Neutron Sources

Oxford School on Neutron Scattering

3rd September 2019

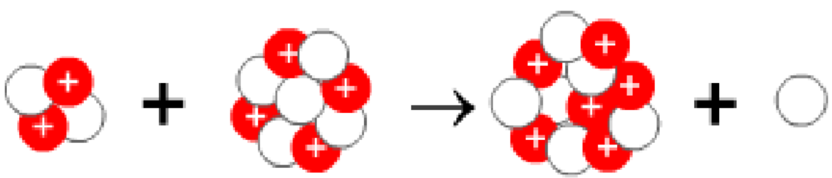
Ken Andersen

Summary

- Neutron facilities
  - history, overview & trends
- Reactor-based sources
  - Institut Laue-Langevin
- Short-pulse spallation sources
  - ISIS
- Components of a spallation neutron source
  - accelerator
  - target
  - moderators
- Neutron source time structure
  - the time of flight method
- Long-pulse neutron sources

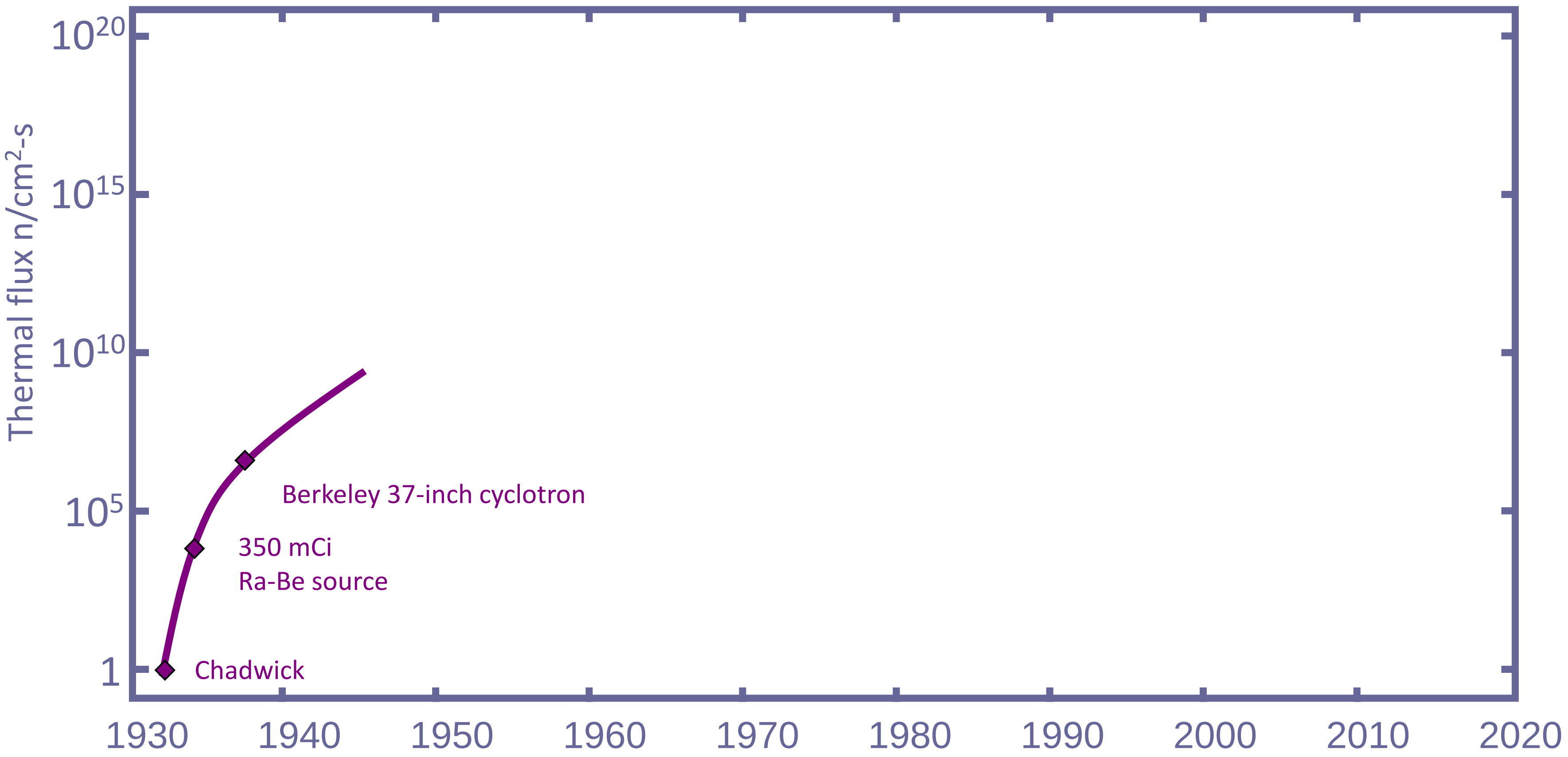
The first neutron source

James Chadwick:
used Polonium as alpha emitter on Beryllium



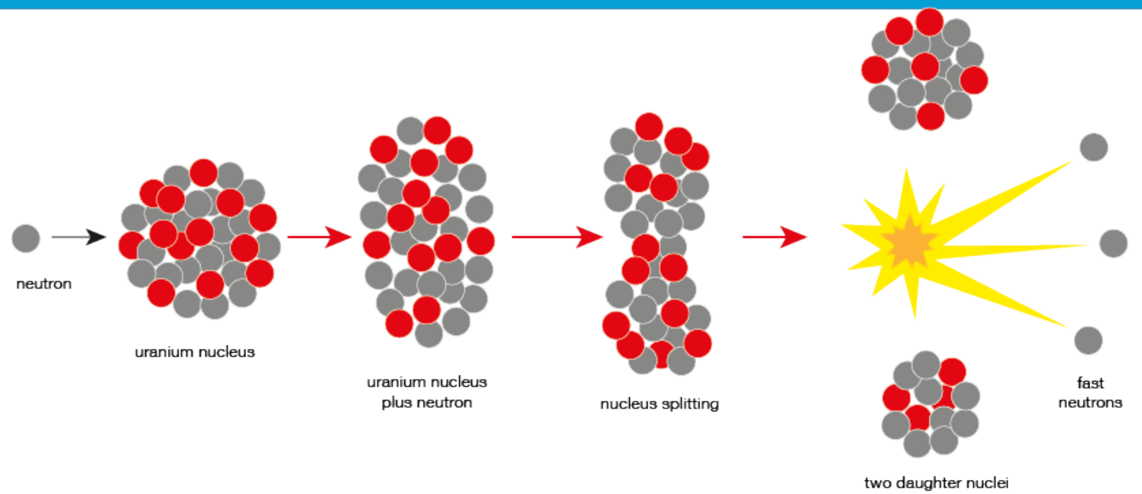
$^{4}He + {}^{9}Be \rightarrow {}^{12}C + \text{neutron}$

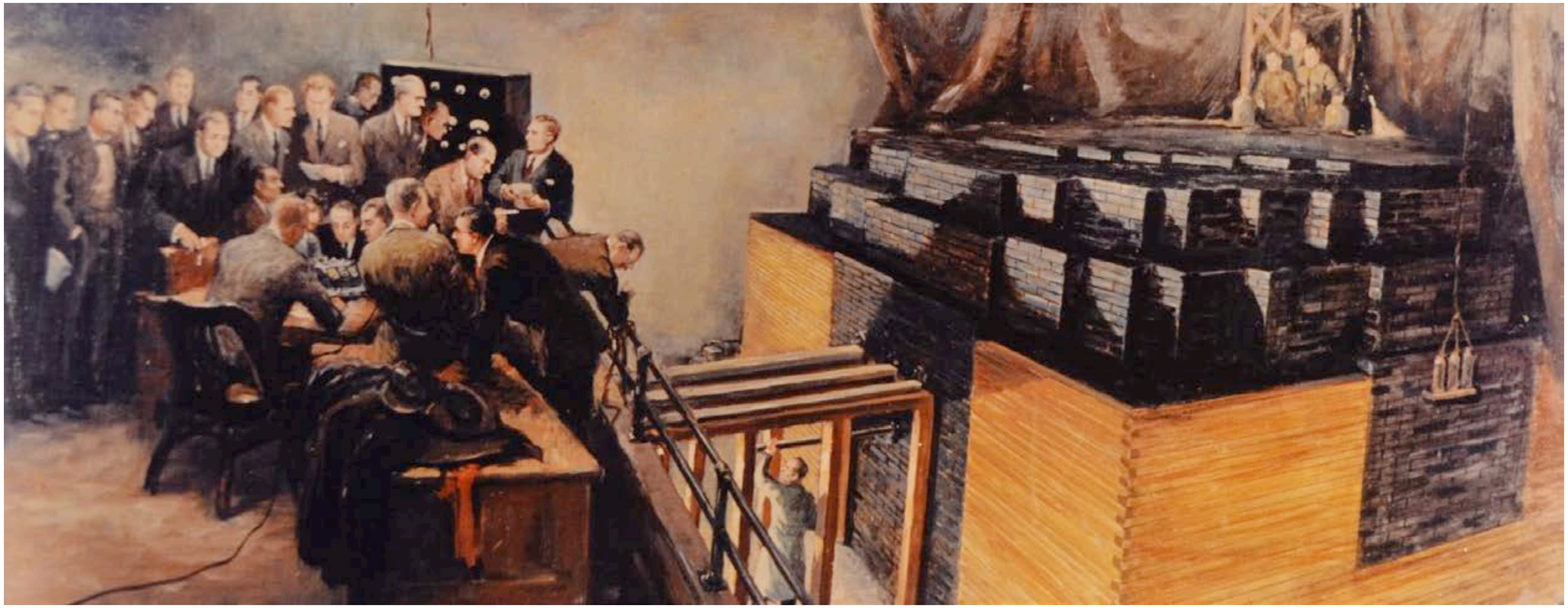
Evolution of neutron sources



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

Nuclear Fission





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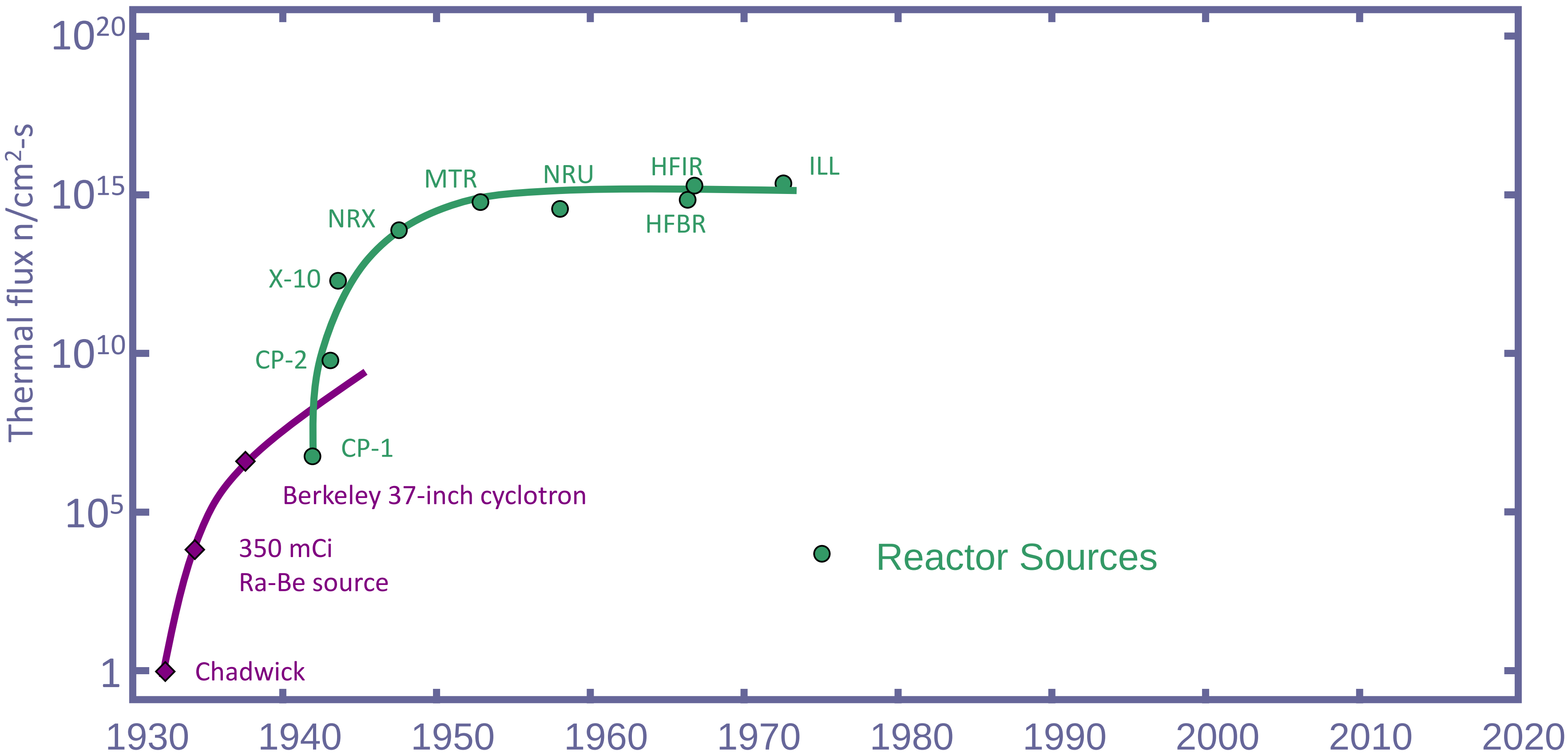

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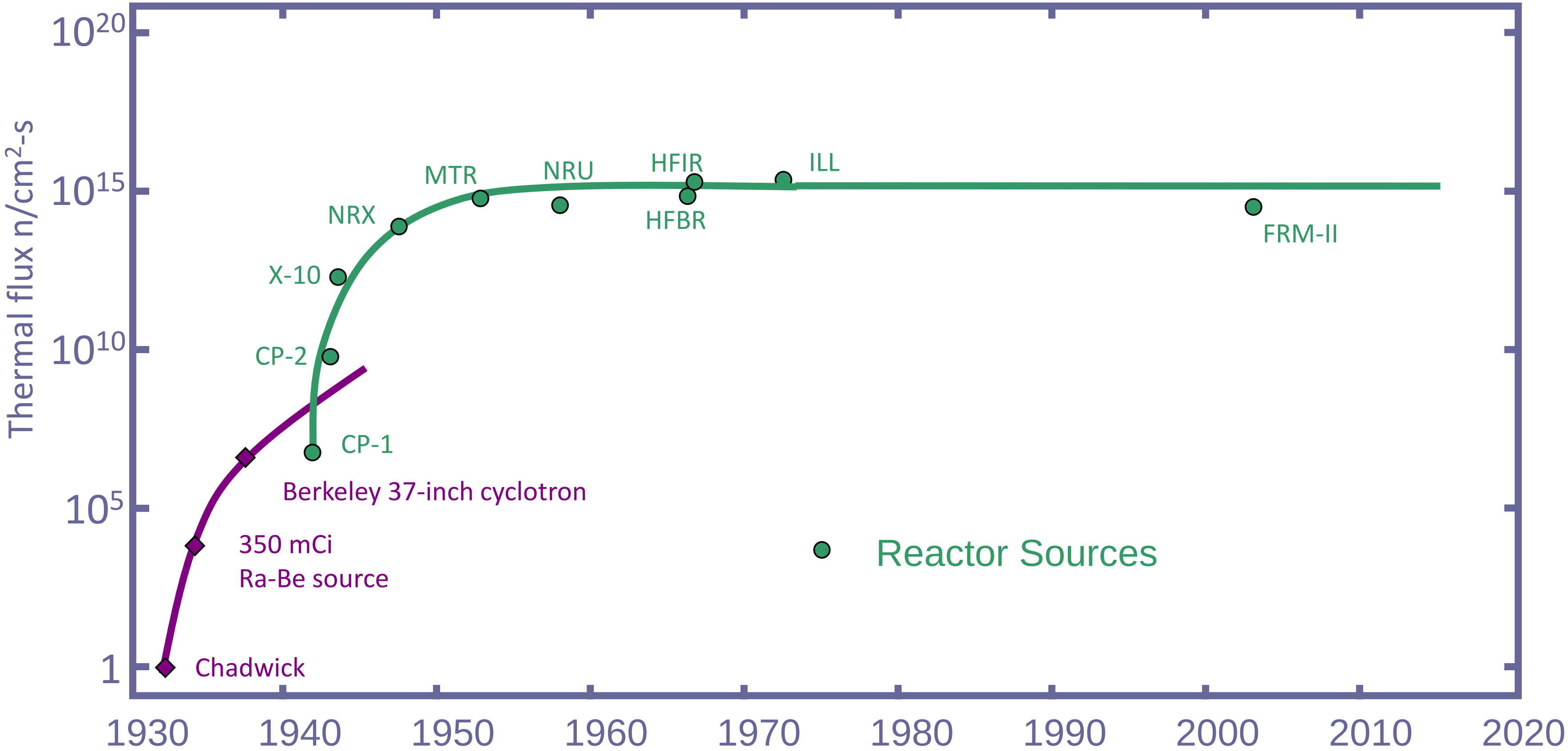

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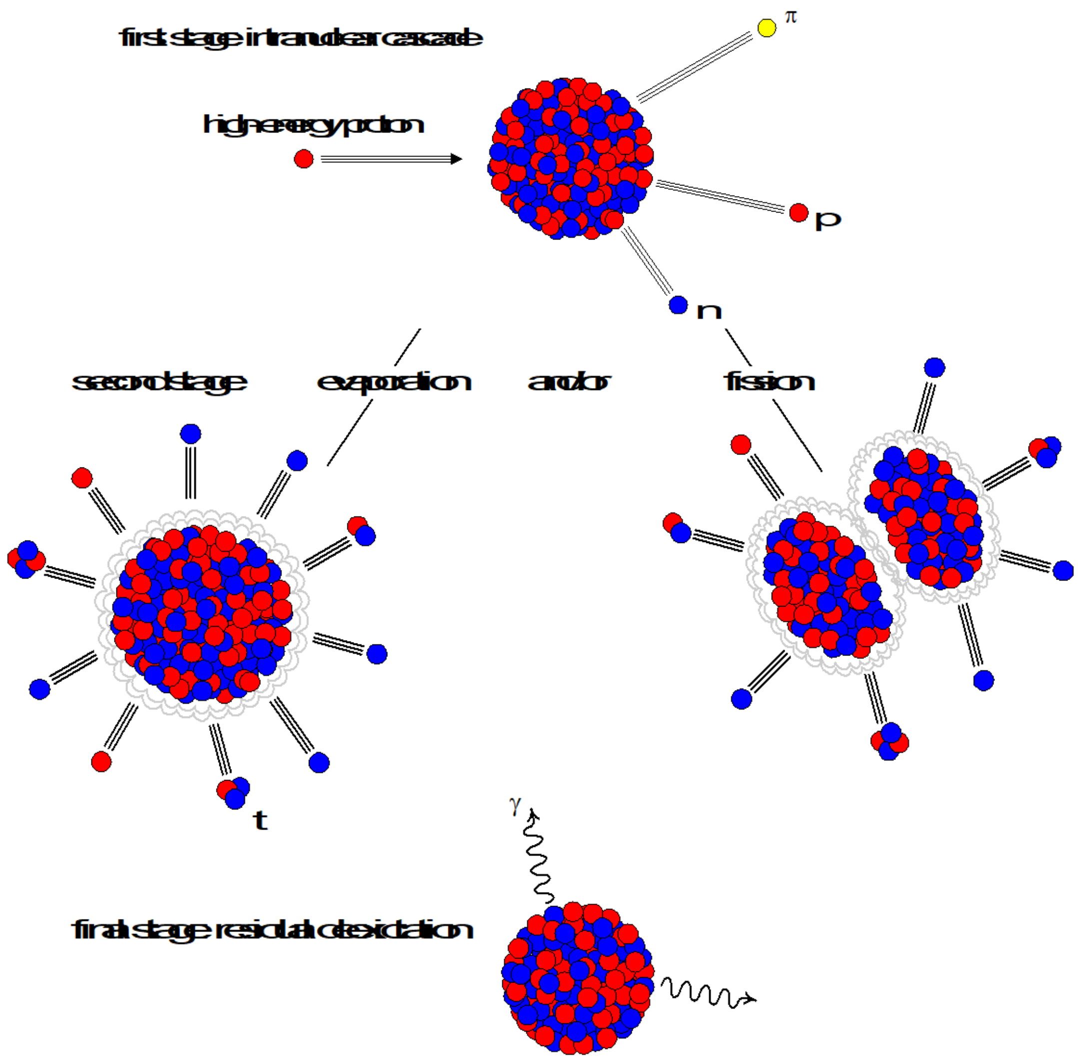
Nuclear Spallation



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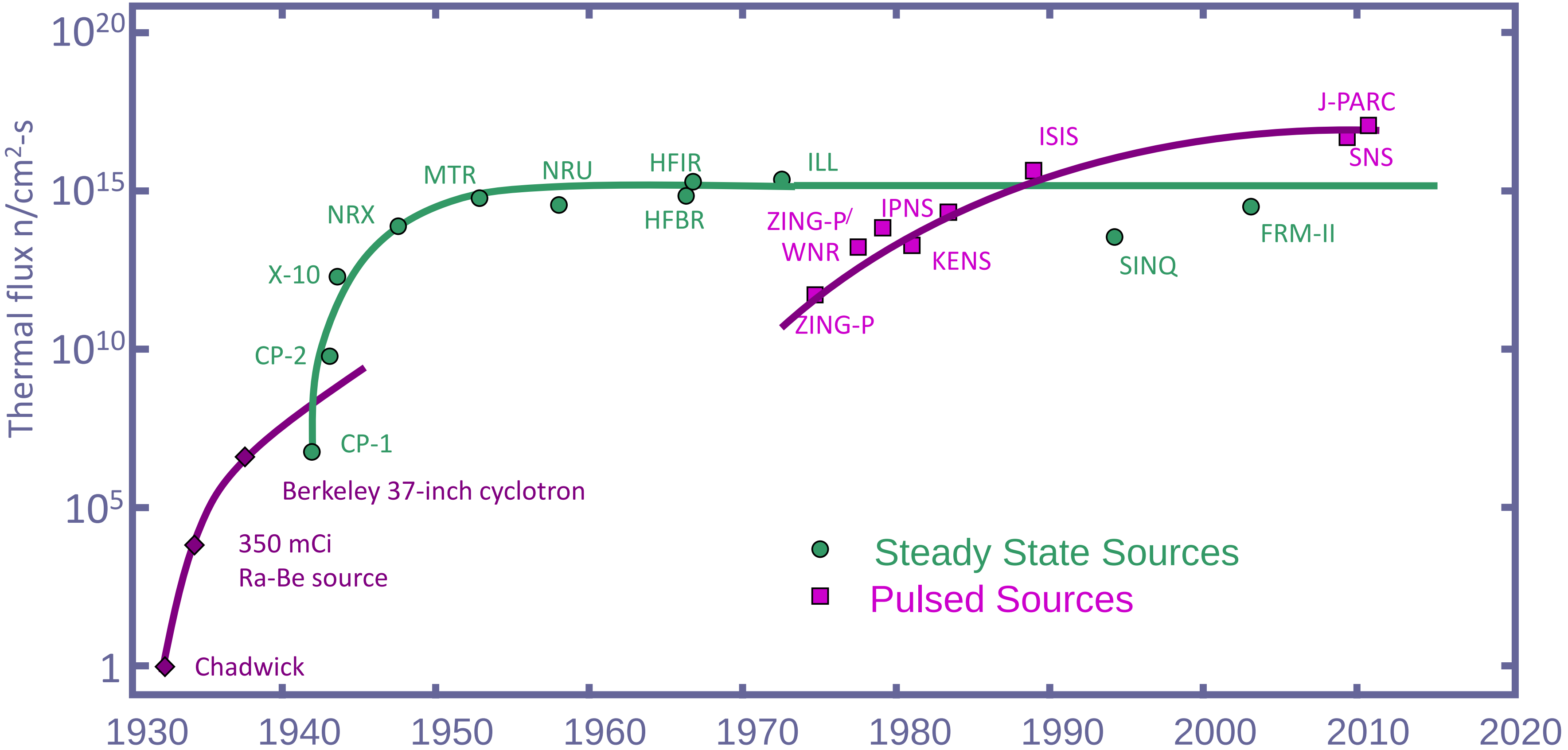

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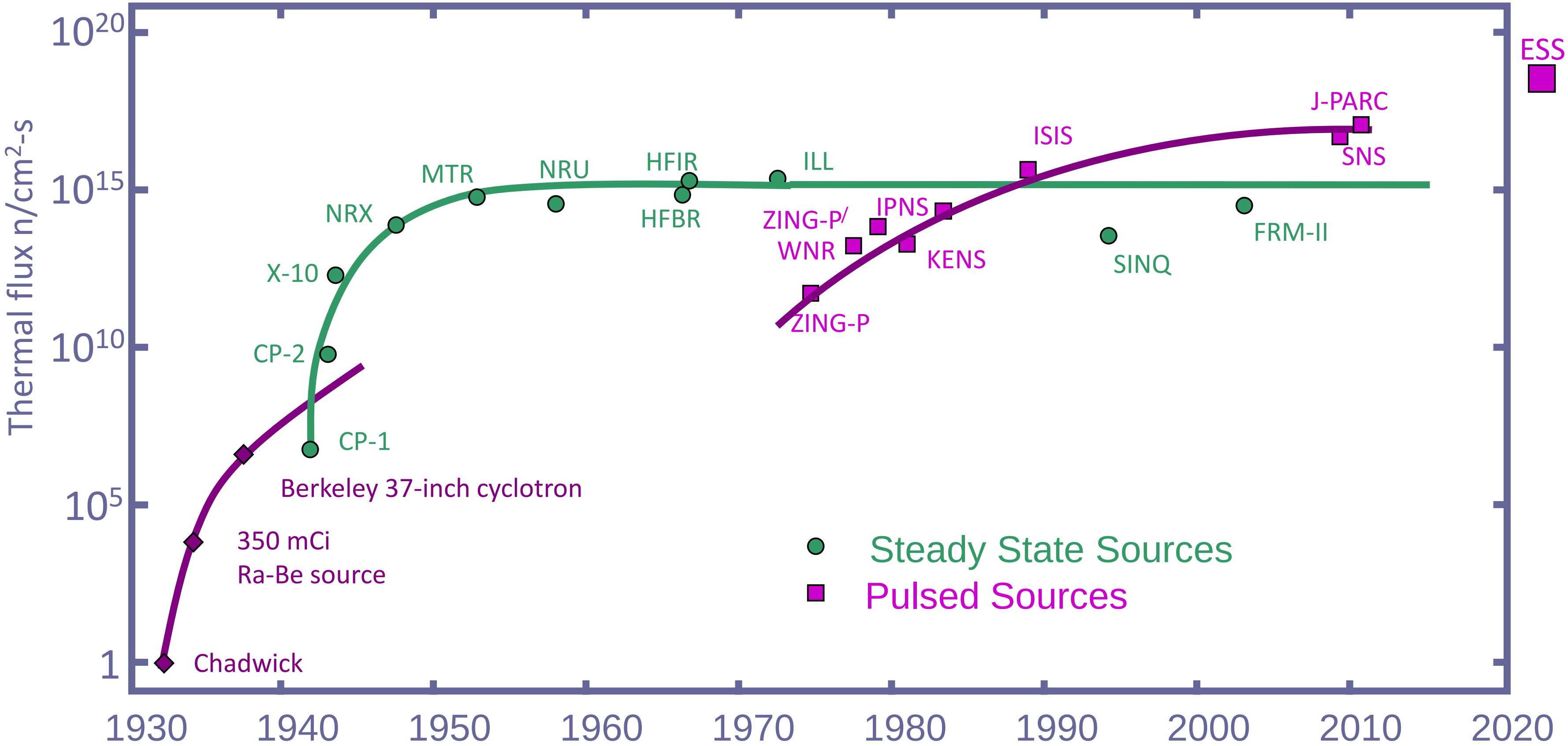

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Slow Neutrons vs Light

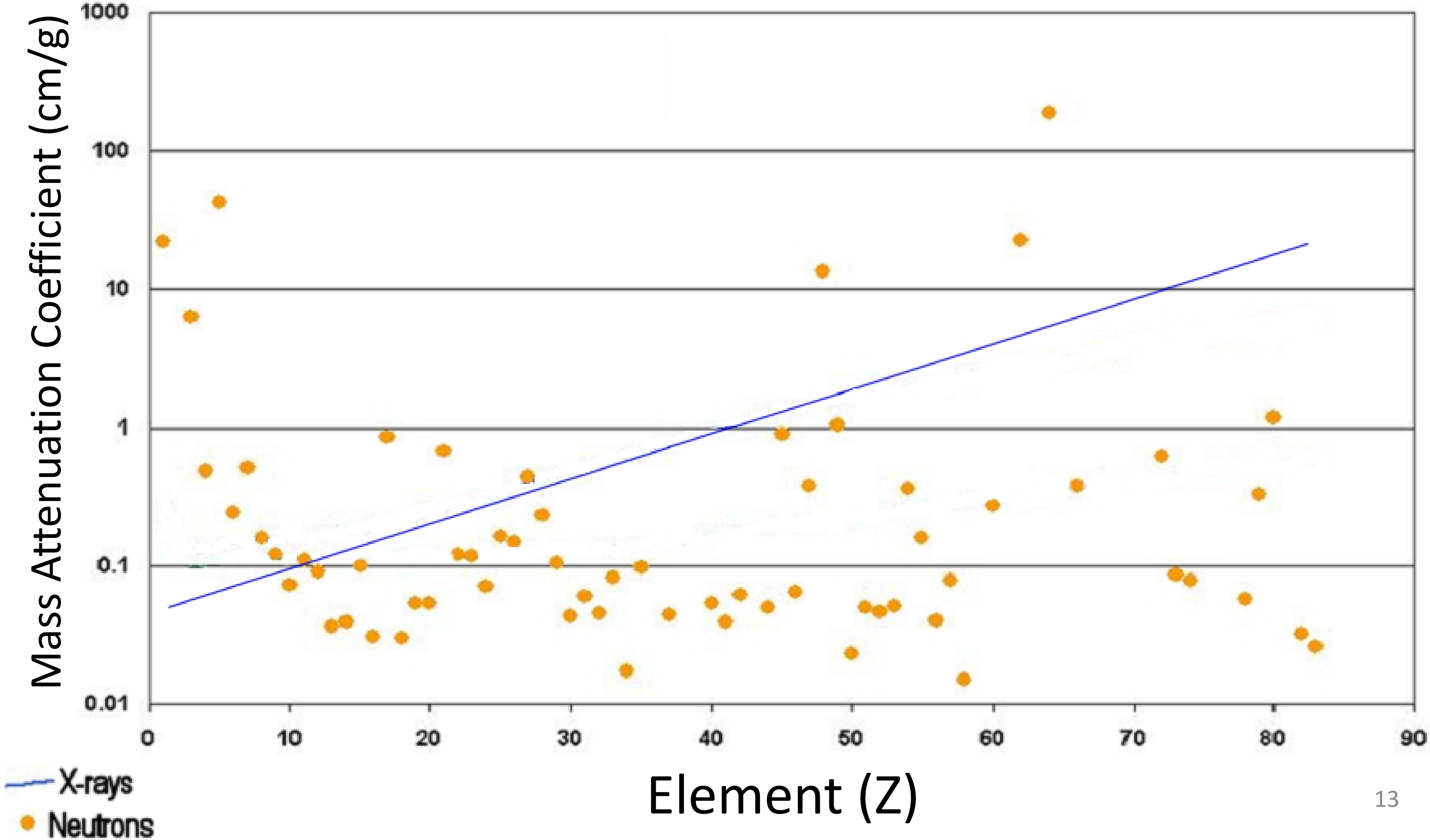
	light	neutrons
λ	< μm	< nm
E	> eV	> meV
penetration	~ μm	~ cm
θ_c	90°	1°
B	10^{18} p/cm²/ster/s (60W lightbulb)	10^{14} n/cm²/ster/s (60MW reactor)
spin	1	½
interaction	electromagnetic	strong force, magnetic
charge	0	0

Why neutrons?

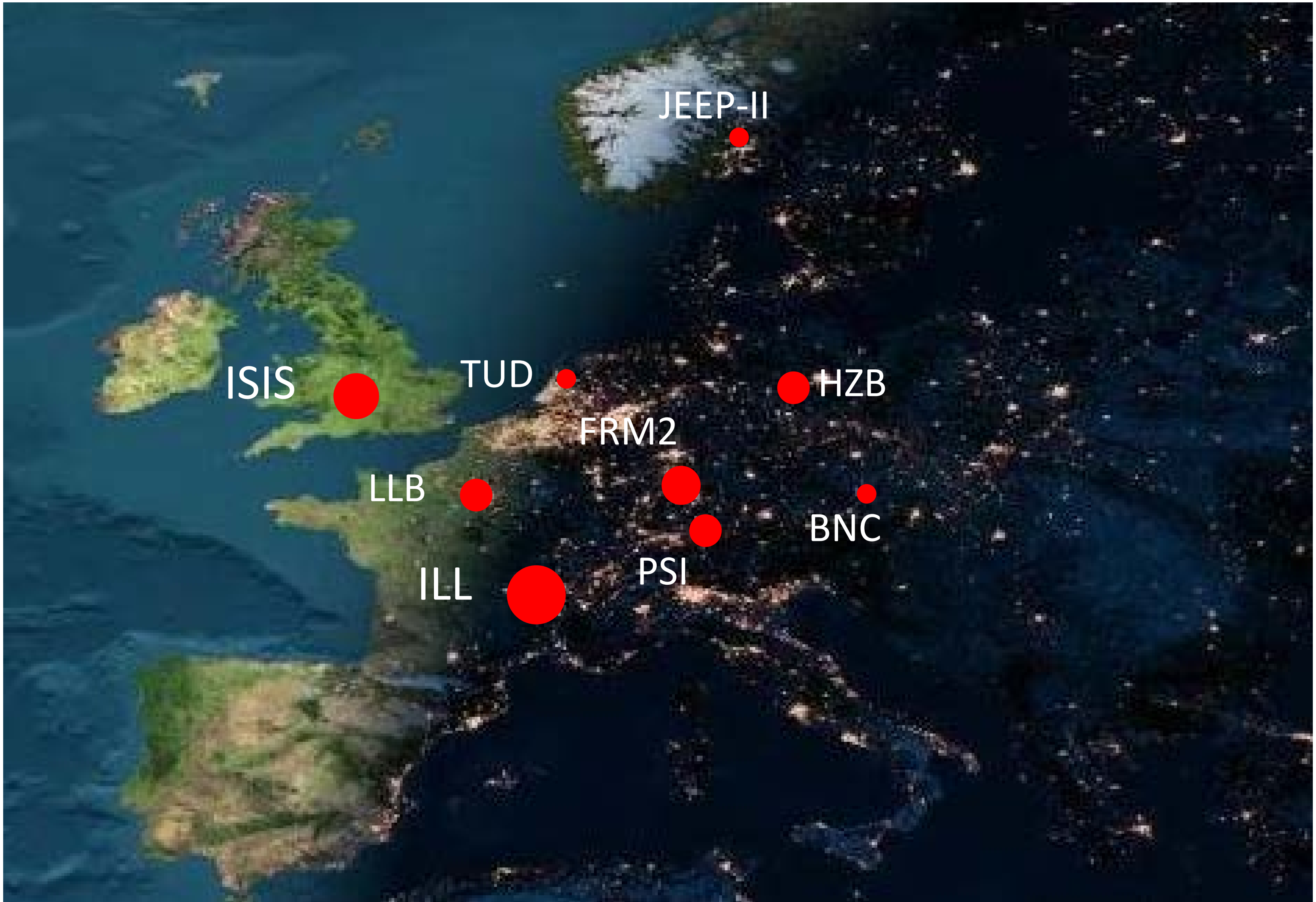
EUROPEAN SPALLATION SOURCE

- Thermal neutron have wavelengths similar to inter-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 is very visible

Why neutrons?



Main European neutron sources 2019



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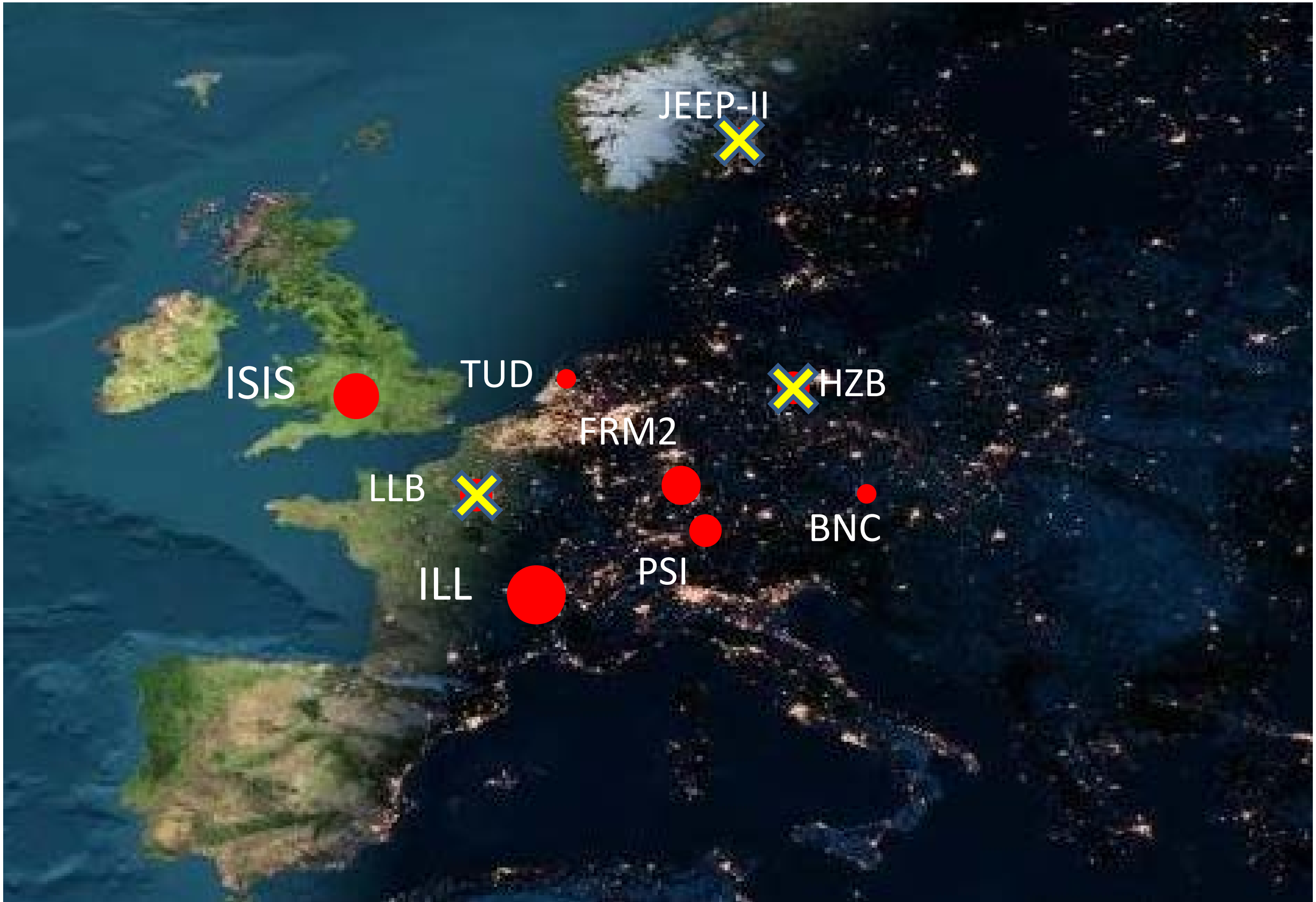
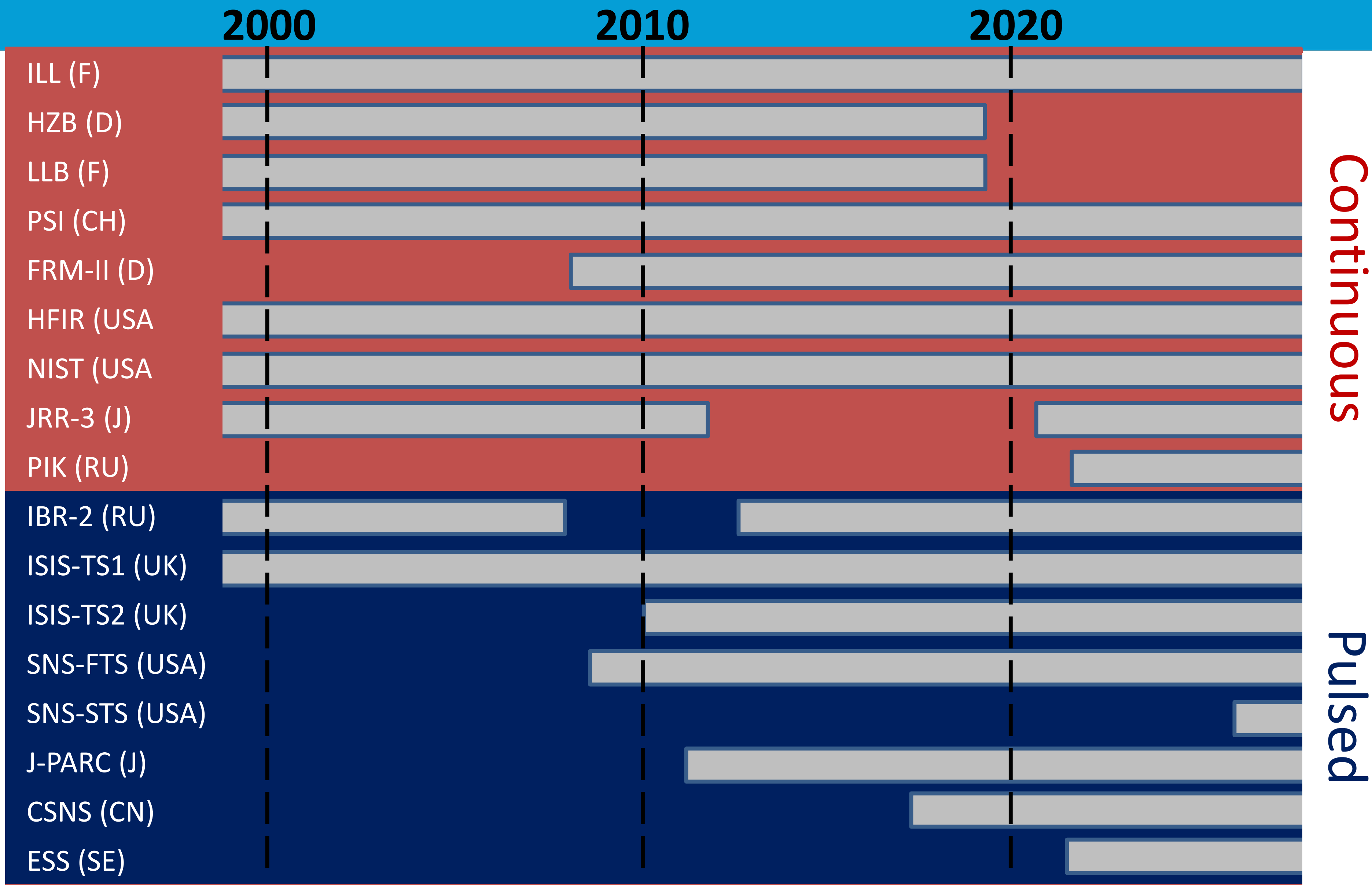


Major neutron sources in the world



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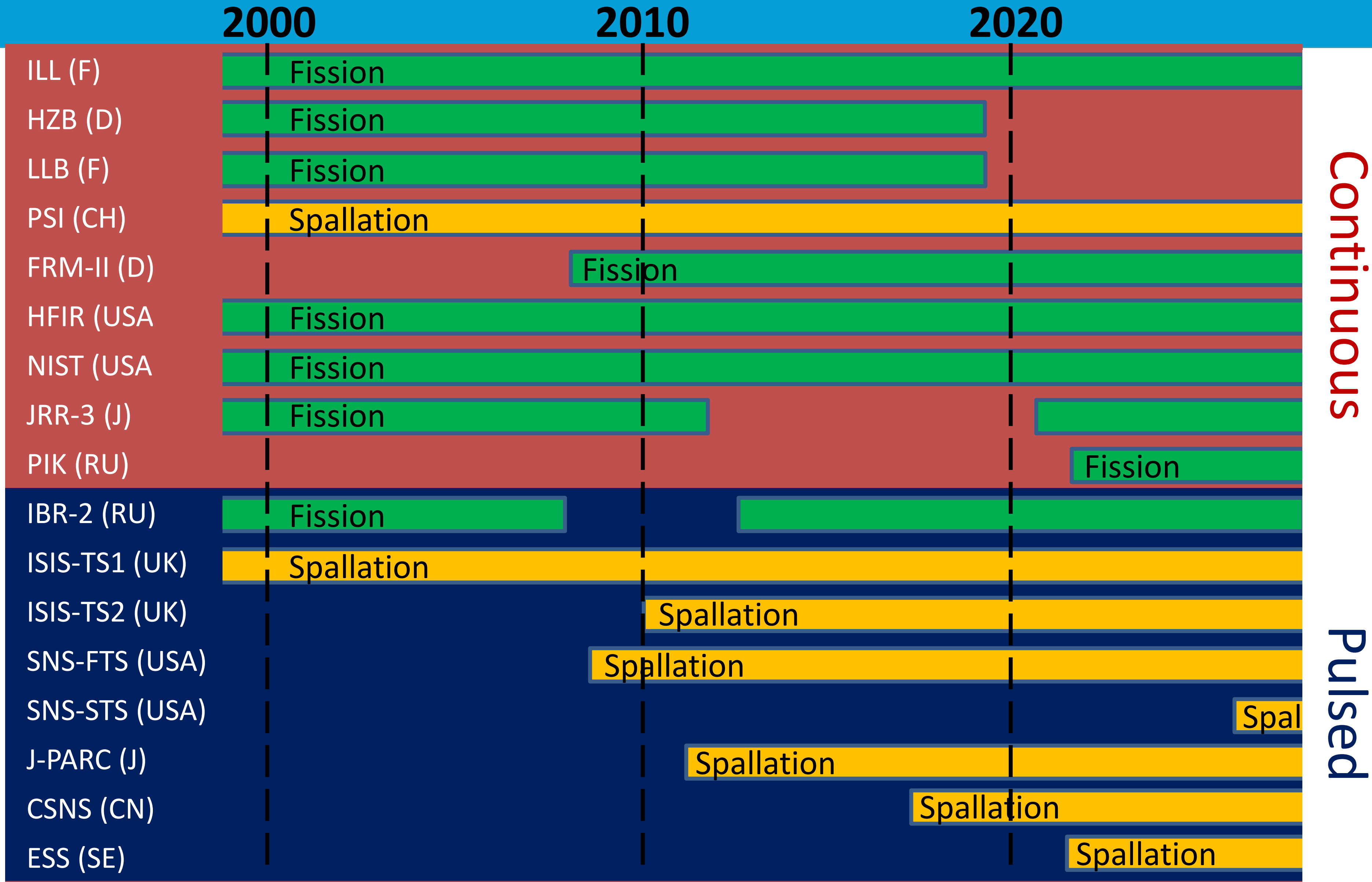
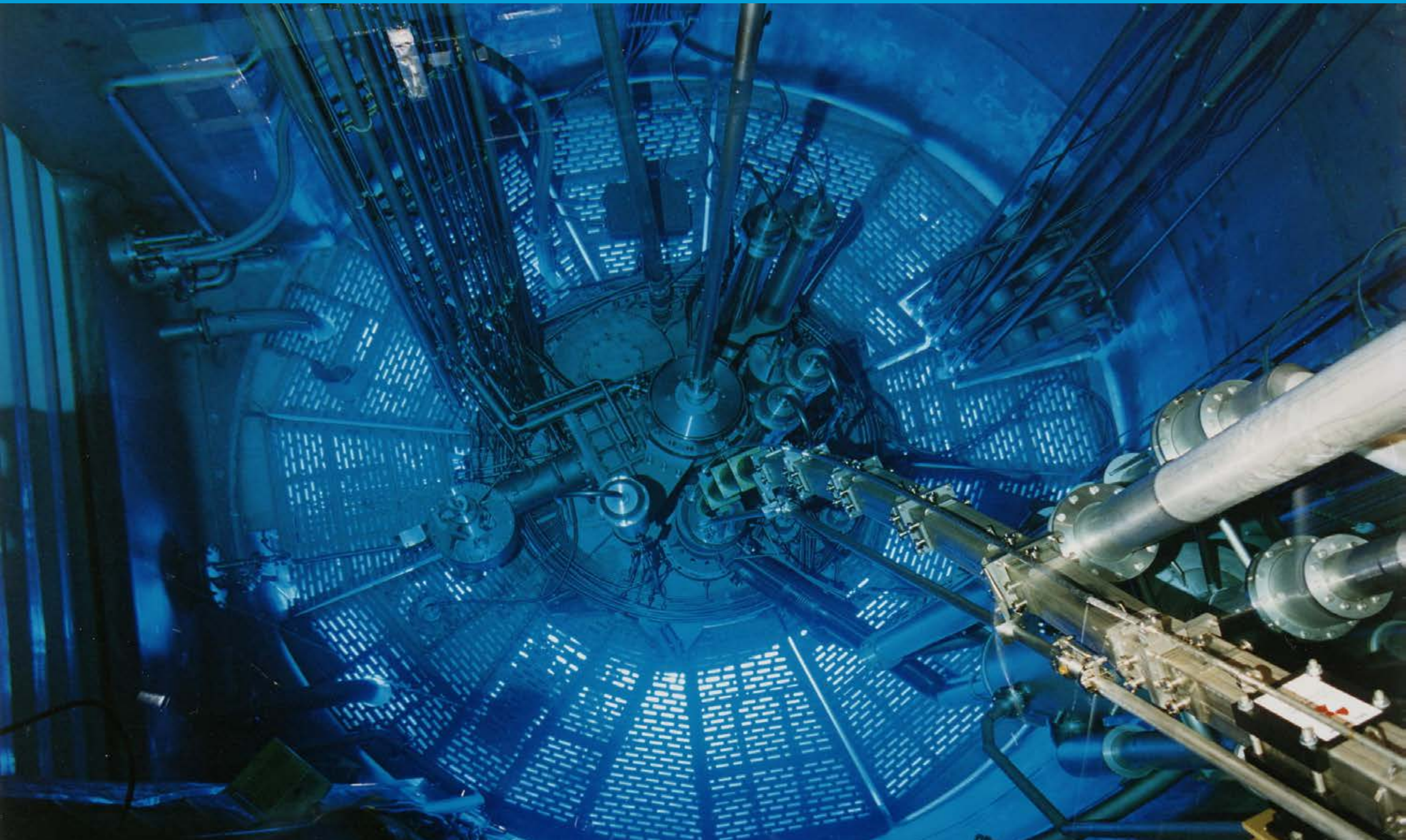


ILL Reactor Neutron Source



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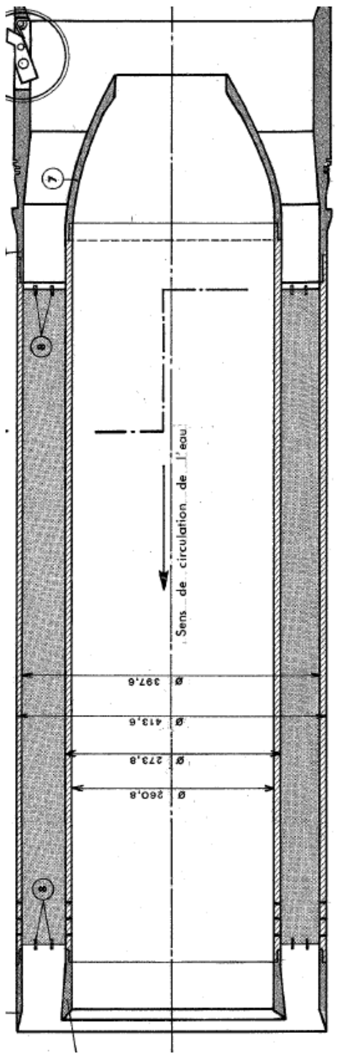
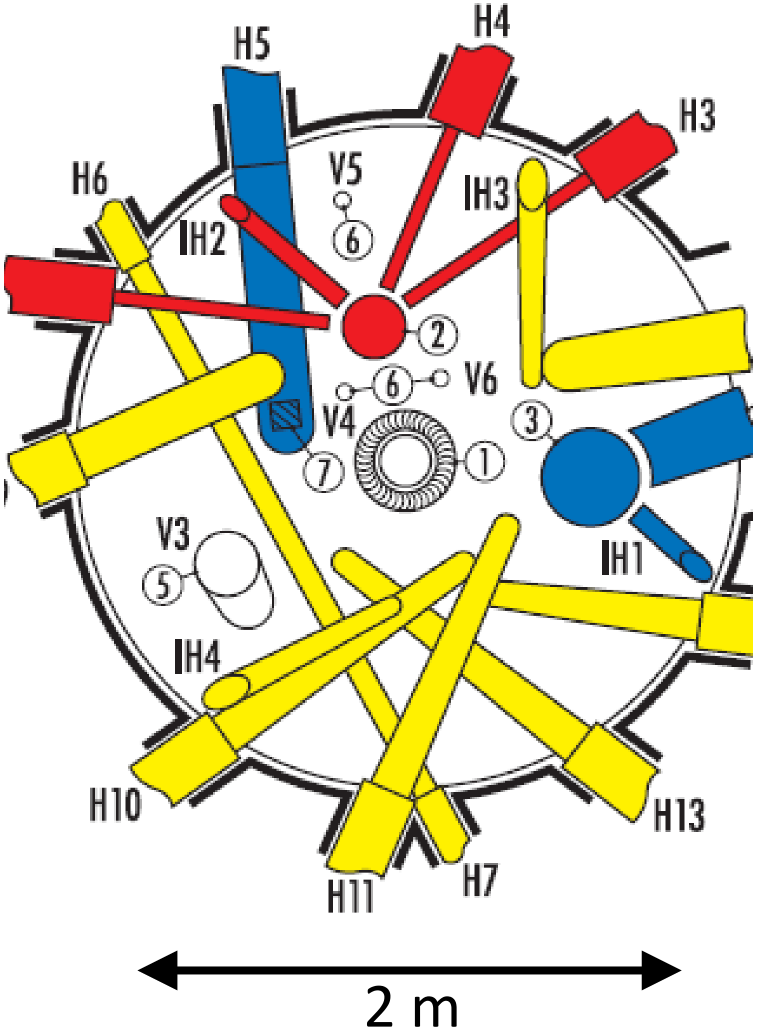


ILL Reactor Neutron Source

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



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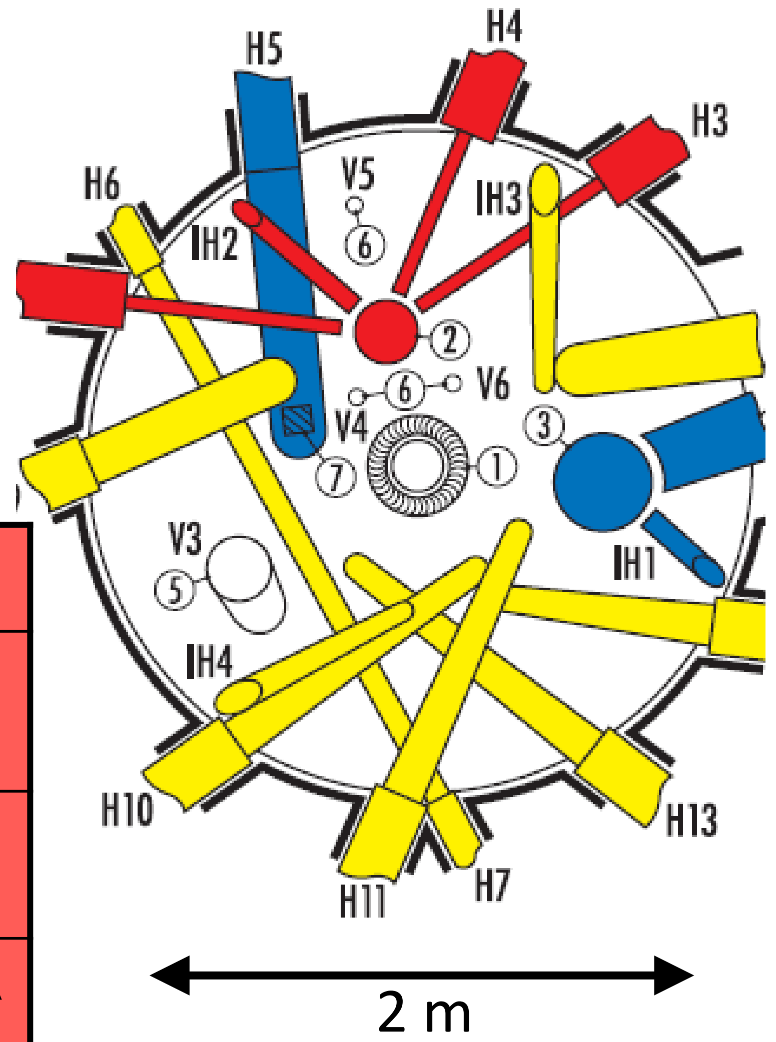
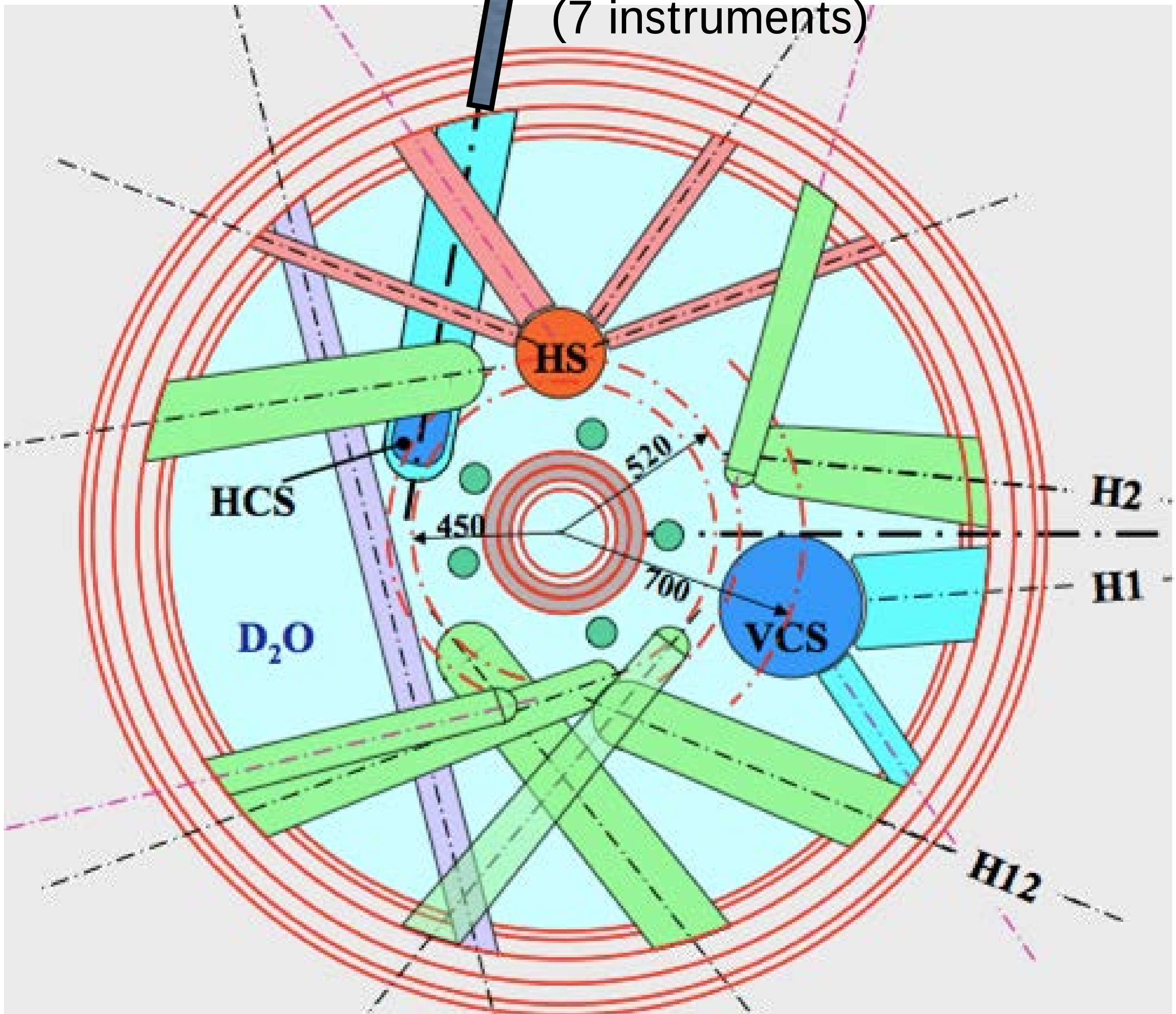
	cold	thermal	hot
moderator	liquid D_2	Liquid D_2O	graphite
moderator temperature	20K	300K	2000K
neutron wavelength	3→20Å	1→3Å	0.3→1Å



ILL Reactor Neutron Source

2nd guide hall
(7 instruments)



1st guide hall
(20 instruments)

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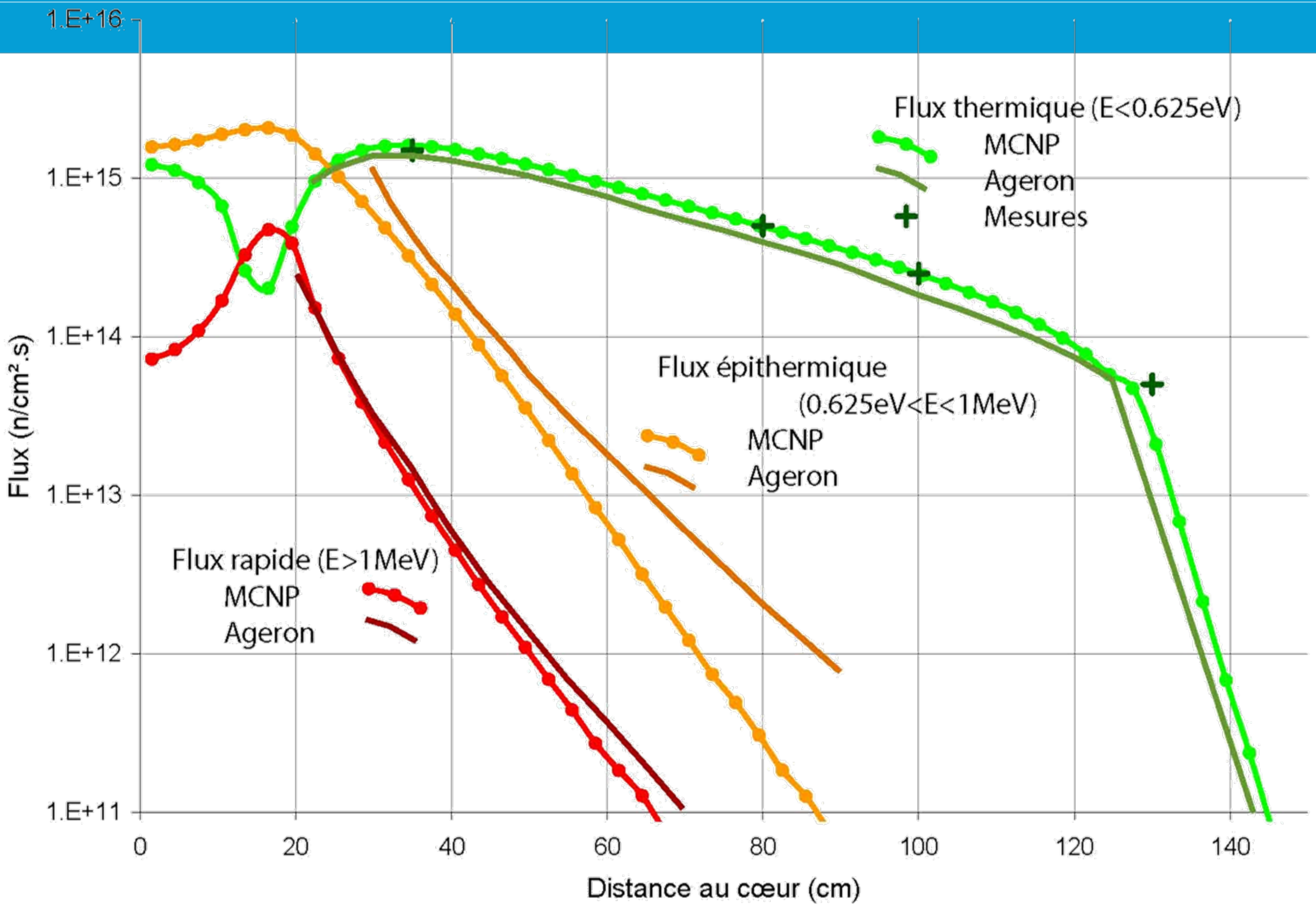

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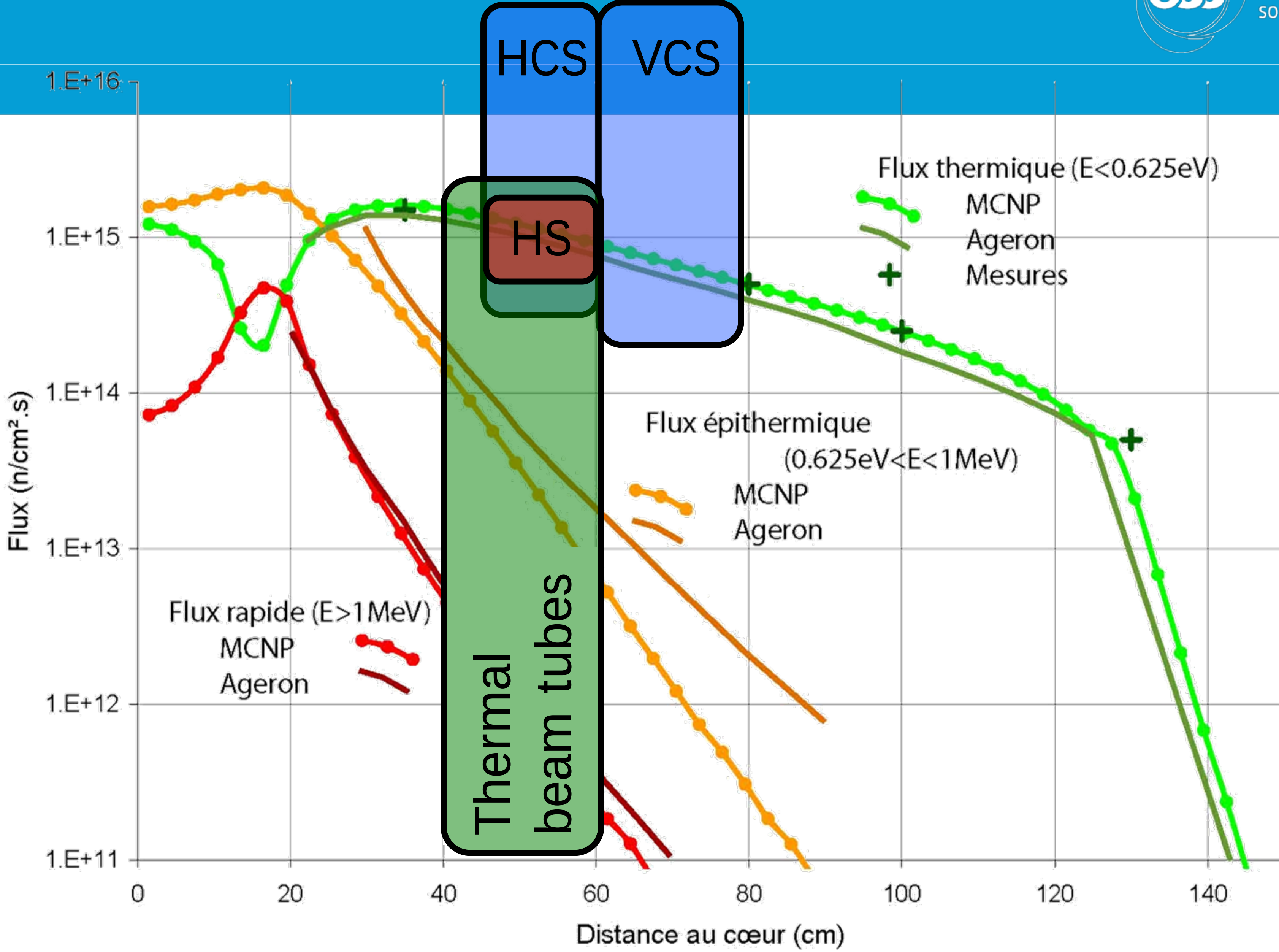
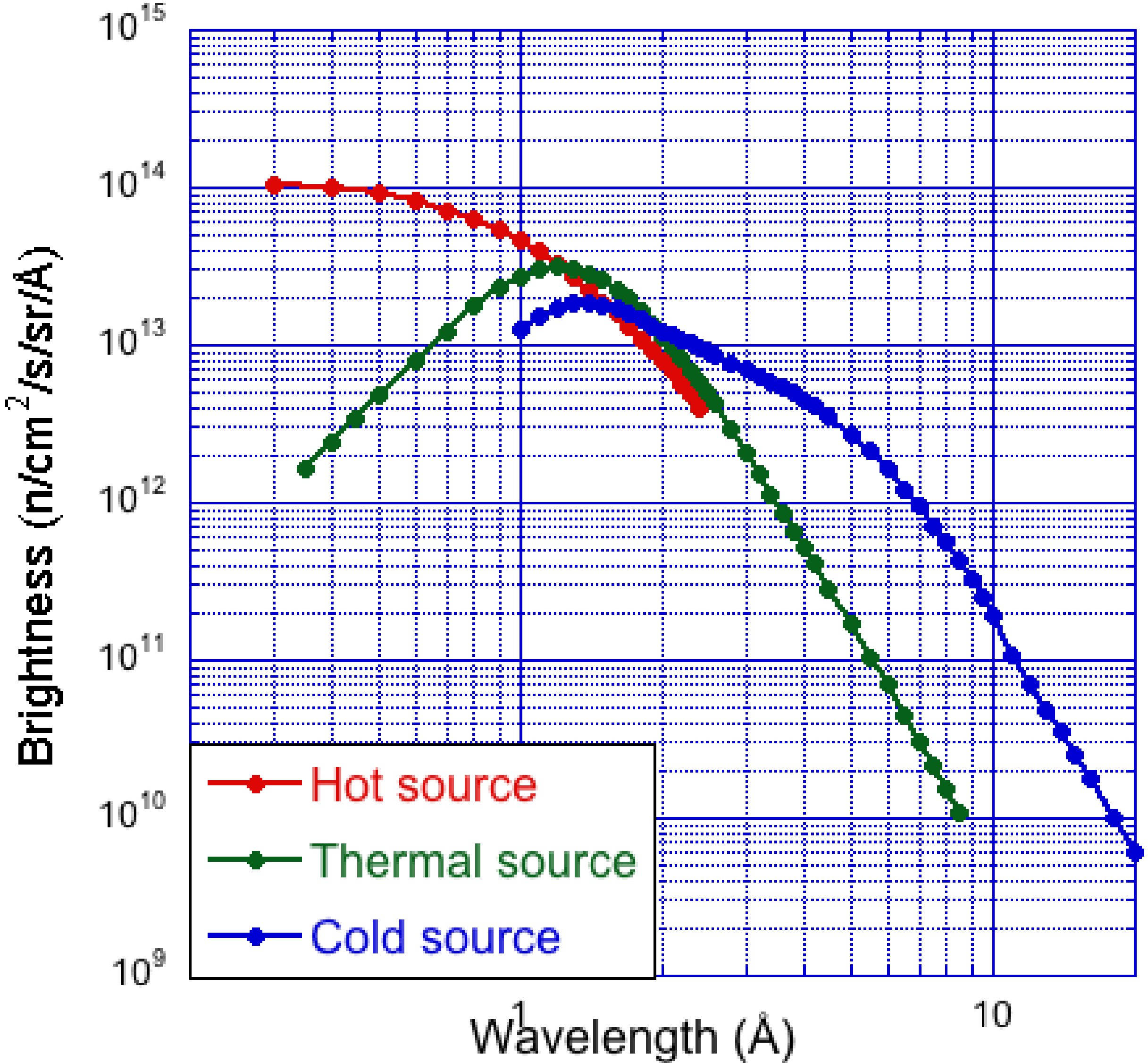


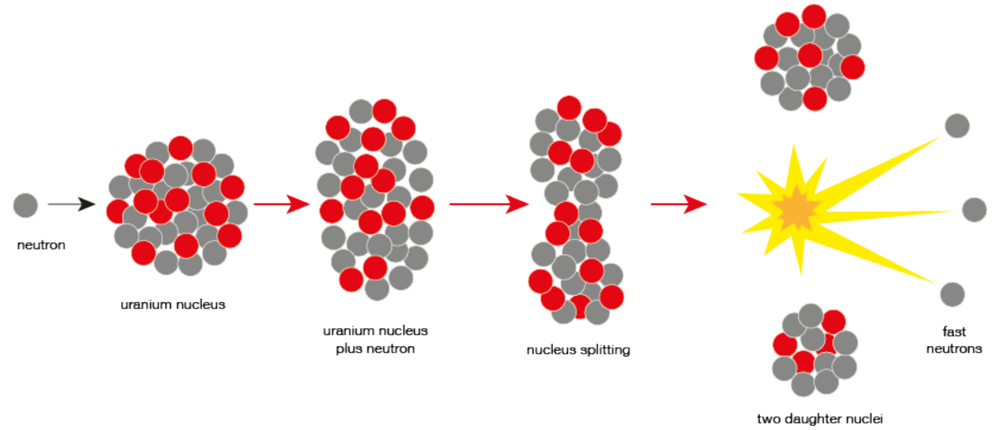
ILL Moderator Brightnesses



Spallation vs Fission

Fission

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



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EUROPEAN SPALLATION SOURCE

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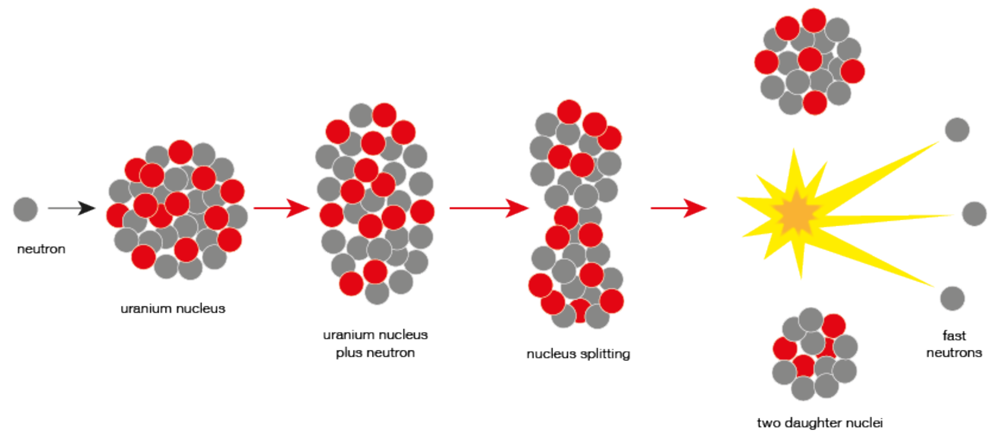
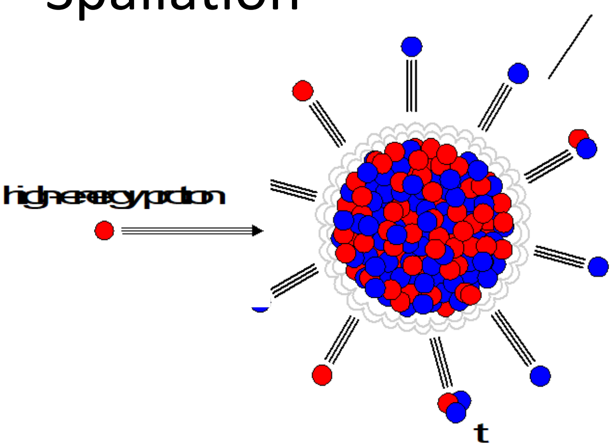


Spallation



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

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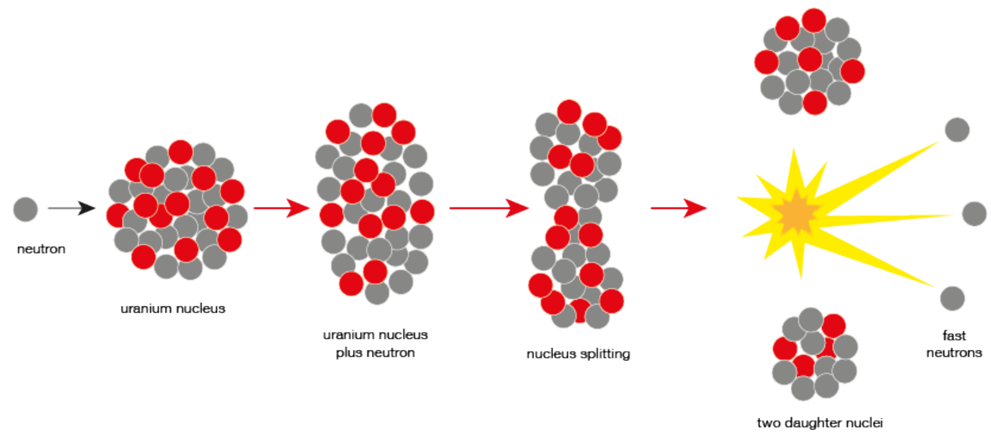

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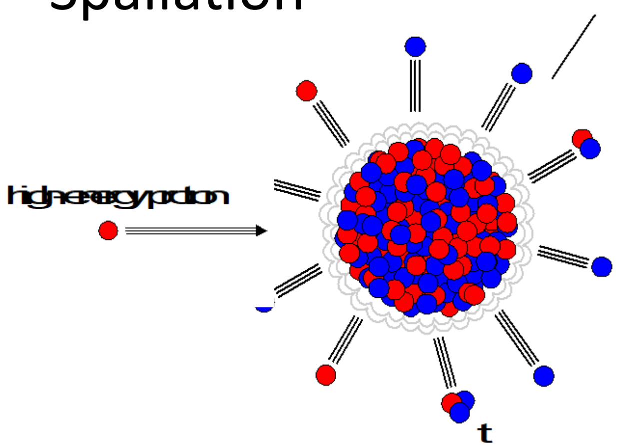

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6x more neutrons per unit heat

Spallation Sources

- Spallation: 10x higher neutron brightness per unit heat
  - about 6x more neutrons per unit heat
  - about ½ the production volume
- 1 MW spallation source = 10 MW reactor
  - e.g. 800 MeV at 1.25 mA (PSI)
  - e.g. 3 GeV at 0.4 mA (J-PARC)
- Peak brightness >> time-average brightness

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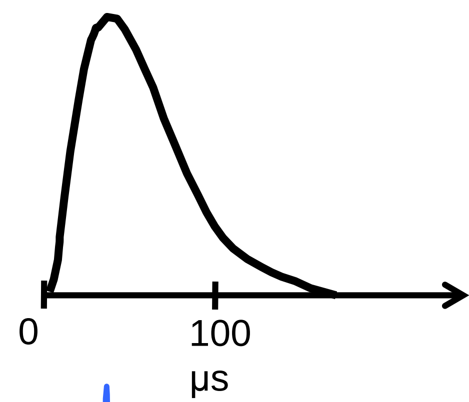
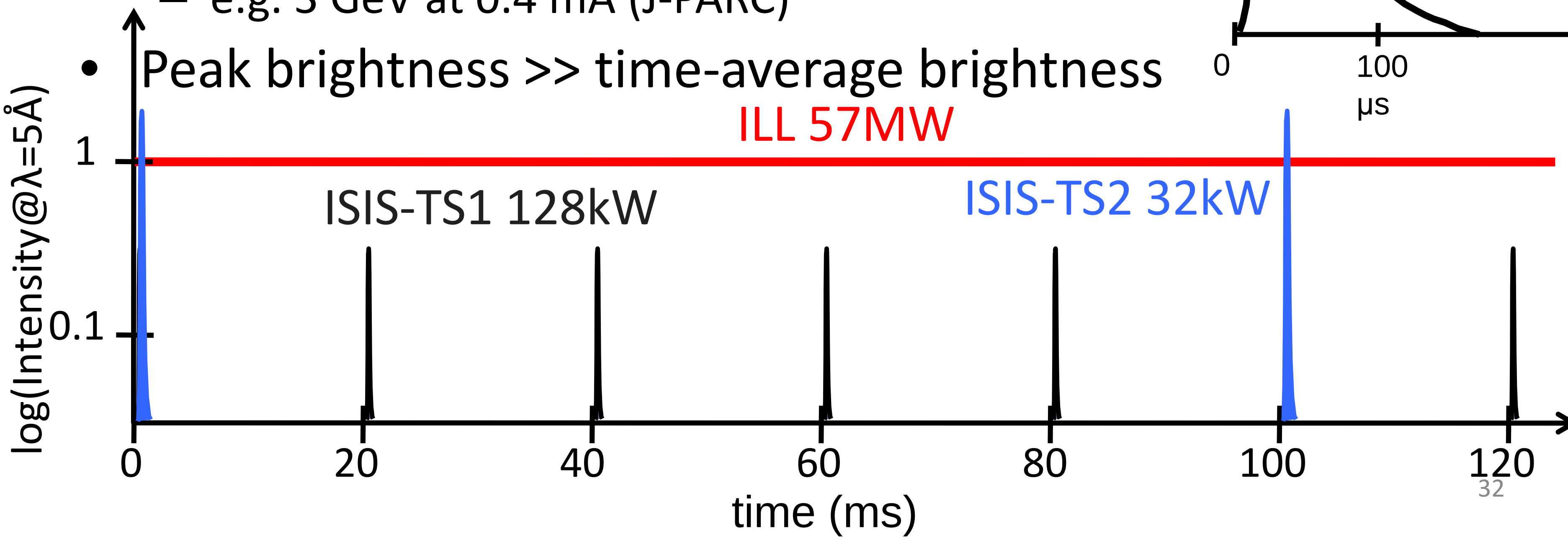




De Broglie Relations

Particle	Wave
$p = mv$ $E = \frac{1}{2} mv^2$	$p = \hbar k = h/\lambda$ $E = \hbar\omega = hf$

$$\hbar = h/2\pi$$

$$h = 6.6 \times 10^{-34}\,\mathrm{J \cdot s}$$

$$m_n = 1.67 \times 10^{-27}\,\mathrm{kg}$$

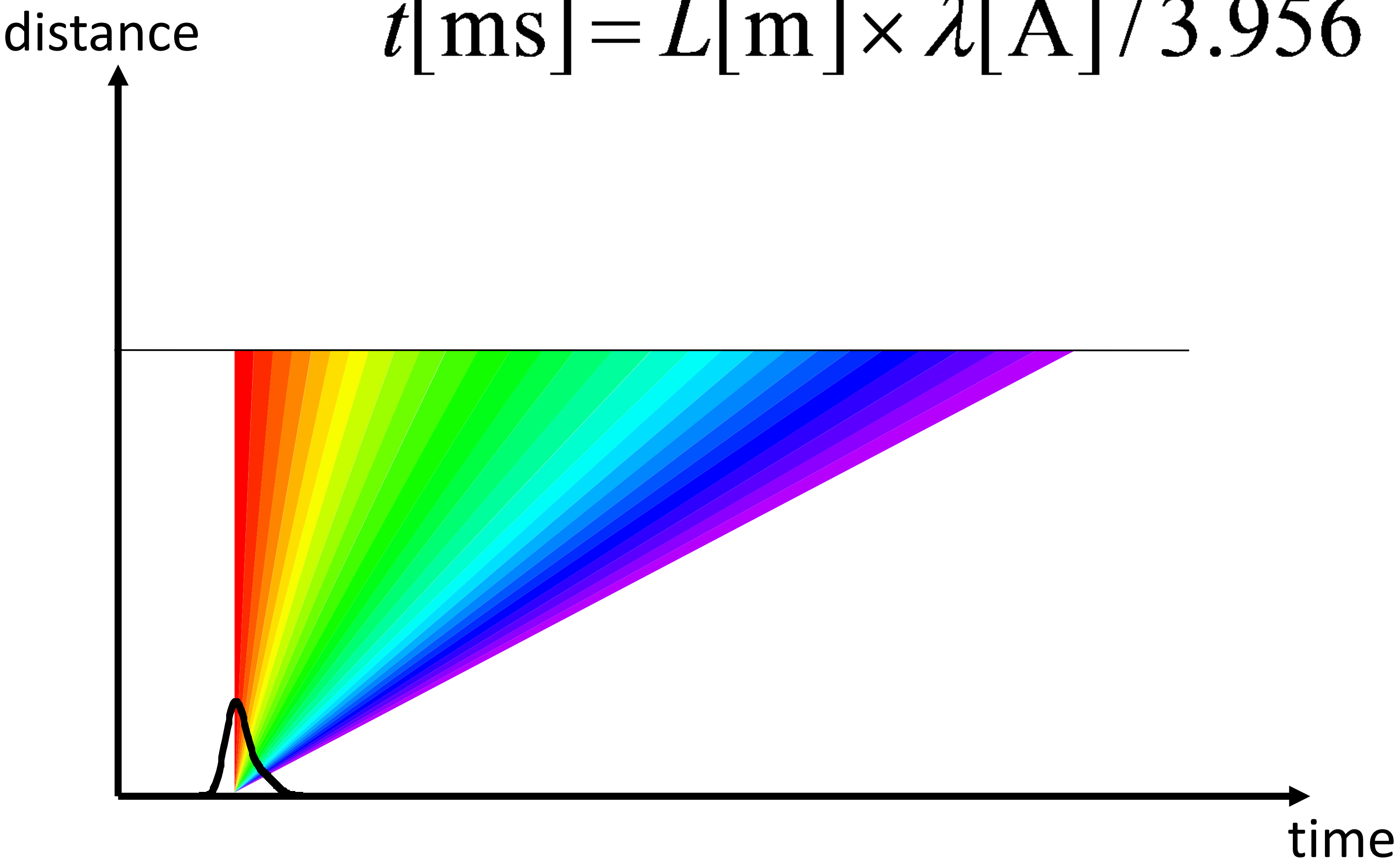
$$\lambda = h / mv$$

$$\lambda[\text{Å}] = 3.956 / v[\mathrm{m/ms}]$$

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

The Time-of-Flight (TOF) Method

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

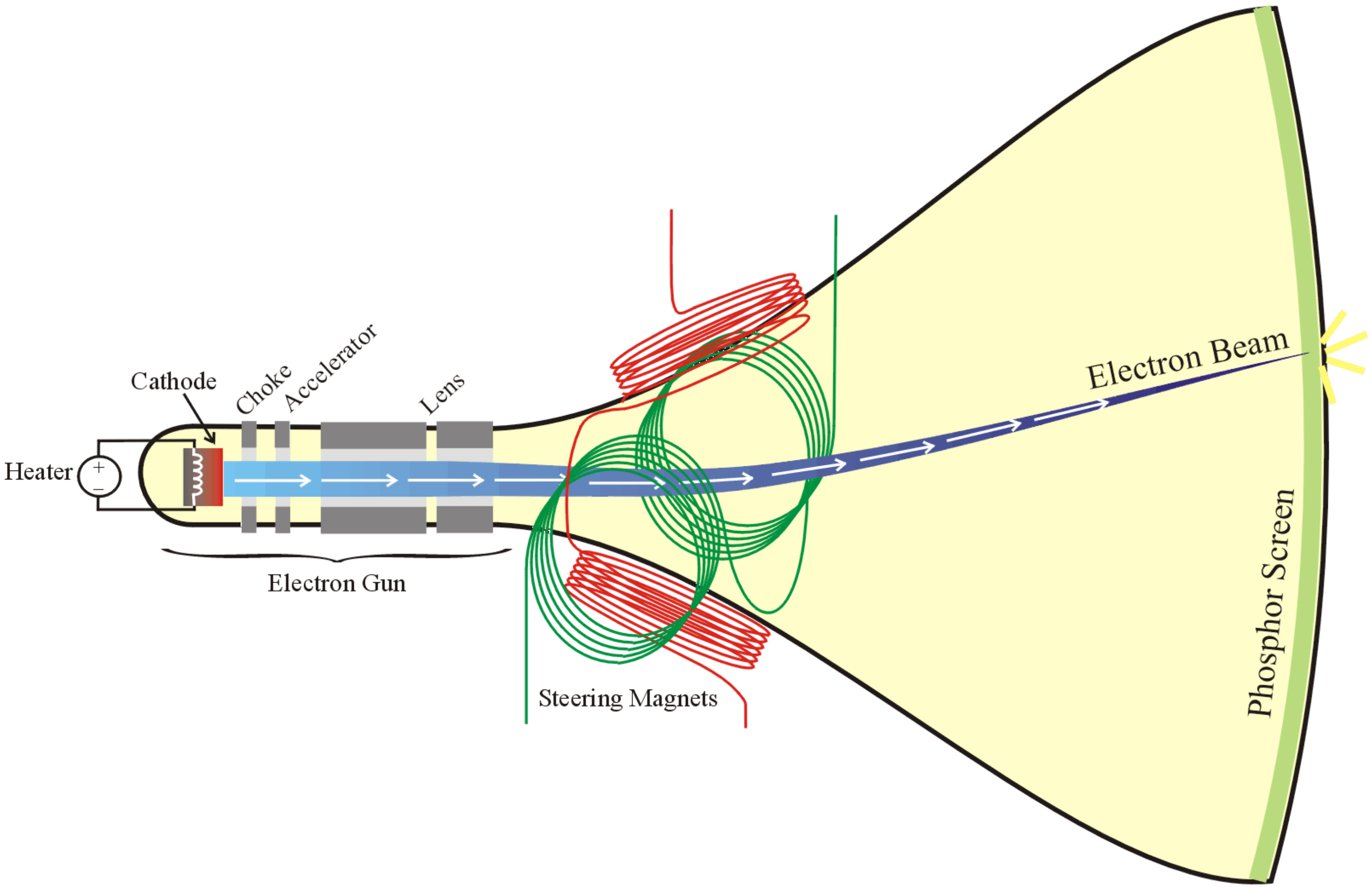


Spallation Sources

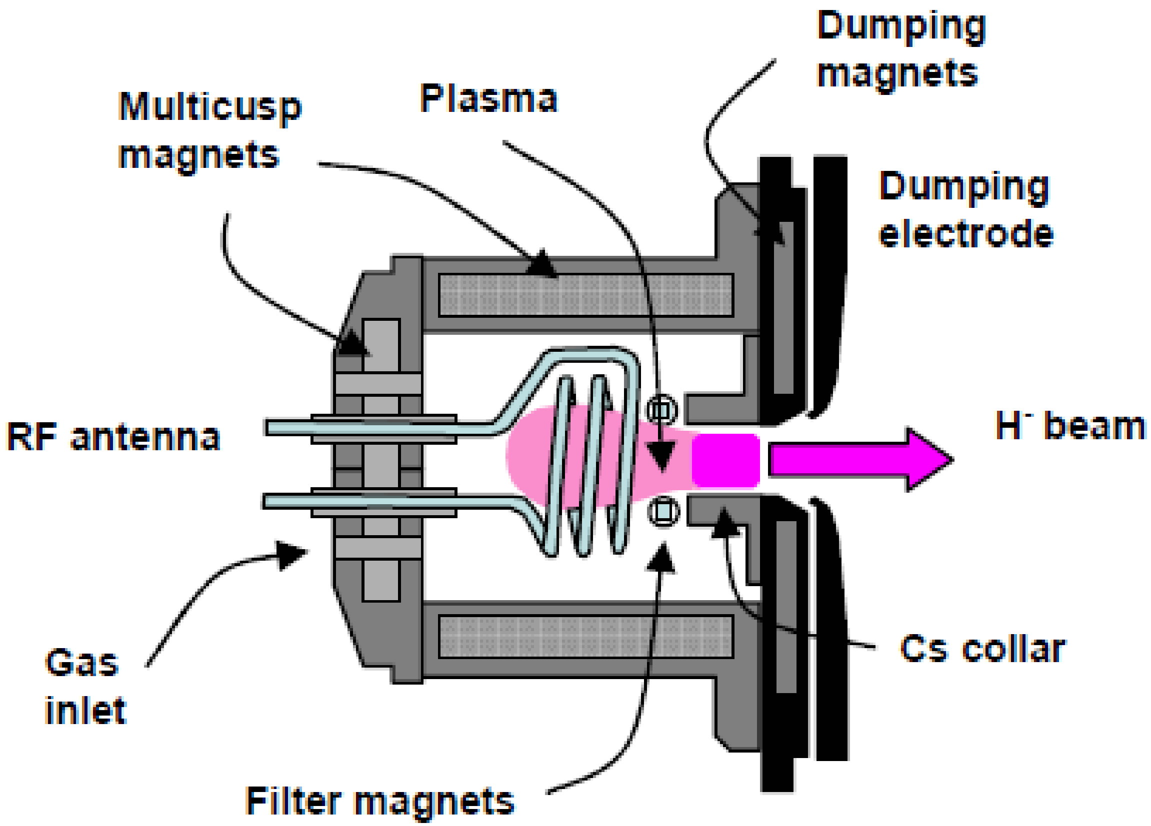
- Ion source
  - H^+ or H^-
- Accelerator
  - linear accelerator “linac”
  - cyclotron
- Compressor ring (for short-pulse sources)
  - stripper to convert H^- to H^+
  - synchrotron
- Target
- Reflector
- Moderators

Linear accelerator: LINAC

Linear accelerator: LINAC

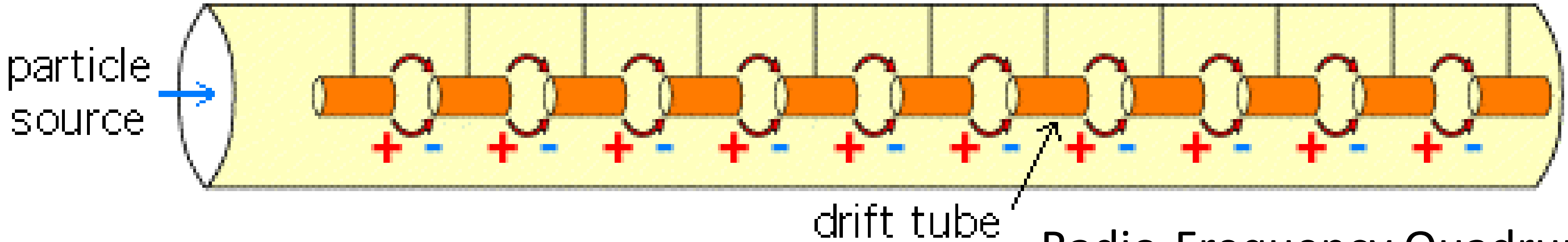


SNS ion source: H^-

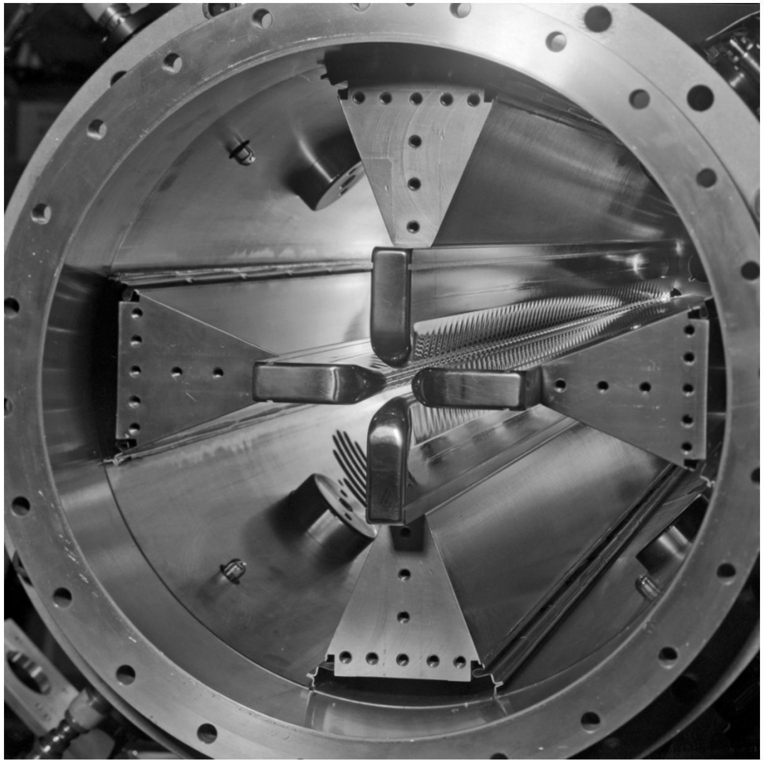


Different types of Linac

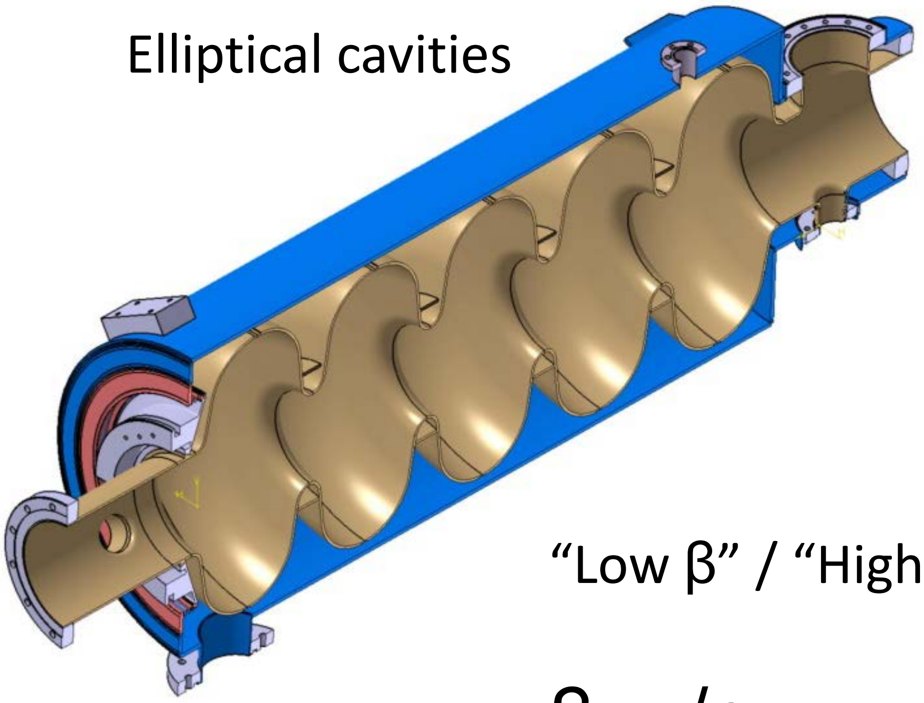
Drift-Tube Linac (DTL)



Radio-Frequency Quadrupole (RFQ)



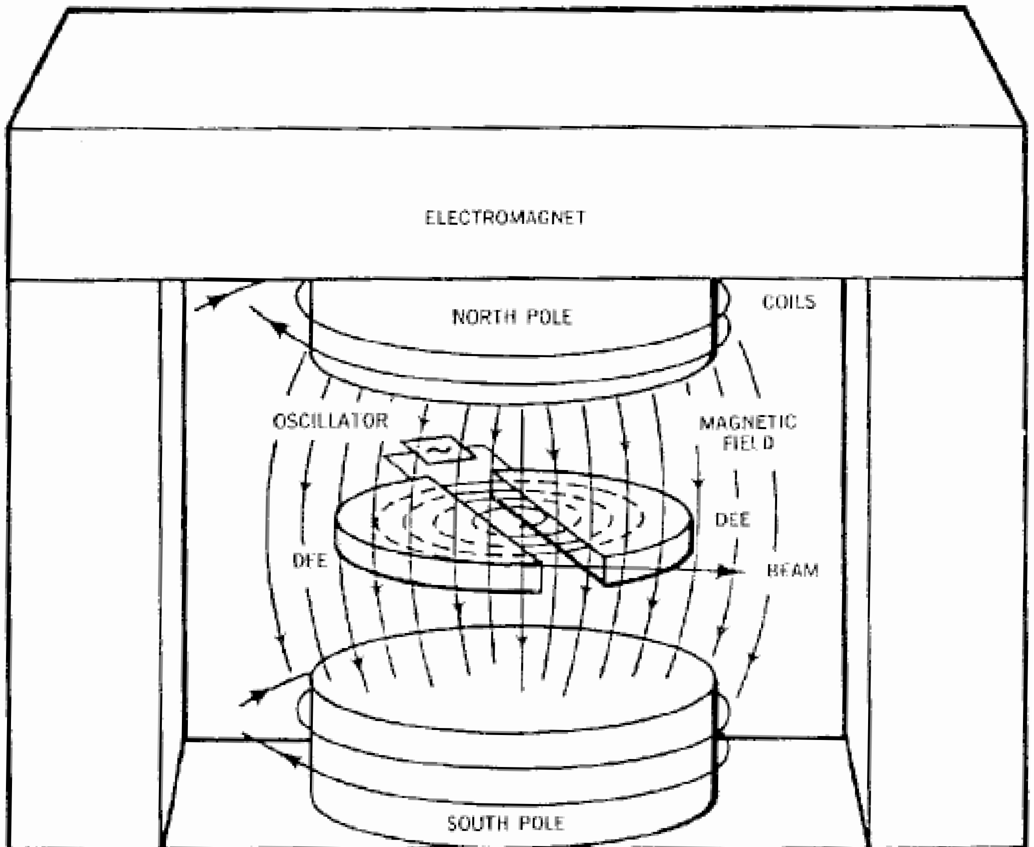
Elliptical cavities



"Low β" / "High β"

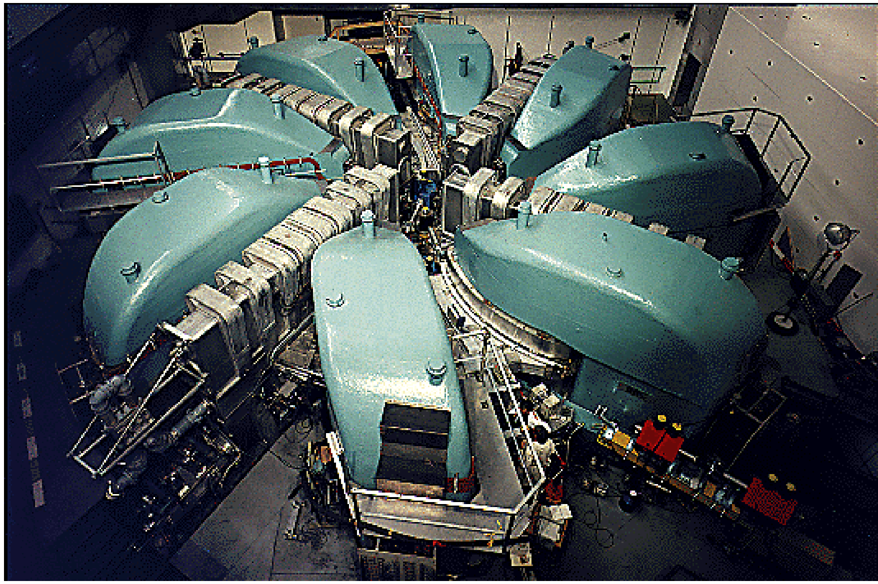
$\beta = v/c$

Cyclotrons



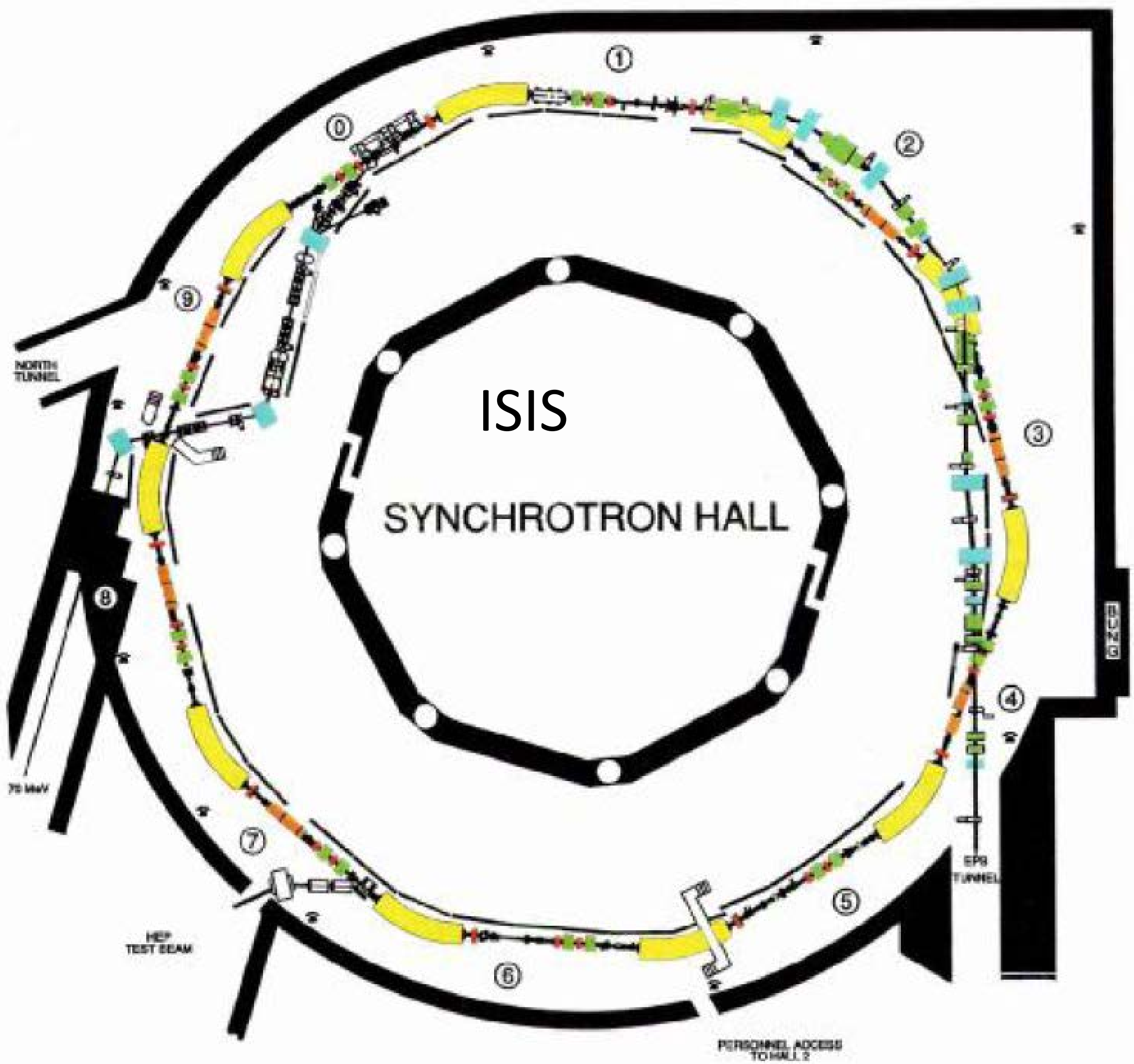
Patented by Lawrence, 1934

PSI 590 MeV cyclotron



Synchrotron

- Synchronise:
  - B-field: bend
  - E-field: accelerate
  - E & B field: focus
  - magnets to each other
- Injection
  - stripper foil
- Extraction
  - kicker magnet



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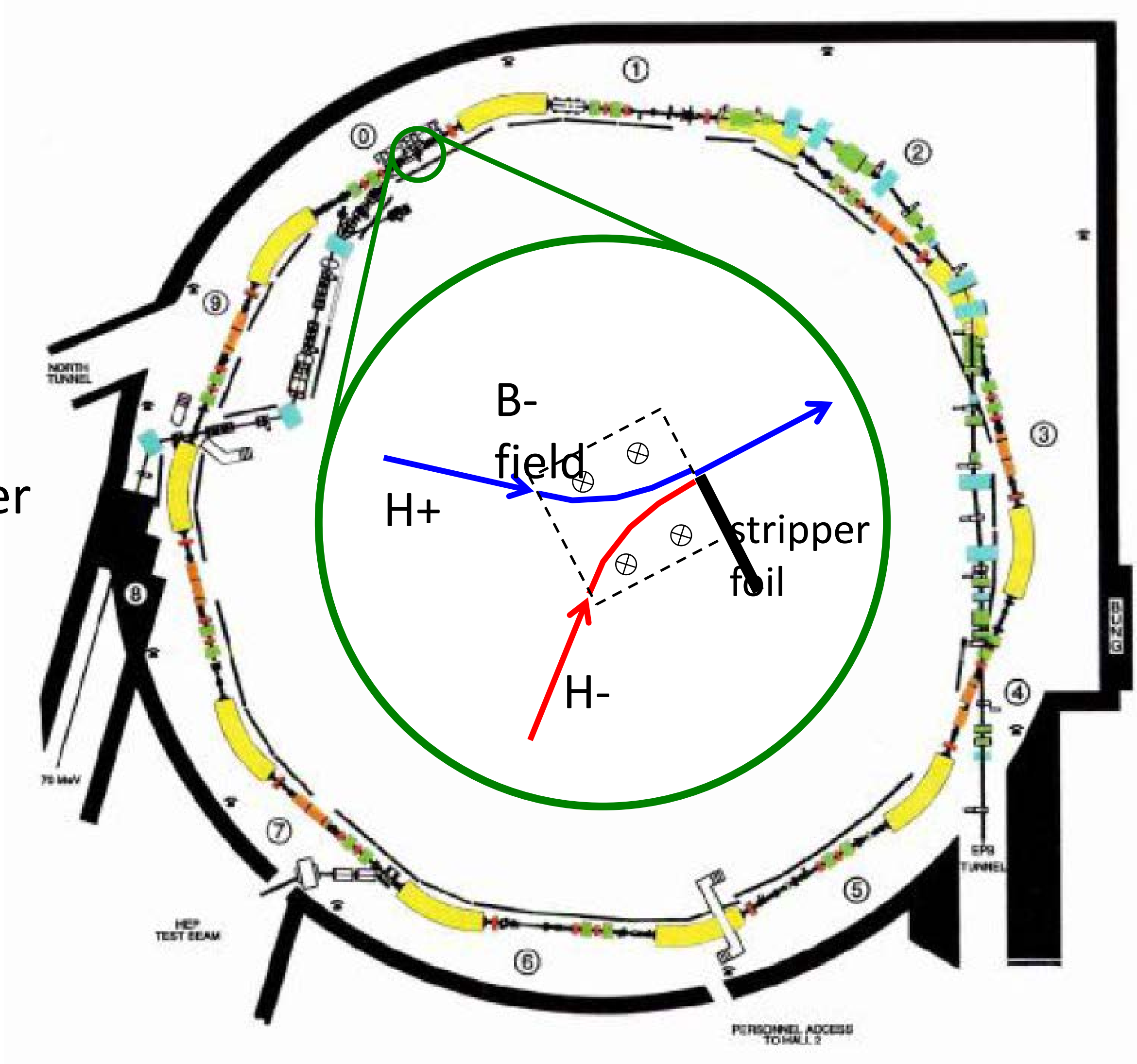
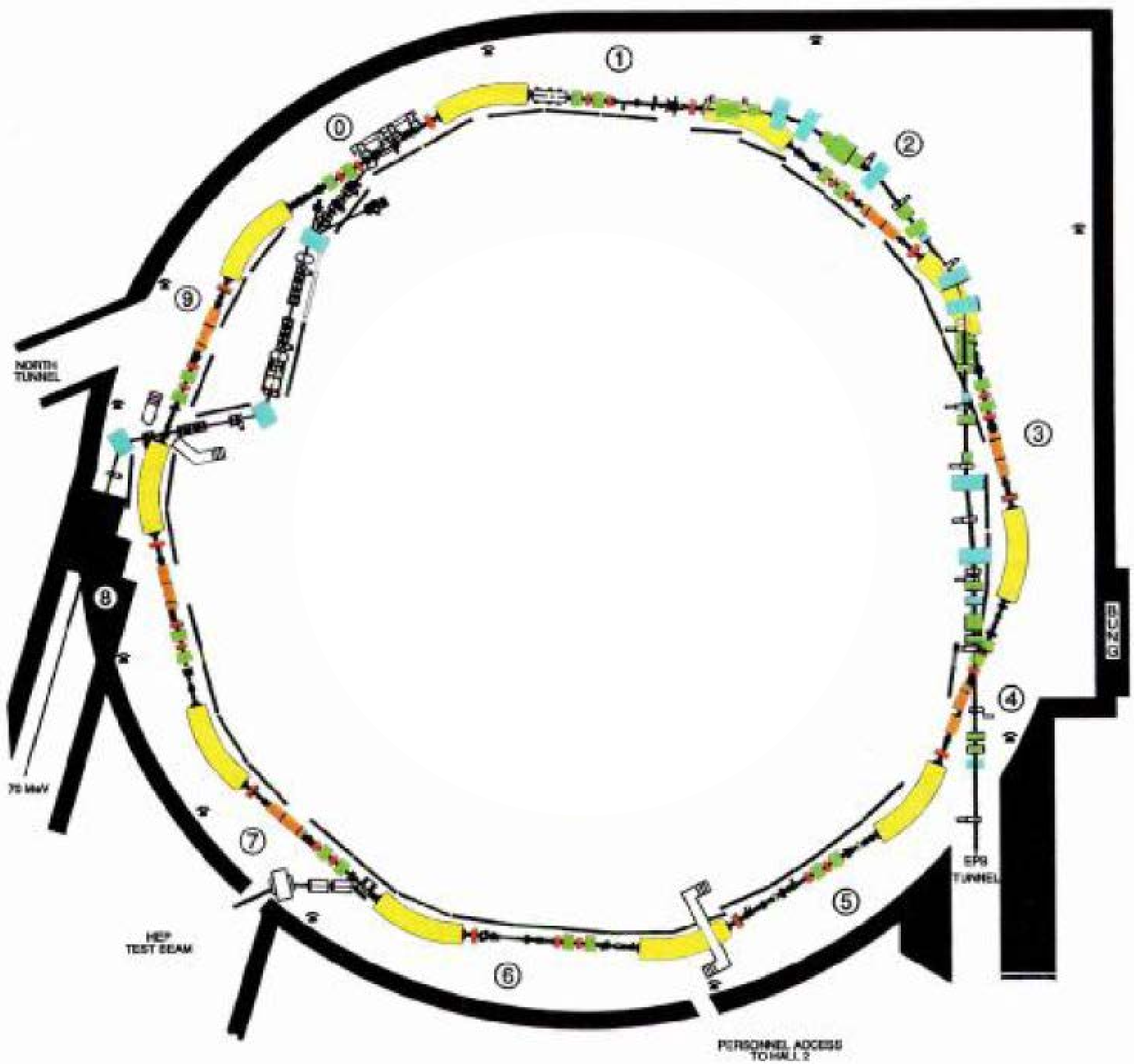


Synchrotron

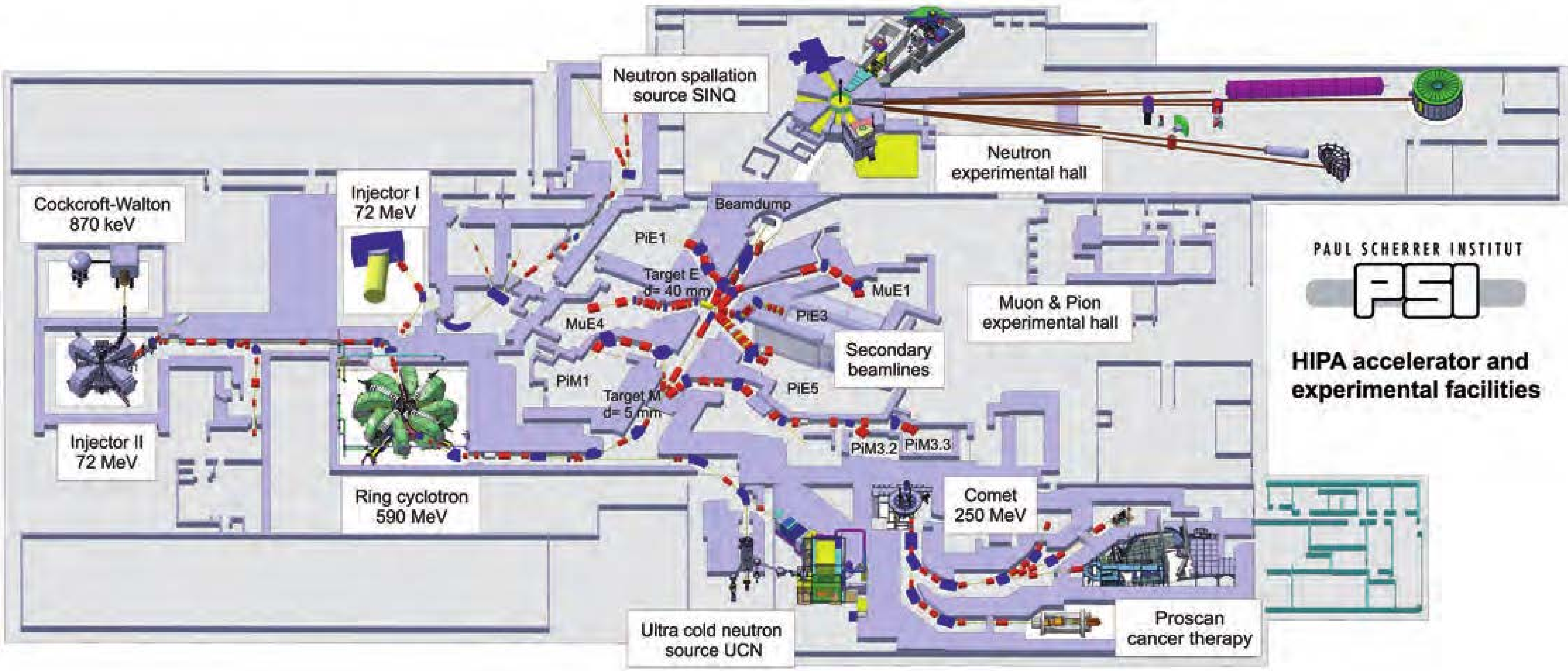
- $\Delta t_{linac} \approx 1$ ms
- $E_{ring} \approx 1$ GeV
  - $v \approx 3 \times 10^8$ m/s
- $L_{ring} \approx 200$ m
- $\Delta t_{ring} \approx 1$ µs



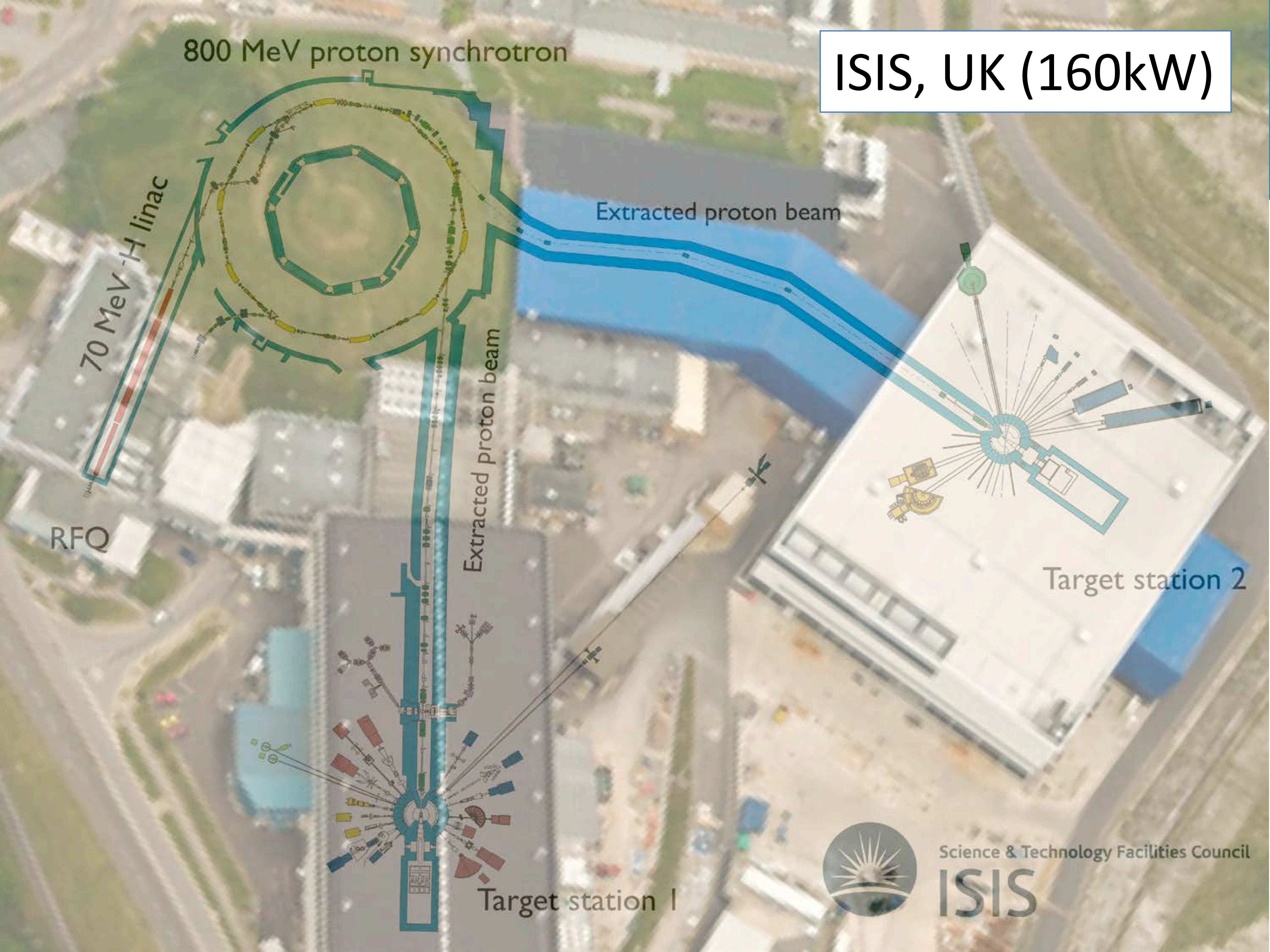
ESS, Lund, Sweden (first neutrons in 2023)

EUROPEAN SPALLATION SOURCE

SINQ, PSI, Switzerland



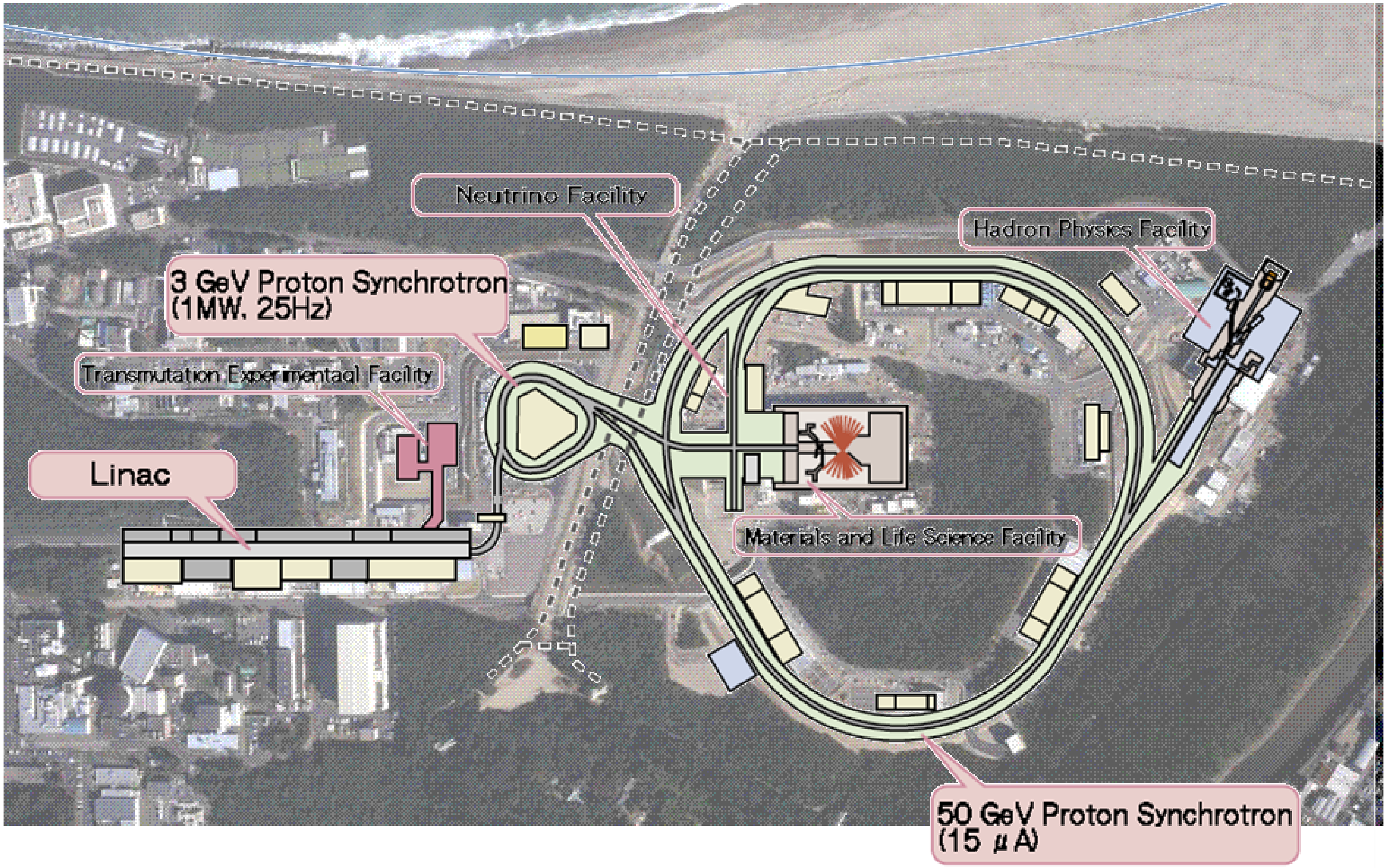
ISIS, UK (160kW)



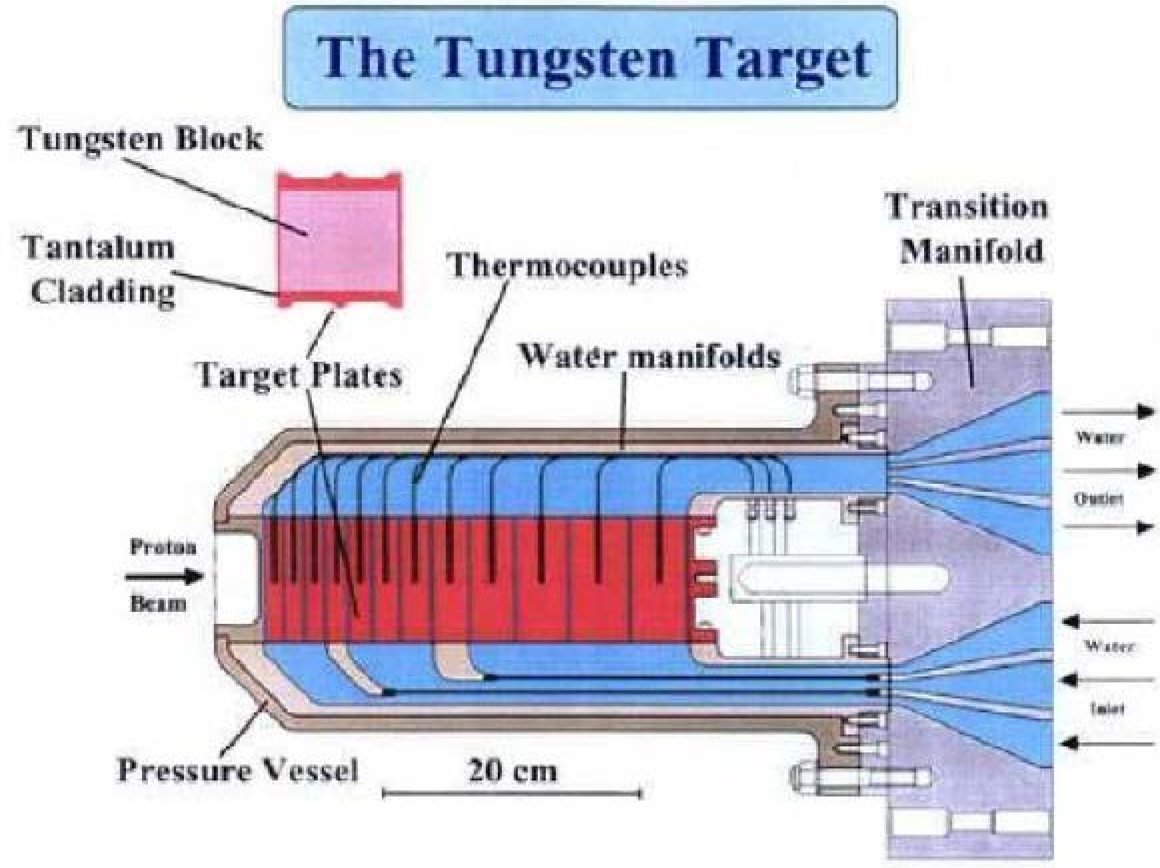
SNS, Oak Ridge, USA (1MW)

J-PARC, Tokai, Japan (500kW)

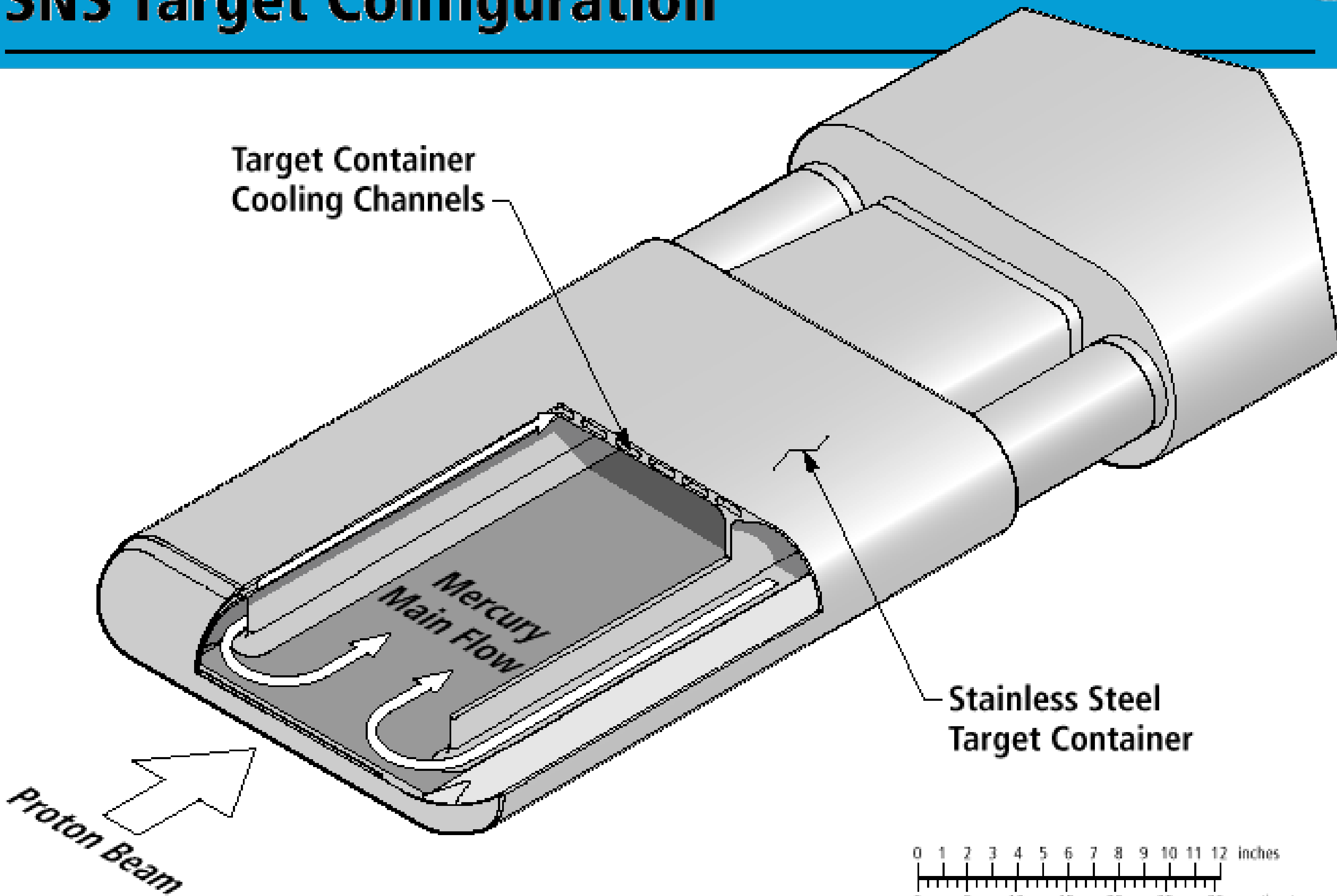
J-PARC, Tokai, Japan (500kW)



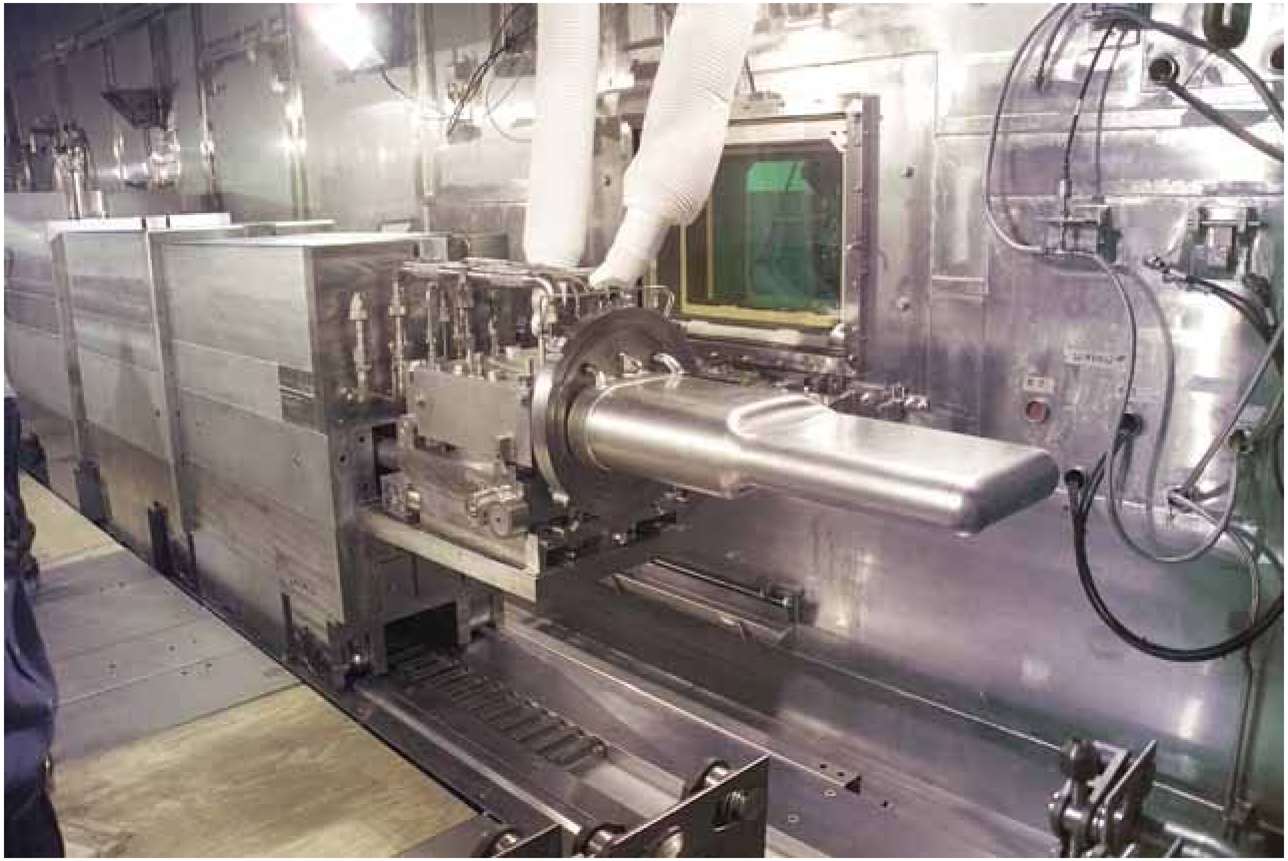
ISIS target 1: solid tungsten



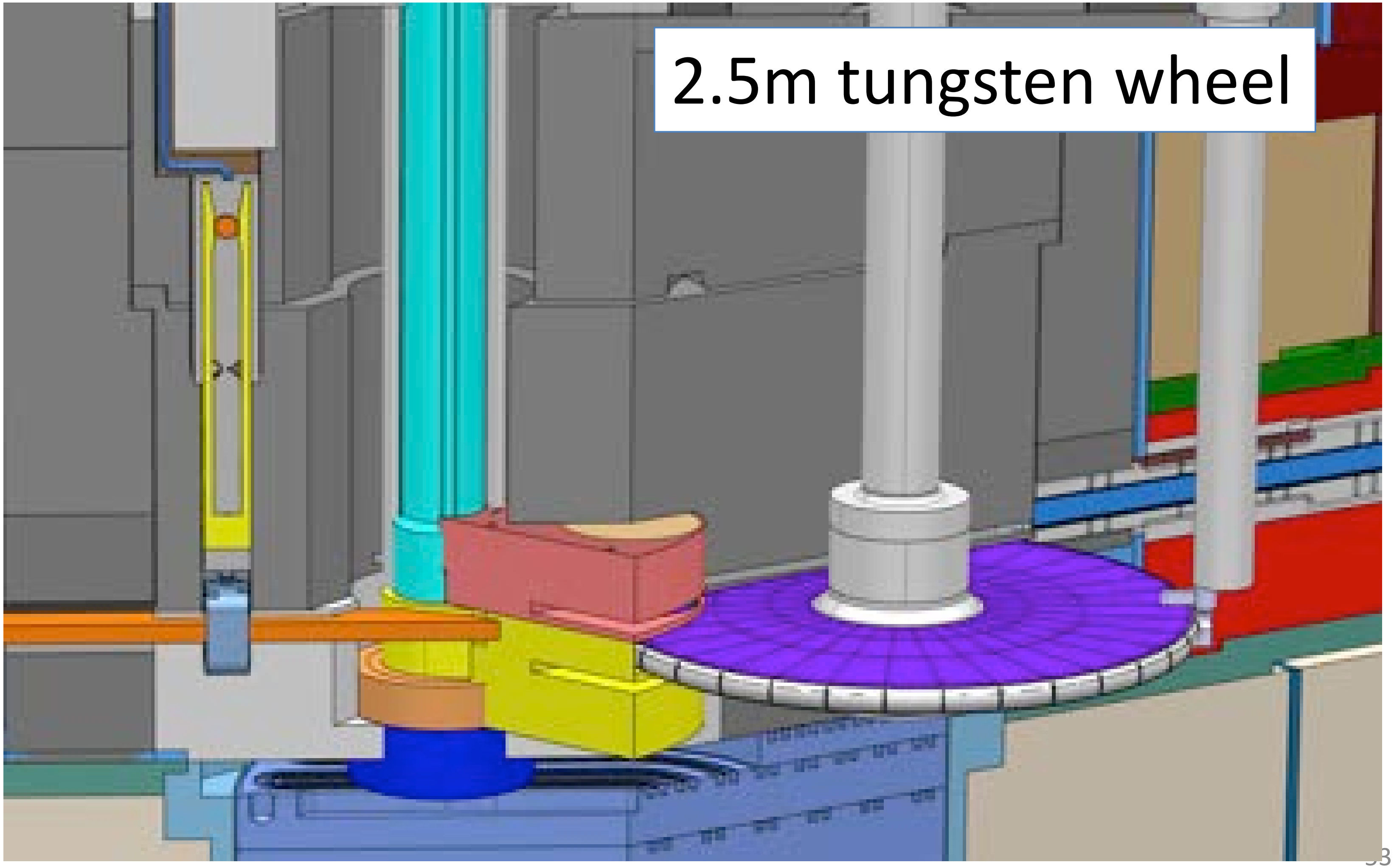
SNS Target Configuration



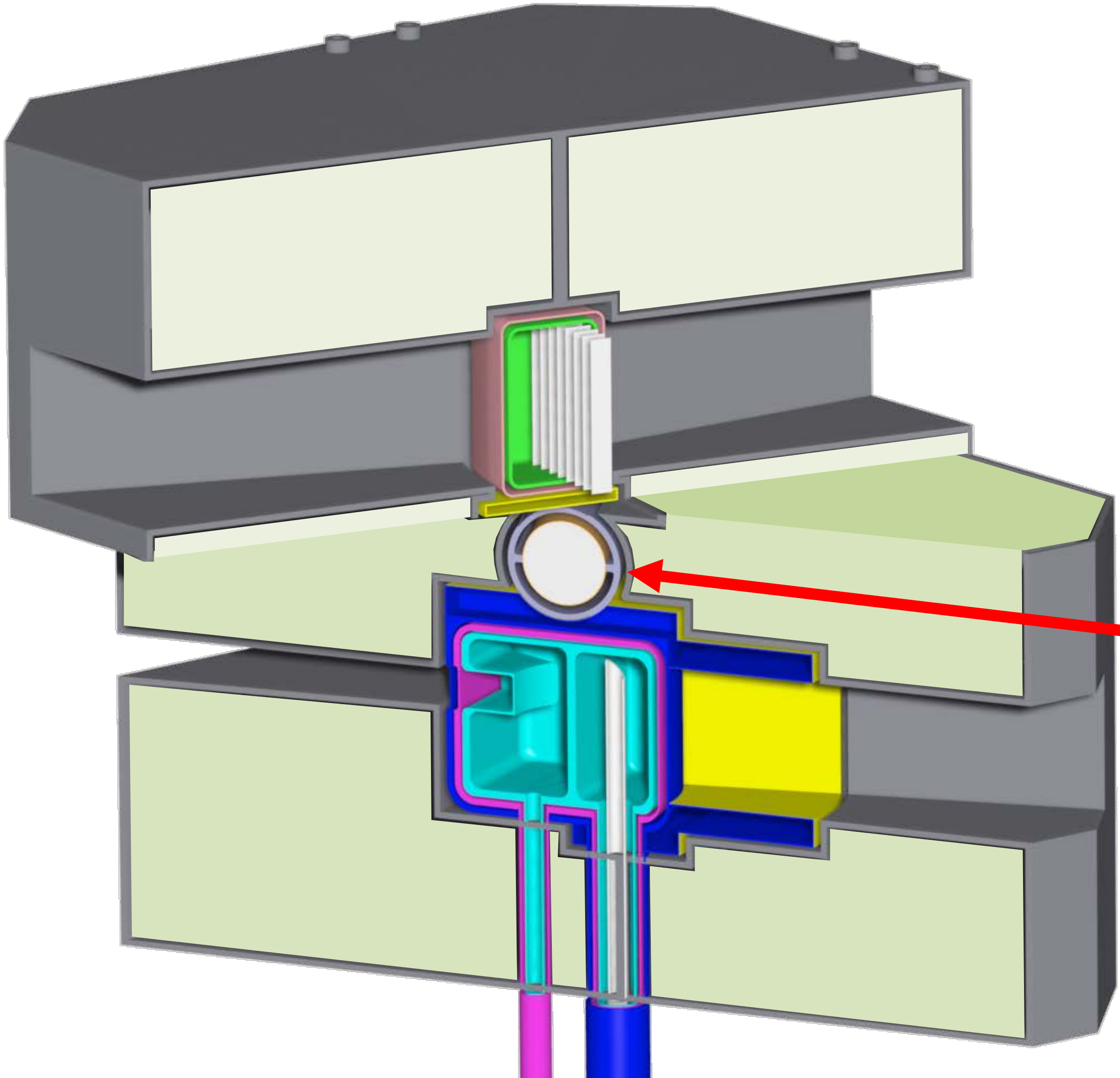
SNS target: liquid mercury



ESS target



ISIS TS2 Target



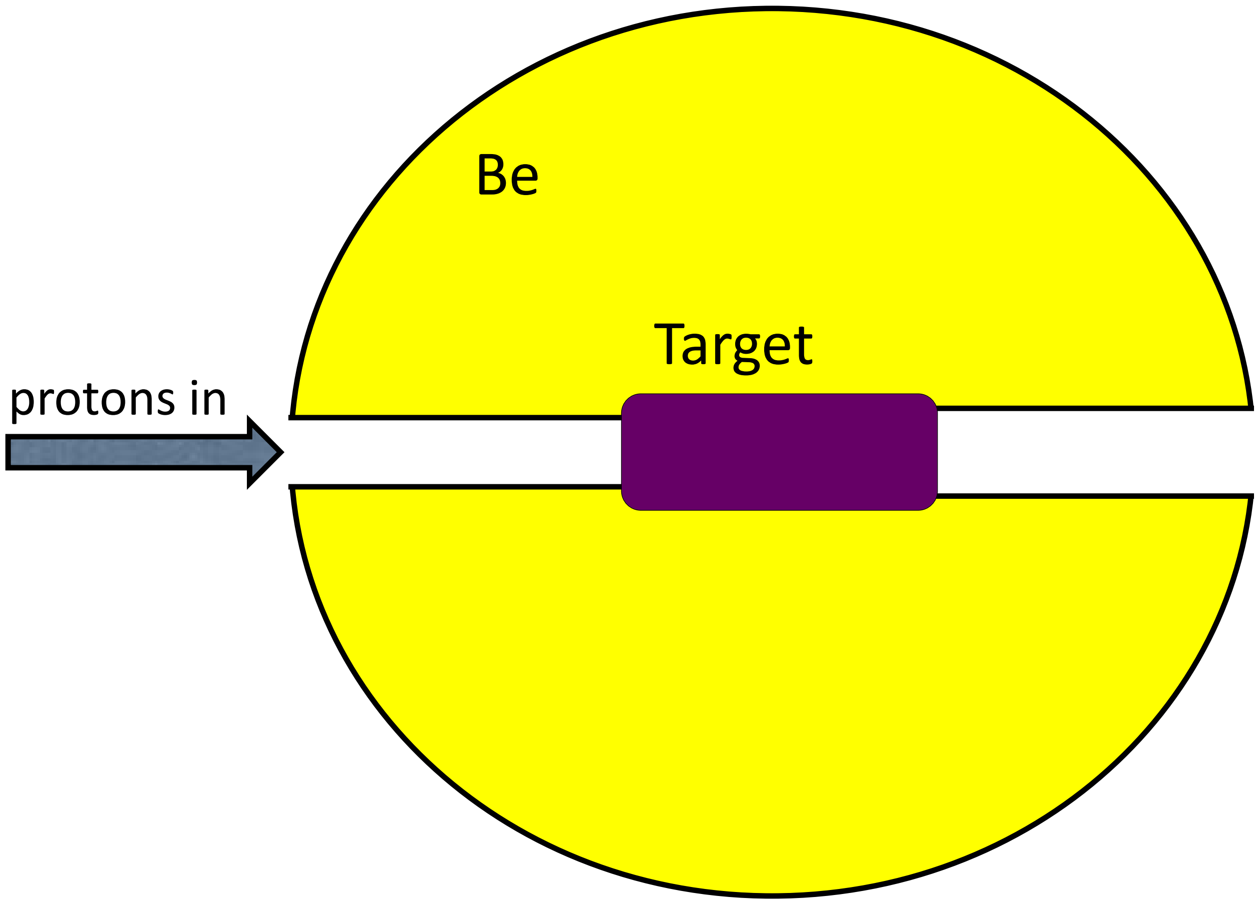
Target-Reflector-Moderator Neutronics

EUROPEAN SPALLATION SOURCE

- Target produces neutrons in > MeV range
- Moderators contain H to thermalise neutrons
  - largest scattering cross-section (80b)
  - lower mass: same as neutron
  - on average, ½ energy lost per collision
  - 100 MeV -> 10 meV 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 plane



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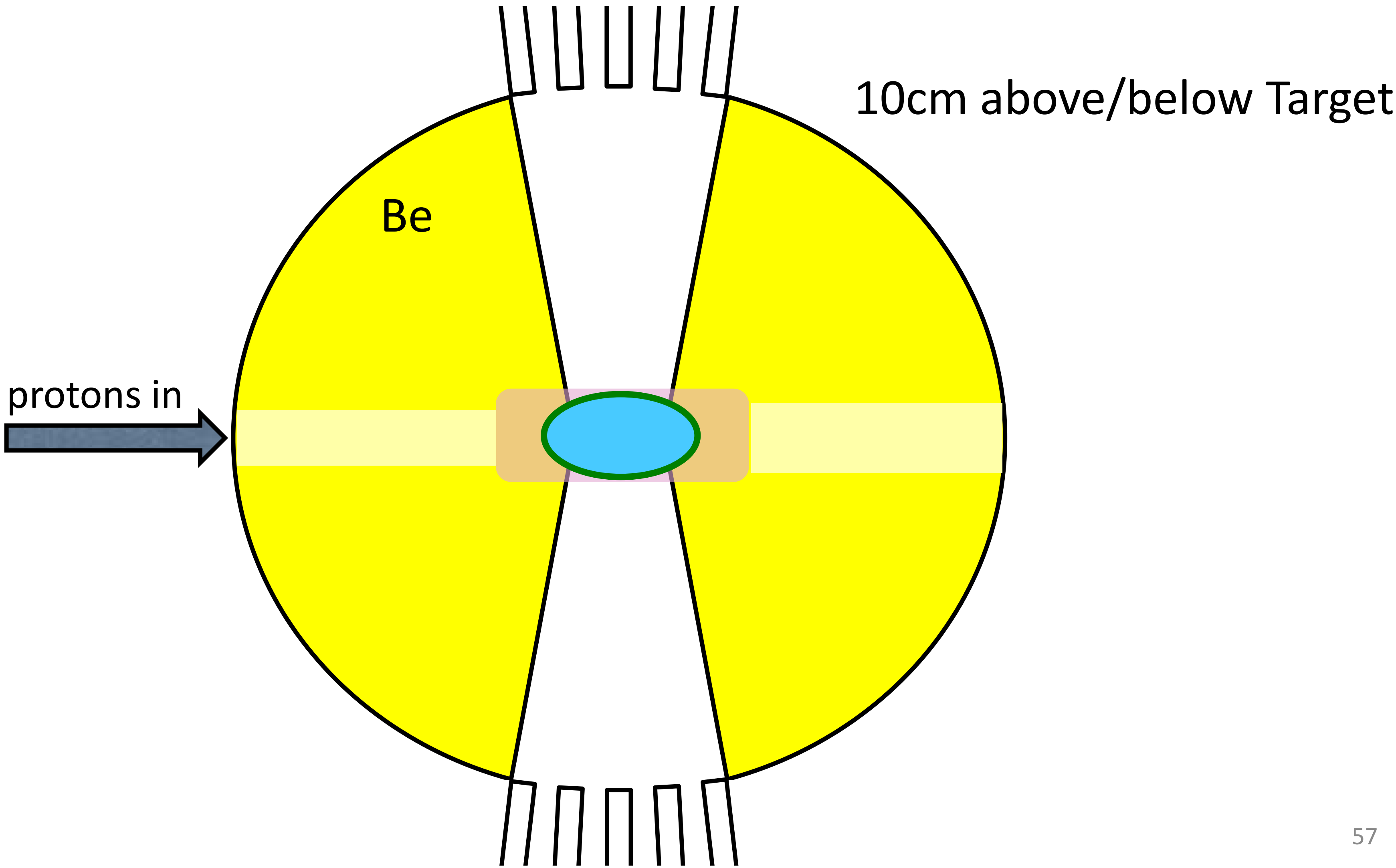
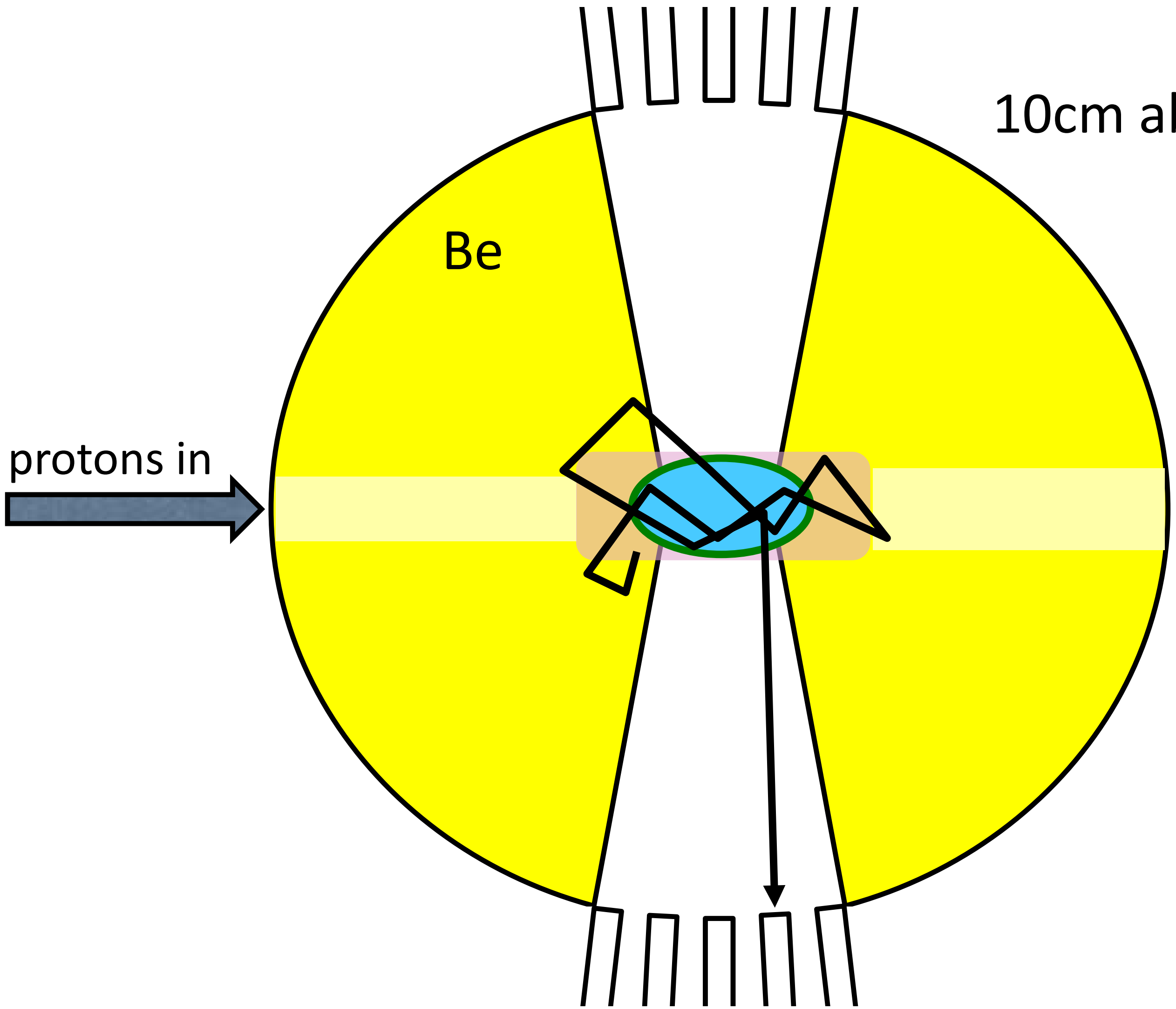


Target-Reflector-Moderator Neutronics

10cm above/below Target



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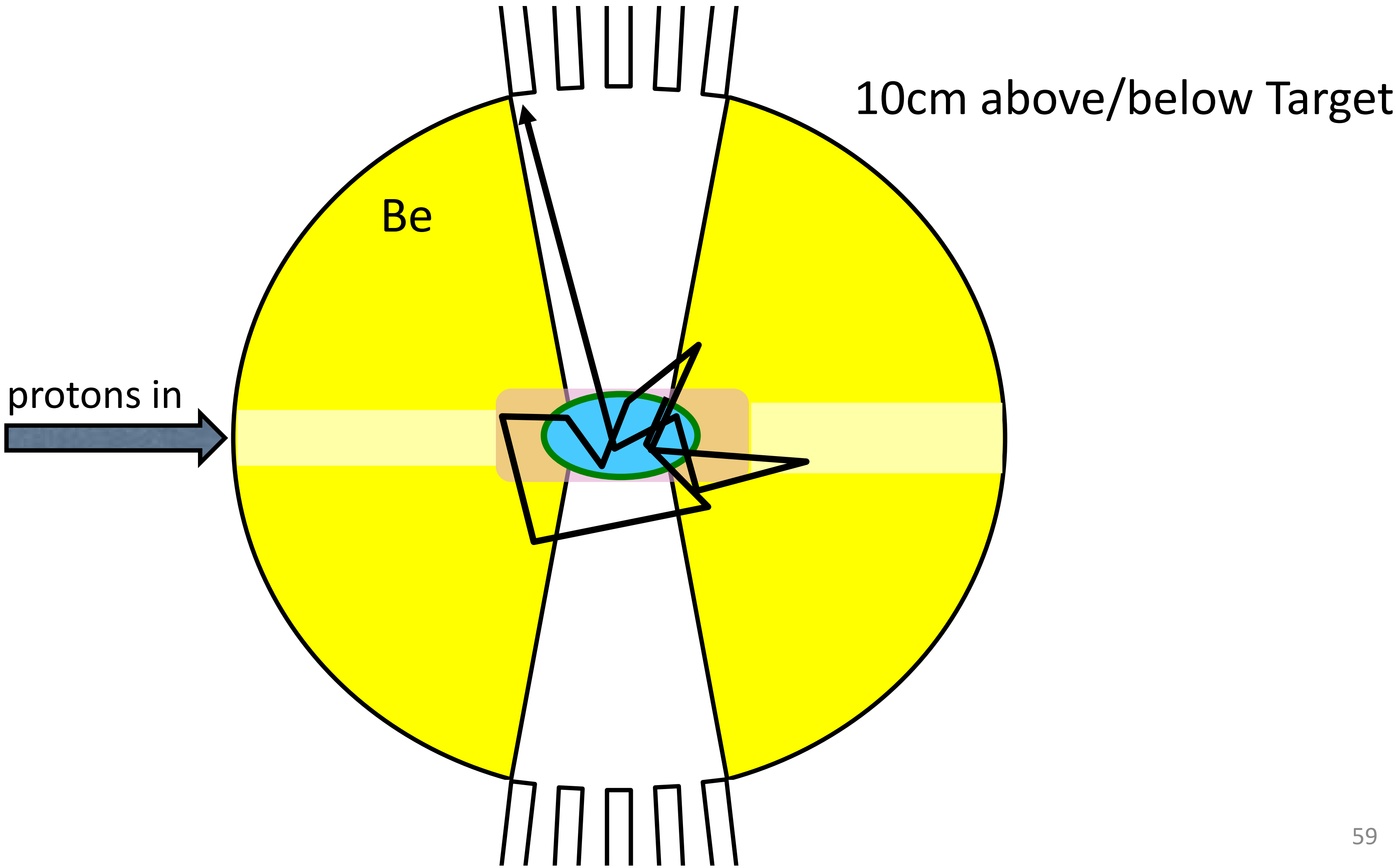

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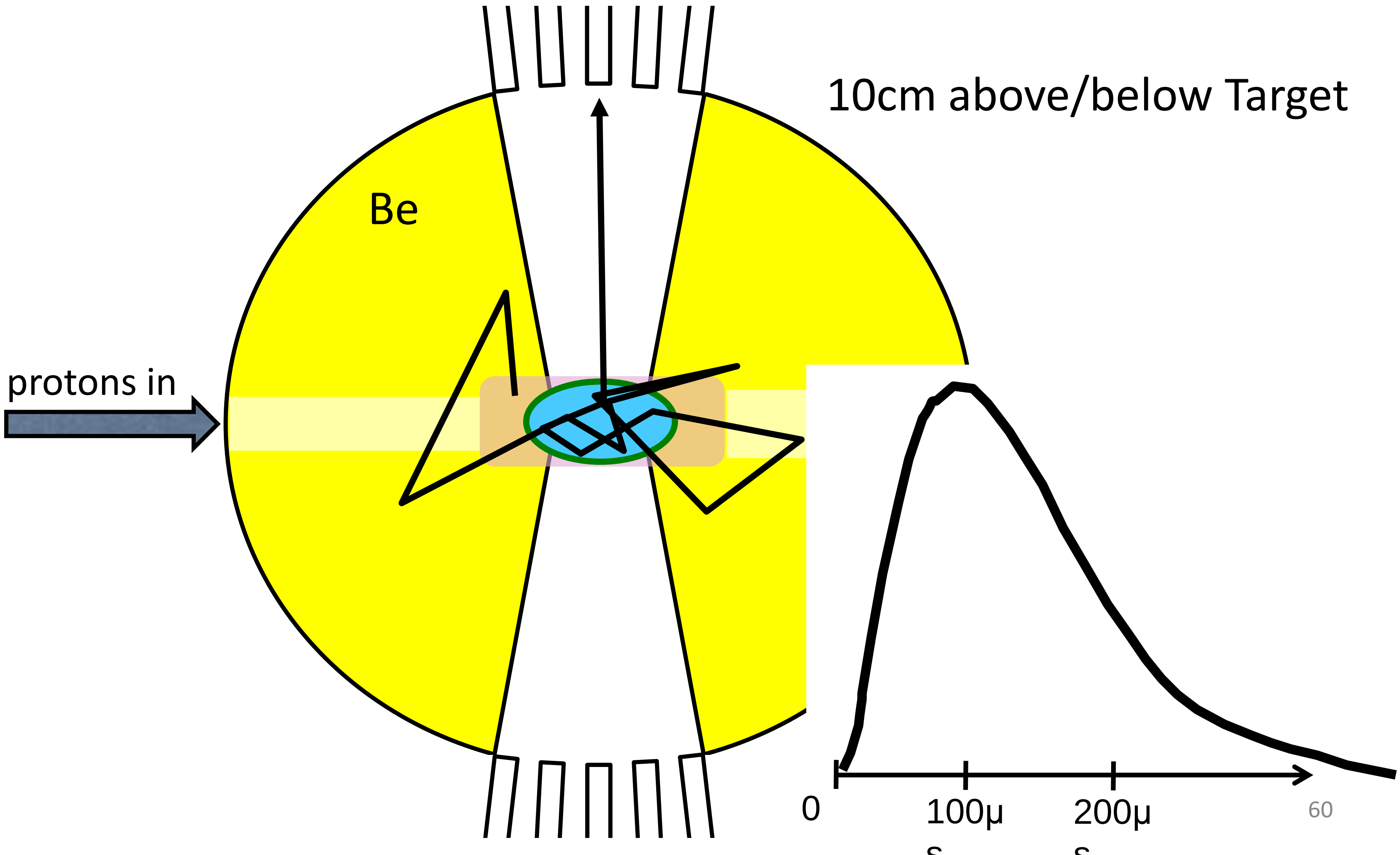

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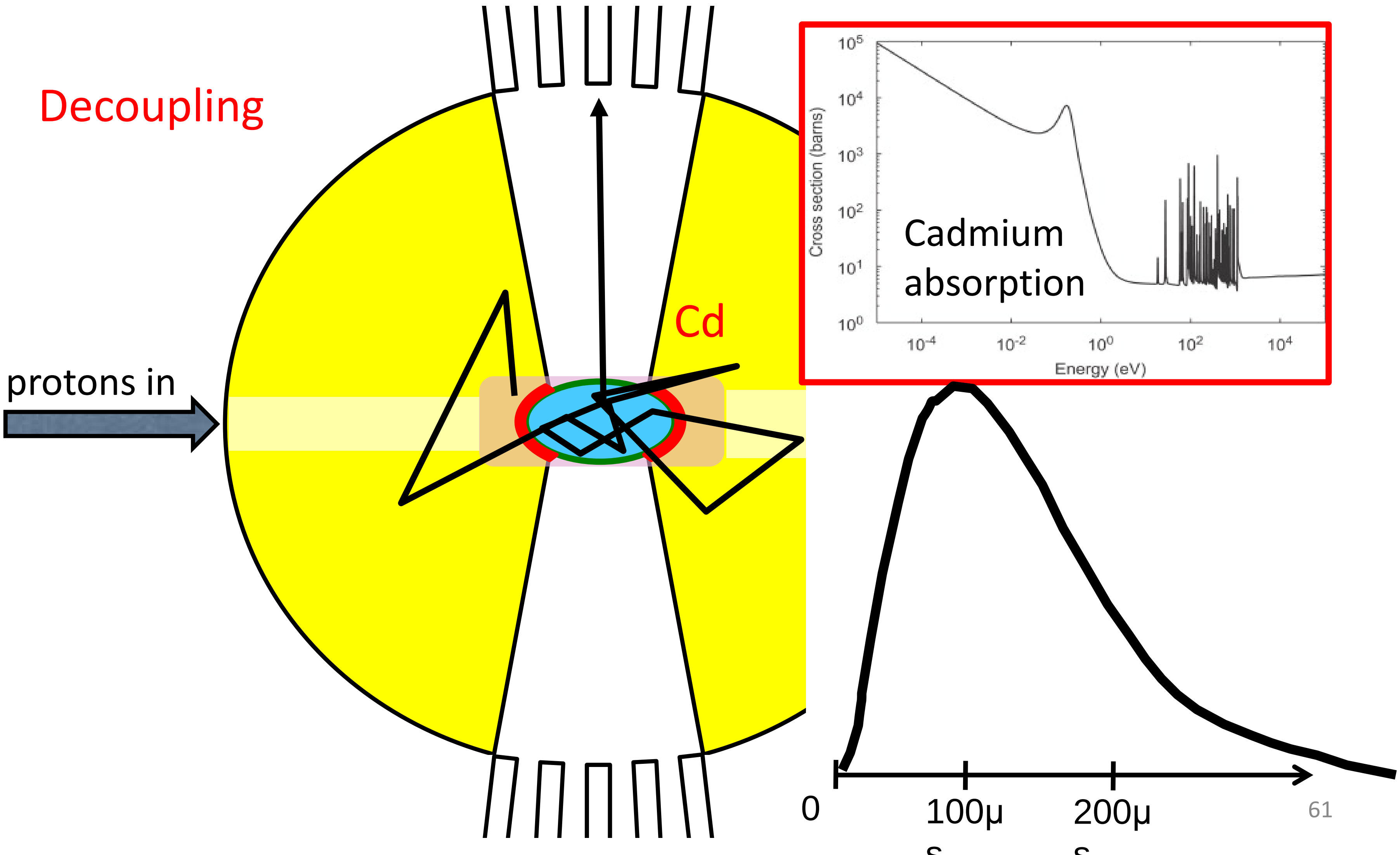

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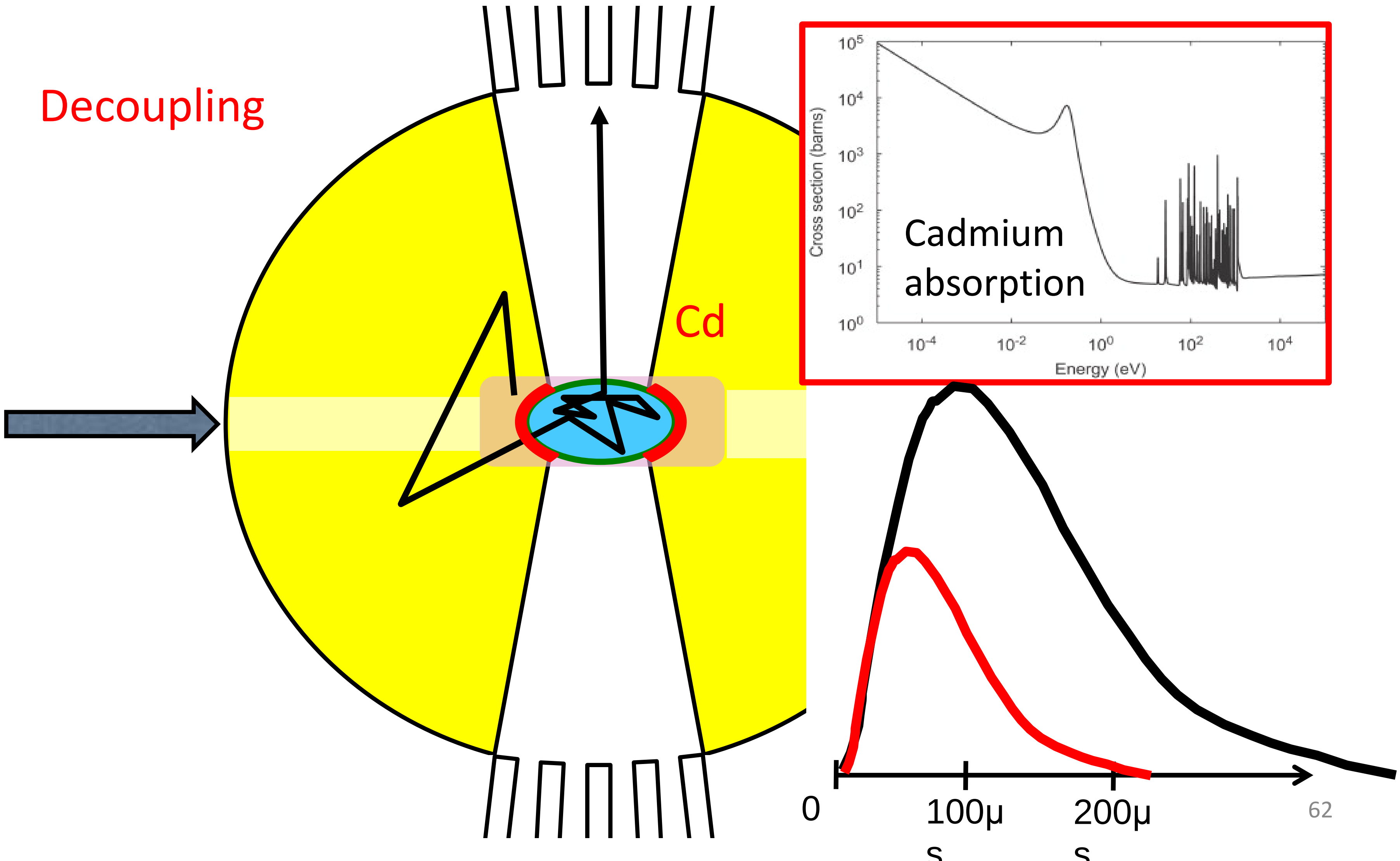
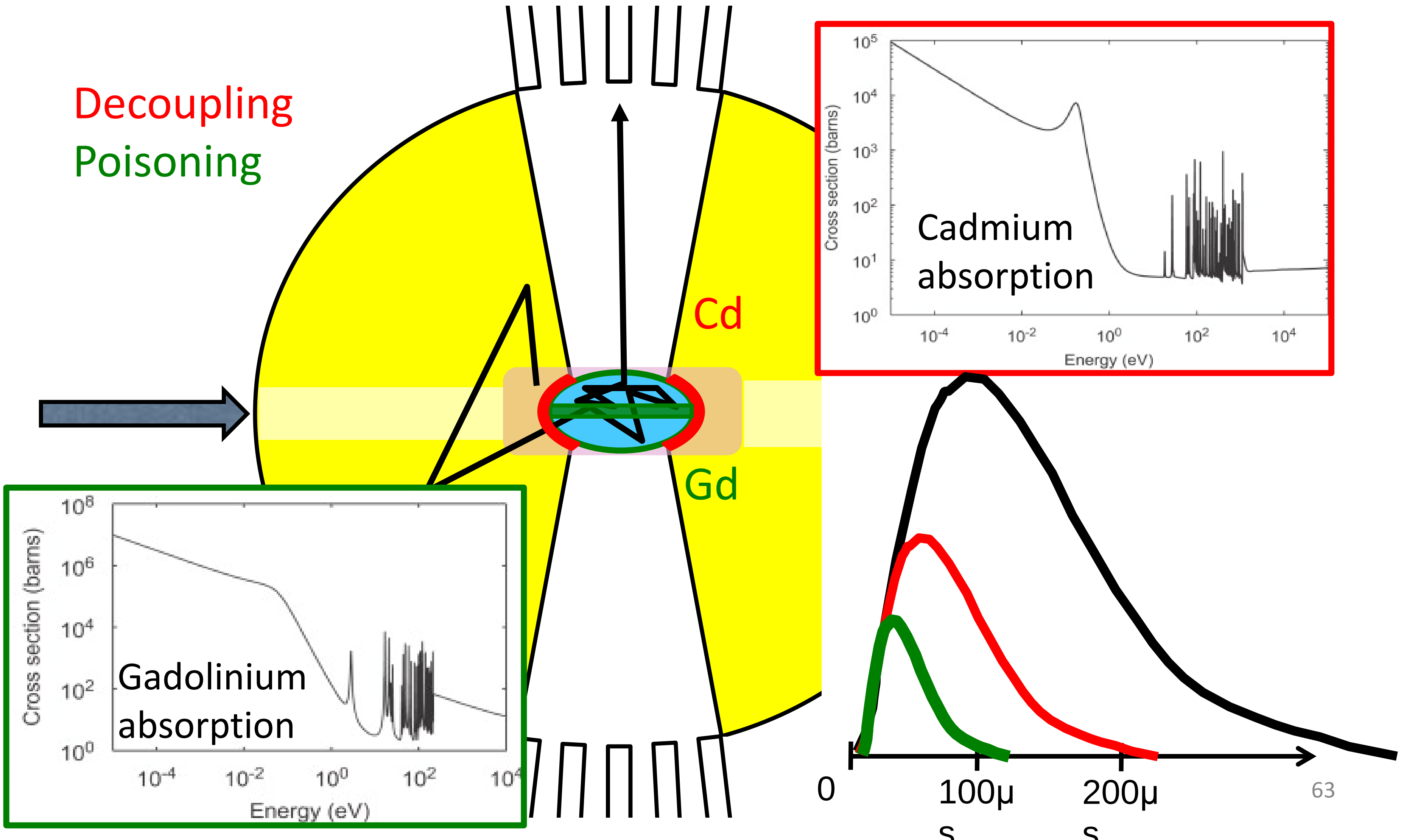
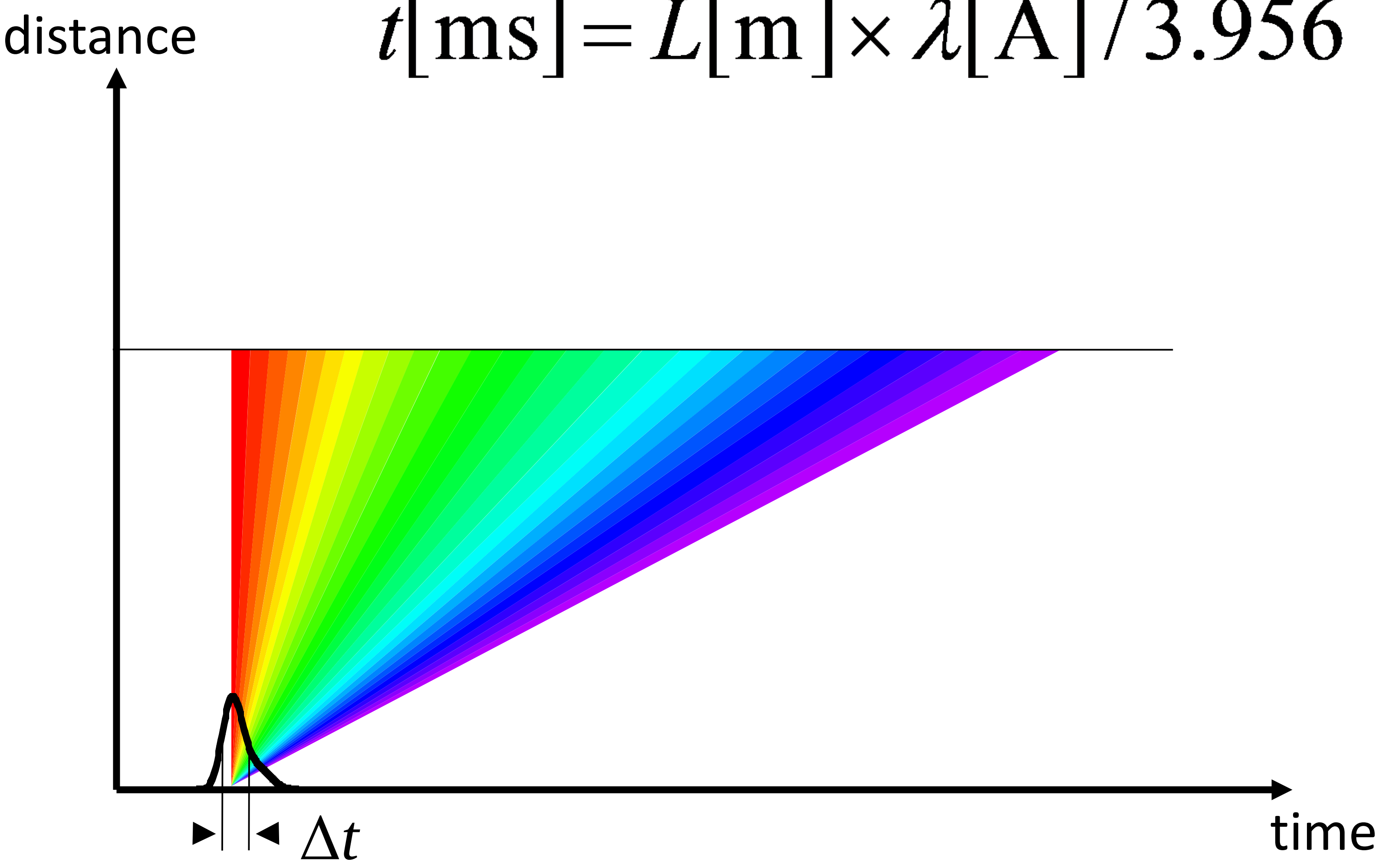


Target-Reflector-Moderator Neutronics



Time-of-flight (TOF) resolution

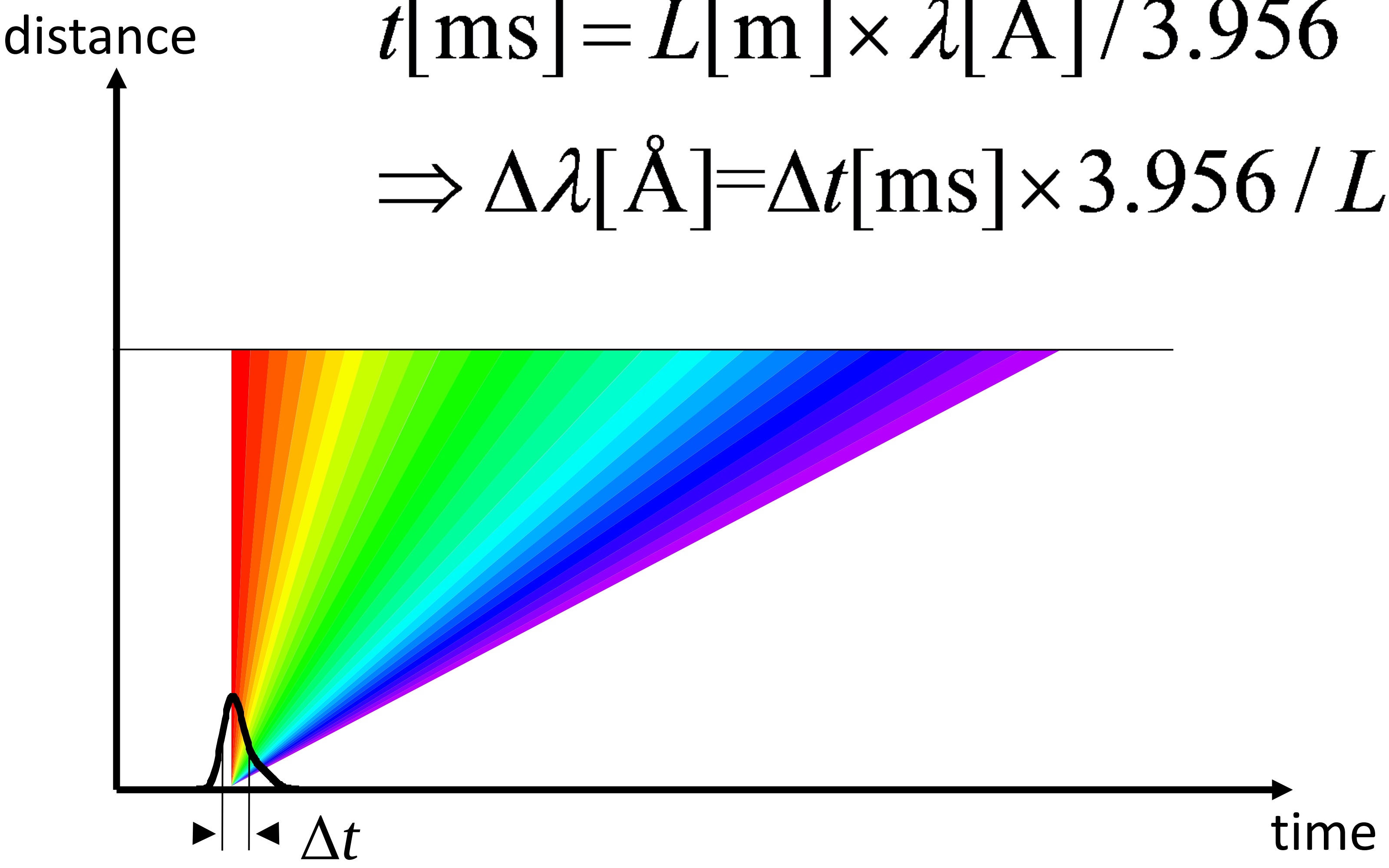
$$t[\mathrm{ms}] = L[\mathrm{m}] \times \lambda[\text{Å}] / 3.956$$



Time-of-flight (TOF) resolution

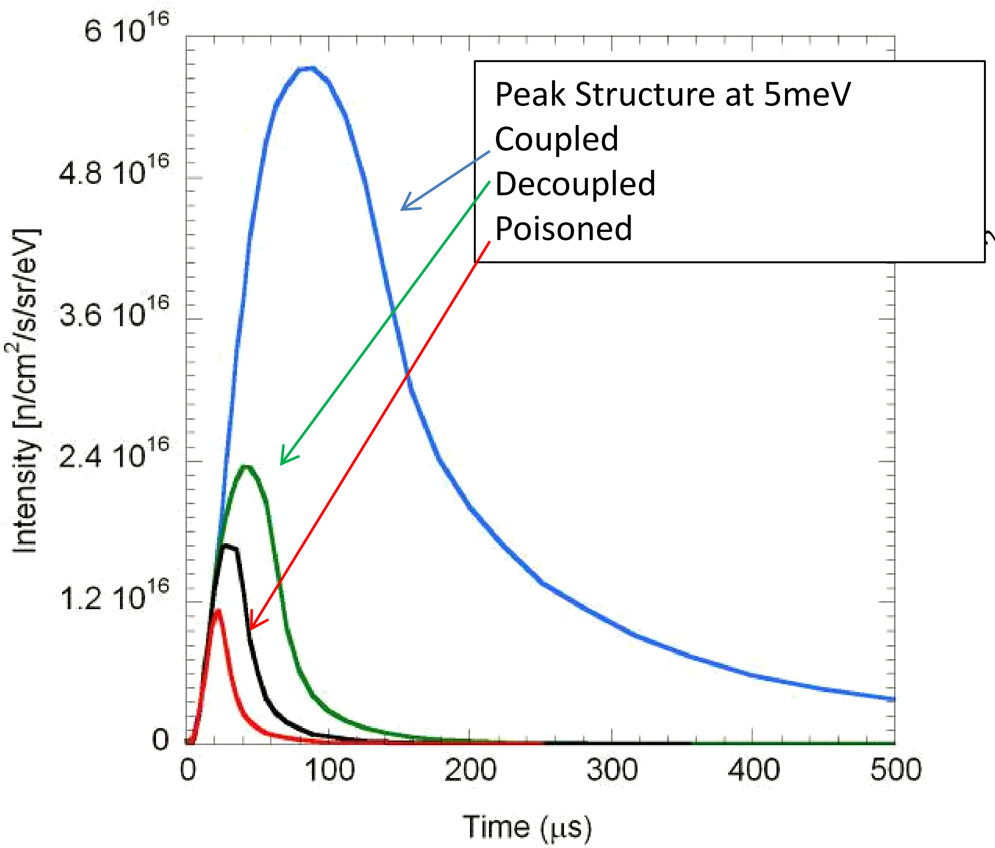
$$t[\text{ms}] = L[\text{m}] \times \lambda[\text{Å}] / 3.956$$

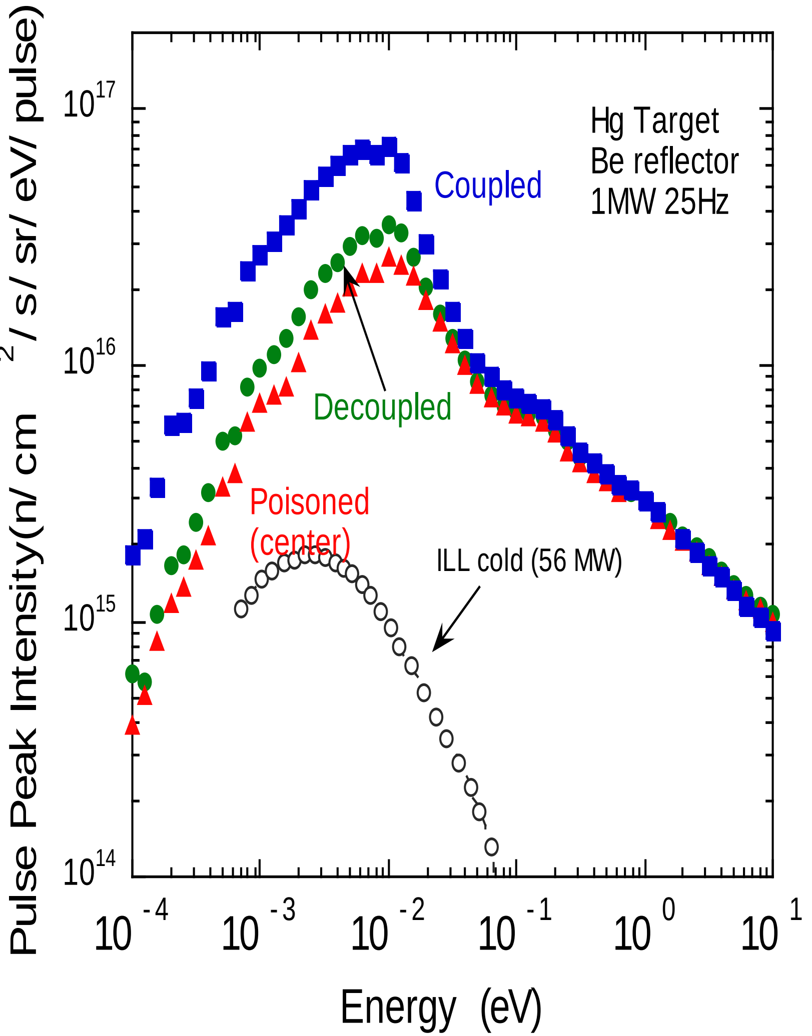
$$\Rightarrow \Delta\lambda[\text{Å}] = \Delta t[\text{ms}] \times 3.956 / L[\text{m}]$$



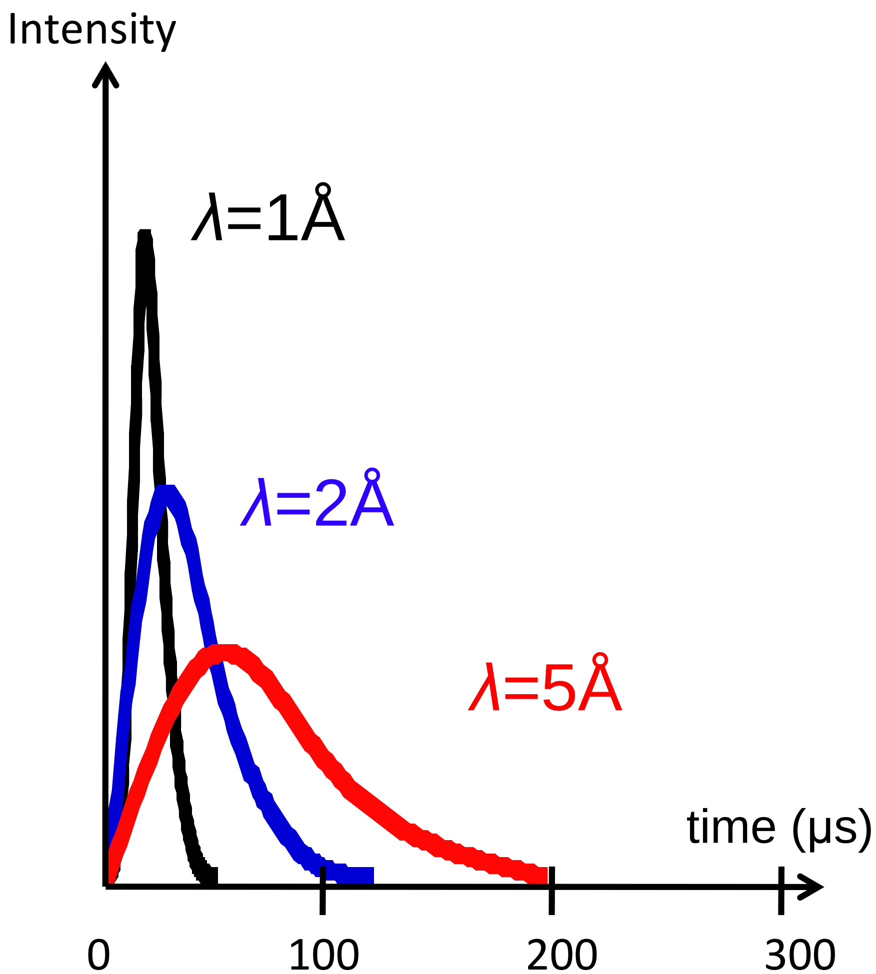
Moderator Decoupling and Poisoning

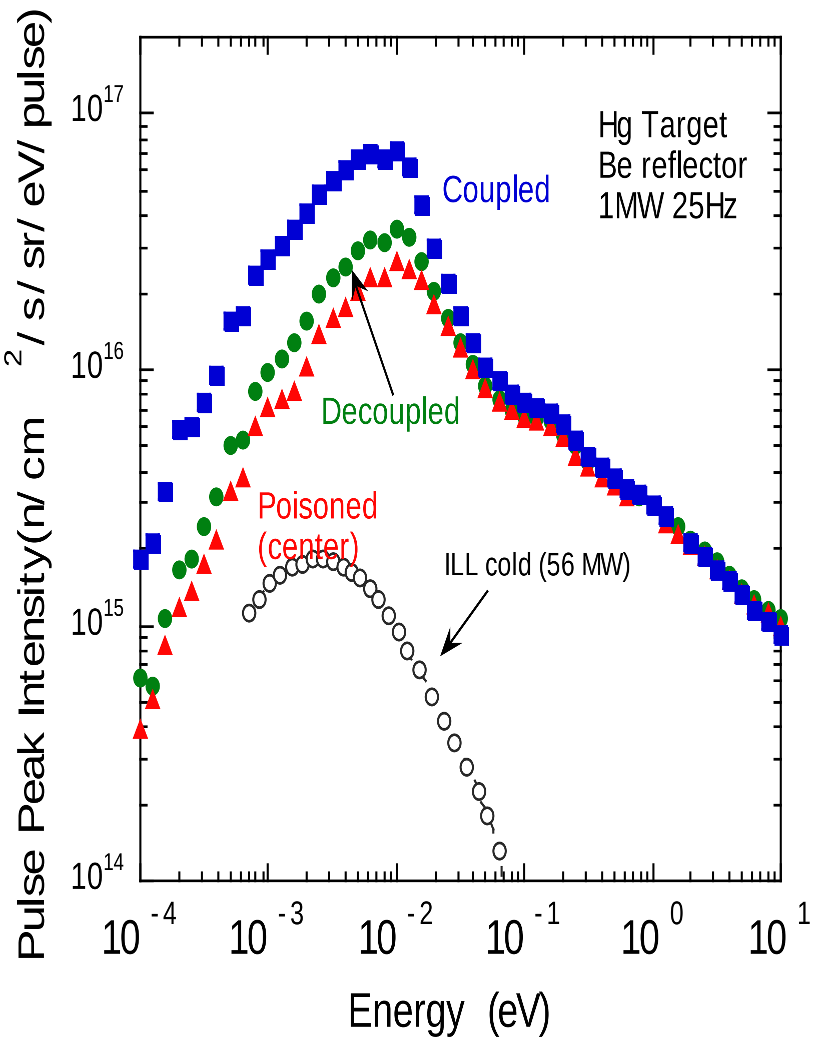
J-PARC H_2 moderators at 1MW



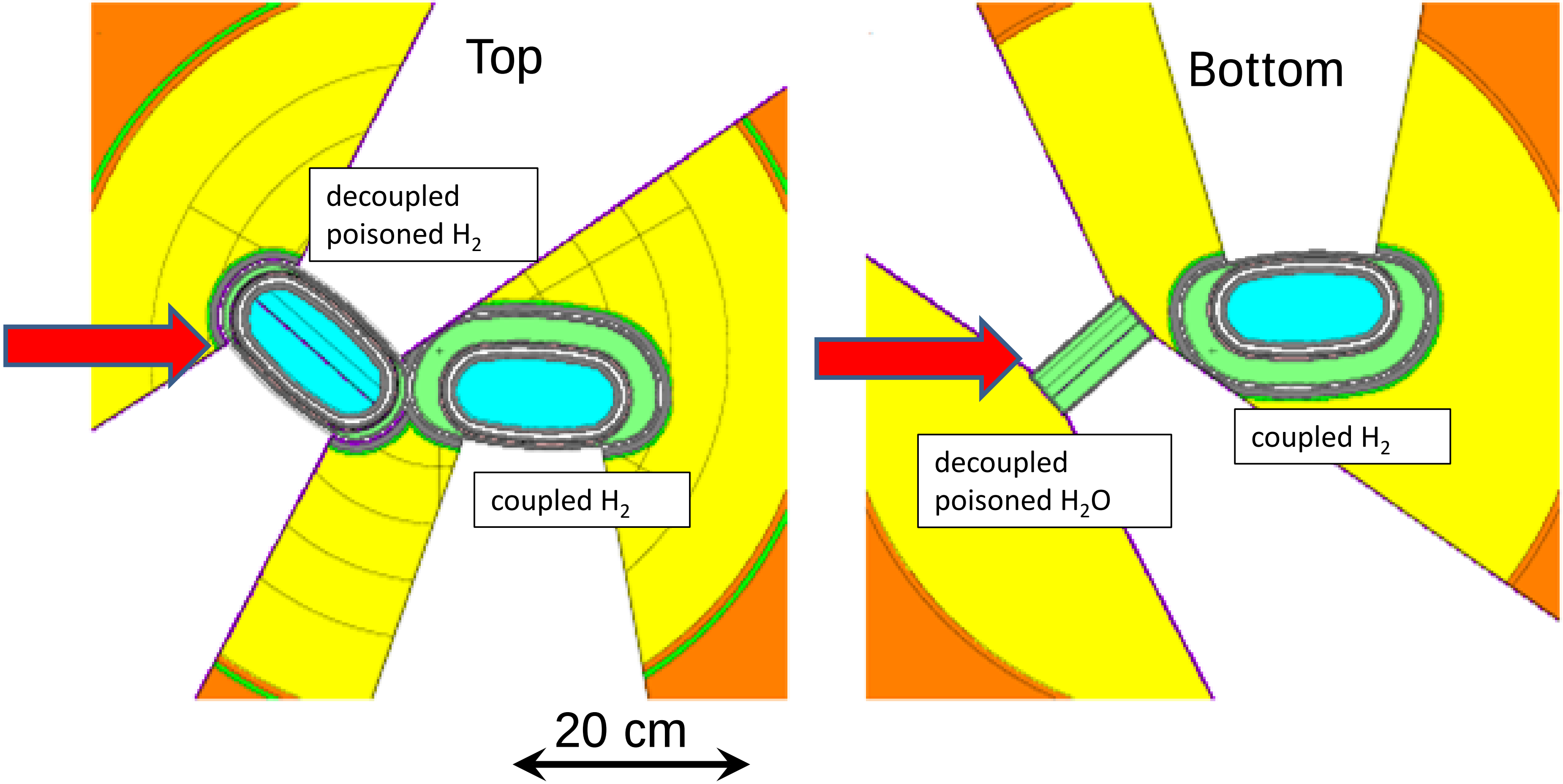


Moderator Decoupling and Poisoning

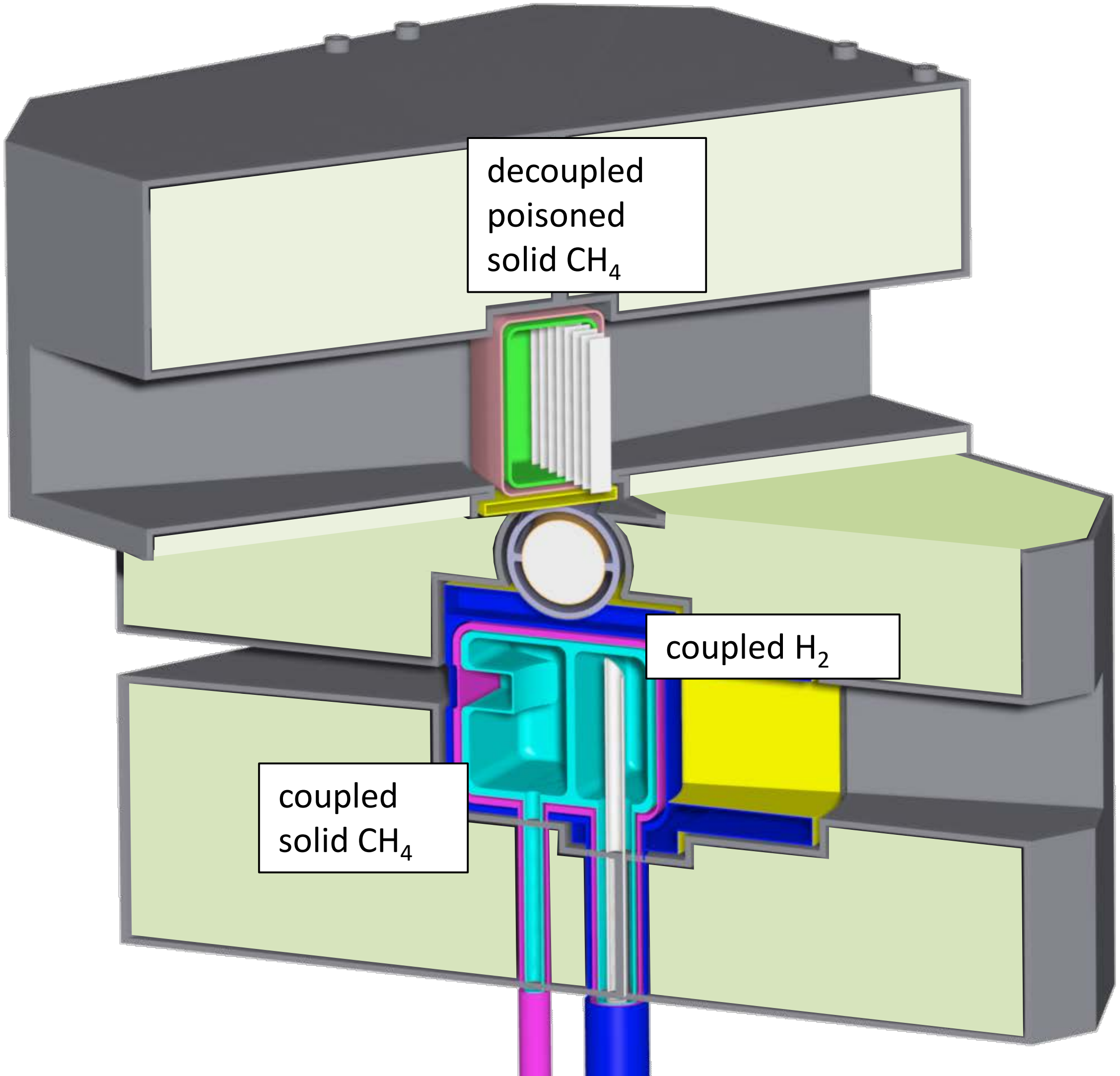




SNS moderators

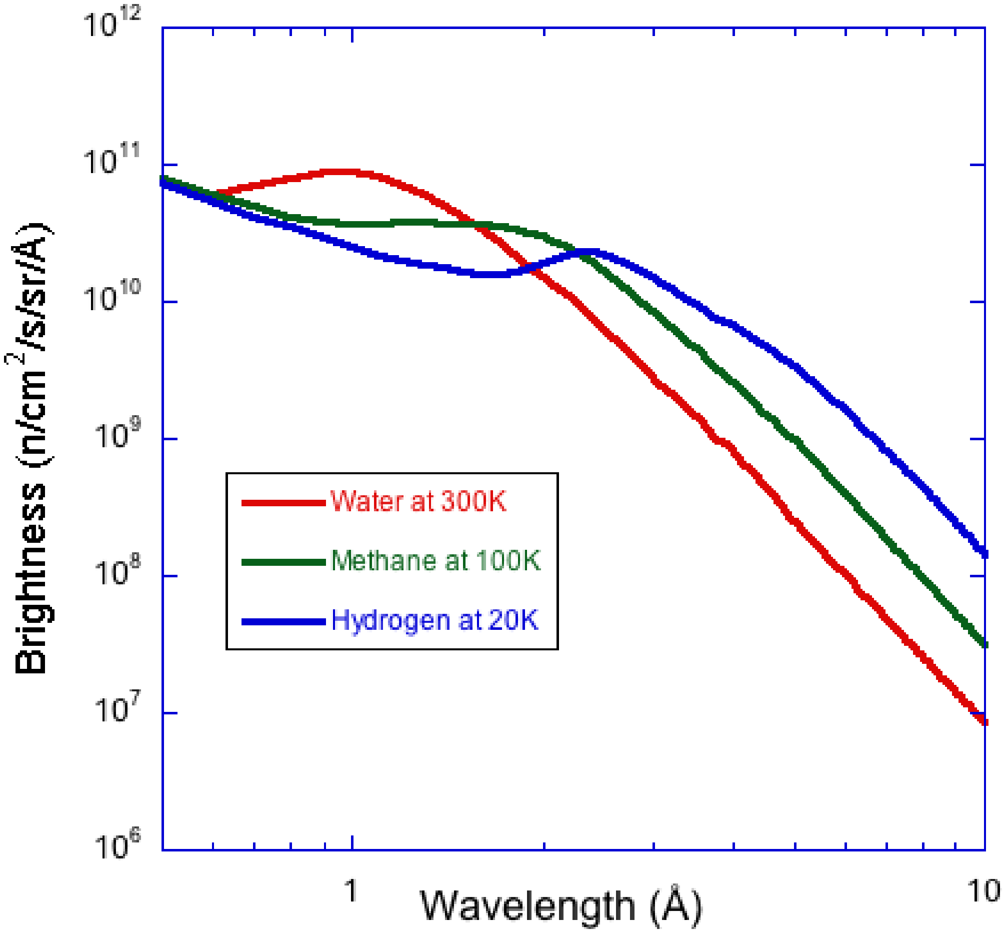


ISIS TS2 Target



Moderator Temperature

ISIS-TS1 moderators at 160kW



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 density in accelerator ring, …

Beyond Short-Pulse Limits

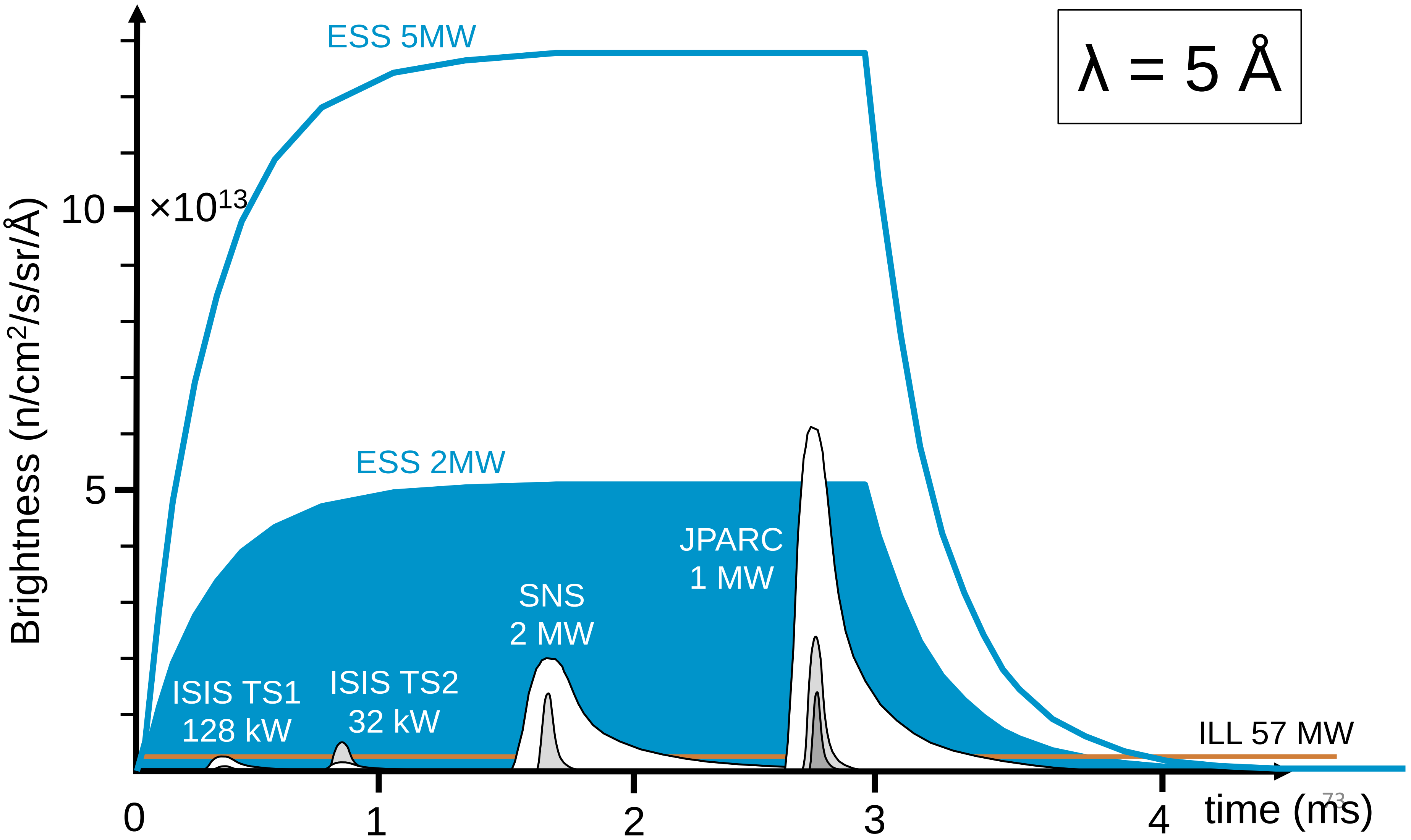
SNS instantaneous power on target:

17kJ in 1µs: 17 x

ESS instantaneous power on target: 125MW

360kJ in 2.86ms

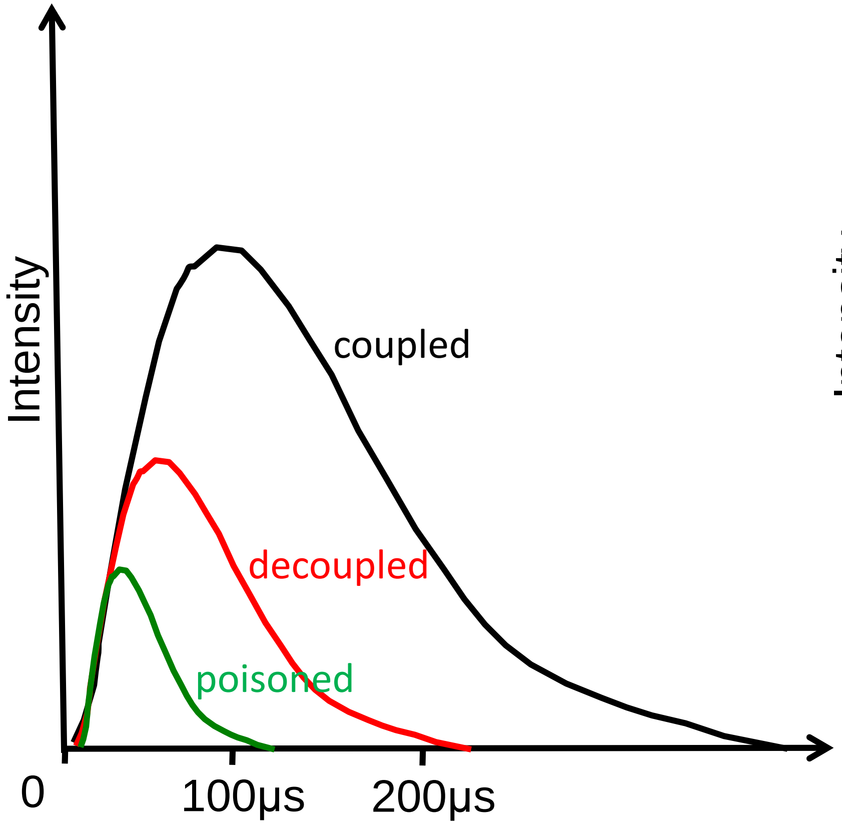
Long-pulse performance



Adapting the pulse width

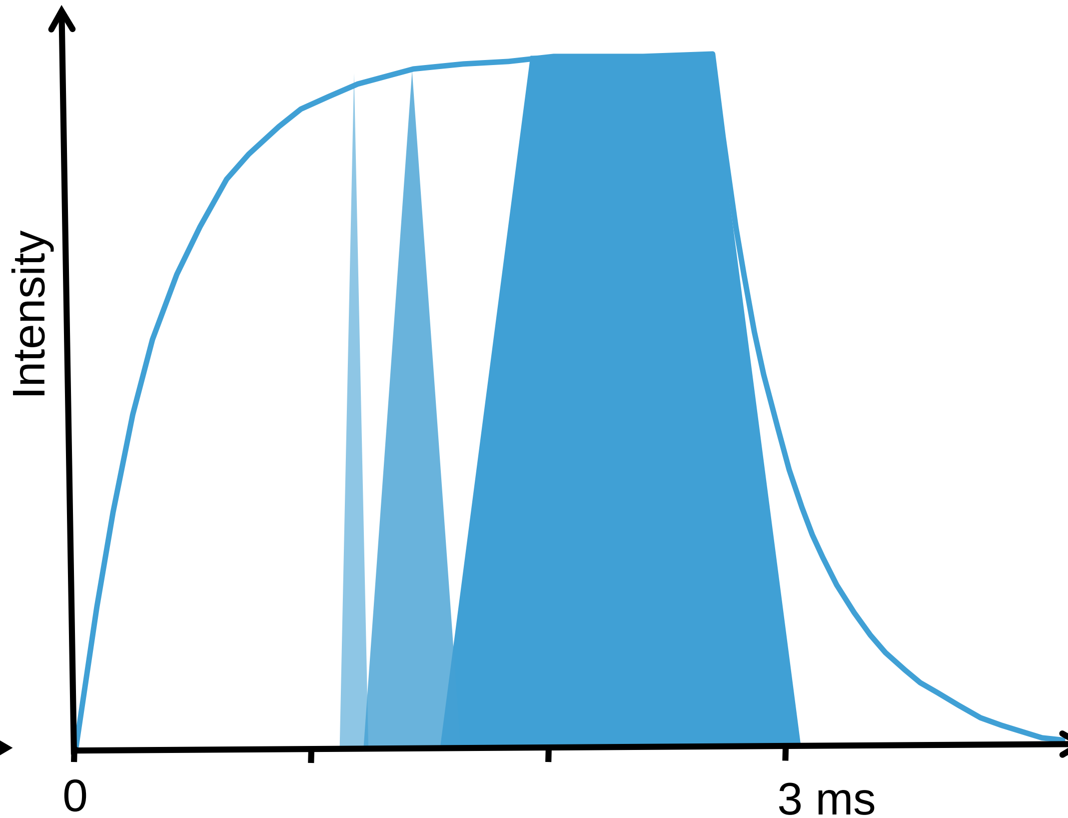
Short-Pulse Source

- set pulse width by choosing moderator



Long-Pulse Source (ESS)

- set pulse width using pulse-shaping chopper



Summary

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

Thank You!