2010-08-16

Neutronic Design on a Small Accelerator based ^{7}Li (p, n) Neutron Source for Neutron Scattering Experiments

Fujio Hiraga, Takanori Okazaki and Yoshiaki Kiyanagi
Hokkaido University

Technical background

- Small accelerator neutron sources with an intensity more than 10^{12} s^{-1} are necessary to facilitate the application of cold neutron scattering experiments such as transmission measurements and small angle neutron scattering.

- A small proton linear accelerator with the proton energy of 2.5MeV has been put to practical use.

- The neutron intensity of 10^{12} s^{-1} is expected to be produced by a Li target and the small proton linear accelerator with the beam current of 1mA.

Neutronic advantages of the ^{7}Li(p, n) source using 2.5 MeV protons

- The larger yield of neutrons than other methods with low energy protons around 3MeV.
- The smaller energies of neutrons (less than **800keV**) than the evaporation neutrons.

- **Higher efficiency for the neutron moderation at the ^{7}Li source than a Bremsstrahlung (γ, n) source,** and
- **The decrease of the volume of the shield for neutrons around the source**

are expected.

The aim of this research

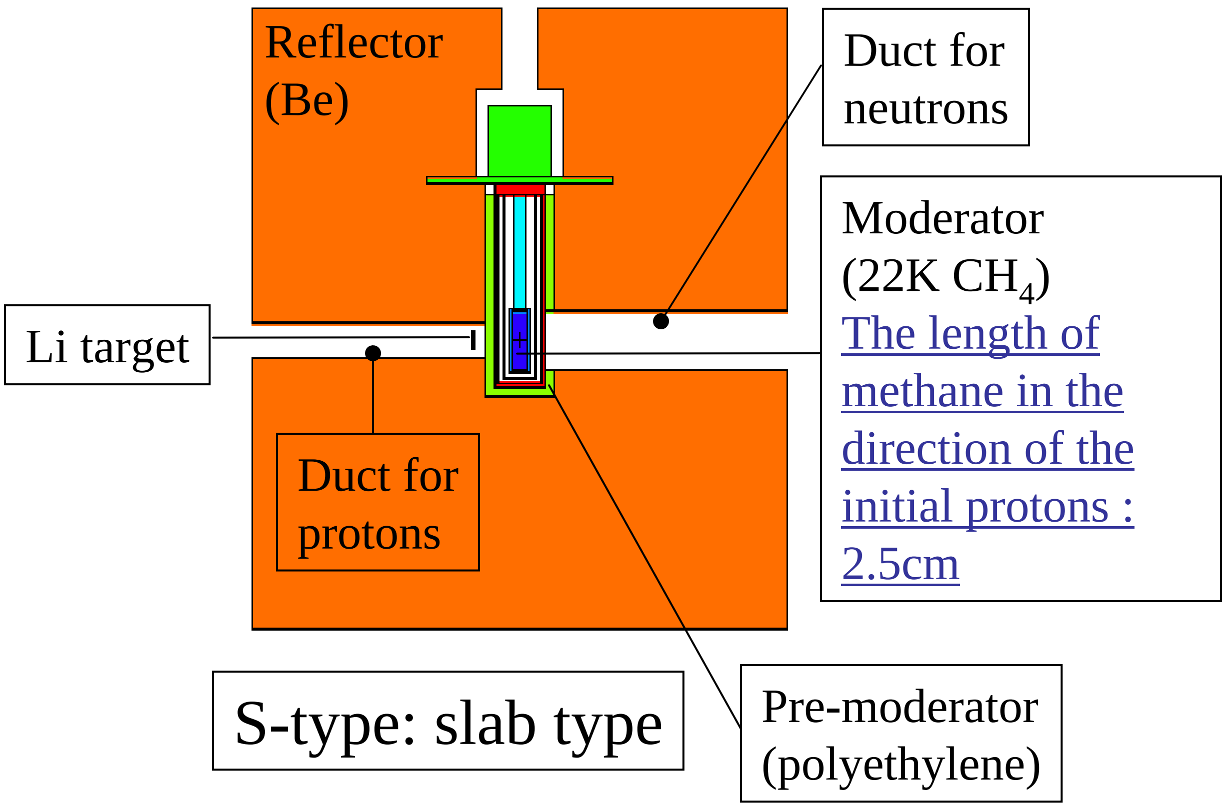
- **Examining the performance of models for the ^{7}Li (p, n) cold neutron source.**

- We study **the neutronic performance** using practical models where the neutron absorption in the structure materials and the neutron streaming in the channels around the moderator were taken into account,
  and make **comparison** of the performance with two different neutron production methods, ^{9}Be(p, n) and Bremsstrahlung (γ, n).
- We next **designed the shielding components for neutrons and γ-rays** to reduce the volume and the weight of the shield around the source.

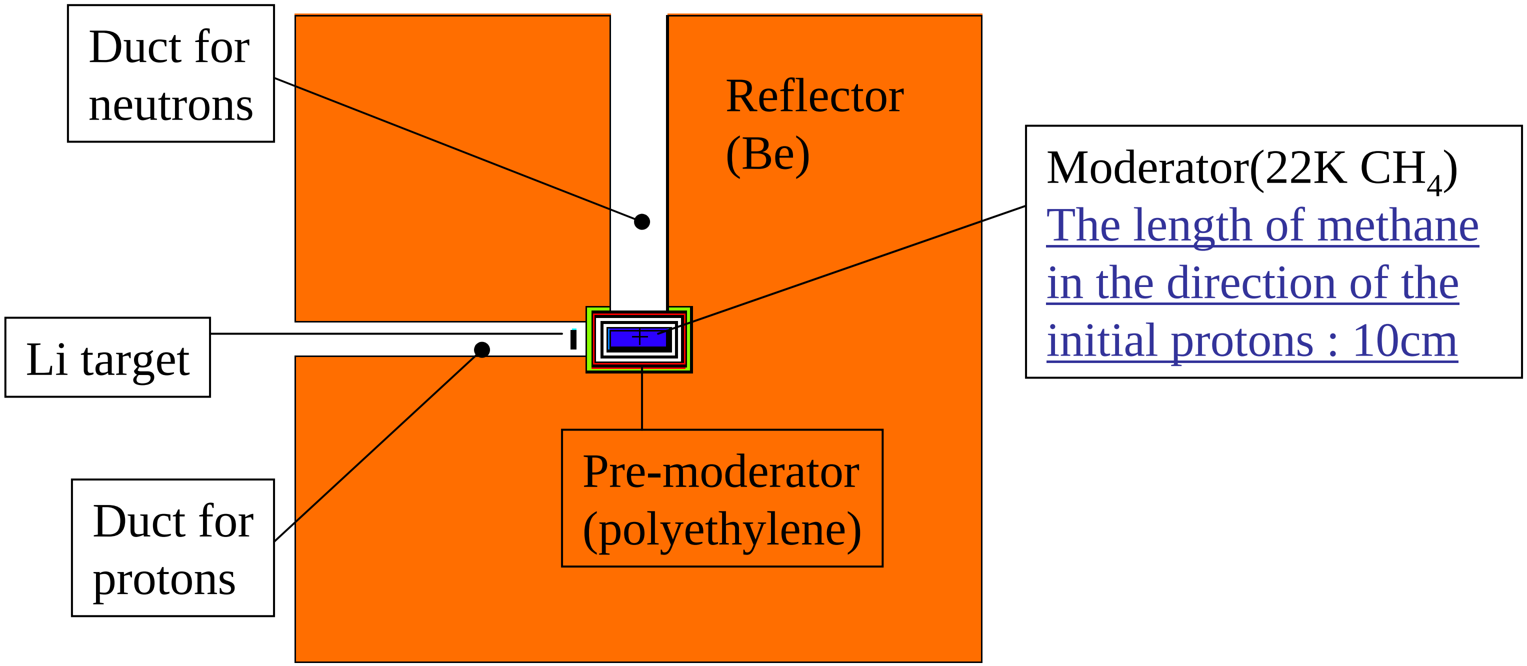
Part -1

The study on the neutronic performance, comparison of efficiency of neutron moderation among three neutron production methods

Longitudinal section of the calculation model of the S-type cold neutron source

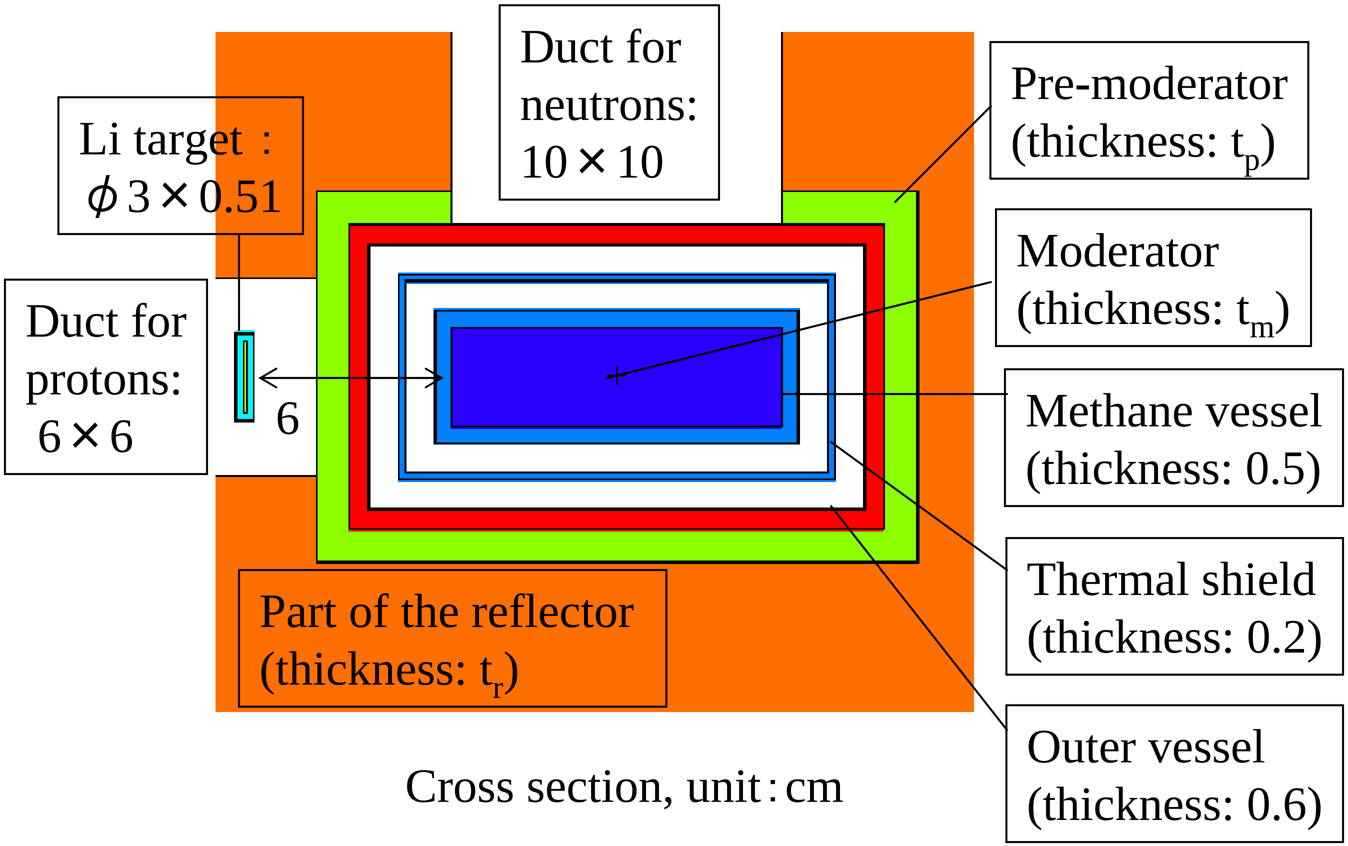


Cross section of the calculation model of the L-type cold neutron source



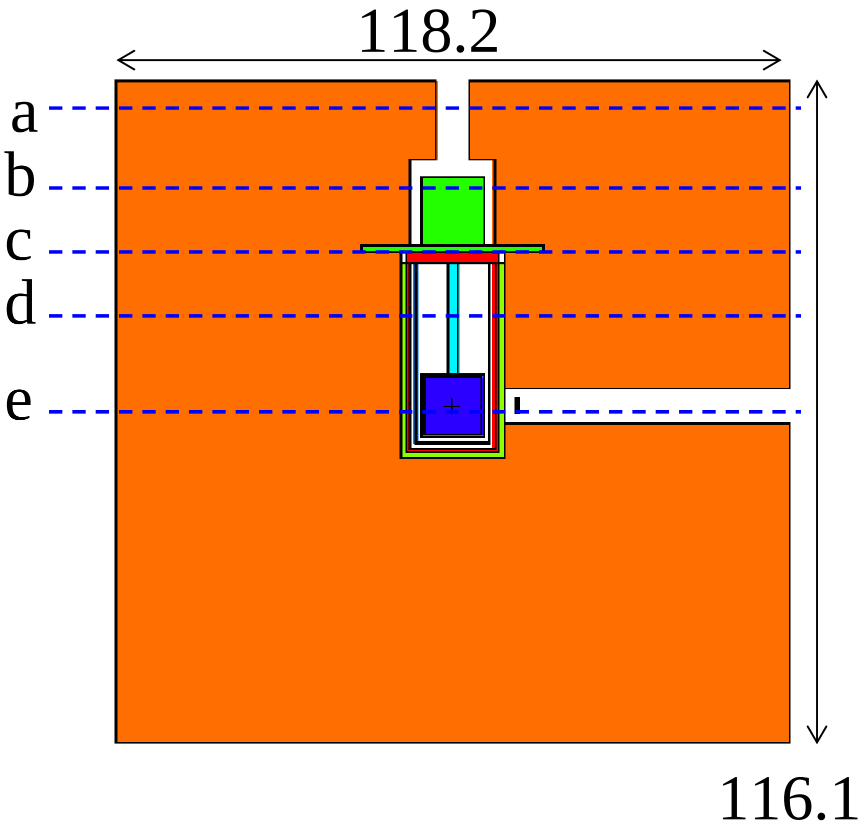
L-type: lateral type

Detailed structure around the moderator for the L-type source

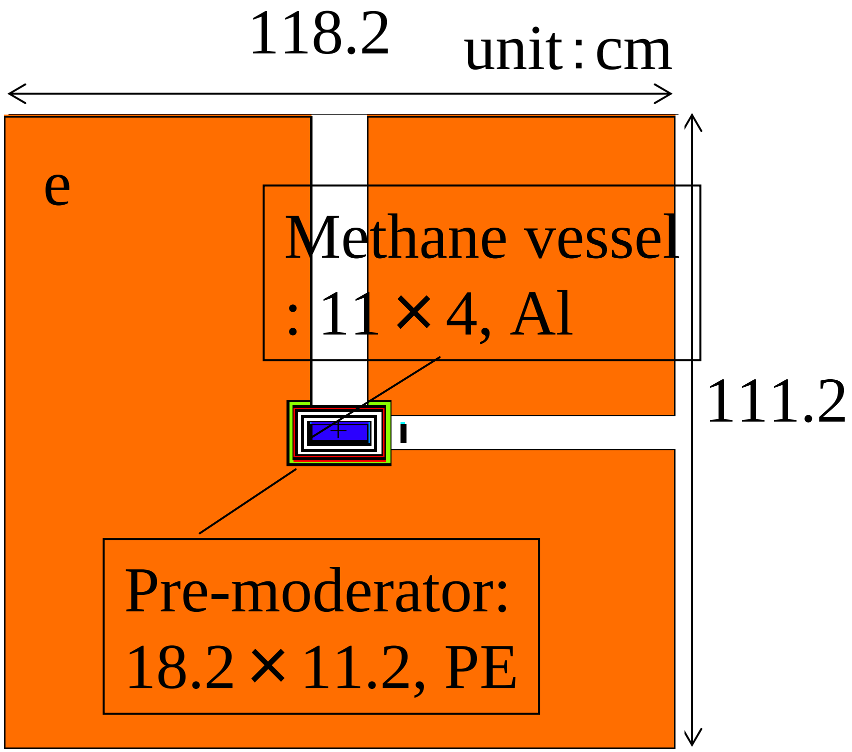


- The Li target: Li foil (t0.01) is installed on Cu can (t0.5).
- We also examined the cases where the Li foil was replaced by the Be foil (^{9}Be(p, n)) or the tungsten foil (Bremsstrahlung (γ, n)).

Details of the L-type source

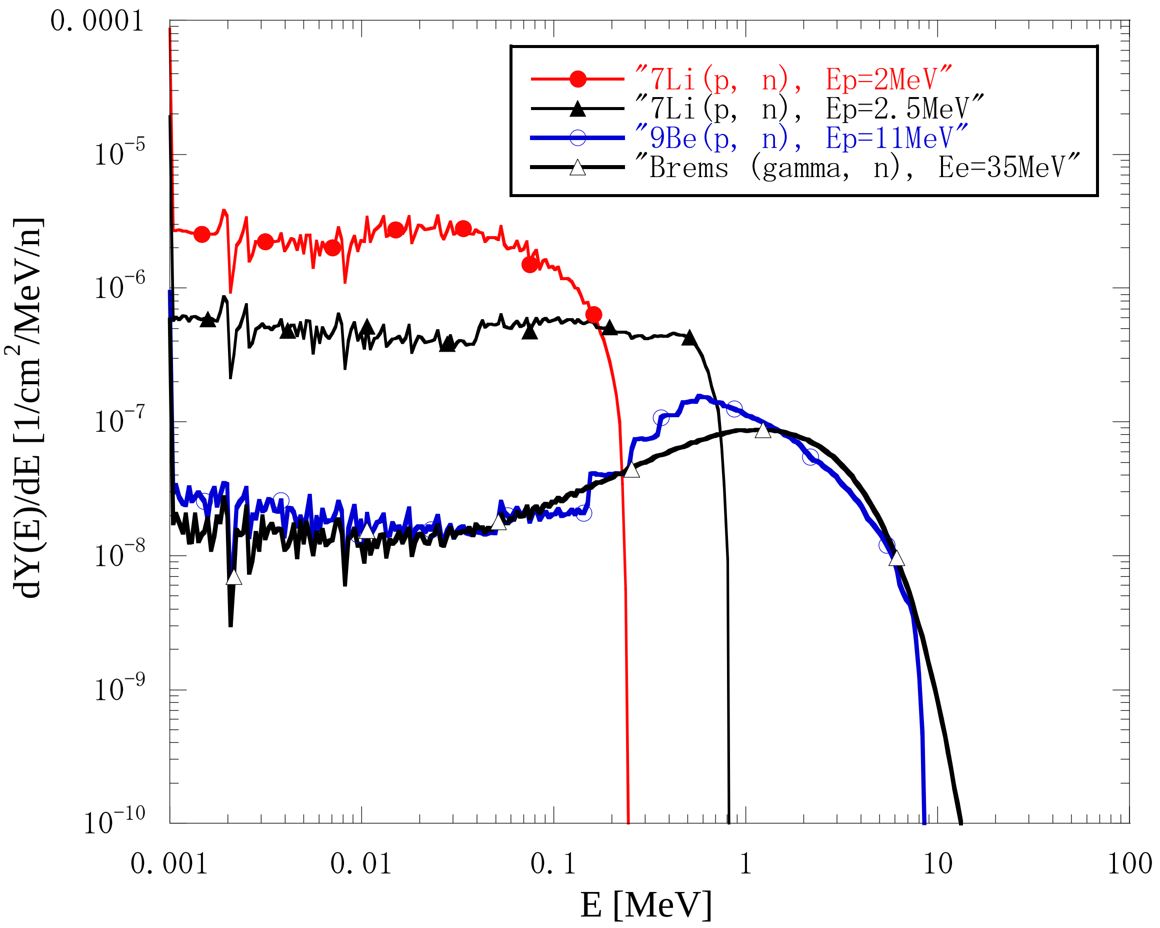


Longitudinal section



Cross section

Neutron energy spectra per produced neutron from various targets



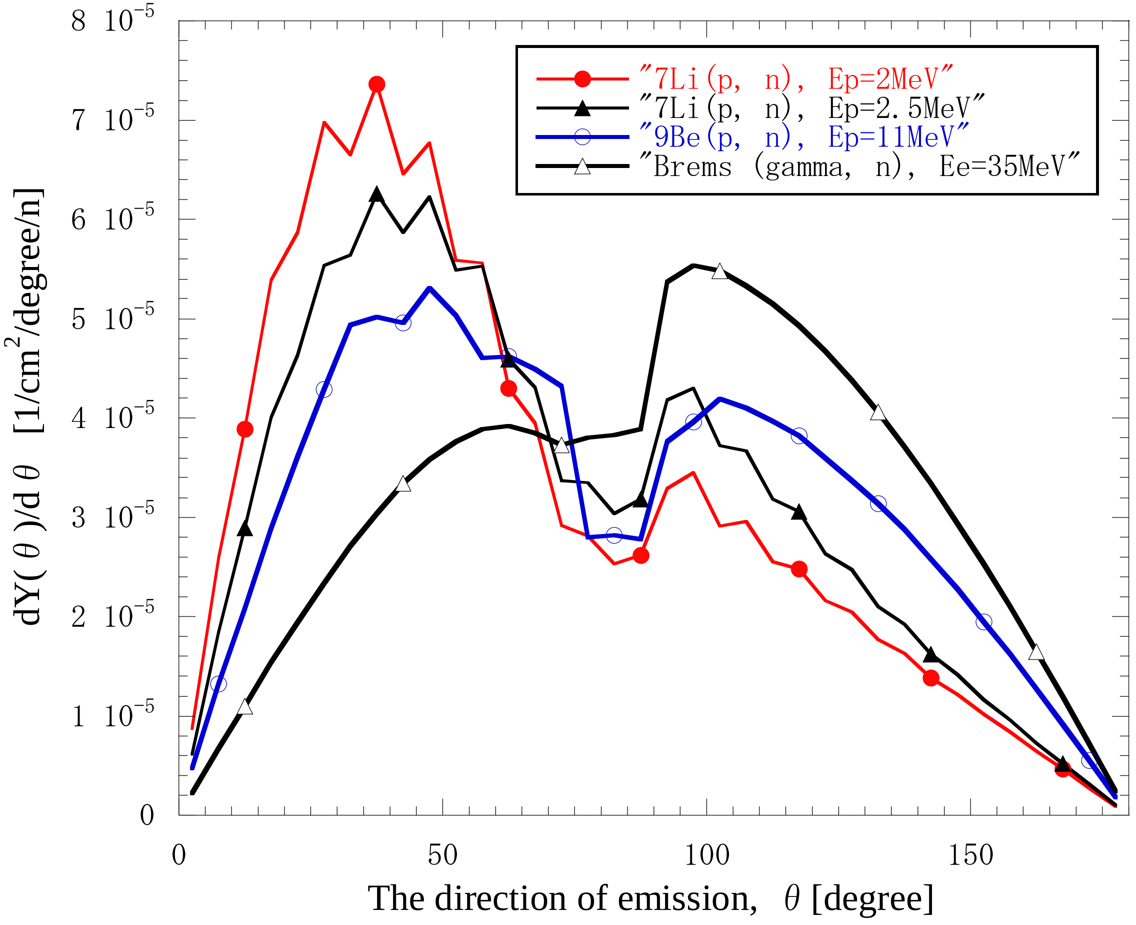
The differential neutron yield:

^{7}Li(p, n): C.L. Lee, X.-L. Zhou, LIYIELD, Nucl. Instr. Meth. B 152, 1 (1999)

^{9}Be(p, n): S. Kamada, et al., Preprints 2006 Spring Meeting of At. Energy Soc. Jpn., K42, (2006)

(γ, n): J. F. Briesmeister (ed.), MCNPX, LA-12625, (1993)

Neutron angular distribution per produced neutron from various targets

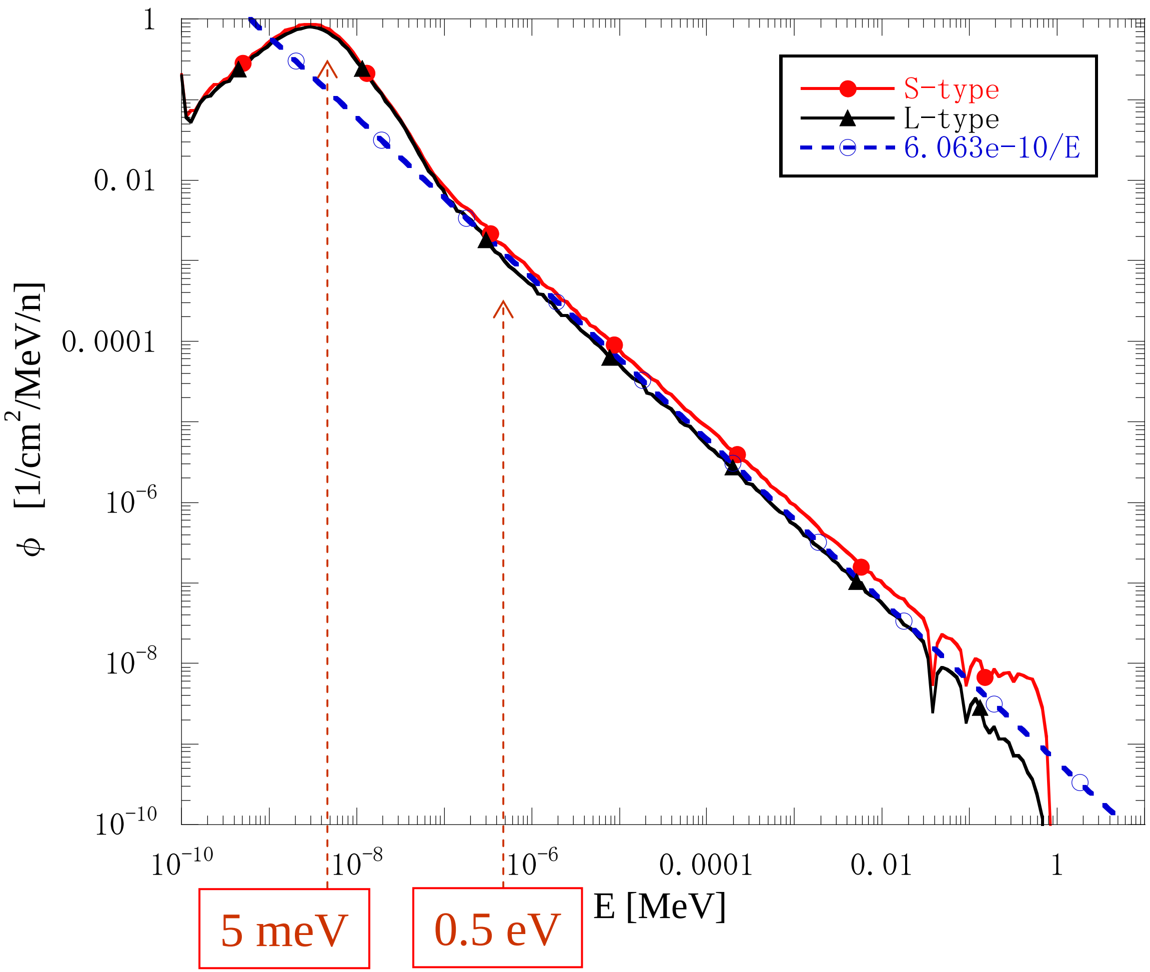


Optimal dimensions of the moderator, pre-moderator and reflector for various cases of cold neutron sources

The dimensions shown below were found by parametrical calculations so that the intensity of cold neutrons (E<5meV) is maximized.

Type of source		The moderator thickness [**cm**]	The pre-moderator thickness [**cm**]	The reflector thickness [**cm**]
^{7}Li(p, n), E_p=**2MeV**	S-type	2.5	1.5	**40**
	L-type	3.0	1.0	**50**
^{7}Li(p, n), E_p=**2.5MeV**	S-type	2.5	1.5	**40**
	L-type	3.0	1.0	**50**
^{9}Be(p, n), E_p=**11MeV**	S-type	2.5	1.5	**50**
	L-type	2.5	1.0	**50**
Bremsstrahlung (γ, n), E_e=**35MeV**	S-type	2.5	1.0	**50**
	L-type	2.5	1.0	**60**

Comparison of neutron spectra per produced neutron between the S- and the L-type ^{7}Li sources driven by 2.5MeV protons

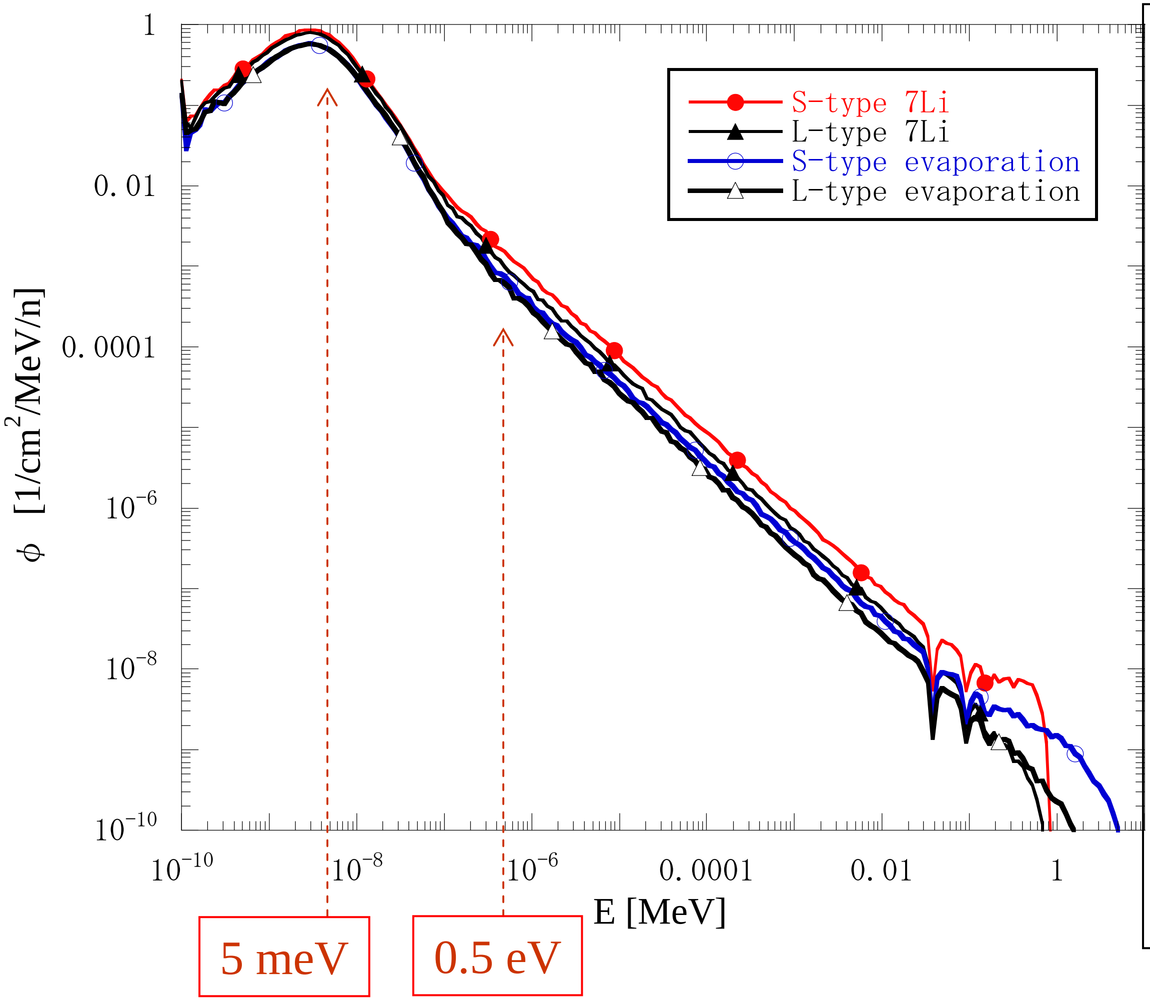


The yield of neutrons from the Li target peaks in the angle of 40 degree to the direction of the initial protons
and, moreover,
the configuration between the Li target and the methane moderator for the L-type model differs from that of the S-type model.

↓

The moderator of the L-type slows neutrons down more efficiently than the S-type.

Comparison of neutron spectra per produced neutron between the ^{7}Li and the Bremsstrahlung sources



A part of the high energy neutrons from the (γ, n) target passes thorough the moderator.

↓

The intensity of cold neutrons with the energies less than 5meV for the ^{7}Li sources are 1.4 times larger than that of the (γ, n) sources.

The difference in the angular distribution of neutrons between the ^{7}Li and the (γ, n) targets.

↓

The difference in the inclination of spectra above 0.5eV between the ^{7}Li and the (γ, n) sources.

Fast neutron yield from the target, the average energy of neutrons from the target and the cold neutron flux per produced neutron for the L-type sources with various reactions

Type of source	The fast neutron yield from the target [**1/s/mA**]	The average energy of neutrons from the target [**MeV**]	The cold neutron flux [**$1/cm^2/n_f$**]
$^{7}Li(p, n)$, E_p=**2MeV**	1.10×10^{11}	0.075	3.02×10^{-8}
$^{7}Li(p, n)$, E_p=**2.5MeV**	8.80×10^{11}	0.326	2.66×10^{-8}
$^{9}Be(p, n)$, E_p=**11MeV**	2.15×10^{13}	2.04	2.07×10^{-8}
Bremsstrahlung (γ, n), E_e=**35MeV**	5.60×10^{13}	2.52	1.92×10^{-8}

The calculation results show that

- The ^{7}Li source of 2.5KW (E_p=2.5MeV, I=1mA) produces the intensity of cold neutrons of 2.34×10^4 [**1/cm²/s**] at 5 m from the moderator, which corresponds to a typical Bremsstrahlung source of 0.77KW (E_e=35MeV, I=0.022mA).

- Higher efficiency for neutron moderation per beam power of the accelerator is obtained not by the ^{7}Li source but by the Bremsstrahlung source; however, we have to study the shielding components around the source to achieve a compact neutron source.

Part-2

The design of the shielding components,

comparison of the volume of the shield between the ^{7}Li source and the Bremsstrahlung source

The aim of designing the shielding components

- The reduction of the total surface dose of photons and neutrons on the shielding components <u>down to 20 μSv/h</u>,

  since a 2.5 MeV proton linear accelerator having the surface radiation dose of <u>less than 20 μSv/h</u> on the shielding components is permitted to be used anywhere by the regulation in Japan.

Radiation sources used for the design of the shielding components

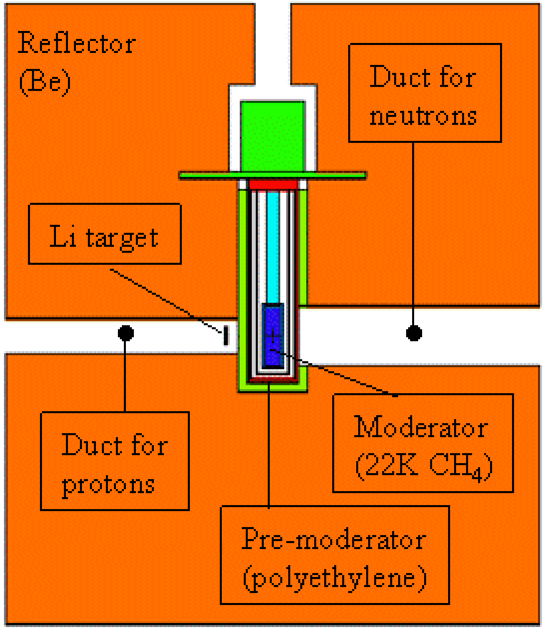
^{7}Li(p, n) of 2.5KW (E$_p$= 2.5MeV, I = 1mA)
Fast neutron yield: 8.8×10^{11} s^{-1}, estimated by LIYIELD.

Reactions of photon production	^{7}Li (p, n γ) ^{7}Be	^{7}Li (p, p γ) ^{7}Li	^{7}Li (p, α γ) ^{4}He
Energy of photons [**MeV**]	**0.429**	**0.478**	**14**
Photon yield at the target [**1/s**]	4.1×10^{10} ††	2.1×10^{11} †	5.7×10^{6} ☆

†: C.L. Lee, X.-L. Zhou, 1999,
†† : A. Z. KISS et al, 1984, ☆ : C. L. LEE et al, 2000.

The Bremsstrahlung (γ , n) of 0.77KW (E$_e$= 35MeV, I = 0.022mA)
Fast neutron yield: 1.23×10^{12} s^{-1} (1.4 times larger than ^{7}Li(p, n) of 2.5KW),
Photon yield: 1.05×10^{16} s^{-1} (42,000 times larger than ^{7}Li(p, γ) of 2.5KW),
estimated by MCNPX.

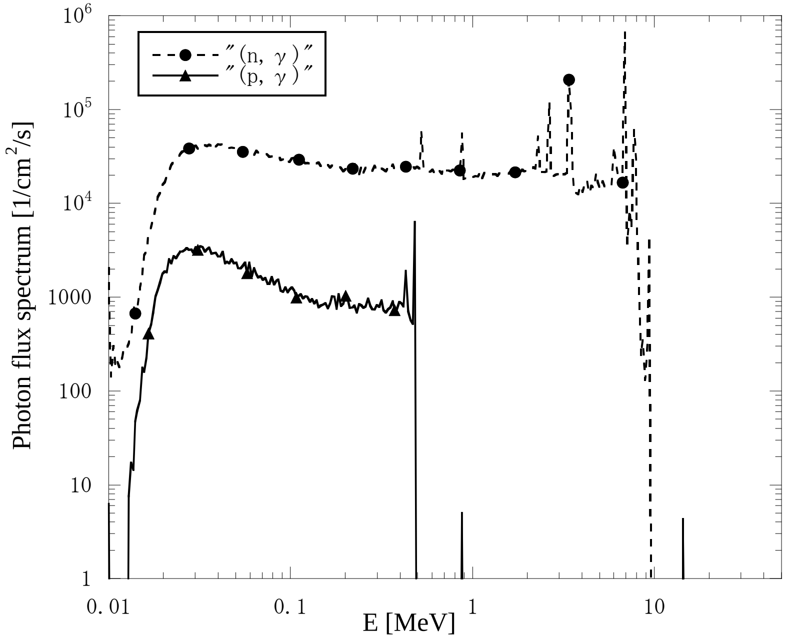
Longitudinal section of the model for specifying the initial photon source that dominates the surface photon dose of the ^{7}Li cold neutron source



- We calculated the average spectrum of photons escaping from the surfaces of the reflector of the ^{7}Li source of 2.5KW.

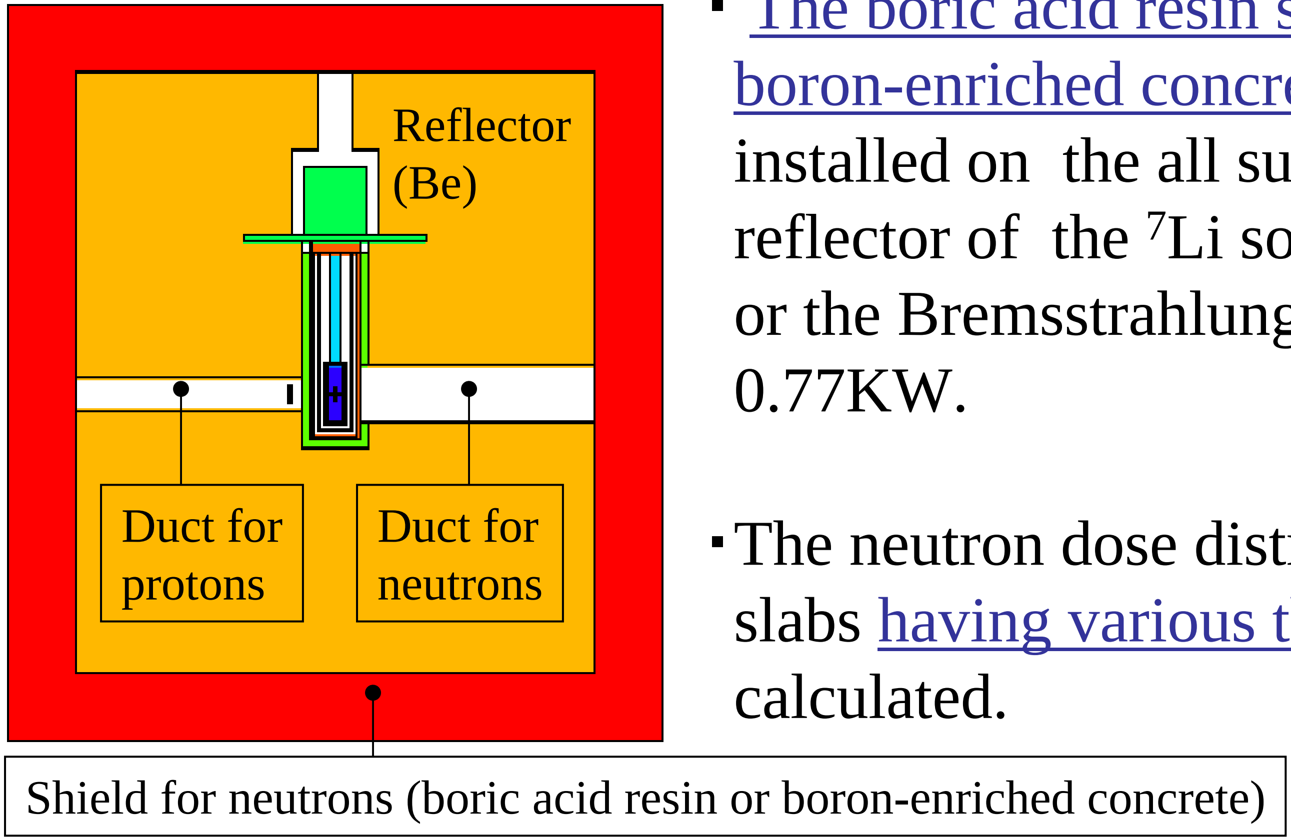
- We compared photons from the (n, γ) reactions in various components in the cold neutron source with those of the (p, γ) reactions in the lithium target.

Average spectrum of leakage photons from the (n, γ) reactions in various components in the L-type source and that of the (p, γ) reactions in the lithium target



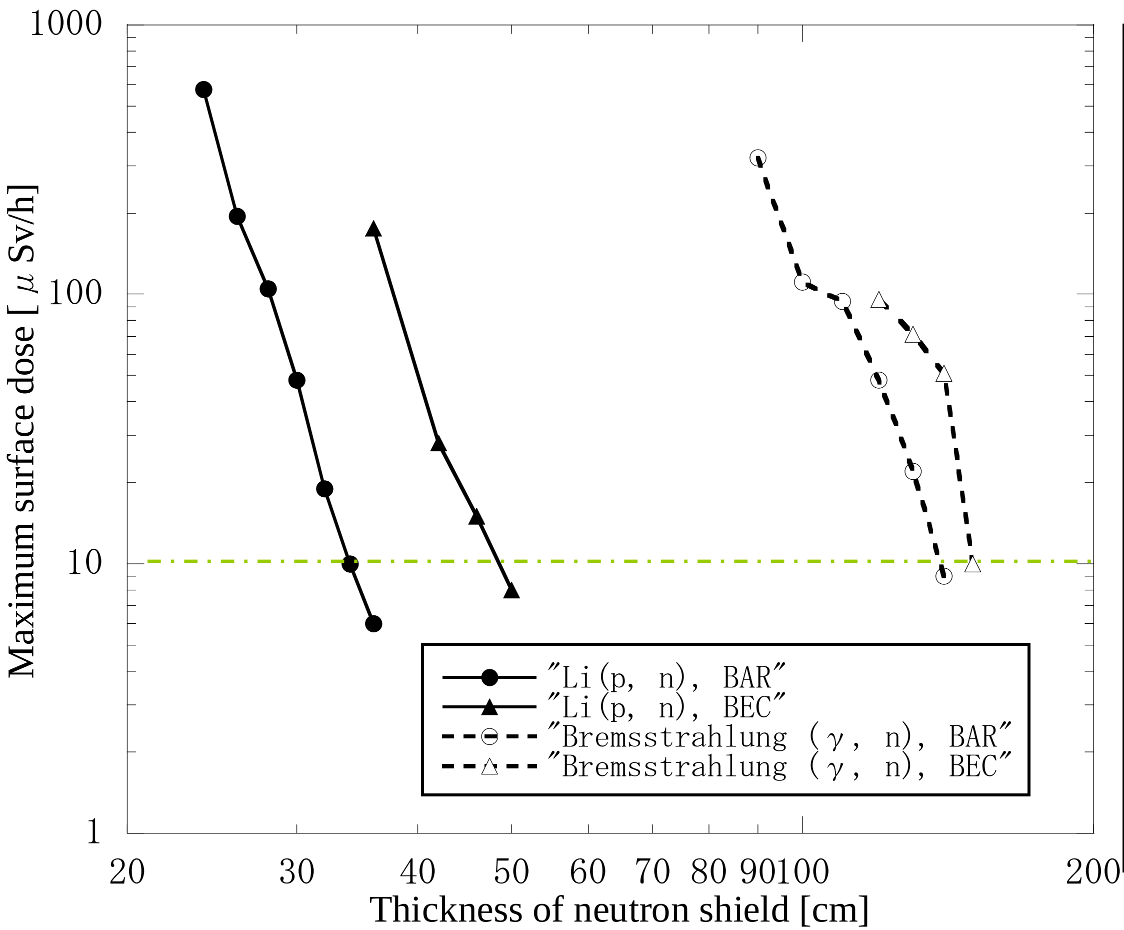
- The intensity of leakage photons is dominated not by the (p, γ) reactions but by the (n, γ) reactions.
- We adopted two layered shields consisting of the inside boric acid resin slabs for neutrons and the outside lead slabs for photons to reduce the thickness of shields around the source.

Longitudinal section of the model for examining the thickness of the shield for neutrons around the S-type source



- The boric acid resin slabs (BAR) or the boron-enriched concrete slabs (BEC) are installed on the all surfaces of the reflector of the ^{7}Li source of 2.5KW or the Bremsstrahlung source of 0.77KW.
- The neutron dose distributions on the slabs having various thickness were calculated.

Maximum neutron dose depending on the thickness of the slab



Abbreviation:
BAR: boric acid resin, BEC: boron-enriched concrete

^{7}Li of 2.5kW :

36 cm thick BAR slab,
50 cm thick BEC slab.

Bremsstrahlung of 0.77kW:

140 cm thick BAR slab,
150 cm thick BEC slab.

This is attributed to the neutrons with energies more than 800 keV emitted from the Bremsstrahlung target.

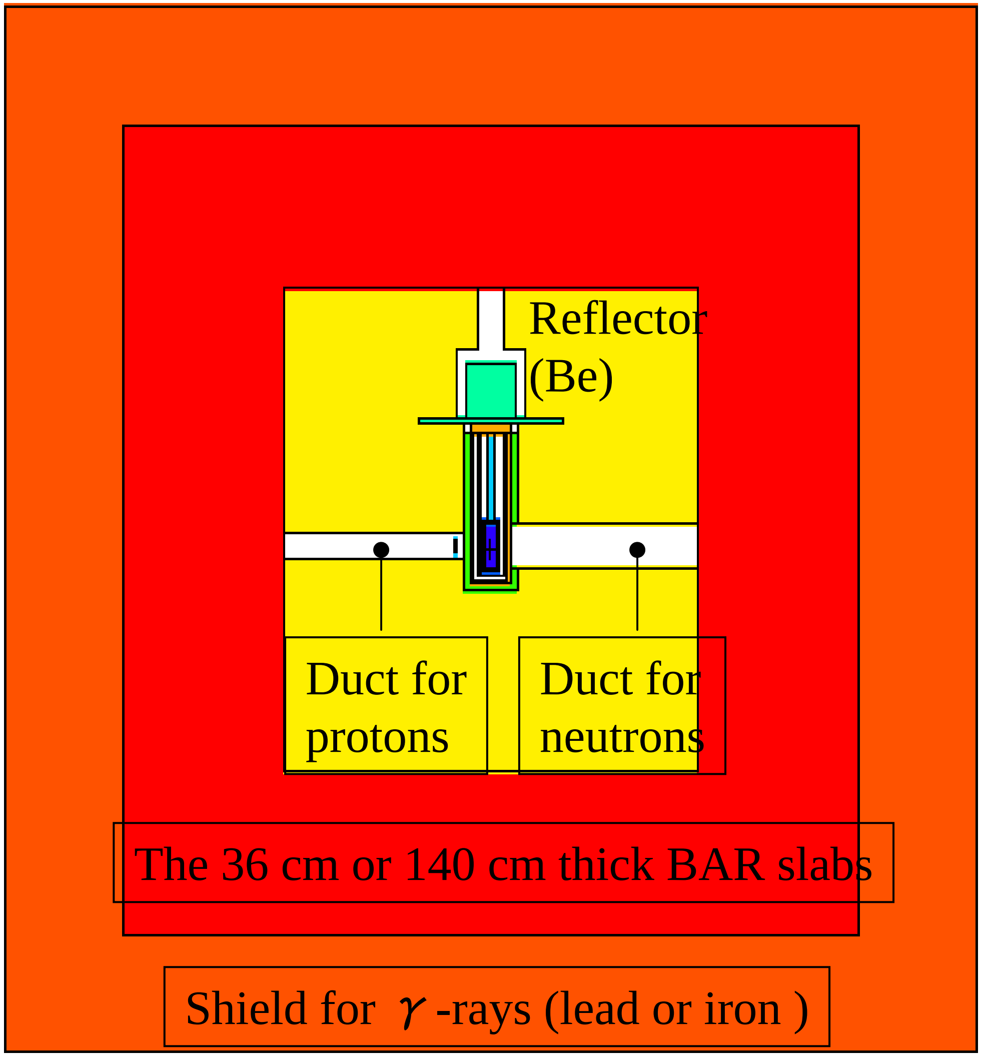
The necessary shielding components for neutrons around the ^{7}Li source of 2.5MeV, 1mA

- The 36cm thick boric acid resin slabs (1.33g/cm^3, H (4.71×10^{22} cm^{-3}), B (9.04×10^{21} cm^{-3}), *etc.*) : 6.7 tons weight
  (89.8 tons for Bremsstrahlung of 35MeV, 0.022mA)

- The 50cm thick boron-enriched concrete slabs (2.2g/cm^3, H (2.49×10^{22} cm^{-3}), B (1.54×10^{21} cm^{-3}), *etc.*) : 18.6 tons weight
  (171.8 tons for Bremsstrahlung of 35MeV, 0.022mA)

- The use of the boric acid resin as a substitute for the boron-enriched concrete may make the construction cost for the shielding components decrease.

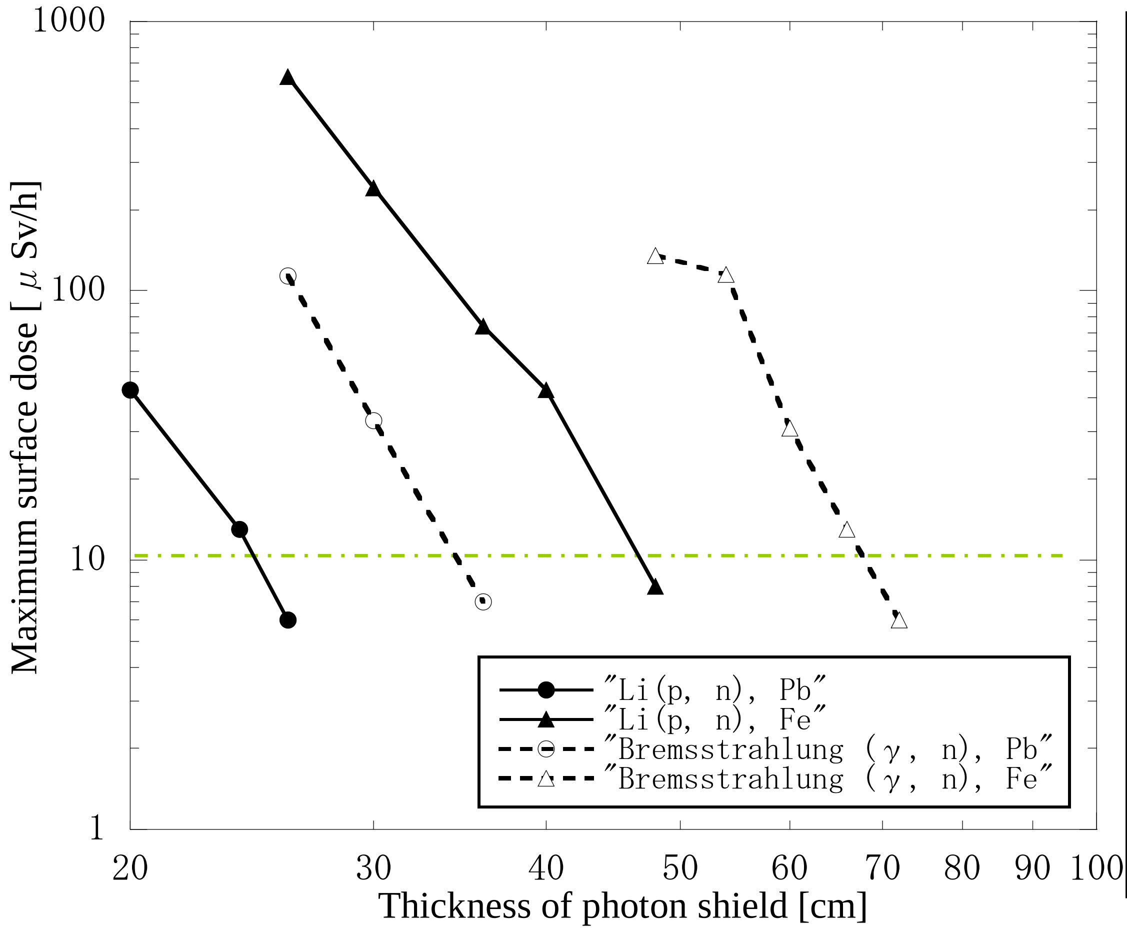
Longitudinal section of the model for examining the thickness of the shield for γ-rays around the S-type source



- The lead slabs or the iron slabs are installed on the 36 cm or 140 cm thick BAR slabs for the ^{7}Li or the Bremsstrahlung sources respectively.

- The photon dose distributions on the slabs having various thickness were calculated.

Maximum photon dose depending on the thickness of the slab



^{7}Li of 2.5KW:

26 cm thick lead slab,

48 cm thick iron slab.

Bremsstrahlung of 0.77kW:

36cm thick lead slab,

70 cm thick iron slab.

This is caused by that the Bremsstrahlung source not only yields more photons but also contains the more energetic photons than the ^{7}Li source.

The necessary shielding components for photons around the ^{7}Li source of 2.5MeV, 1mA

- The 26cm thick lead slabs (11.35 g/cm^3) :80.9 tons weight
  (492.3 tons for Bremsstrahlung of 35MeV, 0.022mA)
- The 48cm thick iron slabs (7.86 g/cm^3) :126.9 tons weight
  (800.1 tons for Bremsstrahlung of 35MeV, 0.022mA)
- We should use the lead slab shields for the ^{7}Li source of 2.5 KW from the weight point of view.

The calculation results show that

- The shielding components consisting of the inside boric acid resin slabs and the outside lead slabs are effective in dropping the weight and the volume of shields for the ^{7}Li source of 2.5 KW.

- The ^{7}Li source of 2.5 KW needs a much smaller volume of the shielding components than those of typical Bremsstrahlung sources of 0.77 KW.

Conclusion

- The ^{7}Li source of 2.5 KW allows flexibility for installation in any facility with a low construction cost, since a 2.5MeV proton linear accelerator having the surface radiation dose of less than 20 μSv/h on the shielding components is permitted by the regulation in Japan to be used anywhere.

Calculations of the energy spectra and the angular distribution of neutrons from the target

- dY(E)/dE was estimated so that the target was placed in the center of a sphere with a radius of 100 cm and the neutron flux shape on the sphere per produced neutron was tallied by the MCNPX.

- dY(θ)/dθ was obtained by multiplying the neutron flux shape by $2\pi \sin\theta$ term from the solid angle differential element.