Reactor & Spalla
Neutron Sources

EUROPEAN
SPALLATION
SOURCE

Ken Andersen

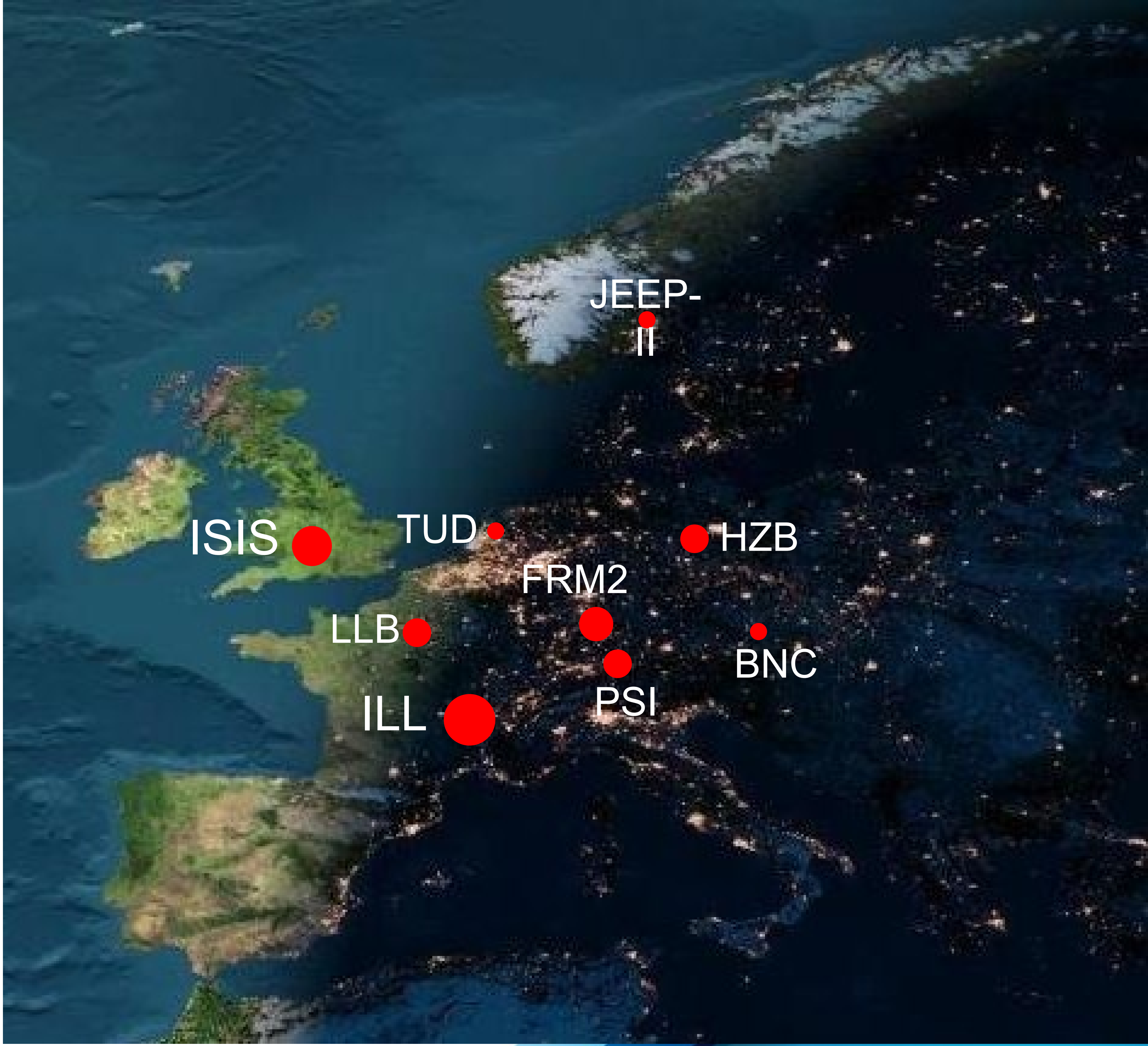
ESS Neutron Instruments Division

Oxford School of Neutron Scatt

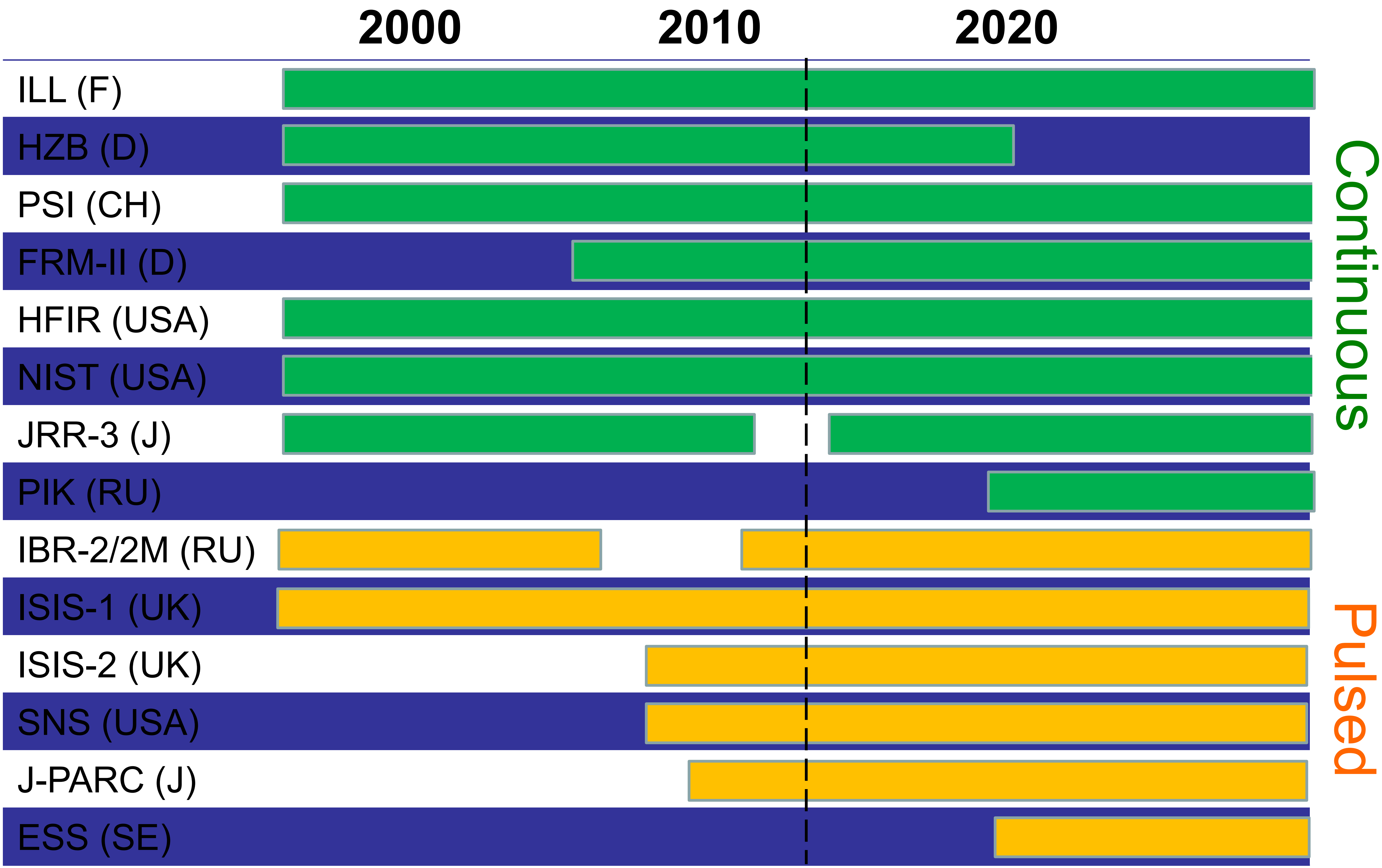
Oxford, 2013-09-04

Overview

- Neutron Facilities
  - overview & trends
- Reactor-based sources
  - Institut Laue-Langevin
- Fission vs Spallation
  - principles & limitations
- Components of a pulsed spallation neutron source
  - accelerator
  - target
  - moderators
- Neutron source time structure
  - the time-of-flight method
- Long-pulse neutron sources


JEEP-
II
ISIS
TUD
HZB
FRM2
LLB
BNC
PSI
ILL

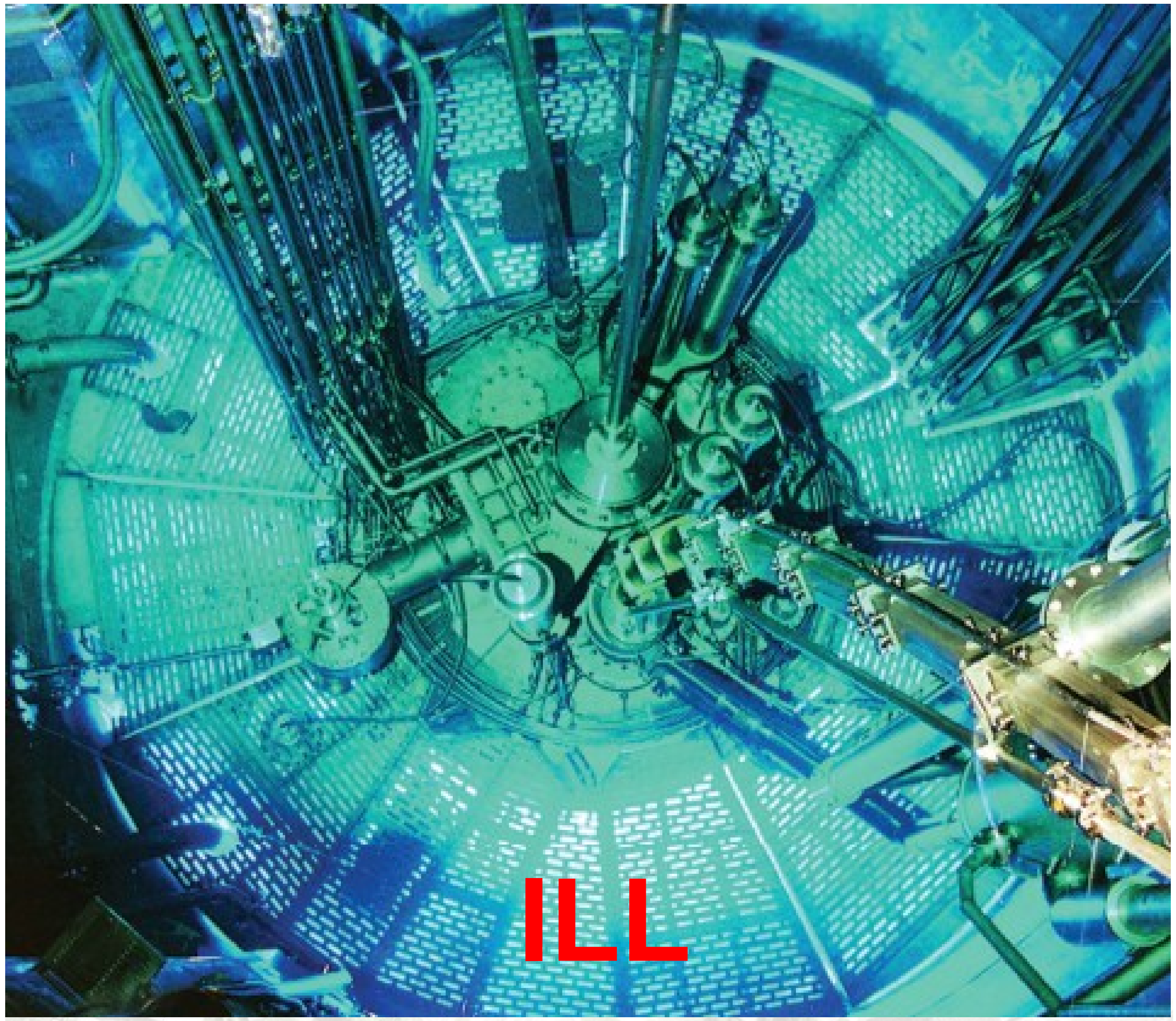
Major neutron sources in the world

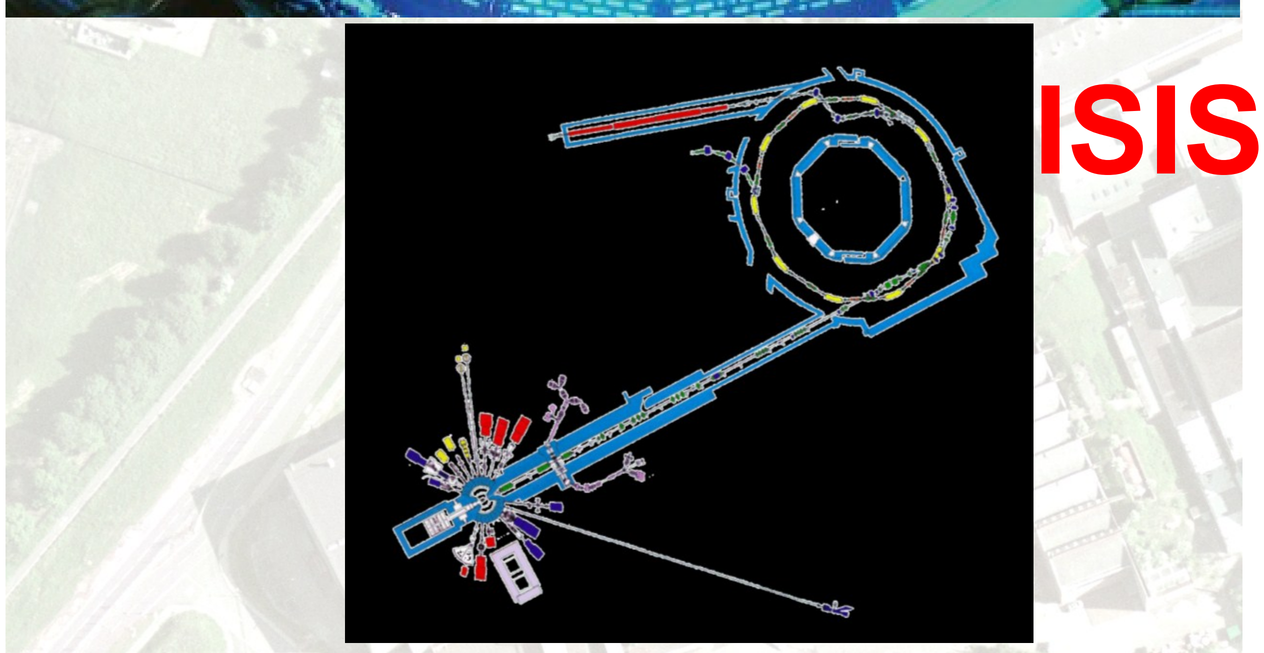


Major neutron sources in the world

	Fission/Spallation	Continuous/Pulsed
ILL (F)	X	X
HZB (D)	X	X
PSI (CH)	X	X
FRM-II (D)	X	X
HFIR (USA)	X	X
NIST (USA)	X	X
JRR-3 (J)	X	X
PIK (RU)	X	X
IBR-2/2M (RU)	X	X
ISIS-1 (UK)	X	X
ISIS-2 (UK)	X	X
SNS (USA)	X	X
J-PARC (J)	X	X
ESS (SE)	X	X

Neutron Sources

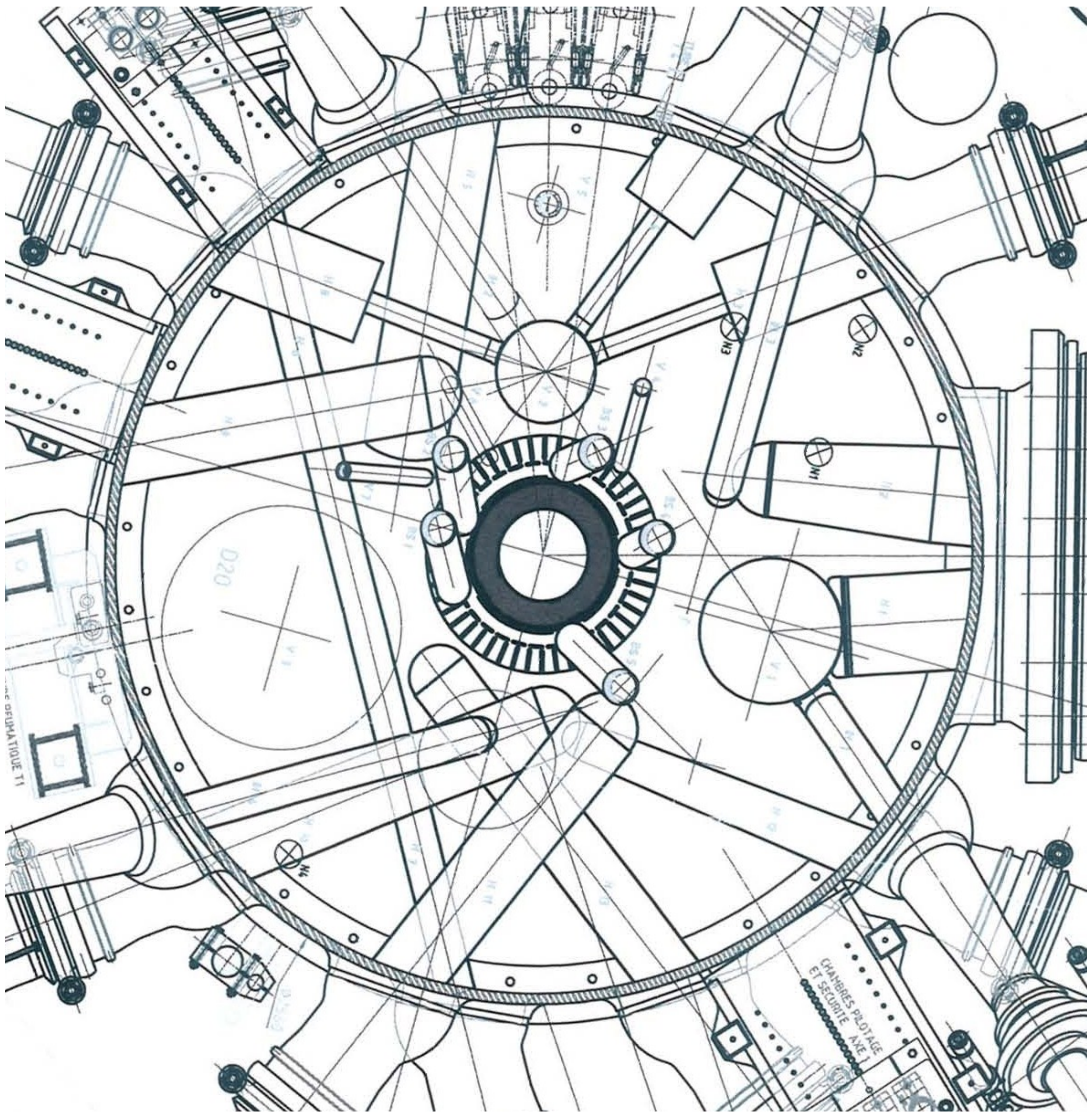




- About 10 major neutron facilities worldwide
- Fission (continuous)
- Spallation (pulsed)
- User facilities
- Number 1 is Institut Laue-Langevin (ILL) in Grenoble, France
    - 40 instruments
    - 700 experiments a year
    - Mainly condensed-matter physics, chemistry and soft matter

EUROPEAN SPALLATION SOURCE

ILL Reactor Neutron Source

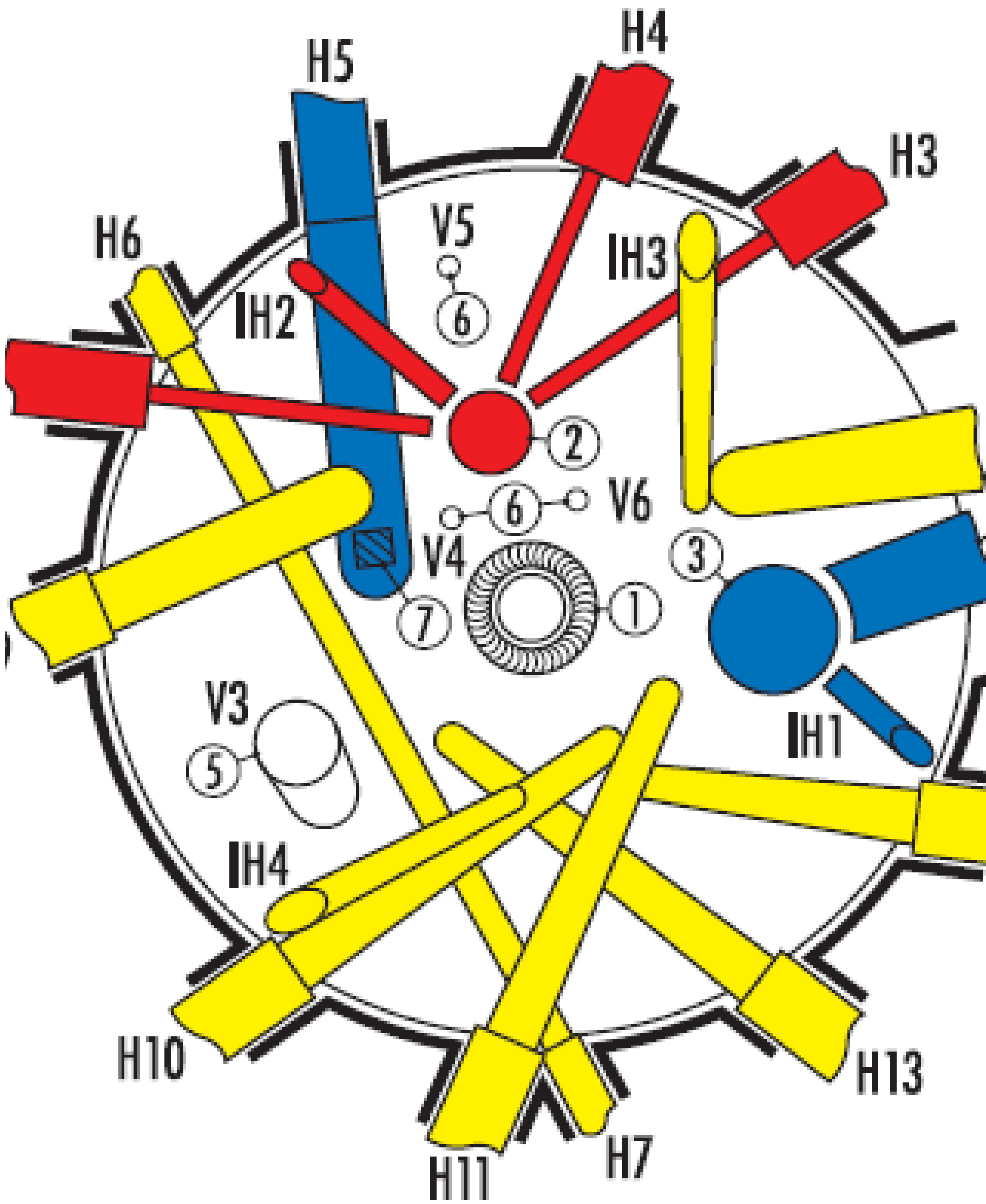


2.5 m

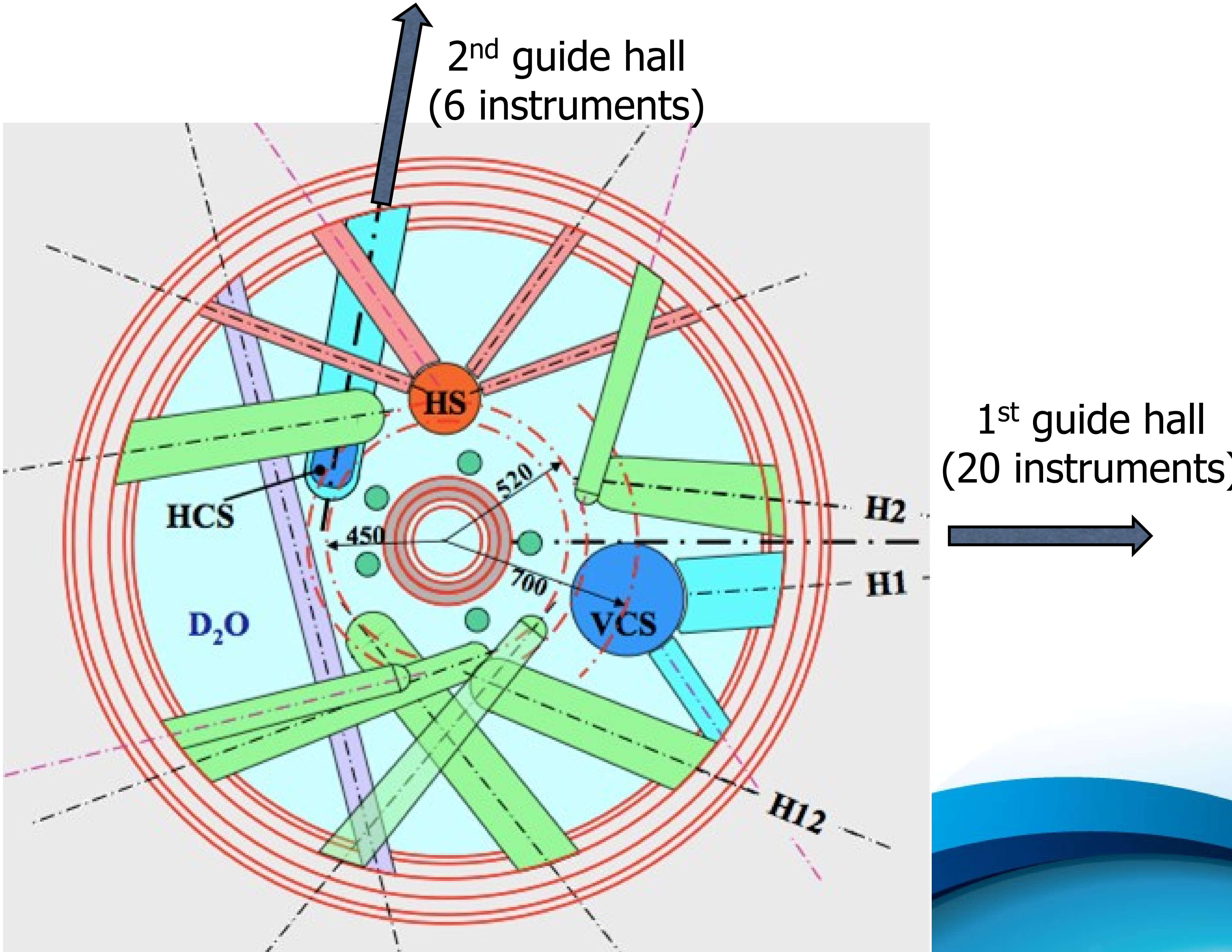
- Highly-enriched uranium
- Compact design for high brightness
- Heavy-water cooling
- Single control rod
- 57MW thermal power

ILL Reactor Neutron Source

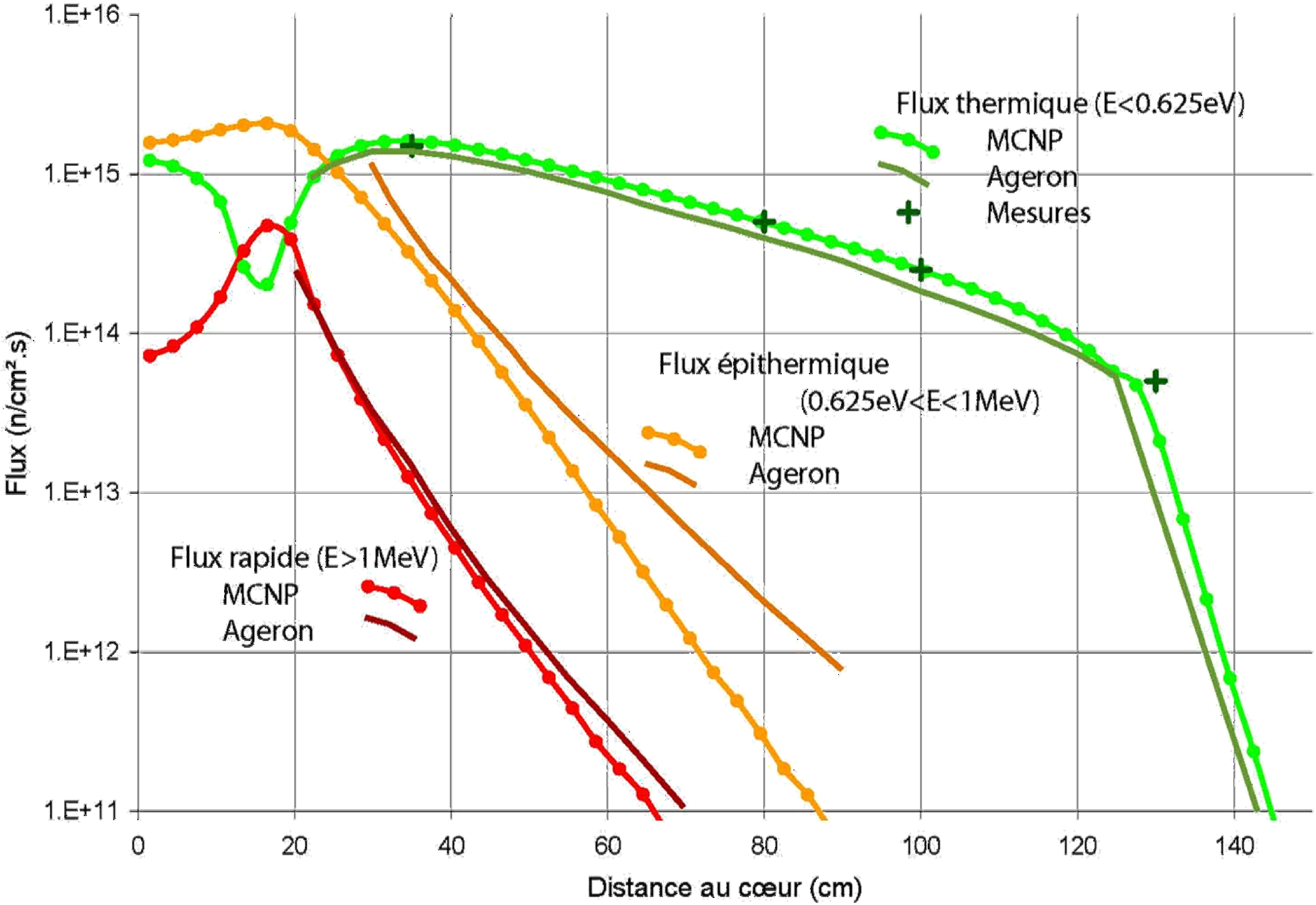
	cold	thermal	hot
moderator	liquid D_2	Liquid D_2O	graphite
moderator temperature	20K	300K	2000K
neutron wavelength	3→20Å	1→3Å	0.3→1Å
sample lengthscale	1Å→100 nm	0.3→5Å	0.1→2Å
sample timescale	1kHz→1 THz	0.1→10 THz	1→100 THz



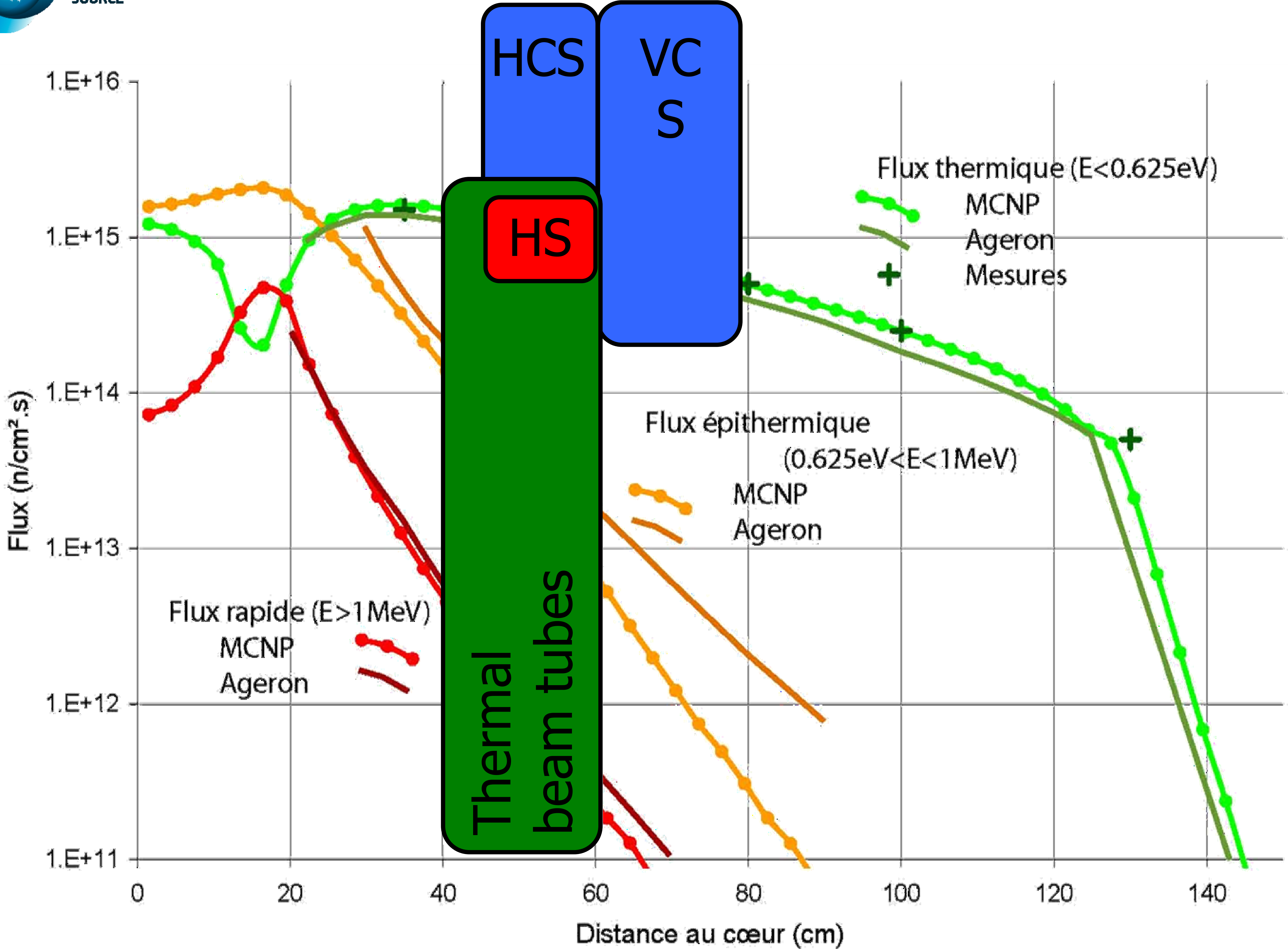
ILL Reactor Neutron Source



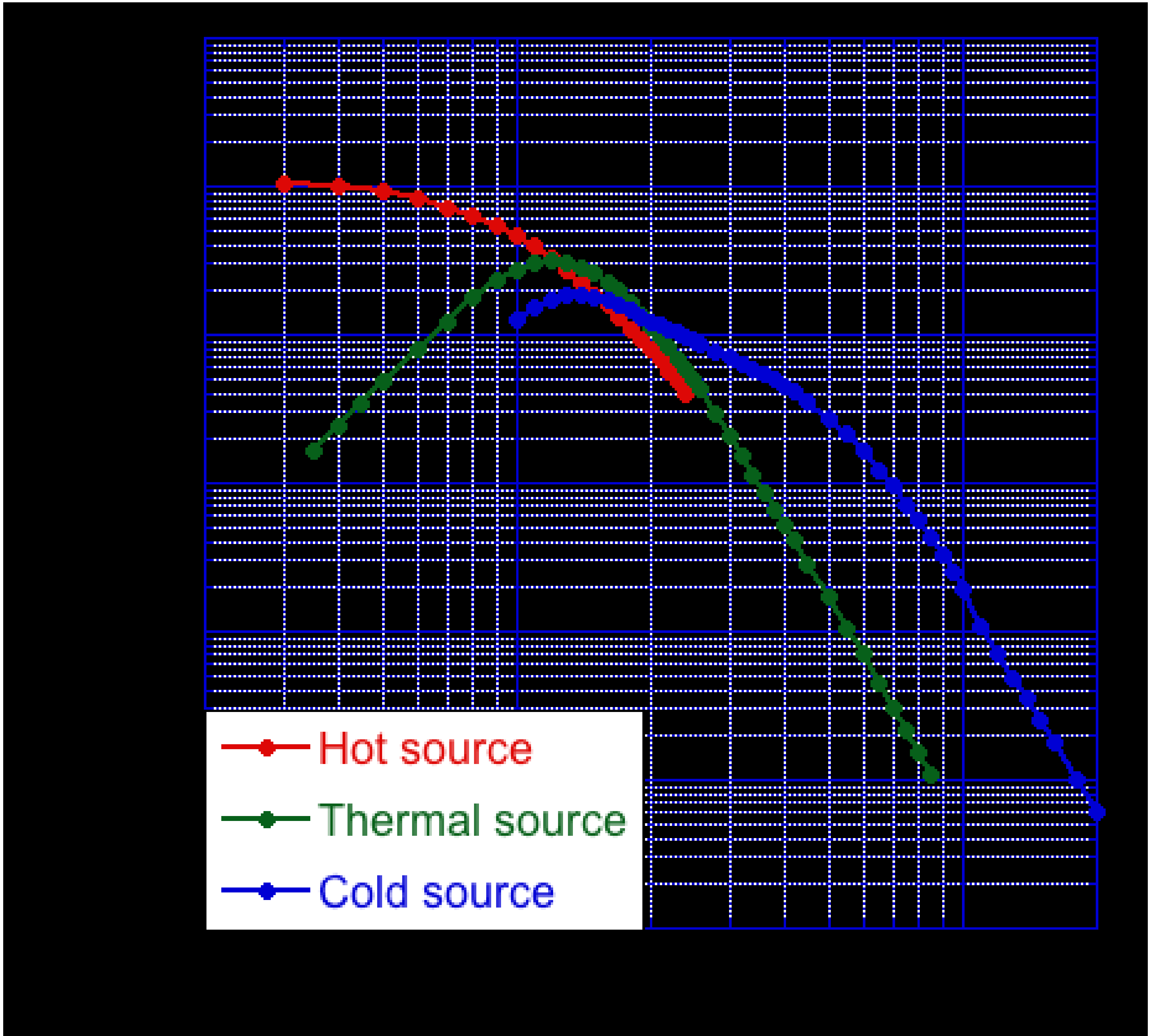
ILL Reactor Neutron Source



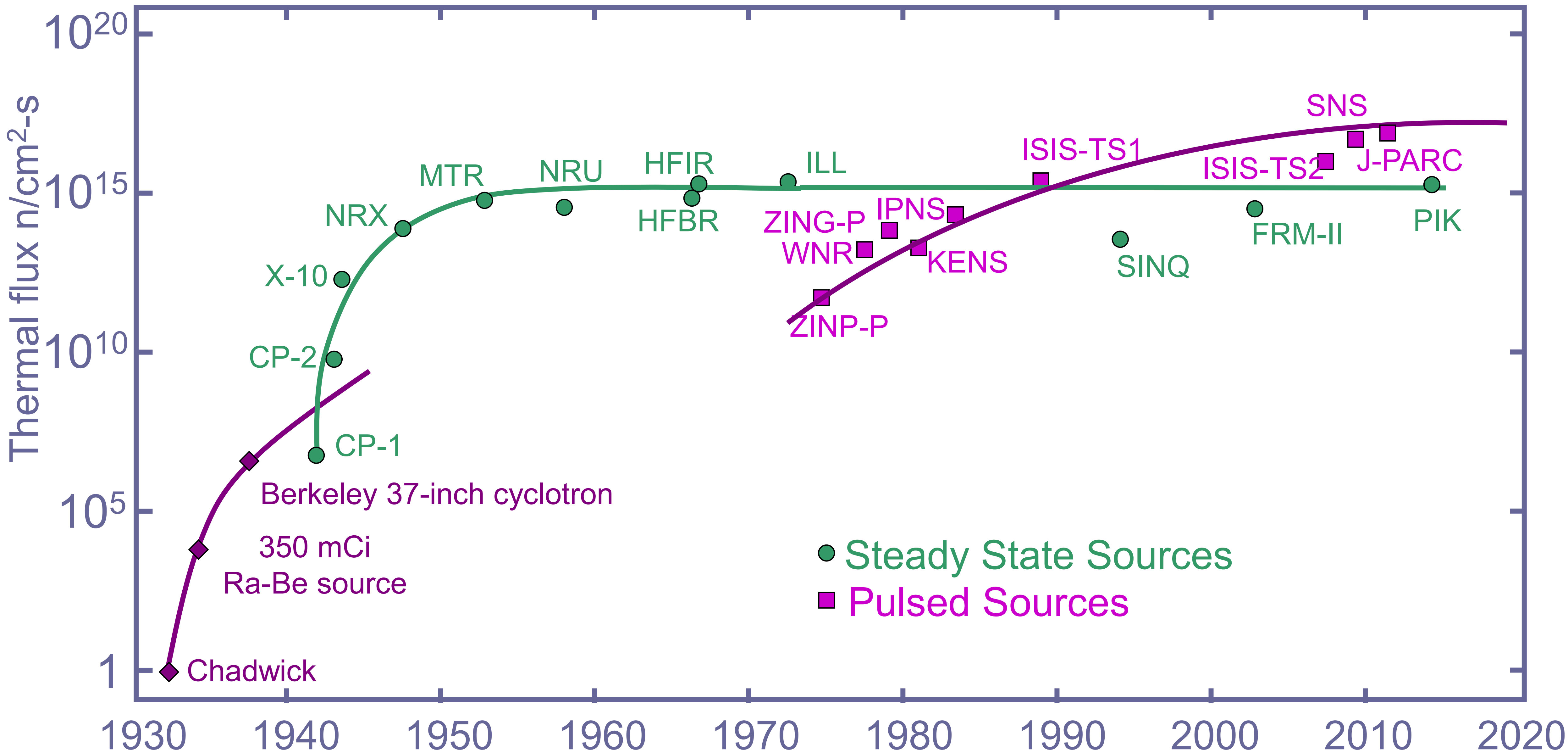
ILL Reactor Neutron Source



ILL Moderator Brightnesses



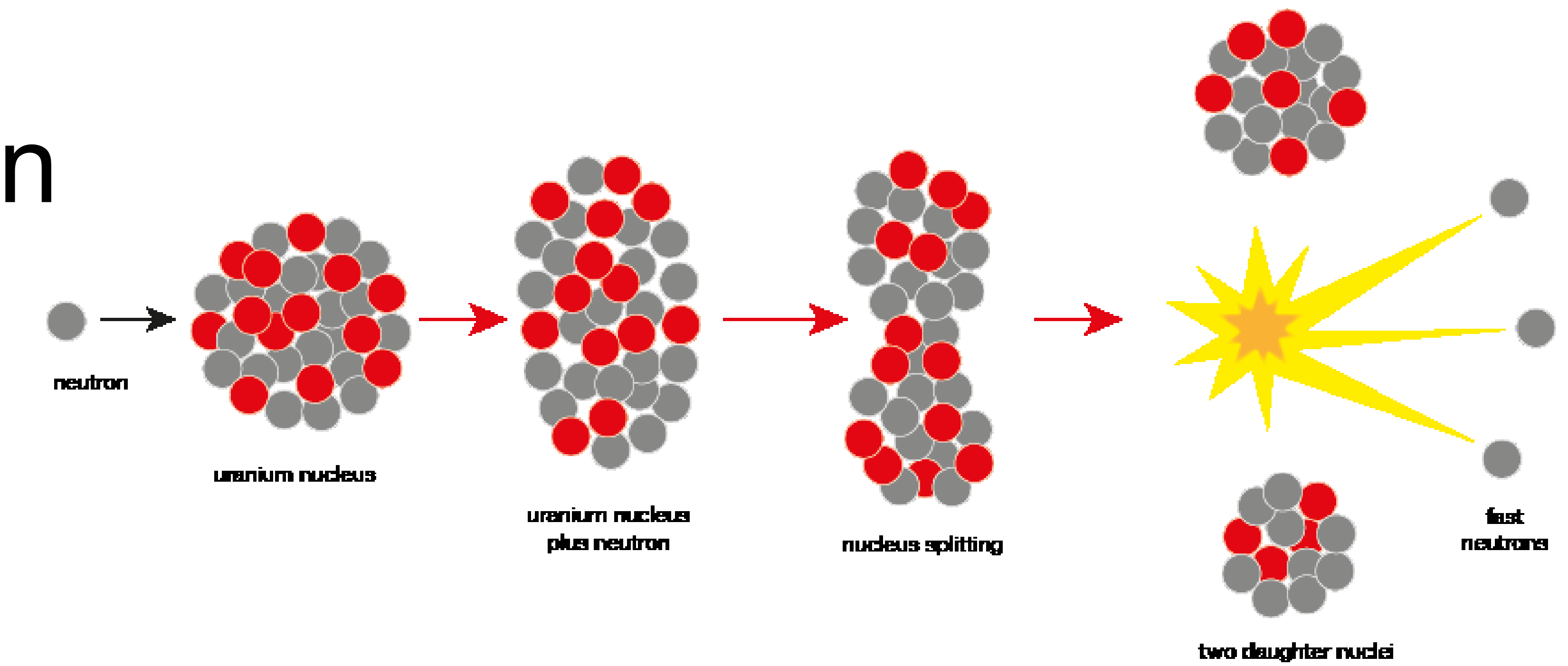
Evolution of neutron sources



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

Spallation vs Fission

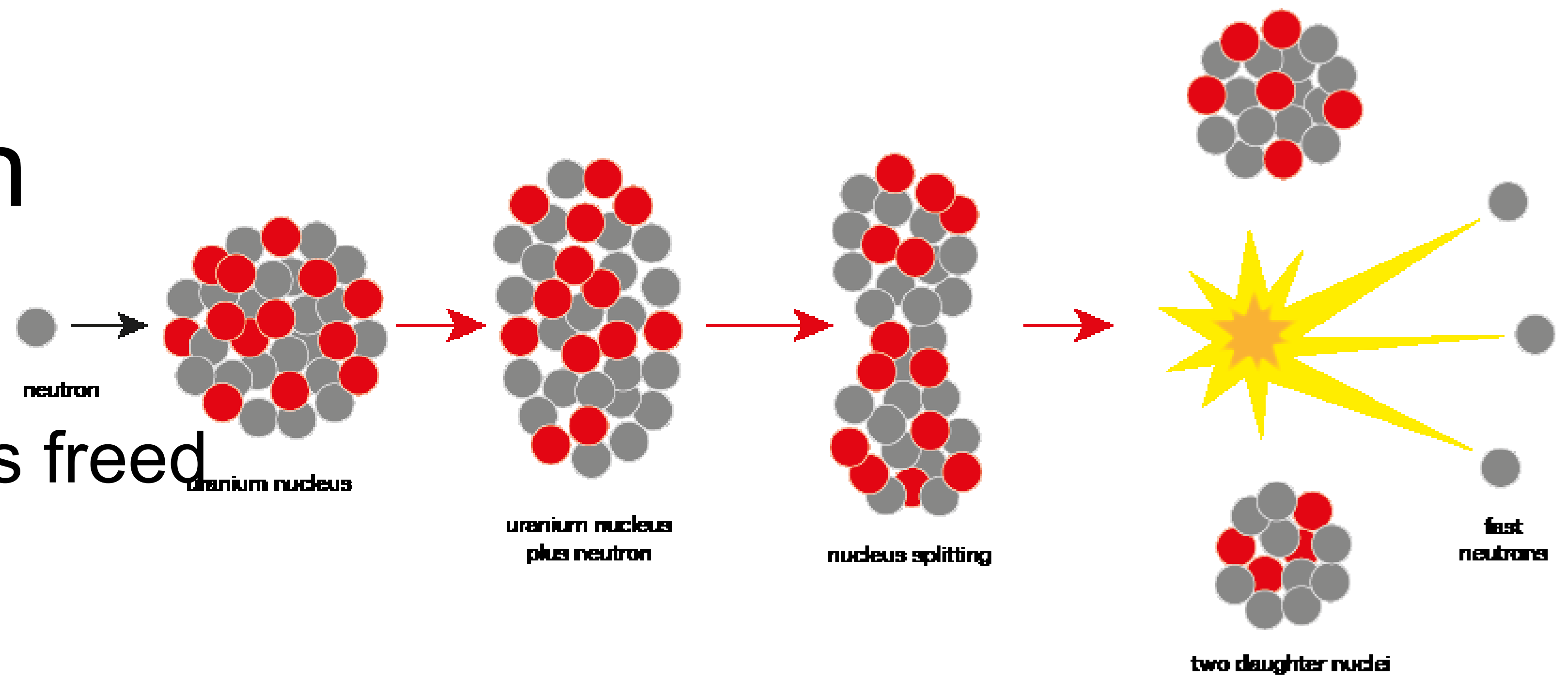
Fission



Spallation vs Fission

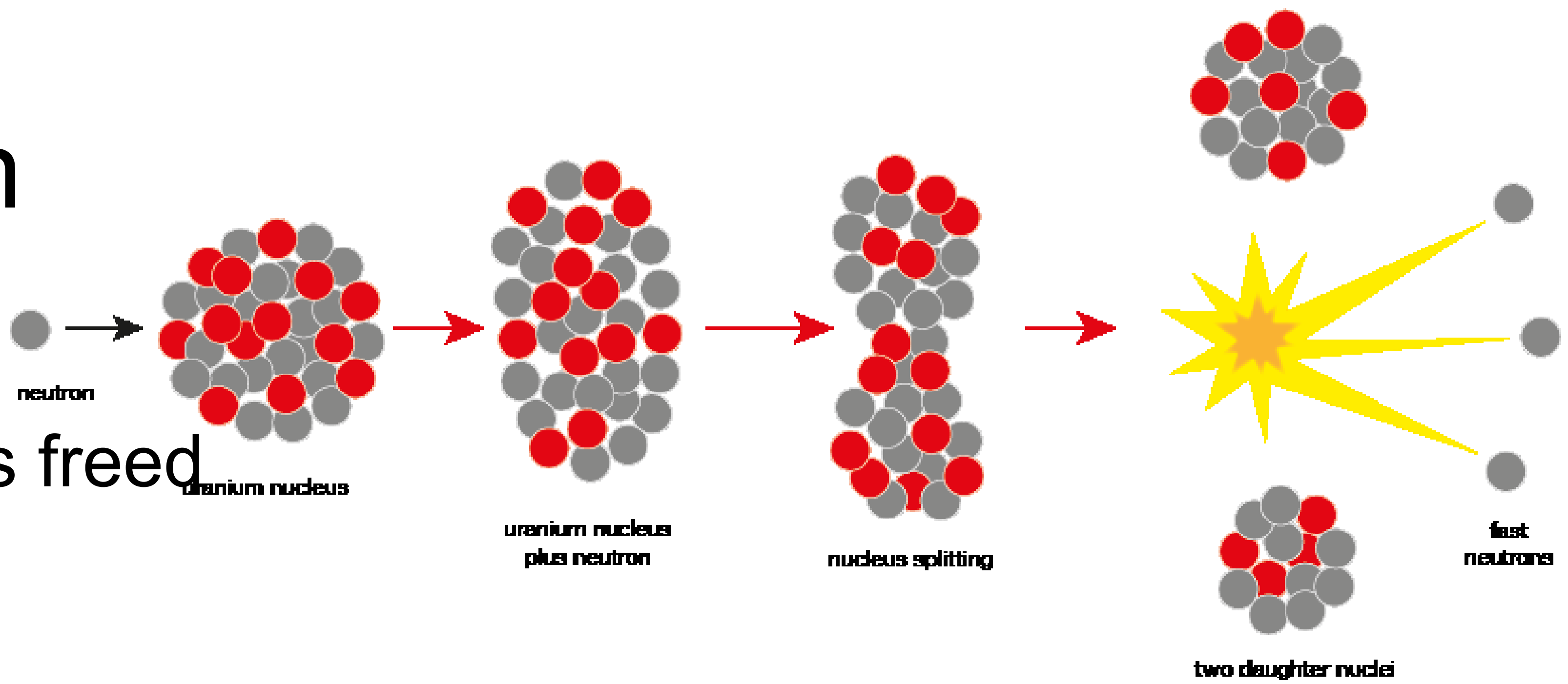
Fission

200 MeV/fission
2.35 – 1 = 1.35 neutrons freed
=> 150 MeV/neutron



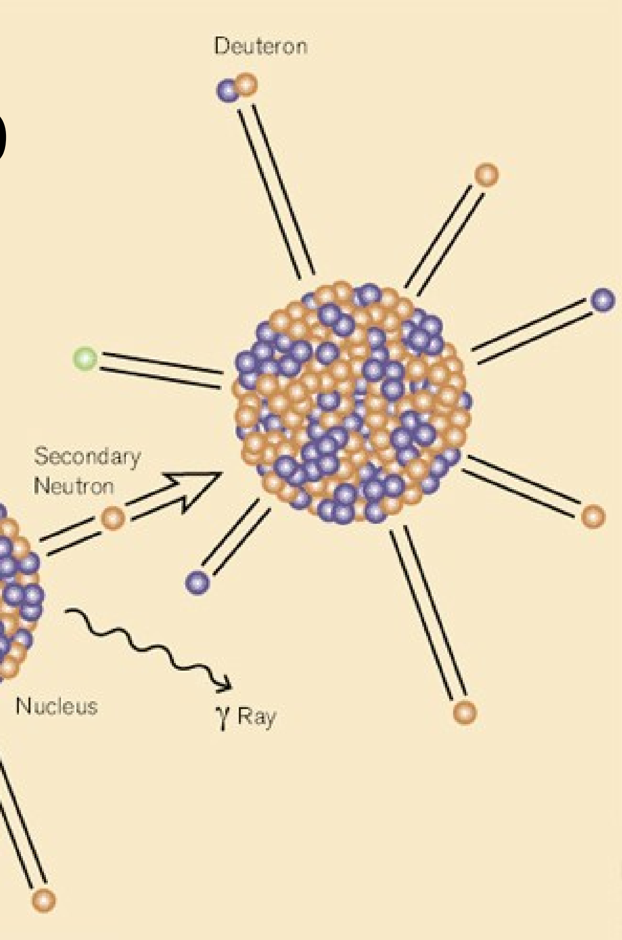
Spallation vs Fission

Fission



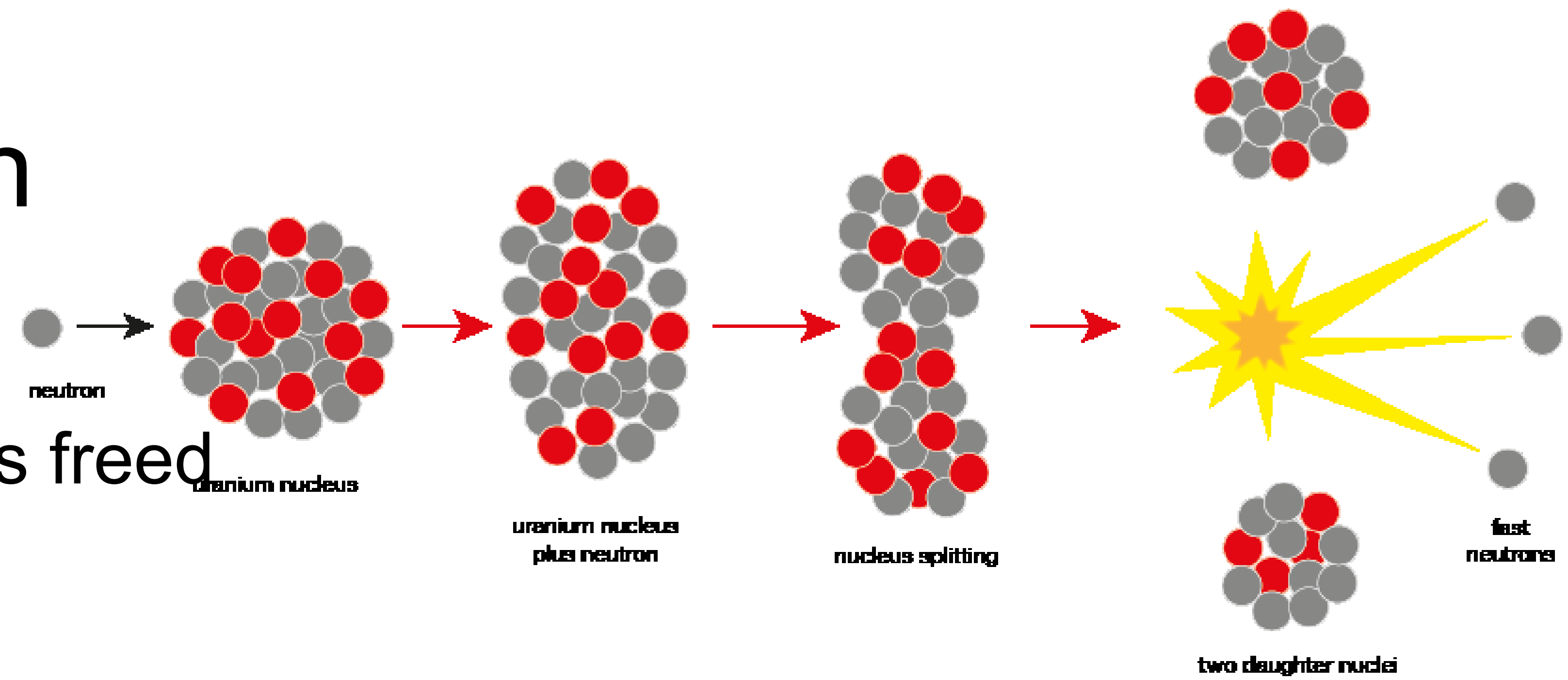
200 MeV/fission
2.35 – 1 = 1.35 neutrons freed
=> 150 MeV/neutron

Spallation:



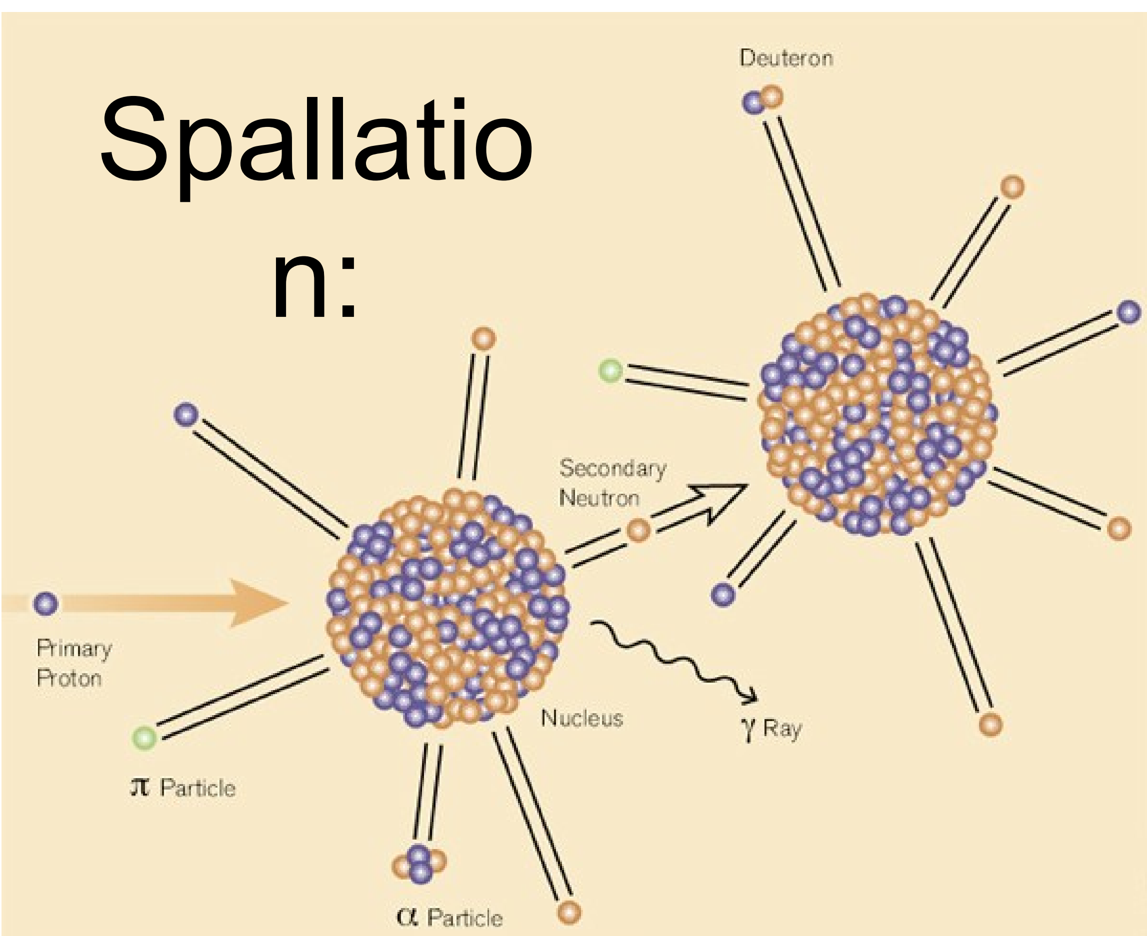
Spallation vs Fission

Fission



200 MeV/fission
2.35 – 1 = 1.35 neutrons freed
=> 150 MeV/neutron

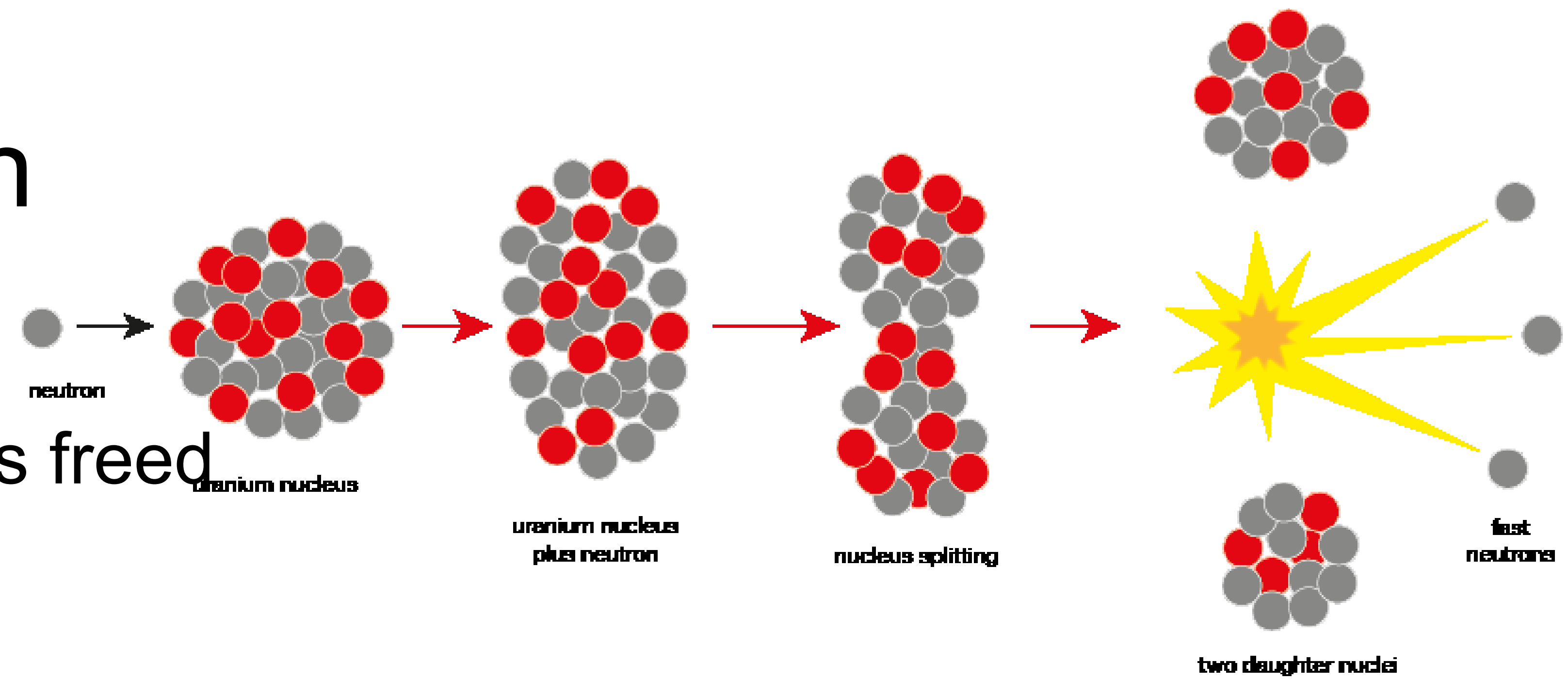
Spallation:



1 GeV proton in:
250 MeV becomes mass (endothermic reaction)
30 neutrons freed
=> 25 MeV/neutron

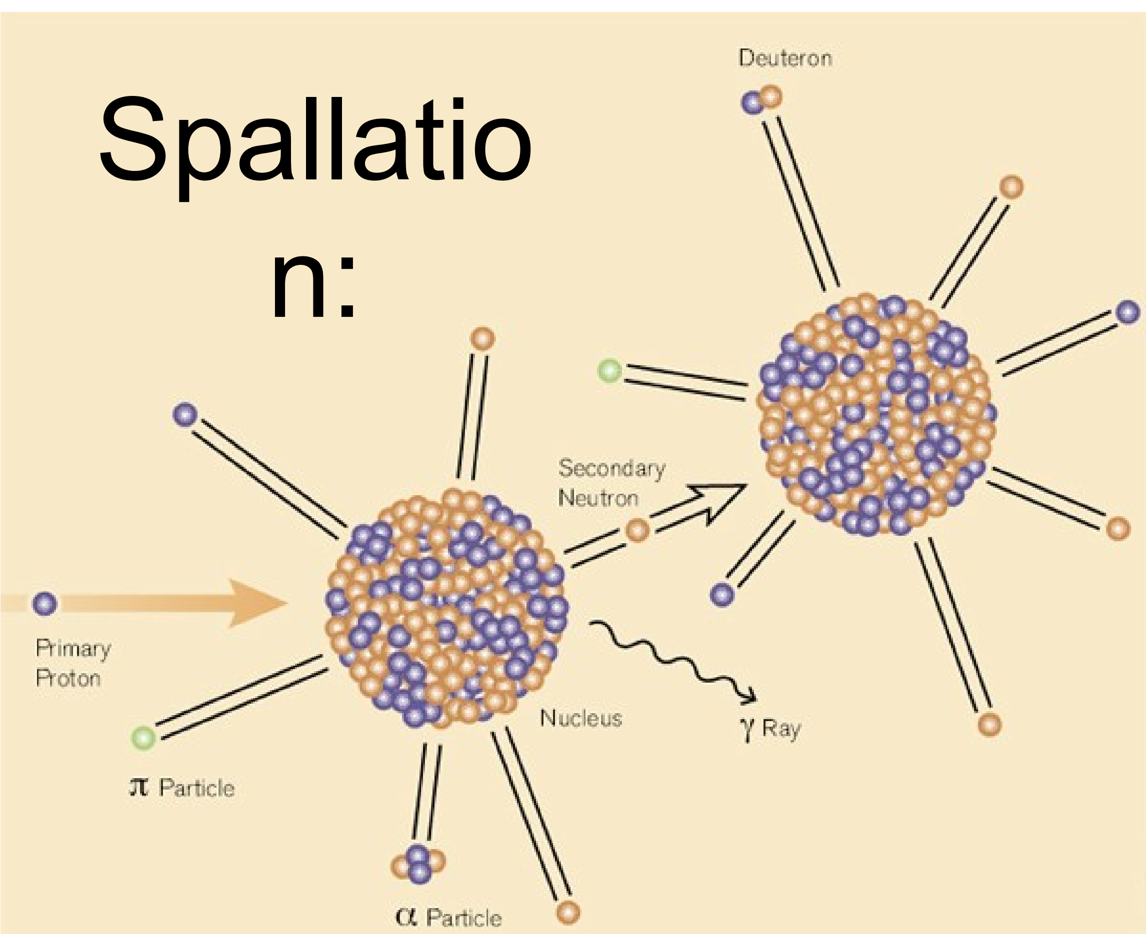
Spallation vs Fission

Fission



200 MeV/fission
2.35 – 1 = 1.35 neutrons freed
=> 150 MeV/neutron

Spallation:

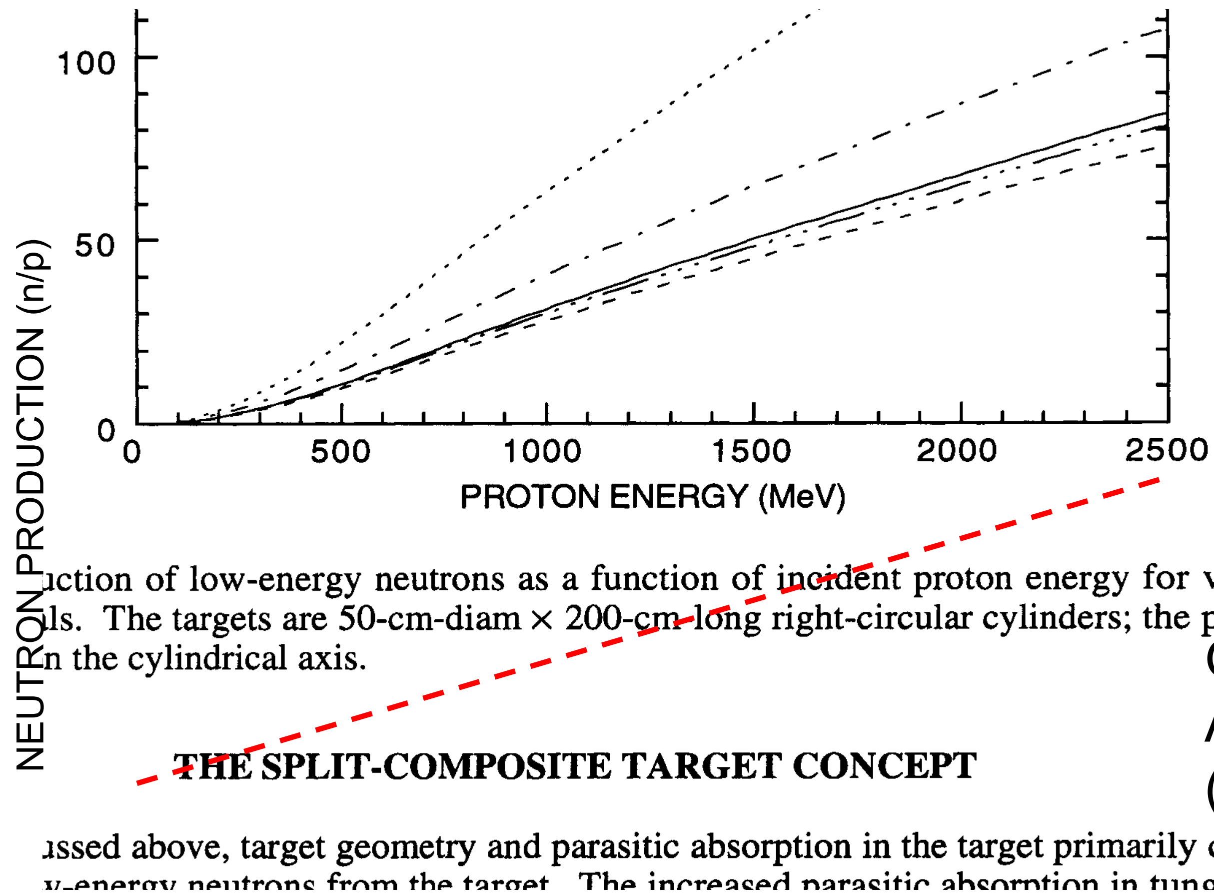


<u>1 GeV proton in:</u>
250 MeV becomes mass (endothermic reaction)
30 neutrons freed
=> 25 MeV/neutron

6x more neutrons per unit heat

Spallation Sources

- Proton beam parameters: energy (=voltage) and current
- Current: neutron production is proportional to number of protons
- Energy: neutron production is proportional to proton energy (E>500MeV)



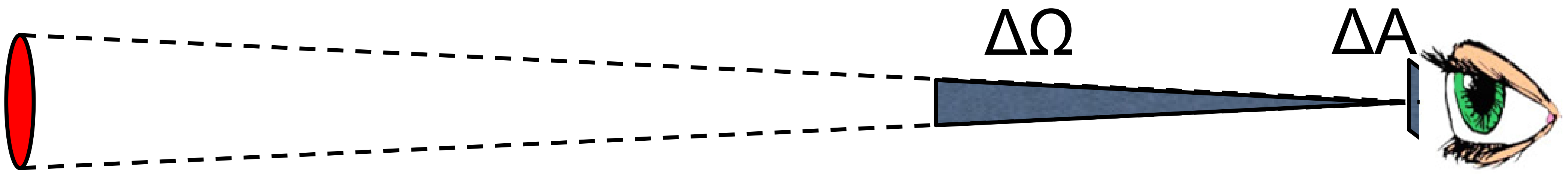
G.J. Russell et al,
AIP Conf. Proc. 346, 93 (1995)

- Neutron production is proportional to Power = Voltage x Current
  - e.g. ISIS: 800MeV x 200uA = 160kW
  - e.g. ESS: 2.5GeV x 2mA = 5MW

Spallation Sources

- Spallation: 10x higher neutron brightness per unit heat
  - about 6x more neutrons per unit heat
  - about ½ production volume

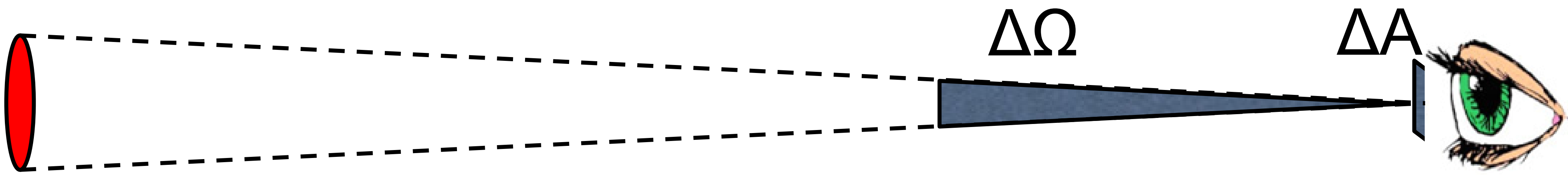
$$B = \frac{\partial^3 N}{\partial A \partial t \partial \Omega}$$



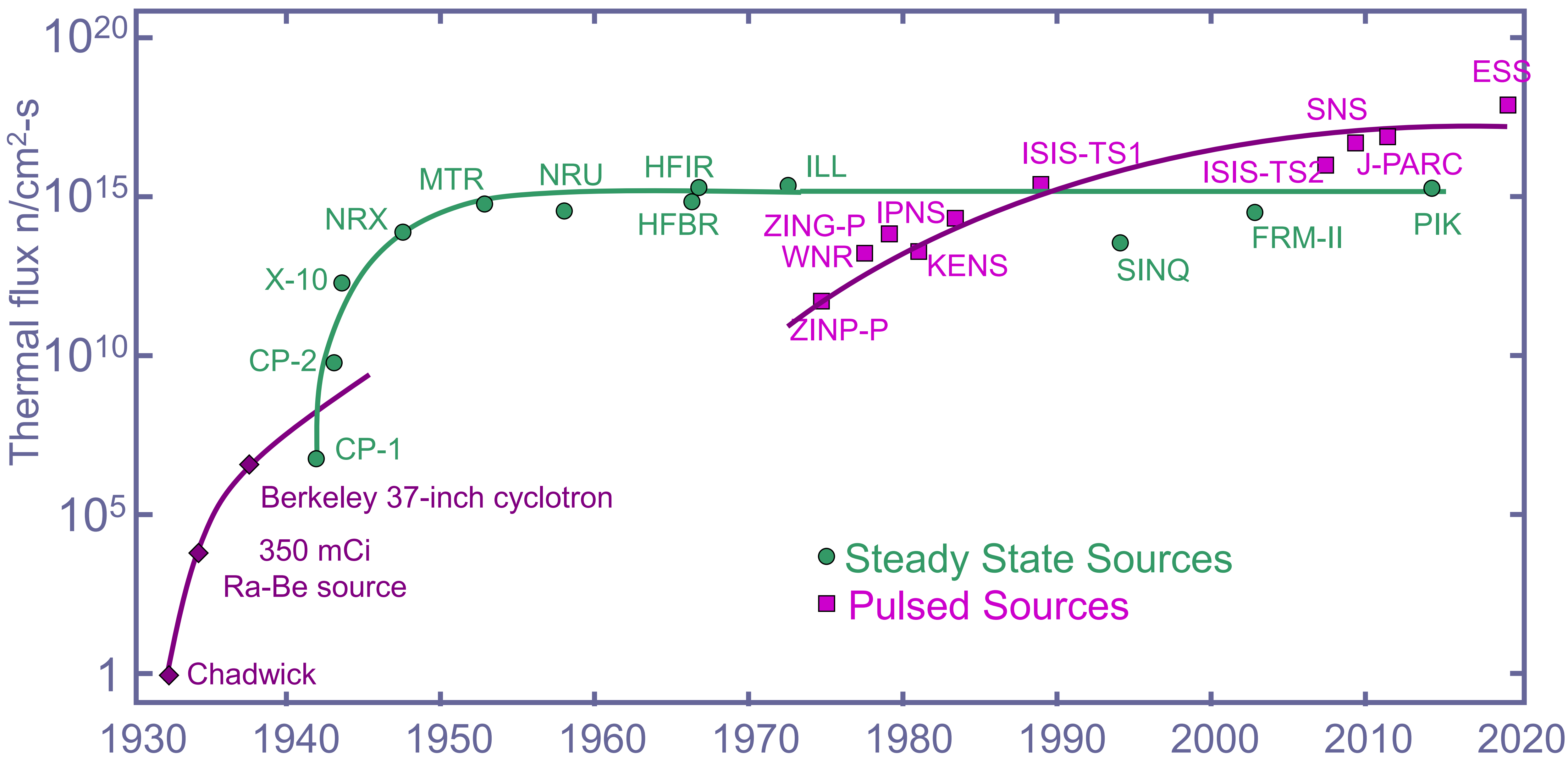
Spallation Sources

- Spallation: 10x higher neutron brightness per unit heat
  - about 6x more neutrons per unit heat
  - about ½ production volume

$$B = \frac{\partial^3 N}{\partial A \partial t \partial \Omega}$$



- 1MW spallation source = 10MW reactor
  - e.g. 800MeV at 1.25mA
  - e.g. 2.5GeV at 0.4mA
- Pulsed nature gives additional information
- Spallation has not yet reached the limit imposed by cooling power
  - Short-pulse limitations: peak power on target



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

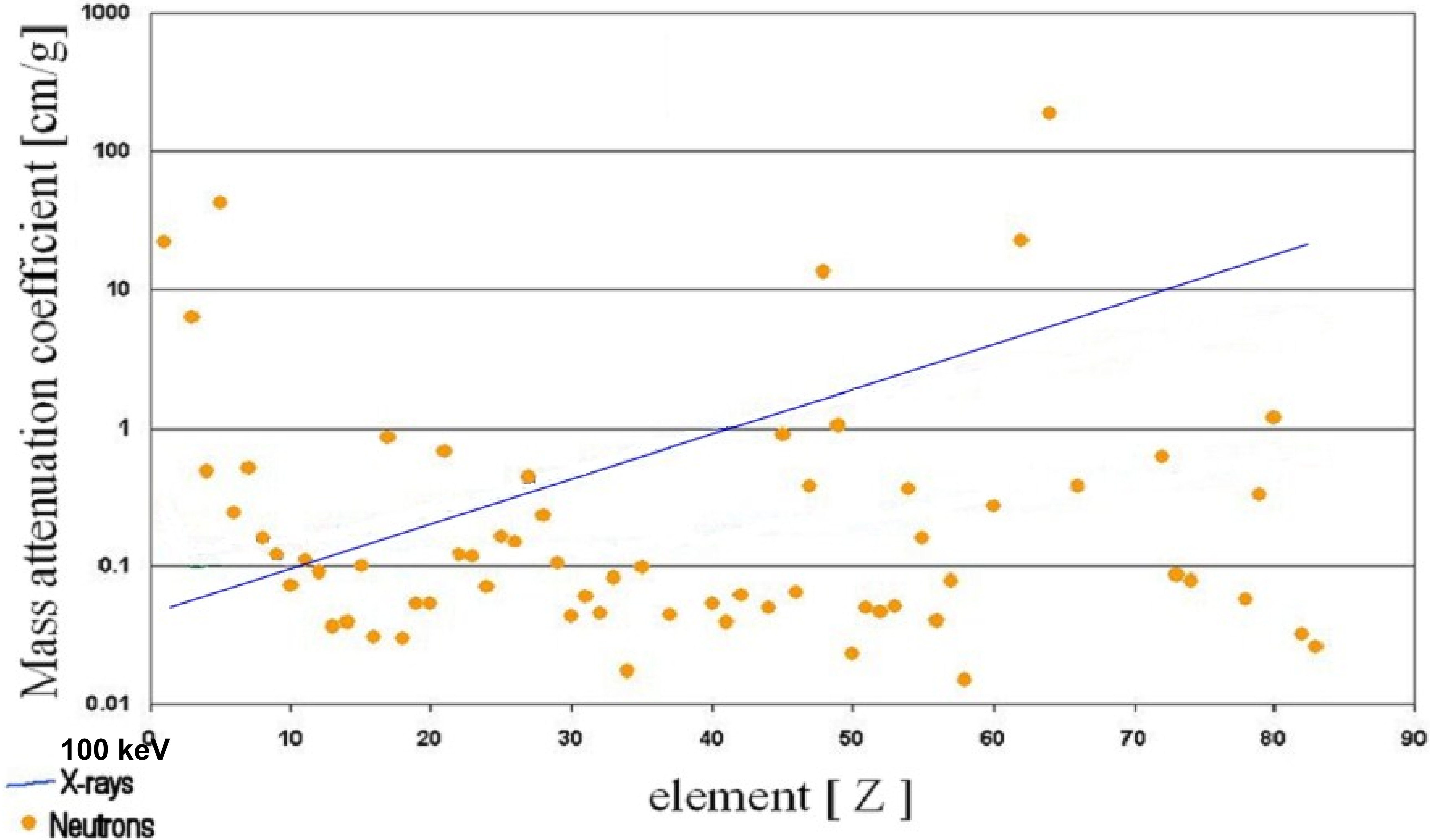
Neutrons vs Light

	light	neutrons
λ	< µm	< nm
E	> eV	> meV
n	$1 \rightarrow 4$	$0.9997 \rightarrow 1.0001$
θ_c	90°	1°
$\Phi/\Delta\Omega$	10^{18} p/cm²/ster/s (60W lightbulb)	10^{14} n/cm²/ster/s (60MW reactor)
P	left-right	up-down
spin	1	½
interaction	electromagnetic	strong force, magnetic
charge	0	0

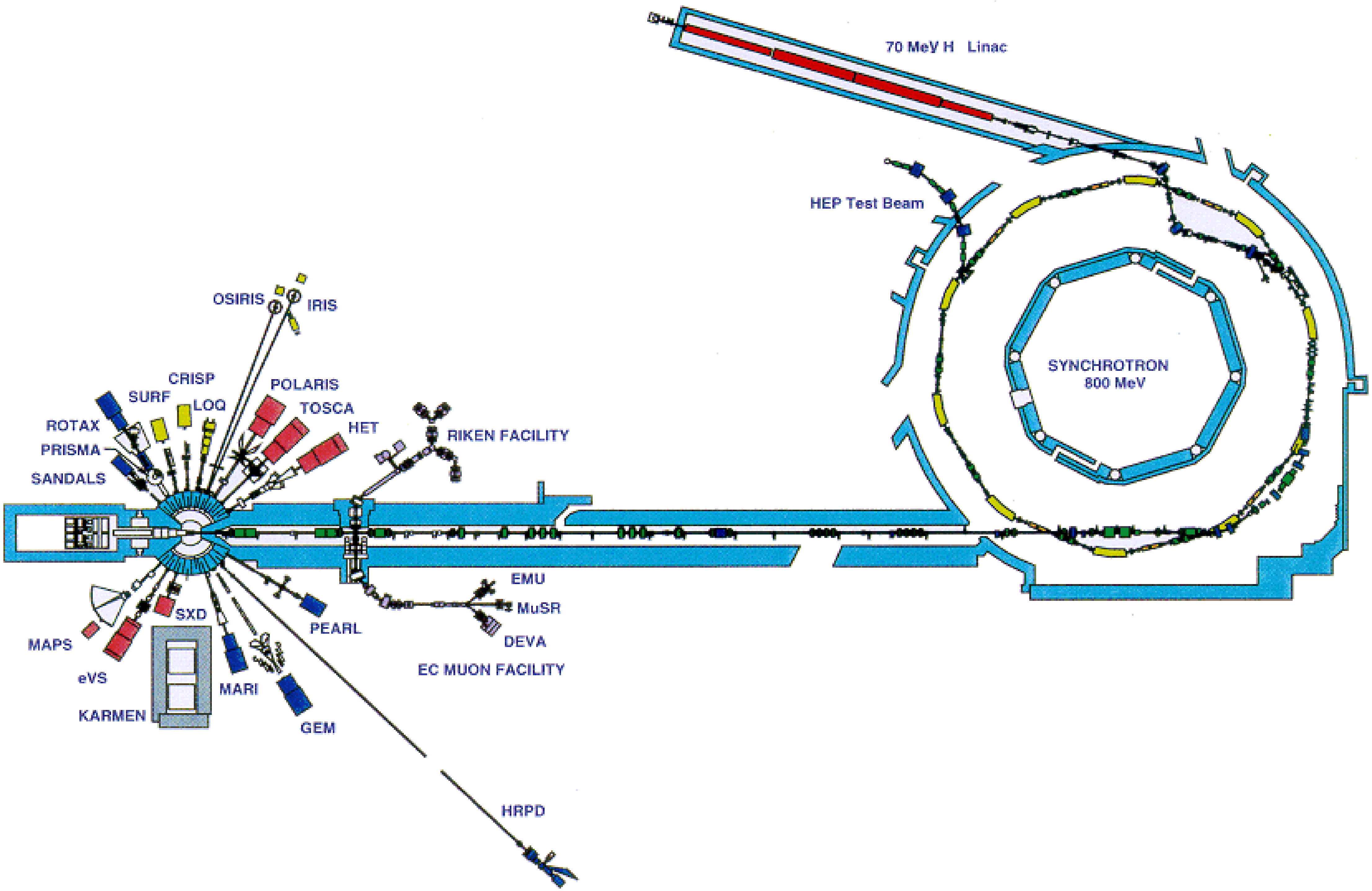
Why neutrons?

- Thermal neutrons have wavelengths similar to atomic distances
- Thermal neutrons have energies comparable to lattice vibrations
- Neutrons are non-destructive
- Neutrons interact weakly:
  they penetrate into the bulk
- Neutrons interact via a simple point-like potential:
  amplitudes are straightforward to interpret
- Neutrons have a magnetic moment:
  great for magnetism
- Neutrons see a completely different contrast to x-rays
  e.g. hydrogen very visible

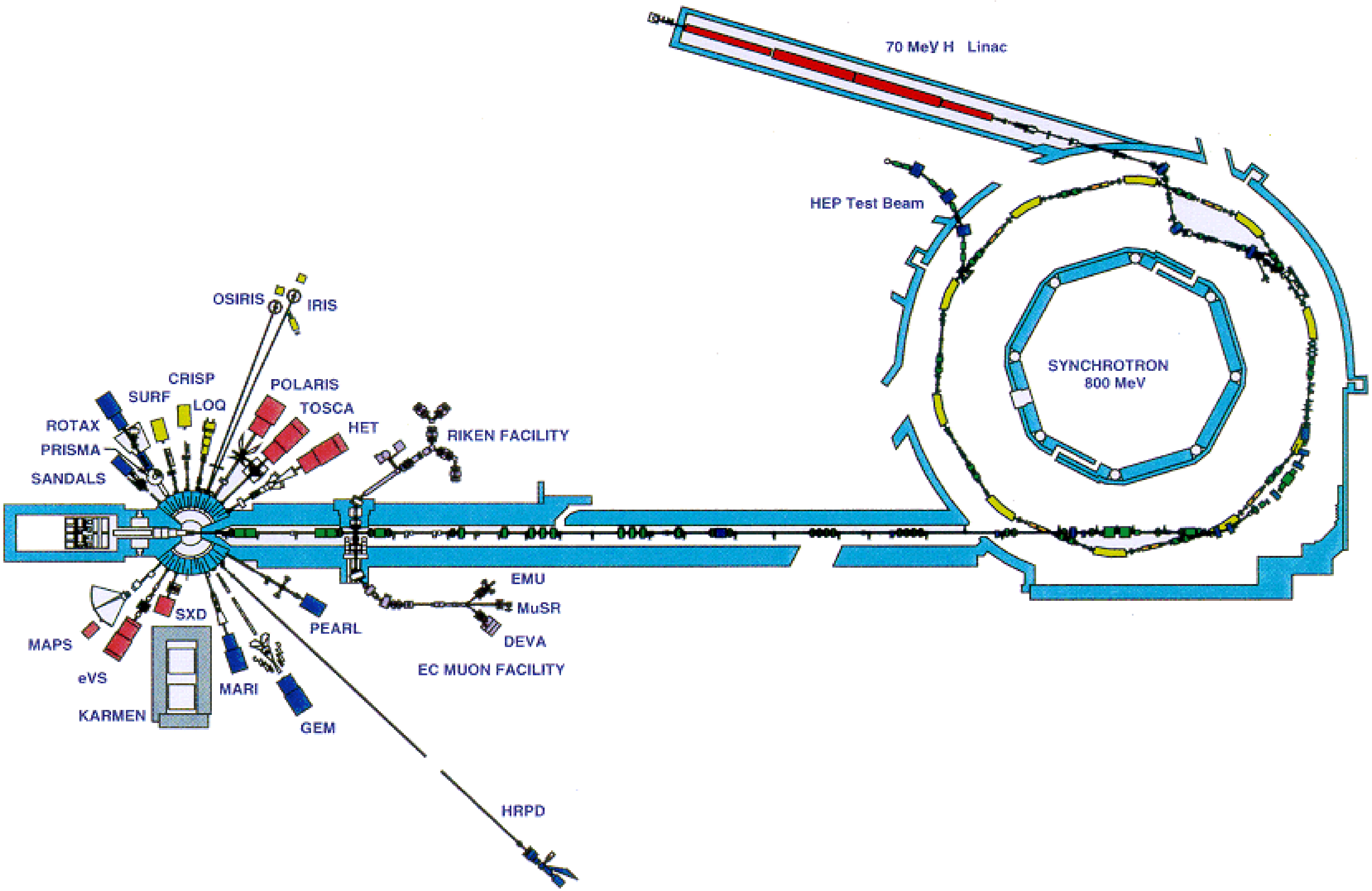
Why neutrons?



ISIS, Oxfordshire, UK (160kW)



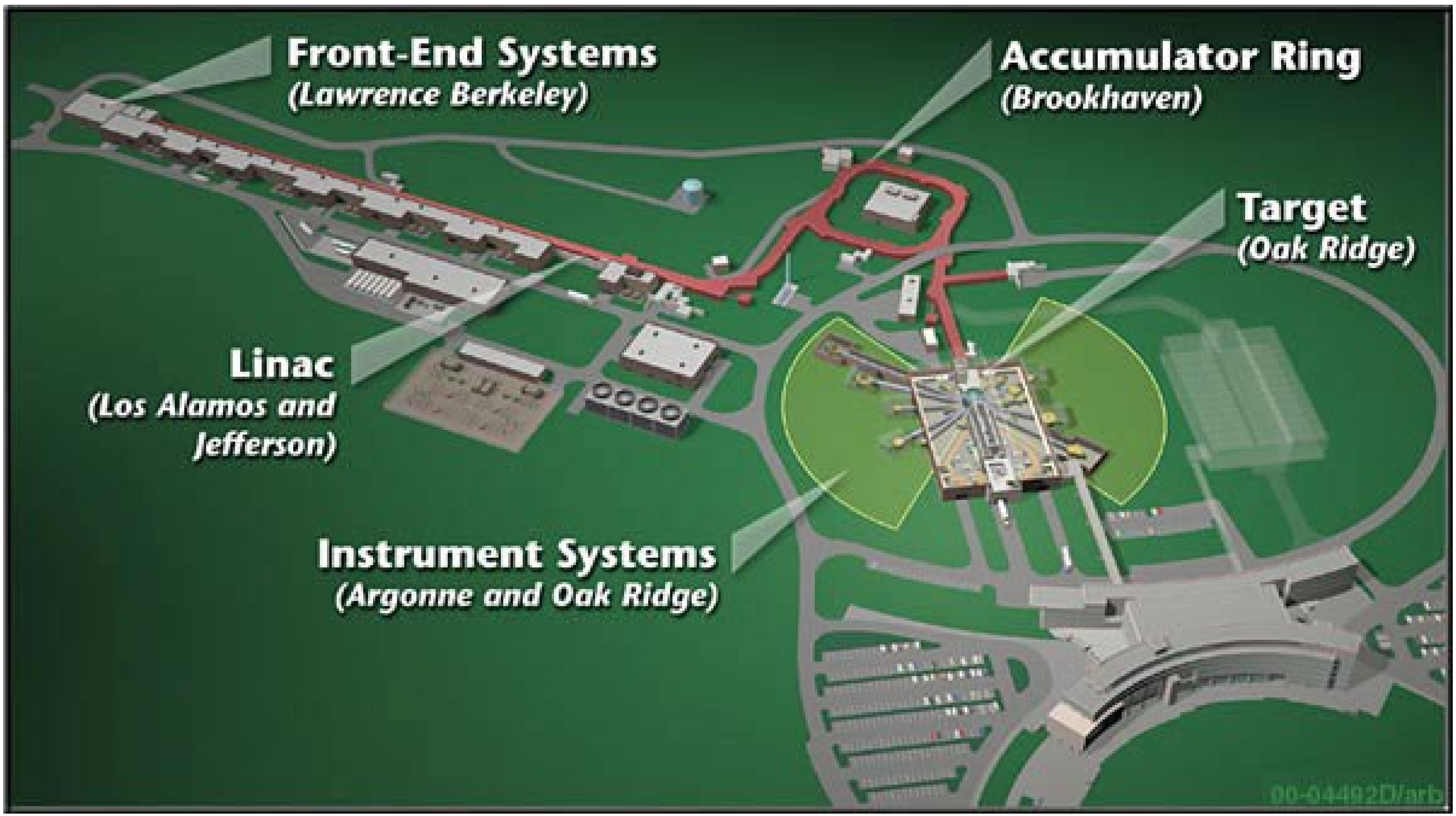
ISIS, Oxfordshire, UK (160kW)



EUROPEAN
SPALLATION
SOURCE

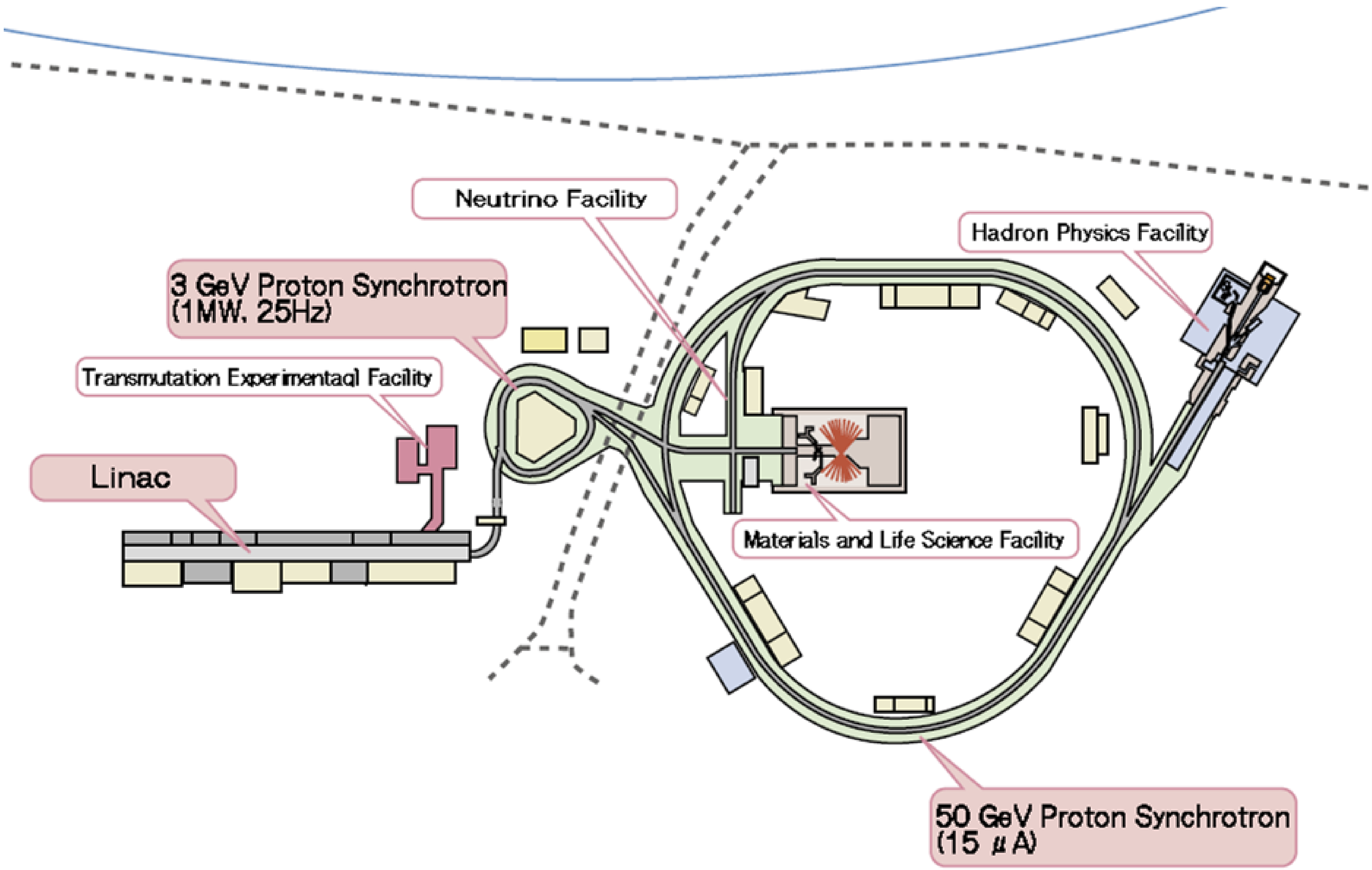
ISIS: Today's leading spallation neutron source 160kW

SNS, Oak Ridge, USA: 1MW today



J-PARC, Tokai, Japan: 1MW soon

J-PARC, Tokai, Japan: 1MW soon

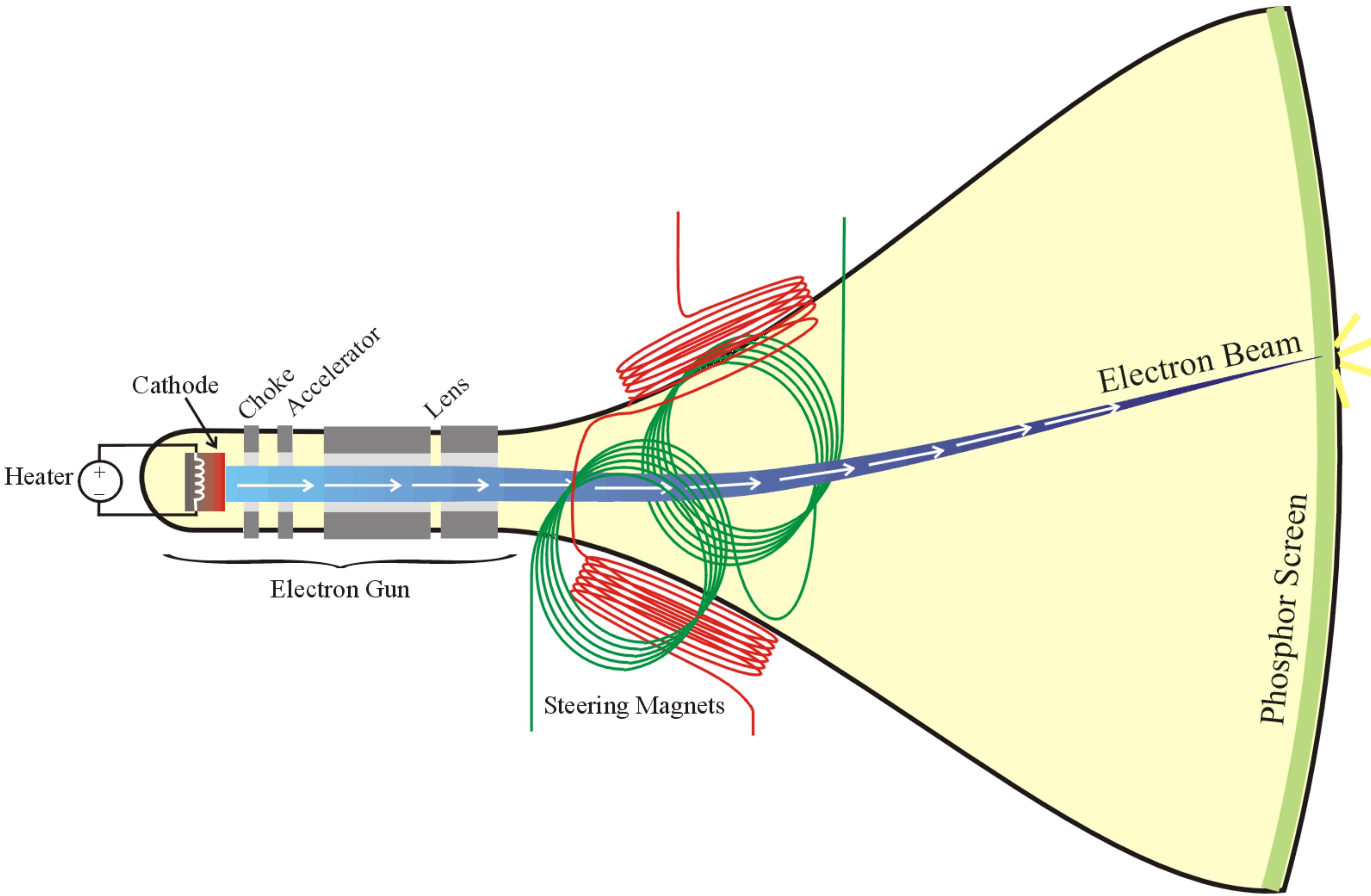


Short-Pulse Spallation Sources

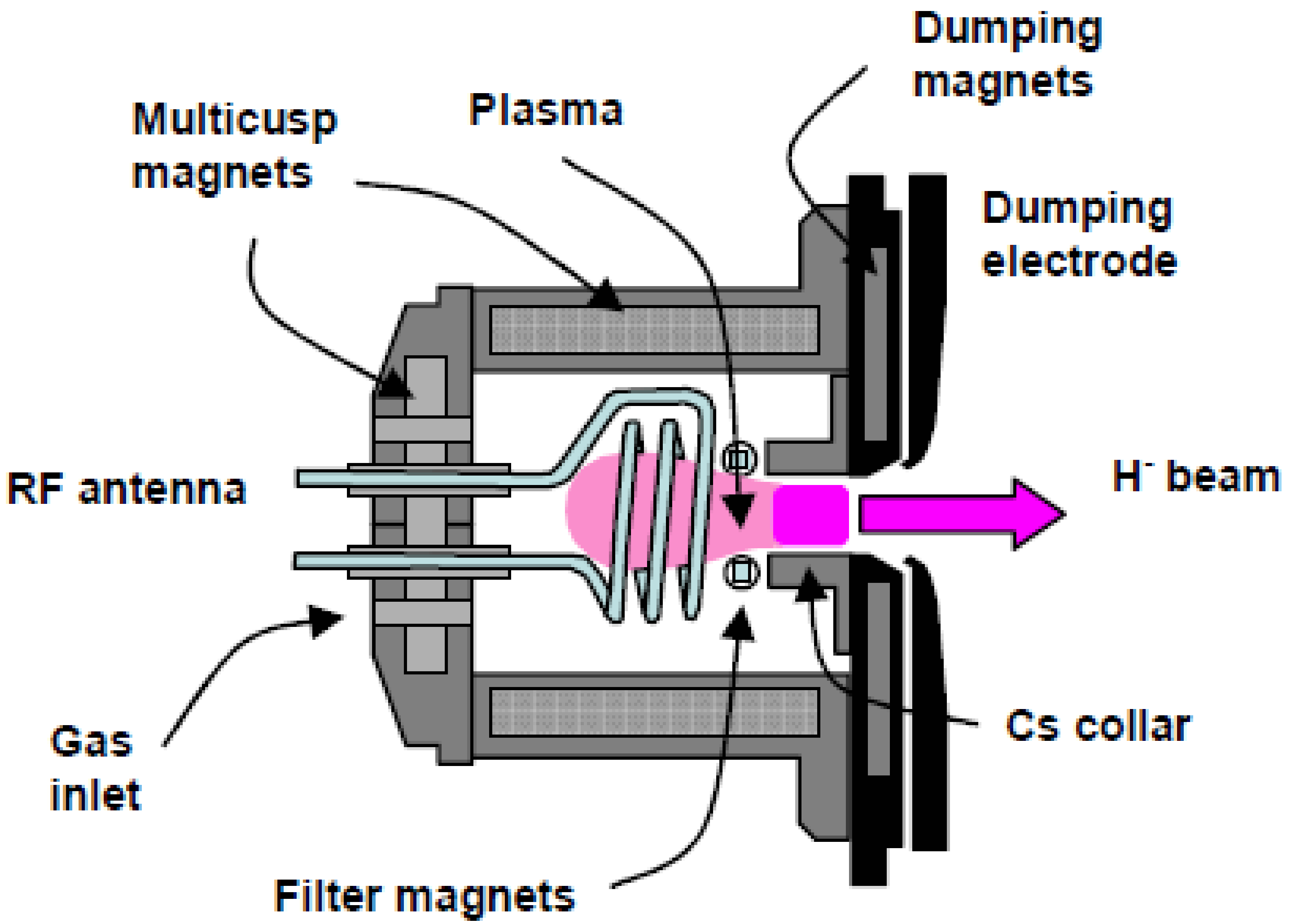
- Accelerator
  - H- ion source
  - Linear accelerator
  - Stripper converts H- to H+
  - Synchrotron
- Spallation target
- Reflector
- Moderators

Linear accelerator: LINAC

Linear accelerator: LINAC

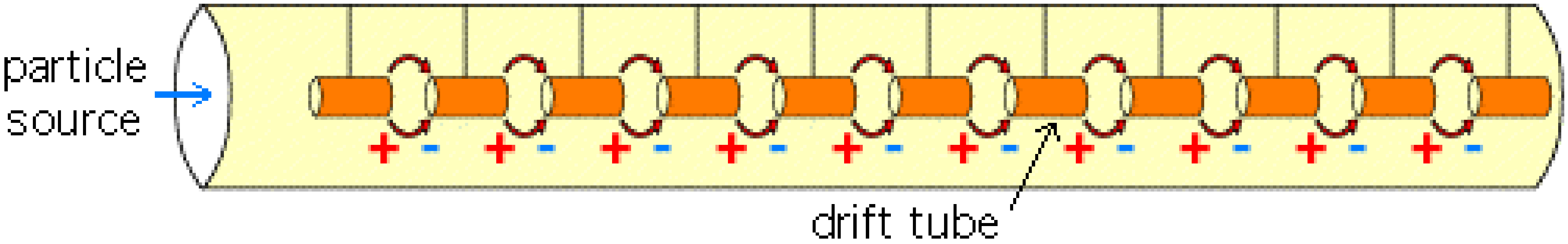


SNS ion source: H-

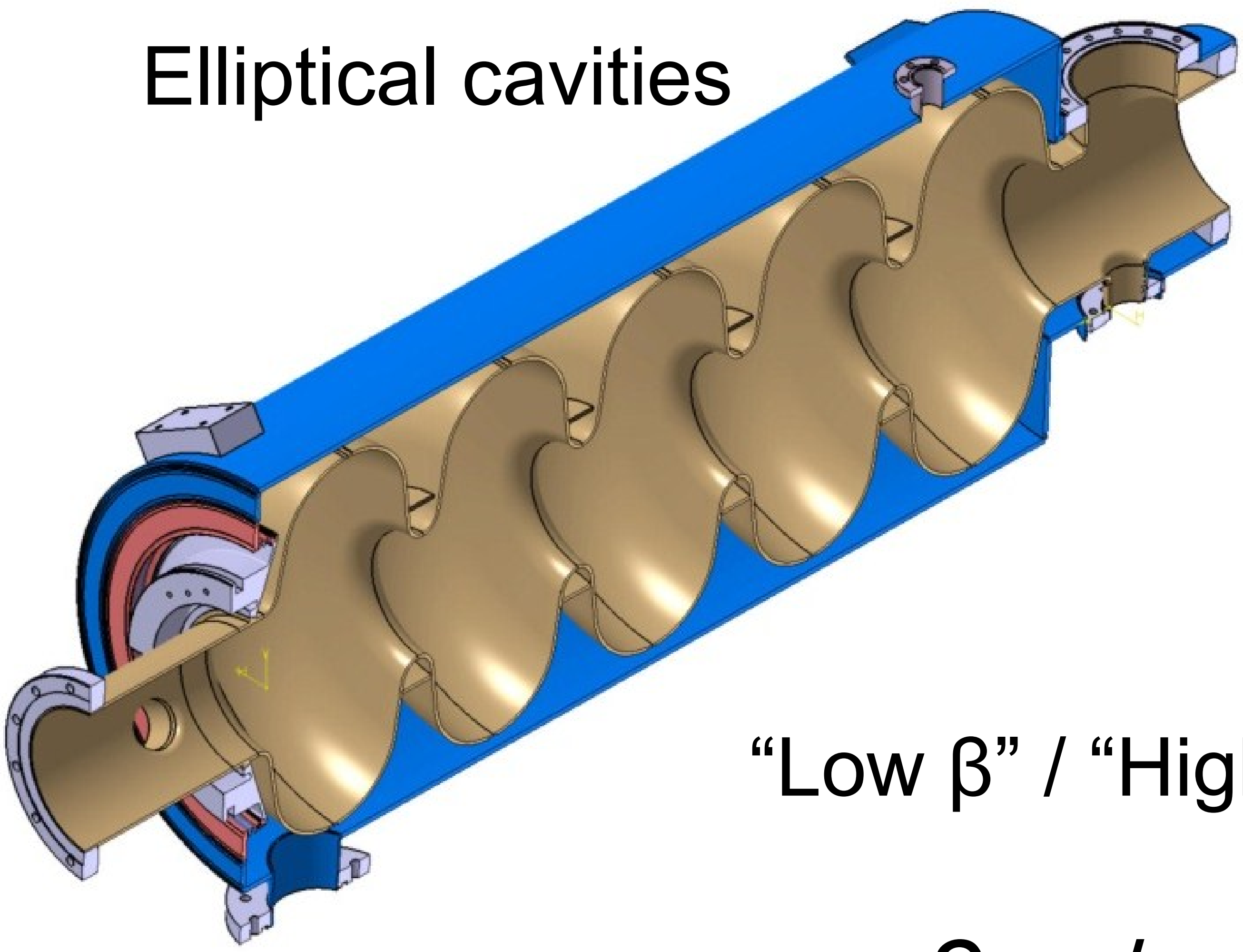


Different types of Linac

Drift-Tube Linac (DTL)



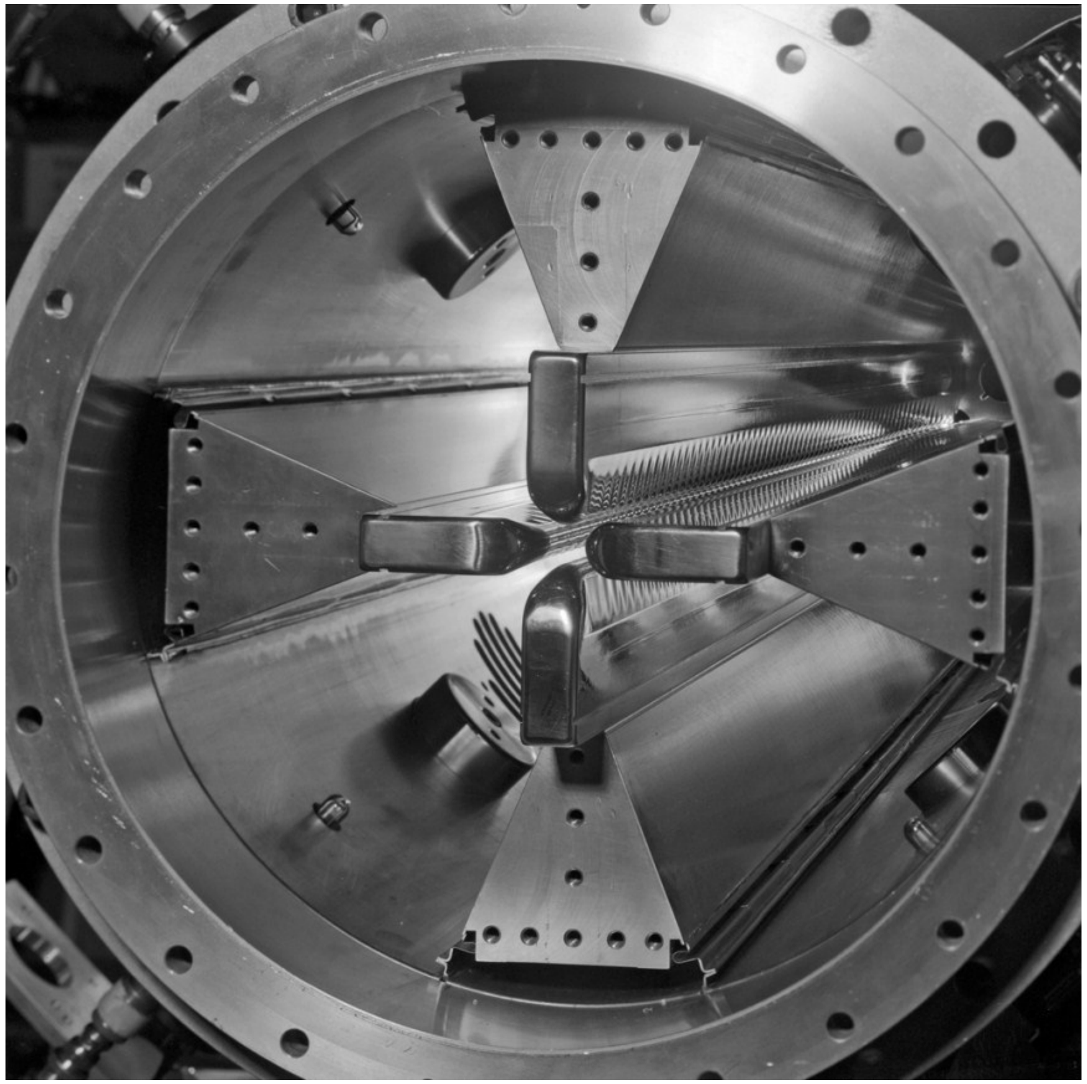
Elliptical cavities



"Low β" / "High β"

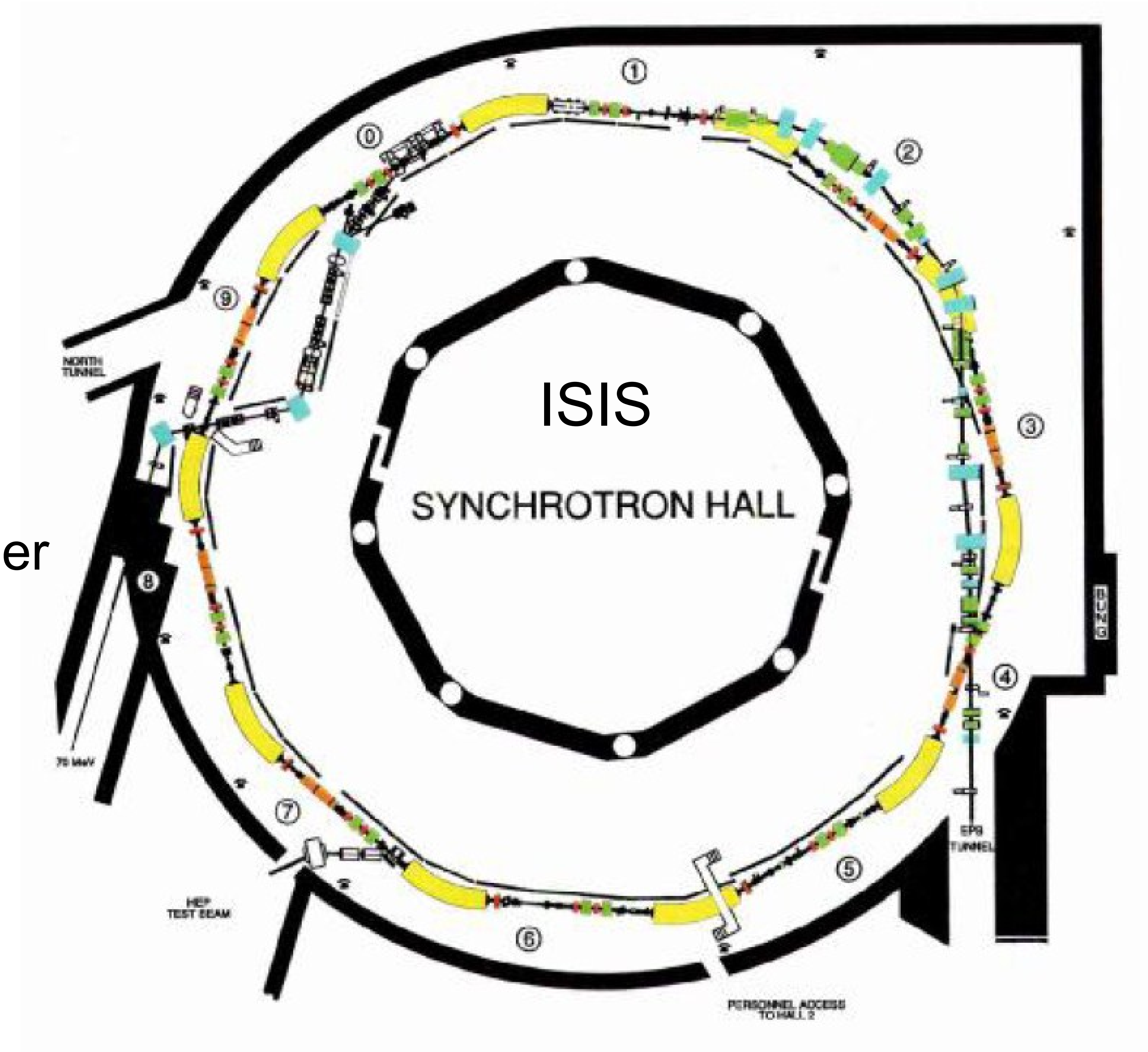
$$\beta = v/c$$

Radio-Frequency Quadrupole (RFQ



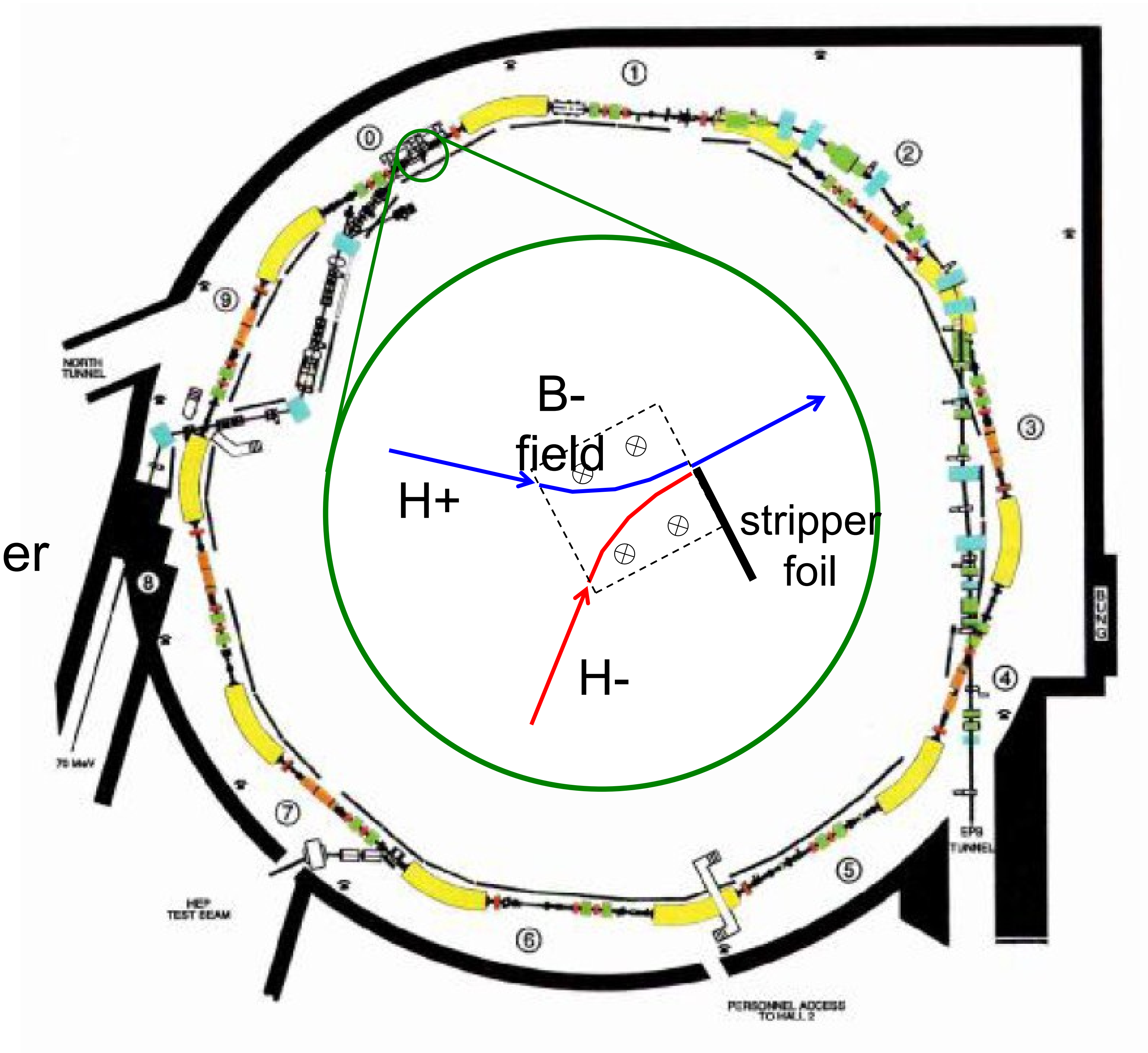
Synchrotron

- Synchronise:
  - B-field: bend
  - E-field: accelerate
  - E & B field: focus
  - Magnets to each other
- Injection
  - Stripper foil
- Extraction
  - Kicker magnet



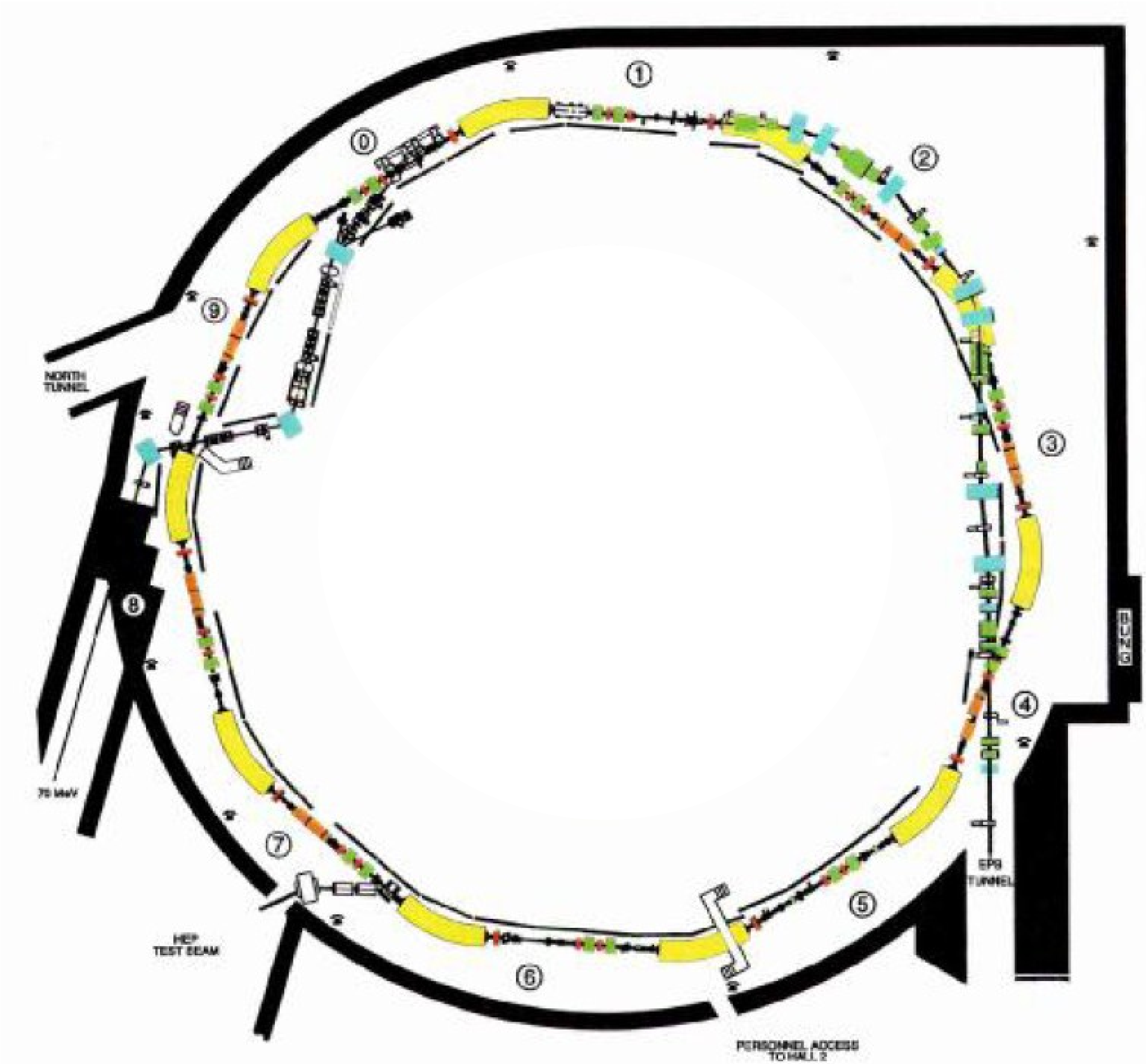
Synchrotron

- Synchronise:
  - B-field: bend
  - E-field: accelerate
  - E & B field: focus
  - Magnets to each other
- Injection
  - Stripper foil
- Extraction
  - Kicker magnet

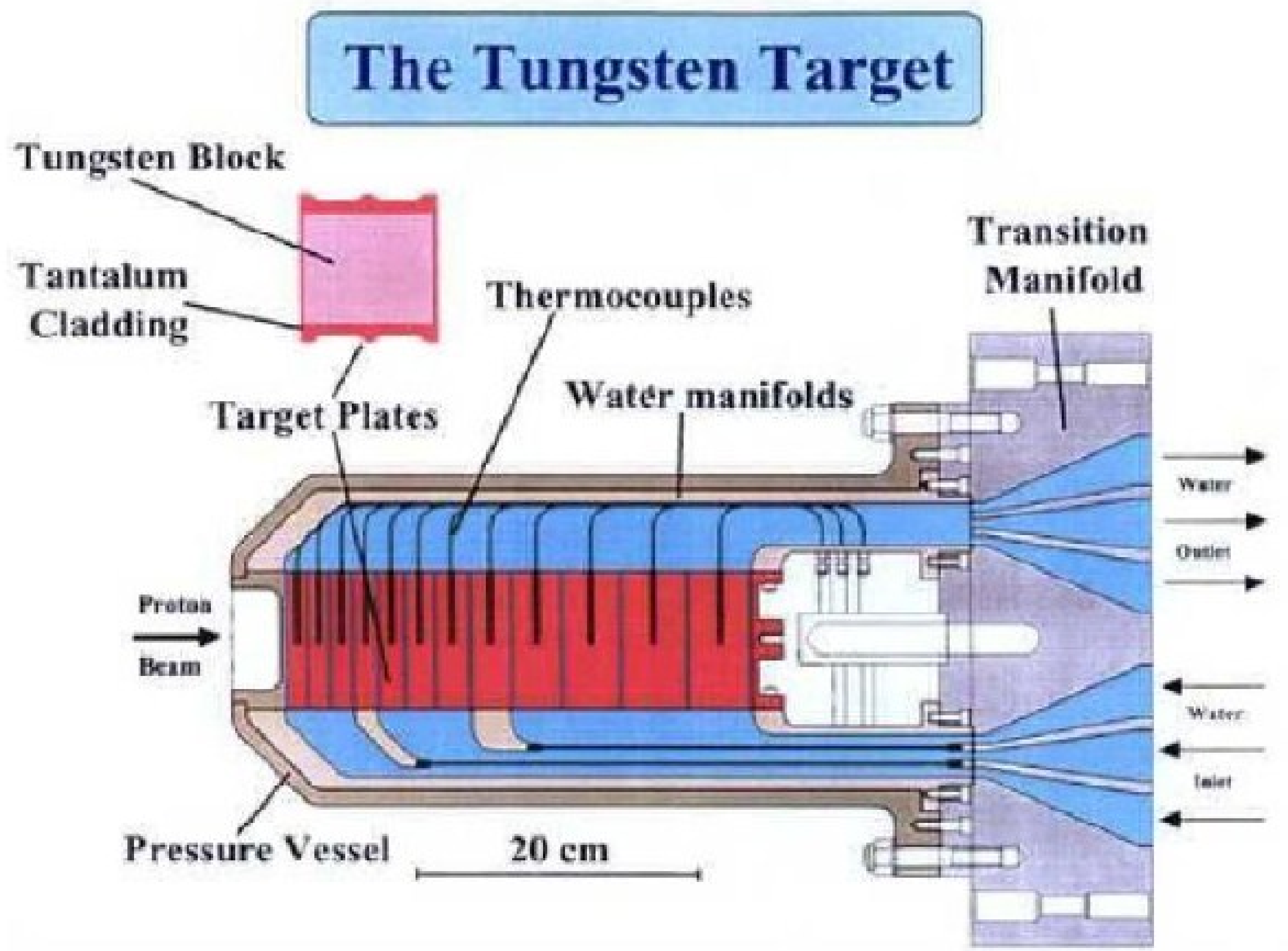


Synchrotron

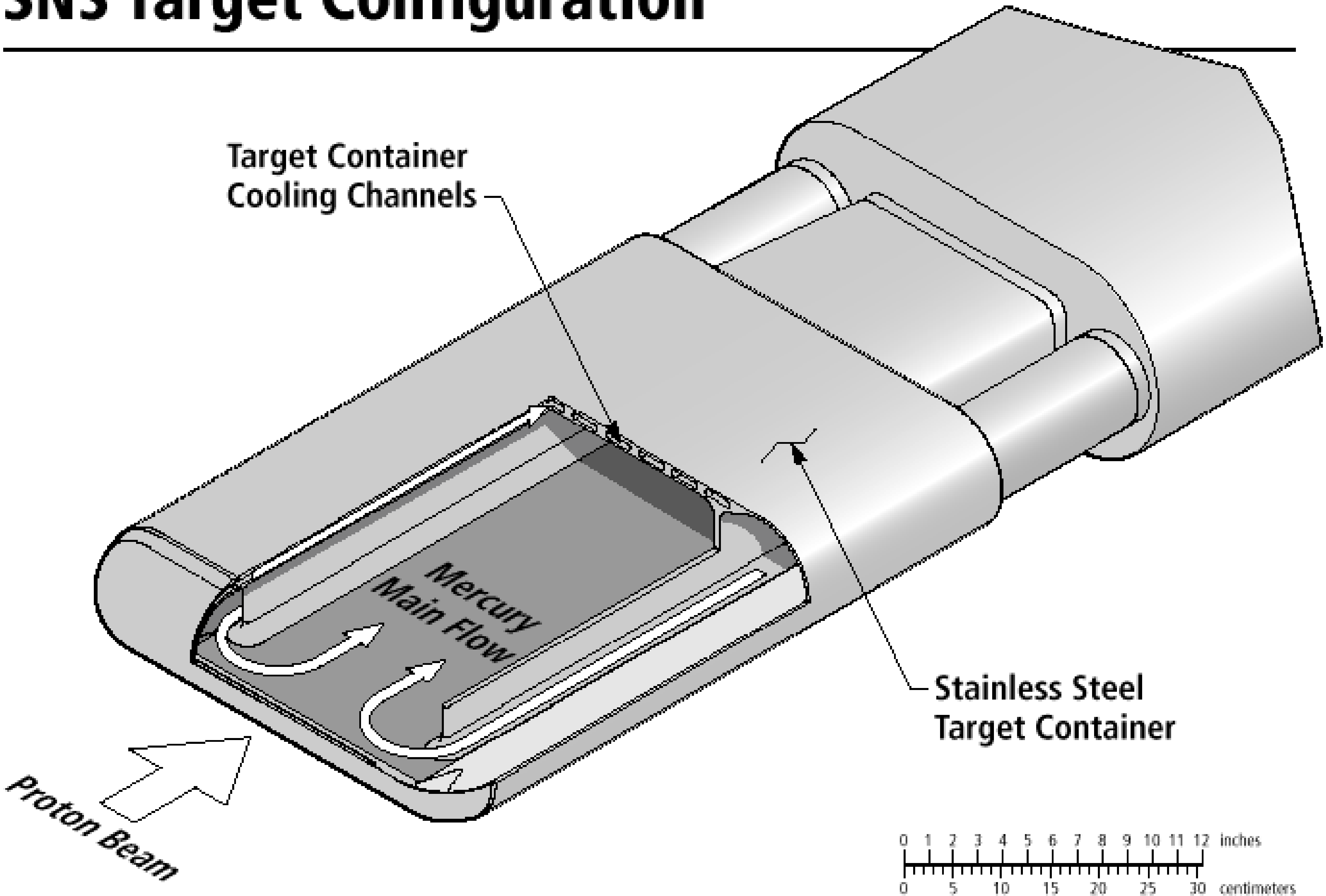
- $\Delta t_{linac} \approx 1$ ms
- $E_{ring} \approx 1$ GeV
  - $v \approx 3 \times 10^8$ m/s
- $L_{ring} \approx 200$ m
- $\Delta t_{ring} \approx 1$ μs



ISIS target 1: solid tungsten

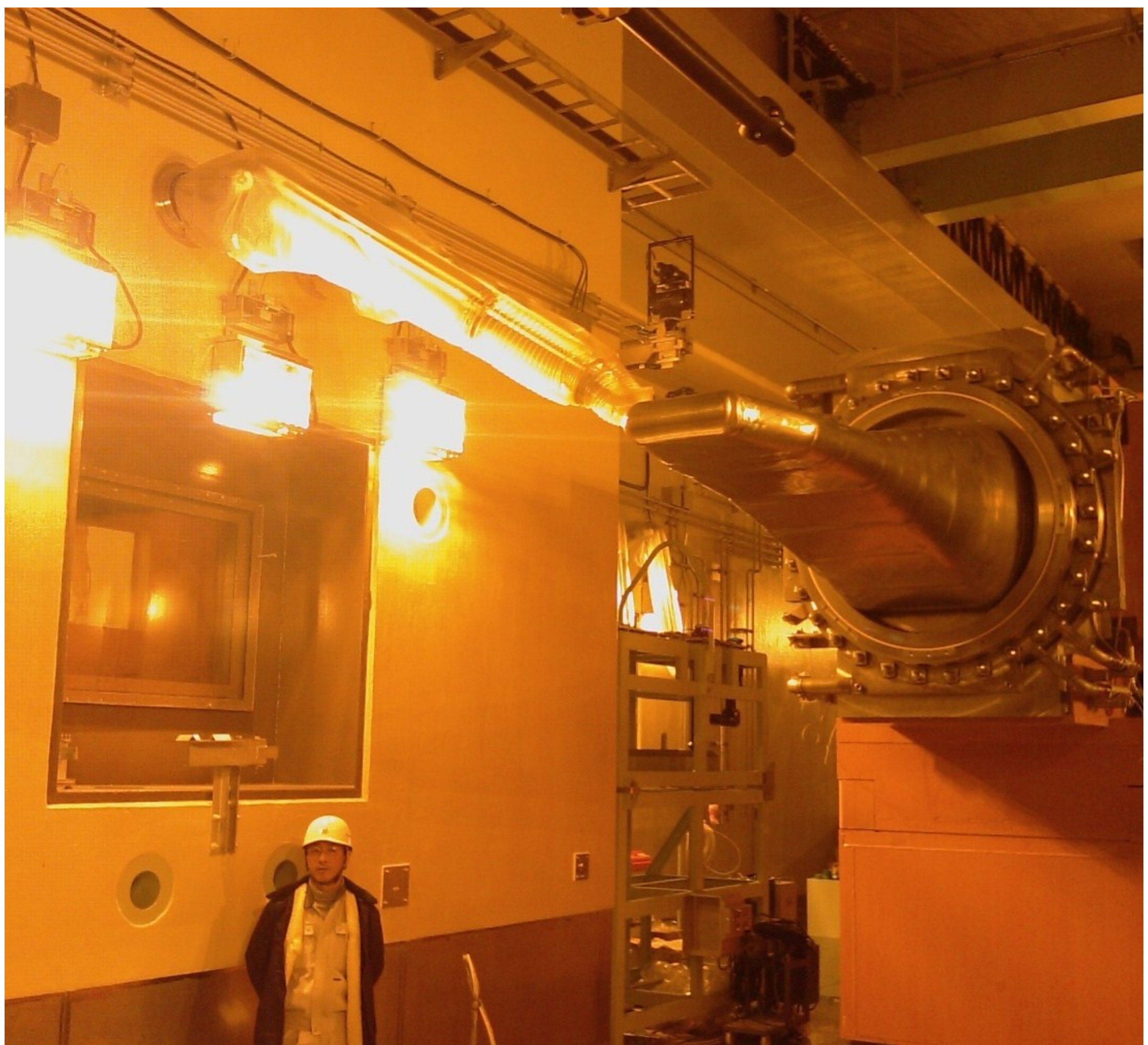


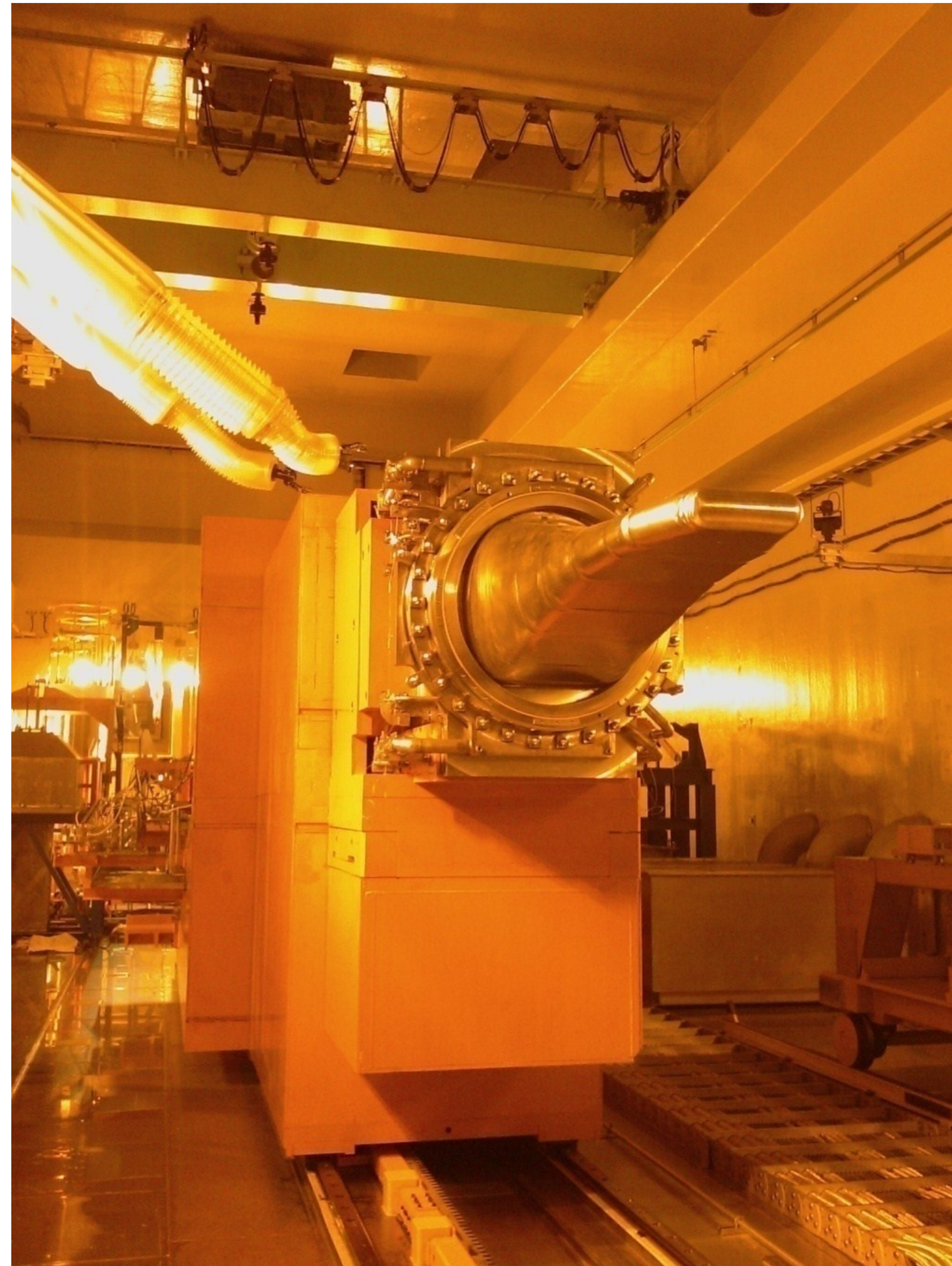
SNS Target Configuration



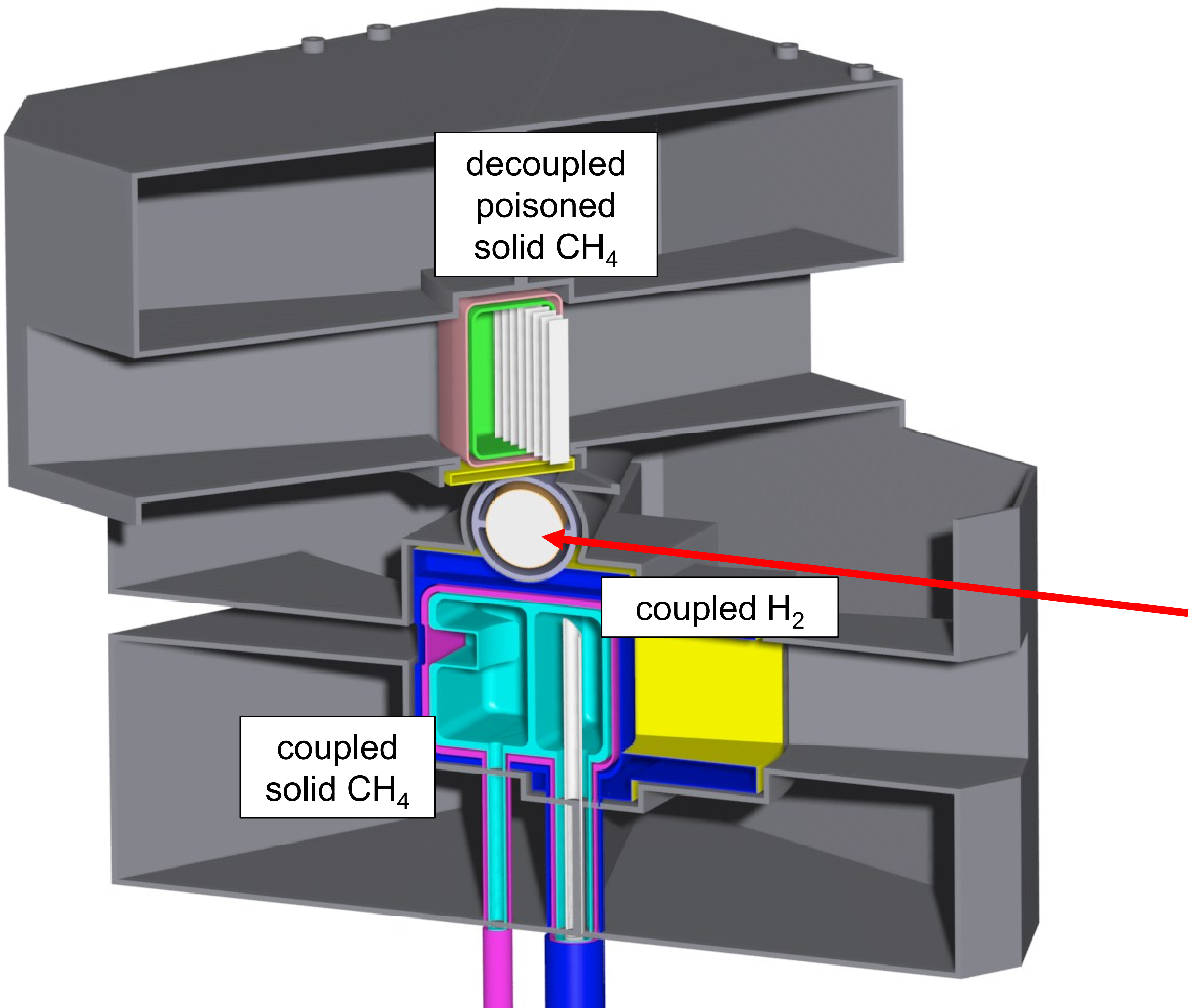
SNS target: liquid mercury

J-PARC target



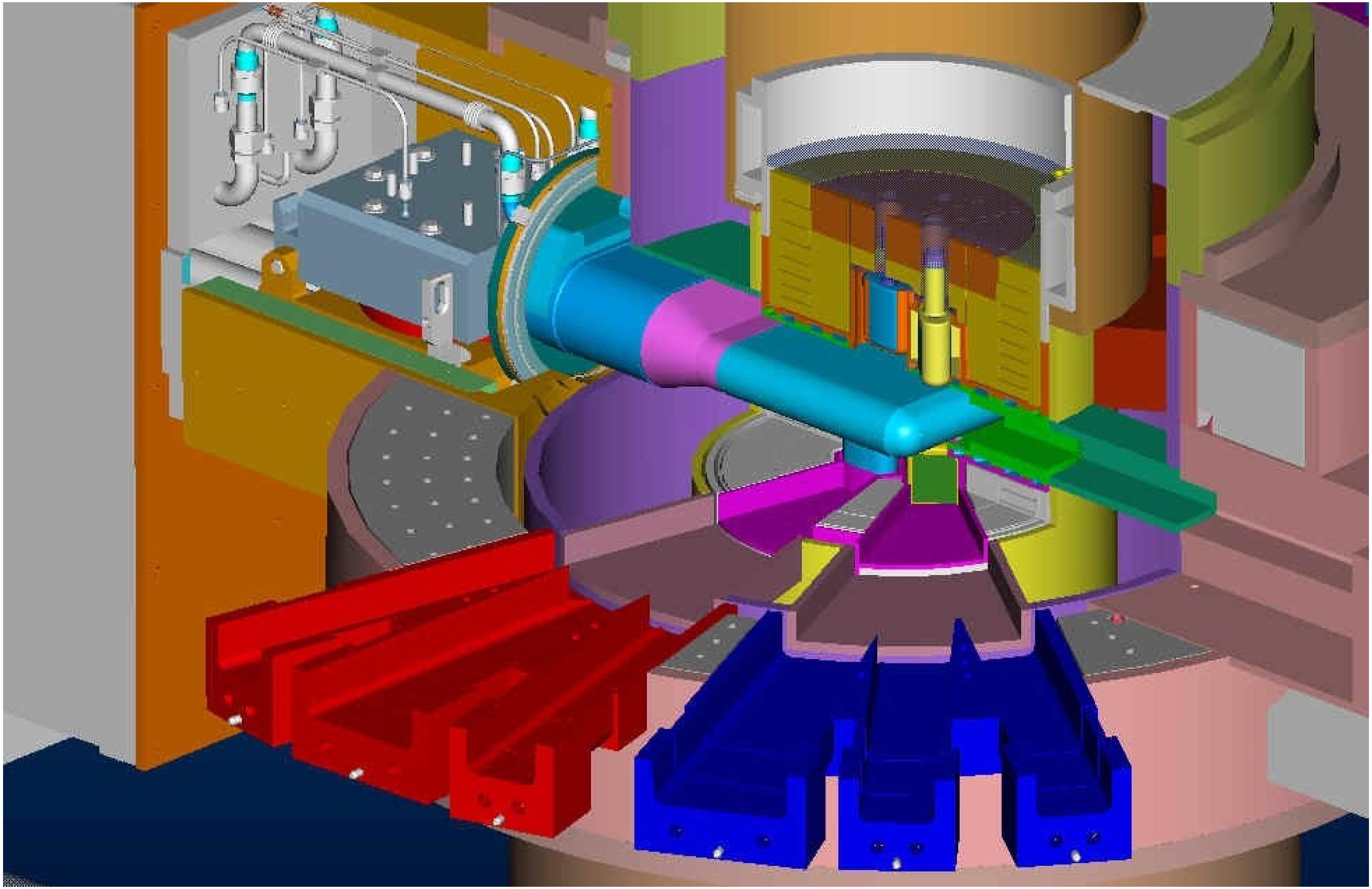


ISIS TS2 Target



Target:
66mm W

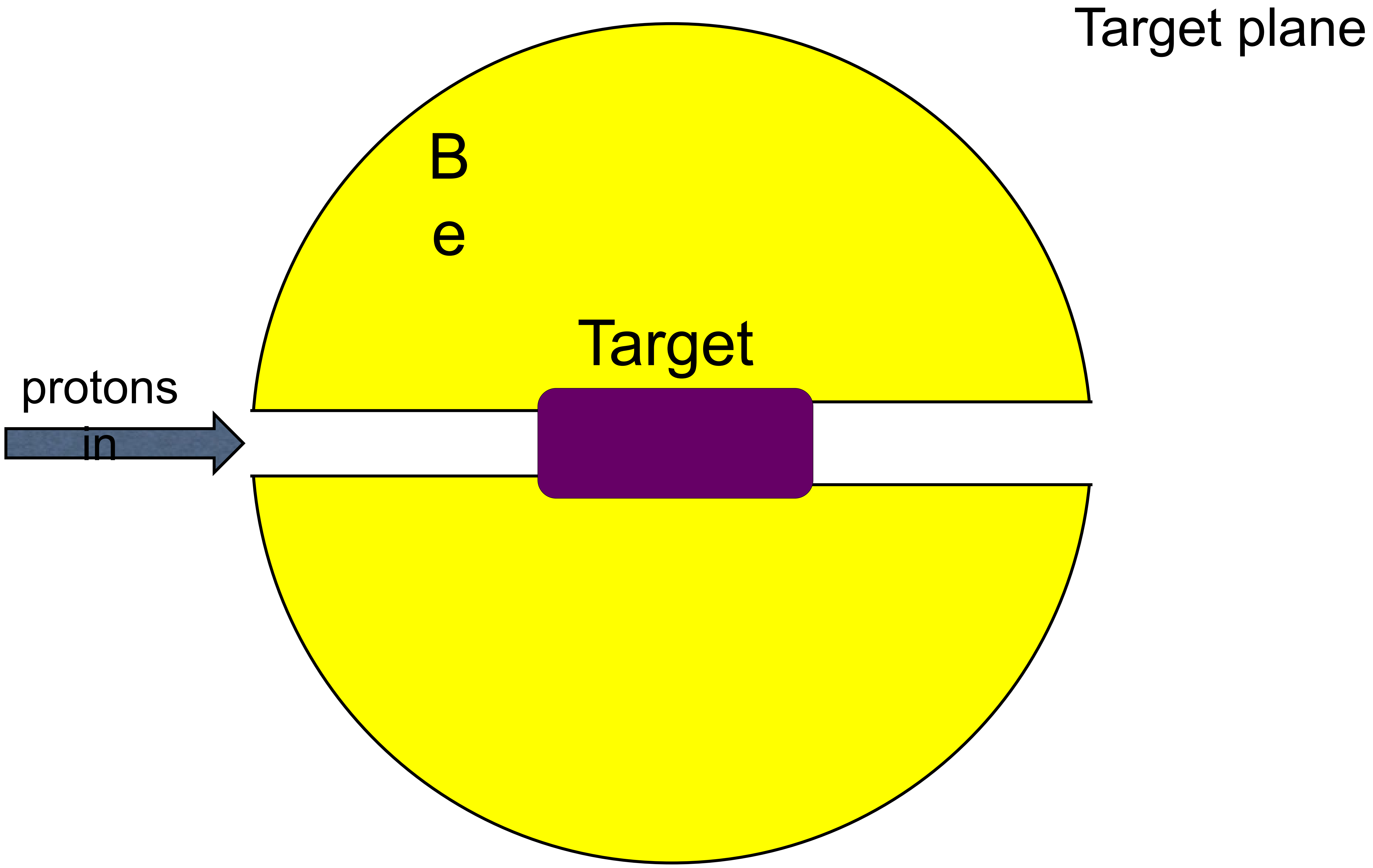
SNS target



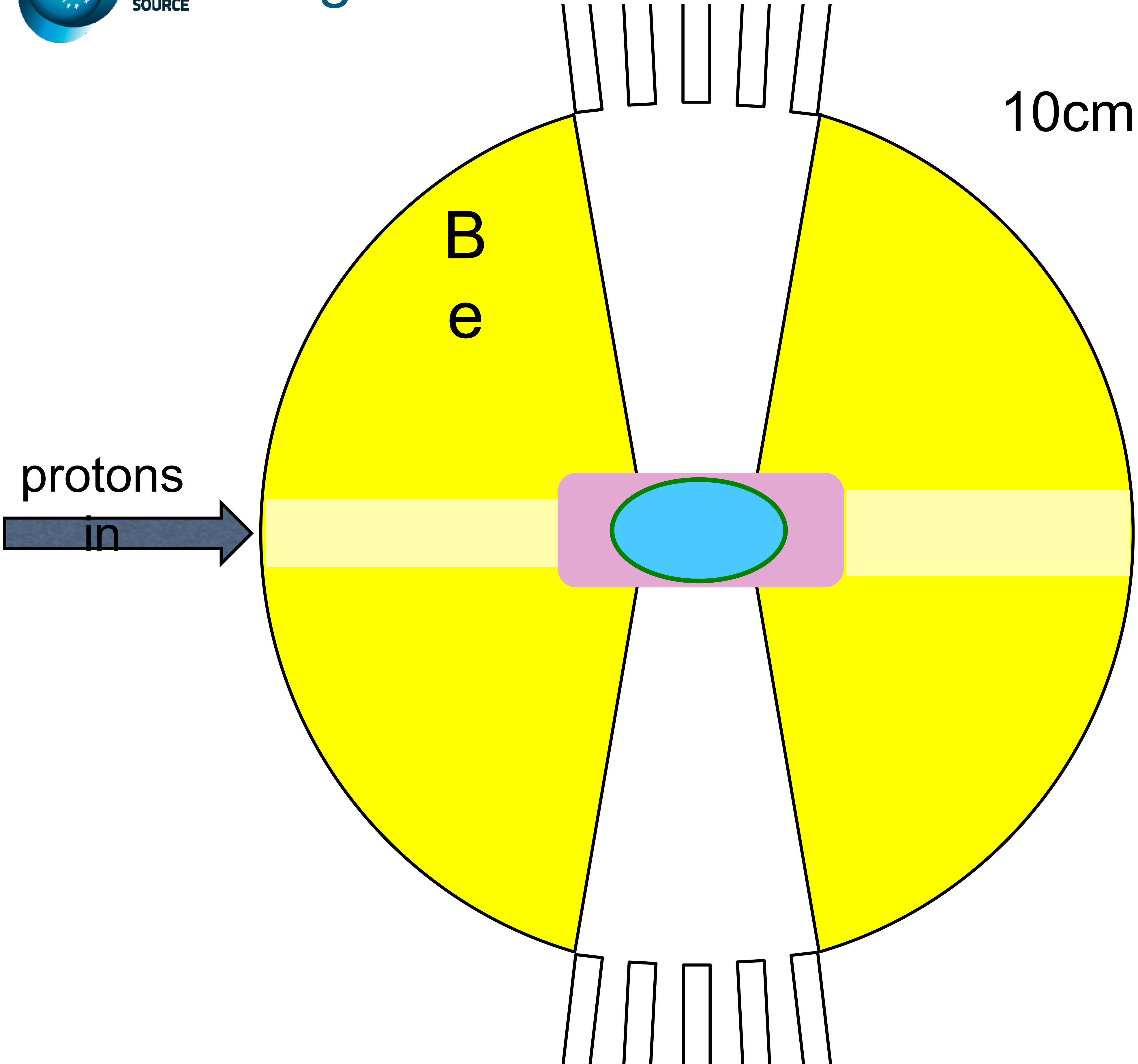
Target-Reflector-Moderator Neutronics

- Target produces neutrons in MeV range
- Moderators contain H to thermalise neutrons
  - Largest scattering cross-section (80b)
  - Lowest mass: same as neutron
    - on average, ½ energy lost per collision
    - 100MeV -> 10meV requires about 25 collisions
- Moderators embedded in reflector, usually D_2O-cooled Be
  - Minimal absorption
  - Large scattering cross-section (8b)
  - Little thermalisation

Target-Reflector-Moderator Neutronics

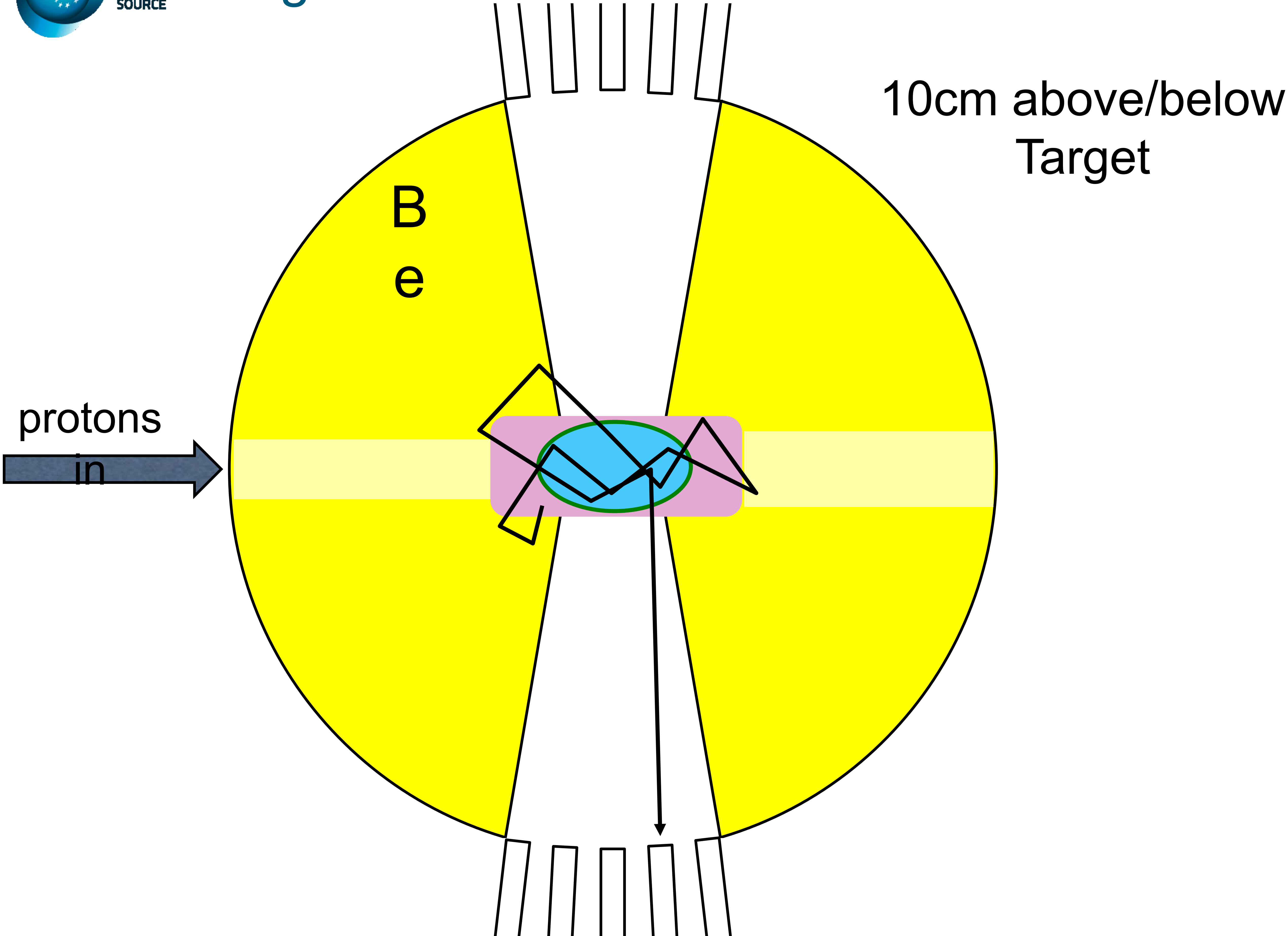


Target-Reflector-Moderator Neutronics

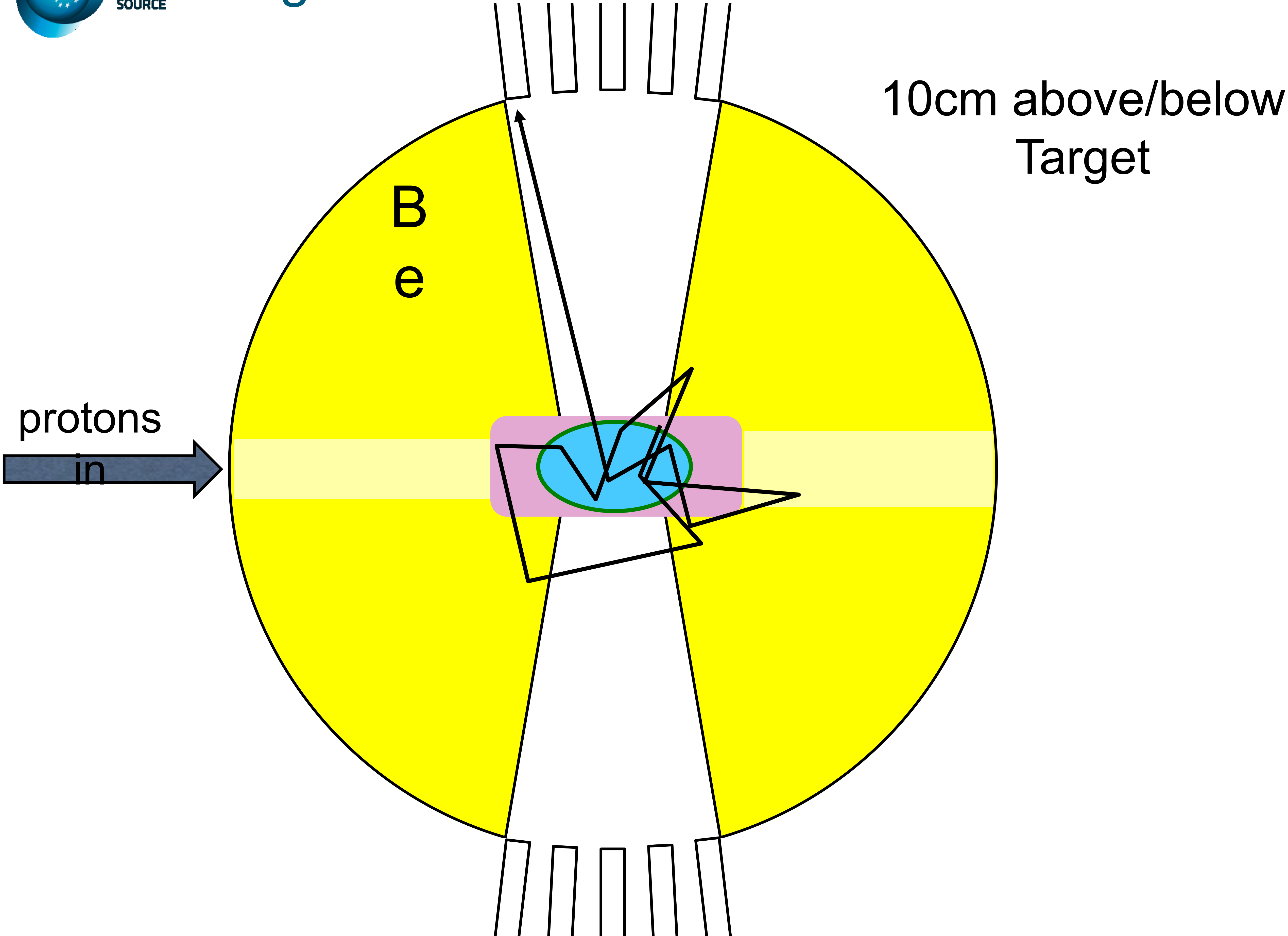


10cm above/below
Target

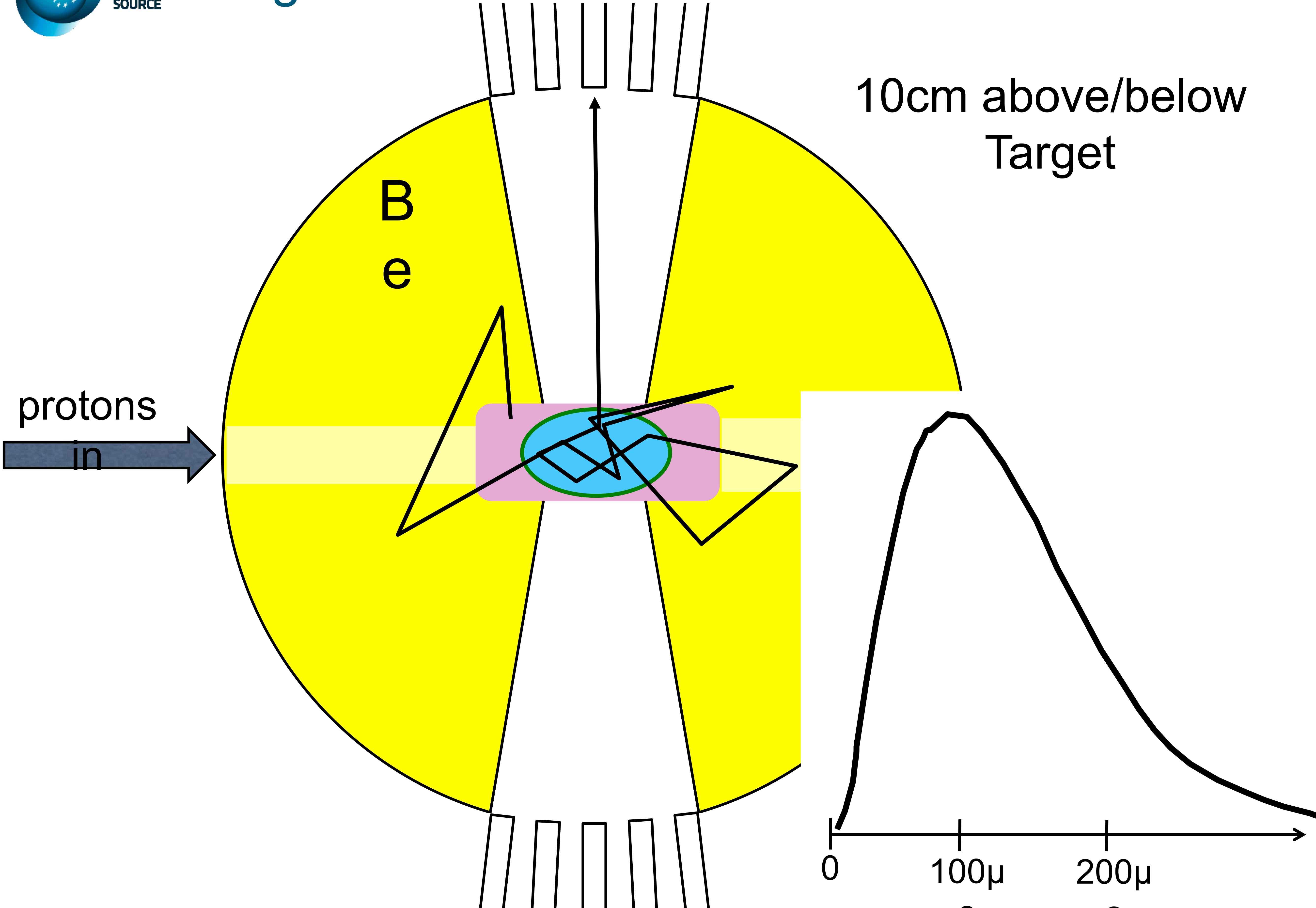
Target-Reflector-Moderator Neutronics



Target-Reflector-Moderator Neutronics



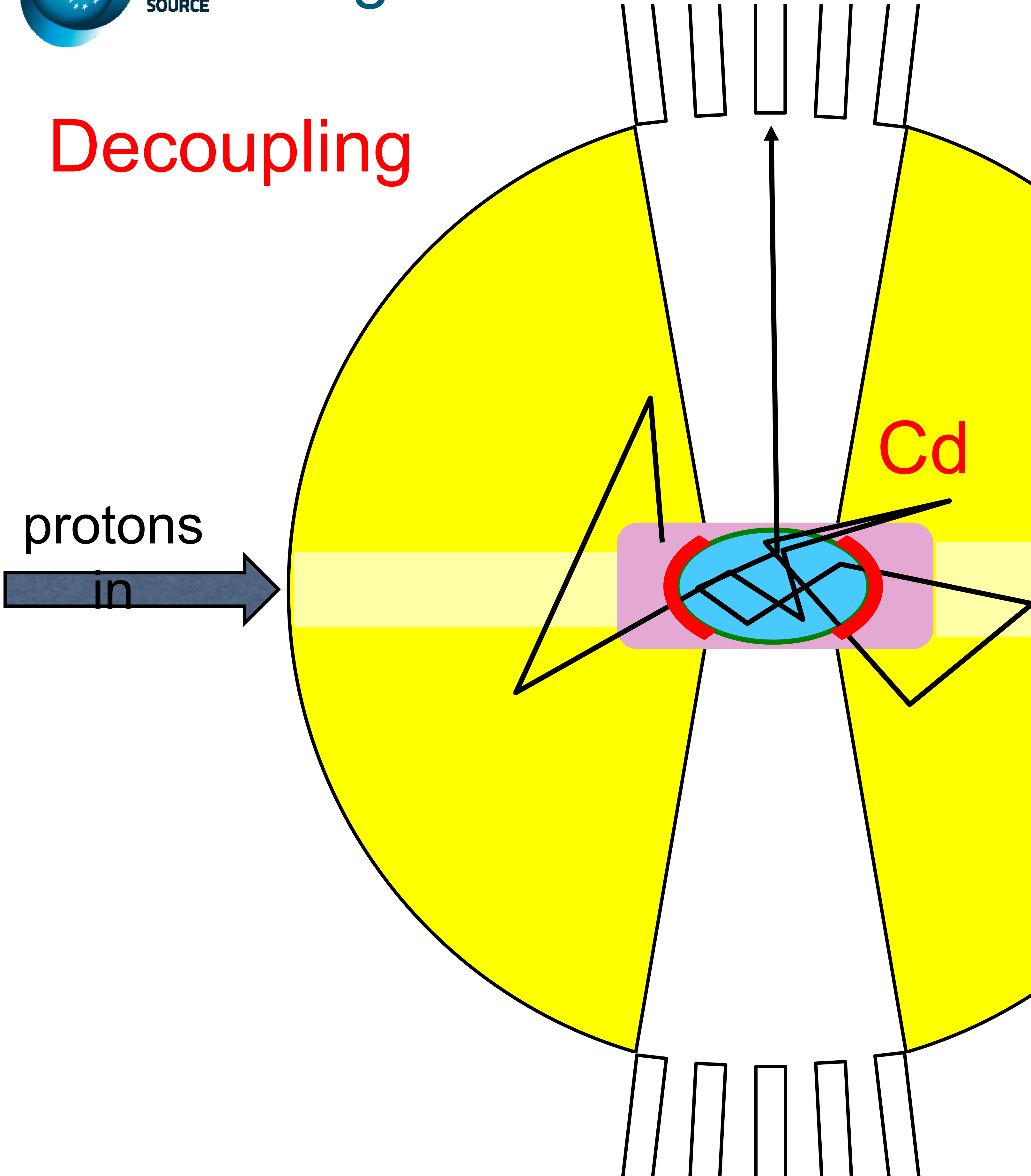
Target-Reflector-Moderator Neutronics

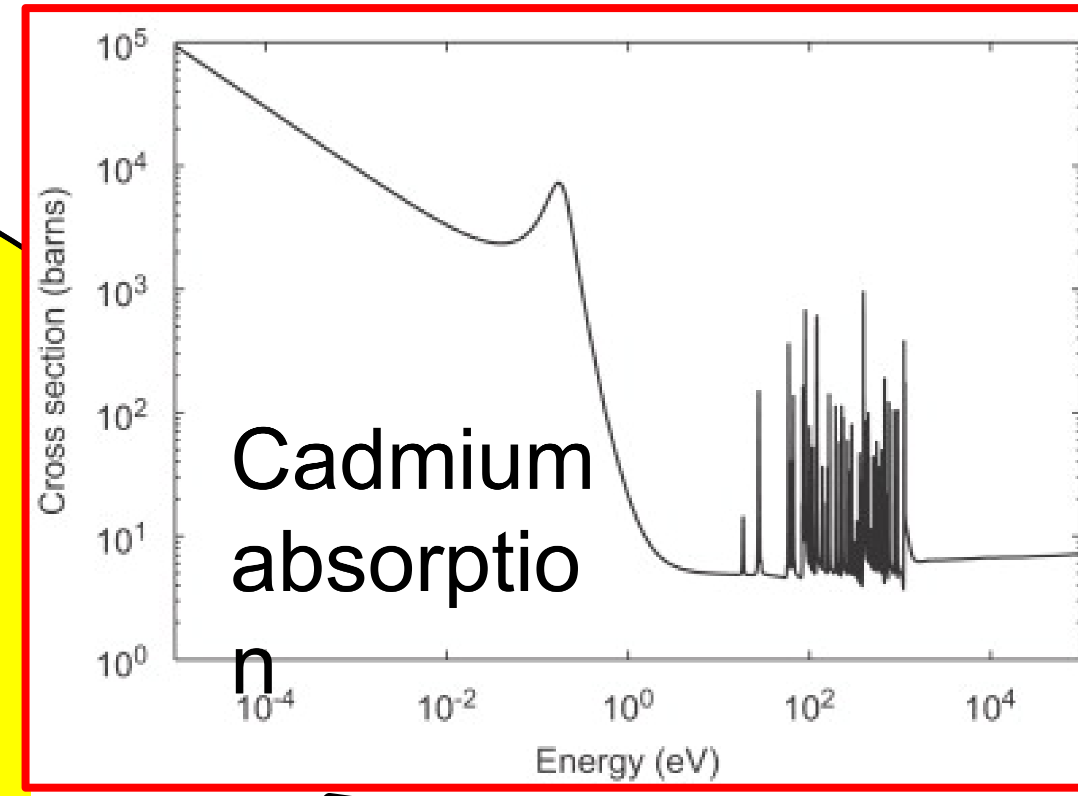


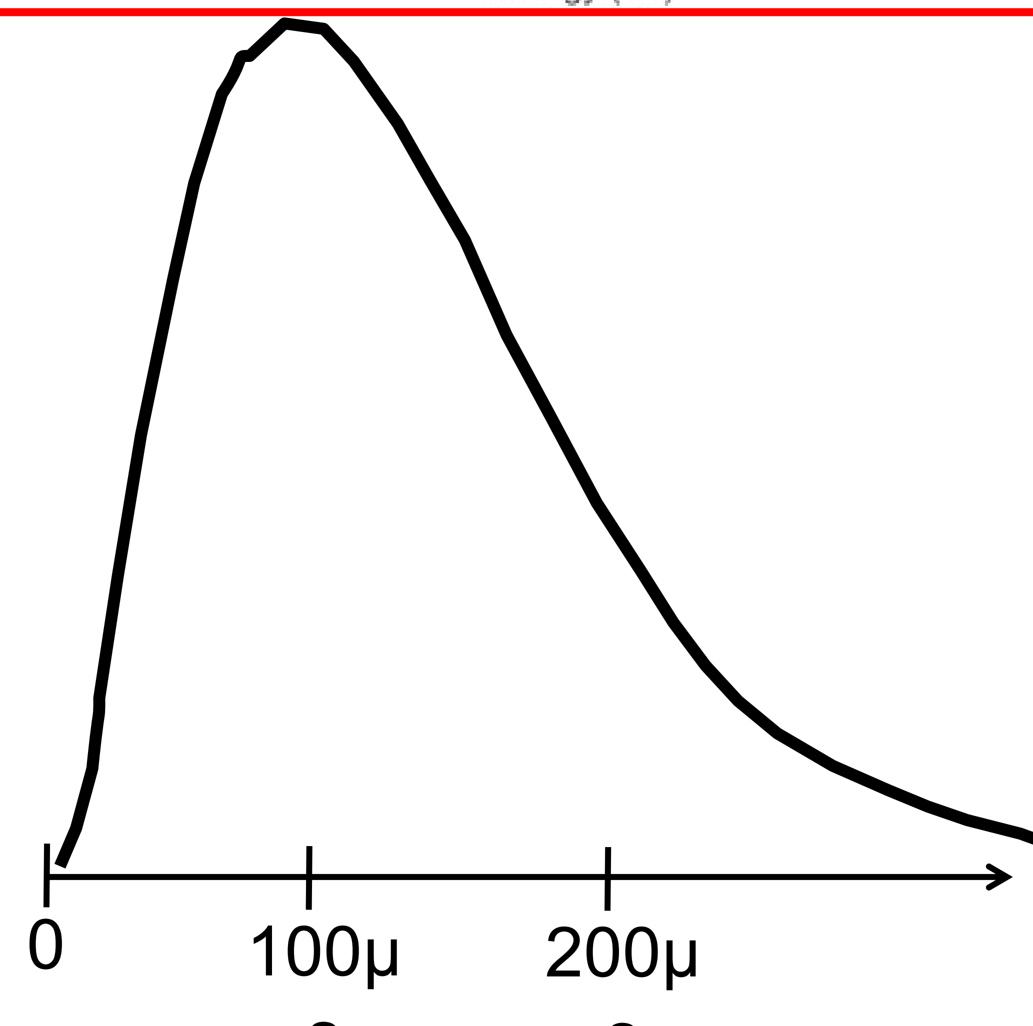
EUROPEAN SPALLATION SOURCE

Target-Reflector-Moderator Neutronics

Decoupling

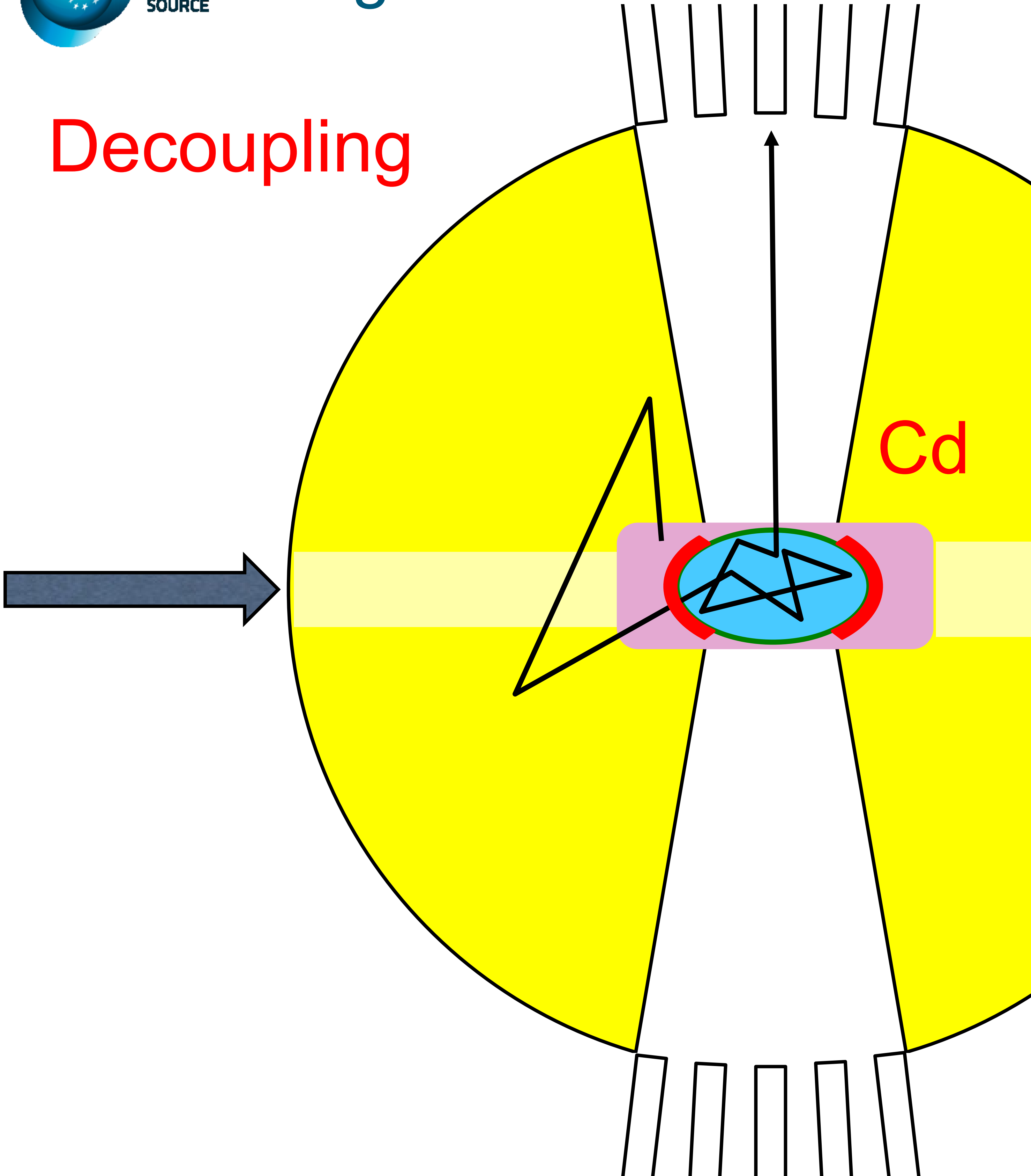


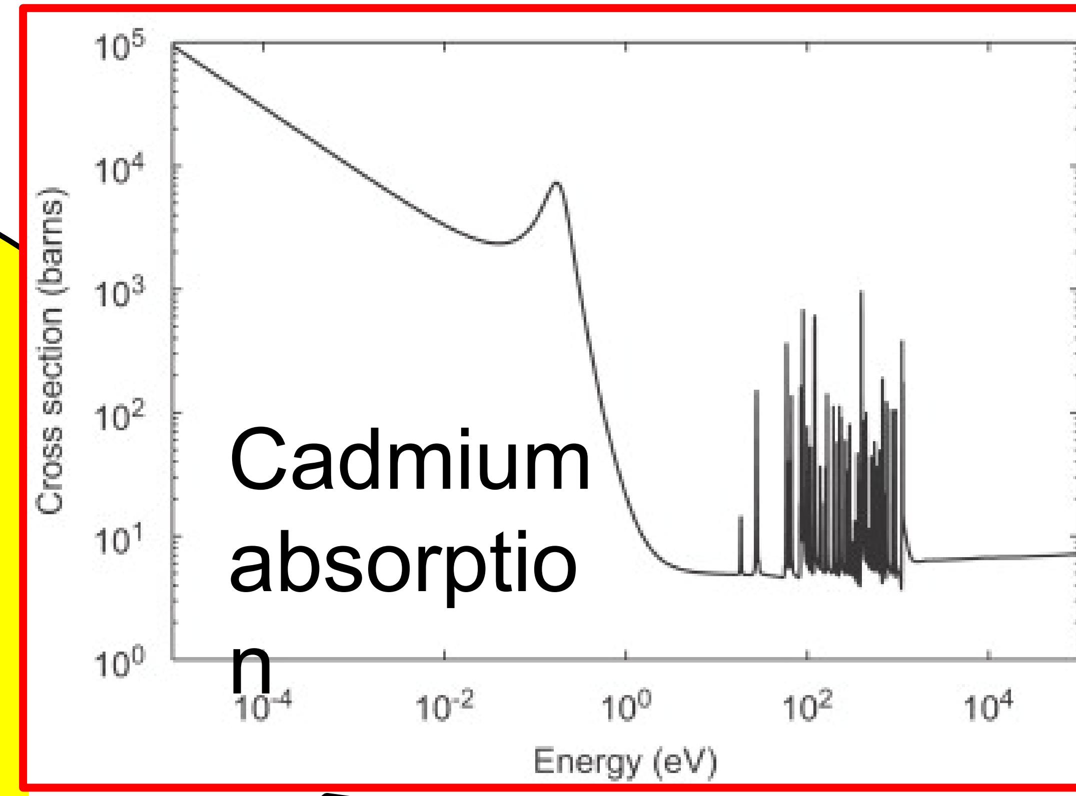


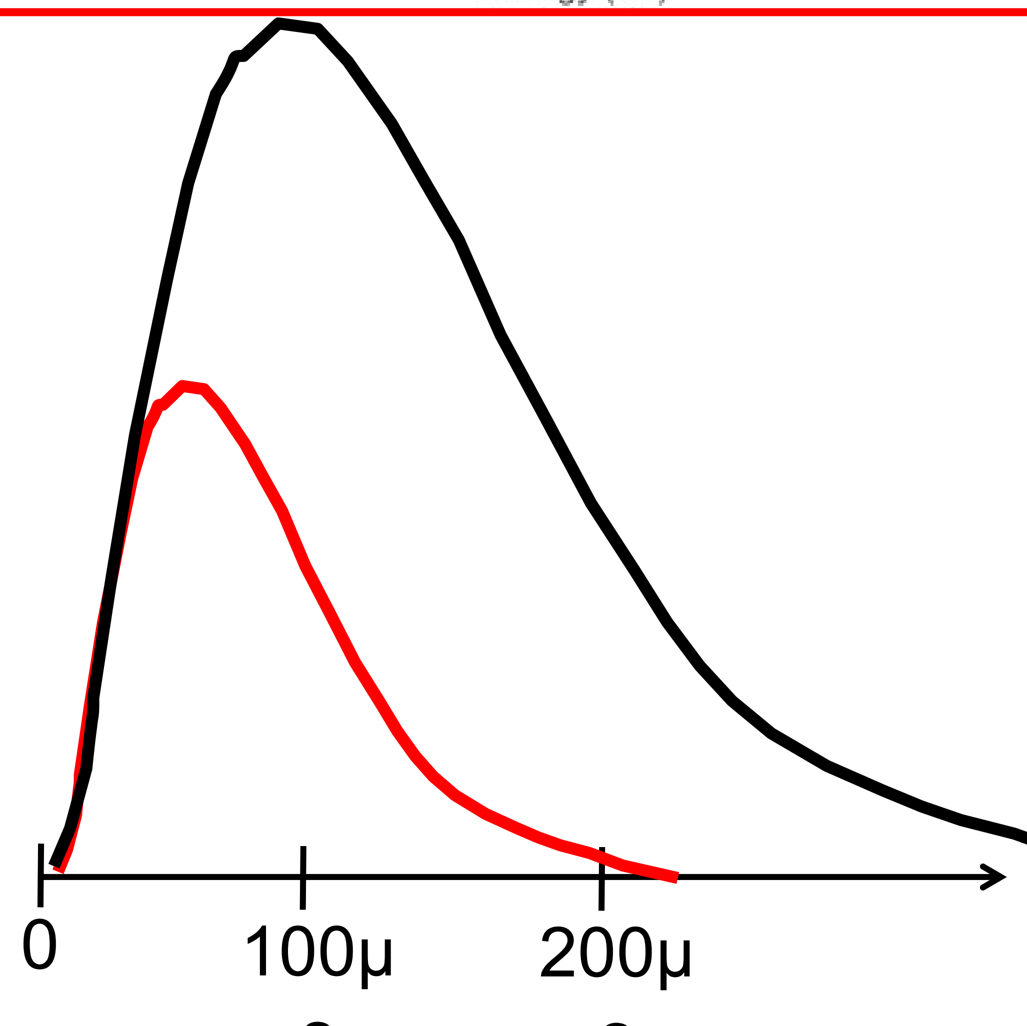


Target-Reflector-Moderator Neutronics

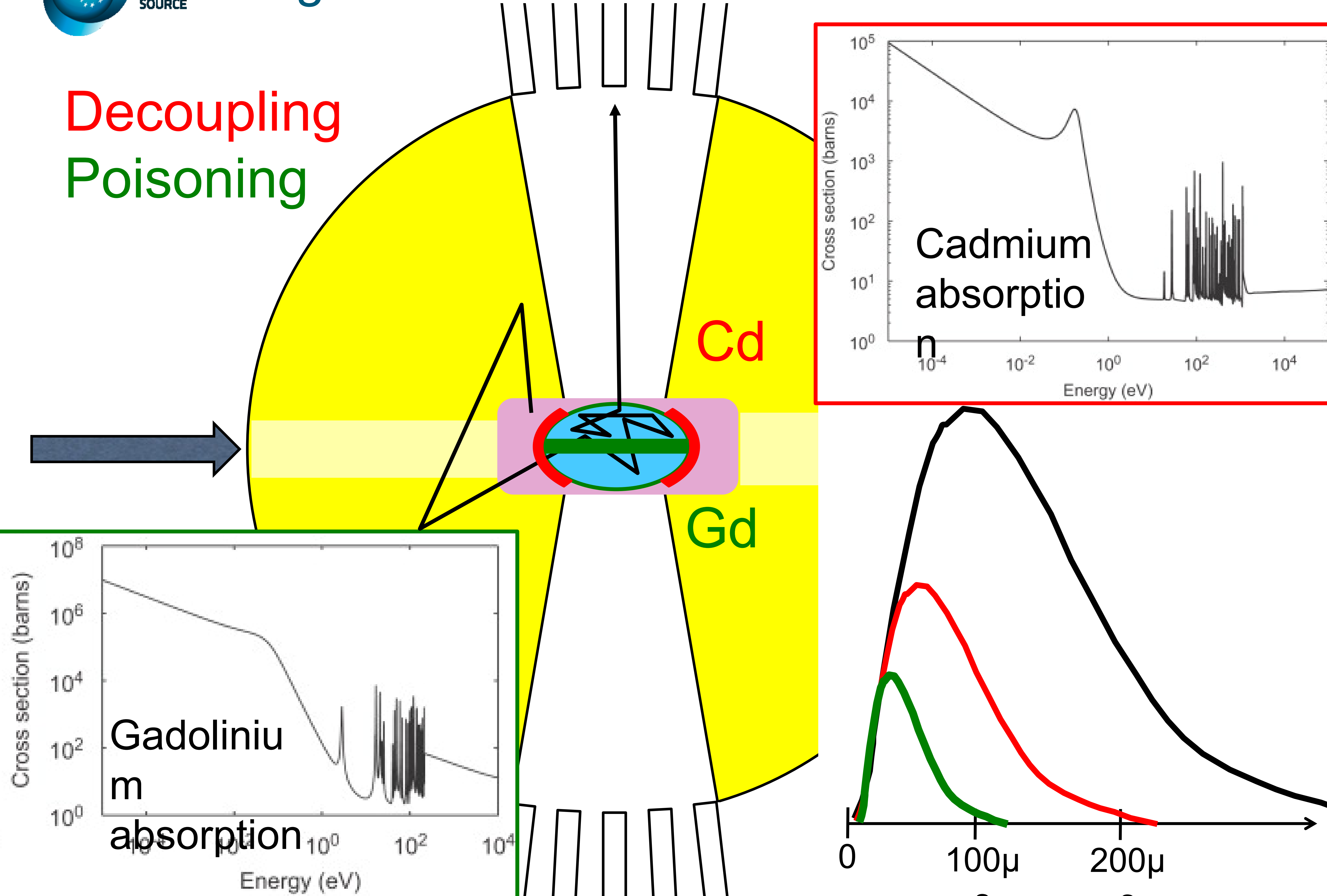
Decoupling



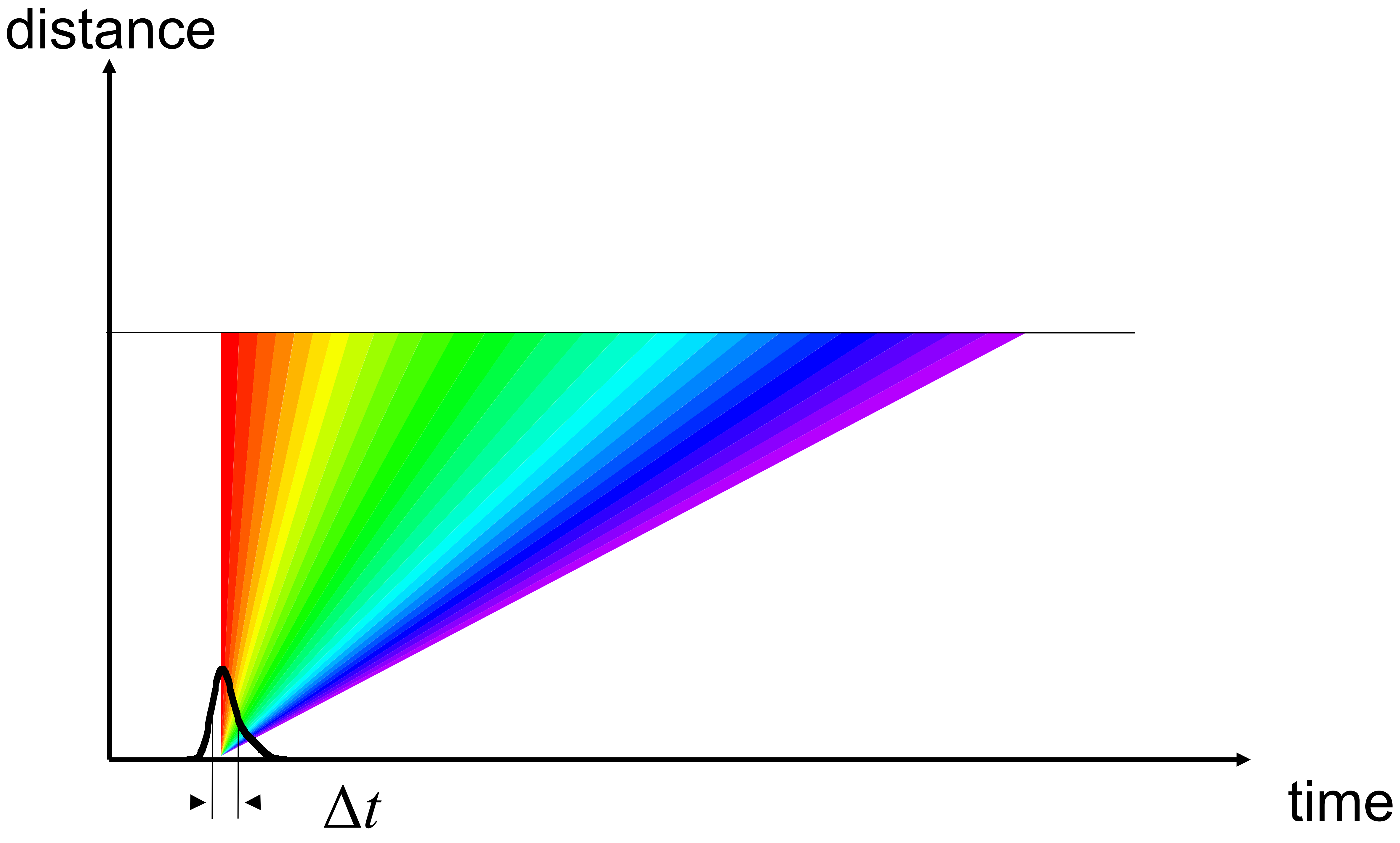




Target-Reflector-Moderator Neutronics



The time-of-flight (TOF) method

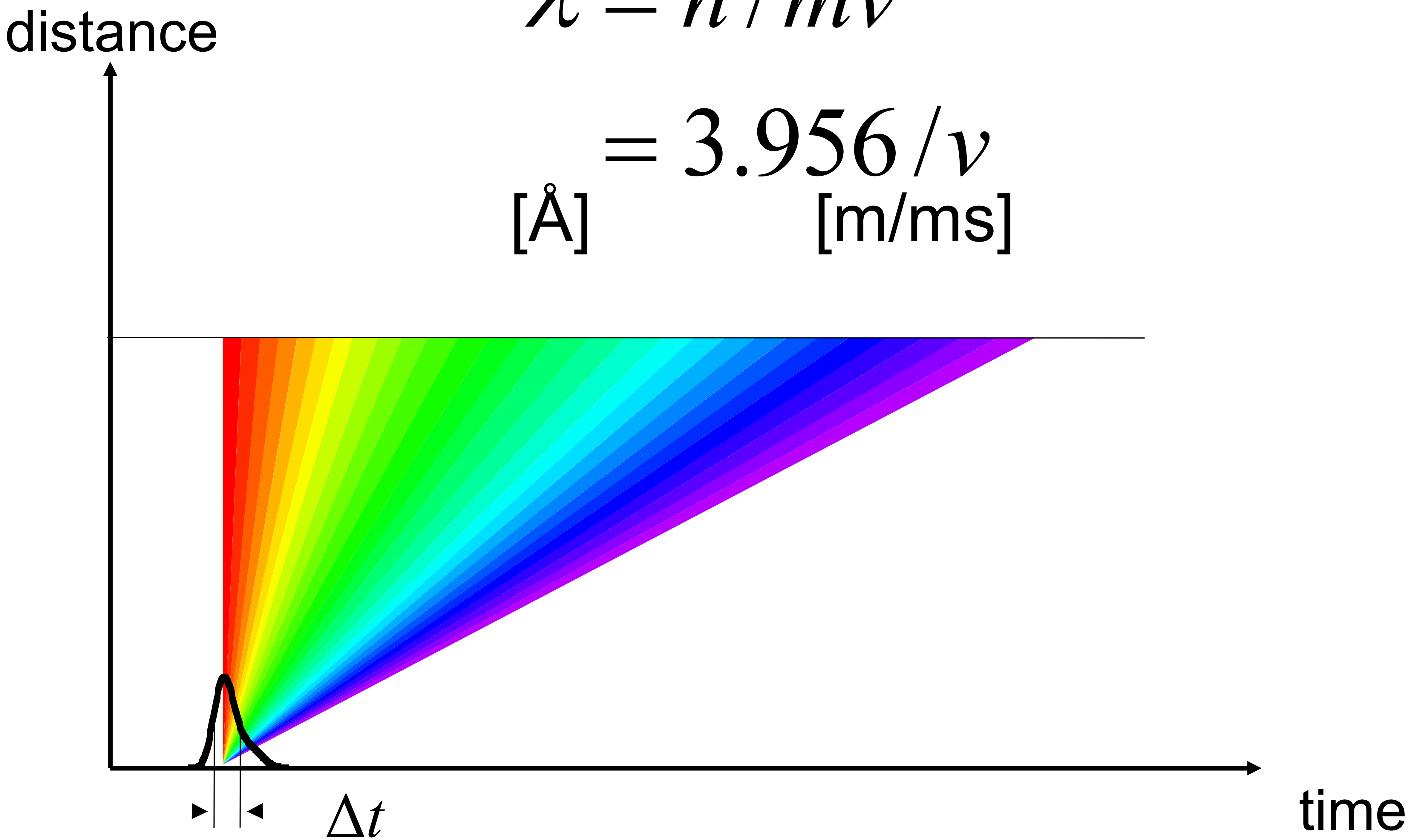


The time-of-flight (TOF) method

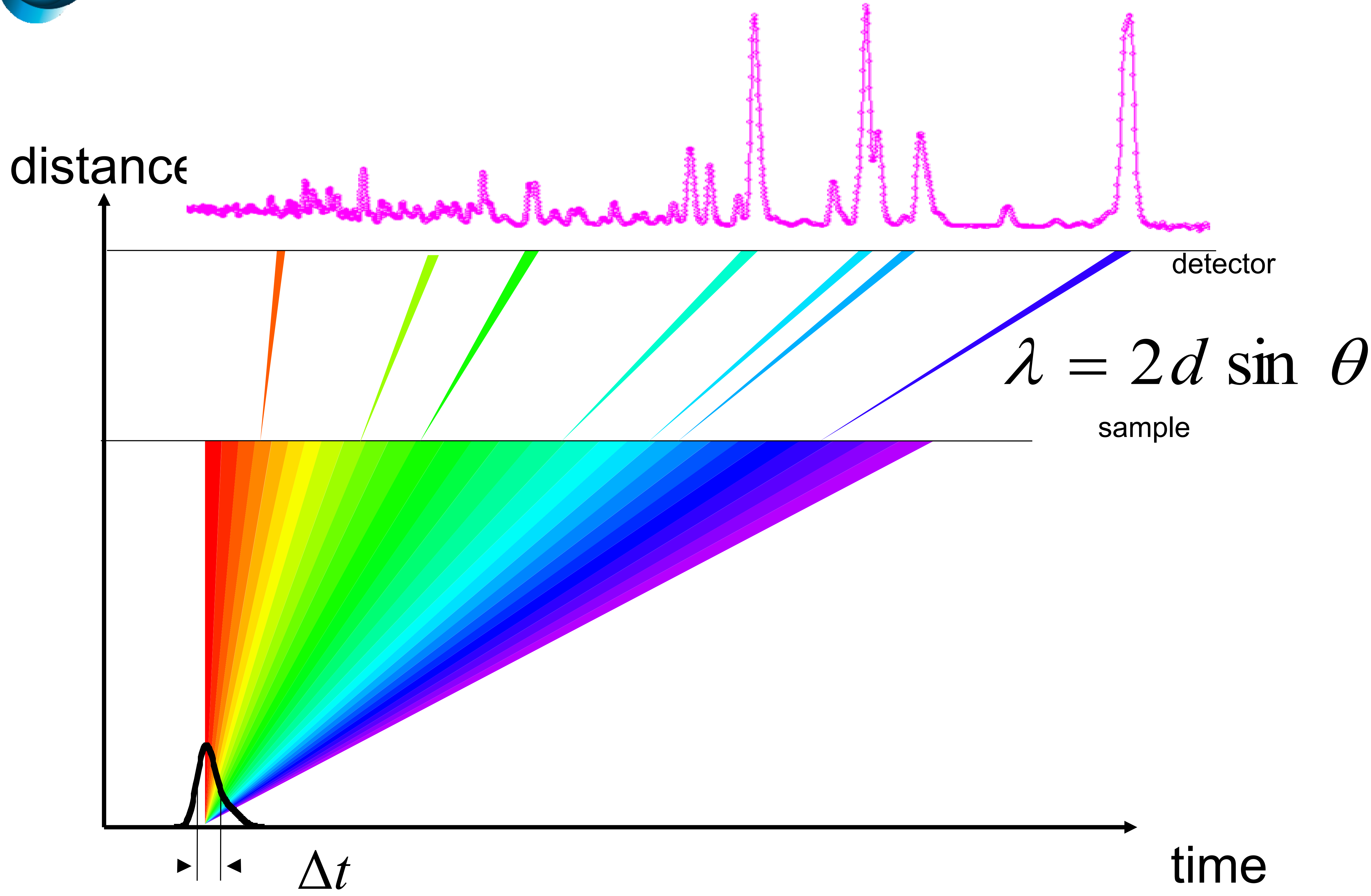
$$\lambda = h / mv$$

$$= 3.956 / v$$

[Å] [m/ms]

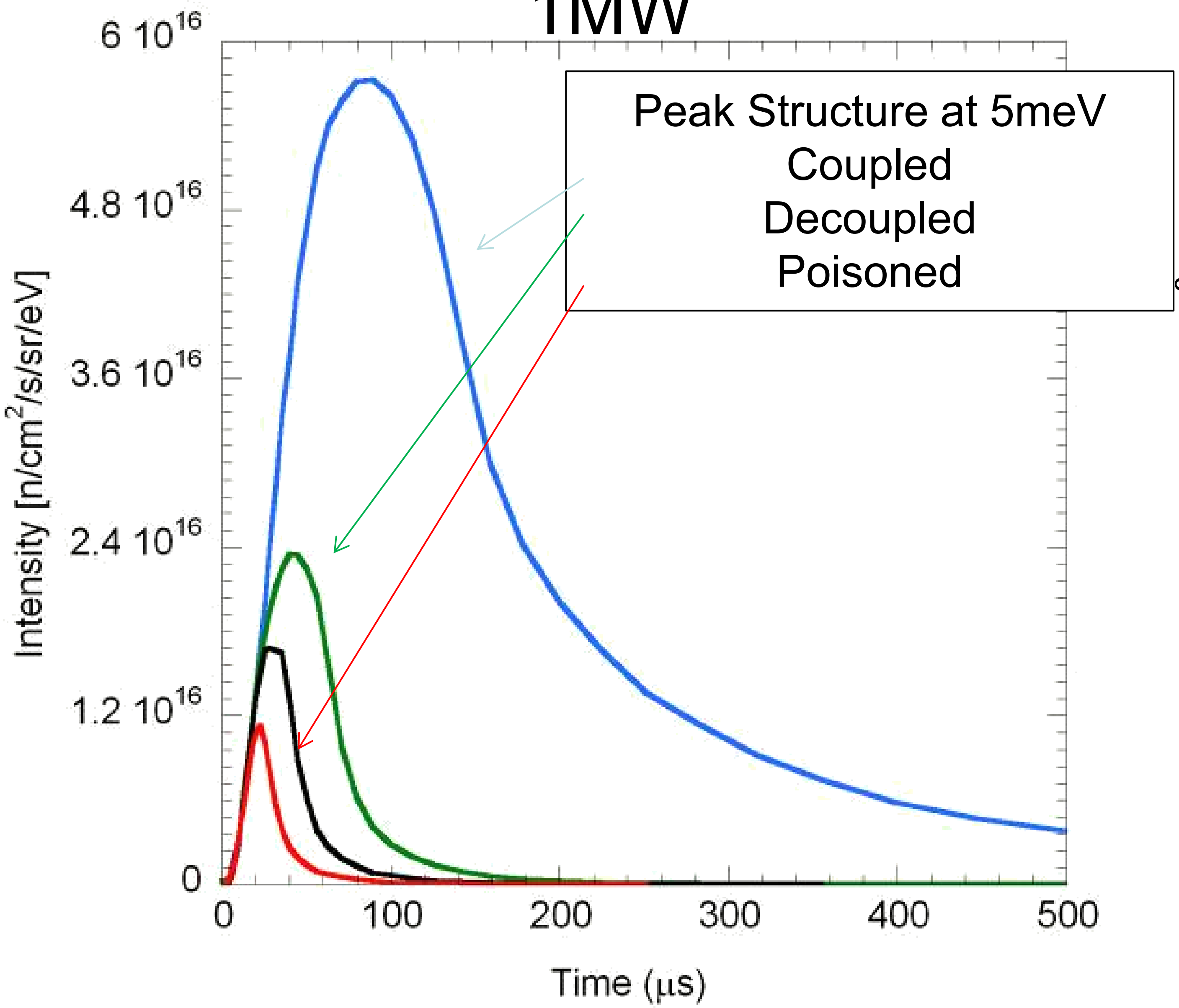


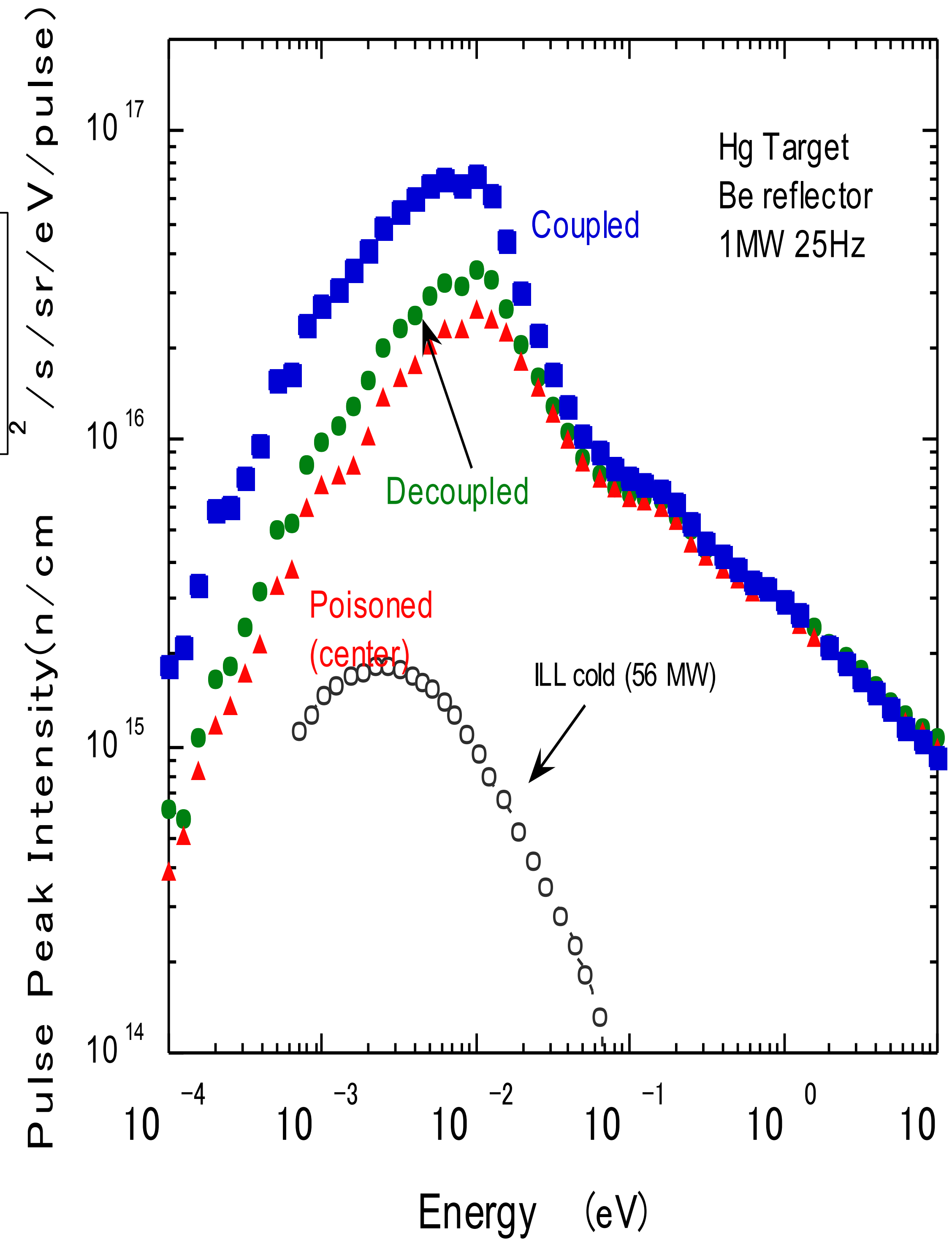
The time-of-flight (TOF) method



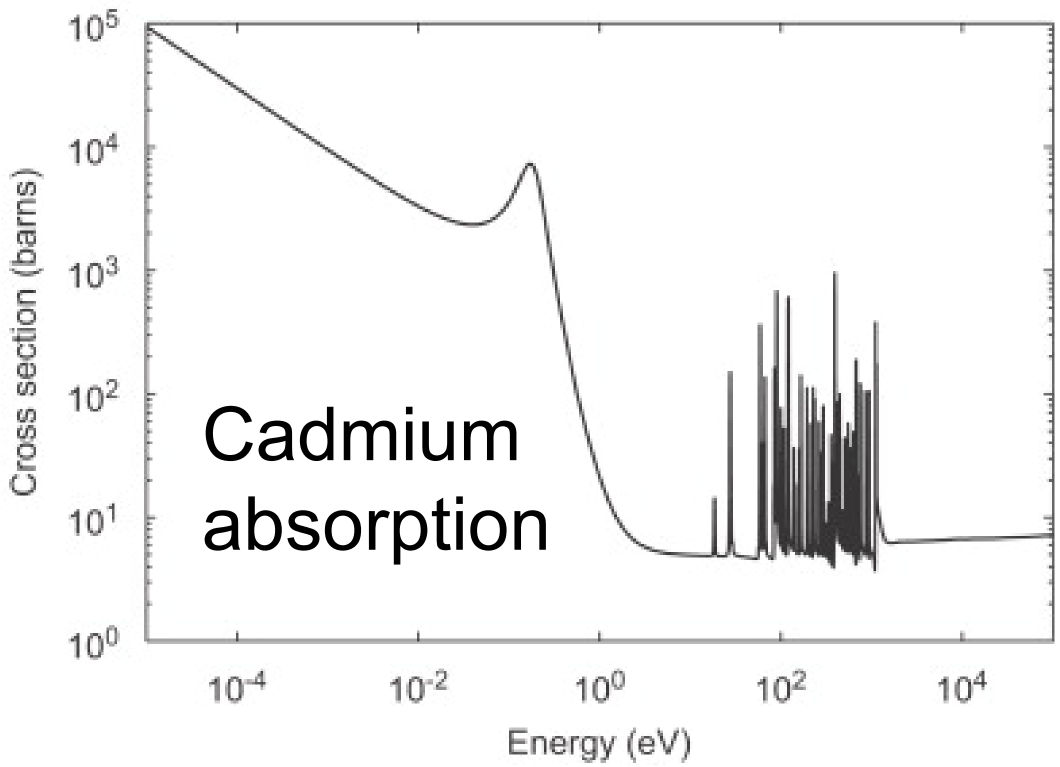
Moderator Decoupling & Poisoning

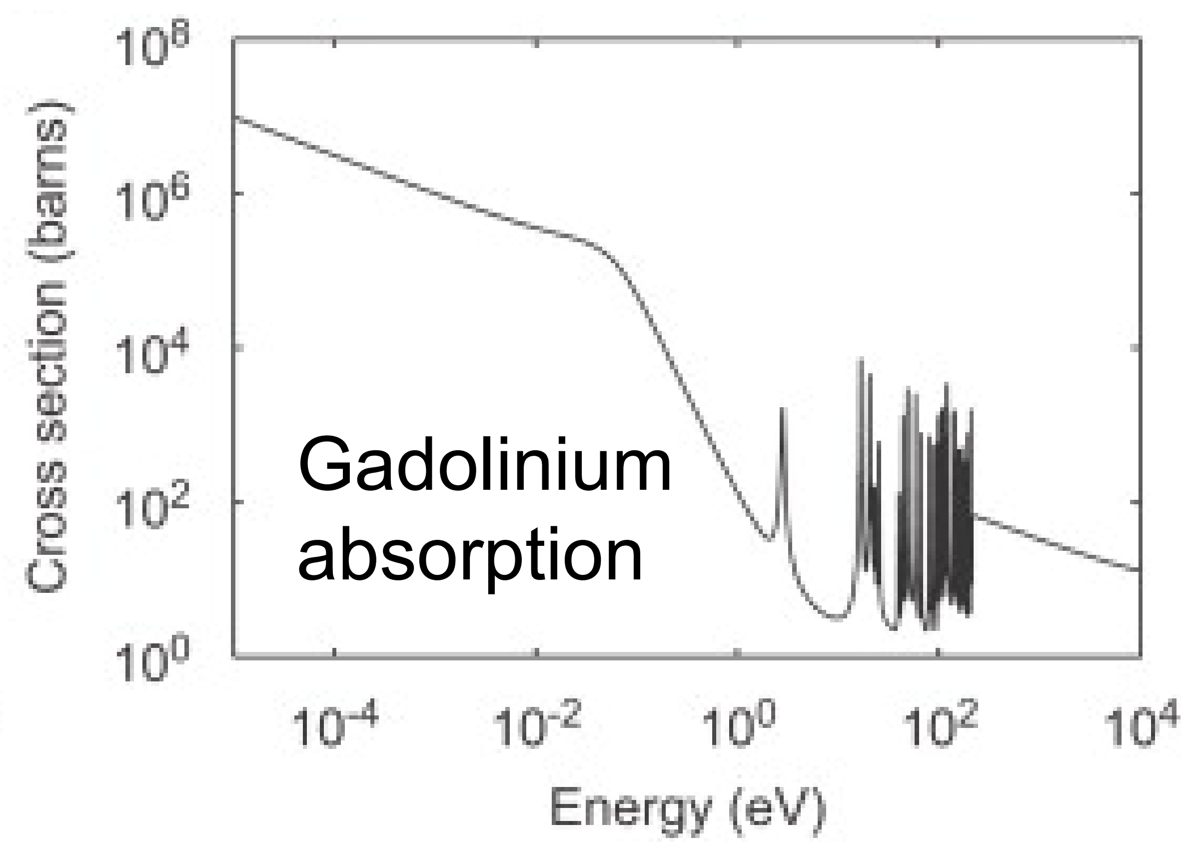
J-PARC H_2 moderators at 1MW

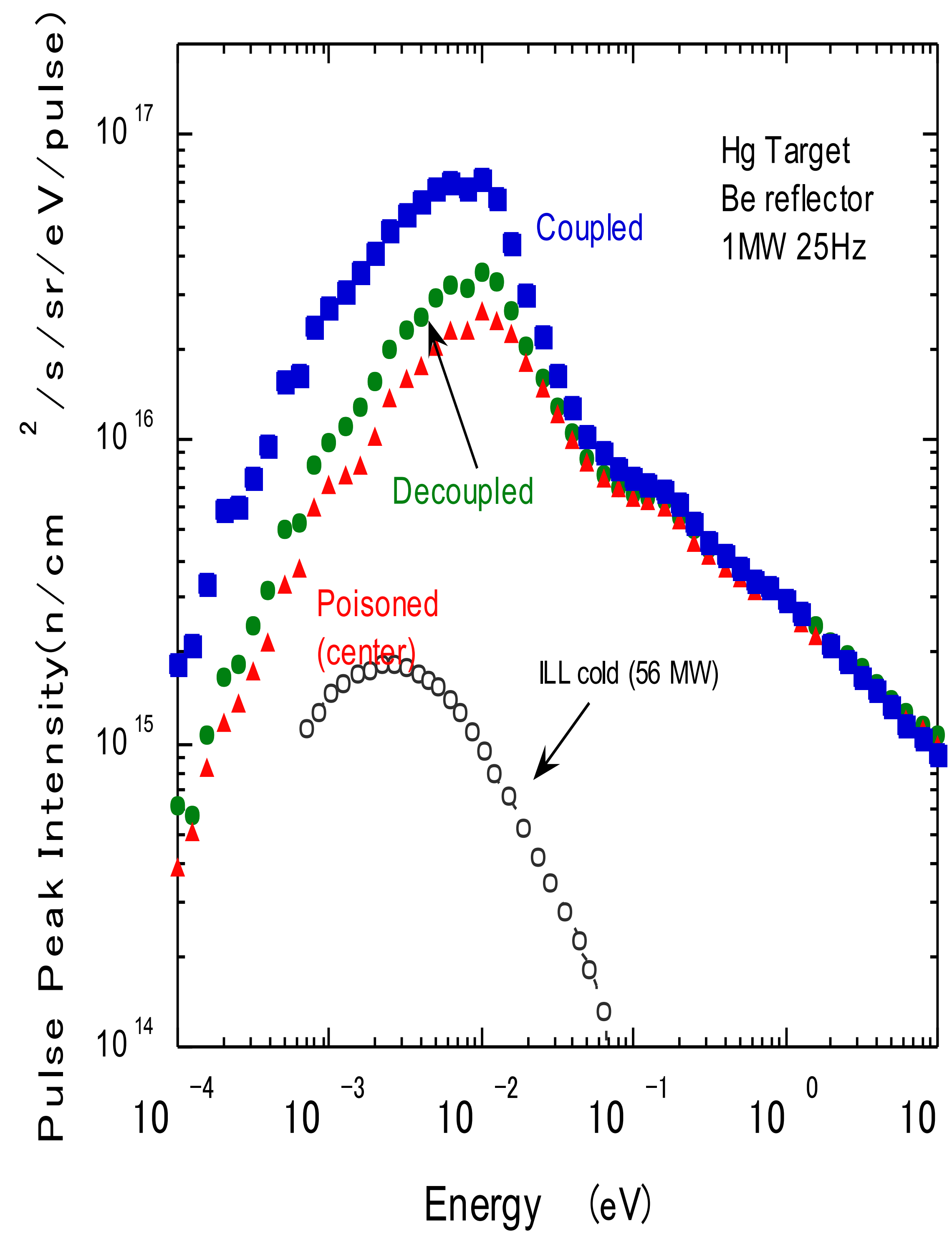




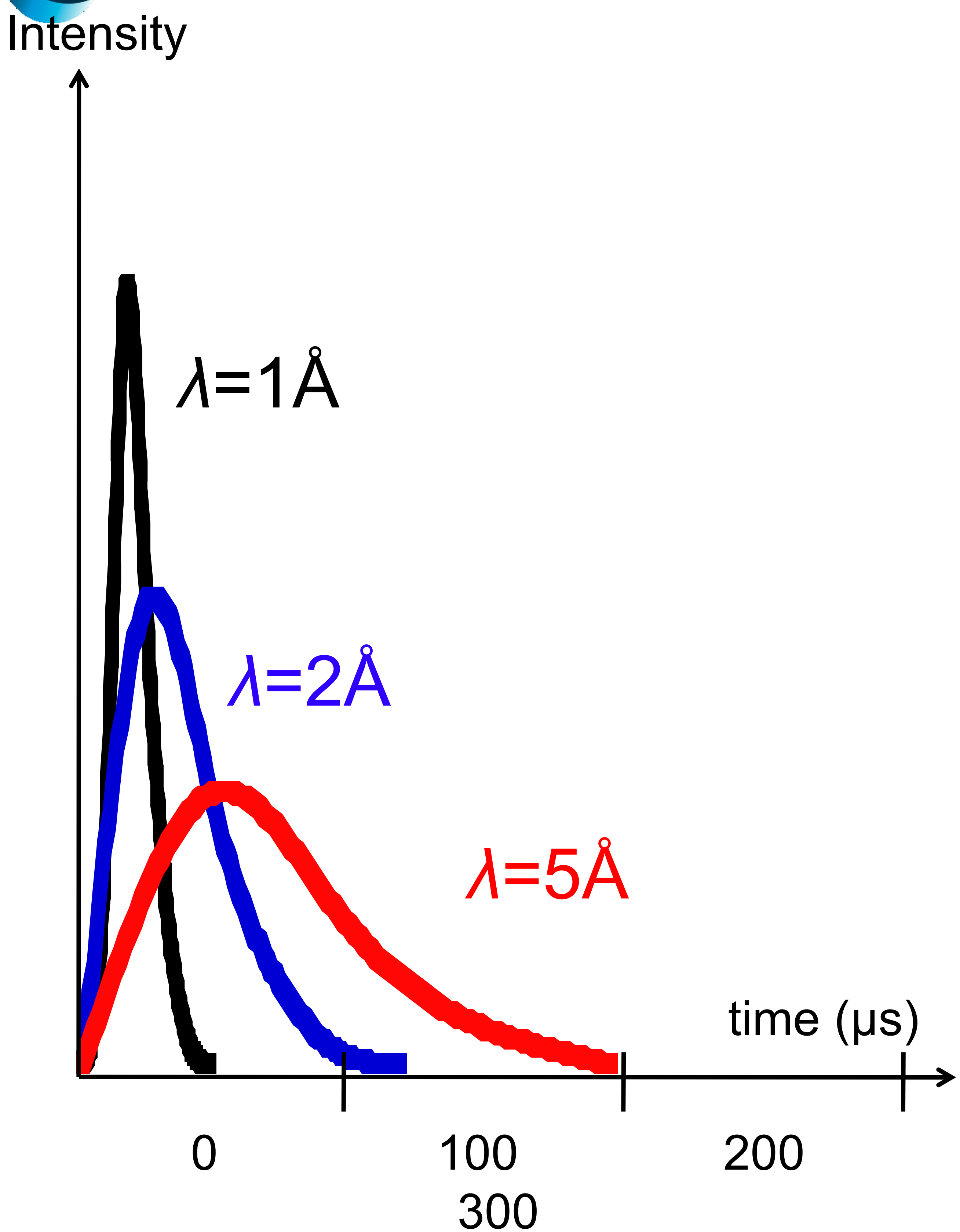
Moderator Decoupling & Poisoning

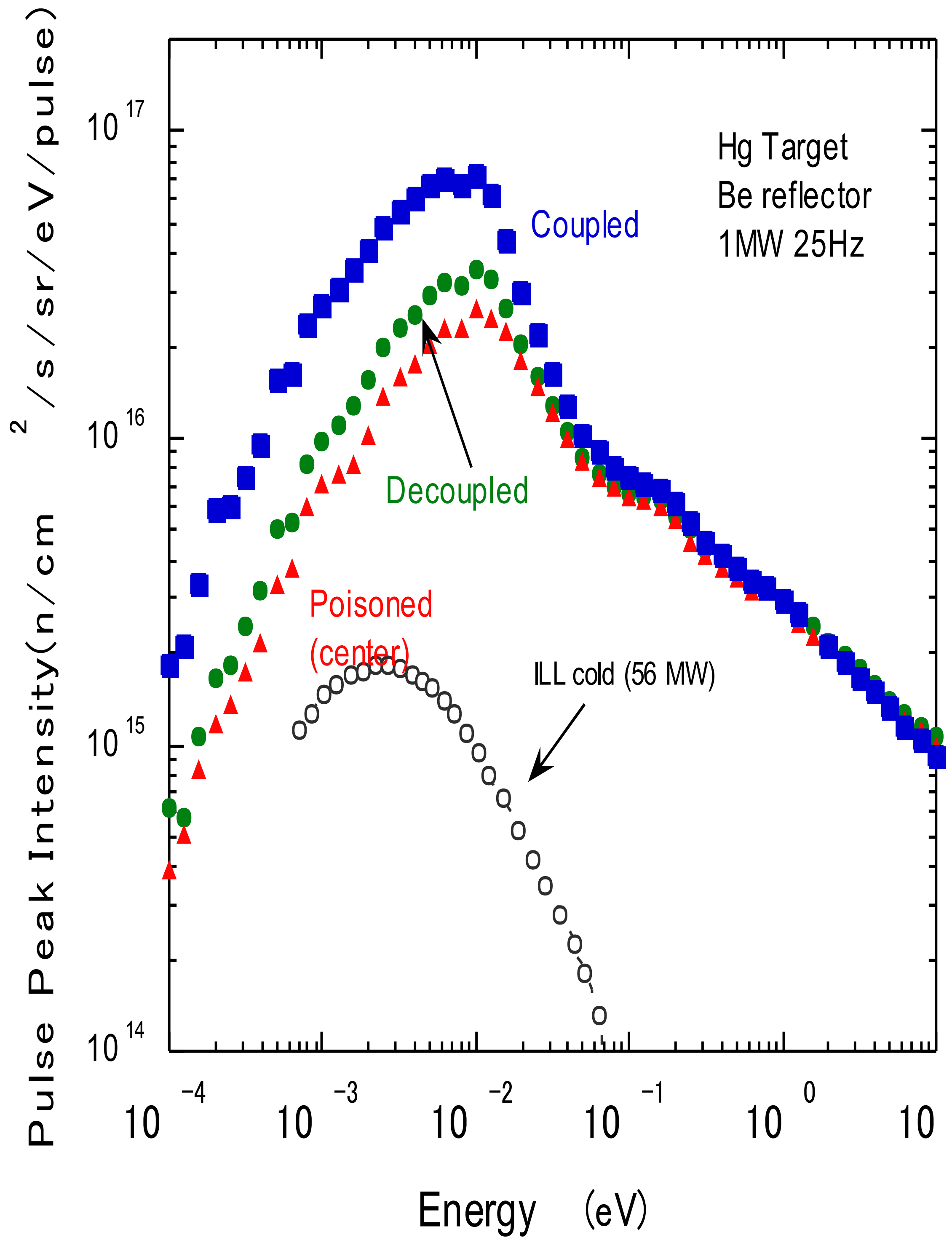




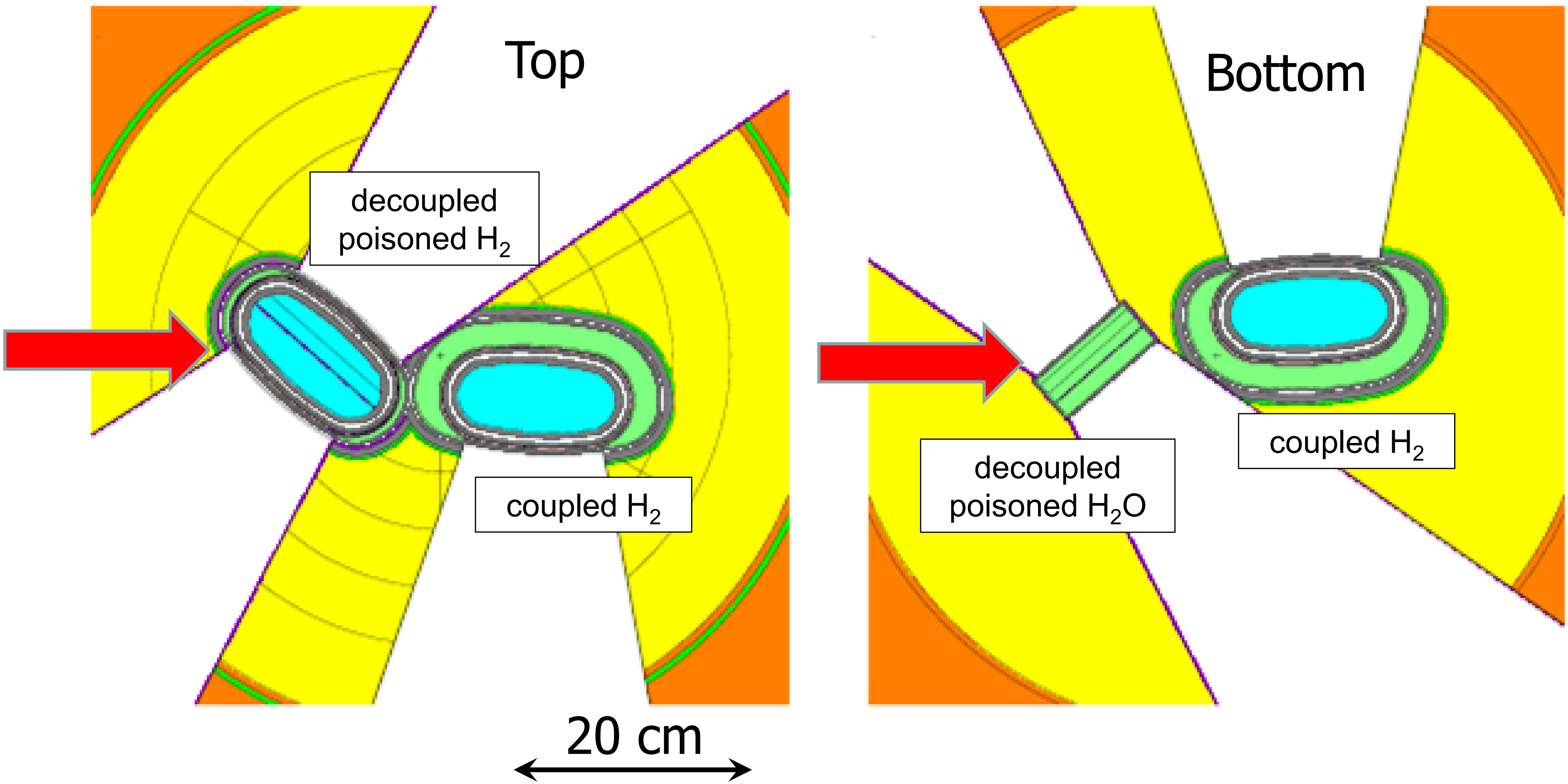


Moderator Decoupling & Poisoning

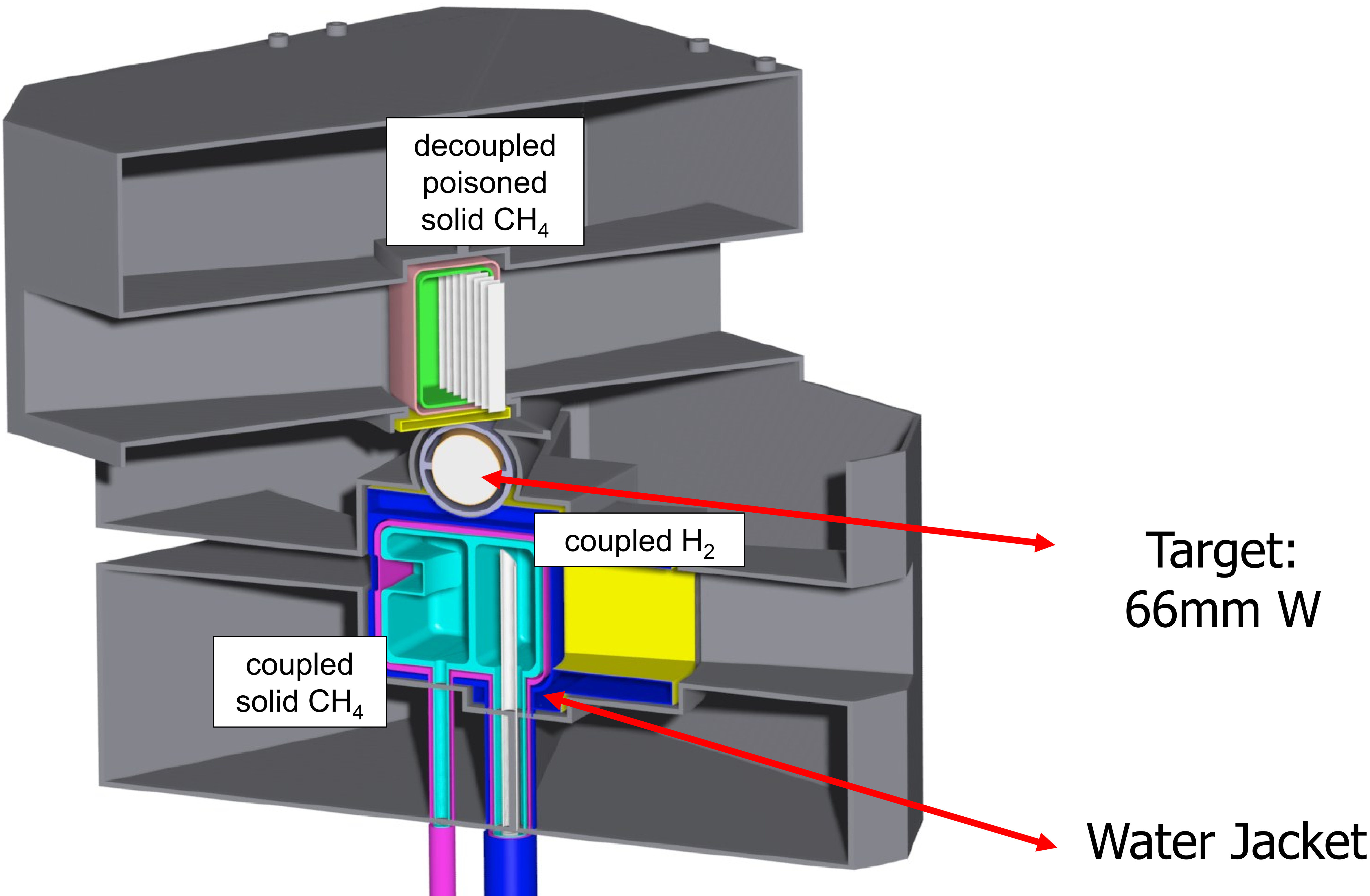




SNS moderators



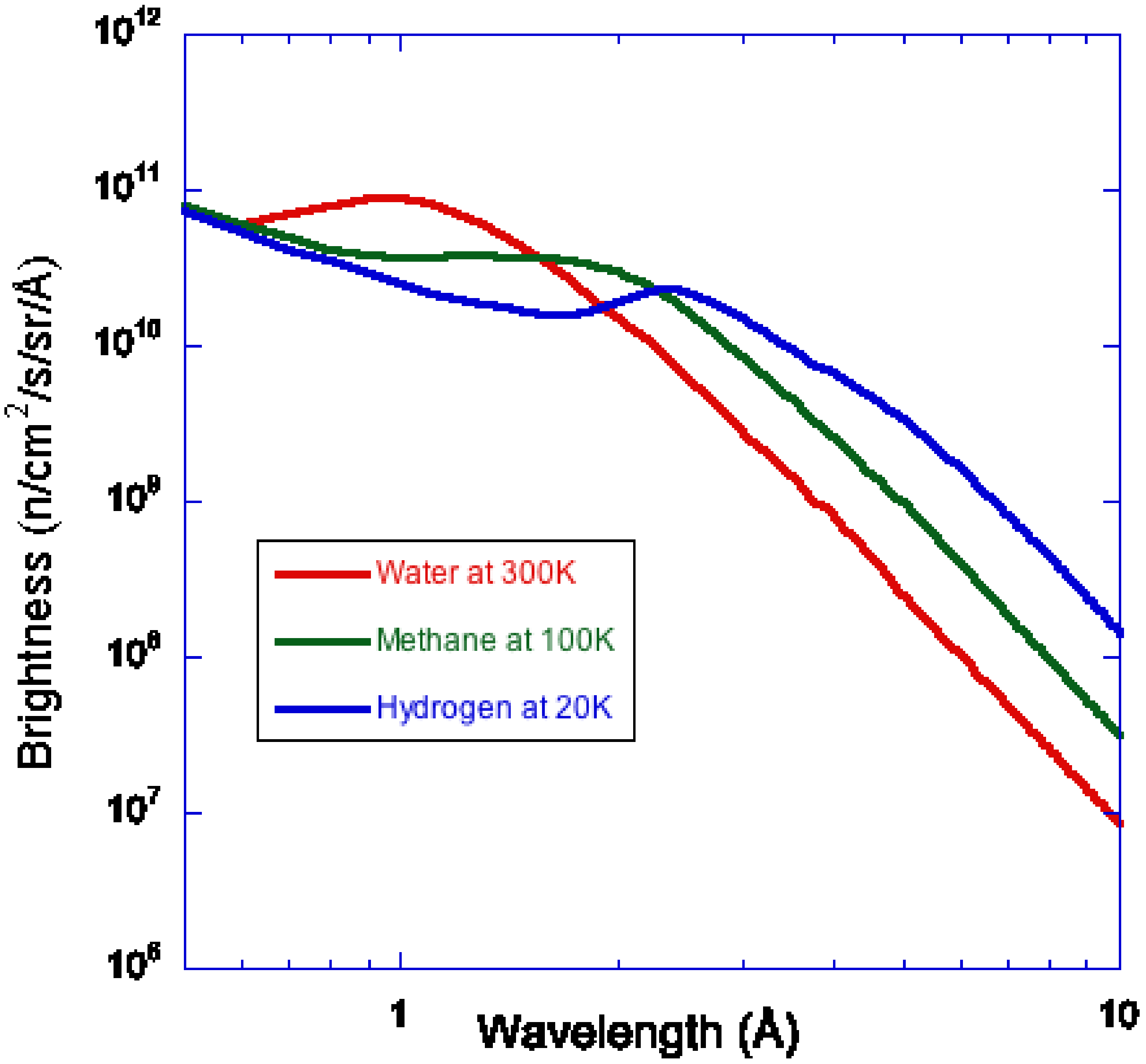
ISIS TS2



decoupled poisoned solid CH_4
coupled H_2
coupled solid CH_4
Target: 66mm W
Water Jacket

Moderator Temperature

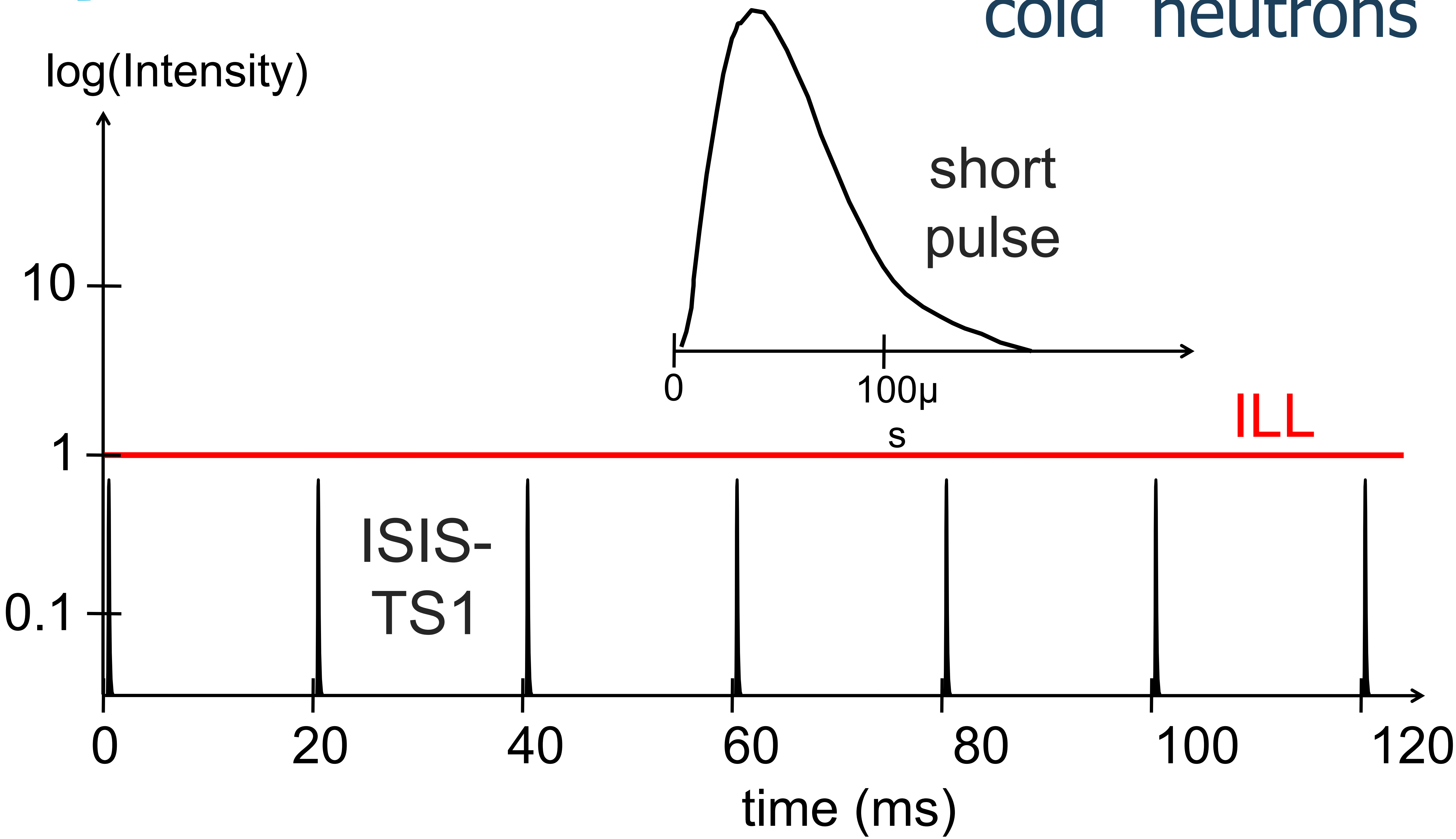
ISIS-TS1 moderators at 160kW



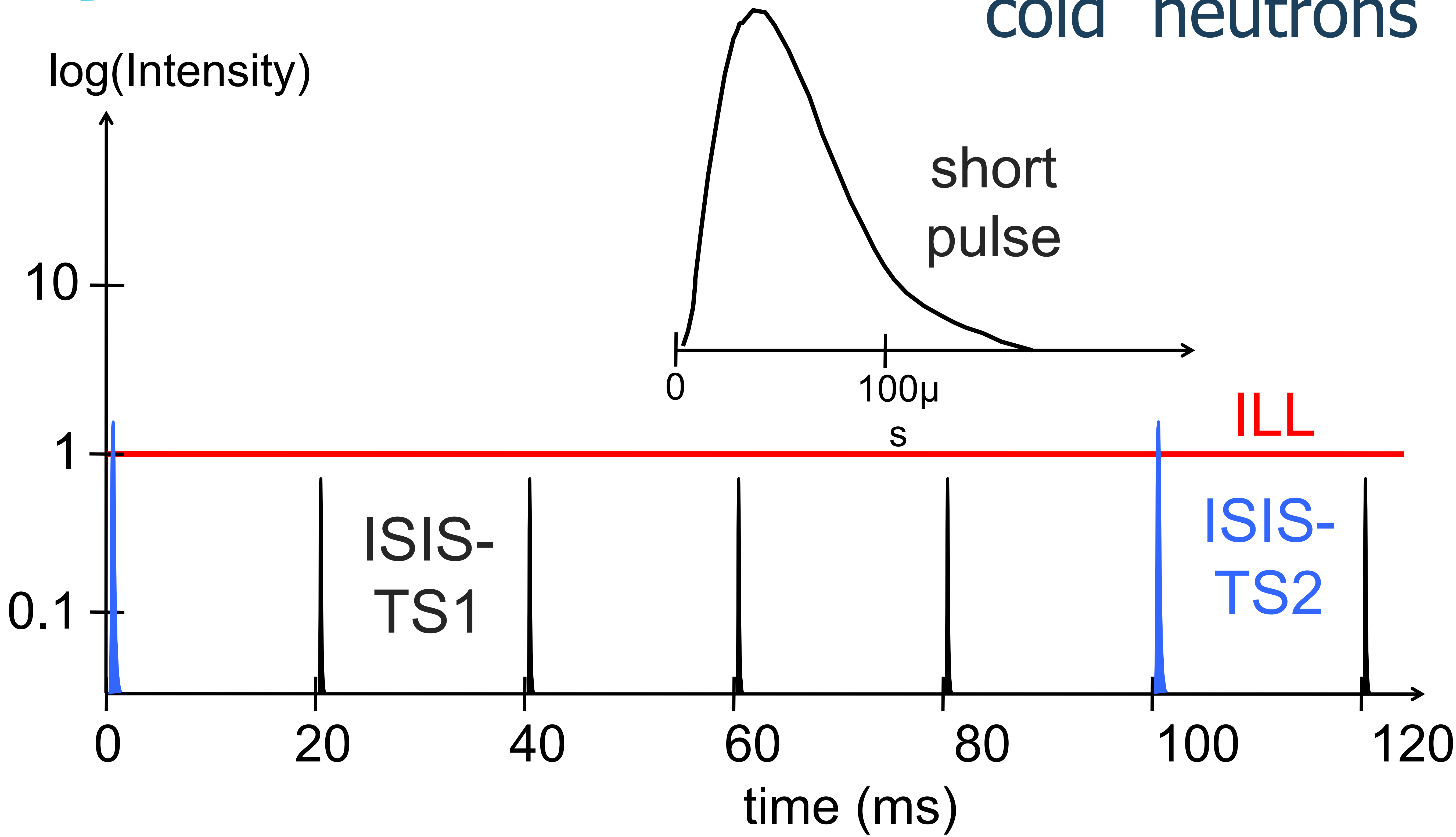
Comparison between pulsed sources

Facility	Power	Rep.Rate	Start	Instr.	Thml AvB @1.5Å	Thml PkB @1.5Å	Cold AvB @3Å	Cold PkB @3Å
ILL	57/57 MW	-	1971	38	$2.6x10^{13}$	$2.6x10^{13}$	$7x10^{12}$	$7x10^{12}$
ISIS-TS1	128/192 kW	50 Hz	1984	18	$4x10^{10}$	$5x10^{13}$	$1.5x10^{10}$	$7x10^{12}$
ISIS-TS2	32/48 kW	10 Hz	2009	11	$1.1x10^{10}$	$4x10^{13}$	$2.7x10^{10}$	$1.8x10^{13}$
SNS	0.9/1.4 MW	60 Hz	2006	20	$2.7x10^{11}$	$1.5x10^{14}$	$5x10^{11}$	$5x10^{13}$
J-PARC	0.3/1.0 MW	25 Hz	2009	21	$1.4x10^{11}$	$2x10^{14}$	$5x10^{11}$	$1.3x10^{14}$
ESS	-/5 MW	14 Hz	2019	22	$1.1x10^{13}$	$2.8x10^{14}$	$9x10^{12}$	$2x10^{14}$

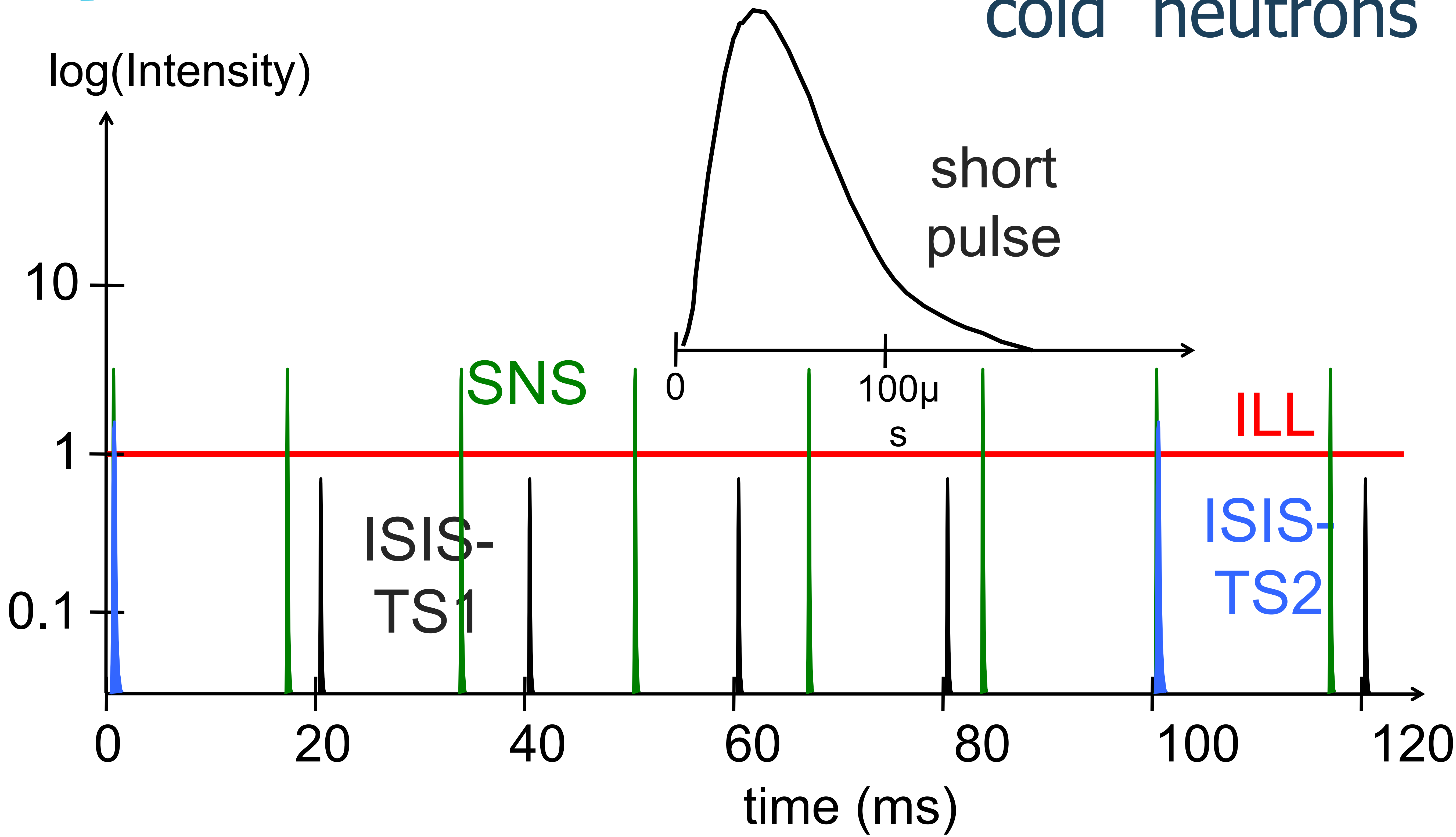
Pulsed-source time structures cold neutrons



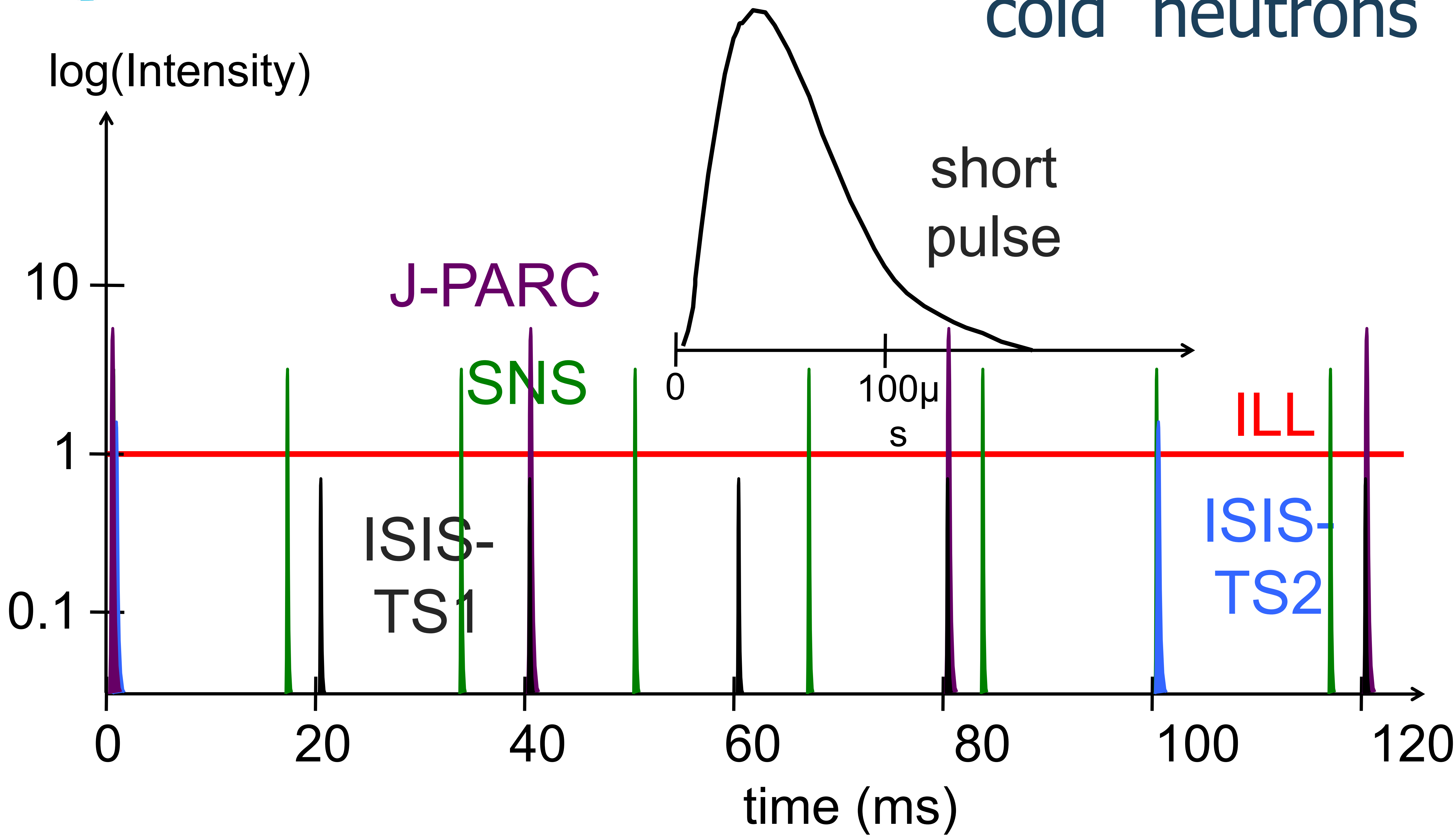
Pulsed-source time structures cold neutrons



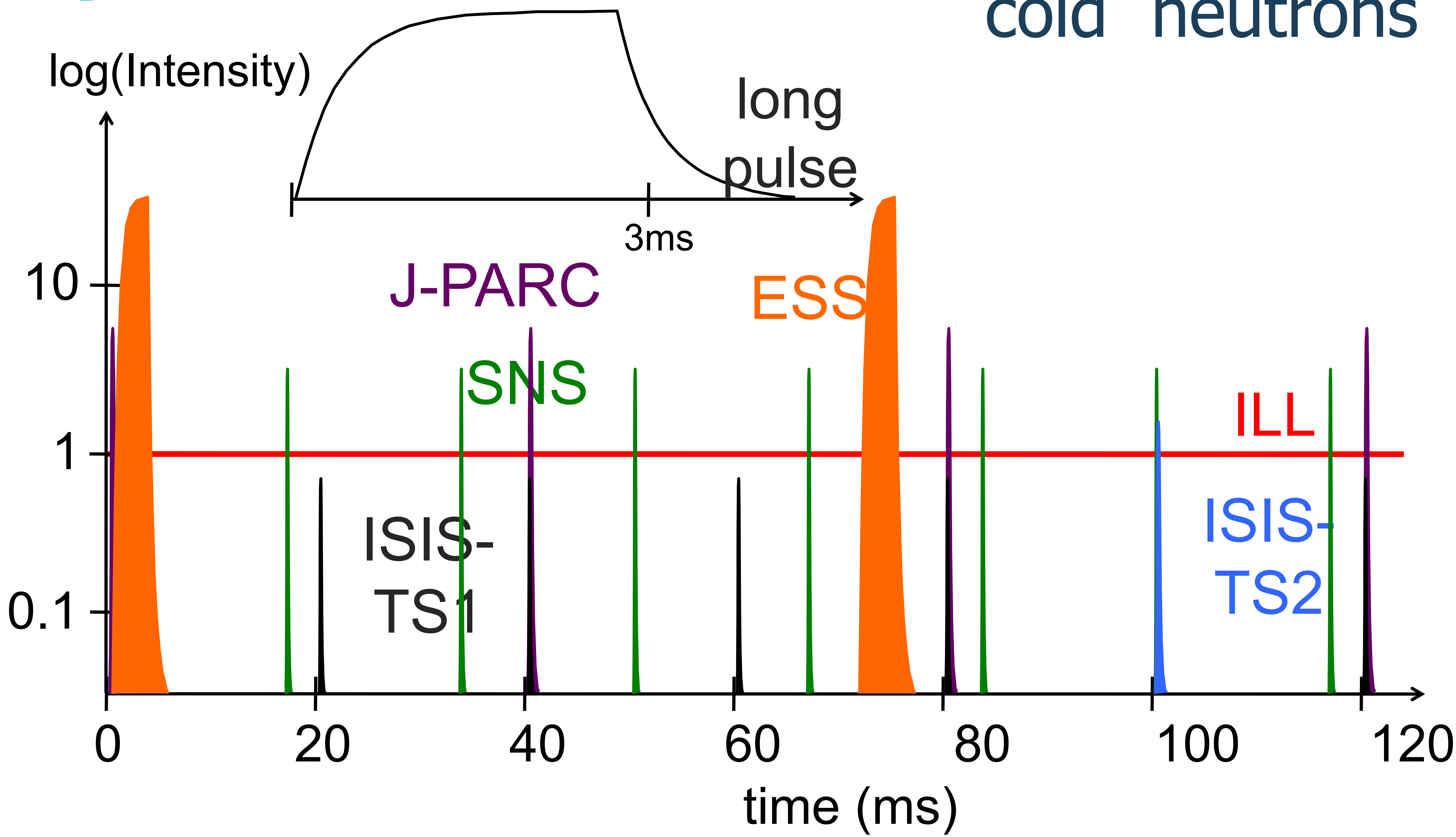
Pulsed-source time structures cold neutrons



Pulsed-source time structures cold neutrons



Pulsed-source time structures cold neutrons



Beyond short-pulse limits

SNS instantaneous power on target:
17kJ in 1µs: 17 x

Reaches limits of spallation source technology:

shock waves in target, space charge

Beyond short-pulse limits

SNS instantaneous power on target:

17kJ in 1μs: 17

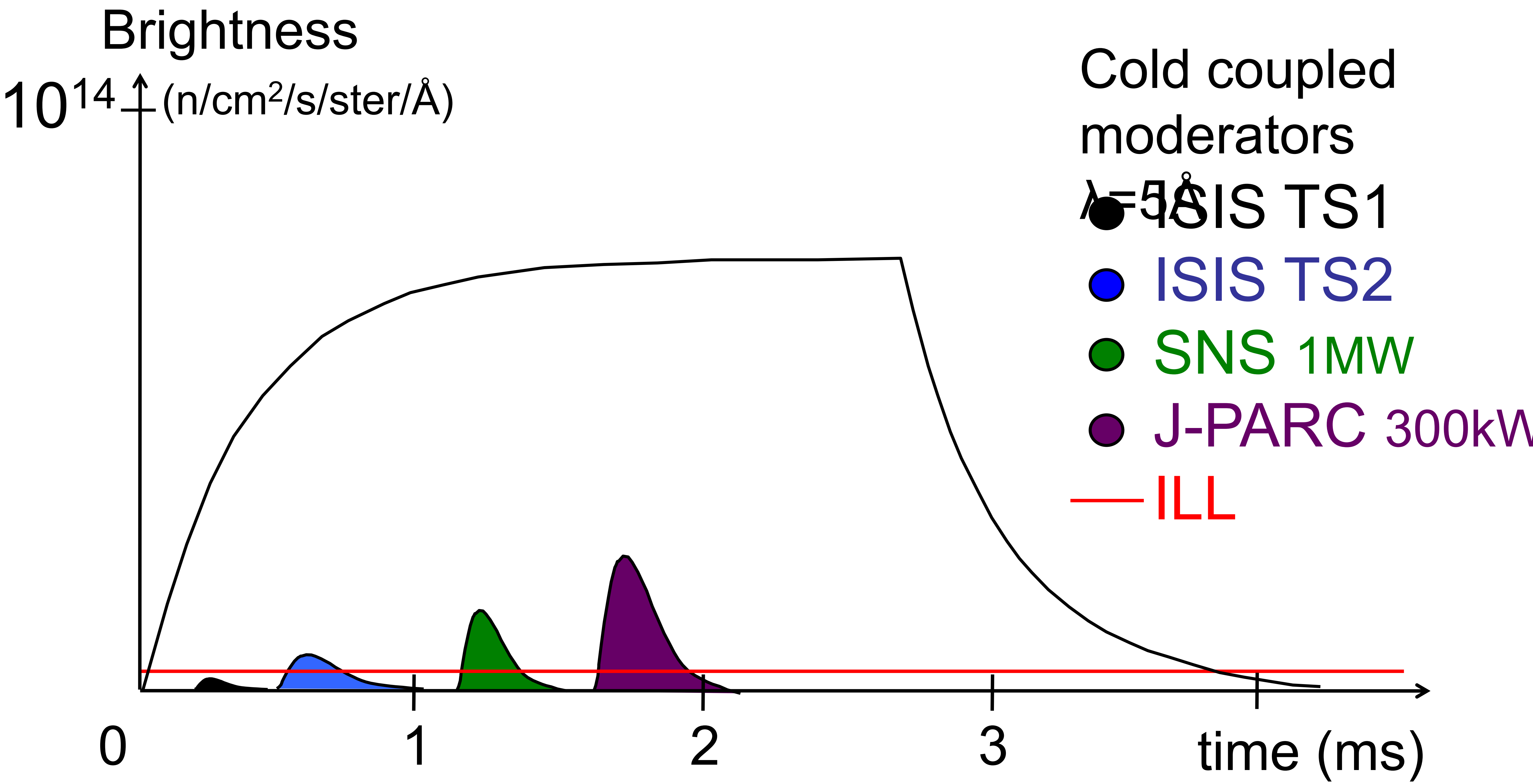
x

ESS instantaneous power on target:

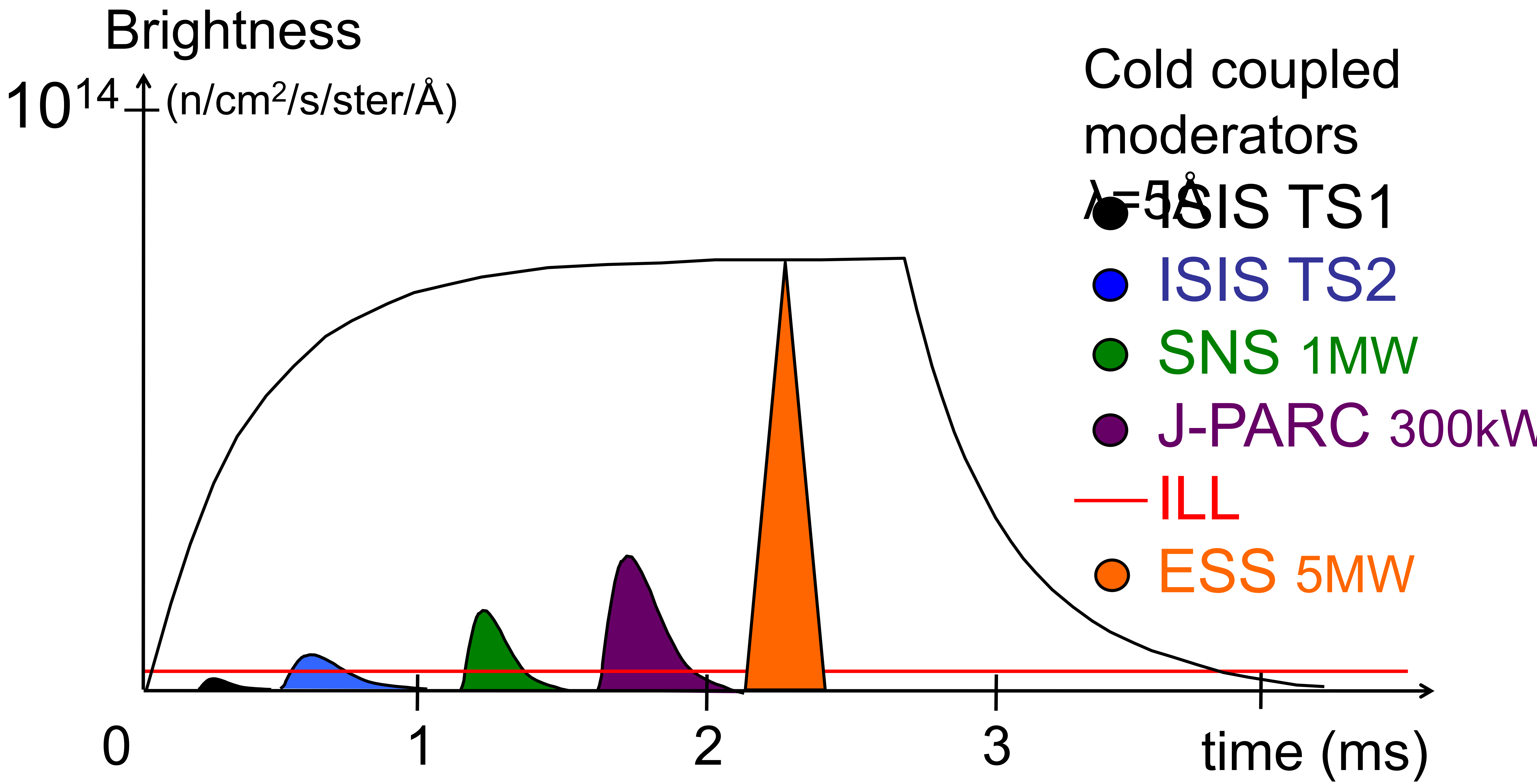
125MW

360kJ in 2.86ms

Long-Pulse Principle

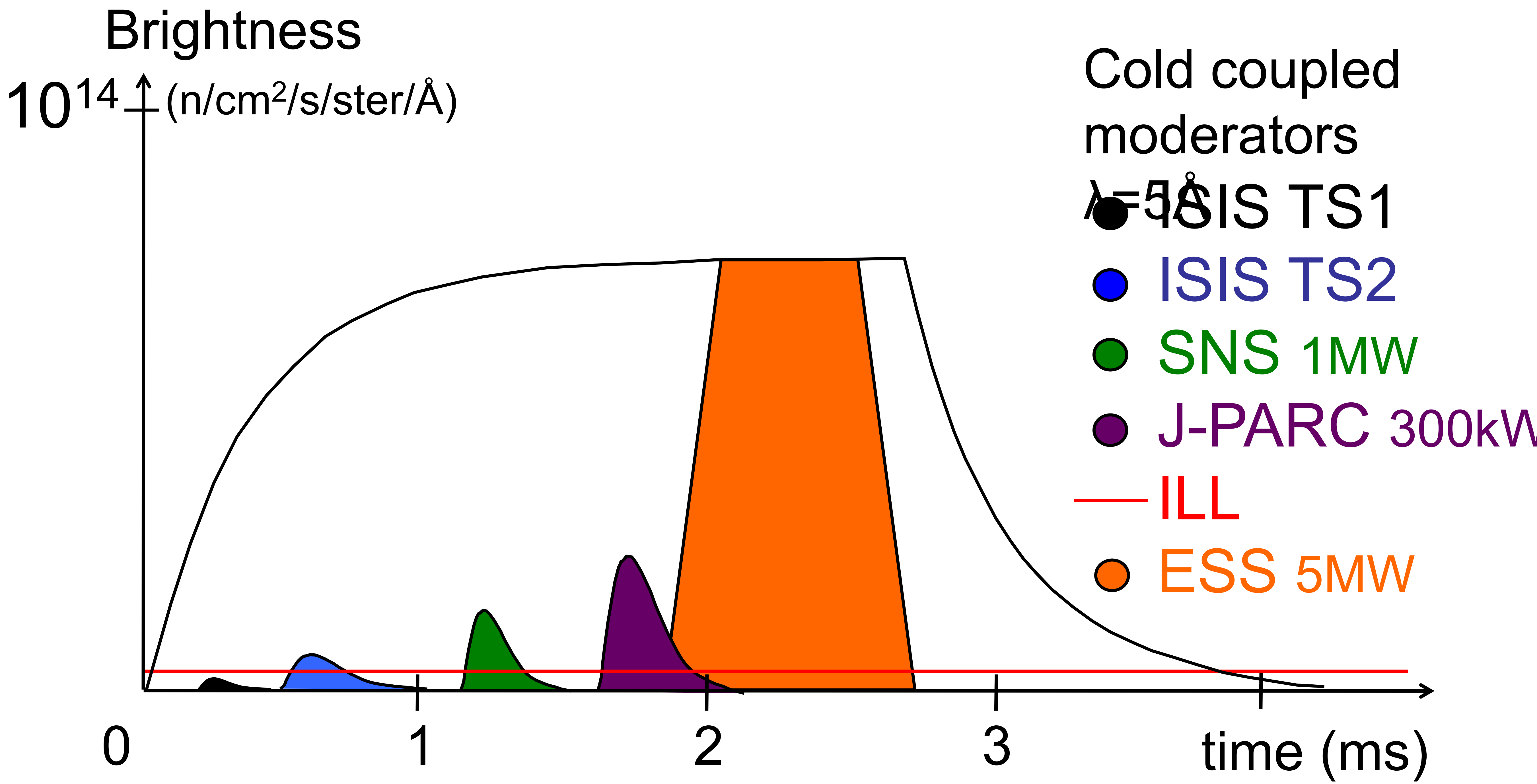


Long-Pulse Principle

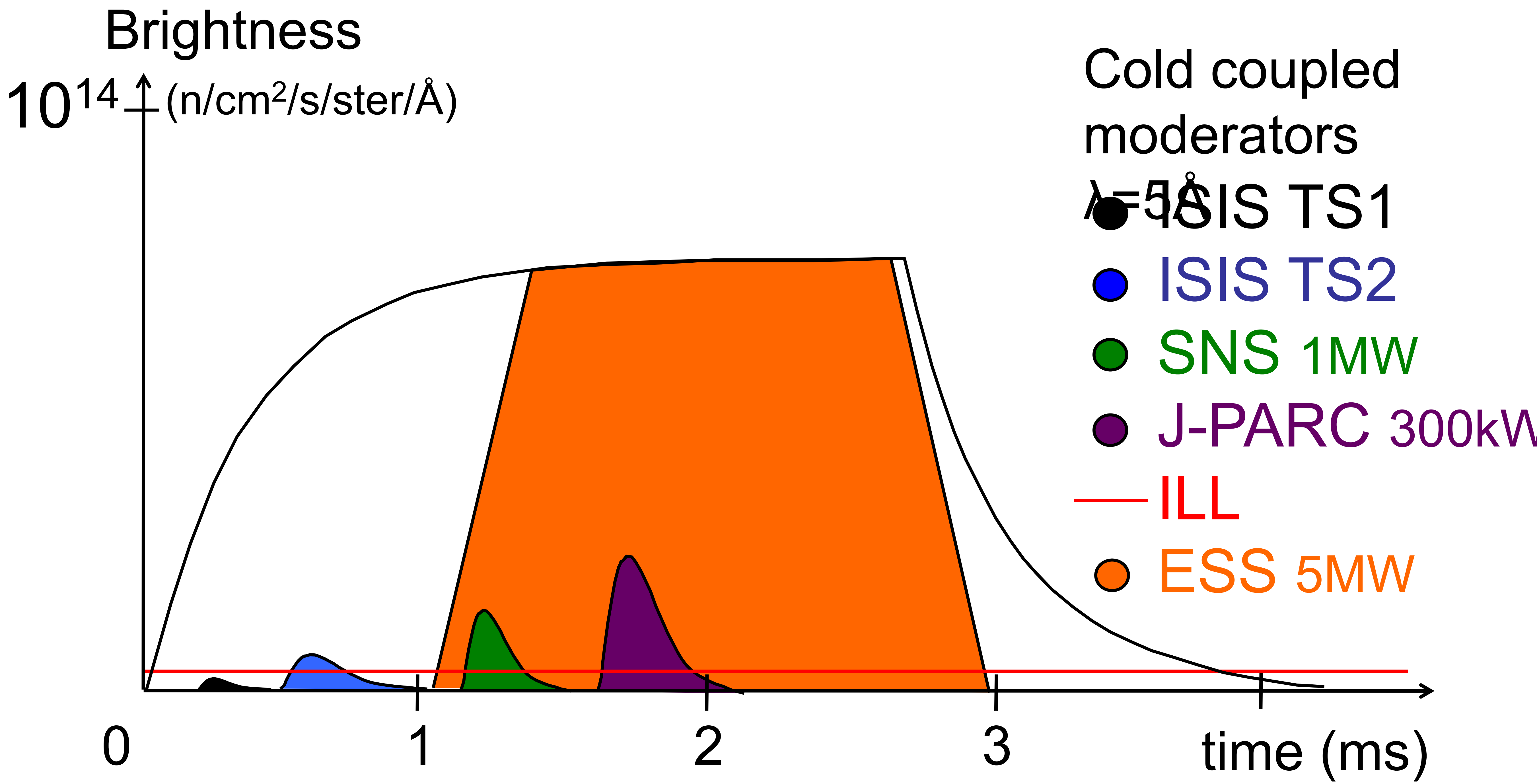


EUROPEAN SPALLATION SOURCE

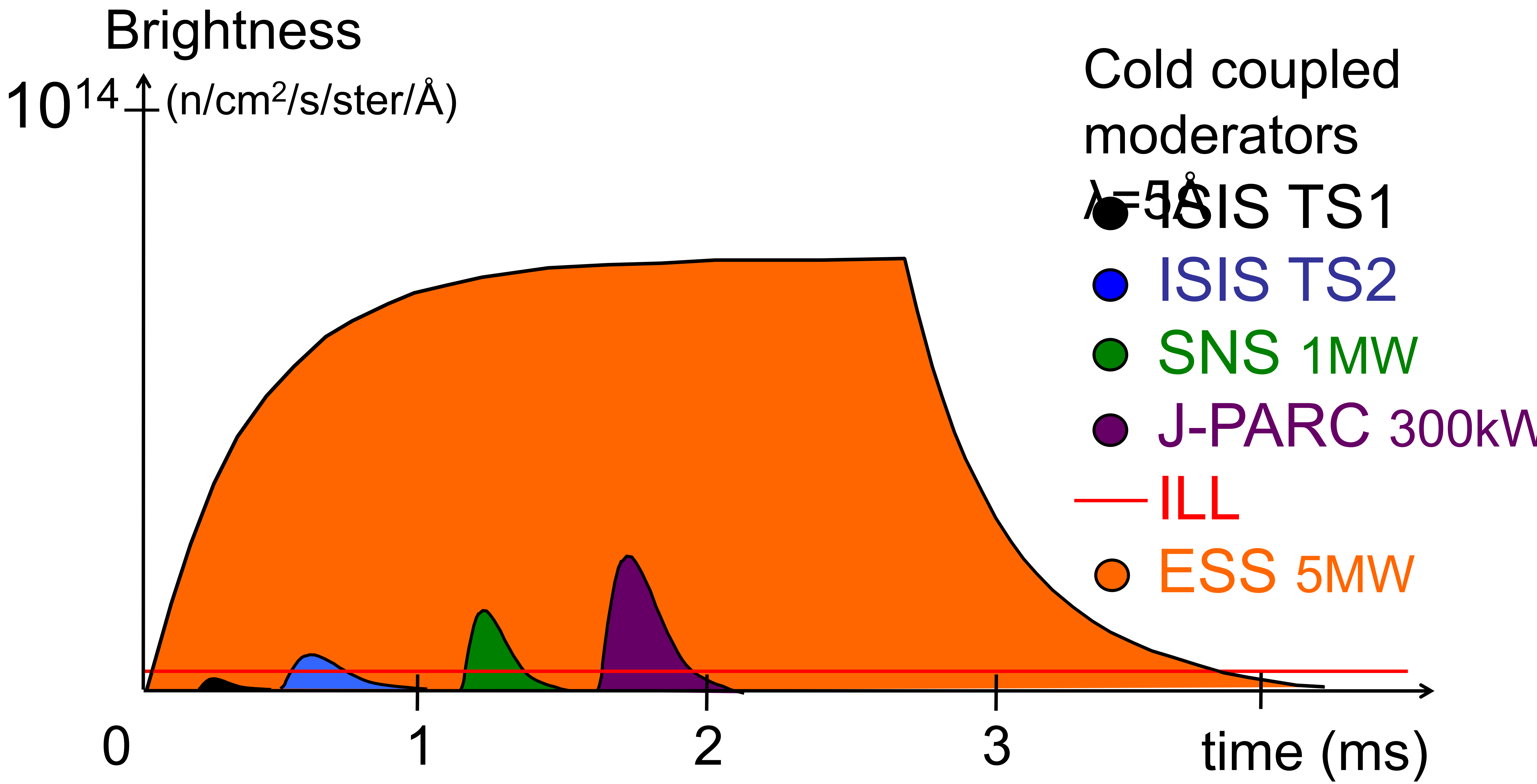
Long-Pulse Principle



Long-Pulse Principle



Long-Pulse Principle



EUROPEAN
SPALLATION
SOURCE

Thank you!

Oxford School of Neutron Scatt

Oxford, 2013-09-04

Ken Andersen

ESS Neutron Instruments Division