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A TARGET-MODERATOR-REFLECTOR CONCEPT OF THE JAERI 5 MW PULSED SPALLATION NEUTRON SOURCE

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In Japan Atomic Energy Research Institute the construction of a 5 MW(short) pulsed spallation neutron source is under planning using a projected high power superconducting proton (or H^-) linac of 8 MW in total beam power. In the present paper we report our consideration on target-moderator-reflector concept, based on the layout of the tentative neutron instruments for the assumed neutron scattering experiments in future. The choice of cold neutron moderators for high resolution and high intensity experiments, thermal and epithermal neutron moderators for high resolution uses was discussed and a reference layout of target-moderator-reflector system was proposed for detailed neutronic calculation and optimization. The proposed system was designed like that it can provide, at least, 30 beam lines for more than 40 instruments.

Keywords: Target-moderator-reflector Layout, Layout of Neutron Instruments, JAERI 5 MW Spallation Neutron Source

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JAERI 5 MW短パルス核破砕中性子源におけるターゲット・減速材・反射体システムの概念検討

日本原子力研究所東海研究所中性子科学研究センター
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(1998年2月5日受理)

原研における中性子科学研究計画では、主加速器として陽子エネルギー1.5 GeV、総ビーム出力約8 MWの超伝導リニアックが考えられており、そのうちの約5 MWを用いて世界最大級の短パルス核破砕中性子源施設の計画が目論まれている。本稿では、大強度核破砕中性子源施設の基本的なコンセプトを構築するために、まず、完成時に重要になると考えられる実験の種類、測定器を想定し、それらに必要な冷、熱及び熱外中性子ビームを得るためのモデレータの選定を行い、実験室内における測定器の最適配置を基にターゲット・減速材・反射体システムのコンセプトを提案した。中性子源施設の性能指標としては、各ビームラインの中性子ビーム強度とビームラインの数の積で表せるが、出来る限り多くの測定器が設置出来る様工夫した結果、中性子ビームラインが30本以上、中性子測定器が40台以上設置出来る配置案が得られた。

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1. Introduction

As a next generation neutron source, the construction of an intense pulsed spallation neutron source is under planning in Japan Atomic Energy Research Institute (JAERI) using a projected high-power P/H$^-$ linac. Neutron scattering is the most important field of research together with a nuclear energy science (nuclear transmutation of rare actinides from nuclear wastes). The design study of a neutron scattering facility has recently started. When we consider the construction of a new pulsed spallation neutron source, a superior concept of the target-moderator-reflector system becomes indispensable to realize a higher neutronic performance; i.e., first of all, a new concept of the system must be created, not only from a neutronic point of view but also from the view point of the total performance of the neutron source facility. The performance of the source can be estimated and optimized by various neutronic calculations. The technical feasibility must be studied simultaneously. If the predicted performance is not adequate even after the optimization or if we faced to unsolvable technical difficulties, an alternative idea on the target-moderator-reflector system must be brought about.

We have proposed a concept of the target-moderator-reflector system for the JAERI 5 MW pulsed spallation neutron source. In the present paper we describe this concept and the procedure how we arrived at the present concept.

2. Main assumptions and conditions for target-moderator-reflector concept

Prior to proposing a new system following conditions were assumed.

(1) The design value of the total proton beam power delivered to the neutron generating target is 1.5 MW (1.5 GeV, 1mA) in the early stage, followed by 5 MW (1.5 GeV, 3.33 mA) in the final stage of the project. Main parameters of the planned linac and the compressor ring are summarized in Tables 1 and 2.

(2) A considerable effort has been devoted to compare the neutronic performances of a short pulse spallation source (SPSS) and a long pulse spallation source (LPSS). Judging from the expected neutronic performance in various fields of neutron scattering research, we gave priority to SPSS, with LPSS at the second priority[1-2].

(3) We assumed one target station with one experimental hall at the early stage (1.5 MW), but at the final stage of the project, another target station and experimental hall will be constructed. However, the first target station shall be designed so that the maximum proton beam power of 5 MW is acceptable.

(4) A horizontal proton beam injection scheme was adopted due to various practical reasons.

(5) A wing-geometry in the target-moderator coupling configuration was adopted, which can be considered more favorable for the horizontal injection rather than a flux-trap one. A split target

concept (flux-trap type) was not adopted from the consideration of the signal to background ratio.

(6) We assumed that the number of neutron beams which will be required for cold, thermal and epithermal neutron regions are equally balanced; that is, each region occupies one third of the total beams, or more exactly, of the total angle around the target available for beam experiments (for example, see Fig. 6).

(7) We assumed four moderators, since the high luminosity region in the spatial (axial) distribution of leakage neutrons from the target is too narrow to install more moderators at a reasonably useful (high luminosity) position as described in succeeding paper $^{3)}$.

(8) We assumed that the maximum angular coverage for the slow-neutron extraction from one viewed surface of a moderator is about 50°, i.e., ± 25° from the normal line, considering that the angular dependence of slow neutron intensity from a hydrogenous moderator surface is given by$^{4)}$

$$\psi(\mu) = \frac{1}{2\pi}\phi_0 \frac{1+\sqrt{3}\,\mu}{1+\sqrt{3}/2} \quad for\, 0 \le \mu \le 1 \,,$$

where $\psi(\mu)$ is angular current density, μ the cos θ (θ is the angle from normal line) and

$\phi_0 = \int_{4\pi} \psi(\mu) d\Omega$ is the scalar flux at the surface.

(9) We assumed that the necessary angles around the source for the proton beam injection and for the target remote handling cell (downstream the target) is at least 30°, respectively. The total angle available to the experiments is therefore 300°. This means that six viewed surfaces are necessary in total.

3. Proposed moderators

3.1 Cold neutron moderator

As a cold neutron moderator decoupled solid methane (S-CH_4) moderators have successfully been utilized up to now (for about 18 years) at pulsed spallation neutron sources, KENS at KEK and IPNS at Argonne National Laboratory. A decoupled S-CH_4 moderator gives much higher cold neutron intensity, in the peak height as well as in the time-integrated value, than a decoupled liquid hydrogen (L-H_2) moderator, because the former has a higher hydrogen number density and a useful energy exchange mechanism at lower energies. However at an intense spallation source a S-CH_4 moderator cannot be utilized due to the serious radiation damage; the so-called “burp” which is the sudden release of the stored chemical energy in the solid by irradiation. On the other hand another problem of a decoupled L-H_2 moderator is that although the pulse width of cold neutrons is adequately narrow for low resolution experiments such as small angle scattering, etc., the time-integrated intensity is much lower than that in a high flux reactor.

In some experiments such as small angle neutron scattering, single crystal diffraction from biological substances, etc. the time-integrated cold neutron intensity is much more important than the pulse width, since the wavelength resolution, which is determined from the pulse width and the time-of-flight, is already too good, but by a cost of the intensity.

The figure of merit (FOM) of a cold neutron source can be determined as follows5);

(a) for low resolution experiments the wavelength resolution determined by time-of-flight (TOF) is good enough even with a reasonably short flight path length (for example, at 4 Å the resolution is less than a few percent even for 10 m long path). Thus, FOM is almost proportional to the time-integrated neutron intensity per pulse, independent of the repetition rate, as far as it is above the lowest rate (say,10-15 Hz);

(b) while, for high-resolution inelastic scattering experiments (μ eV and sub μ eV spectroscopy), FOM is proportional to the peak height of the pulse, independent of the repetition rate and the integrated intensity per pulse;

In order to maximize both FOM's, a coupled moderator which consists of L-H_2 and a premoderator (PM) has been developed by a Japanese group, in which one of the present authors is involved, and has been proved to provide the highest peak intensity together with the highest time-integrated intensity among the various moderators so far been studied6-8). They also proposed a coupled grooved L-H_2 moderator with PM to enhance the neutron intensity. It has been confirmed that such a moderator provides more or less higher neutron intensity than from a flat one (without groove)9).

If we adopt a coupled L-H_2 moderator with PM as a cold neutron moderator, only one surface can be viewed by instruments because of the existence of the backside premoderator. This means that two such moderators are necessary to cover the required angles around the source 50° x 2 for cold neutron experiments.

Judging from the proton beam power, the use of supercritical hydrogen may become indispensable instead of L-H_2. This issue will be discussed in ref. 15.

3.2 High resolution thermal neutron moderator

For experiments using thermal neutrons, we assumed that high resolution (narrow pulses) thermal neutrons are much more important than high intensity ones, since high resolution experiments are the most promising fields of neutron scattering research at pulsed neutron sources.

Decoupled S-CH_4 moderators have successfully been utilized for this purpose at KENS and IPNS. Since the proton beam power in such facilities is relatively small (5-10 kW), the use of S-CH_4 moderator has been possible in spite of the occurrence of the "burp". However, at a neutron source of a higher proton beam power, for example at ISIS (the world's largest pulsed spallation neutron source in Rutherford Aplleton Laboratory), a S-CH_4 moderator cannot be utilized due to the serious radiation damage, since the proton beam power is much higher (~160 kW) than the formers. In order to avoid the burp, a decoupled poisoned liquid methane (L-CH_4) moderator at 100 K was developed at ISIS. The neutronic performance of this moderator has been proved to be very useful. However, even at the present power level of ISIS the lifetime of the moderator is very short (~ 6 months) due to the polymerization and carbonization of the decomposition products of methane in the moderator chamber, suggesting that a L-CH_4 moderator cannot be used at a 5 MW SPSS. Some alternative moderators have been proposed as a high resolution thermal neutron moderator.

A decoupled L-H_2 moderator could be a candidate. This moderator can provide narrow pulses of thermal neutrons in the thermal neutron region (say, 10-200 meV). However the neutron intensity is rather low due to a smaller hydrogen number density of L-H_2 compared to other moderator materials as L-CH_4, S-CH_4 and H_2O. One idea is a poisoned L-H_2 moderator of a larger volume (say 12 cm x12 cm x10 cm thick) with an interleave poison plate at an appropriate depth. This configuration could compensate to some extents the shortage in the hydrogen number density without appreciable broadening in the pulse shape.

The second candidate is a L-H_2 moderator with a hydrogenous material at the same temperature, for example , L-H_2 plus ZrH_2. The preliminary neutronic measurement on such a moderator has been performed and some intensity gains have already been confirmed[10)]. However the pulse shape above 50 meV must be remeasured again more carefully using a instrument with a higher time-resolution to confirm whether the pulse widths above this energy are acceptable for the present purpose.

The third candidate is a mixed moderator consisting of hydrogenous particles plus L-H_2. Lucas et al.[11)] proposed such a moderator of S-CH_4 particles plus L-H_2. A mixed moderator consisting of polyethylene particles plus L-H_2 has been studied by Ogawa et al[12)]. A finite intensity gain was confirmed without additional pulse width broadening. We think a mixed moderator of solid H_2O particles plus L-H_2 may be a good candidate.

Anyhow at the present stage we have not decided the moderator for this propose. We therefore assigned a decoupled S-CH_4 moderator tentatively, just as a reference moderator in the present optimization study.

3.3 Epithermal neutron moderator

As an epithermal neutron moderator, we assumed a decoupled water (H_2O) moderator of an appropriate thickness at ambient temperature. We tentatively chose a thickness of 3 cm to cover a wide energy range.

The main parameters of the proposed moderators are summarized in Table 1.

4. Target-moderator-reflector layout

4.1 Original layout

After extensive discussions on a tentative lineup of possible neutron instruments and their allocations to the respective moderators, we proposed a layout of the instruments as shown in Fig. 1. Based on this layout we eventually reached at a configuration of a target-moderator-reflector system as shown in Fig. 2. Two coupled L-H_2 moderators with PM are located above the target, in order to ensure a smooth L-H_2 flow.

When we inspected this configuration, we found some inconvenience and disadvantage. The first problem is that the distance between two moderators above or below the target is fairly large; too much separated. This may results in a poor target-moderator coupling efficiency, judging from the predicted axial distribution of leakage neutrons from the target as shown in Fig. 3. The next problem is the use of a coupled grooved L-H_2 moderator with PM. In spite of its higher performance in the neutron intensity, the use of such a moderator may not be practical, because the maximum angular range viewed by neutron instruments is rather narrow due to the existence of the side premoderators. Another important drawback is how to circulate L-H_2 in the grooved structure.

4.2 Improved layout[13)]

In the improved reference system we replaced the grooved moderator by a flat one; two identical coupled flat L-H_2 moderators with PM above the target. We have discussed various possibilities on the configuration of the two coupled moderators as shown in Fig. 4 and finally adopted the Case B, although the neutronic performance must be examined by calculations later on. The backside premoderator is shared by both moderators to minimize the separation between the two. The relative position of the moderators to the target shall be optimized later on by computer simulation.

The configuration of two decoupled moderators below the target was also improved to minimize the separation between the two, by reconsidering the layout of the instruments and the moderator angling relative to the target center line. In this configuration a possible cross talk between two decoupled moderators (the left side surface of the high resolution thermal neutron moderator and the backward surface of the H_2O moderator) must be checked by a computer simulation. If the cross talk is unavoidable, we propose to mask the backward surface of the H_2O moderator by Cd or Gd foil to prevent thermal neutron flow into the another moderator. Epithermal neutrons can be extracted through this filter and the pulse width broadening due to epithermal neutron cross talk will not be important. Figure 5 shows the improved configuration of a reference target-moderator-reflector system for detailed neutronic and nuclear heat calculations. Figure 6 shows an overall layout of the instruments in the experimental hall for the improved target-moderator-reflector system.

In the succeeding papers we will report on the results of bare target neutronic performance$^{14)}$, slow neutron intensities from the various moderators in the reference system$^{3)}$, and the energy deposition in the target and cryogenic moderators$^{15)}$. The results shall be compared with those in other similar projects.

5. Concluding remarks

We proposed a concept of target-moderator-reflector system for a JAERI 5 MW pulsed spallation neutron source envisaging a higher neutronic performance. This concept provided a reference model for the neutronic, thermodynamical and mechanical studies. An example of the optimal layout of the neutron instruments was also proposed combined with this target-moderator-reflector concept. It was confirmed that, in principle, more than 30 beam lines in total for cold, thermal and epithermal neutrons can be supplied. However, a thermal neutron moderator for high resolution experiments has to be determined in due course.

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Table 1 Main parameters of the linac

Particle	Proton and H^-
Energy	1.5 GeV
Peak beam current	30 mA
Repetition rate	50 Hz
Duty cycle	20 % in the early stage 100 % in the final stage
Total beam power	8 MW
Beam power for the projected neutron source	5 MW

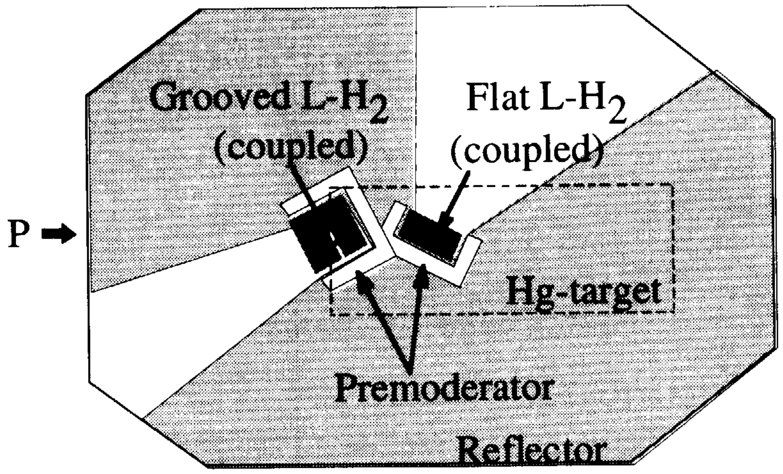
Table 2 Main parameters of compressor ring

Energy	1.5 GeV
Current	3.3 mA
Pulse duration	< 1 μ sec
Repetition rate	50 Hz

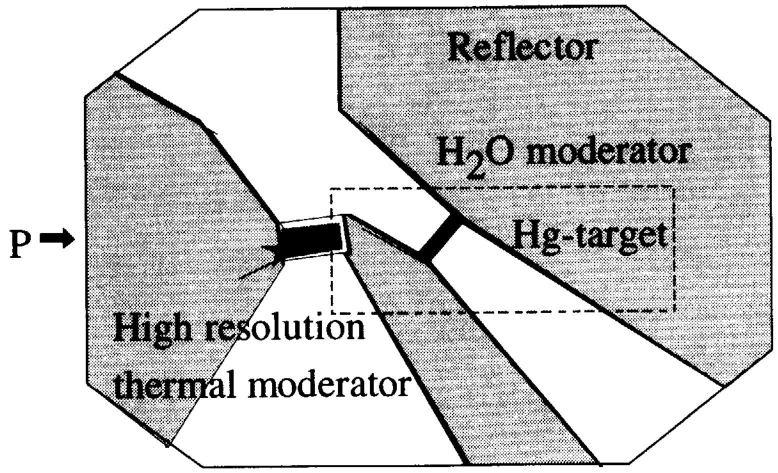
Table 3 Reference moderators in JAERI Pulsed Spallation Neutron Source

	Cold neutron	Thermal neutron	Epithermal neutron
Purpose	High resolution & high intensity	High resolution	High resolution
Main moderator	L-H_2 (normal)	Poisoned L-H_2, L-H_2+ZrH_2 or a mixed mod. of (S-CH_4 or S-H_2O) particles + L-H_2	H_2O
size (cm)	12 x 12x 5	10 x 10 x 5*	10 x 10 x 3
Moderator temp.(K)	20	20	Room temp.
Premoderator	H_2O (2.5 cm thick)	Non	Non
Coupling	Coupled	Decoupled	Decoupled
Cut - off energy (eV)	--	1	10
Angular coverage / viewed surface	50°	50°	50°
No. of viewed surface	1	2	2
No. of moderators	2	1	1

* 10 cm thick in the case of a poisoned L-H_2 moderator



Above target



Below target

Fig. 1 Target-moderator-reflector system based on the original layout of the instruments

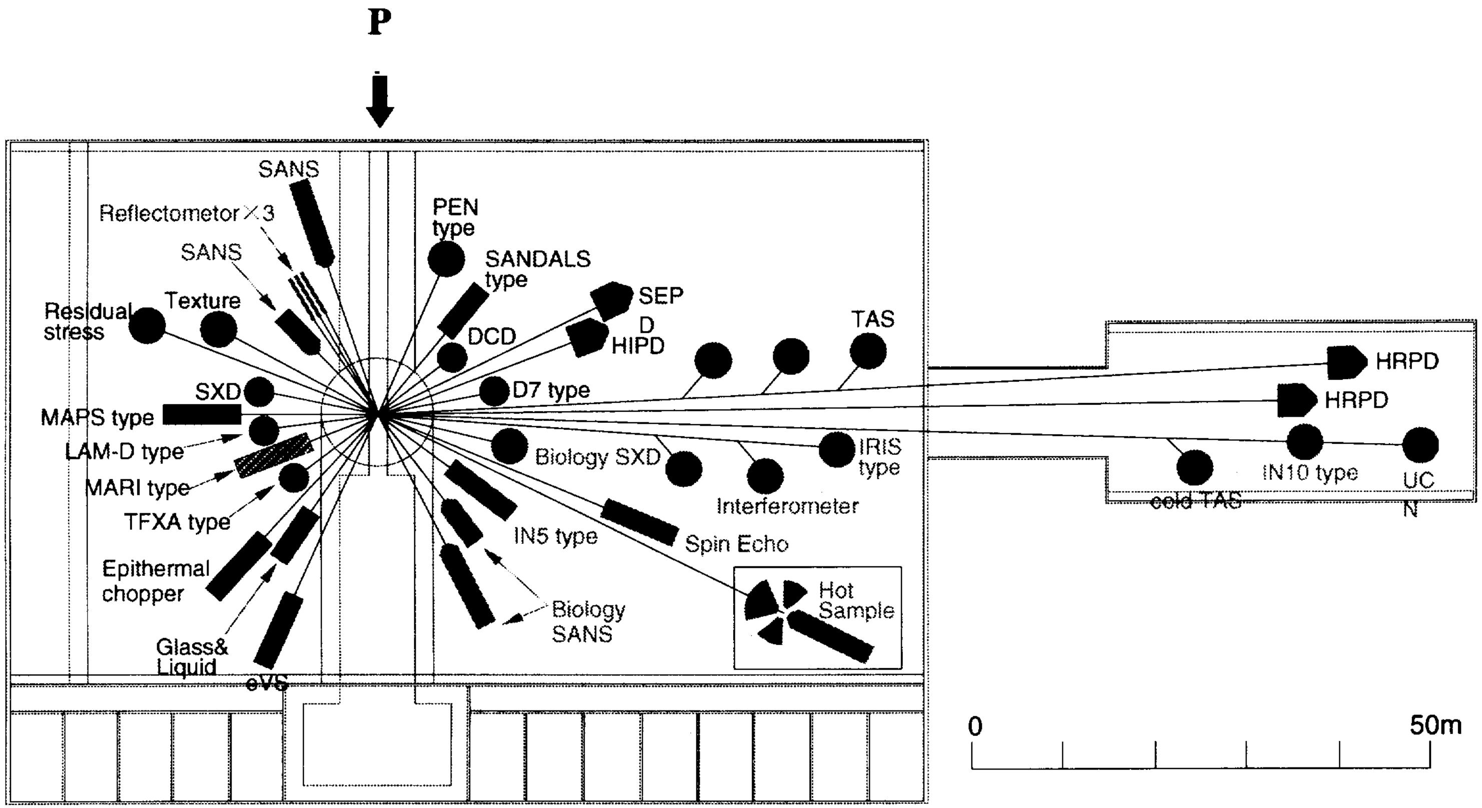


Fig. 2 Layout of tentative neutron instruments in the experimental hall (original plan)

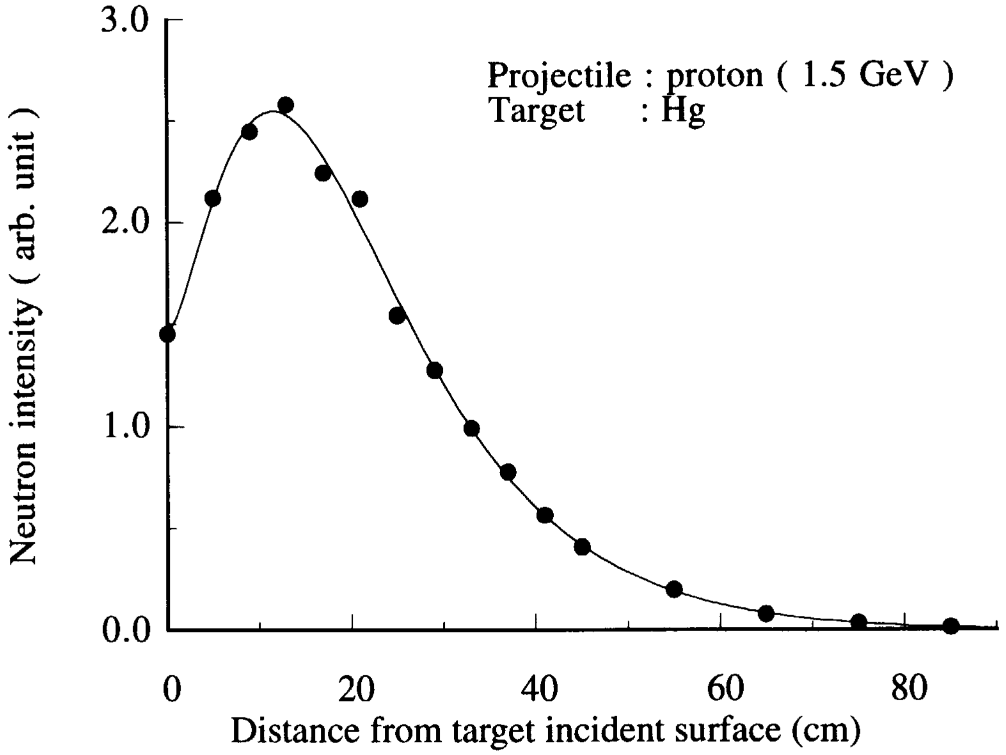


Fig. 3 Spatial (axial) distribution of leakage neutrons from a Hg target

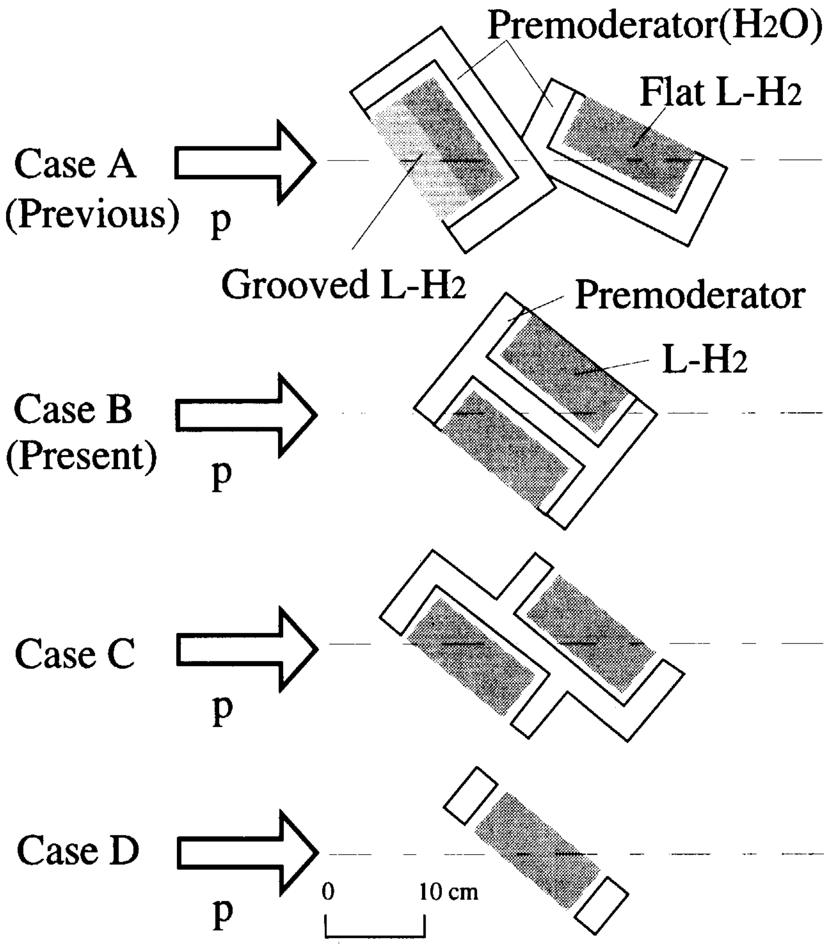


Fig. 4 Geometrical consideration on two coupled moderators above the target

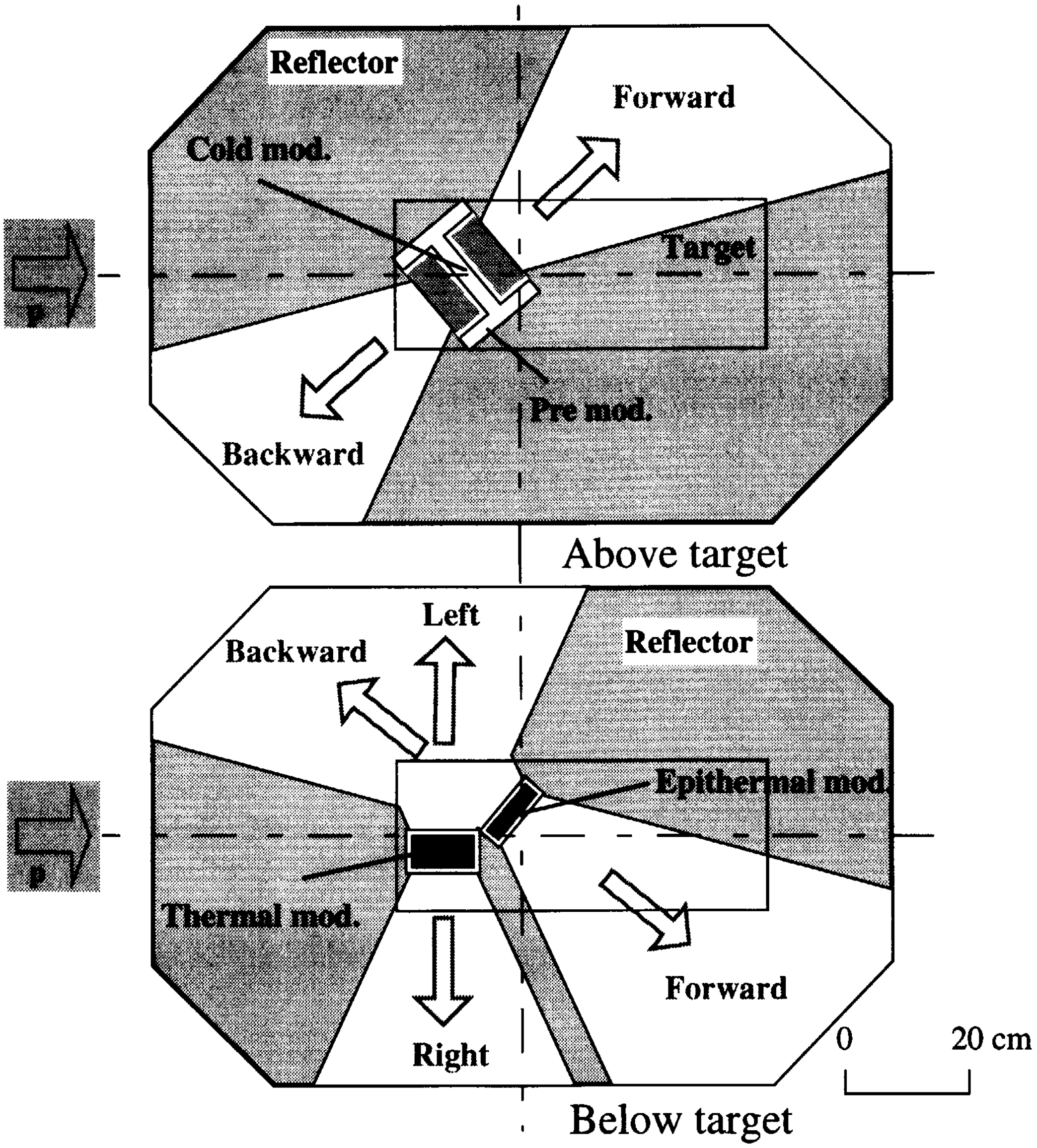


Fig. 5 Configulation of improved target-moderator-reflactor system

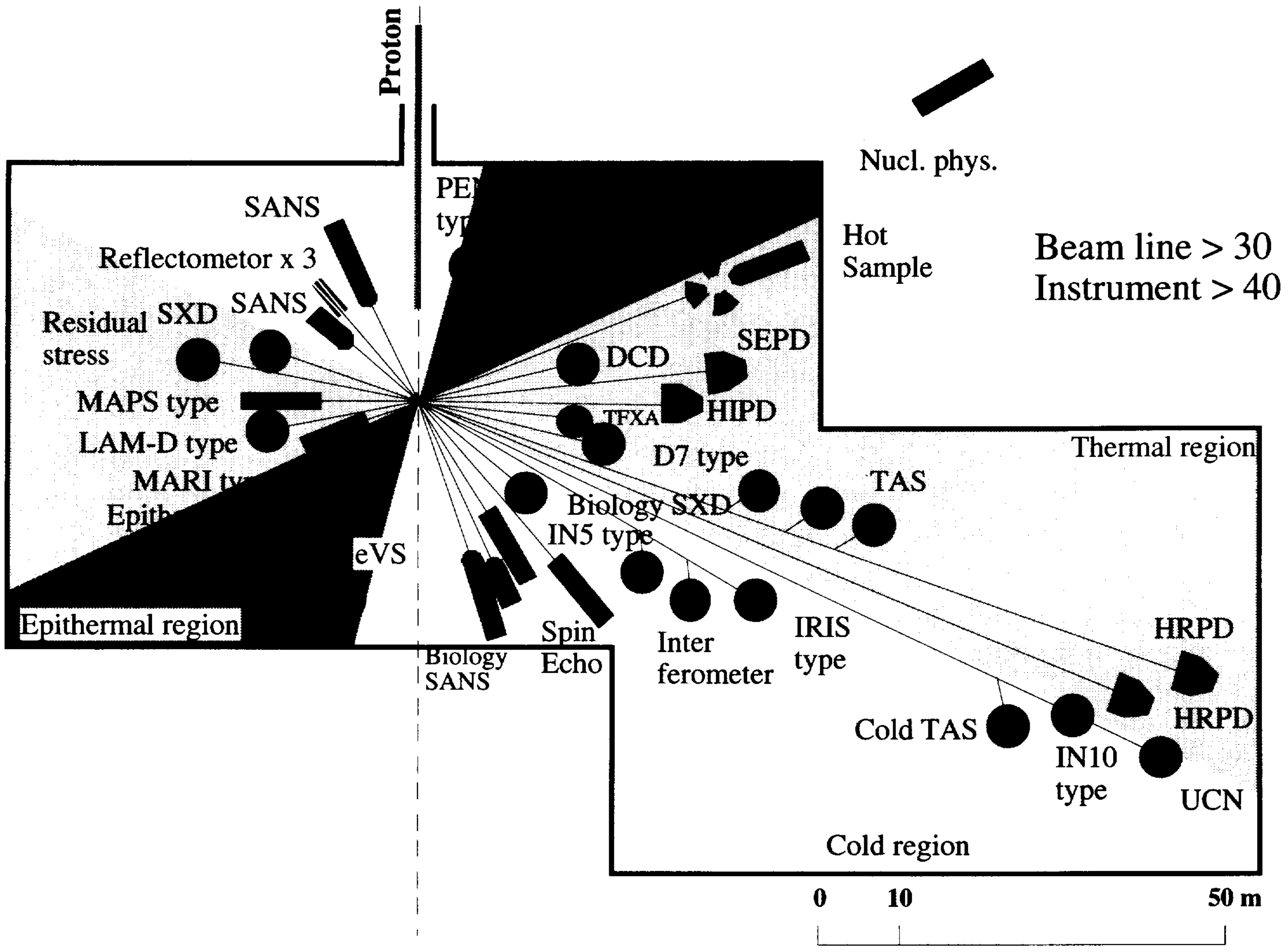


Fig. 6 Layout of tentative neutron instruments in the experimental hall based on the improved target-moderator-reflector system

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国際単位系 (SI) と換算表

表 1 SI基本単位および補助単位

量	名称	記号
長さ	メートル	m
質量	キログラム	kg
時間	秒	s
電流	アンペア	A
熱力学温度	ケルビン	K
物質量	モル	mol
光度	カンデラ	cd
平面角	ラジアン	rad
立体角	ステラジアン	sr

表 2 SIと併用される単位

名称	記号
分，時，日	min, h, d
度，分，秒	°, ′, ″
リットル	l, L
トン	t
電子ボルト	eV
原子質量単位	u

1 eV = 1.60218 × 10^{-19} J

1 u = 1.66054 × 10^{-27} kg

表 5 SI接頭語

倍数	接頭語	記号
10^{18}	エクサ	E
10^{15}	ペタ	P
10^{12}	テラ	T
10^{9}	ギガ	G
10^{6}	メガ	M
10^{3}	キロ	k
10^{2}	ヘクト	h
10^{1}	デカ	da
10^{-1}	デシ	d
10^{-2}	センチ	c
10^{-3}	ミリ	m
10^{-6}	マイクロ	μ
10^{-9}	ナノ	n
10^{-12}	ピコ	p
10^{-15}	フェムト	f
10^{-18}	アト	a

表 3 固有の名称をもつSI組立単位

量	名称	記号	他のSI単位による表現
周波数	ヘルツ	Hz	s^{-1}
力	ニュートン	N	m·kg/s^2
圧力，応力	パスカル	Pa	N/m^2
エネルギー, 仕事, 熱量	ジュール	J	N·m
工率，放射束	ワット	W	J/s
電気量，電荷	クーロン	C	A·s
電位, 電圧, 起電力	ボルト	V	W/A
静電容量	ファラド	F	C/V
電気抵抗	オーム	Ω	V/A
コンダクタンス	ジーメンス	S	A/V
磁束	ウェーバ	Wb	V·s
磁束密度	テスラ	T	Wb/m^2
インダクタンス	ヘンリー	H	Wb/A
セルシウス温度	セルシウス度	℃	
光束	ルーメン	lm	cd·sr
照度	ルクス	lx	lm/m^2
放射能	ベクレル	Bq	s^{-1}
吸収線量	グレイ	Gy	J/kg
線量当量	シーベルト	Sv	J/kg

表 4 SIと共に暫定的に維持される単位

名称	記号
オングストローム	Å
バーン	b
バール	bar
ガル	Gal
キュリー	Ci
レントゲン	R
ラド	rad
レム	rem

1 Å = 0.1 nm = 10^{-10} m

1 b = 100 fm^2 = 10^{-28} m^2

1 bar = 0.1 MPa = 10^5 Pa

1 Gal = 1 cm/s^2 = 10^{-2} m/s^2

1 Ci = 3.7 × 10^{10} Bq

1 R = 2.58 × 10^{-4} C/kg

1 rad = 1 cGy = 10^{-2} Gy

1 rem = 1 cSv = 10^{-2} Sv

（注）

1. 表1−5は「国際単位系」第5版，国際度量衡局 1985年刊行による。ただし，1 eV および1 uの値はCODATAの1986年推奨値によった。
2. 表4には海里，ノット，アール，ヘクタールも含まれているが日常の単位なのでここでは省略した。
3. barは，JISでは流体の圧力を表わす場合に限り表2のカテゴリーに分類されている。
4. EC閣僚理事会指令ではbar，barnおよび「血圧の単位」mmHgを表2のカテゴリーに入れている。

換算表

力	N(=10^5dyn)	kgf	lbf
	1	0.101972	0.224809
	9.80665	1	2.20462
	4.44822	0.453592	1

粘度　1 Pa·s(N·s/m^2) = 10 P(ポアズ)(g/(cm·s))

動粘度　1 m^2/s = 10^4St(ストークス)(cm^2/s)

圧	MPa(=10 bar)	kgf/cm^2	atm	mmHg(Torr)	lbf/in^2(psi)
	1	10.1972	9.86923	7.50062 × 10^3	145.038
力	0.0980665	1	0.967841	735.559	14.2233
	0.101325	1.03323	1	760	14.6959
	1.33322 × 10^{-4}	1.35951 × 10^{-3}	1.31579 × 10^{-3}	1	1.93368 × 10^{-2}
	6.89476 × 10^{-3}	7.03070 × 10^{-2}	6.80460 × 10^{-2}	51.7149	1

	J(=10^7 erg)	kgf·m	kW·h	cal(計量法)	Btu	ft·lbf	eV
エネルギー・仕事・熱量	1	0.101972	2.77778 × 10^{-7}	0.238889	9.47813 × 10^{-4}	0.737562	6.24150 × 10^{18}
	9.80665	1	2.72407 × 10^{-6}	2.34270	9.29487 × 10^{-3}	7.23301	6.12082 × 10^{19}
	3.6 × 10^6	3.67098 × 10^5	1	8.59999 × 10^5	3412.13	2.65522 × 10^6	2.24694 × 10^{25}
	4.18605	0.426858	1.16279 × 10^{-6}	1	3.96759 × 10^{-3}	3.08747	2.61272 × 10^{19}
	1055.06	107.586	2.93072 × 10^{-4}	252.042	1	778.172	6.58515 × 10^{21}
	1.35582	0.138255	3.76616 × 10^{-7}	0.323890	1.28506 × 10^{-3}	1	8.46233 × 10^{18}
	1.60218 × 10^{-19}	1.63377 × 10^{-20}	4.45050 × 10^{-26}	3.82743 × 10^{-20}	1.51857 × 10^{-22}	1.18171 × 10^{-19}	1

1 cal = 4.18605 J (計量法)
= 4.184 J　(熱化学)
= 4.1855 J　(15 °C)
= 4.1868 J (国際蒸気表)

仕事率　1 PS (仏馬力)
= 75 kgf·m/s
= 735.499 W

放射能	Bq	Ci
	1	2.70270 × 10^{-11}
	3.7 × 10^{10}	1

吸収線量	Gy	rad
	1	100
	0.01	1

照射線量	C/kg	R
	1	3876
	2.58 × 10^{-4}	1

線量当量	Sv	rem
	1	100
	0.01	1

(86年12月26日現在)

A TARGET-MODERATOR-REFLECTOR CONCEPT OF THE JAERI5MW PULSED SPALLATION NEUTRON SOURCE