# Neutron Sources

Oxford School on Neutron Scattering

8th September 2015

Ken Andersen

# Summary

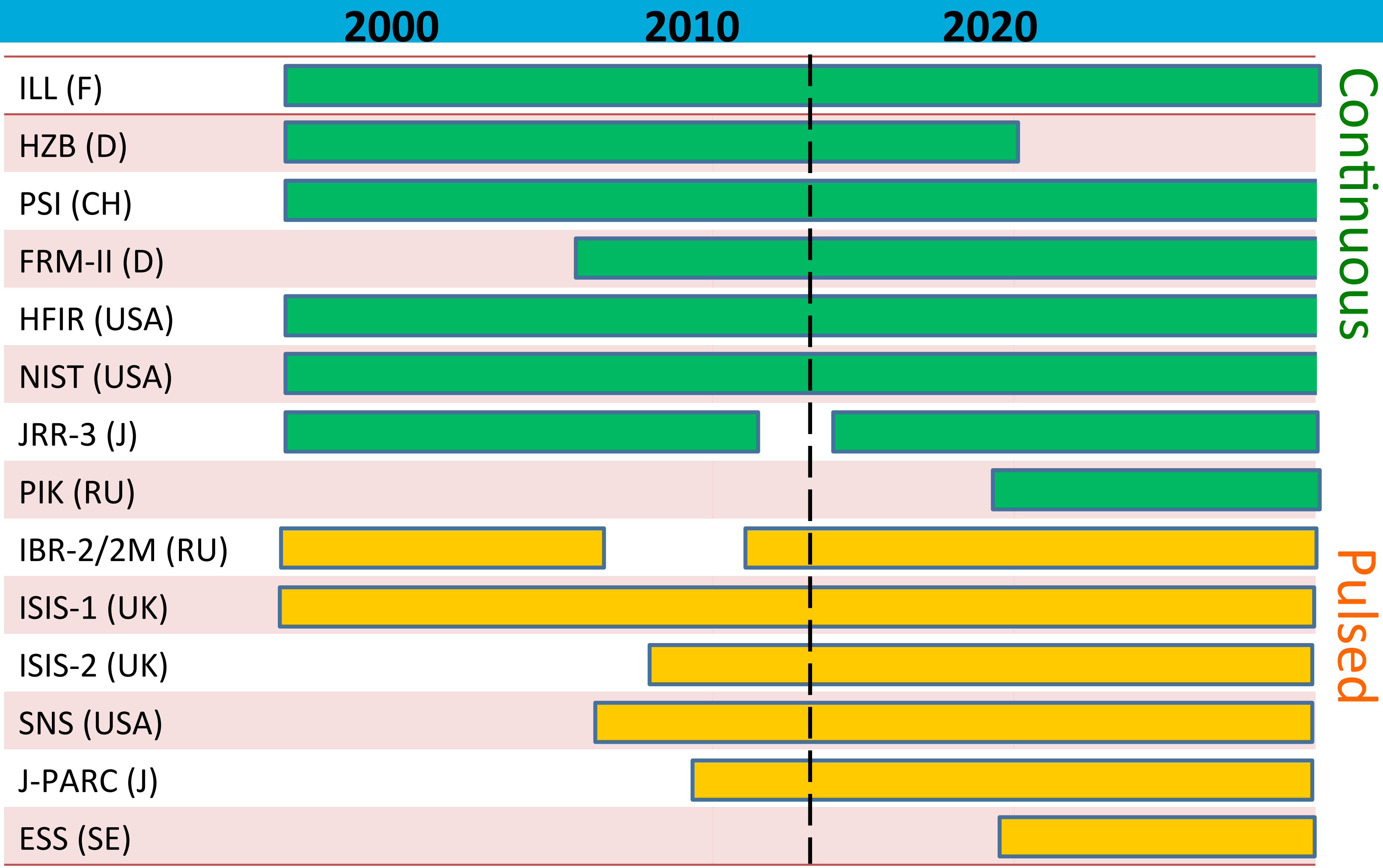
EUROPEAN SPALLATION SOURCE

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

# Main European neutron sources 2015

EUROPEAN SPALLATION SOURCE

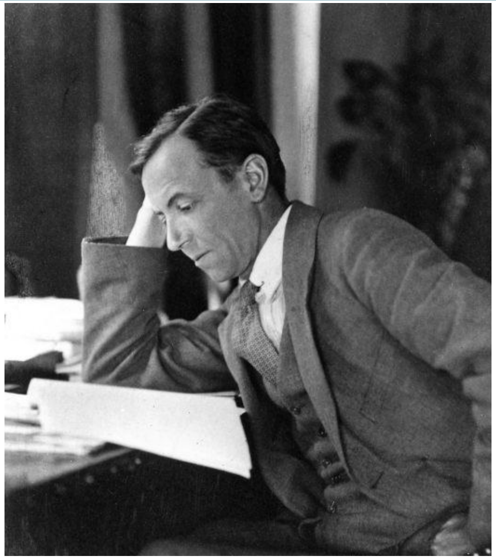
# Major neutron sources in the world



# 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 |

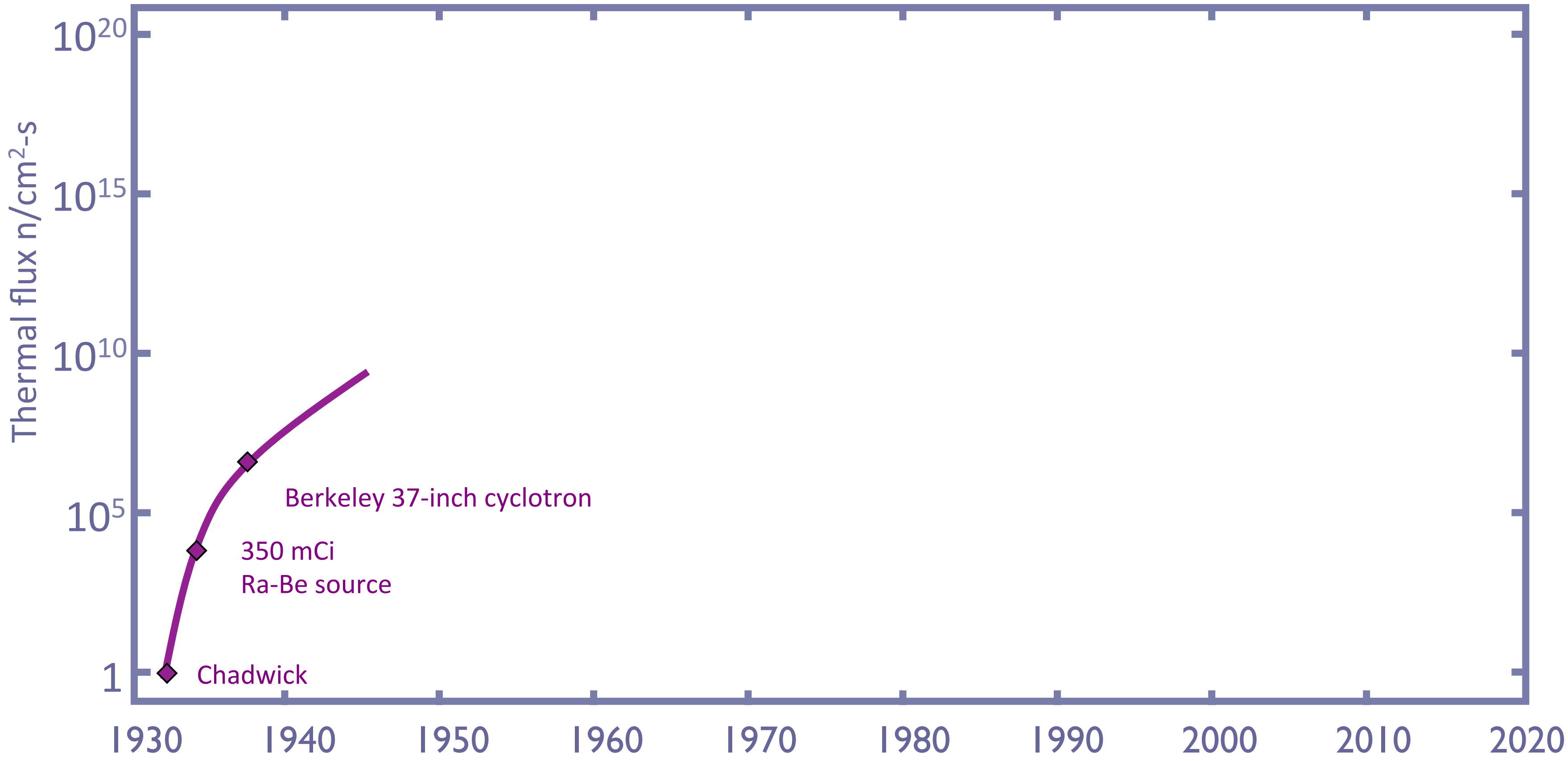
# The first neutron source



James Chadwick:
used Polonium as alpha emitter on Beryllium

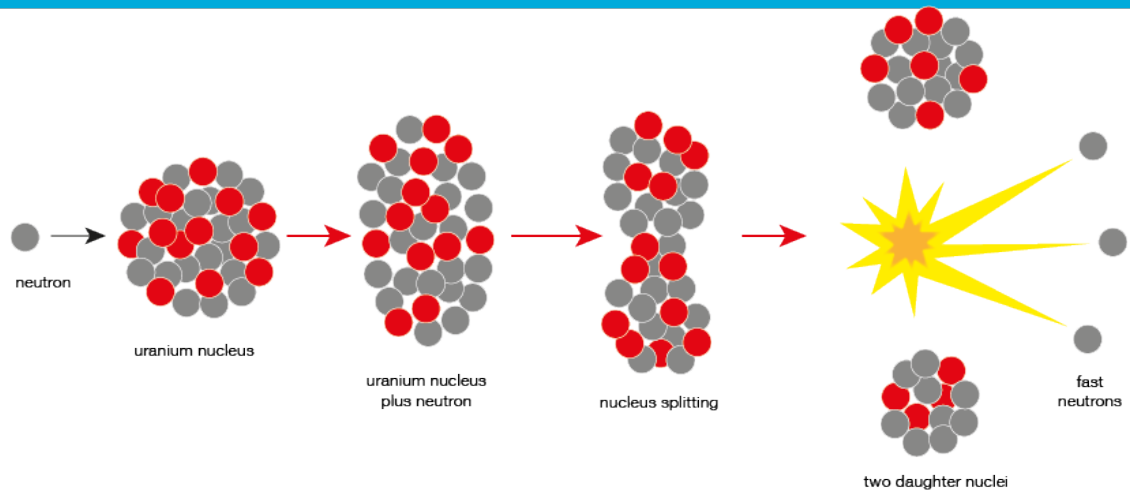
$$^{4}He + {}^{9}Be \rightarrow {}^{12}C + \text{neutron}$$

# Evolution of neutron sources

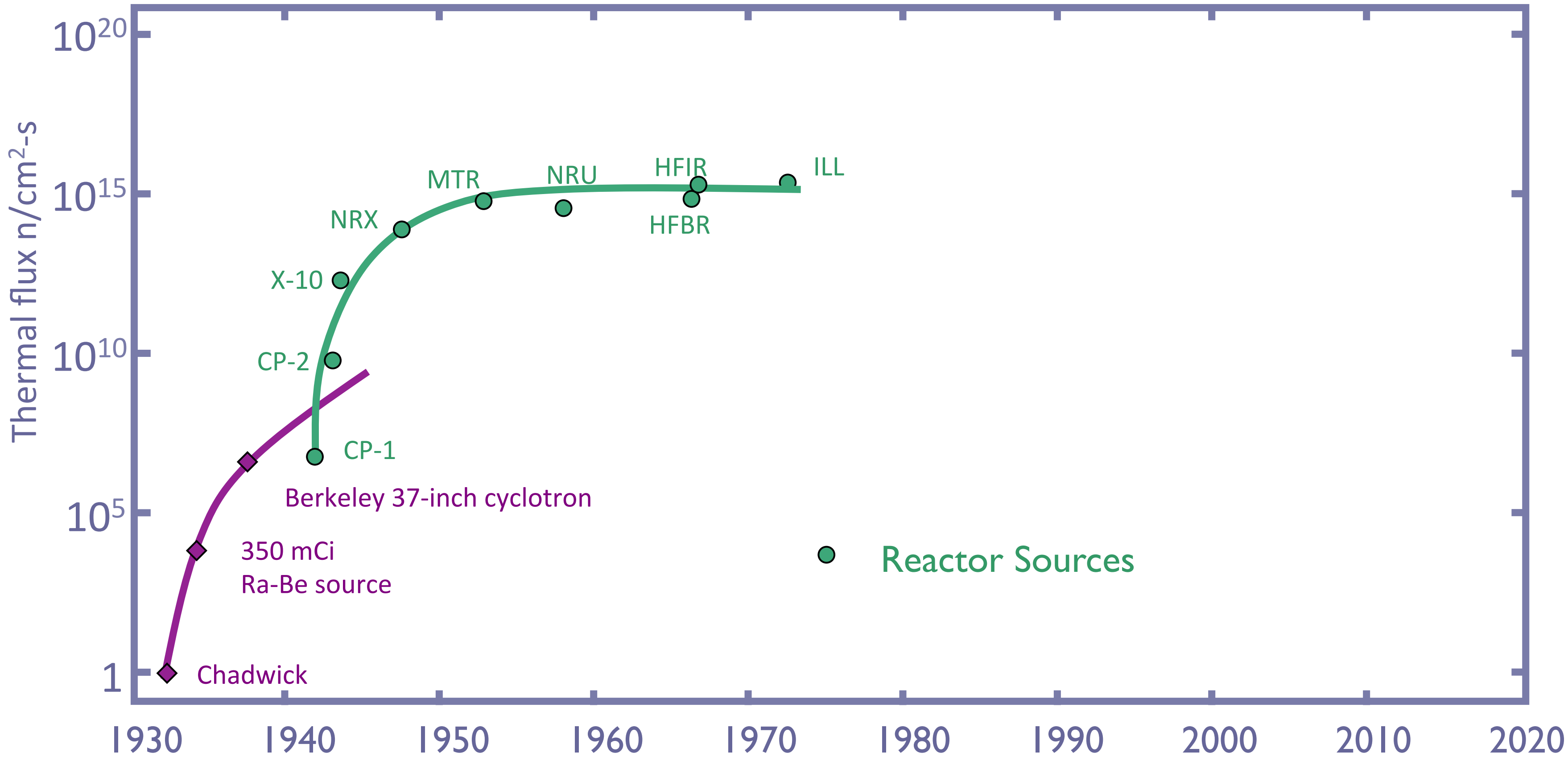



(Updated from *Neutron Scattering*, K. Sköld and D. L. Price, eds., Academic Press, 1986)

# Nuclear Fission




# Evolution of neutron sources

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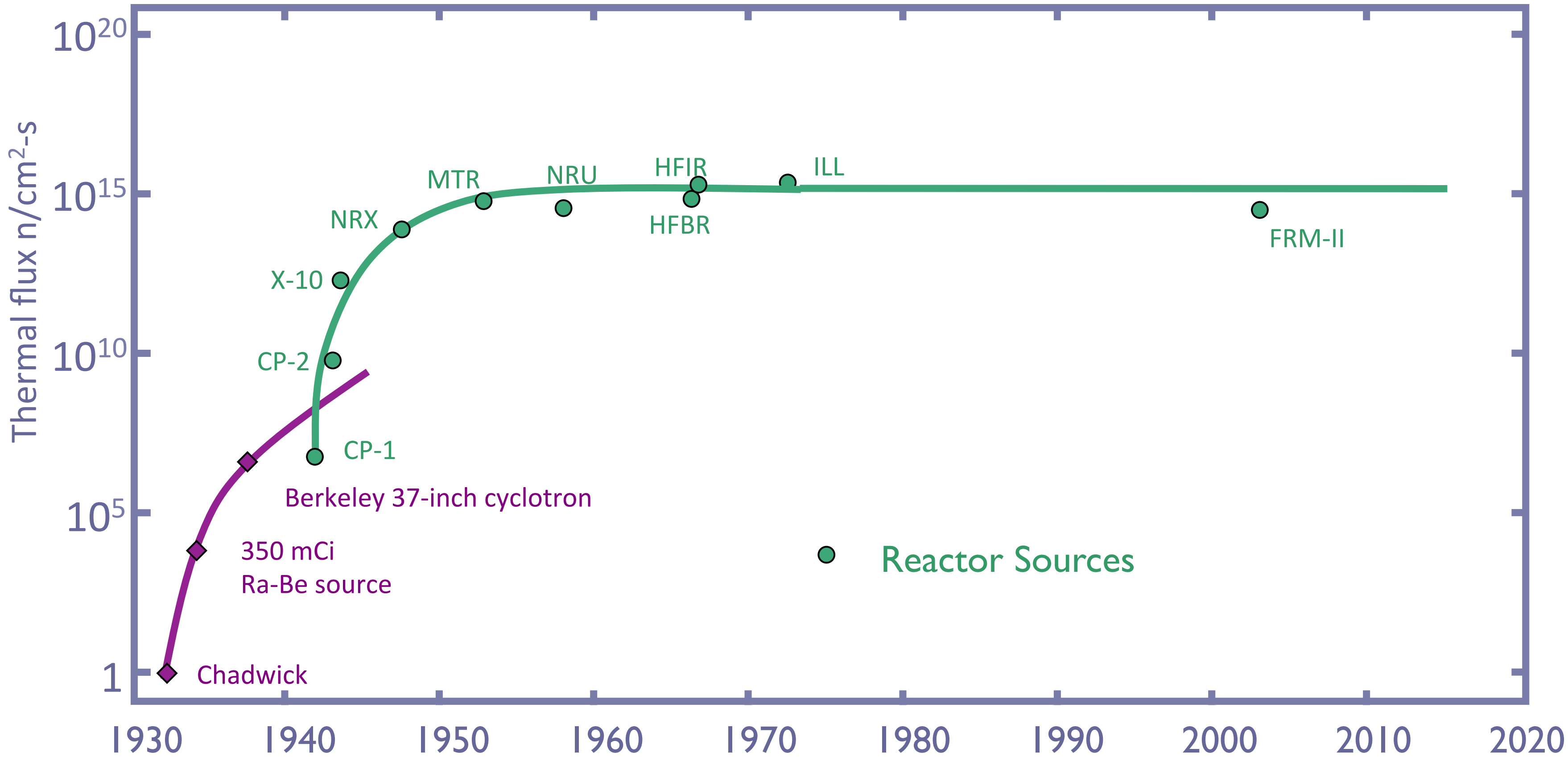


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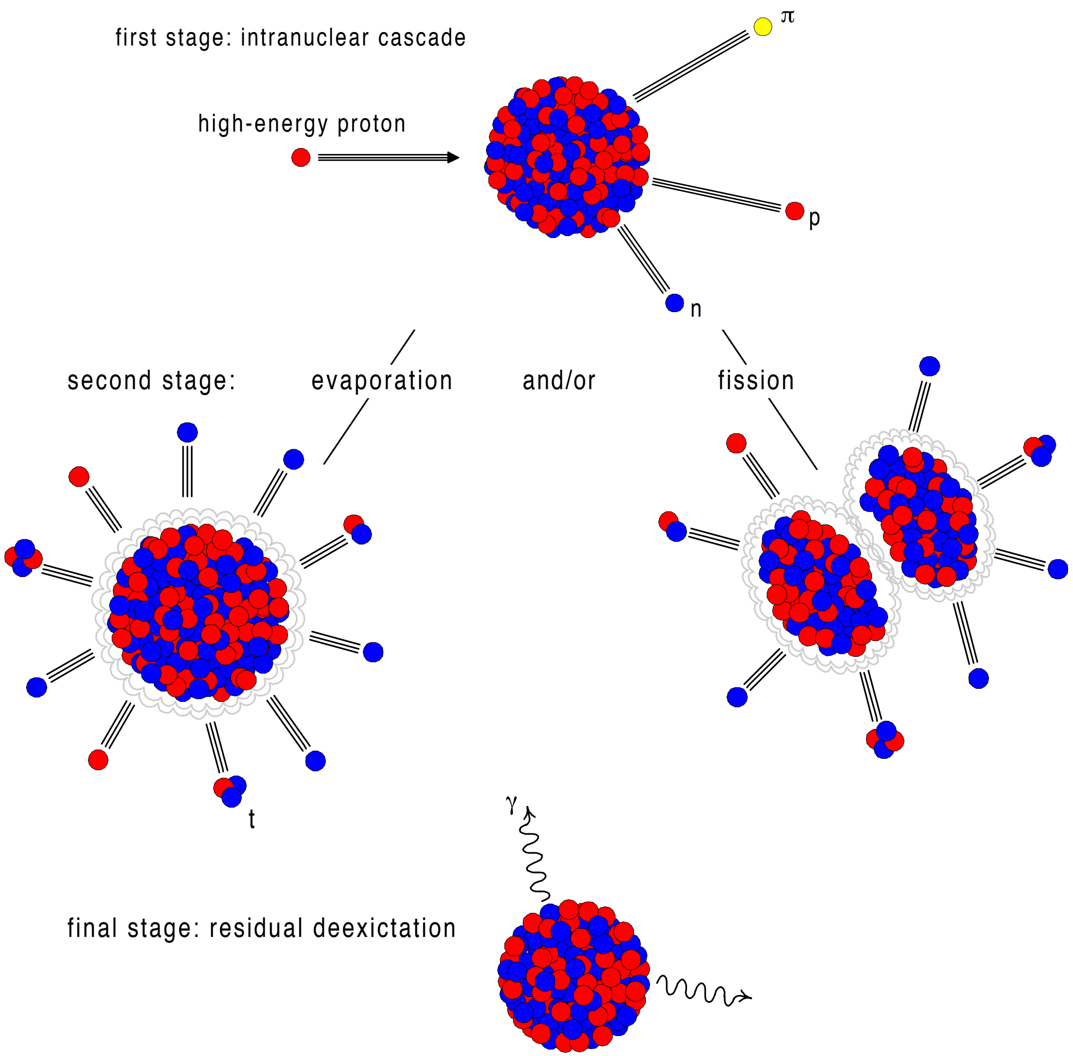
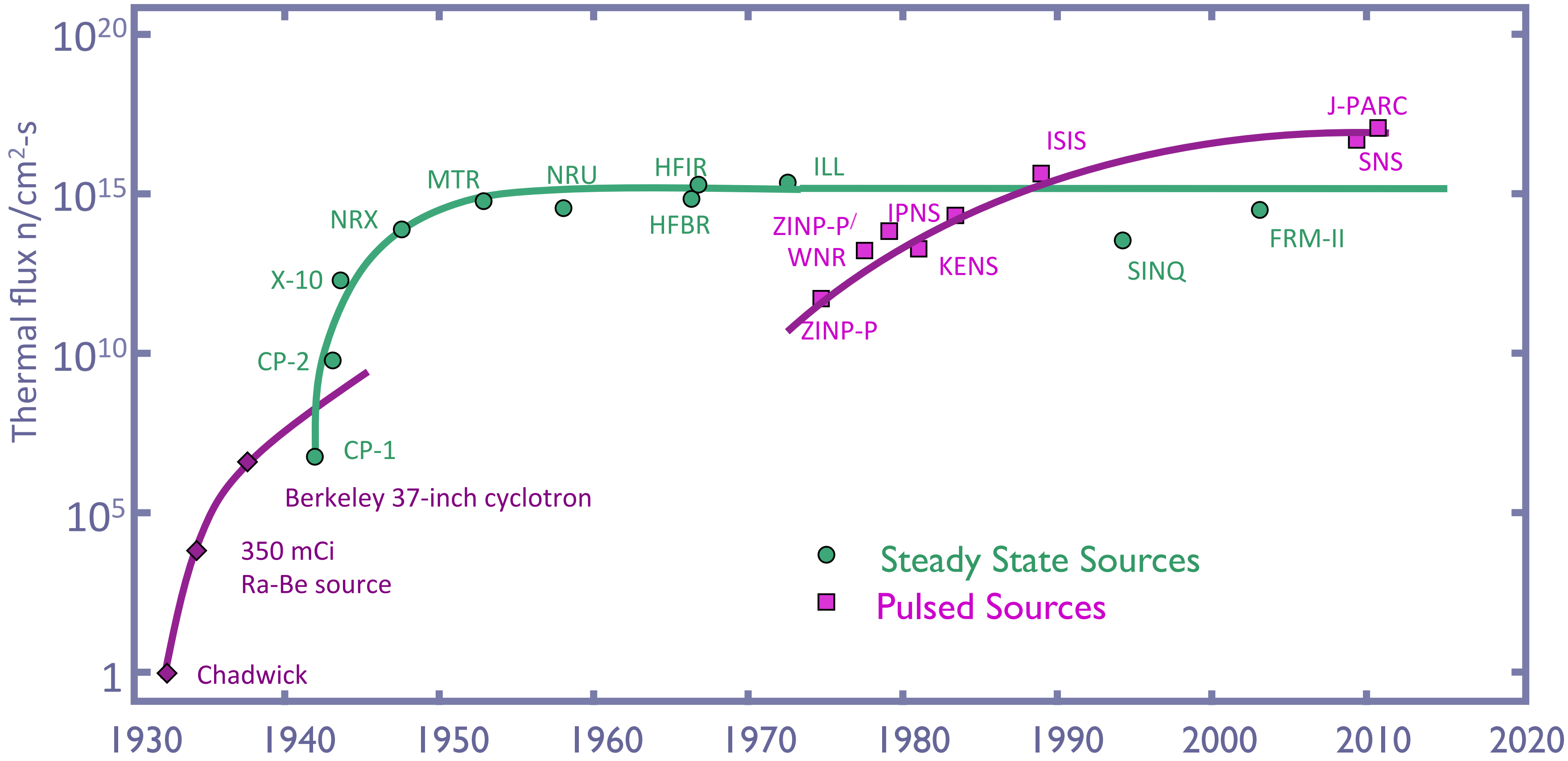
# Nuclear Spallation



# Evolution of neutron sources

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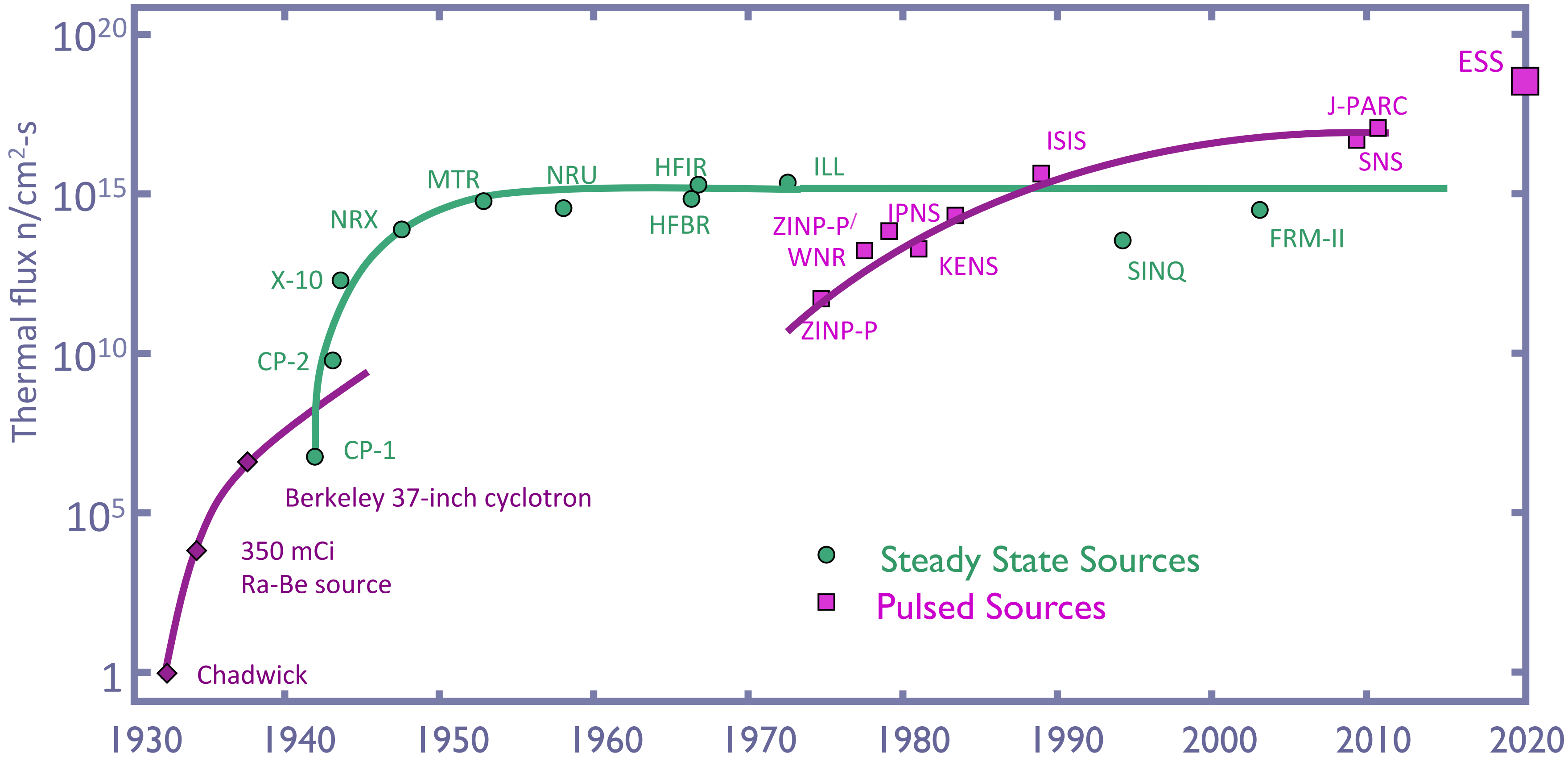
# Evolution of neutron sources

EUROPEAN SPALLATION SOURCE

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# Slow Neutrons vs Light

| | light | neutrons |
|---|---|---|
| $\lambda$ | < μm | < nm |
| E | > eV | > meV |
| penetration | ~ μm | ~ cm |
| $\theta_c$ | 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 |

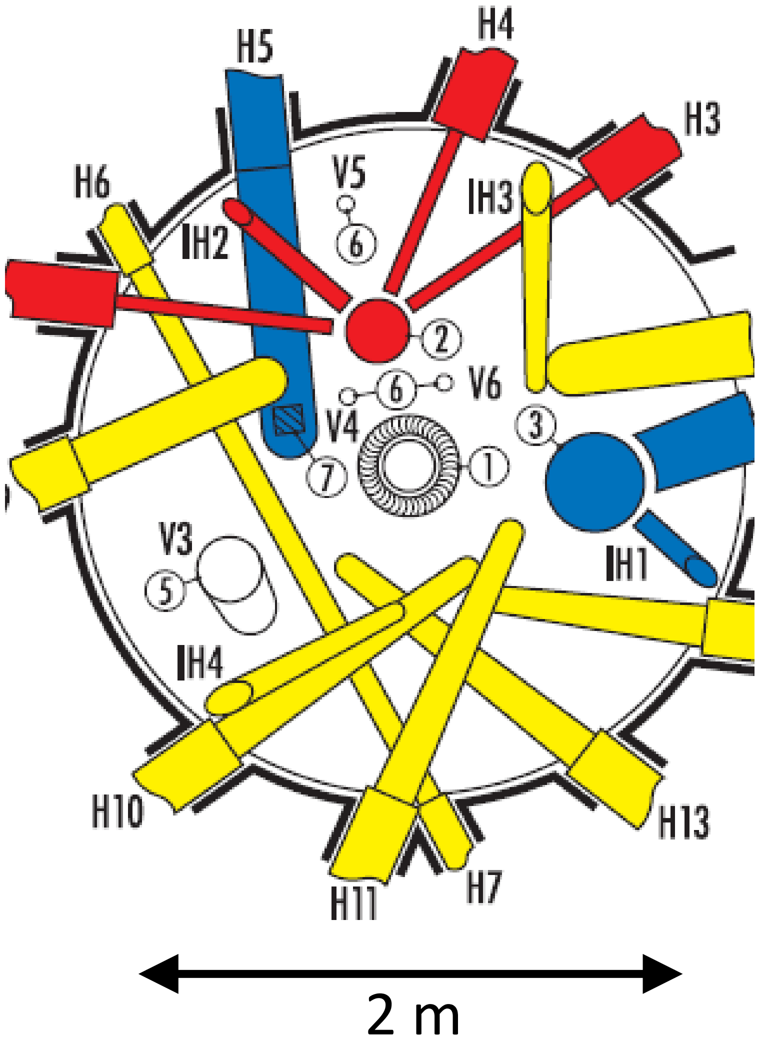
# Why neutrons?

- 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

# ILL Reactor Neutron Source

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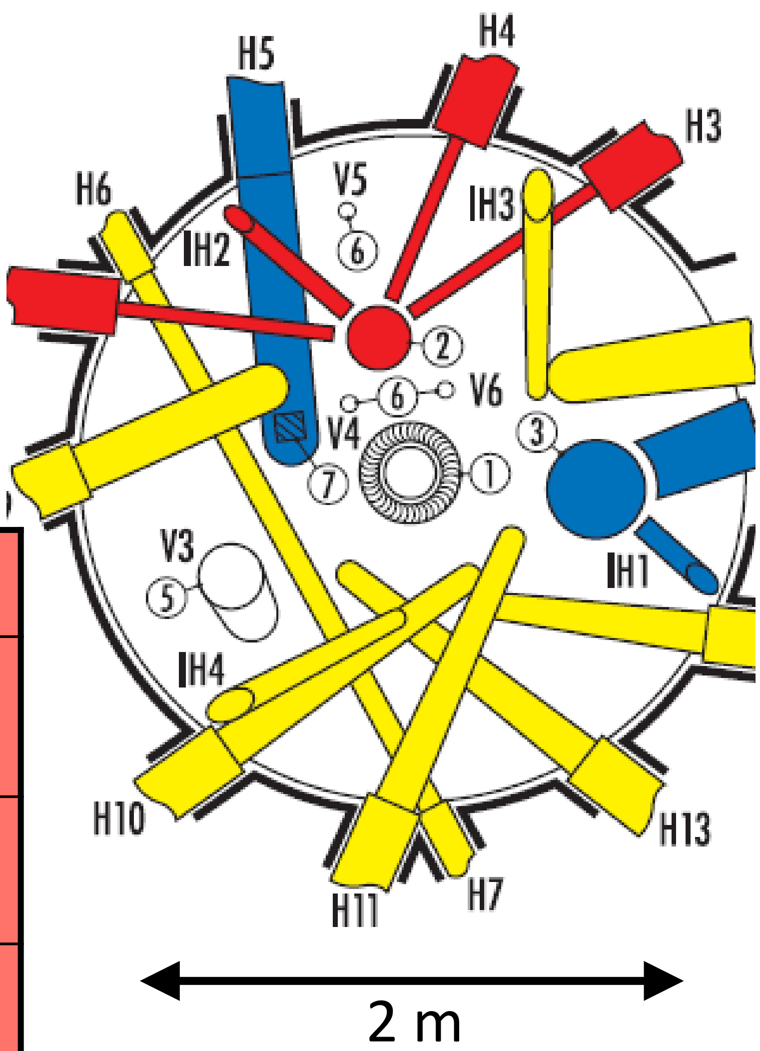
| | cold | thermal | hot |
|---|---|---|---|
| moderator | liquid $D_2$ | Liquid $D_2O$ | graphite |
| moderator temperature | 20K | 300K | 2000K |
| neutron wavelength | 3→20Å | 1→3Å | 0.3→1Å |



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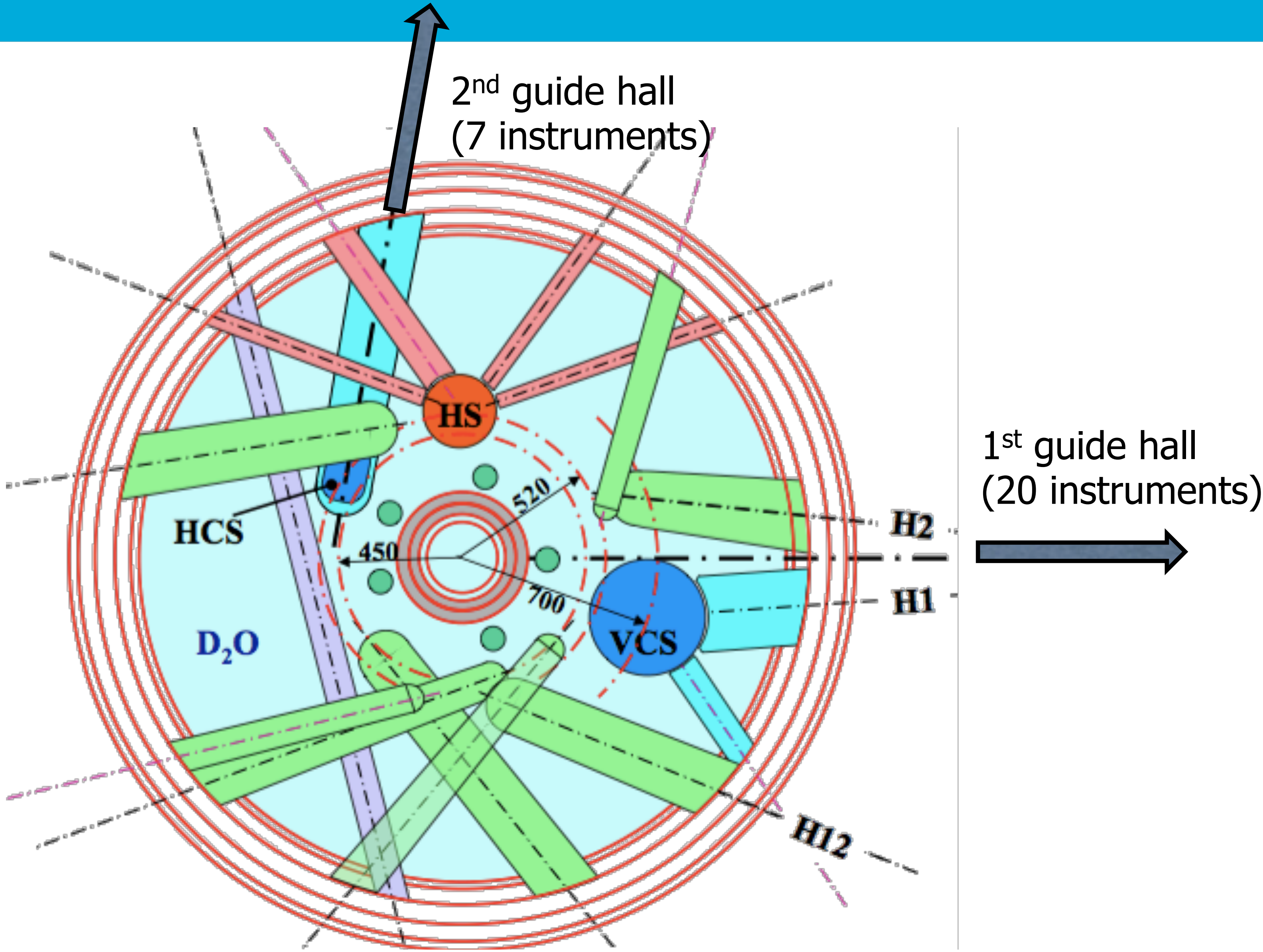

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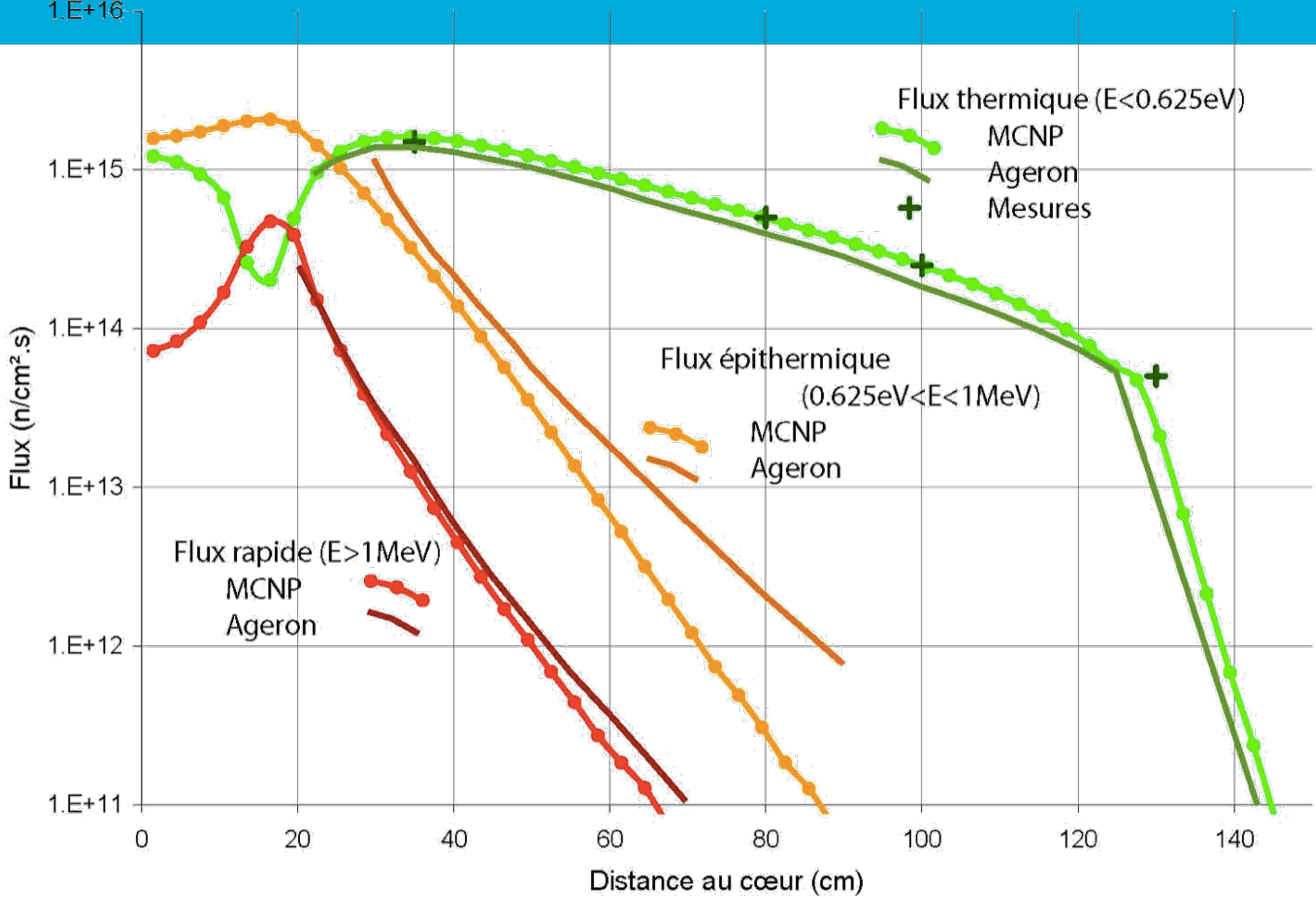

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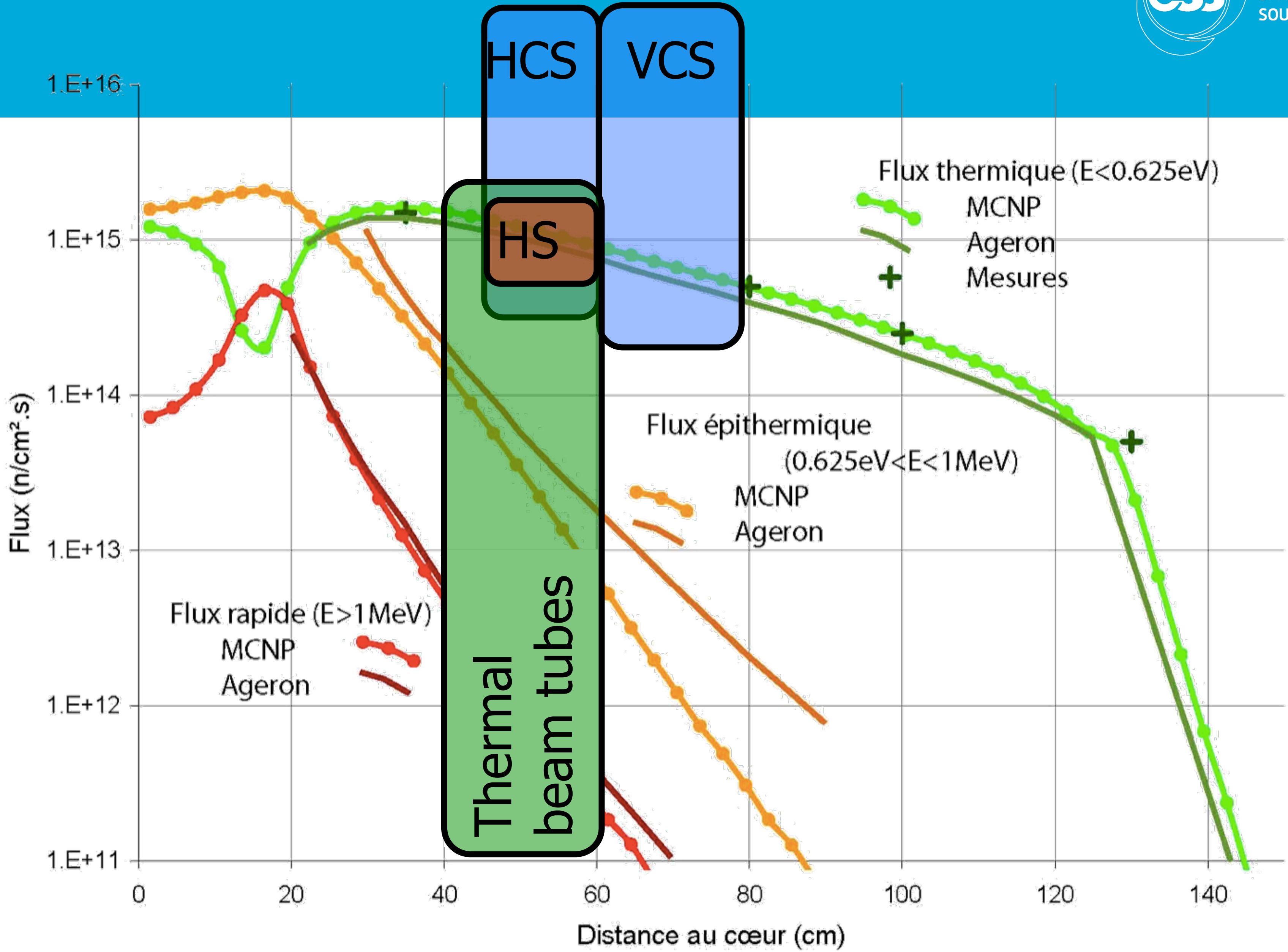
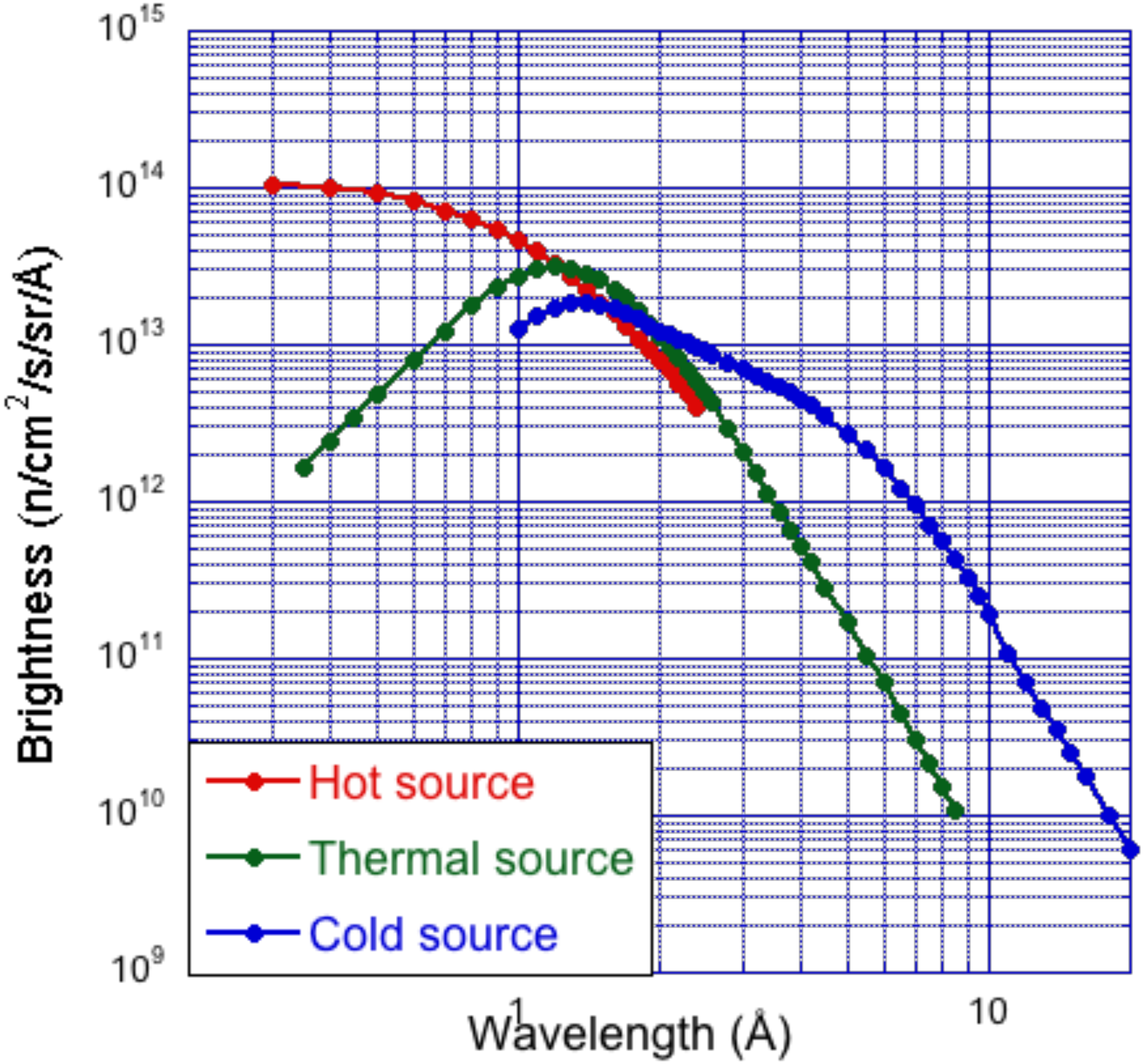


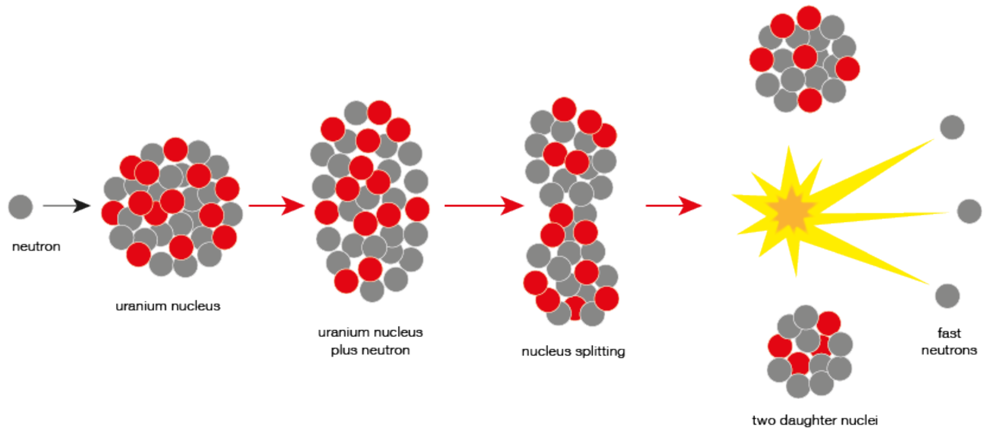
# ILL Moderator Brightnesses



# Spallation vs Fission

## Fission

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



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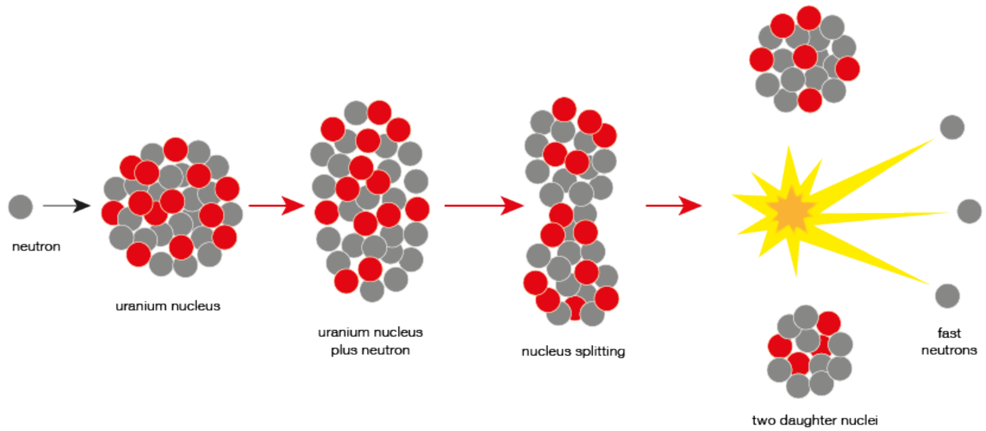
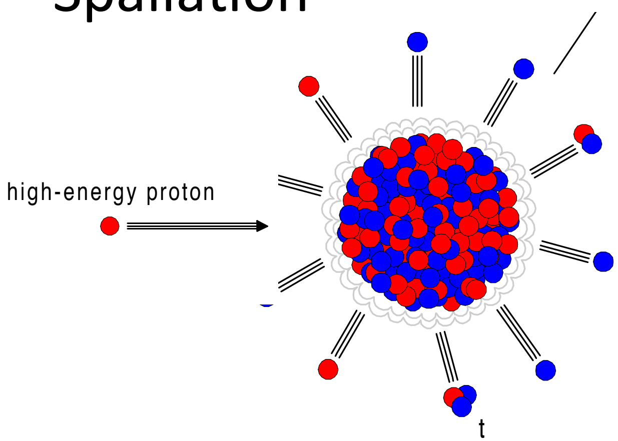



## Spallation




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

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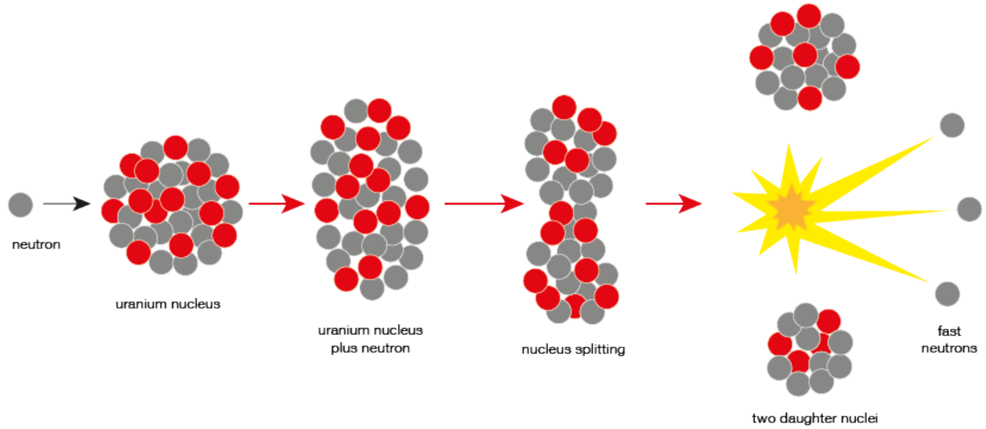


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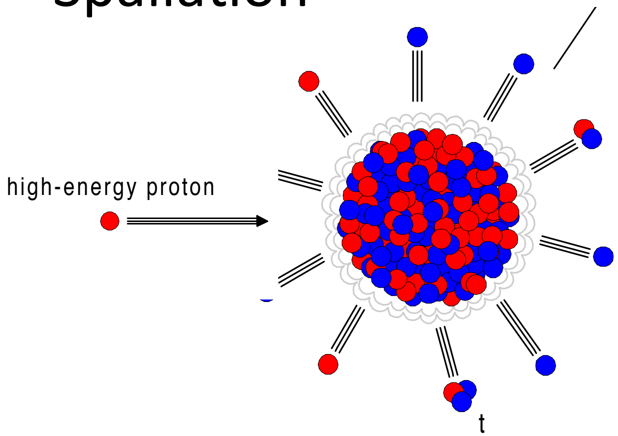


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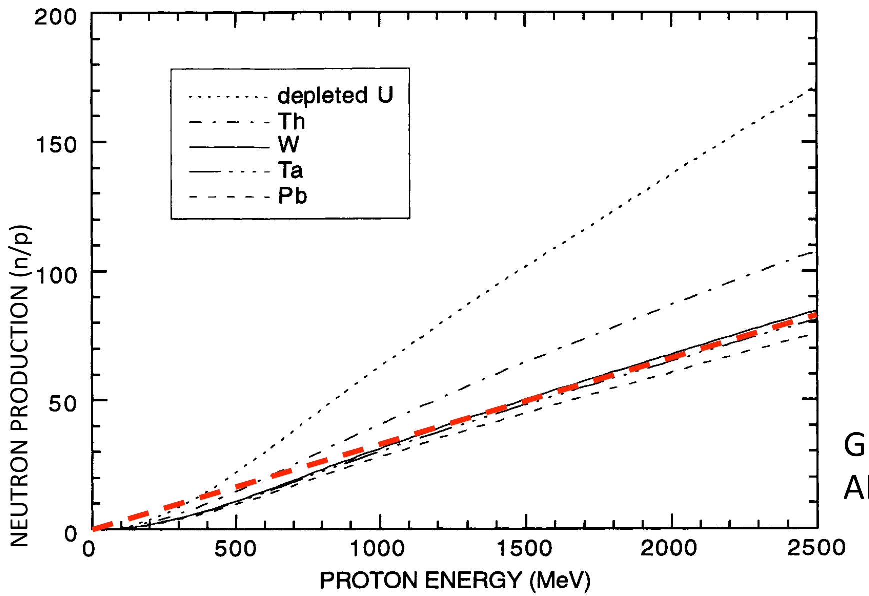
6x more neutrons per unit heat

# Spallation Sources

- 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 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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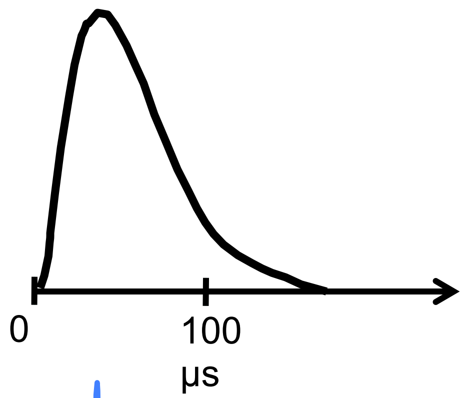
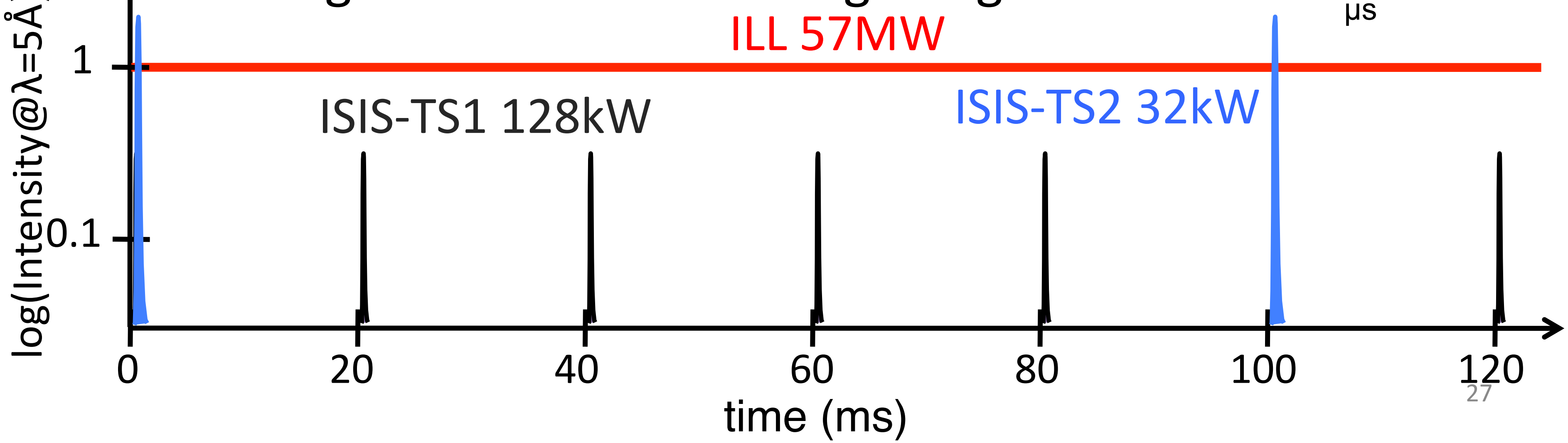


# De Broglie Relations

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

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

$$h = 6.6\times10^{-34}\,\mathrm{J\cdot s}$$

$$m_n = 1.67\times10^{-27}\,\mathrm{kg}$$

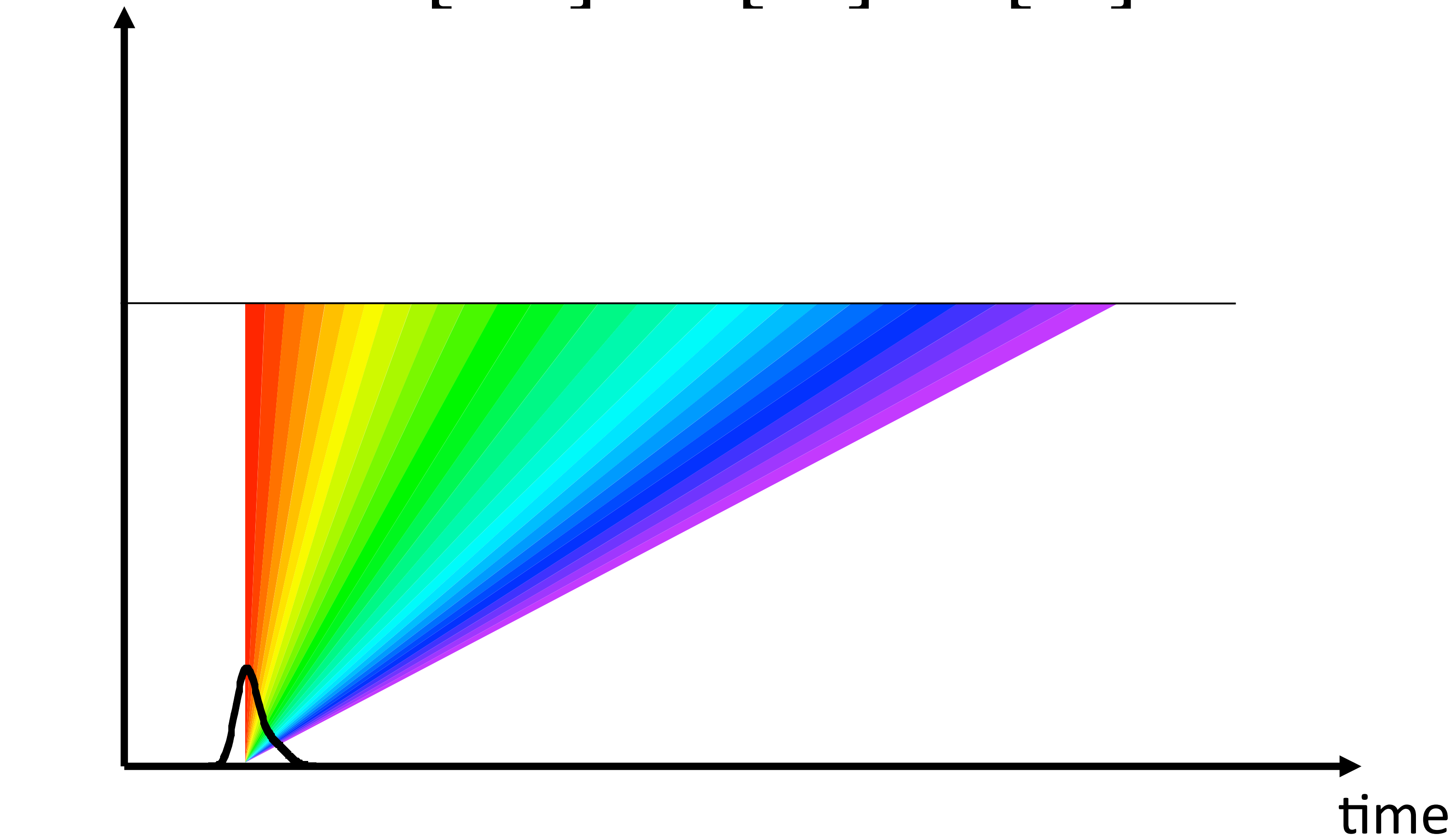
$$\lambda = h/mv$$

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

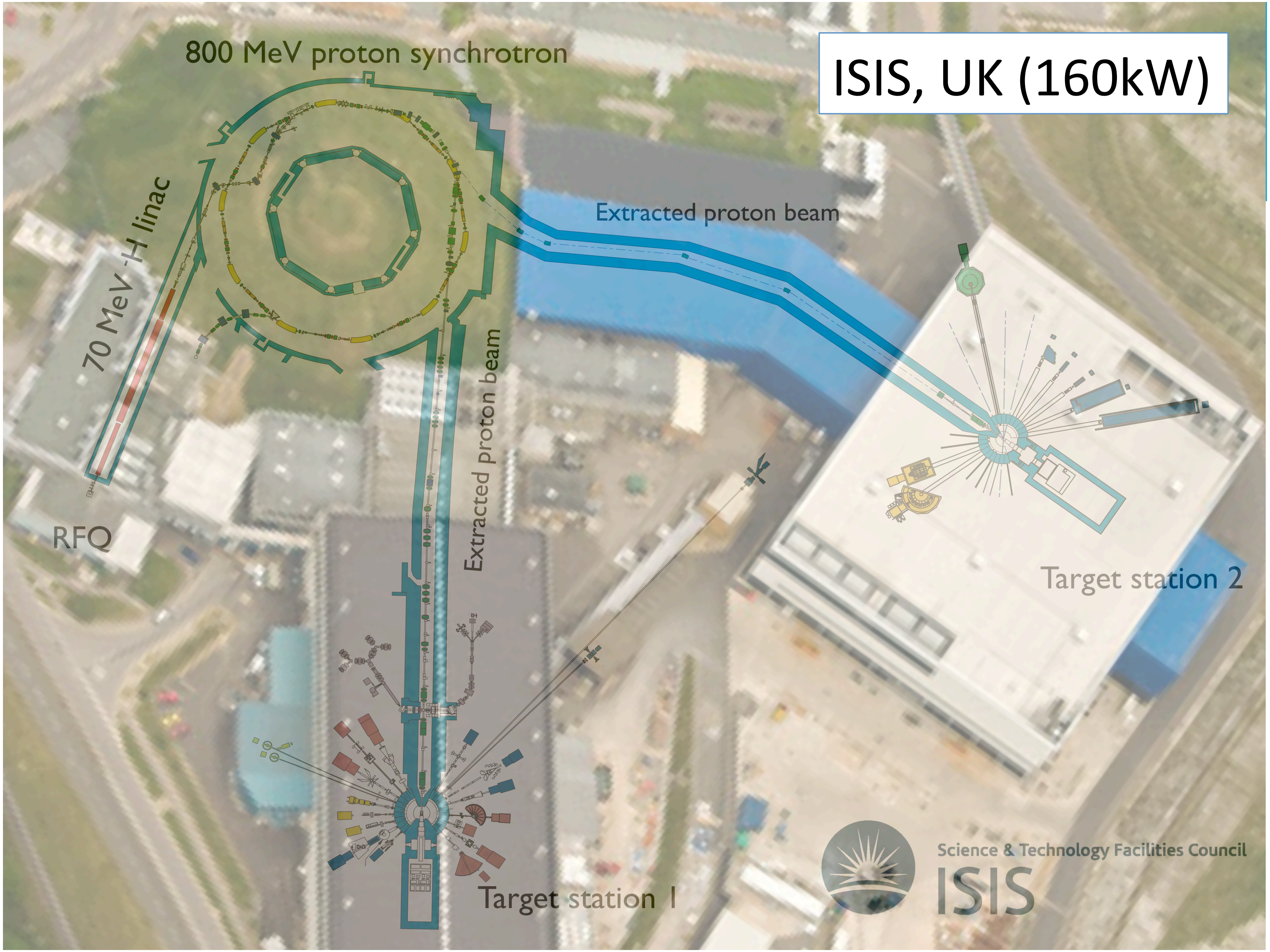
$$t[\mathrm{ms}] = L[\mathrm{m}]\times\lambda[\text{Å}]/3.956$$

# The Time-of-Flight (TOF) Method

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



# ISIS, UK (160kW)

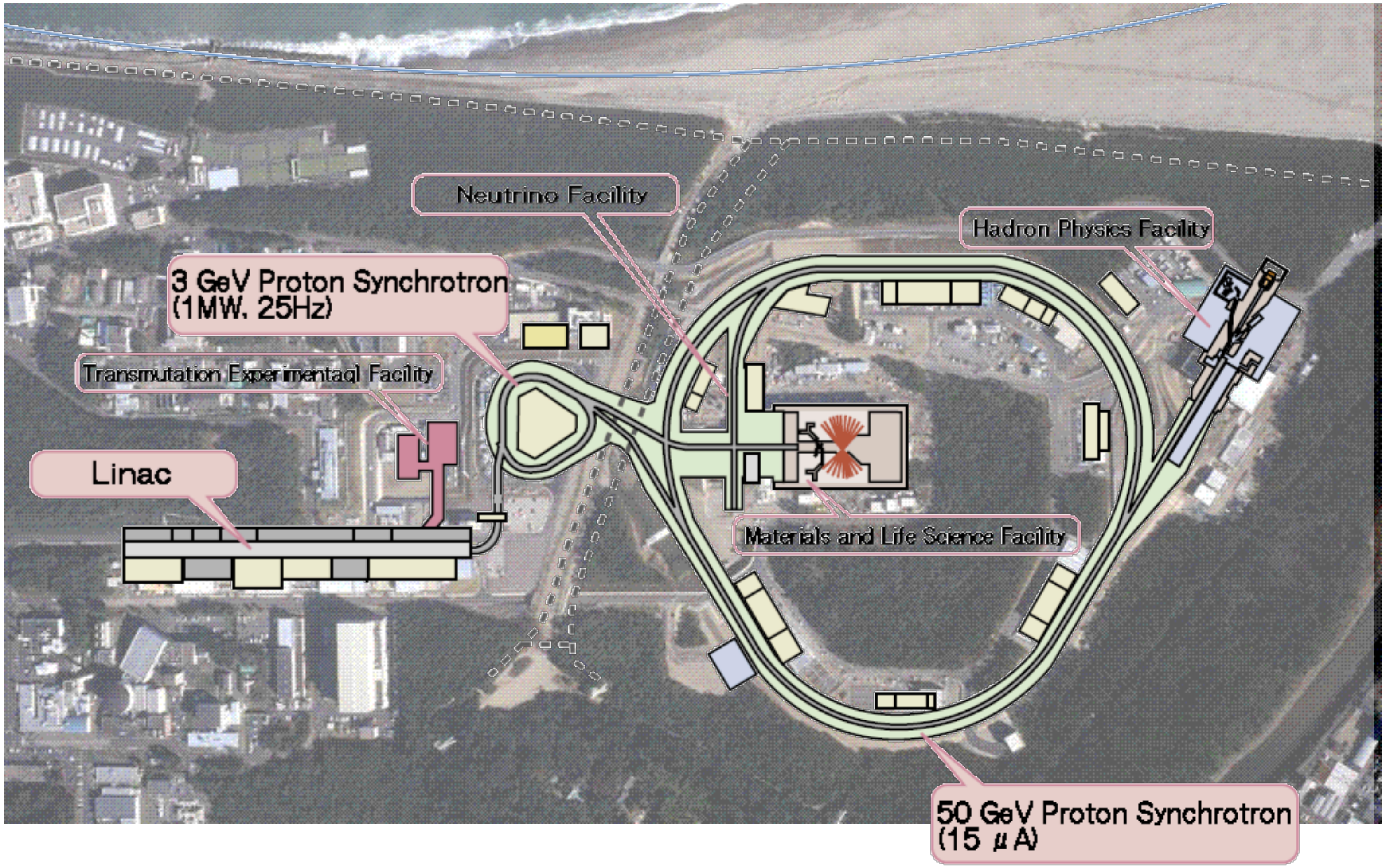


# SNS, Oak Ridge, USA (1MW)

# J-PARC, Tokai, Japan (500kW)

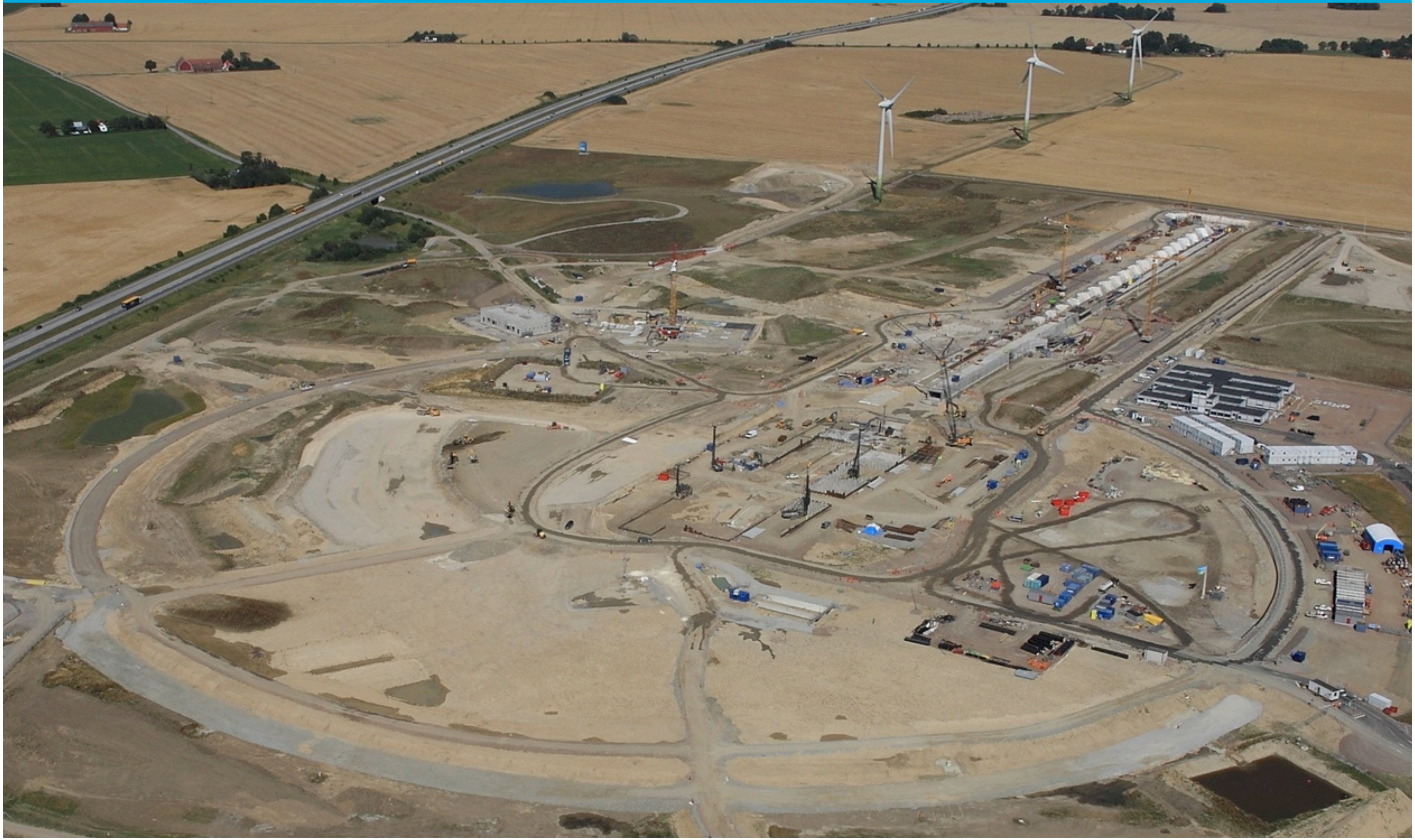
EUROPEAN SPALLATION SOURCE

# J-PARC, Tokai, Japan (500kW)



# ESS, Lund, Sweden (5MW in 2025)

EUROPEAN SPALLATION SOURCE



# Short-Pulse Spallation Sources

EUROPEAN SPALLATION SOURCE

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

# Linear accelerator: LINAC

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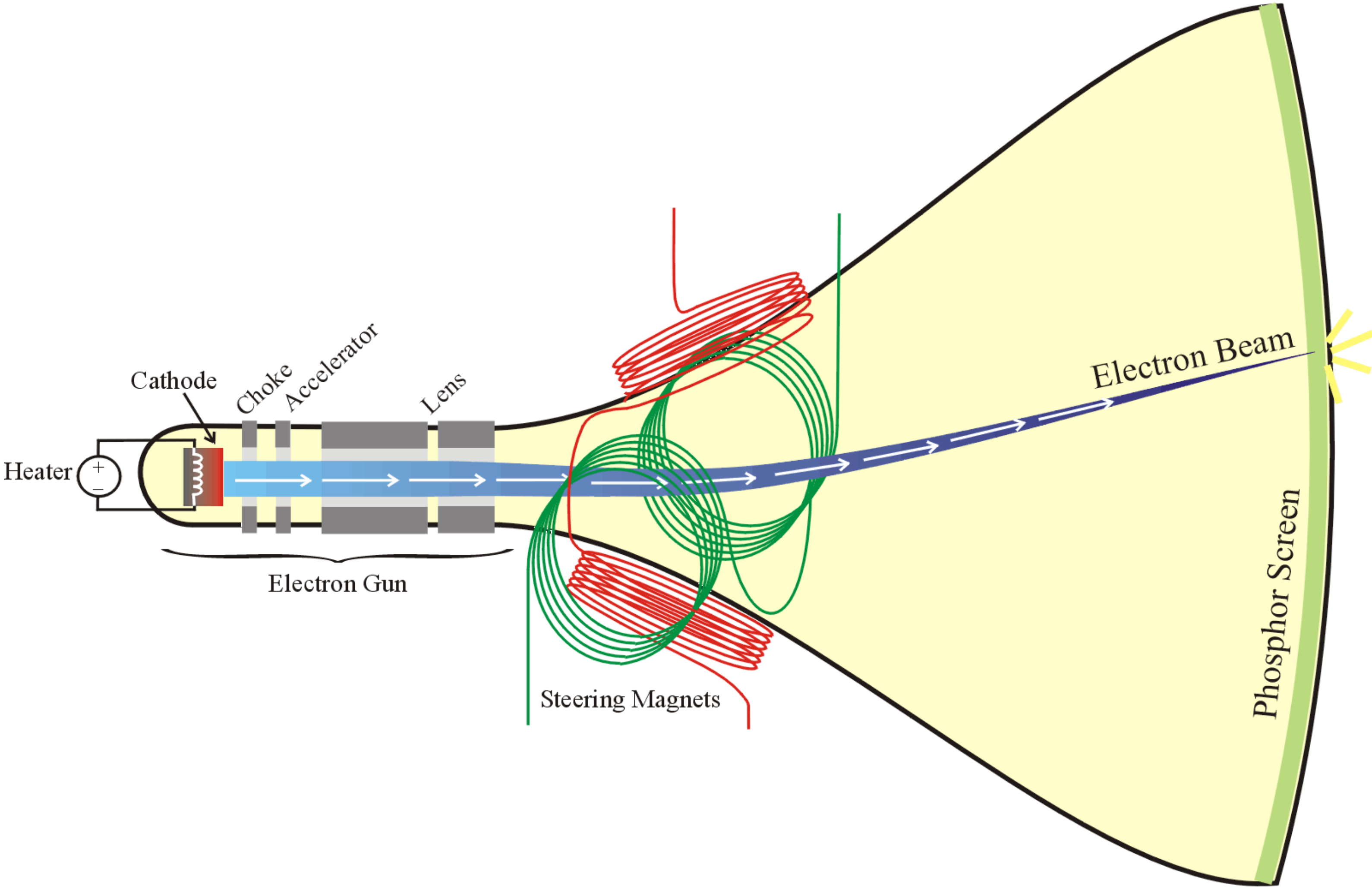
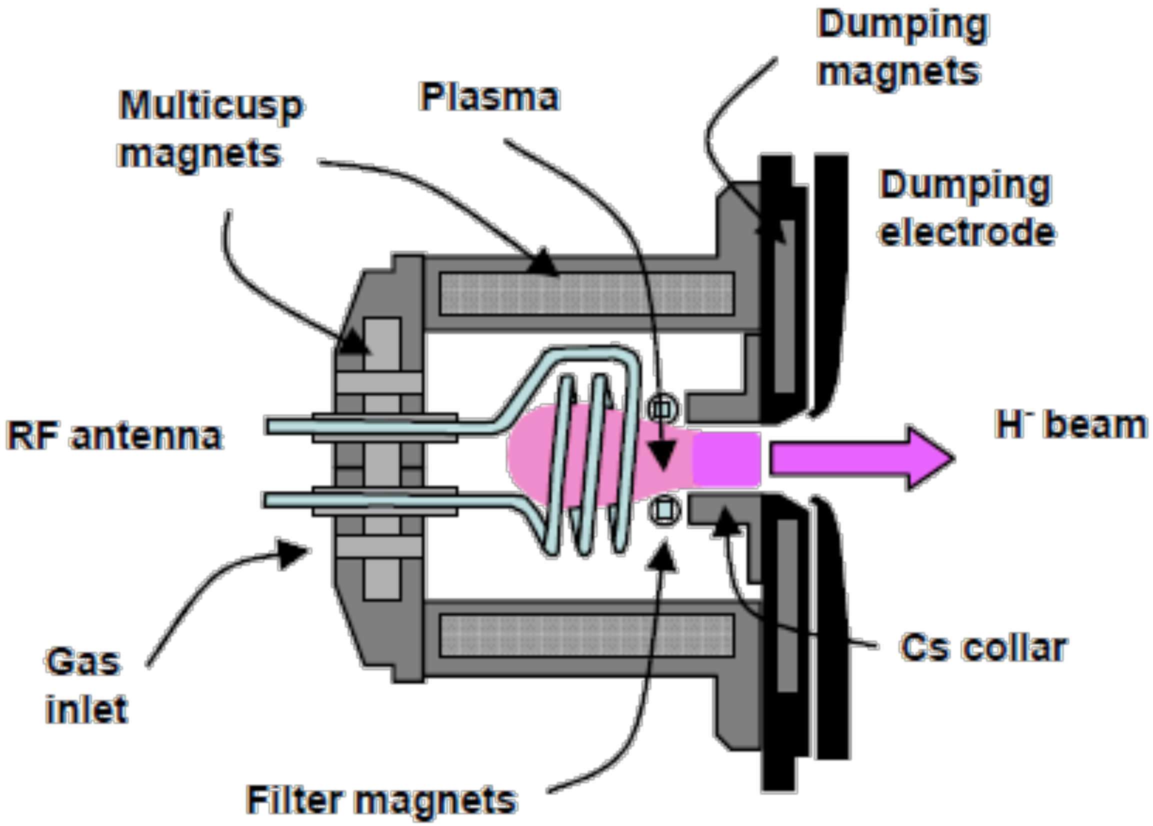
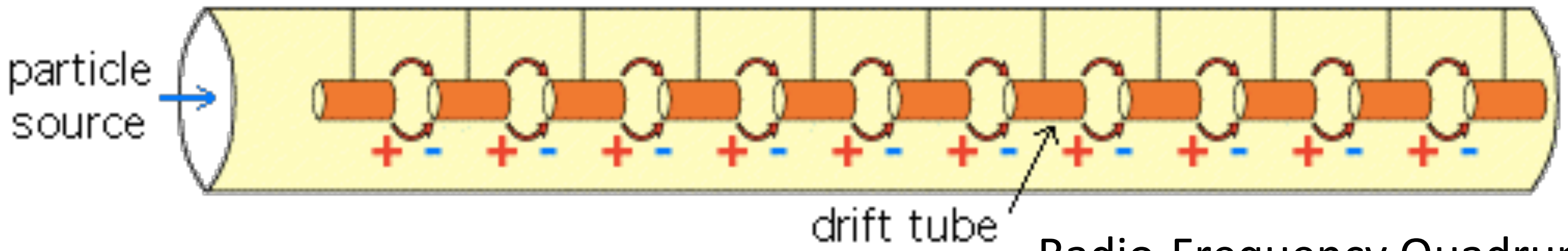


# SNS ion source: H-

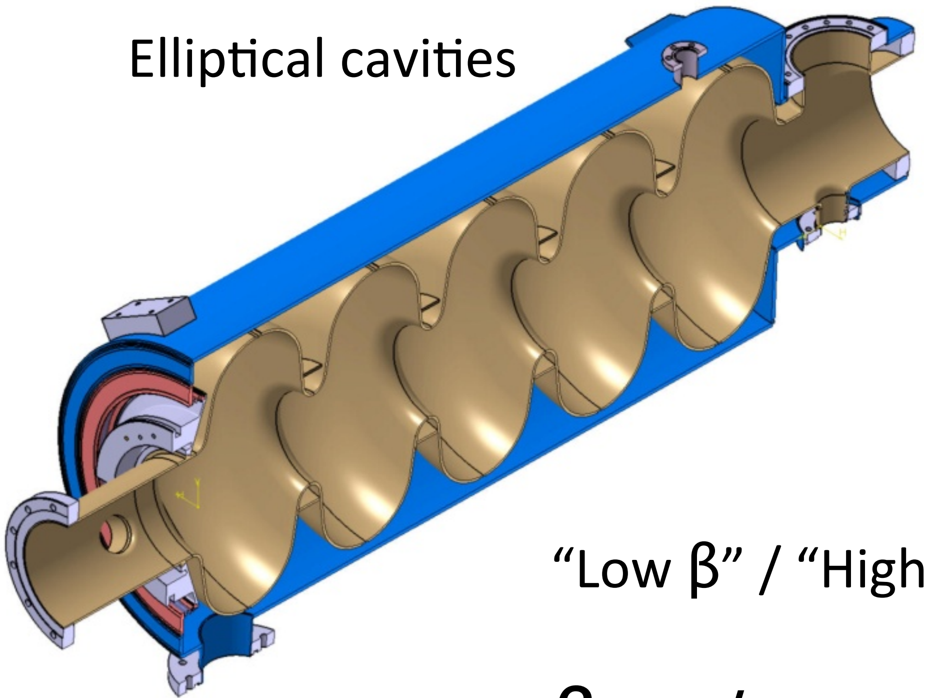


# Different types of Linac

Drift-Tube Linac (DTL)



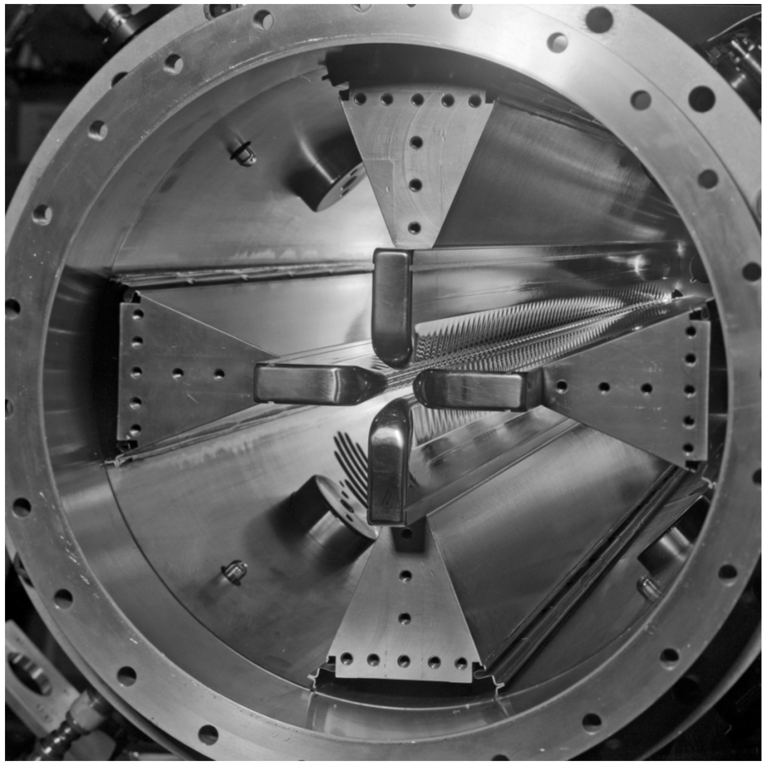

Elliptical cavities



“Low β” / “High β”

$$\beta = v/c$$

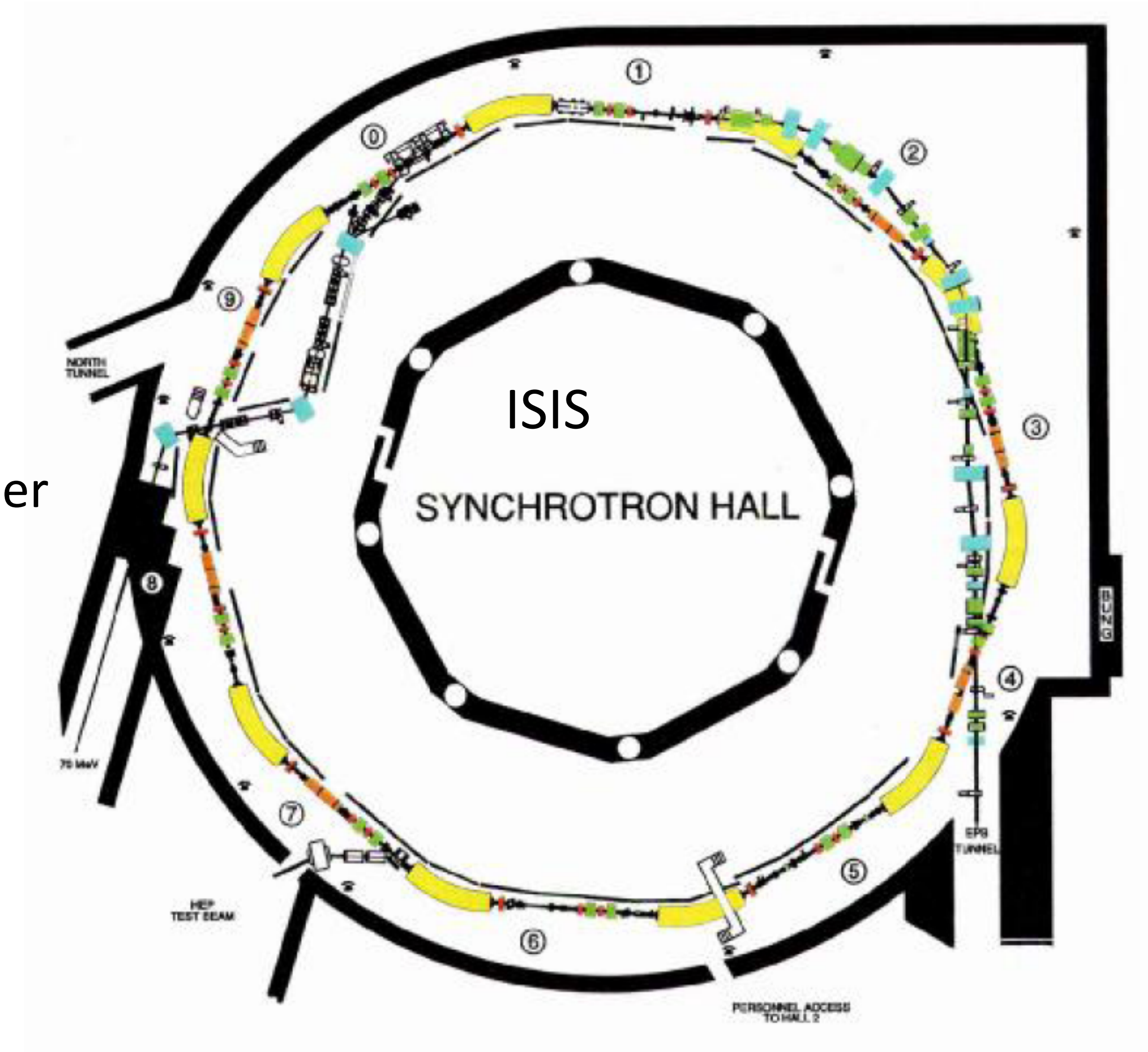
Radio-Frequency Quadrupole (RFQ)



# Synchrotron

EUROPEAN SPALLATION SOURCE

- 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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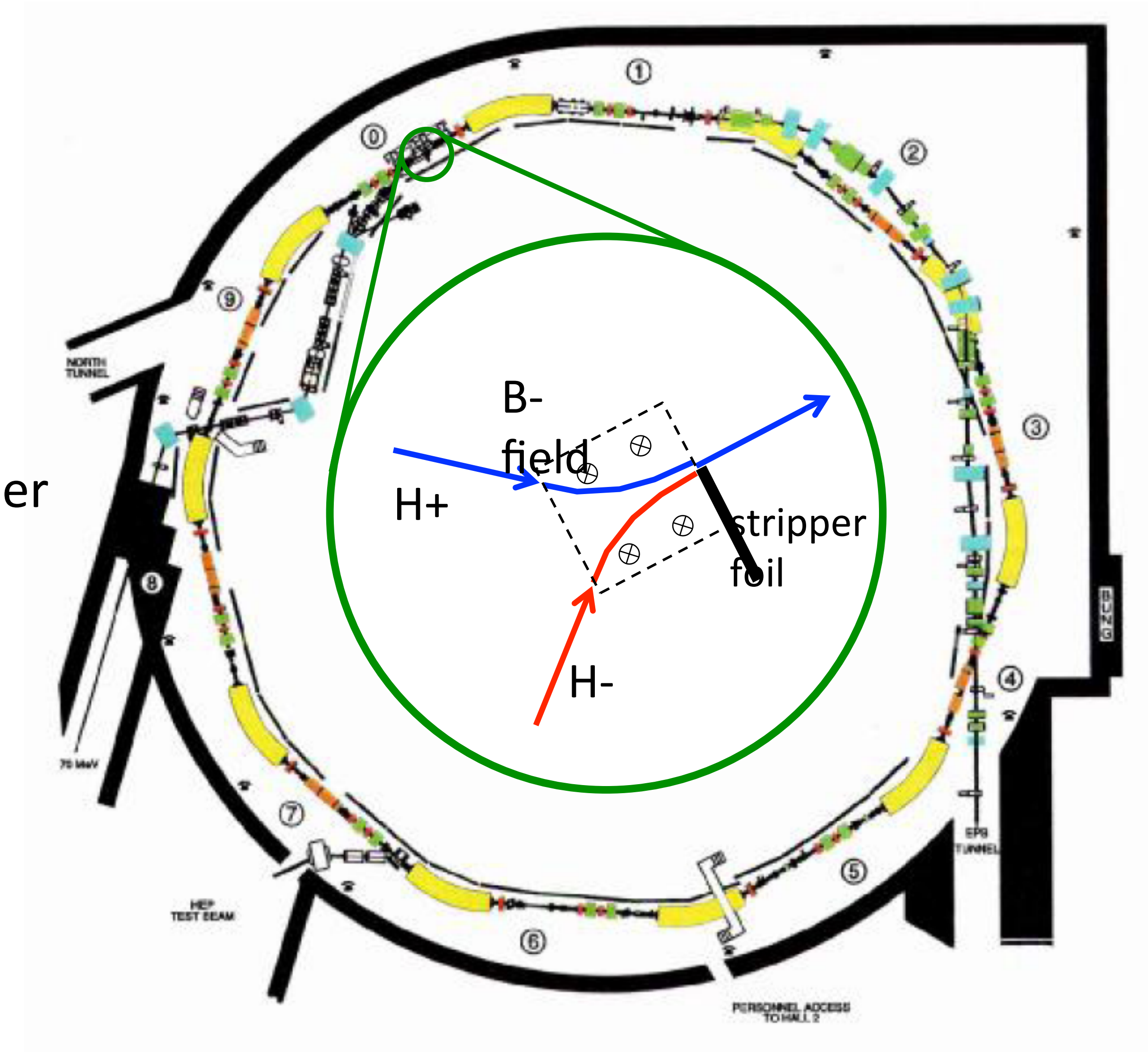
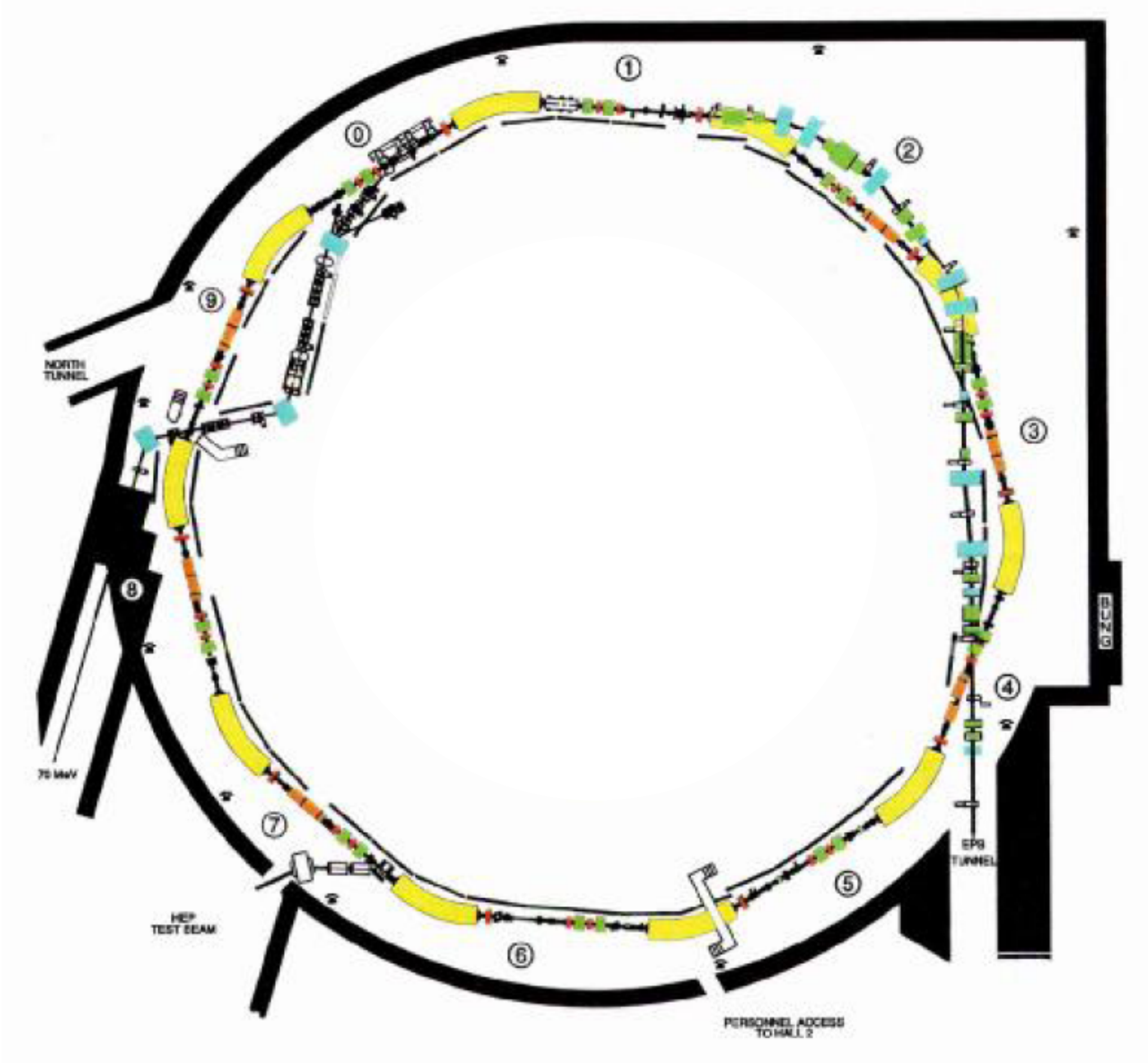
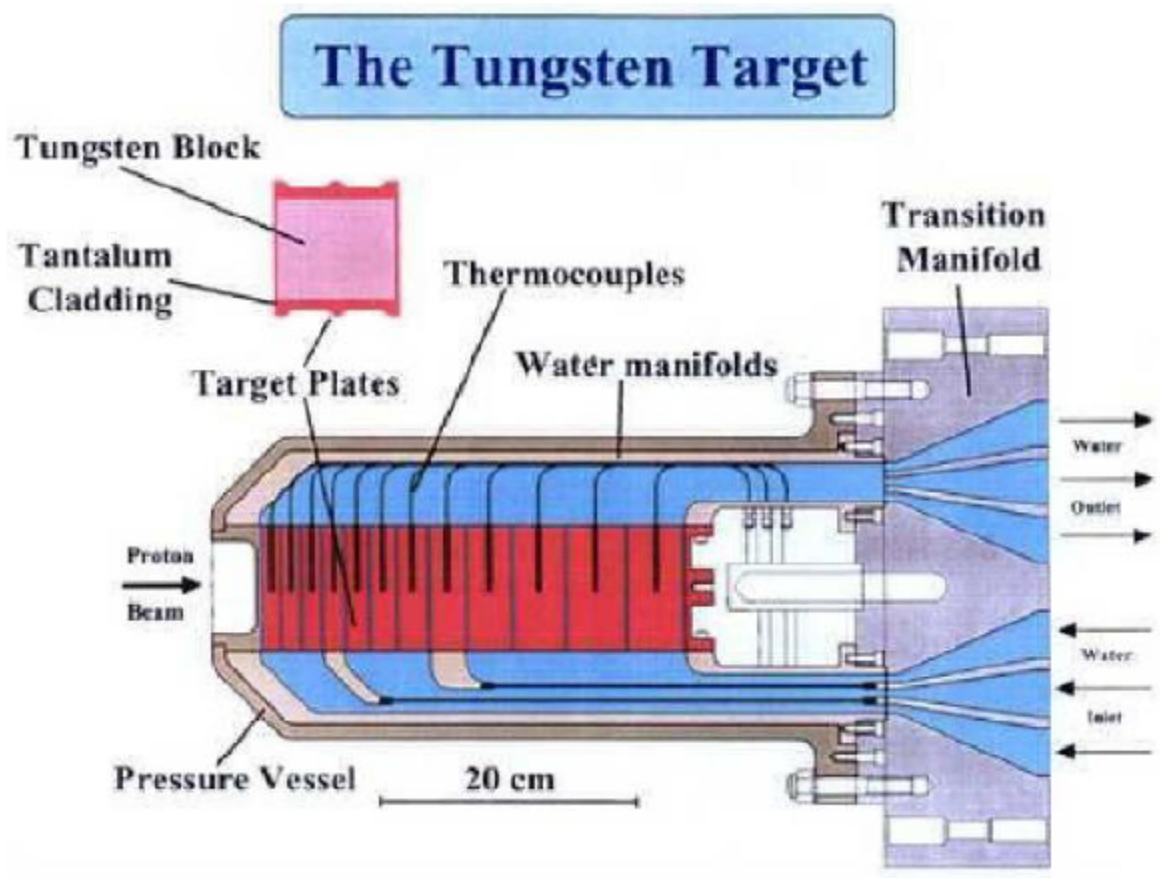


# Synchrotron

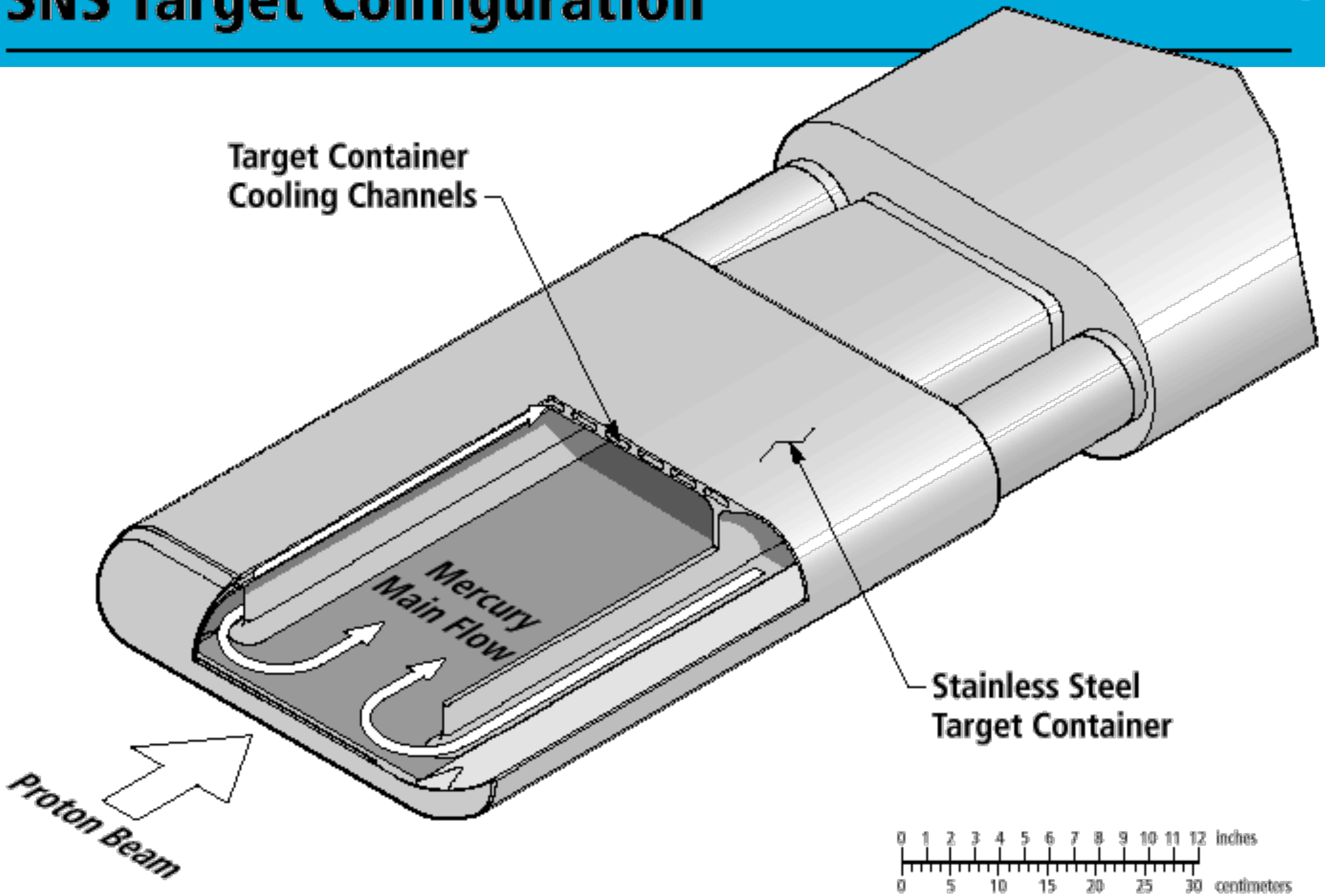
- $\Delta t_{linac} \approx 1$ ms
- $E_{ring} \approx 1$ GeV
  - $v \approx 3\times10^8$ m/s
- $L_{ring} \approx 200$ m
- $\Delta t_{ring} \approx 1$ µs



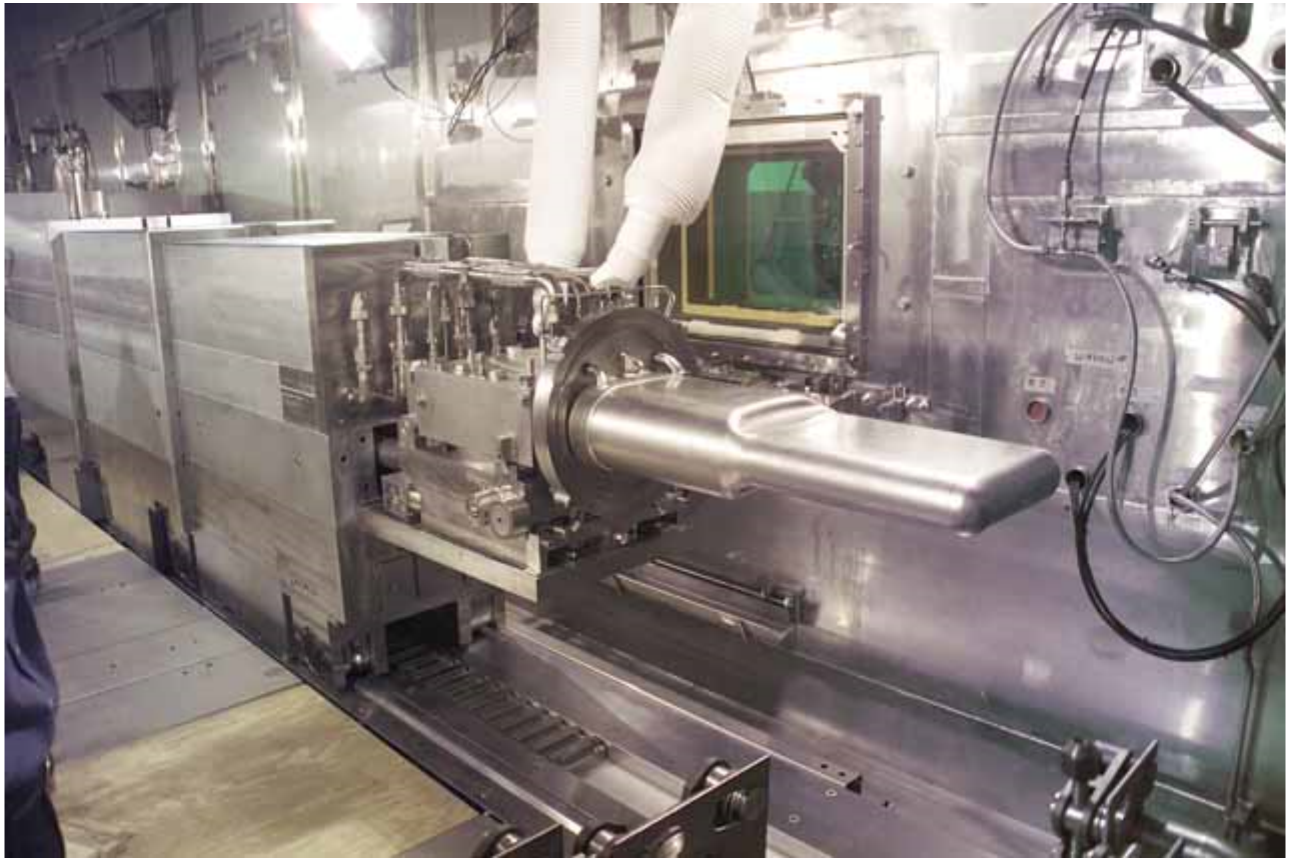
# ISIS target 1: solid tungsten



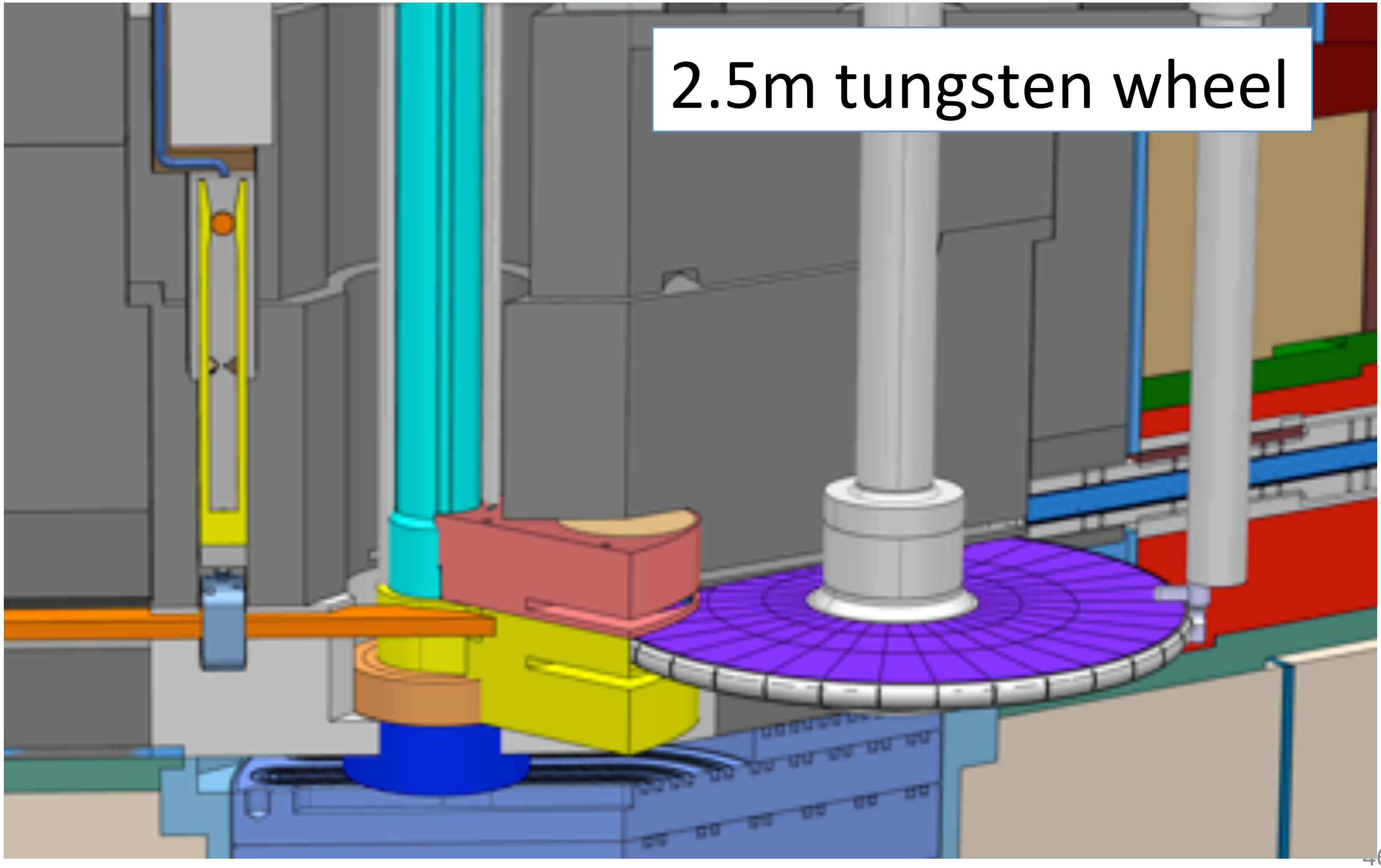
# SNS Target Configuration



# SNS target: liquid mercury

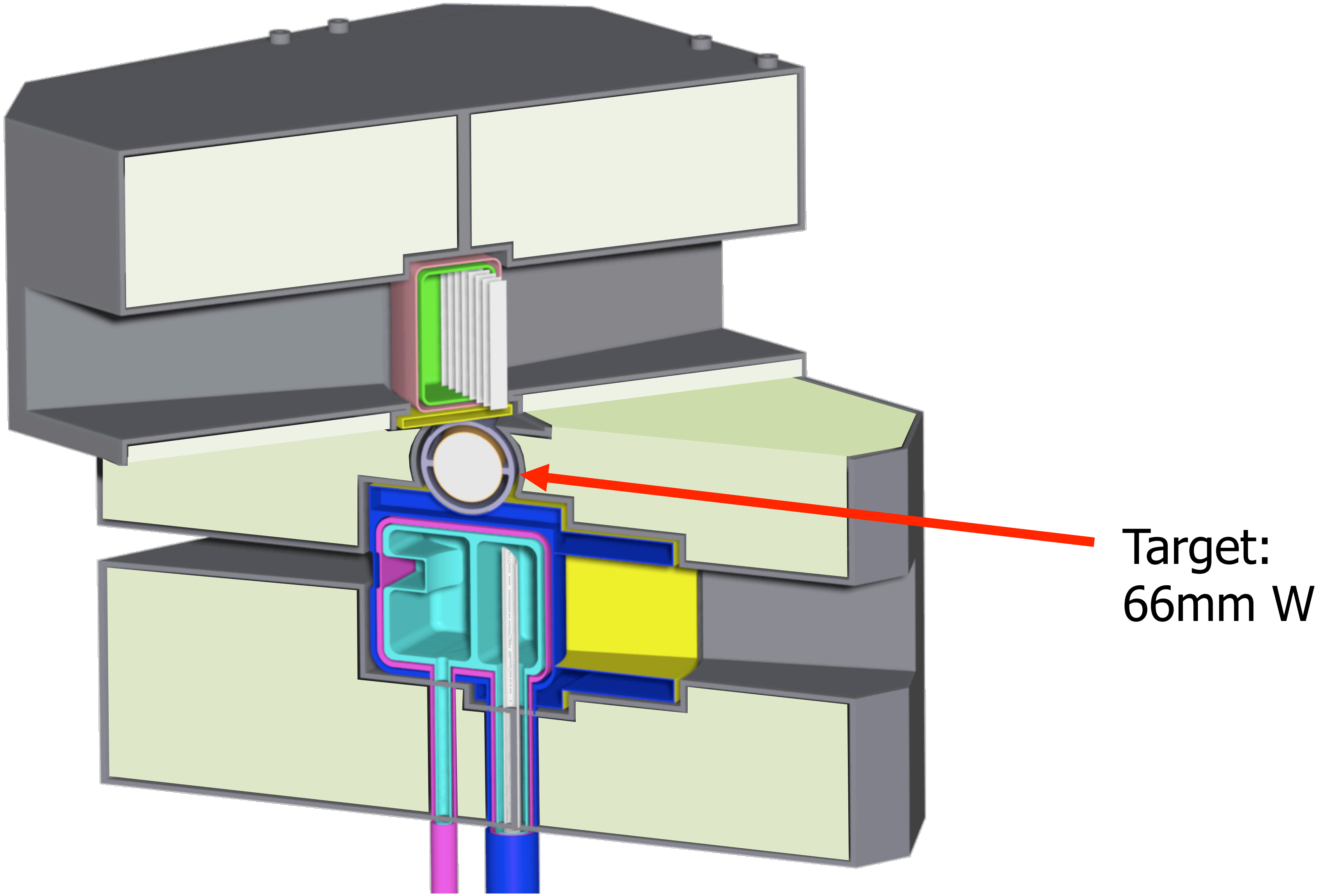


# ESS target



# ISIS TS2 Target

EUROPEAN SPALLATION SOURCE

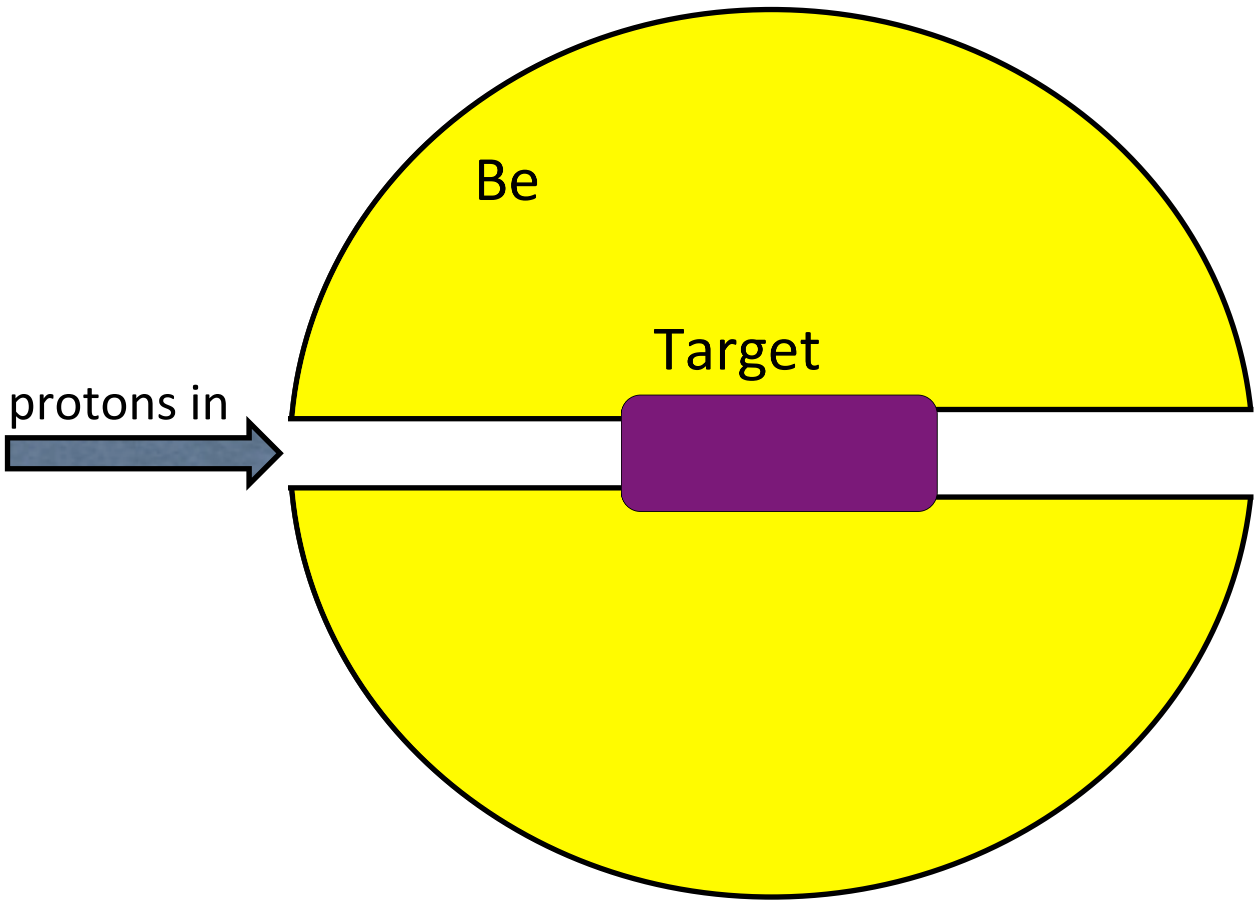


# Target-Reflector-Moderator Neutronics

- 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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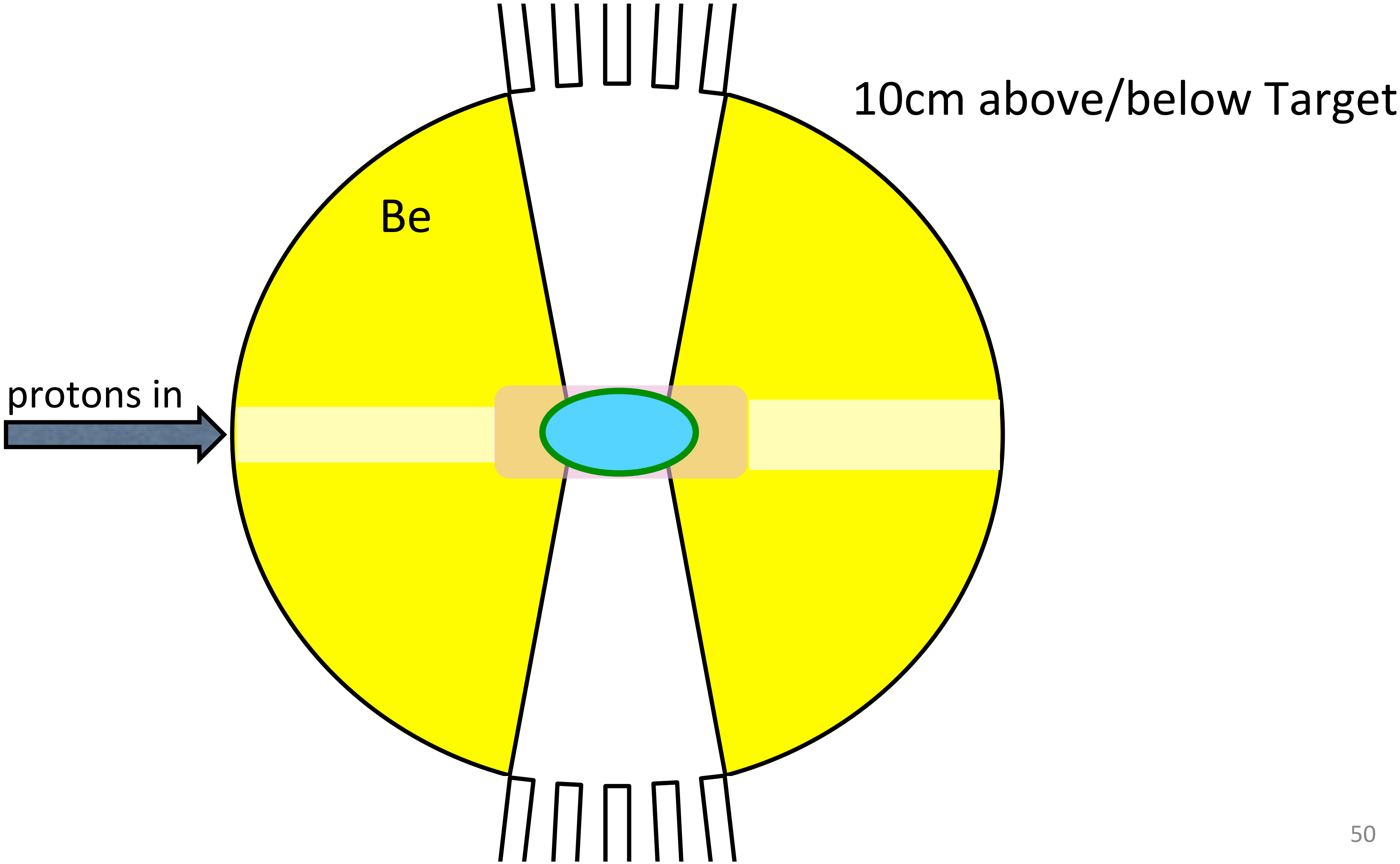
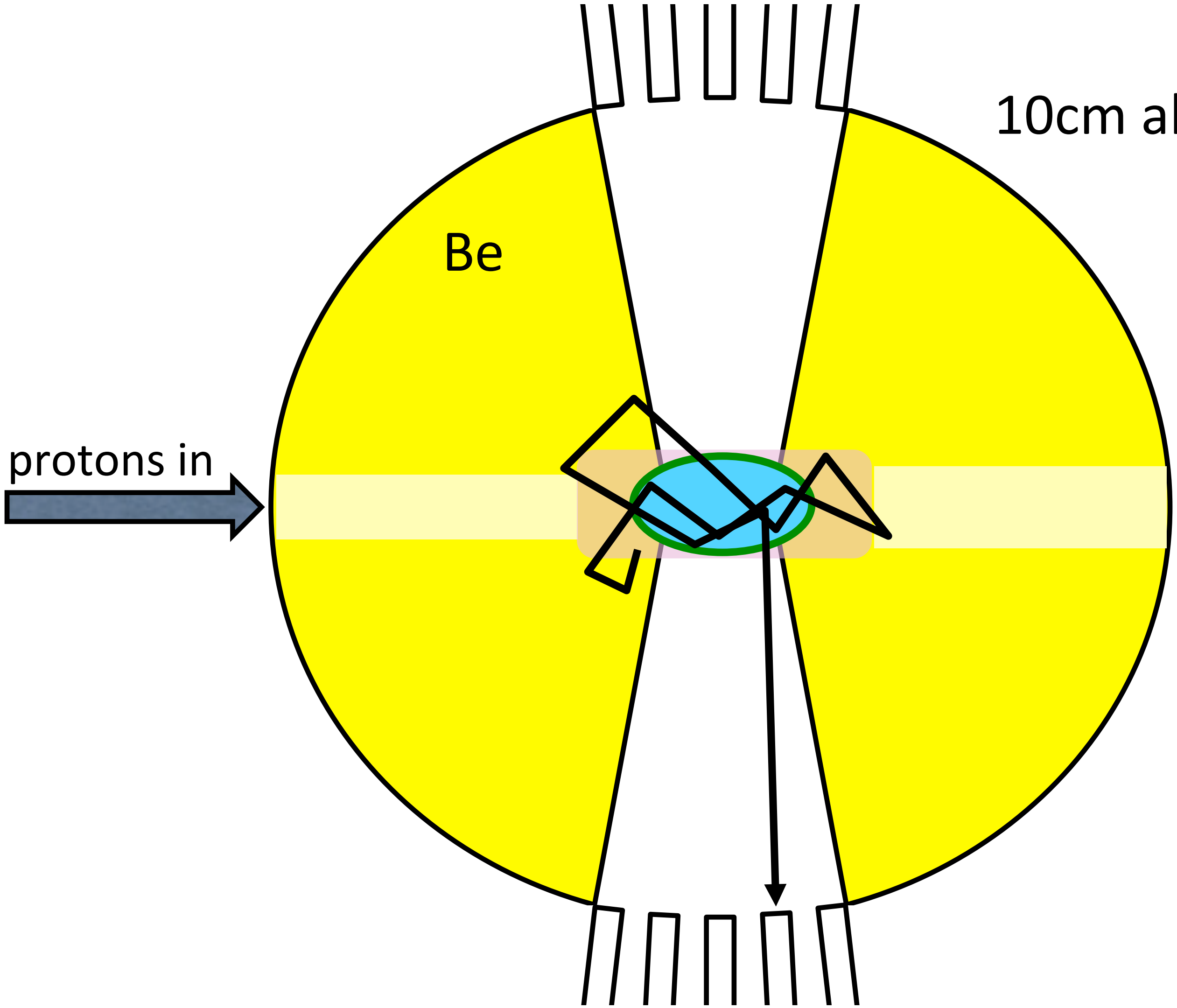


# Target-Reflector-Moderator Neutronics

10cm above/below Target



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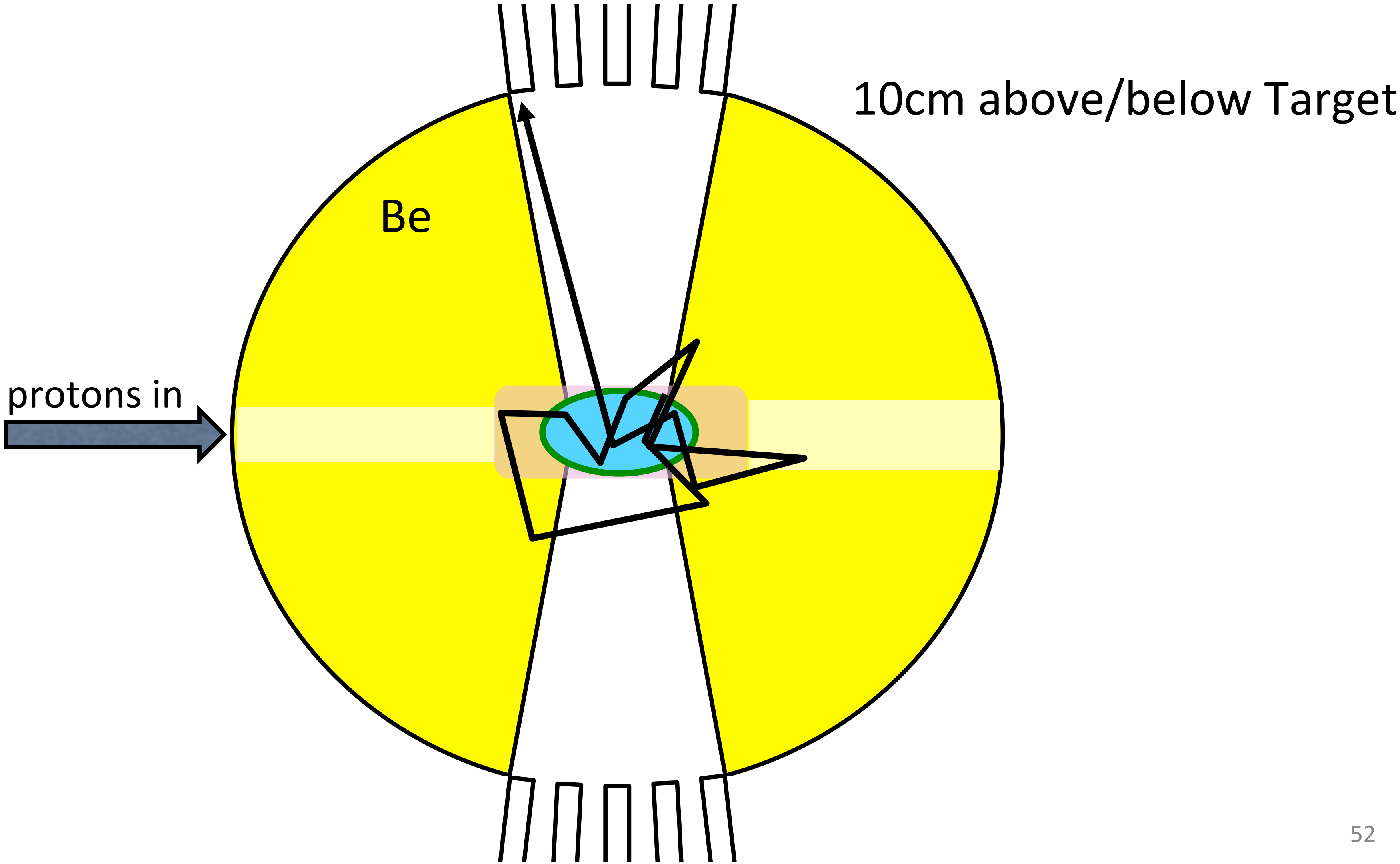

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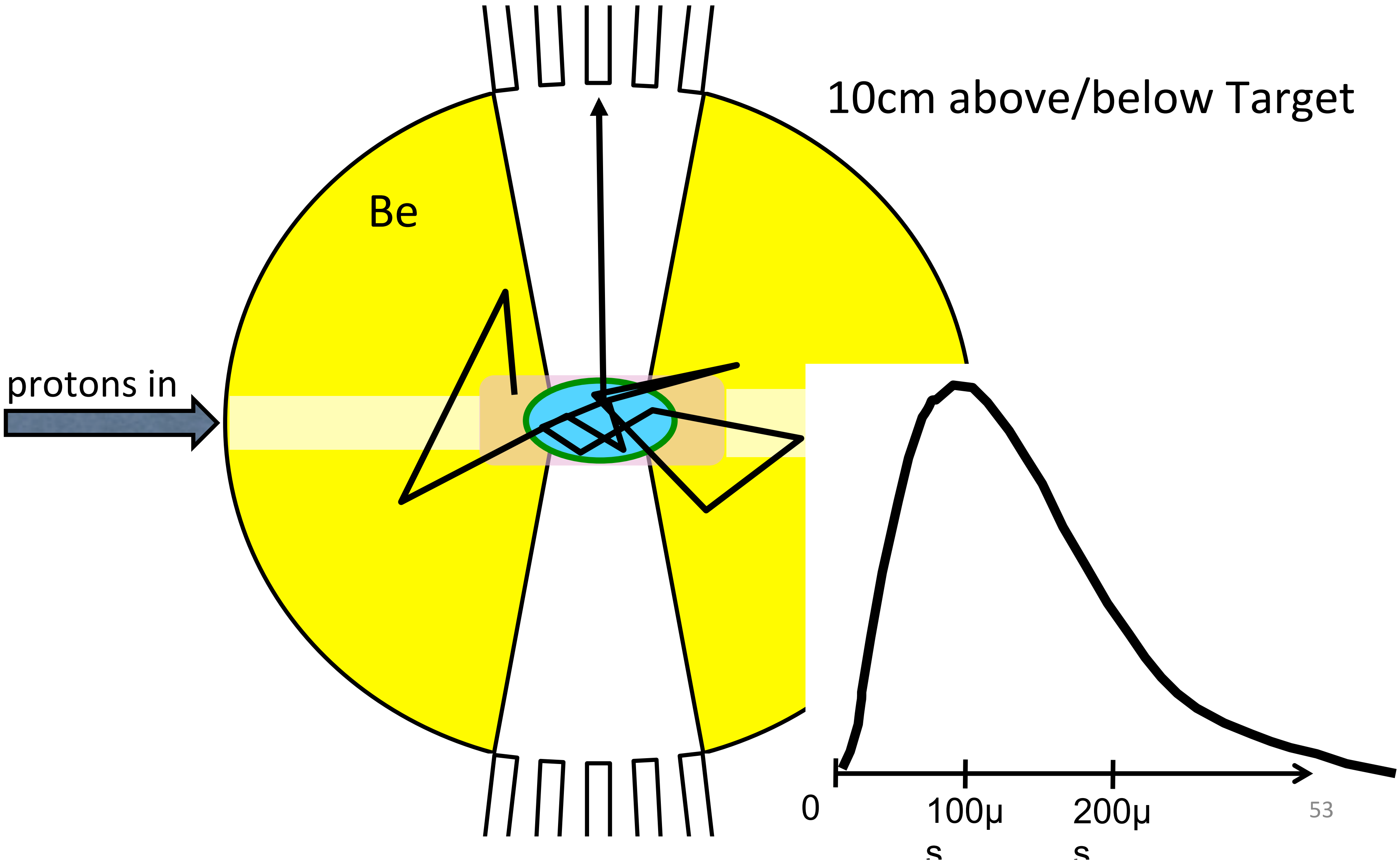

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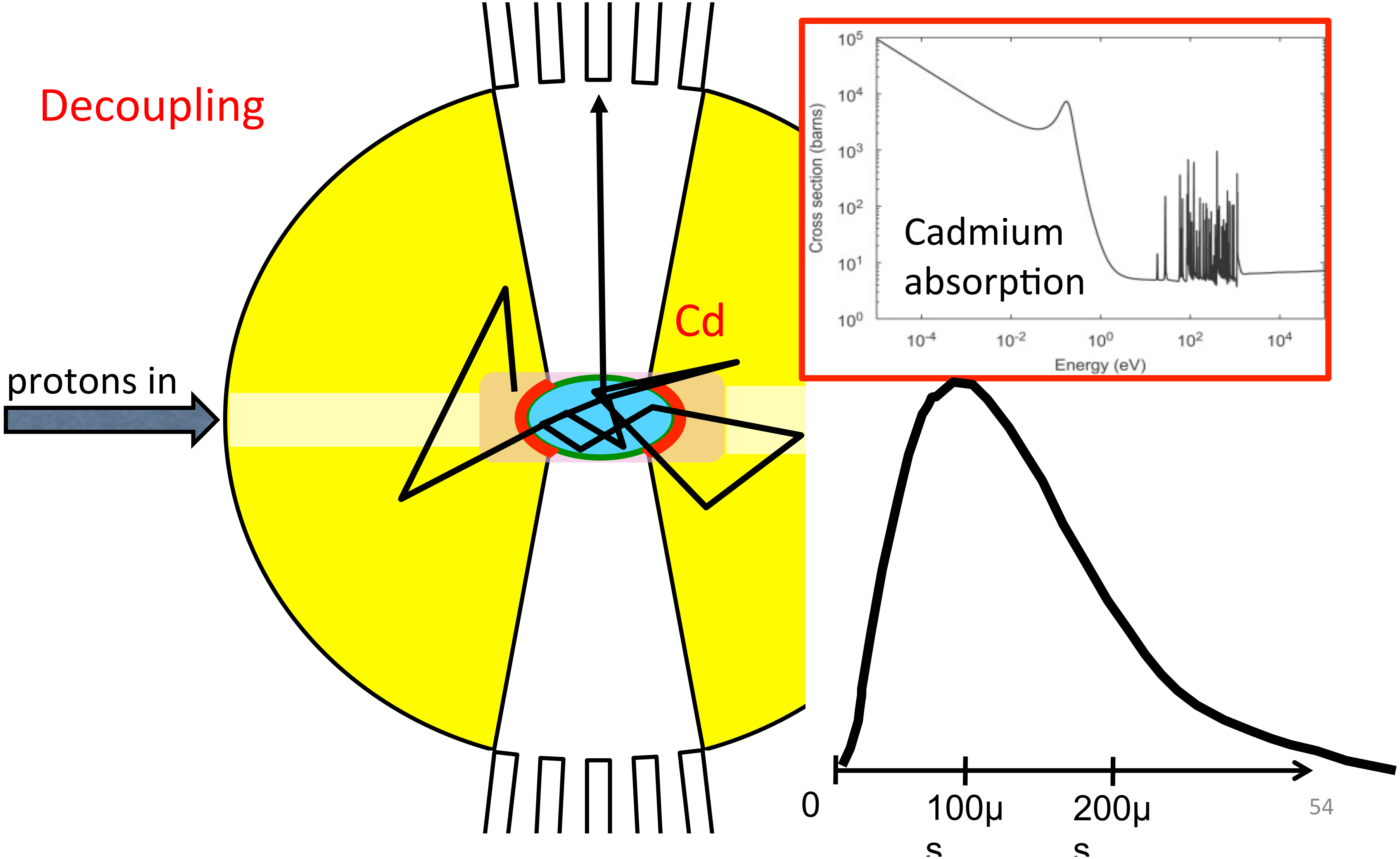

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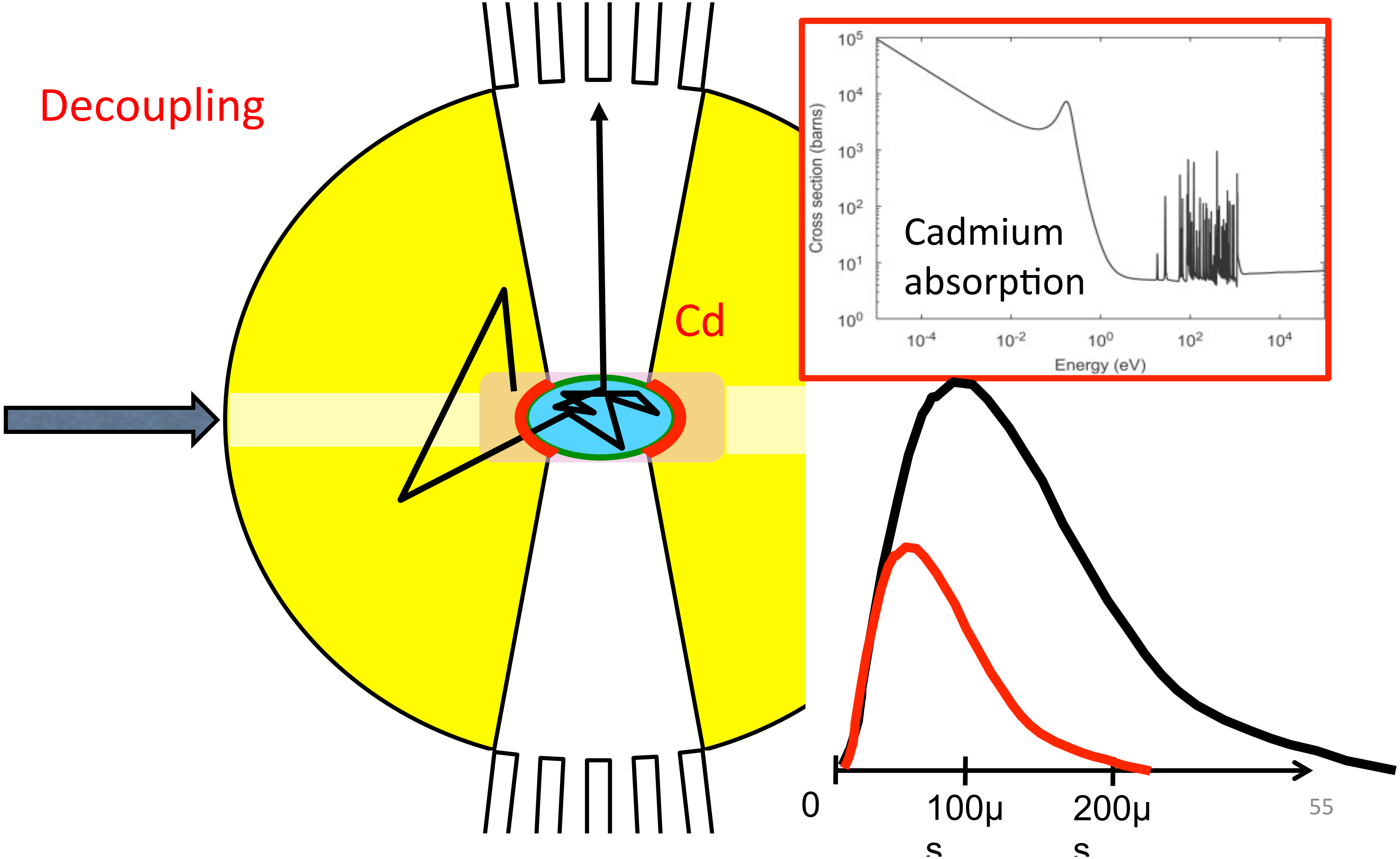

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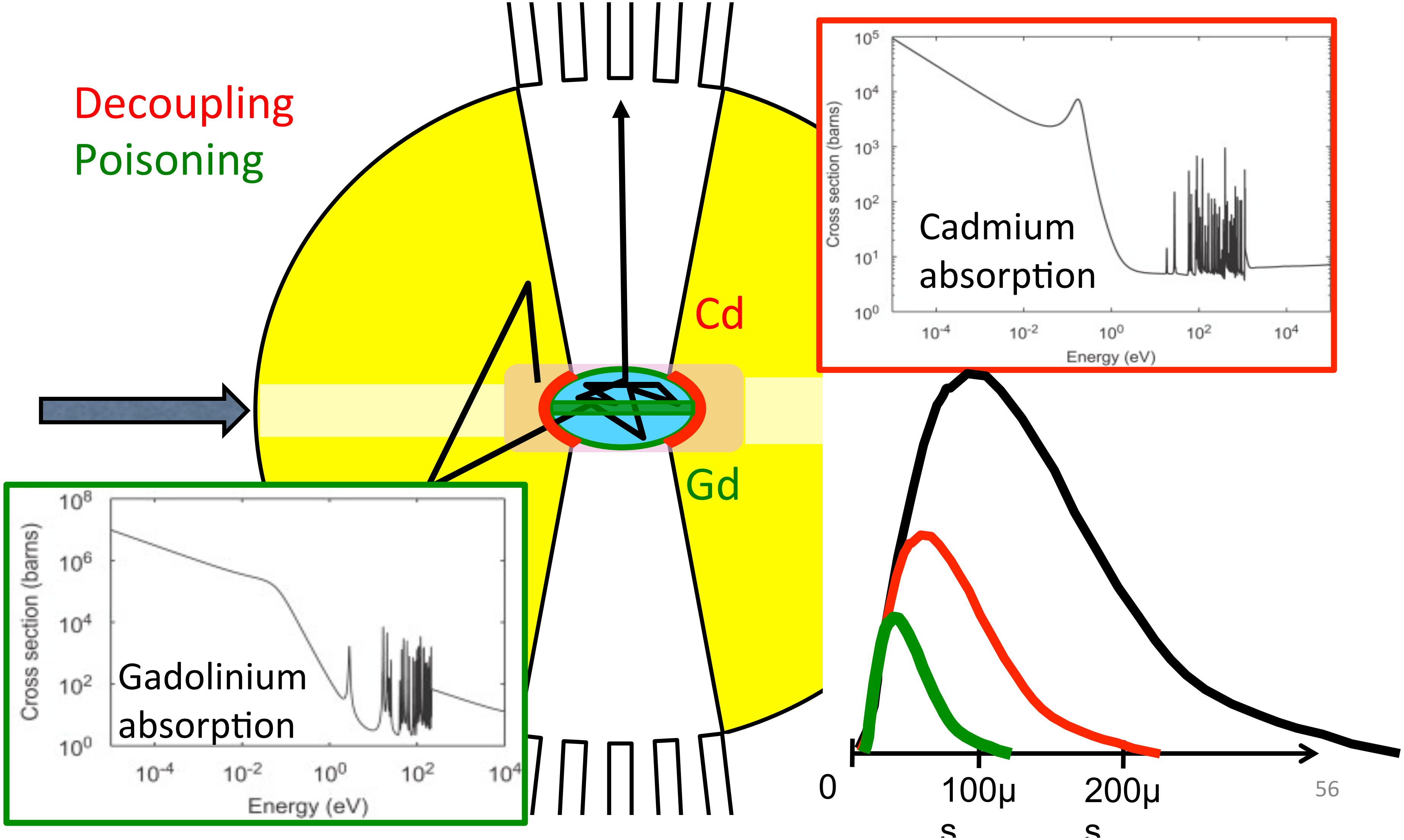
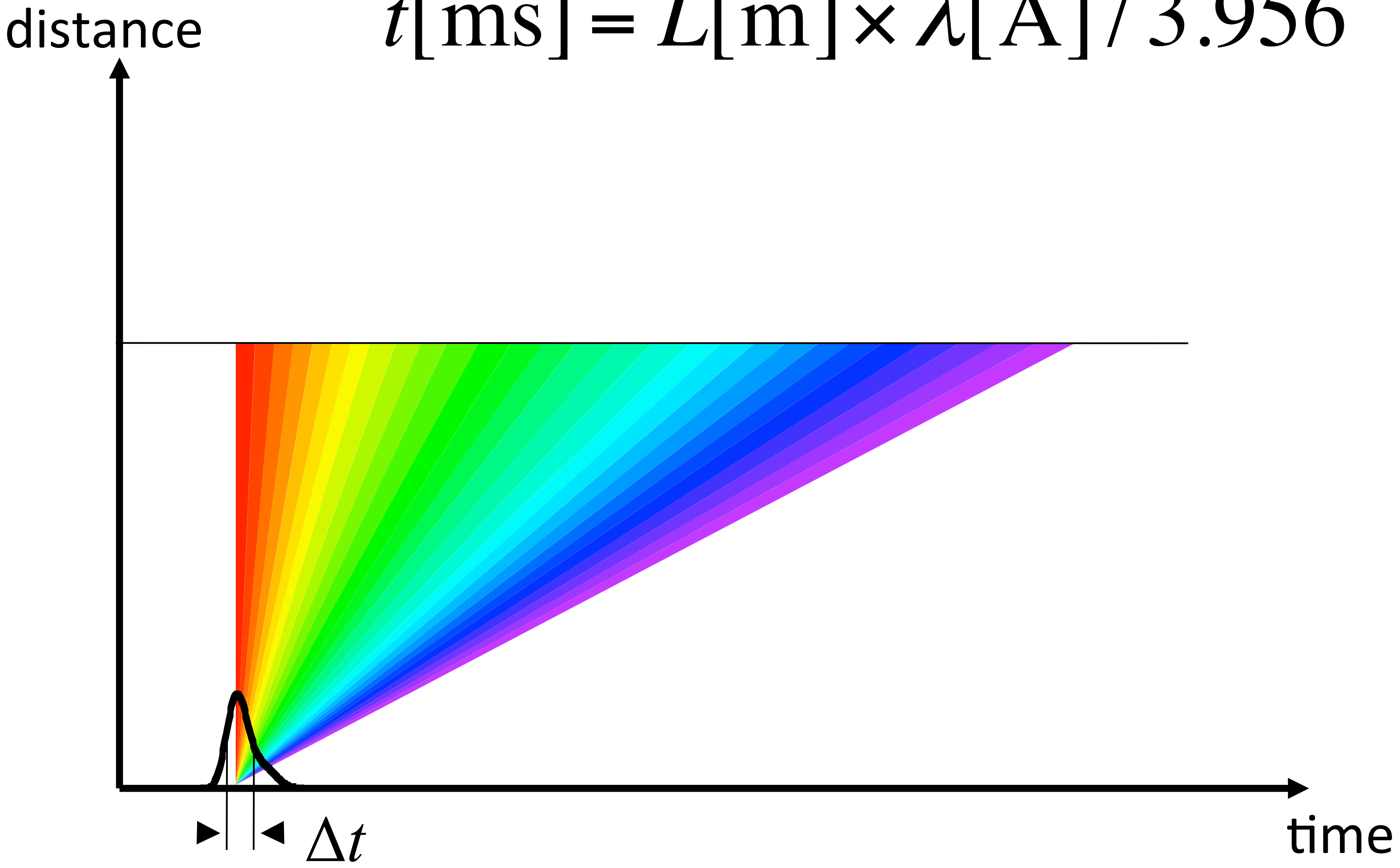


# Time-of-flight (TOF) resolution

EUROPEAN SPALLATION SOURCE

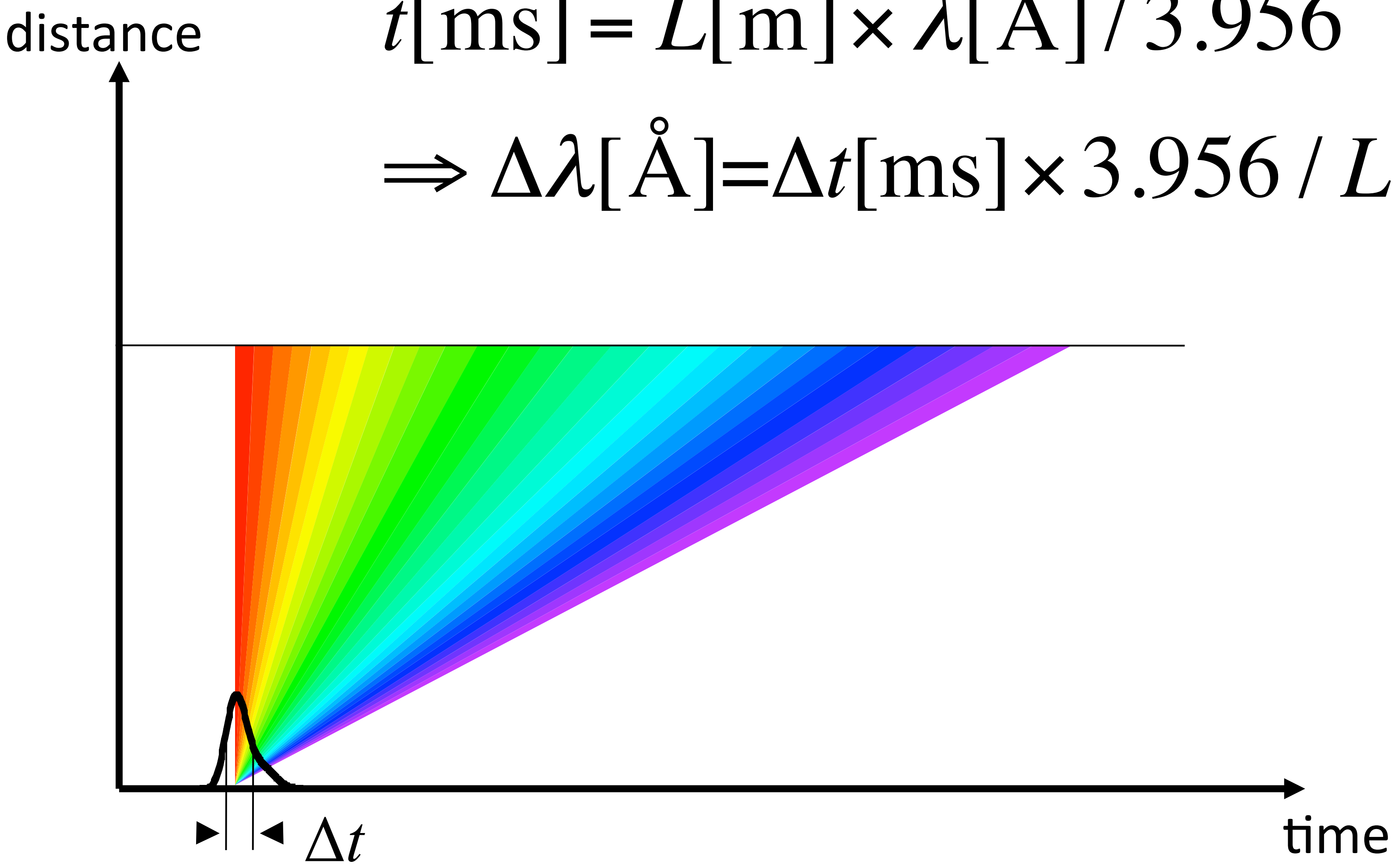
$$t[\text{ms}] = L[\text{m}] \times \lambda[\text{Å}] / 3.956$$



# Time-of-flight (TOF) resolution

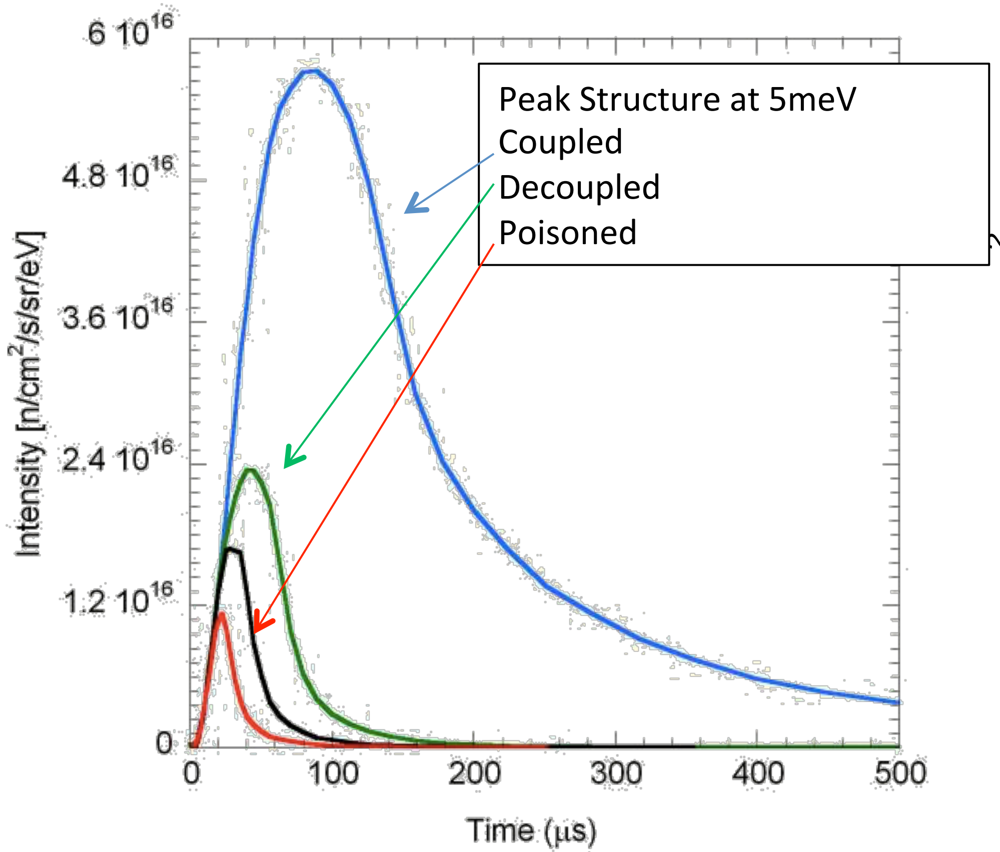
$$t[\text{ms}] = L[\text{m}] \times \lambda[\text{Å}] / 3.956$$

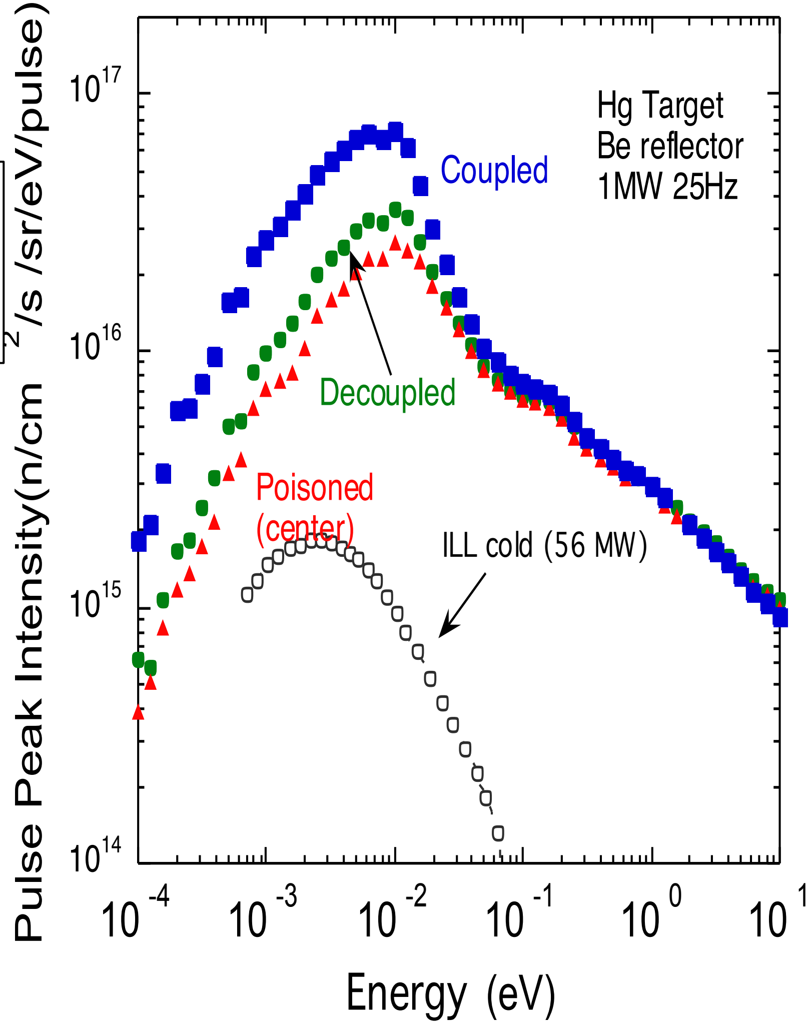
$$\Rightarrow \Delta\lambda[\text{Å}] = \Delta t[\text{ms}] \times 3.956 / L[\text{m}]$$



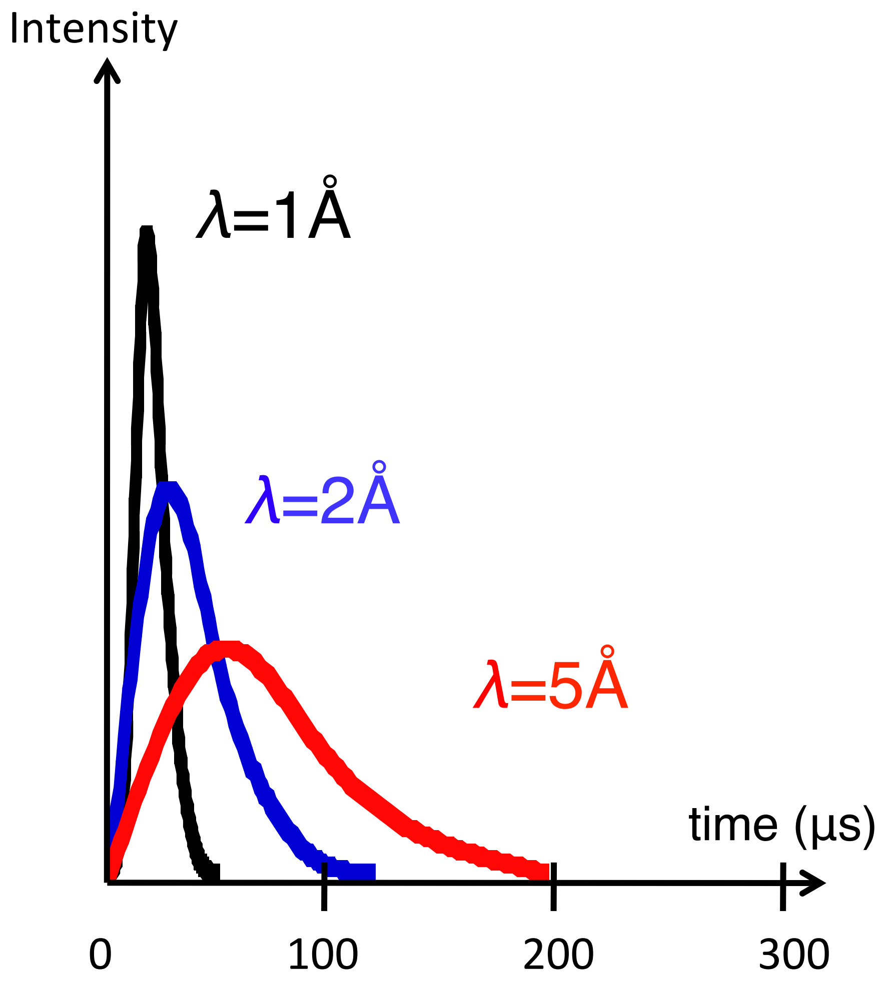
# Moderator Decoupling and Poisoning

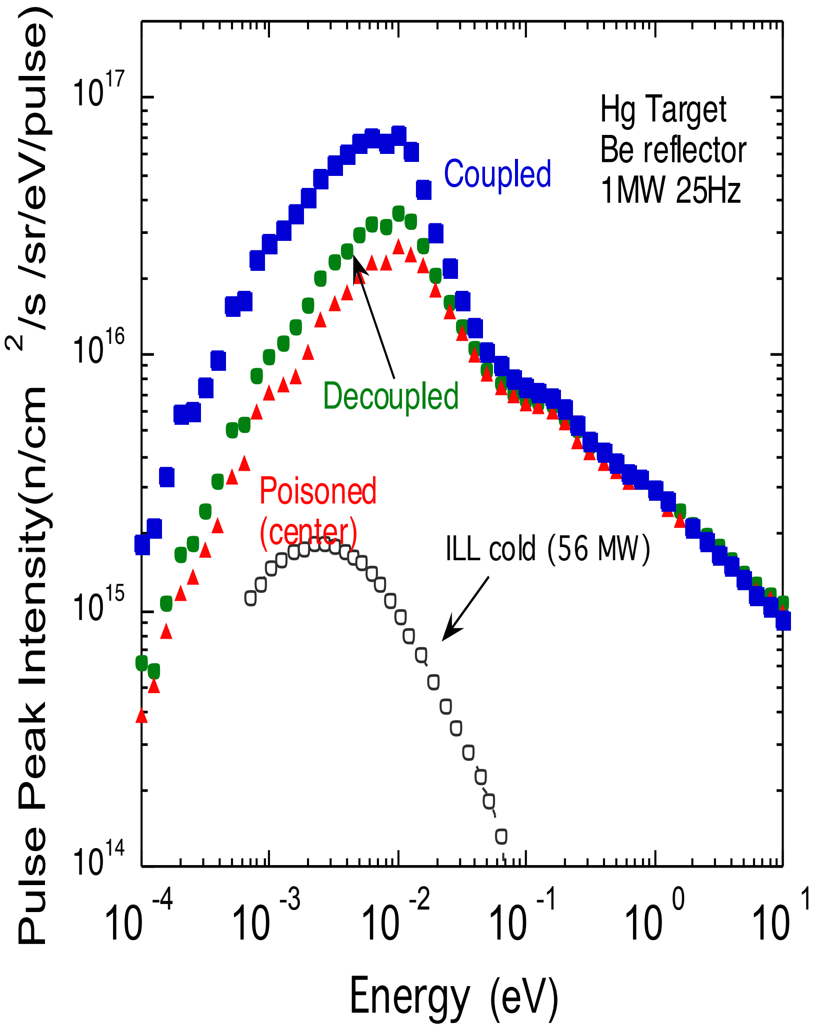
J-PARC $H_2$ moderators at 1MW



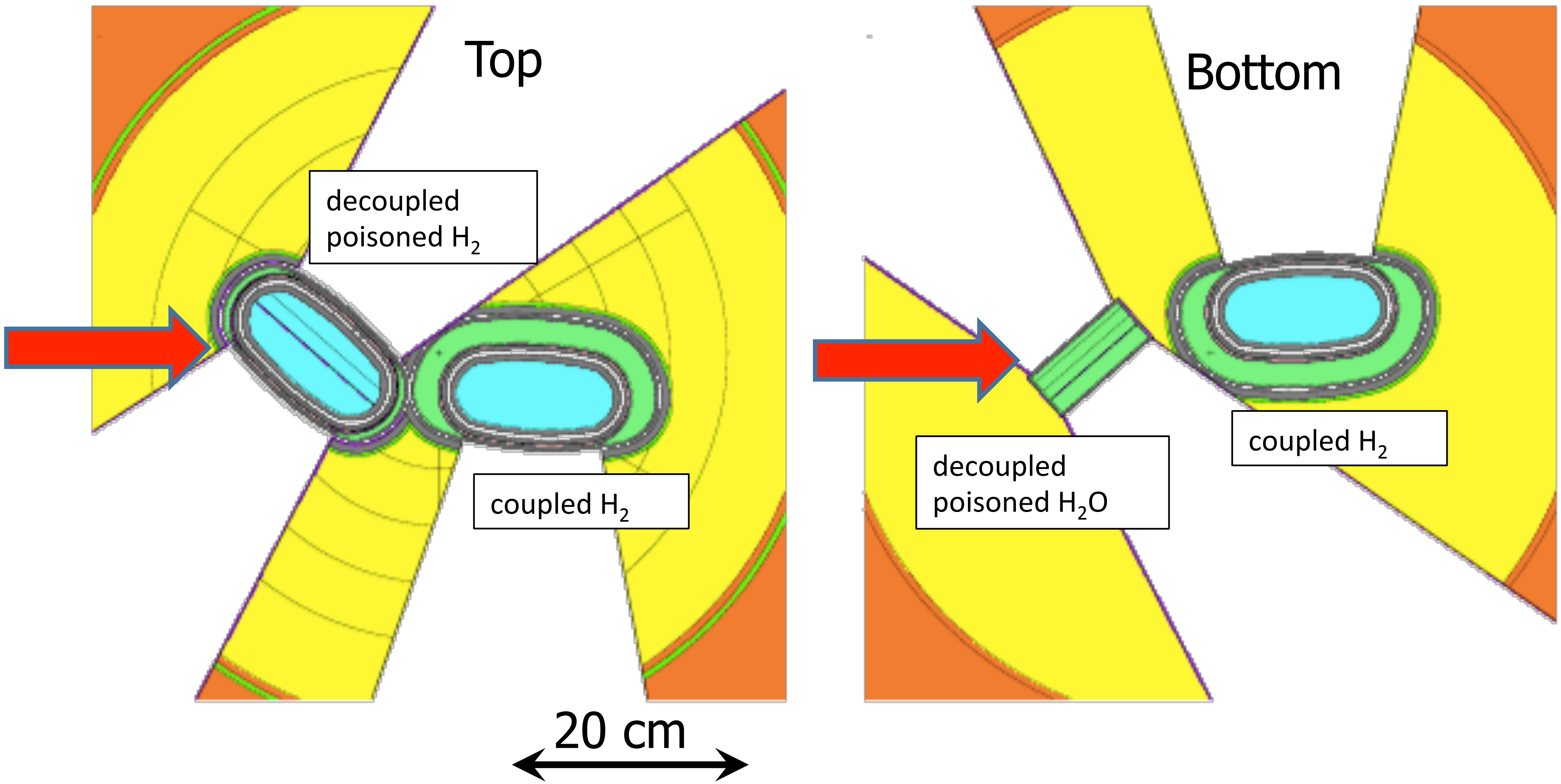



# Moderator Decoupling and Poisoning

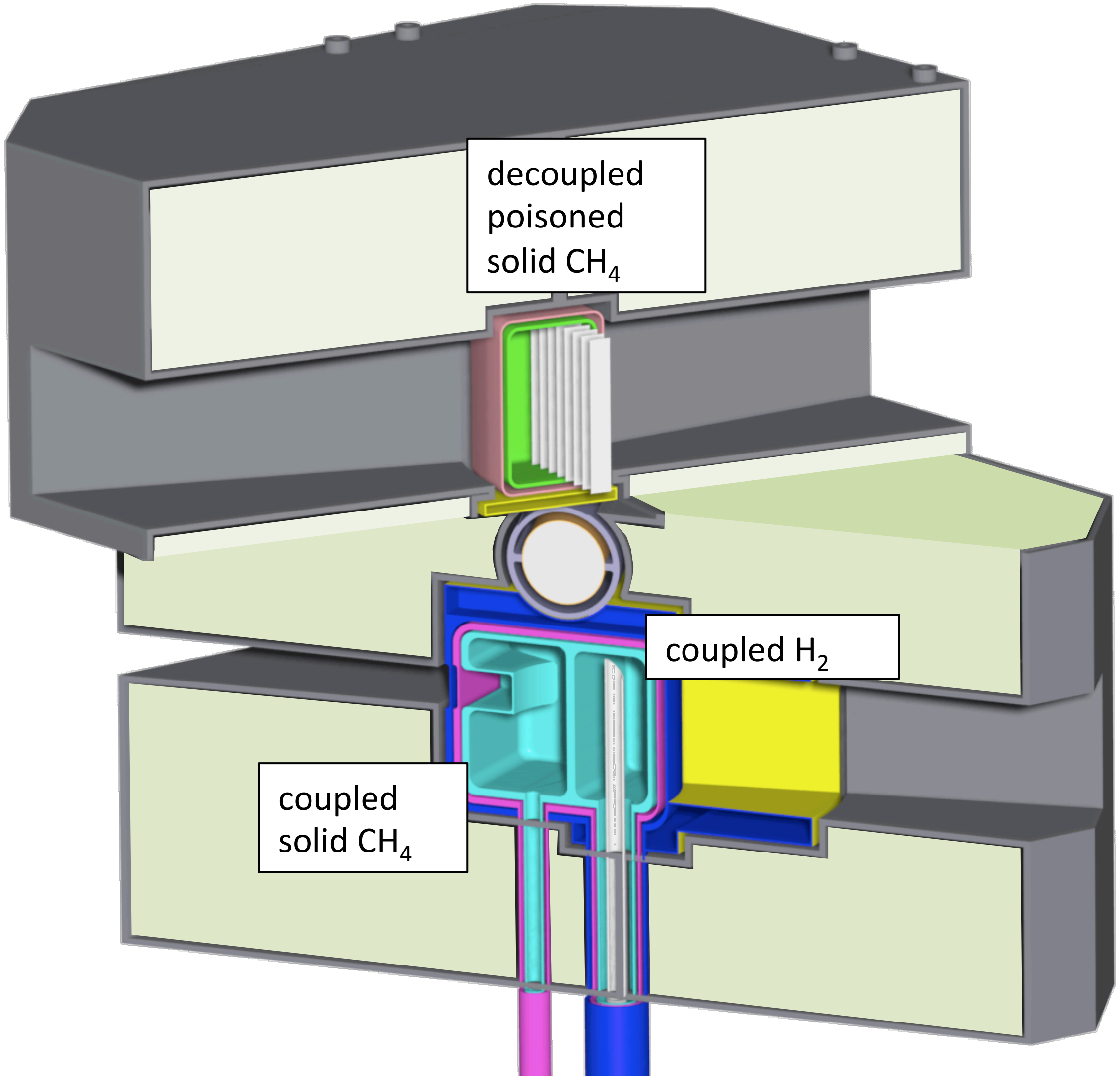


# SNS moderators



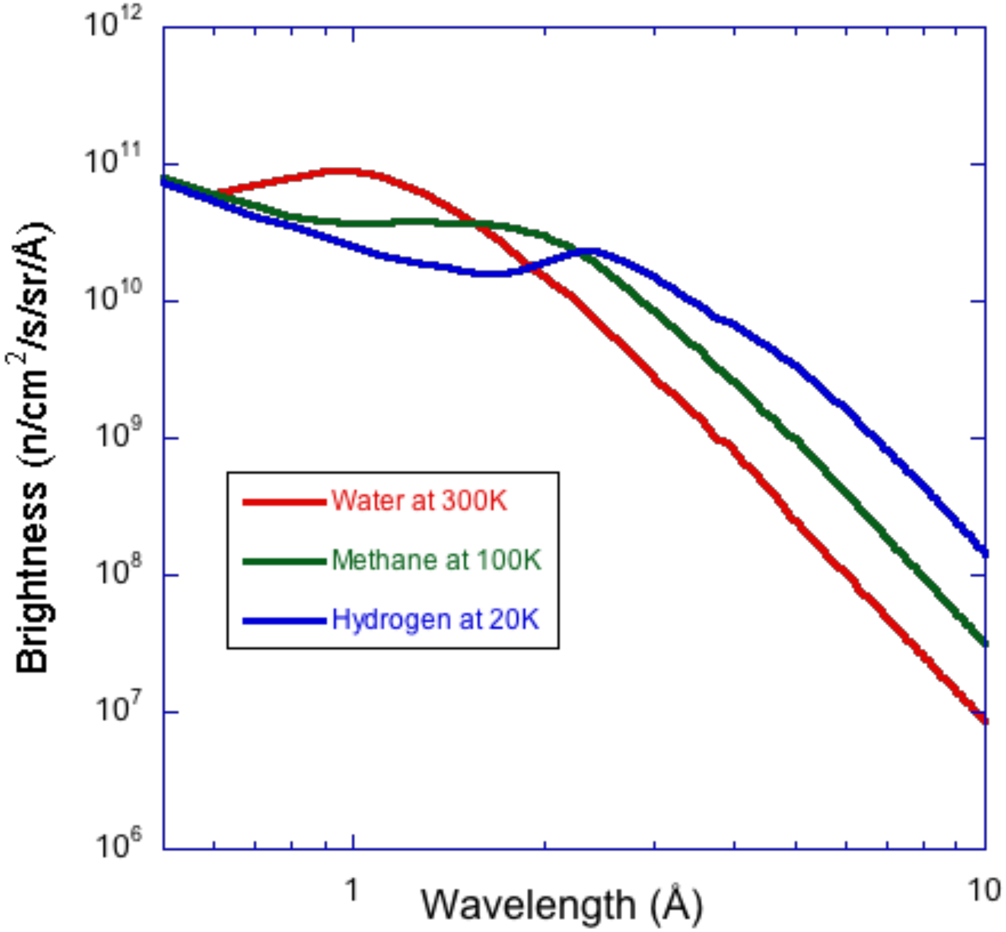
# ISIS TS2 Target



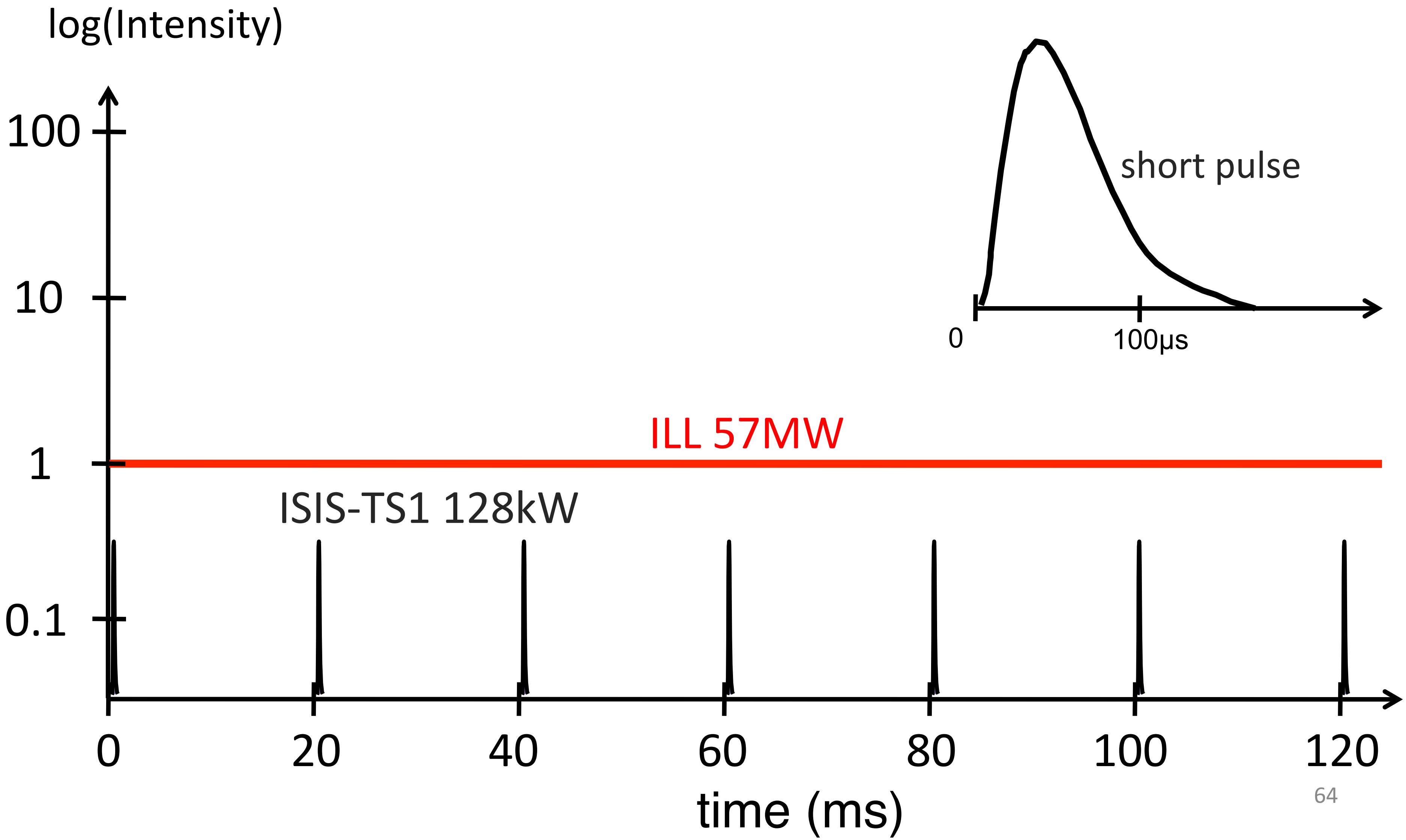
# Moderator Temperature

EUROPEAN SPALLATION SOURCE

ISIS-TS1 moderators at 160kW

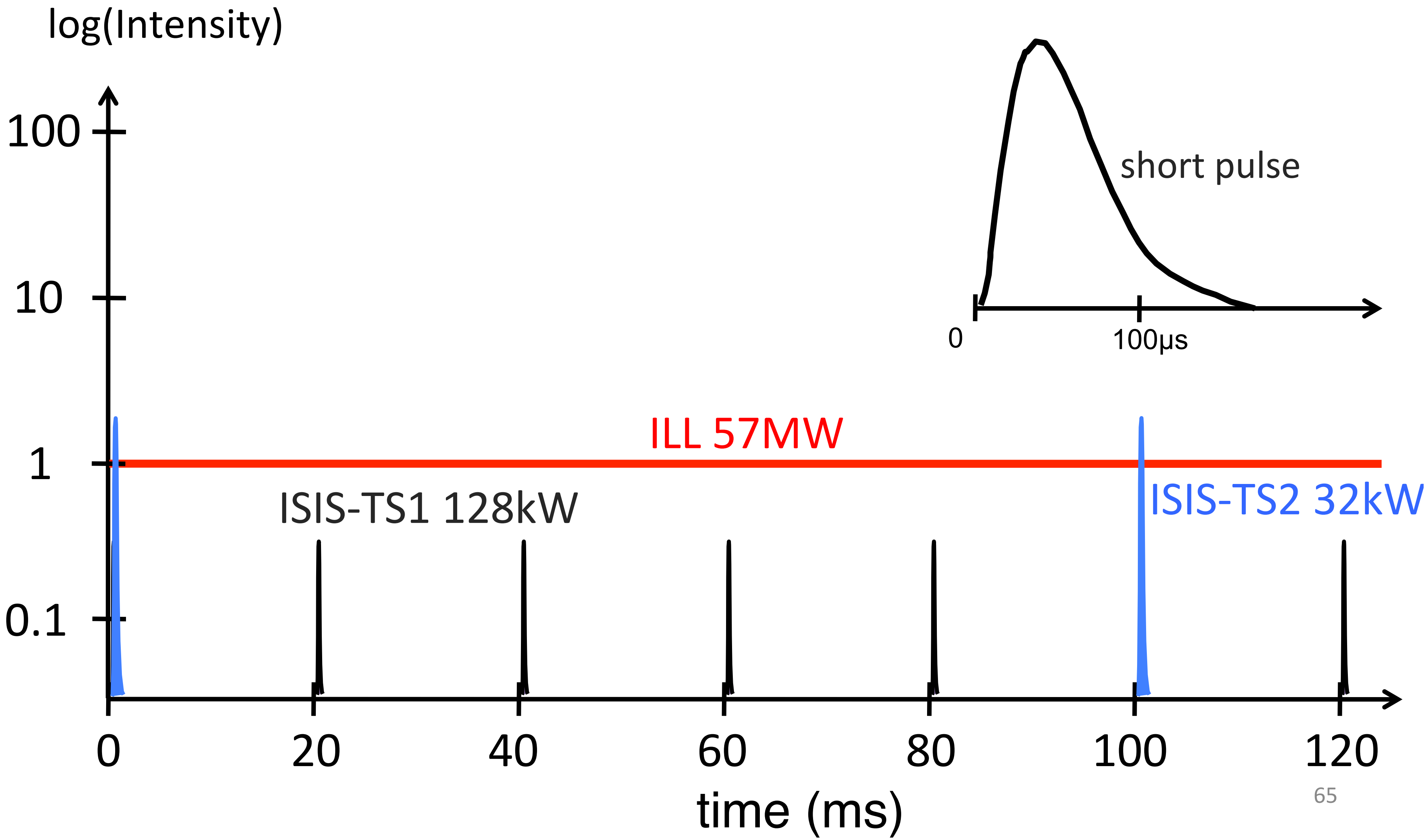


# Pulsed source time structures (λ=5Å)

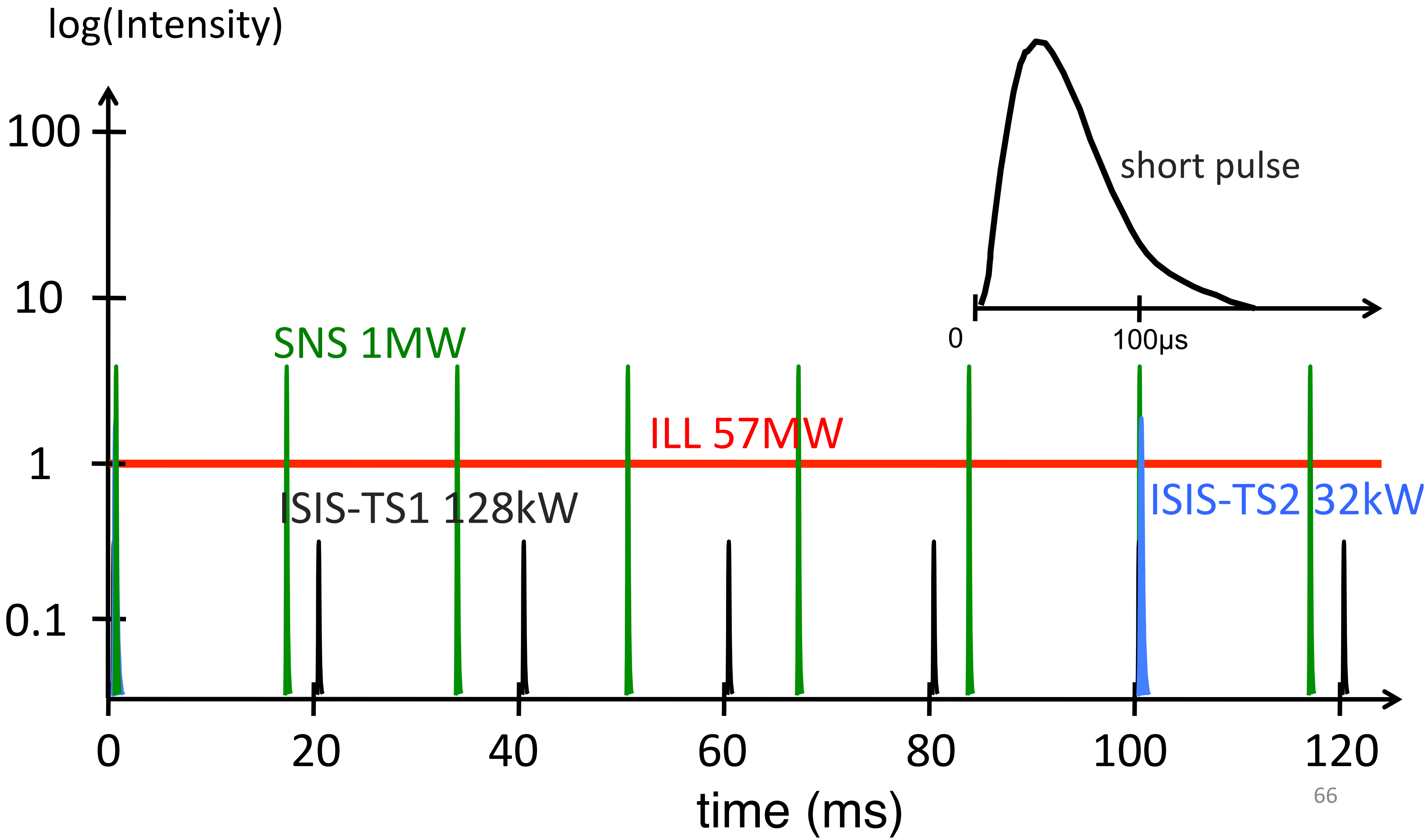


# Pulsed source time structures (λ=5Å)

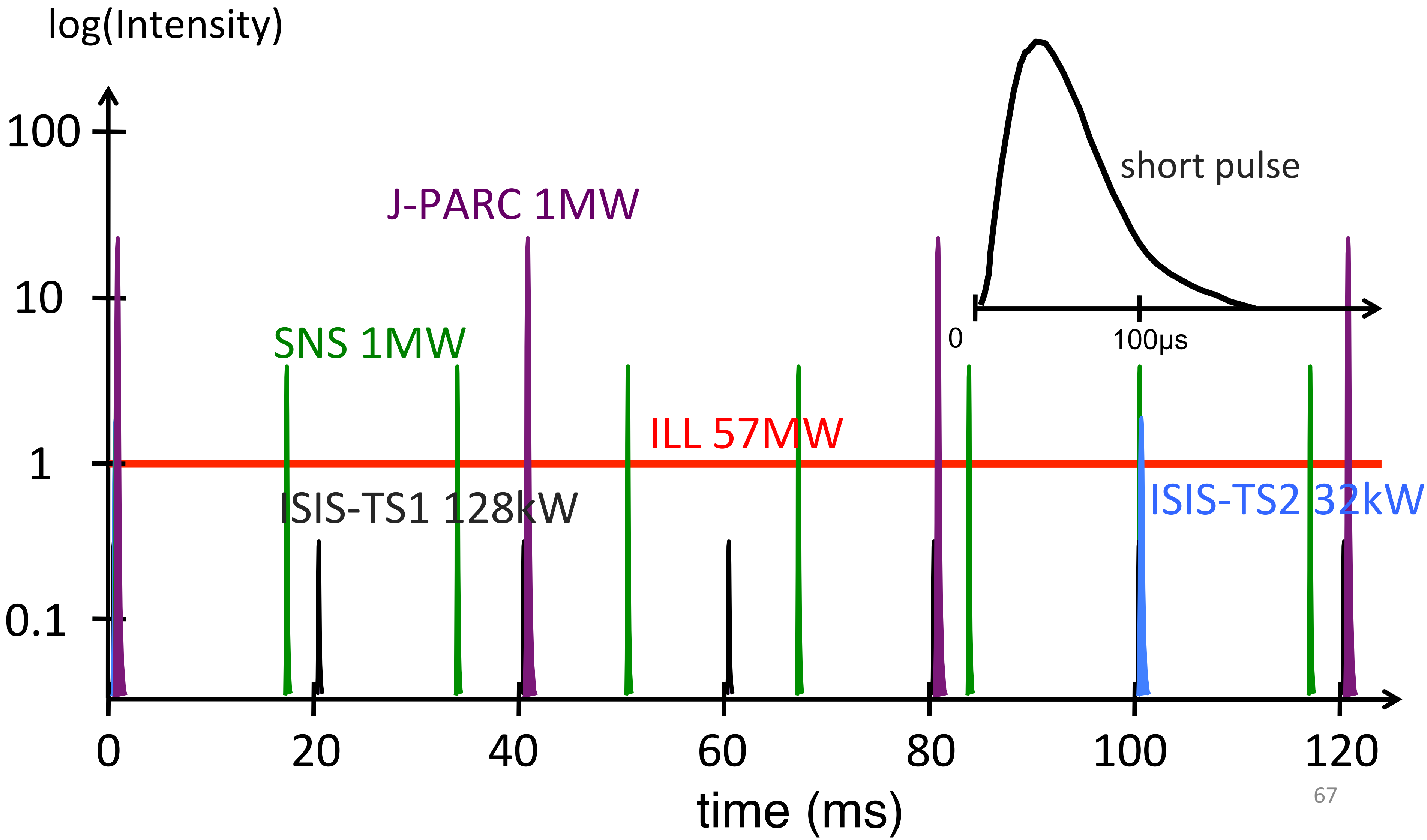
EUROPEAN SPALLATION SOURCE



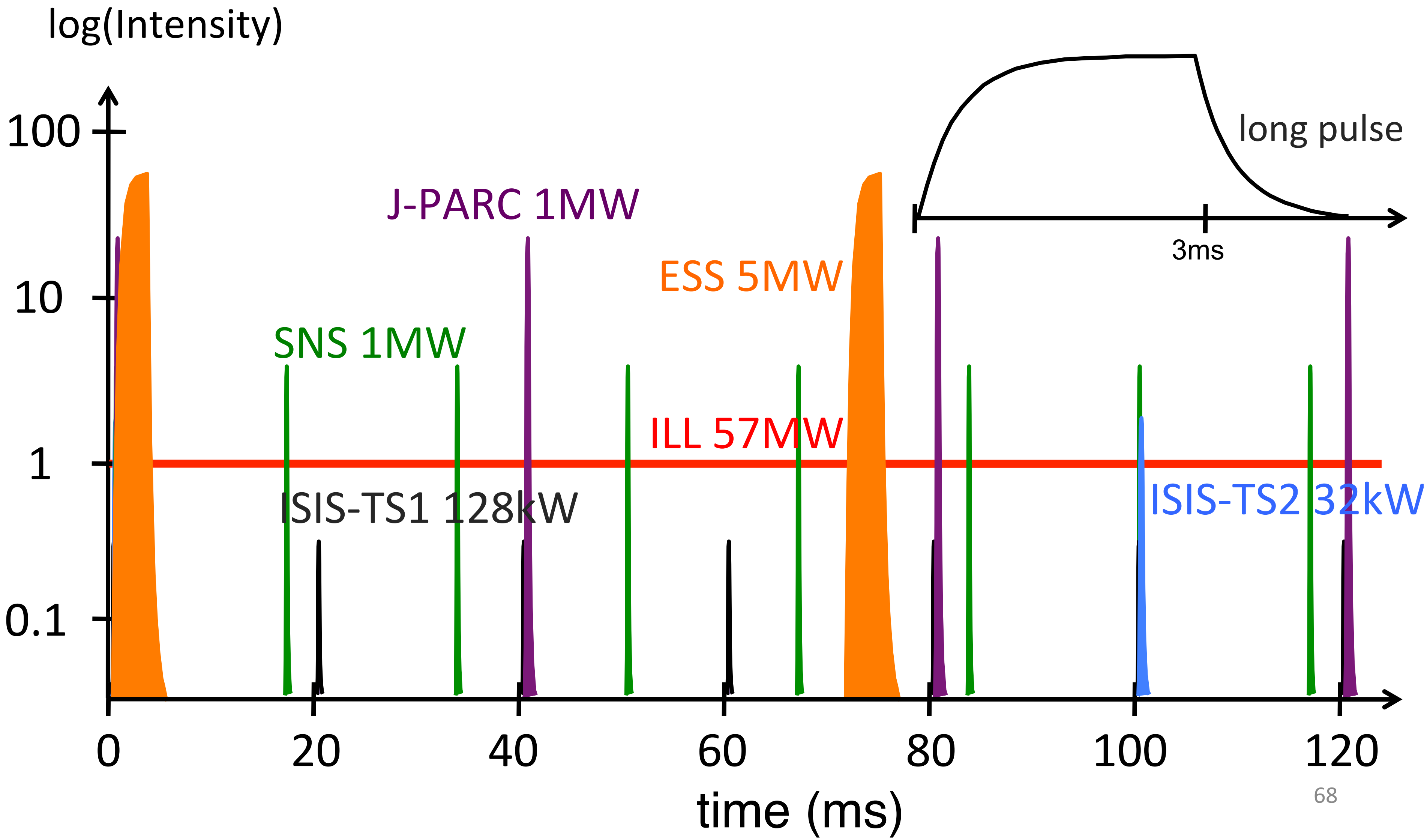
# Pulsed source time structures (λ=5Å)



# Pulsed source time structures (λ=5Å)



# Pulsed source time structures (λ=5Å)



# 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

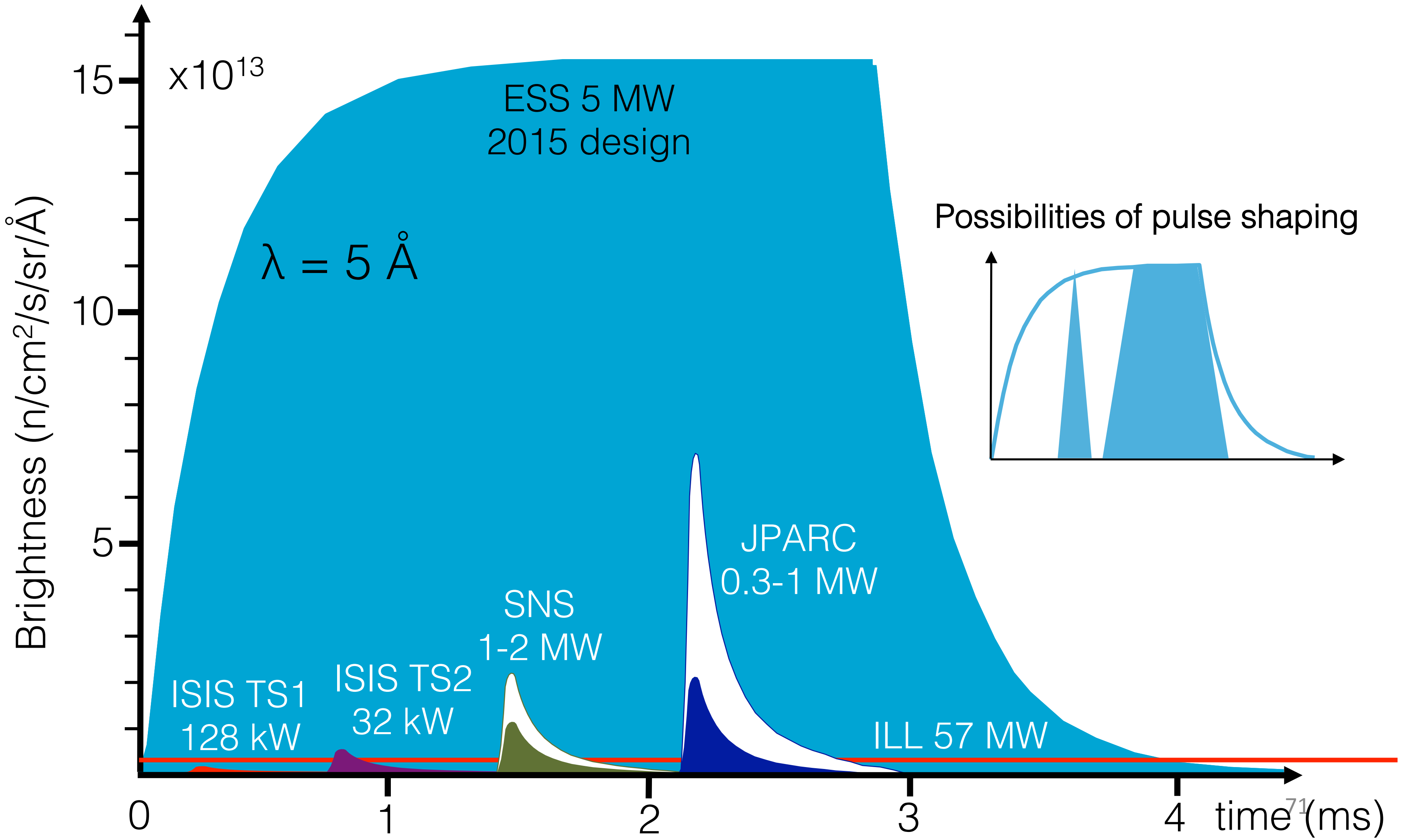

SNS instantaneous power on target:

17kJ in 1µs: 17 x


ESS instantaneous power on target: 125MW

360kJ in 2.86ms

# Long-pulse performance



# Thank You!

EUROPEAN SPALLATION SOURCE