EUROPEAN
SPALLATION
SOURCE

Neutronics dictionary

Günter Muhrer

www.europeanspallationsource.se

Outline

- Targets
  - Flat target
  - Compact target
  - Split target
  - Thin target
- Moderator parameters
  - Neutron surface current
  - Neutron surface flux
  - Neutron volume flux
  - Neutron brightness
  - Time distribution/buckling term
- Moderators
  - Coupled moderator
  - Decoupled moderator
  - Poisoned moderator/pre-moderator
  - Wing moderator
  - Grooved moderator/re-entry hole
  - Backscattering moderators
  - Flux-trap moderators
  - Reflector filter
  - Thermal moderator
  - Cold moderator
  - Low dimensional moderator
  - Ortho/Para-Hydrogen

What is a target?

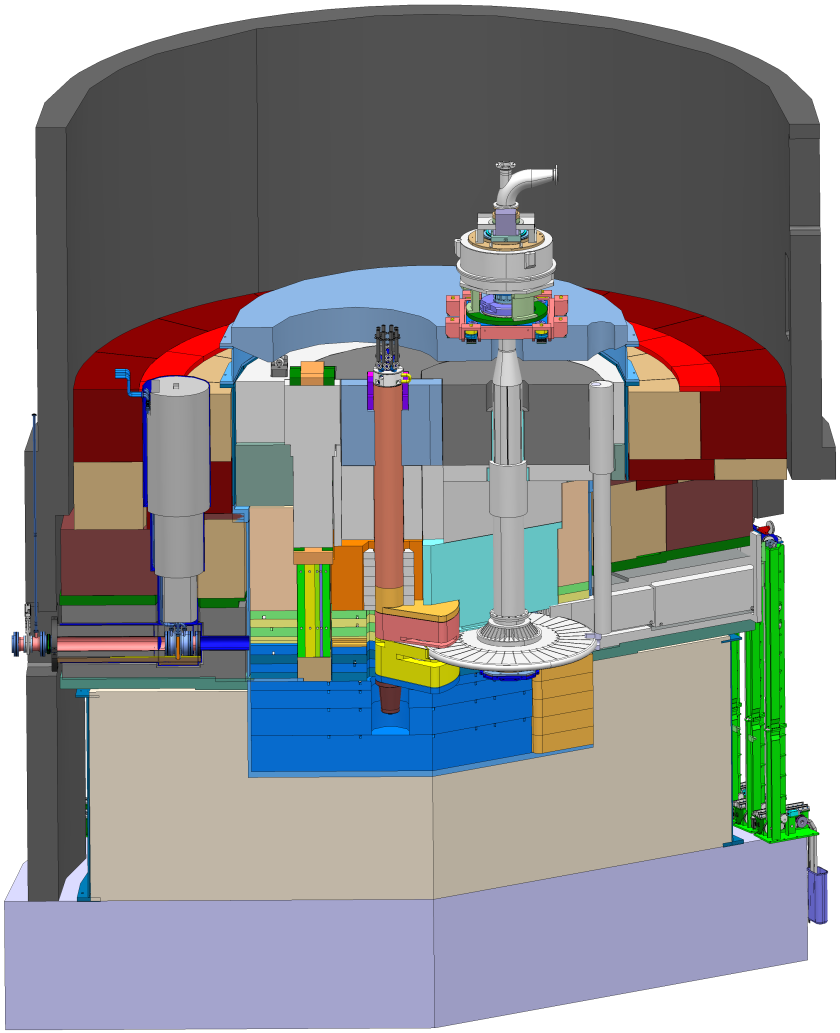
- A target is in the terminology of spallation neutron sources is a material that through the bombardment of protons emits neutrons.
- The target material and geometry is chosen to optimize the performance of the source.
  - Efficiency/performance
  - Operability
  - Reliability

Why flat target

- Flat targets can be operated at MW class spallation sources
- Flat targets are more efficient than volume targets
- Not as efficient as compact targets

SNS flat mercury target

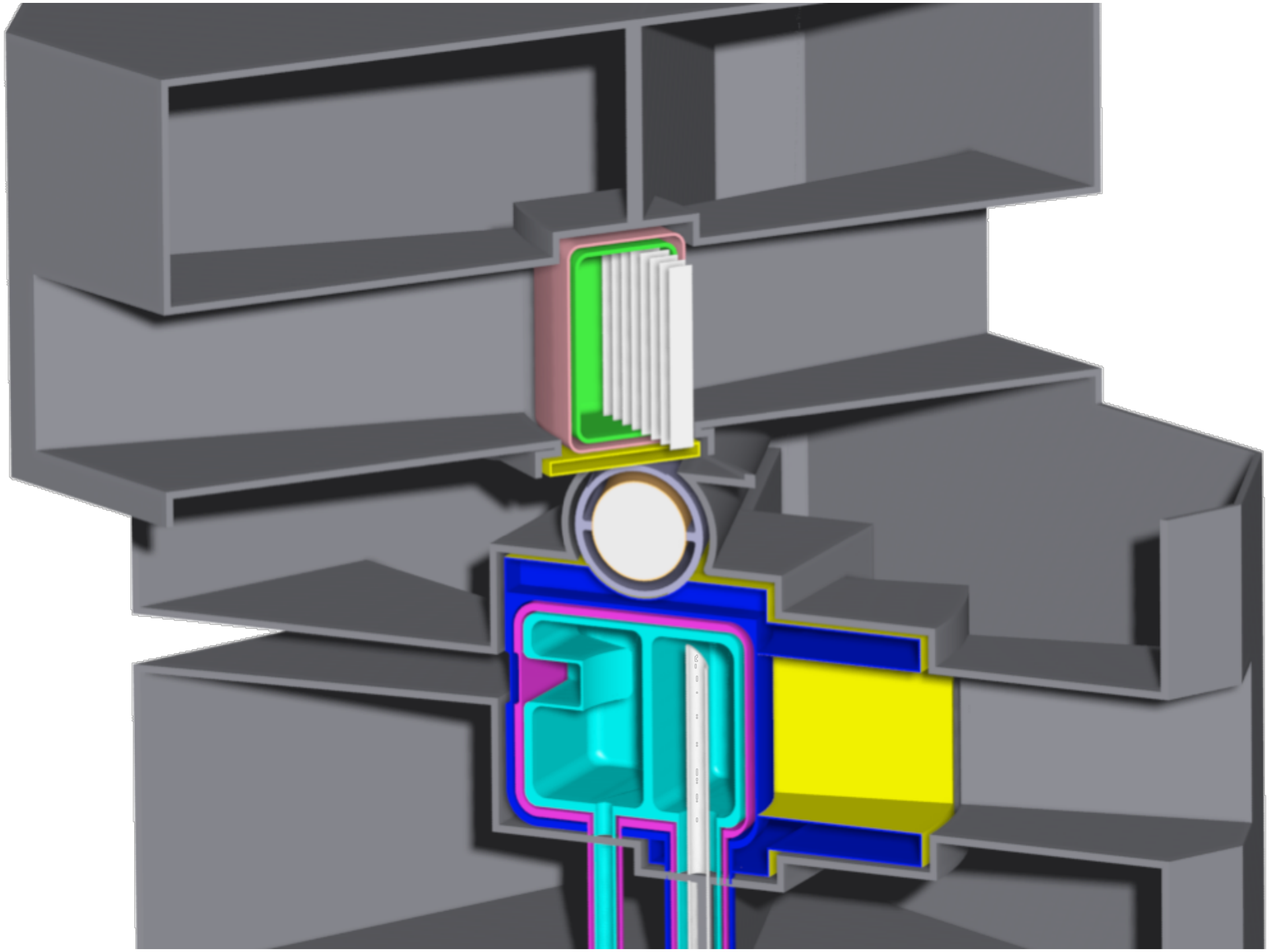
ESS flat rotating tungsten target



Why compact target

- Compact targets are very efficient
- Compact targets cannot efficiently be operated at MW class facilities

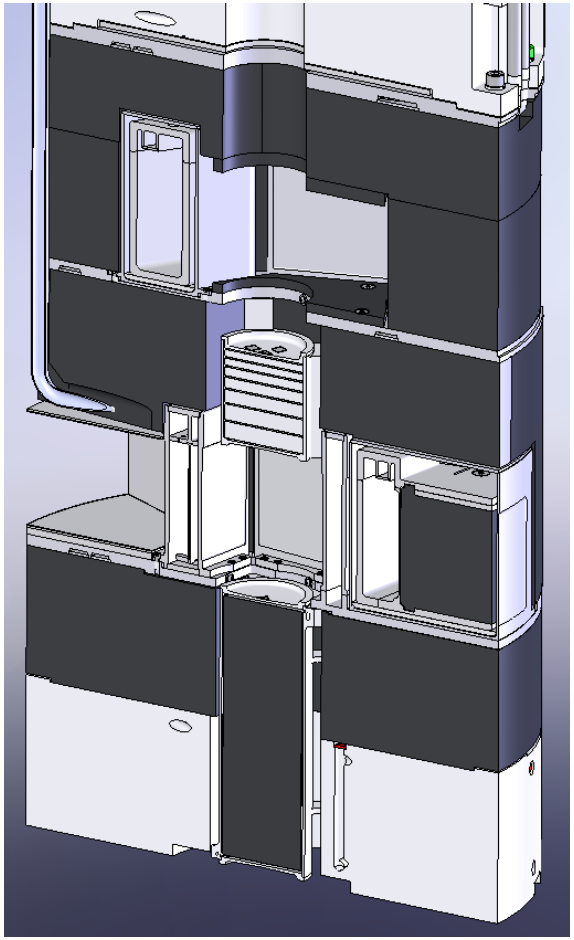
ISIS TS2 compact target

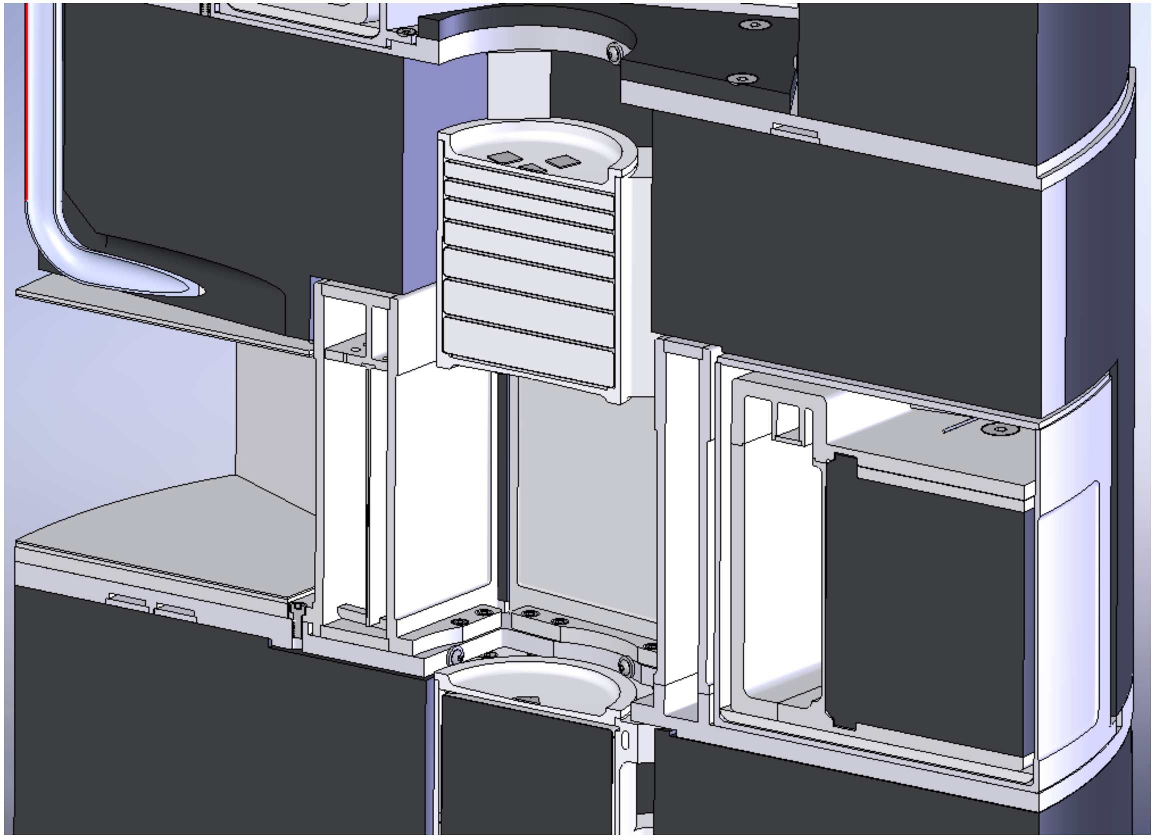


Why split target

- Is a compact target, but the target is split.
- Improves the signal to noise ratio.

LANSCE split target

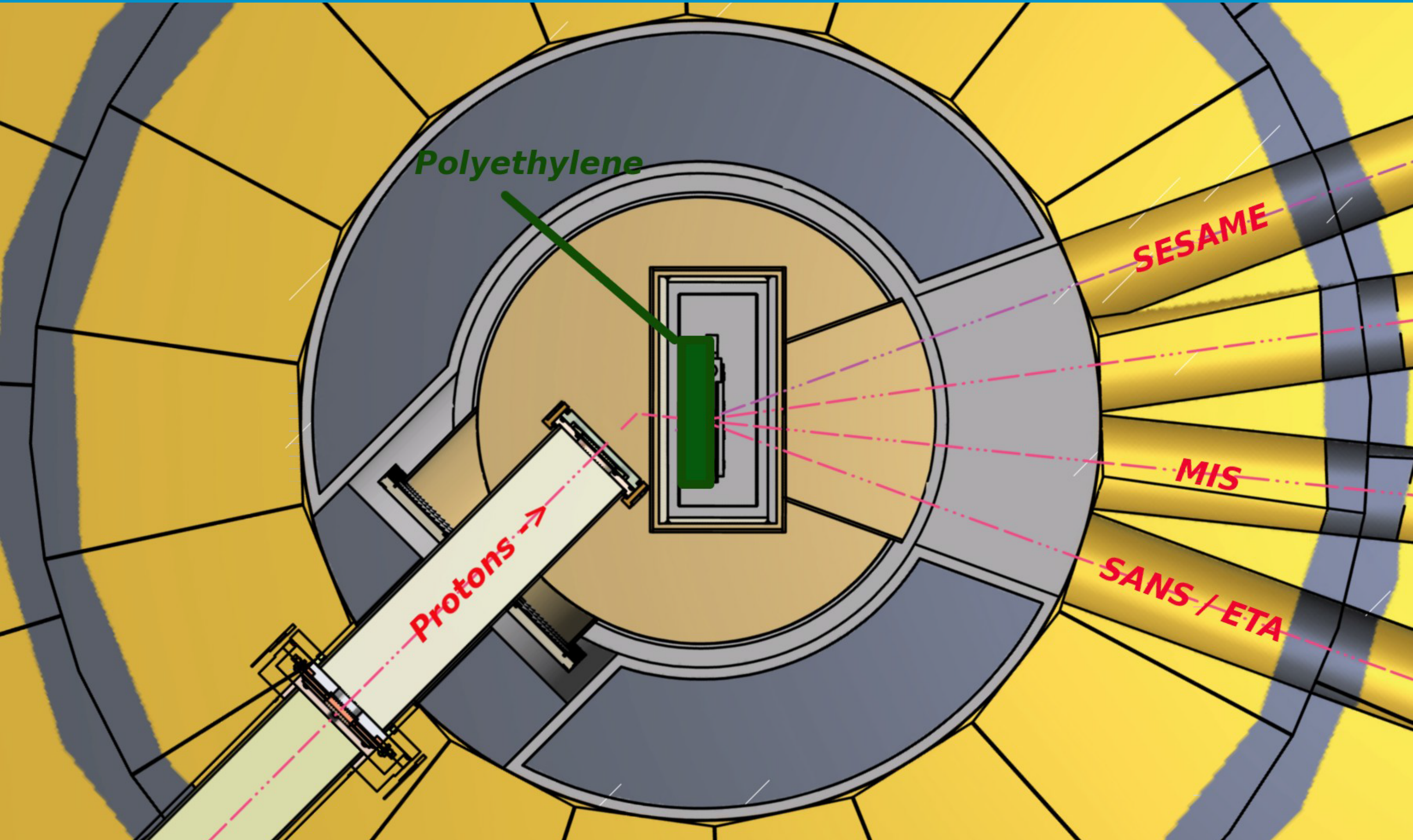




Why thin target

- Thin targets are used with low power accelerators.

LENS thin beryllium target



Moderator parameter definitions

- **Neutron surface current:** The neutron surface current is the number of neutrons that cross a given surface per unit time and per unit area. Typical unit [neutrons/(cm^2*s).

- **Neutron surface flux:** The neutron surface flux is the number of neutrons that cross a given surface per unit time and per unit area normalized by the cosine of the angle between the trajectory of the neutron and the direction perpendicular to the surface. Typical unit [neutrons/(cm^2*s)]

- **Neutron volume flux:** Neutron volume flux, also referred to as track length flux is the defined as the number of neutrons in a volume times the average distance traveled by these neutrons in this volume per unit volume and per unit time. Typical unit [neutrons/(cm^2*s)] or [neutrons*cm/(cm^3*s)]

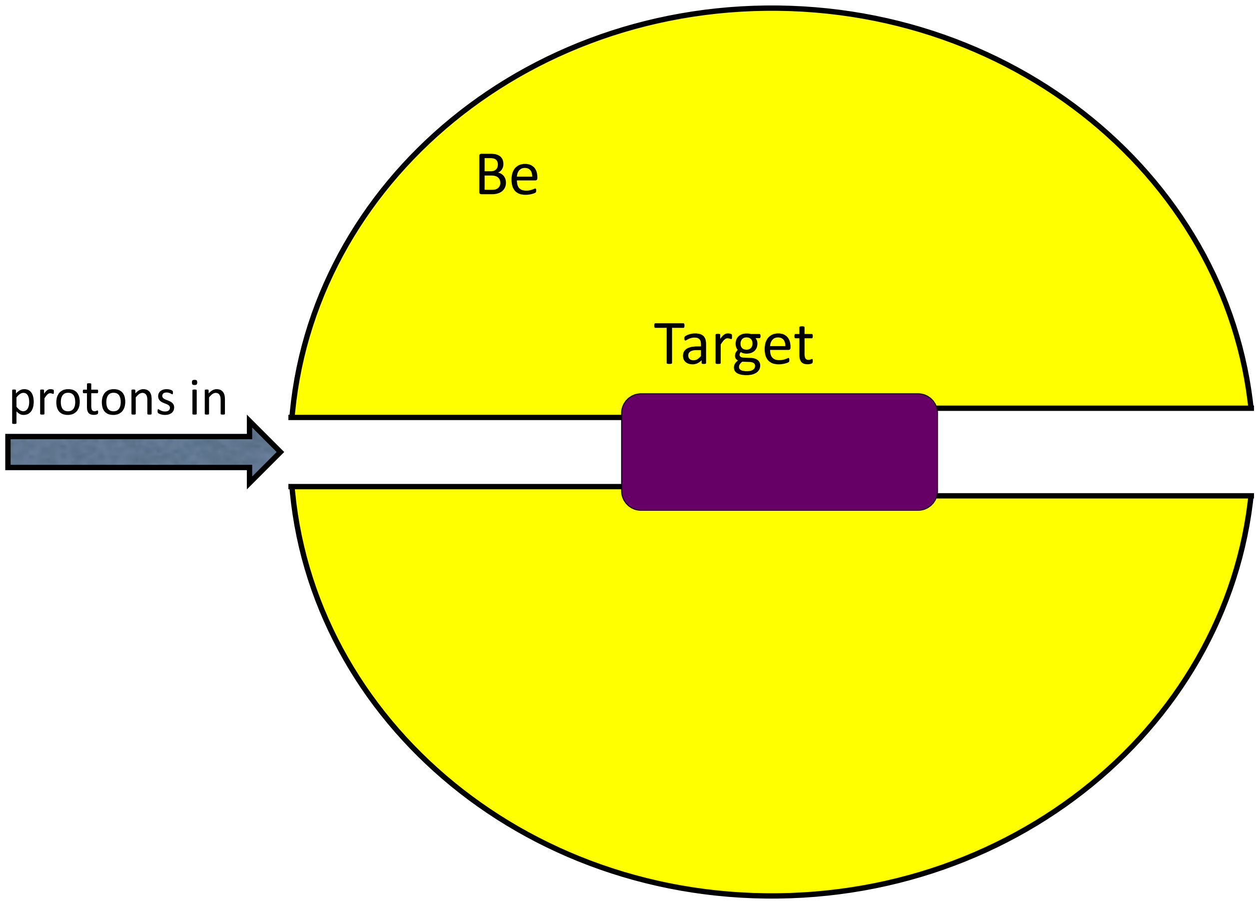
Moderator parameter definitions

EUROPEAN SPALLATION SOURCE

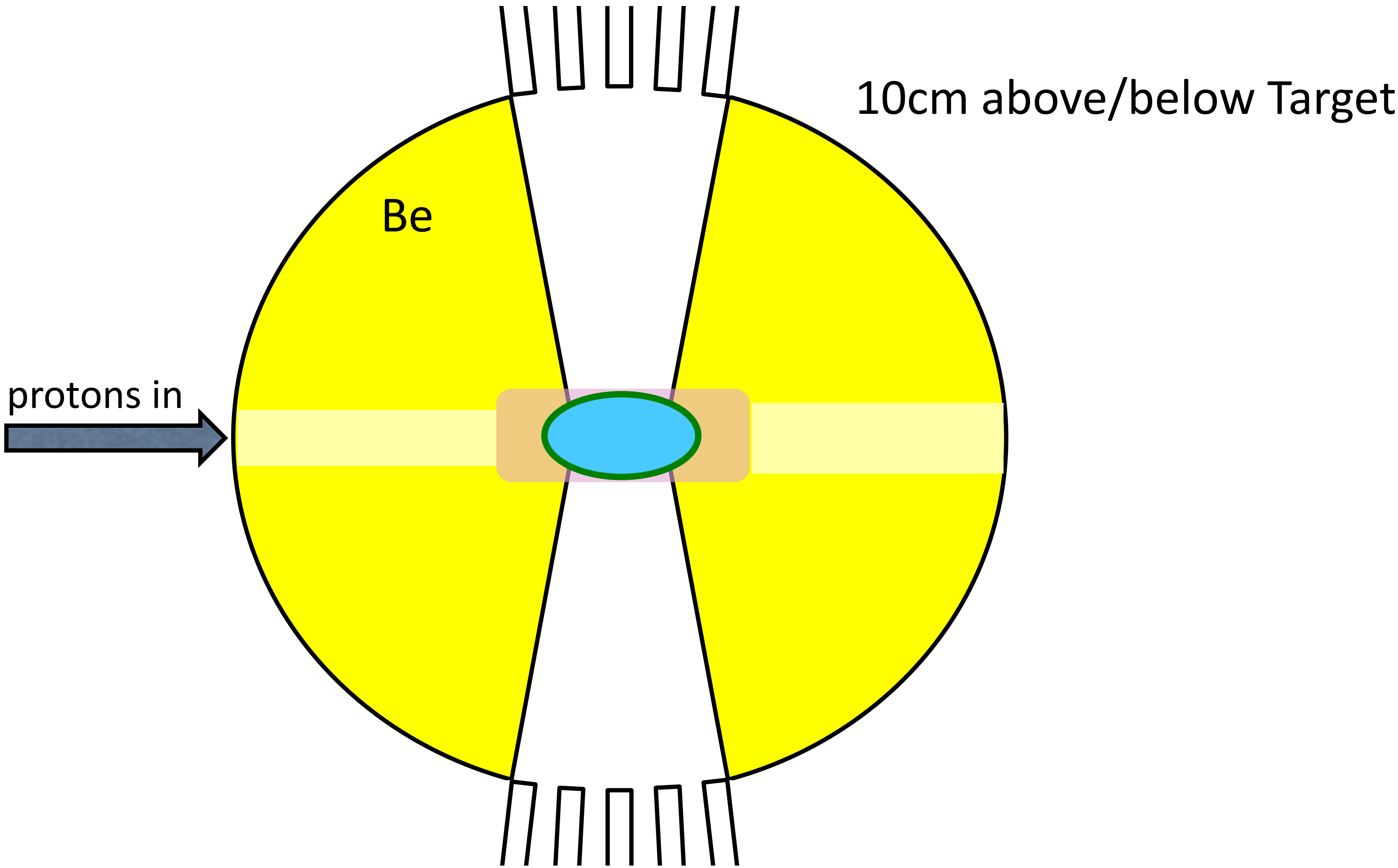
- **Neutron brightness:** The neutron brightness is the number of neutrons that cross a given surface per unit time, per unit area and unit angle. Typical unit [neutrons/(cm^2*s*sr).
- **Moderator time distribution:** The moderator time distribution is the neutron flux emitted from the moderator surface as a function of time. Typical unit [neutrons/(cm^2*s)]
- **Buckling term:** It the mathematical description of the storage time of the neutrons in a component based on the geometry of the component.

Target-Reflector-Moderator Neutronics

Target plane

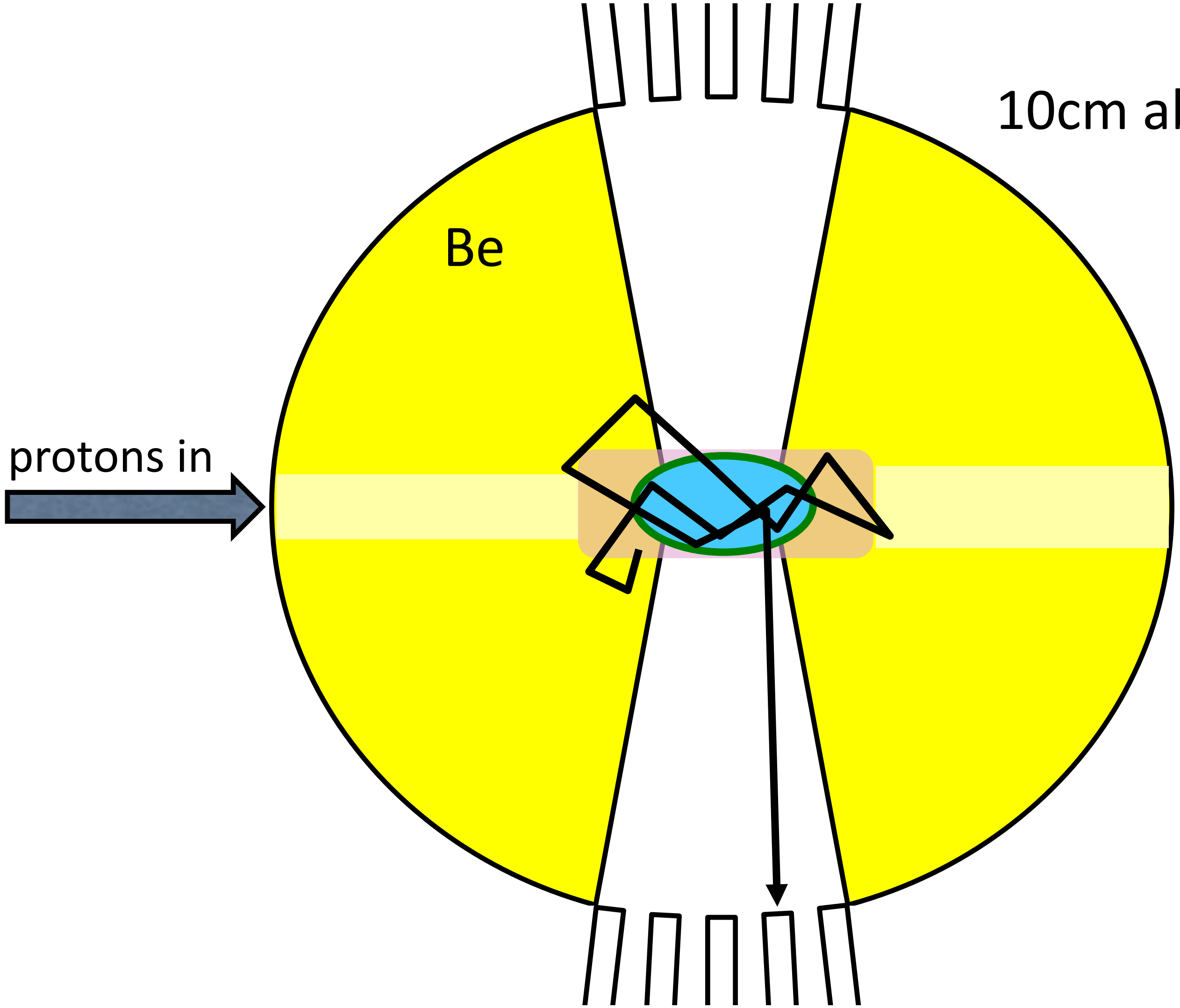


Target-Reflector-Moderator Neutronics



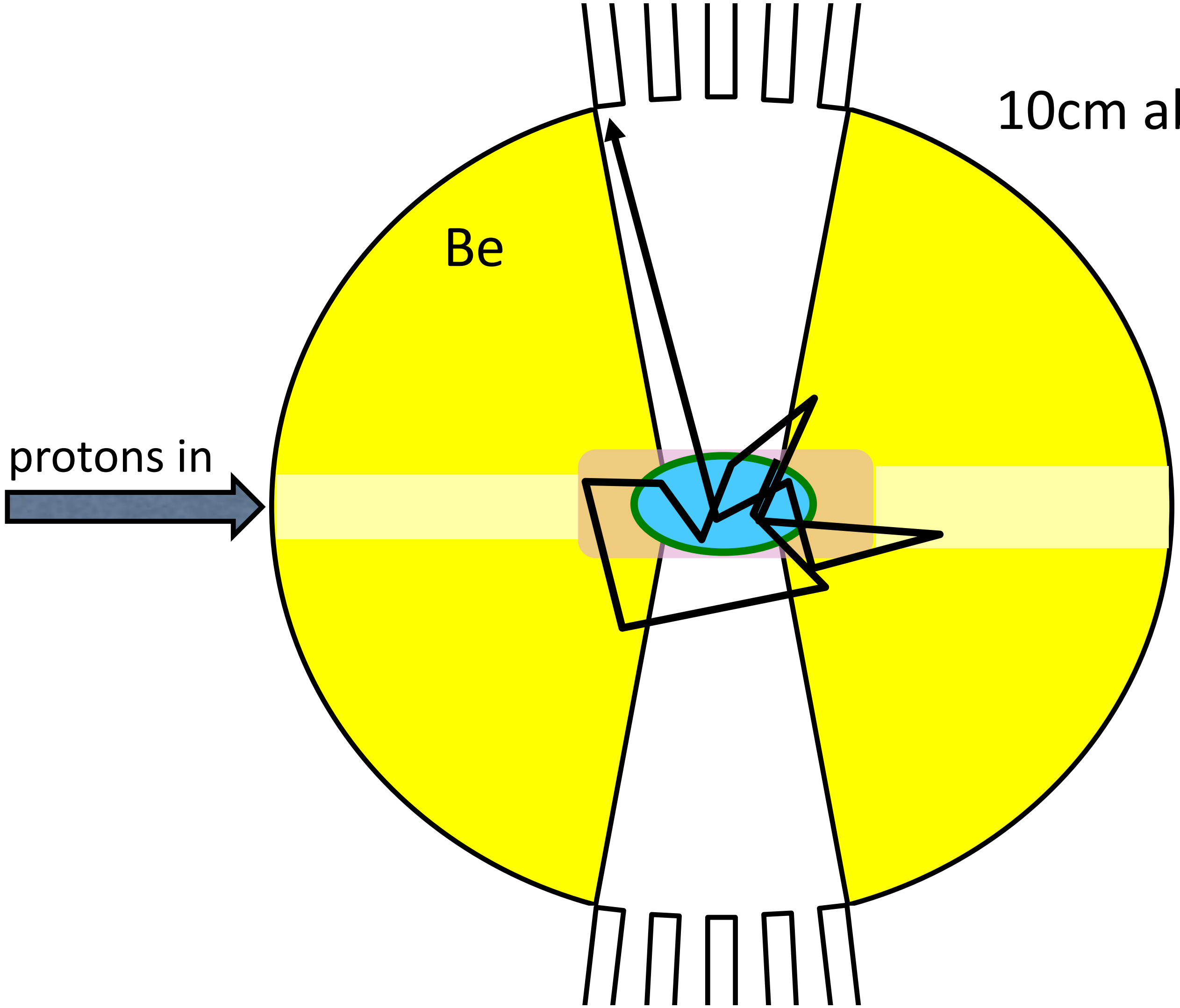
Target-Reflector-Moderator Neutronics

10cm above/below Target

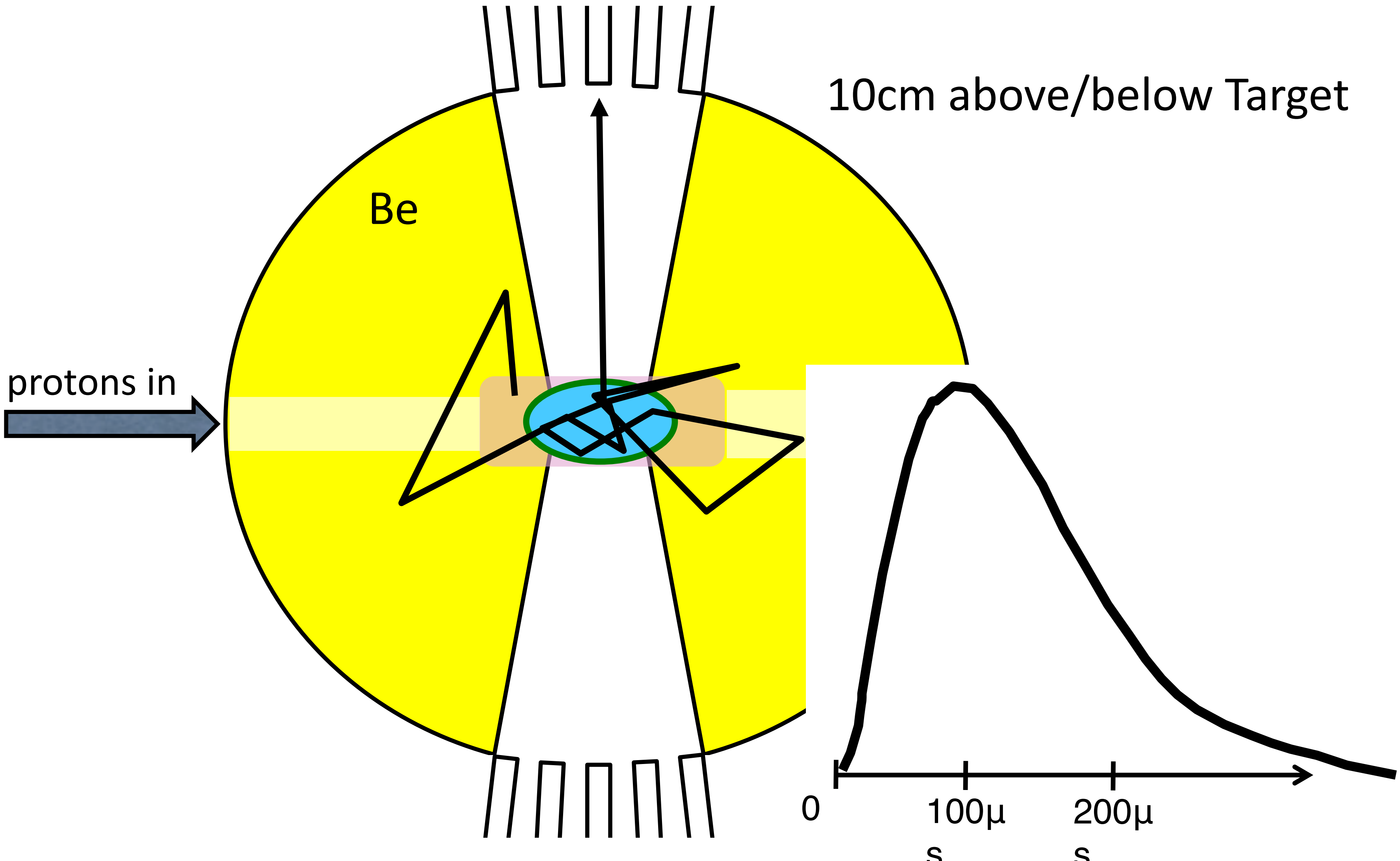


Target-Reflector-Moderator Neutronics

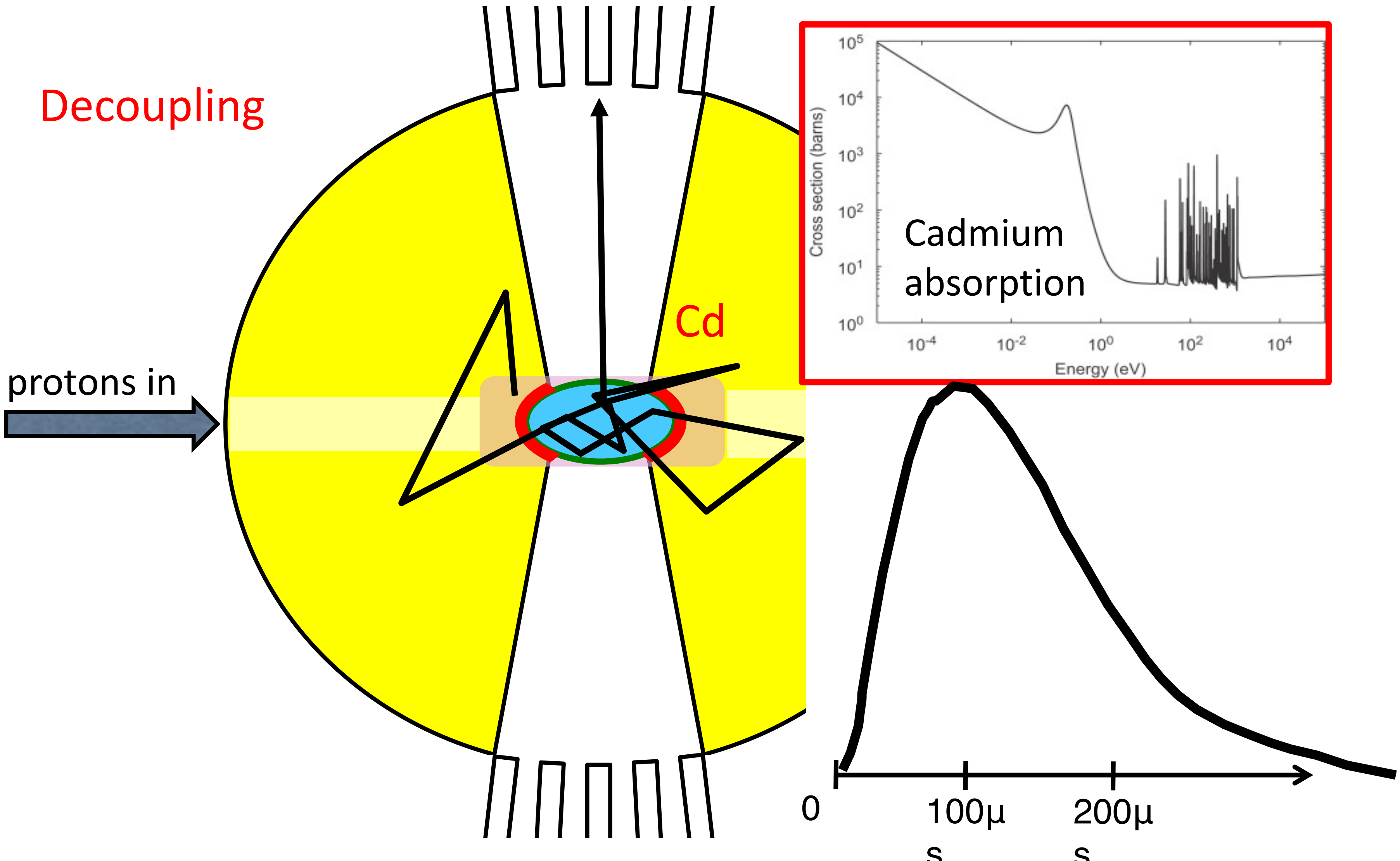
10cm above/below Target



Coupled moderator

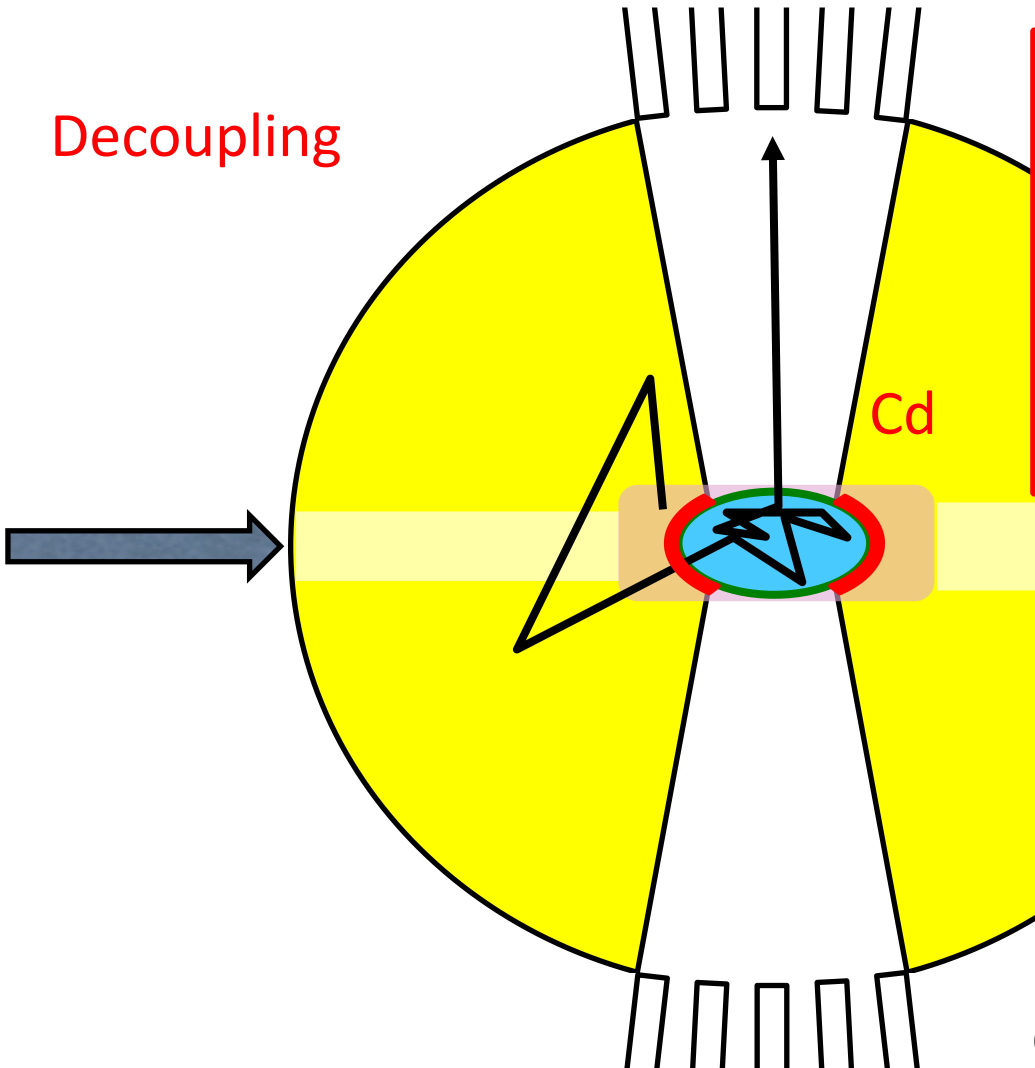


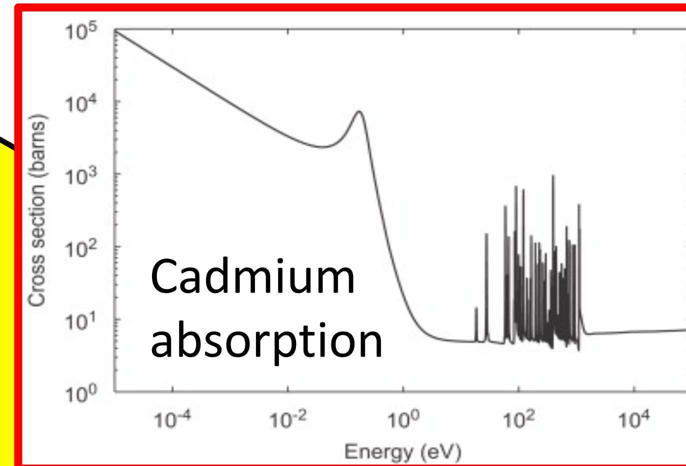
Decoupled moderator

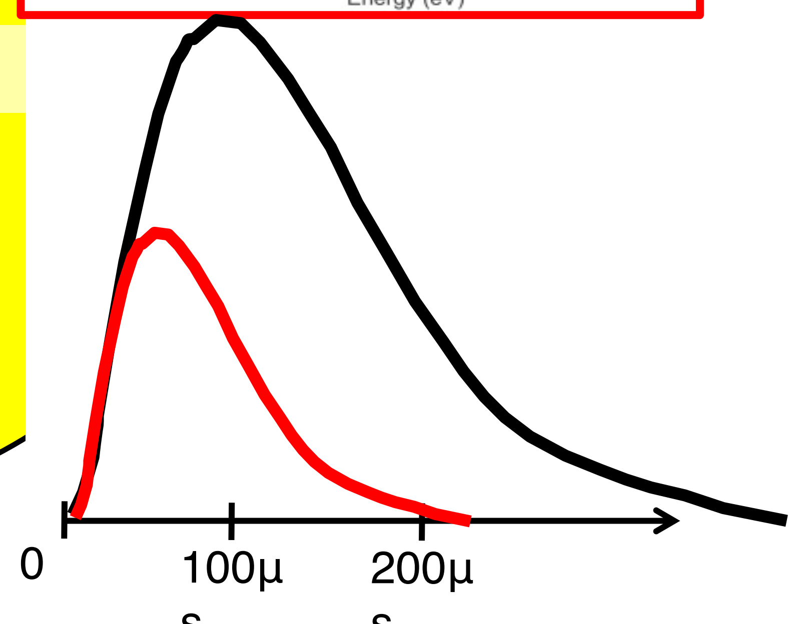


Decoupled moderator

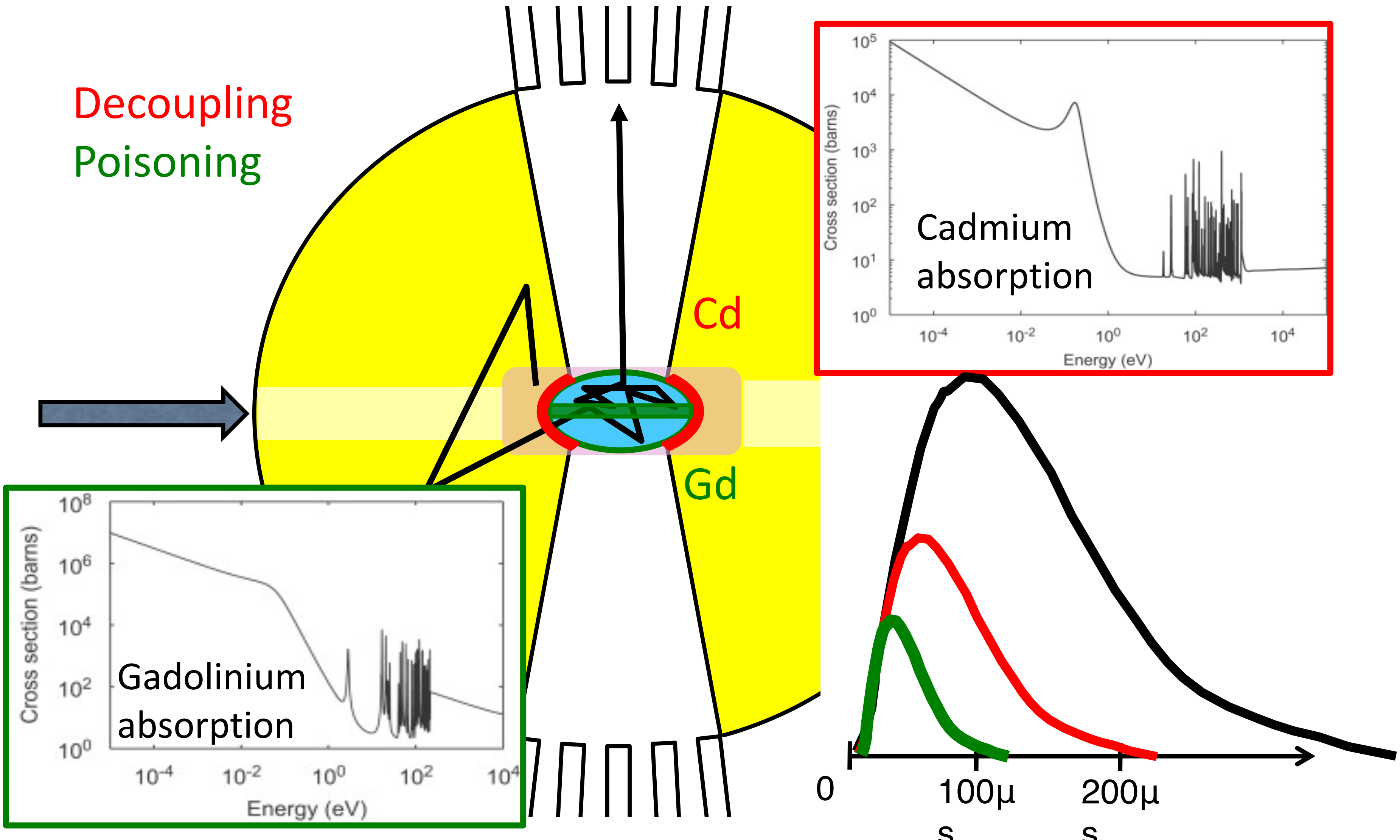
Decoupling



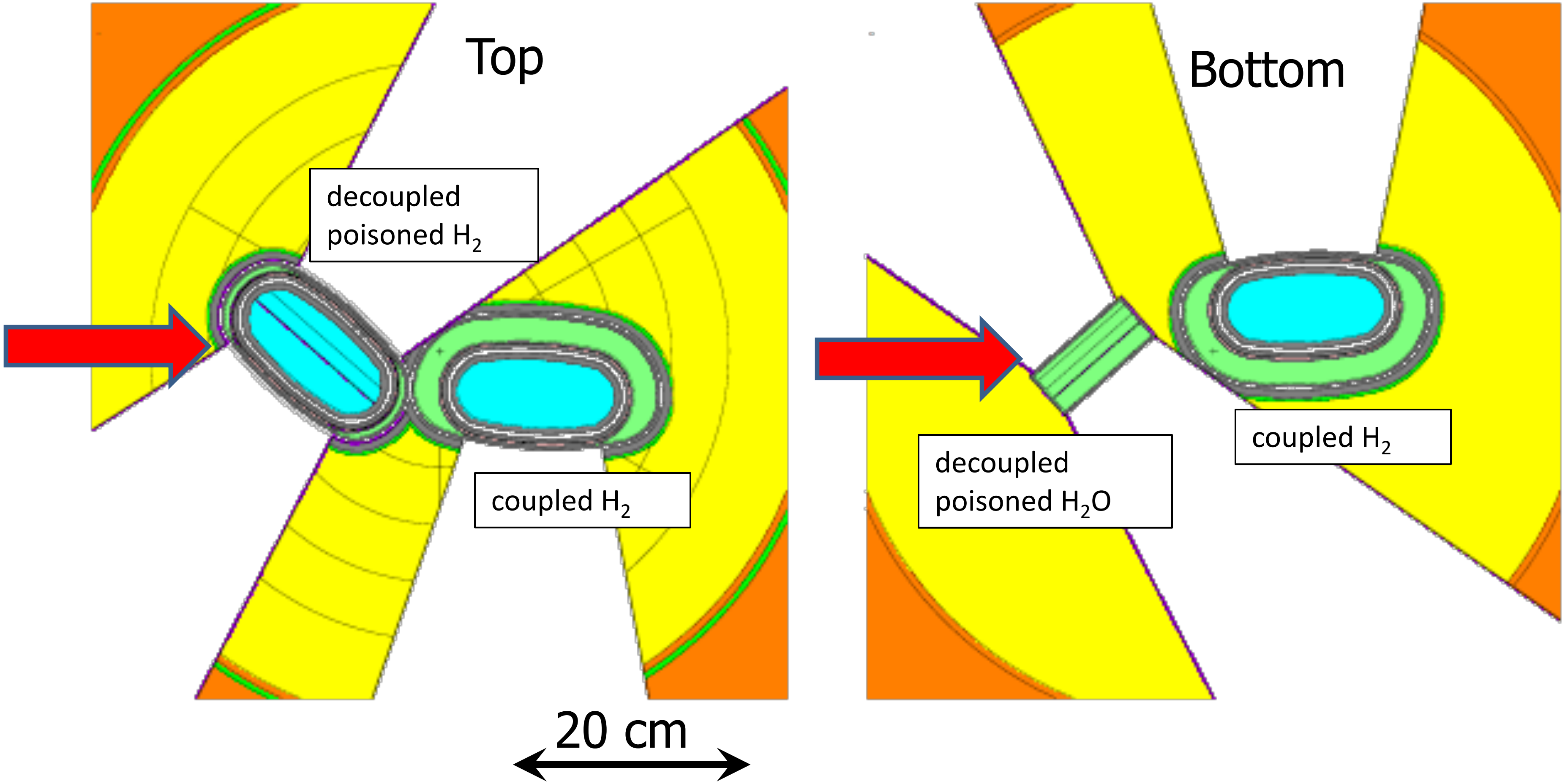




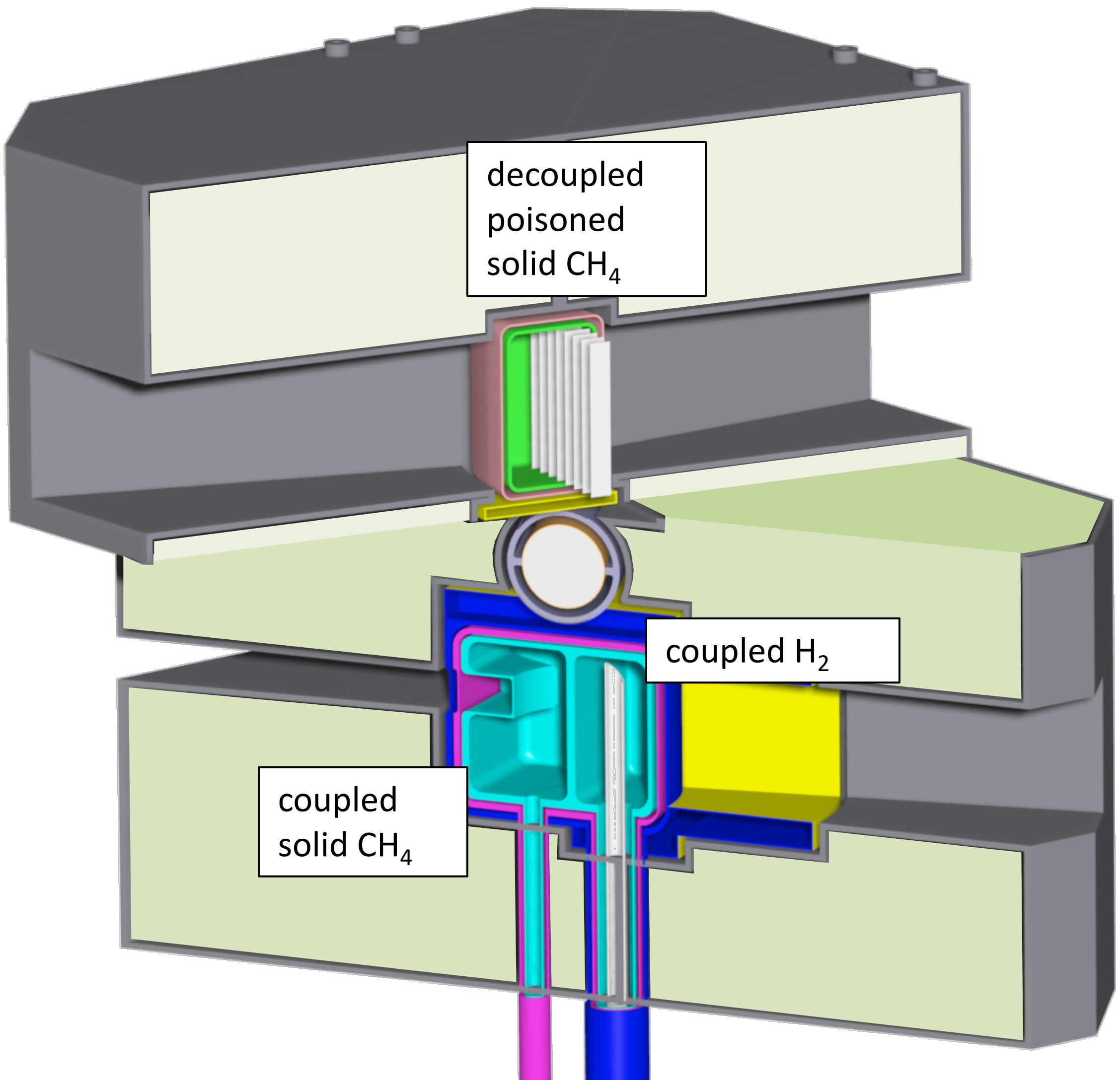
Poisoned moderator/Pre-moderator



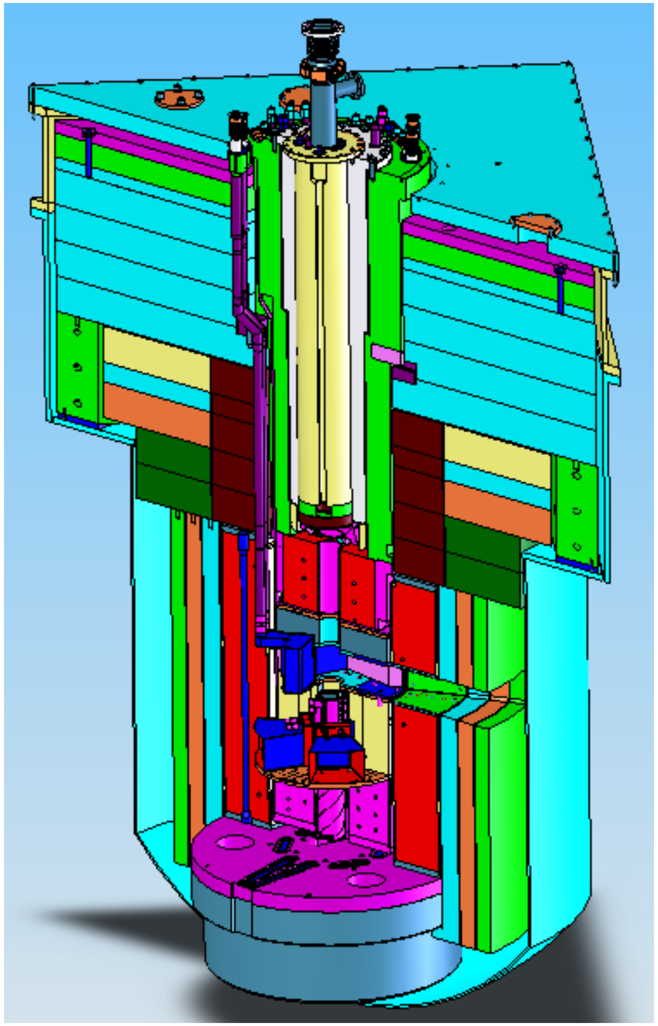
SNS moderators

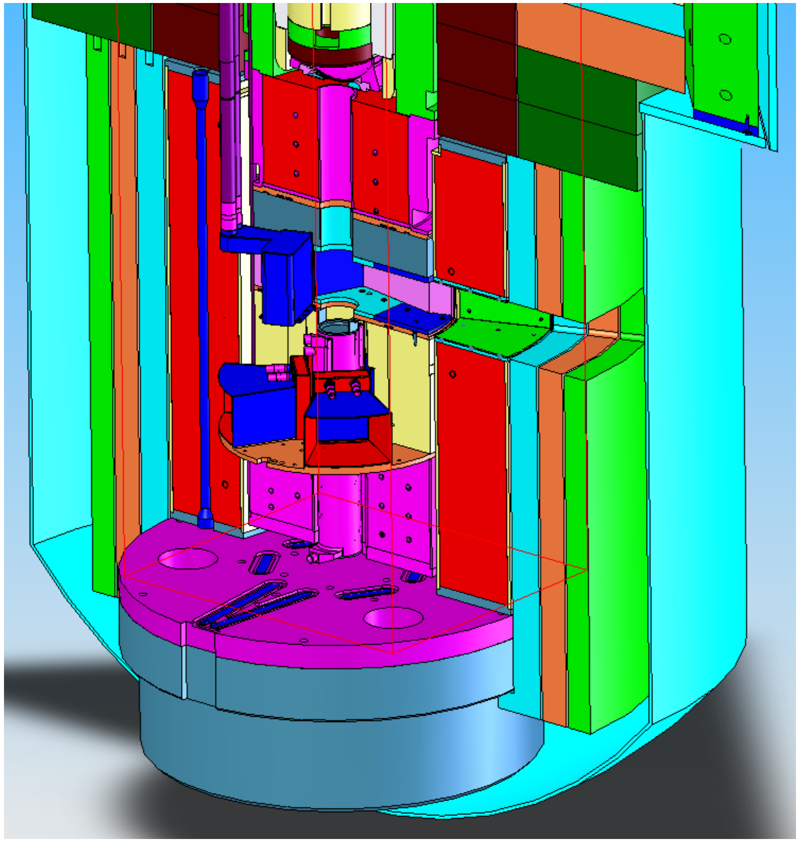


Wing/Grooved moderator/re-entry hole (ISIS TS2)

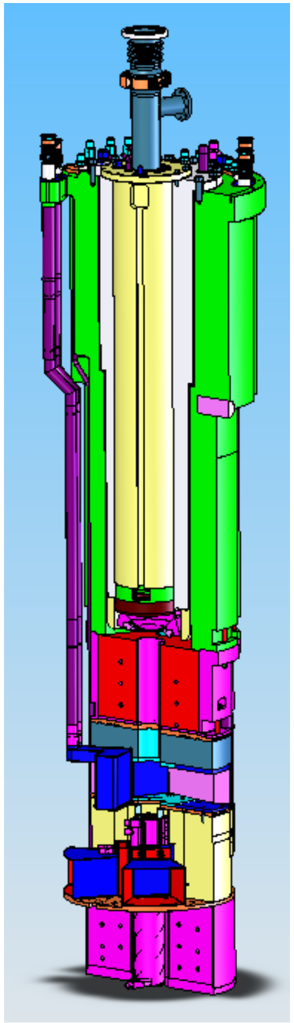


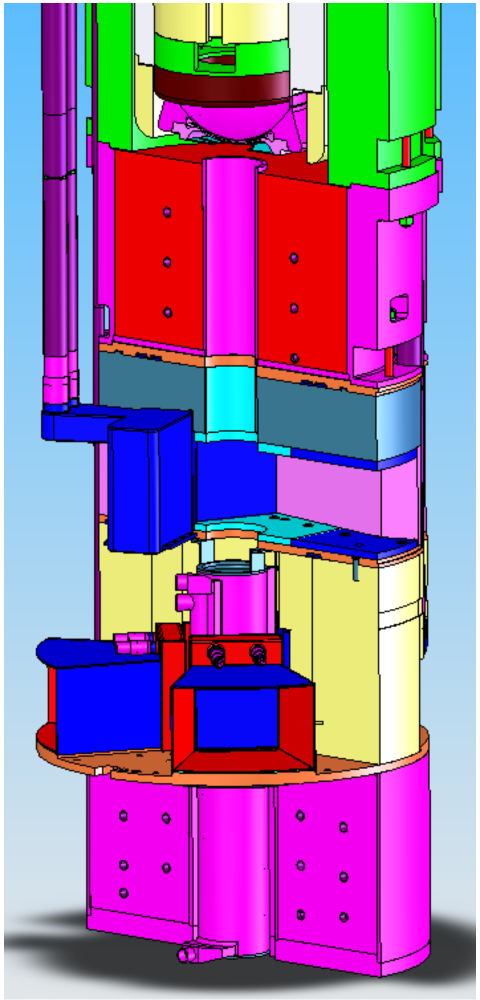
Backscattering moderator, flux-trap moderator and reflector filter (LANSCE 1L target)

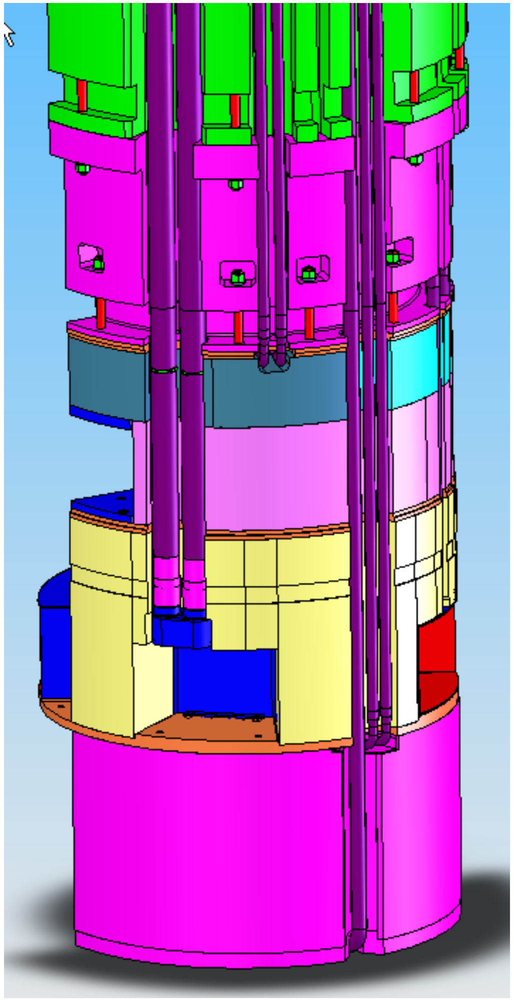




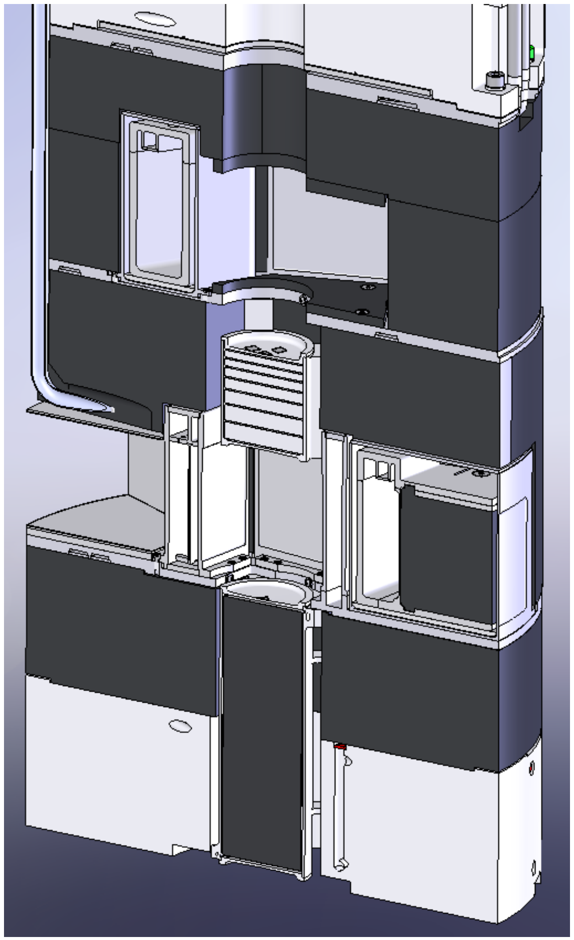
Backscattering moderator, flux-trap moderator and reflector filter (LANSCE 1L target)

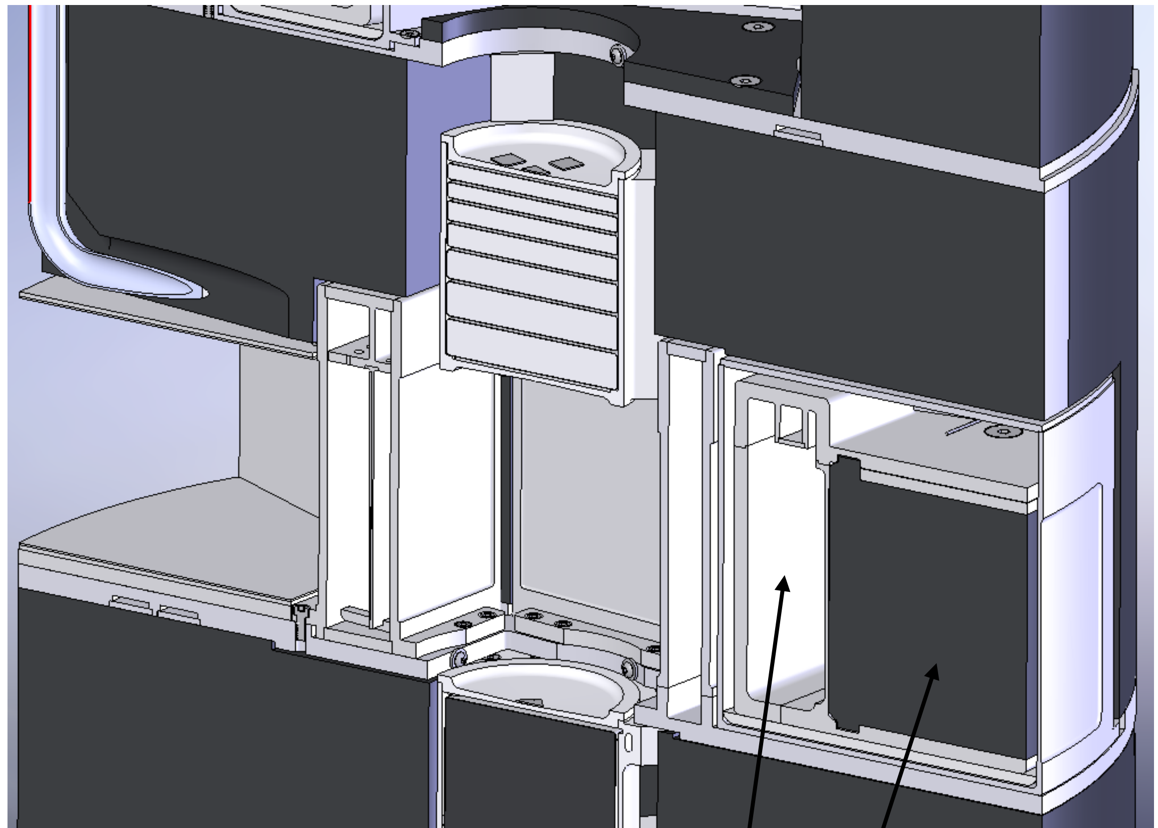






Backscattering moderator, flux-trap moderator and reflector filter (LANSCE 1L target)

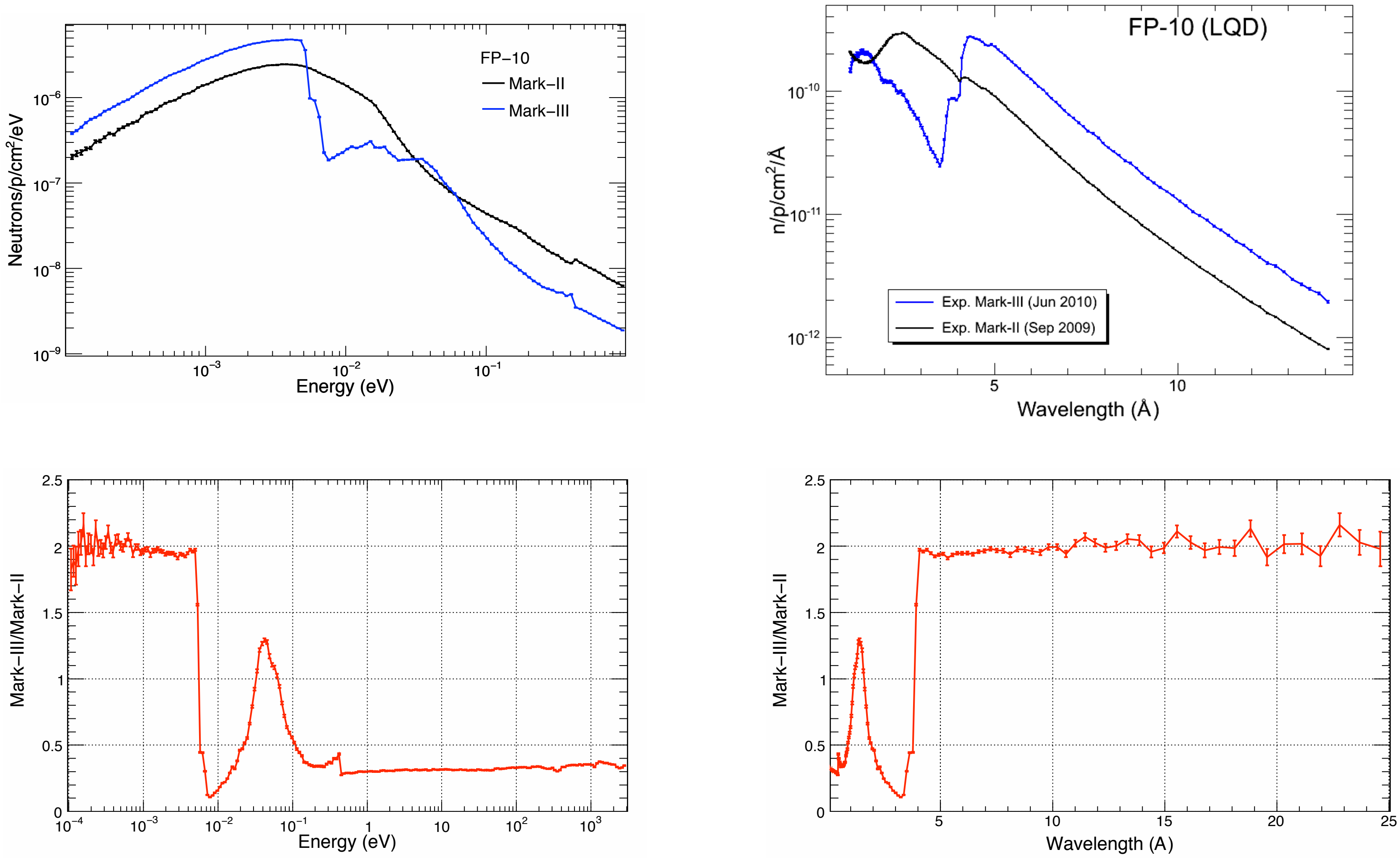




Lower Liquid Hydrogen Moderator

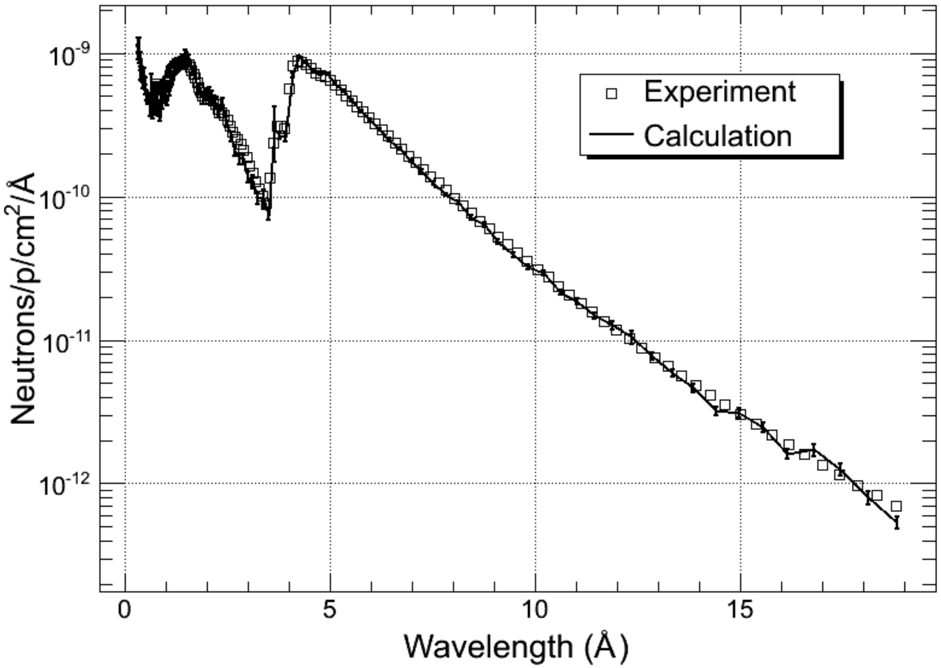
Cold Beryllium Reflector/Filter

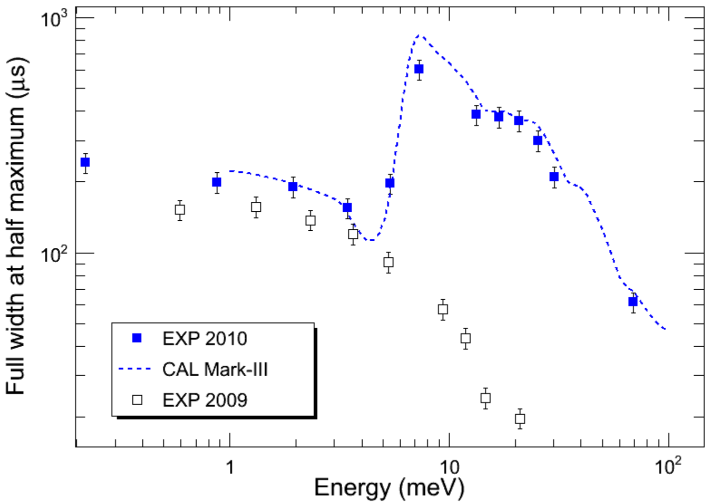
Cold Reflector Filter effect



Cold Reflector Filter effect

Excellent understanding of performance





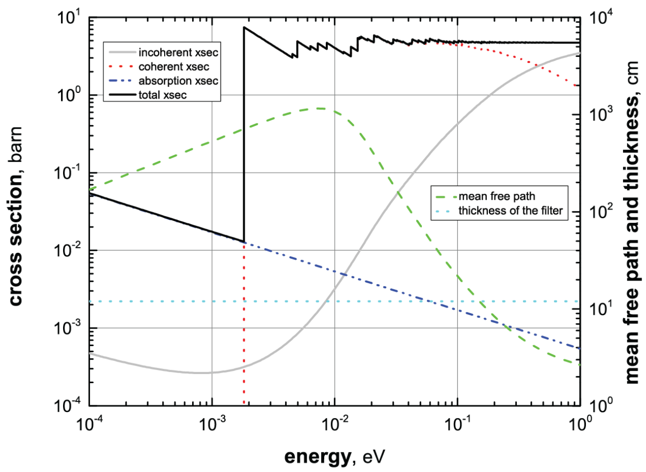
Measure of resolution

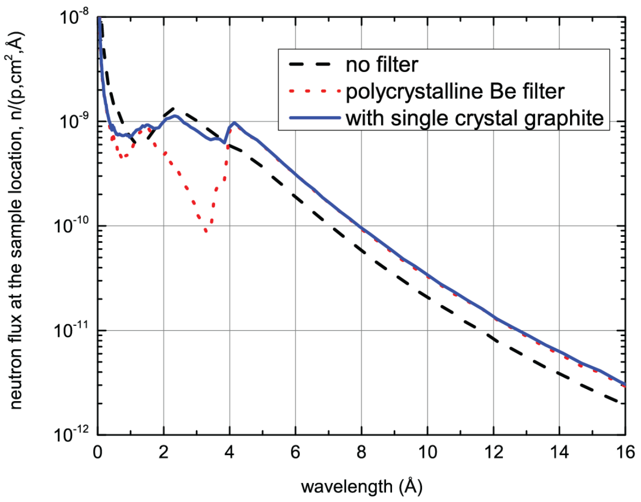
Neutron flux at sample location for SPEAR instrument

M. Dubey, M. S. Jablin, P. Wang, M. Mocko, J. Majewski; Eur. Phys. J. Plus 126 (2011) p110

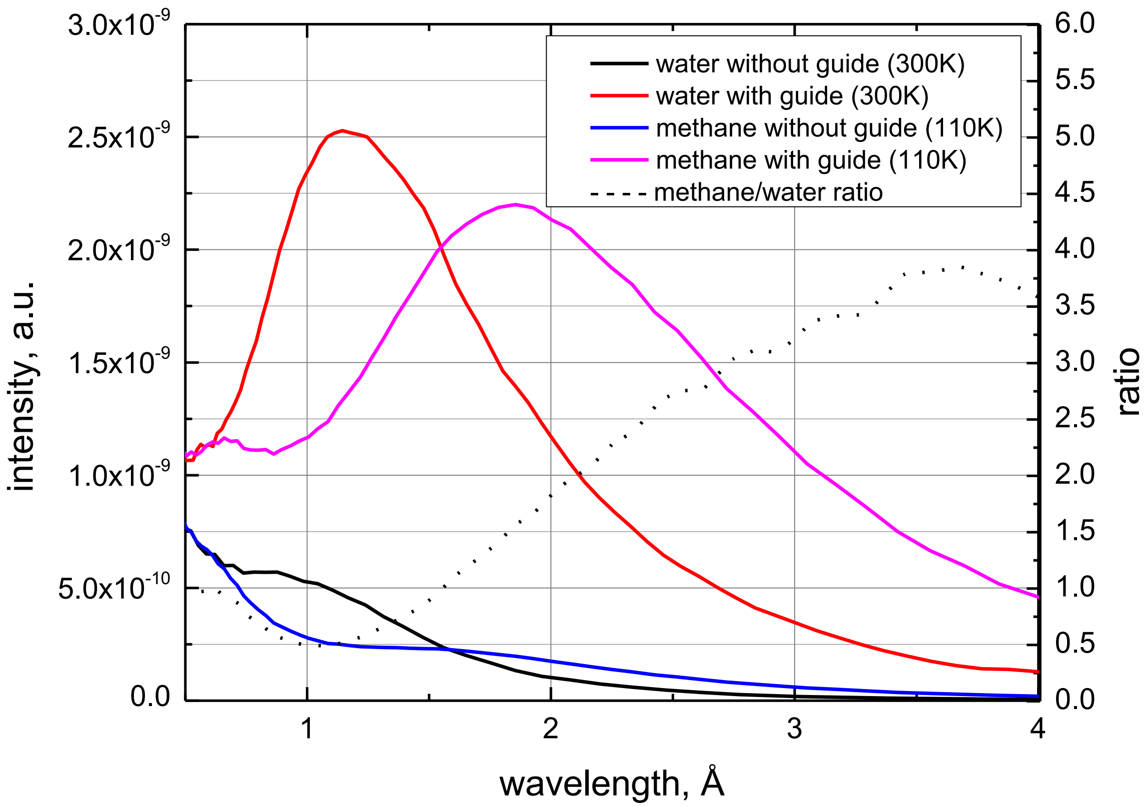
Single crystal reflector filter

- Single crystal oriented in off Bragg condition in the transmission direction
- Only inelastic and absorption important
- Simulations done suppressing the coherent cross section in the scattering kernel

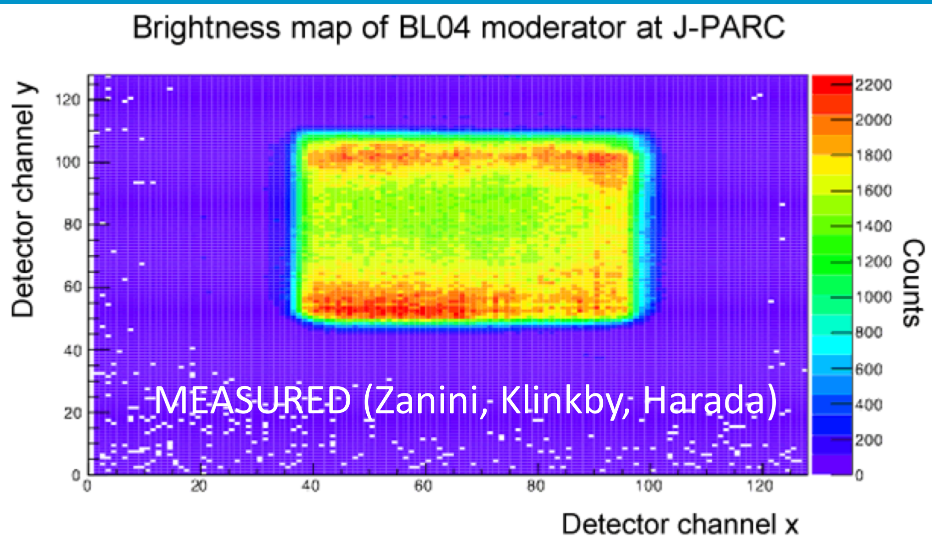


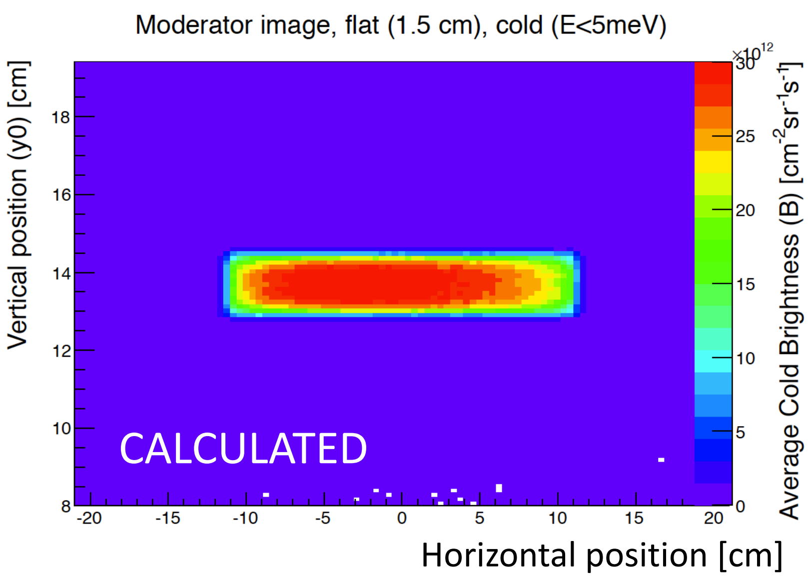


Thermal – cold neutrons (temperature effect)

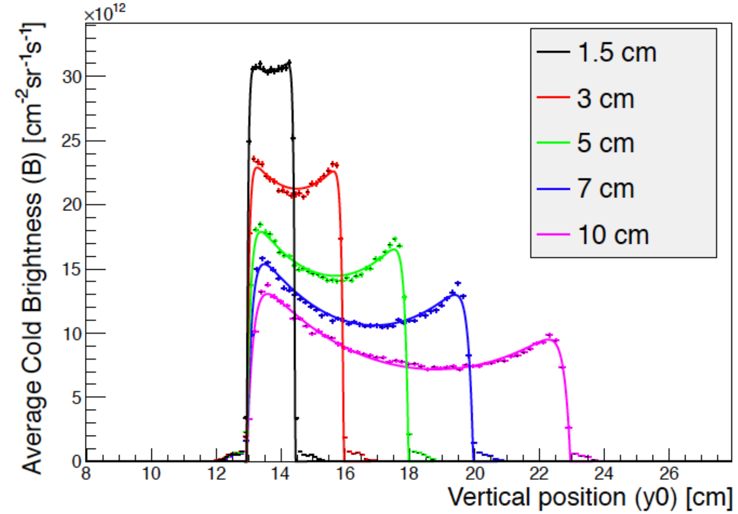


Principle of the low dimensional moderator



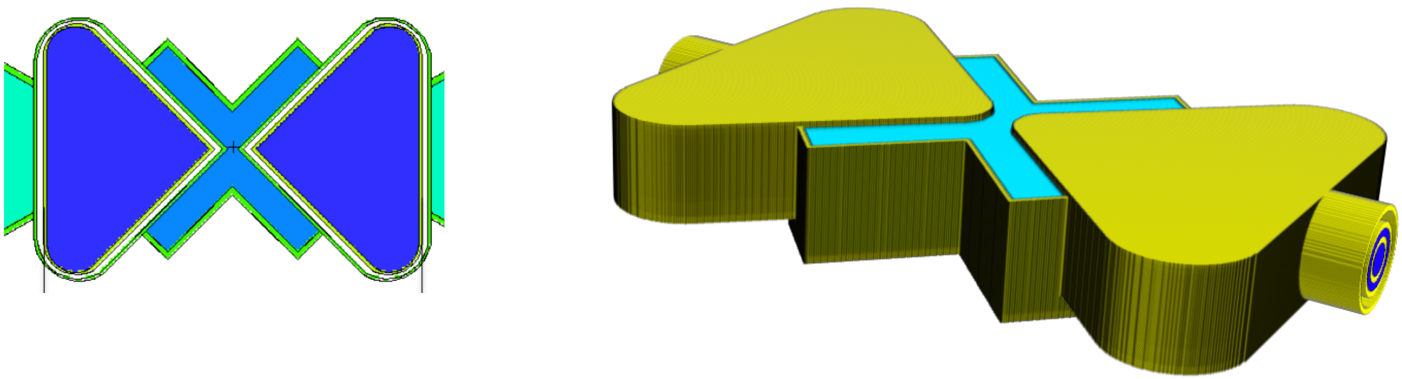


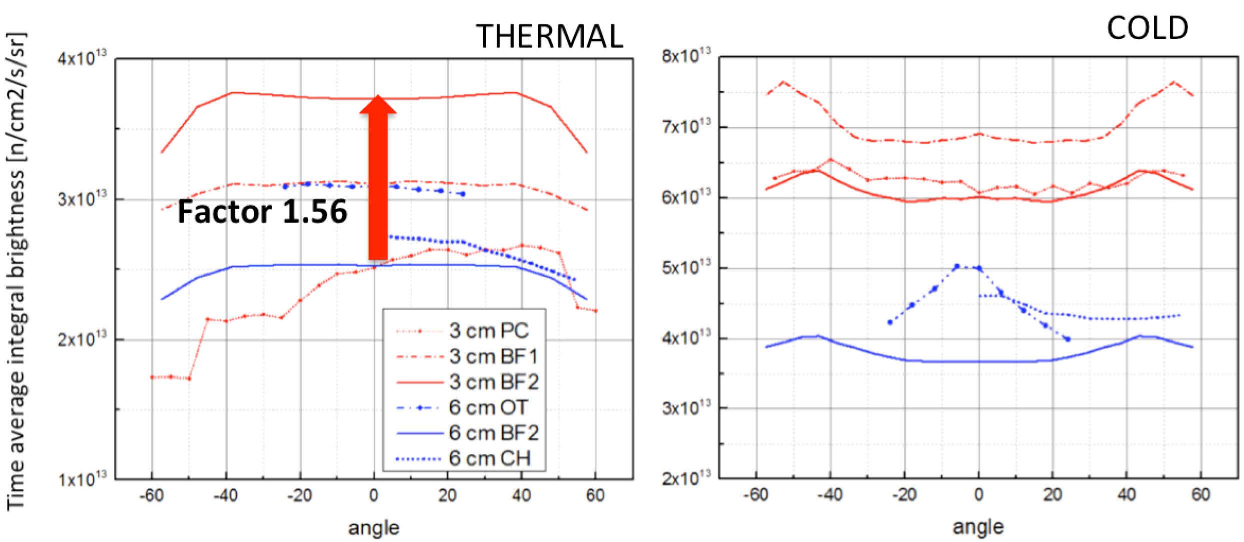
Integrated number of neutrons from 3 cm moderator is 70% of a 10 cm



- ❑thermal neutrons arriving from the surroundings are transformed into cold ones within about 1 cm of the walls of the moderator vessel
- ❑ along the direction of these walls this intense layer of cold neutrons can be seen from the outside into depths comparable to 10 cm.

ESS Low dimensional moderators





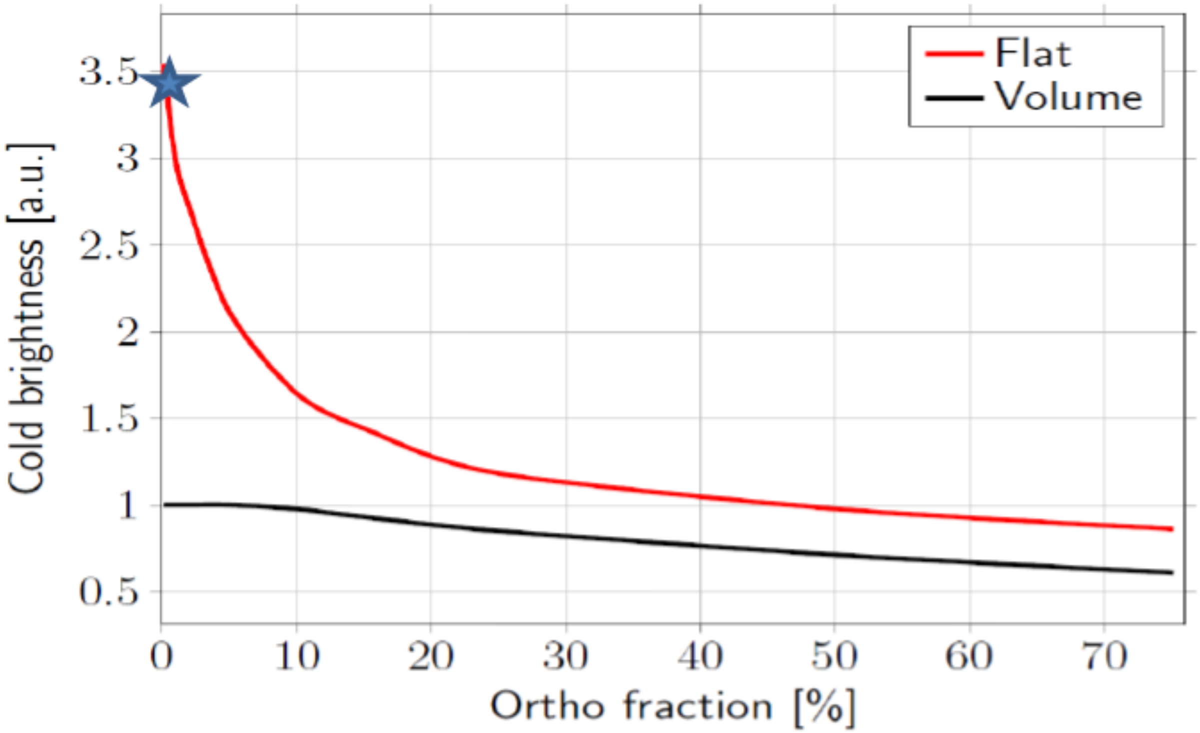
K. Batkov et al, Nucl. Instrum. Methods A 729, 500, 2013

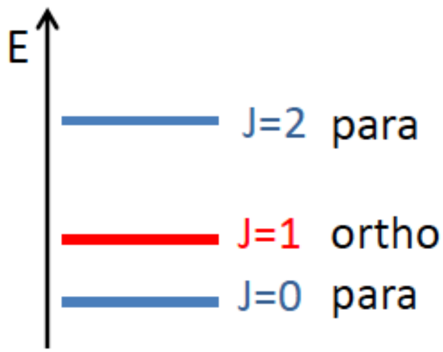
The ortho – para hydrogen question

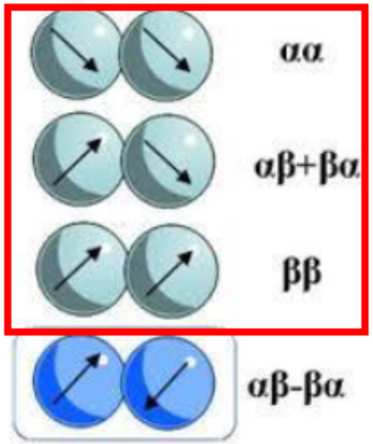
EUROPEAN SPALLATION SOURCE

- Calculated brightness as function of o-H_2 fraction in flat and volume moderator.

(source: ESS Neutronics Group)



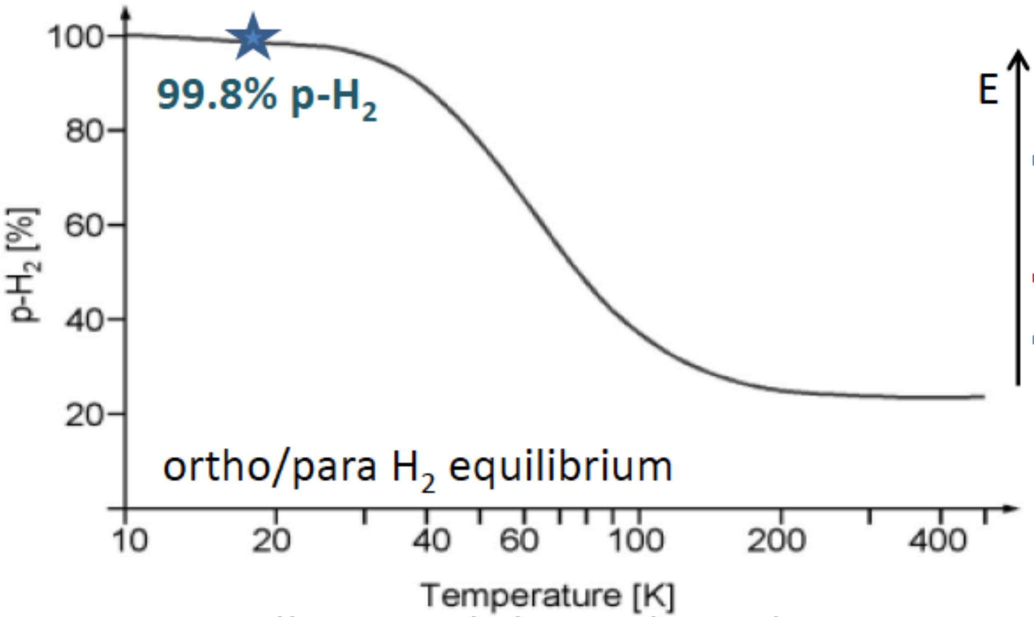




ESS/STS liquid hydrogen moderators are low-dimensional: require a p-H_2 fraction of >99 %

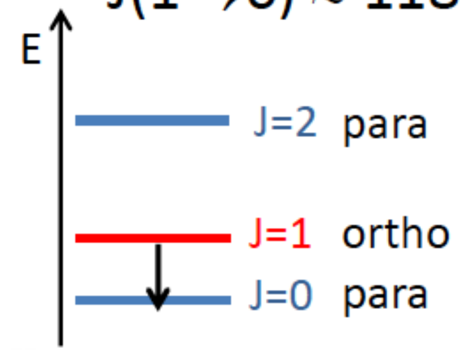
The ortho – para hydrogen question

EUROPEAN SPALLATION SOURCE



(source: http://hydropole.ch/en/hydrogen/abouth2/)

J(1→0) ≈ 118 cm^{-1}≈14.7 meV



- ESS and SNS TS2 moderator operating at 20 K.

$$\frac{dc}{dt} = -kc^2 \qquad c = \frac{1}{\frac{1}{c_0} + kt}$$

k(l-oH$_2$)=3.17*10^{-6} 1/s

KINETICS! - Long NATURAL conversion times

→ **Catalysis**

Mechanism of catalytic conversion of o- to p-H_2
Which catalyst? How much?

Hartl et al., PCCP 18 (2016)17281

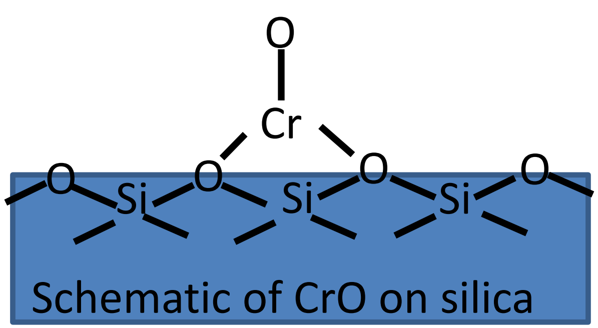
Effect	Conversion steps:	Effect
Fast: large area	-adsorption on surface	strong bond, small surface
H_2 diffuses fast	-diffusion along surface	not necessary
few centers	-spin flip at magnetic centers (Fe(III), Cr(II))	more centers
Fast - weak bond	-desorption	Slow-stronger bond

OXISORB®: $Cr^{II}O$ (2%) on SiO_2

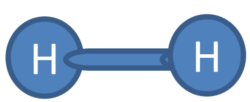
- high surface area (~600 m^2/g)
- efficient hydrogen adsorption
- weaker bond to hydrogen
- "magnetically dilute"

IONEX®: $Fe_2O_3 \cdot 2\%\ H_2O$

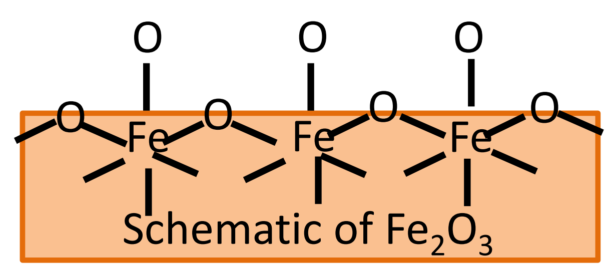
- low surface area (200 m^2/g)
- less efficient hydrogen adsorption
- strong bond to hydrogen
- "magnetically dense"



Schematic of CrO on silica



Conversion heat:
o to p: 670 J/g



Schematic of Fe_2O_3

Shielding

Outline

- Why do we need shielding?
- Requirements
- Physics

Why do we need to shield against radiation?

- Damage to the human body (Sievert or Rem)
- Damage to the equipment (Gy or Rad)
- Damage to experimental data (noise level of the data)

Where to start? Requirements

- Protecting people
  - Governmental and facility regulations
    - Dose to the worker
    - Dose to the public
- Protecting equipment (Gy or Rad)
  - Availability and reliability
- What is the source term?
- What are the performance requirements for the instrument?
- Protecting experimental data (noise level of the data)
  - Performance metric of the designed beamline
  - Performance metric of the neighboring beamlines

Protecting people: The "Safety First" thingy – Rest risk

- First step: "Ensuring safe operation is an absolute necessary requirement, but be itself not a sufficient requirement for operation.
- Rest risk: 100% perfect safety does not exist (Kurt Gödel's incompleteness theorems (1931))
- The law defines what rest risk is tolerated by the society.

Source: Reactor versus spallation source

EUROPEAN SPALLATION SOURCE

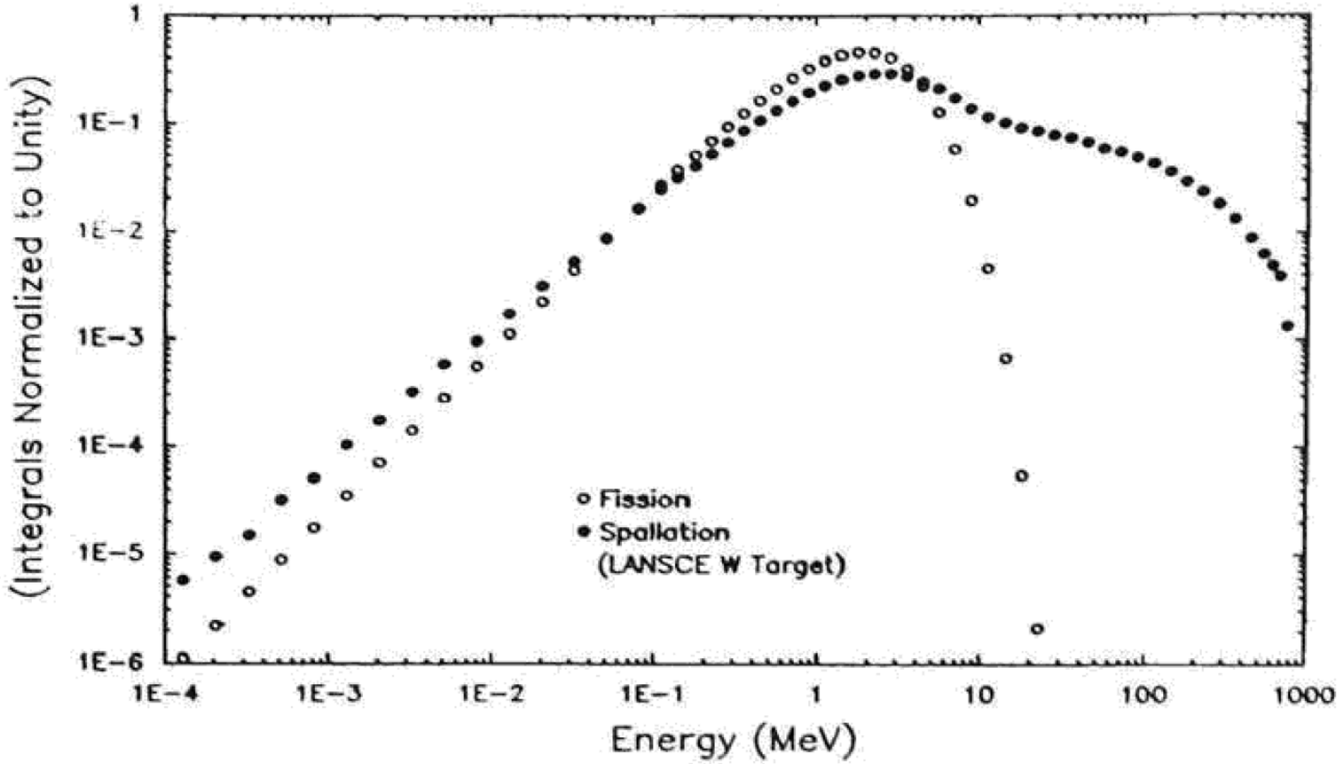


Figure 4. Spallation neutron spectrum compared to a typical neutron spectrum from thermal neutron fission of ^{235}U. The spallation spectrum is at 90 degrees from a "finite" 10-cm-diam by 30-cm-long tungsten target bombarded by 800-MeV protons.

G. J. Russell et al, Fundamental Physics with Pulsed Neutrons Beams (2000) p 19

Source: Angular dependency of the source

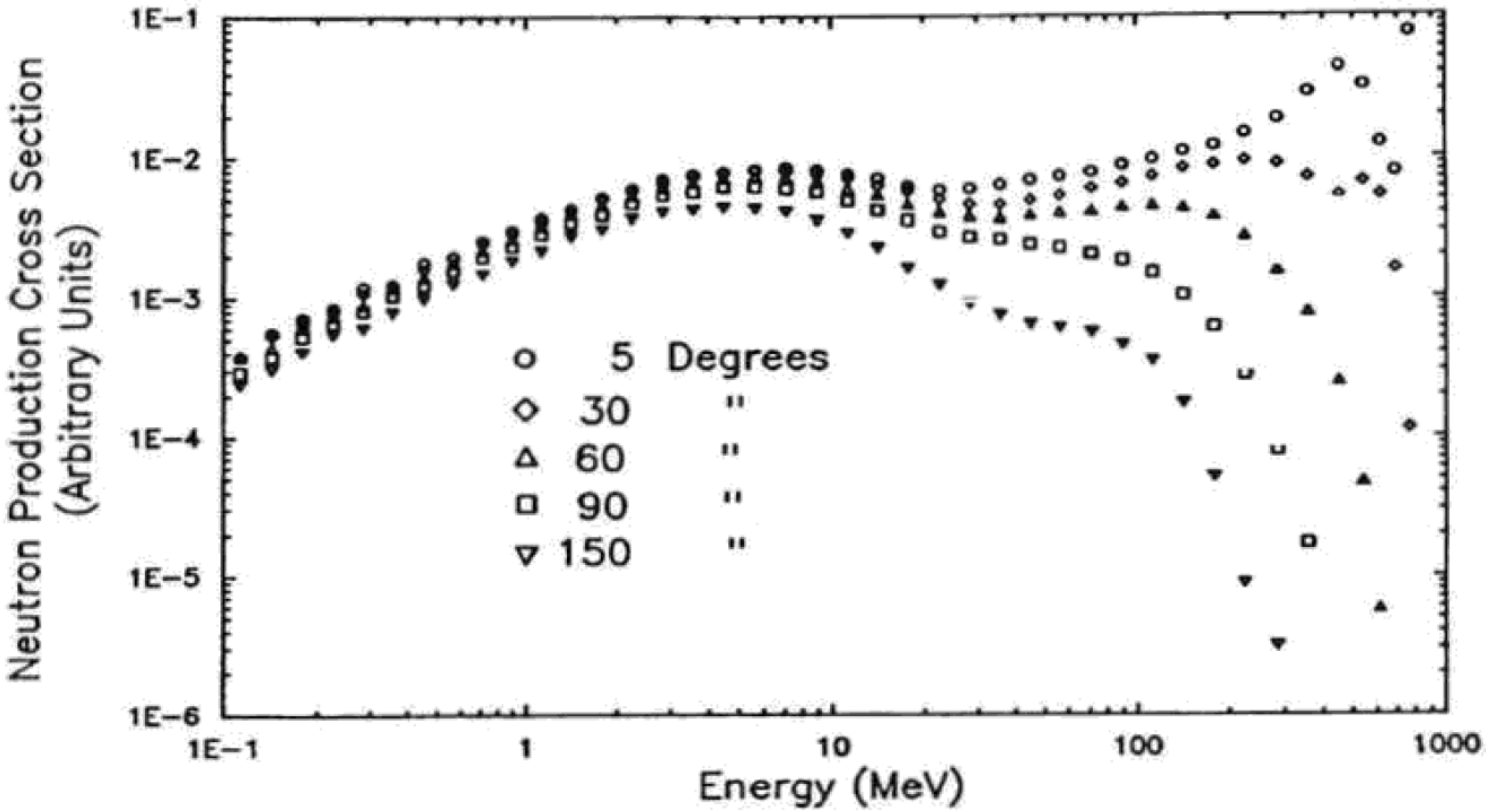
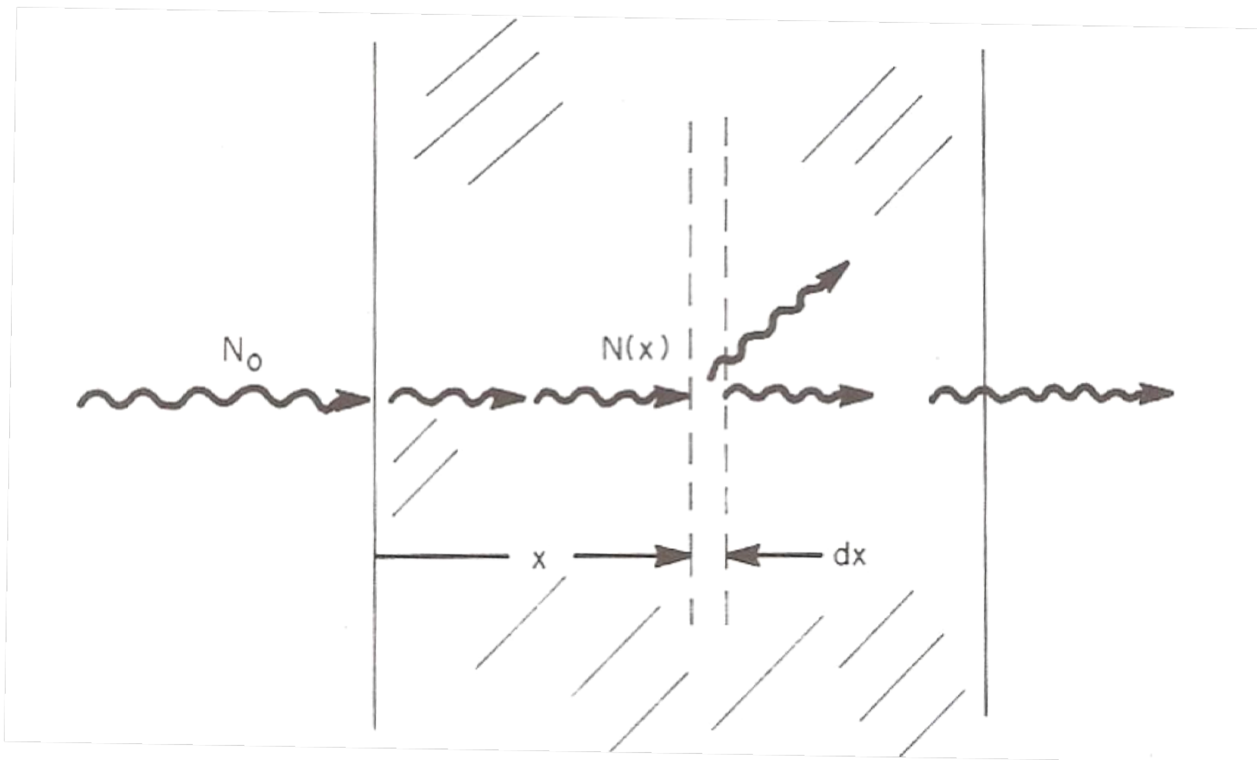


Figure 3. Neutron production from a thin iron target bombarded by 800-MeV protons.

G. J. Russell et al, Fundamental Physics with Pulsed Neutrons Beams (2000) p 19

Physics: Attenuation



$$dN = -\mu N dx \Rightarrow N(x)=N_0 e^{-\mu x}$$

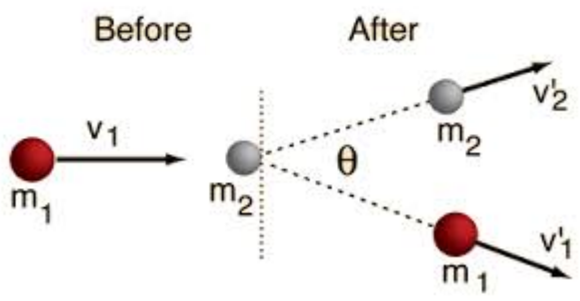
Physics: Neutrons

- Slowing down process:

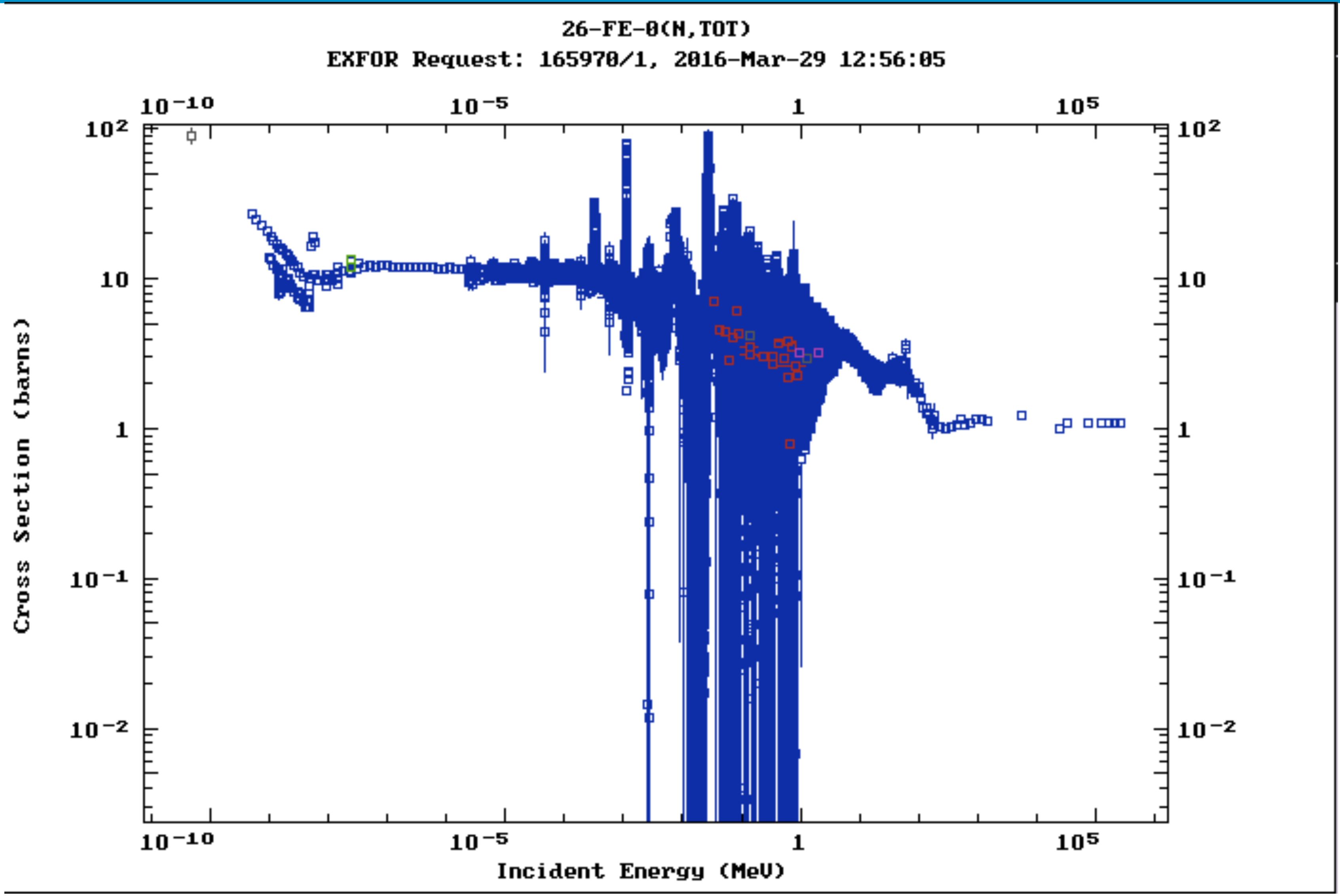
  The slowing down process of neutrons in matter can be described by the two body problem from classical mechanics.

  Nuclear physicist define this as an elastic process, because the neutron-nucleus system does not loose energy.

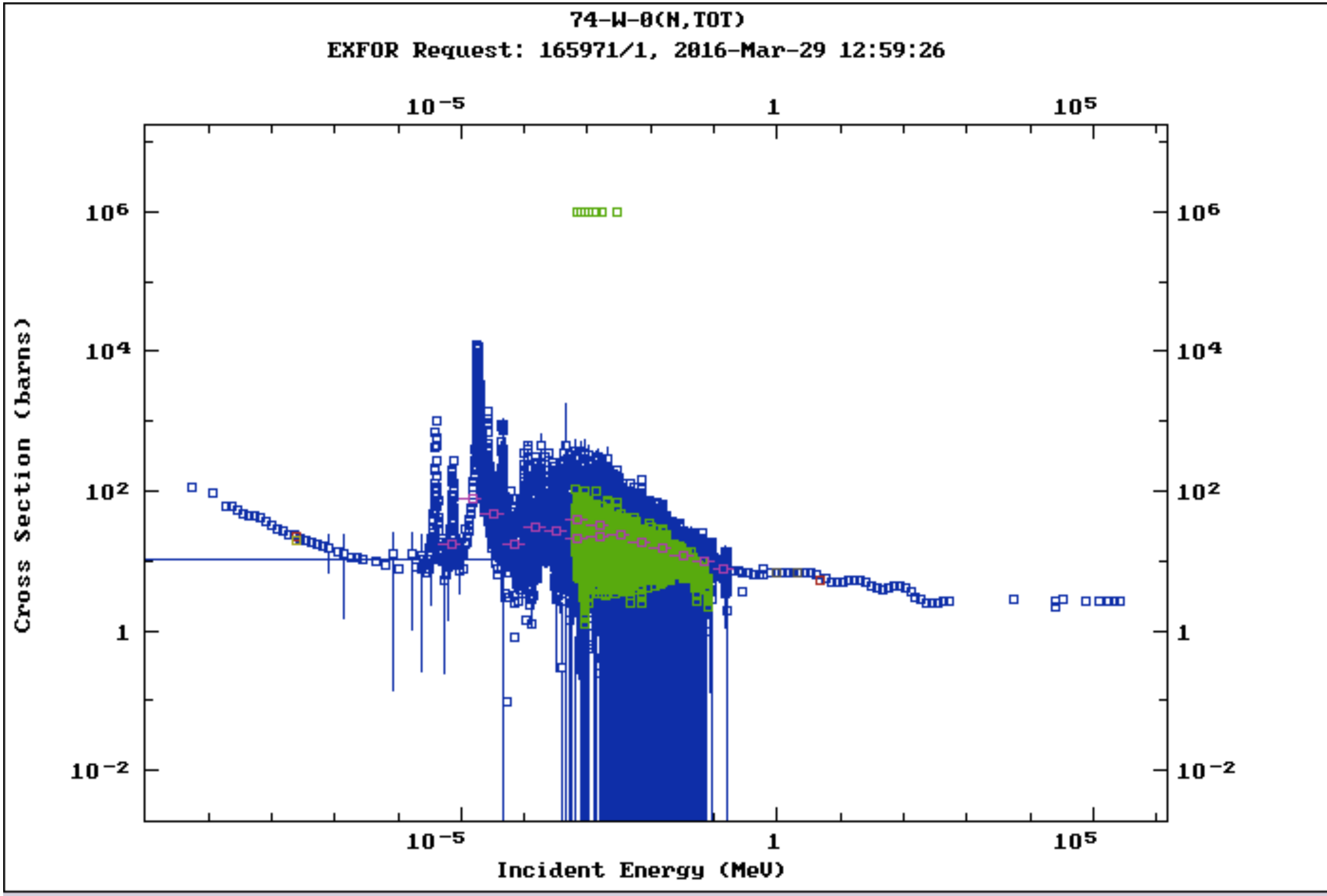
  Neutron scattering define this as an inelastic process, because the neutron looses energy.



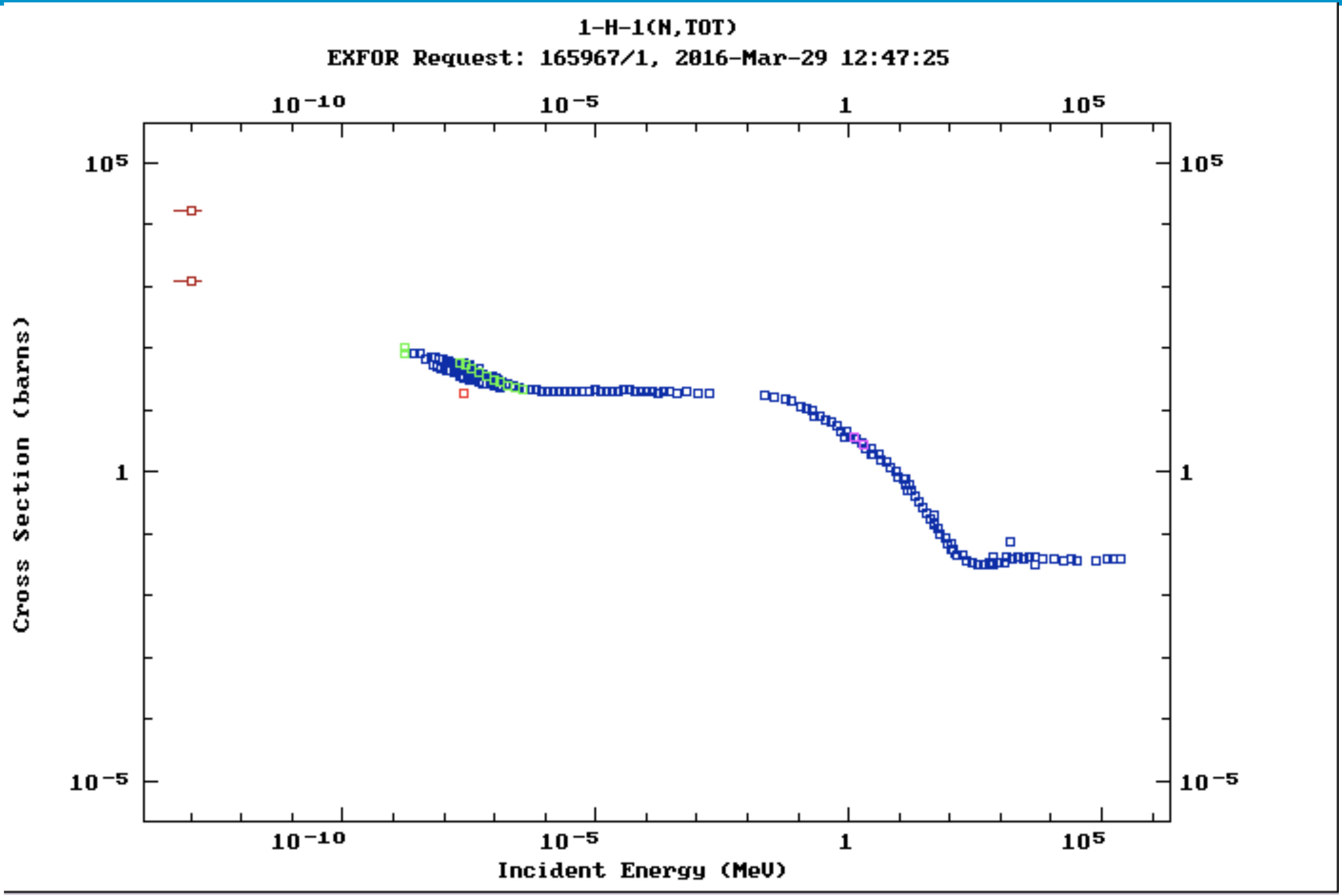
Physics: Iron cross-section



Physics: Tungsten cross-section



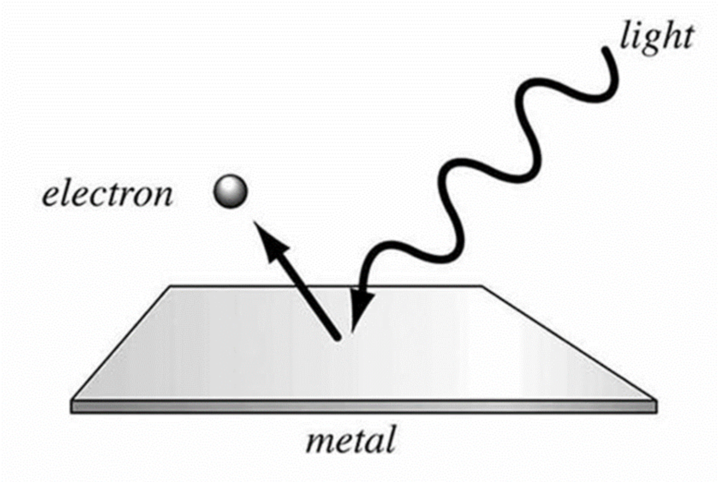
Physics: Hydrogen cross-section

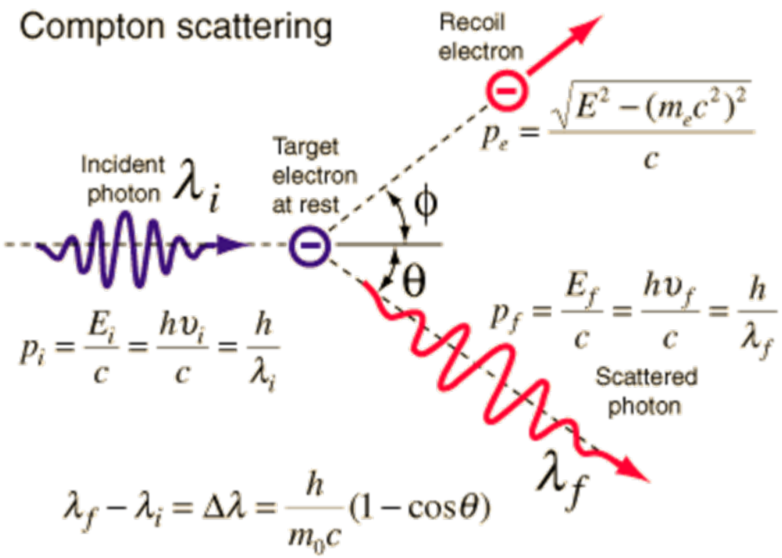


Physics: Photons

- Photoelectric effect

  During the photoelectric effect the photon will be absorbed by the matter and an electron will be emitted.





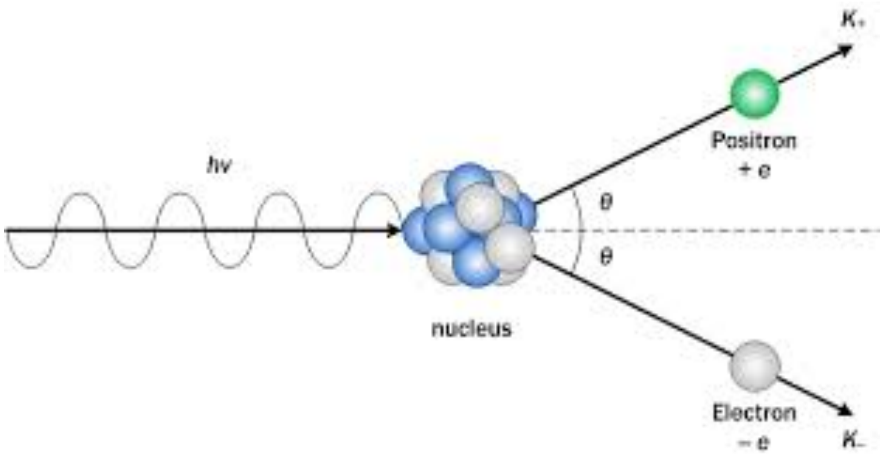
- Compton effect

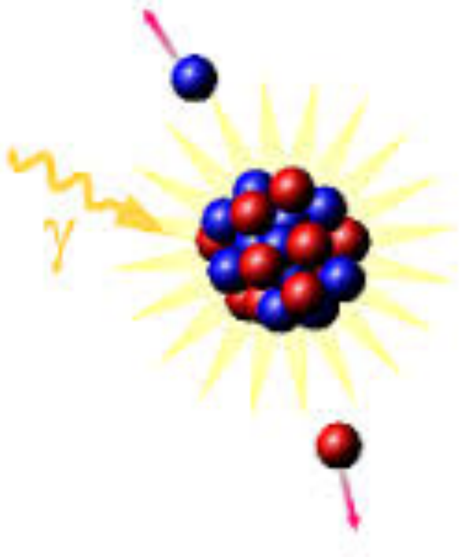
  Compton effect is the inelastic scattering of a photon on a charged particle, unusually electron. It results in a reduction of the photon energy and a momentum change of the photon (Compton scattering.) or the photon gets absorbed and a different photon with a lower energy will be emitted (Compton absorption).

Physics: Photons

- Pair production

  A photon with an energy of at least twice the electron rest mass, can be converted into a electron-positron pair.

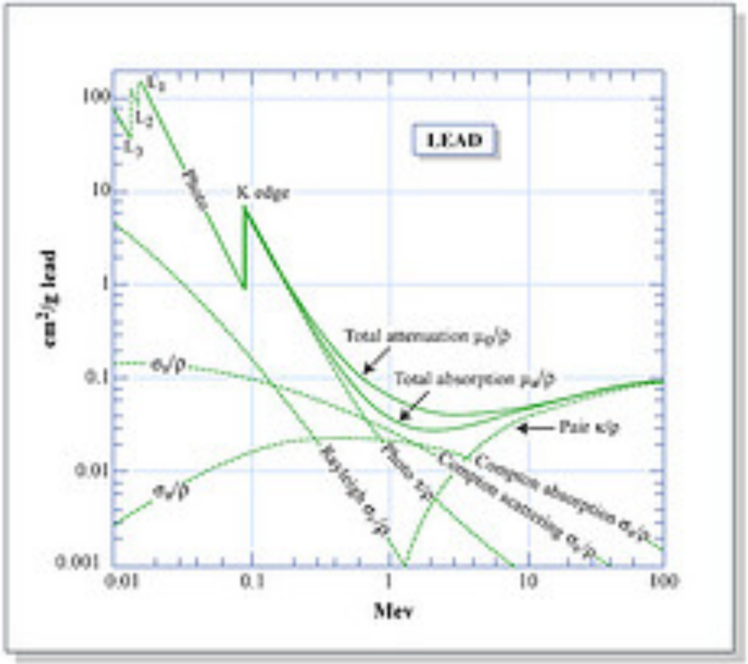


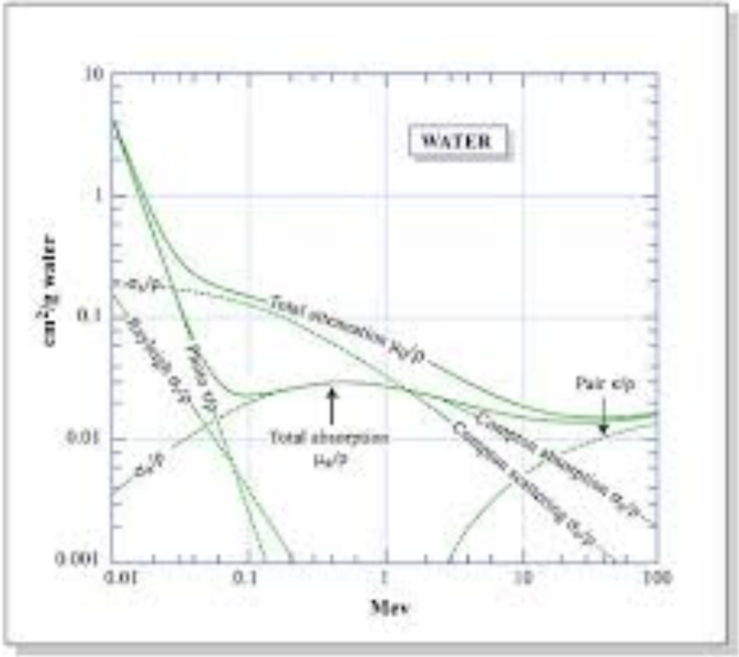


- Photonuclear reactions

  Photons can be absorbed by an atomic nucleus and a nucleon will be emitted (e.g. (γ,n) reaction).

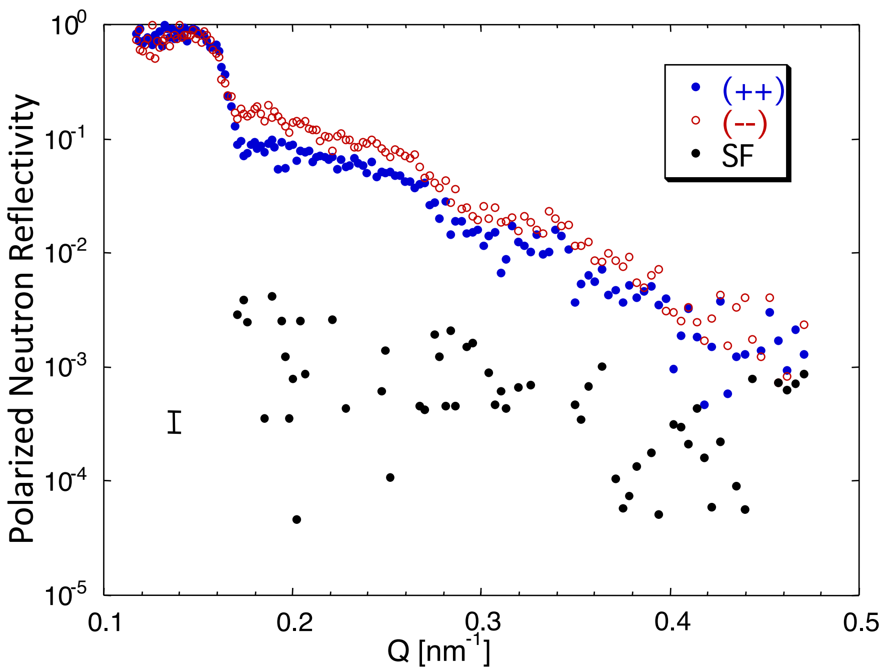
Photon mass attenuation factor in lead and water



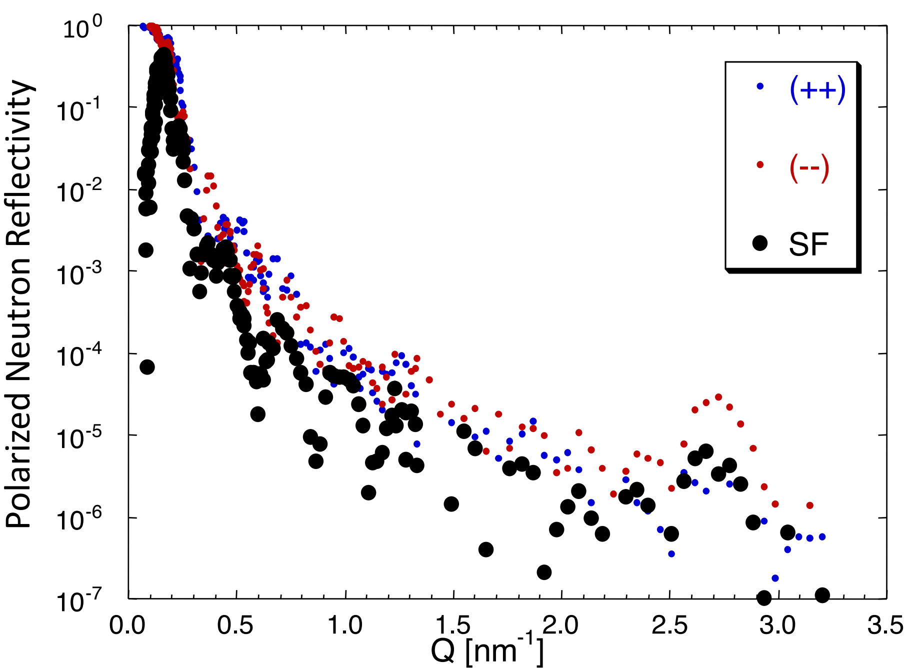


Metric: Background metric

P-SPEAR ('98)
24+h measurement



Asterix ('02)
19h measurement



Neutron Shielding Tools

Tools

- Handbook calculations

  e.g: A.H. Sullivan: “A Guide to Radiation and Radioactivity Levels Near High Energy Particle Accelerators.” Nuclear Technology Publishing Ashford, Kent, TN23 1JW, England

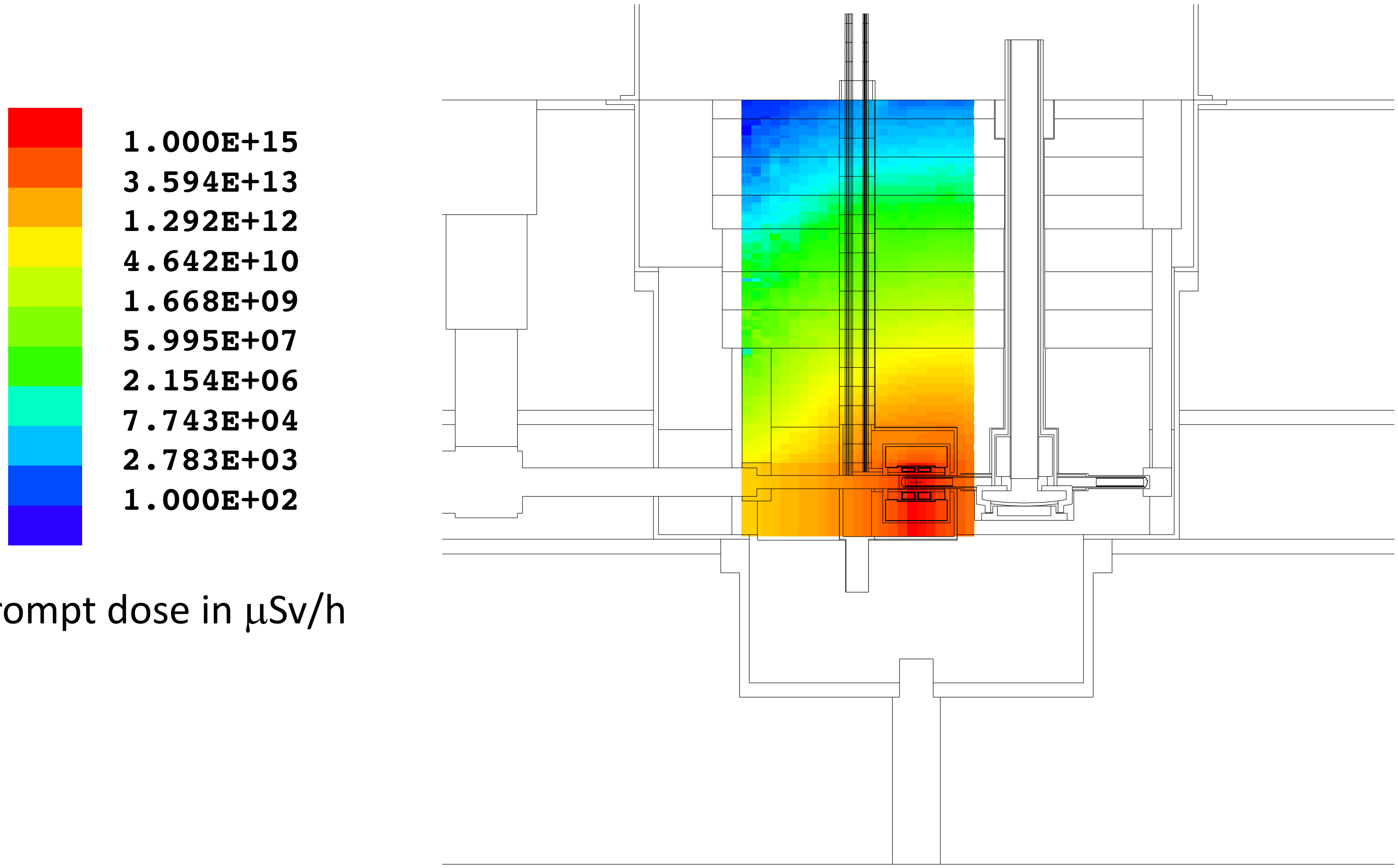
- Monte Carlo Particle transport codes

  Variance reductions

Variance reductions

- Variance reductions are very power full, while very dangerous methods to cheat time in Monte Carlo simulations.

Variance reductions: Why?

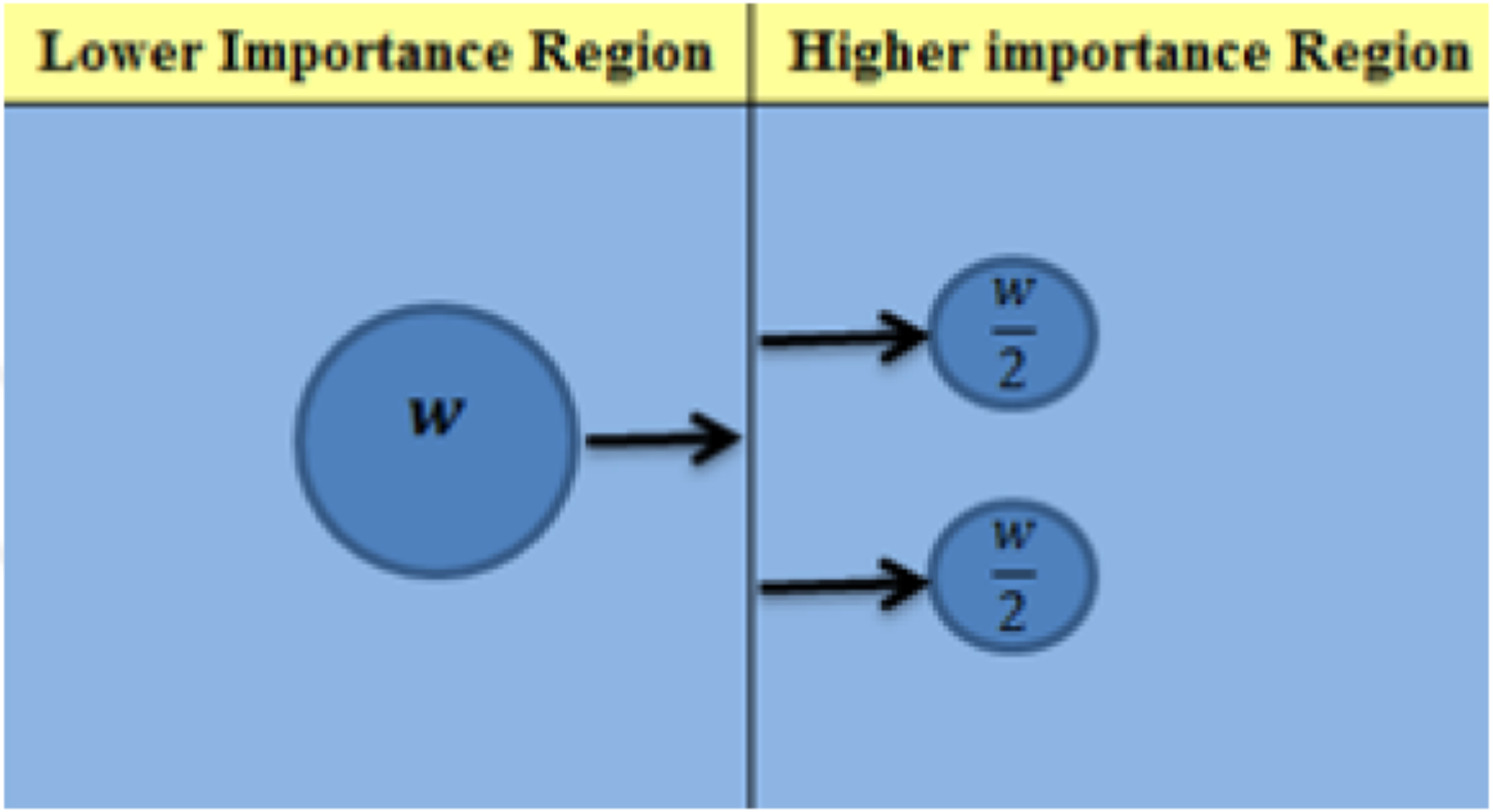


Prompt dose in μSv/h

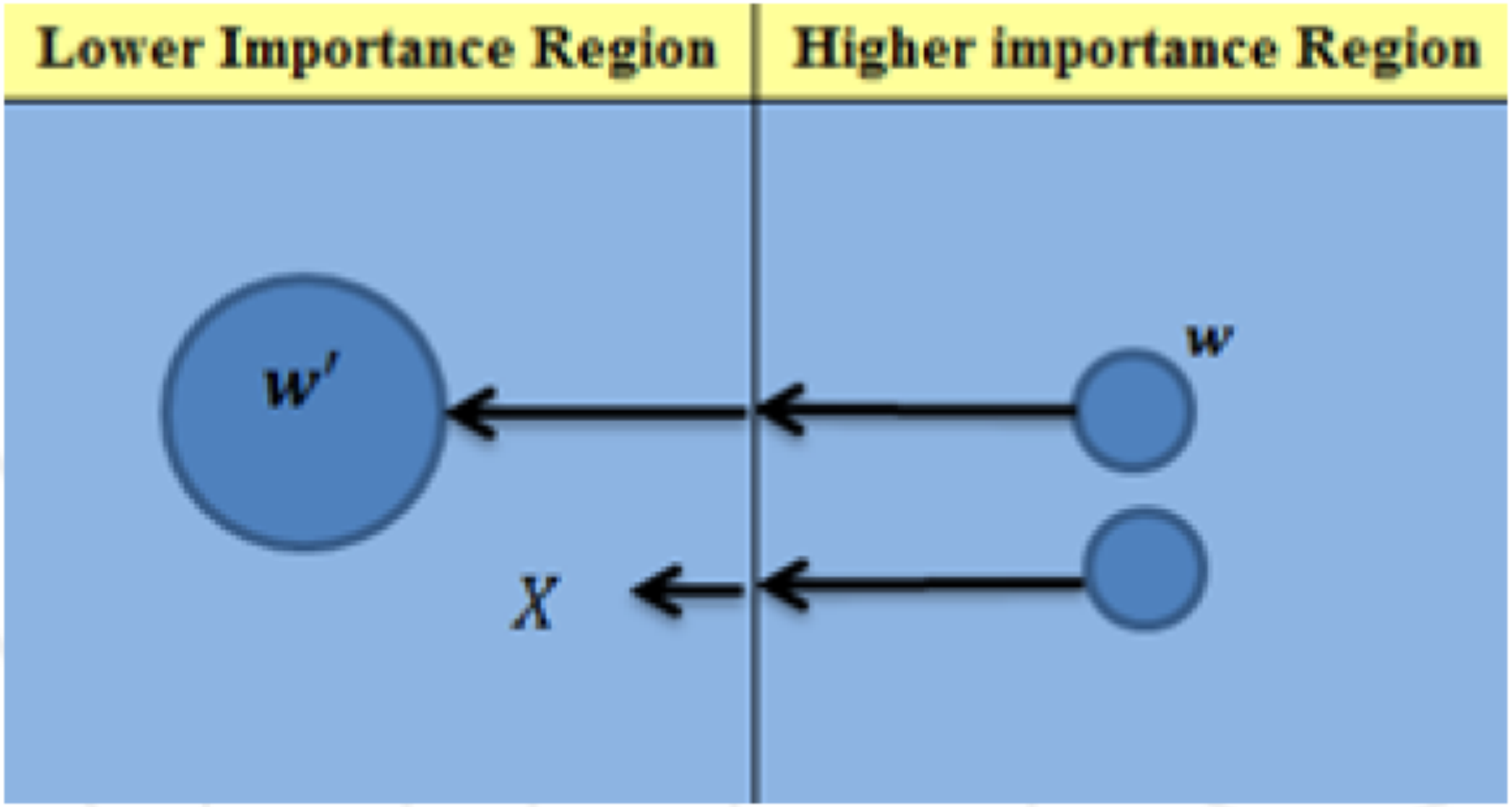
Variance reductions

- Cell importance
- Weight windows
- DXTRAN sphere
- Forced collision
- Energy splitting
- Second particle biasing

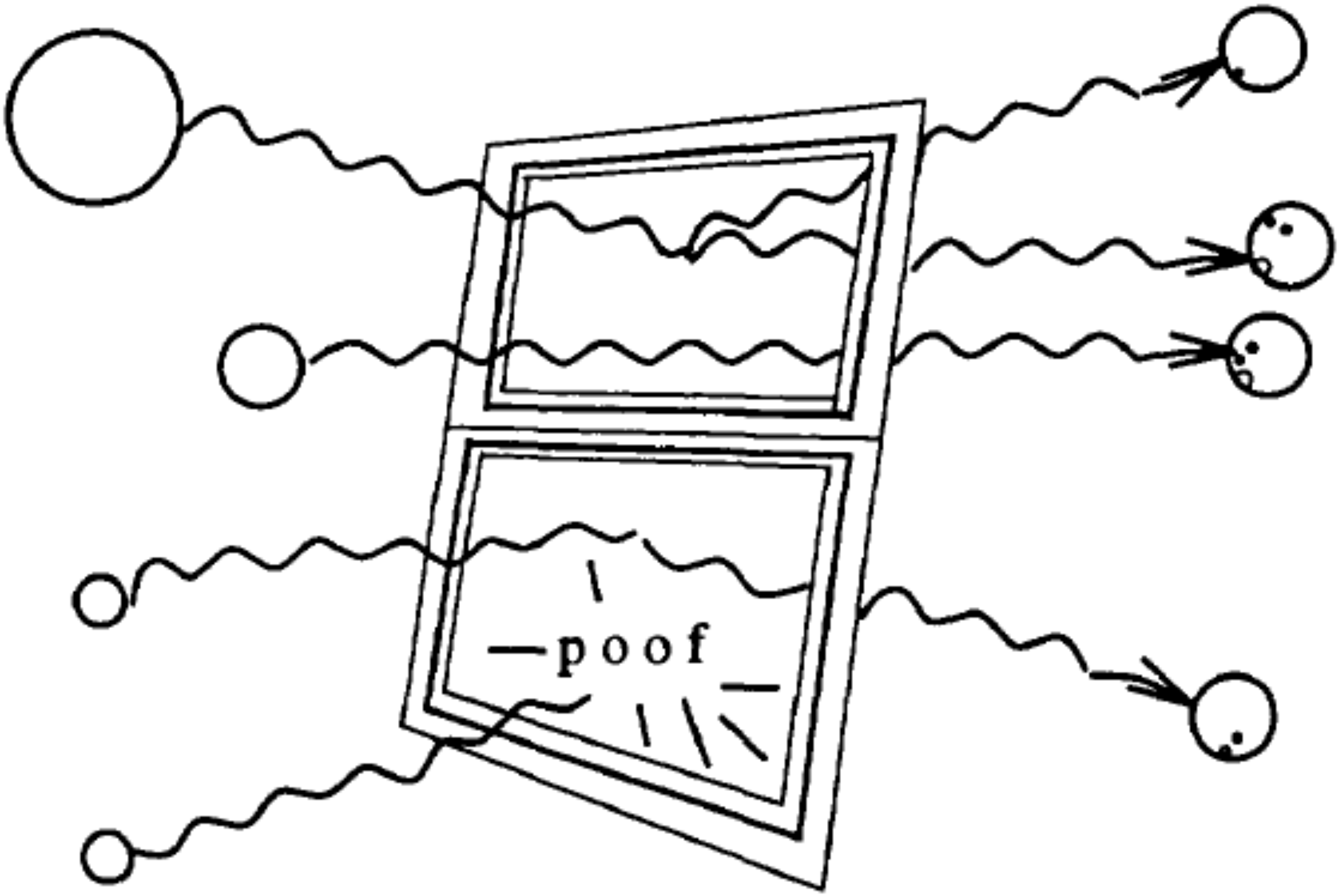
Geometry splitting



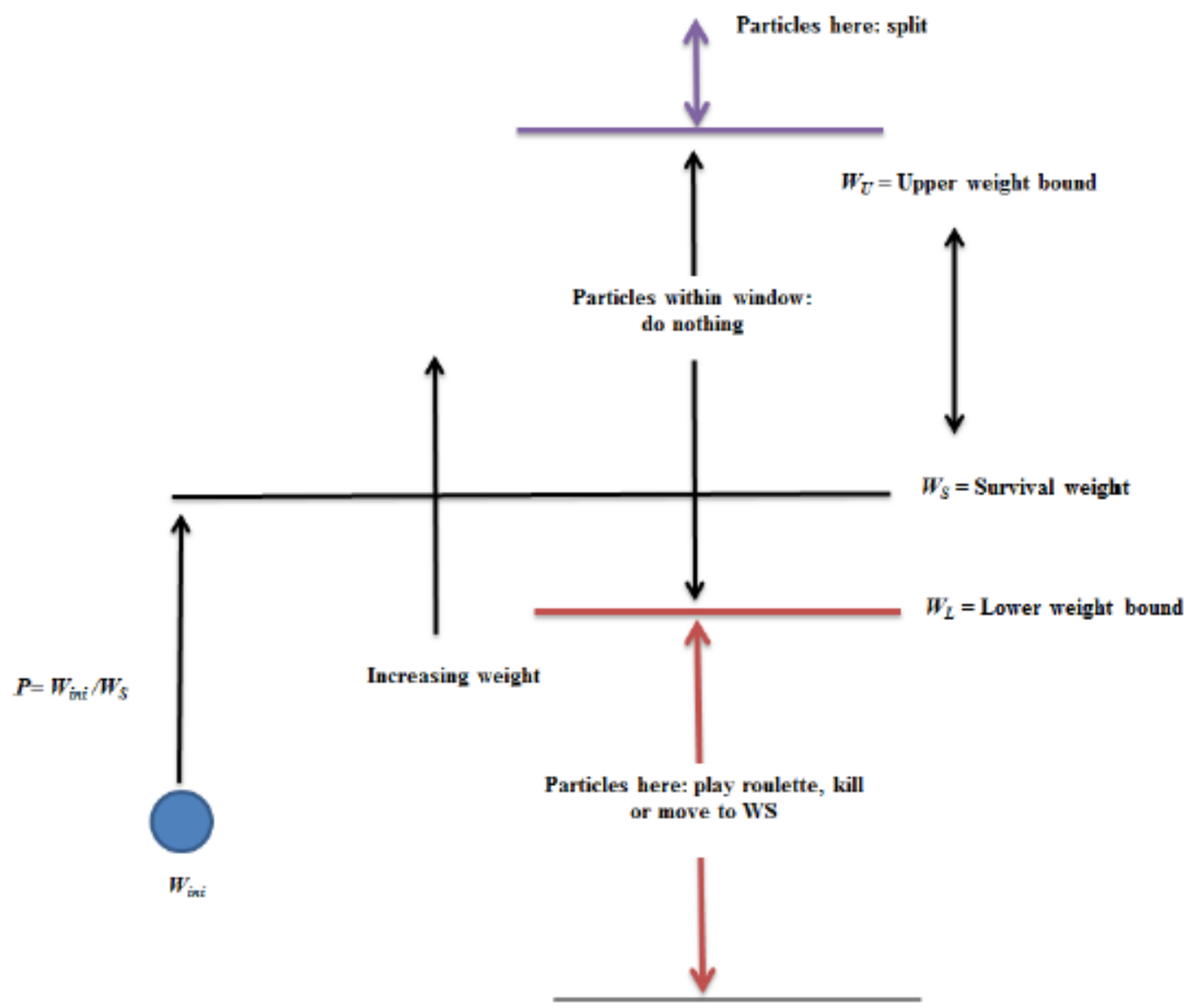
Russian roulette



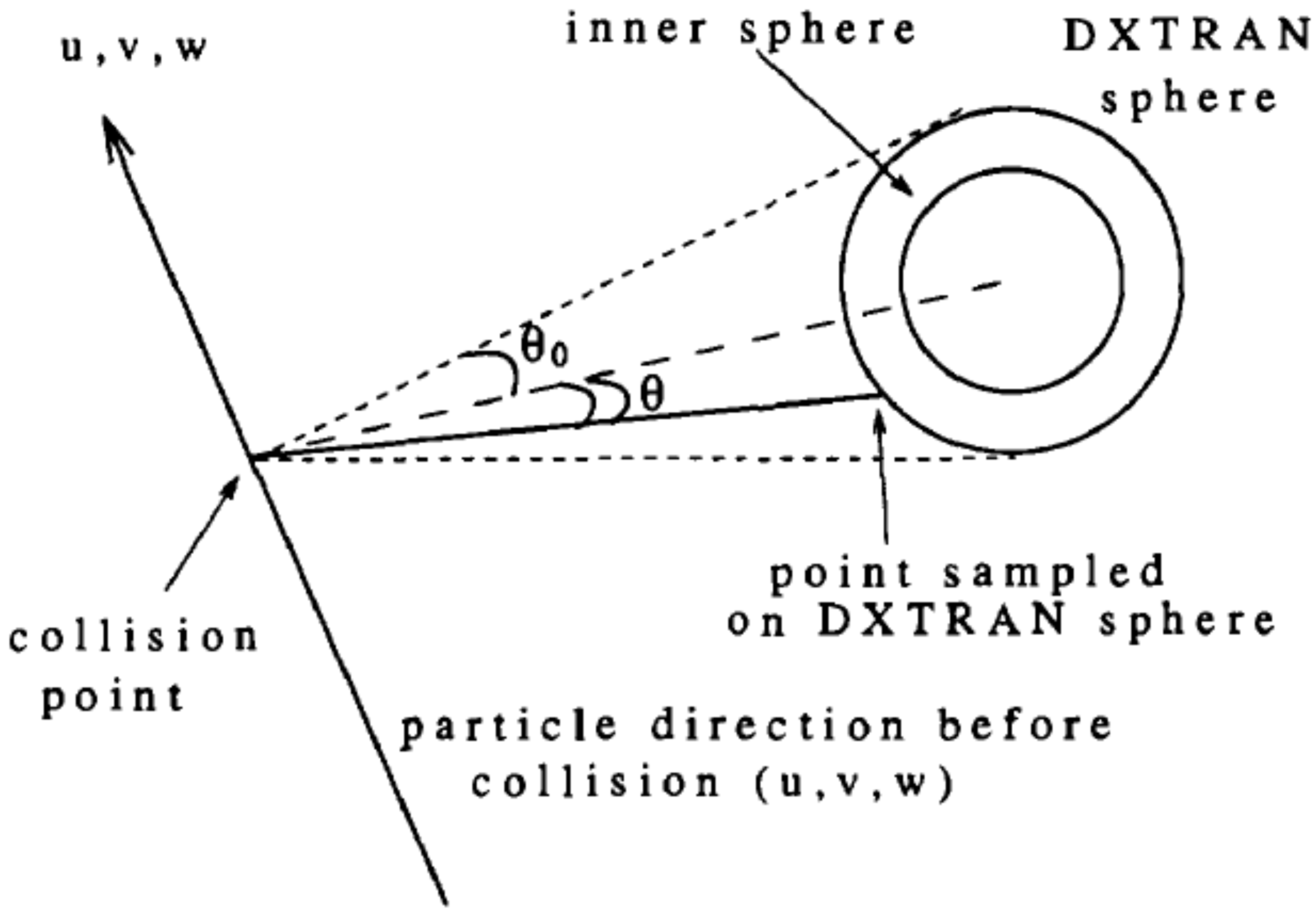
Weight window principle 1(2)



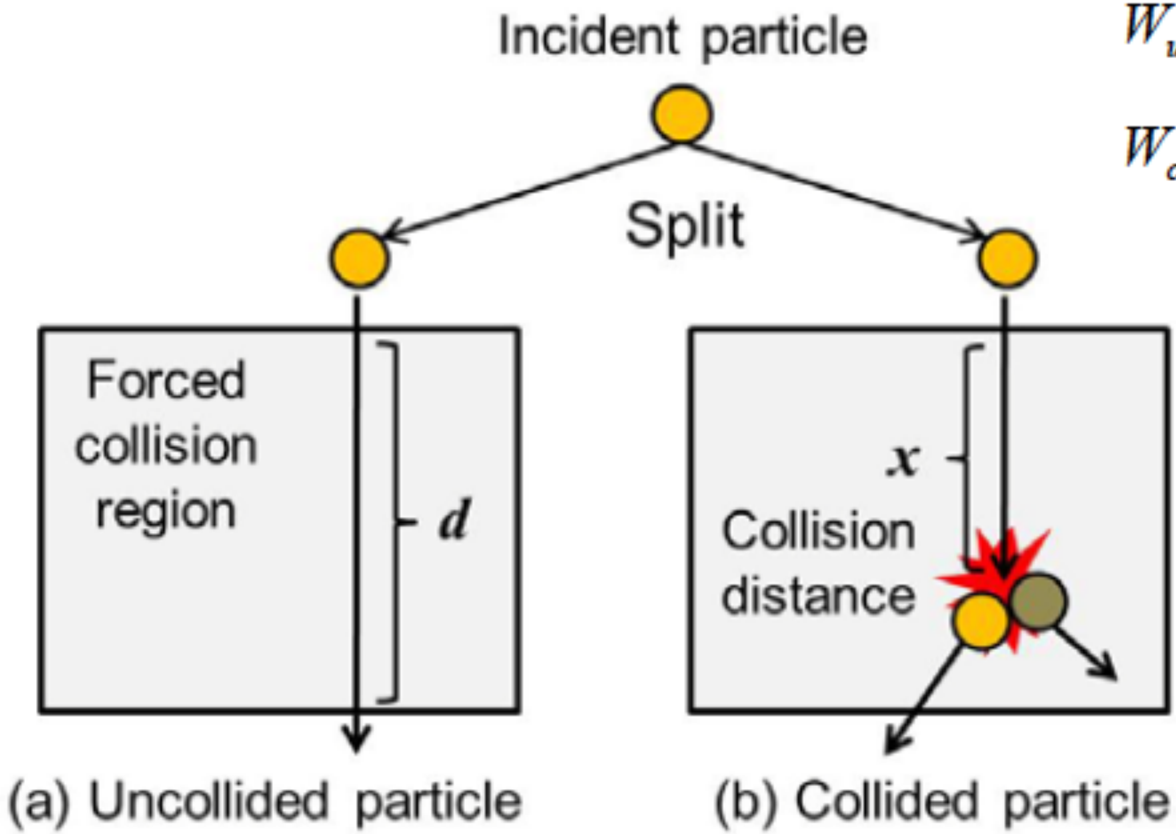
Weight window principle 2(2)



Dxtran sphere



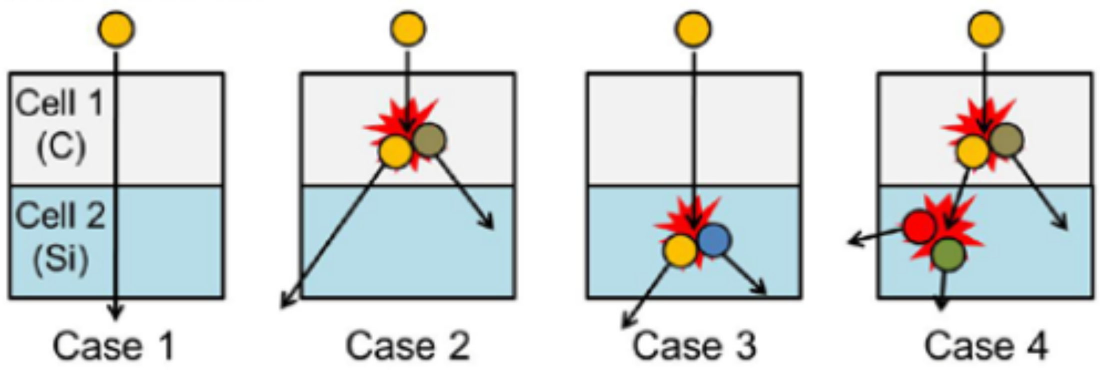
Forced collision 1(2)

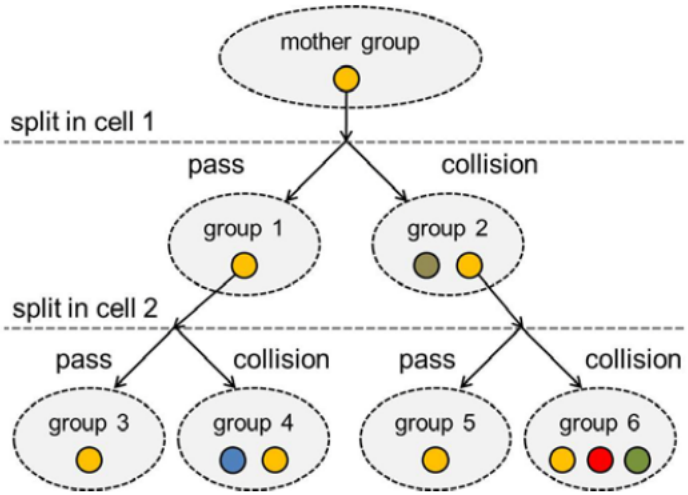


$$W_{uncoll} = W_0 \exp(-\Sigma_t d),$$

$$W_{coll} = W_0 \{1 - \exp(-\Sigma_t d)\}$$

Forced collision 2(2)





$$E_{mother} = 0, \quad W_{mother} = W_0$$
$$E_1 = 0, \quad W_1 = W_{mother} \exp(-\Sigma_1 d_1)$$
$$E_2 = e_C, \quad W_2 = W_{mother} [1 - \exp(-\Sigma_1 d_1)]$$
$$E_3 = 0, \quad W_3 = W_1 \exp(-\Sigma_2 d_2)$$
$$E_4 = e_{Si}, \quad W_4 = W_1 [1 - \exp(-\Sigma_2 d_2)]$$
$$E_5 = 0, \quad W_5 = W_2 \exp(-\Sigma_2 d_2)$$
$$E_6 = e_{Al} + e_p, \quad W_6 = W_2 [1 - \exp(-\Sigma_2 d_2)],$$

Energy splitting

- Energy splitting is like geometry splitting put in energy space.

Secondary particle biasing

- Secondary particle biasing is like geometry splitting but in secondary particle space.