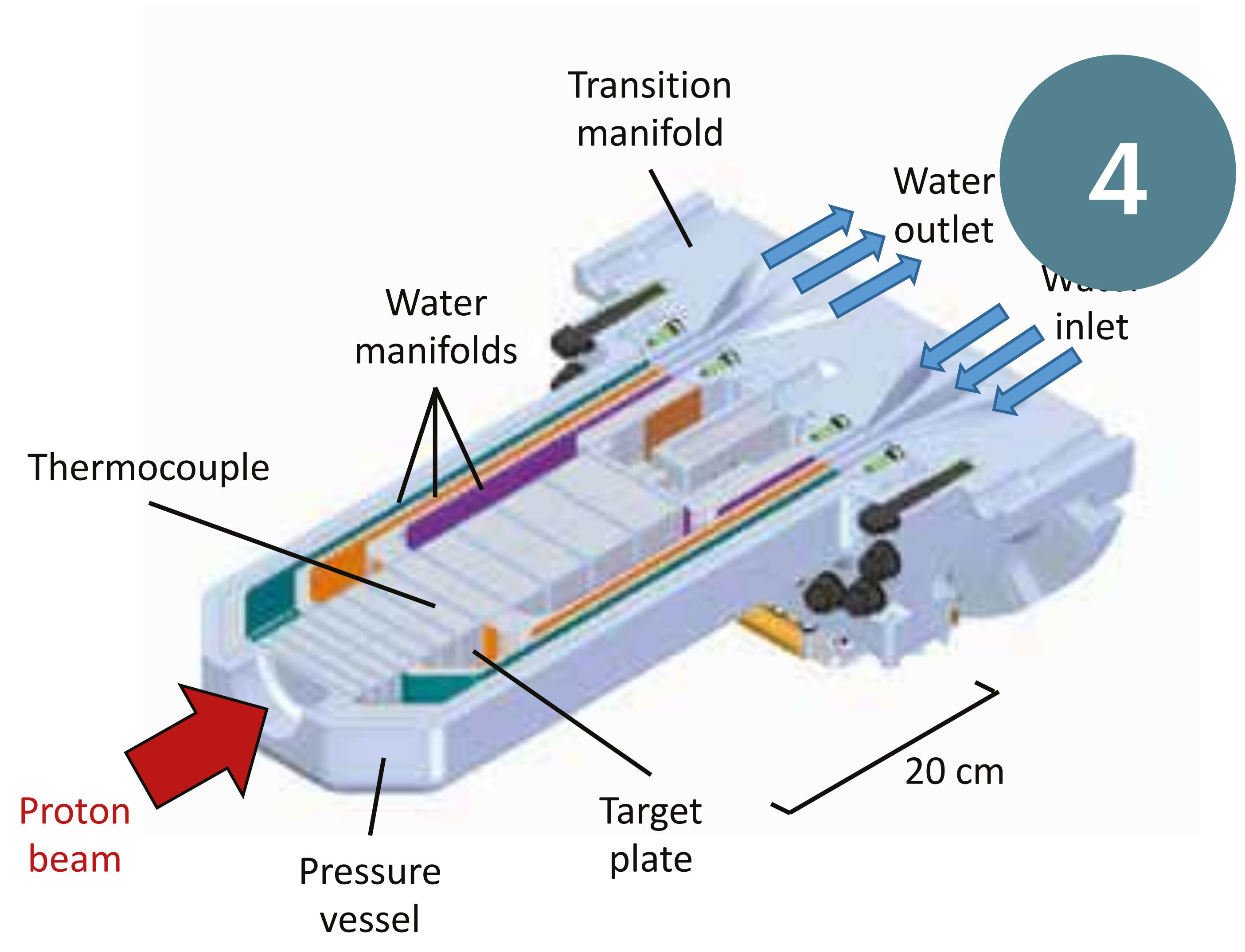
*Spallation neutron sources can offer the extra advantage of a time structure of the neutron beam that should best match certain experimental techniques (TOF)*

## The ion source



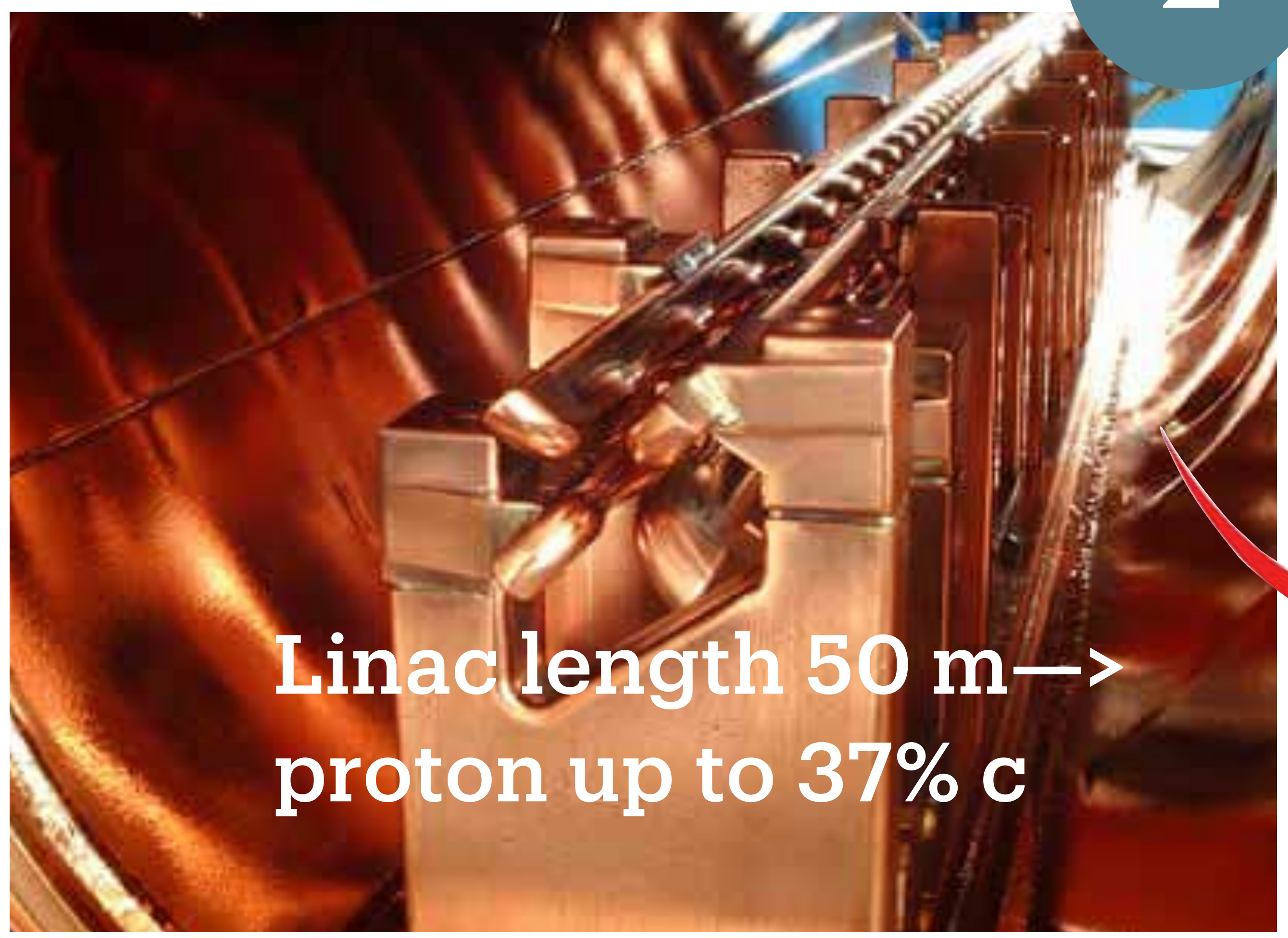

Moderator(s) close to the target slow down fast neutrons to energies useful for applications.



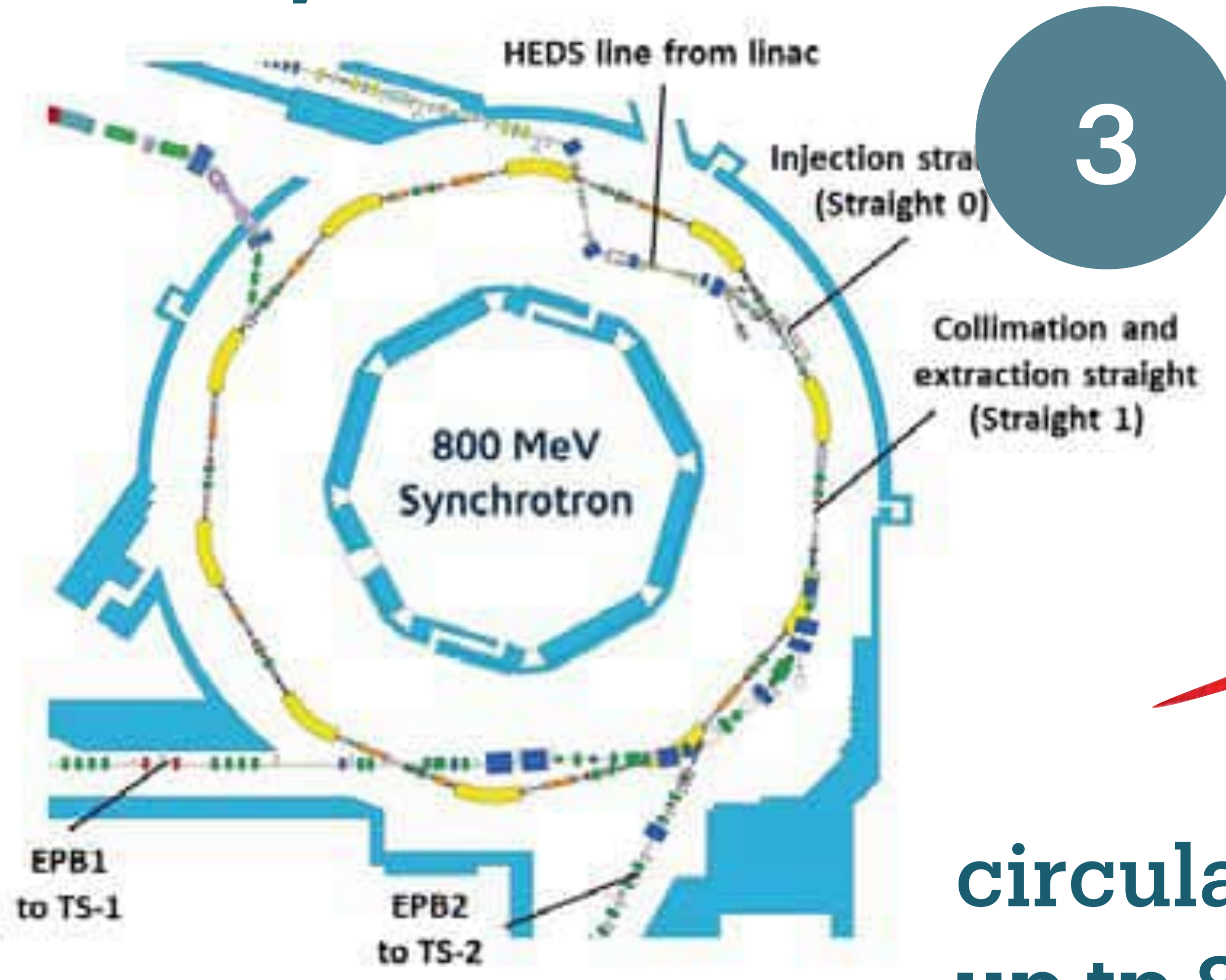

. Schematic diagram of TS-1 neutron-producing target.

## RFQuadrupole

## The RF LINAC



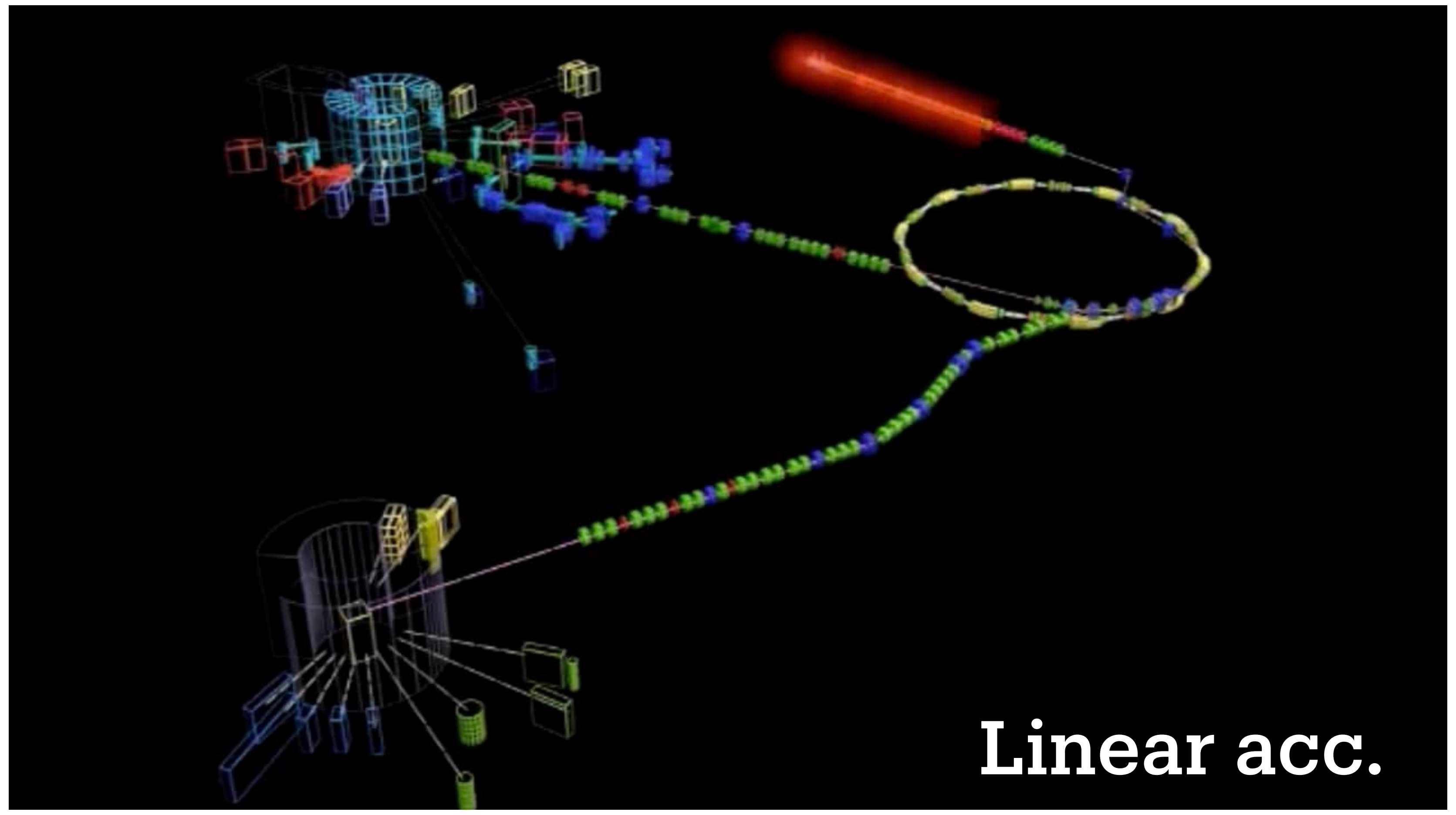

## The Syncrotron

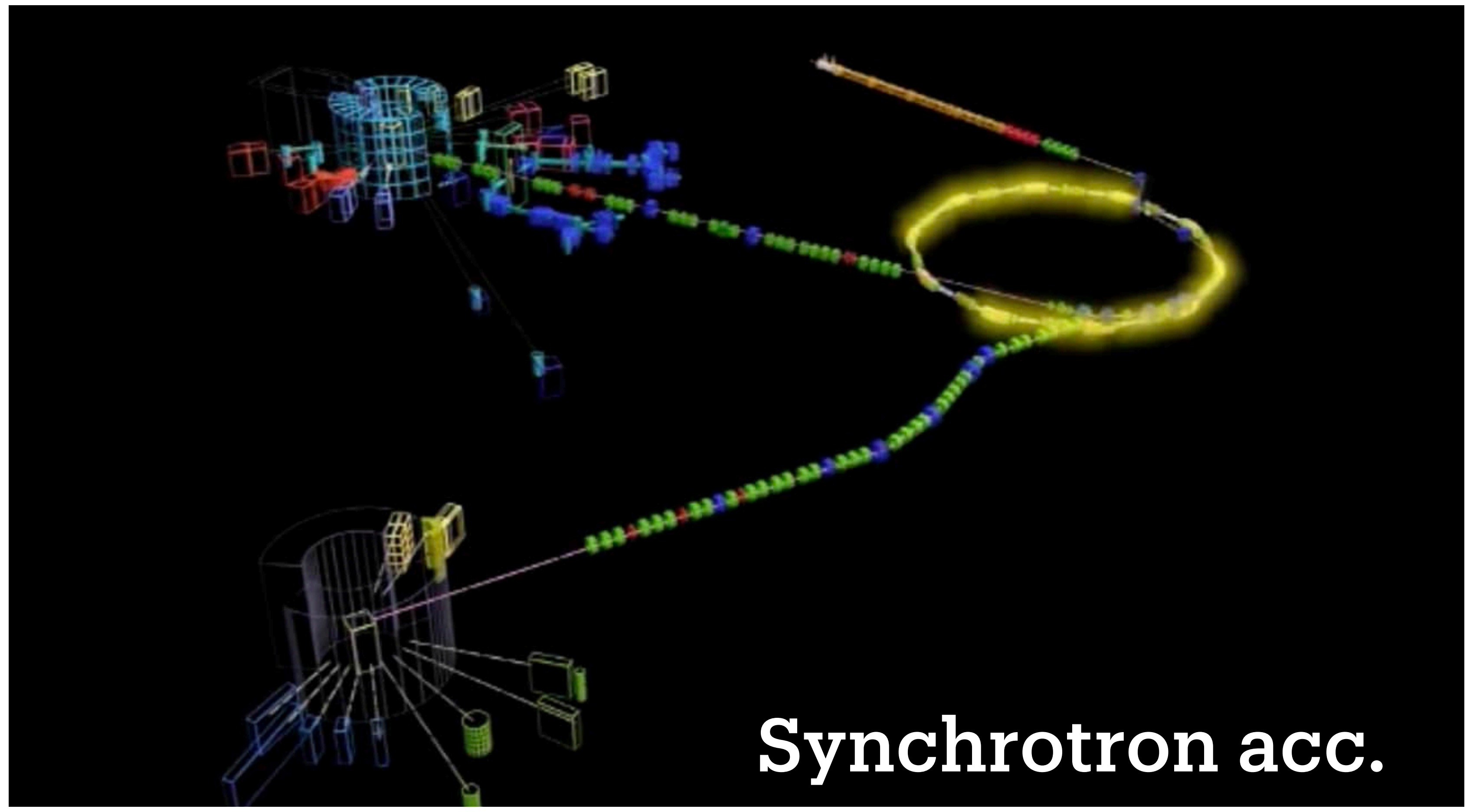


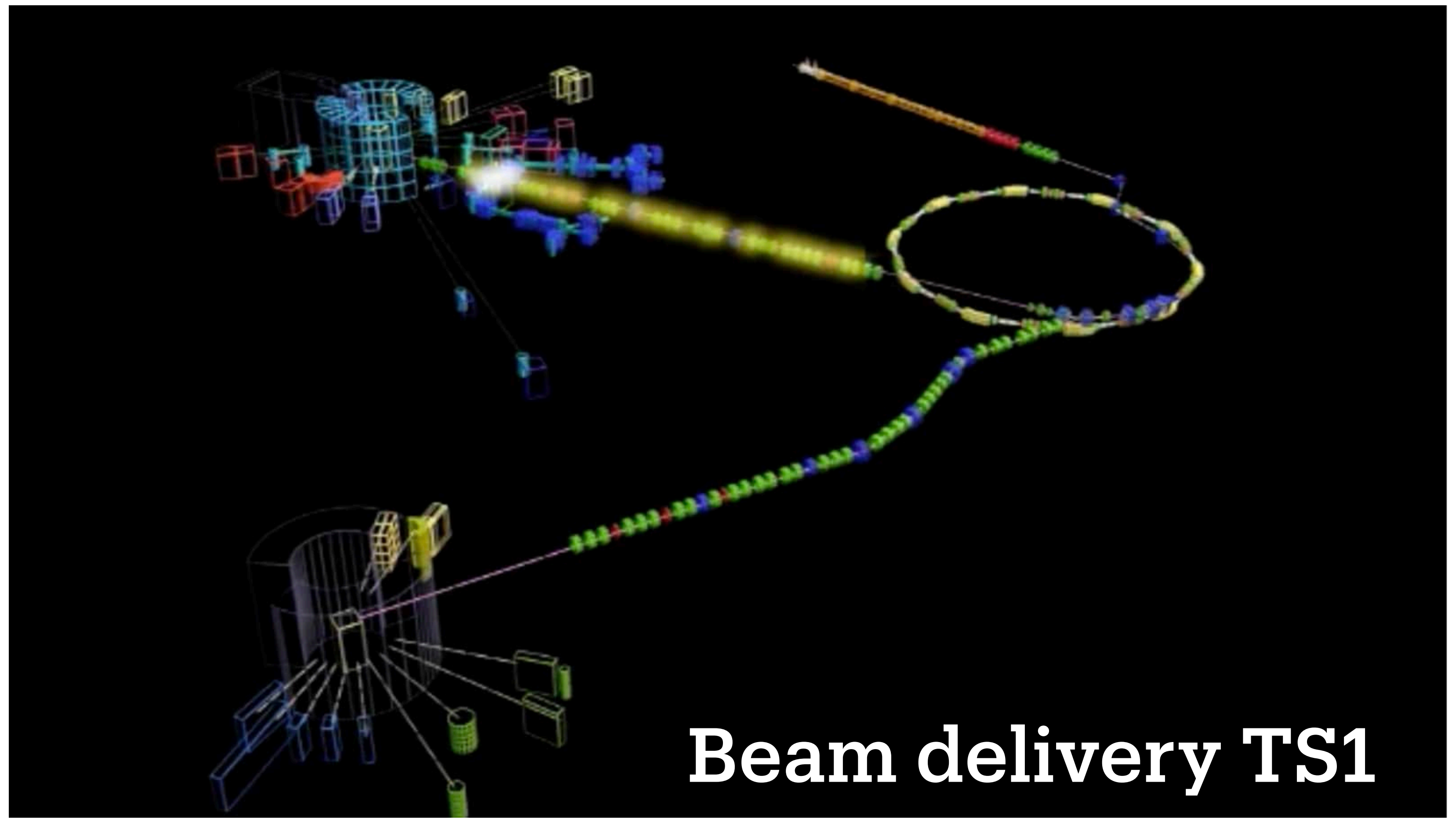

## Kicker magnet

**circular orbit 163 m—> up tp 84% c**

# BEAM Time Lapse in ISIS TS1




ISIS ion source creates negatively charged hydrogen ions made up of two electrons and one proton. These are fed into two linear accelerator sections through which they are focused and accelerated up to 36 % the speed of light

The third final accelerator is a circular synchrotron.
At the entrance the ions are stripped of their electrons by a thin alumina foil leaving the bare protons

The synchrotron is made up of ten sections each consisting of a bending magnet to keep the protons on their circular path and five focusing magnets

The beam is separated in 2 bunches

After 12000 revolutions of the synchrotron the protons are traveling at 84% of the speed of light at this speed they could travel six times around the earth in just one second. Through a kick magnet they are delivered to the TS1 or TS2 station

Every 5 pulses TS1 1 is delivered to TS2

# Design of Target for Spallation Sources

- The essential function of the targets in spallation sources is to convert the high-energy proton beam into as many neutrons as possible, whilst occupying as small a volume as possible.
- Minimising the volume within which protons are converted to neutrons results in the highest neutron fluxes.
- Within the target, most of the power in the proton beam appears as heat, which has to be carried away by cooling .
- For neutron production to occur, nuclear collisions must take place before the incident particle reaches the end of its range.

**Choosing the right thickness for a given $E_p$ :**

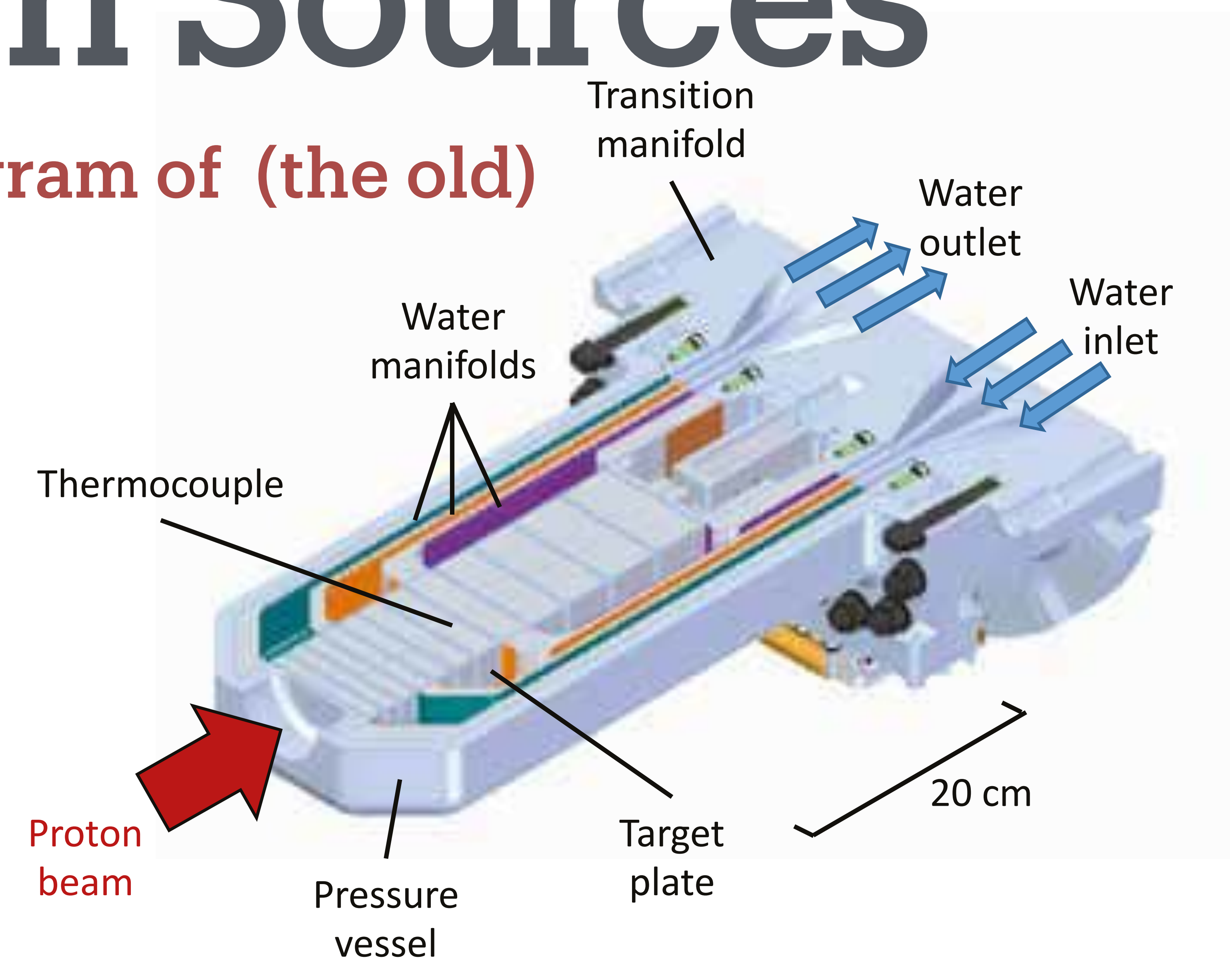
$\lambda$ is almost constant above 100 MeV and approximately expressed by $\lambda = 33A^{1/3}$, giving about 200 g cm−2 for heavy nuclei—> $\lambda$ =10cm

The probability for the nuclear collision, Pn:
Pn = 1 – exp(–R/$\lambda$), where R is the particle range

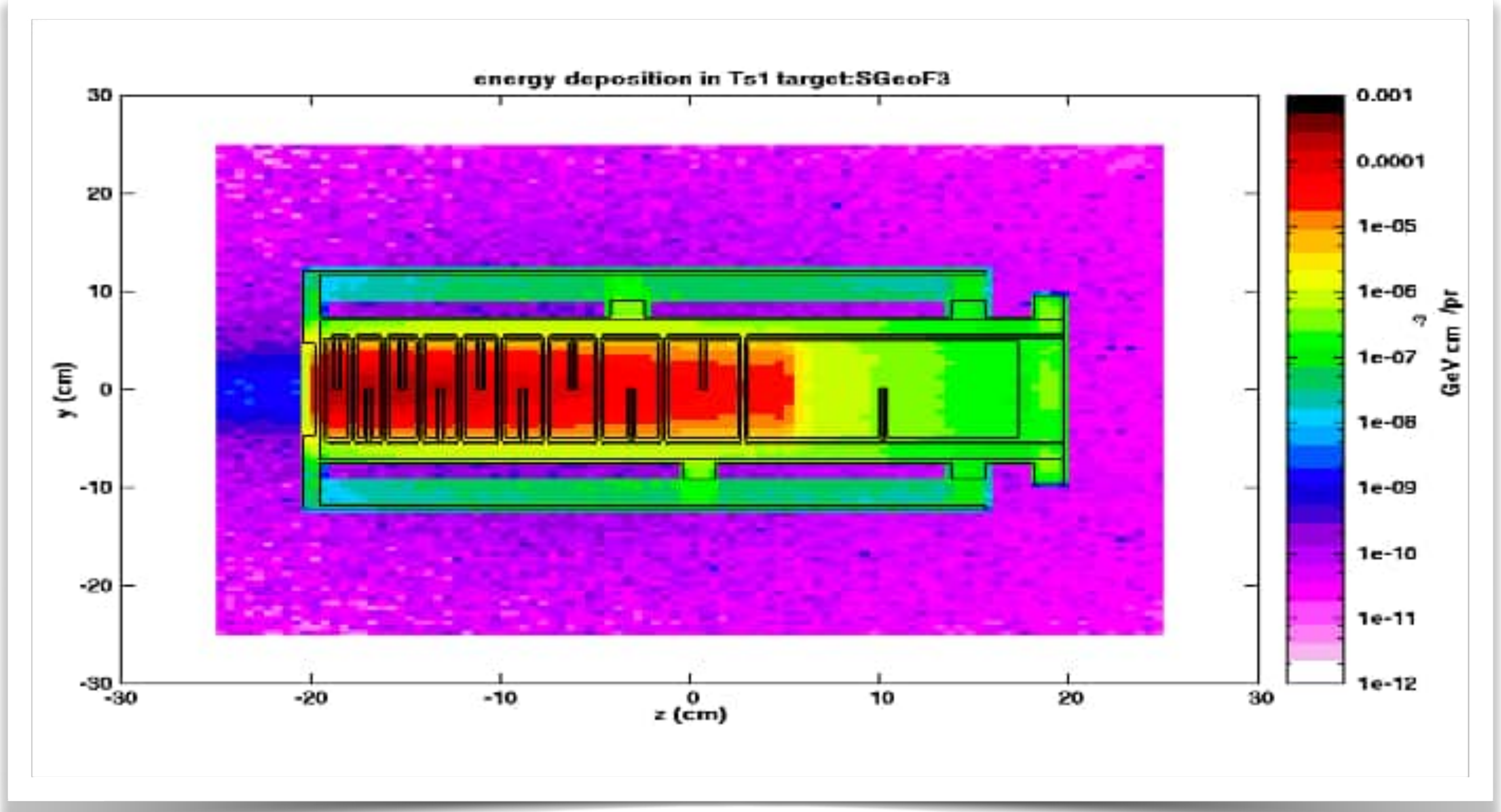
To get Pn >90%—> R(E)> 2.5 $\lambda$—>R>25 cm
proton of 800 MeV in W —> R($E_p$)= 25 cm

A target thickness larger than 25 cm satisfies the above condition—>
The ISIS target L =40cm (sum of plate thickness =30 cm)

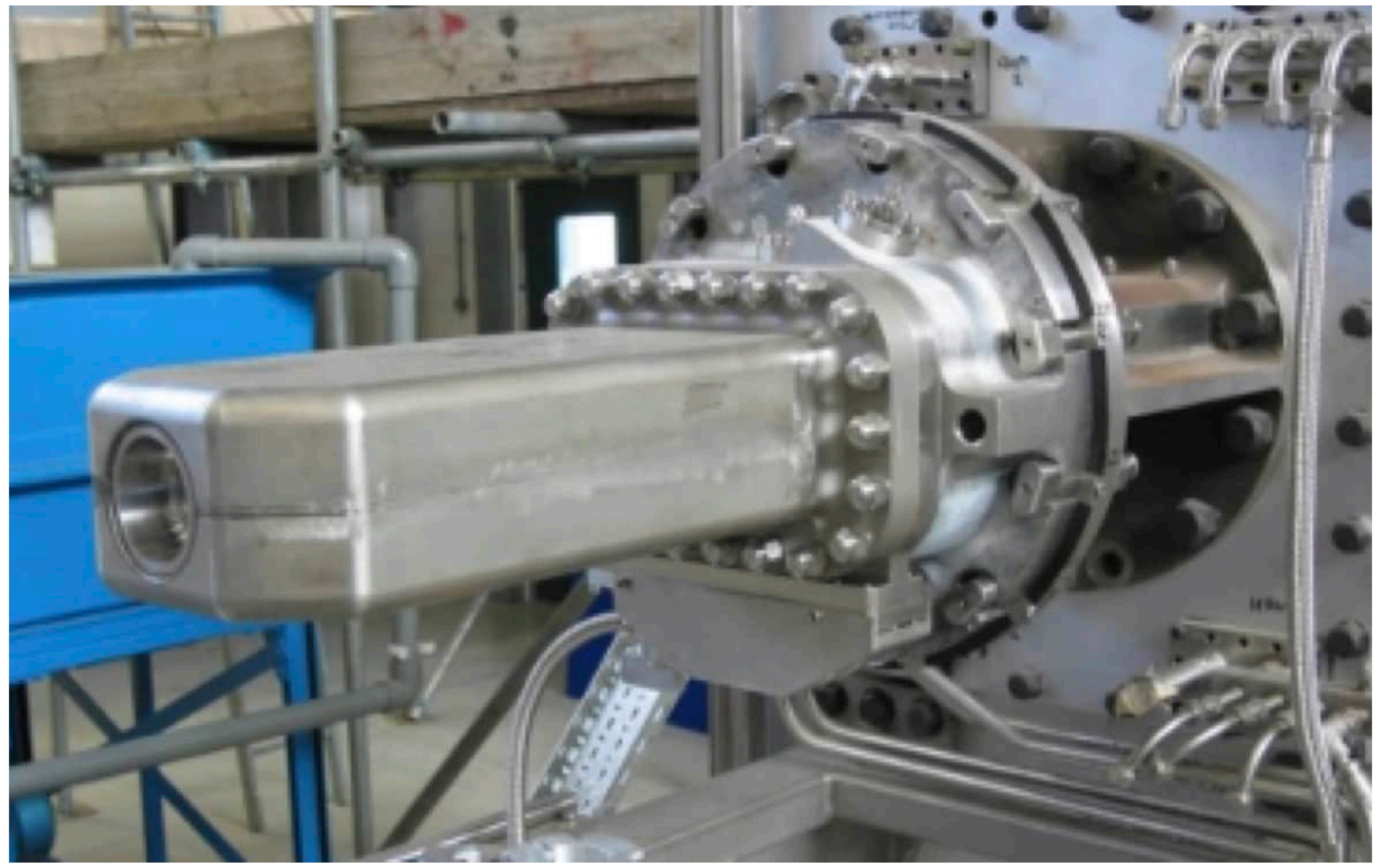
## Schematic diagram of (the old) ISIS-TS1 target

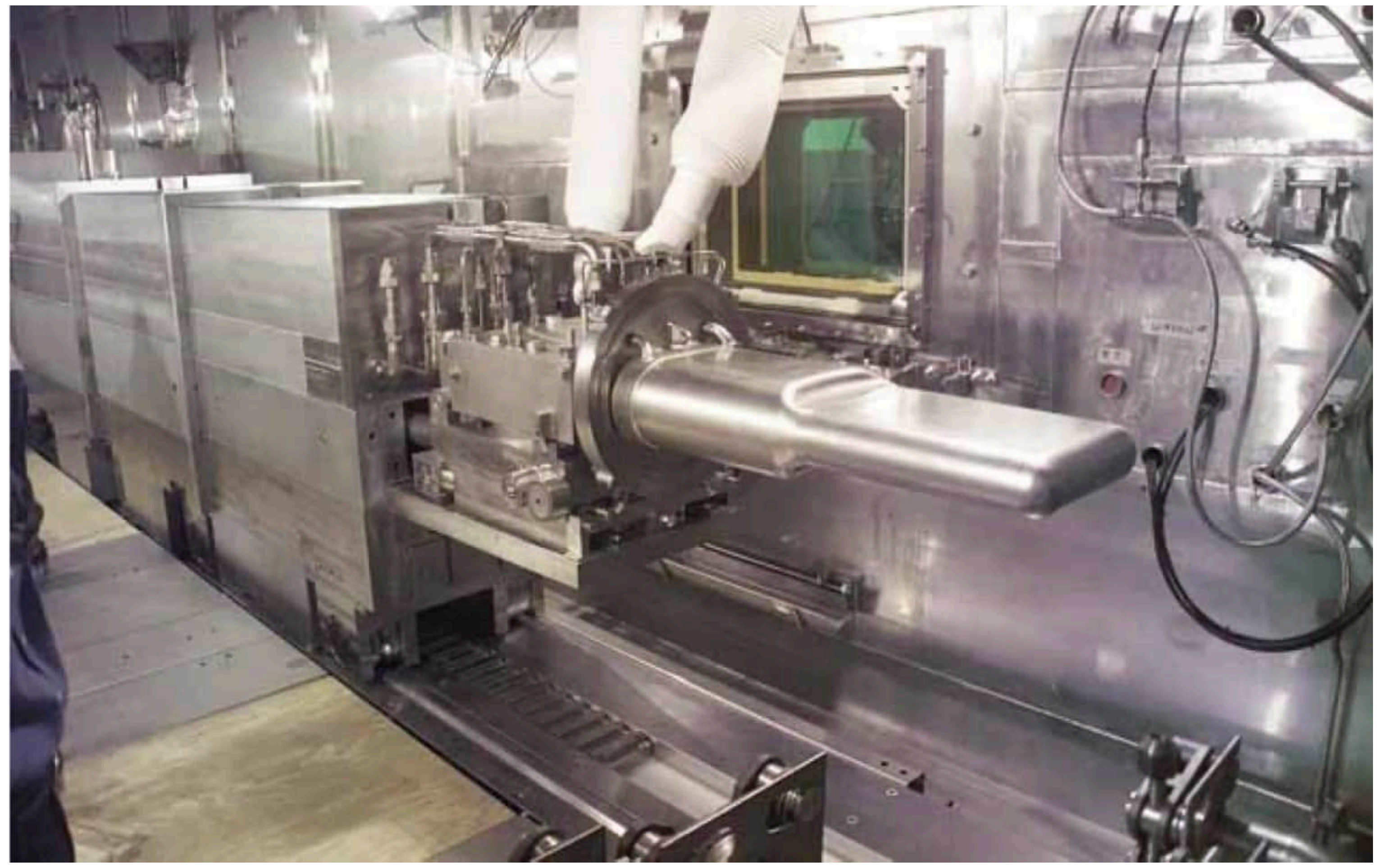


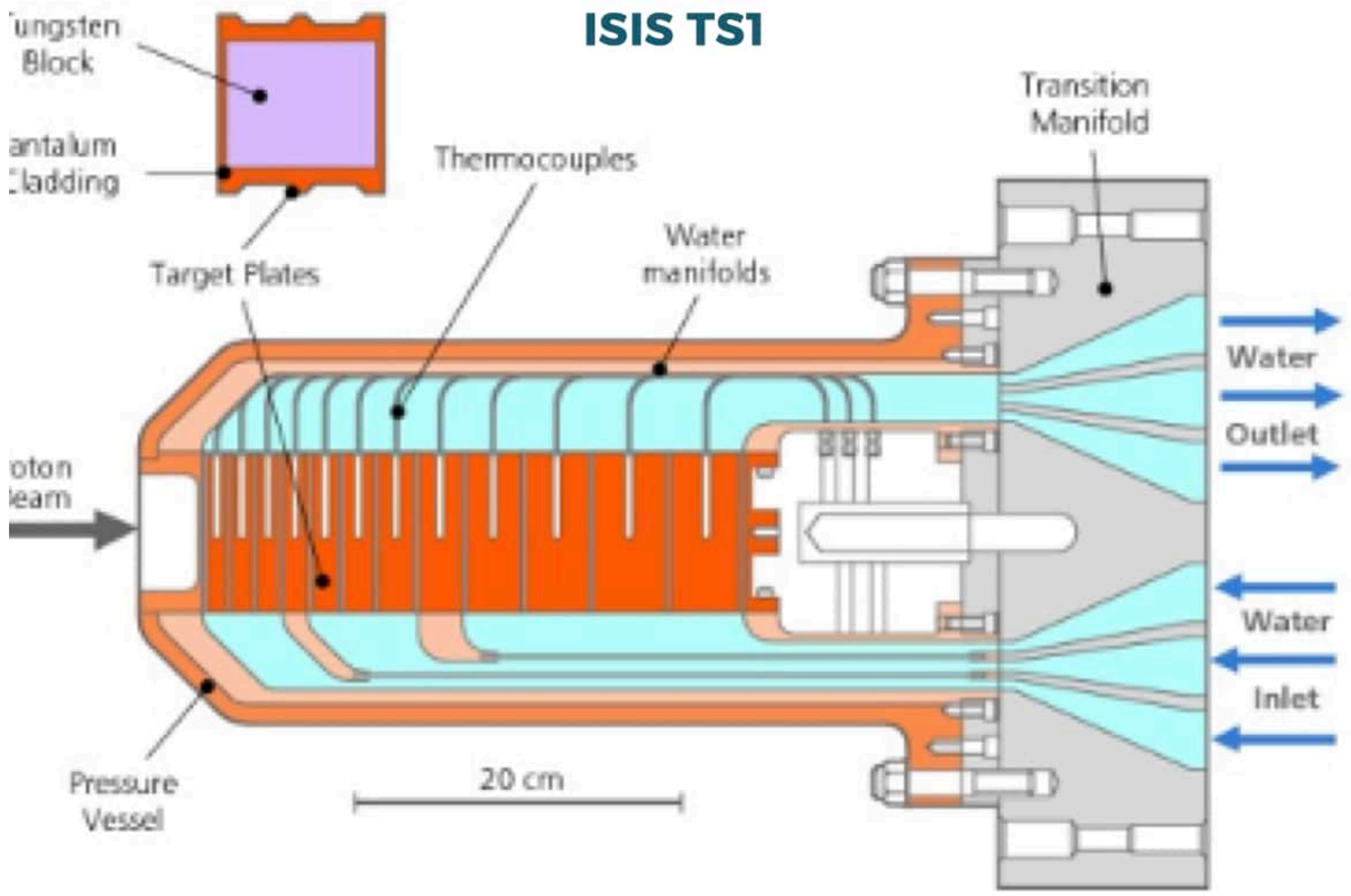

## Results of MC Simulation of Energy deposited in the target

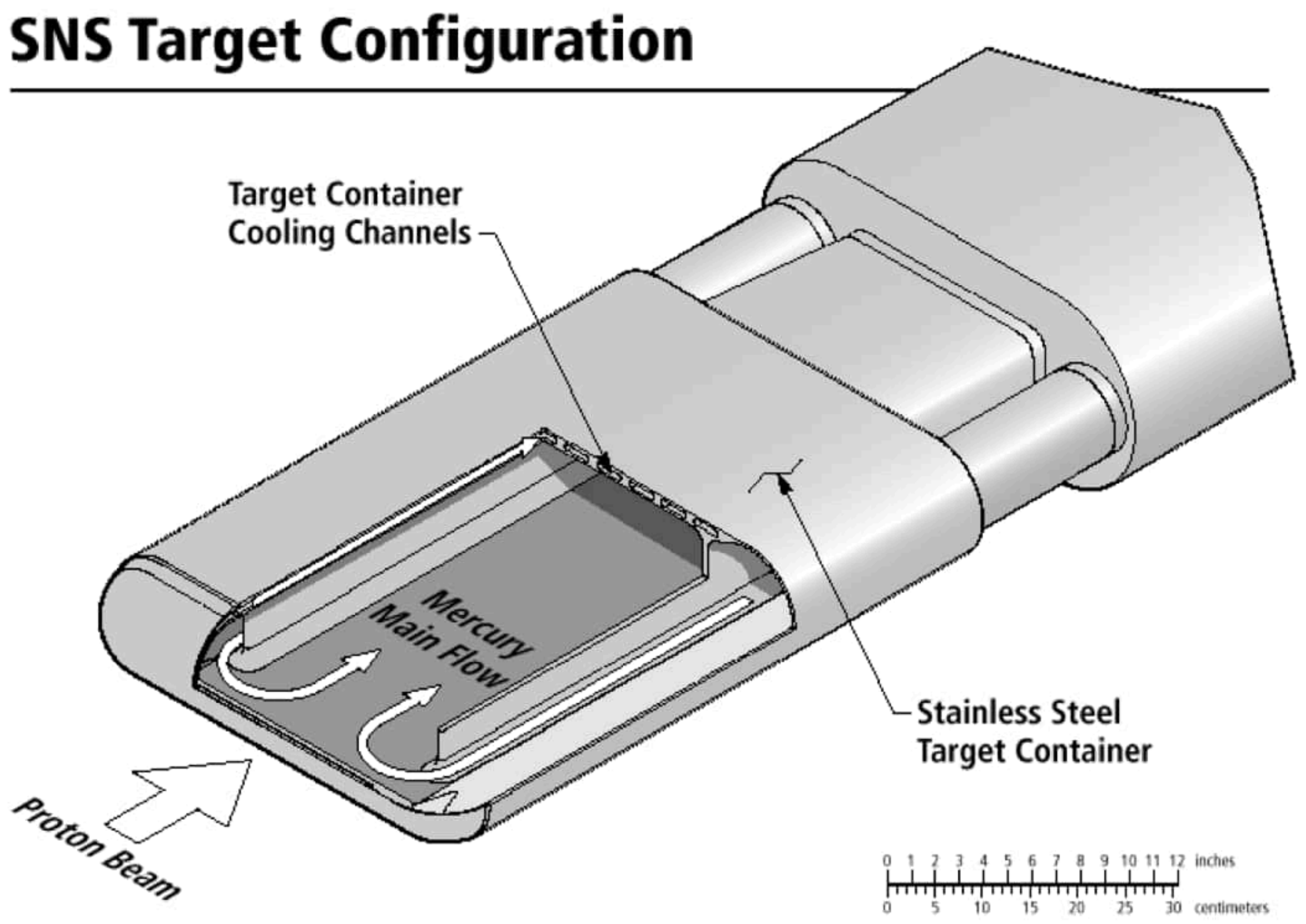


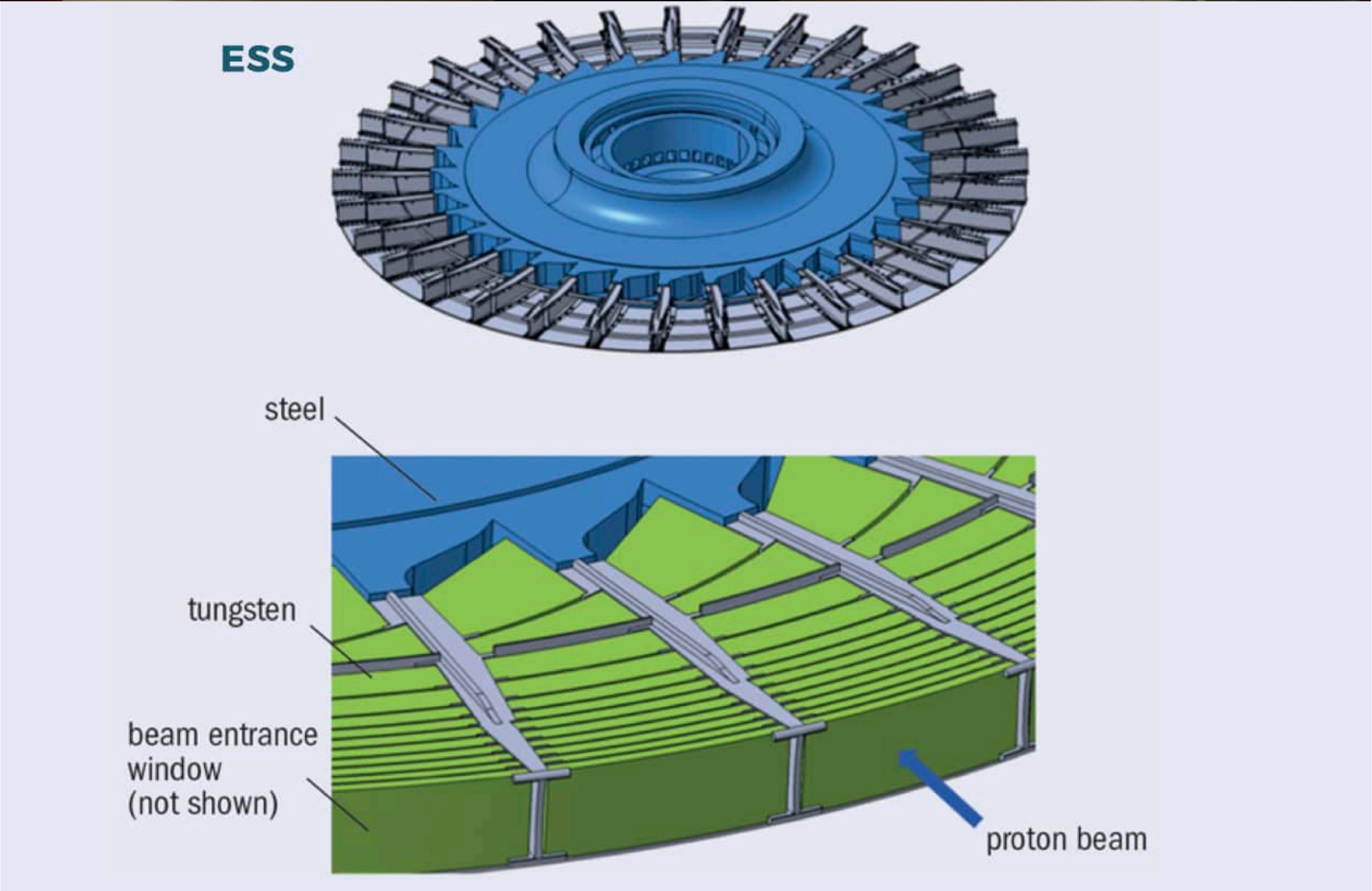
# Spallation Targets as a Function of Beam Power








160 kW in TS1 | 1.4 MW | 5 MW

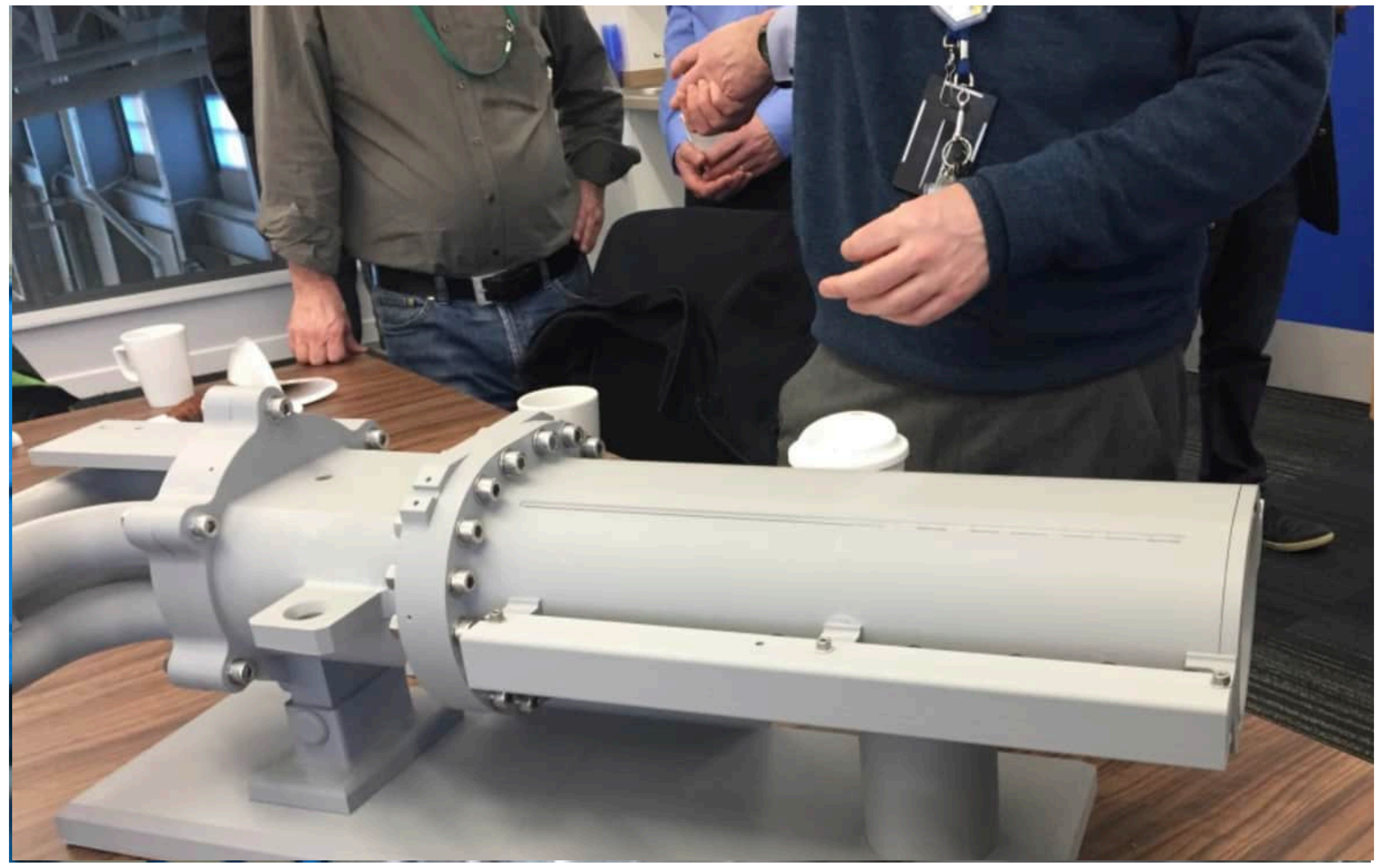
Beam Power

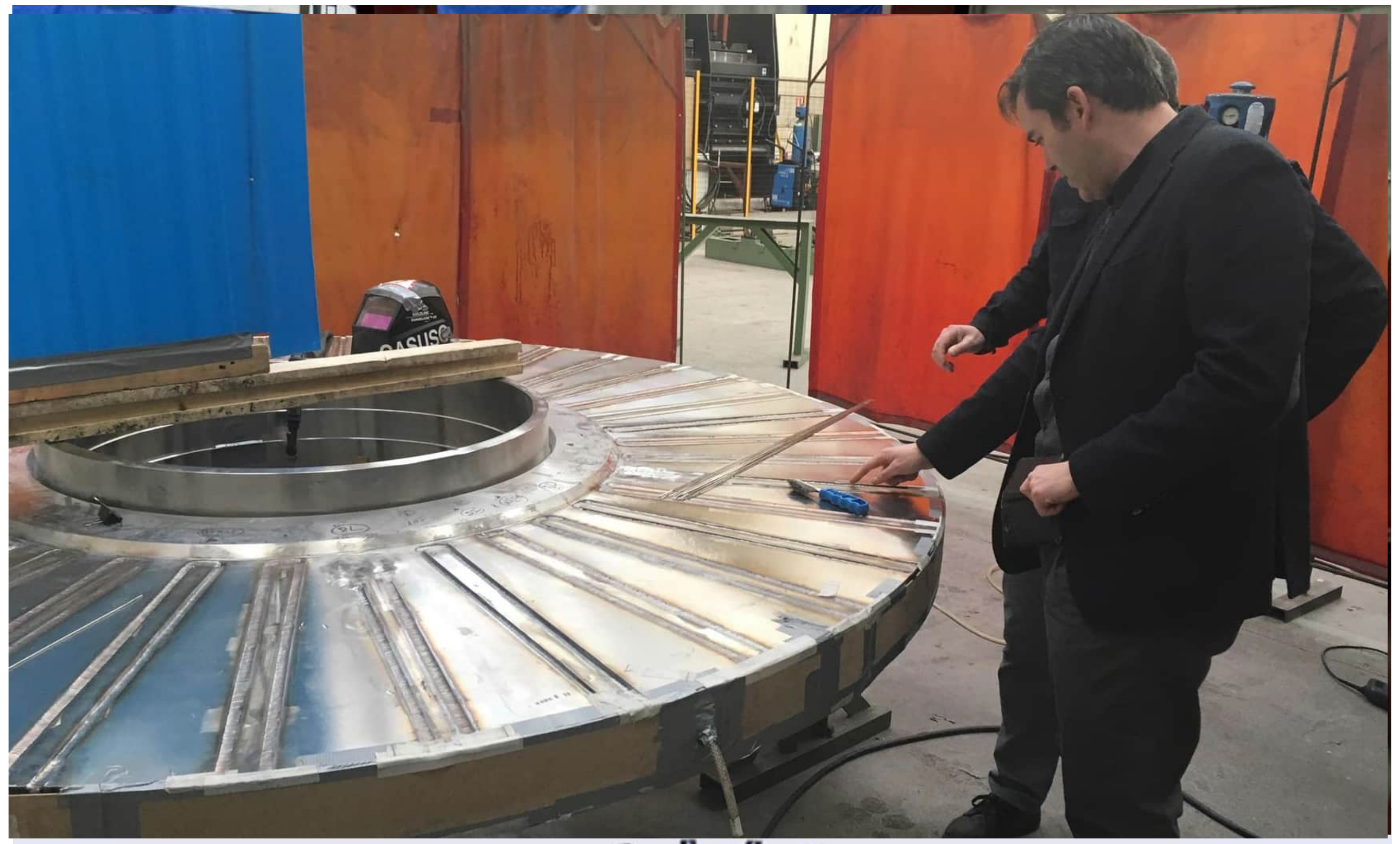
**ISIS**
Segmented Target

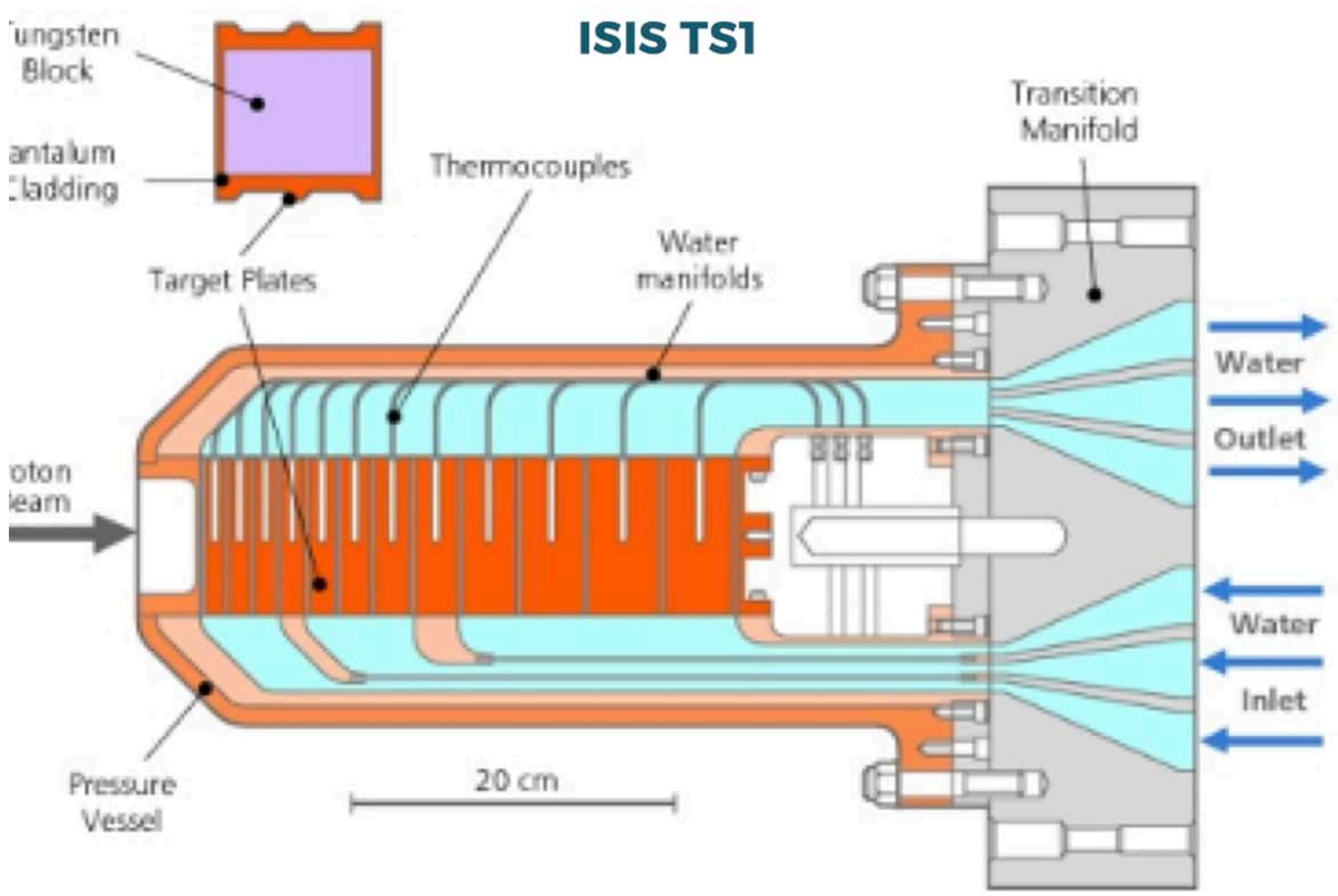
**SNS**
Liquid Circulating Target

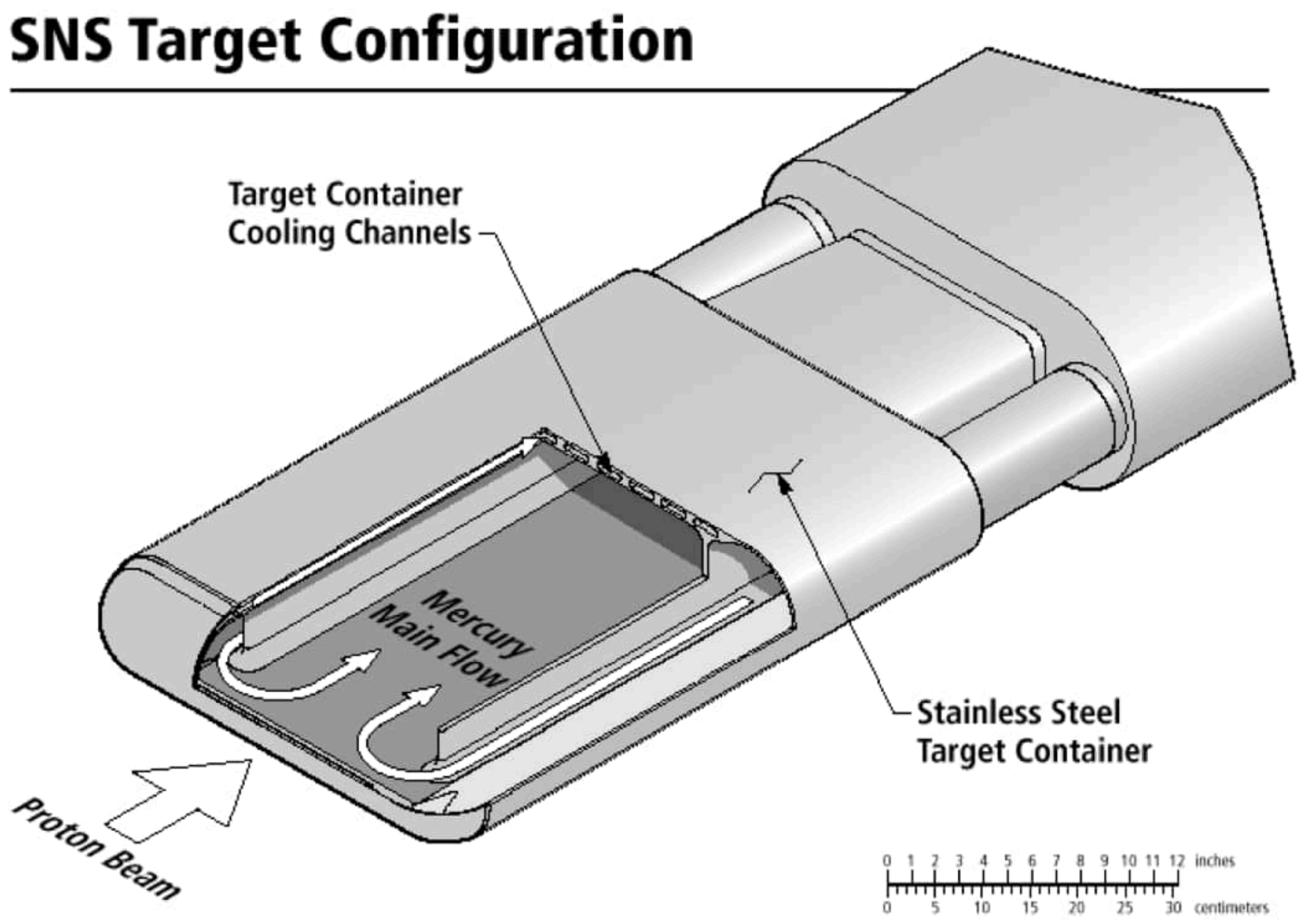
**ESS**
Rotating Target

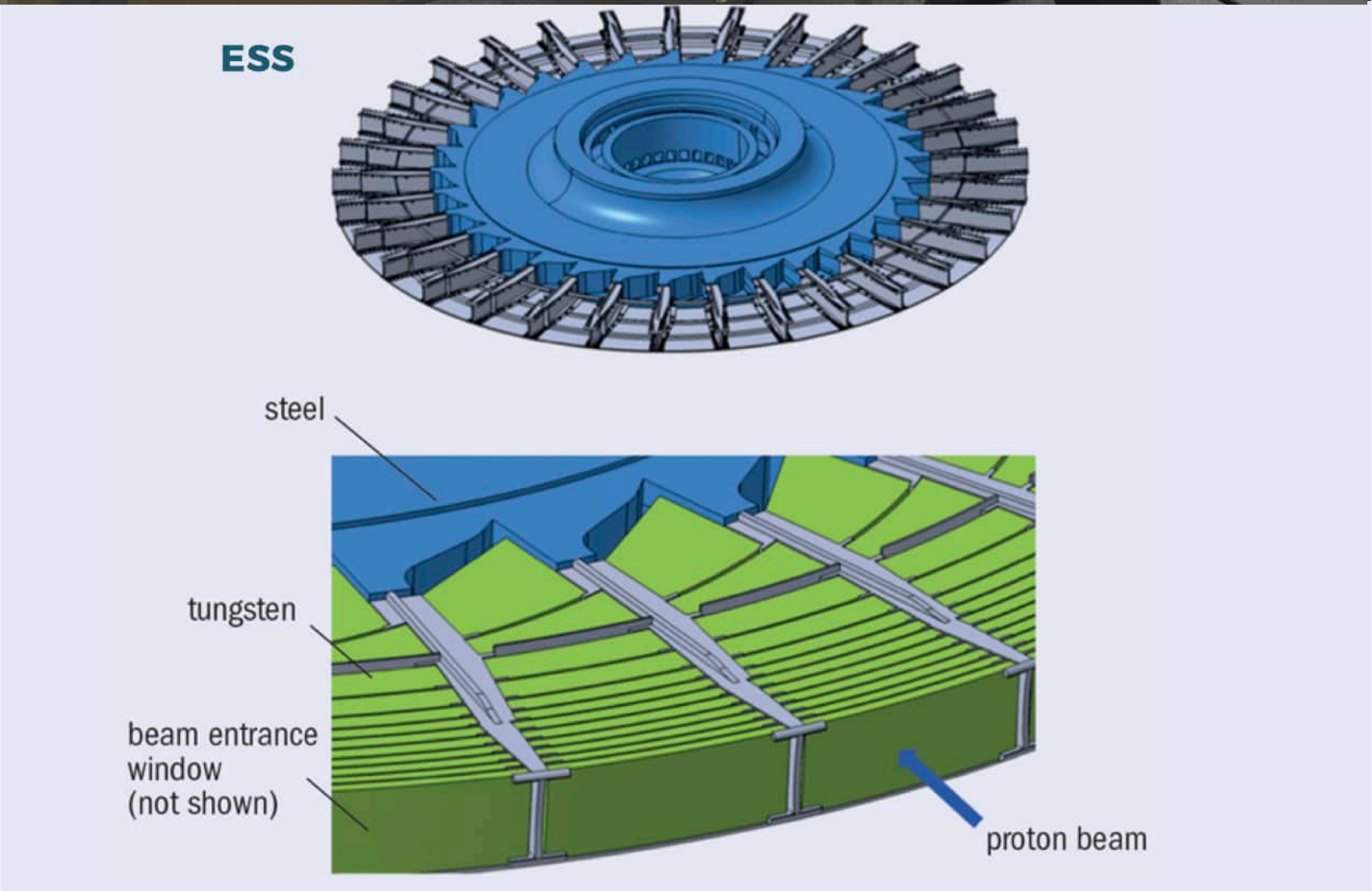
# Spallation Targets as a Function of Beam Power








160 kW in TS1 | 1.4 MW | 5 MW

Beam Power

**ISIS**
Segmented Target

**SNS**
Liquid Circulating Target

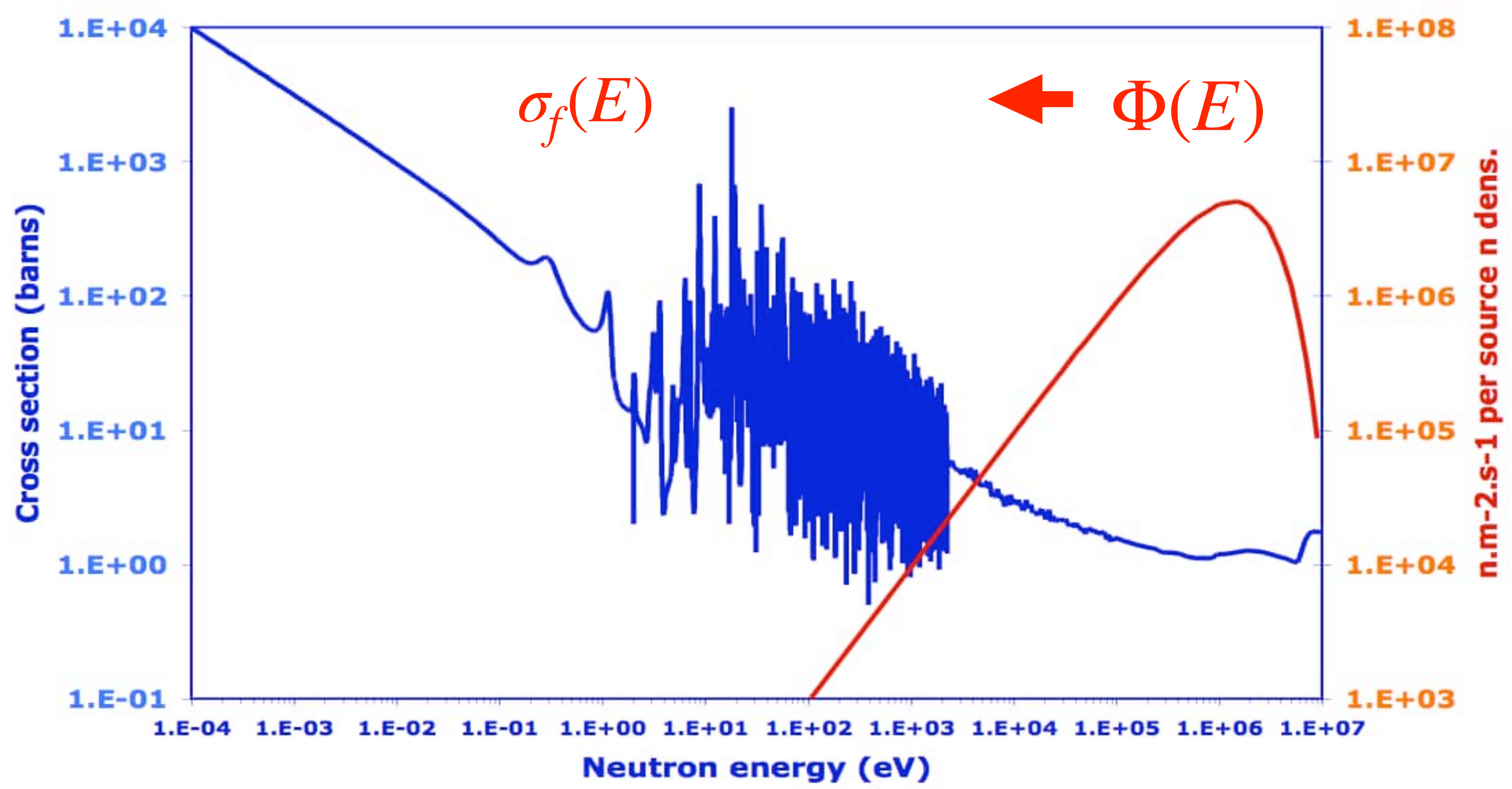
**ESS**
Rotating Target

# Design of a Nuclear Research Reactor Core

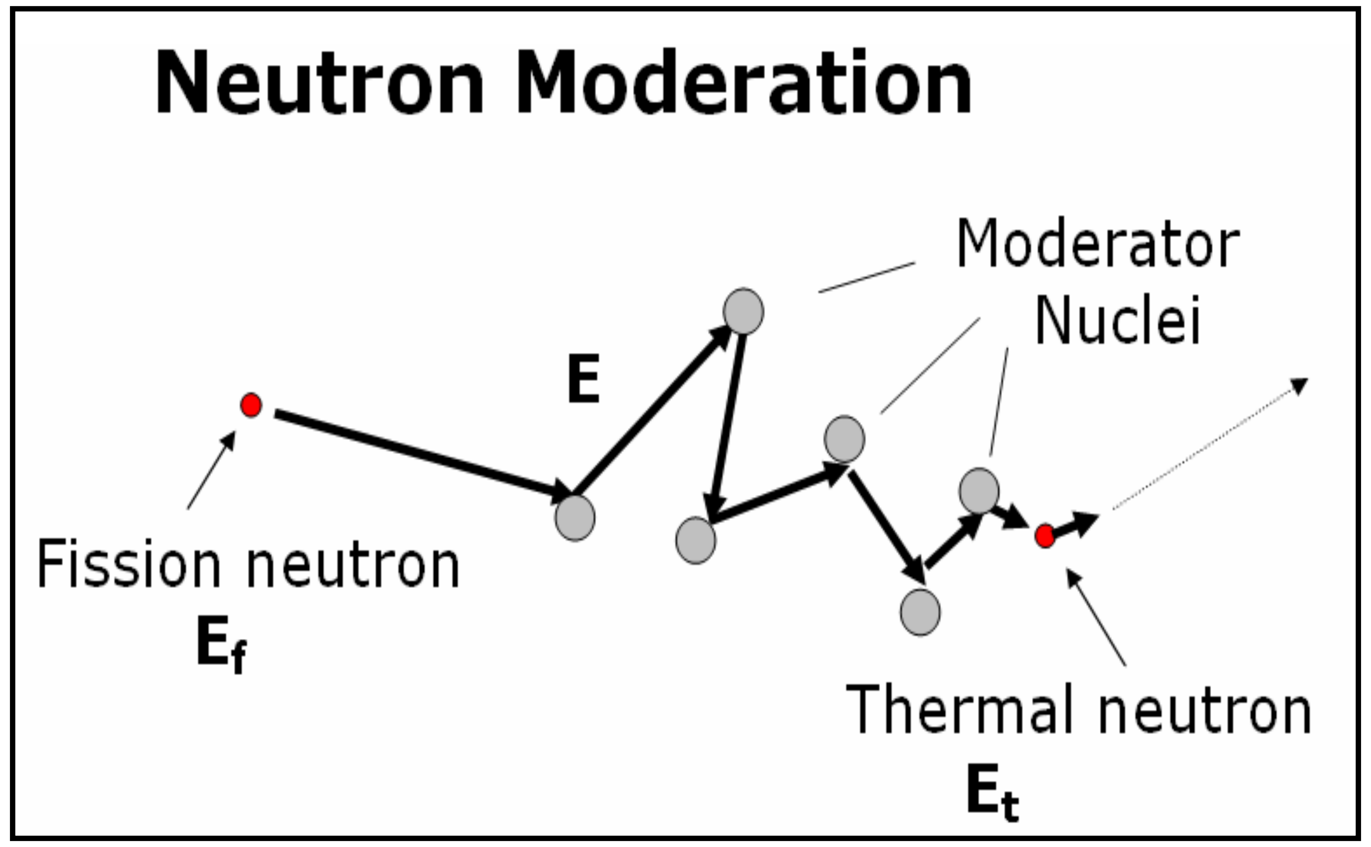
(Where Fission Neutrons Are Produced)

# The Chain Reaction and the Critical Mass

## Reactors are device used to initiate and control a chain of nuclear fission reaction.



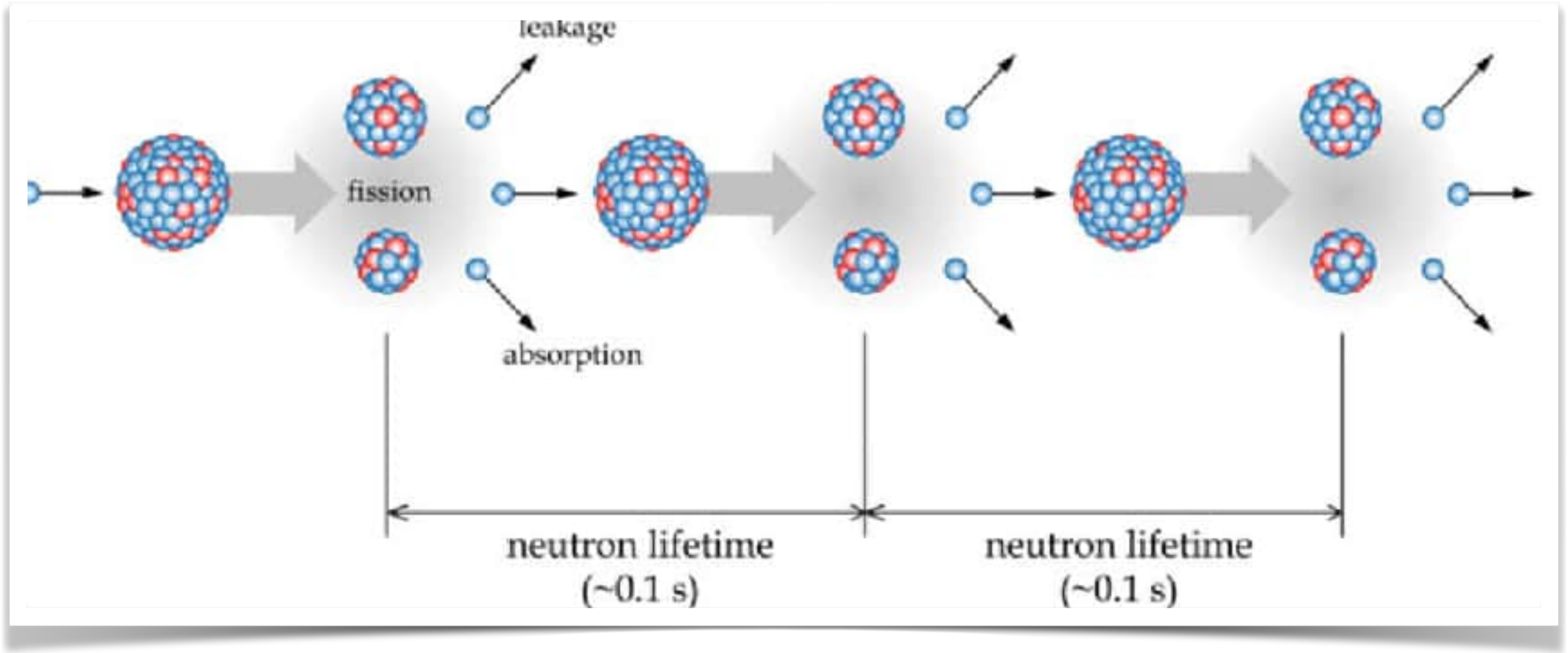

Fission spectrum and $^{235}$U(n,f) cross section




### Critical reactor

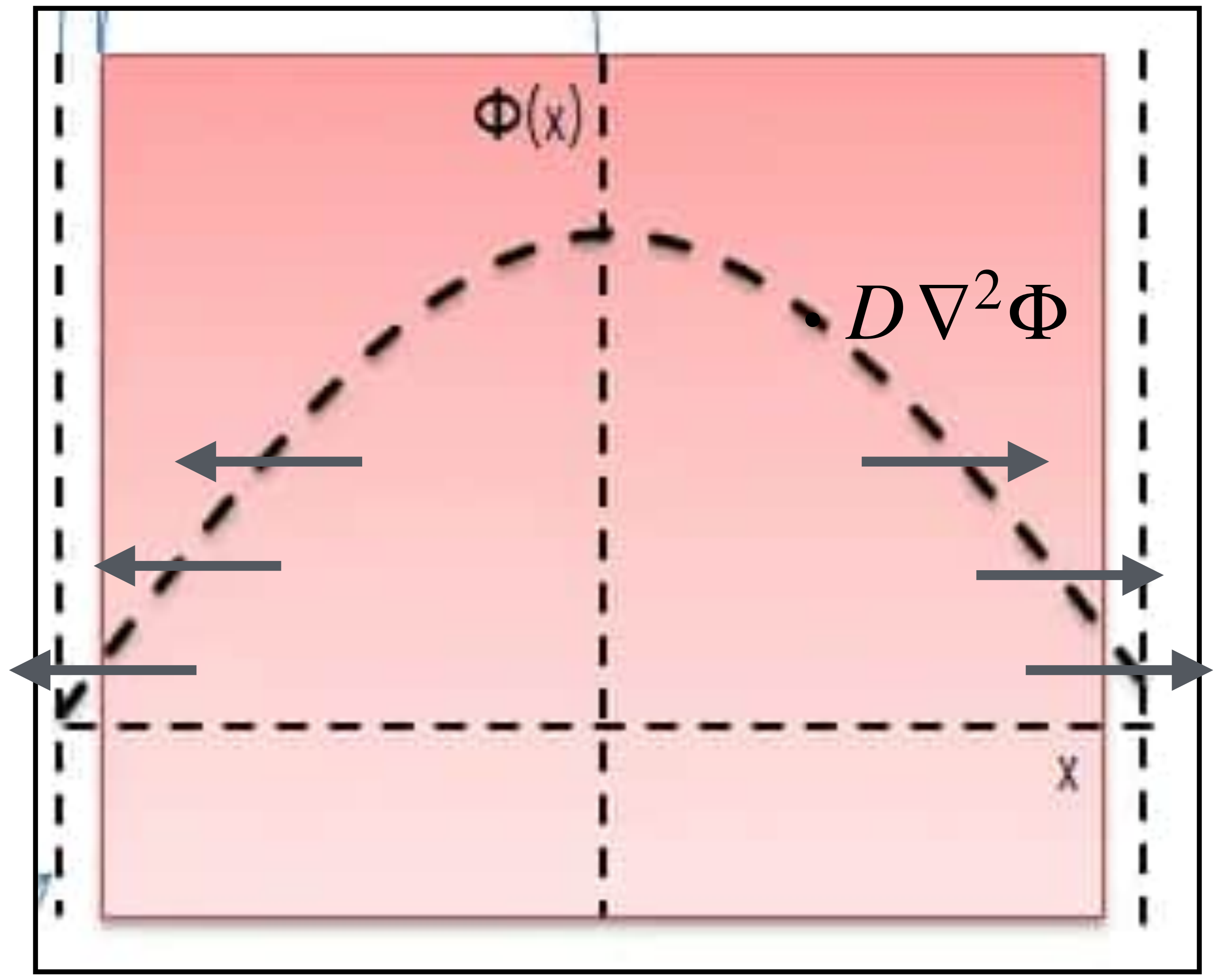
$$k = \frac{\text{number of fissions in one generation}}{\text{number of fissions in preceding generation}} = 1$$

- Neutron population is not increasing neither decreasing—> then reactor is called critical
- When production is less than losses due to leakage and absorption, k>1 —> supercritical reactor
- if k<1 subcritical




Scheme of a self stustaining fission chain

### Criticality means sustaining fission chain wo external source




$$RR = N\sigma\Phi = \Sigma\Phi$$

$$D\nabla^2\Phi - \Sigma_a\Phi + S = 0$$

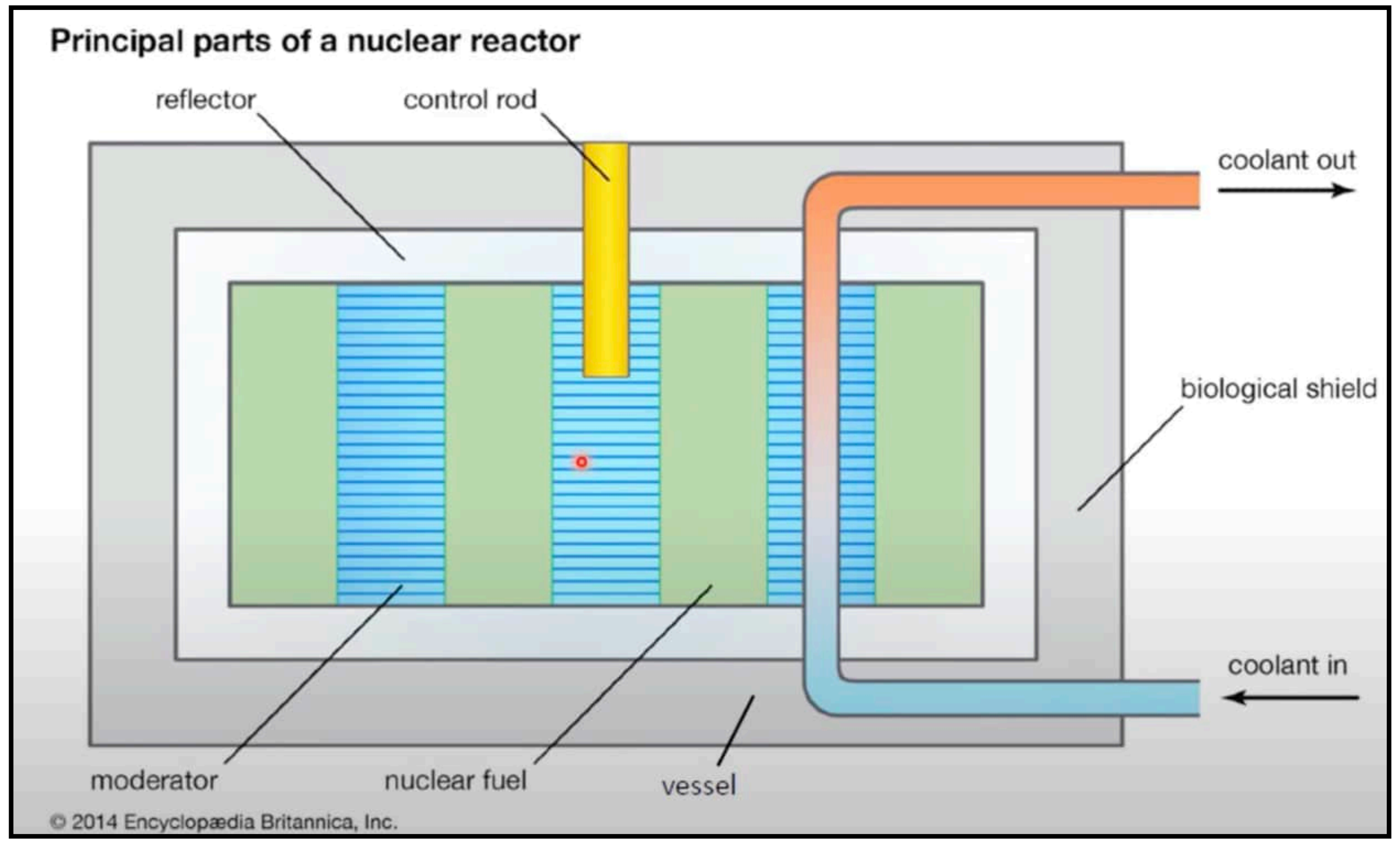
Leakage | Absorption capture | Source (fission)

$$S = \nu N_f \sigma_f \Phi \quad N_f = N_{235} \ per\ unit\ volume$$

N.B.—>The spallation process, in contrast to fission, is not an exothermal process: energetic particles are required to drive it

# Reactor Core: NPP vs RR

Main components of a nuclear reactor code: fuel, moderator control rod, containment vessel






**NPP**

Energy produced from fission reaction is used to generate electricity

**Research Reactor**

Neutrons and ionizing radiation are applied for research purposes: production of radionuclides, scattering experiments, medical applications

| Parameter | NPP (isar2) | RR (FRM II) |
| --- | --- | --- |
| Thermal power | 3950 MW | 20 MW |
| Electric power | 1485 MW | 0 |
| Diameter | 3.37 m | 24 cm |
| Active length | 3.66 m | 70 cm |
| Enrichment | <5% | 83% |
| N.fuel elem. | 193 (ca. 103 t Uranium) | 1 (8,1 kg Uranium) |
| Coolant temperature | 293-328 °C | 39-52 °C |
| Coolant pressure | 155 bar | Open Pool |

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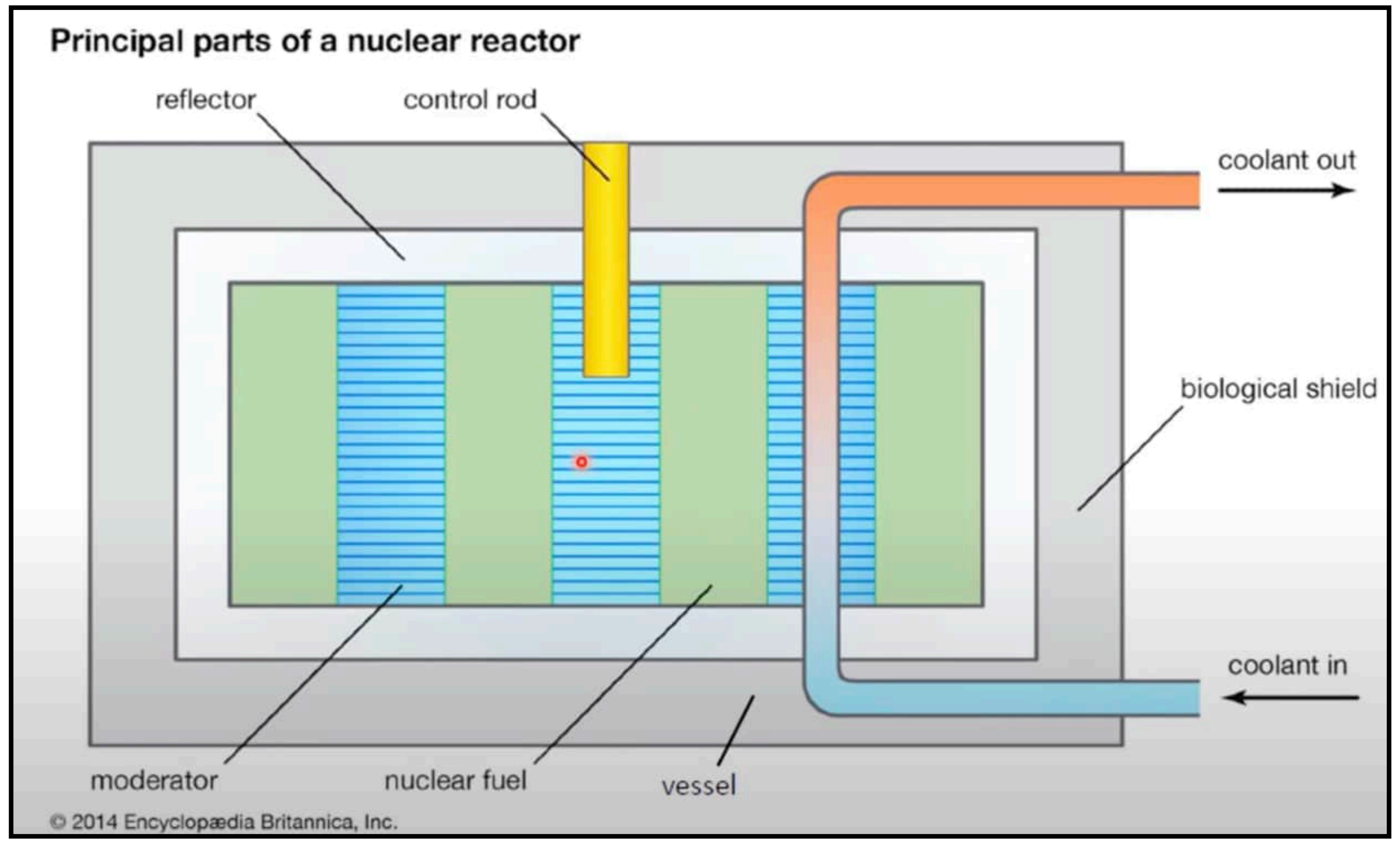


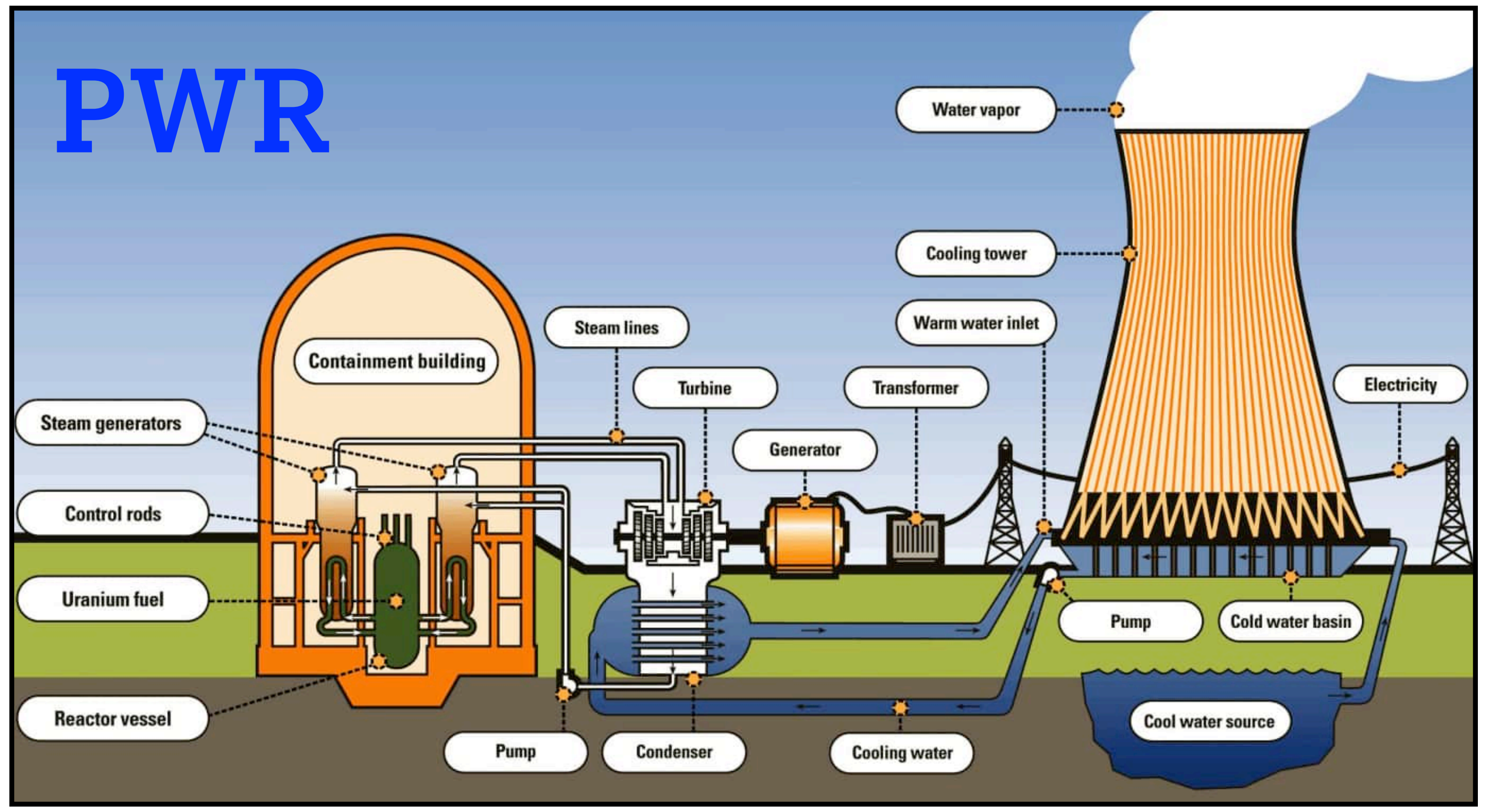


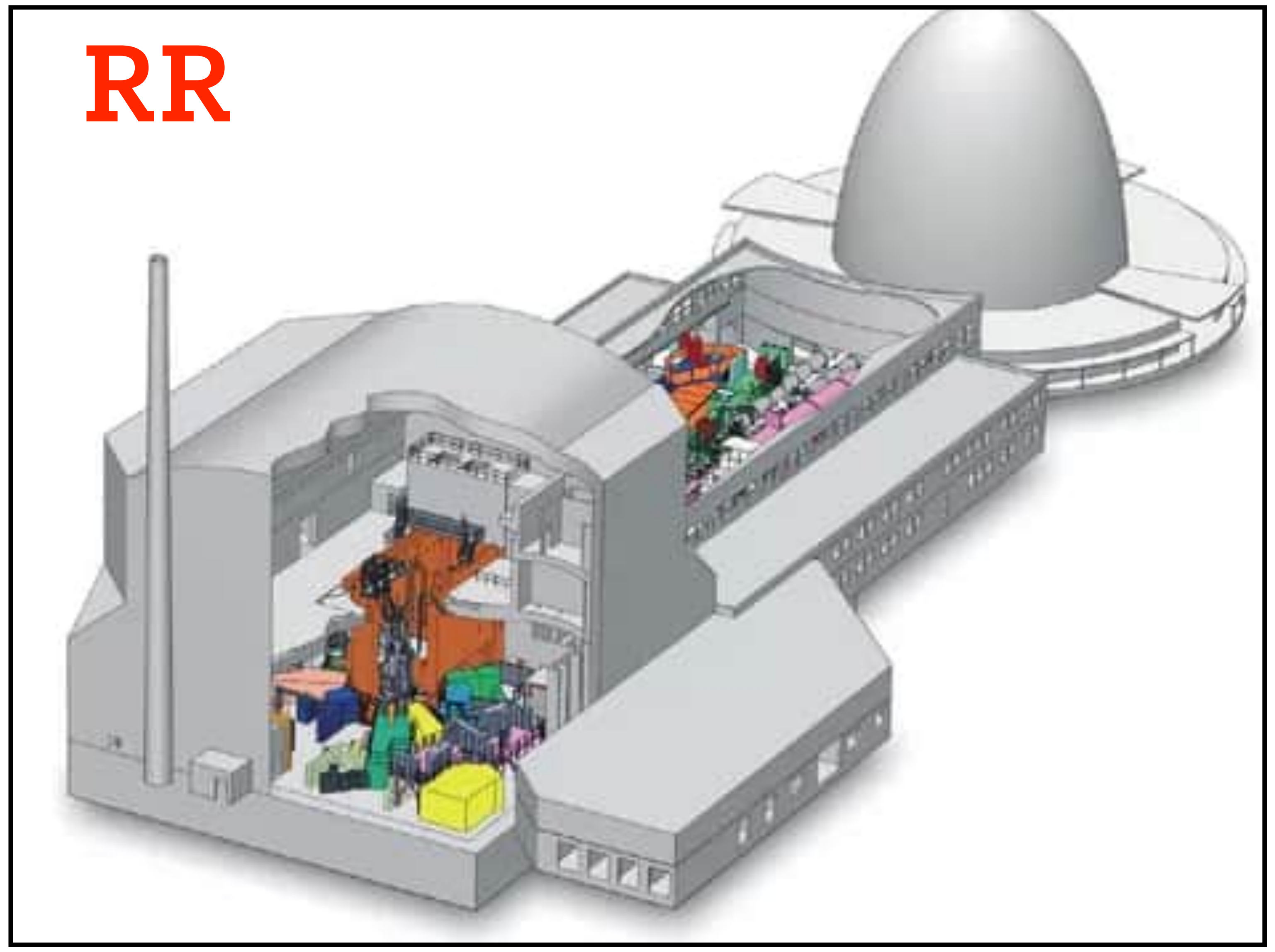


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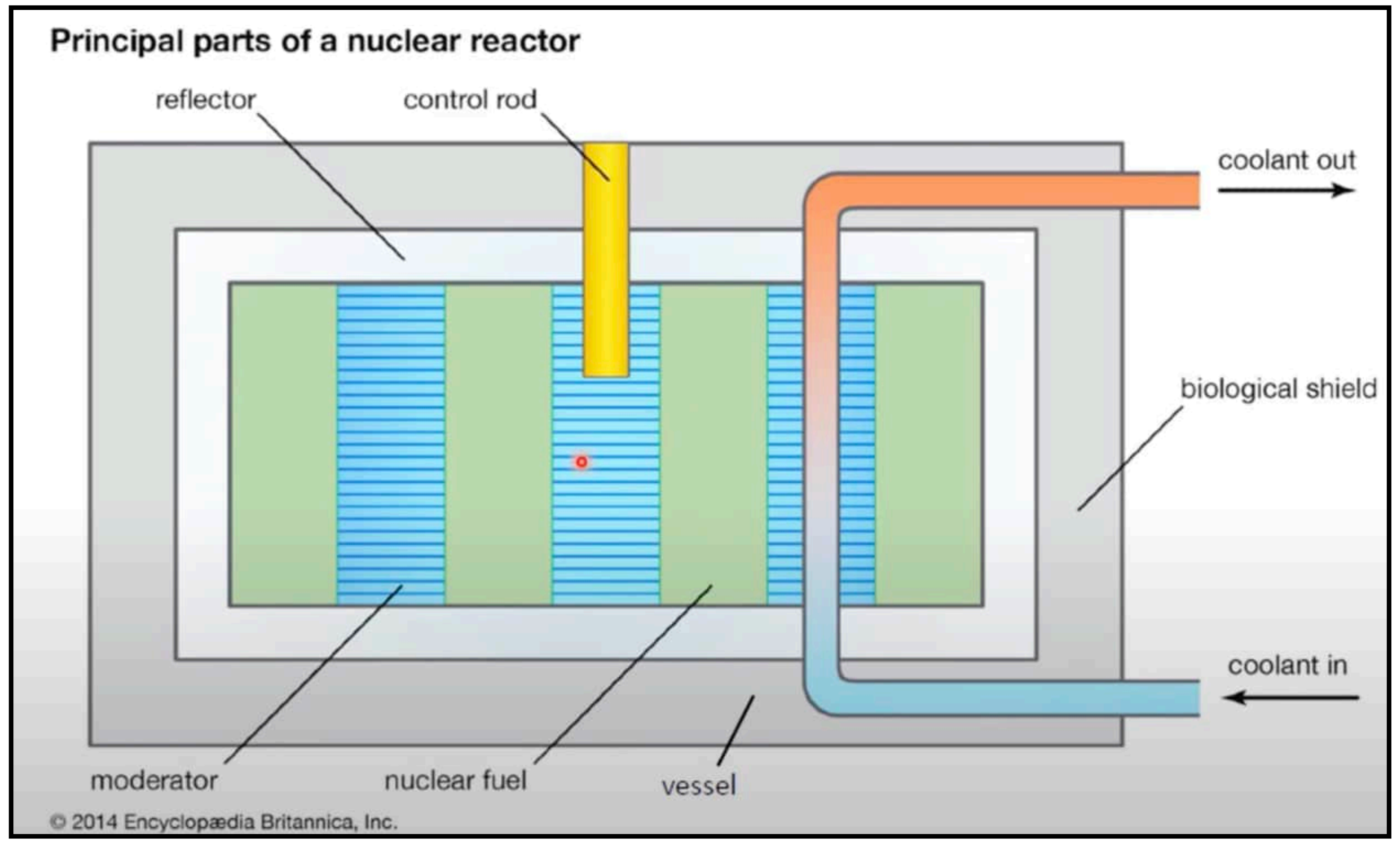


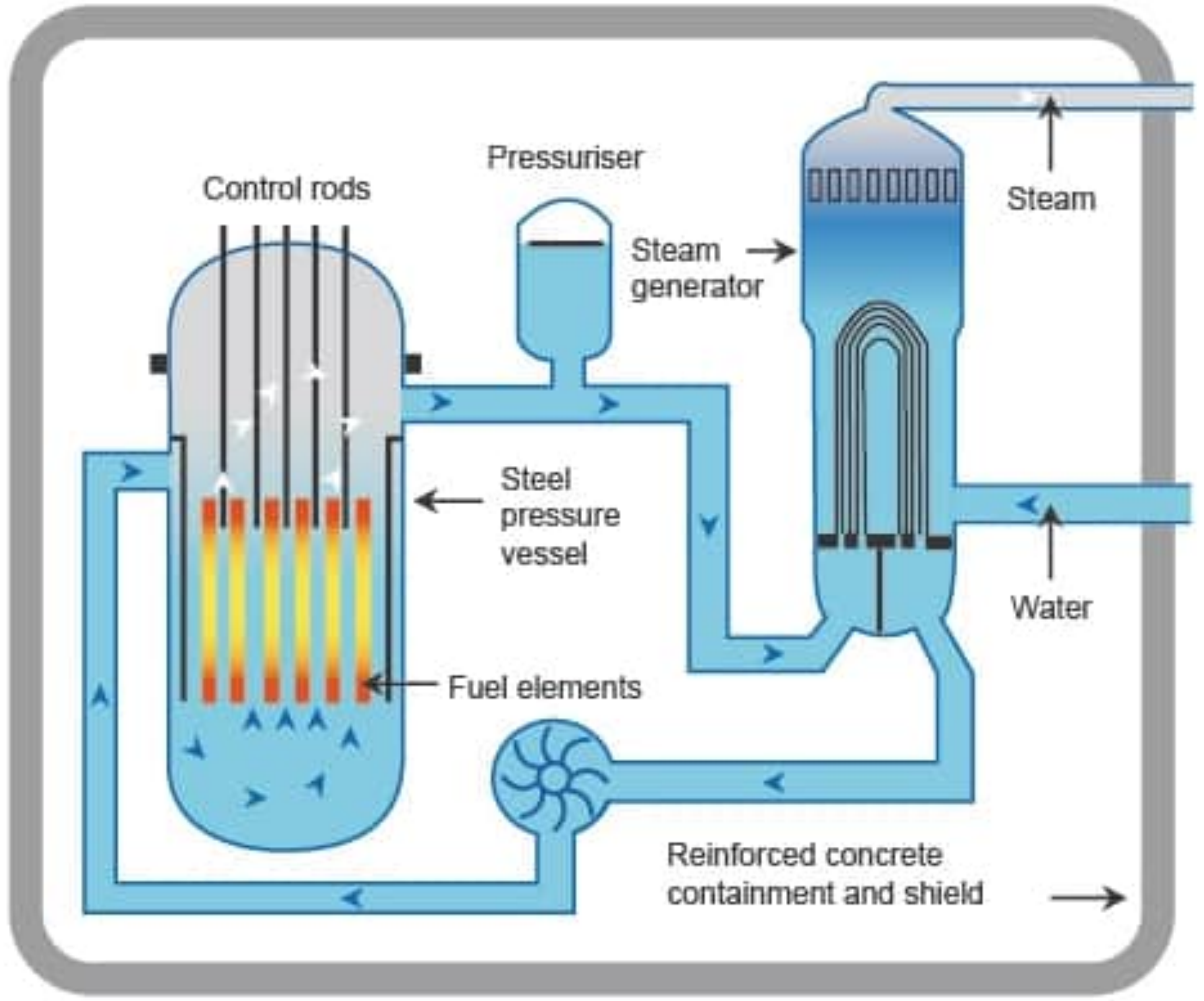


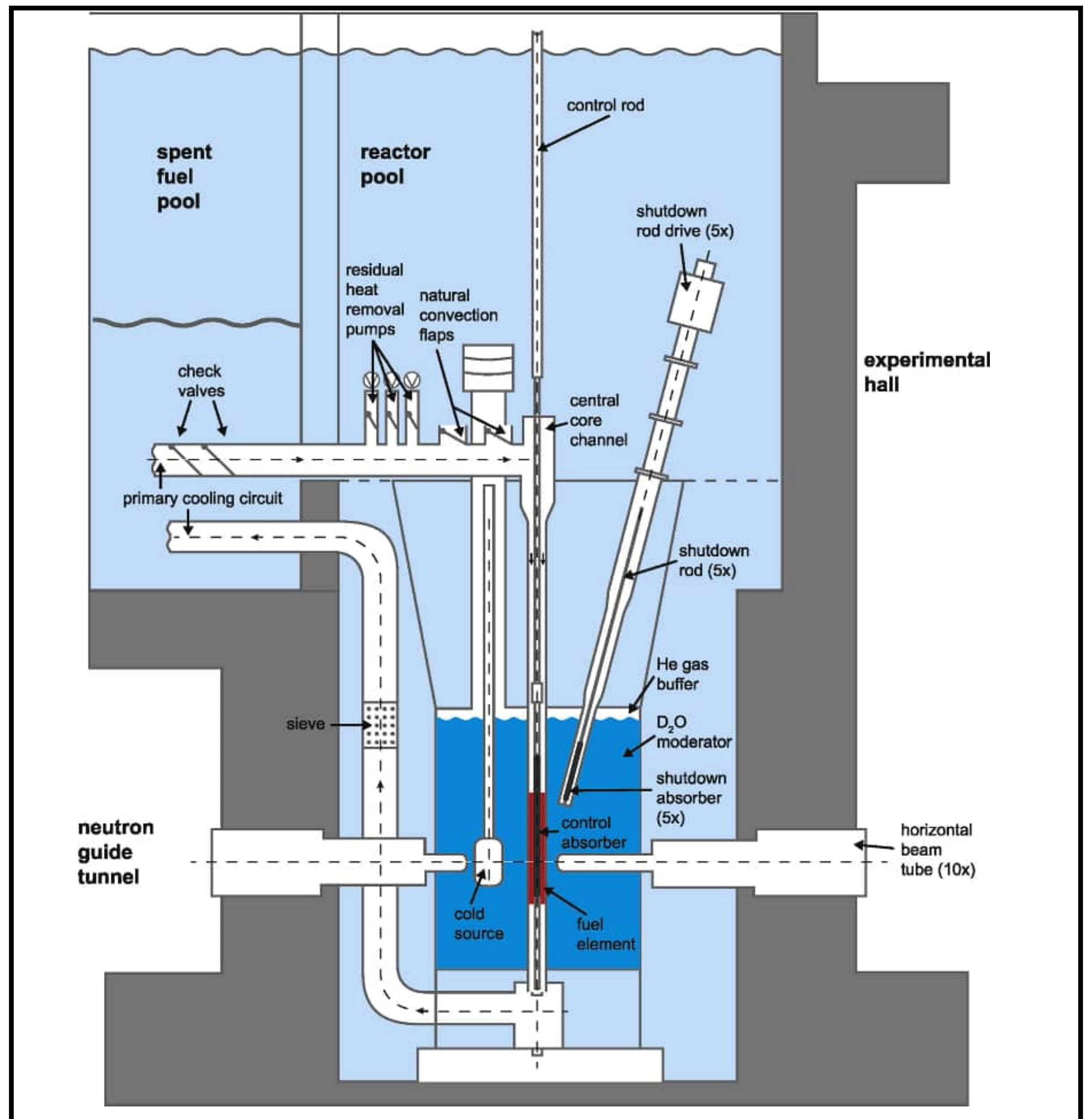


Schematic vertical cut through the FRM II reactor indicating major technical components and scientific support systems. FRM II/TUM

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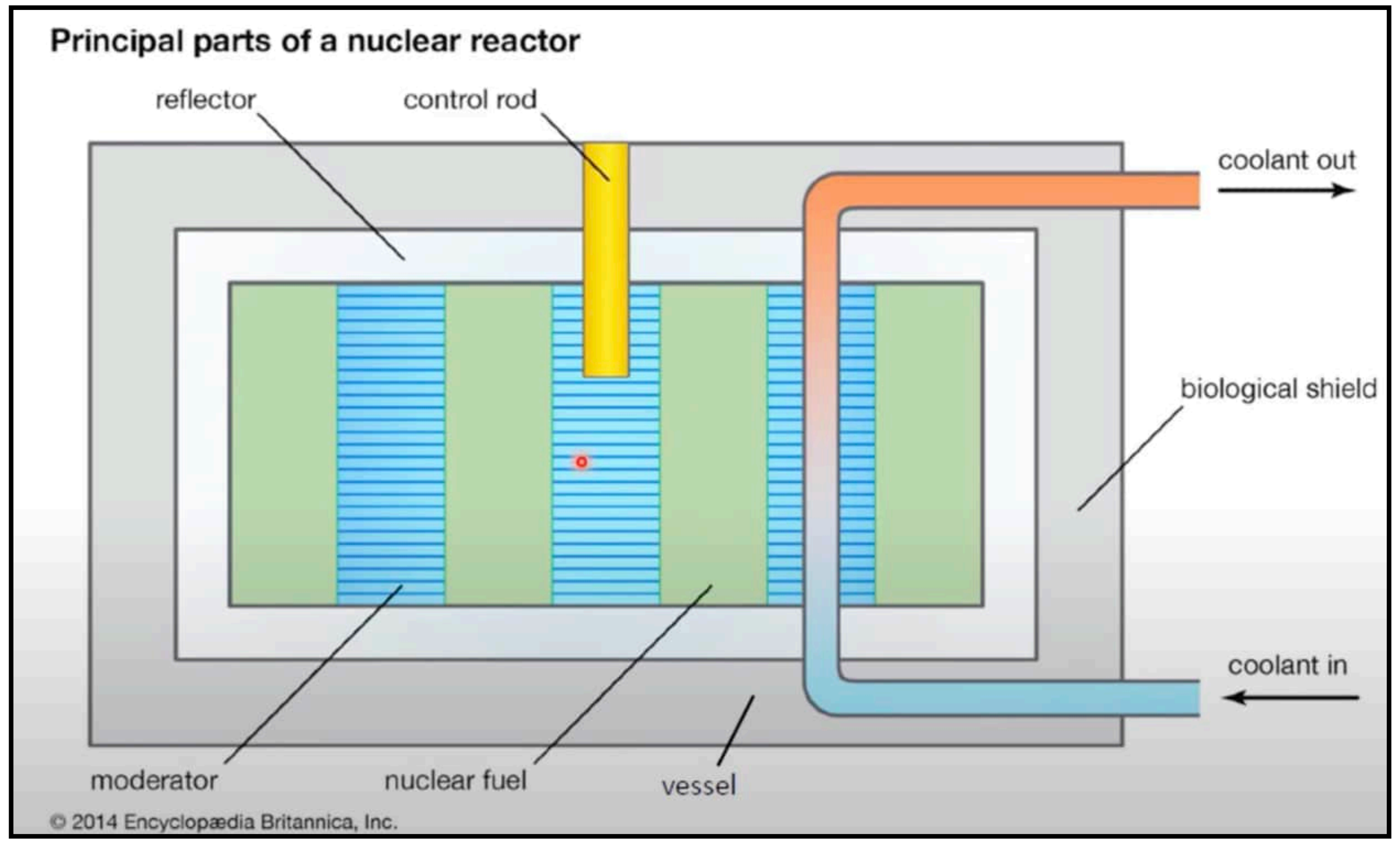
# Reactor Core: NPP vs RR

Main components of a nuclear reactor code: fuel, moderator control rod, containment vessel



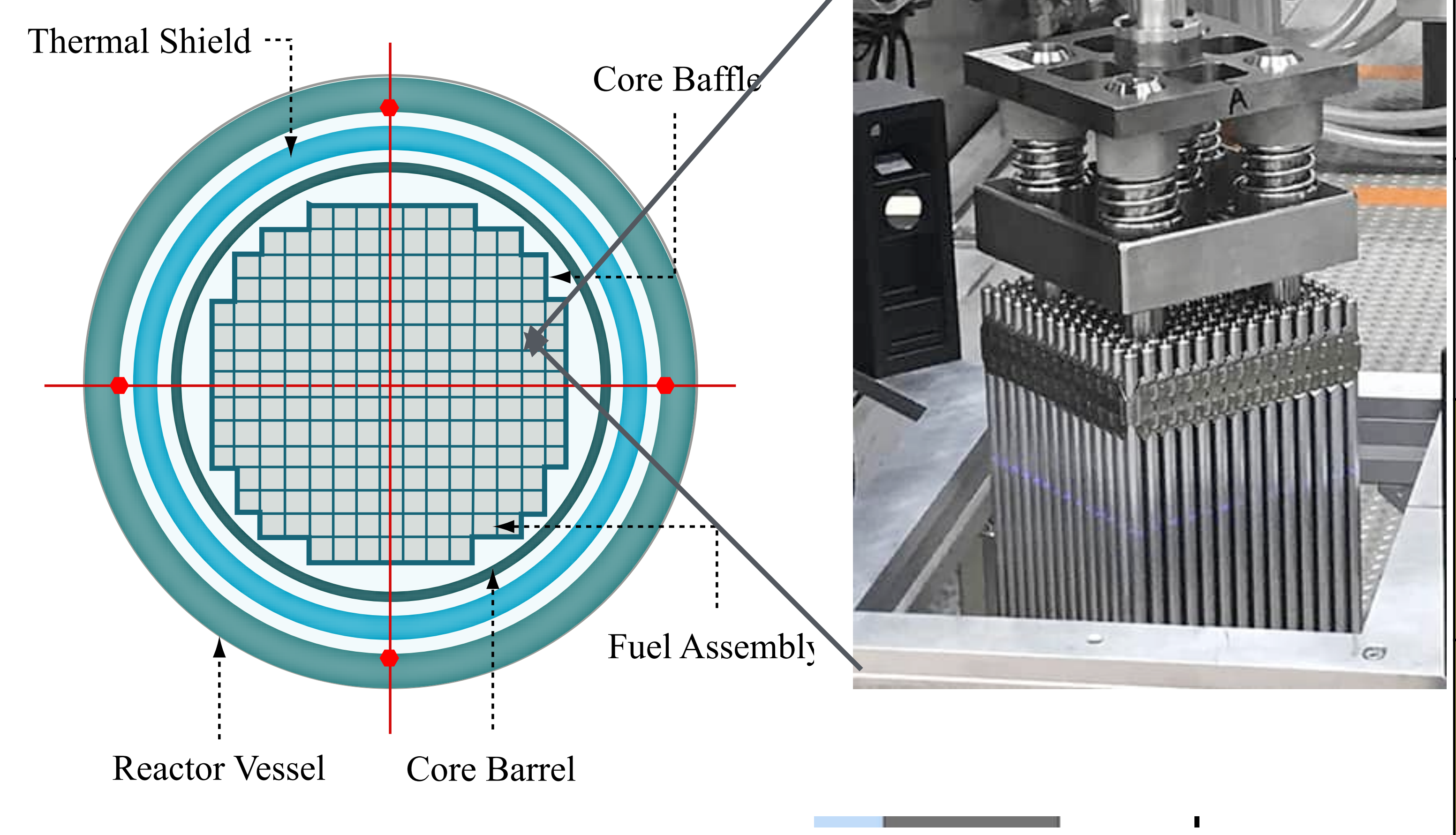

## NPP

Energy produced from fission reaction is used to generate electricity

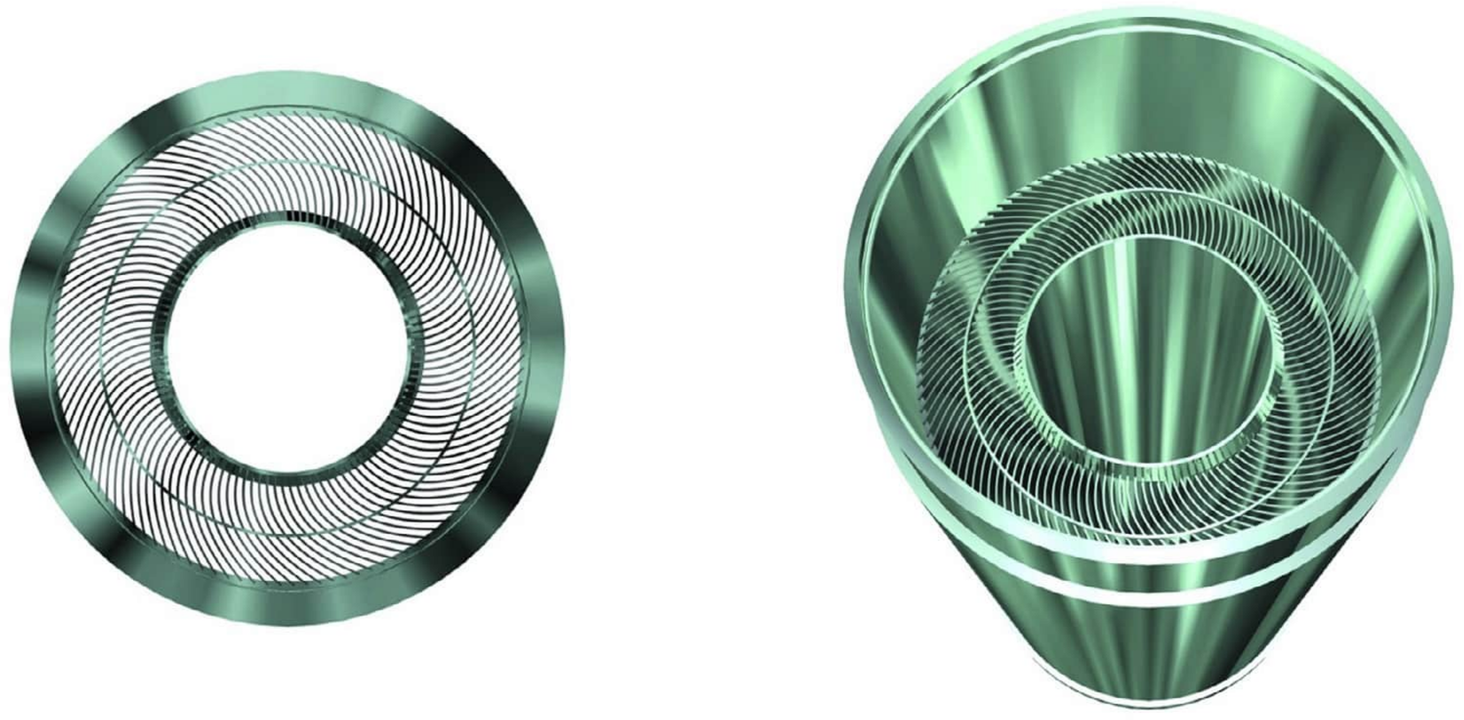
## Research Reactor

Neutrons and ionizing radiation are applied for research purposes: production of radionuclides, scatteri experiments, medical applications

## PWR: fuel element




## RR: fuel element



View of the FRM II compact fuel element from different perspectives. FRM II/TUM

| Parameter | NPP (isar2) | RR (FRM II) |
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# Making “Good” Neutrons for Scattering Experiments

(Slowing Down Neutrons)

# Doing Science with Low Energy Neutrons

- Neutrons always born fast. So they need to be moderated to be usable for scattering experiment

Some examples of applicative energy range for Bragg peaks

Bragg's Law

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

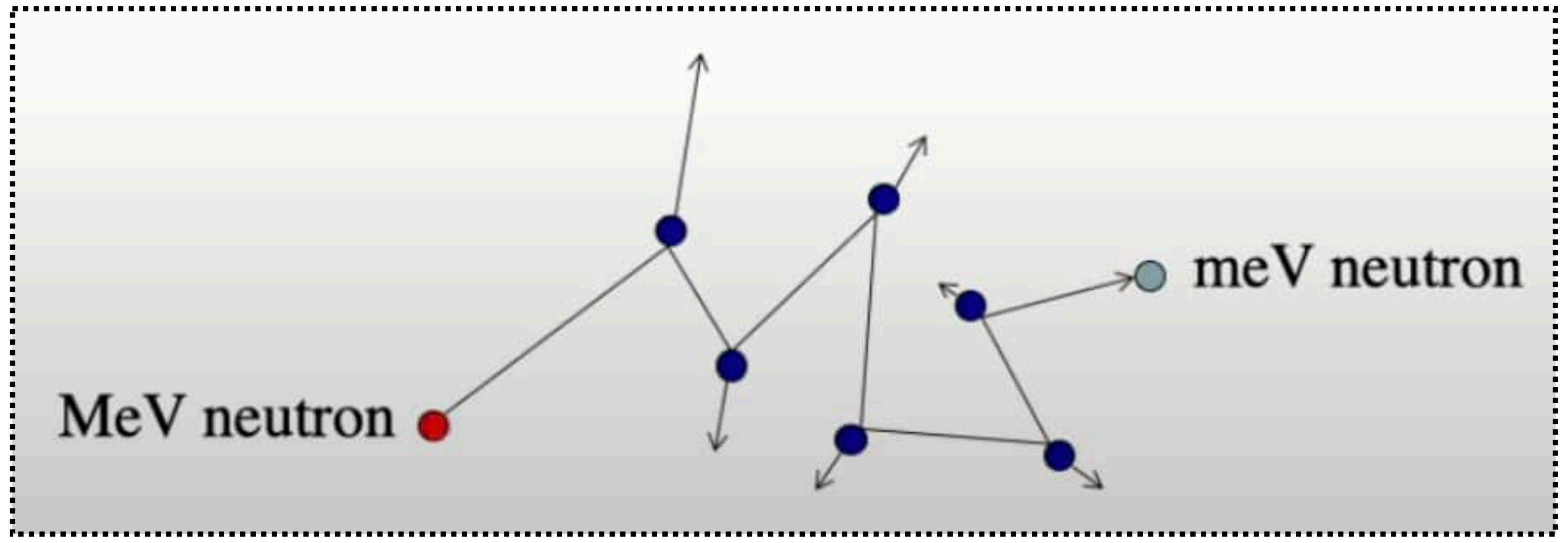
| Science | $d$ (Å) | $Q$ (Å$^{-1}$) | $\lambda$ (Å) | $\theta$ | $E$ (meV) |
|---|---|---|---|---|---|
| Polymers | 10 000 | 0.001 | 20 | 0.1° | 0.2 |
| Micelles | 1 000 | 0.01 | 10 | 0.6° | 0.8 |
| Metallurgy | 100 | 0.1 | 5 | 3° | 3.3 |
| Crystal structures | 10 | 1 | 2 | 11° | 20.4 |
| Glasses | 1 | 10 | 1 | 52° | 81 |
| High precision crystallography | 0.25 | 45 | 0.25 | 64° | 1300 |

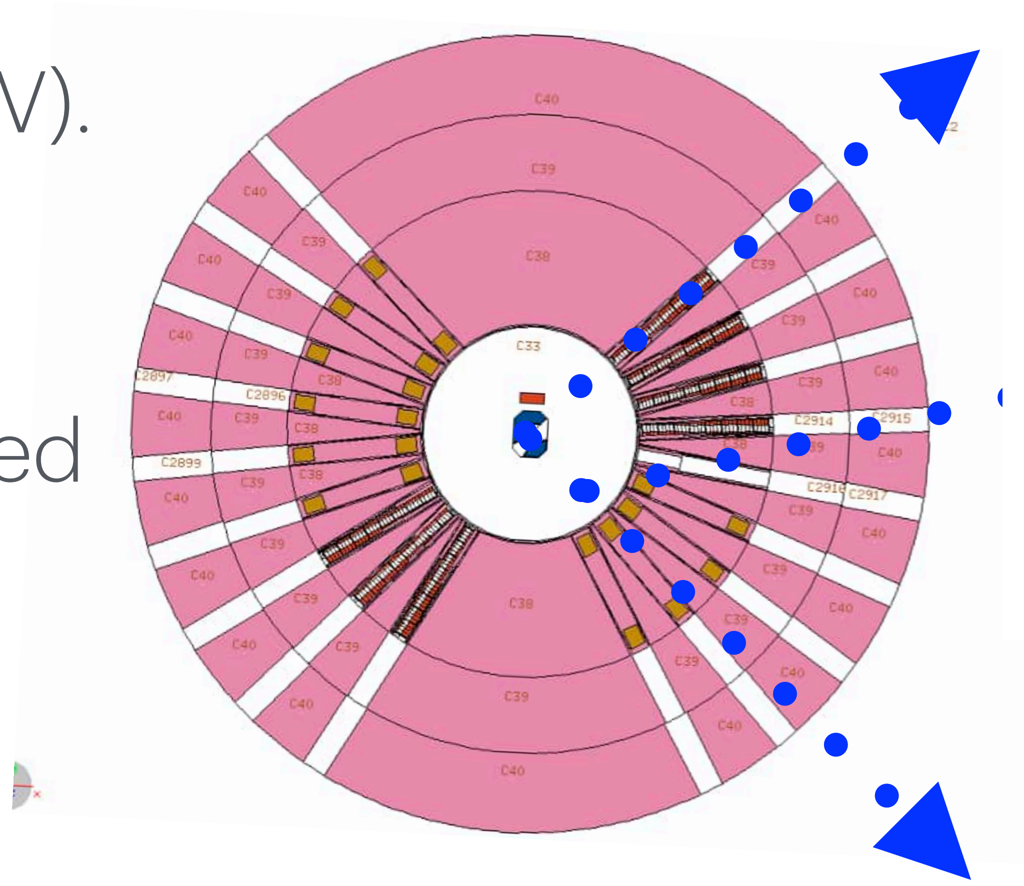
In order to get an optimal design for moderators, it is needed to make an accurate choice of :

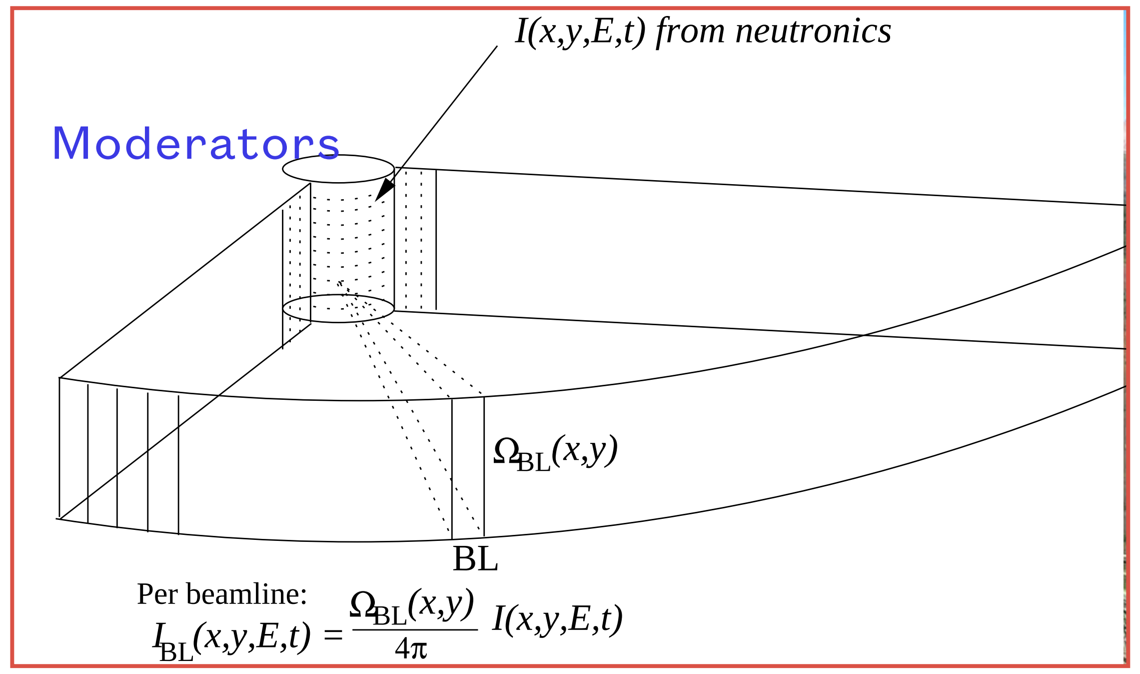
1. **material** (scattering xs)
2. **lay-out** (optimal arrangement between the source and the instrument beamlines, around the target, for SNS)
3. geometry shape and **thickness**
4. **coupling** with reflector (PSNS)
5. combination with pre moderating material for cold & ultra cold neutron

we cannot cope the whole range of science applications with only thermal neutrons (i.e 25 meV).

In order to be able to carry out different science experiment that involves different d spaces we need a broad range of lambda





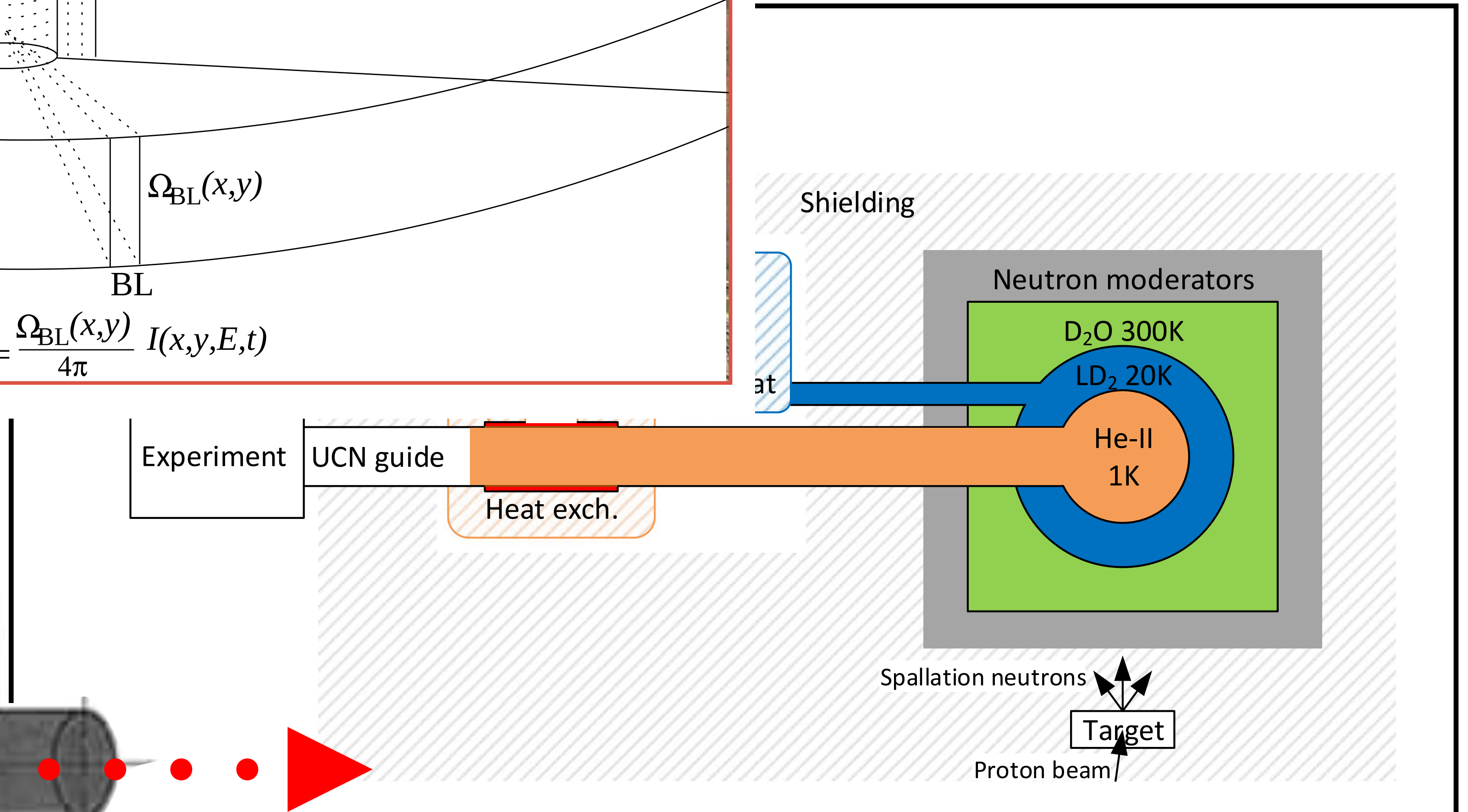
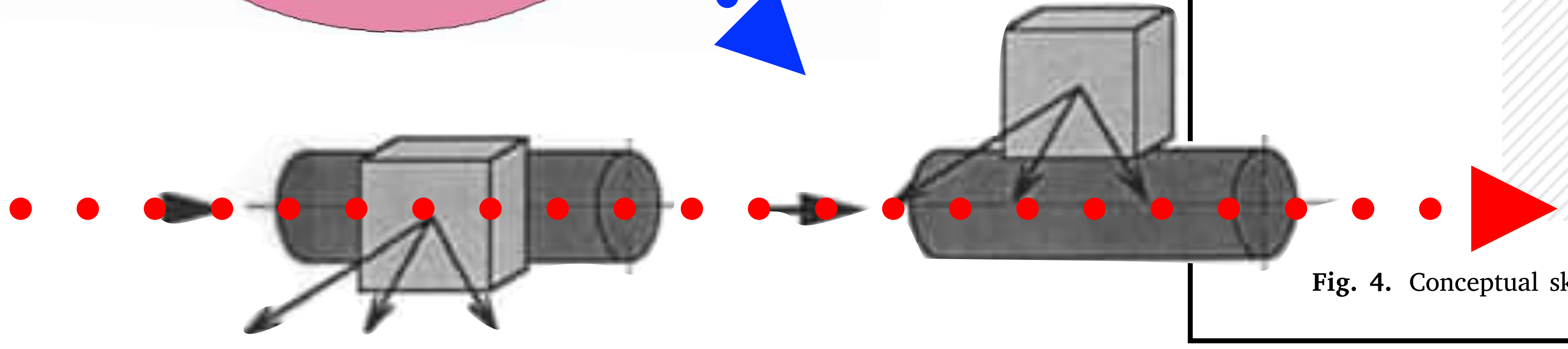



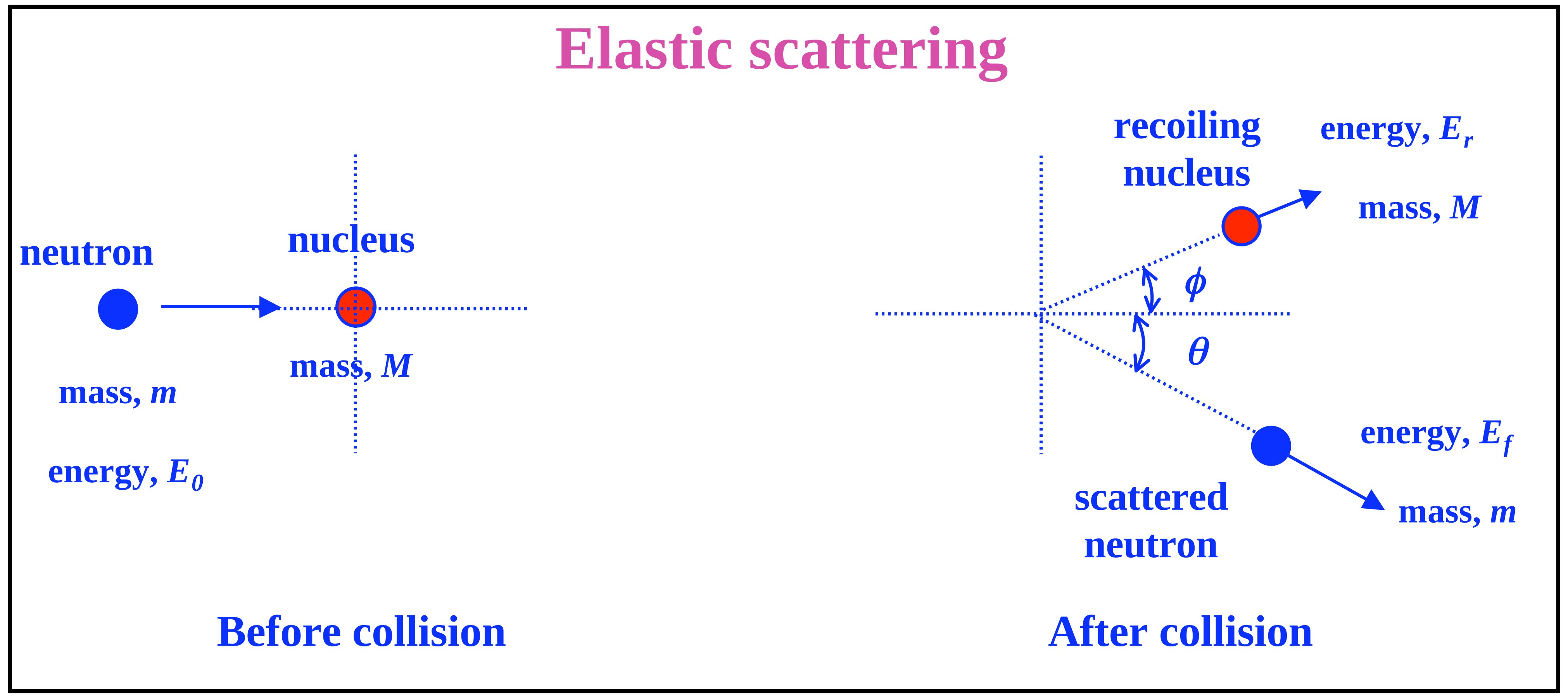

Fig. 4. Conceptual sketch of the upgraded UCN source at TRIUMF. The proton beam points into the page.



# Moderator Material

# Slowing Down Neutrons

Slowing-Down theory describes the loss of energy through repeated elastic collisions with effectively free nuclei. Neutron moderation occurs by “elastic” collision of neutrons with atoms of the moderator material




In any collision with a given scattering nucleus a neutron loses ON AVERAGE a constant fraction of the energy it had BEFORE THE COLLISION

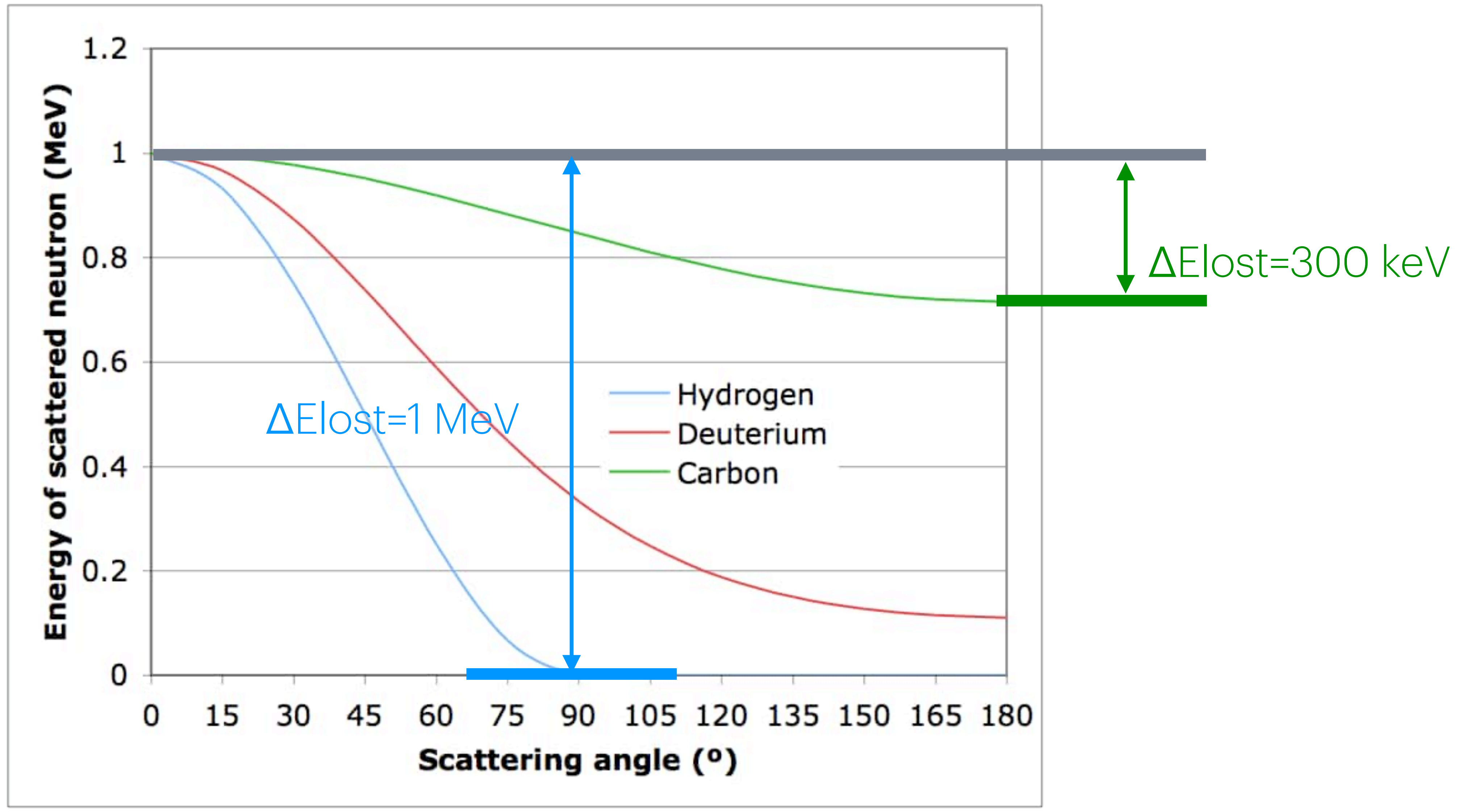
$$\zeta = \overline{ln\left(\frac{E_1}{E_2}\right)} = 1 + \frac{\alpha}{1-\alpha} ln(\alpha) \qquad \alpha = \left(\frac{A-1}{A+1}\right)^2$$

- ξ=1 for A=1 —> full energy loss in single collision

$$\#col = \frac{\ln(E_0/E_1)}{\xi_s}$$

## Elastic scattering

If we plot: $E_f = \frac{E_0}{(A+1)^2}\left[A^2 + 2A\cos\vartheta + 1\right]$ for a 1 MeV neutron and different scattering substances we obtain:




As you can see all the neutrons that would be scattered through 90° or more are basically stopped (and thermalised) in one collision with a hydrogen nucleus (proton). In the case of carbon the maximum energy loss is only about 300 keV even for a scattering angle of 180° (π) so several collisions would be necessary to thermalise the neutrons.

# How to Choose a Good Moderator

| Moderator | $\xi$ energy average loss per collision | Collisions 2 MeV to 1 eV | $\xi\Sigma s/\Sigma a$ | $\Sigma s$ (1/cm) mean free path between collisions | Time to 1 eV ($\mu$s) |
|---|---|---|---|---|---|
| $H_2O$ | 0.926 | 16 | 71 | 1.50 | 1.5 |
| $D_2O$ | 0.510 | 29 | 5670 | 0.35 | 9.7 |
| Be | 0.206 | 69 | 143 | 0.87 | 8.5 |
| C (graphite) | 0.158 | 91 | 192 | 0.38 | 25 |
| Fe | 0.035 | 411 | 35 | 0.96 | 43 |

Moderation Ratio: $M=\zeta\,\Sigma_s/\Sigma_a$

The moderating ratio or moderator quality is the complete measure of a moderator's effectiveness because it also takes into account the absorption effects.When absorption effects are high, the moderator will absorb most of the neutrons, leading to lower moderation or lower availability of thermal neutrons.

- Lighter nuclei require fewer collisions to slow the neutron and thermalise neutron faster
- The quicker neutrons slow down, the less the initial narrow time distribution is corrupted
- Anything with high hydrogen density is fast, and can make a slow neutron from a single collision
- Water, beryllium, and heavy water are all good moderators

# ......and Eventually Neutron Thermalisation

– Loss of energy – “slowing-down” only until up-scattering is relevant, that is up to thermalisation

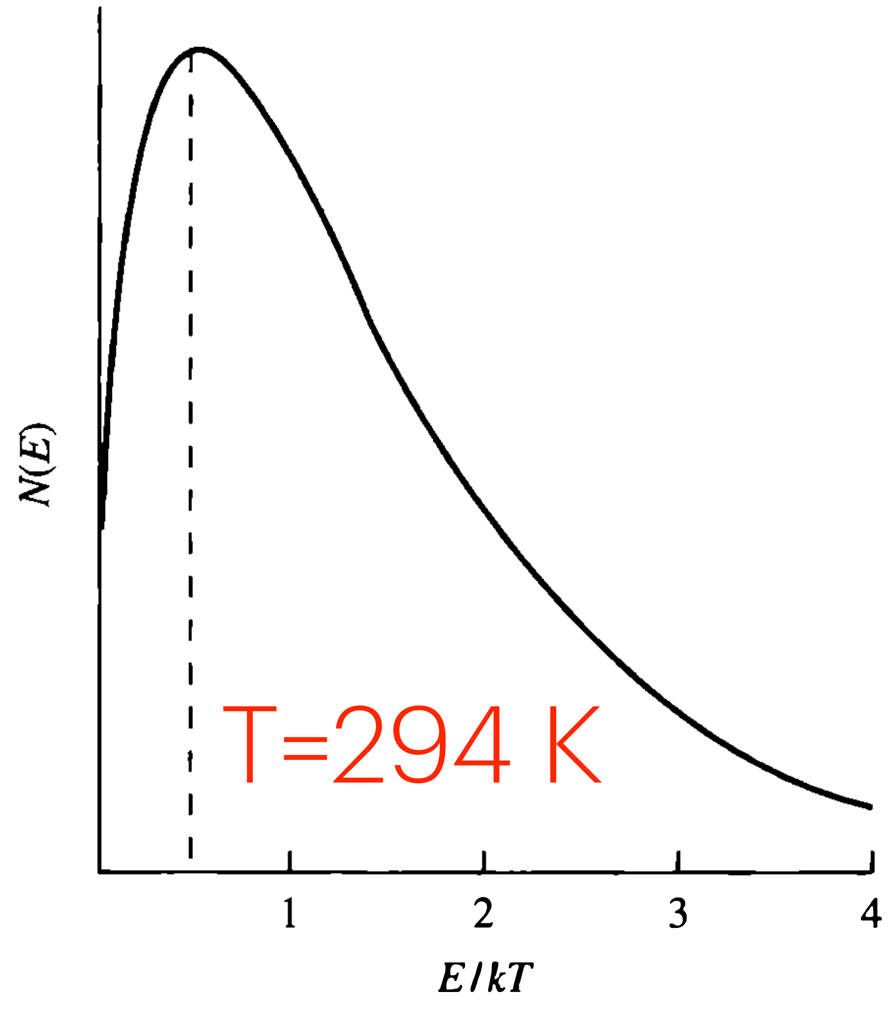
$$N(E) = \frac{2\pi N}{(\pi kT)^{3/2}} E^{1/2} e^{-E/kT}.$$

$E = \frac{1}{2}kT$ The most probable Energy

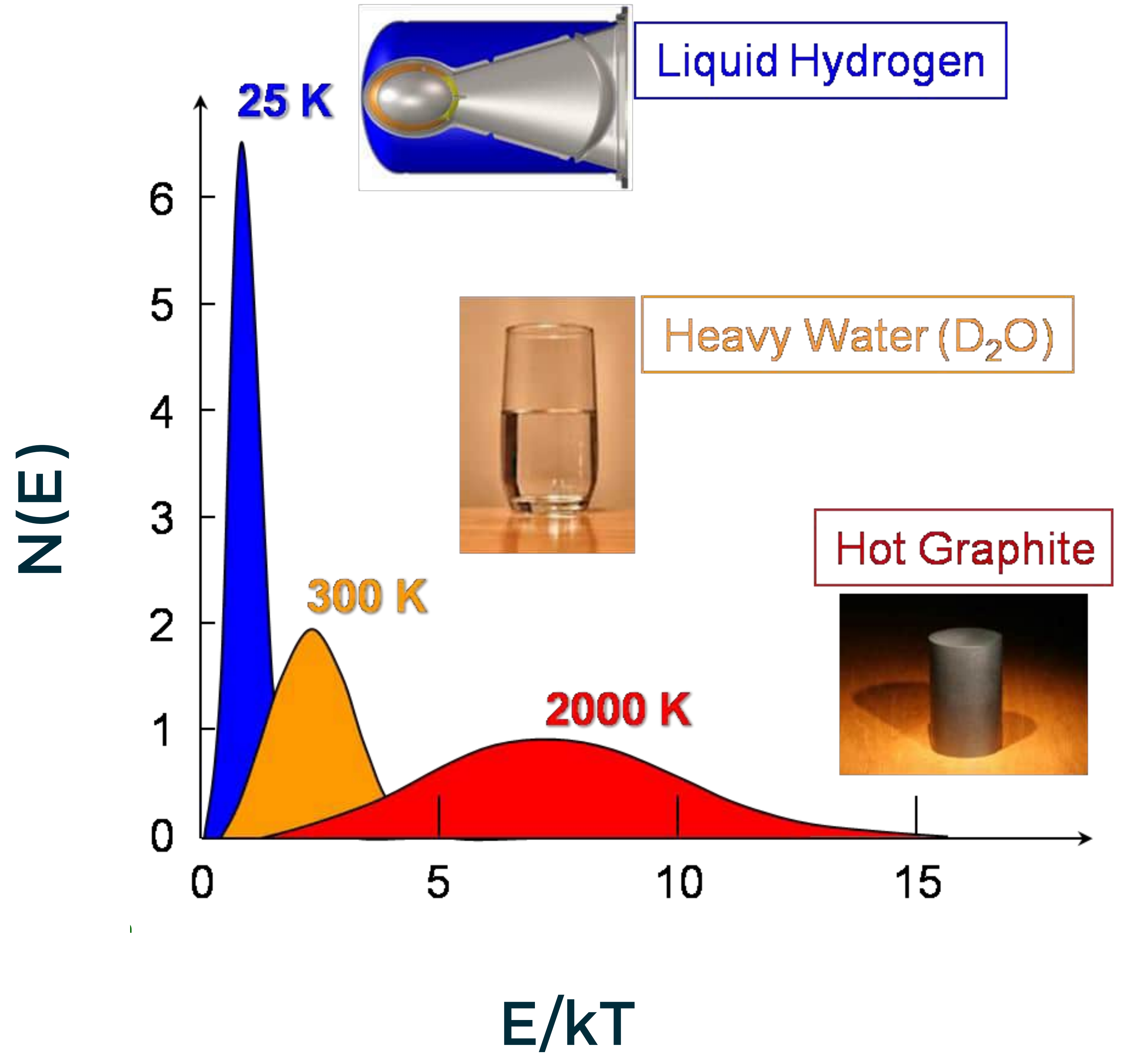
$T_0 = 293.61°K,\quad kT_0 = 0.0253 \text{ eV} \simeq \frac{1}{40} \text{ eV}$

$$v(E) = \left(\frac{2E}{m}\right)^{1/2}$$

v(293.61 K)= 2200 m/s E= 25 meV




The Maxwellian distribution function.




By changing the moderator temperature one can shift the thermal equilibrium (i.e most probable Energy in the spectrum) to a higher or lower energy

Whilst the atom free approx is considered reasonable in the range of energy > 1eV, below this energy accurate scattering kernel able to describe the mechanisms of energy loss by excitation of vibrational and rotational modes in molecules (nuclei have to be considered bound and no more free)

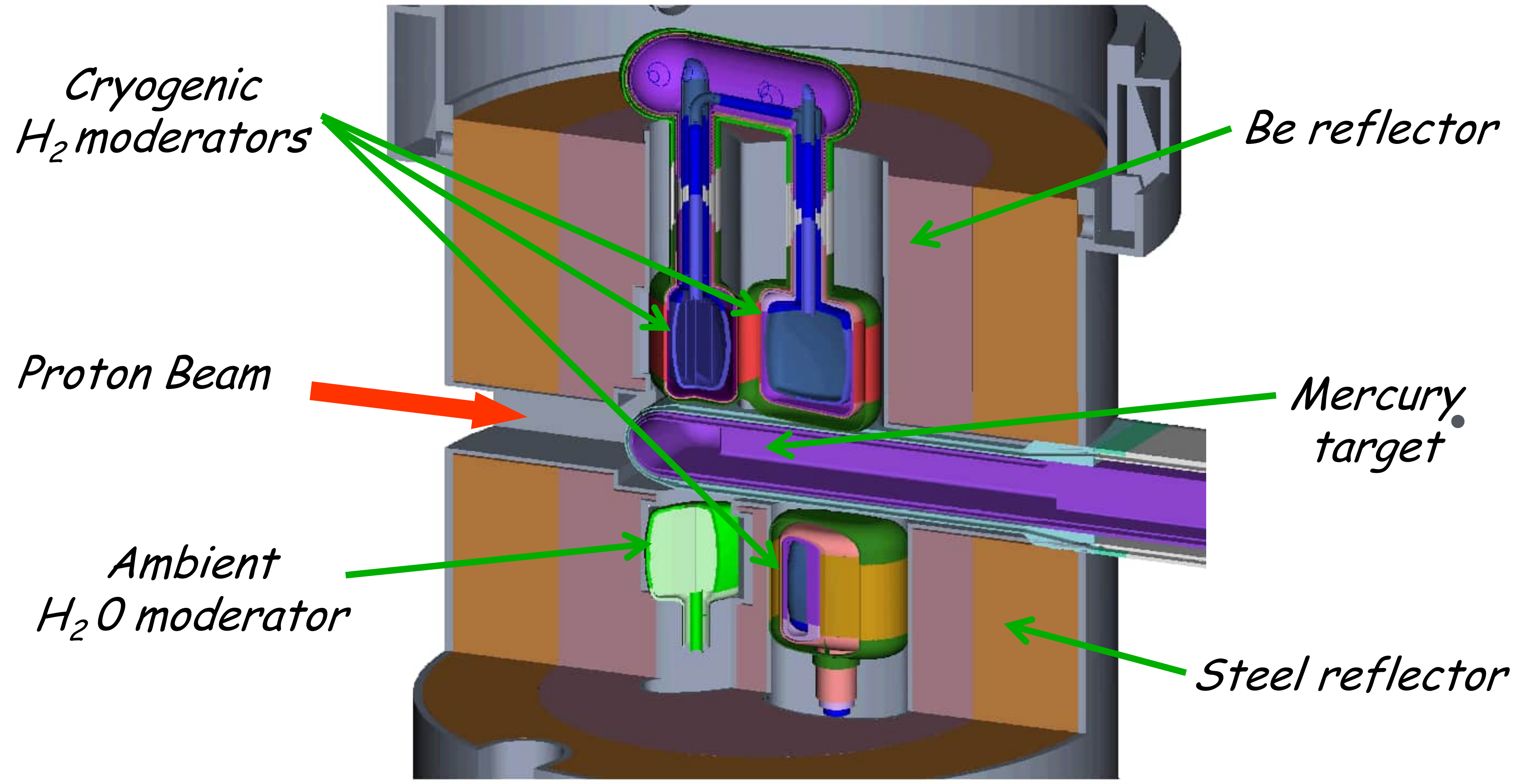
# Moderators:

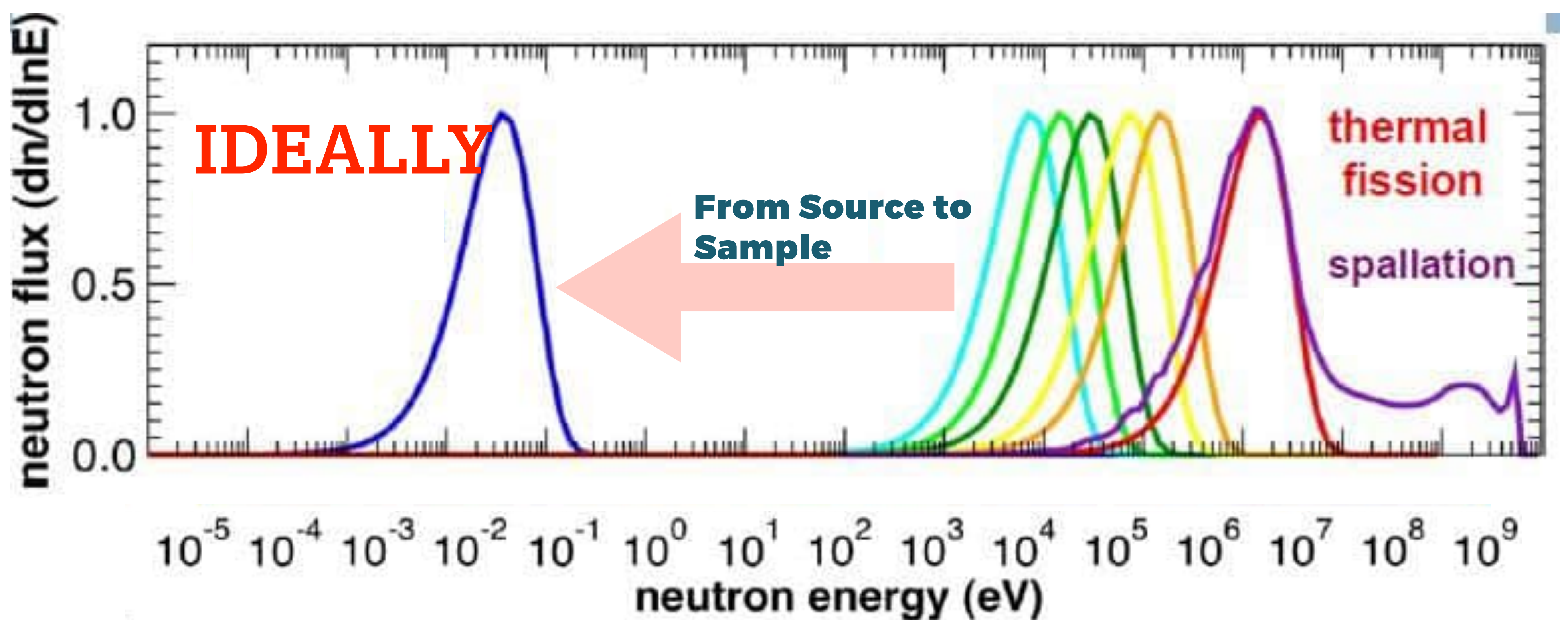
# Layout and Geometrical Shape

# Moderators: Effective Source for Instruments

## Moderators layout in spallation sources and in reactors

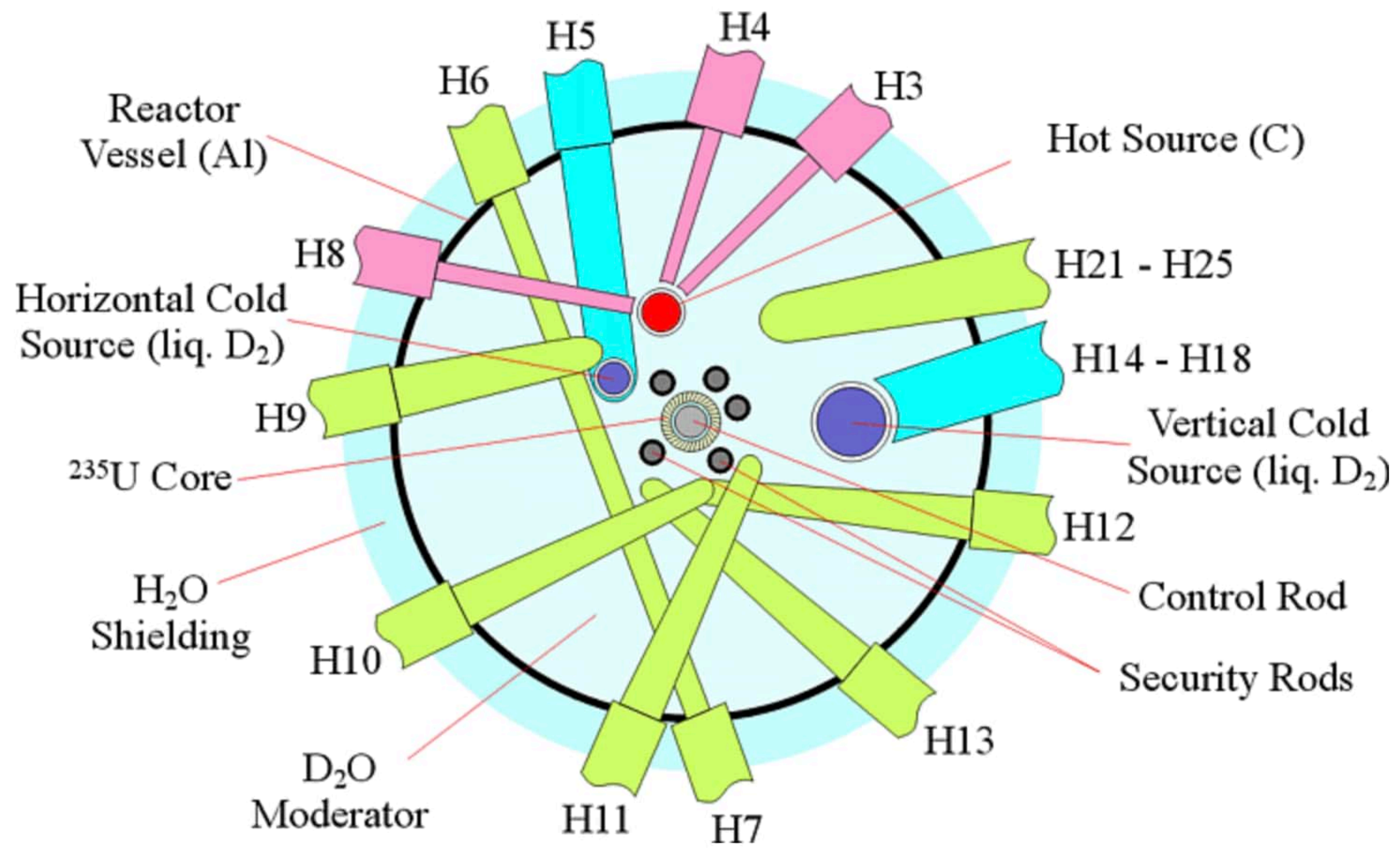
### SNS vertical cross section




- Main goal of moderators: shift the pulse down in energy saving the intensity and reducing the broadening (for pulsed source)
- BUT many neutrons are absorbed or lost on the road from the source to the sample and long tail could be added to the pulse!
- Usually target stations have a reflecting material (such as beryllium) to help the moderation process and improve the moderator efficiency.

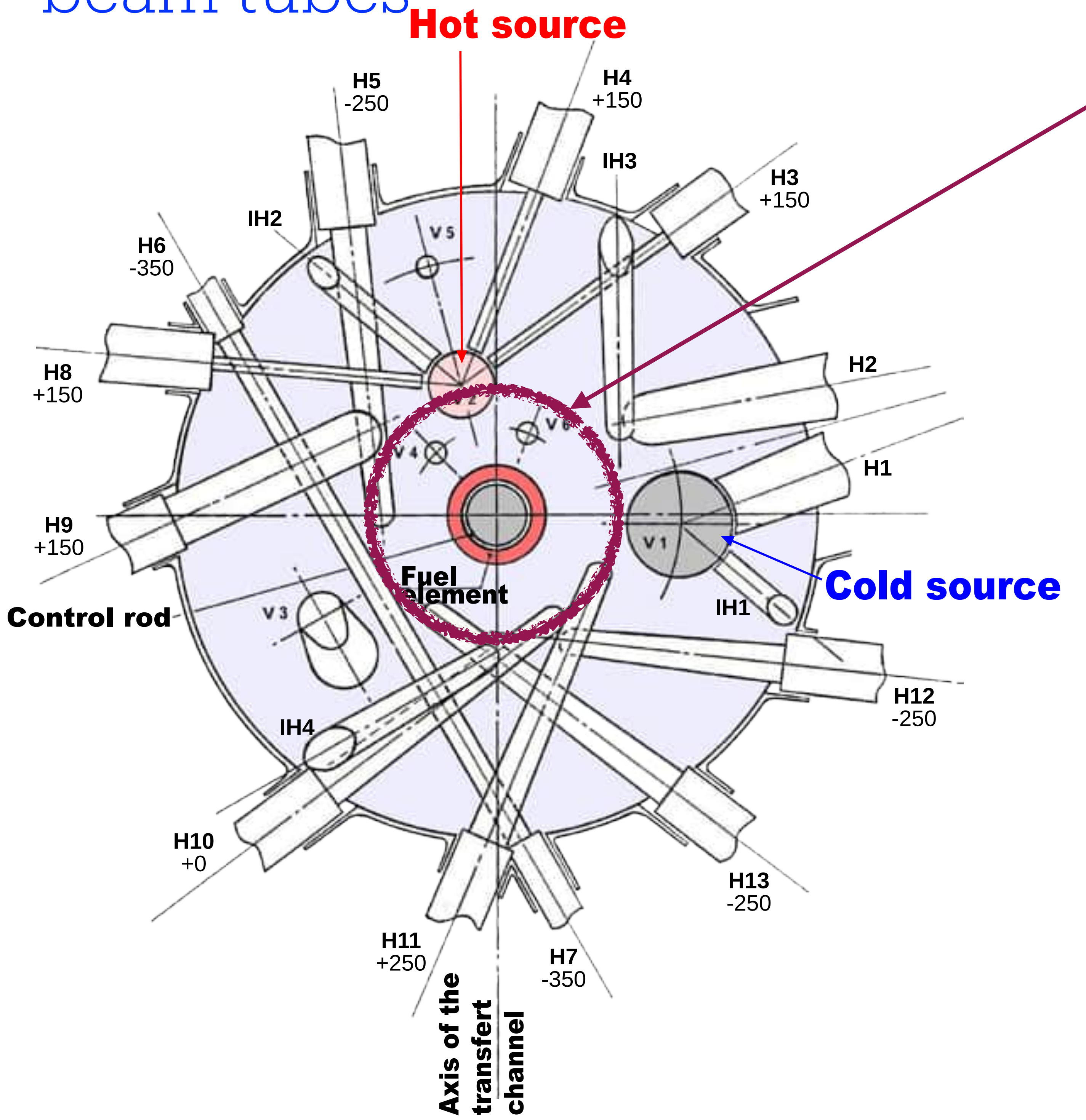
### ILL horizontal cross section

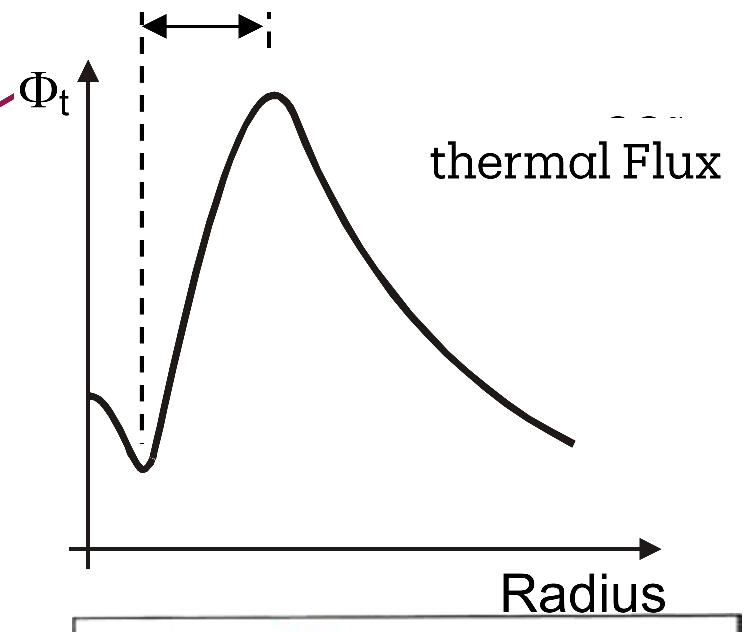


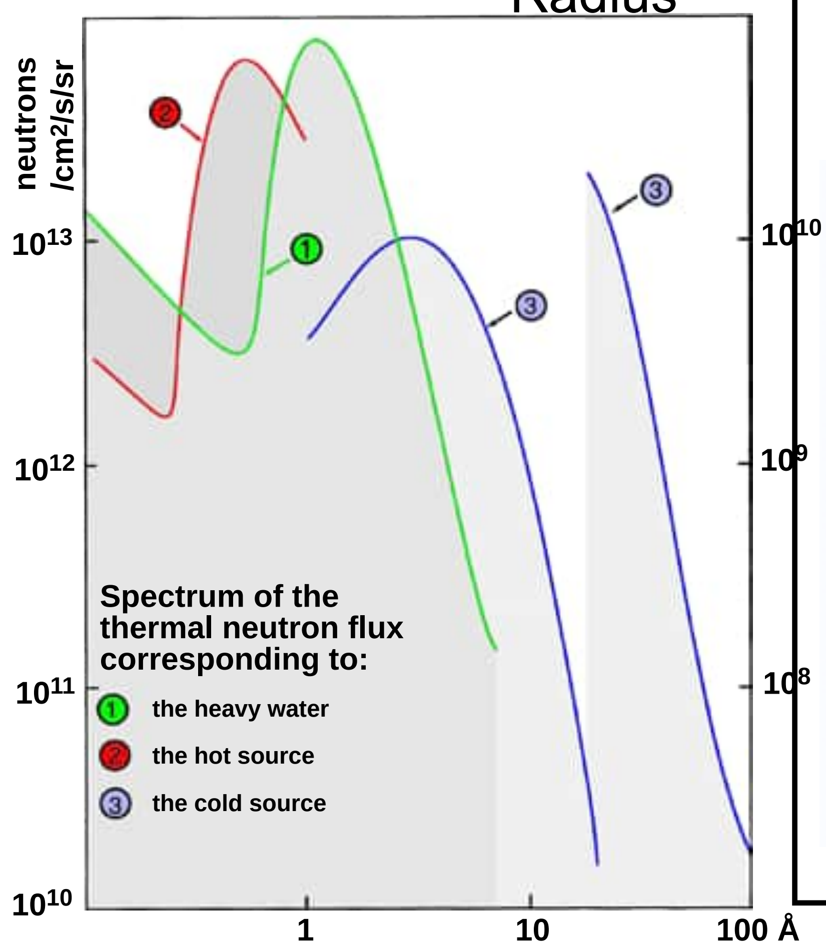

- Thermal reactors already need to slow-down neutrons to keep the chain reaction working
- But additional moderators could be required to reach lower energy range.
- Typically in research reactors, moderator for feeding the instruments are separated from moderator used for operational purposes
- Produce and provide access to the neutrons from external beams

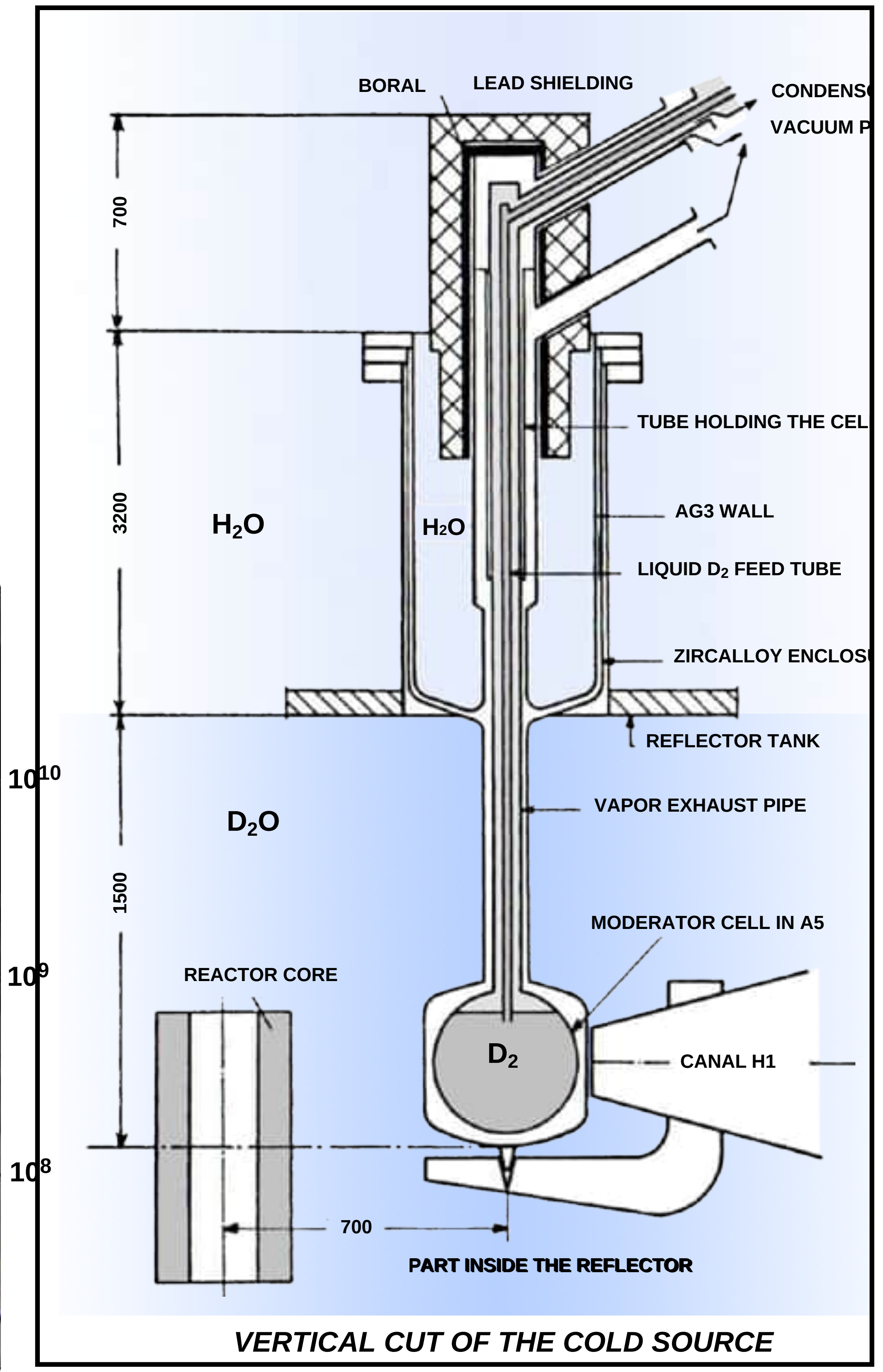
# RR thermal, Cold and Hot Moderators

- Arrangement of the experimental beam tubes



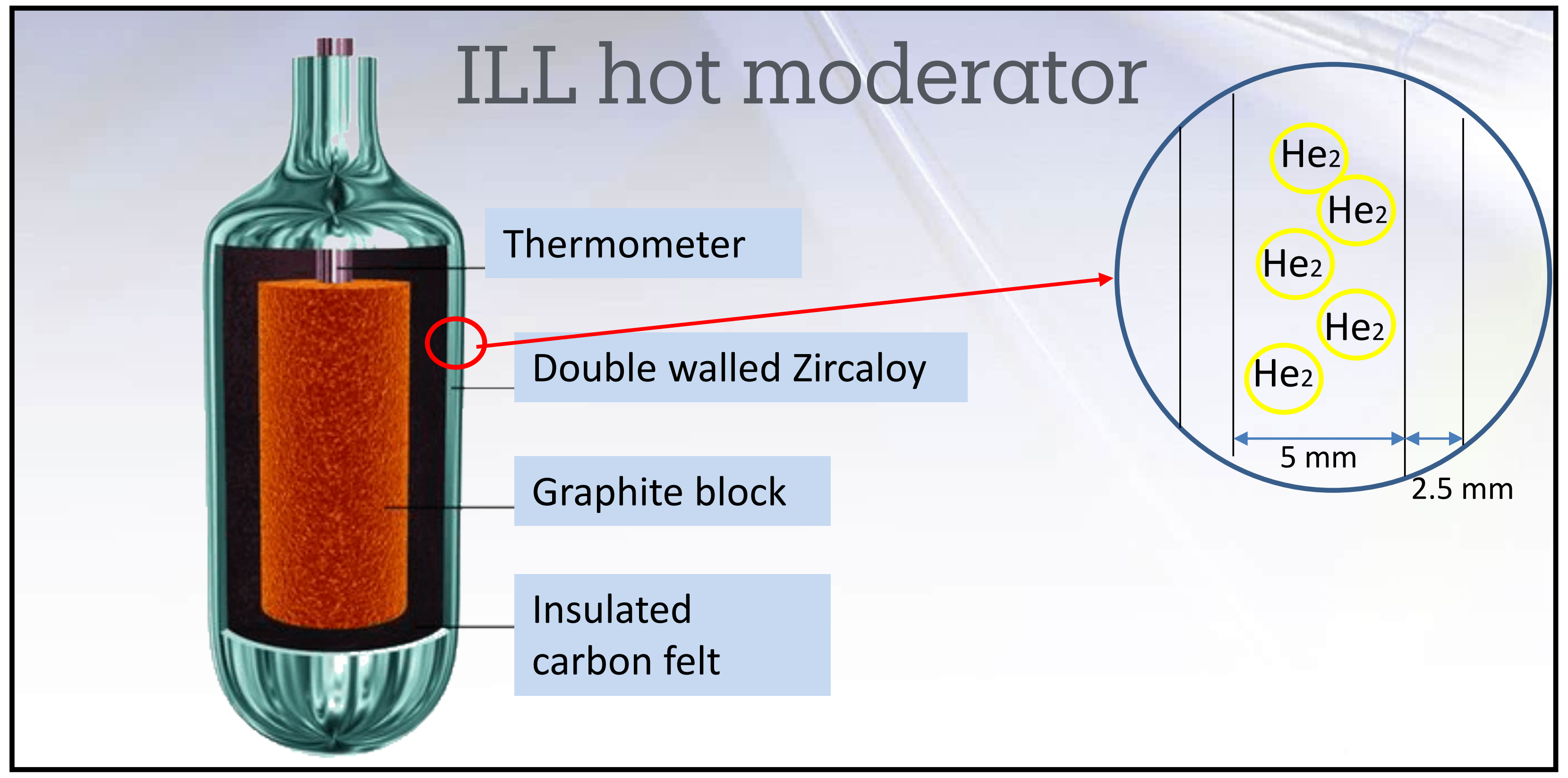




- Highly enriched uranium (93% U235)
- Compact design for high brightness
- heavy water cooling
- heavy water reflector
- Single control road
- 57 MW thermal power
- Cold, Thermal and hot sources

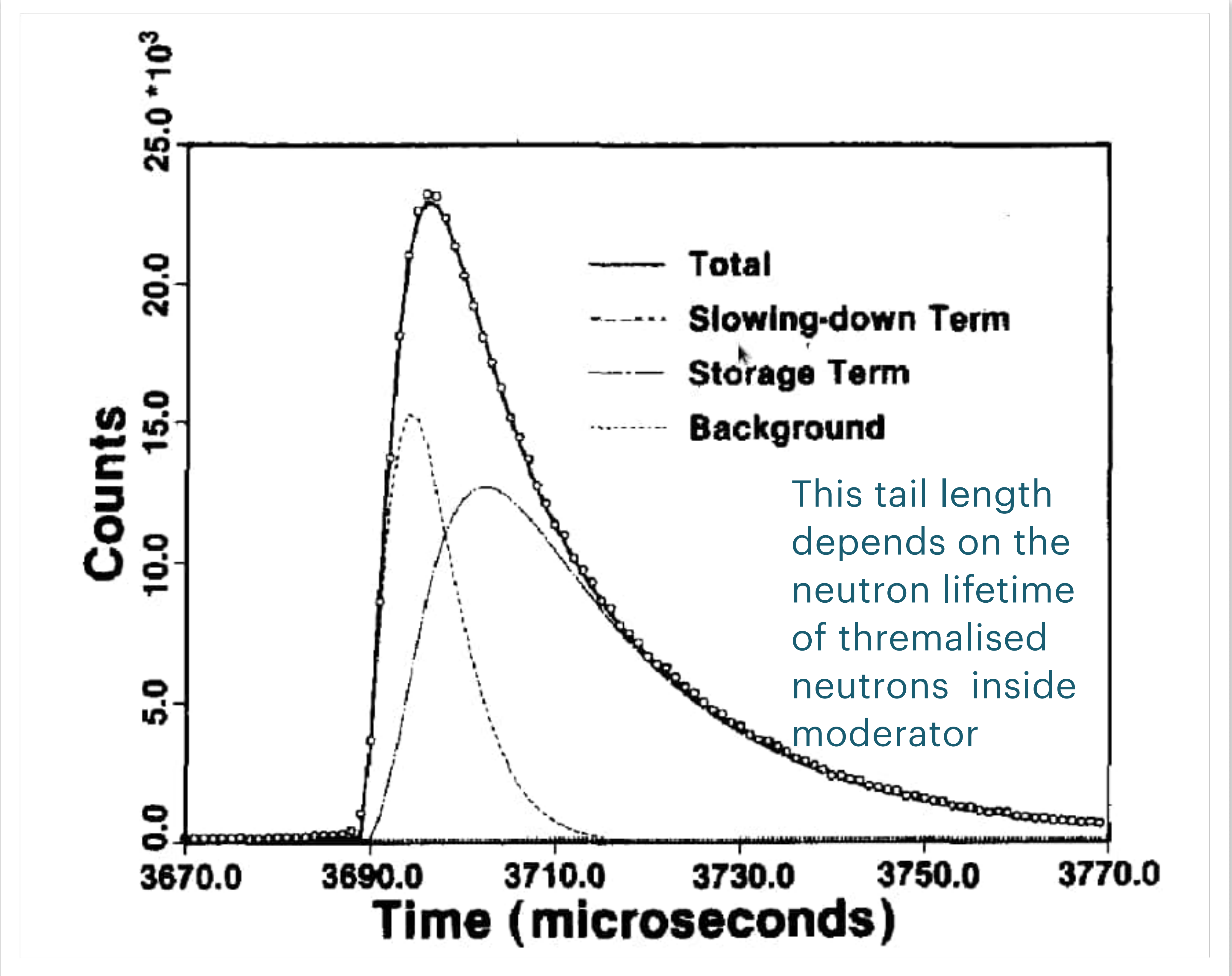
| ILL | cold | thermal | hot |
|---|---|---|---|
| moderator | liquid D2 | liquid D2O | graphite |
| Mod. Temp. | 20K | 300K | 2000K |
| neutron wavelenght | 3—>20 A | 1—> 3A | 0.2—>1 A |



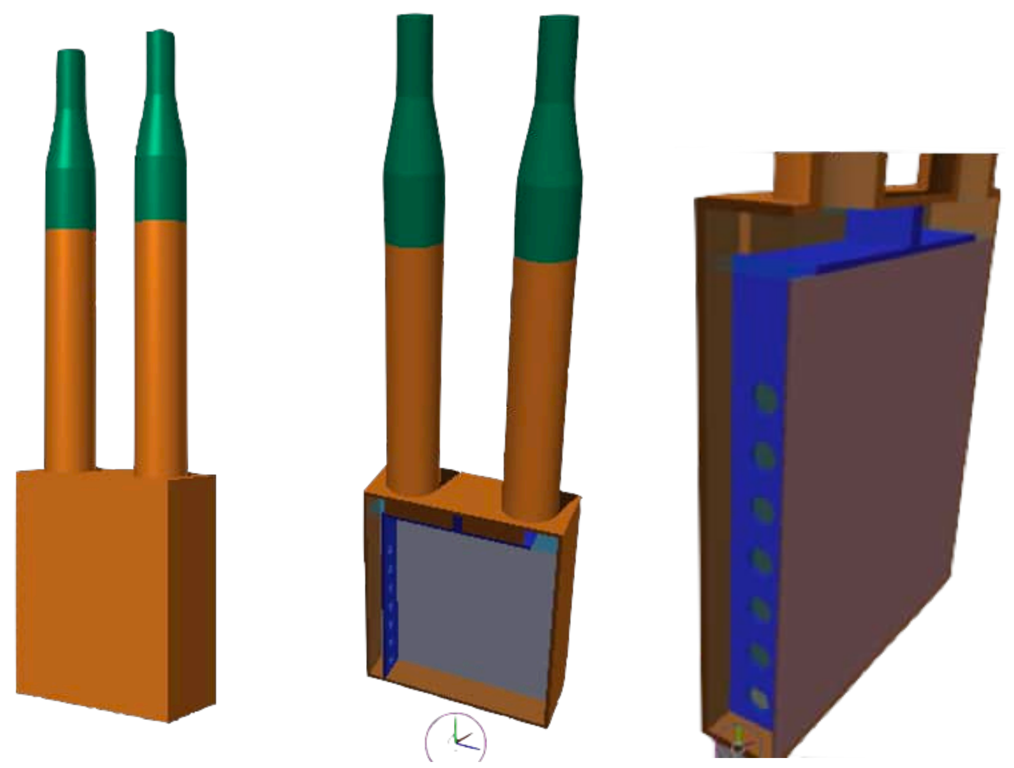
# Neutron Pulses from the Moderator Surface

**The function of a moderator is to convert leakage-neutrons (from a target) to slow-neutrons with energy spectrum and pulse characteristics as required for experiments.**

- A relatively small hydrogenous moderator is essential for Pulsed SNS to obtain reasonably narrow pulses, but at a large penalty in time-integrated and peak intensities.
- Neutrons reach thermal equilibrium with the scattering material.
  1. **Slowing-down neutrons come out quickly**
  2. **Thermalised population decays more slowly;**
- Overall emission is the sum of slowing-down term and thermalised one
- Both the slowing-down and storage component will always be present in a moderator




Aluminum box dimension 10x10x5cm



ISIS water moderator

**For short pulses: fast slowing down component and slow neutron lifetime in the moderator after the thermalisation are desirable (absorbing material inside the moderator)**

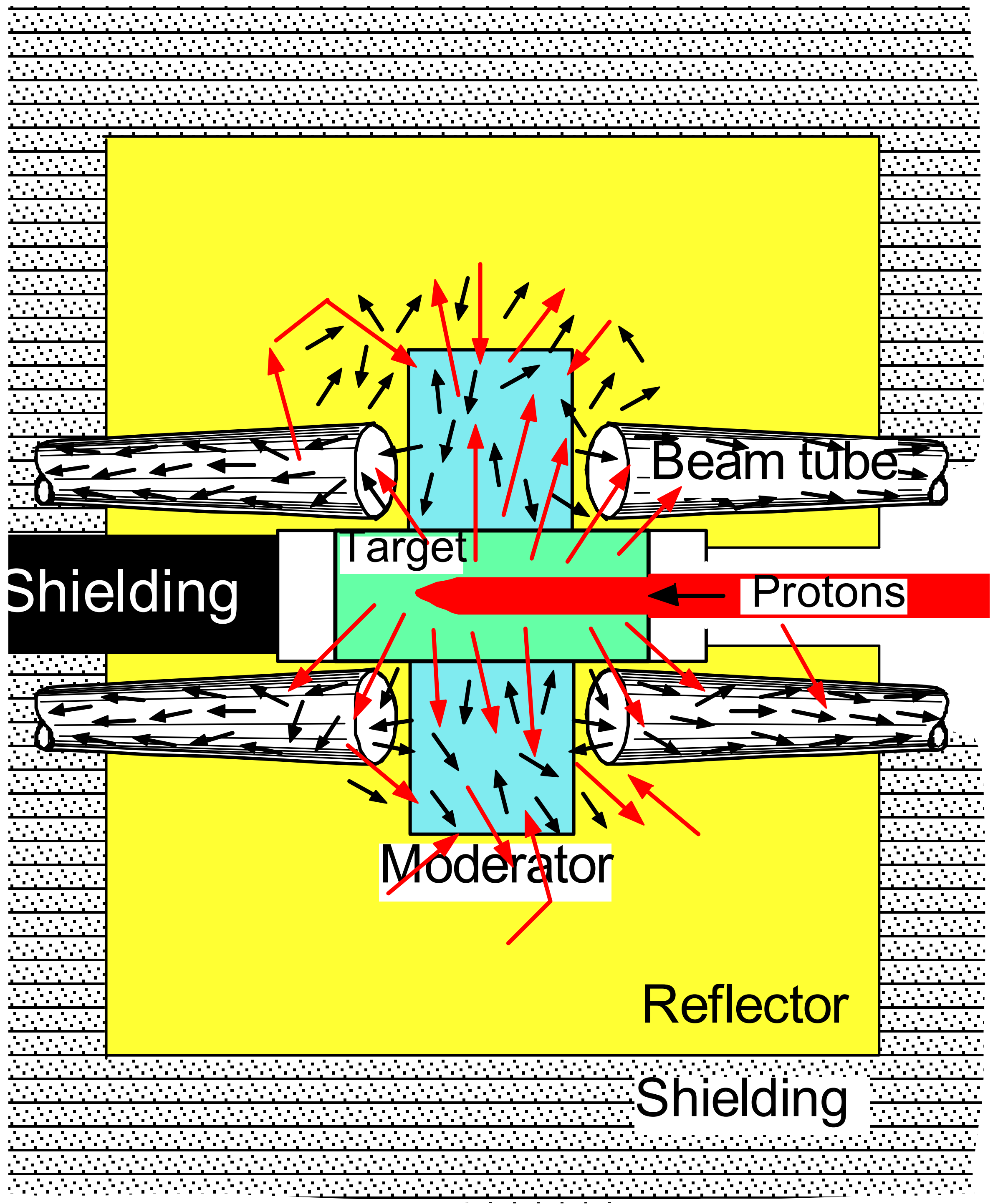
# Target Reflector And Moderator Assembly

Fast neutrons are generated by proton beam injected in a target

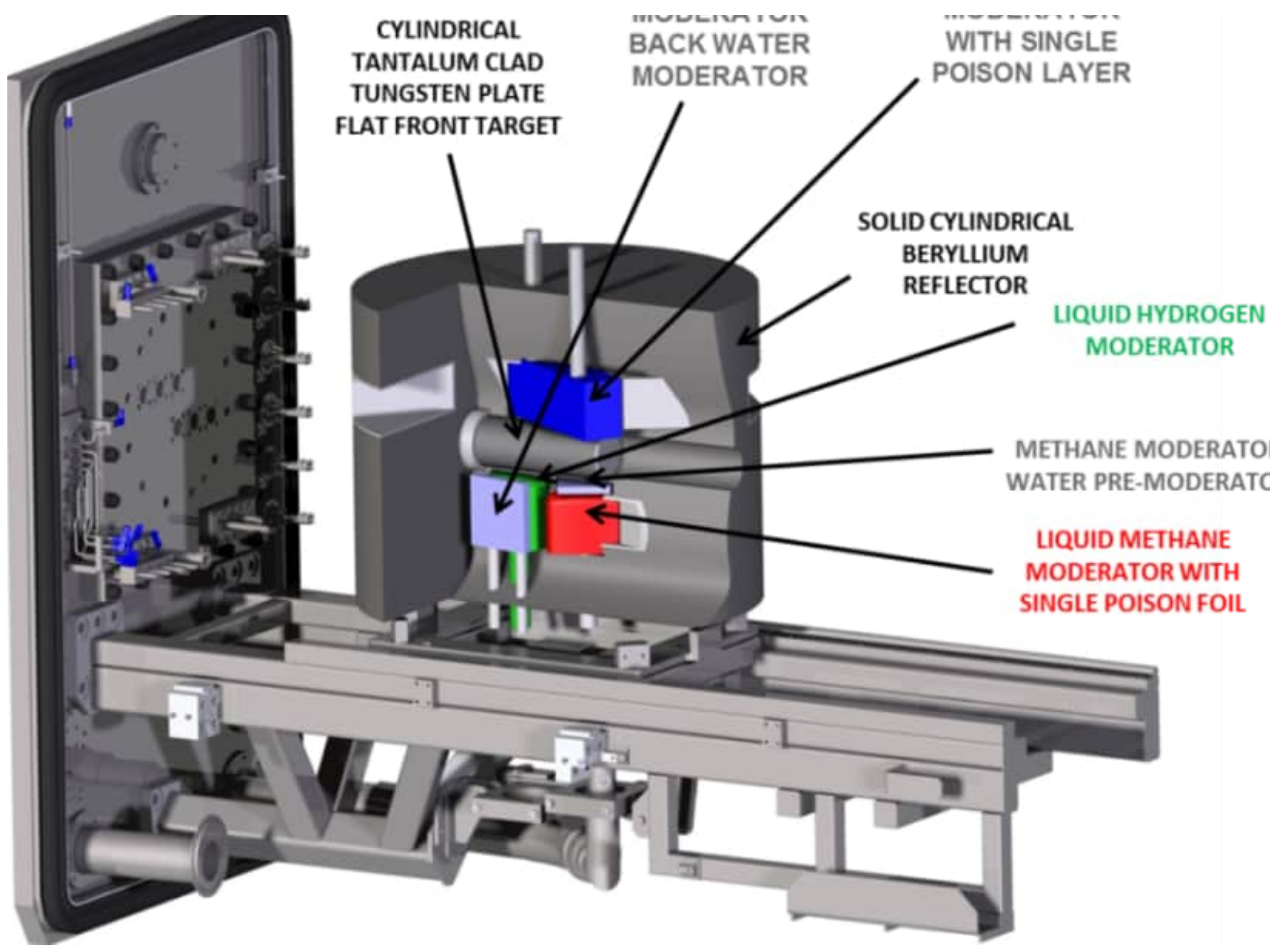
In order to be useful for scattering experiments neutrons must be slow-down to meV energy range by MODERATORs

Optimal coupling between moderator and target is required

In order to increase this coupling, moderator are surrounded by reflector whose task is to scatter those missing the moderator back into moderators




**ISIS TRAM module**




## The reflector role

The function of the reflector is to enhance the slow-neutron intensity by reflecting leakage-neutrons from the target that do not directly enter the moderators.

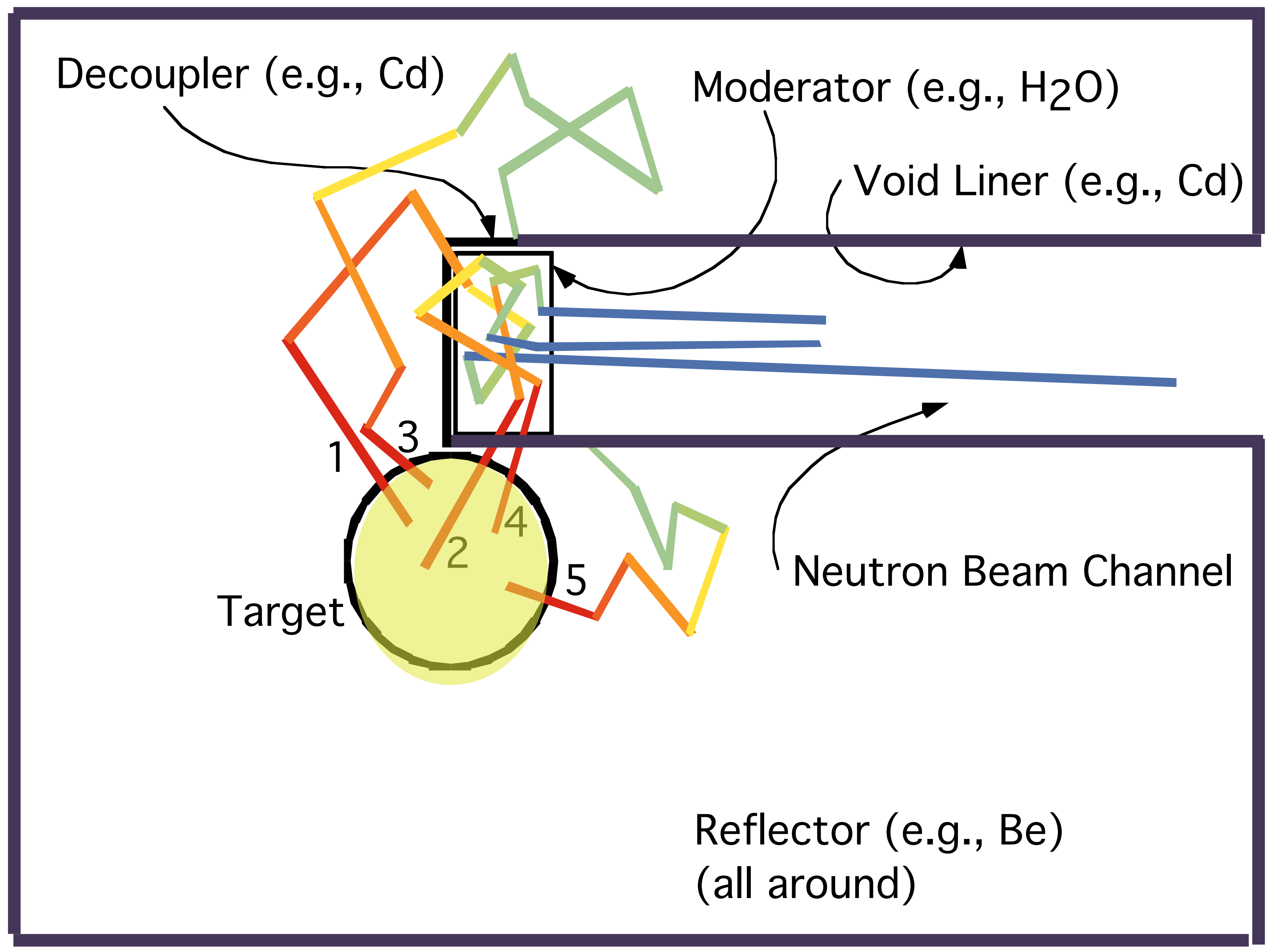
Typical reflector material: $D_2O$, Be, Fe, Pb

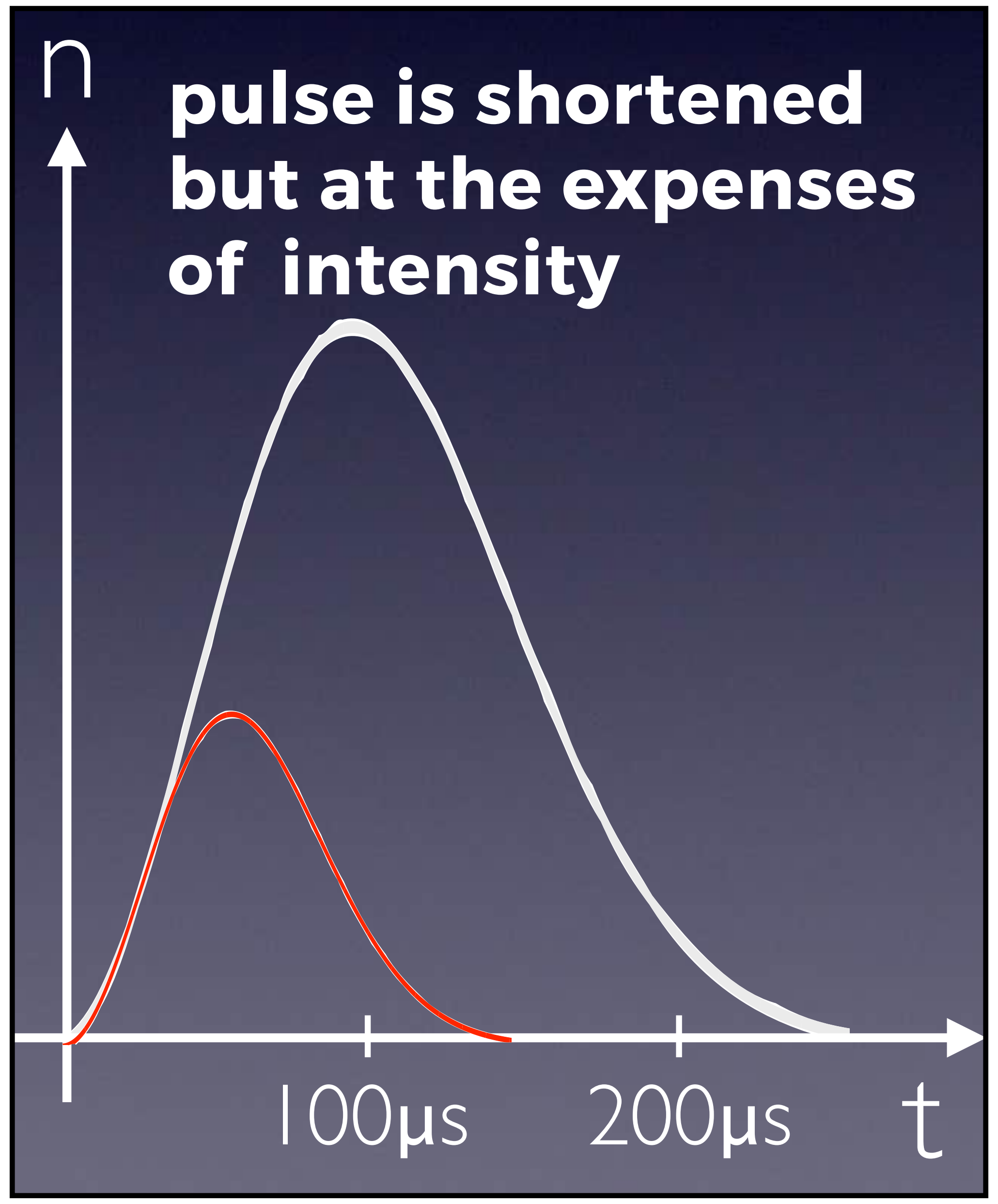
Neutrons can be also produced by inelastic interaction in reflector

Reflector are classified in 2 categories: moderating (Be) and not moderating (Pb)

# PSNS specific feature: Coupled and Decoupled Moderators

Spallation neutron sources offer a wide variety of choices for moderator and reflectors and require different technical solutions for different optimisation criteria.
This peculiarity makes spallation source more flexible than reactor ones




Purpose of a decoupled moderator: provide the narrowest possible neutron pulses with the highest possible peak intensities,

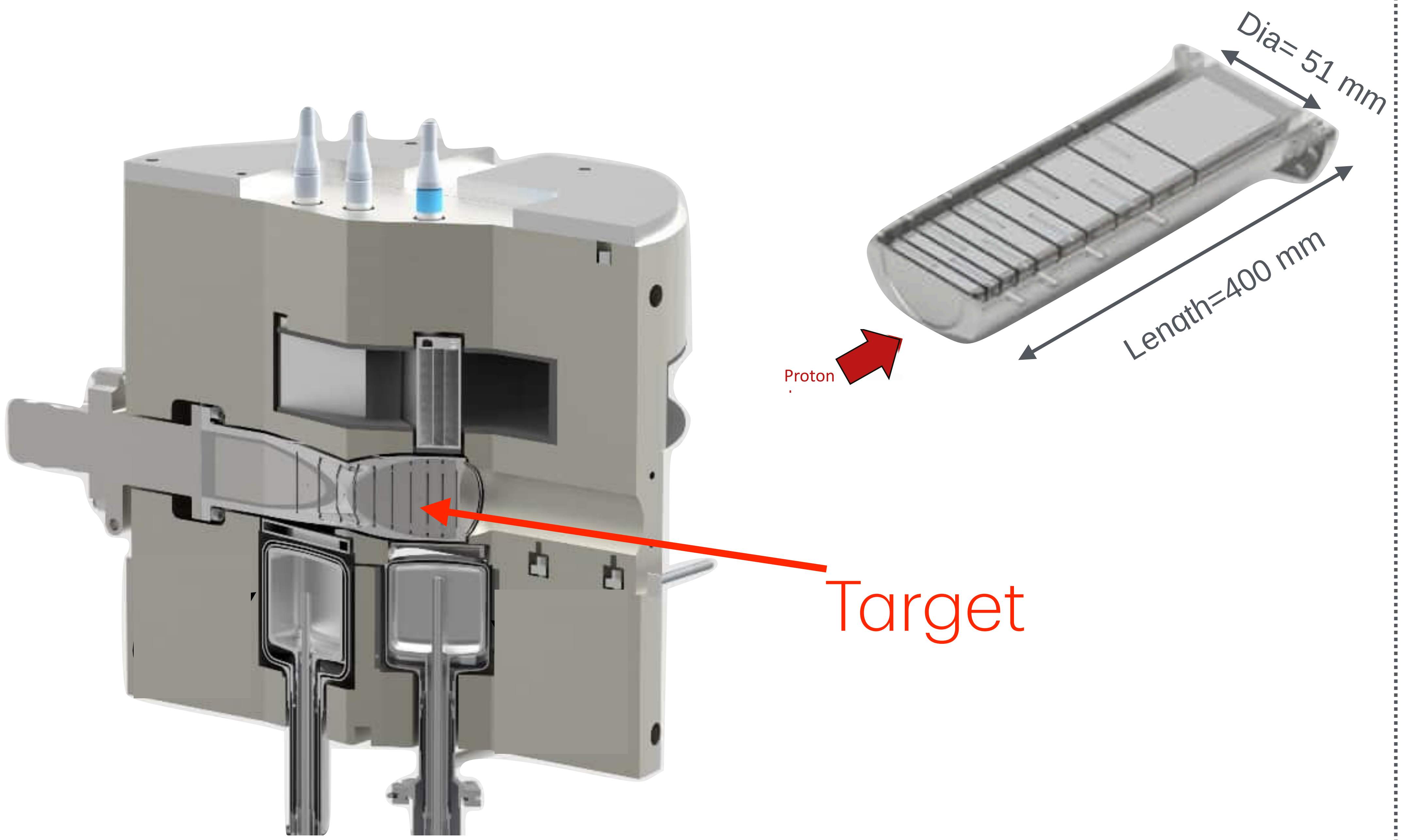
The use of a reflector is very important to enhance the slow-neutron intensity but it can cause broadening of pulses

Idea: decoupling the moderator from the reflector below the “decoupling Energy” by using a sheet of absorber material (B4C, Cd, Ag–In–Cd). Ed <0.4 eV for B4C, Ed>0.5 for Cd

Only neutrons with E> Ed can pass through

On the contrary in case of maximum time average flux requirement (application for which intensity of the flux is more important than resolution )—>minimise neutron absorption in reflector and moderator (D2O preferred to H2O) and so moderator is fully coupled to reflector

# ISIS TS1 and TS2 TRAM



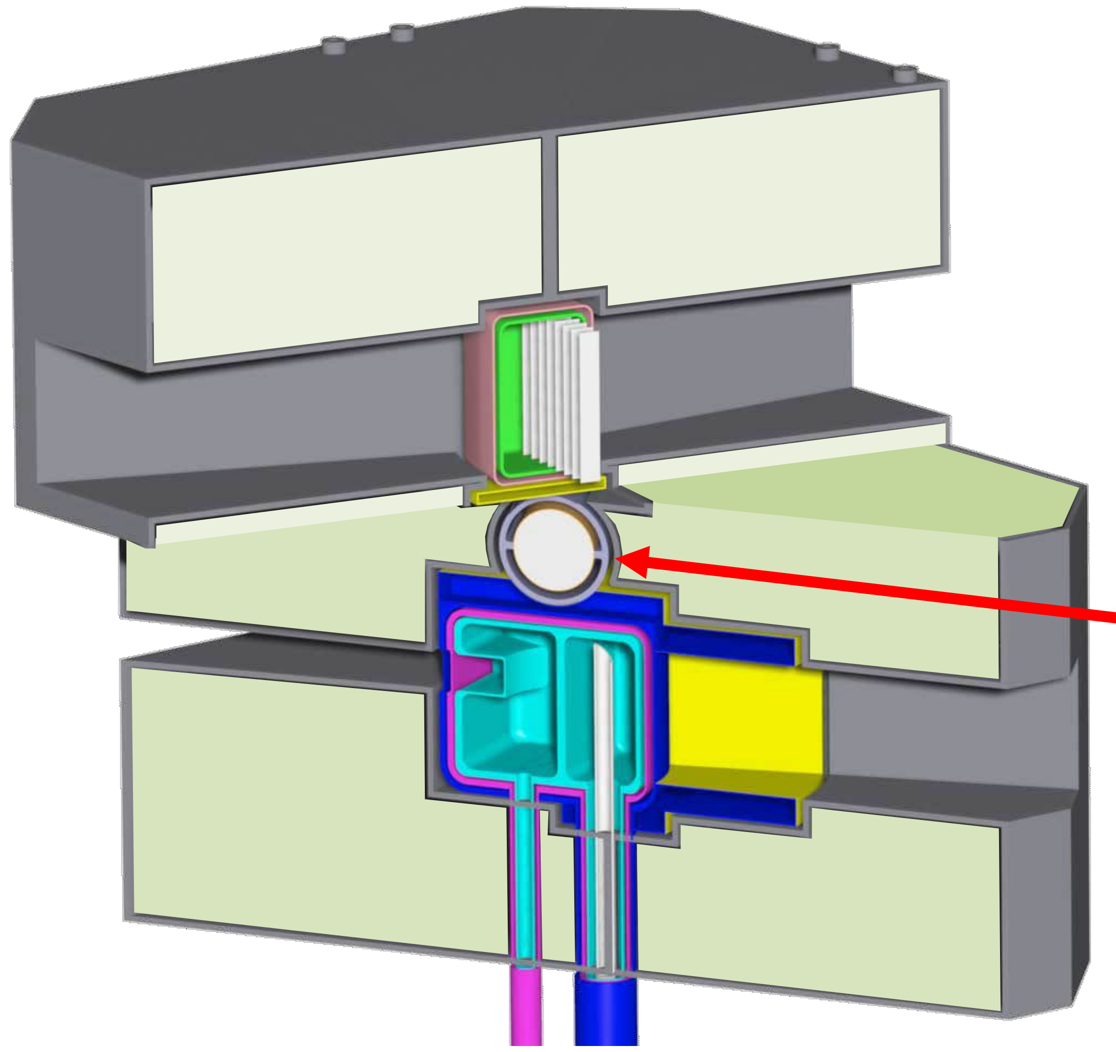

**TS1 TRAM (160 kW):**

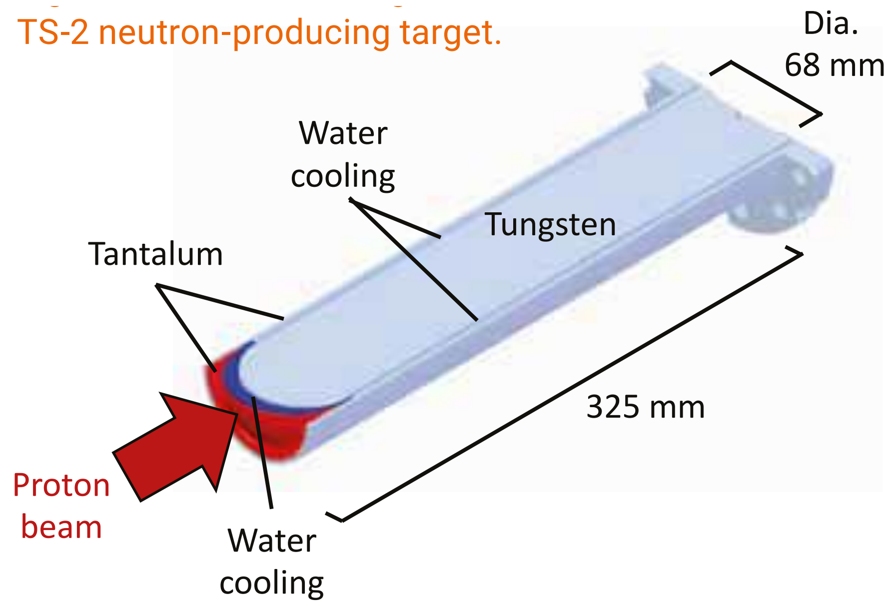
target—> of 10 W plates, R=4.9 cm, Ta cladded (thickness = 0.2 cm). L= 398 mm

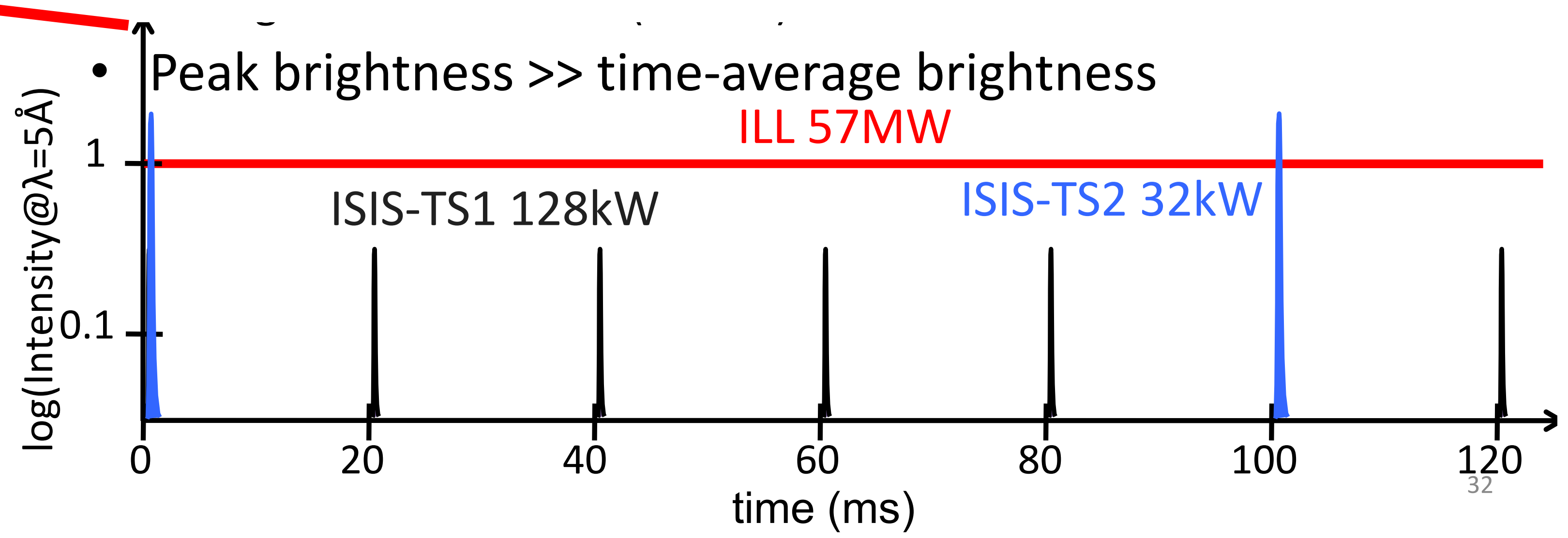
above—> 2 water moderators (decoupled and poisoned)

below—> 2 cryogenic moderators (LH2, LCH4)

reflector—>Beryllium (maximum room 70x70x70 cm) coated with $B_4C$






**TS2 TRAM (40 kW):**

TS2 was developed to produce bright beams of low-energy neutrons enabling the ISIS science programme to expand in the key research areas of soft matter, advanced materials and bio-science

target—> bulk W cylinder D= 68 mm, L=325 mm , Ta Clad.

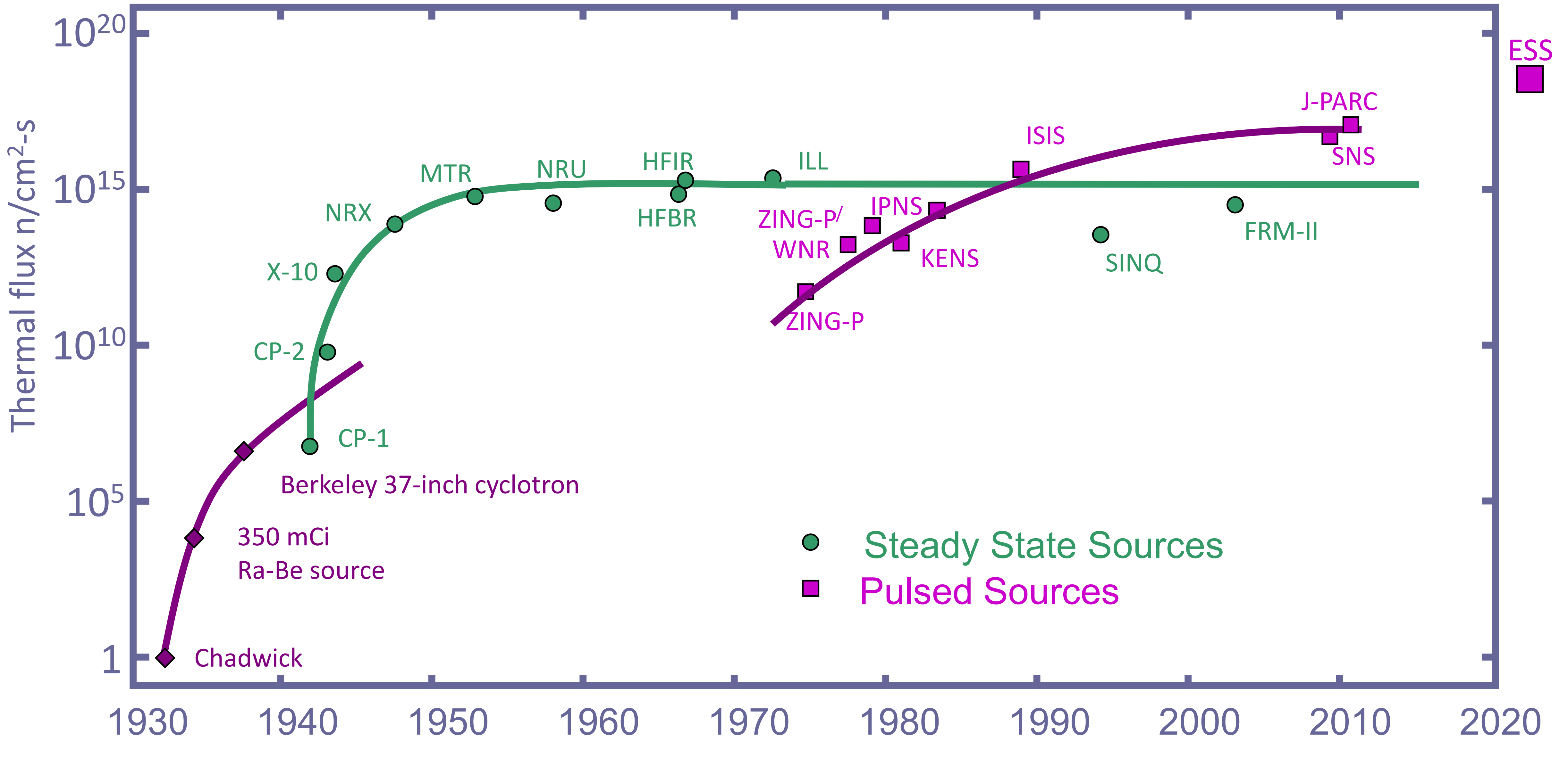
above—>coupled moderator with two viewed surfaces: LH2 and grooved S-CH4 (tapered hole to focus the beam and increase the brightness)

below —> decoupled moderator LH2 (for shorter pulses)

reflector—>solid beryllium blocks plated in Nickel

# Pulsed vs Continuous Neutron Source

# Development of Neutron Science Facilities




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

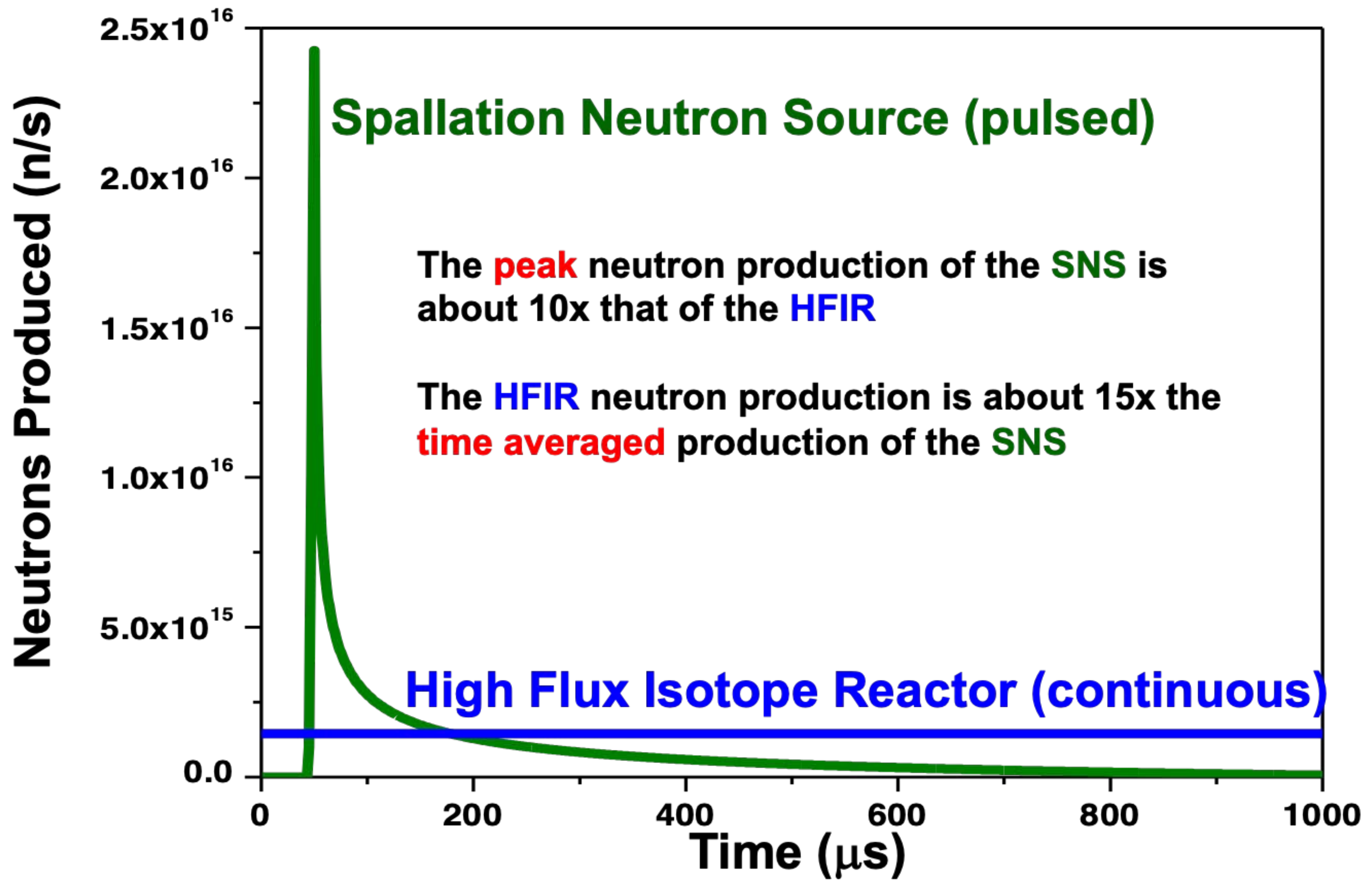
| Source type | Examples | Power (MW) | Typical approximate neutron output ($s^{-1}$) |
|---|---|---|---|
| Proton accelerator | CSNS | 0.1 | $1\times10^{16}$ |
| | ESS (~2023) | 5 | $1\times10^{18}$ |
| | ISIS | 0.2 | $2\times10^{16}$ |
| | J-PARC | 1.0 | $1\times10^{17}$ |
| | Los Alamos | 0.1 | $1\times10^{16}$ |
| | PSI (not pulsed) | 1.3 | $1\times10^{17}$ |
| | SNS | 1.3 | $1\times10^{17}$ |
| Reactor | ILL, Grenoble | 58 | $1.5\times10^{15}$ flux ($cm^{-2}\ s^{-1}$) |
| | HFIR, ORNL | 85 | $2.5\times10^{15}$ flux ($cm^{-2}\ s^{-1}$) |

Reactors: great contribution to neutron scattering research, but the highest neutron flux available saturated since the early 1970s.

Pulsed spallation neutron sources (PSNS) came out in the late 1970. The available flux is gradually getting higher with developments of high-intensity proton accelerators.

The neutron flux at the pulse-peak from PSNS could be 1–2 orders of magnitude higher than that from a high-flux reactor.

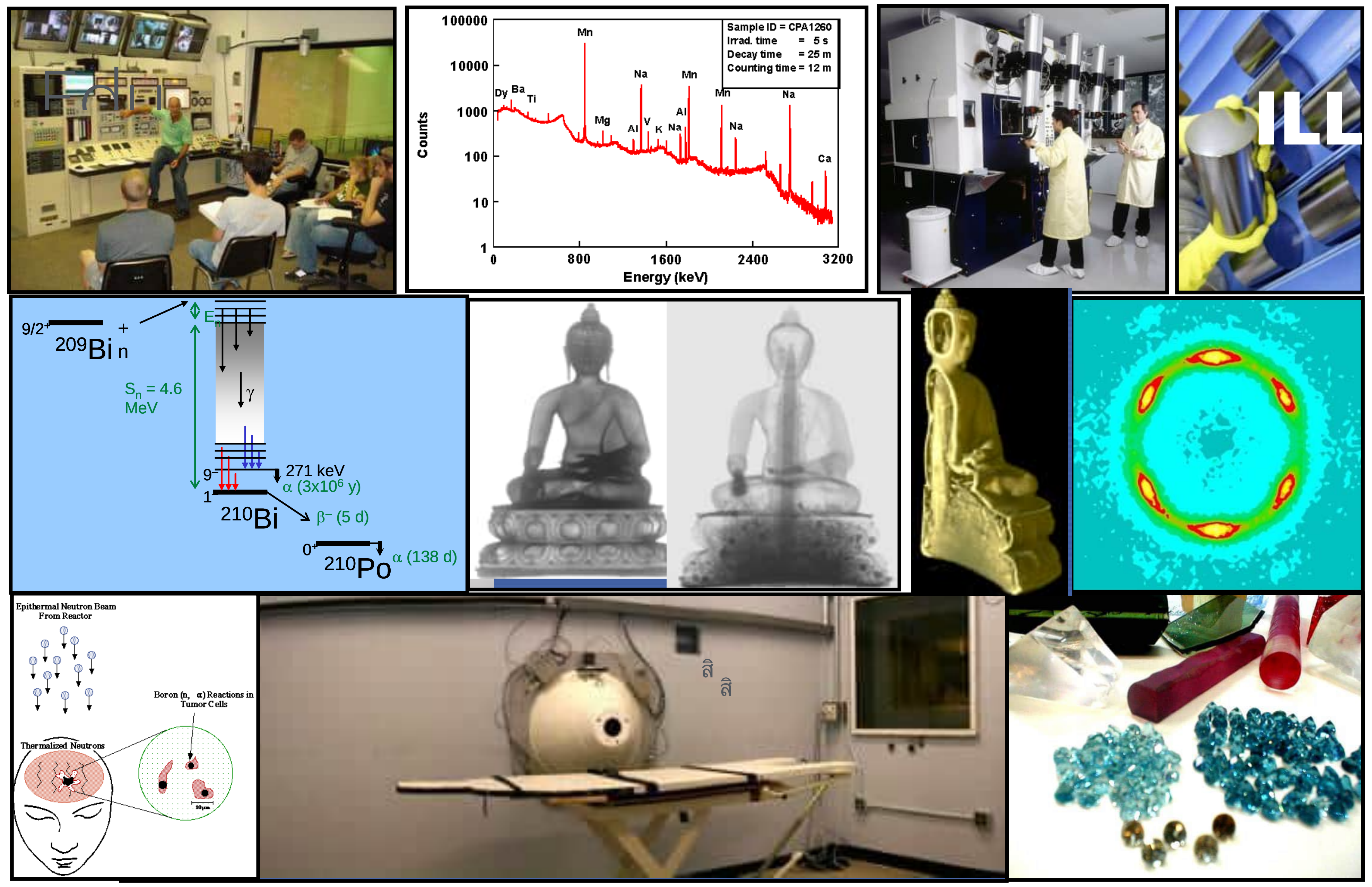
In new generation of long pulse sources (ESS 5MW), even the time-averaged flux is approaching a comparable level



# Large Scale Neutron Sources: Research Reactor Worldwide

About 220 RRs operational in 53 countries . They are basically neutron factories

| Country research | Operational research |
|---|---|
| Russia | 52 |
| USA | 50 |
| China | 16 |
| India | 7 |
| Argentina | 5 |
| Canada | 5 |
| Germany | 5 |
| Italy | 5 |
| Brazil | 4 |
| Iran | 4 |
| Kazakhstan | 4 |
| Belarus | 3 |
| Belgium | 3 |
| Czech Republic | 3 |
| France | 3 |
| Indonesia | 3 |
| Japan | 3 |
| Ukraine | 3 |
| Others | 45 |
| Total | 223 |




Main application fields

- Education & Training
- Neutron Activation Analysis &PGNAA
- Radioisotope production
- Neutron radiography
- Material/fuel testing/irradiations
- **Neutron scattering**
- Nuclear Data Measurements
- Si doping
- many others



Most powerful RRs for neutron scattering experiments:

ILL (France):
1.5 10^15 n/cm2/s

HIFR(USA):
2.5 10^15 n/cm2/s

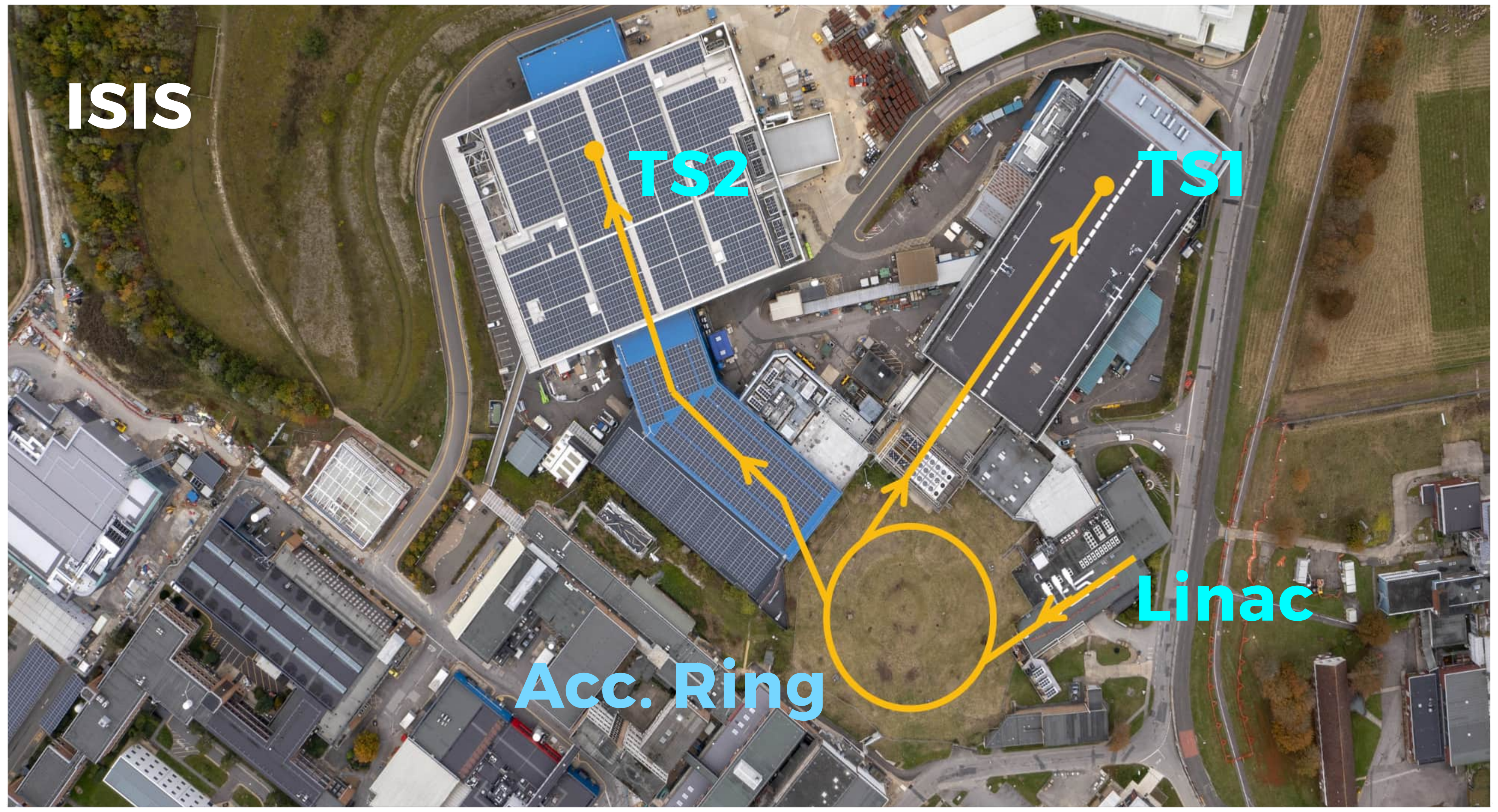
# Large Scale Accelerator-Driven Neutron Sources Worldwide

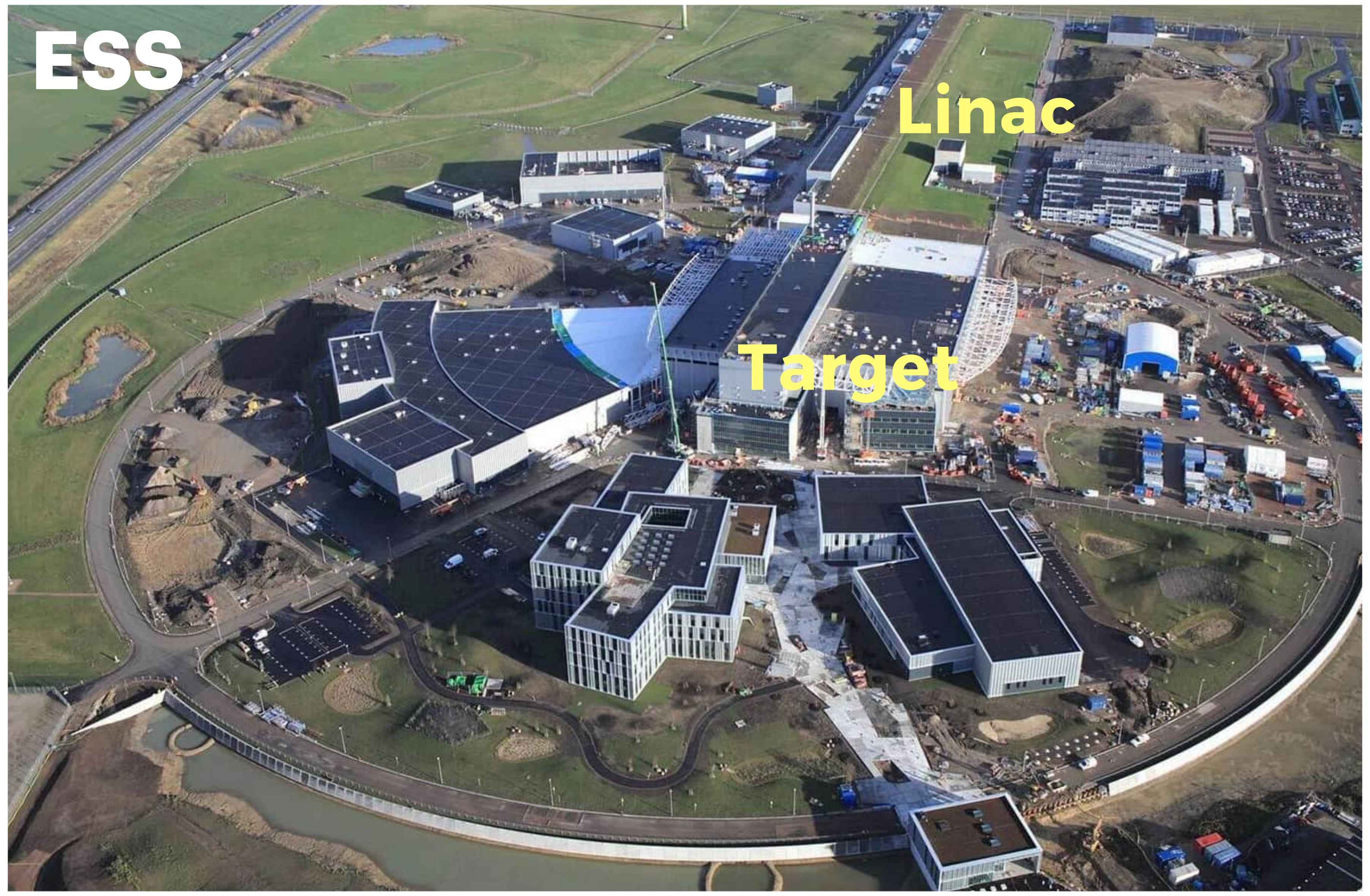
**By Spallation**

- **SNS** (Spallation Neutron Source) at **Oak Ridge, TN, USA**
- **ISIS** (Spallation Neutron Source) at **STFC, Harwell, UK**
- **n-TOF** (Spallation Neutron Source) at **CERN, Geneva**
- **IPNS** (Intense Pulsed Neutron Source) at **Argonne National Lab, IL, USA**
- **LANSCE** (Spallation Neutron Source) at **Los Alamos, NM, US**
- **LENS** (Low energy Neutron Source) at **Indiana University, IN, USA**
- **SINQ** Paul Scherrer Institut (PSI) in **Villengen PSI, Switzerland**
- **ESS (European Spallation Source) in Lund, Sweden**

**By high energy e-**

- **Gelina** (Geel Electron Linear Acceleration) in **Belgium**
- **n-ELBE** in **Dresden, Germany**
- **PNF** (Pohang Neutron Faility) in **Korea**
- **ORELA** at **Oak Ridge, TN, USA**




# Large Scale Accelerator-Driven Neutron Sources Worldwide

By Spallation | By high energy e-

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| | |
|---|---|
| **ISIS**<br>**Accelerator:**<br>Energy 800 MeV<br>Rep.Rate =40 Hz<br>Current =200 μA<br>Pulse length=120 ns | **TS1:**<br>Water (80%D2O-20%H20) cooled W<br>Avg. Power 160 kW<br>Neutron beam ports=18 +5(mu) |
| **Accelerator:**<br>Energy 800 MeV<br>Rep.Rate =10 Hz<br>Current =180 μA<br>Pulse length=120 ns | **TS2:**<br>Heavy Water cooled W<br>Avg. Power 32kW<br>Neutron beam ports=11 |

| | |
|---|---|
| **ESS**<br>**Accelerator:**<br>Prot. Energy 2 GeV<br>Rep.Rate =14 Hz<br>Avg Current =62.5 mA<br>Pulse length=2.86 ms | **Target station:**<br>He-gas cooled rotating W-target<br>Avg. Power 5 MW<br>**Pulse power:** 125 MW<br>Neutron beam ports=42 |

| | |
|---|---|
| **SNS**<br>**Accelerator:**<br>Prot. Energy 1.0 GeV<br>Rep.Rate =60 Hz<br>Avg Current =26 mA<br>Pulse length=0.7 ms | **Target station:**<br>material Liquid Hg<br>Avg. Power 1.4 MW<br>Neutron beam ports=24 |

# Pulsed and Continuous Neutron Sources

**Pulsed sources-> neutrons are provided in bursts with a given repetition rate. These source are mainly accelerator driven sources**

- More High energy neutrons
- Measure when off (low backgrounds)
- Higher peak power possible
- Sharp pulses-high resolution
- Time of flight bandwidth controlled by source frequency
- Broader range of energy/wavelength
- Lower environmental footprint

**Continuous—-> constant flux of neutrons over the running time. Mainly reactors**

- More Low energy neutrons (since the higher moderator efficiency)
- Easier to shield (low backgrounds)
- High average flux
- Sequence of choppers can be used to cut the continuous beam in pulses
- Experimental flexibility
- Environmental footprint

# C vs P: Technical and Applicative Differences

The attraction of pulsed source is obvious: intense burst of neutrons is produced in a time which is short compared with the period between pulses and so the heat generated during pulses can be efficiently removed.

**Accelerator main differences**

- ✓ Synchrotrons or accumulator (compressor) rings provide short neutron pulses (ISIS,SNS)
- ✓ Linear accelerators provide long neutron pulse (ESS).Long pulses do not to require pulse compressing ring
- ✓ Cyclotrons provide continuous beams of protons—> neutrons (PSI)

**Continuous source** favour those applications that require high time average flux (much lower fast and very high energy neutron background)—->**PSI**

**Long Pulse** length of proton beam longer than time to slowdown the neutrons in the moderator. They are more suitable for high intense cold neutron beams or for application requiring high resolution with low wavelength, such as small-angle scattering —->**ESS**

**Short pulses** are required for epithermal neutron spectrum or for highest resolution in thermal region (serve better those applications with high peak flux at appropriate rate—-> **ISIS**)

| Spallation source | Short pulse | Long pulse | Continuous |
|---|---|---|---|
| Imp. Length | a few μs | a few ms | - |
| Facilities | ISIS, SNS, JPARC | ESS | PSI |

| Reactor | Long pulse |
|---|---|
| Imp. Length | a few tens of ms |
| Facilities | IBR-2 DUBNA |

Long pulse do not suffer from thermal shock one has to deal with in the targets of high power short pulse source

# Remarkable Exceptions: “Pulsed Reactor” and “Continuous Spallation Source”

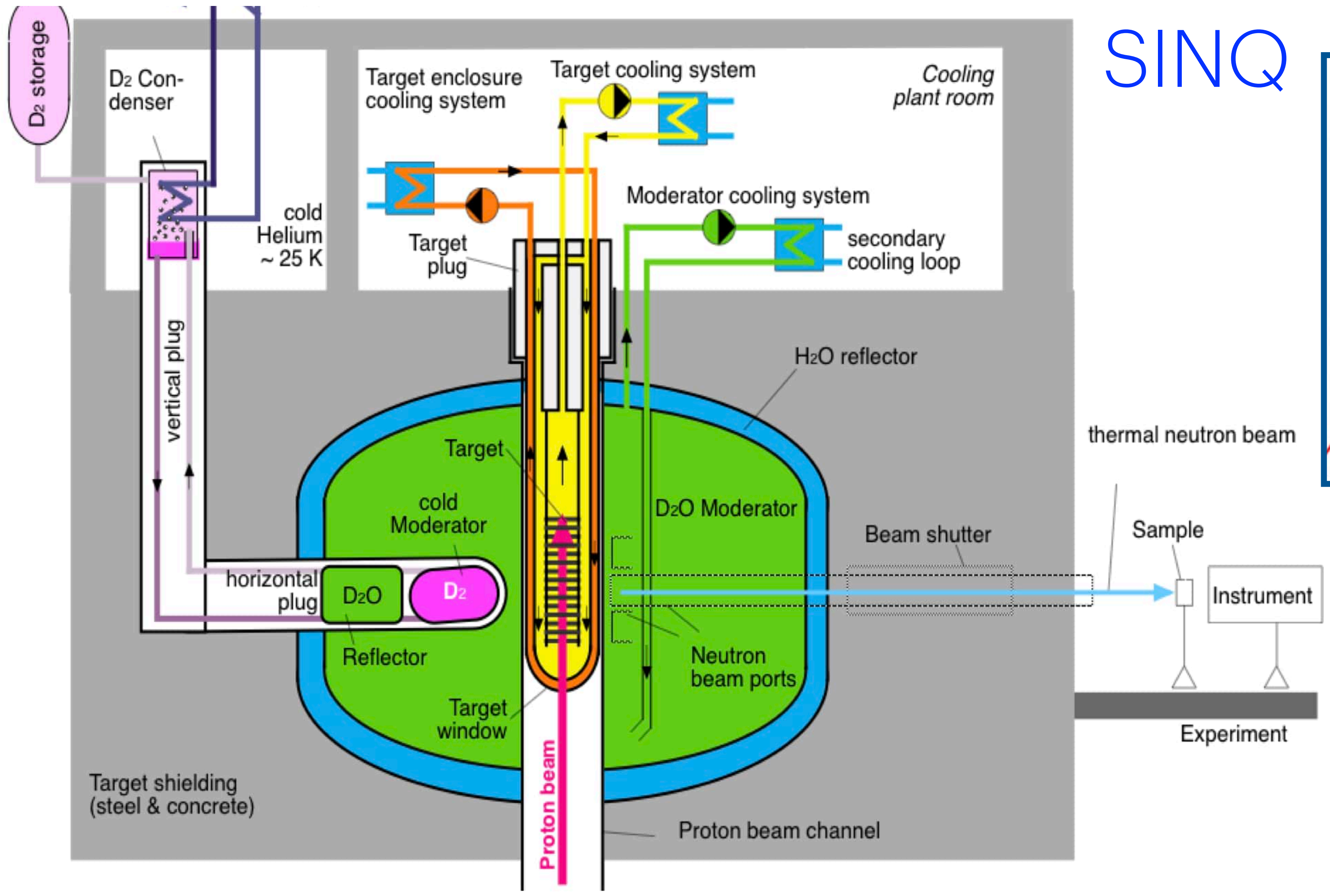
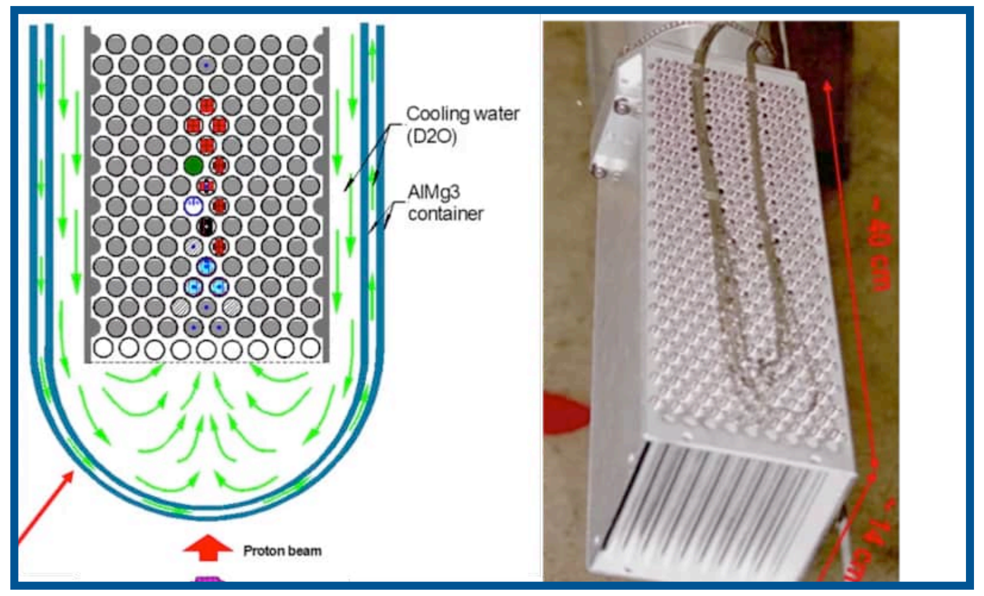



**Figure 1:** Schematic layout of the SINQ cooling and moderation systems

SINQ




Cannelloni rod target

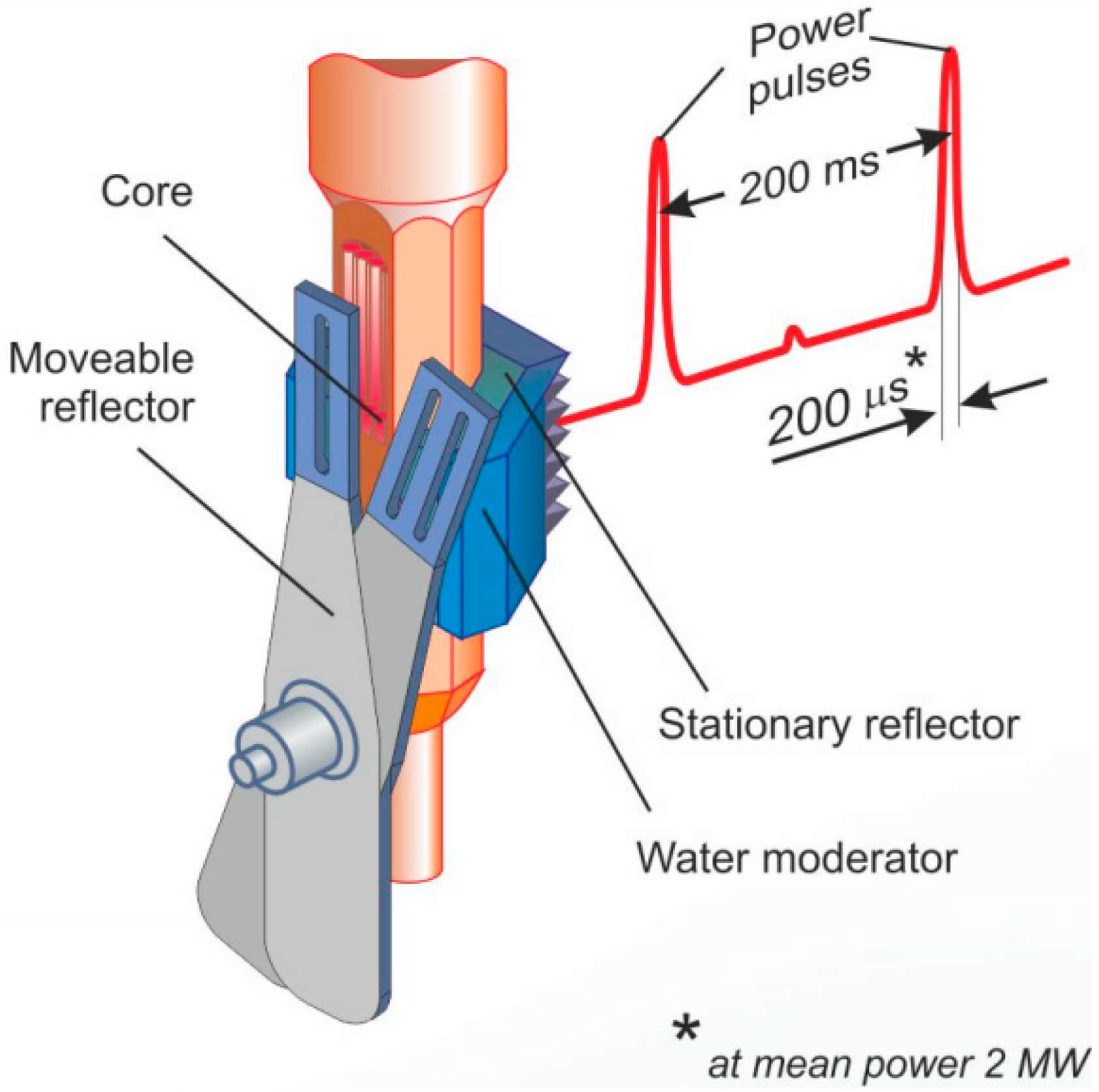
590 MeV proton and a current of approximately 1.2 mA.The beam power available for SINQ will thus be roughly 0.75 MW.

The proton beam is diverted by bending magnets vertically upwards from underneath into the heavy metal target (on Pb/Zr )

Spallation continuous source - the first and only one of its kind in the world - with a flux of about 10^14 n/cm2/s.

Beside thermal neutrons, a cold moderator of liquid deuterium (cold source) slows neutrons down and shifts their spectrum to lower energies.

IBR2



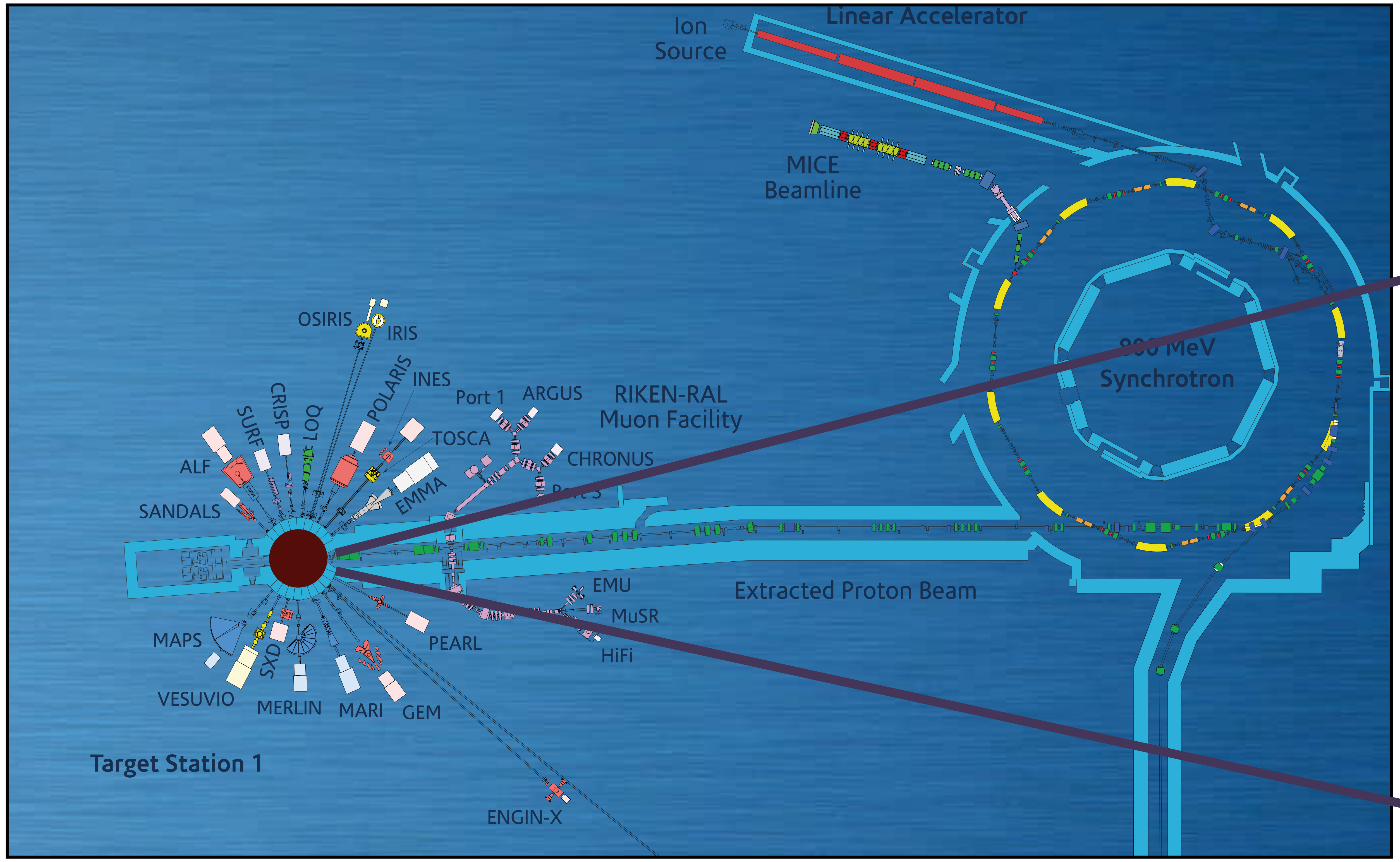

Pulsed fast reactor, IBR-2,

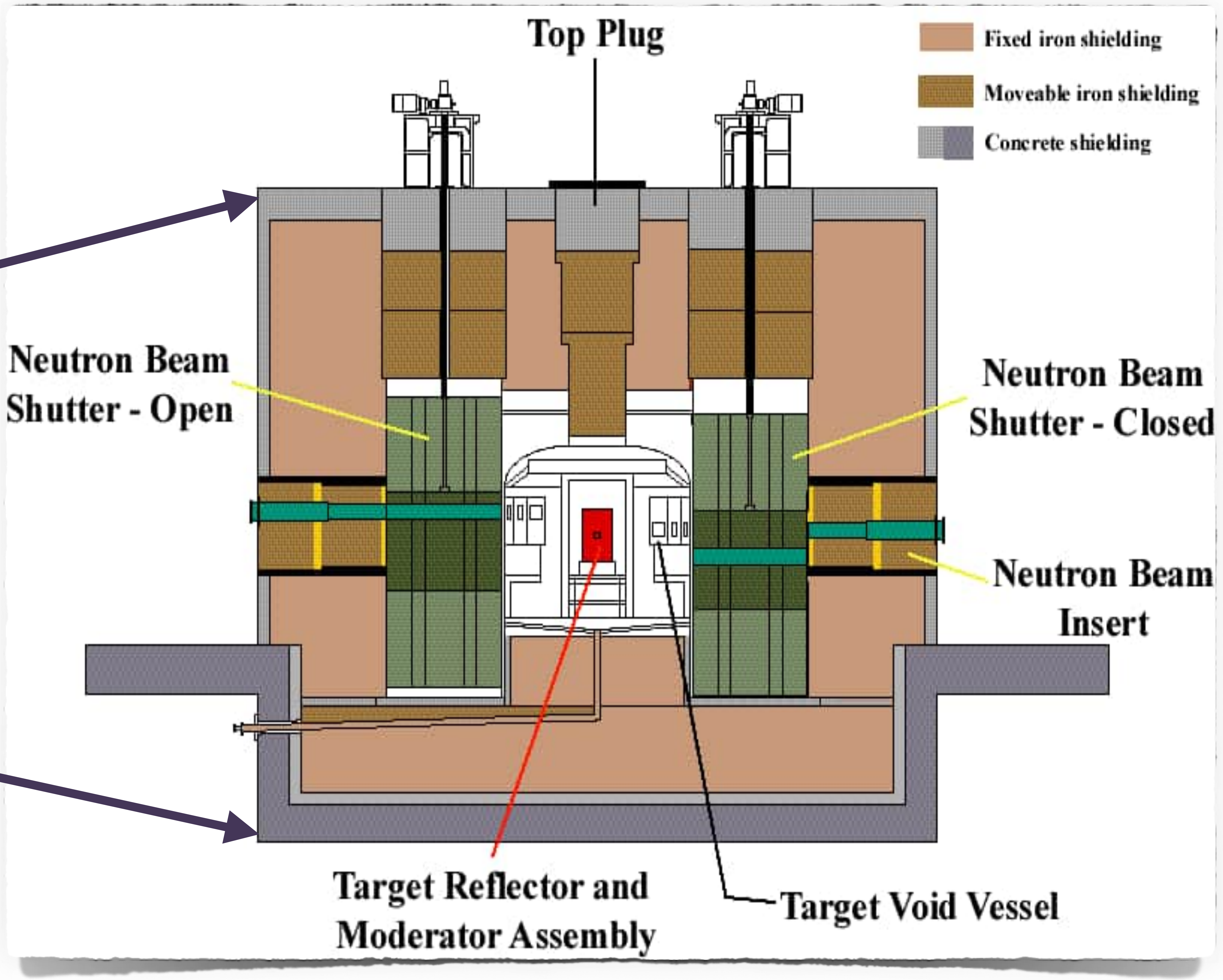
In this type of reactors neutron pulses with widths of several tenths of microseconds are generated periodically by mechanical modulation of reactivity.

The IBR-2 reactor with its unique technical approach produces one of the most intense neutron fluxes at the moderator surface among the world's reactors: ~10^16 n/cm2/s, with a power of 1850 MW in pulse

# Neutron Beam Lines &
# Time of Flight Technique

# Shield, Shutter and Instruments Layout (TS1 ISIS)




| Instruments | Flight path to sample |
|---|---|
| Maps | 12m |
| Vesuvio | 11 m |
| Merlin | 11.8 m |
| Mari | 11.739 m |
| Pearl | 12.8 m |
| Ines, Tosca | 23.8 m |
| Polaris | 14m |

Instruments are located at several tens of meters from moderators. The detailed distances for ISIS TS1 is reported in the table

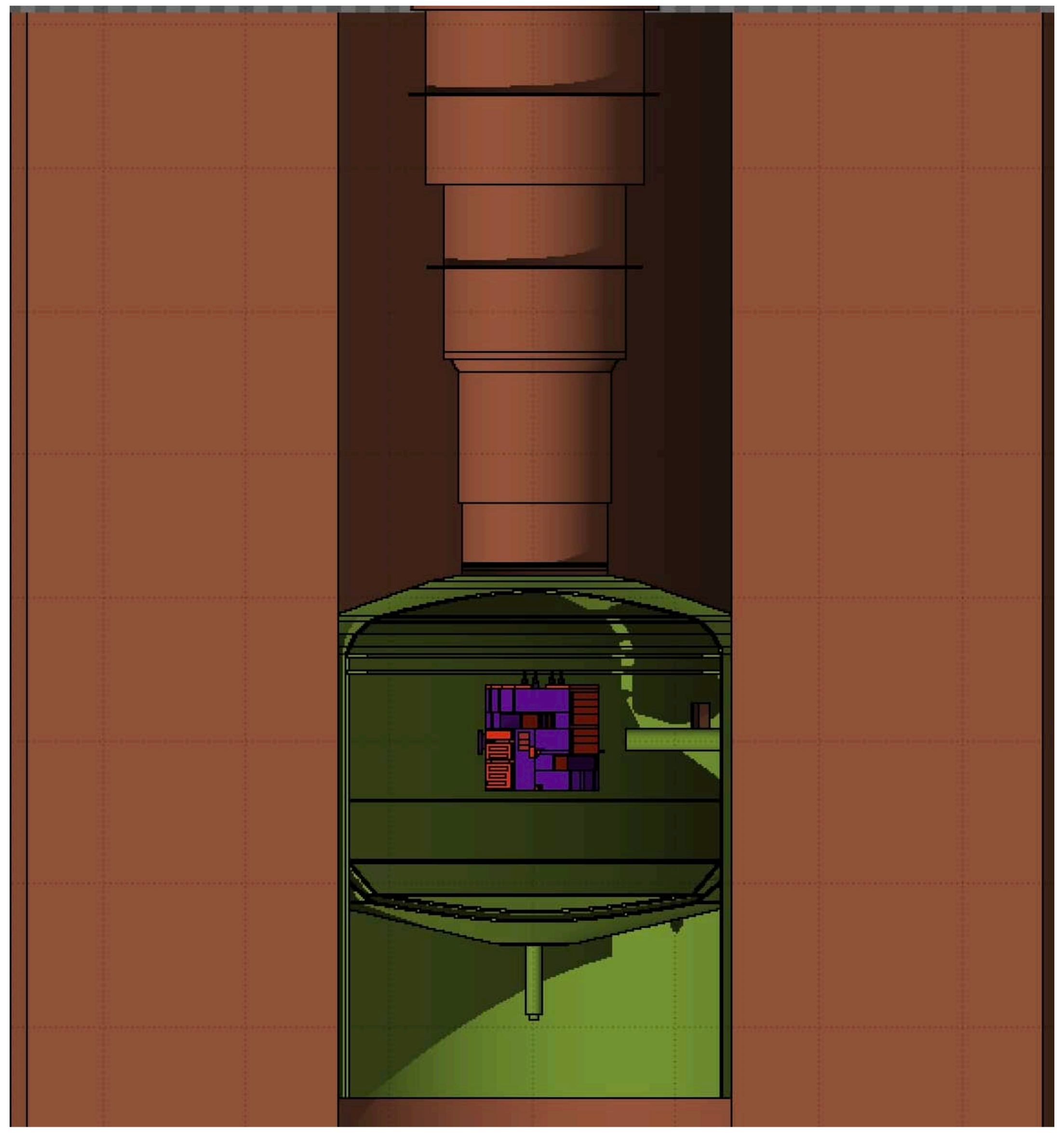
Shutter =2 m of iron and concrete

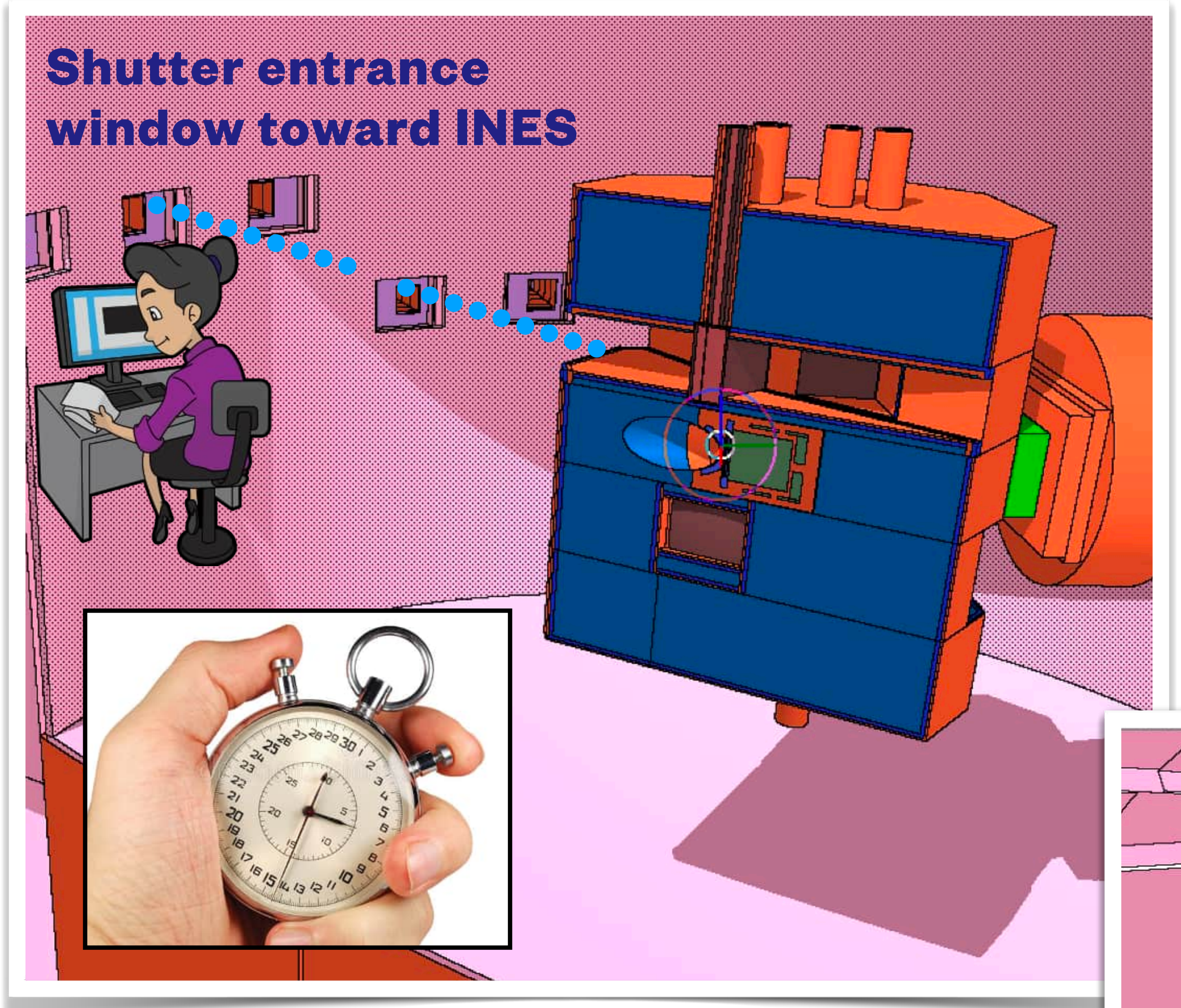
Dose rate at the shield surface < 0.75 mSV/h

Take as reference that the dose of 1Ci AmBe at 10 cm from the center is about 0.35mSV/h

# Spallation Sources for Scattering: Main Energy and Time Requirements

Time distribution of neutrons at the shutter inlet is of the order of a few microseconds



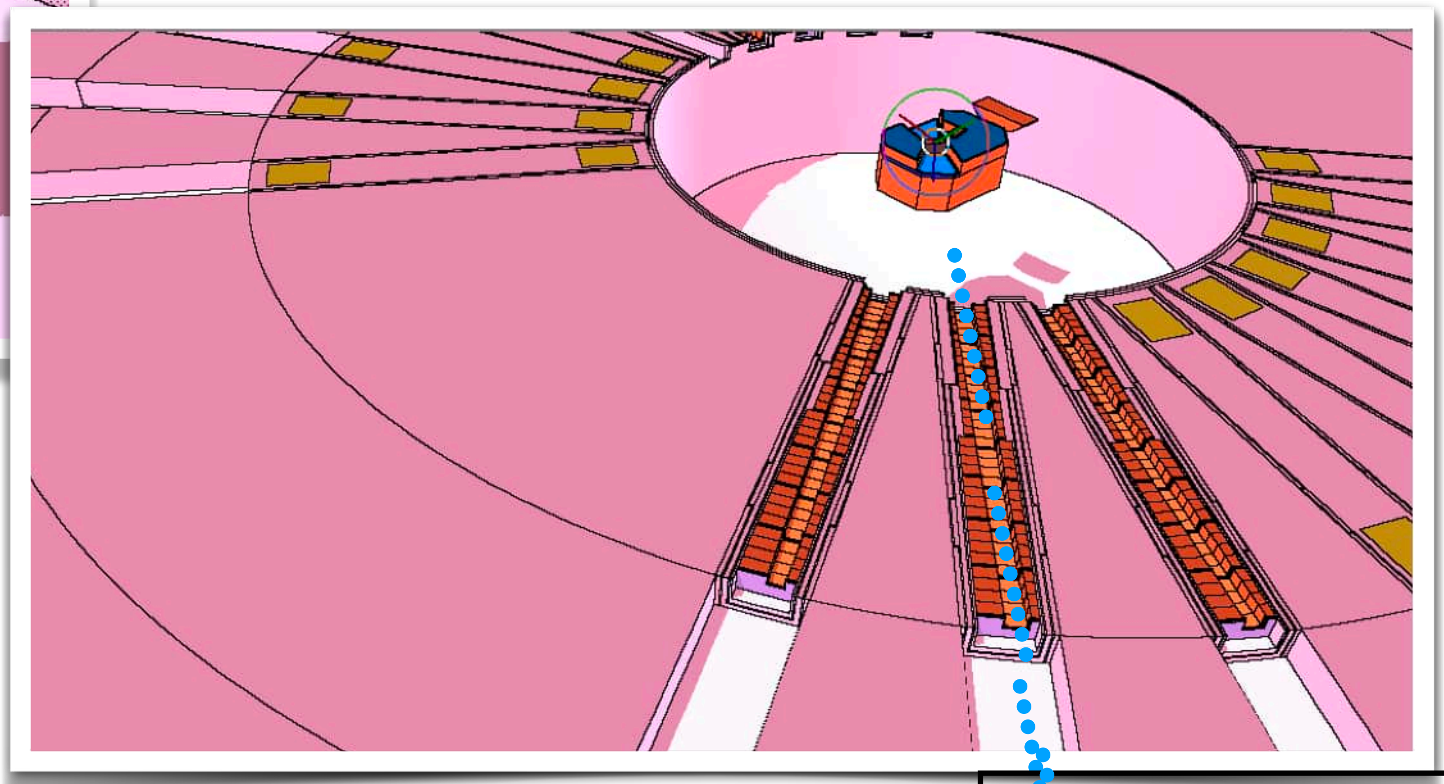



In order to use neutron scattering for condensed matter study by TOF:

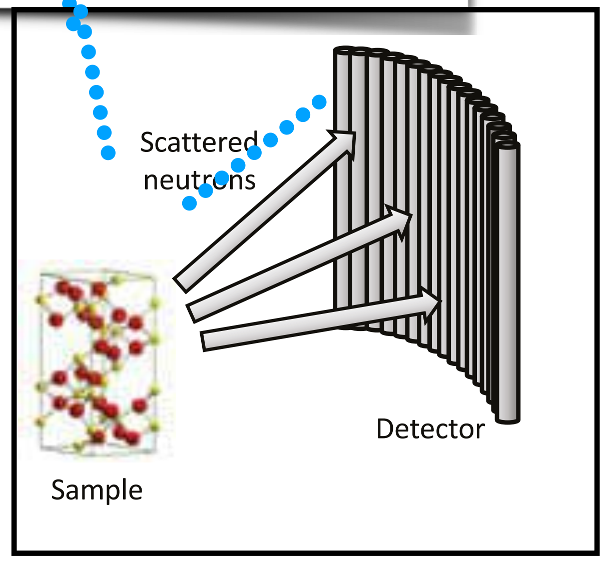
- Neutrons have to be between 10 eV and 0.1 meV (MODERATOR)
- Short beam pulses at the shutter entrance

**Time-of -flight techniques rely on approximation that all neutrons start out down a flight path at the same time.**

The distribution in emission time must be much smaller than the flight time: order of microseconds rather than tens of milliseconds.



Thermal neutrons take about 10 ms to arrive at the sample, 20 m downstream from neutron moderators



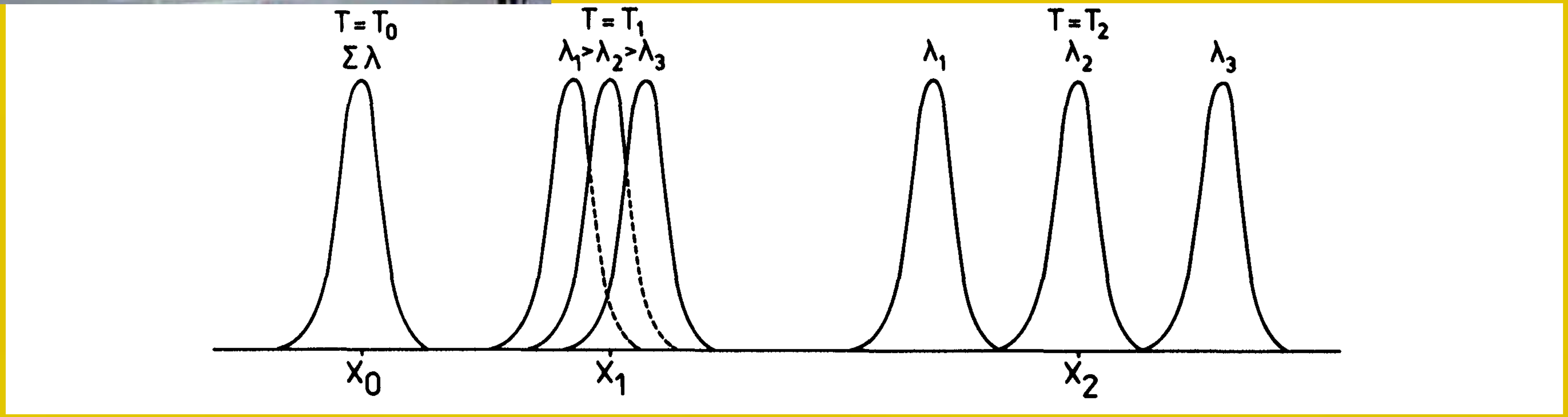

The difference between arrival and departure is the time-of-flight, and knowing the distance (classical approach is applicable), the neutron velocity can be derived. It directly also gives energy and wavelength.

Time-of-flight technique relies on approximation that all neutrons start out down a flight path at the same time.

At time $t_0$ the pulse leaves the moderator surface. It contains all wavelengths.

After a short time t the neutrons arrive at the point X1. The λ3-neutrons have passed it already, the λ1 neutrons are slower.

Passing a long flight path x2 (long time t2) the three different wavelength pulses are separated completely.


# TIME OF FLIGHT NEUTRON SPECTROMETRY

**ToF=Difference between arrival and departure time-of-flight**

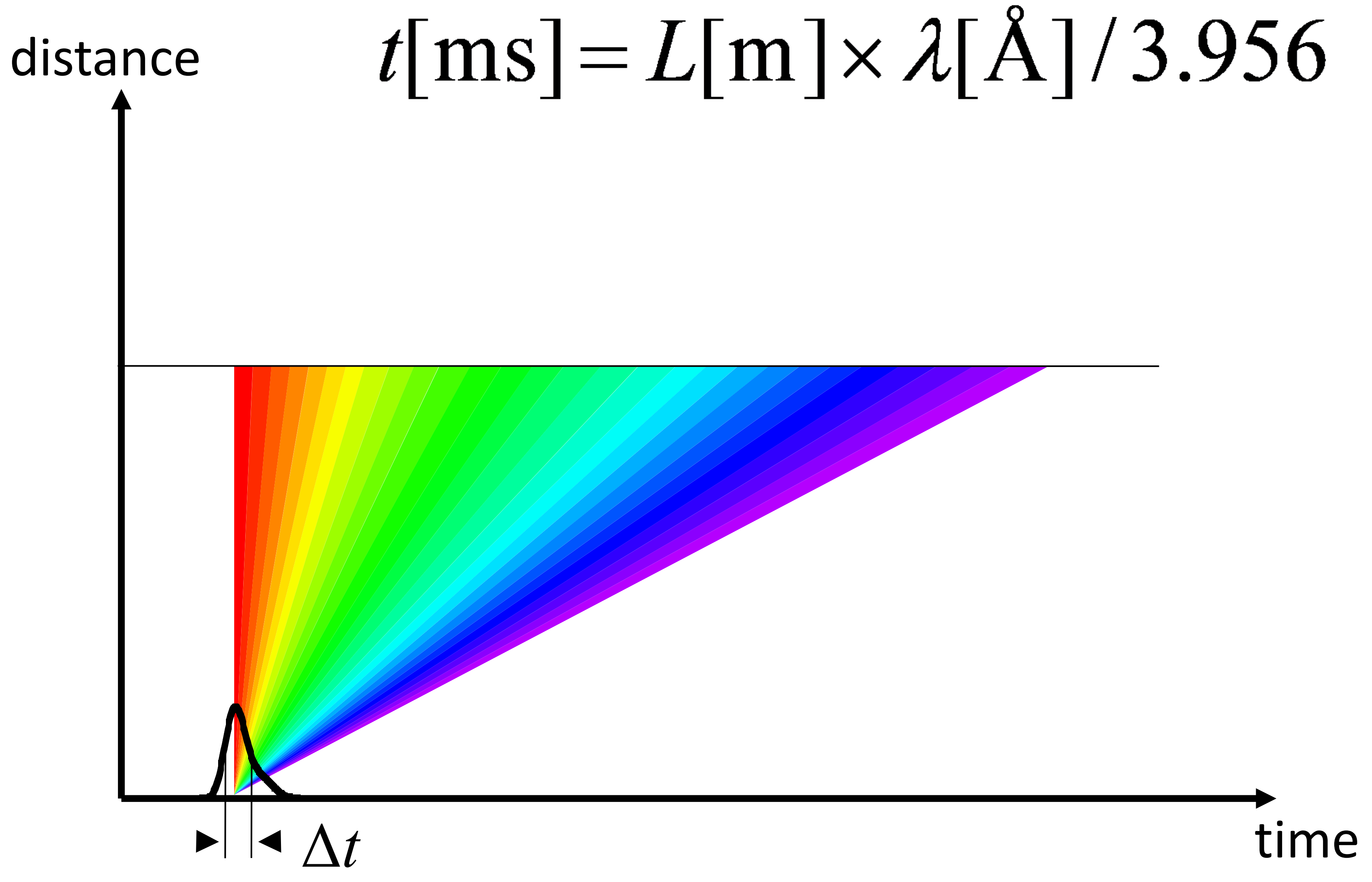
**Knowing the distance, the neutron velocity can be derived.**

**It directly also gives energy and wavelength.**

# Neutron Energy Measurements: TOF (Time of Flight)

- Time of flight method: to measure neutron energy of white spectrum
- Time t: Time for a neutron to reach the sample after pulse beam hit the neutron target
- Kinetic energy is determined by measuring t, knowing the fight length (L)

$$t[\mathrm{ms}] = L[\mathrm{m}] \times \lambda[\text{Å}] / 3.956$$




$$E = K\left(\frac{1}{\sqrt{1-\frac{v^2}{c^2}}} - 1\right)$$

E: Energy
K: Rest mass of neutron
v: Neutron velocity
c: Speed of light

$$E(eV) = \left(72.3 \times \frac{L(m)}{t(\mu\sec)}\right)^2$$


- Better energy resolution: Decreasing Δt or Increasing L
- Increasing L—-> Decreasing flux, therefore try to decrease Δt
- L should be decided by considering the energy resolution and neutron flux required for an instrument

- Energy resolution:

$$\frac{\Delta E}{E} = 2\frac{\Delta t}{t} = 0.02766\frac{\Delta t(\mu sec)}{L(m)}\sqrt{E(eV)}$$

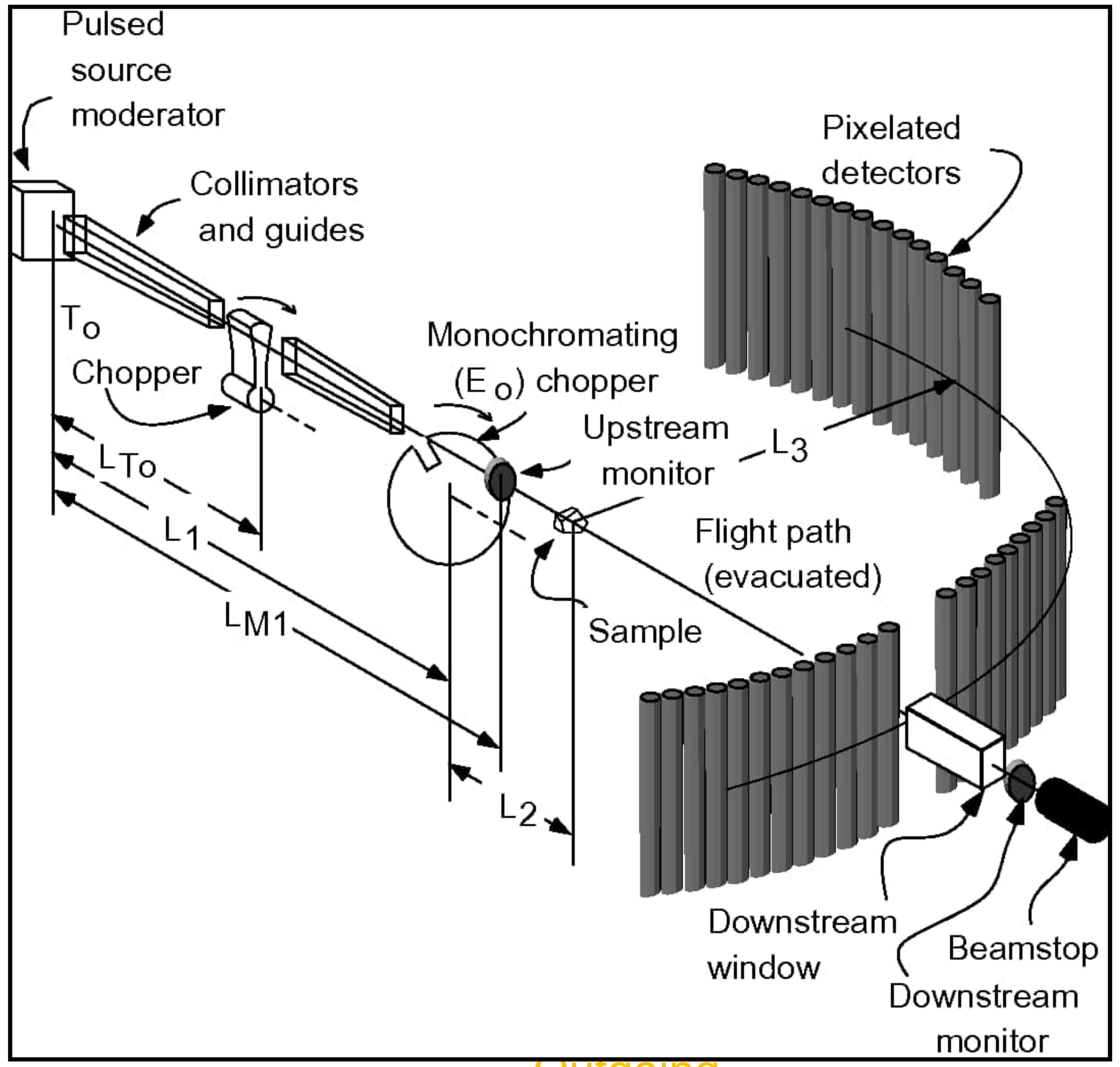
$$\Delta t = \sqrt{\Delta t_1^2 + \Delta t_2^2 + \Delta t_3^2}$$

$$\Delta t_1 \rightarrow Proton\ \ Beam\ \ Pulse\ \ Width$$

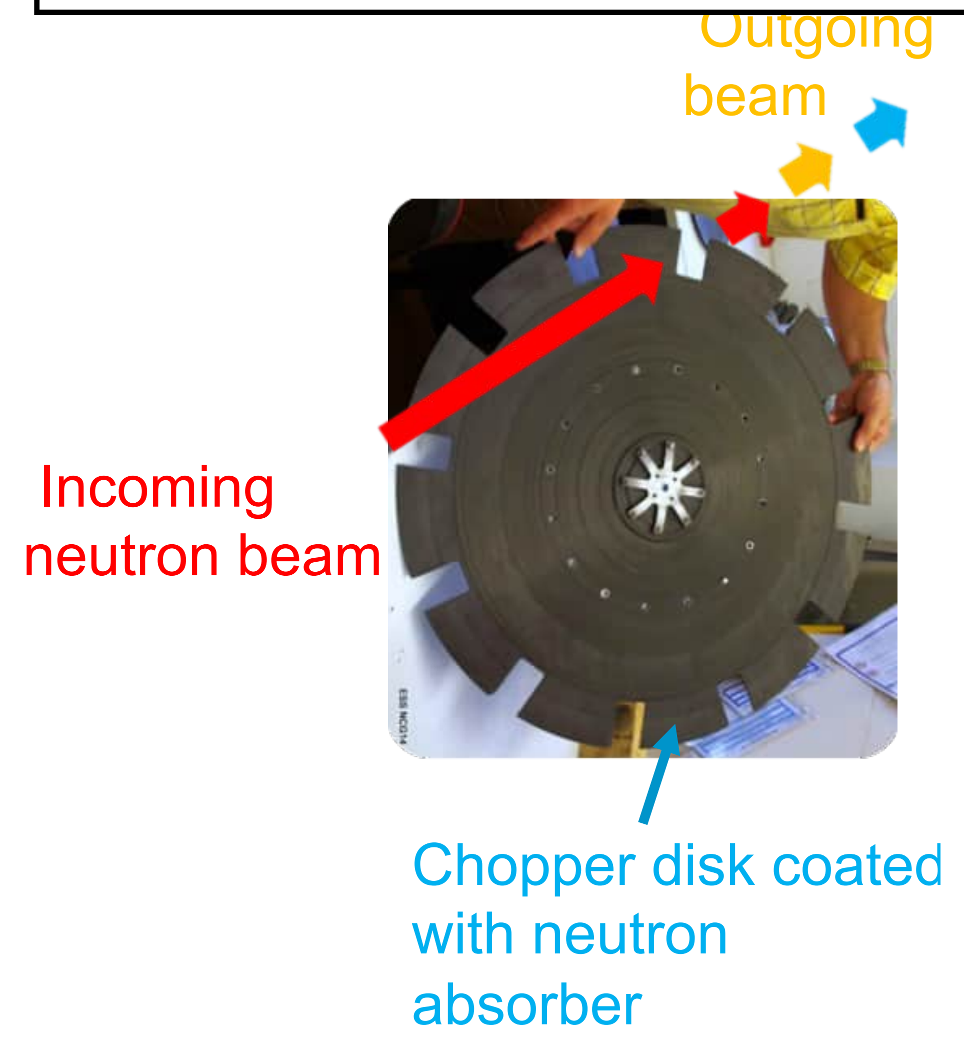
$$\Delta t_2 \rightarrow Target\ \ Moderator\ \ Scattering\ \ time\ Width$$

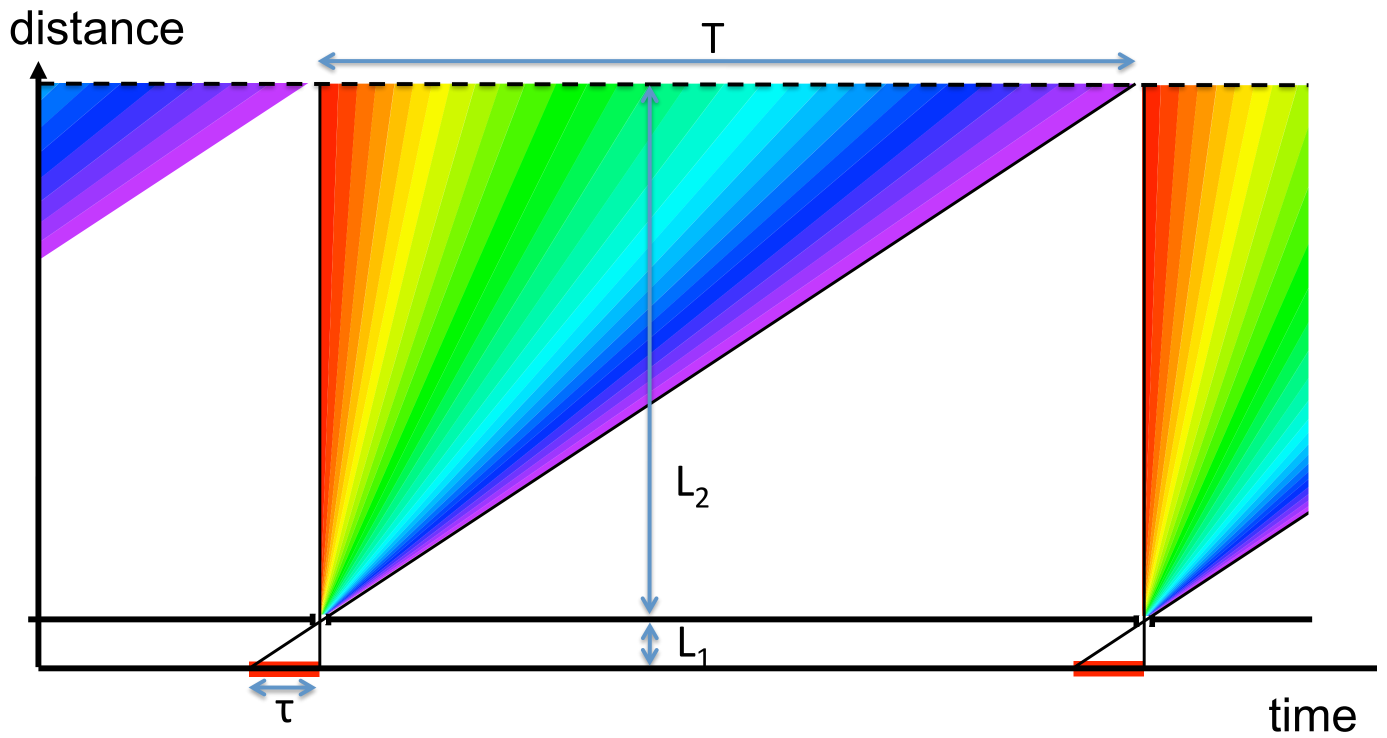
$$\Delta t_3 \rightarrow Detector\ \ \&\ \ DAQ\ \ response\ \ Width$$

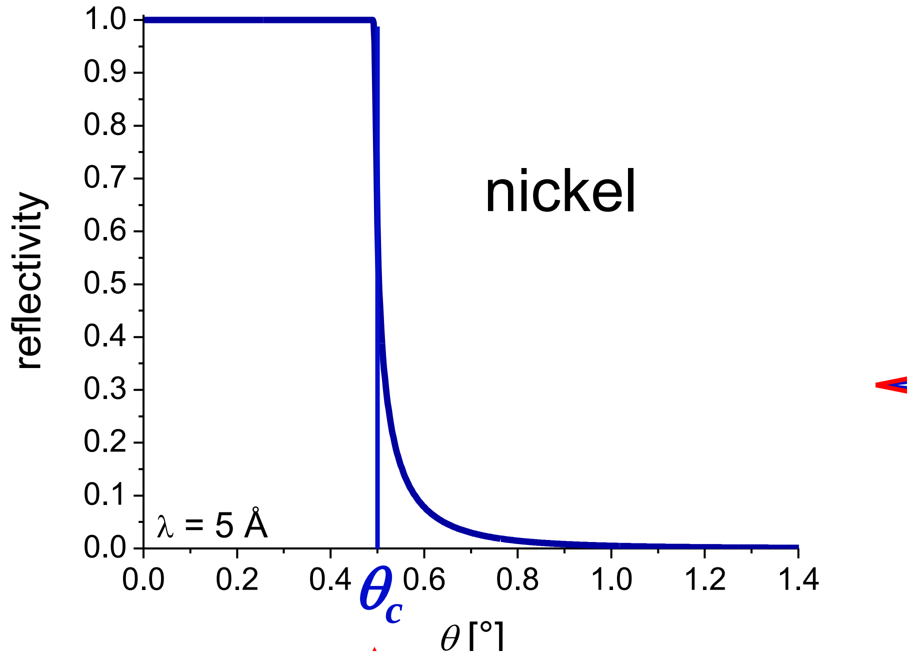
# Typical Components of an Instrument Beam Line

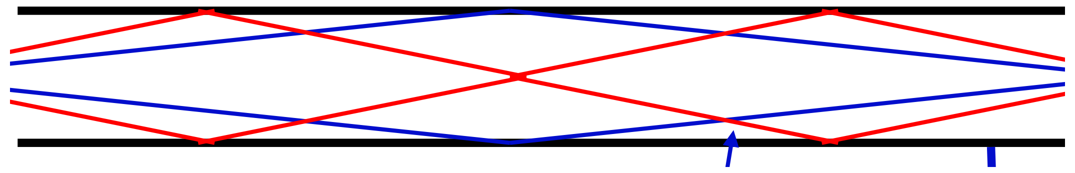



- **Collimators**: define the spatial and angular distributions of neutron beam on the sample, acting independently of wavelength. They are made of apertures trough materials opaque to neutrons.
- **Mirrors and waveguide**. Neutrons reflect perfectly from some surfaces which acts as mirrors provided that the grazing angle of incidence is smaller than the critical angle for the given wavelength (usually made of very flat Ni surface )
- **Chopper** (spectrometers): It is essentially a disc rotated at high speeds with some apertures through which neutrons may only pass during certain periods of the discs rotation. It consists of disk, motor, photosensor, and a housing. The chopper disk is generally made of two stainless steel slices with an absorber material (i.e cadmium) between them. Both steady and pulsed sources have several chopper spectrometers optimised for different applications (i.e high resolution, access the desired Q. etc)
- **Detector**—-> neutron detection for getting sample properties measurements . Specific for each instruments. High efficiency and prompt answer are required



use of chopper at distance L1 for long pulse or reactor

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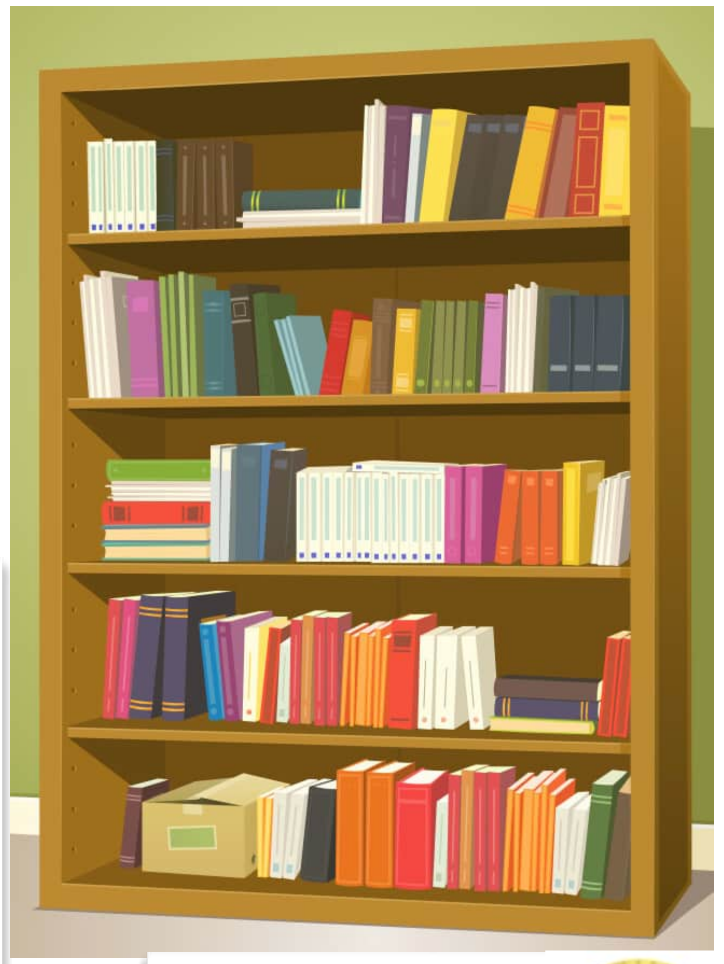
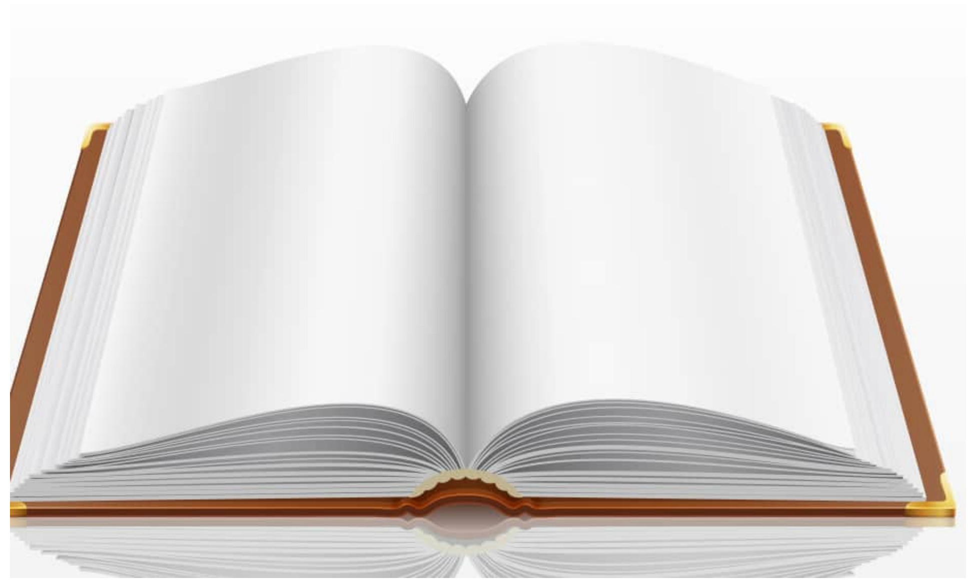
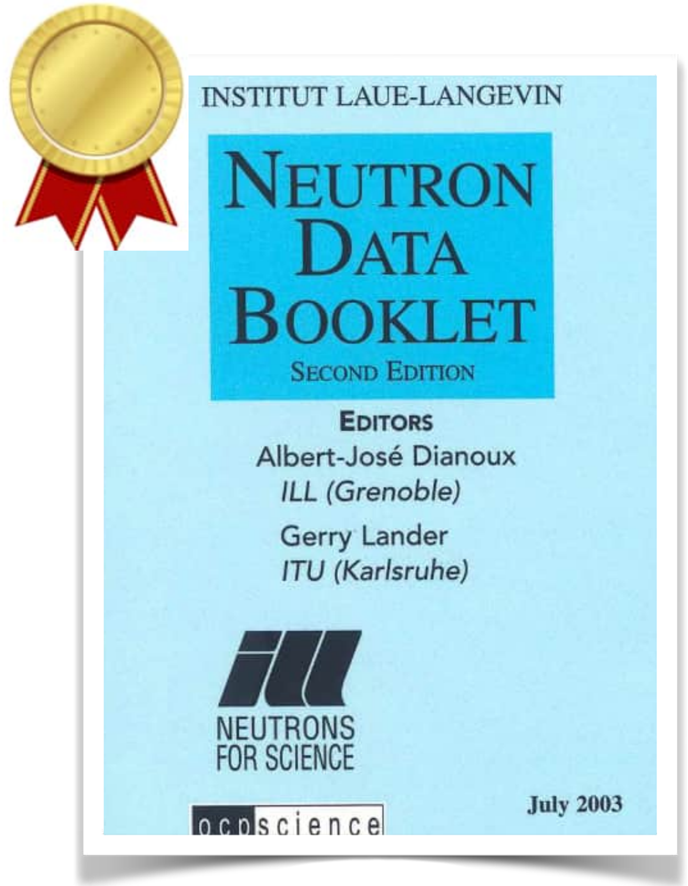



downloadable for free from the web

# A Mention for Neutron D booklet

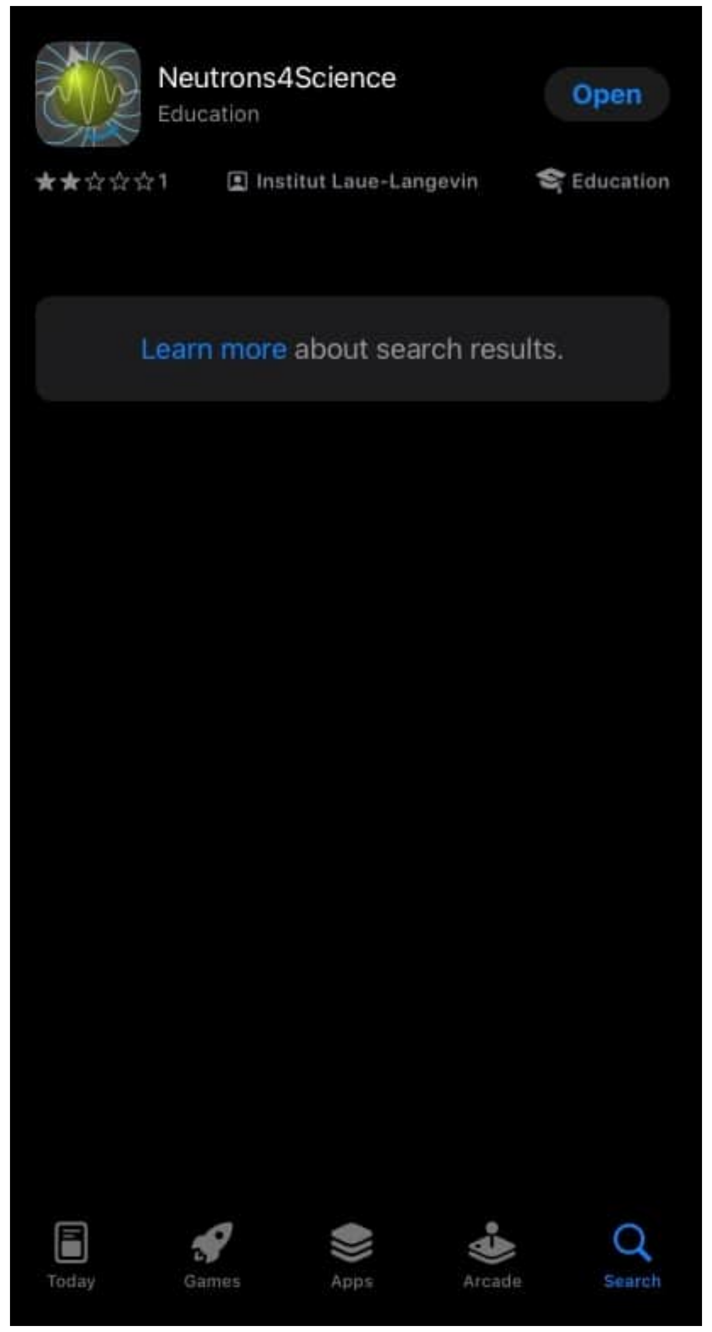


https://www.ill.eu/fileadmin/user_upload/ILL/1_About_ILL/Documentation/NeutronDataBooklet.pdf

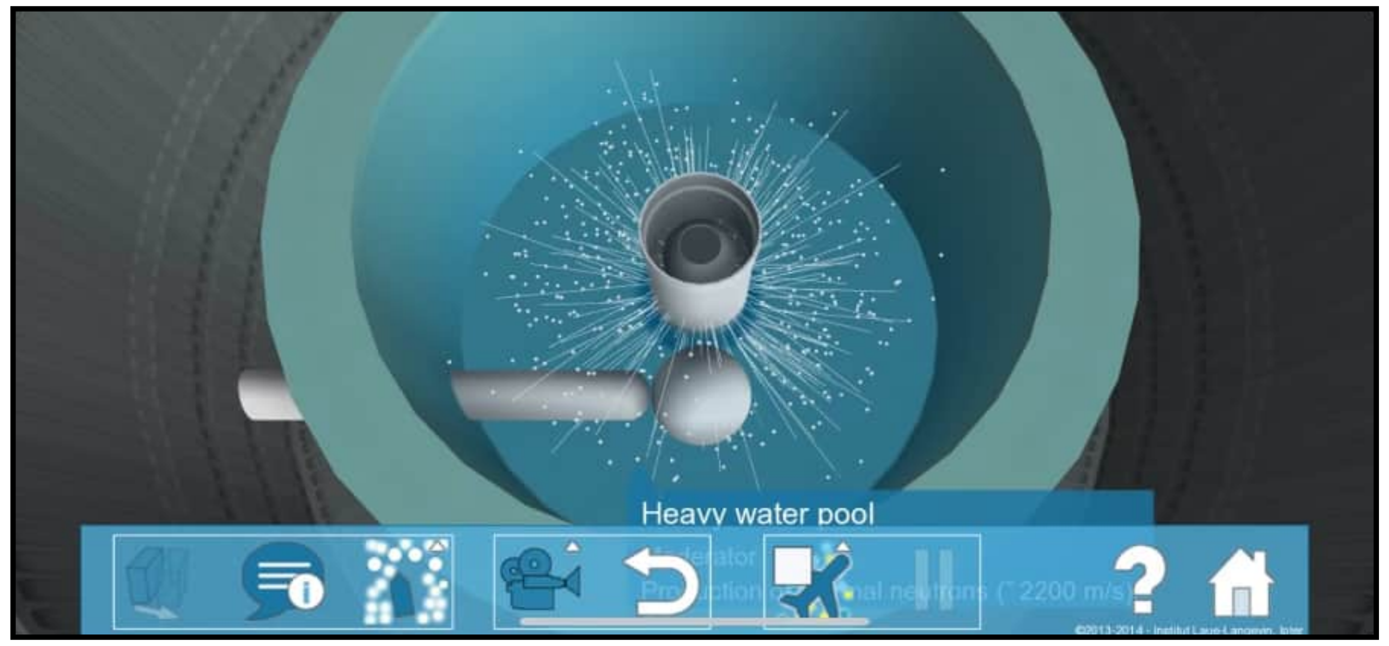


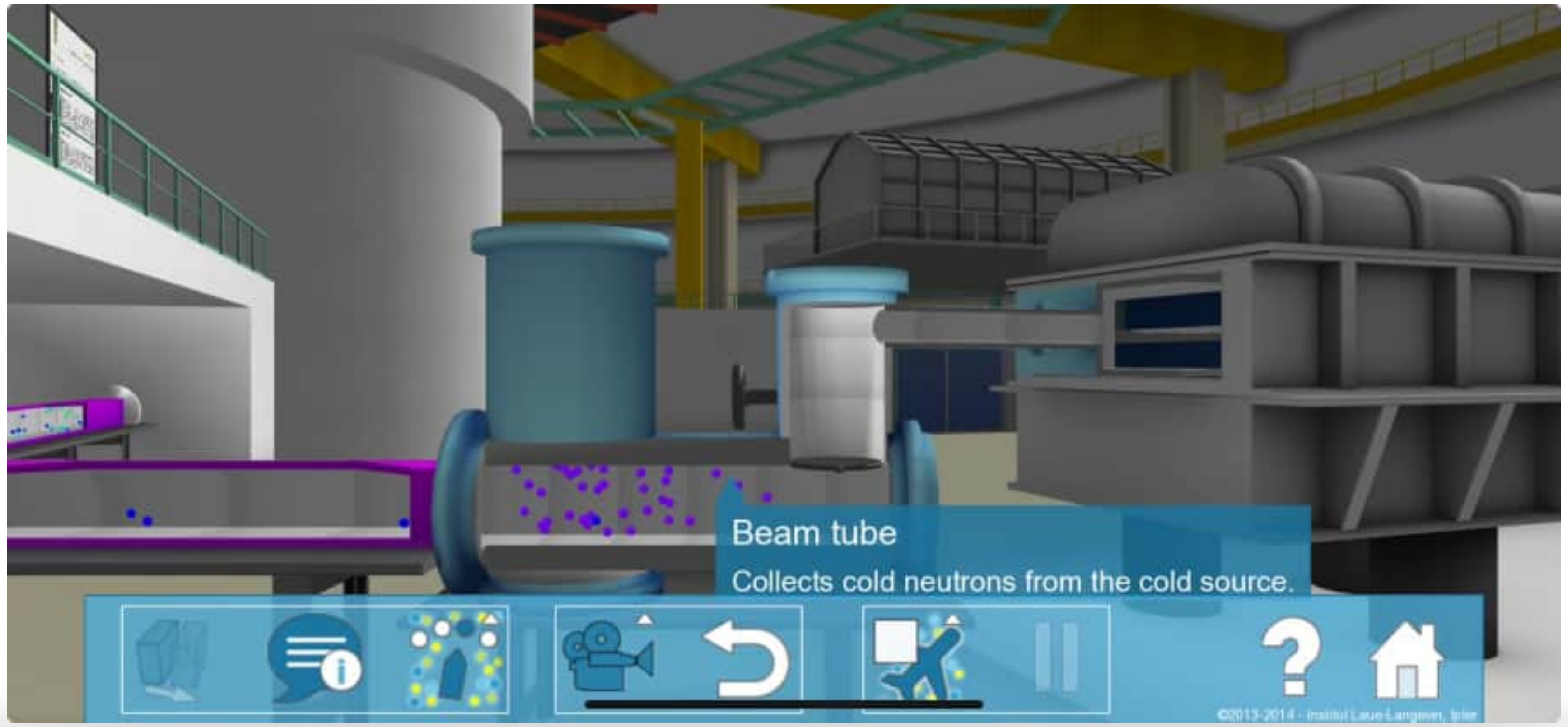

CONTENTS

# Useful Links and Funny Apps….on Neutrons

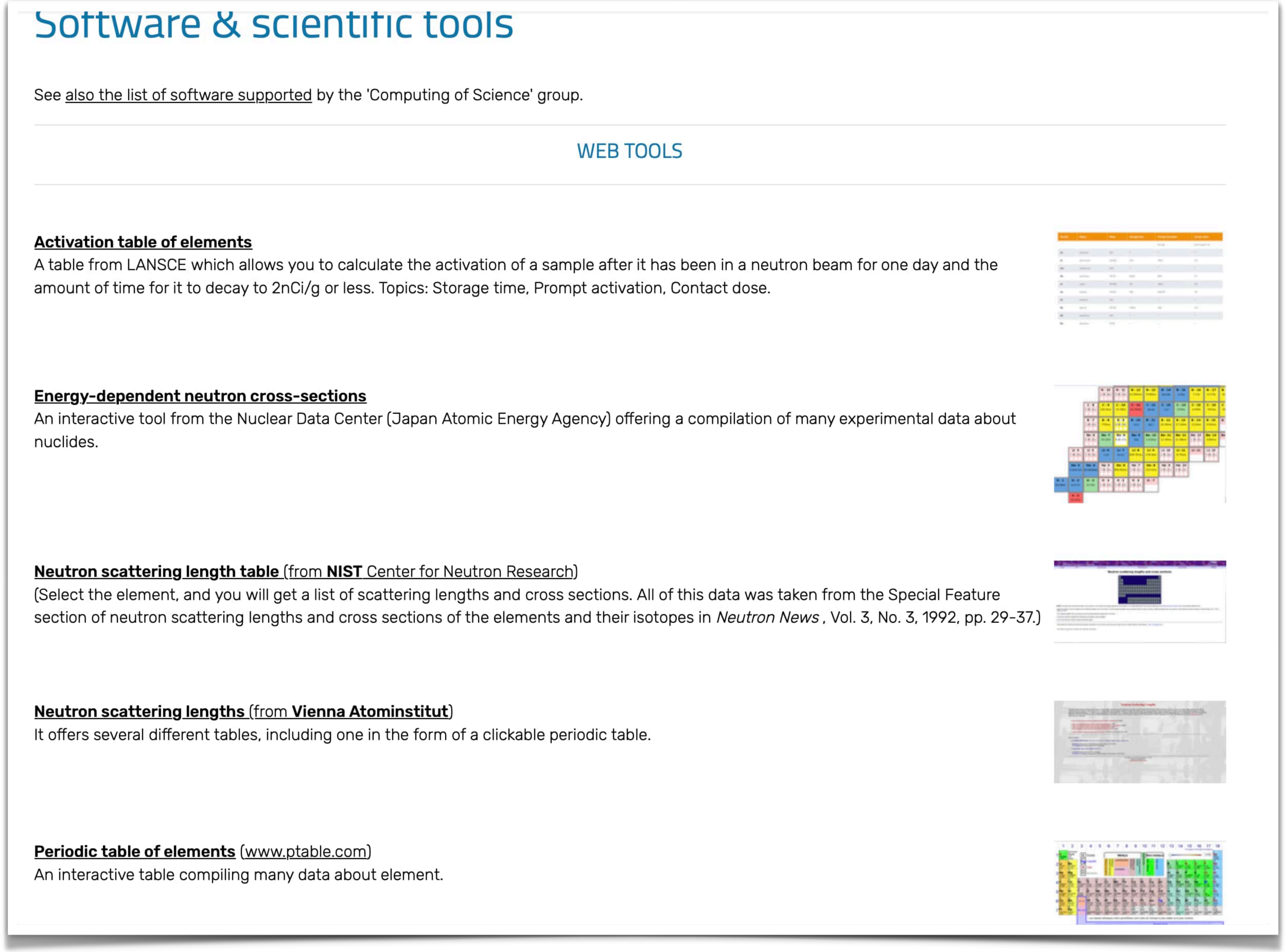







https://www.ill.eu/users/support-labs-infrastructure/software-scientific-tools



Software & scientific tools

See also the list of software supported by the 'Computing of Science' group.

WEB TOOLS

**Activation table of elements**
A table from LANSCE which allows you to calculate the activation of a sample after it has been in a neutron beam for one day and the amount of time for it to decay to 2nCi/g or less. Topics: Storage time, Prompt activation, Contact dose.

**Energy-dependent neutron cross-sections**
An interactive tool from the Nuclear Data Center (Japan Atomic Energy Agency) offering a compilation of many experimental data about nuclides.

**Neutron scattering length table** (from **NIST** Center for Neutron Research)
(Select the element, and you will get a list of scattering lengths and cross sections. All of this data was taken from the Special Feature section of neutron scattering lengths and cross sections of the elements and their isotopes in *Neutron News* , Vol. 3, No. 3, 1992, pp. 29-37.)

**Neutron scattering lengths** (from **Vienna Atominstitut**)
It offers several different tables, including one in the form of a clickable periodic table.

**Periodic table of elements** (www.ptable.com)
An interactive table compiling many data about element.

# BEST WISHES IN HONOUR OF JOHN M. CARPENTER

<<I wish you all good "neutron" sources>>

**The father of the technique for utilising accelerator-induced intense pulses of neutrons for research and developer of the first spallation slow neutron source based on a proton synchrotron, "the Intense Pulsed Neutron Source (IPNS) at Argonne"**

**He left us on 10th March 2020**

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# THANK YOU !