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Proton energy dependence of slow neutron intensity

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Abstract

The choice of the proton energy is an important issue for the design of an intense-pulsed-spallation source. The optimal proton beam energy is rather unique from a view point of the leakage neutron intensity but not yet clear from the slow-neutron intensity view point. It also depends on an accelerator type. Since it is also important to know the proton energy dependence of slow-neutrons from the moderators in a realistic target-moderator-reflector assembly (TMRA). We studied on the TMRA proposed for Japan Spallation Neutron Source. The slow-neutron intensities from the moderators per unit proton beam power (MW) exhibit the maximum at about 1-2 GeV. At higher proton energies the intensity per MW goes down; at 3 and 50 GeV about 0.91 and 0.47 times as low as that at 1 GeV. The proton energy dependence of slow-neutron intensities was found to be almost the same as that of total neutron yield (leakage neutrons) from the same bare target. It was also found that proton energy dependence was almost the same for the coupled and decoupled moderators, regardless the different moderator type, geometry and coupling scheme.

1. Introduction

When we consider the construction of an intense-pulsed-spallation source, the choice of the proton energy becomes the most important issue. Since the maximum available proton beam power depends on an accelerator type or a combination of accelerators, For example, a higher energy but with a modest beam current would be more realistic for a synchrotron, while a lower energy but with a higher current would be more likely for a full energy proton (H^-) linac plus compressor ring (s). In Japan, an intense-pulsed-spallation neutron source of a 5 MW class has been proposed. For simplicity, we tentatively refer to JSNS (Japan Spallation Neutron Source). However, at the initial stage it was decided to start the project at 1 MW. Thus we had extensive discussions for the upgrade path to 5 MW ; for example, 5 MW H^- linac + compressor rings vs. two 6 GeV synchrotrons.

Another important issue is the choice of the pulse repetition rate. In the JSNS project one 3 GeV synchrotron is considered to supply 1 MW pulsed proton beam at 25 Hz. This repetition rate is favorable for low repetition rate experiments. However, at 5 MW such a low repetition rate would be difficult. In this paper we concentrate on the proton energy issue.

Concerning leakage neutrons from a target, there are some measurements and calculations at higher proton energies. Jerng et al.[1] studied the intensities and the spatial distributions of leakage neutrons from a bare tantalum (Ta) target by calculations up to 12 GeV using the LCS code system. On the total neutron yield, Nikolaev et al.[2] reported measured values up to 3.5 GeV, Vassil'kov et al.[3] up to 7 GeV and Arai, et al.[4] at 12 GeV. Dementyev et al[5] performed calculations up to1OO GeV using the SHIELD code. These measurements and calculations were performed mostly for lead (Pb) targets (20 cm in diam. and 60 cm long). The measured yields are fairly well agreed with the calculations. Concerning the spatial distribution of leakage neutrons from a mercury (Hg) target, measurements were performed using the AGS synchrotron at the Brookheaven National Laboratory by an international collaboration (ASTE) at proton energies 1.5, 7.0 and 24 GeV using the threshold-activation-detector method[6]. Calculations were also performed on the ASTE experimental system and it was found that the measured reaction rate of the threshold detectors were fairly well reproduced by calculations. Generally, it is known that the neutron production rate per unit proton beam power is highest in the proton energy range of 1-2 GeV. It decreases at higher energies because of the energy consumption for the pion production, etc. The distribution of leakage neutrons becomes broader along the proton beam direction with increasing proton energy, resulting in the decrease of the peak intensity of leakage neutrons per unit proton beam power.

In spite of various available data on the neutron yield and the spatial distributions of leakage neutrons from a bare target as mentioned above, there is very scarce available data on the proton energy dependence of slow-neutron intensities at higher proton energies. Kiyanagi, et al[7] calculated slow-neutrons below 1 eV from a reference decoupled H_2O moderator (10 x 10 x 5 cm^3) in a beryllium (Be) reflector for proton energy up to 3 GeV. However, above 3 GeV there is no data. Such information would be more important for the choice of the proton energy. Since a moderator in a target-moderator-reflector assembly (TMRA) could collect leakage neutrons from the target to some extent more widely, the proton energy dependence of slow-neutrons would be more or less different from those of the leakage neutrons, and might depend on the moderator type, target shape, etc.

Therefore, the calculation model must be as close as the real system. Such investigation has not been performed yet in detail. In this paper we report the proton energy dependence of the slow-neutron intensities based on the proposed TMRA for JSNS.

2. Calculation

2.1 Calculation model for the bare target system

In order to calculate the proton energy dependence of slow-neutrons beyond 3 GeV, we must prepare a high-energy hadron transport code which can work at high energies (in the present study up to 50 GeV). There are a few available codes for this purpose; HETC, LAHET, LCS, etc. A new code JAM[8-9], recently developed at Japan Atomic Research Energy Institute (JAERI), involves almost all particles and photons associated with higher energies and treats their interactions very precisely. Although, the validation of this code has already been performed, here we would try to compare calculated results using this code with those using other codes on the total neutron yield from a bare Pb target, 20 cm in diam. and 60 cm long, since there exist some measurements[2-4] and calculations up to 12 GeV. Measured and calculated values are compared in Fig. 1. The results shows that up to 12 GeV, the agreement between our calculation using the JAM code and the measured data seems to be satisfactory. Our calculated values are also consistent with those using LCS, HETC/KFA2.

The calculation model of the bare target system is illustrated in Fig. 2. Mercury as the target

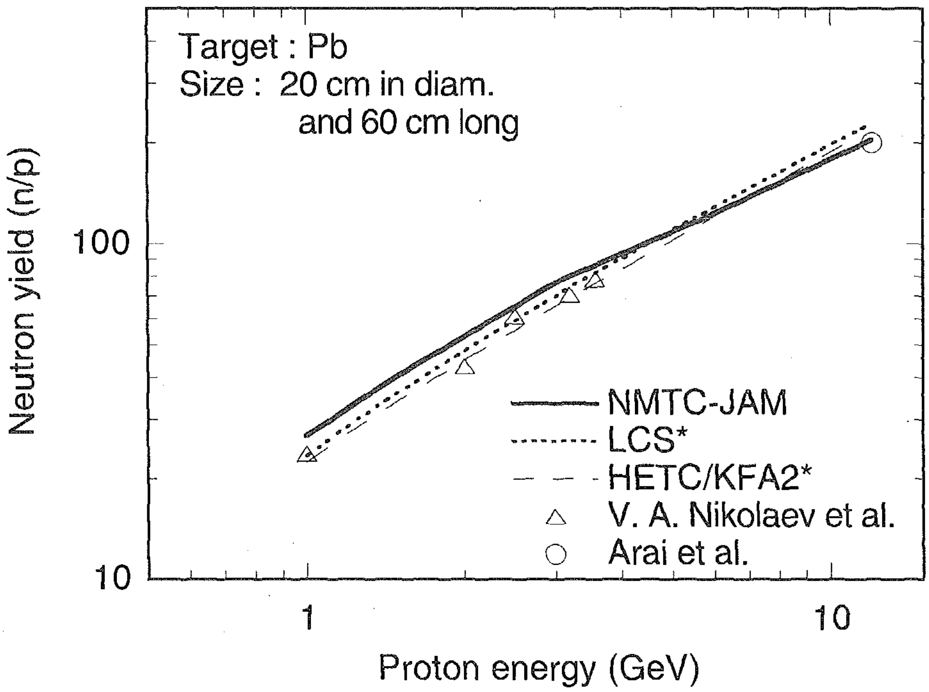

Fig. 1 Comparison of measured and calculated neutron yields.

* from Arai et al[4]

material is contained in a stainless steel vessel (316L, 2.5 mm thick) of a rectangular cross section (flat target) with a hemicylindrical beam window. A flat target shape was adopted from a neutronic point of view as proposed[10]. The smallest lateral dimensions of the target were assumed; the beam height plus 3 cm in the vertical size and the beam width plus 4 cm in the horizontal size. The maximum acceptable beam-current-density on the target was assumed to be 48 $\mu A/cm^2$ at the beam power of 5 MW in the case of proton energy of 1.5 GeV, judging from the integrity of the target beam window under the proton irradiation[11]. An uniform beam-current-distribution was assumed since we have confined that the neutronic performance with a parabolic or Moffet distribution was approximately the same as an uniform one. At other energies the current density was assumed to be inversely proportional to the proton energy. The detector tallies for the calculations of neutron intensities along the target axis, energy spectra, etc. were

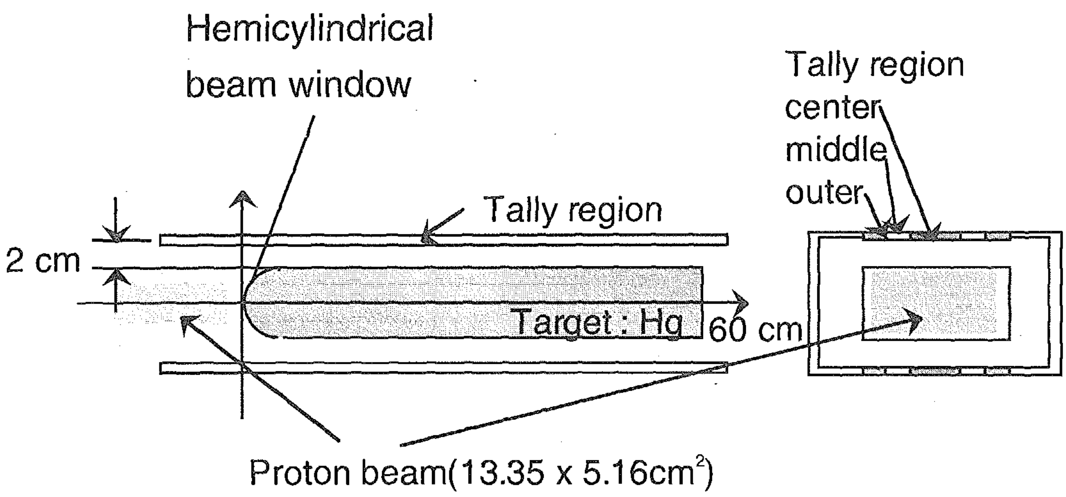

Fig. 2 Calclation model for bare target system.

located at 2 cm from the flat targets.

2.2 Calculation model for TMRA

Figure 3 shows an illustration of the TMRA model used for the present calculations as proposed for JSNS[12]. The layout of the target-moderator in the reflector is shown in Fig. 4. The coupling scheme of the target and the moderators was a wing geometry type.

The target size and proton-current profile were the same as the case of the bare target system. In the present model a double wall container was assumed for a more realistic modeling instead of a single wall used in the previous bare target model. The separation of the two walls was 5 mm. The space between the two walls was filled with cooling water (heavy water (D_2O)).

In order to predict the effect of the target shape on proton energy dependence of slow-neutron intensities, we also calculated on the cylindrical targets with a hemispherical beam window. The one had dimensions of 12.37 cm diam. and 60 cm long (including unirradiated annular part of 3 cm thick) and the same proton beam incident cross section with the flat target. The other had dimensions of 21.73 cm diam. and 60 cm long also including same unirradiated part. The latter one had two different beam cross section (the same area as the flat one and 4 times larger one which means one forth current density). These cylindrical targets were also in a double wall container made of a stainless steel as described above. The targets were moved to back and forth along the proton beam direction to obtain the maximum slow-neutron intensity for each proton energy. One coupled supercritical hydrogen moderator (12 x 12 x 5 cm^3) at 20 K with extended light-water (H_2O) premoderator (2.5 cm thick and 15 cm extension[13]) was located above the target both for high-intensity and very high-resolution uses (the highest peak intensity together with the highest time-integrated intensity). Hereafter, we call this moderator "coupled H_2 mod. with extended premoderator (EPM)". One decoupled H_2 moderator (upstream) and one decoupled H_2O moderator at ambient temperature (downstream), both for high-resolution use, were located below the target. We assumed rather small dimensions for decoupled moderators; 10 cm x10 cm x 5 cm for the decoupled H_2 moderator and 10 cm x 10 cm x 3 cm for the decoupled H_2O moderator. In the calculation model boron carbide (B_4C) decouplers were used with a cut off

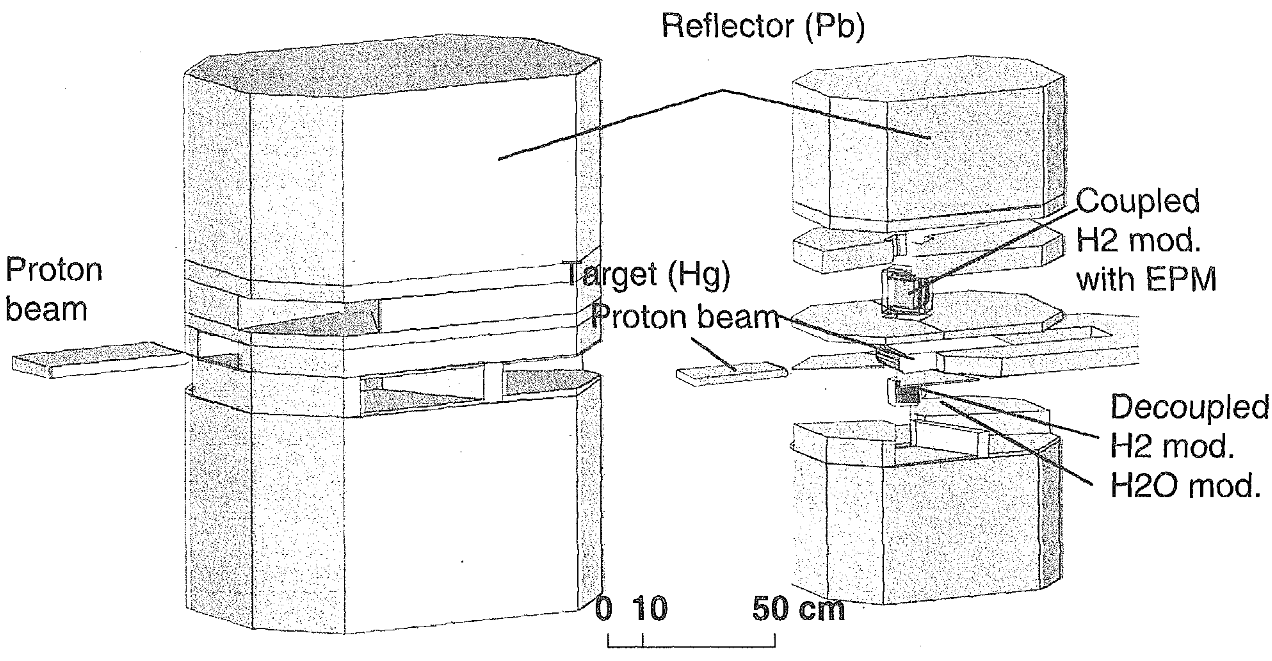

Fig. 3 Calclation model of full system (Taget-moderator-reflecotor).

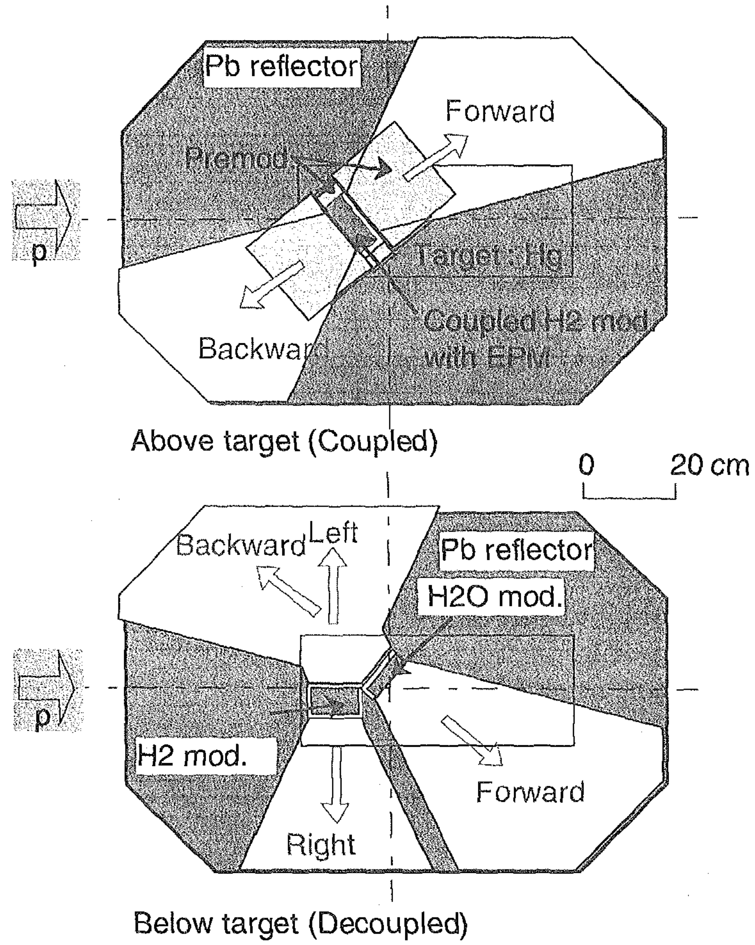

Fig. 4 Calclation model of full system (Taget-moderator-reflecotor).

energy of 1eV.

A Pb reflector with dimensions of 100 cm wide x 120 cm long x 180 cm high was assumed. For slow-neutron intensity calculations point detector tallies located at 2 m from the moderator viewed surfaces were used.

2.3 Calculation methods

In order to predict leakage neutrons from the bare target and slow-neutrons from the moderators in the TMRA, we performed neutronic calculations using the high energy hadron transport codes (NMTC/JAERI[14,15] and NMTC-JAM[7-8]) combined with low energy transport code MCNP-4A[16]. JENDL[17] cross section library including recently evaluated the Hg cross section at JAERI[18] was used in MCNP-4A calculation. The neutron numbers detected at the tallies were determined so that the statistical error is less than 0.05 at the peak intensity for the bare target and at the Maxwellian peak of thermalized neutrons from the TMRA 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 n^{th}. In order to obtain a time-integrated intensity, J, integrated over the Maxwellian part and the slowing-down intensities at a selected energy of 1 eV, ϕ_{1eV} the calculated spectral intensity data were fitted using semi-empirical formulas[19].

3 Results and discussions

3. 1 Proton energy dependence of leakage neutrons (Bare target system)

Figure 5 shows the total leakage neutrons (neutron yield) per proton from the cylindrical (20 cm in diam. and 60 cm in length) and rectangular Hg targets : It has already been proven that the latter gave the maximum slow-neutron intensities from the moderators[20]. Although a larger target (the cylindrical one) brings about a higher neutron production at the same proton energy, it is not optimal for obtaining the maximum slow-neutron intensities from the moderators as discussed later. With increasing target size the slow-neutron intensities are decreasing due to a worse coupling efficiency between target and moderator. For comparison, we also show the result from a Pb target of the same cylindrical size in Fig. 5. It turns out that the energy dependences of neutron yields for cylindrical Hg and Pb targets are almost the same for this target size.

Figure 6 shows the axial distributions of leakage neutrons from the target detected at 2 cm from the surface faced to the moderators. It can be seen from this figure that the peak neutron intensity drastically decreases with proton energy. The peak intensity at 50 GeV decreases to about 0.27 as low as at 1 GeV. The peak position and the half width of the distribution (FWHM) are important for installing the moderators at the highest luminosity position. If four moderators, two above and another two below the target, are necessary to be installed on the target as usual, it is generally difficult to put all the moderators at the best luminosity region. The peak width in the leakage neutron distribution seems to be too narrow, especially at lower proton energies for this requirement.

At higher proton energies the reduction in the peak intensity will be an important disadvantage. The broader distribution along the target axis may partly compensate the demerit above, if we look at the total slow-neutron intensity from all of the moderators. The existence of a reflector would also compensate the demerit of a narrow distribution. Therefore, the full system (TMRA)

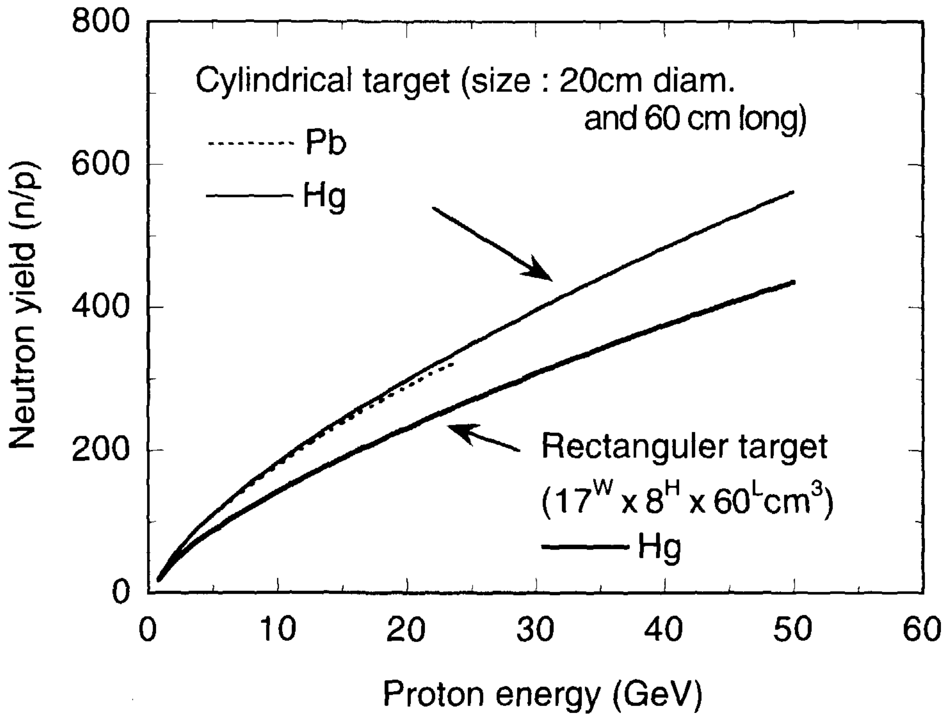

Fig. 5 Comparison of proton energy dependence of leakage neutrons of different target shapes.

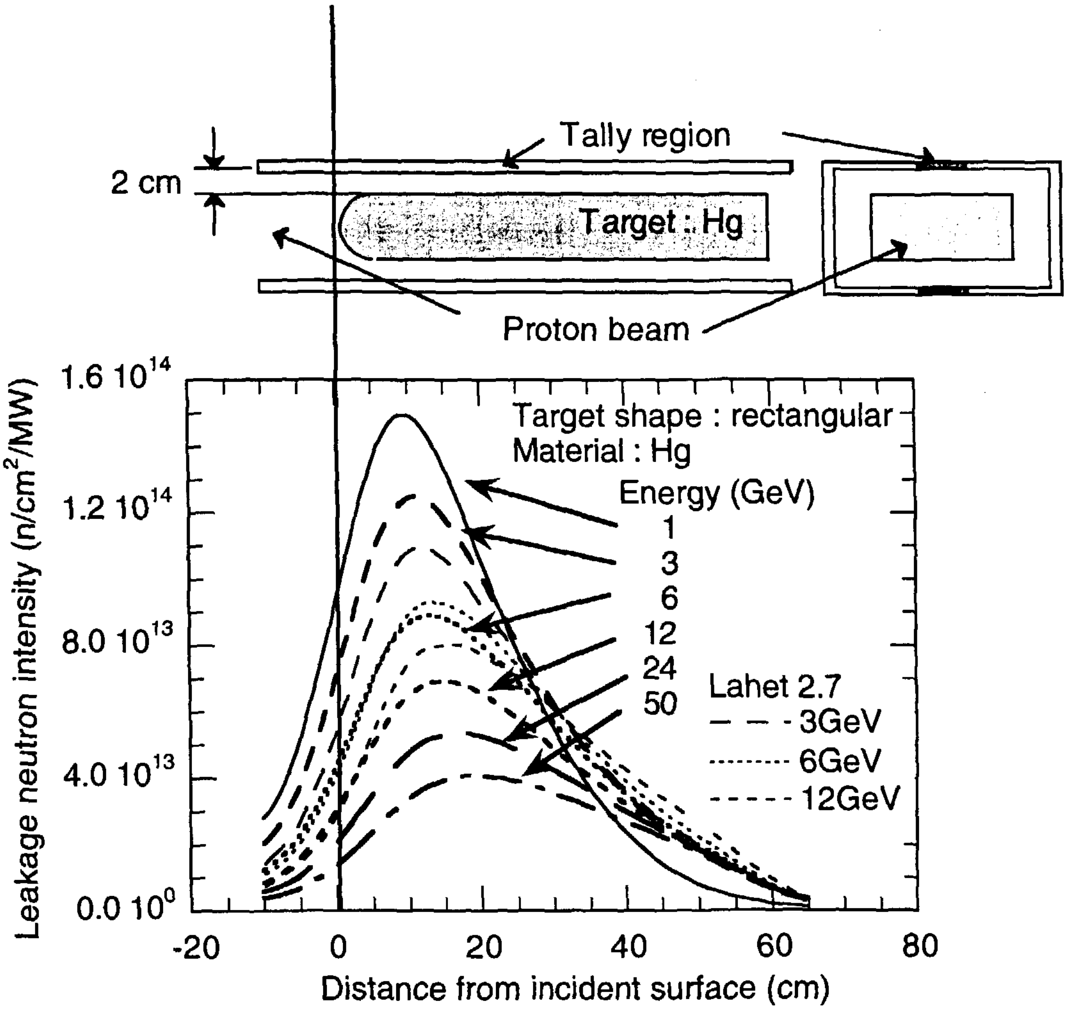

Fig. 6 Comparison of axial leakage neutron intensity distributions using NMTC-JAM and Lahet 2.7.

must be studied for discussing the proton energy dependence of slow-neutron intensities. This will be discussed in the next section. Calculated distributions using different codes are also shown in Fig. 6 for comparison. The results with LAHET tend to give lower intensities than those with NMTC-JAM up to about 6 GeV. Above this energy, the results are reversed since the differential cross section (p, xn) of LAHET 2.7 in the forward direction ($0 < \theta < 35$) or the backward direction ($145 < \theta < 180$) in the neutron energy range from about 10 MeV to several hundred MeV is larger than that of NMTC-JAM[9].

3. 2 Proton energy dependence of slow-neutron intensities (TMRA system)

The time-integrated slow-neutron intensities per unit beam power (MW) from the coupled H_2 moderator with EPM are shown in Fig. 7 as a function of proton energy and moderator position relative to the target (distance from incident surface). Slow-neutron intensities were averaged over both viewed surfaces. For convenience in Fig. 8 the position dependence of slow-neutron intensities shown in Fig. 7 is directly compared with axial distribution of leakage neutron shown in Fig. 6. The former are much smeared than the latter. This is partly due to the fact that a moderator has a finite dimensions in the axial and the vertical directions (this means that the moderator can collect leakage neutrons more widely than the leakage distribution shown in Fig. 6) and partly due to the existence of a reflector. The wider moderator position dependence makes two moderator installation on each side of the target more easy.

Figure 9 shows the ratio of the position dependence of slow-neutron intensities from de-

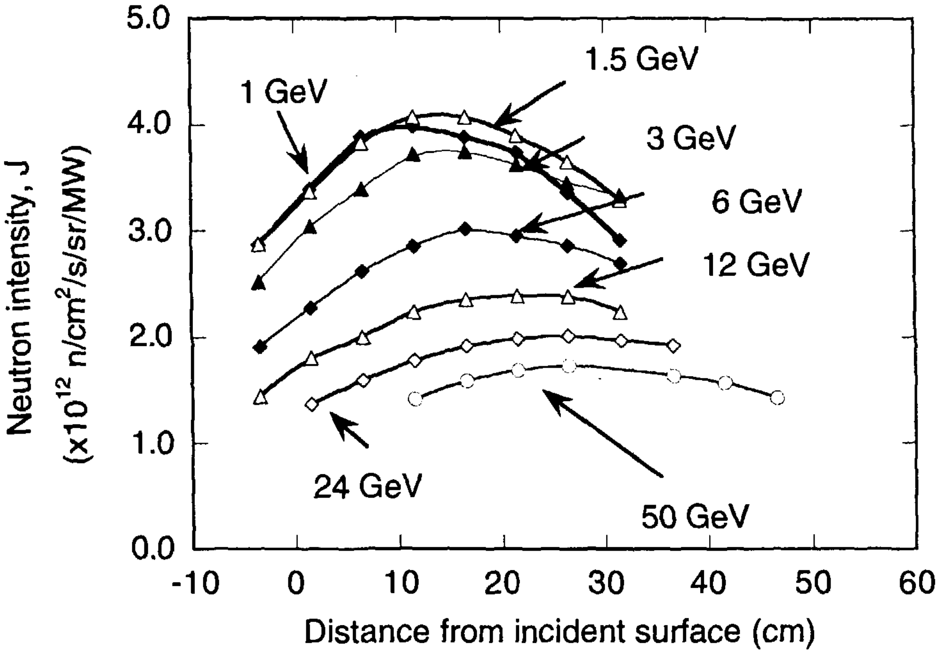

Fig. 7 Time -integrated slow-neutron intensities, J, for the coupled H_2 mod. with EPM in the Pb reflector as a function of proton energy and position relative to the target (distance from incident surface).

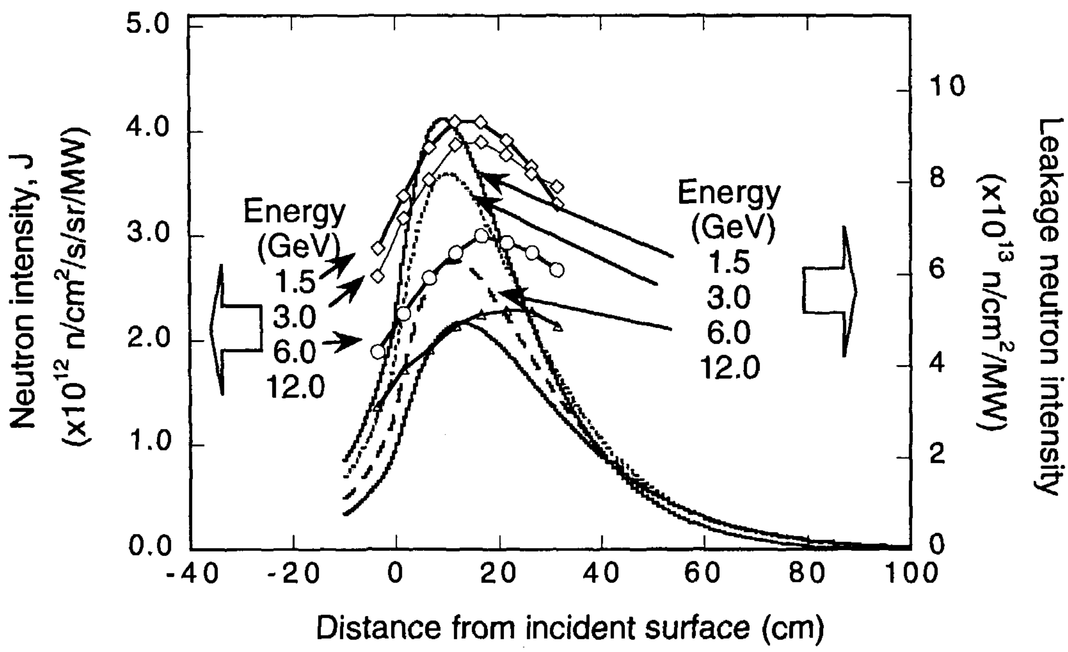

Fig. 8 Comparison of position dependence of slow-neutron intensities from a moderator (relative to target) in TMRA and leakage neutron intensity distribution.

coupled moderators (H_2 and H_2O) relative to the coupled H_2 moderator. The ratios are normalized at each peak position. The abscissas is the distance from the peak position in each position dependent slow-neutron intensity. Unexpectedly the ratios are almost unchanged for different moderator types. It has been thought that the position dependence for a decoupled moderator is different from that for a coupled moderator because the effective moderator size is quite different (for example, a coupled H_2 moderator is larger than decoupled H_2O moderator and the former has an extended premoderator). Furthermore a coupled moderator has no slow-neutron absorbing material such as decouplers nor liners around the moderator, while a decoupled one has on such material.

Proton energy dependence of slow-neutron intensities from each moderator per proton and per unit beam power (MW) at the peak position in Fig. 7 is plotted in Fig. 10 as a function of proton energy compared with that of the leakage neutrons from the bare system (total leakage and peak values). Each proton energy dependence is normalized at 1 GeV. Slow-neutron intensity per MW has a maximum at about 1-2 GeV and then goes down with increasing energy. i.e., at 3, 6 and 50 GeV the intensities is smaller by about 9, 24 and 53 %, respectively, than that of 1 GeV. This means that if we construct an intense-neutron-source with a higher proton energy, the neutronic performance goes down, for example, a 5 MW spallation source with a proton energy of 6 GeV is only equivalent to that of 3.8 MW with 1 GeV. The result is important for the development of an intense-pulsed-spallation source (5 MW). It is noteworthy that the proton

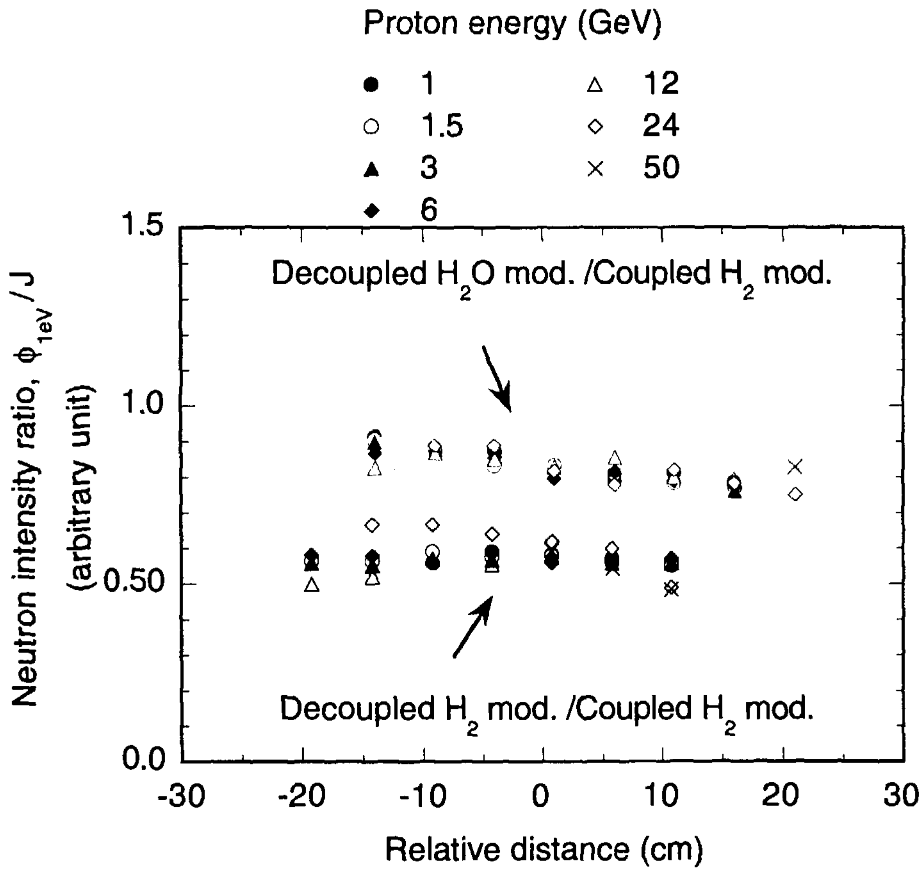

Fig. 9 Ratio of position dependent slow-neutron intensity from decoupled moderators to that of coupled moderator. The abscissas is the distance from the peak position in each position dependence.

energy dependence of the slow-neutron intensity per proton or per MW is almost the same as that of total leakage neutrons rather than that of the peak intensity. It is rather natural to understand the present result, since moderators could collect leakage neutrons a more wide region as mentioned above, compensating the reduction of the peak intensity.

To understand whether such proton energy dependence varies with target shape, we investigated for different target shapes. Figure 11 shows the comparison of slow-neutron intensities and total leakage neutrons for different target shapes and proton beam cross sections as a function of proton energy. Both intensities are normalized at the proton energy of 1 GeV for each case. The target shapes for the bare system were the same as that for TMRA.

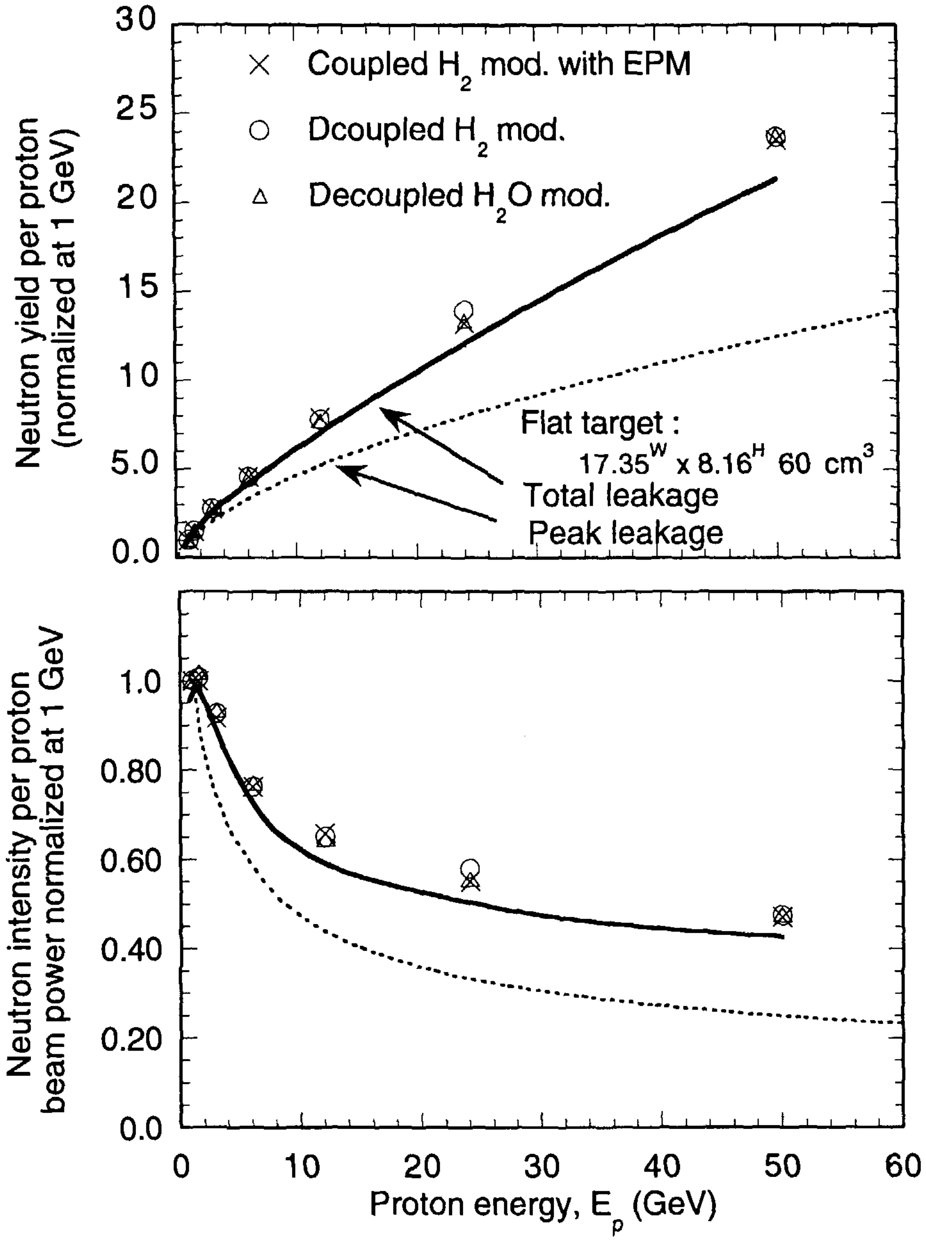

Fig. 10 Proton energy dependence of slow neutron intensity and leakage neutron from target per proton and beam power normalized at 1 GeV.

Roughly speaking, proton energy dependence of slow-neutron intensities from a TMRA exhibits the almost the same dependence with total leakage neutrons from the same bare target. An optimized flat target gives higher slow-neutron intensity than a cylindrical one. The proton energy dependence of slow-neutron intensity does almost not depend on the beam current density (see lower two curves for a cylindrical target shape : one is with a reference current density, while the other is for a reduced current density by a factor of 1/4 (4 times larger than beam cross section). The upper two curves show those for a flat and cylindrical targets with smaller cross sections than for the cylindrical one of the lower two curves. Slow neutron-intensities for the smaller targets (upper two curves) are larger than for the larger target (lower two curves), but proton energy dependence is similar. More exactly speaking the energy dependence becomes a little bit different with increasing proton energy as seen in the figure. At higher proton energies, the difference for different target size / shape becomes smaller. This is due to the fact that the leakage neutron distribution becomes wider with proton energy.

Slow-neutron	Total leakage neutron	Targt shape	Relative beam cross section*	Target cross section (cm^2)
○	———	Flat (optimized)	1	141.6
△	– – -	Cylinder	1	120.2
◇	— -	Cylinder	4	370.9
×	·········	Cylinder	1	370.9

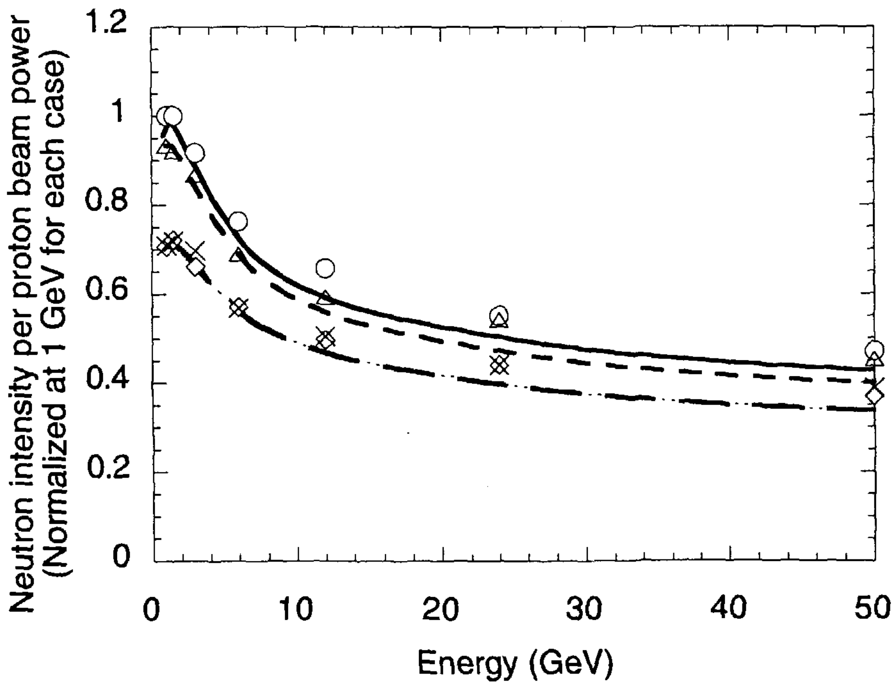

Fig. 11 Comparison of slow-neutron intensities and total leakage neutrons per MW normalized at 1GeV for each case.

* normalized at 68.9 cm^2 of beam cross section

4. Conclusions

From the present study we arrived at the following conclusions :
(1) The slow neutron intensities per unit proton beam power (MW) from the moderators has a maximum at about 1-2 GeV and then decreases with proton energy. For example, the intensities at 3, 6 and 50 GeV decrease to about 0.91, 0.76 and 0.47 times as low as at 1 GeV, respectively.

(2) The proton energy dependence of slow neutron intensities is almost the same as that of total leakage neutrons from the bare target with same shape.

(3) Proton energy dependence from the coupled and decoupled moderators is almost unchanged, in other word the energy dependence of slow neutron intensity does not depend on the moderator type nor the geometry.

References

[1] Dong W. Jerng and J M. Carpenter, "Heat Generation and Neutron Beam Characteristics in A High Power Pulsed Neutron Source", Proc. ICANS-XII, Abingdon, Oxfordshire, U. K., May 24-28, 1993, T-105.
[2] V. A. Nikolaevet al. , ICANS-XI, Tsukuba (1990) p. 612.
[3] R. G. Vassil'kov, and V. I. Yurevich, Proc. 11 th Meeting of Int. Collaboration on Advanced Neutron Sources ICANS-11 KEK, Tsukuba, Japan, Oct. 22-26, 1990 KEK Report 90-25 (1991) vol. 1 p. 340.
[4] M. Arai, Y. Kiyanagi, N. Watanabe, R. Takagi, H. Shibasaki, M. Munajiri, S. Itoh, T. Otomo, M. Fususaka, Y. Inamura, Y. Ogawa, Y. Suda and S. Satoh, J. Neutron Res. V.2 (1999).
[5] A. V. Demetyev, N. M. Sobolevsky, Yu. Ya. Stavissky : NIM A 374 (1996) p. 70-72.
[6] H. Takada, Y. Kasugai, H. Nakashima, Y. Ikeda, Y. Oyama, N. Watanabe, M. Arai, Y. Kiyanagi and ASTE Collaboration, Proc. ICANS XIV, Utica Illinois, ANL, USA, June 14-19, 1998, p. 468-477.
[7] Y. Kiyanagi, N. Watanabe and M. Arai : J. Appl. Phys. 33 (1994) 2774
[8] Y. Nara, N. Otuka, A. Ohnishi, K. Niita and S. Chiba : submitted to Phys. Rev. C, and Comp. Phys. Comm. (1999).
[9] K. Niita, Y. Nara, H. Takada, H. Nakashima, S. Chiba and Y. Yujiro, JAERI-Tech 99-065.
[10] N. Watanabe, M. Teshigawara, K. Aizawa, J. Suzuki and Y. Oyama. "A Target-moderator-reflector Concept of the JAERI 5 MW Pulsed Spallation Neutron Source", JAERI Tech. 98-011.
[11] N. Watanabe, M. Teshigawara, H. Takada, H. Nakashima, Y. Oyama, T. Nagao, T. Kai and K. Kosako, " A Conceptual Design Study of Target-Moderator-Reflector System for JAERI 5 MW", Proc. ICANS XIV, Utica Illinois, ANL, USA, June 14-19, 1998, p. 728-742.
[12] M. Teshigawara et al. Private communication.
[13] T. Kai, M. Teshigawara, N. Watanabe, M. Harada, H. Sakata and Y. Ikeda, " Optimization Study of Coupled Hydrogen Moderator with Extended Premoderator", Proc. ICANS-XV, Tsukuba, Japan, Nov. 6-8, to be published.
[14] Y. Nakahara, T. Tsutsui, "NMTC/JAERI, "A Code System for High Energy Nuclear Reactions and Nucleon-Meson Transport Code", JAERI-M 82-198 (1982) (in Japanese).
[15] H. Takada, N. Yoshizawa, K. Kosako and K. Ishibashi, "An Upgrade Version of Nuclear Meson Transport Code NMTC / JAERI - 97", JAERI - Code, to be published (1998).
[16] J. F. Briesmeister (Ed.), "MCNP, A General Monte Carlo N-Particle Transport Code, Version 4A", LA-12625 (1993).
[17] T. Nakagawa, S. Shibata, S. Chiba, T. Fukahori, Y. Nakajima, Y. Kikuchi,T. Kawano,

Y. Kanda, T. Ohsawa, H. Matsunobu, M. Kawai, A. Zukeran, T. Watanabe, S. Igarasi, K. Kosako and T. Asami, J. Nucl. Sci. Technol., 32(12), (1995) p. 1259-1271.
[18] K. Shibata, T. Fukahori, S. Chiba and N. Yamamuro, J. Nucl. Sci. Tech. 34 (1997) 1171.
[19] T. O. Brun, C. A. Beard, L.L.Daemen, E. J. Pitcher, G. J. Russel and W. B. Wilson, "LAHET Code System/CINDER,90 Validation Calculations and Comparison With Experimental Data", Proc. ICANS XII, Abingdon, Oxfordshire, U. K, May 24-28, 1993, T-26.
[20] N. Watanabe, M. Teshigawara, T. Kai, M. Harada, H. Sakata, Y. Ikeda, M. Kaminaga, R. Hino and Y. Oyama, "RECENT PROGRESS IN DESIGN STUDY OF JAPANESE SPALLATION NEUTRON SOURCE", Proc. ICONE 8, Baltimore, MD USA, April 206, 2000, ICONE-8457.