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Effects of reflector parameters on neutronic performance of coupled hydrogen moderator with extended premoderator

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

Japan Atomic Energy Research Institute, Tokai 319-1195, Japan
E-mail : sakata@shield4.tokai.jaeri.go.jp

Abstract

Extensive neutronic optimization studies on the reflector for a coupled hydrogen moderator with extended premoderator have been performed with various parameters such as reflector material, size, cooling water and the existence of decoupled moderators located at the opposite side of the target. Time-integrated and peak intensities, pulse widths and decay times from a coupled hydrogen moderator (12 x 12 x 5 cm^3) with optimized premoderator in a lead (Pb) and a beryllium (Be) reflectors have been studied as a function of reflector dimensions with and without an iron outer reflector-shield. The effects of cooling water (H_2O or D_2O) fraction were also studied. A larger inner reflector (Pb or Be) and a larger outer reflector-shield give a higher neutron intensity for both reflector systems. The neutron intensities are saturating with increasing reflector sizes for each reflector system. The optimized Pb reflector system provides higher peak intensity than the optimized Be one, while the latter gives higher time-integrated intensity in the Maxwellian portion than the former. The intensity penalty with cooling water is rather significant, especially in case of H_2O. For example, 10% H_2O fraction in the reflector reduces the time-integrated intensity by about 14% and 11% for the Pb and the Be reflector systems, respectively. Time-integrated and pulse peak intensities decrease by installing decoupled moderators at the opposite side of the target. The existence of decoupled moderators causes a significant intensity decrease by about 15% and 7% for the Pb and the Be reflector systems, respectively. This is mainly due to the reflector missing produced by neutron beam extraction holes in the reflector.

1. Introduction

As a most important part of the joint project[1] for constructing a high-intensity proton accelerator with experimental facilities by Japan Atomic Energy Research Institute (JAERI) and High Energy Accelerator Research Organization (KEK), the development of an intense pulsed spallation neutron source (JSNS) is going on. The proton beam power at the first stage is 1 MW but finally will be upgraded to 5 MW. Generally, in the construction of a new pulsed source, it is important to obtain a higher neutron intensities, narrower pulses and shorter decay times. In JSNS, we proposed three moderators; one coupled hydrogen (H_2) moderator with optimized premoderator (PM) for high intensity and very high resolution uses and two decoupled moderators for high resolution uses. In this paper we report the reflector optimization for a coupled H_2 moderator with H_2O PM in a lead (Pb) and a beryllium (Be) reflectors. It is already known that a premoderator enhances neutron intensities and mitigates the energy deposition in hydrogen, resulting in the less engineering difficulty[2-3]. Further premoderator optimization studies have shown that an extend PM (EPM) brought about an additional intensity gain and a further decrease in the energy deposition[4]. The neutronic performance significantly depends on the choice of the reflector material and sizes. Some investigations have been carried out for the effect of the reflector material and sizes on neutron intensity and pulse shapes[4-7]. However, these investigation were for a system without PM. The existence of cooling water (light or heavy water) which is inevitably needed for a MW class source is also another important factor which determines the neutronic performance. The neutronic performance is also influenced by the existence of decoupled moderators, since beam extraction holes in the reflector for decoupled moderators cause the reflector missing. For the decoupled moderators, which are located at the opposite side of the target, if it is necessary to choose a different reflector material in order to optimize the neutronic performance of those moderators, such a reflector will also affect the neutronic performance of the coupled one.

Therefore we performed a neutronic studies on following items;

(1) effect of reflector material and sizes;
(2) effect of outer reflector-shield;
(3) effect of cooling water in reflector;
(4) effect of different reflector material for decoupled moderators;
(5) effect of reflector missing due to decoupled moderators.

2. Calculations

The calculation model of the target-moderator-reflector system is shown in Fig. 1. The coupling scheme of the target-moderators is a wing geometry. One coupled supercritical H_2 moderator with $12 \times 12 \times 5\ cm^3$ at 20 K with extended H_2O premoderator (EPM) was located above the target both for high-intensity and very high-resolution uses. The premoderator shape was optimized for each reflector (Pb or Be) system. One decoupled H_2 moderator (upstream) and one decoupled H_2O or a poisoned H_2 moderator (downstream), both for high-resolution use, were located below the target. For H_2 moderator we assumed a ortho / para ratio of 75 % / 25 % (normal hydrogen). Neutron viewed surface was fixed at $10 \times 10\ cm^2$. A beam extraction hole in the reflector had an opening angle of 45 degrees. A mercury (Hg) target was assumed with sizes of 60 cm in width, 12 cm in height and 160 cm in length including the target container and the outer jacket. For the incident protons following parameters were assumed; energy : 3 GeV, beam power : 1 MW, beam sizes (foot print) : 13 cm wide x 5 cm high (rectangular), current density : 5.1 $\mu A/cm^2$ (uniform distribution). We selected Pb and Be as a reflector material. A cylindrical reflector was assumed. We studied the neutron intensities as a function of the inner reflector dimensions (diameter and height) for the cases of the inner reflector only and with the outer reflector-shield. In the latter case the total diameter and height were kept at and 300 cm. The effect of the cooling water was studied as a function of the cooling water (H_2O or D_2O) fraction in a range of 10%-50%. In the case with the outer reflector-shield the water (H_2O) fraction was fixed at 10%. In this study the dimensions of inner reflector was fixed at 60 cm.

In order to study the effect of dedicated reflector for decoupled moderators below the target we calculated the intensities from the coupled H_2 moderator with different materials (Pb, Be or Hg) for the lower half reflector.

We performed neutronic calculations using a high energy hadron transport code of NMTC-JAM[8-9] combined with a low energy transport code MCNP-4A[10]. The cross section library based on JENDL[11] was used in MCNP-4A calculations. Point detector tallies located at 2 m from the moderator surfaces to the normal direction were used to obtain the time-integrated intensity integrated the Maxwellian part, J and pulse peak intensity at 2 meV. The pulse width (FWHM) and the pulse decay times (τ_1 and τ_2) were also calculated. The calculated spectral intensity data were fitted using a semi-empirical formula[12] to obtain J. The decay times (τ_1 and τ_2) were determined as shown in Fig. 2.

3. Results and discussions

3.1 Effects of the reflector material and sizes

Figure 3 shows the pulse shapes of cold neutrons at 2 meV from the coupled H_2 moderator with EPM for various inner reflector sizes and materials (Pb or Be) without the outer reflector-shield and no cooling water. A larger Pb reflector (inner) gives higher peak intensity than a Be reflector (inner), while the latter gives somewhat higher time-integrated intensity (see Fig. 4) but with a longer pulse tail than the former. Figure 4 shows the reflector size dependence of cold neutron performance for the case of the inner reflector only and the case with the outer reflector-shield. The effect of the outer reflector-shield is discussed in the next section. In the former case the J values and the peak intensities for both reflector systems increase with reflector sizes but saturate at larger sizes. The saturated intensity for the Be reflector system is higher than for the Pb one. The saturated peak intensity in the Pb reflector system is higher than in the Be one. For the Pb reflector system the increase in J is due to the increase of the peak intensity, since the pulse width (FWHM) and the decay times (τ_1 and τ_2) are almost unchanged with increasing reflector sizes as shown in Fig. 4. While for the Be reflector system, the increase in J is due to longer decay times. The choice of larger reflector sizes for the Pb reflector system results in the higher peak intensity and shorter decay times, but somewhat lower J compared with Be reflector system.

3.2 Effect of outer reflector-shield

As shown in the right hand of Fig. 4 (right hand side), the use of an outer reflector-shield gives higher J and peak intensity from the case of the inner reflector only. The results means that even with a small inner reflector, if there is an outer reflector-shield up to 300 cm in diameter, the neutron intensities are the same as that in the case of a larger inner reflector only. The pulse width and the decay times are almost unchanged by adding the outer reflector-shield compared to the case of the inner reflector only.

3.3 Effect of cooling water in reflector

Figure 5 shows the effect of cooling water (D_2O or H_2O) in the reflector on the neutron pulse shapes for each inner reflector (Pb or Be). Some important parameters of neutron pulse characteristics (J, peak intensity, pulse width and decay times) are shown in Figure 6. Obviously the use of H_2O decreases both J and peak intensities much seriously than the case of D_2O. Therefore the use of D_2O would be indispensable. However, even the case of D_2O, the increase of the cooling water fraction reduces the intensities significantly and gives a longer pulse tail. The result suggests that the fraction of cooling water must be as small as possible. If we compare the effect of the cooling water fraction in a Pb and a Be inner reflector, the intensity for the former decreases more rapidly than for the latter. In JSNS we are aiming at realizing a D_2O fraction of 5-10%.

The dependence of the cooling water fraction on the pulse width is rather small for both inner reflectors.

The dependence on the faster decay time (τ_1) is also rather small, although the values for the Be system are much longer than for the Pb system. In case of the Pb system there is almost no difference between D_2O and H_2O, but τ_1 slightly increases with water fraction. On the other hand in case of the Be system, τ_1 decreases with H_2O fraction. This is considered due to the fact that the increase of H2O results in the increase of the macroscopic absorption cross section in the Be reflector.

The longer decay time (τ_2) is also larger in the Be system than the Pb one. In the Pb system τ_2 increase with D_2O fraction. This is due to the increase of the storing time of cold (thermal equilibrium) neutrons in the reflector by the D_2O adding.

3.4 Effect of different reflector material for decoupled moderators

It has been proposed to use a mercury (Hg) reflector for decoupled moderators[14]. An Hg reflector brings about a higher neutronic performance and engineering advantages; a higher peak intensity with a faster decay, no need to use liners, a lower decoupling energy for a required decay time, no need to cooling water (Hg itself can be coolant). However, The most important disadvantage with the use of an Hg reflector is the significant decrease in the neutron intensity from a coupled H_2 moderator. In order to solve this problem, we are proposing to use a composite reflector; the upper half reflector consisting of Pb or Be for a coupled H_2 moderator and the lower half consisting of Hg for decoupled moderators. In order to examine this idea, we performed same calculations. On composite reflector system, three materials (Hg, Pb and Be) are assumed for the lower half reflector to compare the performance.

Figure 7 shows the results; the intensity J in each composite inner reflector system is almost not affected by the combination of materials for the upper and the lower. In other wards, even with an Hg reflector for the lower half, if we use a Pb or Be inner reflector for the upper half, the cold neutron intensity from the coupled H_2 moderator is almost the same as a full monolith reflector case.

3.5 Effect of reflector missing due to decoupled moderators

Figure 8 shows the effect of reflector missing, which is caused by the installing of decoupled moderators and their beam holes, on J from a coupled H_2 moderator with EPM. The reflector missing reduces J by about 15 and 7% for Pb and Be reflector system, respectively. A larger decrease in J from the Pb reflector system is due to the reason that the reduction of reflector size decrease J more rapidly than a Be one (see Fig. 4). A larger volume reduction due to the beam extraction holes is equivalent to a reflector size reduction.

The results suggest that full system calculations are indispensable to study the neutron performance even for a specific moderator.

4. Summary

From the present reflector studies for the coupled H_2 moderator, we arrived at the following conclusions

1) A larger Pb reflector brings about a higher peak intensity with a shorter pulse tail compared to the Be reflector system, although J for the former is somewhat smaller (about 15%) than for the latter.

2) The reflector saving effect of an outer reflector-shield is large even for a smaller inner reflector of Pb or Be. It also useful to shield high energy neutrons, especially in case of a Be inner reflector.

3) The use of D_2O reflector cooling water is indispensable. Even in case of D_2O the intensity reduction is significant. A water fraction as small as 5-10% would be a design goal.

4) For decoupled moderators the use of an Hg reflector is the best but it decreases J and the peak

intensity from a coupled H_2 moderator significantly. The use of a composite reflector, Pb or Be at upper half for a coupled H_2 and Hg at lower half reflector, could give almost the same neutronic performance for a coupled H_2 moderator.

5) The effect of reflector missing due to the existence of decoupled moderators is rather significant. The intensity decrease is more pronounced in case of a Pb reflector system than a Be one.

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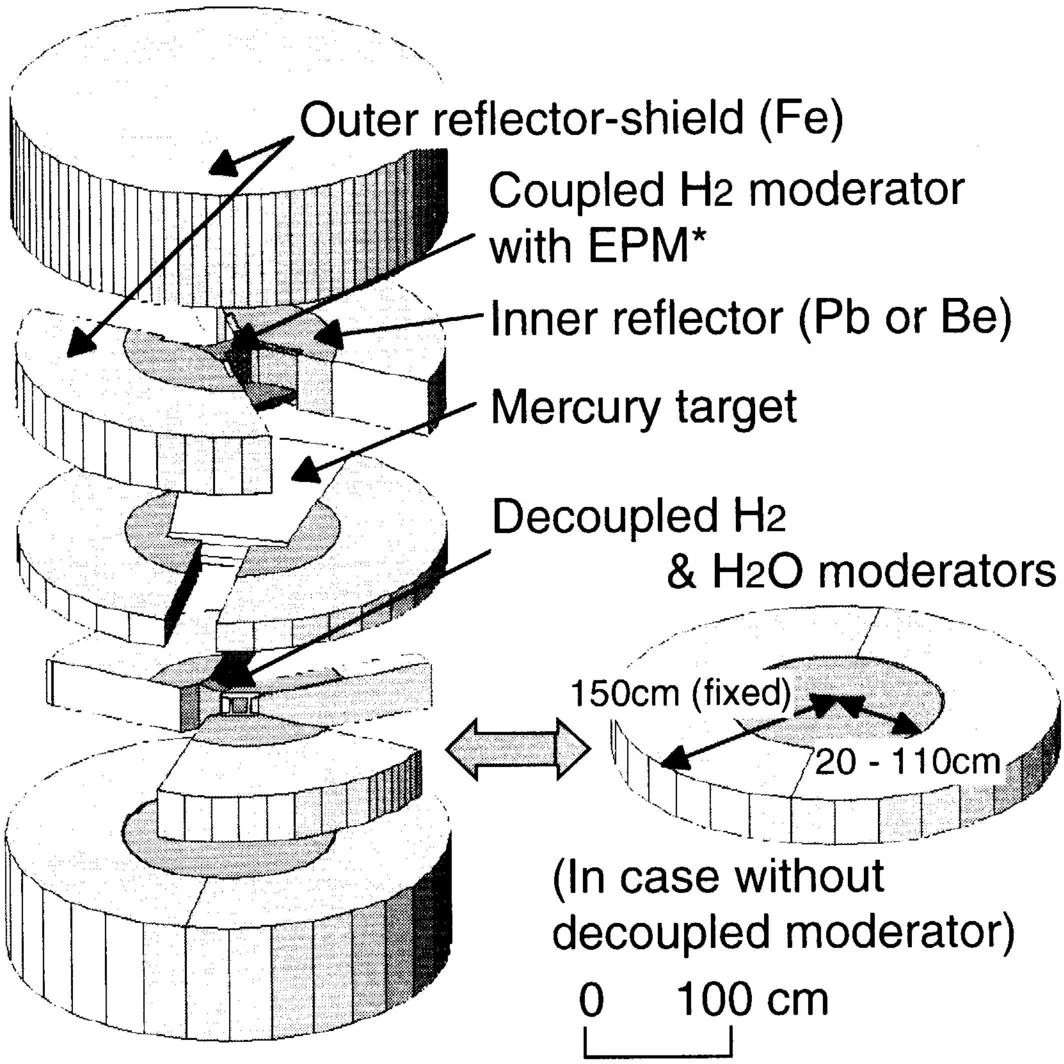

Fig. 1 Calculation model for reflector study. (Exploded view)
*EPM : extended premoderator

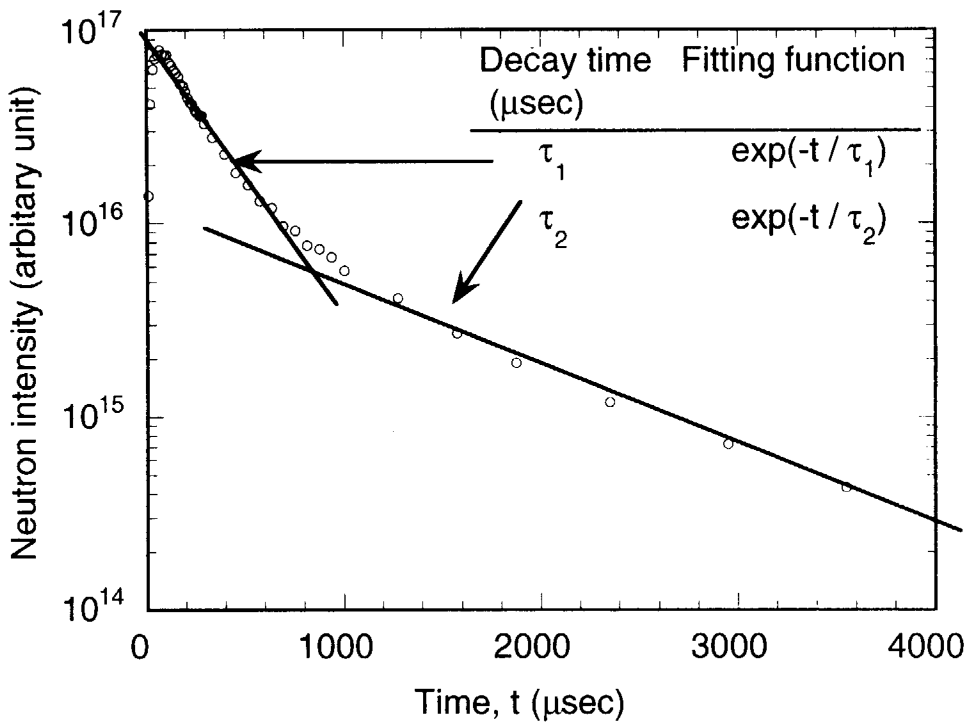

Fig. 2 Decay times (τ_1 and τ_2)

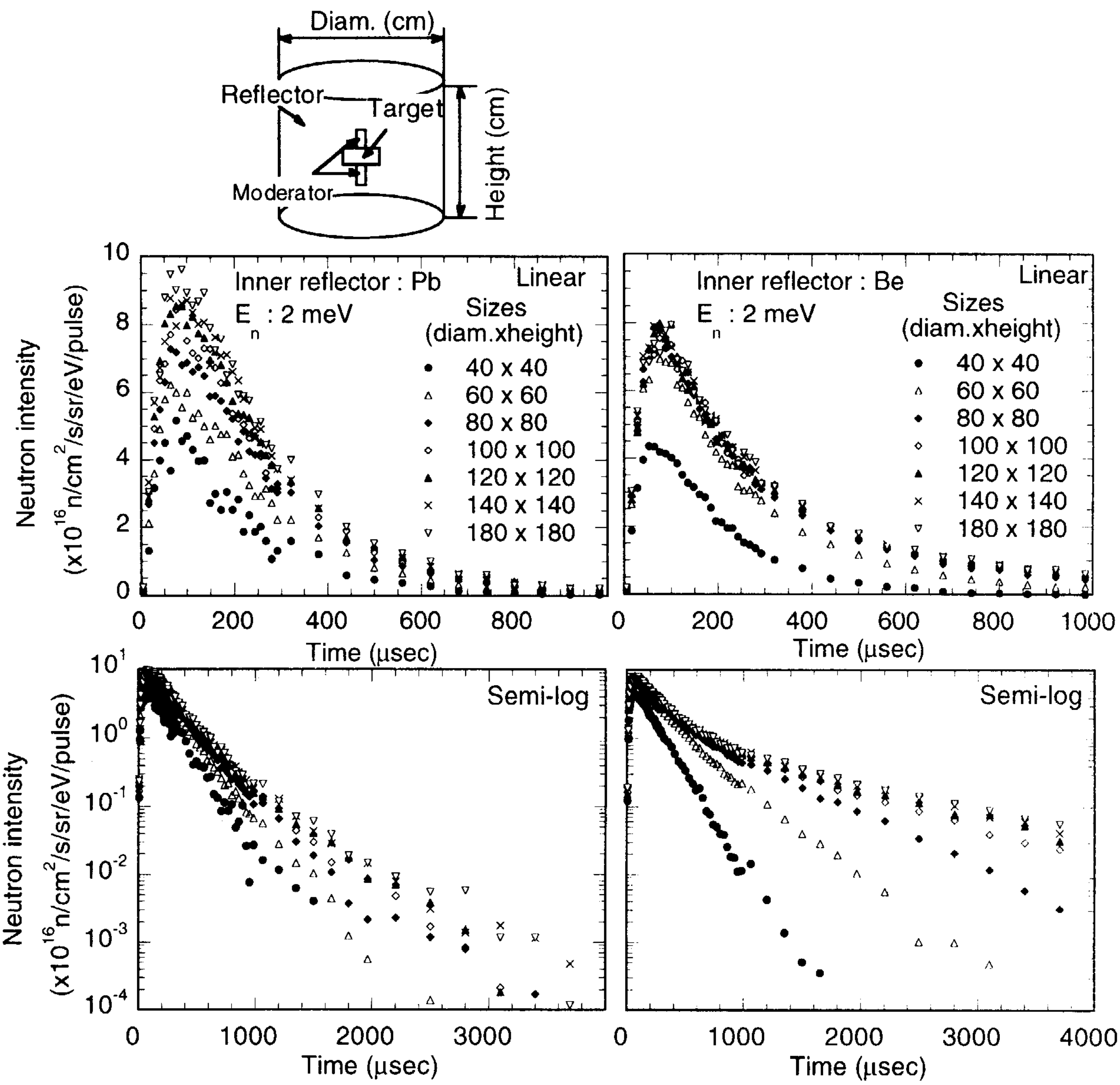

Fig. 3 Pulse shapes of cold neutron at 2 meV from coupled H_2 moderator with EPM for various reflector sizes (Proton : 3GeV, 1 MW and 25 Hz)

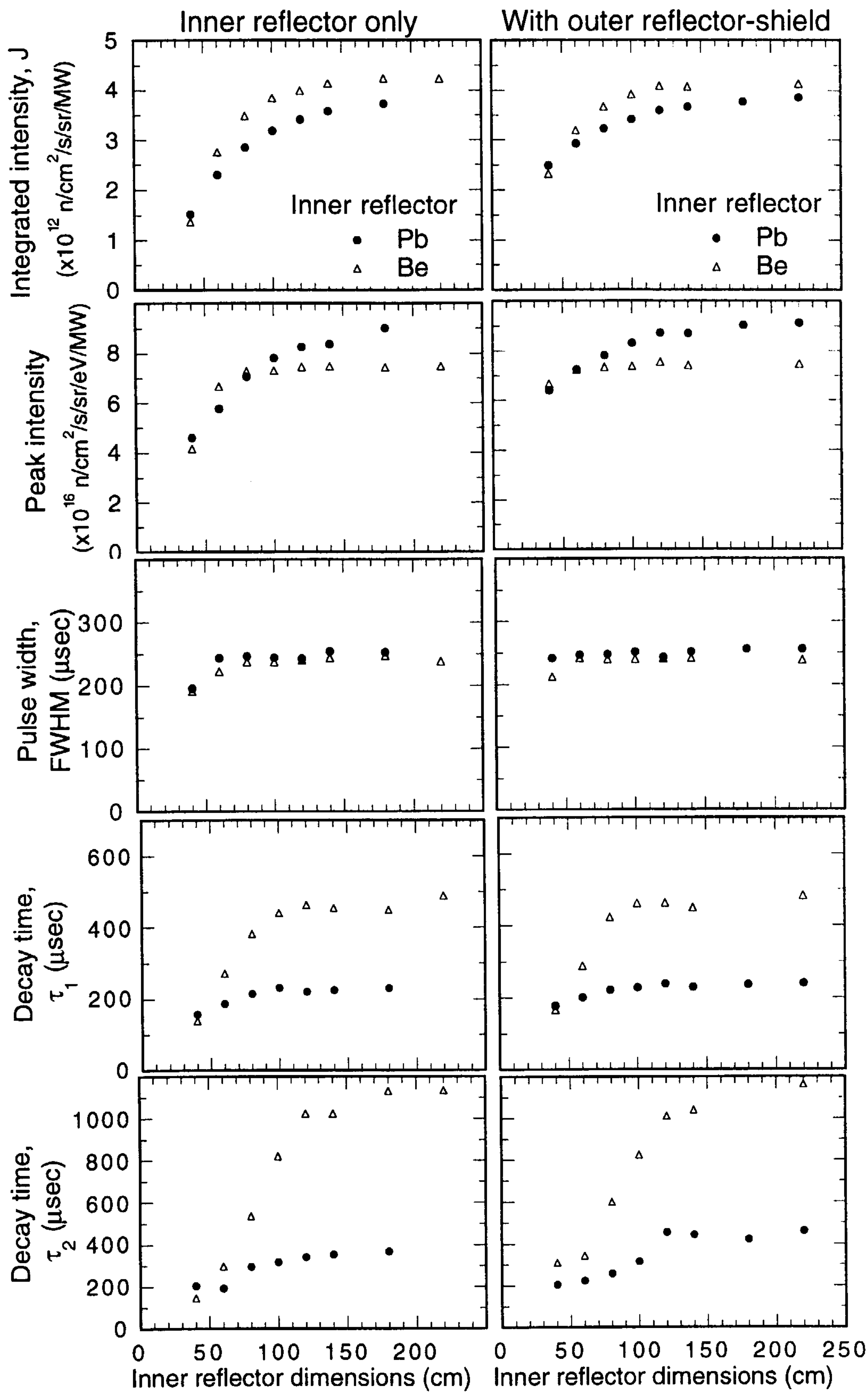

Fig. 4 Inner reflector size dependence of time integrated intensity, J, peak intensity, pulse width (FWHM) and decay time (τ_1 and τ_2) (Proton : 3GeV, 1 MW and 25 Hz) (The parameter expect for J are for cold neutron at 2 meV)

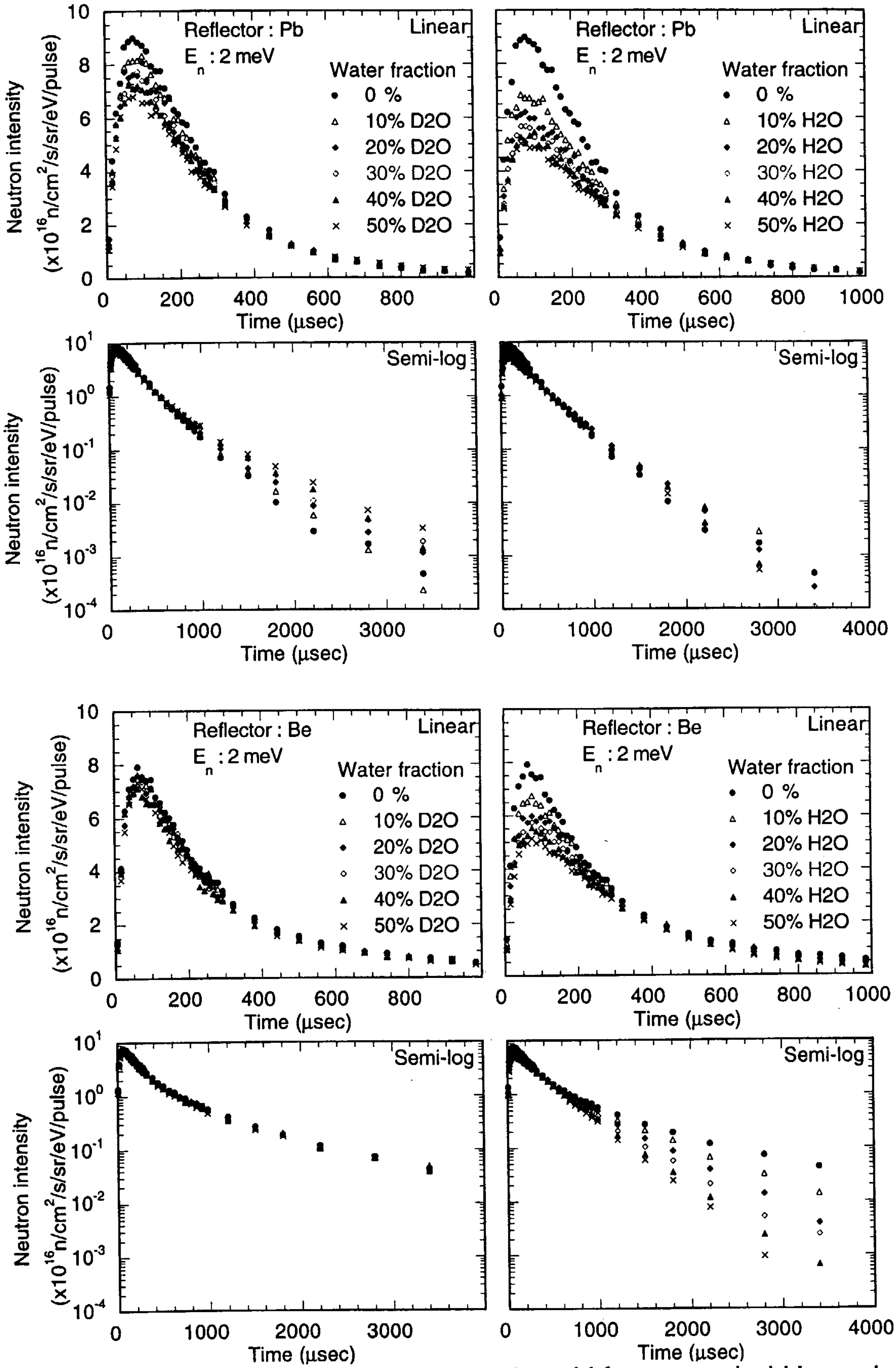

Fig. 5 Pulse shapes of cold neutrons at 2 meV from coupled H_2 moderator with EPM for various water fraction (Proton : 3GeV, 1 MW and 25 Hz)

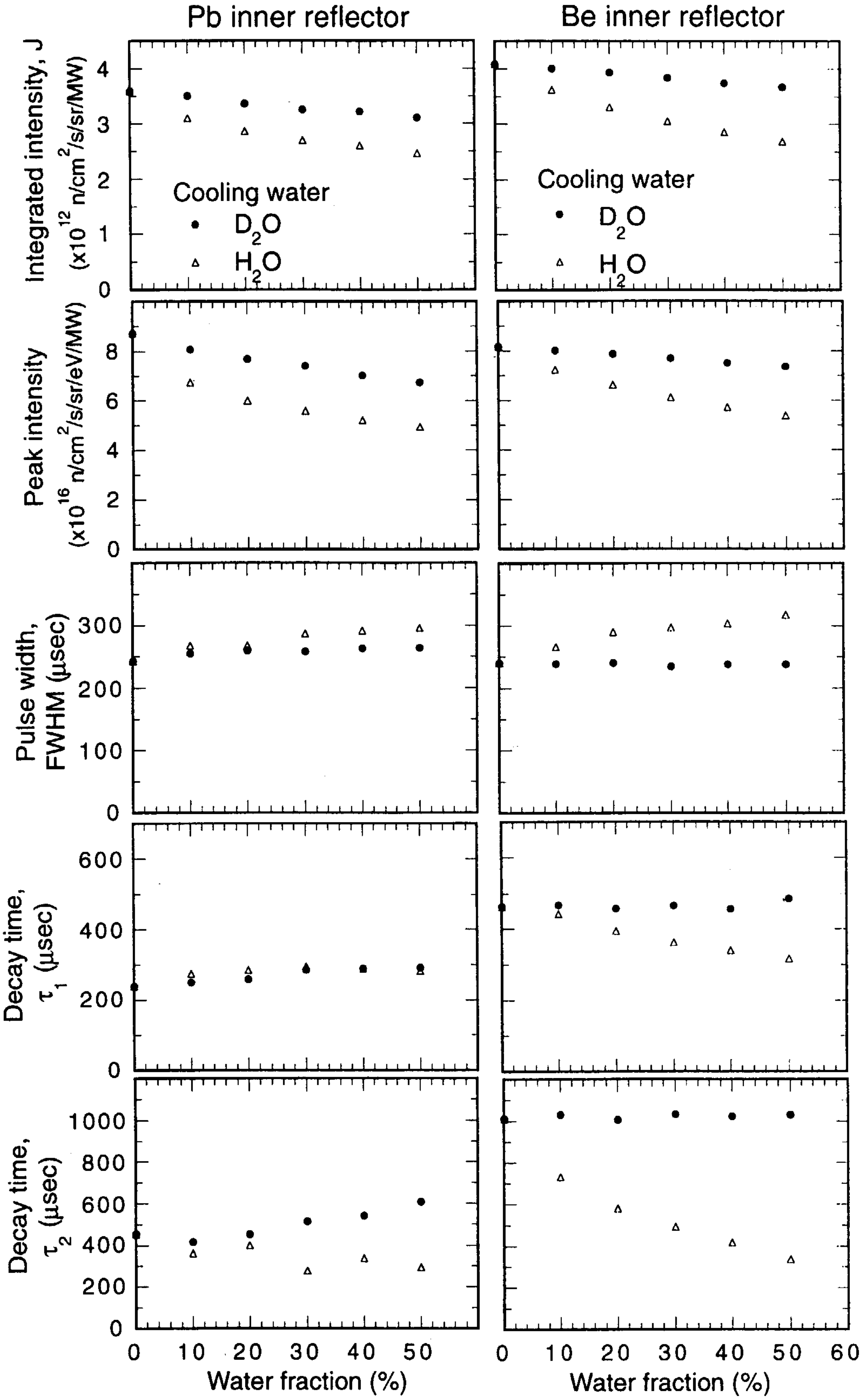

Fig. 6 Cooling water dependence of time integrated intensity, J, peak intensity, pulse width (FWHM) and decay time (τ_1 and τ_2) (Proton : 3GeV, 1 MW and 25 Hz) (The parameter expect for J are for cold neutron at 2 meV)

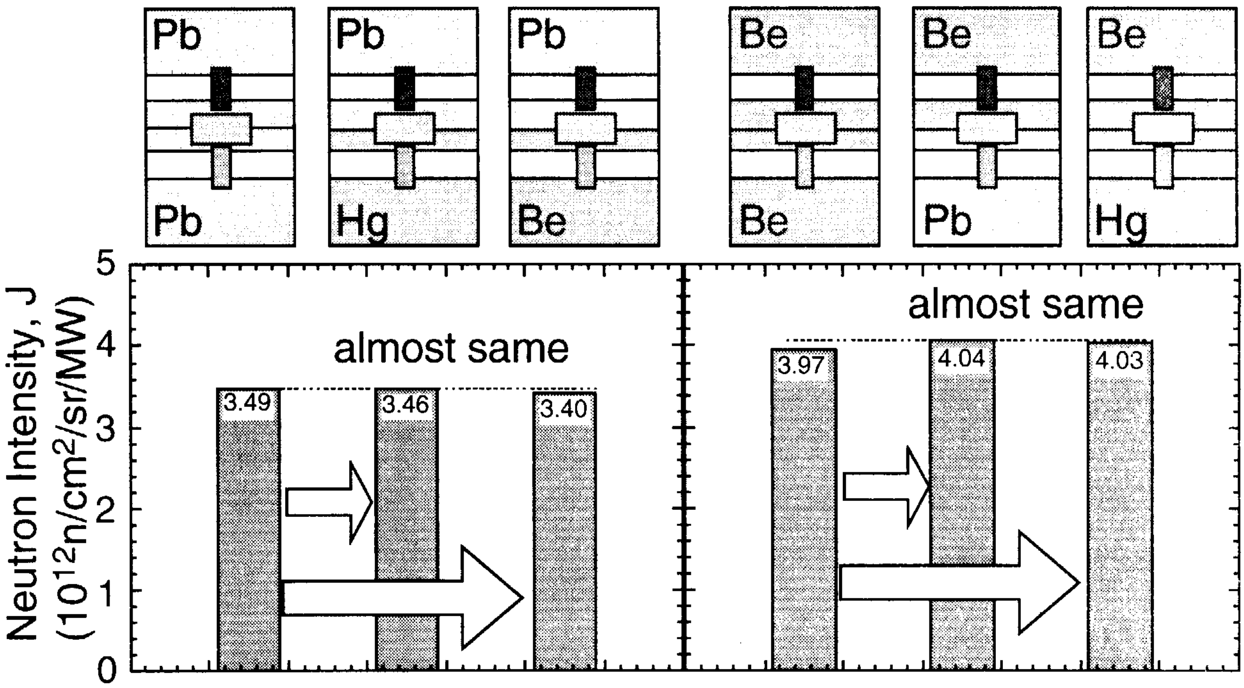

Fig. 7 Effect of reflector material of the decoupled moderators on neutronic intensity, J for the coupled moderator

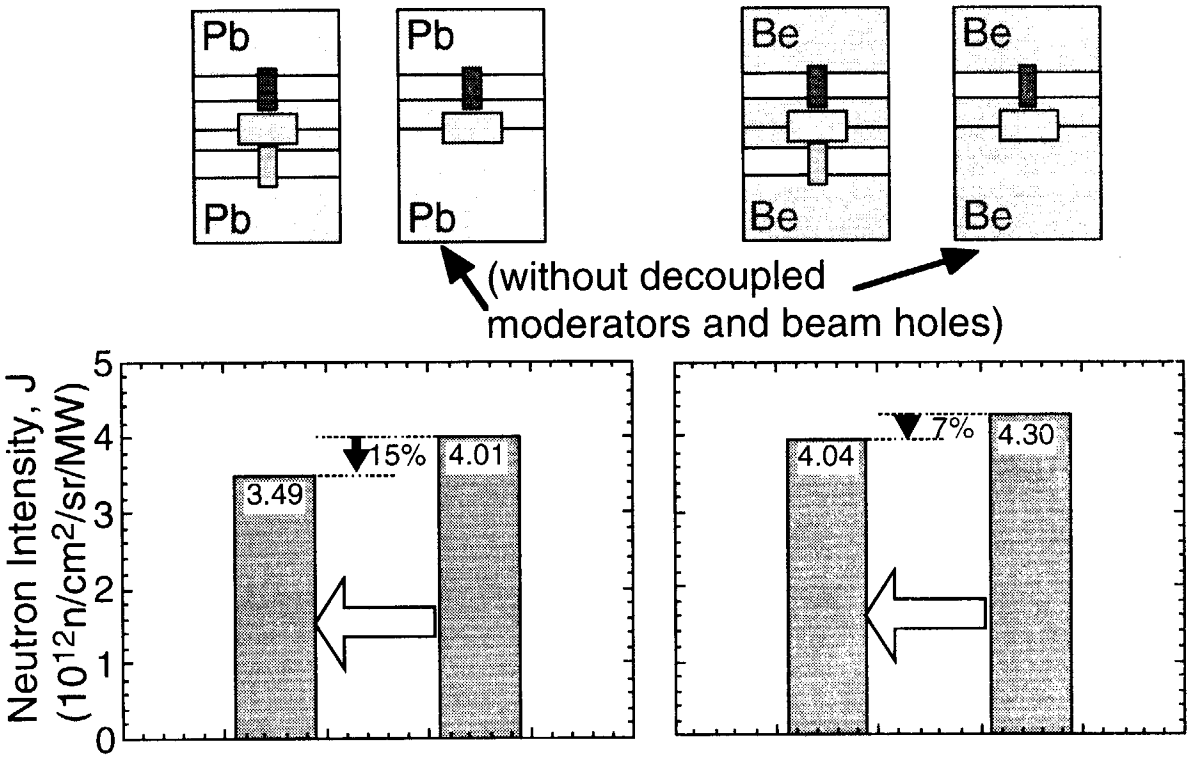

Fig. 8 Effect of the reflector missing with the decoupled moderators and thier beam holes on neutron intensity, J for coupled H_2 mod. with EPM