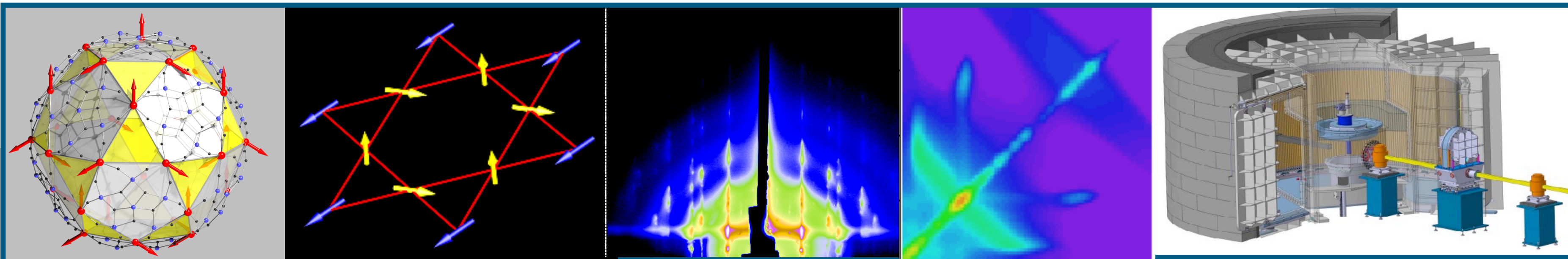
JÜLICH FORSCHUNGSZENTRUM



Neutron sources for Science

Jörg Voigt

Jülich Centre for Neutron Science JCNS

14. September 2017

Contents:

1. Why do we want free neutrons?
2. What neutrons do we want?
3. How do we get free neutrons?
4. How do we tailor their properties?

Neutrons:
A Special Gift for Science

„Neutrons tell us where the atoms are and how they move.“

Clifford Shull
Nobel Prize Physics

- holds also for atomic magnetic moments -

Neutrons:
A Special Gift for Science

Ultra cold	E <0.5 μeV	λ > 400 Å
Very cold	E=0.5μeV-0.05 meV	λ = (40-400) Å
Cold	E=(0.05-10) meV	λ = (3-40) Å
Thermal	E=(10-100) meV	λ = (0.9-3) Å
Hot	E=100 meV -1eV	λ = (0.3-0.9) Å

Clifford Shull
Nobel Prize Physics

Length- and Time Scales Covered by Research with Neutrons

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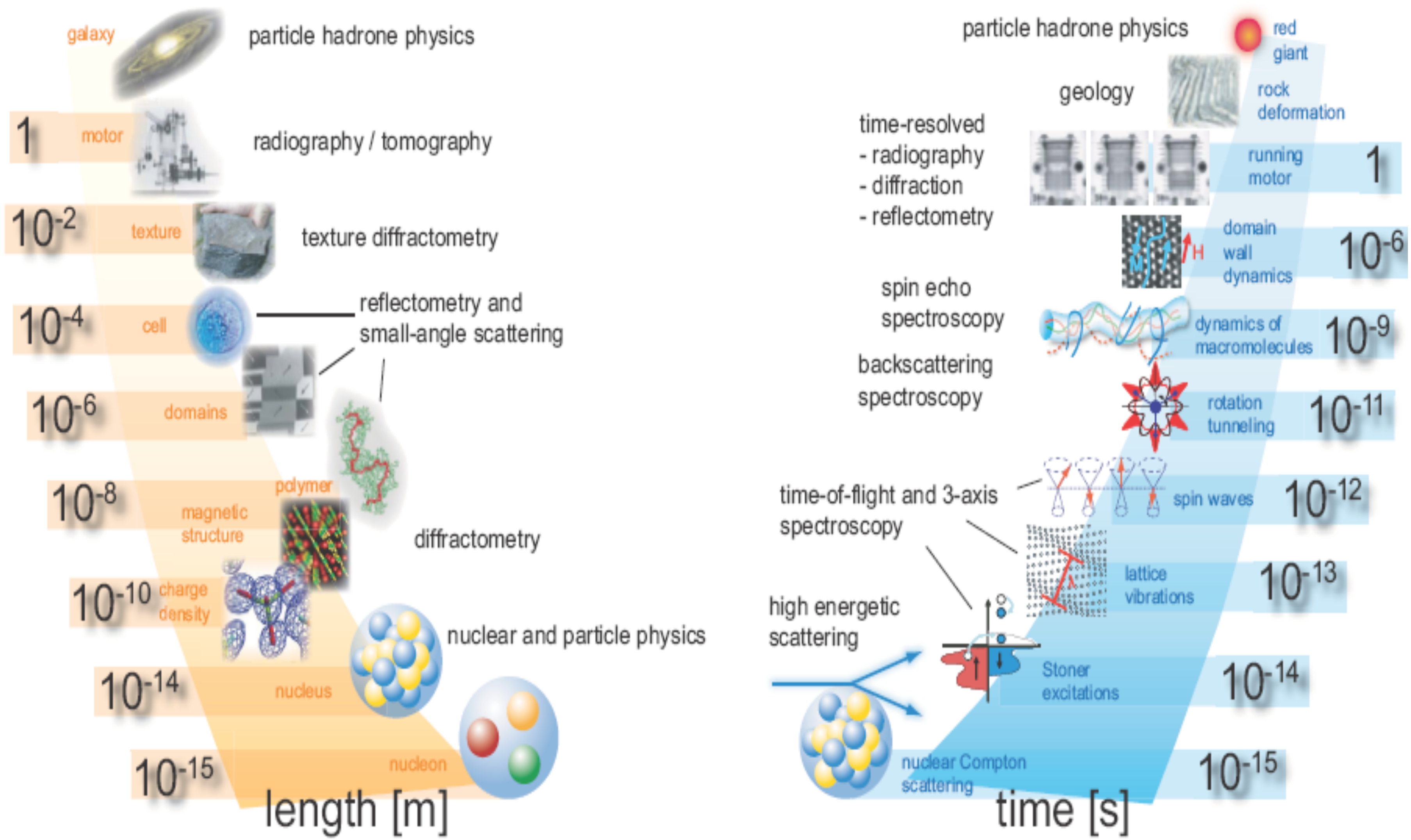
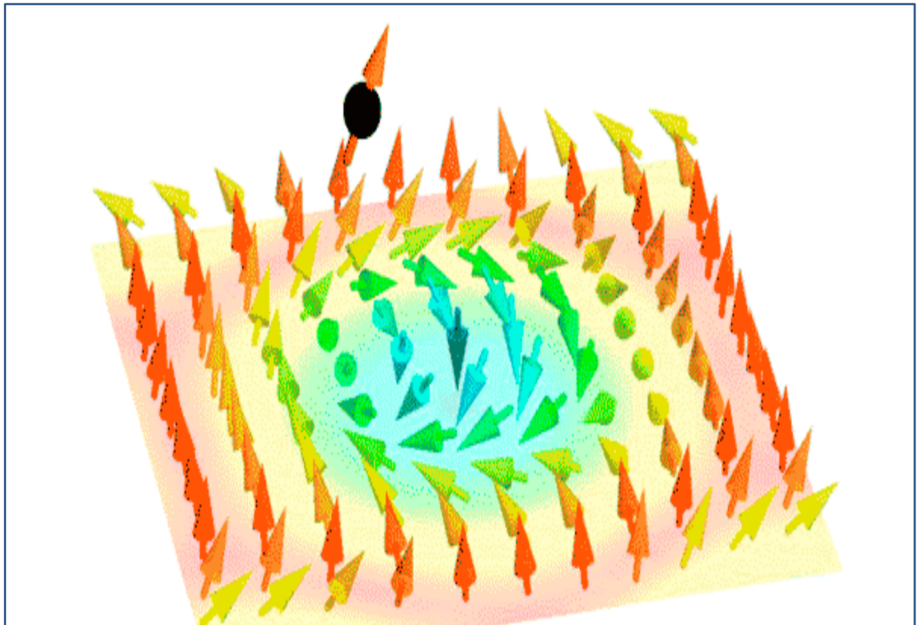


Information Technologies



CMD Europhysics Prize 2016
Ch. Pfleiderer, P. Böni MLZ

Skyrmions:
- topologically stabilized spin vortices
- possible elements of a future energy efficient IT - spintronics
- discovered by neutrons at MLZ

What drives the formation of skyrmions?

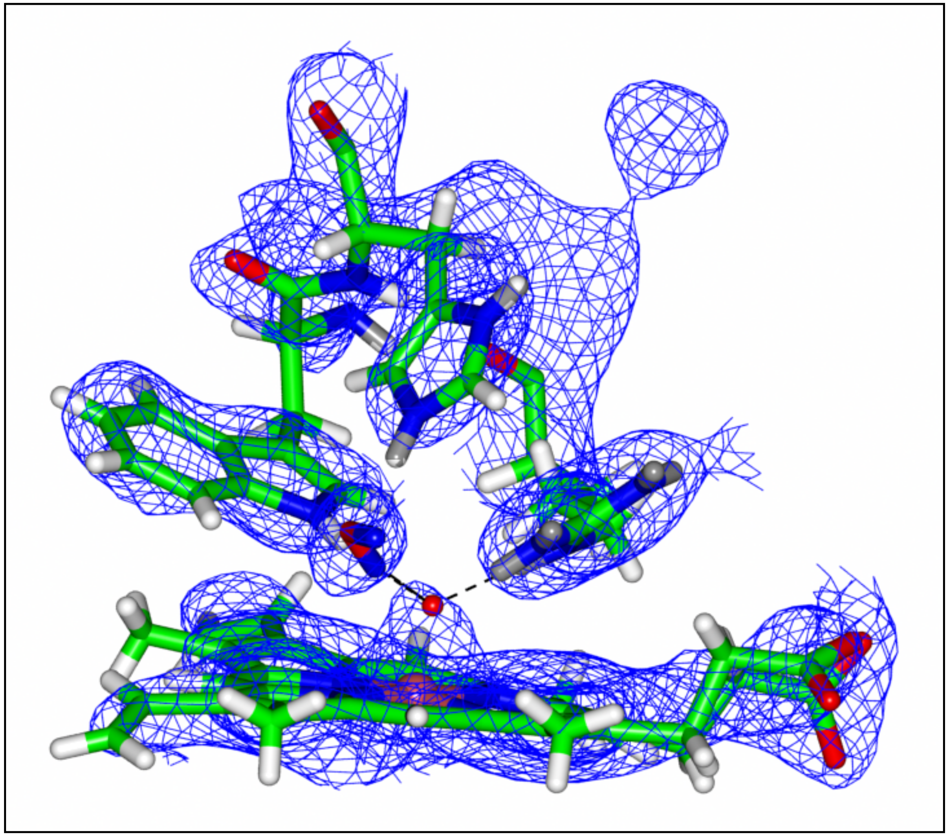
compare:
Physics-Nobelprize 2016
David J. Thouless,
F. Duncan M. Haldane
and J. Michael Kosterlitz

Neutron triple axis spectroscopy reveals the underlying interaction parameters

Magnon spectrum of the helimagnetic insulator Cu_2OSeO_3
P. Y. Portnichenko, et al.;
Nature Communications 7, 10725 (2016); DOI: 10.1038/ncomms10725

neutrons: sensitive to magnetism & elementary excitations

Health



“waste disposal” of the cell:

- H_2O_2 as metabolite of toxicological concern has to be decomposed

How is toxic waste removed from the cell?

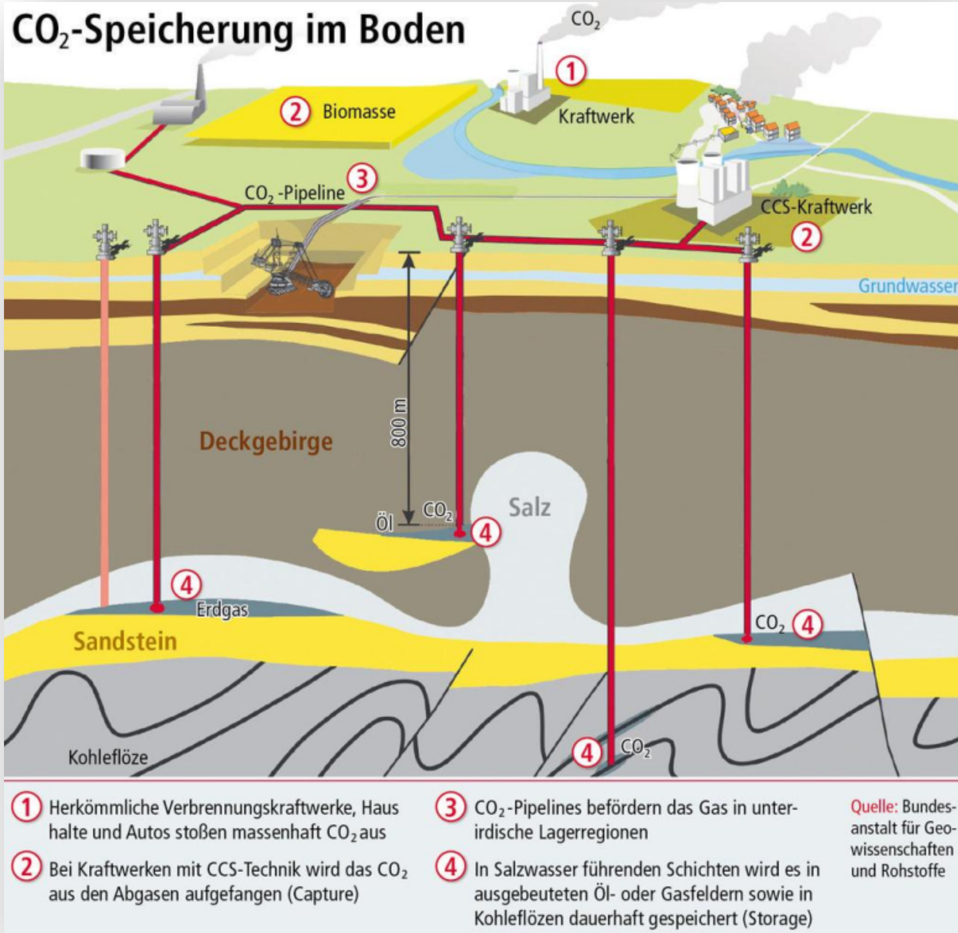
compare:
Medicine-Nobelprize 2016
Yoshinori Ohsumi

Neutron diffraction:
Cytochrome c Peroxidase decomposes toxic substances in the cell; neutron diffraction detects the decisive hydrogen in the intermediate state

Neutron cryo-crystallography captures the protonation state of ferryl heme in a peroxidase
Cecilia M. Casadei, et al.; Science 345 (2014), 193; DOI: 10.1126/science.1254398
Direct visualization of a Fe(IV)-OH intermediate in a haem enzyme
Hanna Kwon, et al.; Nature Communications 7, (2016), 13445; doi:10.1038/ncomms13445

neutrons: sensitive to light atoms (hydrogen!)

Environment



anthropogenic CO_2 :

- ➢ gas contributing to the climate change.

Can it be stored over million of years in caprock formations taking also reactive processes into account?

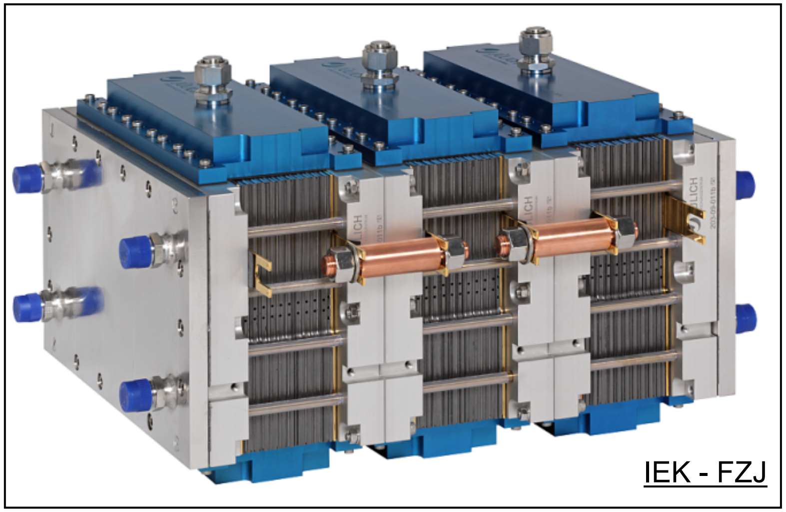
Neutron Small Angle Scattering:

- ➢ determination of porosity and inner surfaces
- ➢ confirmation of feasibility

Observational evidence confirms modelling of the long-term integrity of CO_2-reservoir caprocks;
N. Kampman et al.;
Nature Communications 7, (2016), 12268; DOI: 10.1038/ncomms12268

neutrons: penetrating & absolute units over many length-scales

Energy



high-temperature polymer electrolyte fuel cells:

- auxiliary power units for e.g. trucks, planes, ships
- stationary applications based on natural gas, methanol or heating oil

Why does the conductivity depend on the catalyzer concentration?

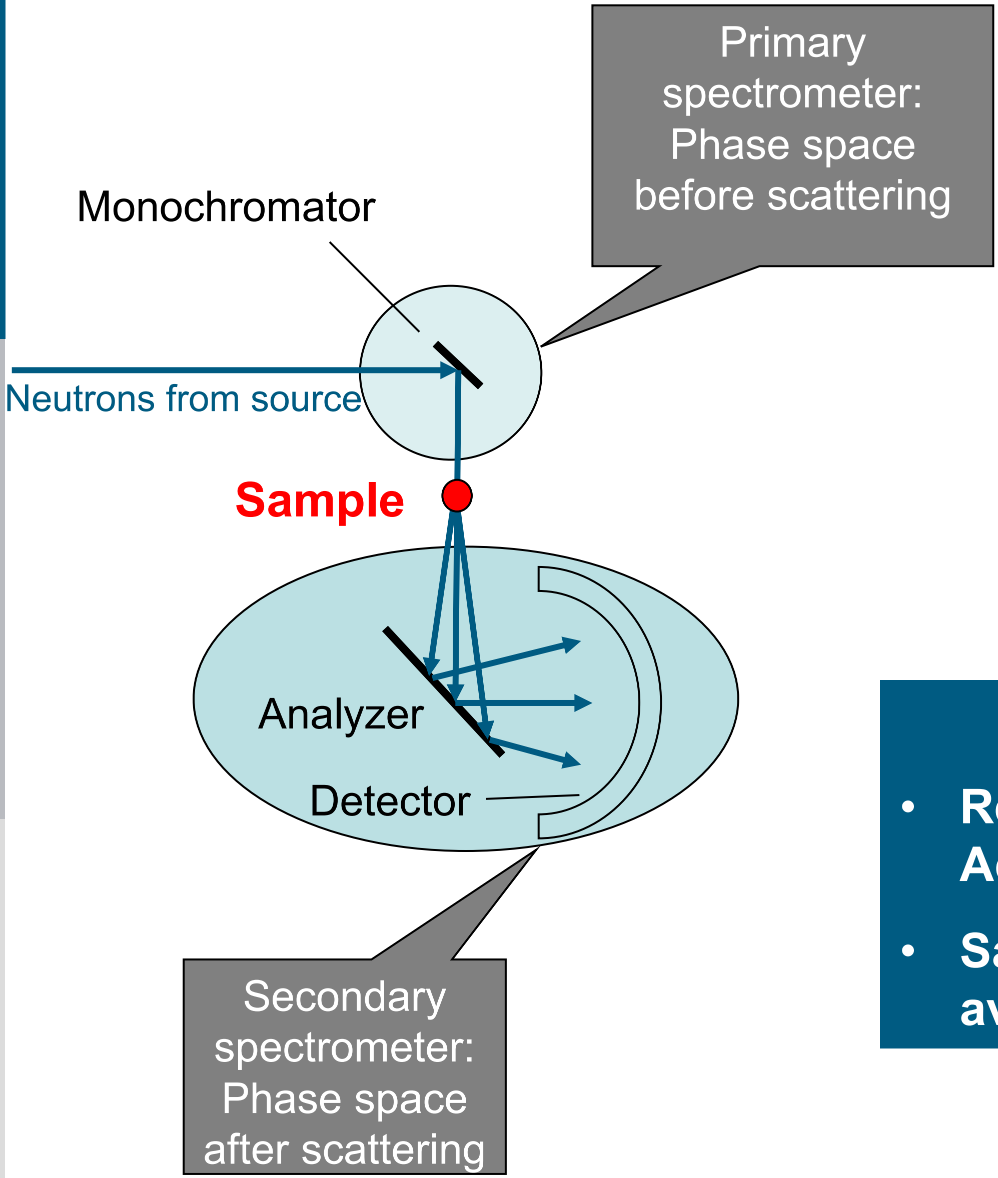
Neutron back scattering:

- observe proton diffusion through the membrane
- proton diffusion depends on catalyzer concentration
- phosphoric acid trapped around Pt particles

Structure and Proton Dynamics in Catalytic Layer of HT-PEFC
M. Khaneft, O. Holderer, O. Ivanova, W. Lüke, E. Kentzinger, M.S .Appavou, R. Zorn, W. Lehnert
Fuel Cells 16 (2016), 406; DOI: 10.1002/fuce.201500167

neutrons: sensitive to diffusion of hydrogen; H-D-contrast

What users want: Good data !!!



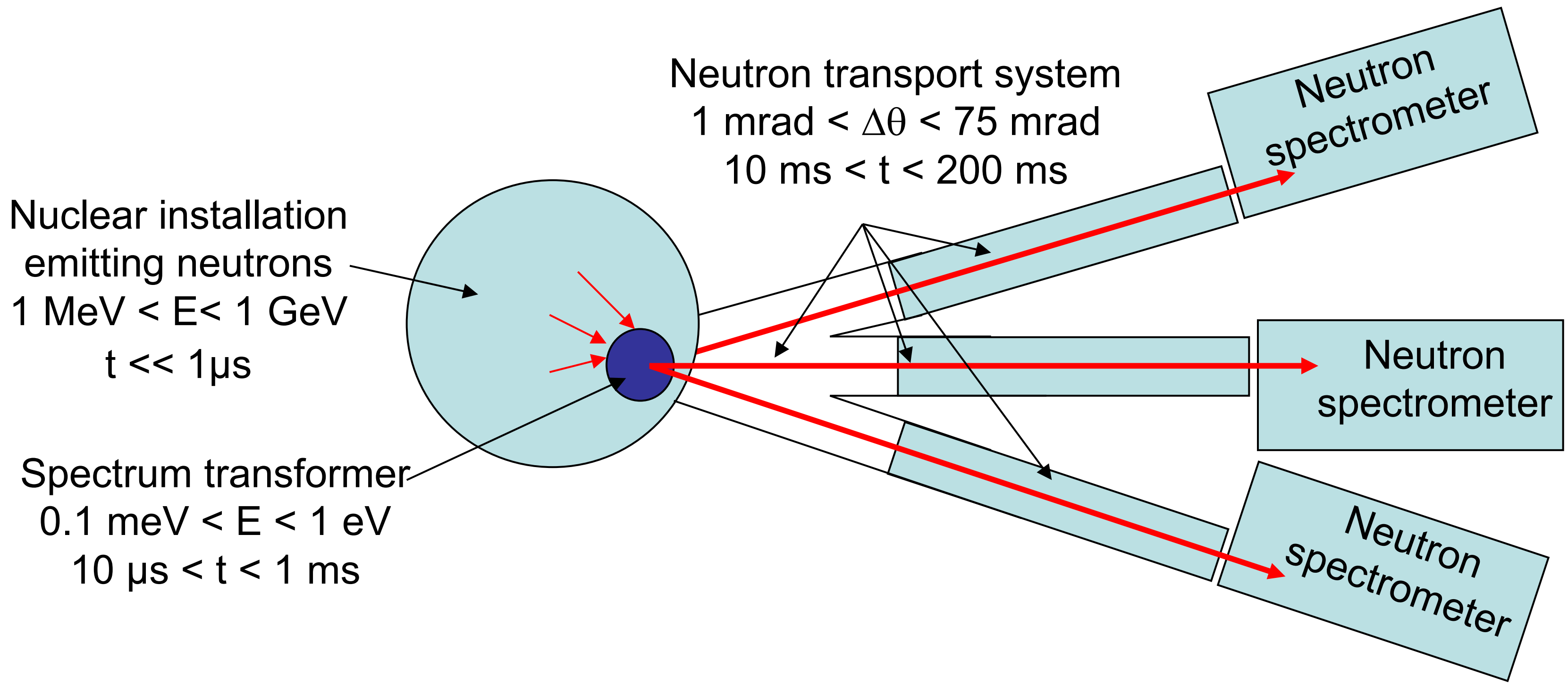
$$I_{\det} = \varepsilon_{pr} \varepsilon_{\sec} \varepsilon_{\det} \cdot \sigma_s \cdot I_0$$

$$I_0 \propto \int \Phi(\vec{x}, \vec{p}) \, \mathrm{d}\vec{x} \mathrm{d}\vec{p}$$

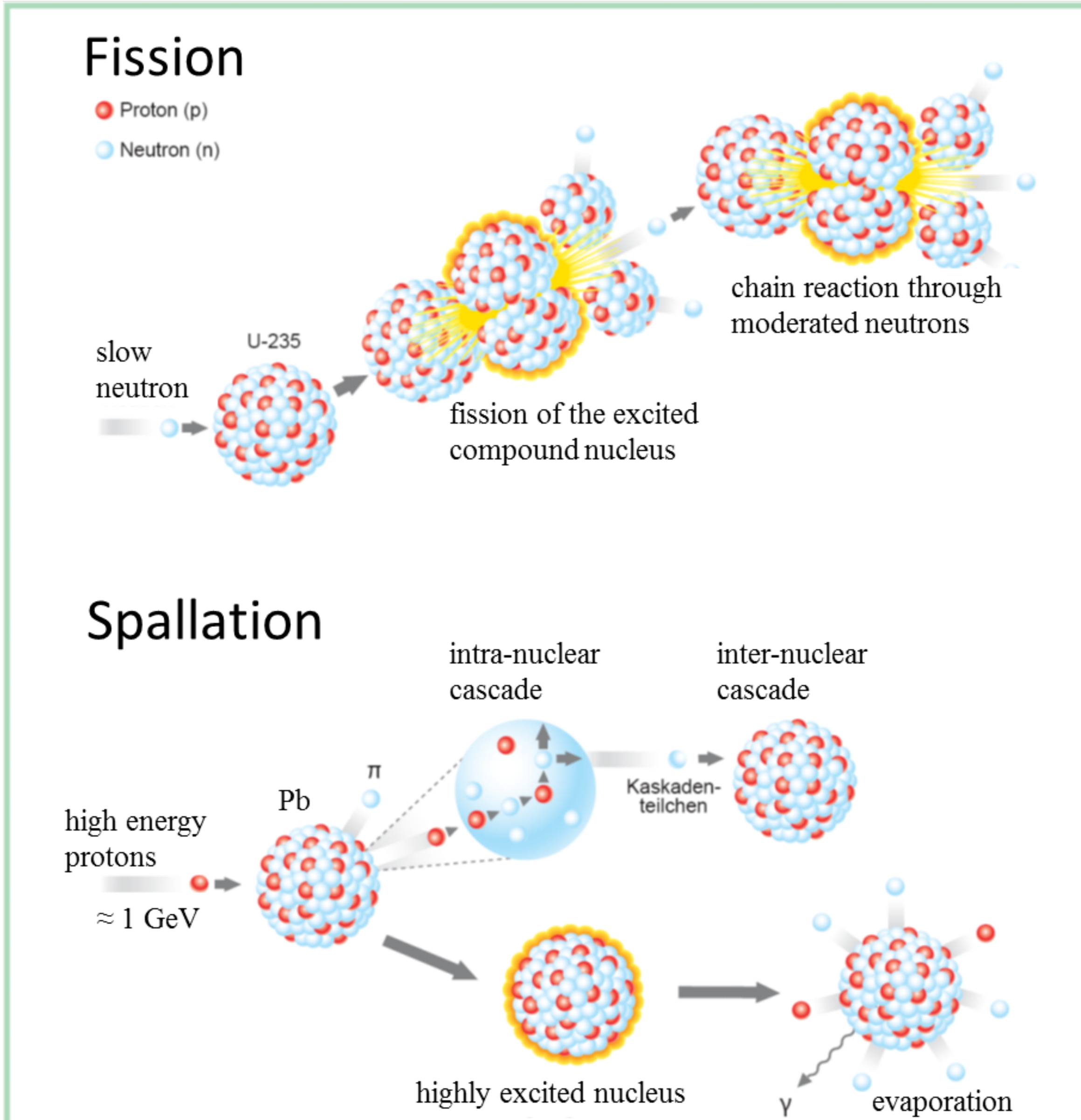
Integration limits

- **Requested resolution**
  Accepted divergence and bandwidth
- **Sample size:**
  avoid over/under illumination

The life cycle of a scattering neutron



Nuclear reactions to release neutrons



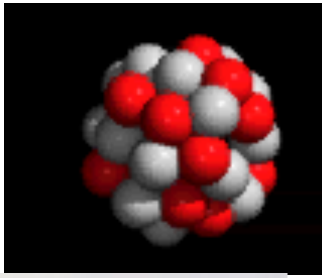
180 MeV/n
Heat

30-50 MeV/n
Heat

Large scale facilities

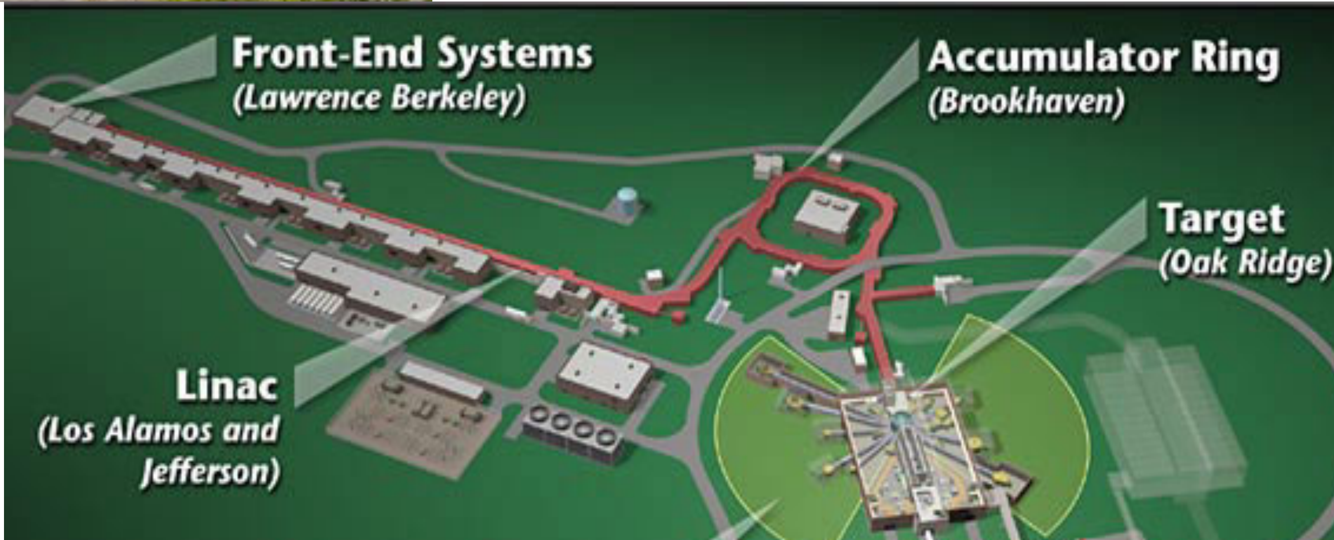
<u>Fission nuclear reactions</u>

are used in modern continuous neutron sources.



<u>Spallation nuclear reactions</u>

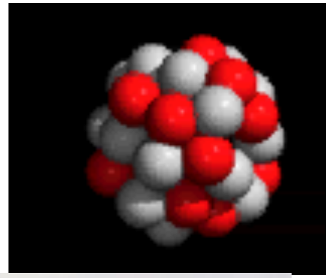
are used in modern pulsed neutron source



How to obtain free neutrons on a large scale?

Fission nuclear reactions

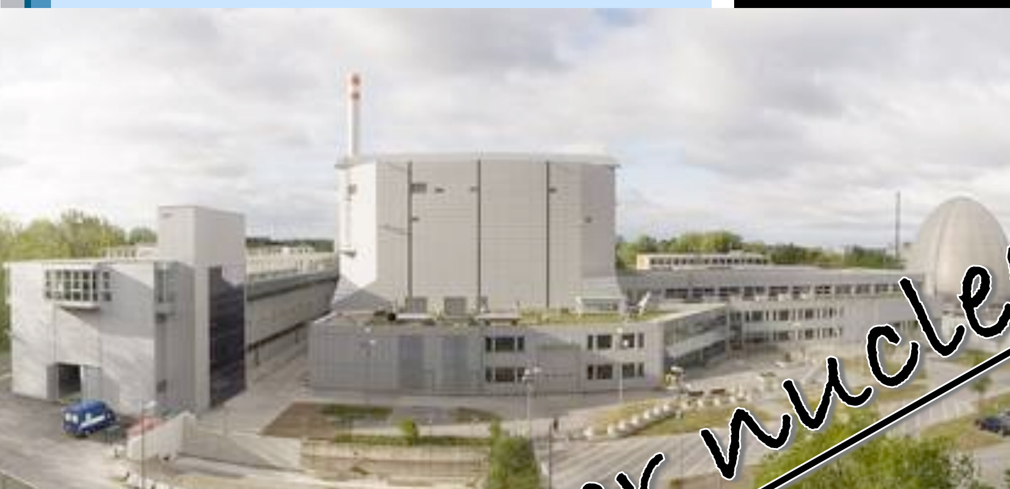
are used in modern continuous neutron sources.



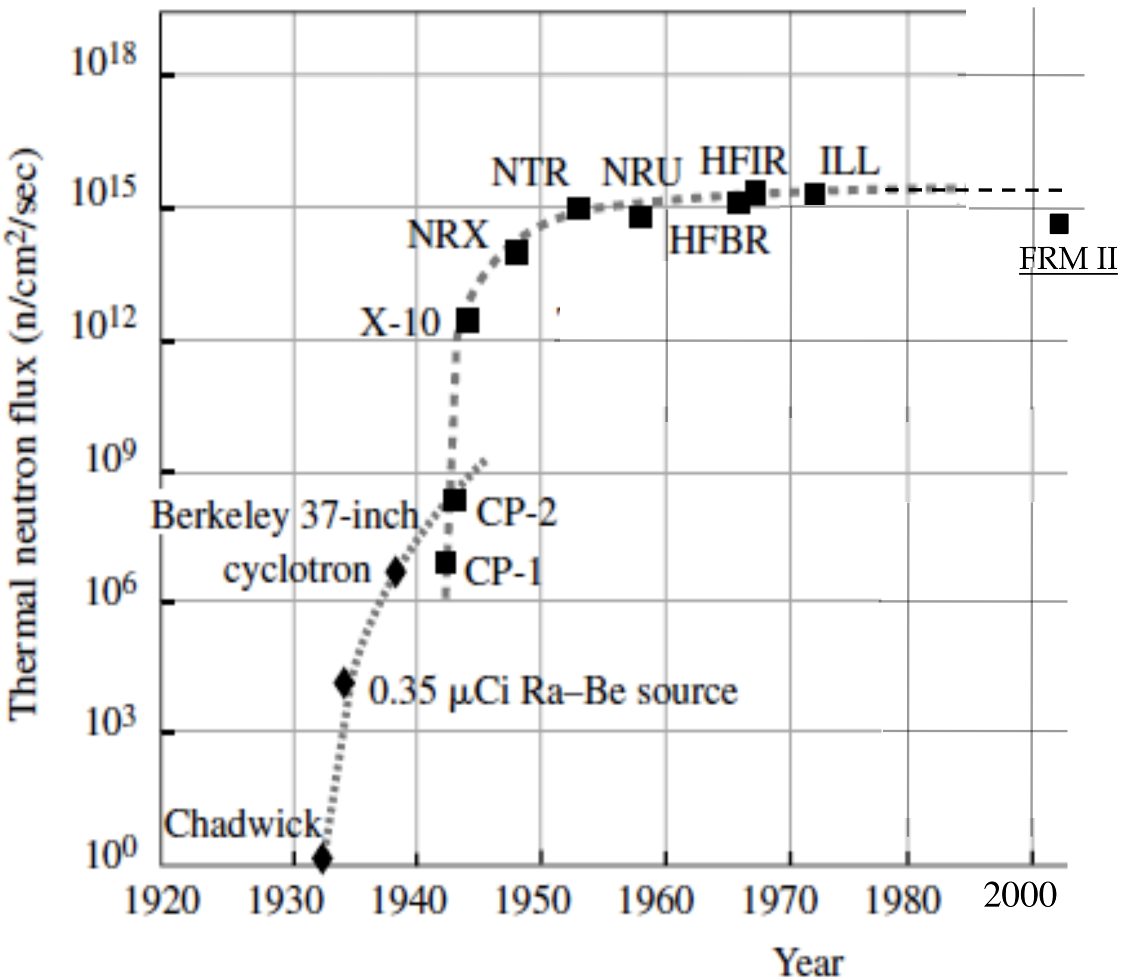
Spallation nuclear reactions

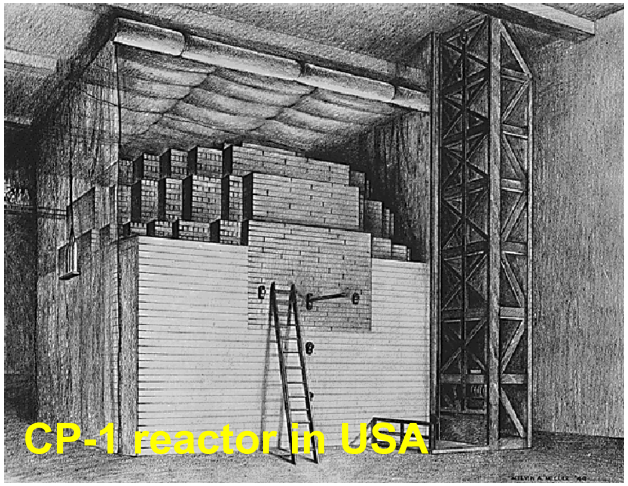
are used in modern pulsed neutron source

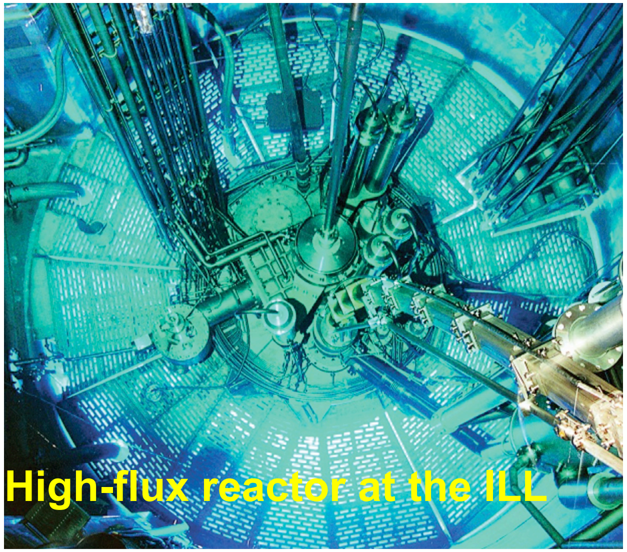
+ other nuclear reactions



Thermal neutrons from fission reactors







Fission

^{235}U + neutron → fission fragments + 2.5 neutrons + 180 MeV

Source strength:

$$Q = 1\, n/180\, MeV = 1\, n/2.9 \cdot 10^{-11} Ws$$

$\Longrightarrow \quad Q \approx 3.5 \cdot 10^{16} \frac{n}{s}$ per MW of reactor power

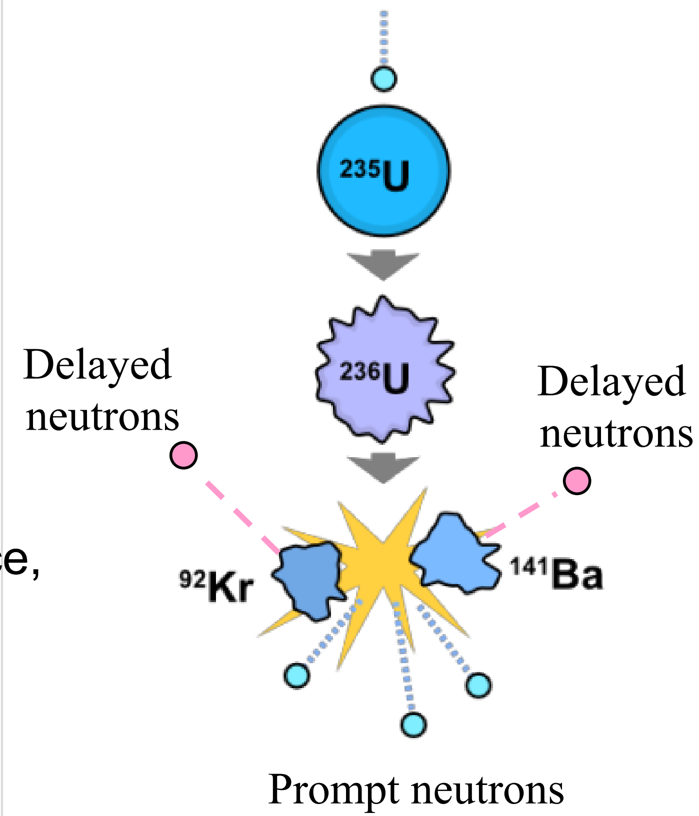
e.g. for the FRM II:

$$Q \approx 7 \cdot 10^{17} \frac{n}{s}$$

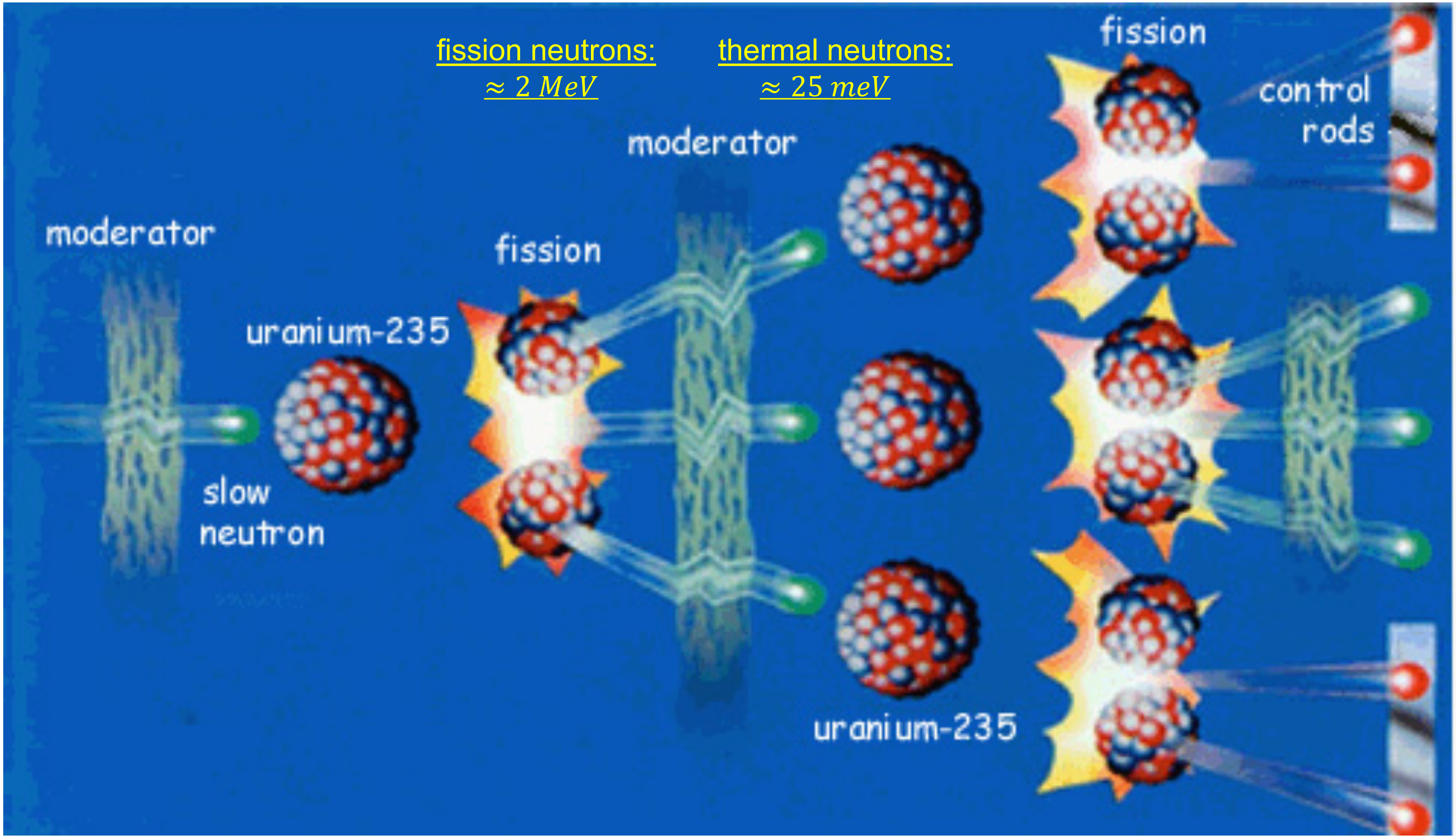
Current density of fast neutrons, in 15 cm distance, assuming a point source:

$$j = \frac{Q}{4\pi R^2} = 2.5 \cdot 10^{14} \frac{n}{s \cdot cm^2}$$

(compare: $8 \cdot 10^{14} \frac{n}{s \cdot cm^2}$ thermal for FRM II)



Moderation and Control

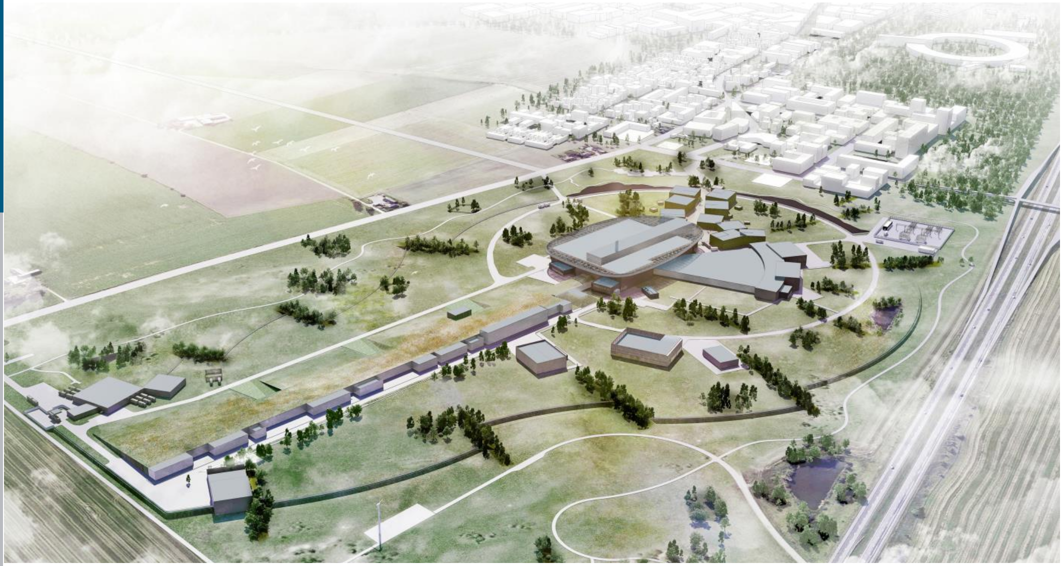


Non-resonant absorption $\sim \frac{1}{v} \sim \lambda$

moderation by collision with light atoms (e.g. thermalization after 30 collisions with D_2O)

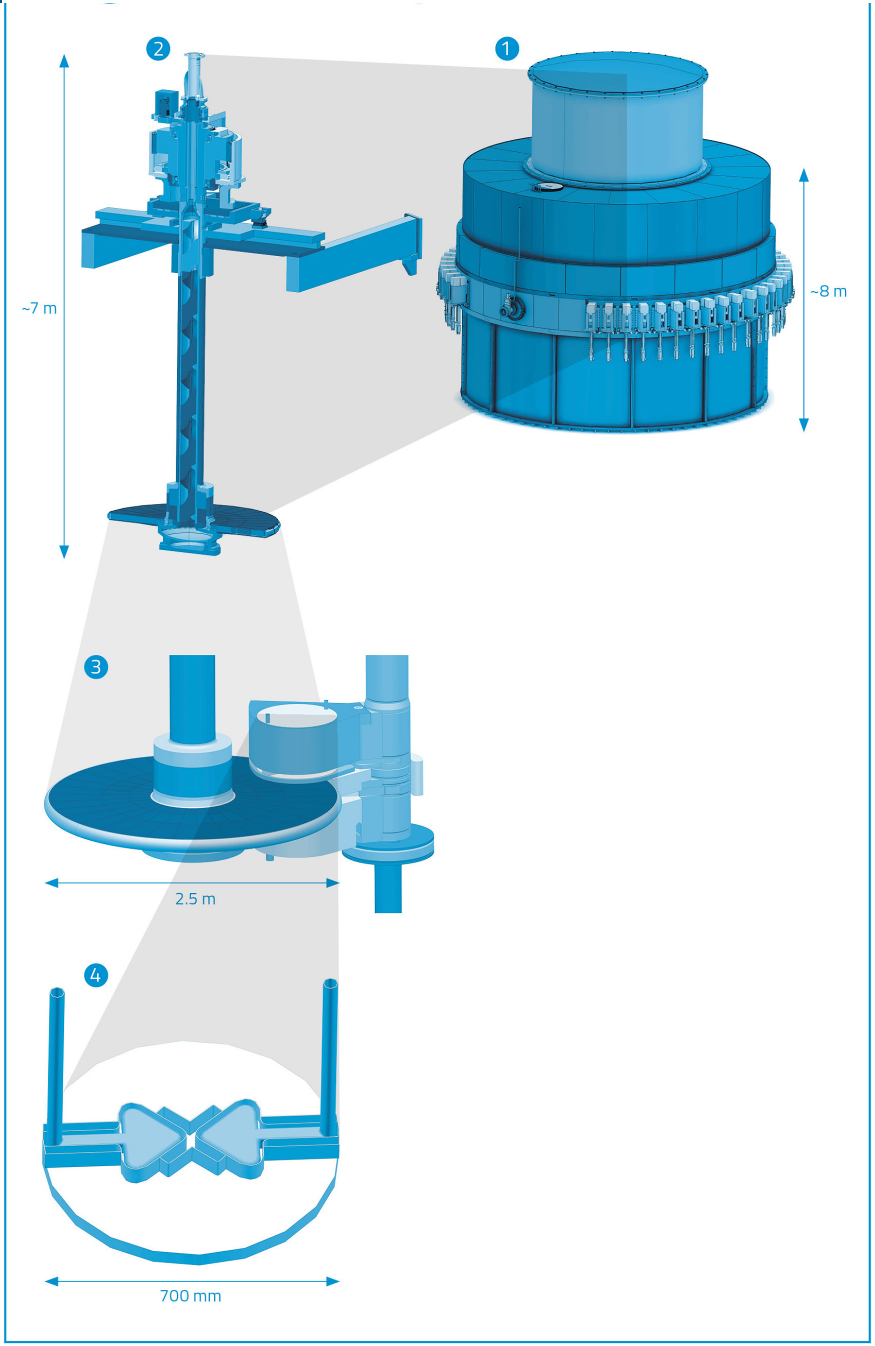
control by absorbing control rod (e.g. Cd, Hf); delayed neutrons!

Spallation sources



Long pulse (ESS):
LINAC
2.86 ms pulse length
14 Hz frequency
5 MW beam power
~1 GeV beam energy

Short pulse (e.g SNS):
LINAC + accumulator ring
~ 1μs pulse length
60 Hz frequency
1.4 MW beam power
~1 GeV beam power

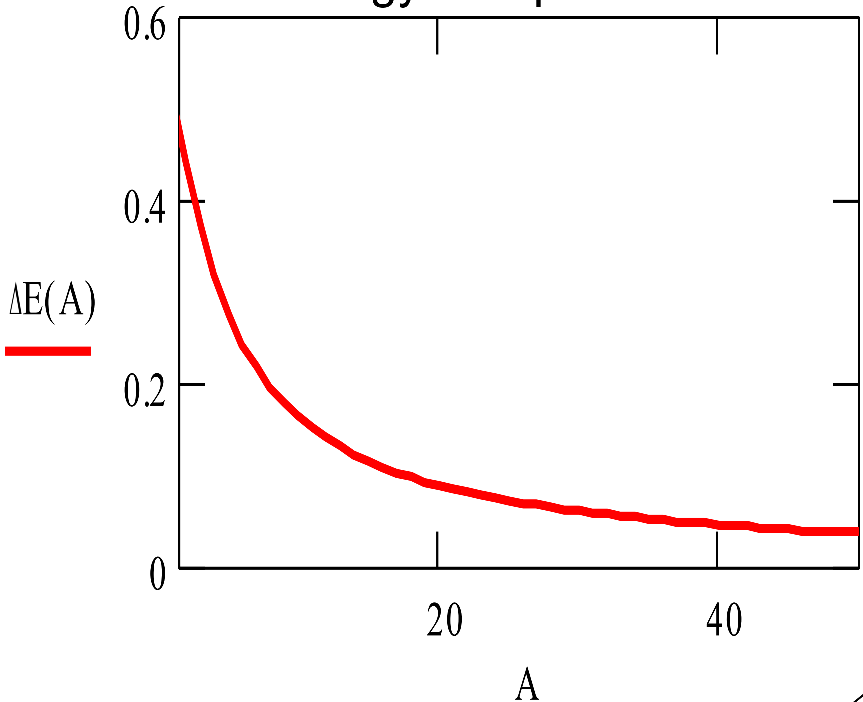


ESS Target design

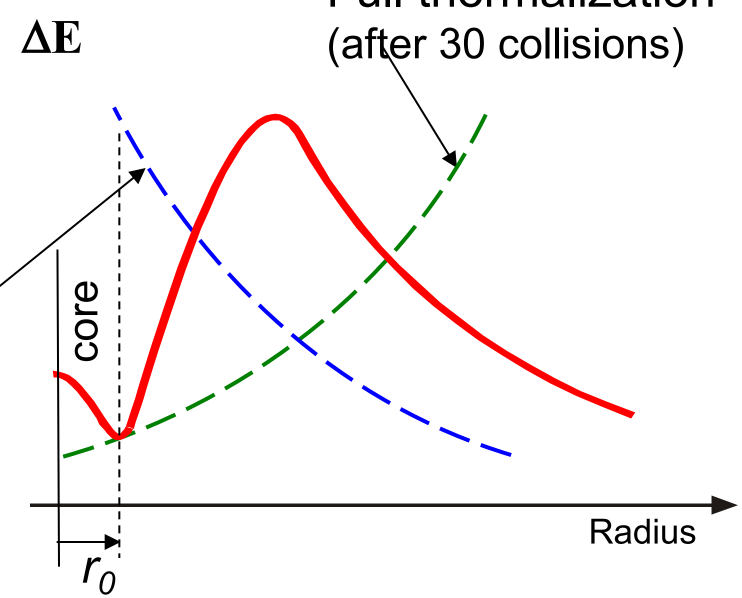
- 2.5 m diameter tungsten wheel
- Moderator/reflector plug below/above wheel
- 6000 t steel monolith to shield high energy particles

From MeV to meV:
Thermalization by collisions with Deuterium in heavy water

Energy loss per collision



Increasing density of thermal neutrons



Absorption ~ v_n^{-1}
-> Decreasing flux of thermalized neutrons

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

Neutrons in Equilibrium with moderator

Cold	E=(0.05-10) meV	λ = (3-40) Å
Thermal	E=(10-100) meV	λ = (0.9-3) Å
Hot	E=100 meV -1eV	λ = (0.3-0.9) Å

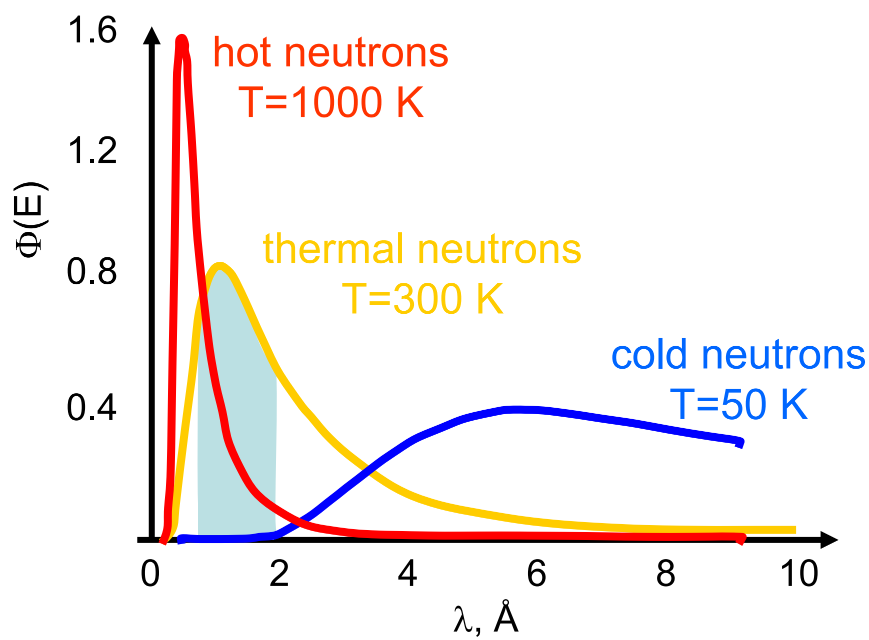
Maxwellian distribution

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

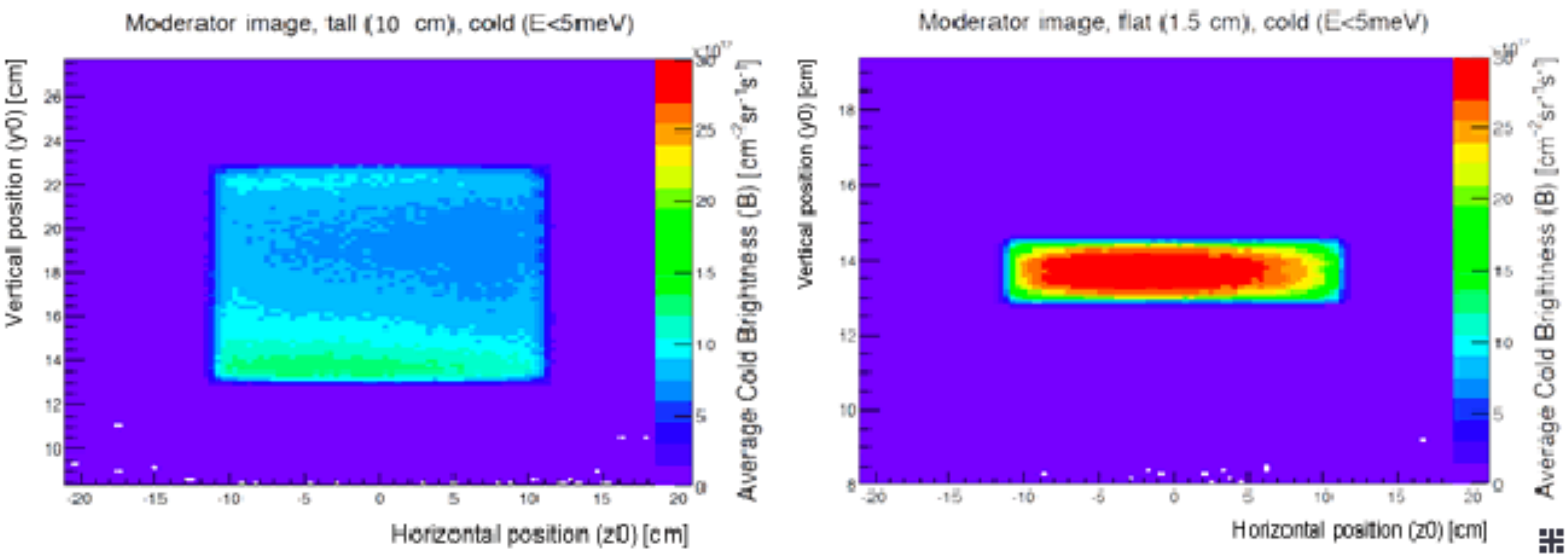
Cold neutrons: Larger distance or lower energies

Hot neutrons: Small lattice spacing or higher energies

$\Rightarrow$ heating or cooling of the moderator



The Path to Higher Brilliance: Moderator Materials and Geometry

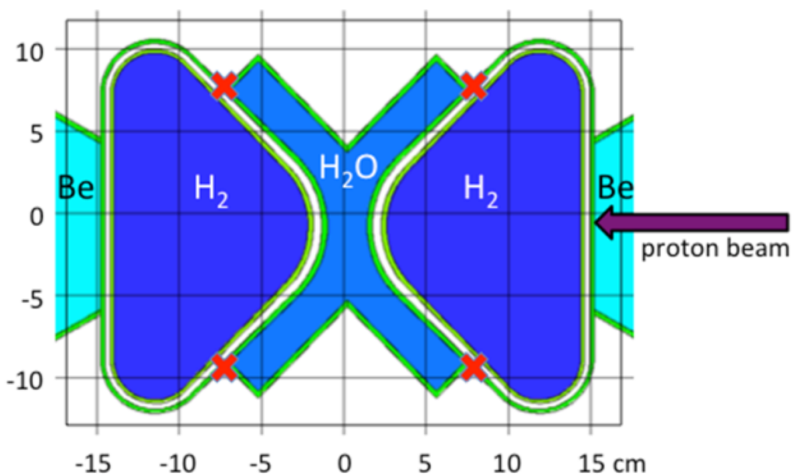


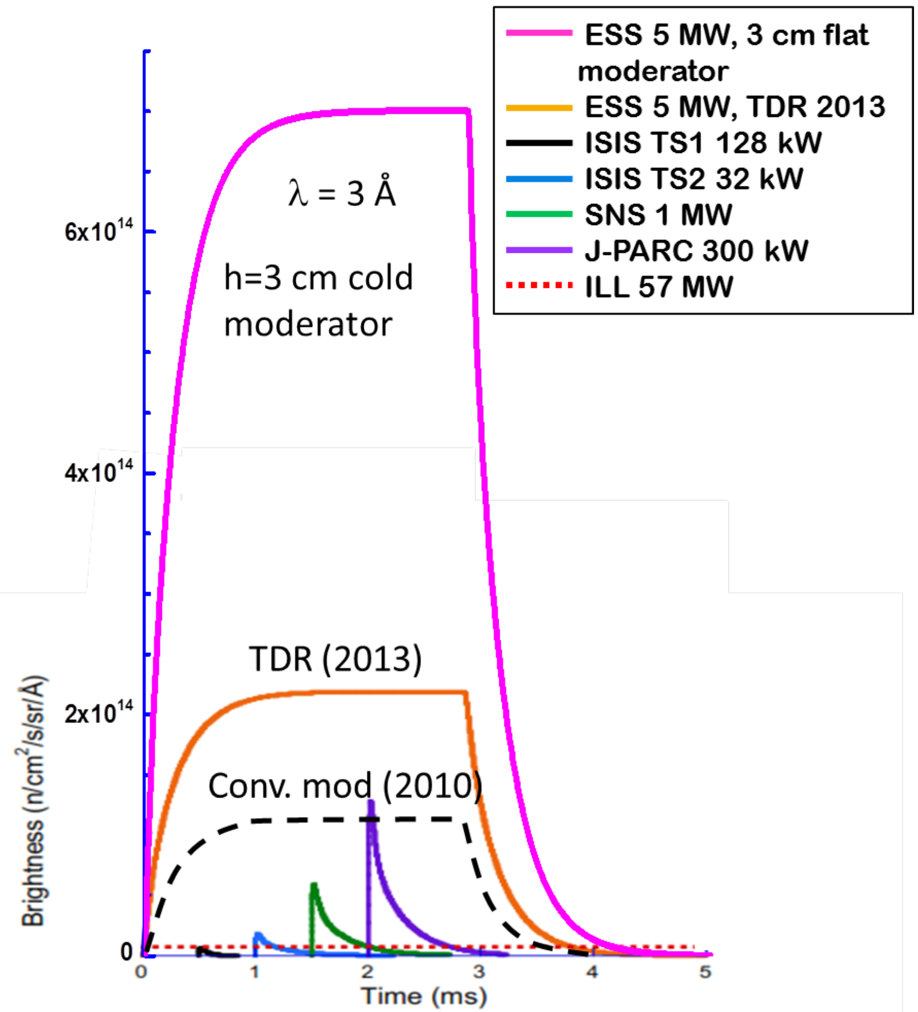
Mezei, F., et al. (2014).
"Low dimensional neutron moderators for enhanced source brightness."
Journal of Neutron Research **17**(2): 101-105.

The Path to Higher Brilliance: Moderator Materials and Geometry

New ESS moderators 2015

cold: 20 K para-H_2
thermal: RT water
height: 3cm above target
6cm below target





Mezei, F., et al. (2014).
"Low dimensional neutron moderators for enhanced source brightness."
Journal of Neutron Research **17**(2): 101-105.

From Table-Top to Flagship Devices: X-Rays

Laboratory

Galaxi

Petra III (DESY)

XFEL (DESY)

And Neutrons?

? ?

FRM II (TUM)

ESS (Lund)

Fill the Gap for Neutrons !

Table-Top HBS FRM II (TUM) ESS (Lund)

With a scalable source concept!

HBS:
Alternatives to spallation?

HBS - novel concept:

optimize the accelerator driven source from ion source to detector for every single instrument:

- ✓ adapted pulse time structure
- ✓ dedicated moderator
- ✓ dedicated optics

"every instrument has its own adapted neutron source!"

Brilliance: $$B = \frac{particles}{s \cdot mm^2 \cdot mrad^2 \cdot 0.1\% \frac{\Delta E}{E}}$$

Liouville's theorem: $$\prod_{i=1..3} (\Delta q_i \cdot \Delta p_i) = const$$

no "one fits all"
produce less (minimize cost!) - waste less (maximize brilliance!)

- Projectile and Target

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Nuclear Reactions Producing Neutrons

Nuclear Process	**Example**	**Neutron Yield**	**Heat Release [MeV/n]**
D-T in solid target	400 keV D on T in Ti	4×10^{-5} n/d	10 000
Deuteron stripping	40 MeV D on liquid Li	7×10^{-2} n/d	3500
Nuclear photo effect from e-bremsstrahlung	100 MeV e^- on ^{238}U	5×10^{-2} n/e^-	2000
^{9}Be(d,n)^{10}Be	15 MeV D on Be	~~1 n/d~~ 1.5E-2 n/d	1000
^{9}Be(p,n;p,pn)	11 MeV p on Be	5×10^{-3} n/p	2000
Nuclear fission	Fission of ^{235}U by thermal neutrons	1n/fission	180
Spallation	800 MeV p on ^{238}U or Pb	27 n/p or 17 n/p	55 or 30

neutron gener.

HUNS (Hokkaido)

LENS The Low Energy Neutron Source

MLZ Heinz Maier-Leibnitz Zentrum

EUROPEAN SPALLATION SOURCE

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

Producing Neutrons

Comparison of production efficiency of fast neutrons

U+e: preliminary results, target geometry not optimized concerning photon absorption

ion	E [MeV]	n/nps_ion	n/s/mA	n/s/kW
Be+p	5	0.015%	9.49E+11	1.899E+11
Be+p	10	0.110%	6.86E+12	6.856E+11
Be+p	25	0.638%	3.98E+13	1.593E+12
Be+d	5	0.063%	3.94E+12	7.887E+11
Be+d	10	0.265%	1.65E+13	1.653E+12
Be+d	25	1.608%	1.00E+14	4.015E+12
Be+d	50	5.724%	3.57E+14	7.145E+12
Be+d	100	20.522%	1.28E+15	1.281E+13
Li+p	2	0.002%	1.02E+11	5.107E+10
Li+p	5	0.050%	3.15E+12	6.299E+11
Li+p	10	0.164%	1.02E+13	1.025E+12
Li+p	25	0.471%	2.94E+13	1.176E+12
U+e	20	0.396%	2.47E+13	1.236E+12
U+e	50	2.520%	1.57E+14	3.146E+12
U+e	100	5.695%	3.55E+14	3.555E+12
U+e	150	8.710%	5.44E+14	3.624E+12
U+e	200	11.861%	7.40E+14	3.702E+12

$^{9}Be(d,n)$

good efficiency, engineering o.k.

$^{7}Li(p,n)^{7}Be$

Efficiency too low, engineering difficult

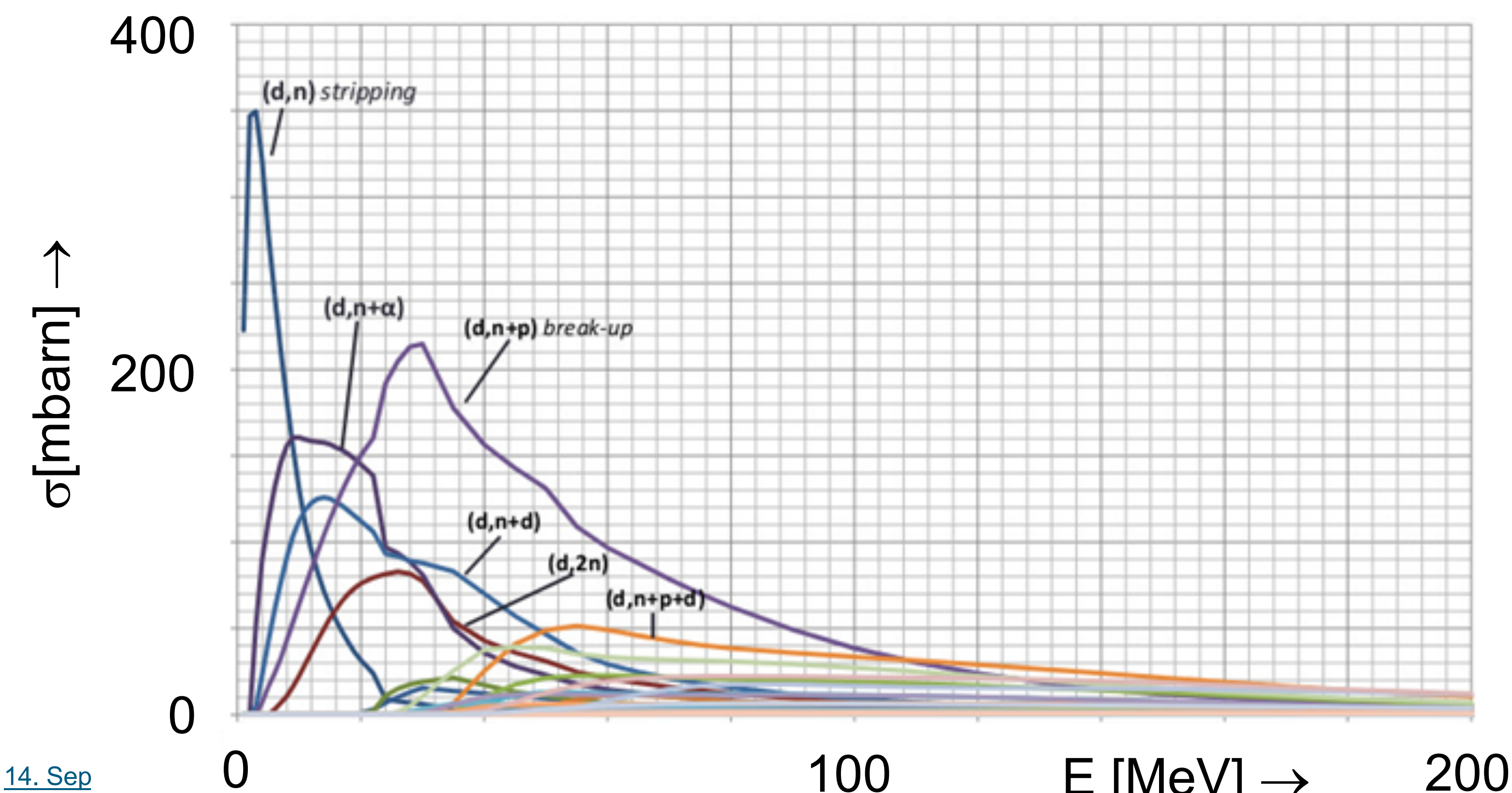
$M(e^{-},\gamma)$ - Bremsstrahlung

$M(\gamma,n)$ - nuclear photoeffect

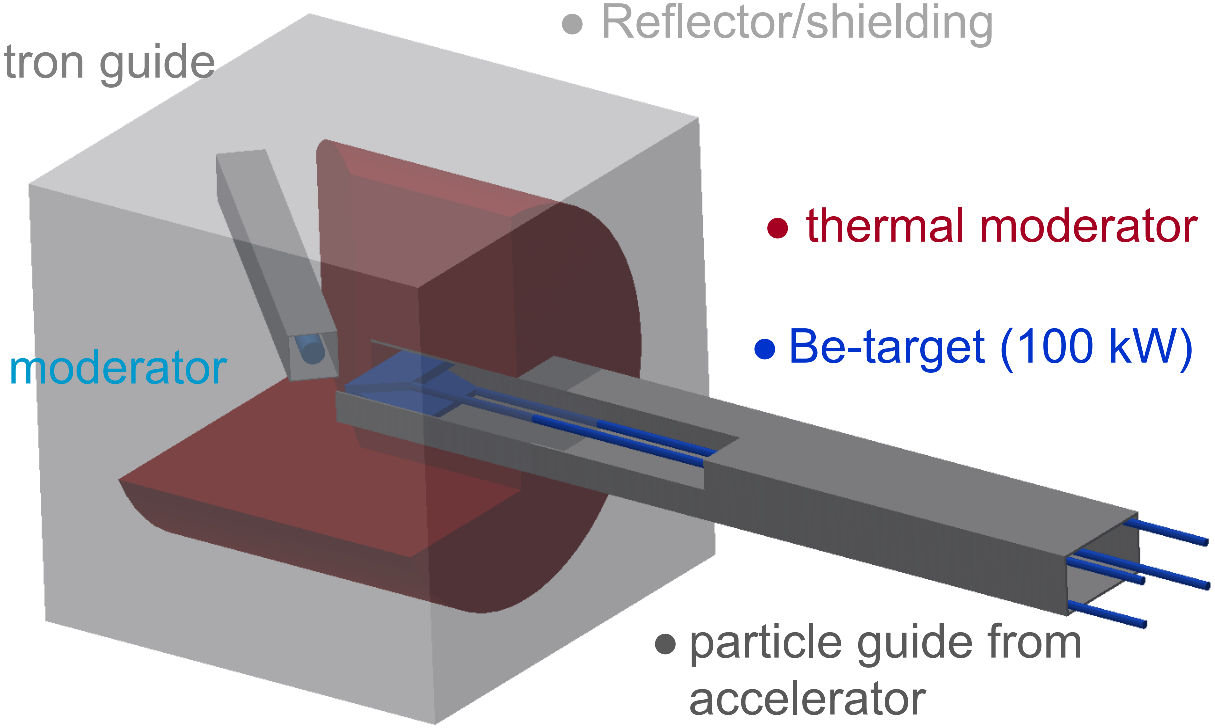
Interesting candidate

Producing Neutrons

Our first choice: $^{9}Be(d,n)$ nuclear reaction

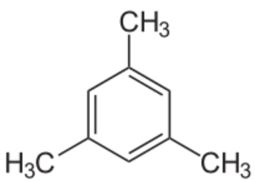
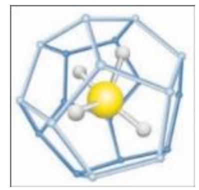
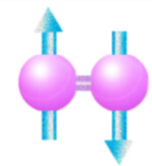
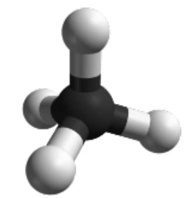


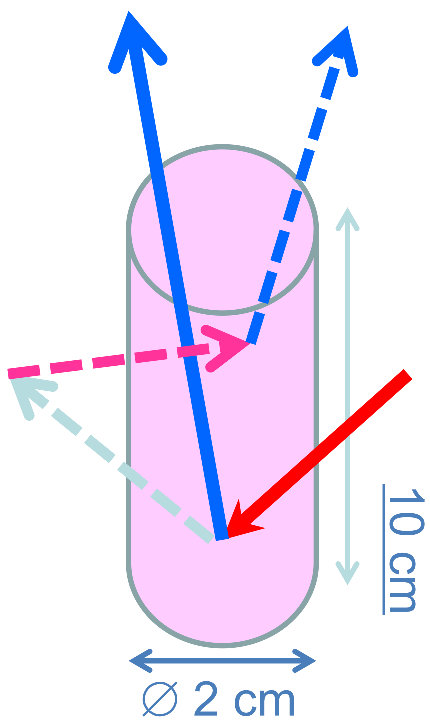
Efficient Coupling of Target to Moderator

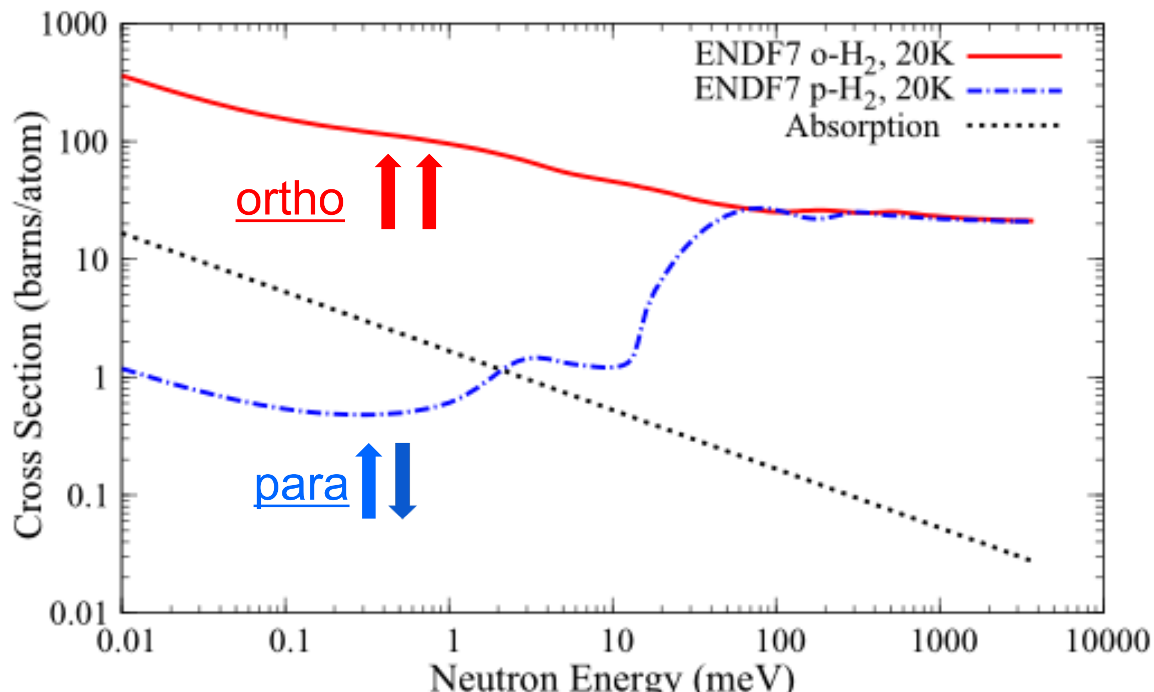


no losses due to solid angle coverage!

Cold Source

Mesitylene	Methane-cladrate	Para-Hydrogen	Methane
			

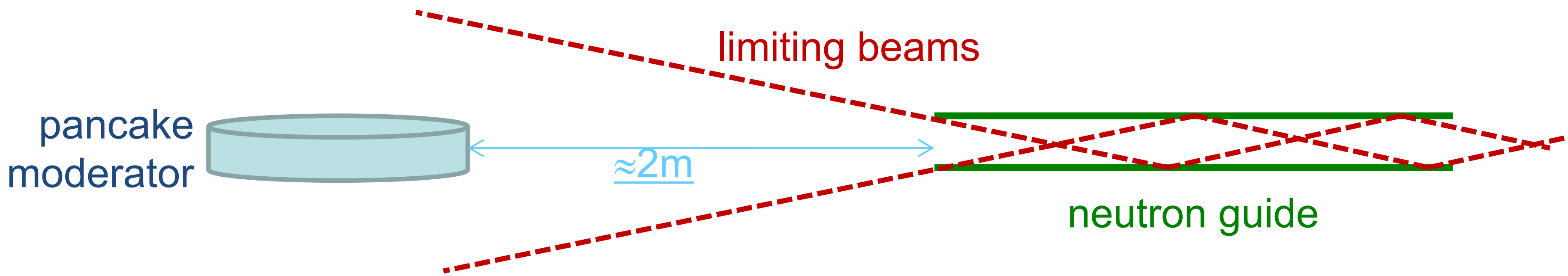




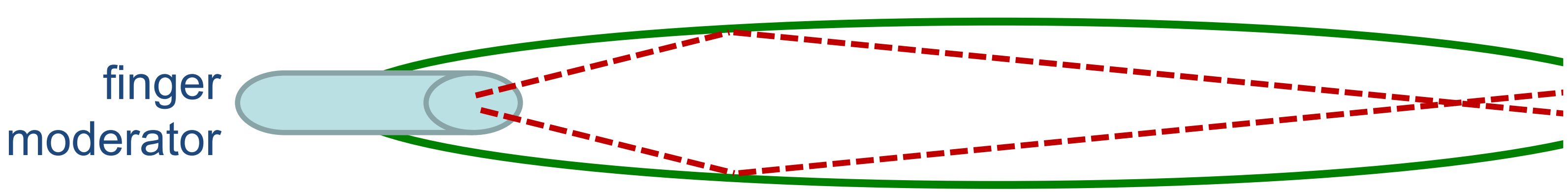
"para-Hydrogen finger moderator"

Beam Extraction

- spallation sources:
  problem to "fill" the neutron guide, if larger divergence is allowed:



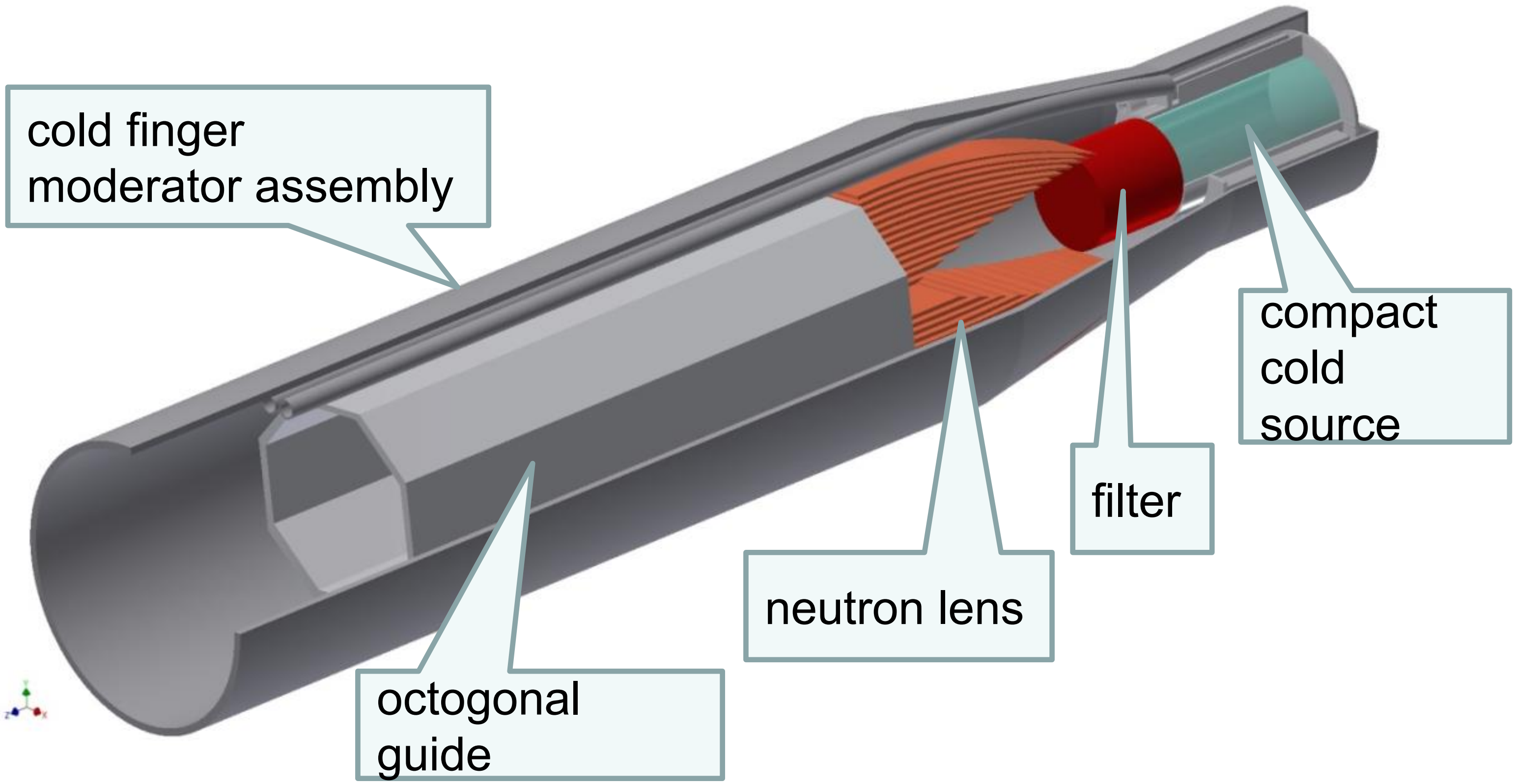
- HBS – relatively low radiation level → guides can start very close to moderator:



⇒ efficient beam extraction in combination
with modern beam transport system

Beam Extraction

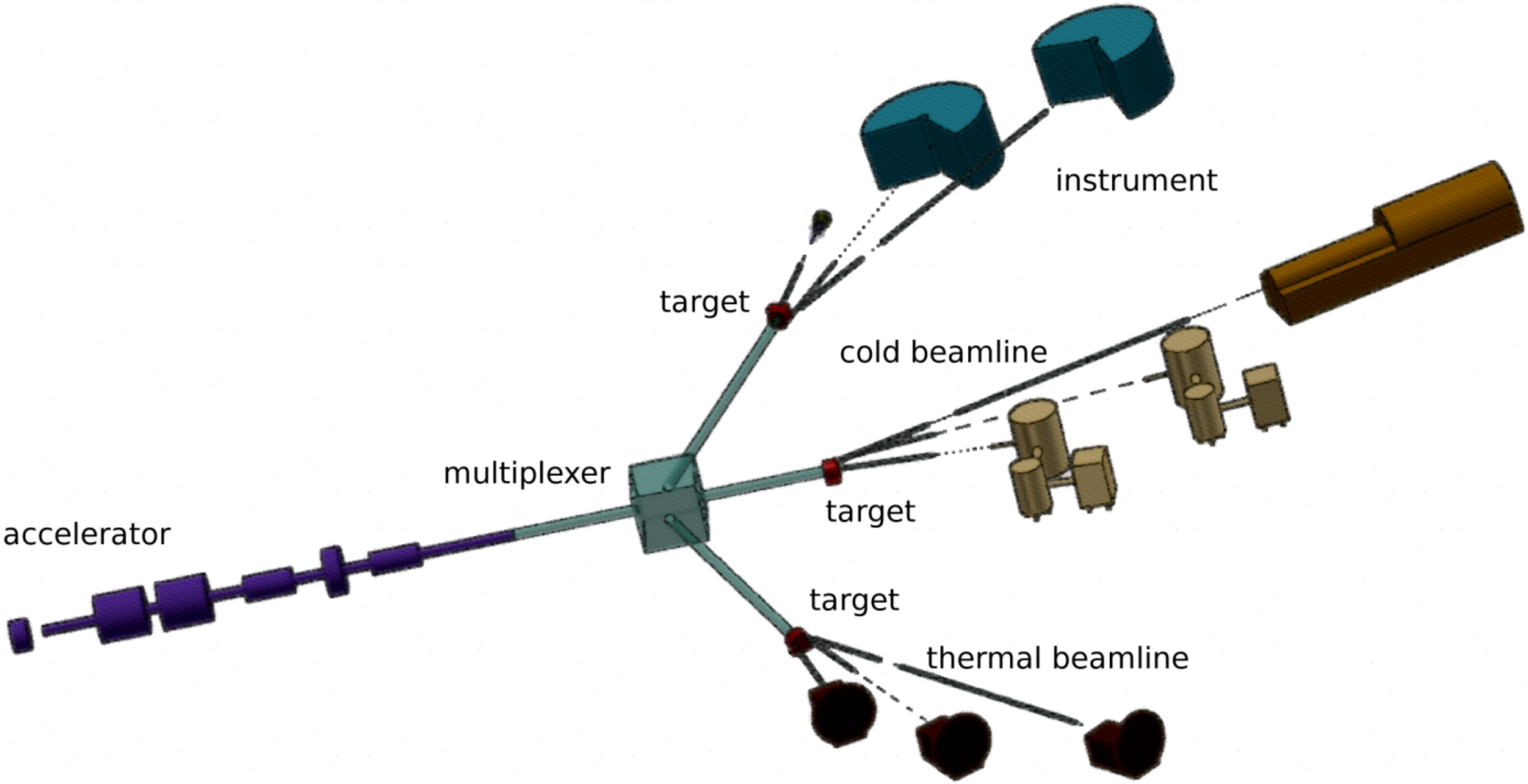
HBS – relatively low radiation level → optics can start very close to moderator



efficient beam extraction in combination with modern beam transport system

Summary: Facility Layout and Parameters

Possible Facility Layout



The Jülich high-brilliance neutron source project

U. Rücker, T. Cronert, J. Voigt, J. P. Dabruck, P. -E. Doege, J. Ulrich, R. Nabbi, Y. Beßler, M. Butzek, M. Büscher, C. Lange, M. Klaus, T. Gutberlet and T. Brückel

Eur. Phys. J. Plus, 131 1 (2016) 19 | DOI: http://dx.doi.org/10.1140/epjp/i2016-16019-5

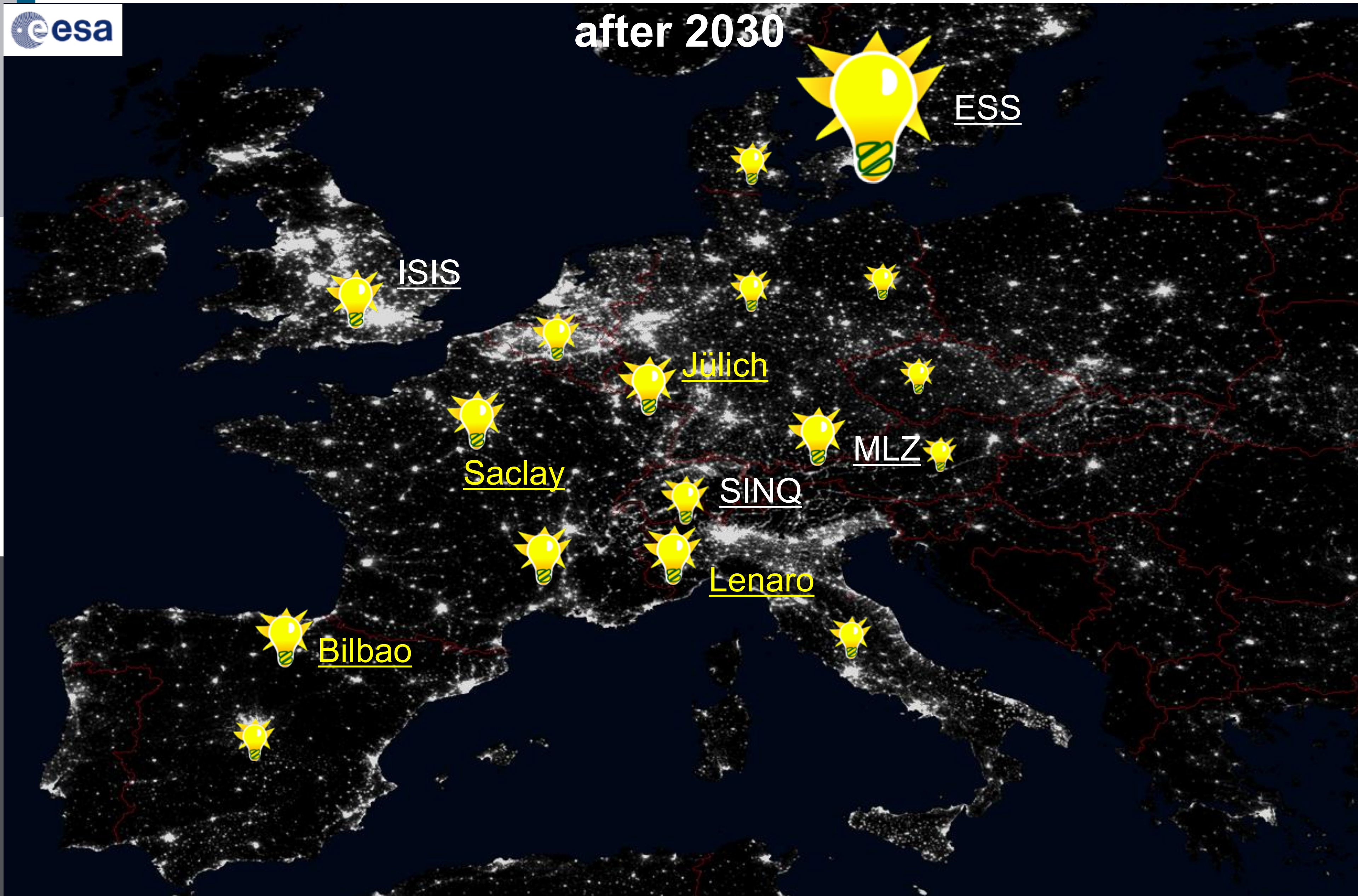
Simulated Instrument Performance

For a medium flux HBS with 100 kW beam power, 100 mA peak current and 50 MeV deuteron energy

	Backscattering	Cold ToF	Thermal ToF
$E_{i,f}$ (meV)	1.84	5	45
$\frac{\Delta E_i}{E_i}$ (%)	1	2	5
$\Delta\theta(°)$	4	2	0.75
$\Delta t(\mu s)$	120	50	18
Rep. rate (Hz)	200	100	400
Flux ($cm^{-2}s^{-1}$)	2.5×10^7	1.3×10^5	1×10^5
Reference instrument	OSIRIS	LET	MERLIN
Flux reference ($cm^{-2}s^{-1}$)	2.7×10^7	5×10^4	6×10^4

for one Neymar!

Desired Neutron Scenario in Europe



Have Fun With Neutrons !!!!