Neutron Production

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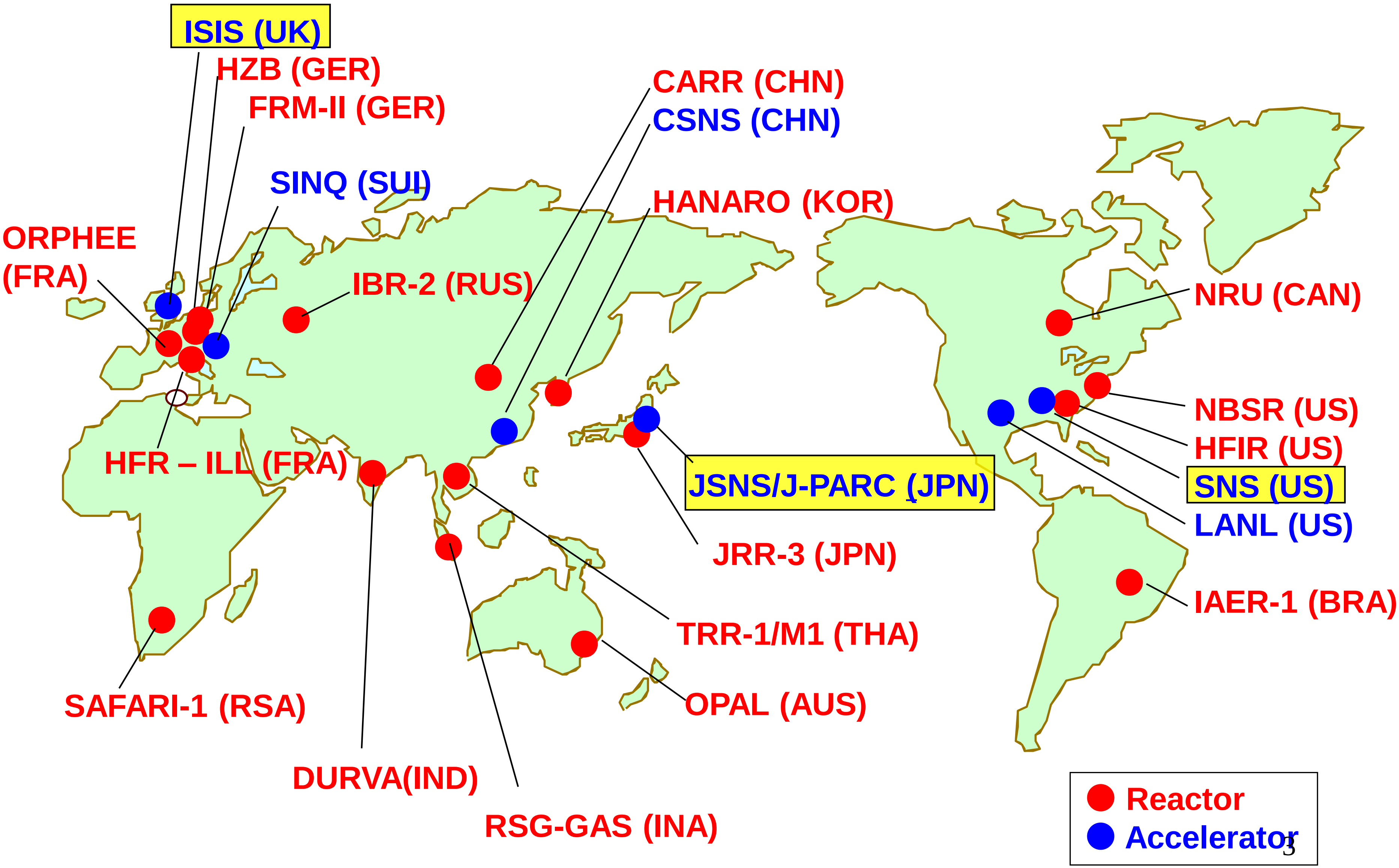
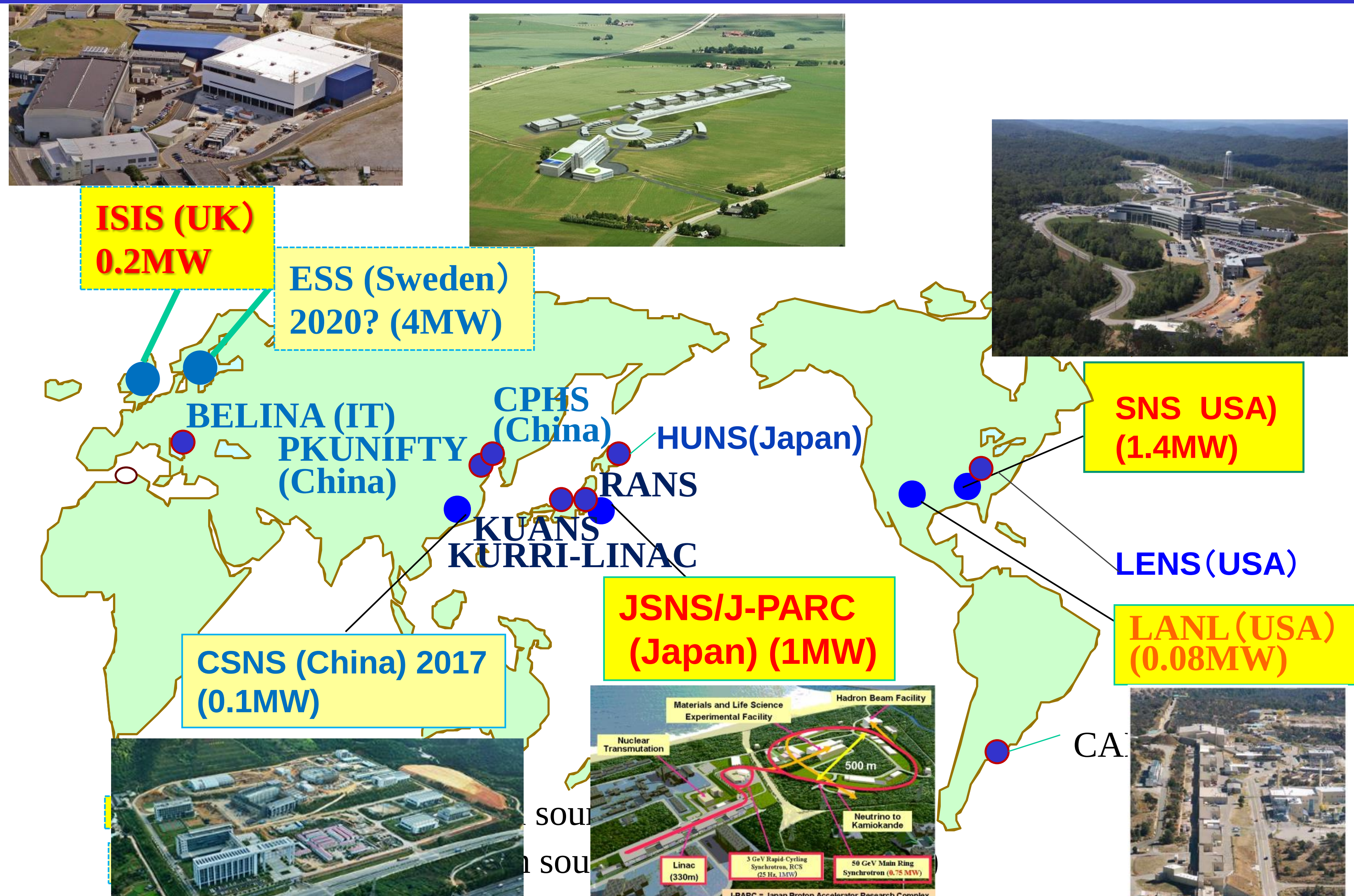
1. Neutron sources and neutron production reactions
2. Neutron slowing down
3. Development of J-PARC neutron source (JSNS)
4. Structure of J-PARC neutron source (JSNS)
5. Summary

1. Neutron sources and neutron production reactions

Major Neutron Sources in the World

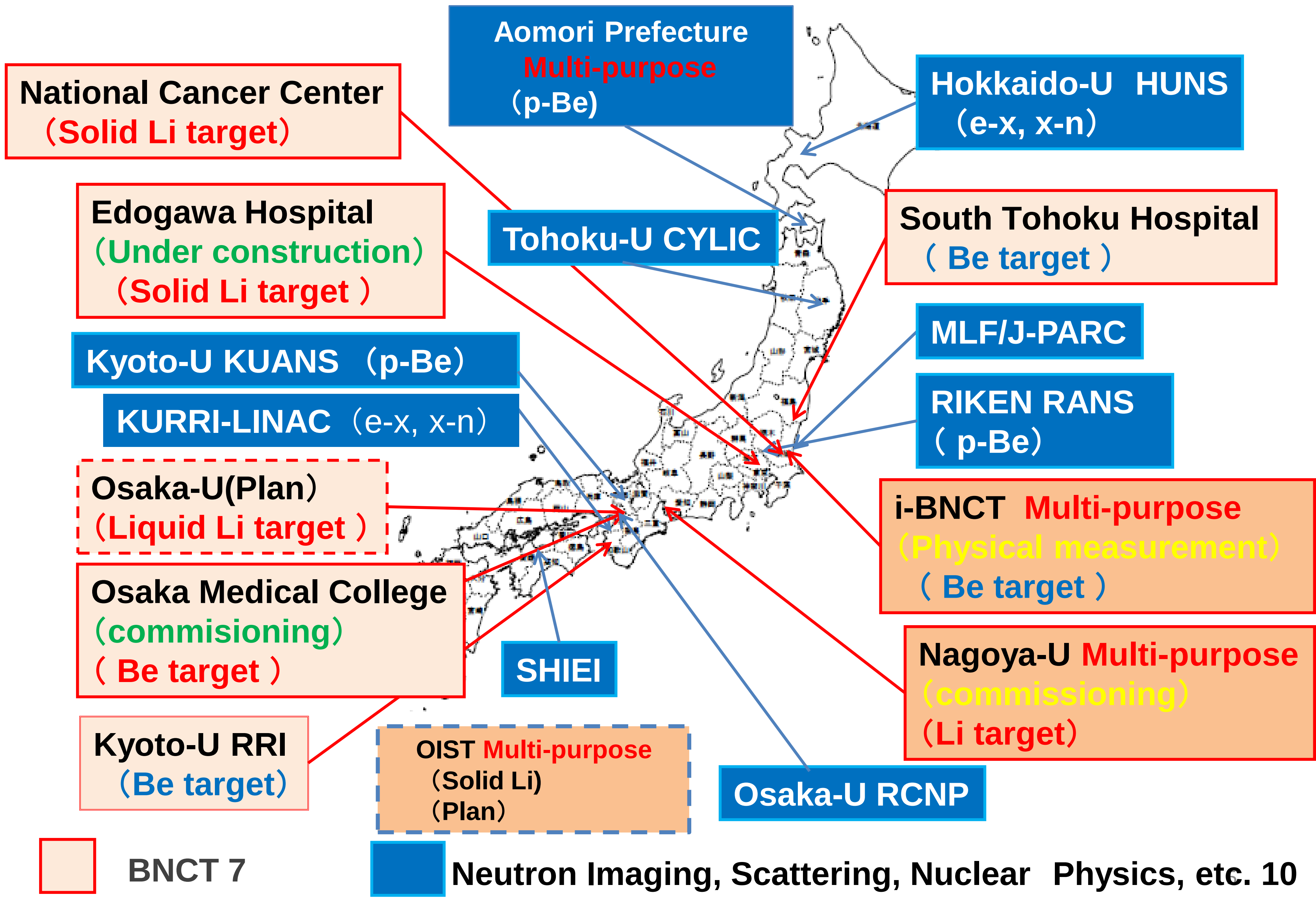


Accelerator driven neutron sources in the world



There are many small accelerator driven neutron sources for nuclear data measurement and imaging.

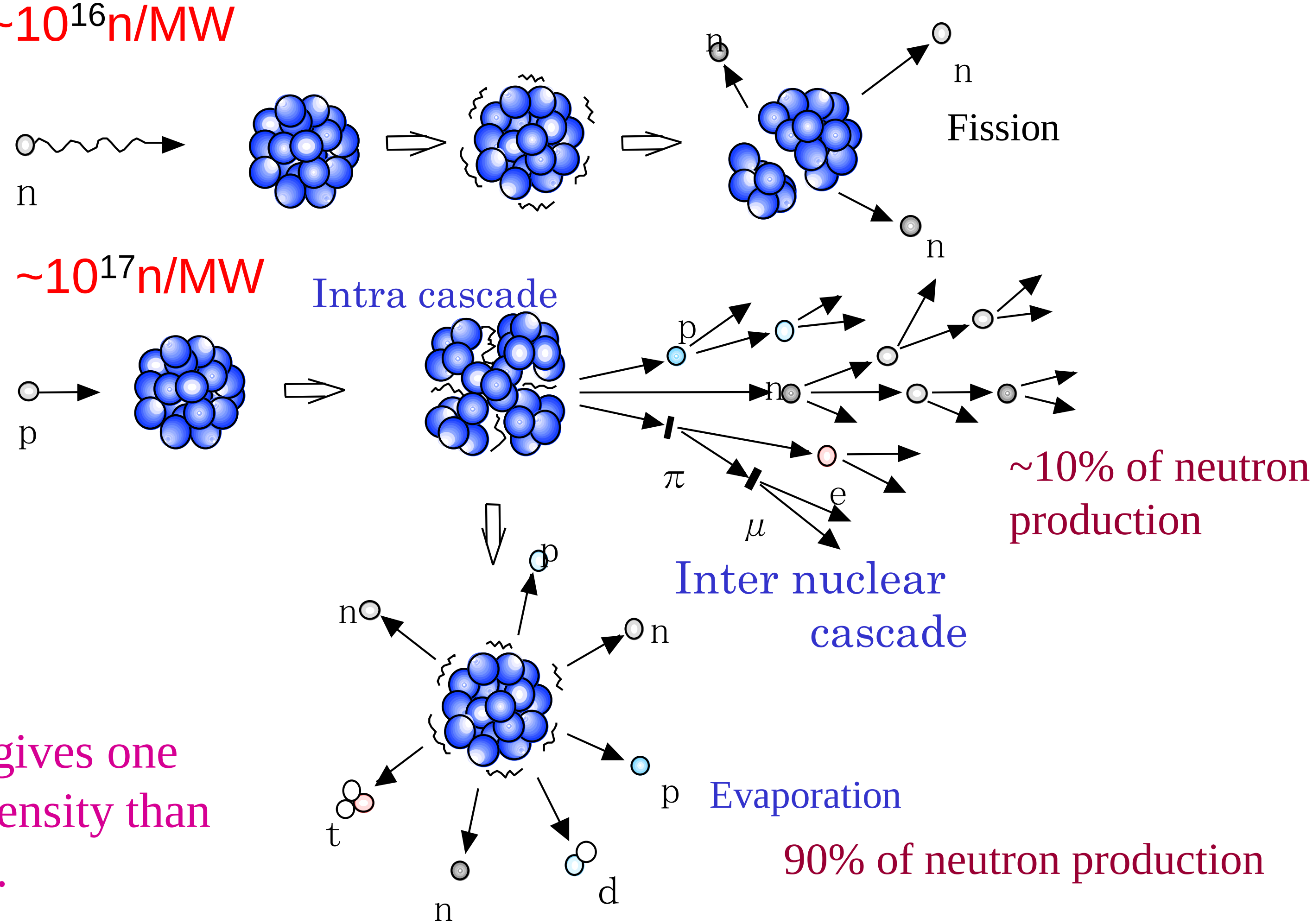
Accelerator-driven Neutron Sources in Japan



Neutron production reactions

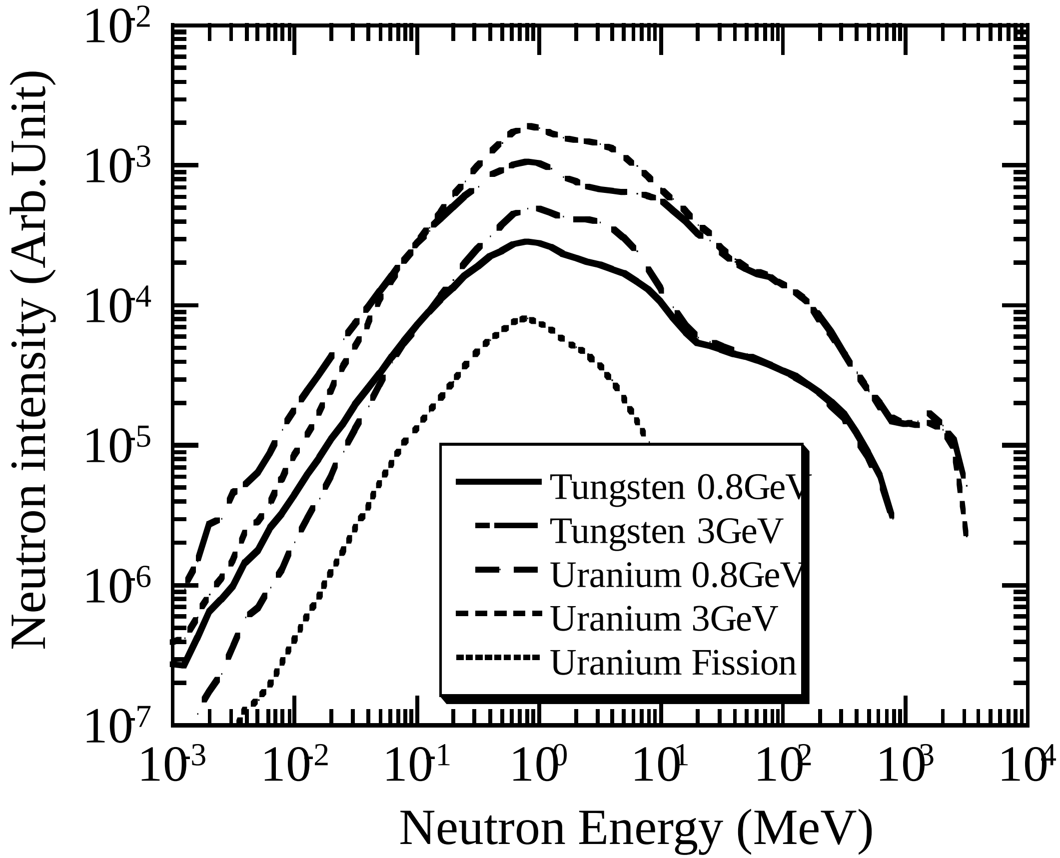
Fission ~10^{16}n/MW

Spallation ~10^{17}n/MW



The Spallation gives one order higher intensity than the fission does.

Energy spectra of produced neutrons by spallation and fission



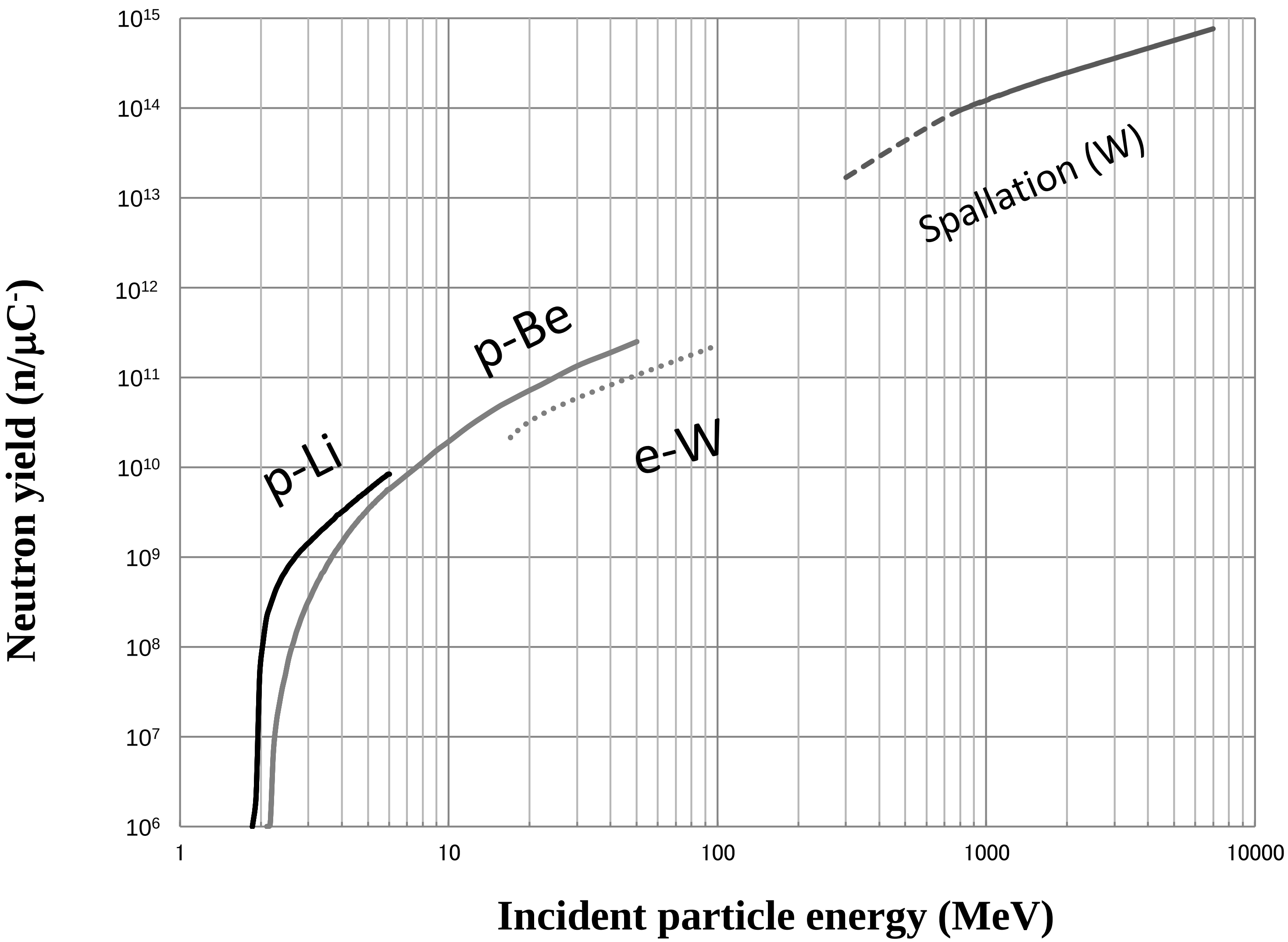
Target materials for the spallation neutron source

Heavy materials

W, Ta, Hg, Pb, U

The energy spectra of the produced neutrons are almost the same around the peak, where the peak energy is around few MeV.

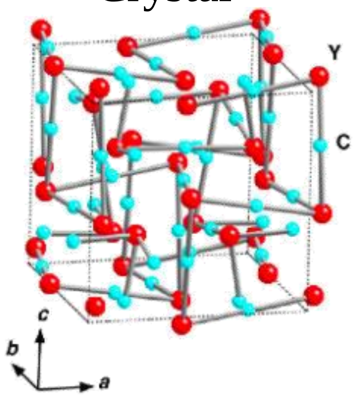
Neutron yields dependent on particle energy



Required energy range for material research

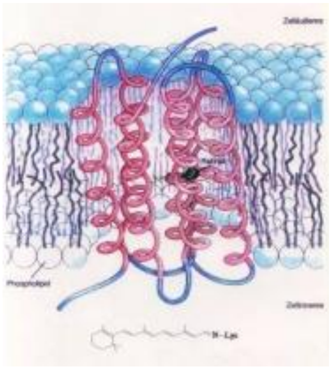
Structure analysis

Crystal



~0.1nm

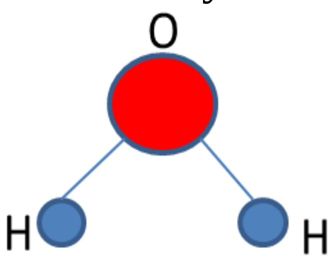
Membrane



~10nm

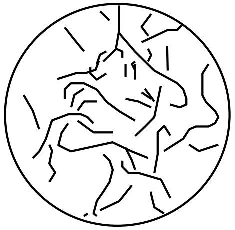
Dynamics

Molecular dynamics



~eV

Diffusion

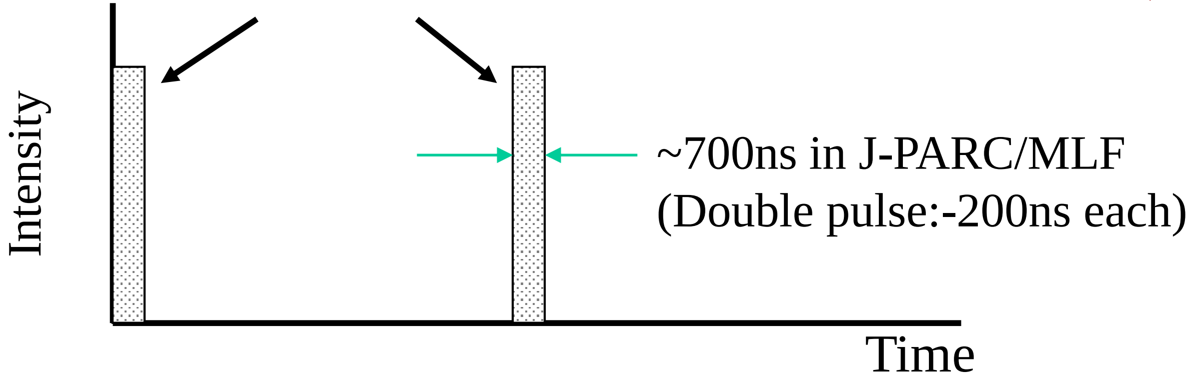


~neV-μeV

The MeV range neutrons have to be moderated to few eV ~ nano eV region

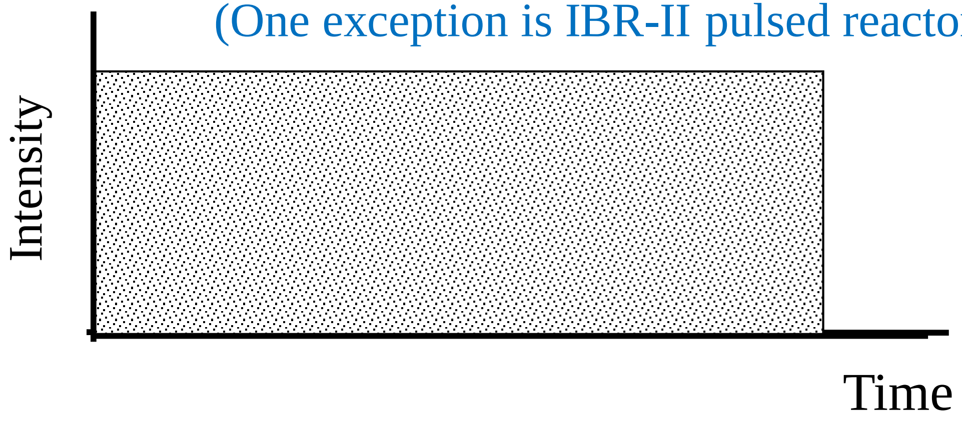
Neutron production scheme in a reactor and a pulsed neutron source

Accelerator-based neutron source (Pulsed neutron source)

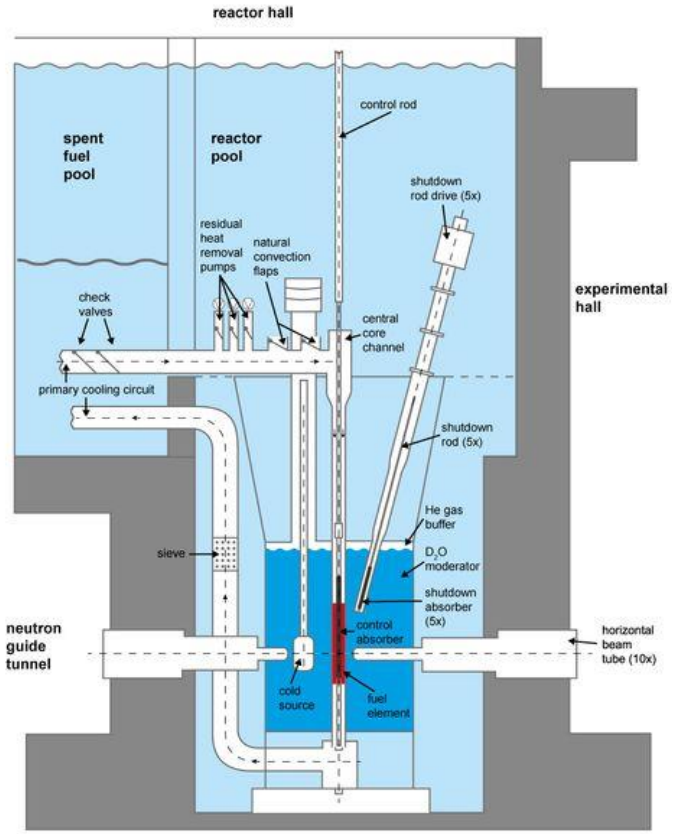


Reactor source (Steady neutron source)

(One exception is IBR-II pulsed reactor in Russia)



Research reactor

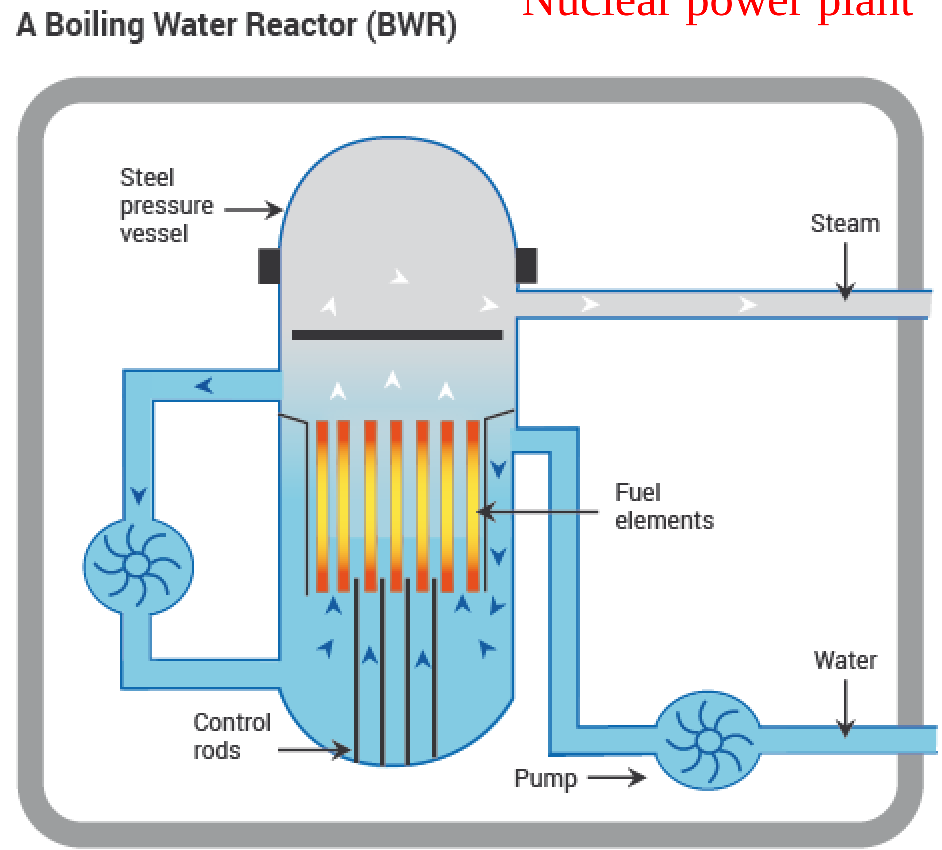


Section of the reactor and spent fuel pool (Copyright: FRM II/TUM)

https://www.frm2.tum.de/en/the-neutron-source/reactor/installations-in-the-pool/

Small and high power density reactor core to produce high neutron flux. Heat density is usually higher than power plants.

Nuclear power plant



http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/nuclear-power-reactors.aspx

Large reactor core to attain high power integrated over the whole core.

2. Neutron slowing down

Moderation by classical collision

Neutrons are moderated from MeV to sub-eV by classical collisions.

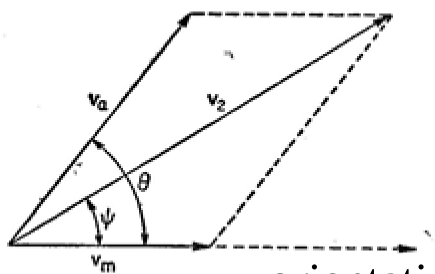
(Classical mechanics of slowing down)

E_1: *Energy before the collision*, E_2: *Energy after the collision*

υ_1 :*Velocity before the collision*, υ_2 :*Velocity after the collision*,

$$\upsilon_a = \frac{A\upsilon_1}{A+1}$$ Neutron velocity at CMS

$$\upsilon_b = \frac{\upsilon_1}{A+1}$$ Velocity of target material at CMS



υ_1 orientation

$$\frac{E_2}{E_1} = \frac{\upsilon_2^{\,2}}{\upsilon_1^{\,2}} = \frac{A^2 + 2A\cos\theta + 1}{(A+1)^2}$$

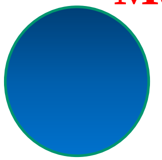
θ: Scattering angle in the center of mass system (CMS)

$$\alpha \equiv \left(\frac{A-1}{A+1}\right)^2$$

$A = M_A/m_n$ ≒ Mass number

Neutron

Material mass A



$$\frac{E_2}{E_1} = \frac{1}{2}\left[(1+\alpha) + (1-\alpha)\cos\theta\right]$$

Minimum energy getting to by one collision $E_{min} = \alpha E_1$

Small A→ small *α, and H is effective.*

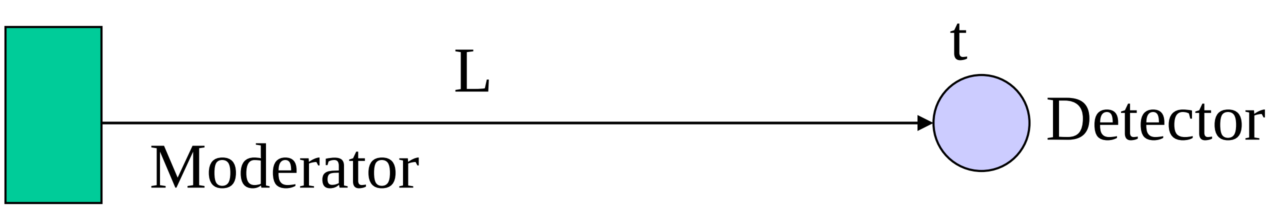
Time of flight energy analysis at a pulsed neutron source

Time-of-flight method

At pulsed neutron sources, we can analyze the neutron energy by measuring the flight time of neutron.

$$t = L/v, \quad \text{then,} \quad v = L/t.$$

Here, t is flight time of neutron,
L is flight path length
v is neutron velocity

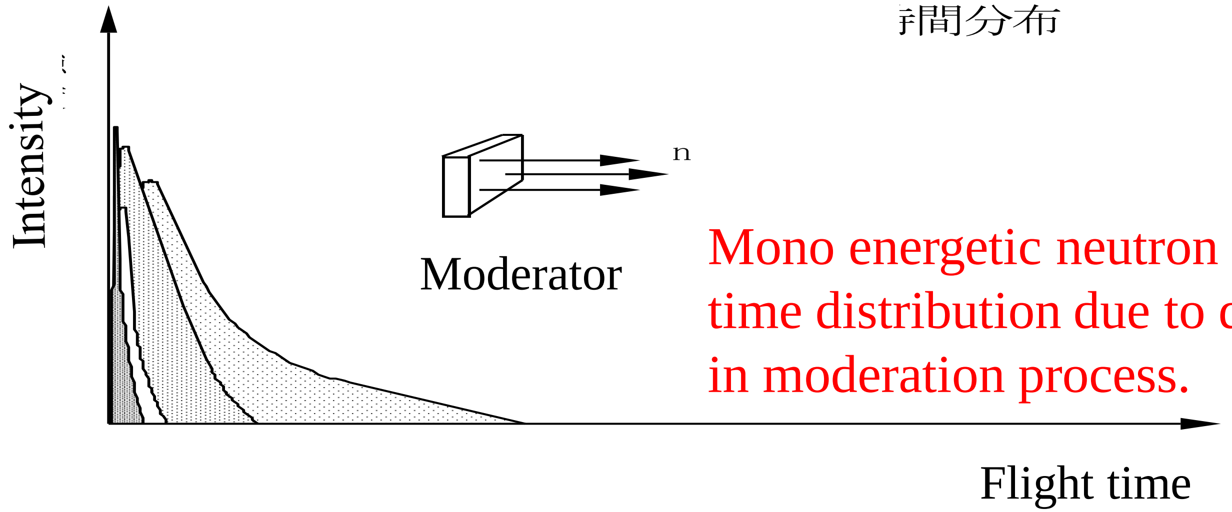


Energy resolution of time-of-flight method

$$\Delta E/E=2|\Delta t/t|$$

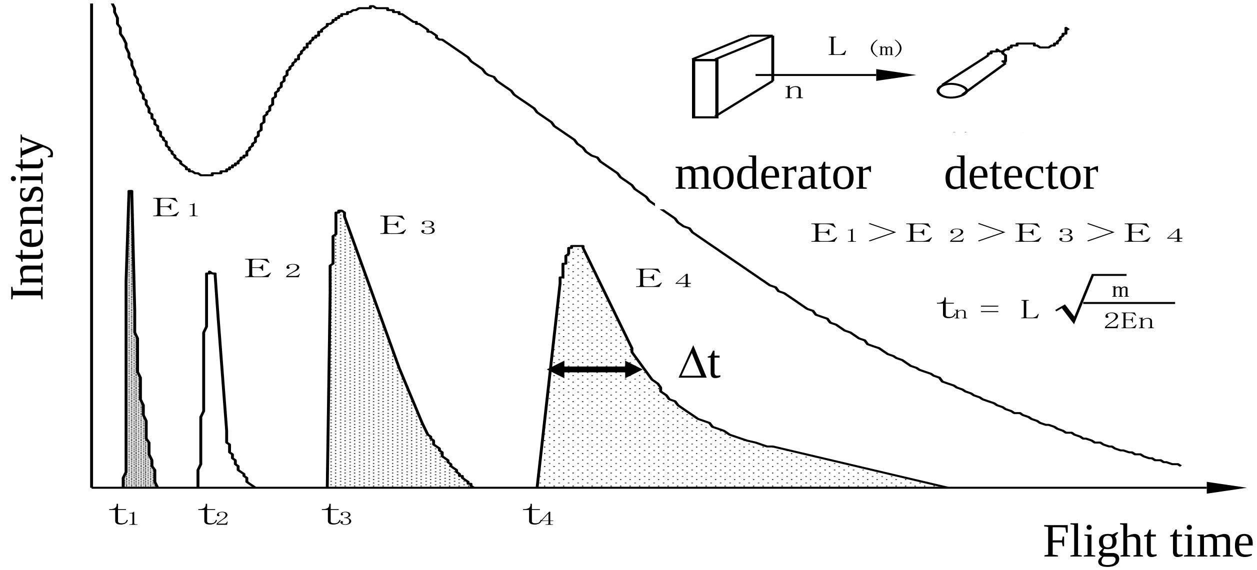
Therefore, to obtain good energy resolution we need a moderator that produces narrower neutron pulse, namely, has short moderation time.

Time distribution (pulse shape) of neutrons at the moderator surface



Mono energetic neutron also has time distribution due to difference in moderation process.

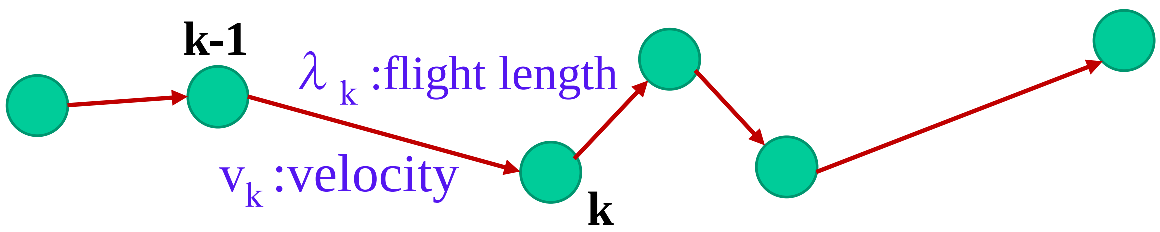
Time of flight spectra at position L and time distribution



Basic consideration on elapsed time desired for moderation process

The number of collisions to get to a certain energy: n,
Flight time from (k-1)-th to k-th collision: t_k,
then, the time required for moderation, t_m is expressed by

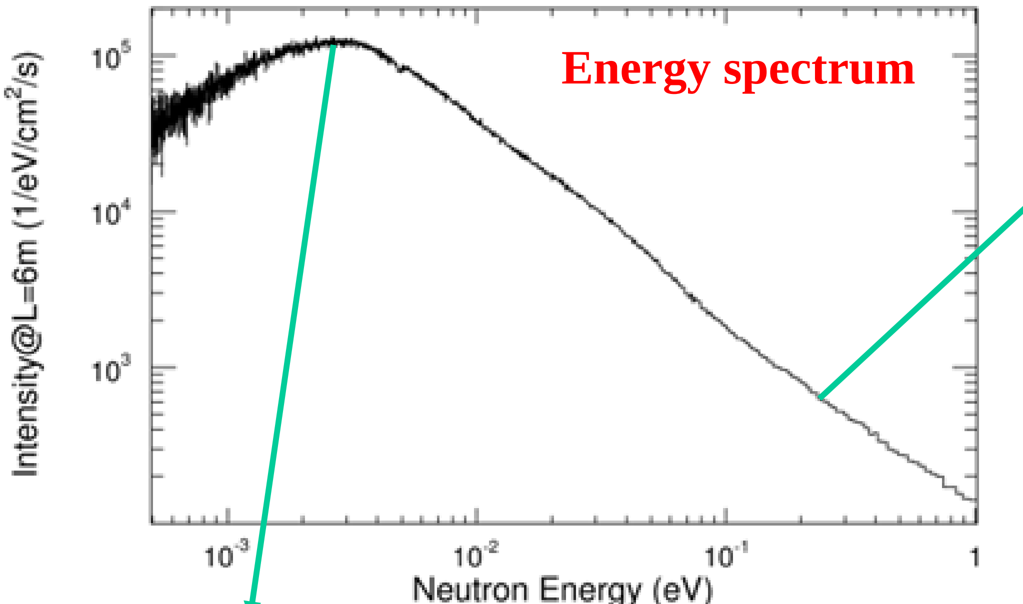
$$t_m = \sum_{k=1}^{n} t_k = \sum_{k=1}^{n} \lambda_k / v_k \propto \sum_{k=1}^{n} (\Sigma_t v_k)^{-1}$$



Therefore, characteristics required for a moderator material are smaller collision number (smaller mass number) and shorter mean free path (large cross section).

The material fulfilling the property is hydrogenous material.

Time distribution



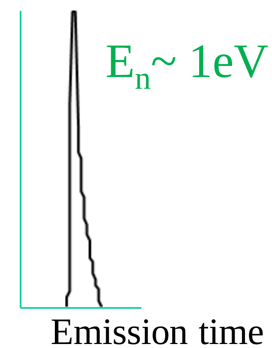
Slowing down region $f_s(v, t)$

$f_s(v,t)=(vt\Sigma_s)^2 exp(-vt\Sigma_s)$.

Standard deviation

$\Delta t_s(v)=3^{1/2}/(v\Sigma_s)$

Σ_s : macro-scattering cross section



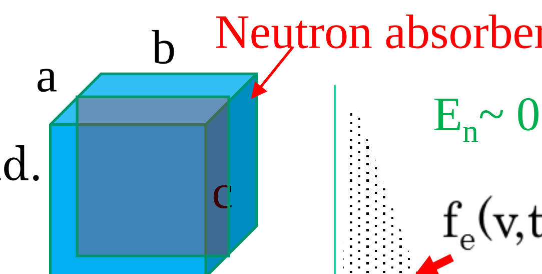
Thermal equilibrium specrrum: $f_e(v,t)$

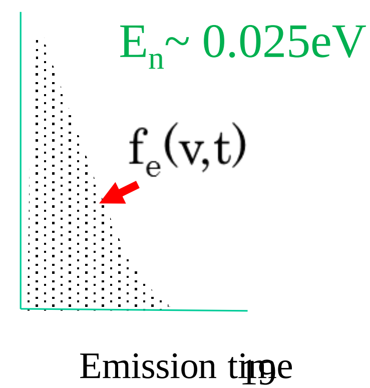
$f_e(v,t)=exp[-vt(\Sigma_a+DB^2)]$

Here, Σ_a is macro-absorption cross section. D is diffusion constant. B^2 is buckling defined as

$B^2=\pi^2(1/a^2+1/b^2+1/c^2)$

Here, a, b and c are lengths of sides of a cuboid.



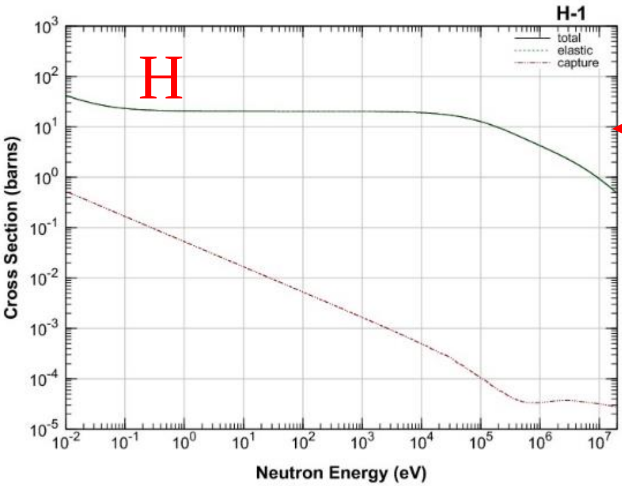


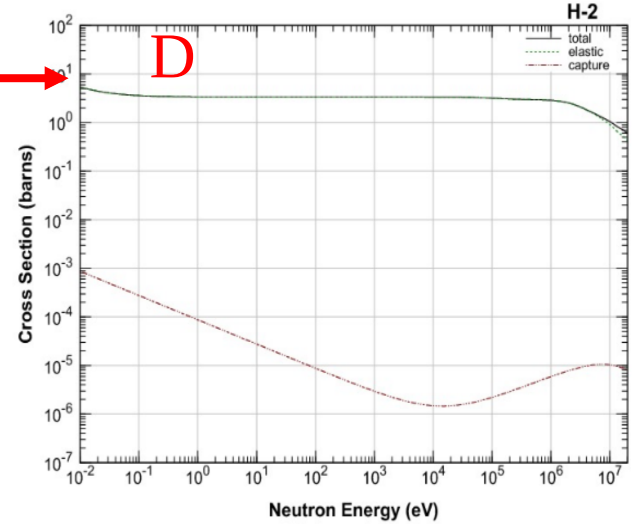
Time distribution $=f_s(v, t)\otimes f_e(v,t)$

Therefore, thin moderator or poisoned moderator give narrower pulse shape.

H vs. D

Neutron cross section of H and D

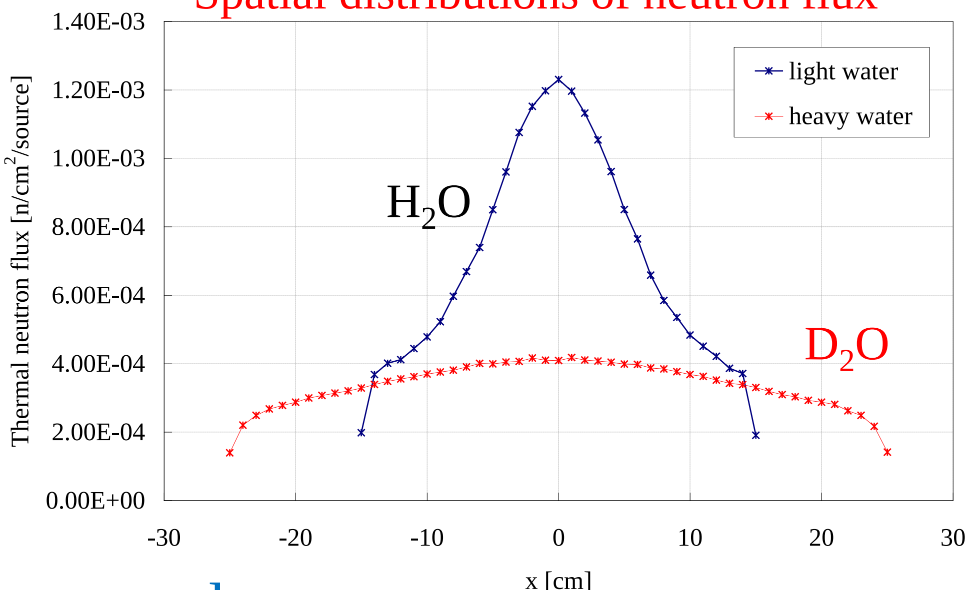




$\sigma_H \fallingdotseq 7\ \sigma_D$

Higher neutron flux

Spatial distributions of neutron flux



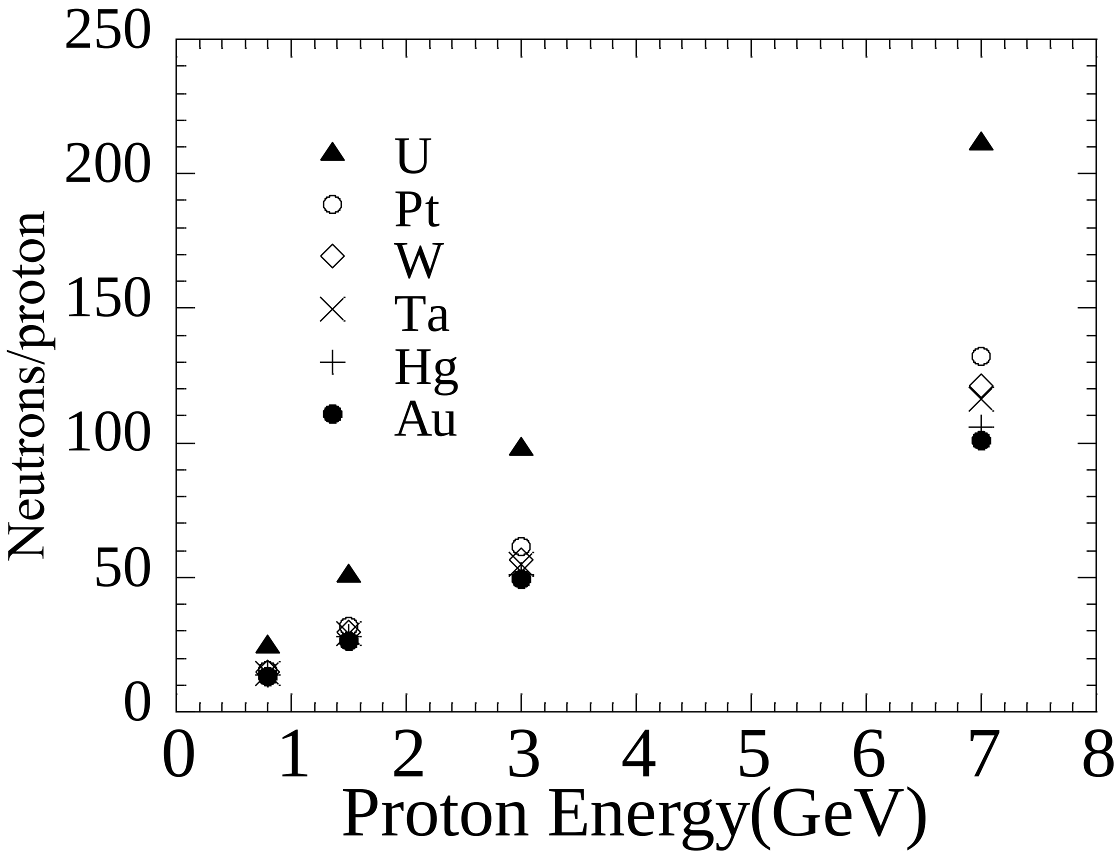
H is much better than D at an accelerator source.

3. Development of J-PARC neutron source (JSNS)

- Why we developed a coupled moderator? -

Target materials

Neutron yield vs. proton energy



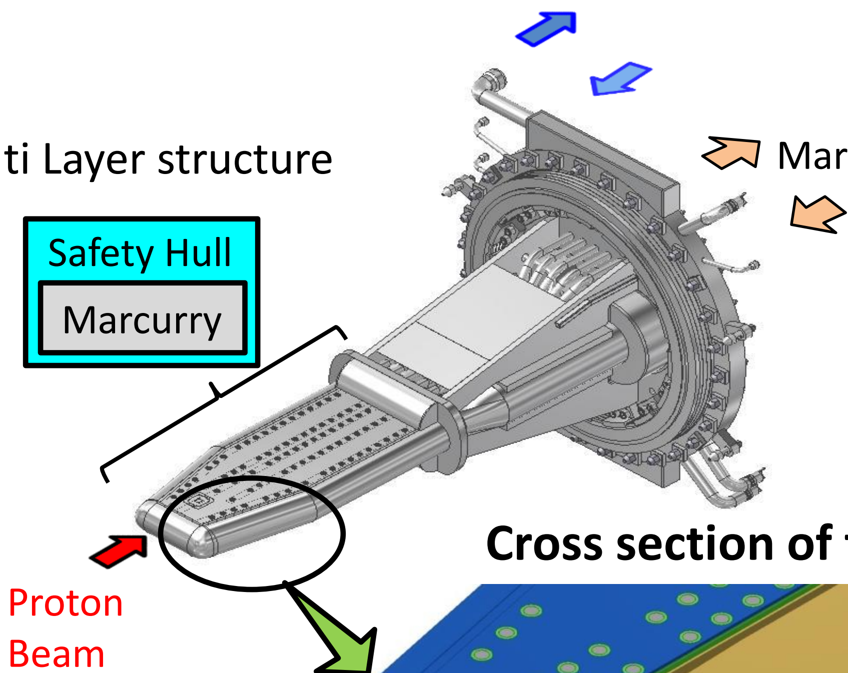
Neutron yield is not so different in heavy materials other than U that produces fission neutrons.

We have chosen Hg due to the reason that Hg can be used at higher power than 1 MW.

Hg target at J-PARC

Water Coolant in Safety Hull

Multi Layer structure



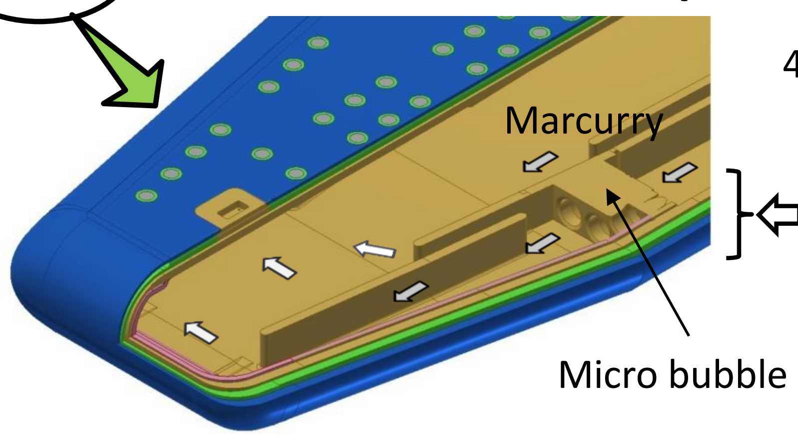
Target Container

Material : SUS316L

Weight : 1.6 t

Length : 2m

Cross section of top area



4 layer walls at a window part

- Inner wall
- Marcurry cantainer
- Safety hull（Inner）
- Safety hull（Outer）

Micro bubble producer

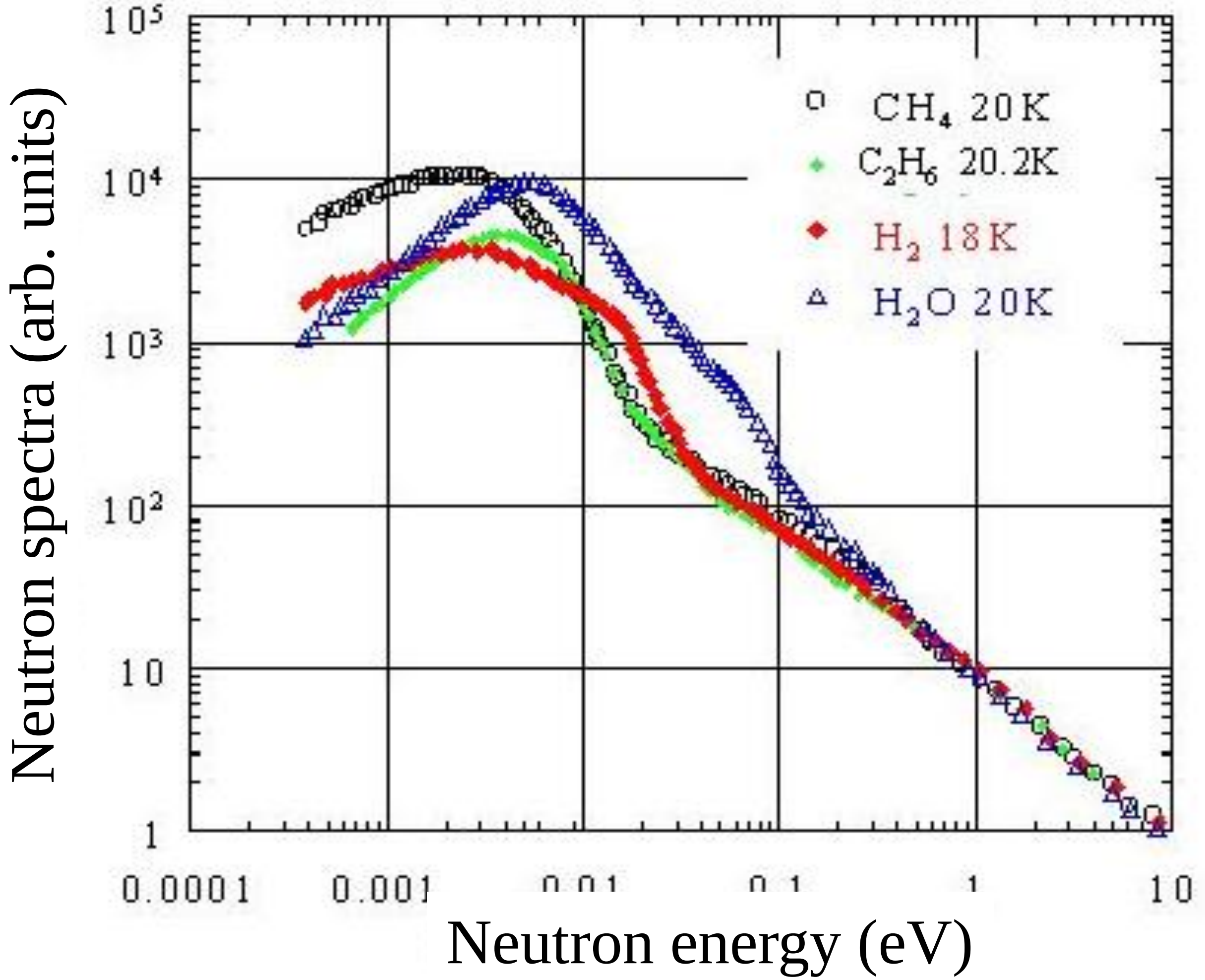
Moderator

We chose three moderators as cold (low temperature) moderator to get wide energy range neutron spectra, so we looked for the best moderator system.

Neutron moderator materials

	Hydrogen density* (*#/cm^3)	Temperature	Melting	Boiling	Used facility
H_2O	6.7×10^{22}	~300K	273K	373K	LANSCE, ISIS
CH_2	8.2×10^{22}	~300K			
CH_4	7.8×10^{22}	20K,105K	99.6K	111.7K	ISIS
H_2	4.5×10^{22}	15K	20.4K	14.7K	LANSCE,ISIS
ZrH_2	7.23×10^{22}				
C_6H_6	4.07×10^{22}				
C_9H_{12}	5.2×10^{22}	300～20K	229K	437K	

Energy spectra from the various low temperature moderators

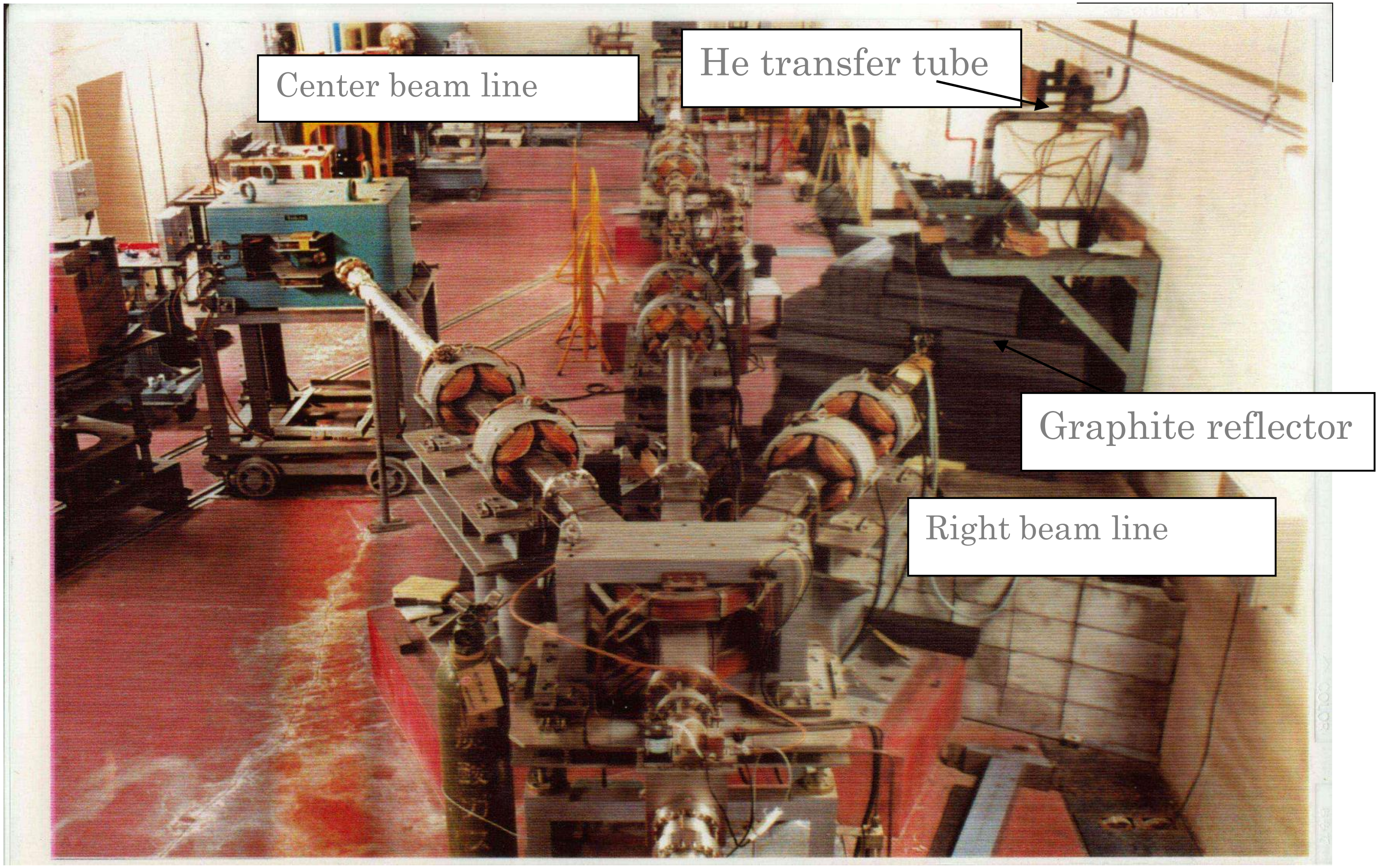


Methane is the best, but this cannot be used due to radiation damage.

Therefore, we had to choose H_2 since it is stable at high power source.

How can we improve the neutronic performance of H_2?

Experiments were performed at Hokkaido electron linac to develop a new type moderator

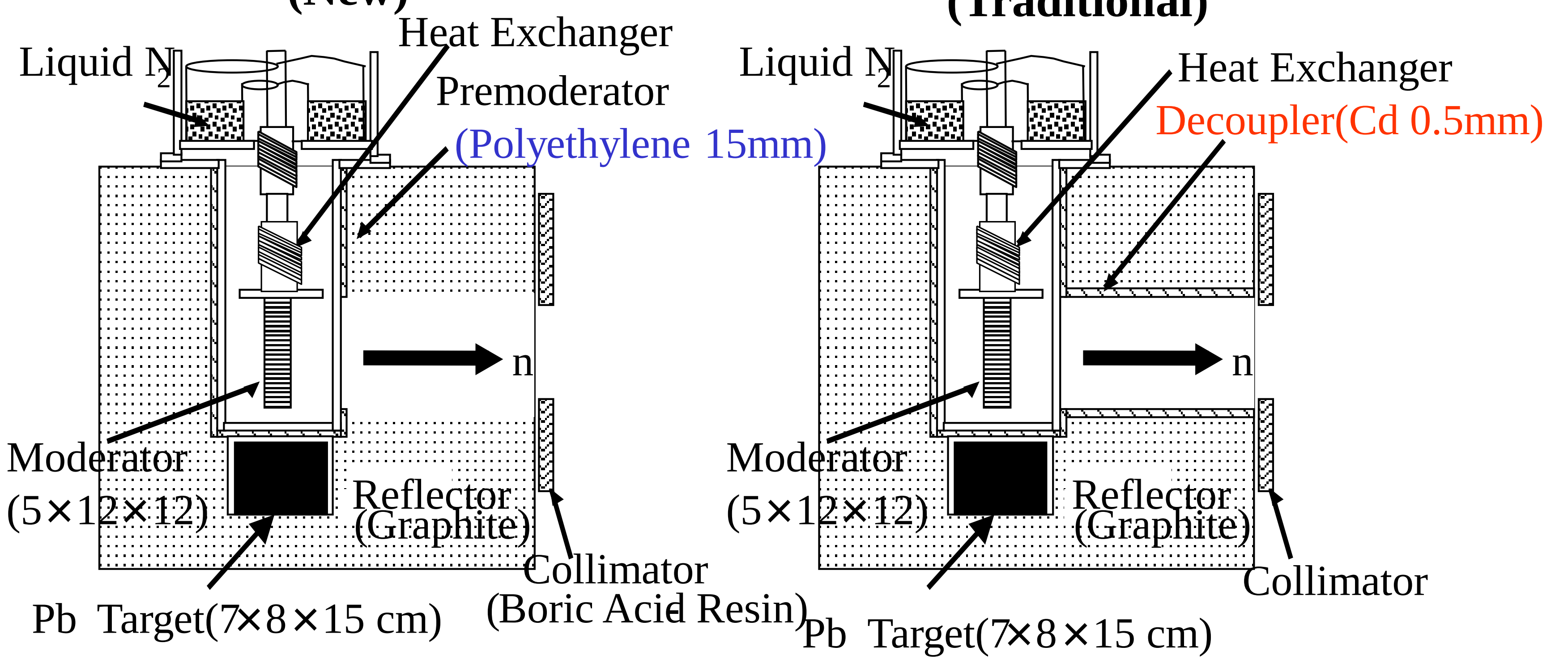


HUNS (Hokkaido University Neutron Source)

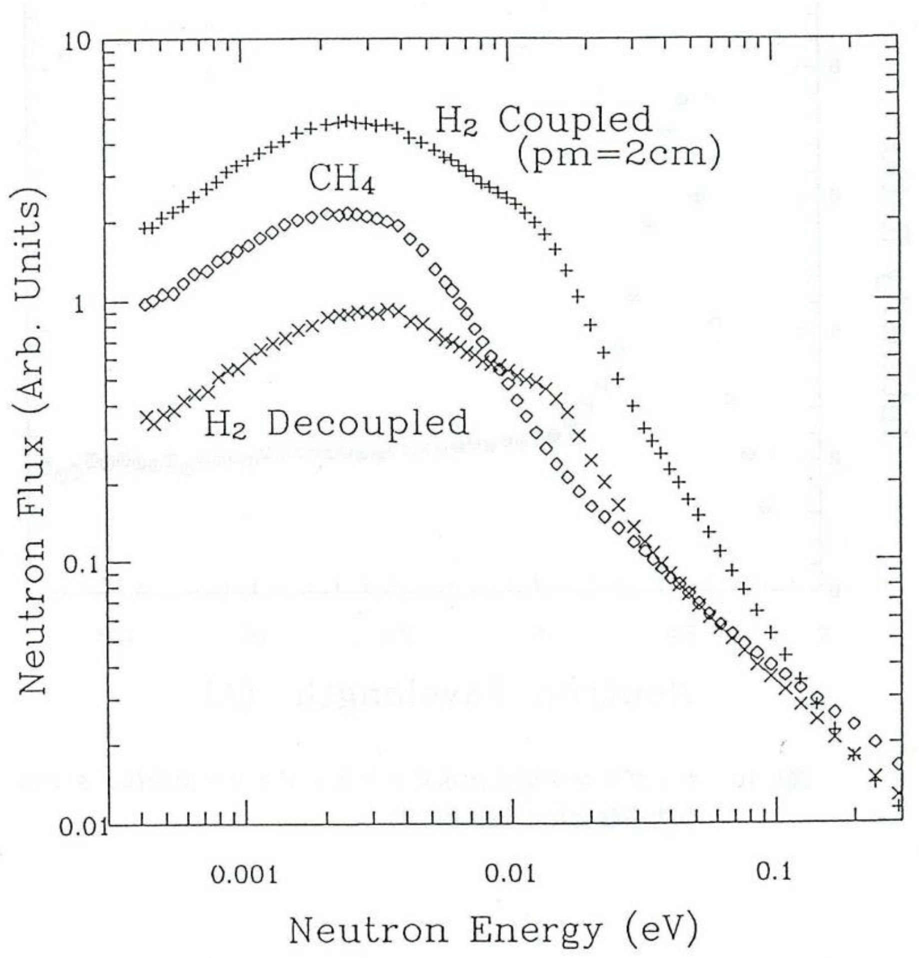
Moderator types

(Examples used for Hokkaido linac experiments)

For high intensity	For high resolution
Coupled moderator	**Decoupled moderator**
(New)	**(Traditional)**



Performance of a coupled moderator



The coupled moderator gives higher intensity than the methane moderator.

Ortho and para hydrogen

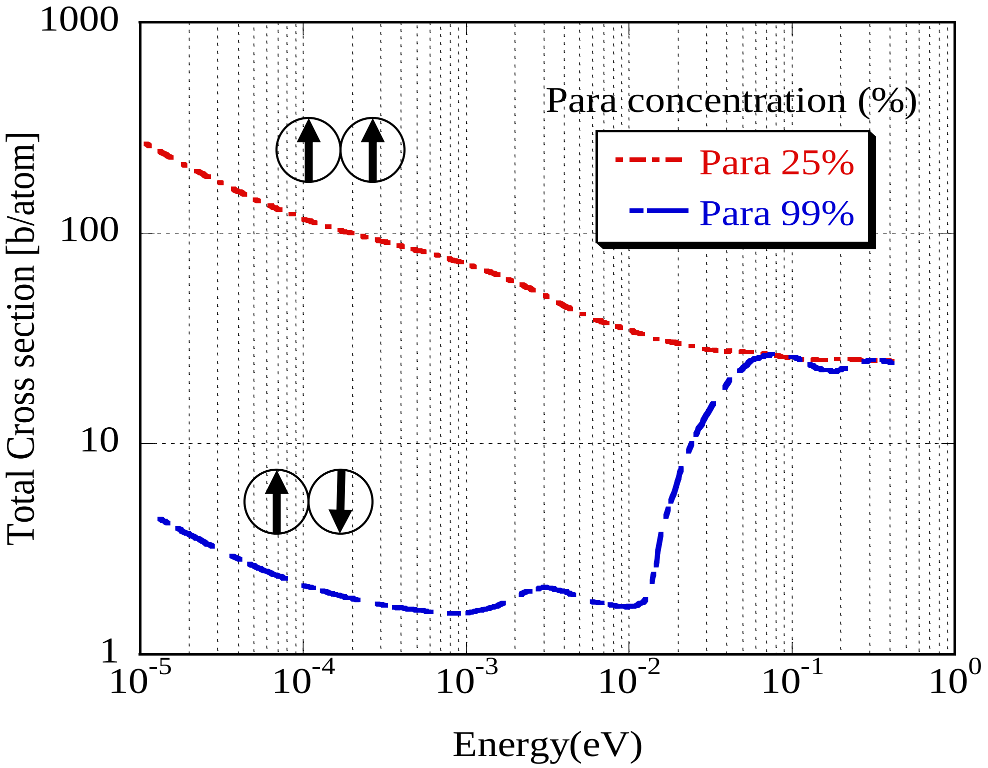
(Idea for further improvement)

Adoption of para H_2

Ortho: Up-scattering

Para: Down-scattering

Cross section of hydrogen

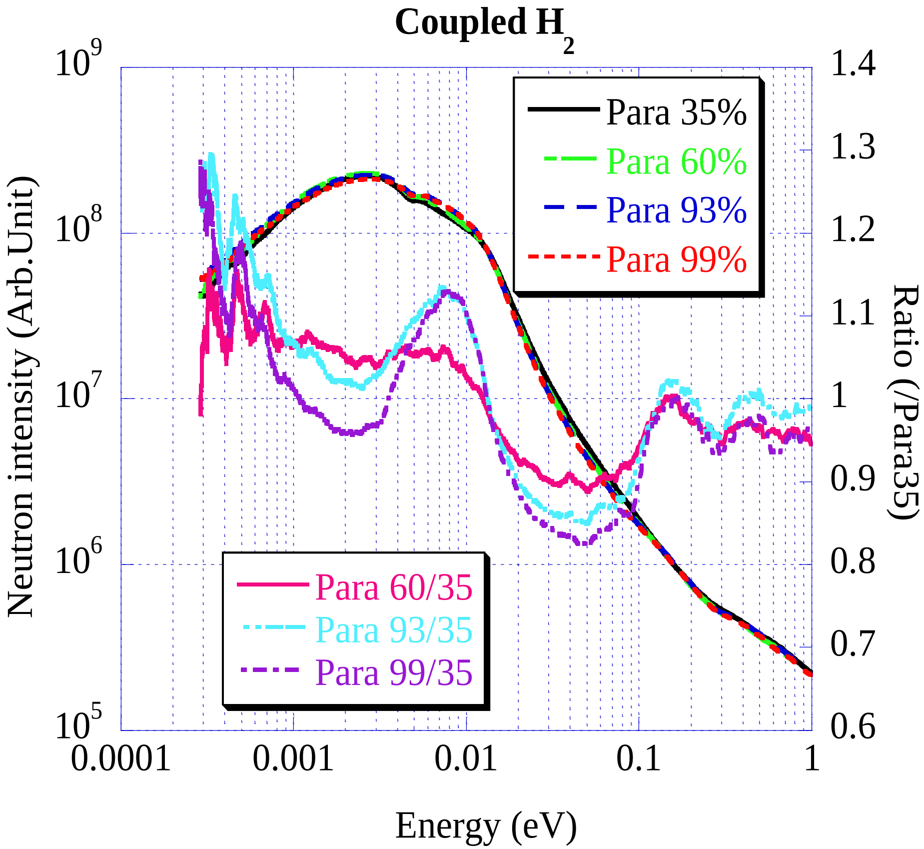


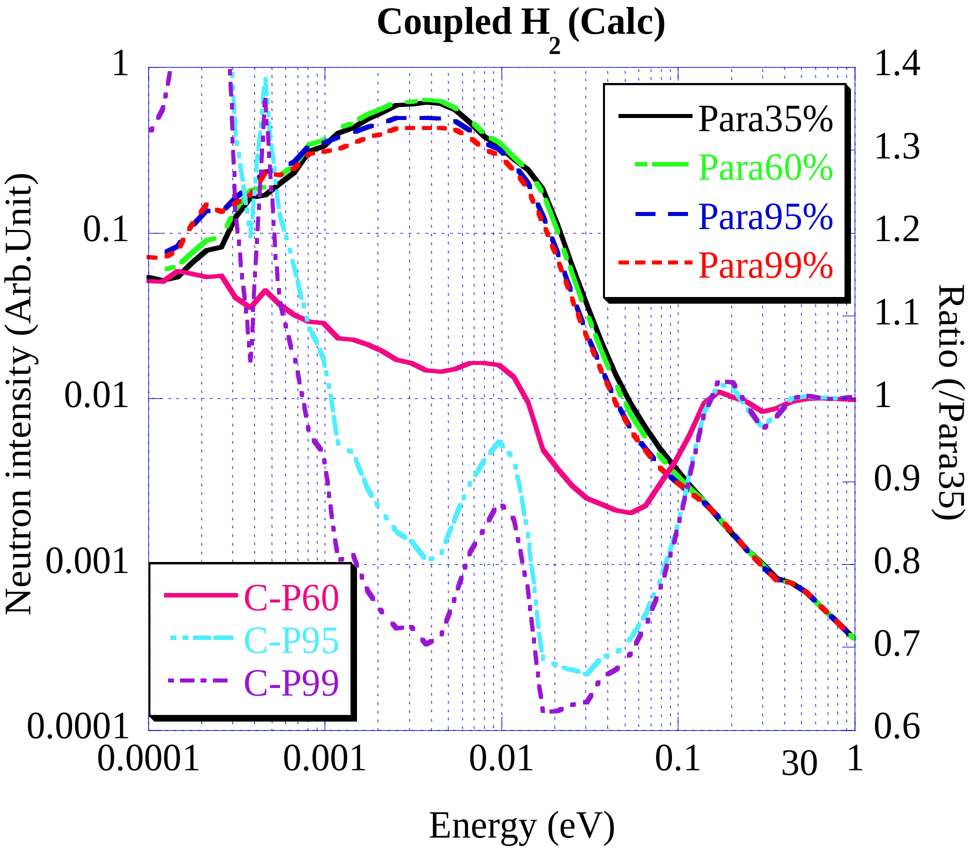
Para hydrogen: higher intensity and narrower pulse shape?

Energy spectra of a coupled moderator

Experiment

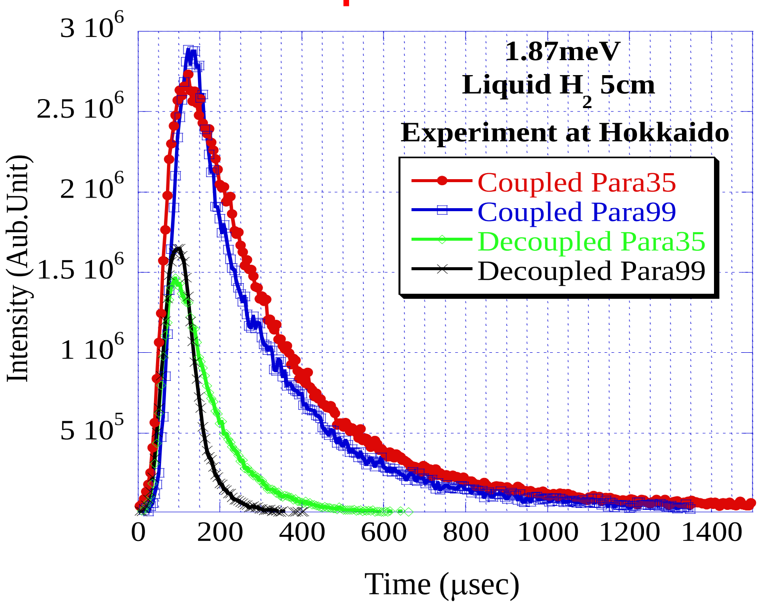
Calculation



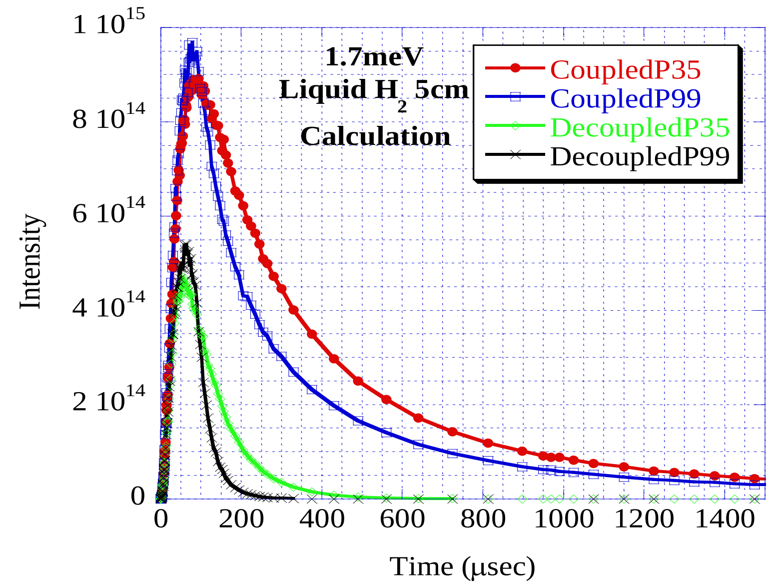


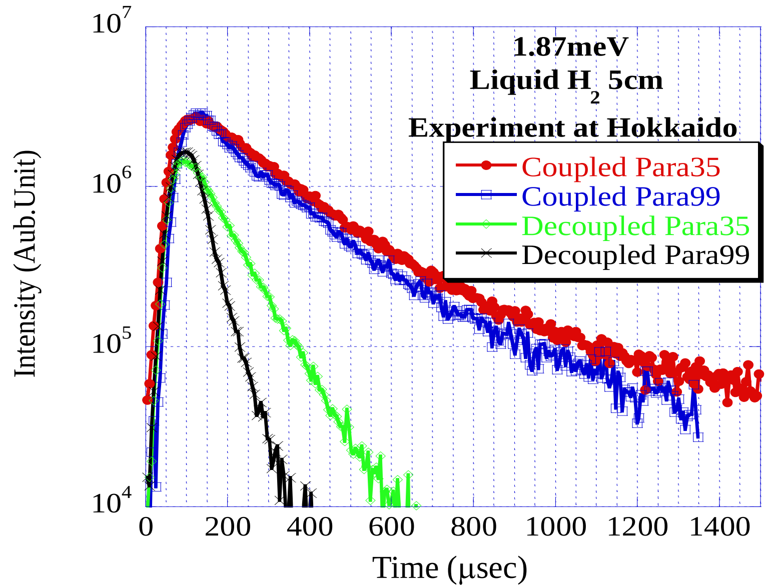
Comparison of pulse shapes at 1.8 meV

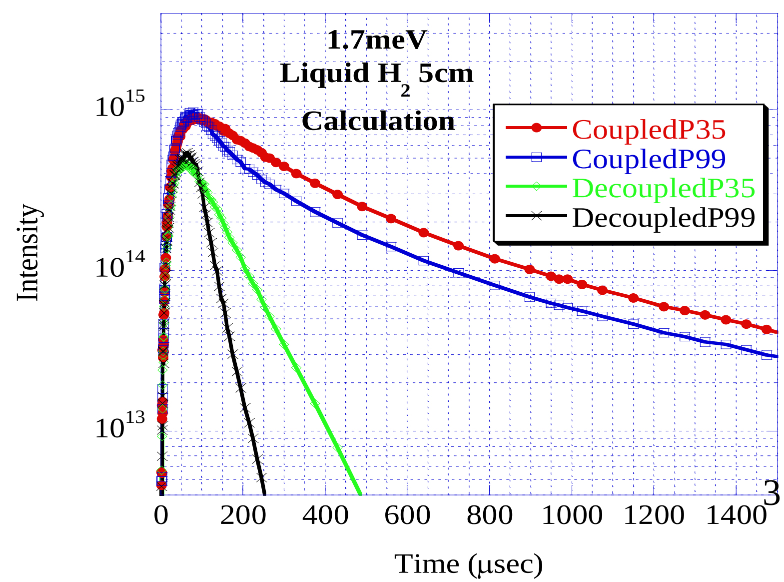
Experiment



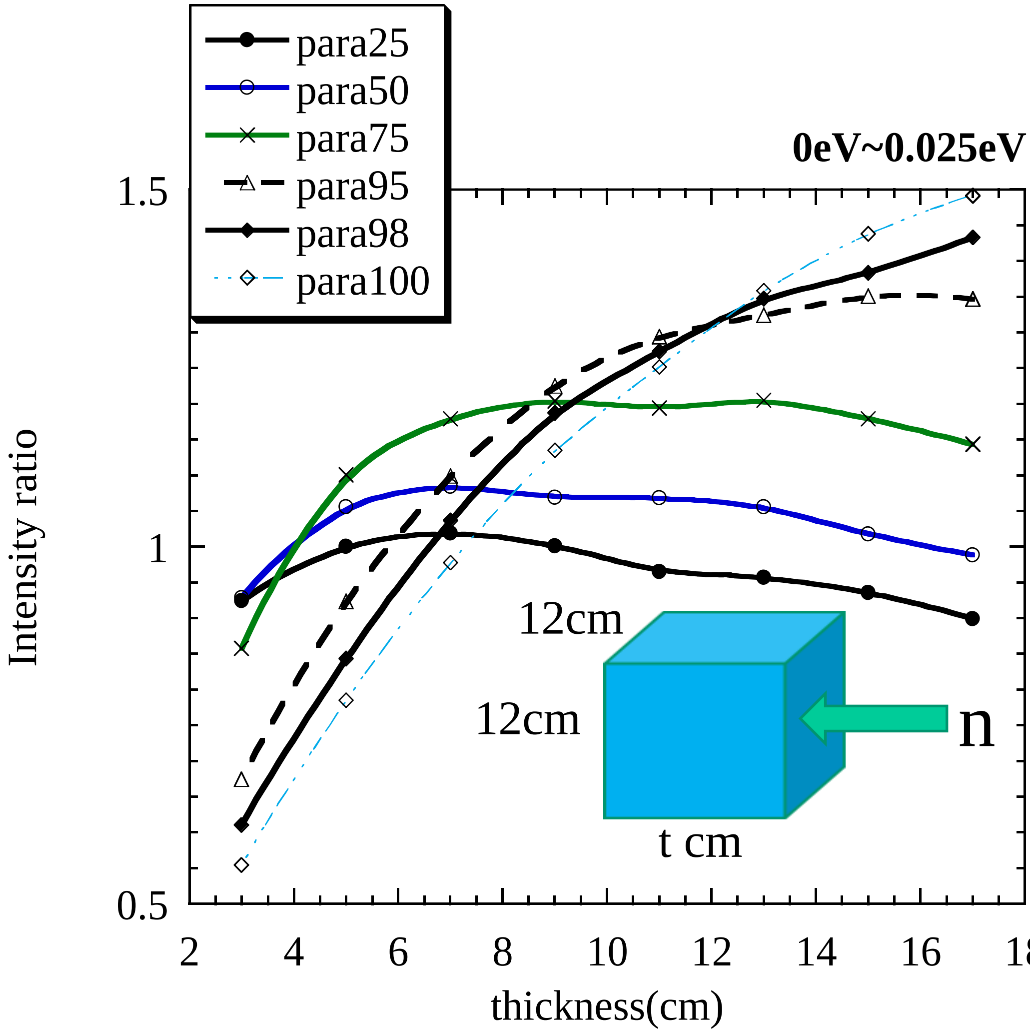
Calculation



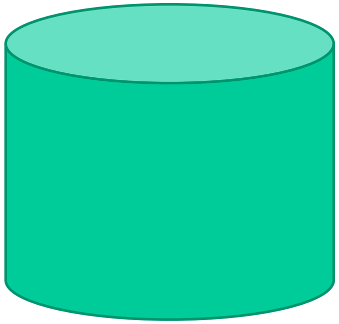




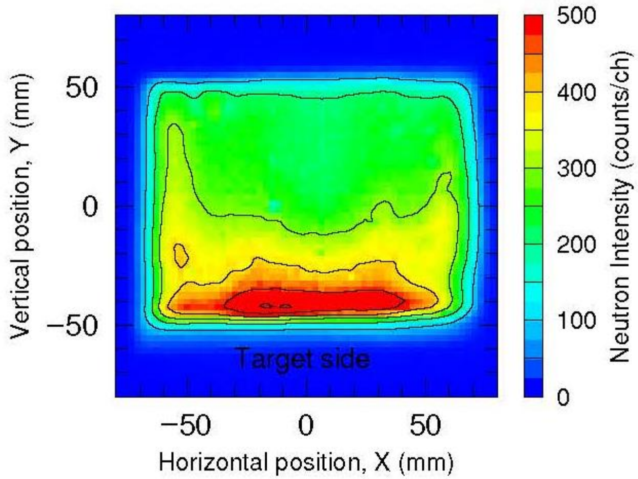
Para-hydrogen concentration vs. neutron intensity of a coupled moderator (Simulation)



J-PARC coupled moderator

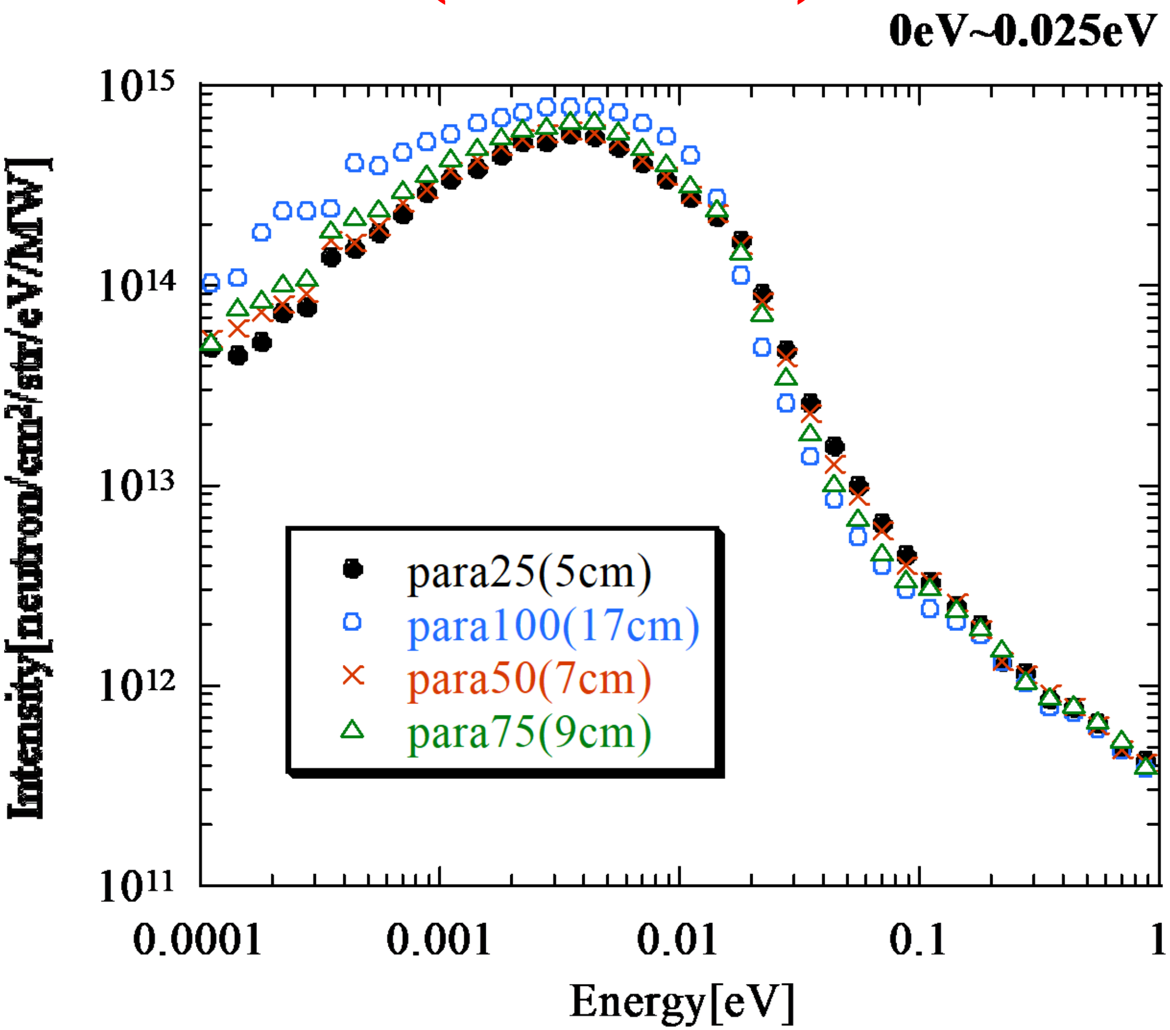


140 mm diameter x 100 mm height

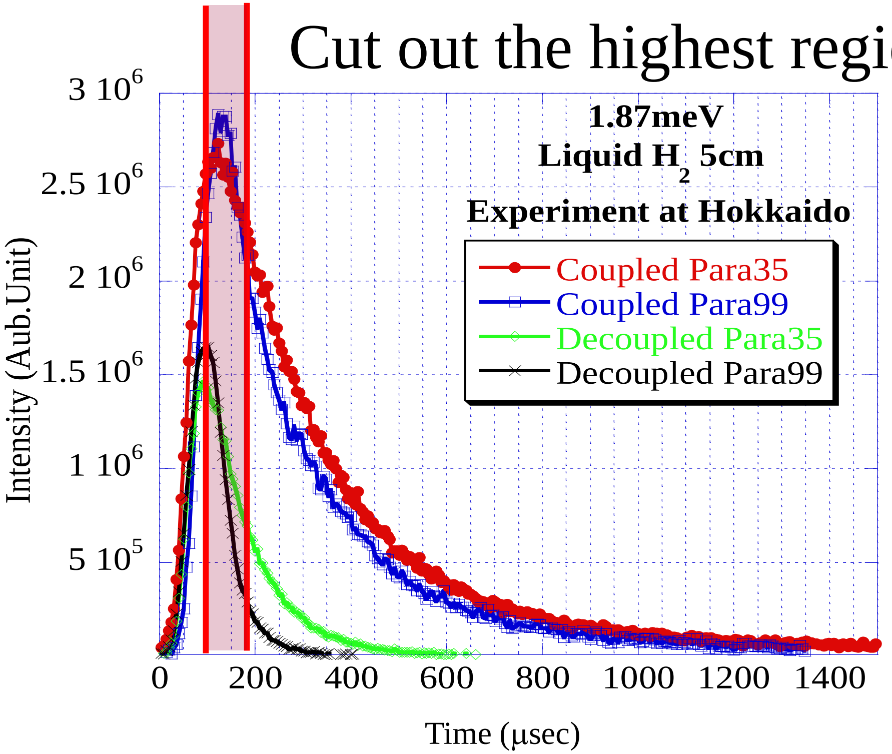


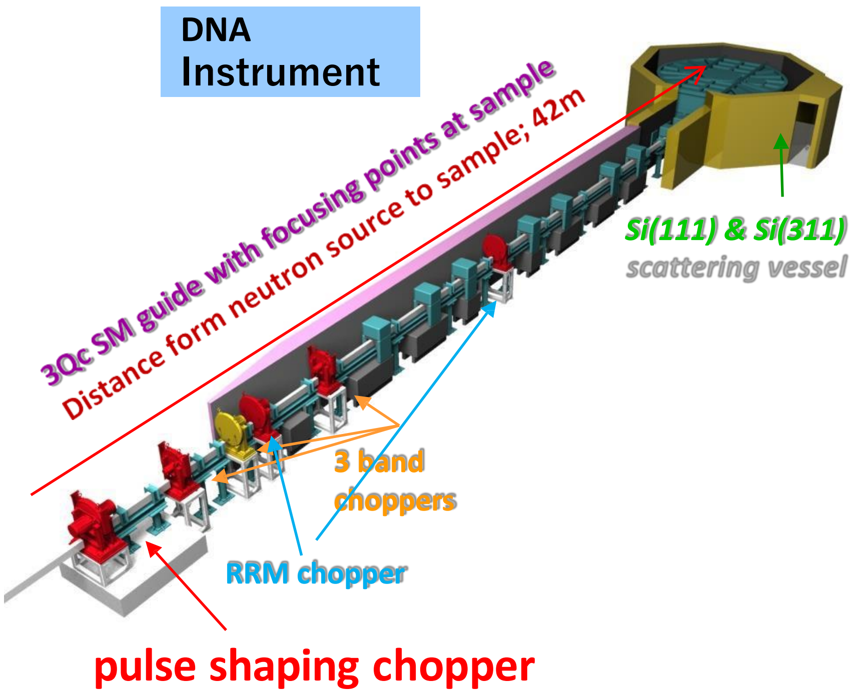
Flat horizontal distribution
(measured at Hokkaido U.)

Energy spectra of a coupled moderator at optimal thicknessess for various para concentration (Simulation)

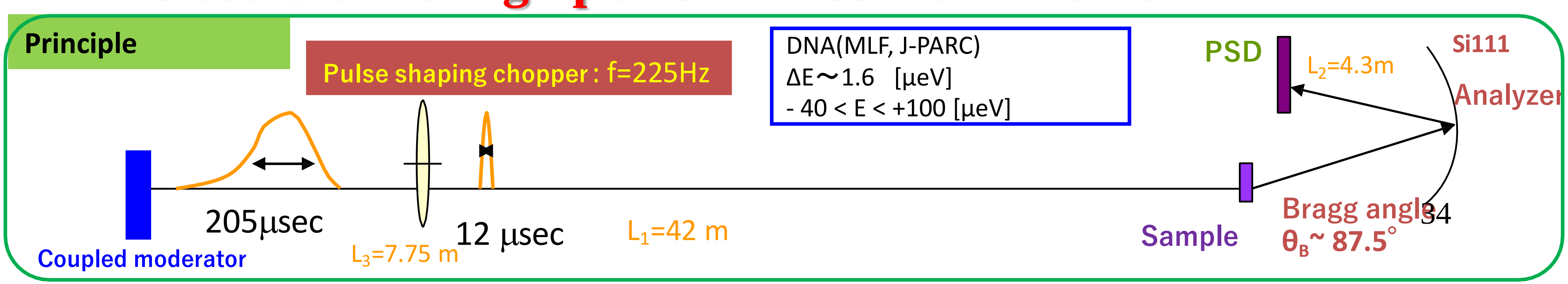


Wide pulse width is demerit?





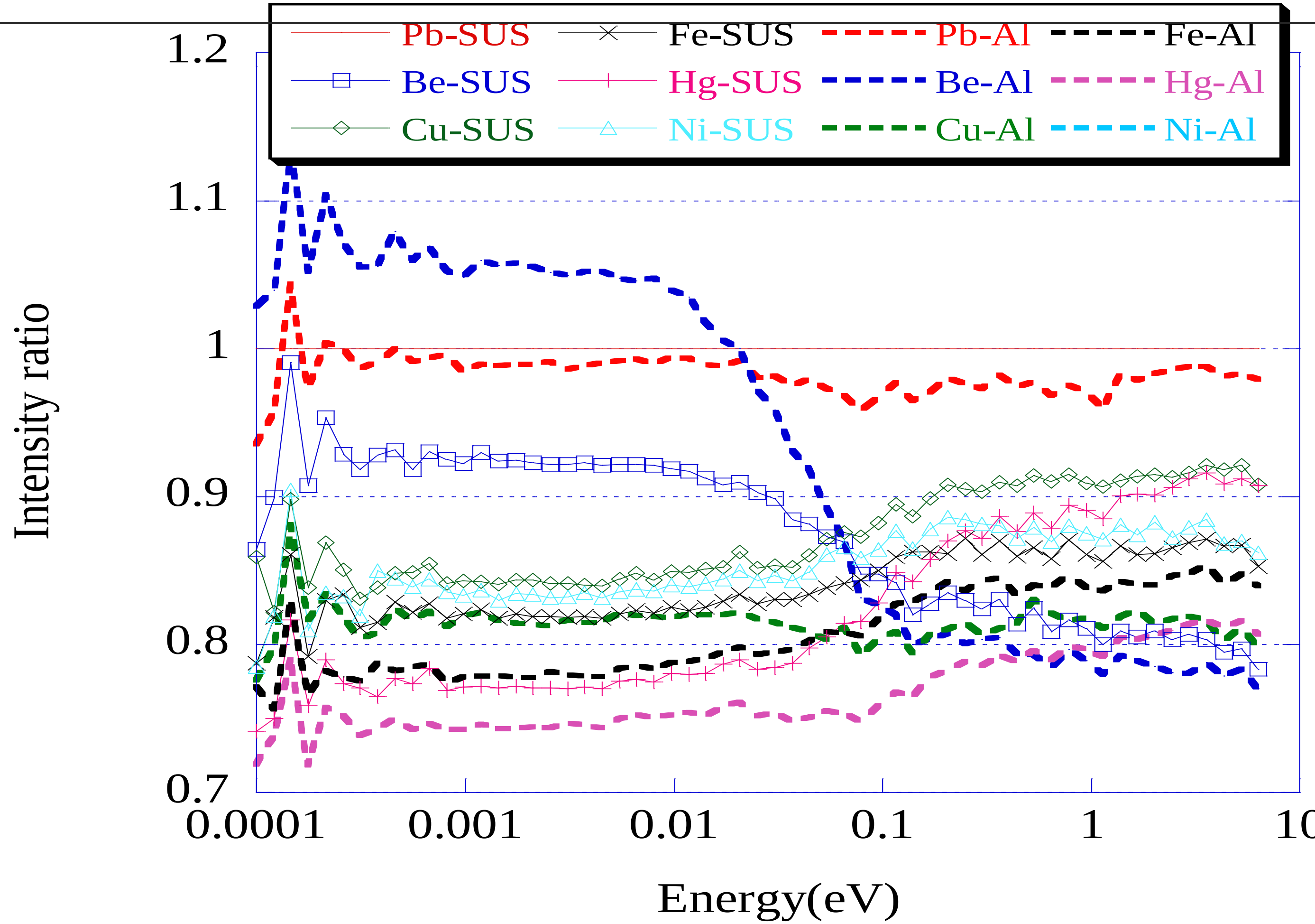
By using a chopper to cut out the high intensity region, we could build high performance instruments.



Reflector

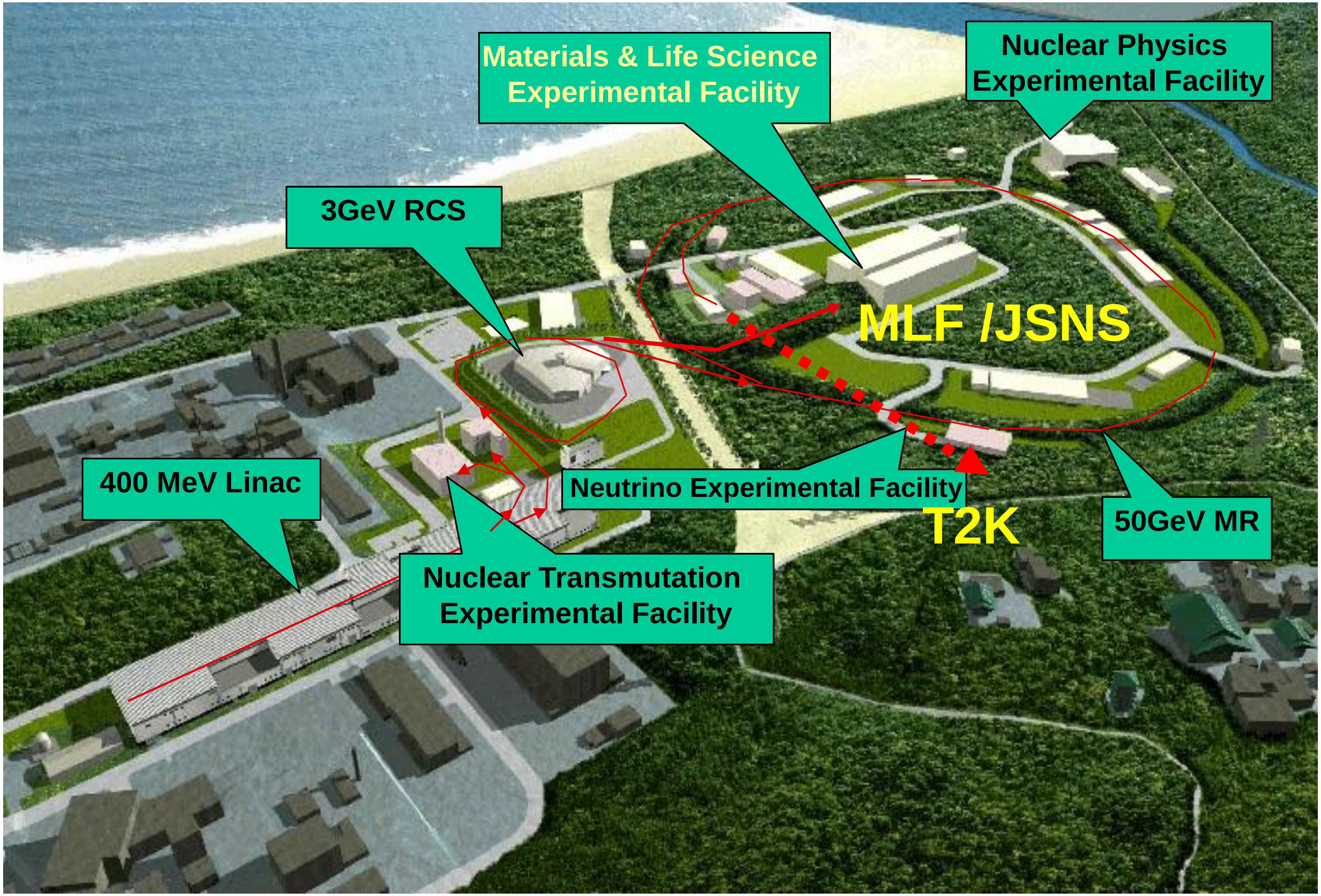
Comparison of intensity ratios of neutrons in the case of various reflector-structure materials

(coupled moderator simulation)

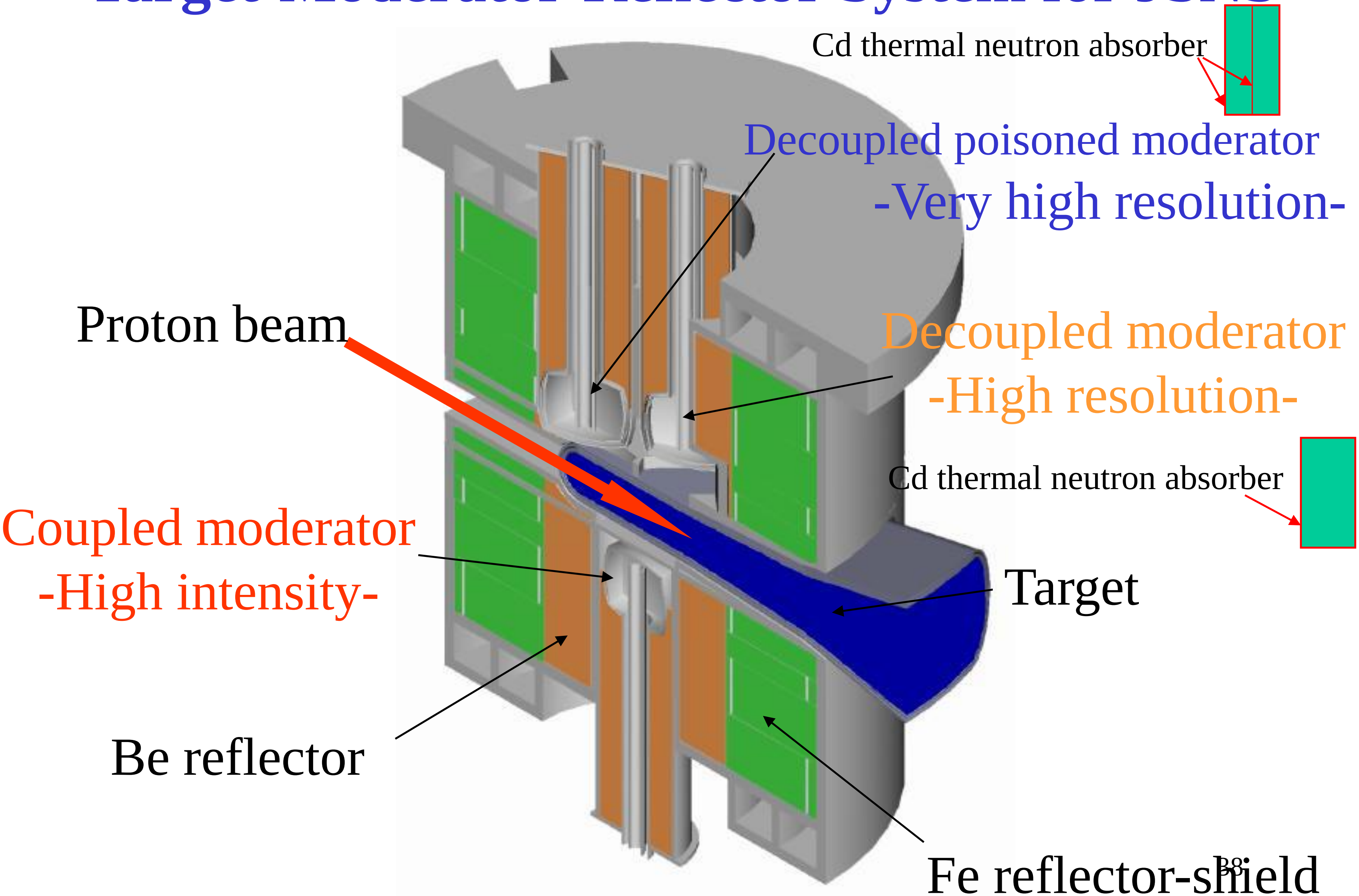


4. Structure of J-PARC neutron source (JSNS)

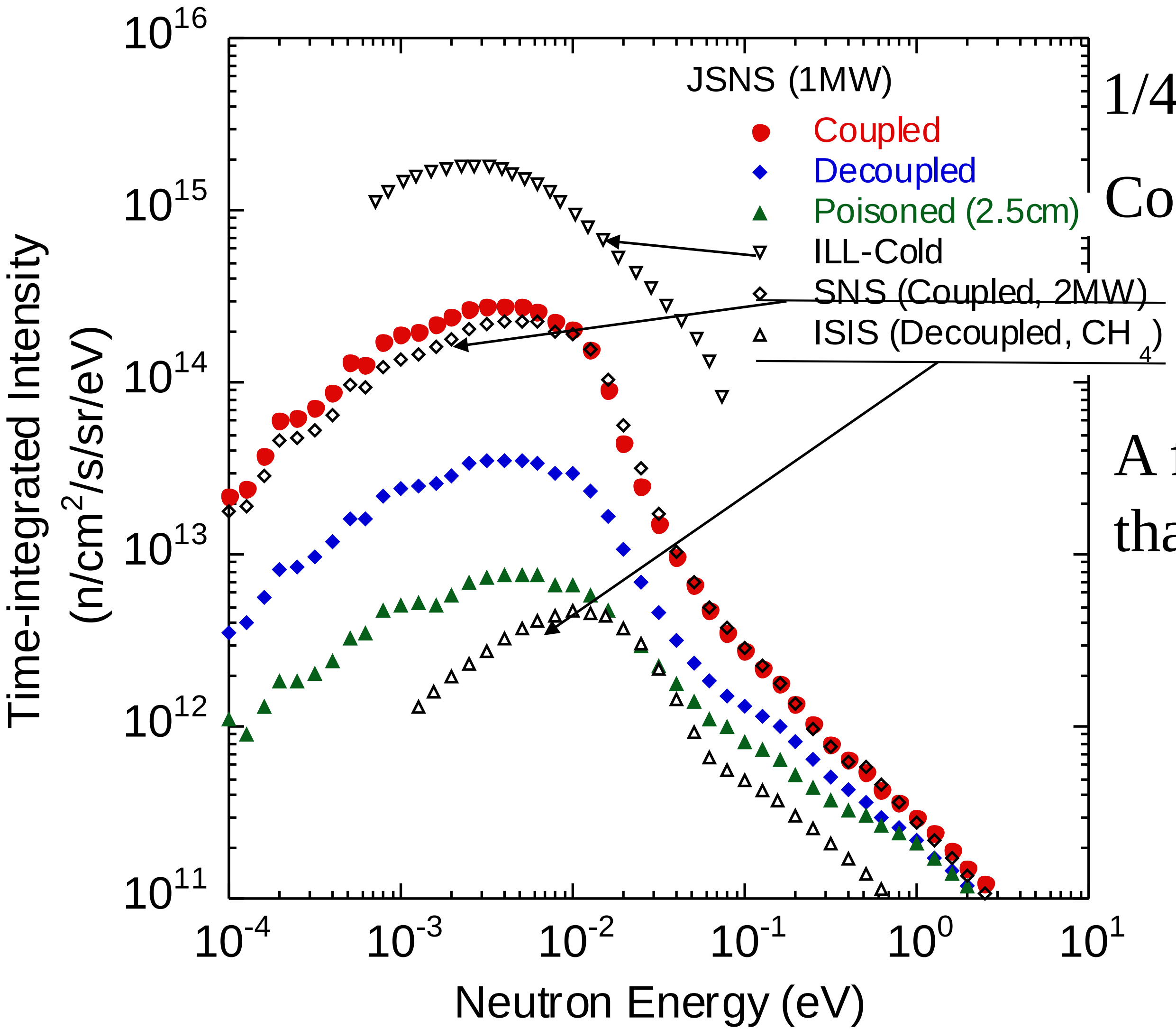
Birds' Eye View of J-PARC



Target-Moderator-Reflector System for JSNS



Time-Integrated Neutron Spectra of JSNS



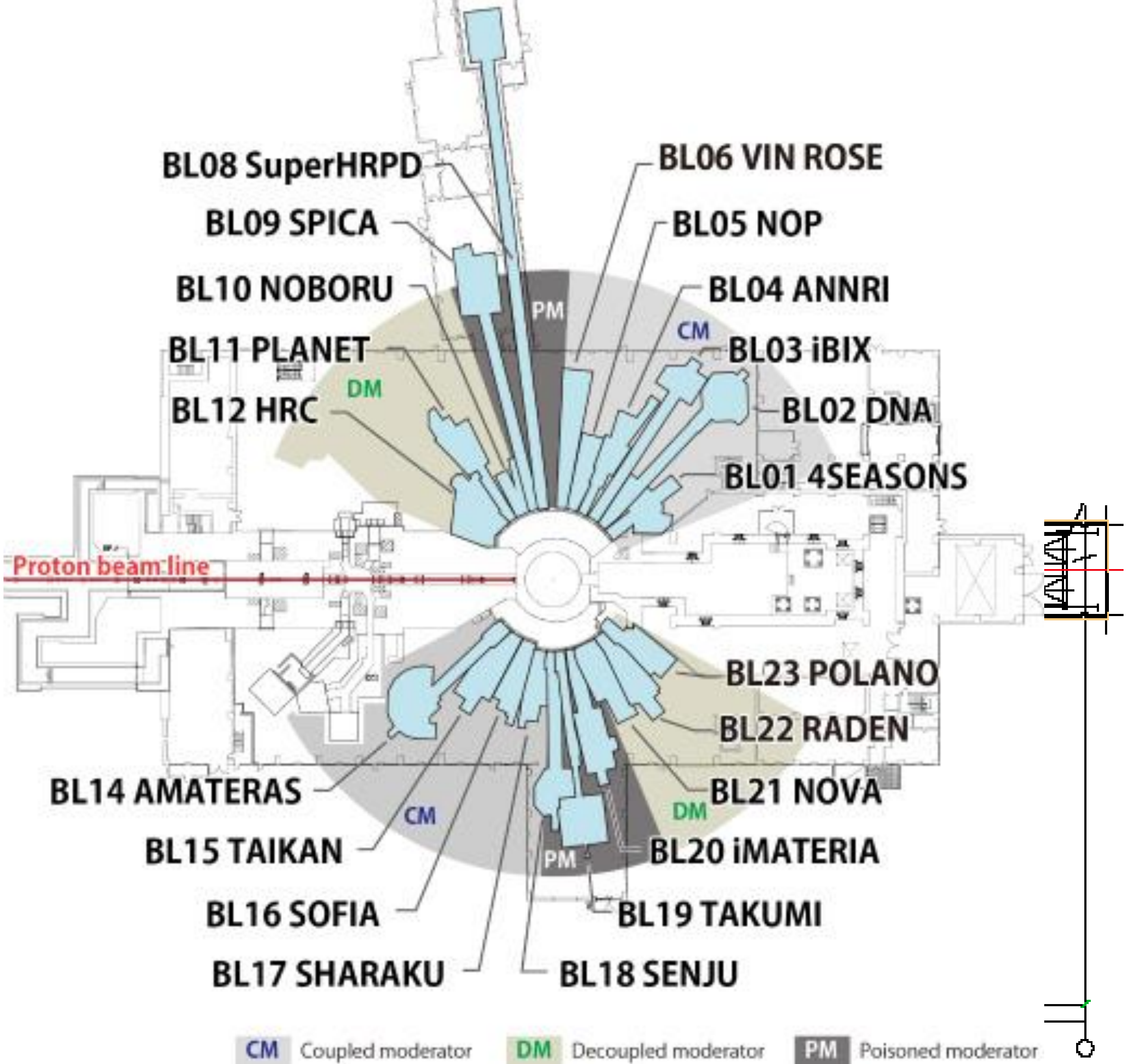
1/4-1/6 of ILL cold source

Comparable to 2MW SNS

A factor of 10 higher than ISIS

Layout of neutron instruments

- 23beamlines with individual shutters.



5. Summary

- We chose for the J-PARC neutron source

  Hg as a target material,

  para-hydrogen as a moderator material, and

  Be as a reflector material.

- Expected performance was attained and it is very high even if compared with other spallation neutron sources in the world.

Thank you for your attention!

Please enjoy the J-PARC power!