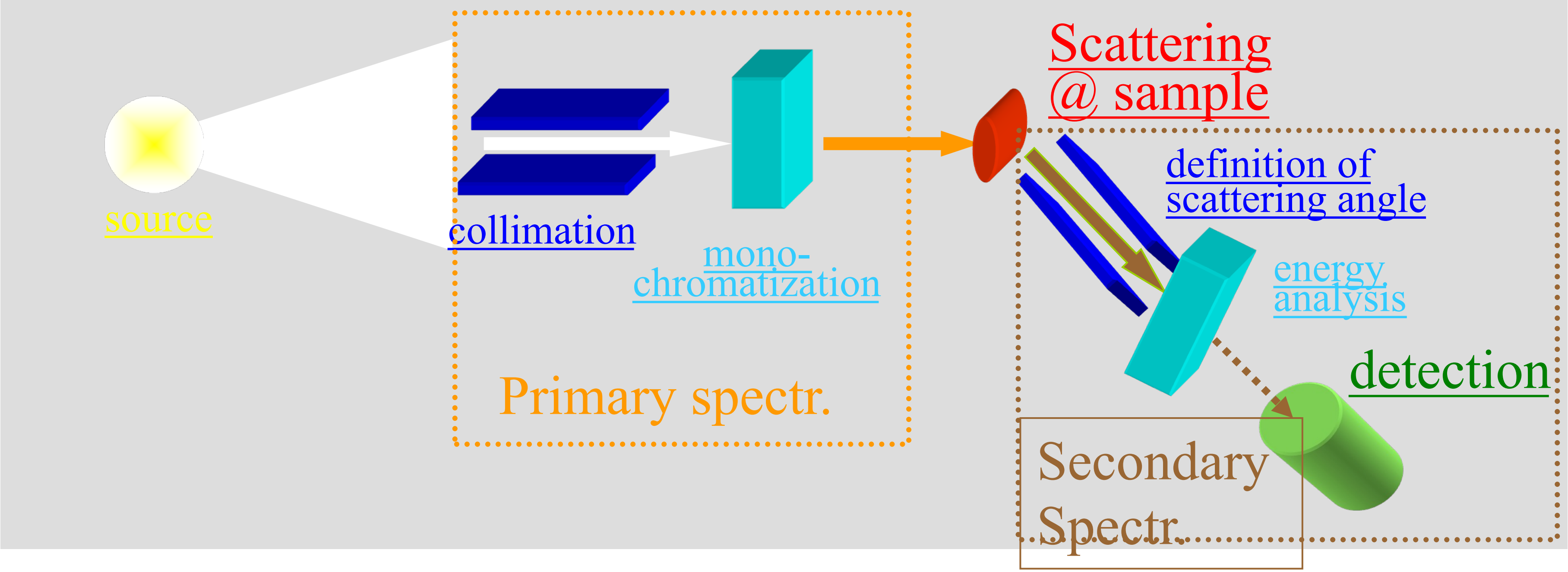
Mitglied der Helmholtz-Gemeinschaft

Neutron sources

Jörg Voigt

9. September 2022

Principle of a scattering experiment



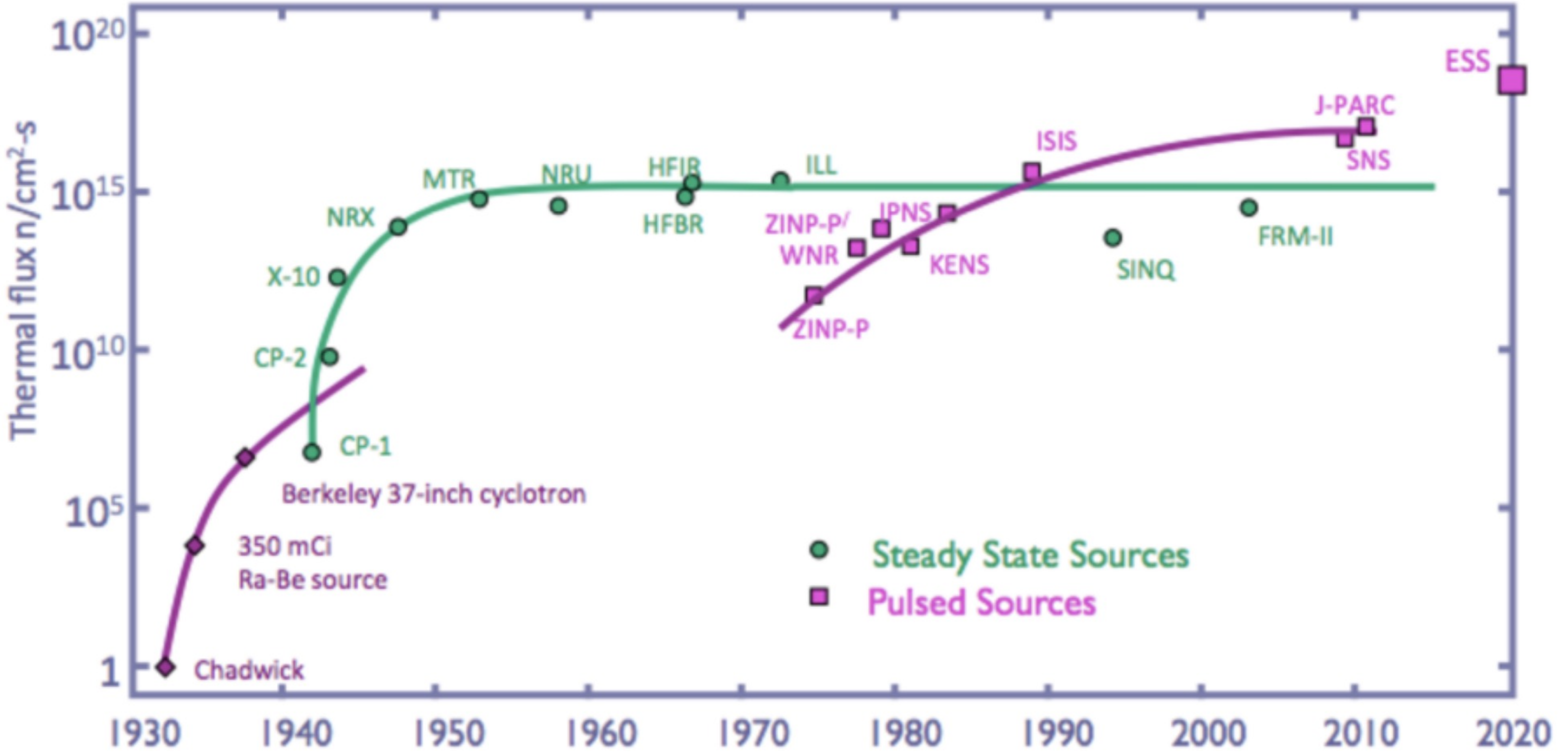
Primary Spectrometer: Define phase space before sample illumination
Secondary Spectrometer: Determine the phase space after scattering

→ Source requirements: Provide high phase space density

➔ Constraint the neutrons in space and energy

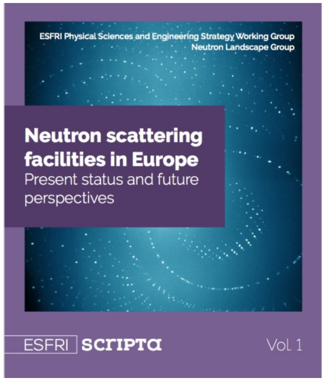
➔ High Brightness $[\Phi] = 1$ neutron cm^{-2}s^{-1}sr^{-1}Å^{-1}

Evolution of neutron sources



K. H. Andersen, C.J. Carlile, Jour. Phys.: Conf. Ser. (2016)

European Neutron Landscape

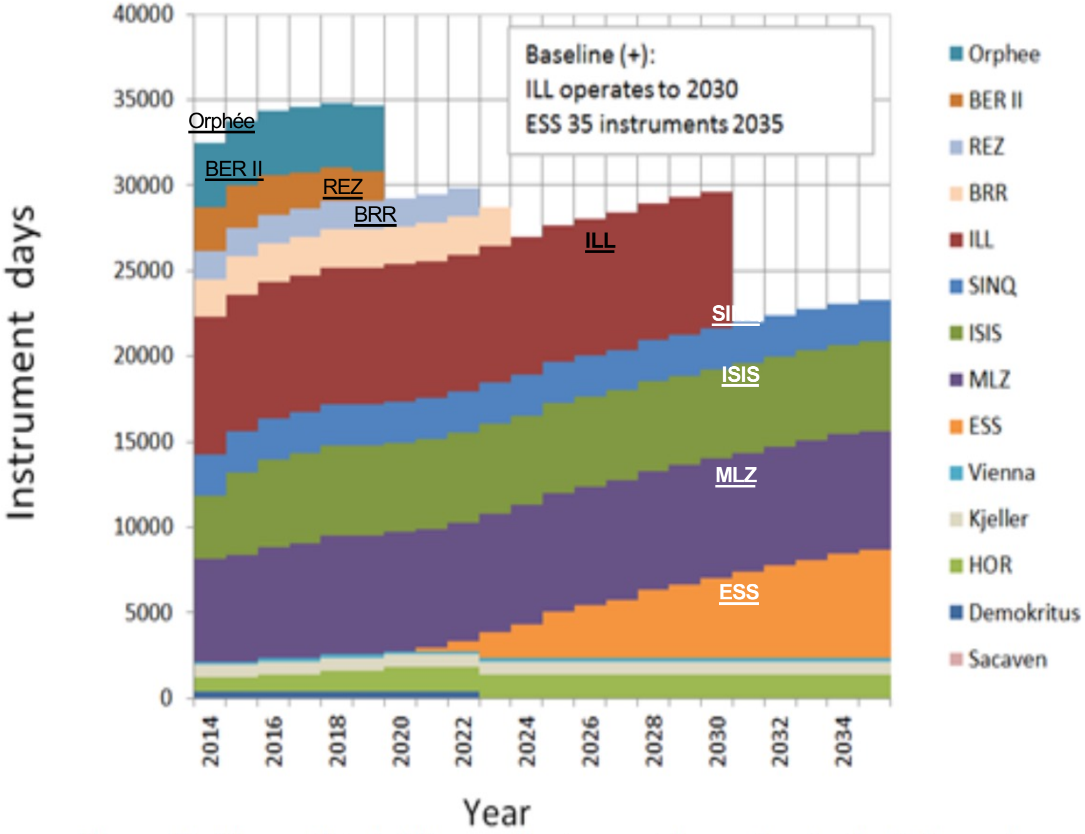


ESFRI Physical Sciences and Engineering Strategy Working Group
Neutron Landscape Group

Neutron scattering facilities in Europe
Present status and future perspectives

ESFRI scripta Vol. 1

www.esfri.eu



Baseline (+):
ILL operates to 2030
ESS 35 instruments 2035

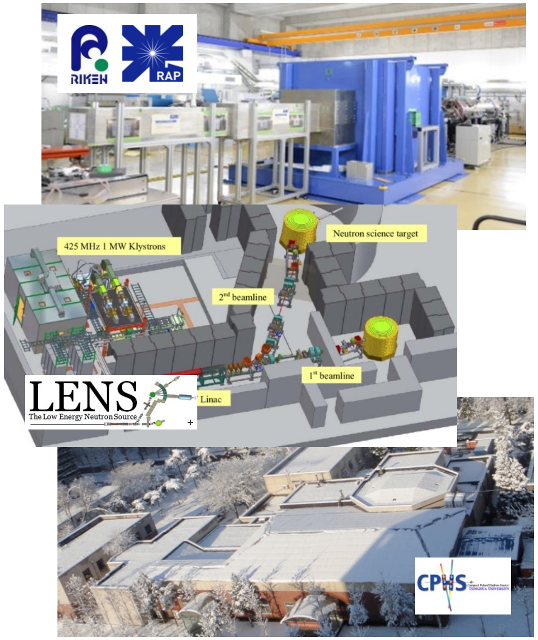
Figure 12. *The predicted delivery of instrument beam days in the Enhanced Baseline Scenario*

Neutron Production

Nuclear fission

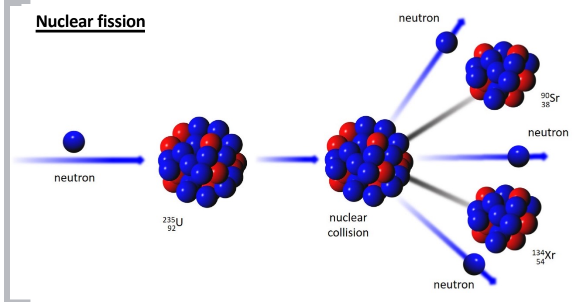
Spallation

Low energy nuclear processes



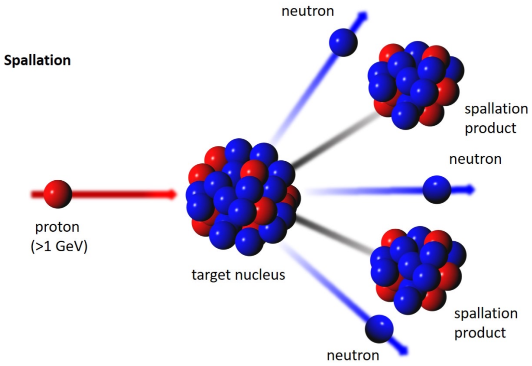
Neutron Release

Nuclear fission



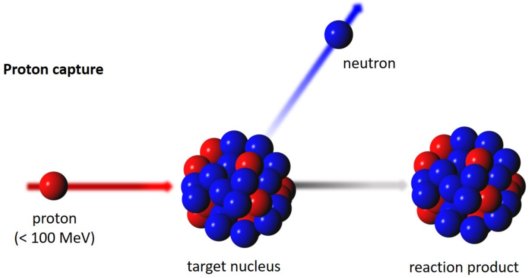
Reactor based
neutron source
(ILL, FRM II, NIST, JINR,
ANSTO a.m.m.)

Spallation



Spallation based
neutron source
(ESS, ISIS, SINQ, SNS,
CSNS, J-PARC, KEK)

Nuclear processes



Accelerator based
neutron source
(LENS, RANS, HUNS, NUANS, IREN
a.o.)

Nuclear Process	Example	Neutron Yield	Heat Release [MeV/n]	Source
D-T in solid target	400 keV d on T in Ti	4 x 10^{-5} n/d	10000	
Deuteron stripping	40 MeV d on liq. Li	7 x 10^{-2} n/d	3500	
Nuclear photo effect from e-Brems-strahlung	100 MeV e^- on ^{238}U	5 x 10^{-2} n/e^-	2000	HUNS, n-ELBE
^{9}Be(d,n)^{10}Be	15 MeV d on Be	1.5 x 10^{-2} n/d	1000	
^{9}Be(p,n:p,pn)	11 MeV p on Be	4 x 10^{-5} n/d	2000	RANS, LENS
Nuclear fission	Fission of ^{235}U by thermal neutrons	1n/fission	180	MLZ, ILL
Spallation	800 MeV p on ^{238}U or Pb	27 n/p or 17 n/p	55 or 30	ISIS, SINQ, ESS

Ref.: G. Mank, G. Bauer, F. Mulhauser, Accelerators for Neutron Generation and Their Applications, Rev. Accl. Sci. Tech 04, 219 (2011)

*CANS: **C**ompact **A**ccelerator based **N**eutron **S**ource
** HiCANS: **Hi**gh-**C**urrent **A**ccelerator based **N**eutron **S**ource

From CANS* to HiCANS**
Accelerator Based Neutron Sources

0.01 kW	0.1 kW	1 kW	10 kW	100 kW
0.001-0.01 mA	0.01-1 mA	0.5-5 mA	1-20 mA	50-100 mA
~10^{11} n/s	~10^{12} n/s	~10^{13} n/s	~10^{14} n/s	~10^{15} n/s

10 Mio EUR → 500 Mio EUR

Running CANS facilities:

LENS, Indiana University (USA)
HUNS, Hokaido University (Japan)
RANS, RIKEN (Japan)
NUANS, Nagoya University (Japan)
CPHS, Tsinghua University (China)
IREN, JINR Dubna (Russia)

HiCANS projects:

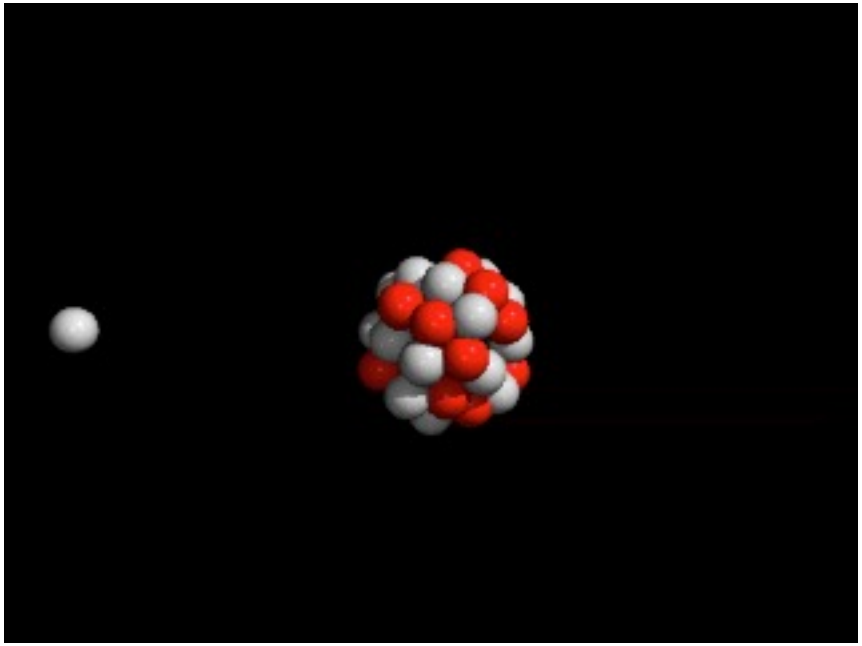
HBS, JCNS (Germany)
SONATE, CEA LLB (France)
ARGITU, ESS Bilbao (Spain)
LENOS, INFN LNL (Italy)
SARAF, SOREQ (Israel)

Nuclear fission reaction

→ capture of a slow neutron

→ deformation of nucleus

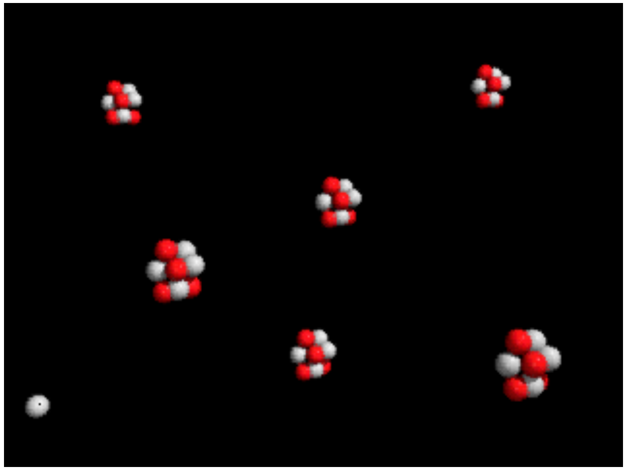
→ splitting into two fragments, simultaneously releasing 2 or 3 (on average 2.5) “prompt” neutrons with energies 1.29 MeV



Chain reaction

Nuclear fission reaction

^{235}U + neutron → fission fragments + 2.52 neutrons + 180 MeV.



The critical mass M_c.

If the mass of fissile material $M>M_c$:

⇒ the number of neutrons will increase exponentially
⇒ the reaction will become uncontrollable very quickly
⇒ a huge energy release (an explosion: A-bomb)

If the mass of fissile material $M<M_c$:

⇒ the number of neutrons will decrease over time
⇒ it is impossible to sustain a chain reaction:

So, this neutron producing reaction is unstable.

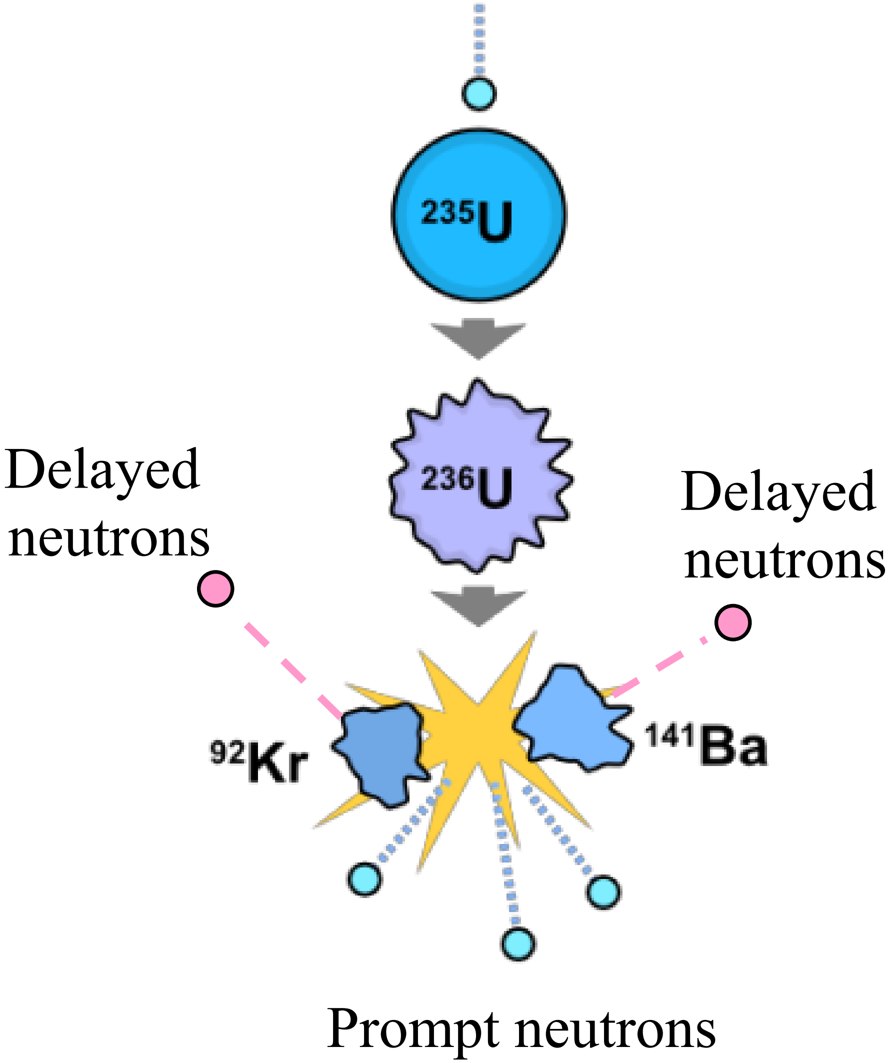
How to obtain a stable neutron flux?

Nuclear fission reactors: delayed neutrons

Considering prompt neutrons in a reactor

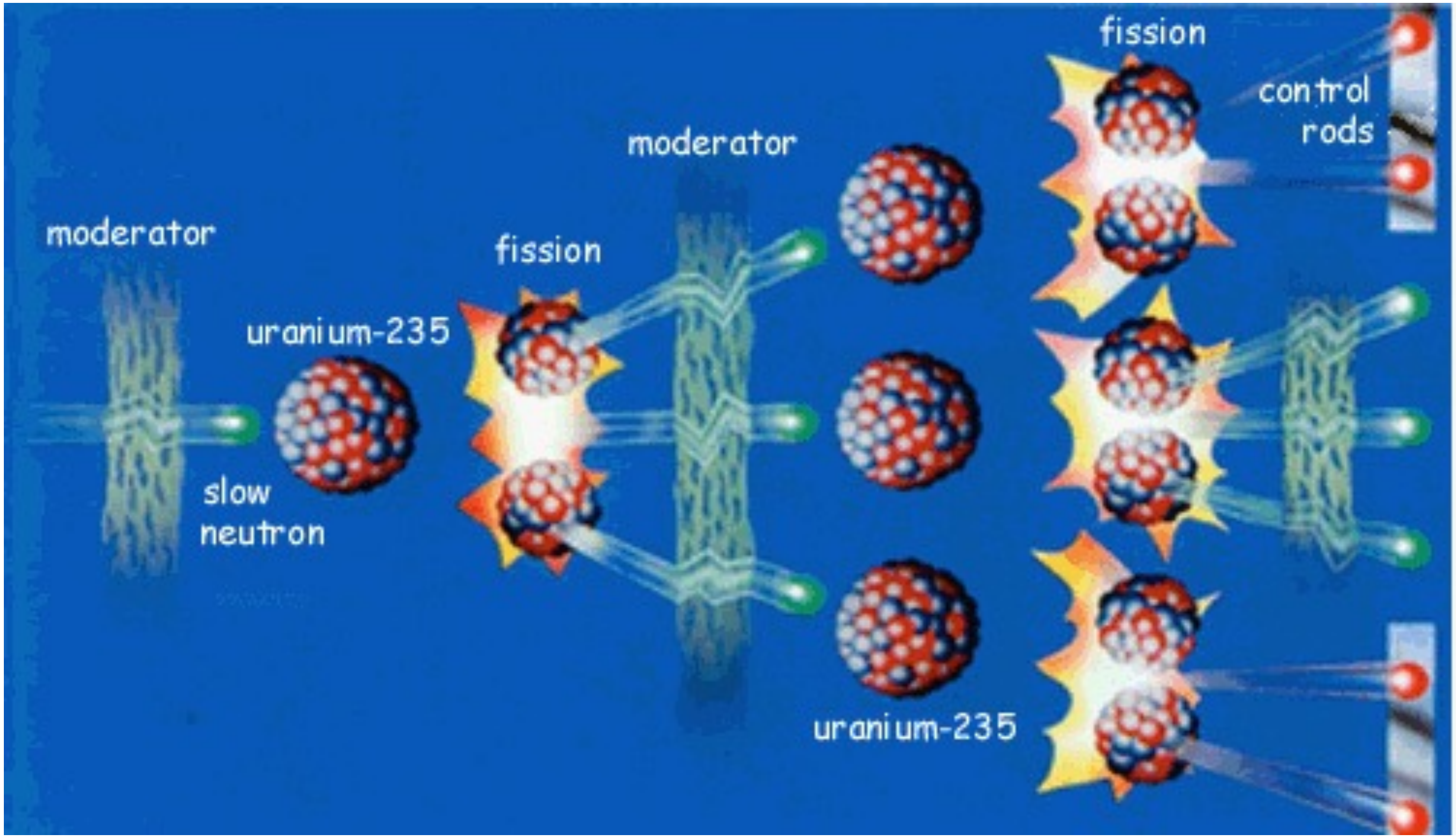
$$M < M_c$$

Delayed neutrons keep reactor burning.



How to control a fission reactor?

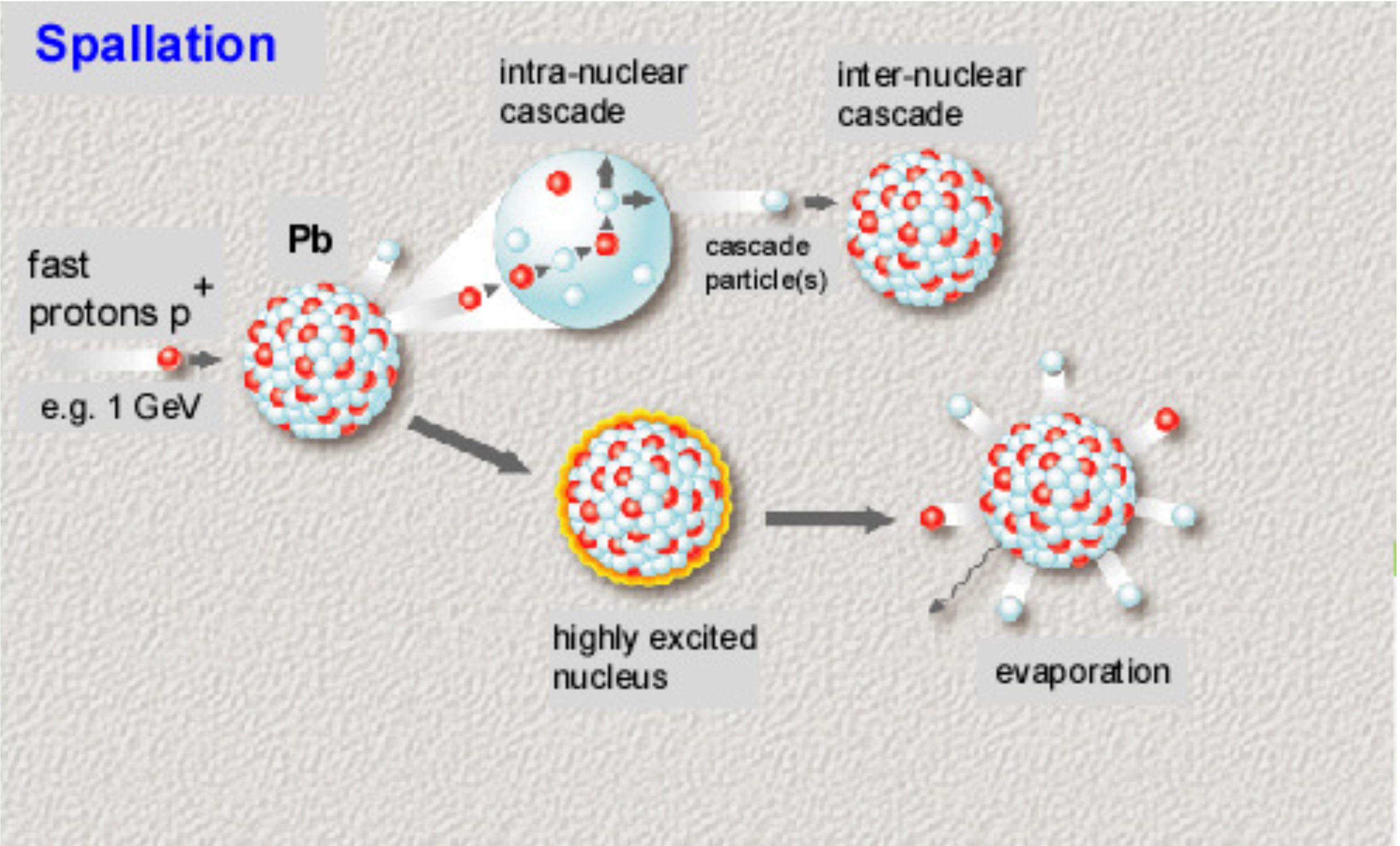
Remove thermal neutrons



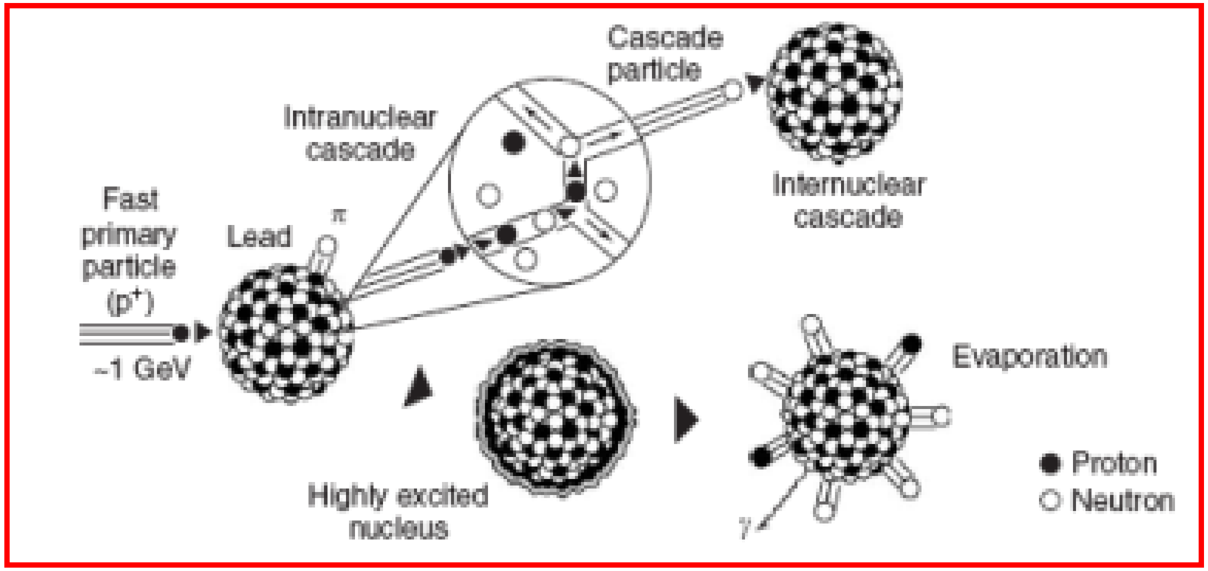
Spallation reaction

A high-energy proton hits a nucleous:

The de Broglie wavelength of the proton $\lambda = \sqrt{h^2/2mE} << d_{nucl}$



Spallation reaction



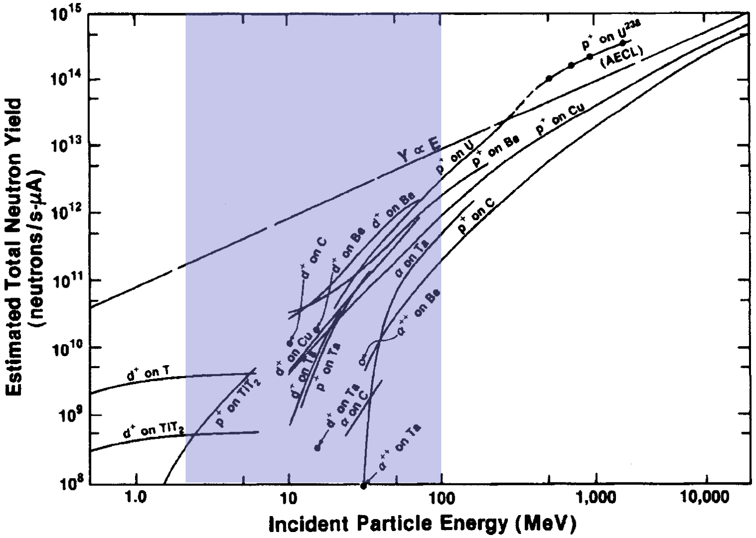
The spallation process takes 10^{-15} s. ⇨ Proton pulse determines primary neutron pulse

This pulse can be made:

- Pulse length > 1 ms (the long pulse spallation source (LPSS)), ESS
- Pulse length < 1 µs (the short pulse spallation source (SPSS)), ISIS, SNS,…

Neutron Production

Low energy nuclear processes

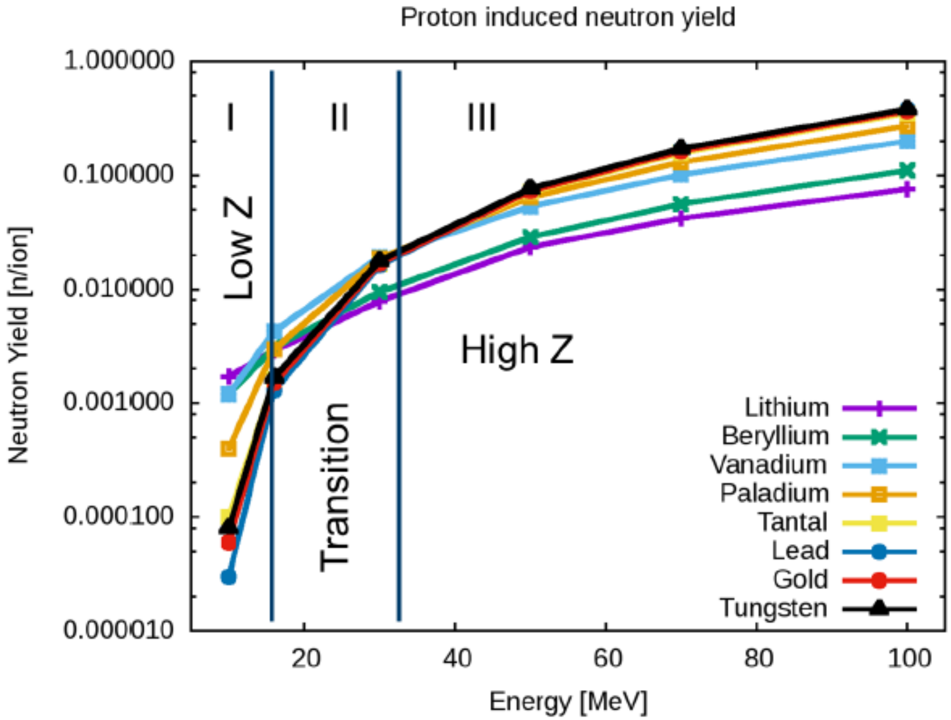


J. Carpenter, C.-K. Loong, Elements of Slow-Neutron Scattering, Cambridge University Press, 2015

Nuclear process	E [MeV]	n/ion	n/(s mA)	n/(s kW)
p ⇒ Be	50	2.70%	1.68E+14	3.37E+12
d ⇒ Be	50	5.90%	3.69E+14	7.38E+12
p ⇒ Li	20	0.33%	2.08E+13	1.04E+12
p ⇒ V	50	5.08%	3.18E+14	6.35E+12
p ⇒ Ta	50	6.40%	4.00E+14	8.01E+12
p ⇒ W	50	6.95%	4.35E+14	8.70E+12

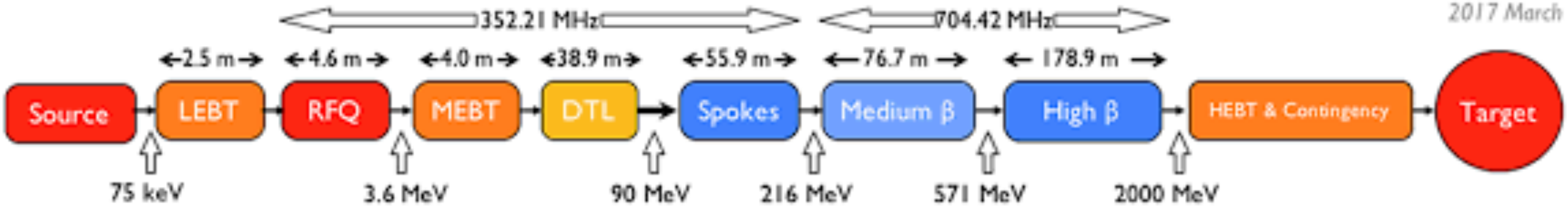
Neutron Production

Target material



- E > 35 MeV: High Z Materials
- Mechanical stability
- Chemically inert
- Manufacturable
- Radiation damage
- Hydrogen inclusions

Accelerator for long pulse spallation source



2017 March

352.21 MHz

704.42 MHz

2.5 m

4.6 m

4.0 m

38.9 m

55.9 m

76.7 m

178.9 m

Source → LEBT → RFQ → MEBT → DTL → Spokes → Medium β → High β → HEBT & Contingency → Target

75 keV

3.6 MeV

90 MeV

216 MeV

571 MeV

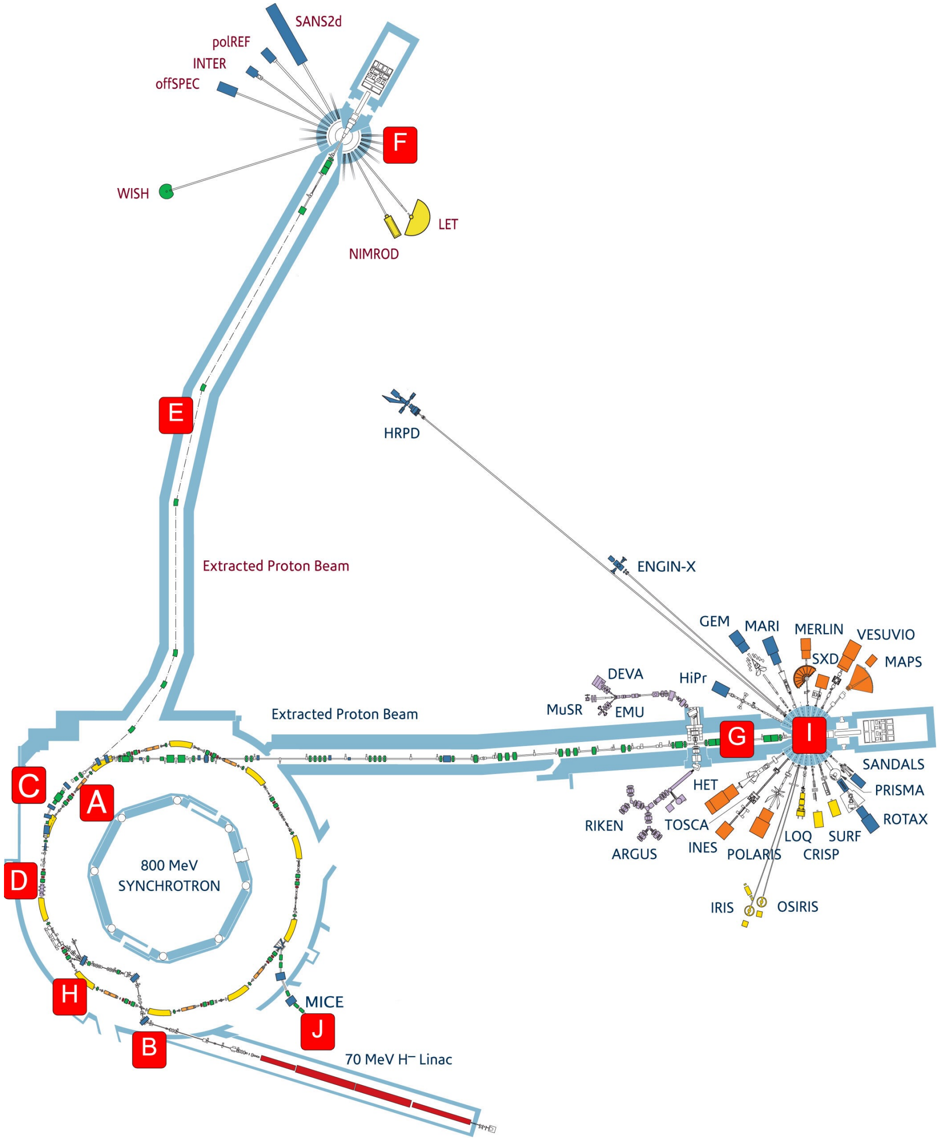
2000 MeV

ESS Design

- Power: 5 (2) MW
- Energy: 2 (0.8) GeV
- Current: 62.5 mA

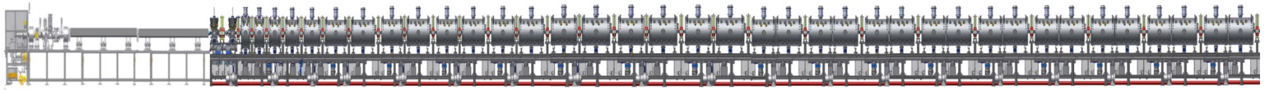
Accelerator for short pulse spallation source

Linac & Synchrotron (Accumulator)
70 MeV & 800 meV
200 µA mean current
40 A peak current

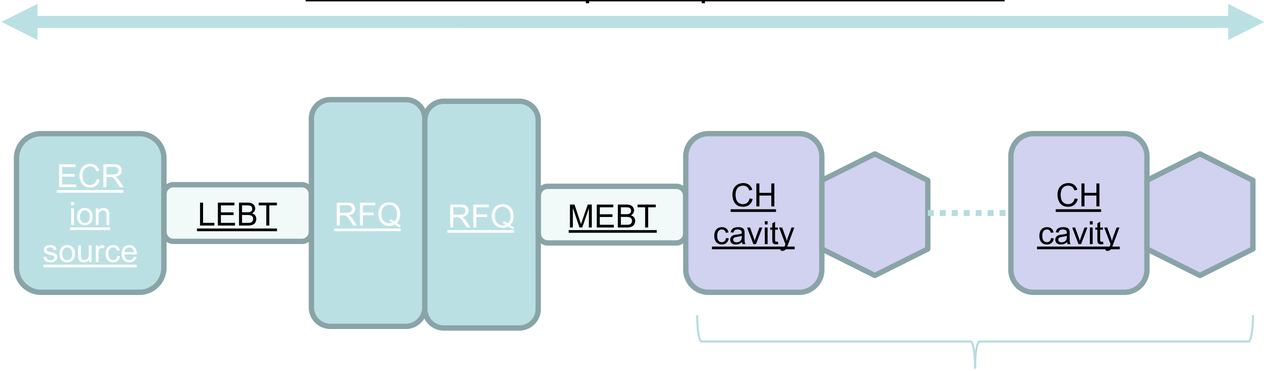


Accelerators for HiCANS

Parameter	Value	Unit
Particles	Protons	
Energy	70	MeV
Current	100	mA
Pulse length	52/208/833	µs
Rep rate	384/96/24	Hz
Duty cycle	6	%
Frequency	176.1	MHz
Beam power	420	kW



100 mA, 70 MeV pulsed proton linac, ~75 m



ECR ion source

LEBT

RFQ

RFQ

MEBT

CH cavity

CH cavity

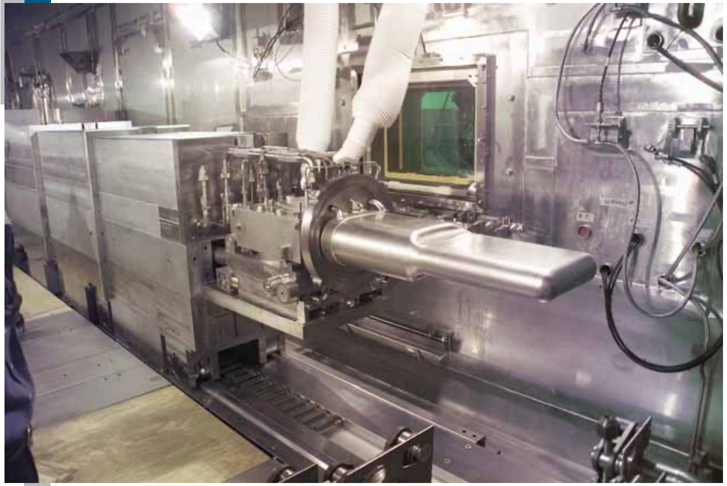
100 mA proton source

175 MHz
(2-4 m, ~5 MeV each)

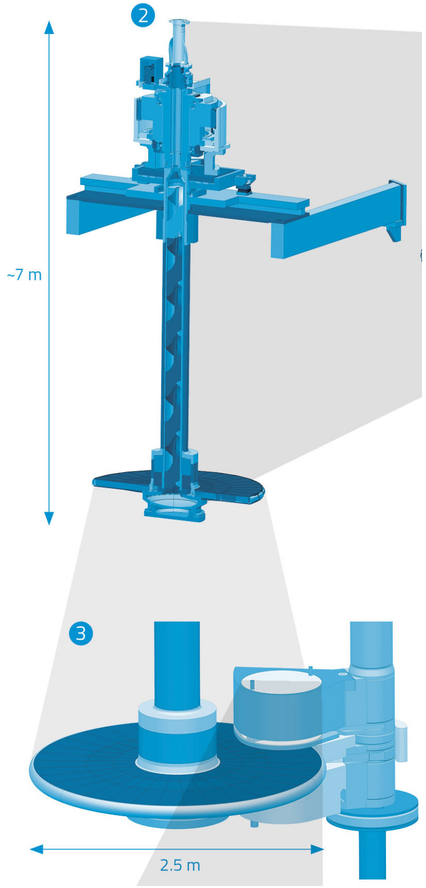
normal conducting CH cavities and quadrupole dublets
(~2.5 m, ~2 MeV each)

Targets for spallation sources

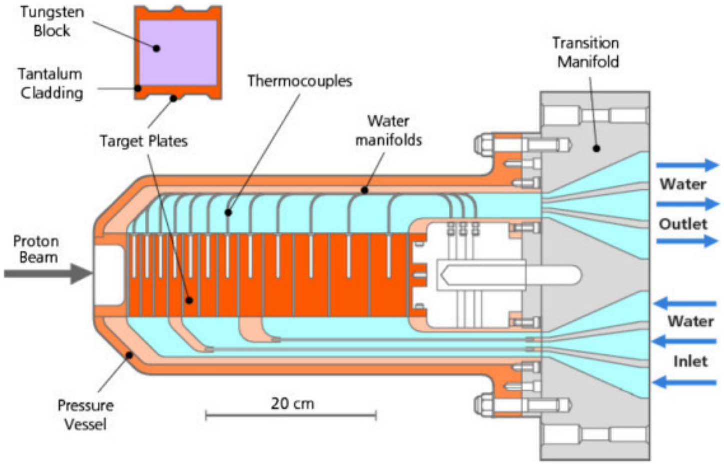
Liquid Hg at SNS



Rotating W-wheel at ESS

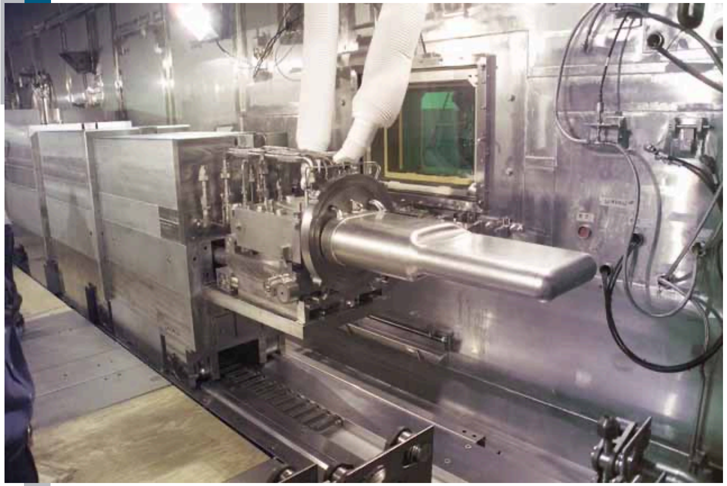


Solid W at ISIS

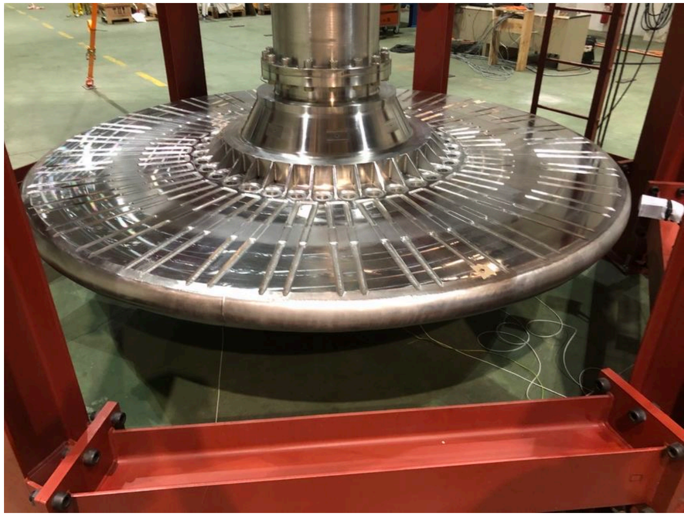


Targets for spallation sources

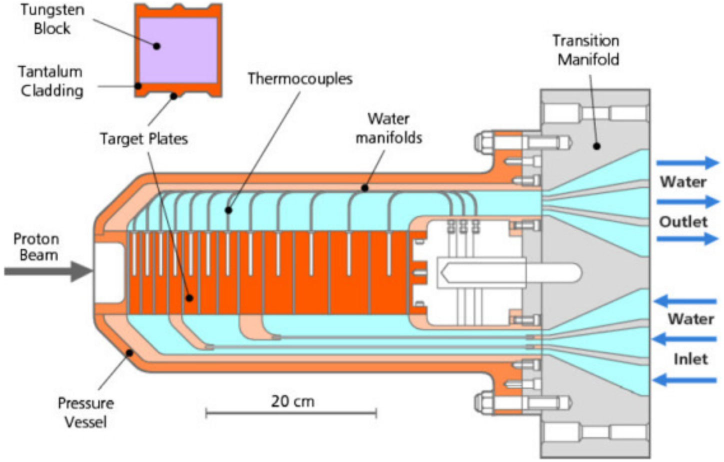
Liquid Hg at SNS



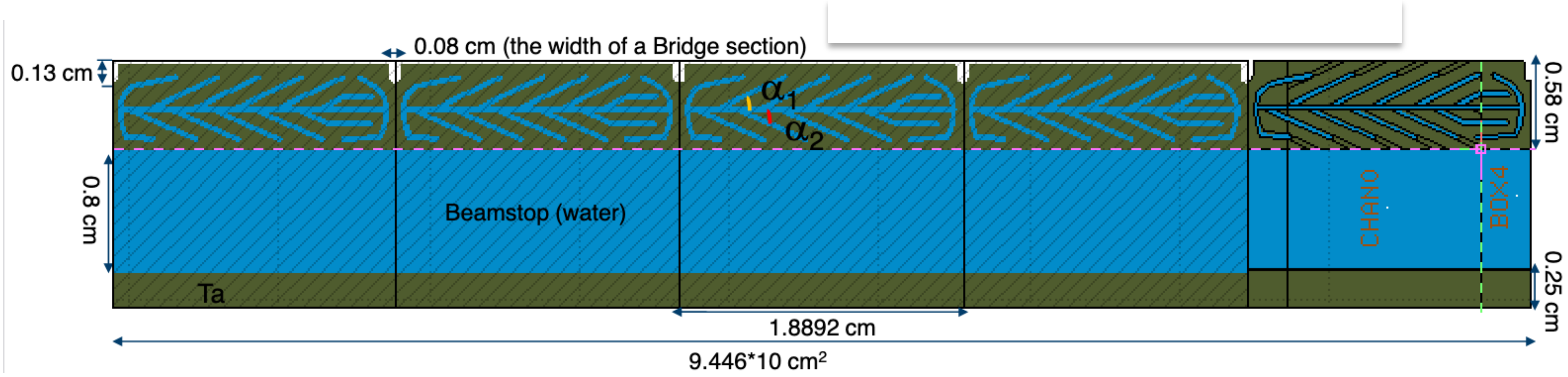
Rotating W-wheel at ESS

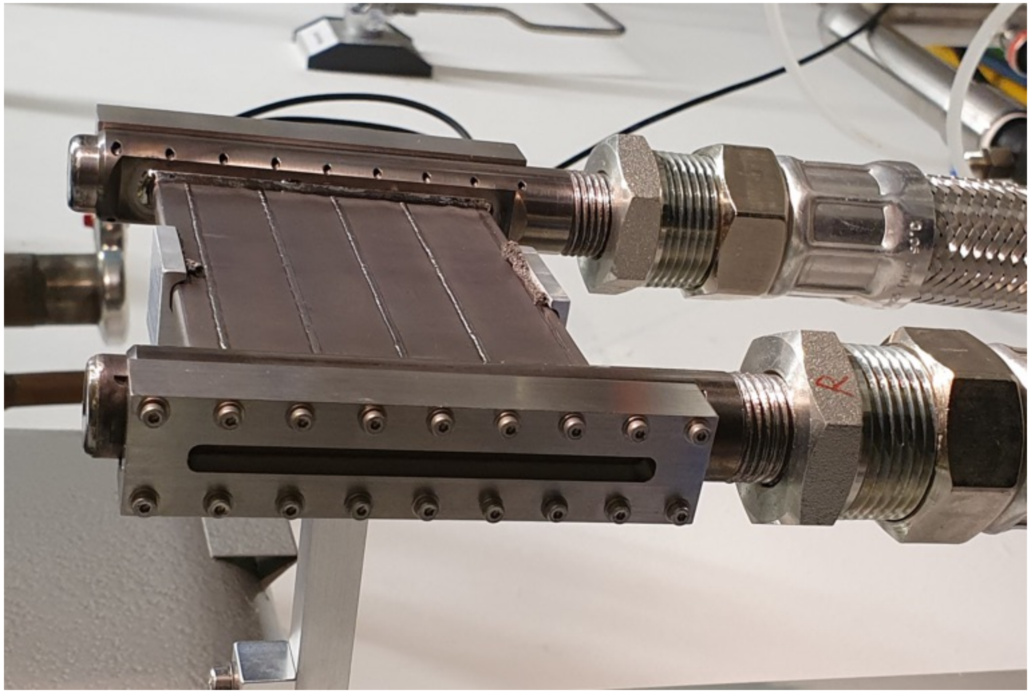


Solid W at ISIS



The HBS Target: Proton beam dumped in water





Release Volume: Neutron density vs. heat removal

Nuclear Process	Example	Neutron Yield	Heat Release [MeV/n]	Target Volume [l]
HBS	70 MeV ^{1}H on Ta	0.14 n/^{1}H	500	0.05
FRM2	Fission of ^{235}U by thermal neutrons	1n/fission	180	17.6
Spallation	800 MeV p on ^{238}U or Pb	27 n/p or 17 n/p	55 or 30	1-2

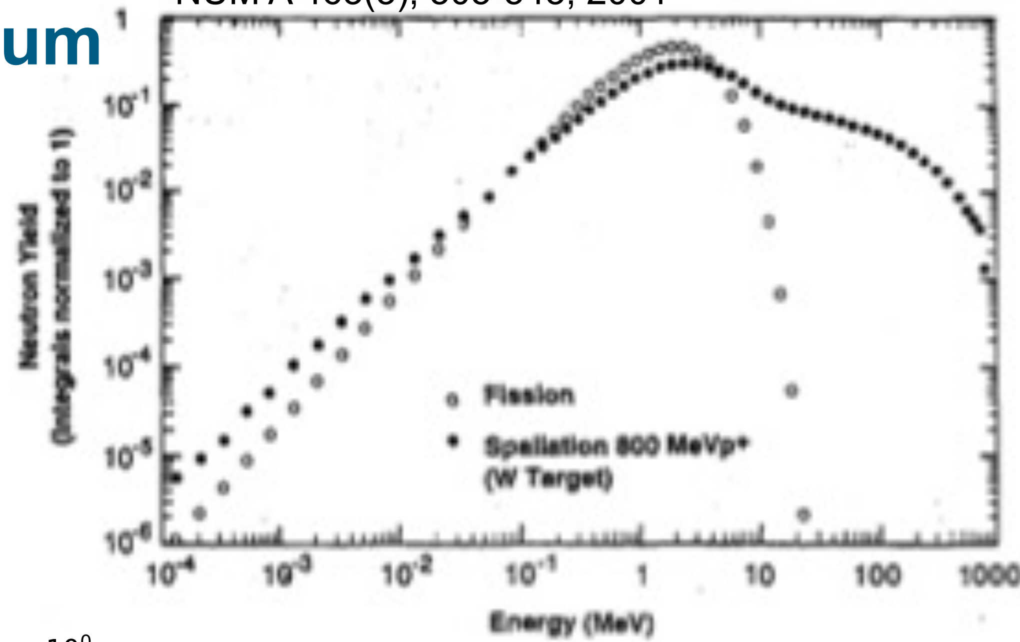
Primary Energy Spectrum

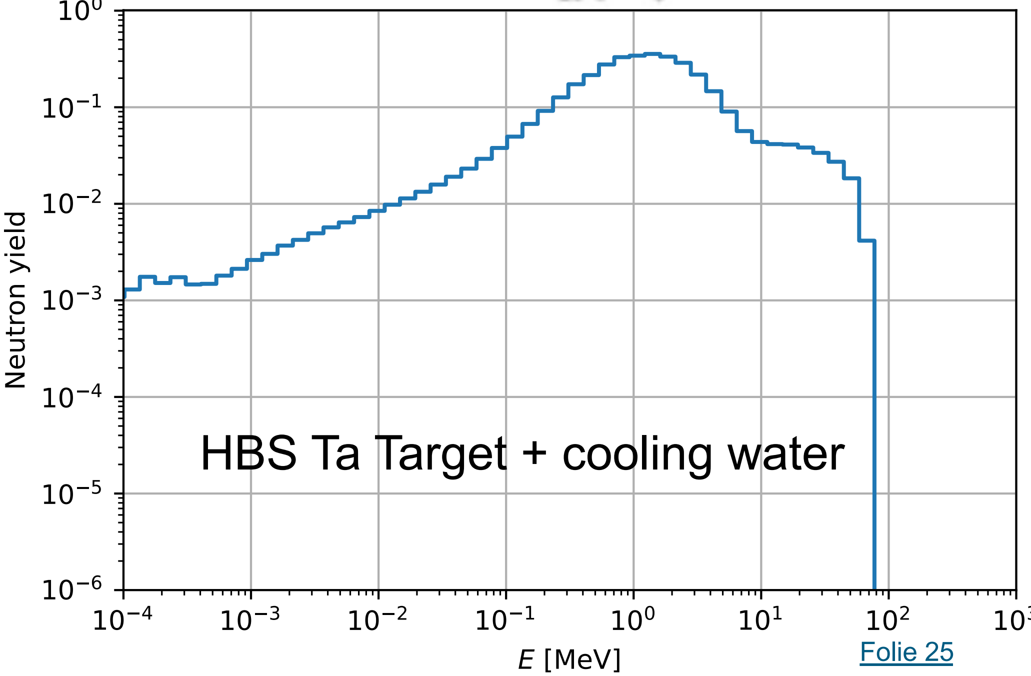
Neutron release from the nucleus
Involves nuclear forces
➔ High neutron energies, fast neutrons

- Massive biological shielding
  ~ 4 m for reactors
  ~ 6 m for spallation sources
  ~ 2 m for HiCANS

- Momentum dimensions of phase space very broad
- Wavelength and energy very different from condensed matter structure and dynamics

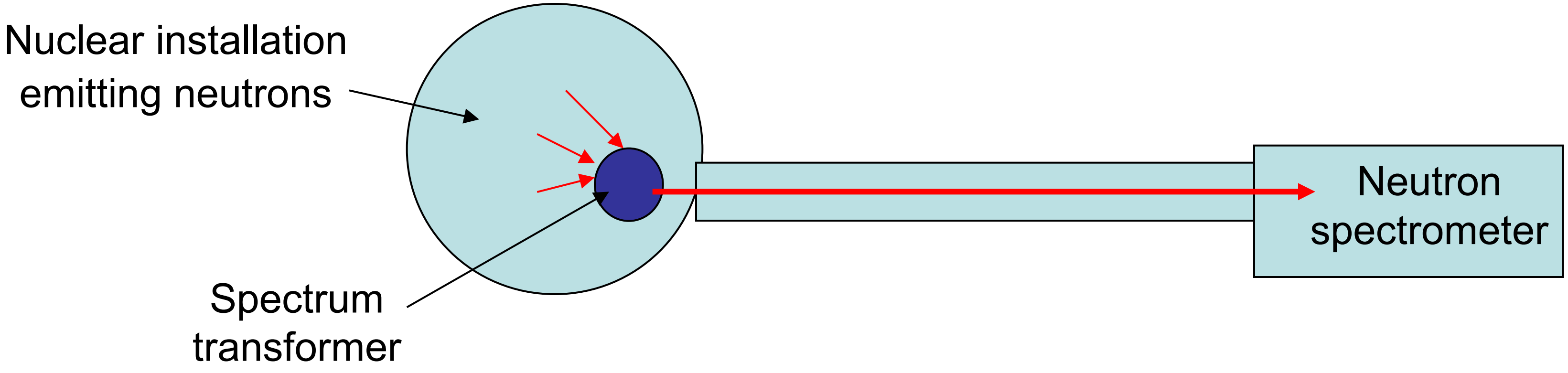
G.S Bauer,
NUM A 463(3), 505-543, 2001





HBS Ta Target + cooling water

Neutron energy classification



Nuclear installation emitting neutrons

Neutron spectrometer

Spectrum transformer

Source spectrum: Fast neutrons

E > 1 MeV

Desired spectrum: Slow neutrons

Ultra cold	E <0.5 μeV	λ > 400 Å
Very cold	E=0.5μeV-0.05 meV	λ = (40-400) Å
Cold	E=(0.05-5) meV	λ = (4-40) Å
Thermal	E=(5-500) meV	λ = (0.4-4) Å
Hot	E>500 meV	λ < 0.4 Å

$$\lambda(\text{Å}) = \frac{h}{mv} = \frac{3956}{v(m/s)} = \sqrt{\frac{81.8}{E(meV)}}$$

How to cool neutrons?

How to slow down neutrons?

⇒ Collisions with atoms (nuclei), until in thermal equilibrium

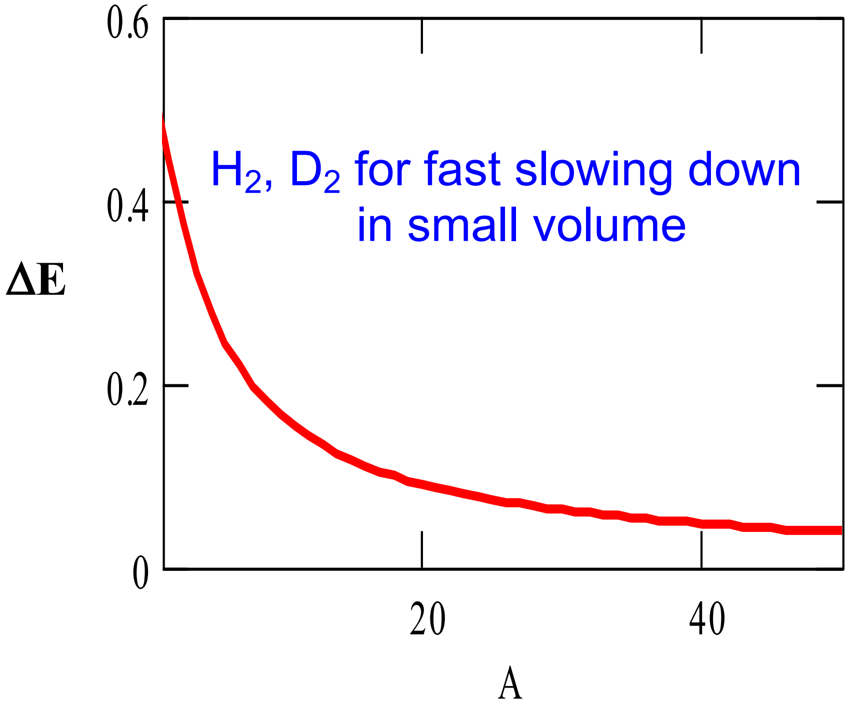
- Energy loss per collision

$$\Delta E = \frac{2A}{(A+1)^2}$$

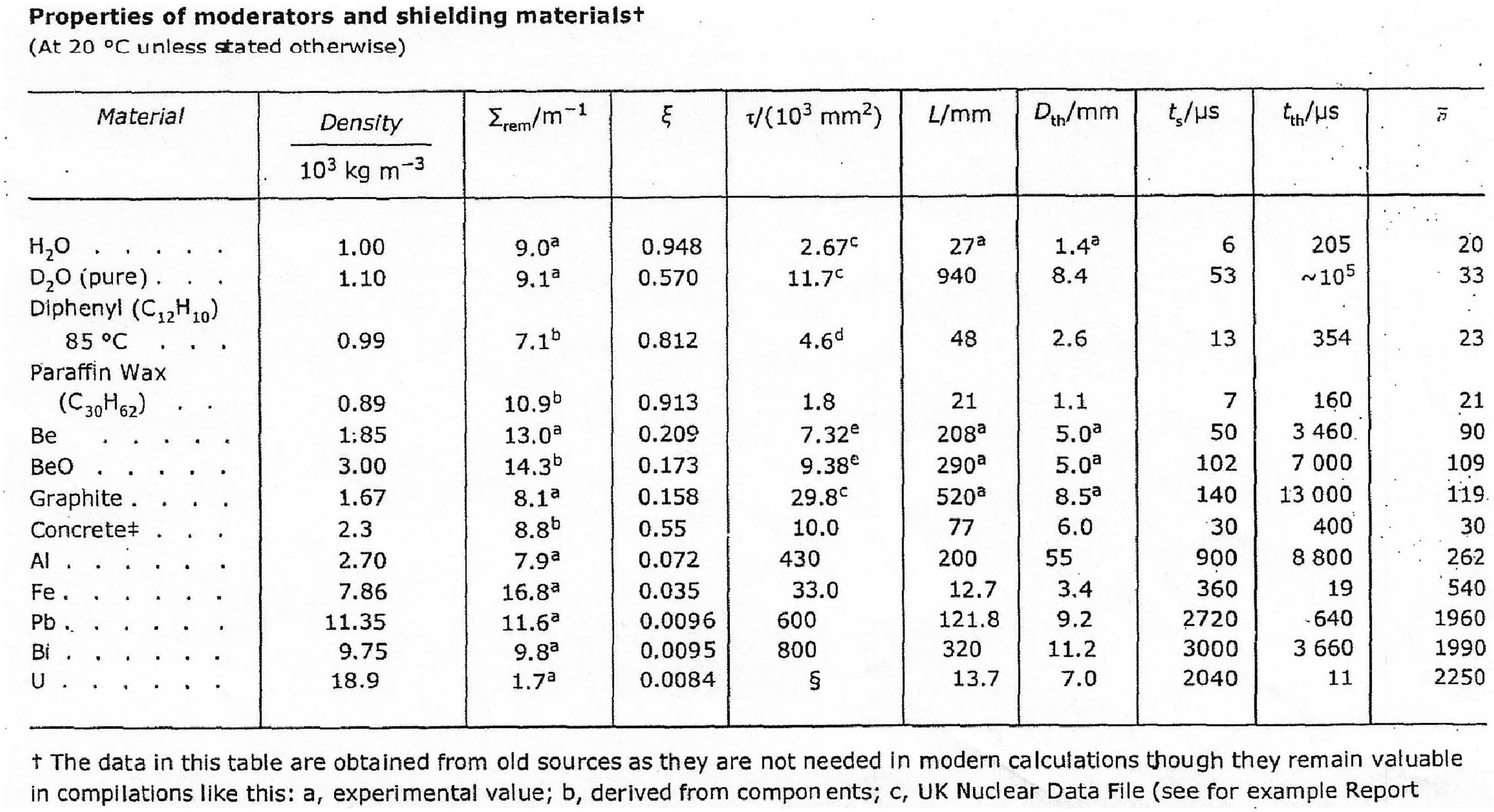
- Light atoms moderate fast
  ~ 20 collisions in 6 µs in ^1H_2O
  ~ 2000 collisions in 3 ms in Pb
- Scattering cross sections
  to be considered

⇒ H best choice for E<10 MeV

⇒ High H particle density:
Water, PE



Materials for moderation and shielding



Properties of moderators and shielding materials†

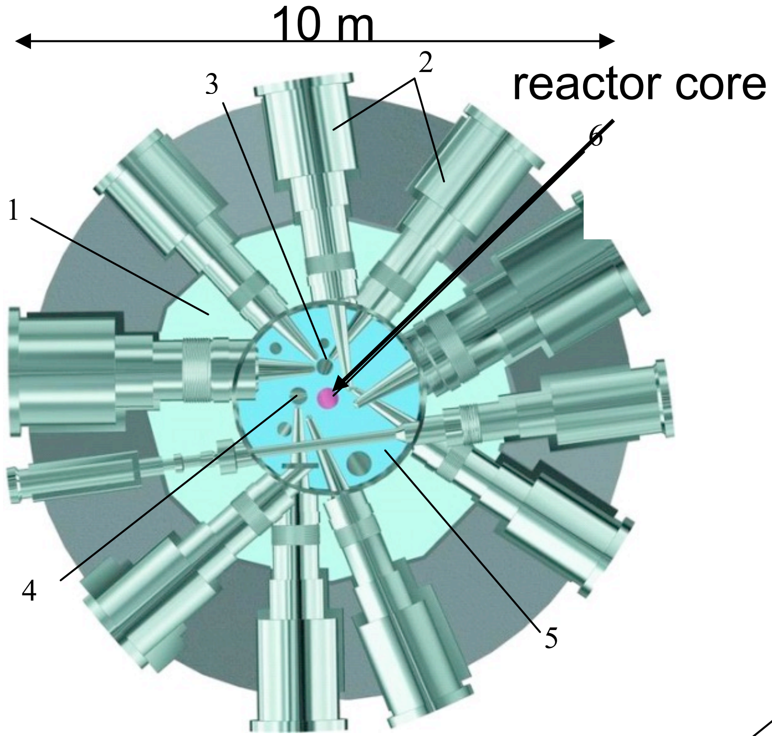
(At 20 °C unless stated otherwise)

Material	Density 10^3 kg m^{-3}	Σ_{rem}/m^{-1}	ξ	$\tau/(10^3\ mm^2)$	L/mm	D_{th}/mm	$t_s/\mu s$	$t_{th}/\mu s$	$\bar{n}$
H_2O	1.00	9.0[a]	0.948	2.67[c]	27[a]	1.4[a]	6	205	20
D_2O (pure)	1.10	9.1[a]	0.570	11.7[c]	940	8.4	53	~10^5	33
Diphenyl ($C_{12}H_{10}$) 85 °C	0.99	7.1[b]	0.812	4.6[d]	48	2.6	13	354	23
Paraffin Wax ($C_{30}H_{62}$)	0.89	10.9[b]	0.913	1.8	21	1.1	7	160	21
Be	1.85	13.0[a]	0.209	7.32[e]	208[a]	5.0[a]	50	3 460	90
BeO	3.00	14.3[b]	0.173	9.38[e]	290[a]	5.0[a]	102	7 000	109
Graphite	1.67	8.1[a]	0.158	29.8[c]	520[a]	8.5[a]	140	13 000	119
Concrete‡	2.3	8.8[b]	0.55	10.0	77	6.0	30	400	30
Al	2.70	7.9[a]	0.072	430	200	55	900	8 800	262
Fe	7.86	16.8[a]	0.035	33.0	12.7	3.4	360	19	540
Pb	11.35	11.6[a]	0.0096	600	121.8	9.2	2720	640	1960
Bi	9.75	9.8[a]	0.0095	800	320	11.2	3000	3 660	1990
U	18.9	1.7[a]	0.0084	§	13.7	7.0	2040	11	2250

† The data in this table are obtained from old sources as they are not needed in modern calculations though they remain valuable in compilations like this: a, experimental value; b, derived from components; c, UK Nuclear Data File (see for example Report

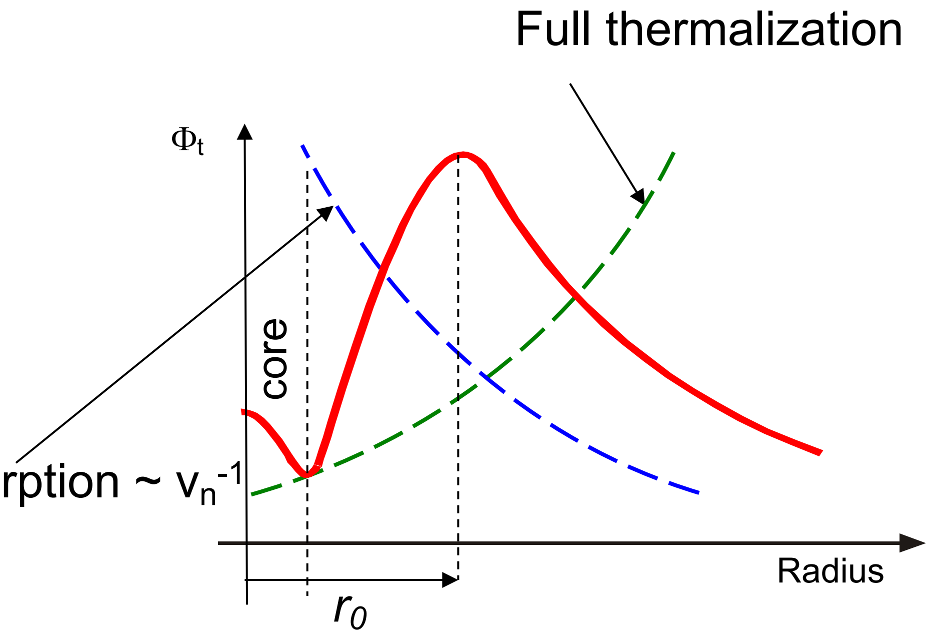
http://www.kayelaby.npl.co.uk/atomic_and_nuclear_physics/4_7/4_7_3.html

Nuclear reactor with compact core

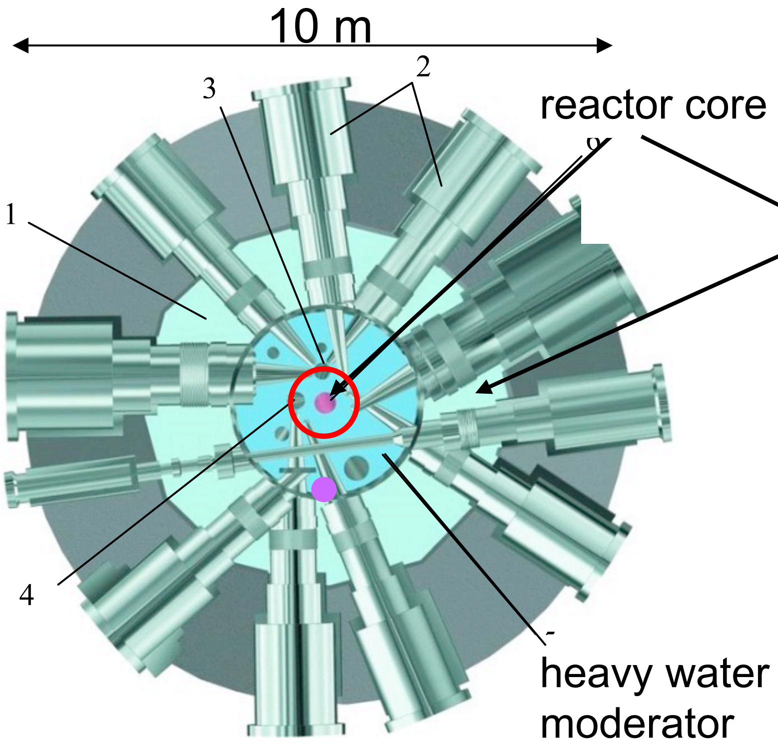


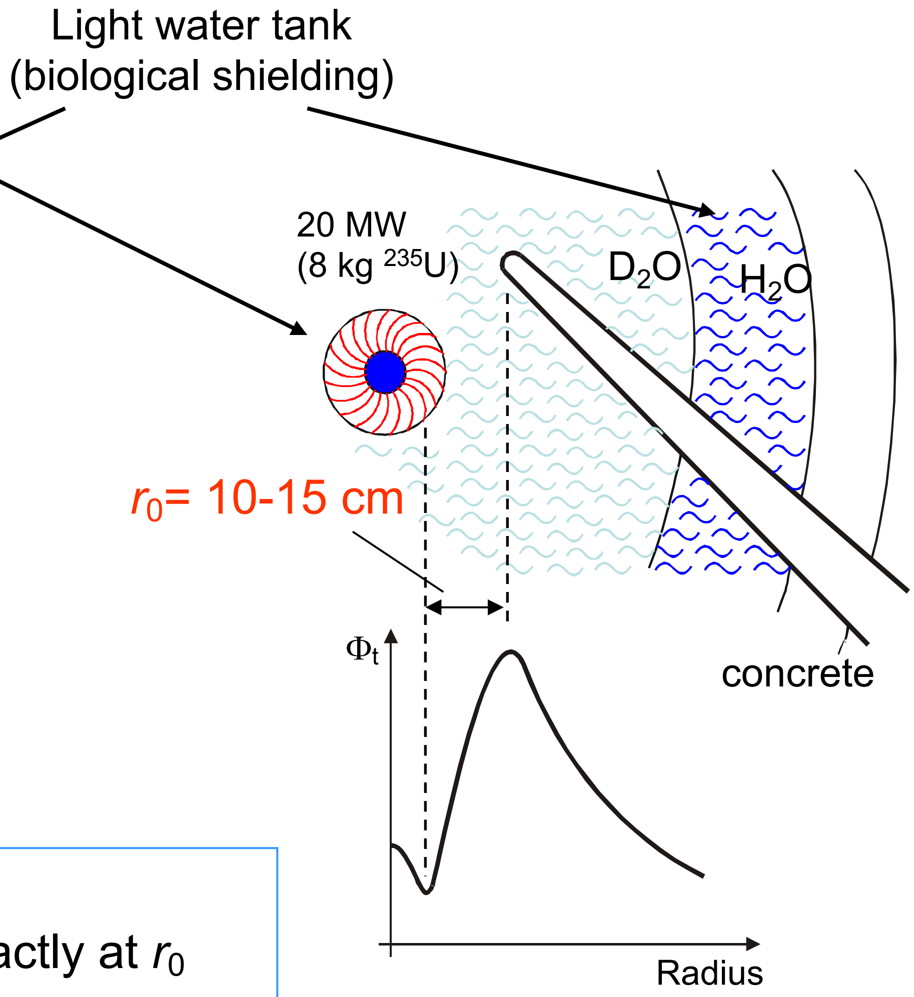
FRM-2 reactor
in Garching, Germany

heavy water moderator of high-energy fission neutrons (T_M =300 K)



Maximum of the thermal neutron flux density is at r = 10-15 cm





Neutron beam tubes

- the entrance should be placed exactly at r_0
- no direct view to the core

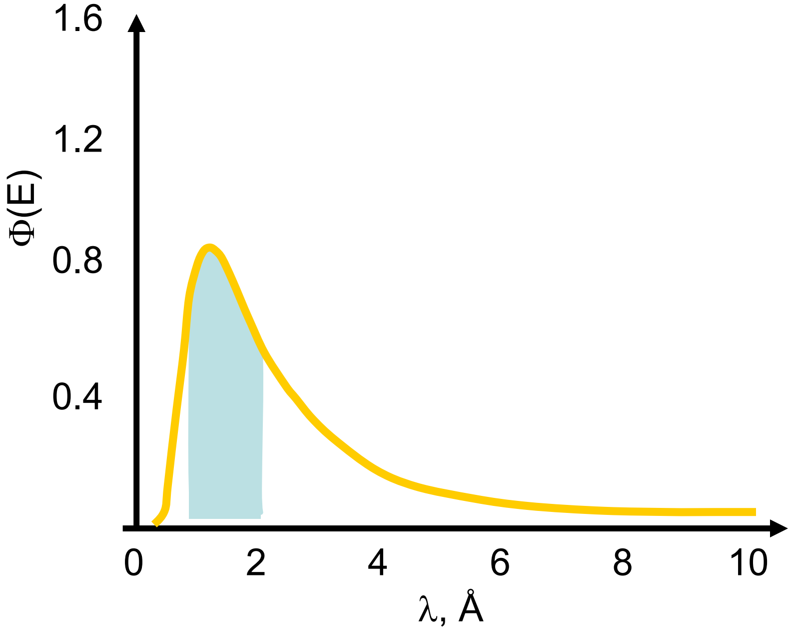
$\Rightarrow$ Tangential beam tubes

Neutrons in a moderator

Maxwell distribution of energy

$$\Phi(E) = \frac{2\sqrt{E}}{\sqrt{\pi k^3 T_M{}^3}} \exp\left\{-\frac{E}{kT_M}\right\}$$

Ultra cold	E <0.5 μeV	λ > 400 Å
Very cold	E=0.5μeV-0.05 meV	λ = (40-400) Å
Cold	E=(0.05-5) meV	λ = (4-40) Å
Thermal	E=(5-500) meV	λ = (0.4-4) Å
Hot	E>500 meV	λ < 0.4 Å



Thermal neutron spectrum (T=300K)

Interatomic distances in solids ~ 5 Å

Lattice energies ~ 10-100 meV

Ultra cold	E <0.5 μeV	λ > 400 Å
Very cold	E=0.5μeV-0.05 meV	λ = (40-400) Å
Cold	E=(0.05-5) meV	λ = (4-40) Å
Thermal	E=(5-500) meV	λ = (0.4-4) Å
Hot	E>500 meV	λ < 0.4 Å

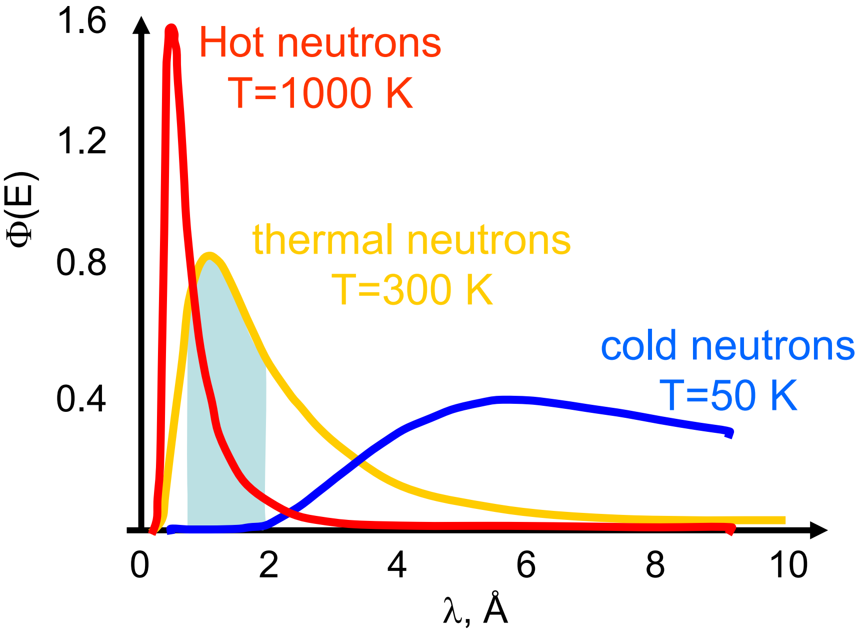
Maxwellian distribution

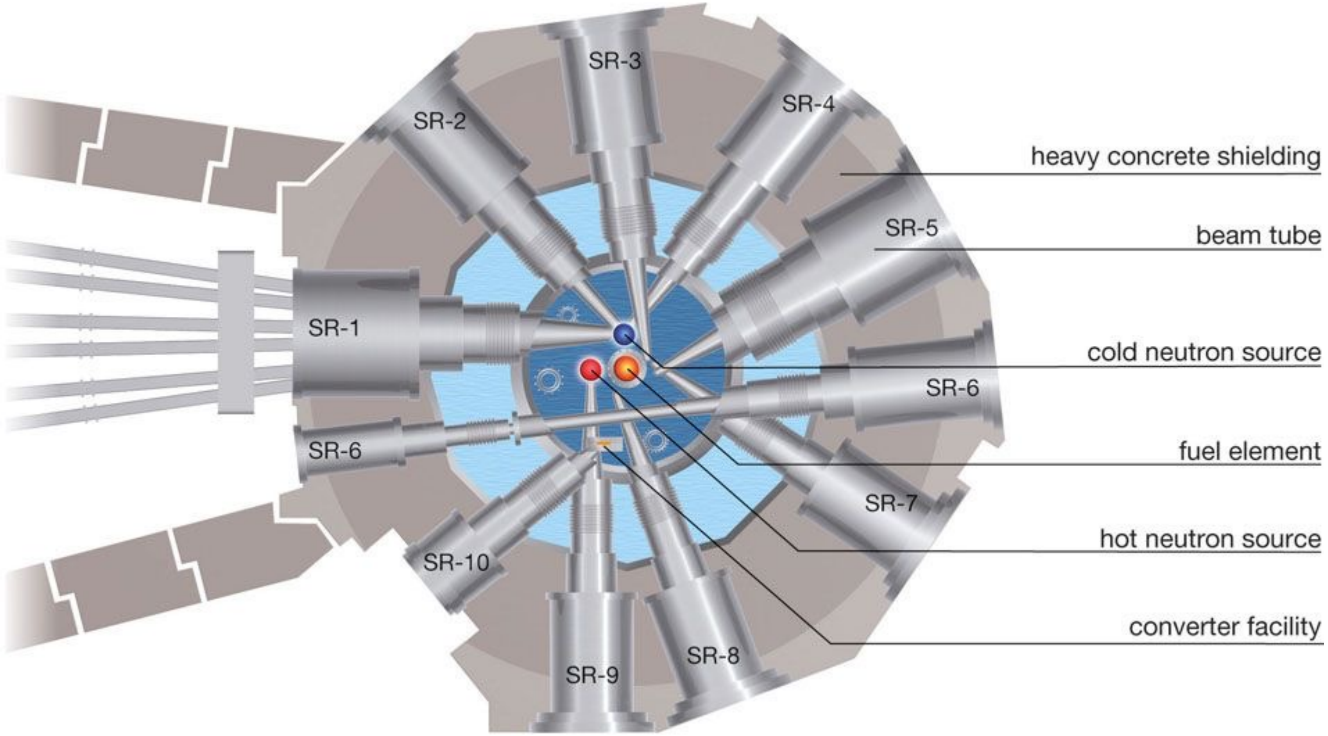
$$\Phi(E) = \frac{2\sqrt{E}}{\sqrt{\pi k^3 T_M^{\ 3}}} \exp\left\{-\frac{E}{kT_M}\right\}$$

Cold neutrons: Larger distance or lower energies

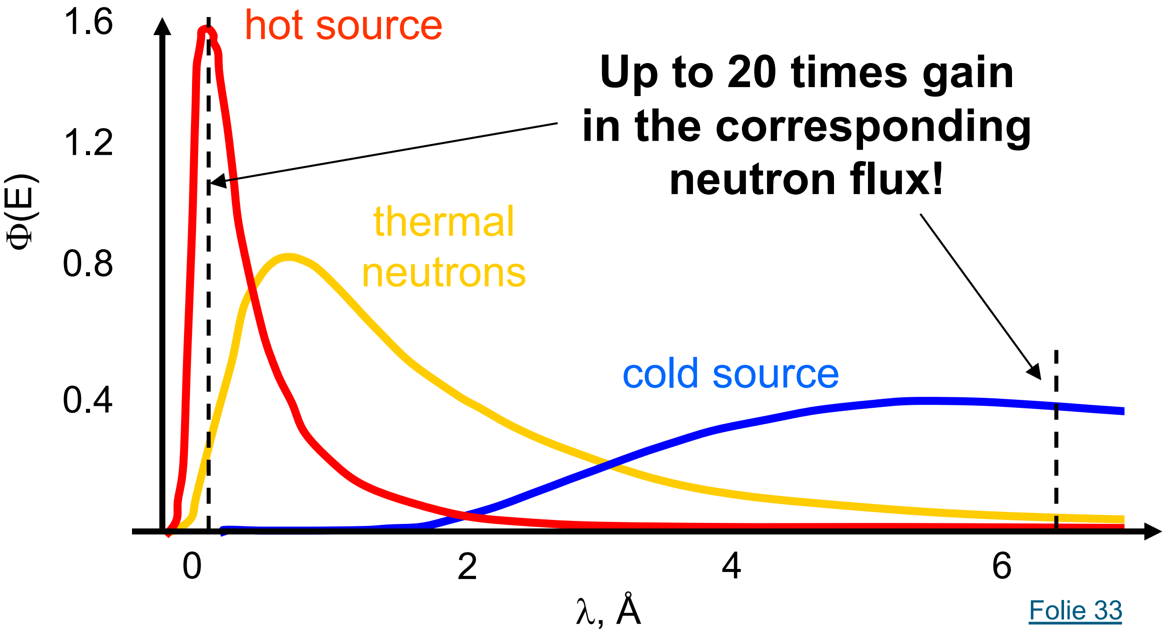
Hot neutrons: Small lattice spacing or higher energies

⇒ heating or cooling of the moderator





- The hot source:
  Graphite block, T = 2400 K
- The cold sources:
  Liquid H_2 or D_2, T = 20 K.



Up to 20 times gain in the corresponding neutron flux!

Cryogenic moderator materials

High proton density + low energy excited states

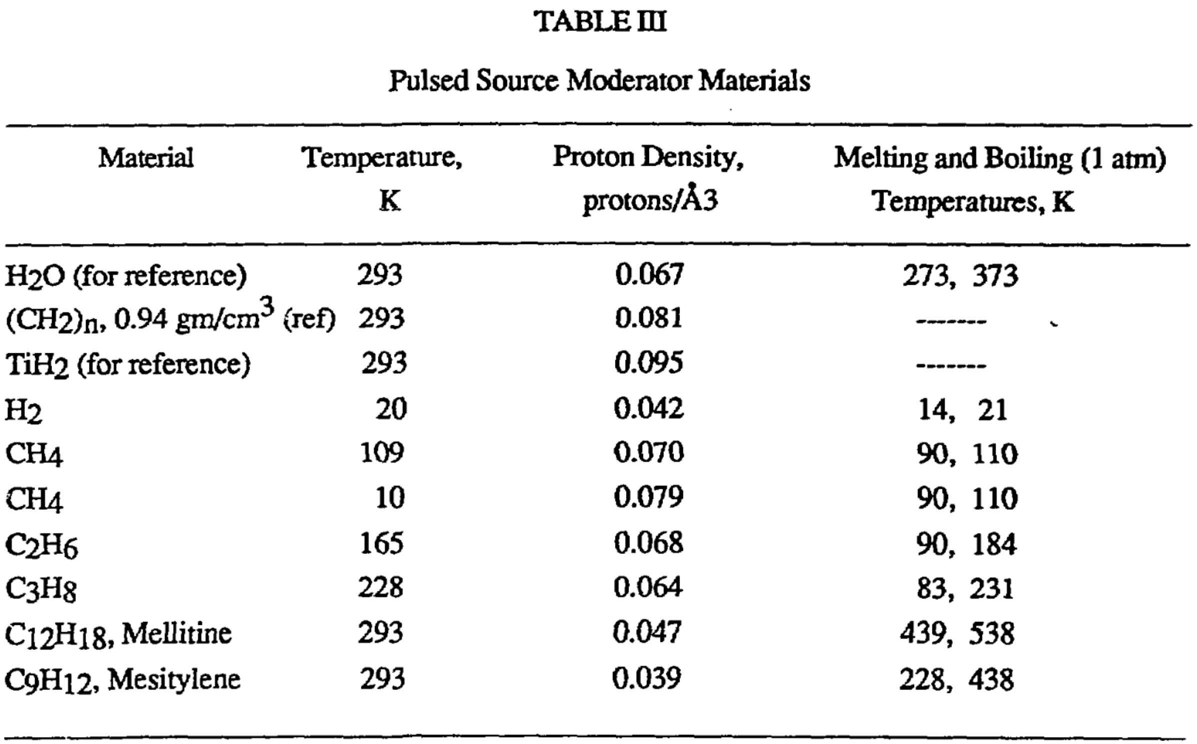


TABLE III

Pulsed Source Moderator Materials

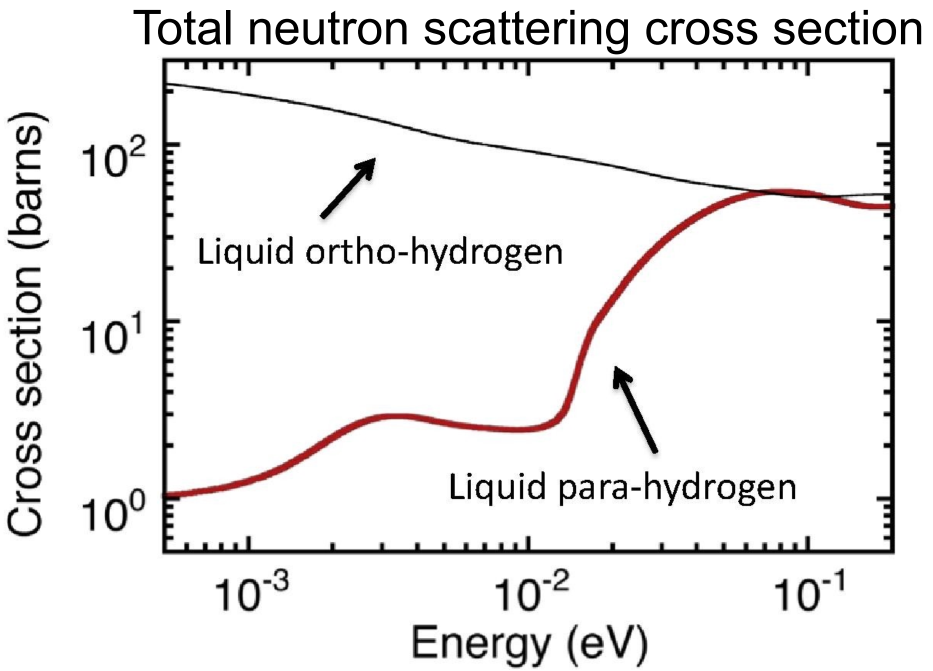
Material	Temperature, K	Proton Density, protons/Å3	Melting and Boiling (1 atm) Temperatures, K
H_2O (for reference)	293	0.067	273, 373
$(CH_2)_n$, 0.94 gm/cm^3 (ref)	293	0.081	-------
TiH_2 (for reference)	293	0.095	-------
H_2	20	0.042	14, 21
CH_4	109	0.070	90, 110
CH_4	10	0.079	90, 110
C_2H_6	165	0.068	90, 184
C_3H_8	228	0.064	83, 231
$C_{12}H_{18}$, Mellitine	293	0.047	439, 538
C_9H_{12}, Mesitylene	293	0.039	228, 438

Issue: Radiation damage in solid materials

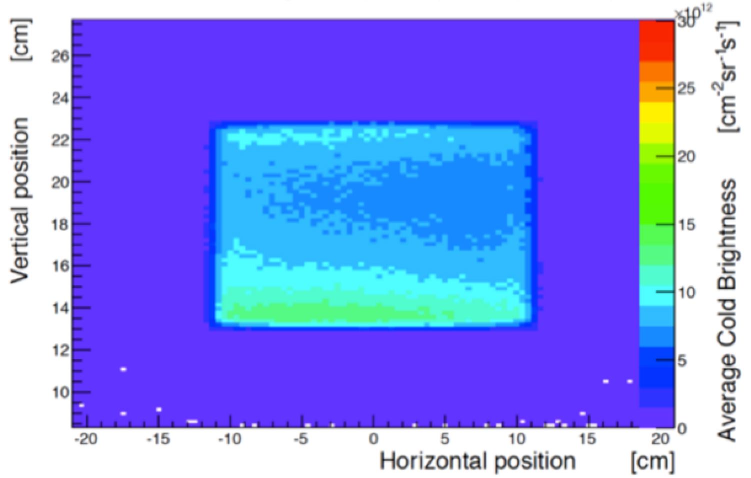
➔ Solid cryogenic moderators at medium intensity sources, e.g. ISIS, HiCANS

Cryogenic moderators

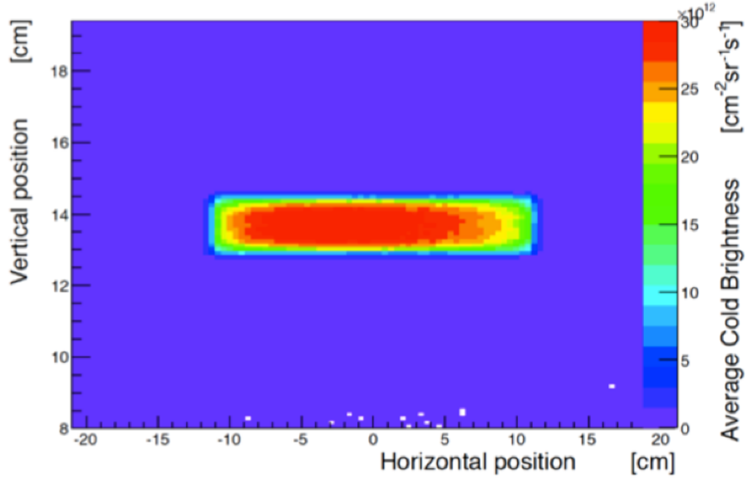
- Liquid Hydrogen
  ~ 20 K
  Para-hydrogen:
  Increased extraction volume
  Low dimensional moderator
  not fully moderated ➔'warmer' spectrum



Volume moderator

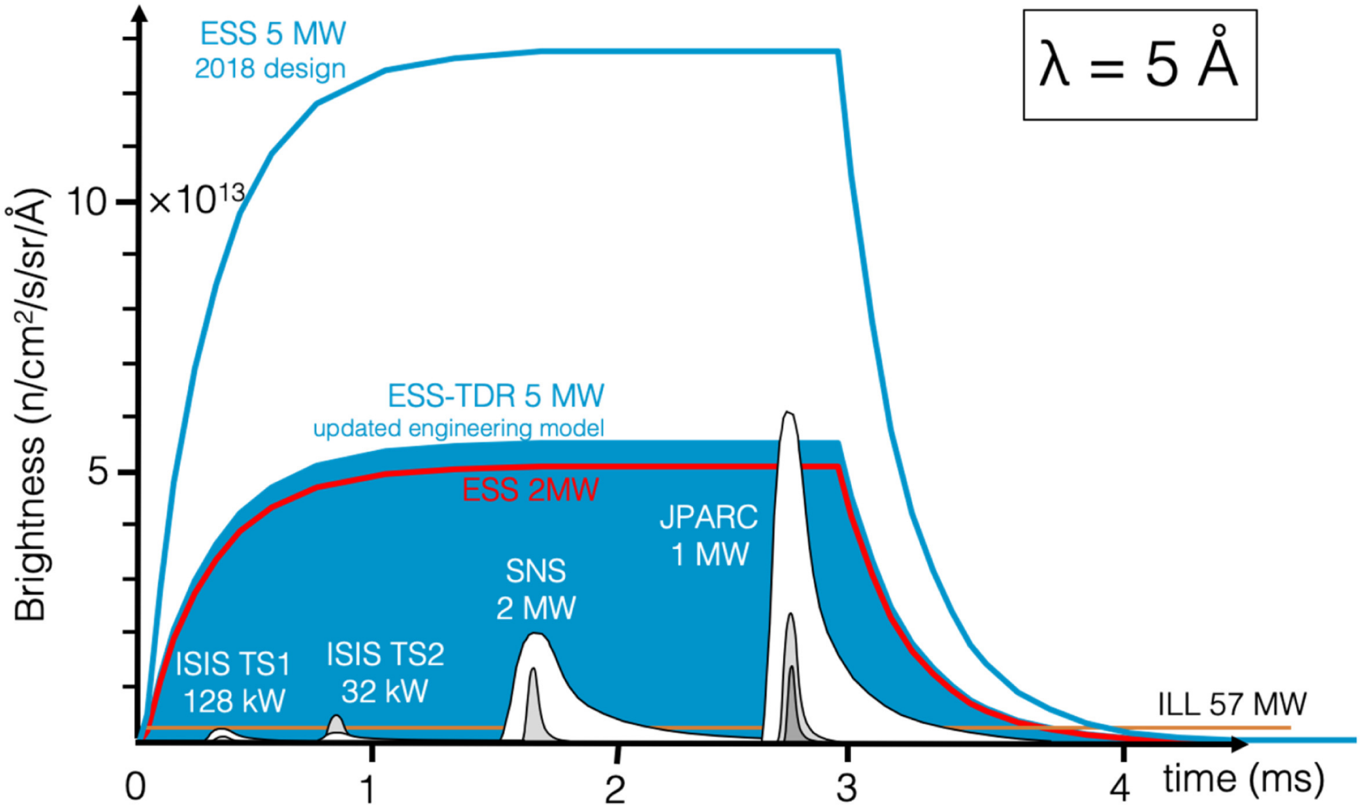


Flat moderator



Moderation at pulsed sources

- Pulse length is used for wavelength/energy definition
  - Should match resolution requirements
  - Must be treated in data analysis ➔ “nice” shape
  - Time-of-Fligth (ToF): $t = 0.25278 \frac{\mathrm{ms}}{\mathrm{m\AA}} \lambda L$



https://europeanspallationsource.se/ess-mandate

Moderater & Reflector

- < 10 µs to moderate to thermal
- < 50 µs to moderate to cold
- Then: Dilution of neutron cloud by diffusion
- Reflector
  - Feed neutrons back into moderator
  - Don’t absorb neutrons
  - Slow diffusion to keep cloud contained

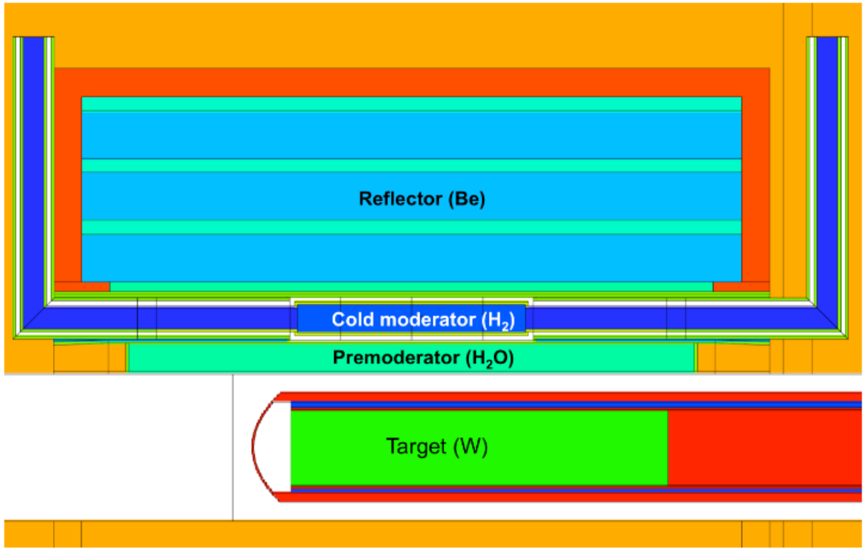
Long Pulse (ESS)

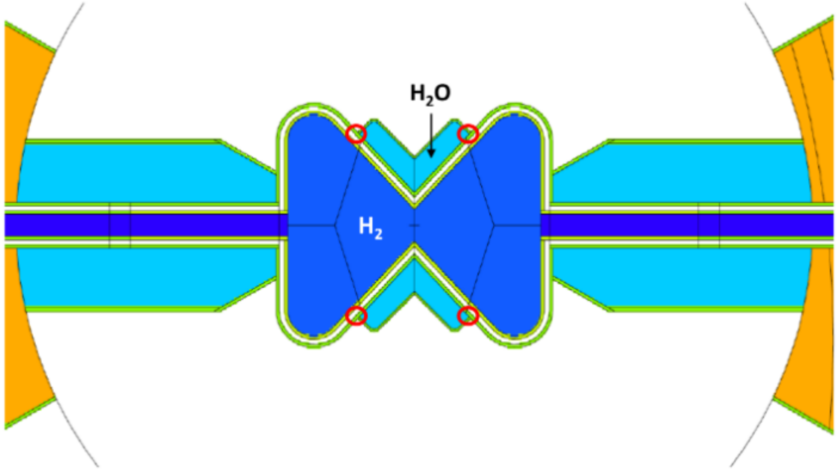
- Low resolution without pulse shaping
- “Normal” resolution: Mechanical neutron choppers

➔ Requirements to moderator:

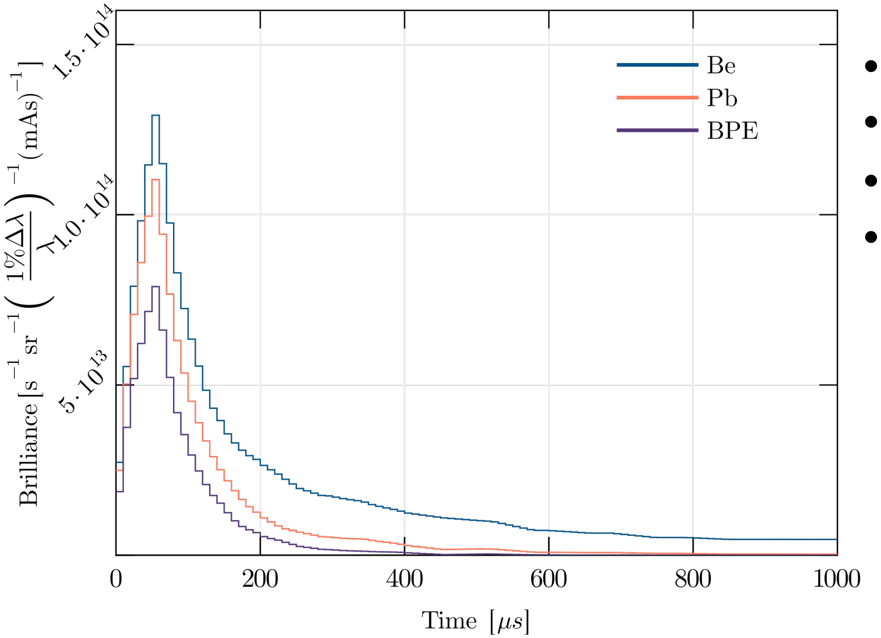
- Low Absorption to keep neutron number high
- Neutron lifetime in reflector ≈ pulse length
  → Be reflector

ESS Target-Moderator-Reflector Assembly,
L Zanini *et al.*, Jour. Phys.: Conf. Ser. 1021 (2018) 012066

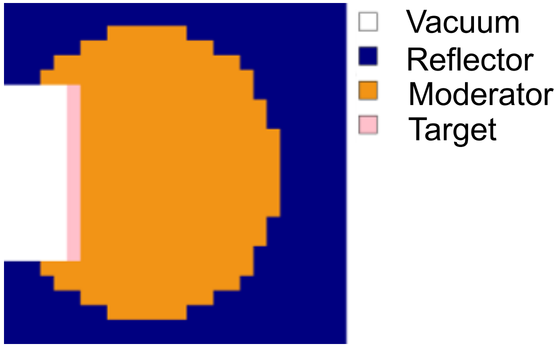


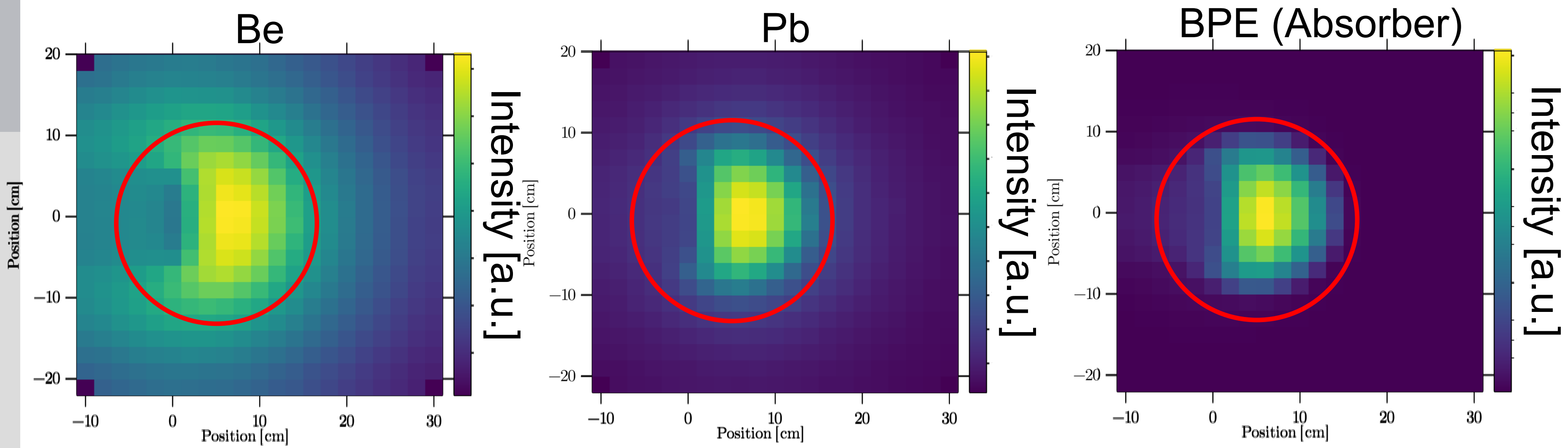


Intermediate Pulse (HiCANS)



- Target embedded
- Slow neutron diffusion
- Pulse length ≈ lifetime in moderator
- Reflector for unmoderated neutrons





Be

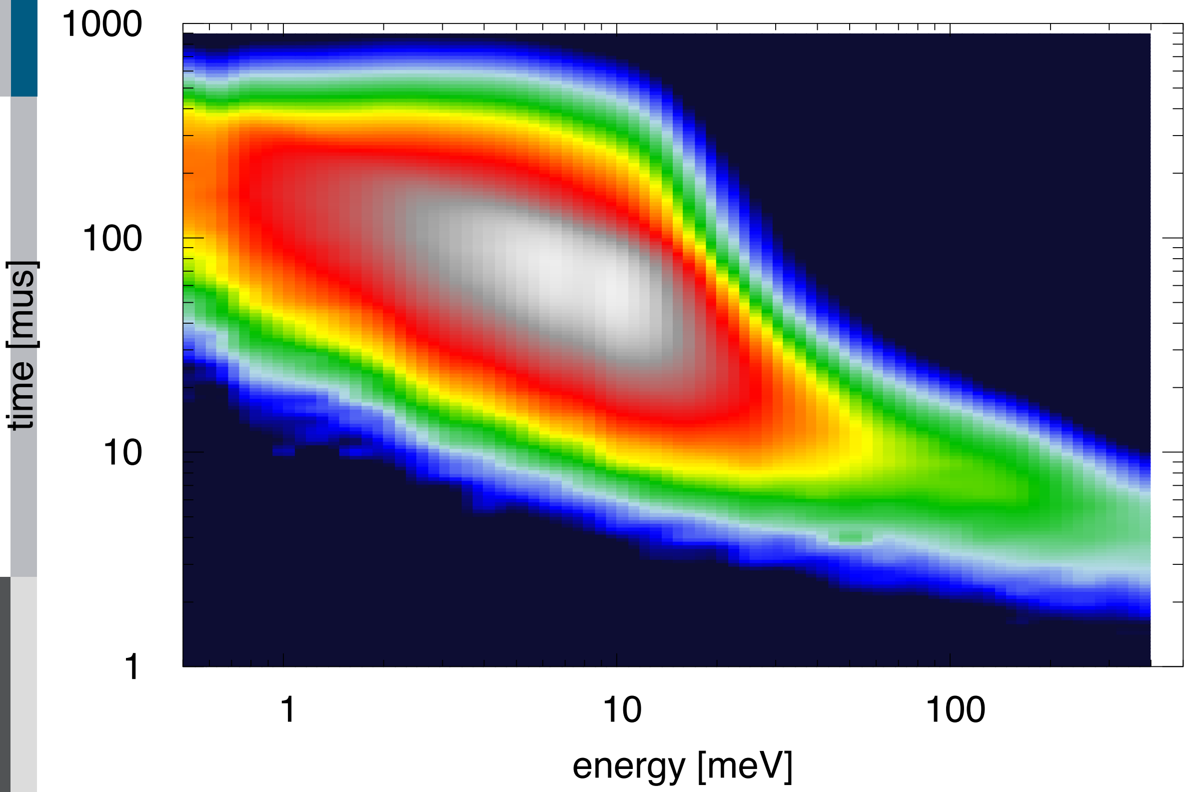
Pb

BPE (Absorber)

1 meV – 120 meV

Short Pulse

Time/Energy emission map of the cold H_2 J-Parc moderator



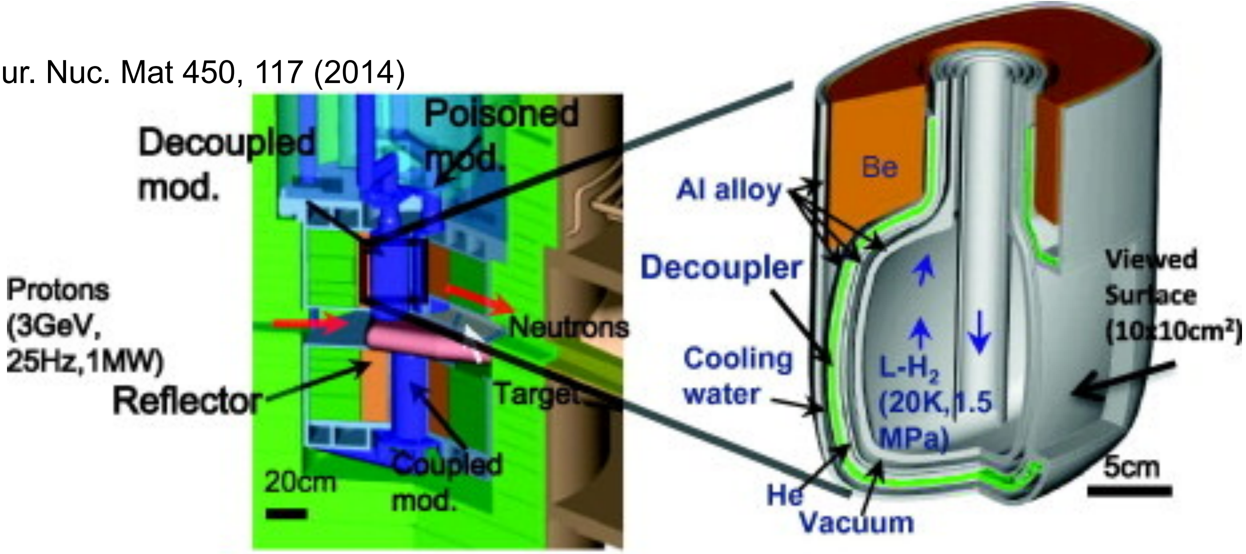
- Transient (epi-)thermal pulse
- Equilibrated neutrons stay in reflector and return to moderator
- Increasing pulse width of equilibrated neutrons

  →escape depth from the moderator

Short pulse: How to get even shorter pulses?

Decoupling: Prevent return of thermal neutrons from reflector to moderator

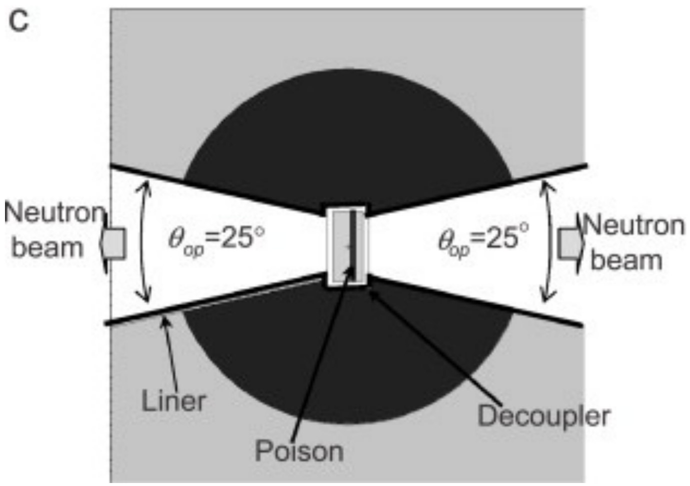
M. Ooi *et al.*, Jour. Nuc. Mat 450, 117 (2014)

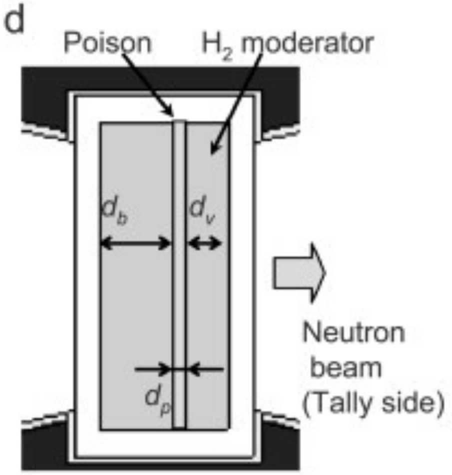


Cross sectional view of Target-moderator-reflector

Cut view of decoupled moderator

Poisoning: Reduce the extraction volume, e.g. by Gd layer

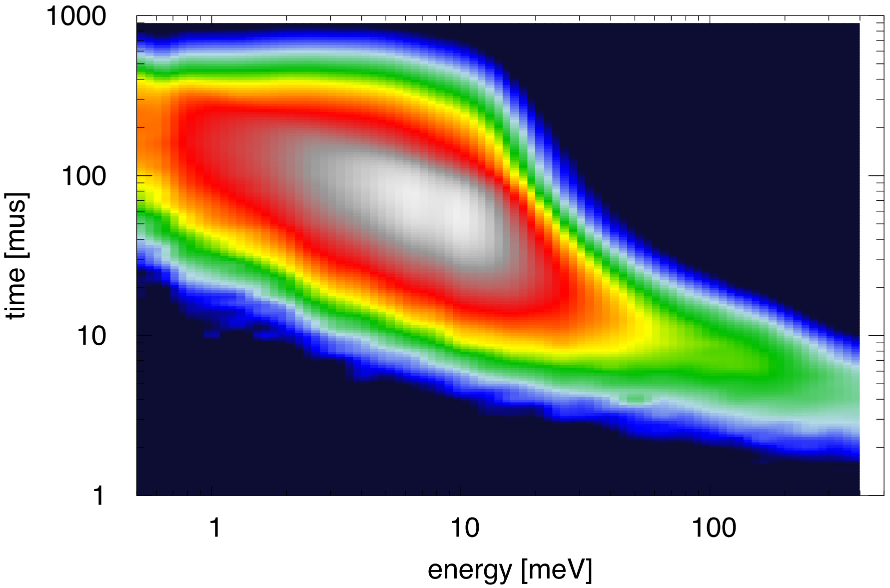


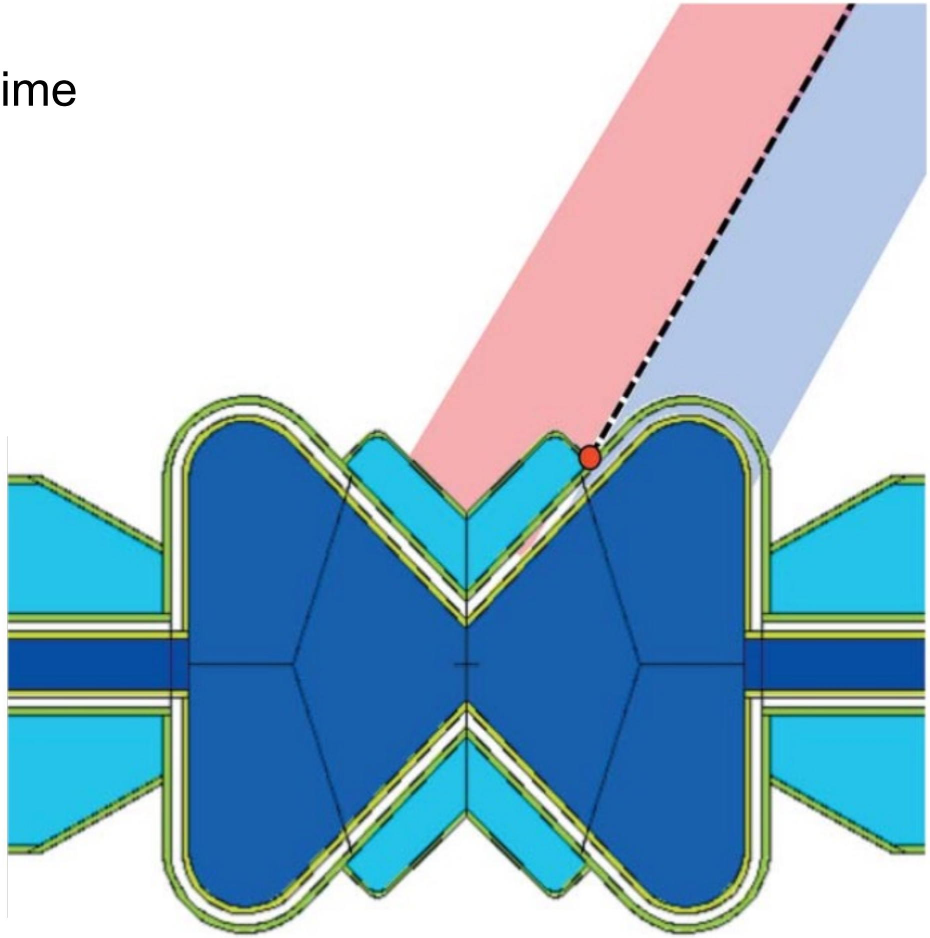


M. Harada *et al.*, NUM A 574, 407 (2007)

Bi-spectral extraction: Increase spectral range for multi scale investigations

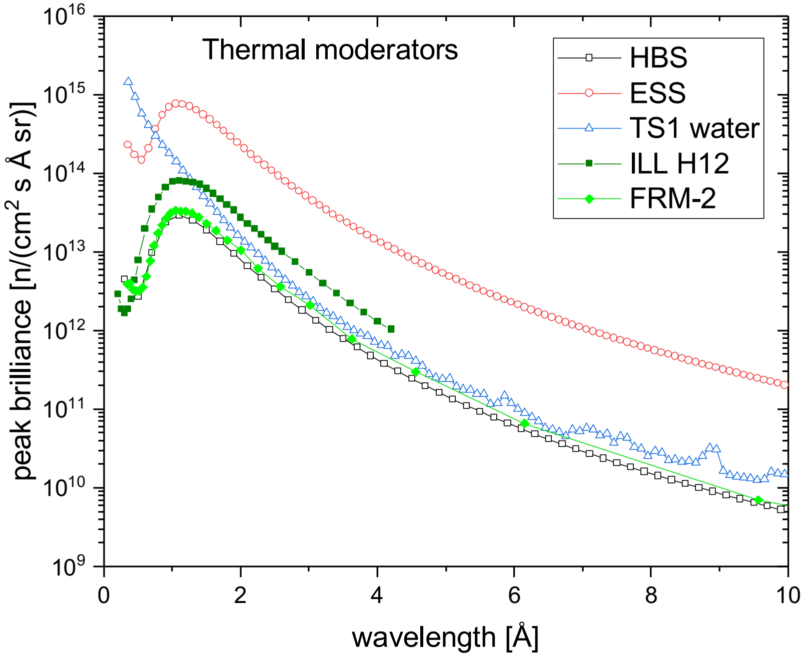
- Increase of spectral range
- At short pulse source separated in time
- At long pulse and steady sources
    - View cold & thermal faces
    - Additional optics to bring beams on one axis

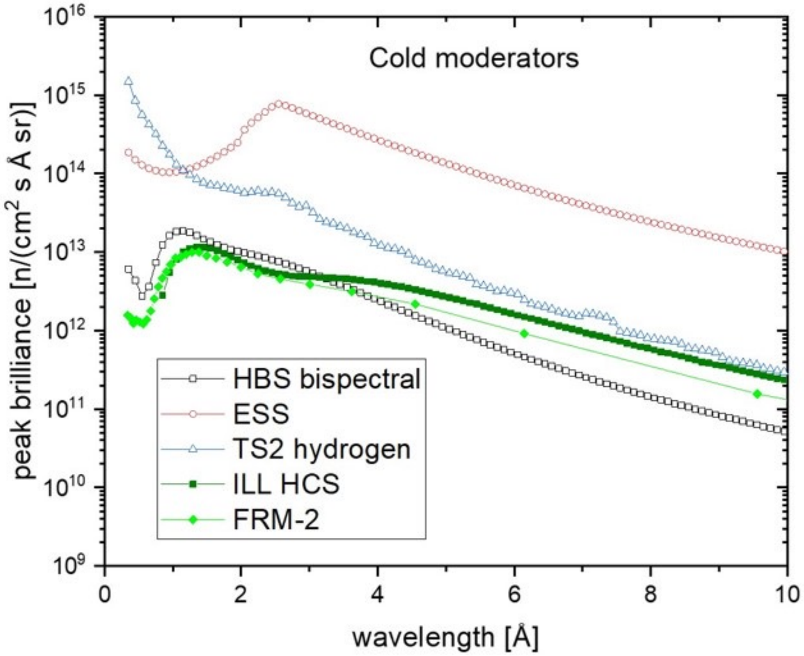




K.H. Andersen *et al.*, Jour. Appl. Crys. 51, 264 (2018)

Comparison of moderator brightness





Take home messages

- ✓ Free neutrons are products of nuclear reactions
- ✓ Small production volume: Brightness vs. cooling
- ✓ High continuous flux from reactor
- ✓ High peak flux from spallation sources
- ✓ HiCANS as prospect to provide sufficient neutrons in future

- ✓ Moderators confine neutrons in space and energy to maximize phase space density aka brightness
- ✓ Adapted spectra & pulse properties

- ✓ Integrated approaches from source to detector to improve instruments & progress neutron science