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A proposal to use mercury as a reflector material for decoupled moderator system

Makoto Teshigawara*, Masahide Harada, Noboru Watanabe,
Tetsuya Kai, Hideaki Sakata and Yujiro Ikeda

Japan Atomic Energy Research Institute,Tokai 319-1195, Japan
*E-mail : teshi@linac.tokai.jaeri.go.jp

Abstract

It is important for a decoupled moderator system to obtain neutron pulses of a higher intensity with a narrower pulse width and a faster decay. To satisfy these requirements we propose to use mercury as a reflector material and report the neutronic performance of a mercury reflector system. The peak intensity is almost comparable to or even higher than that of the optimized lead reflector system and higher than the optimized Be reflector one. Furthermore the pulse shape is almost the same as that of optimized Be reflector system with a decoupling energy of several tens eV. A mercury reflector system does not require decouplers with a higher decoupling energy, liners nor cooling water, since mercury has a reasonably high neutron absorption cross section and could be used also as a coolant.

Thus, the idea of the mercury reflector could bring about a higher neutronic performance with some engineering merits for a decoupled moderator system.

Introduction

As a next-generation neutron source the construction of a 5 MW-class intense-pulsed-spallation-neutron-source (JSNS) is conducted as part of the joint project$^{1)}$ of Japan Atomic Energy Research Institute (JAERI) and High Energy Accelerator Research Organization (KEK) with a high-intensity proton accelerator. The important characteristics required for a high-performance pulse-neutron-source are a higher intensity, a narrower pulse width and a shorter pulse tail.

In JSNS project we proposed following three moderators

(1) One coupled moderator for high-intensity and for very high-resolution

(2) Two decoupled moderators for high resolution

The choice of the moderators and the reflector material is very important. Supercritical hydrogen (H_2) is the only proven material for a cryogenic moderator in a MW class source.

We have mainly investigated Lead (Pb) and Beryllium (Be) as a reflector material. The slowing down time is quite different between these two. For a cold neutron source a coupled H_2 moderator with extended premoderator (EPM) in a Pb or a Be reflector$^{2-4)}$ is a candidate since a

Pb reflector system gives a higher peak intensity than a Be one in the thermal equilibrium (Cold neutron) region, while a Be reflector system gives a higher time-integrated intensity.

In the present investigation, we mainly concentrate on the development of decoupled moderators. It has been proved that a long pulse tail is equivalent to the substantial penalty in the intensity, especially in the high resolution powder diffraction[5], since such tail gives a higher background to successive diffraction peaks.

As a result of neutronic investigations we found out as follows;

(1) For a higher peak neutron intensity;

The use of a premoderator (PM) in a Pb reflector has a large merit[6], because a PM enhances neutron intensities and reduces the heat deposition in H_2. However the use of a Pb reflector gives a longer pulse tail because of a longer slowing down time. Ooi et al.[7] proposed a multi layer decoupler to improve the long pulse tail. However it brings about an engineering complication. As a PM material light water (H_2O) and heavy water (D_2O) are only two realistic candidates. An H_2O PM gives a bit shorter pulse tails, while a D_2O PM gives a slightly higher peak intensity with a bit longer pulse tail. We have not decided yet which PM material is better for JSNS since the choice is to be decided by users.

(2) For a narrower pulse;

The use of a Be reflector system without PM has a merit. A Be reflector provides a pulse shape with a relatively shorter tail as compared with a Pb one. However, the neutron intensity is lower than in a Pb reflector system with optimized PM since a PM in a Be reflector system does not give any intensity enhancement.

(3) Further improvement of pulse shape;

A higher decoupling energy is effective for both reflector system to improve the pulse tail decay characteristics, but a higher decoupling energy decreases neutron intensity. A proven material with a higher decoupling energy is boron carbide (B_4C). The engineering issue, however, is whether the use of B_4C in a high radiation field is feasible due to the serious radiation damage (helium production caused by (n, α) reaction) and a higher local heat load.

In either case, in a MW class intense source, a reflector needs cooling water (H_2O or D_2O), which significantly reduces the neutron intensity and somewhat deteriorates the pulse shapes[8,9]. Moreover, the existence of cooling water makes the system complicated technically.

In order to obtain shorter pulse and a higher intensity taking full advantage of the merit of the PM use, a non-slowing down reflector material having a proper thermal-neutron absorption cross-section is desired. Furthermore it is important that the reflector material itself can work as a coolant.

After extensive material search we reached at a conclusion that mercury (Hg) could be the best candidate material satisfied above requirements. Hg might behave like a decoupler and a liner by itself, suggesting a large possibility for realizing a decoupler and/or linear less system. Such system might have an engineering advantage.

Generally there coexists coupled and decoupled moderators in one target-moderator-reflector system. In JSNS a coupled moderator is put above the target and two decoupled ones below the target. If we choose an Hg reflector, the intensity from a coupled moderator might considerably decrease because of its high thermal neutron absorption cross section.

Therefore, we performed a neutronic study for an Hg reflector system on the following items;

(1) pulse characteristics;
(2) effect of premoderator;
(3) decoupling energy dependence;
(4) possible elimination of decoupler and liner;
(5) effect on coupled moderator.

In this paper we report the neutronic performance of a Hg reflector system.

2. Calculation

The calculation model of the target-reflector-moderator system is shown in Fig. 1. The target-moderator coupling scheme was a wing geometry type. One decoupled moderator with both side neutron beam extraction was put above target. It consisted of H_2 moderator (size : 12 x 12 x 5 cm^3) with light water EPM (1 cm thick and 5 cm extension, ambient temperature). The ortho / para ratio of H_2 moderator was assumed to be 75 % / 25 % (normal hydrogen). The moderator viewed surface was fixed at 10 x 10 cm^2. A beam extraction hole in the reflector has an opening angle of 45 degree. An Hg target was assumed with sizes of 40 cm in width, 8 cm in height and 75 cm in length. A flat rectangular proton beam (energy : 3 GeV, beam size : 13 x 5 cm^2, current density : 5.1 μA/cm^2 at 1 MW and repetition rate : 25 Hz) was assumed for this calculation. An Hg reflector (120 cm in diam., 120 cm in height) surrounding the target and the moderators was assumed as shown in the figure. A B_4C decoupler with a decoupling energy of 1 eV was inserted between H_2 moderator and EPM and B_4C liners with a cut-off energy of 1 eV were put along the neutron extraction beam holes. The thicknesses of the decoupler and the liners were 3 mm. In order to predict the neutronic performance of the decoupled moderator, especially spectral intensity and pulse shapes from the moderator, we used code systems NMTC[10, 11]-JAM[12, 13] and MCNP-4A[14] with JENDL[15] cross section library including recently evaluated the Hg cross section at JAERI[16]. Point detector tallies were located at 2 m from the moderator viewed surfaces for predicting neutronic performance. The total number of protons upon the target in each Monte Carlo simulation was about (0.6-1.2) x 10^6 in NMTC-JAM and the total number of neutrons transferred from the high-energy hadron transport code to the low energy code (MCNP-4A) was (2-5.5) x 10^7. We decided the number of protons like that the statical error at the peak of the slow neutron spectral intensity at the Maxwell region became less than about 5 % for the energy bin $\Delta E = 1/20$. The ΔE satisyfied $E_{n+1} = \Delta E\ E_n$, where E_n was neutron energy of nth.

In order to study the effect of PM on the neutron intensity and pulse shape, we adopted the thickness as shown in Fig. 2 for the bottom, side and top PMs around the H_2 moderator. The

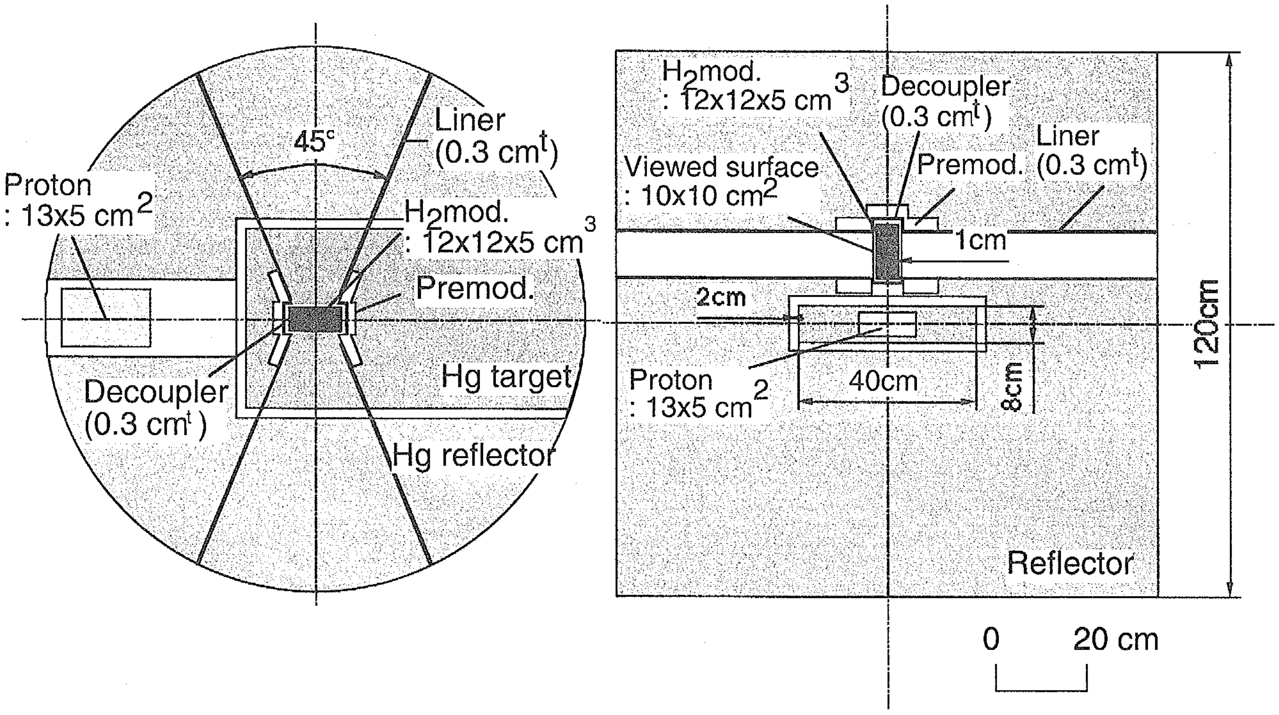

Fig. 1 Calculation model (Layout of target-moderator-reflector).

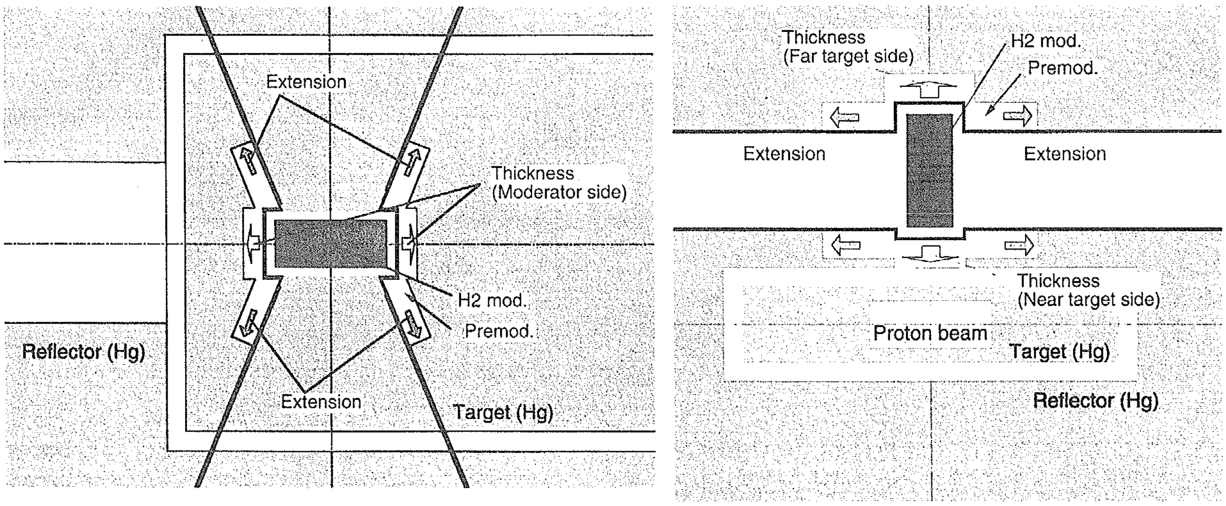

Fig. 2 Layout of premoderator (extension and thickness).

extension of PM along the neutron beam extraction is also shown in the figure. We are mainly interested in pulse shape with a lower decoupling energy, we calculated neutronic performance for a system with a Cadmium (Cd) decoupler (about 0.4 eV). In order to predict the effect of the Hg reflector on the neutronic performance of a coupled moderator, we installed one coupled moderator (H_2 moderator with EPM) at the opposite target side to the decoupled moderator. Only for this calculation we used the same calculation model used in ref[17].

3. Results and discussions

3.1 pulse characteristics

Figure 3 shows pulse shapes at 100 meV from the decoupled H_2 moderator with EPM in the Hg reflector system as compared with those in a Be and Pb reflector systems with various decoupling energies. The PM is optimized at a decoupling energy of 1 eV for the Hg reflector system as described in the next section. The peak intensity for the Hg reflector system is almost comparable to or higher than that of the Pb reflector system9); the highest neutron intensity in our neutronic study. On the other hand, the pulse shape is as good as that of the Be reflector system with the decoupling energy of several tens eV.

3.2 Effect of premoderator

Figure 4 shows the effect of PM (thickness and extension) on the neutron intensity for the Hg reflector system. The use of PM in the Hg reflector system increases the neutron intensity by about 28 % in maximum as shown in the figure.

The procedure of the PM optimization is explained in the figure caption. It is clear from this result that the intensity gain by optimizing thickness of the near target side PM is the largest and with other PM optimization further gain can be obtained which are not as drastic as the near target size PM. It is also found that the PM extension (for all PMs) does not give any appreciable intensity gain. In Fig. 5 the pulse shapes are compared with and without PM at a neutron energy of 100 meV. It is found that the optimized PM increases the peak intensity considerably without sacrificing the pulse shape. The optimized thickness is 1.0 cm; thinner than that of the Pb reflector system9).

3.3 decoupling energy dependence

Figure 6 shows the pulse shape at 100 meV for a lower decoupling energy (Cd decoupler) as

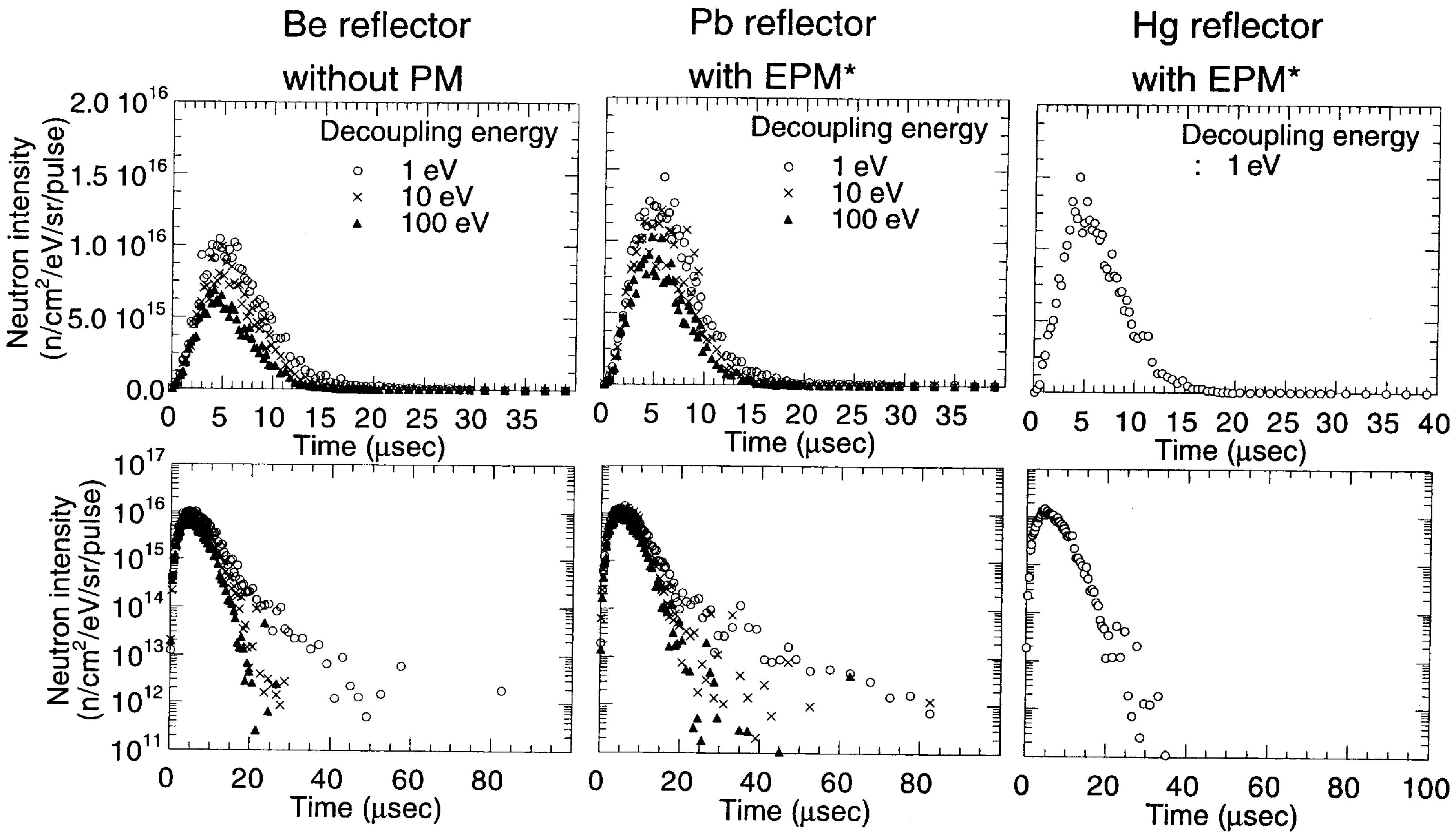

Fig. 3 Comparison of pulse shapes with a Be, Pb and Hg reflector system (E_n : 100 meV, proton : 25 Hz, 1 MW)
*EPM : Extended premoderator.

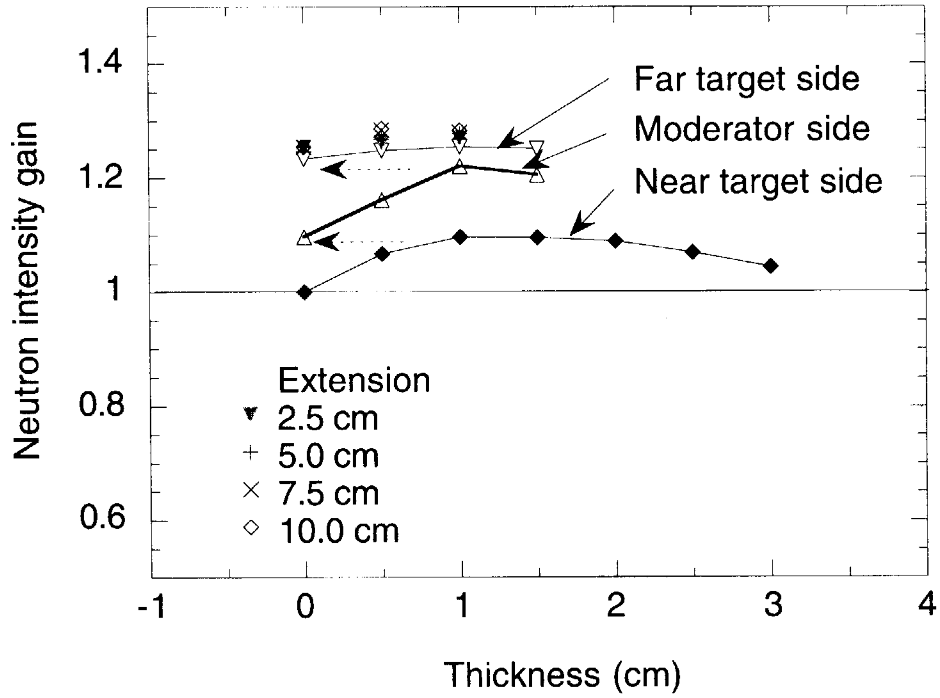

Fig. 4 Premoderator thickness and extension dependence of neutron intenstiy for Hg reflector system.
PM optimization precedure : Firstly find the optimal thickness of the near target side PM; then, keeping this thickness, find the optimal thickness of the moderator side PM; again keeping those PM thickness, find the optimal thickness of the far target PM; finelly study to effect of PM extension (of all PMs).

compared with one of 1 eV. In this investigation the PM was optimized for the Cd decoupler. The peak intensity is higher by about 37 % than that with 1 eV, however, a longer tail can be seen in the figure. As a decoupler material if B_4C cannot be used due to the serious radiation damage, we have no choice but to select the Cd, gadolinium (Gd) and a composite material as Cd + Europium (Eu) + Indium (In), (Cut-off energy is almost 2 eV), Figure 7 shows pulse shapes as compared with the other reflector systems (Be and Pb). The pulse width in full width at half maximum (FWHM) is almost the same regardless the different reflector systems. However, the pulse shape of the Hg reflector system has a fairly shorter tail than the others even with a lower decoupling energy of 0.4 eV (Cd). The pulse shape of the Hg reflector system is rather similar to that of the Be reflector system with a decoupling energy of 1 eV in this figure.

3.4 decoupler or liner is indispensable ?

Figure 8 shows the pulse shapes with and without the decoupler and the liners both with a decoupling or cut-off energy of 1 eV. From the viewpoint of the pulse shape a decoupler put between PM and H_2 moderator, as shown in Fig. 1, is at least needed. However the pulse shape without liner is almost the same as that with liner. From the result it is found that the effect of the liner on neutron pulse shape is not important (almost no effect), but the decoupler is indispensable; in other word, the pulse shape without decoupler may not be acceptable even with a Hg reflector system. For comparison the pulse shape with a Cd decoupler is also plotted in Fig. 8. It would be an user's issue whether the pulse shape with a Cd decoupler is acceptable. Usually, mercury as a reflector material is contained within a stainless steel vessel. We concerned about the effect of the stainless steel container (thickness : 1 cm) without liners on the pulse shape. As shown in Fig. 8, it is found that structure material such as stainless steel (here, stainless 316) has no affect on the pulse shape. We propose to put a decoupler just inside the PM container in which water is flowing to cool the vacuum chamber of the cryogenic moderator. In this concept, the nuclear heat in the decoupler could be removed.

3.5 effect on coupled moderator

Figure 9 shows the effect of the Hg reflector system on the neutron intensity for the coupled moderator. The use of an Hg reflector reduces the time-integrated intensity by about 30 % in the cold neutron region compared with the Pb reflector case : The effect is very large. As a result, mercury could not be used as a reflector material for a coupled moderator. Beside even if we restrict the use of mercury as a reflector for the decoupled moderator only, we have still concerned how about the intensity decrease for the coupled H_2 moderator.

Figure 10 shows the result of such effect on the coupled moderator. It is found that there is almost no effect on the intensity for the coupled moderator, provided that a Be or a Pb reflector is used for the coupled H_2 moderator (the upper half reflector)$^{17)}$. Thus, such composite reflector

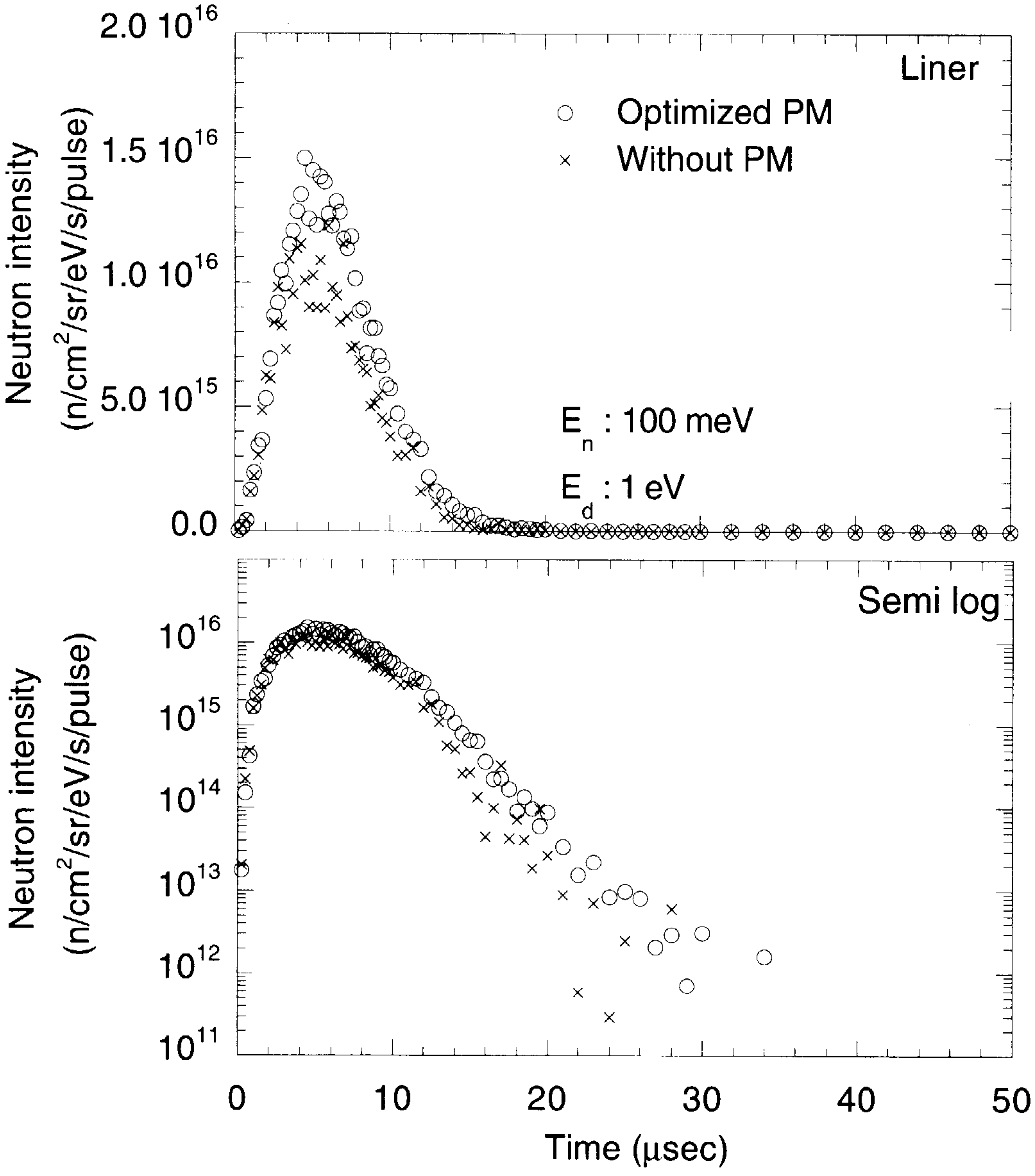

Fig. 5 Comparison of pulse shapes with optimized PM and without PM. (En : 100 meV, Proton : 3 GeV, 1 MW, 25 Hz)

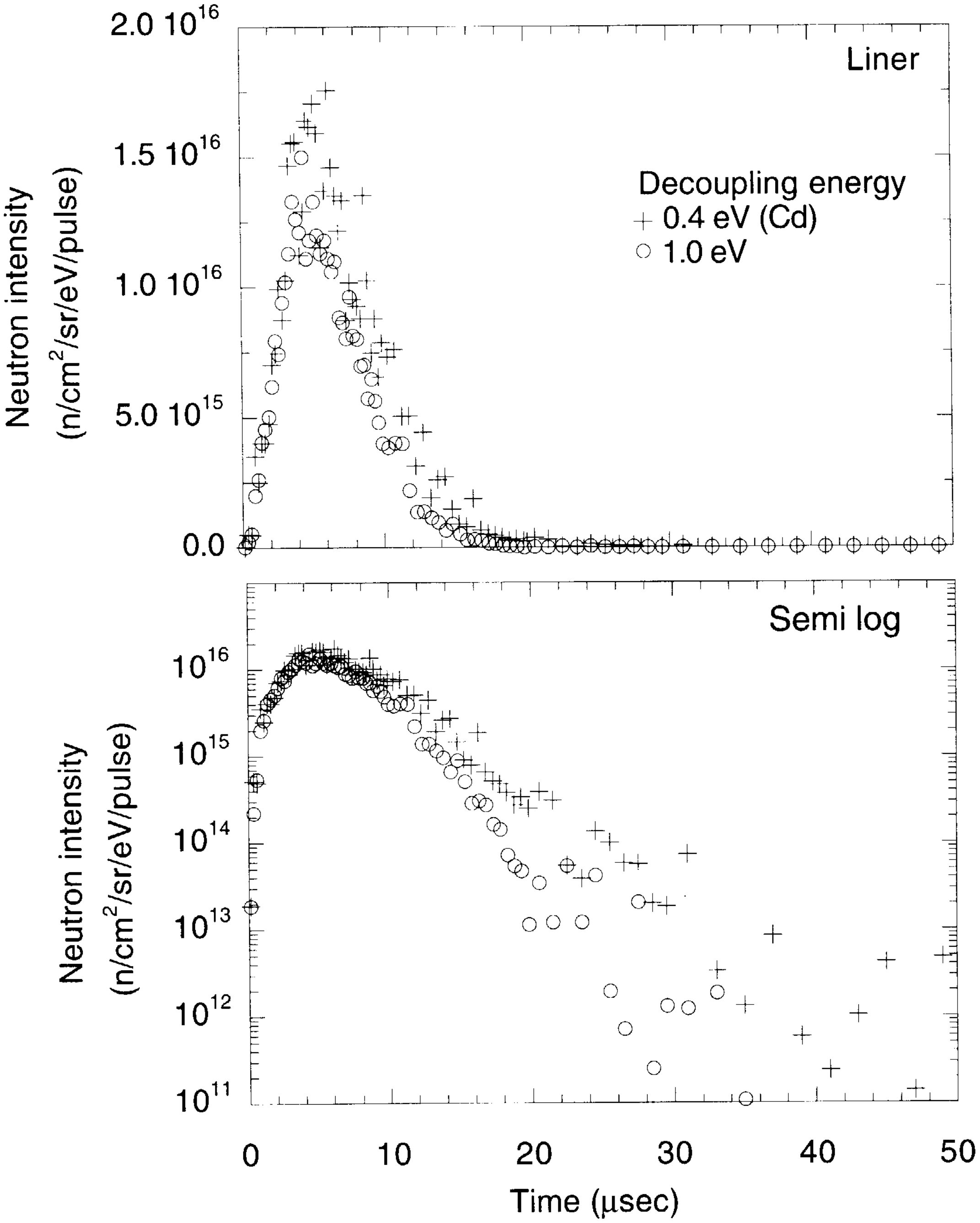

Fig. 6 Comparison of pulse shapes with different decoupling energy. PM was optimized for each decoupling energy.
(En : 100 meV, Proton : 3 GeV, 1 MW, 25 Hz)

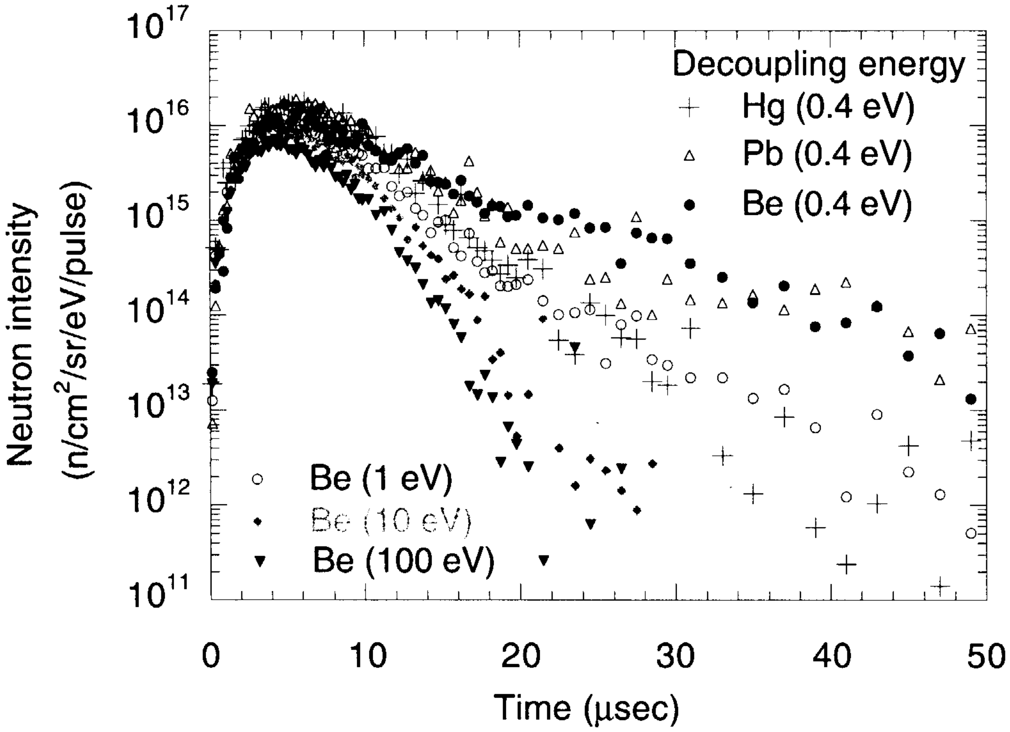

Fig. 7 Comparison of pulse shapes with other reflector system (Be and Pb).
(E_n : 100 meV, Proton : 3 GeV, 1 MW, 25 Hz)

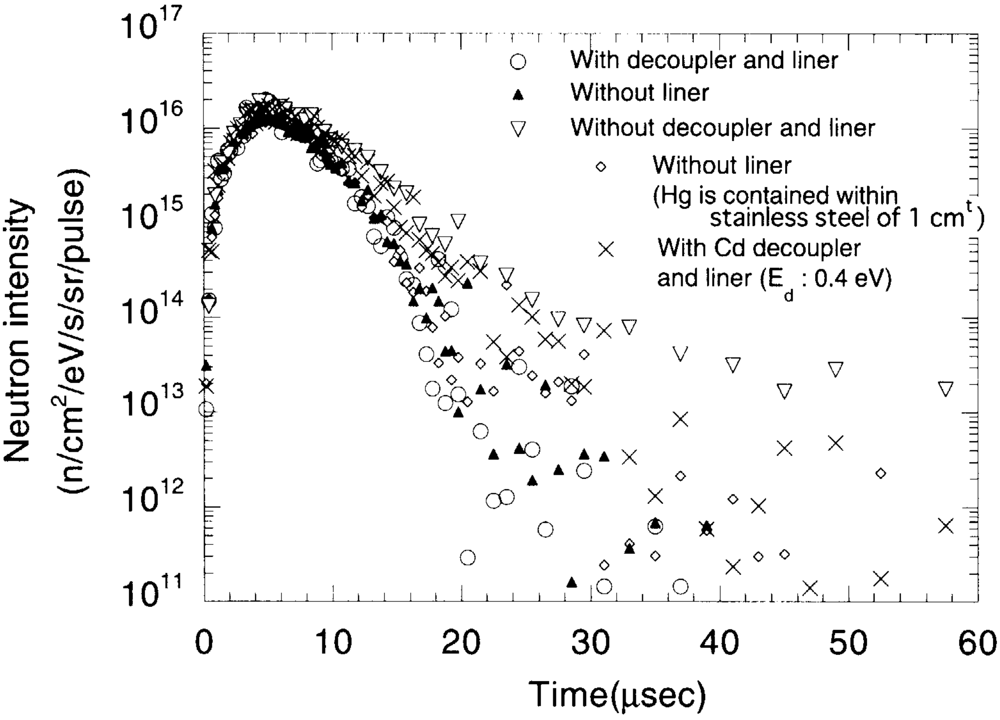

Fig. 8 Effect of decoupler and liner on pulse shape for decoupled H_2 mod. with extended PM.
(E_n : 100 meV, E_d : 1 eV and Proton : 3 GeV, 1 MW, 25 Hz)

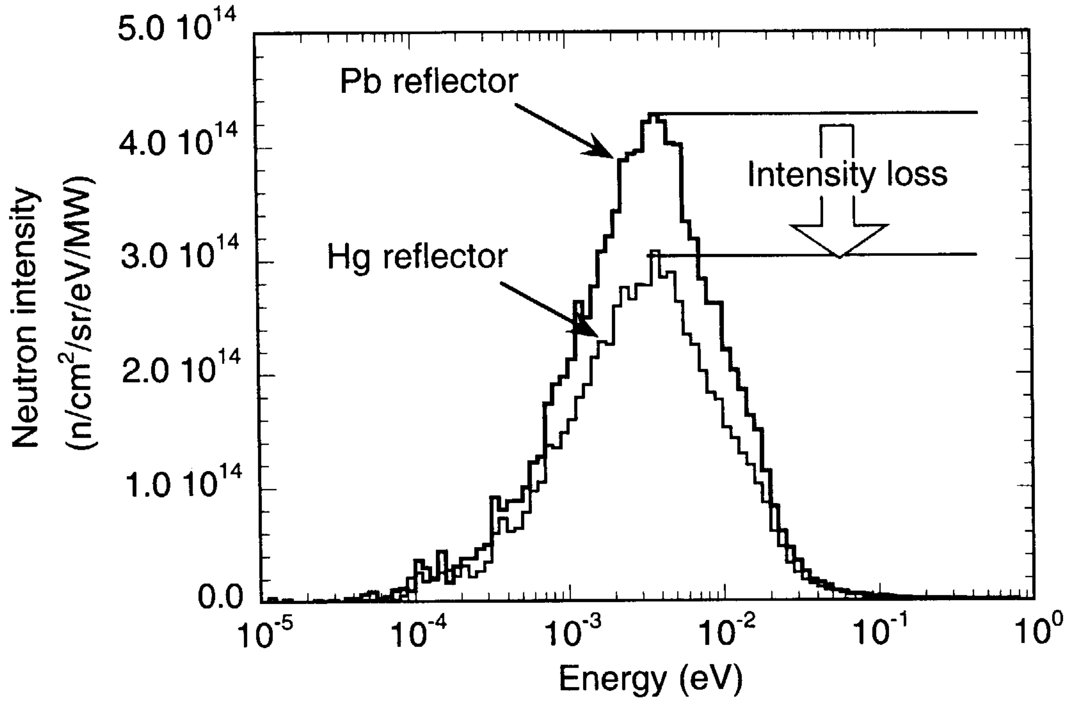

Fig. 9 Effect of Hg reflector on neutron intensity for coupled moderator (H_2 mod. with extended PM (2.5 cm thick, 15 cm extension)).

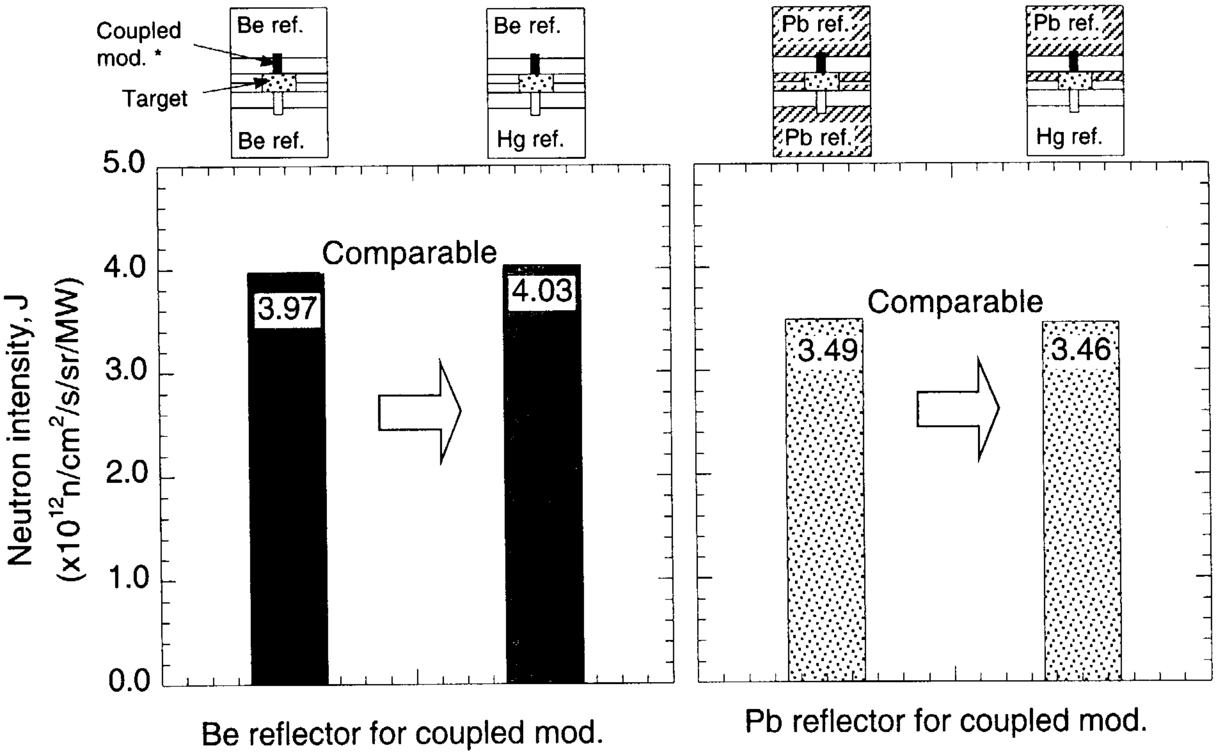

Fig. 10 Effect of separated reflector system on neutron intensity of coupled mod.

* Coupled H_2 moderator with extended PM, PM was optimized for each reflector system

system (Hg with Be or Pb) could make the coexistence of a coupled and a decoupled moderator possible, even with an Hg reflector for a decoupled moderator.

4. Summary

An Hg reflector system could provide a higher neutronic performance with some engineering merits as follows;
(1) an Hg reflector gives excellent pulse characteristics as compared with other reflector (Be or Pb) system. The peak intensity is almost comparable to or even higher than that of the optimized Pb reflector system and higher than the optimized Be reflector one and the pulse shape is almost equivalent to that of optimized Be reflector system with a decoupling energy of several tens eV;

(2) an Hg reflector needs decoupler of a lower decoupling energy, but not of a higher energy, An Hg reflector does not need a liner. Structure material (stainless 316) as a container of Hg does not affect the pulse shape. An Hg reflector does not need the coolant such as H_2O or D_2O because an Hg itself can be a coolant. These would bring about various engineering merits;

(3) an Hg reflector gives a large intensity reduction of neutrons from a coupled moderator. However, a composite reflector system of Hg and Be or Pb reflectors makes the coexistence of coupled and decoupled moderator possible.

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