

Chapter 2

Nuclear Design of Ex-vessel Neutron Yield Monitoring System for ITER

This chapter describes the design consideration on the detector modules for the ex-vessel neutron yield monitor in ITER. The modules are composed of several fission chambers with different sensitivities, and the fission chambers are surrounded by a neutron moderator to improve their sensitivities to fast neutrons. The moderator has been optimized to satisfy the ITER requirements. The two kinds of detector modules have been designed as neutron monitors for the DD and DT phases of the plasma discharges in ITER.

2.1 Requirement of the neutron yield monitoring system for ITER

The main characteristics required for the ITER neutron yield monitoring system are

- (A) 1 ms time resolution with measurement accuracy of 10% for the DT phase
- (B) Neutron/ γ -ray discrimination characteristic
- (C) High reliability and redundancy in a hostile environment such as high temperature and magnetic field
- (D) Wide dynamic range to cover the whole neutron yield from the *in-situ* calibration to the full power operation
- (E) Multi-monitoring involving at least one detector that is operated under pulse counting mode with a high signal to noise ratio
- (F) Appropriate detector response function for the absolute measurement of total neutron yield, which means as a flat energy response as possible

The requirements of the neutron yield monitoring system for ITER are tabulated in Table 2.1. Requirement (A) indicates time resolution to be required in this system. Although the DT burn

control needs time resolution of 10 - 100 ms at most [1], fusion plasma physics demands a real-time monitoring of plasma instabilities with time resolution of 1 ms for study on the confinement effect of high energy particles [2-4]. Therefore, the design consideration has been made so that this system is capable of providing plasma information with time resolution of 1 ms. For the requirement (D), *in-situ* calibrations of neutron yield monitoring system in Tokamak devices generally have used a neutron generator or ^{252}Cf neutron source, which is placed in torus center and moved in toroidal direction. *In-situ* calibration in ITER has been widely considered to be implemented using a DT neutron generator. The ITER experiment has two kinds of burning phase including the DD and DT operations, and produces a two-component neutron source generating DD and DT neutron simultaneously in the high-power operation of the DD phase. Therefore, an *in-situ* calibration using just a DT neutron generator will cause an unacceptable measurement error, details are described in chapter 3. This study was proposed an *in-situ* calibration method using both DT and DD neutron generators, the assumed generation rates are 10^{13} n/s and 10^{11} n/s, respectively. Since neutron generation ratio over 10^{20} n/s is expected in the ITER full power DT operation, an 11-decade dynamic range is required for this system as shown in Fig. 2.1. A flat energy response as described in the requirement (F) is helpful for an absolute neutron yield monitoring in the situation where a large part of source neutron is scattered by a reactor structure before entering the detector. Details are discussed later in section 2.2.4.

2.2 Design consideration of detector module

2.2.1 Neutron detector

Taking account of the requirements (A), (B) and (C), a neutron detector for this system has been selected. Because neutron does not have electrical charge and an ionization effect, it is usually detected through secondary particles such as protons and α particles that are induced from interactions of the incident neutron and nuclei in a detection medium. Since detector responses generally depend on neutron energy, adequate types of detectors should be chosen according to neutron energy to be detected. Common detectors for slow neutron measurement are BF_3 counter, Boron lined proportional counter based on $^{10}\text{B}(\text{n}, \alpha)$ reaction, ^3He proportional counter based on $^3\text{He}(\text{n}, \text{p})$ reaction, Li contained scintillation counter based on $^6\text{Li}(\text{n}, \alpha)$ reaction and fission chamber based on fission reaction. Though some of them can be applied for a measurement of fast

neutron such as DT and DD neutrons, these detectors are generally used with neutron moderator to slow down the incident neutron and improve the efficiency for the incident fast neutrons. Other types of fast neutron detectors use recoiled proton generated from elastic scattering with hydrogen nuclei in the detector medium, for instance, organic scintillators containing hydrogen are widely used for the fast neutron detection. Besides, several types of semiconductor detectors can be operated as fast neutron detectors. They are based on (n, p) and (n, α) reactions induced by the incoming neutrons.

Because scintillation detectors typically have high sensitivities for γ -rays, these types of detectors are not appropriate for the present application in which the high flux of γ -rays of no interest is induced by fusion neutrons. Semiconductor detectors are easily damaged under high radiation field. The gas-filled detectors are hardly damaged by radiation and stably operated in long time. Furthermore, they commonly have a wide dynamic range and a charge collecting time of the order of μs , which is enough for the required time resolution of 1 ms. The candidates for the neutron detector that have been taken here are BF_3 counter, 3He proportional counter, ^{10}B counter and ^{235}U fission chamber; these are gas filled detector based on nuclear reaction. The characteristic comparison of them is in Table 2.2. ^{235}U fission chambers with JT-60U specification have been employed and Fig. 2.2 shows its schematic view. Fission chamber is an ionization chamber, the outside of which is coated with thin fissile material such as ^{235}U . Incident neutron induces fission reactions of the fissile material, and the fission fragments enter the counting gas and lead to ionization of the gas molecules. One of the useful characteristics of this detector is the operation mode. Fission chamber can be operated in pulse mode, current mode and Campbell mode as discussed in the next section. The operation mode can be selected according to event rate of the detector, which means that a wider dynamic range can be realized relatively easily. Neutron produces a large amount of energy about 200 MeV by fission reaction, and more than 160 MeV is deposited in the counting gas. A much larger electric pulse is produced by neutron than is induced by background γ -ray and competitive reaction such as α -decay (5 MeV) of the fissile material itself. The conventional discrimination technique according to pulse height can be easily applied to distinguish the neutron signal of interest from α or γ -ray signal. Fission chamber has been used as a neutron flux monitor in the existing large Tokamaks as well as fission reactors [5-8].

The variances of plasma parameters are in time scale of the order of ms, and time

resolution of 1 ms is required for this system. The detection efficiency of neutron detector in this system should be as high as possible to achieve the required time resolution with high measurement accuracy. The energy response of fission chamber depends on ^{235}U neutron cross-section. Figure 2.3 shows the neutron cross section of ^{235}U . Fission chamber is sensitive to thermal neutrons and decreases its sensitivity as neutron energy increases, according to the energy dependence of the cross section. Fission chamber is surrounded by neutron moderator such as polyethylene or paraffin for use in the fusion devices to improve its detection efficiency to DT and DD neutrons.

2.2.2 Detector operation mode

Fission chamber is generally operated in pulse counting mode, current mode and Campbelling mode (Mean Square Voltage mode). Pulse counting mode can distinguish each pulse induced by respective incident radiations and widely used for radiation detectors. The count rate capability of this mode up to 10^5 or 10^6 cps restricts its use, because it cannot separate series of pulses under high event rate. Current mode or Campbelling mode is usually used in higher event rate. Current mode provides time-averaged current $\overline{I(t)}$ that is derived from time-dependent current $i(t)$ of the detector and represented in Equation (2.1):

$$\overline{I(t)} = \frac{1}{T} \int_{t-T}^t i(t') dt', \quad (2.1)$$

where T is a response time of measurement device. Since time-averaged current only can be recorded in current mode, discrimination of noise contributions due to γ -ray component from neutron signal is impossible.

Campbelling mode records the mean square of the time variance of detector current, and it is given by

$$\overline{\sigma^2(t)} = \frac{1}{T} \int_{t-T}^t \{I(t') - \overline{I(t)}\}^2 dt' = \frac{rQ^2}{T}. \quad (2.2)$$

Where r is radiation event rate, Q is electrical charge produced per event. The signal derived under Campbelling mode $\overline{\sigma^2(t)}$ is proportional to the square of Q . The charge Q consists of contributions of α particle and γ -ray as well as neutron. Thus, equation (2.2) can be written as follow.

$$\begin{aligned}
\overline{\sigma^2(t)} &= \frac{rQ^2}{T} \\
&= \frac{1}{T} (r_n q_n^2 + r_\alpha q_\alpha^2 + r_\gamma q_\gamma^2) \\
&= \frac{q_n^2}{T} \left(r_n + r_\alpha \frac{q_\alpha^2}{q_n^2} + r_\gamma \frac{q_\gamma^2}{q_n^2} \right).
\end{aligned} \tag{2.3}$$

Here, the electrical charges per pulse by neutron, α particle and γ -ray are defined as q_n , q_α and q_γ , respectively. Since q_n is generally much larger than q_α and q_γ , the contributions of α particle and γ -ray are negligible compared to the neutron signal. Besides, it was confirmed that this operation mode has linearity in a higher-flux region than pulse counting mode as shown in Fig. 2.4 [9].

The combined operation of pulse-Campbelling mode has been employed for this system. The detectors are operated by pulse counting mode in low-event-rate region at the beginning of the ITER experiments, and then they will be switched to Campbelling mode along with the reactor power increases, in a region where the pulse counting mode cannot separate each event anymore due to high event rate. Current mode is not used for this system because it cannot discriminate the α particle and γ -ray signals from the neutron signals. This pulse-Campbelling combined operation can expand the dynamic range for single detector up to 9 orders, and the two operation modes has an overlap region of 2 orders each other, which is enough for cross-calibration between the two modes as shown in Fig. 2.4. This combined operation mode is helpful for the requirements (B) and (D).

2.2.3 Peripheral materials of the detectors

I Neutron moderator

As described in section 2.2.1, surrounding fission chamber with a neutron moderator is the conventional way to improve the sensitivity of the detector to fast neutrons by thermalizing the incident neutrons. Neutron generally deposits higher amount of its energy by collision with low-atomic-number nuclei. Polyethylene and Paraffin, which include hydrogen atoms, are the most common moderators for a neutron detector and actually have been used in the existing large Tokamaks. Unfortunately, because of their poor thermal resistance, it is impossible to use them in a high power or high temperature fusion reactor such as ITER. Graphite and beryllium have been

employed as moderators for this system. The melting point of graphite is 3,550 degree Celsius and that of beryllium is 1,280 degree. Because of its high moderating power, graphite has been used as a moderator or reflector in fission reactors. Beryllium has a large cross section of neutron multiplication reaction such as (n, 2n) reaction, the threshold energy of which is 1.67 MeV, and serves as a neutron multiplier for fast neutron. Figures 2.5 and 2.6 show the neutron cross sections of graphite and beryllium, respectively.

II Thermal neutron shield

A certain portion of fusion neutrons is scattered by the materials around the plasma and thermalized before entering the detector. Thermal neutrons come from various directions and can be unintended background factor. The detector modules are surrounded by 1 mm-thick cadmium to shield the modules from the unexpected thermal neutrons. As shown in Fig. 2.7, cadmium has a large cross section for neutrons of 0.5 eV or less and is useful for thermal neutron shielding.

III γ -ray shield

As described in section 2.2.1, fission chamber has a neutron/ γ -ray discrimination characteristic in itself, because it produces a much larger signal by neutron than other background radiations such as γ -rays and α particles. Extremely high-flux γ -ray causes a pulse pile up effect that results in so much higher electrical pulses that cannot be negligible compared to neutron signal. Therefore the fission chambers will be surrounded by a lead layer of 50 mm thickness to reduce incident γ -ray fluxes and surely to satisfy the requirement (B).

2.2.4 Optimization of the moderating region

Figure 2.8 illustrates the basic structure of the detector module, the dimension of which is $1,000 \times 800 \times L$. The module contains 3 fission chambers loaded with 90% enriched $^{235}\text{UO}_2$ and fissile-material-free detector for an electromagnetic noise identification. The 50 mm-thick lead layer surrounds the detectors to shield them from γ -rays of high fluxes. The moderating region is set outside the lead layer. Furthermore, 1 mm-thick cadmium plate is attached to the all of the outer surfaces. Finally, the whole body is contained stainless steel housing.

The moderating regions of the detector module have been optimized so as to achieve a

flat energy response over a wide-energy range from thermal region to 14.1 MeV, as described in requirement (F) of section 2.1. Neutron detector that has a flat energy response is called “long counter” and has been used as a total neutron yield monitor in many situations of neutron physics. Since detector response does not depend on incident neutron spectrum, the long counter is suitable for a total neutron yield monitor in a complicated facility or device such as a fusion reactor where generated neutrons undergo many scatterings with the device structure, and their spectra spread to wide-energy region before entering the detector. In addition, if an *in-situ* calibration is implemented with a radio isotope such as ^{252}Cf neutron source, calibration factor is not significantly affected by the energy difference between the calibration source and the actual plasma neutron source. The particular advantage of the flat energy response in this study other than the common aspect mentioned above is keeping the measurement error within a small level in the advanced DD phase that secondarily generates DT neutrons as well as DD neutrons. Details are discussed in Chapter 3.

The detector responses over a wide-energy region have been calculated by a Monte Carlo simulation code MCNP-4C2 [10] with the ENDF/B-VI neutron data library as shown in Fig. 2.8. MCNP is a three dimensional Monte Carlo N-Particle code that can be used for neutron, photon, electron, or coupled neutron-photon-electron transport and widely used in neutronics calculations. The detector response means here the fission reaction rate of the $^{235}\text{UO}_2$ inside a fission chamber per unit neutron flux. Figure 2.9 shows the standard deviations of detector responses for each energy group. The standard deviation has been used as an indicator for the flatness of the detector response and strongly depends on moderating region L . From the results, it is found that 550 mm-thick graphite leads to a flat response within $\pm 14.4\%$, and the most appropriate thickness for beryllium moderator is 230 mm. The detector response function over the energy range of interest is presented in Fig. 2.10. The both response functions severely get down under the energy range of 1.0 eV according to the cross section of neutron capture reaction of cadmium. Although the thickness of beryllium layer 50 mm is too thin as a neutron moderator, the response for high energy neutron over 1 MeV is successfully improved by (n, 2n) reaction of beryllium and realized a response within $\pm 40.8\%$ over the whole energy range. The expected detection efficiency for the graphite moderated fission chamber loaded with 200 mg $^{235}\text{UO}_2$ is 0.15 ± 0.03 cps/(n/cm²·s), while the beryllium moderated one is 0.12 ± 0.05 cps/(n/cm²·s). Because beryllium moderator is much thinner than the graphite one, it is useful for the downsizing the detector module.

2.2.5 Detector module designs

Two types of modules have been designed. One is GMDM (Graphite Moderated Detector Module), and the other is BMDM (Beryllium Moderated Detector Module); their schematic views are shown in Fig. 2.11. The thicknesses of the moderators have been optimized to make the energy response as flat as possible. The moderating region of GMDM ($1,000 \times 800 \times 550$ mm) is 210 mm. The dynamic range for one module is increased by mounting several fission chambers with different amount of $^{235}\text{UO}_2$. In the ITER FDR (Final Design Report), the approved locations of the neutron flux monitor are the outer space behind the Limiter system in the Equatorial ports named as Eqs. 8 and 17 [11]. Through the preliminary estimations by Monte Carlo calculations, it has been found that monitoring all of the experimental phases with the required accuracy cannot be realized only by the detector modules incorporated at the approved positions, because the detector efficiency is much poor than its requirement especially for the DD phase and the *in-situ* calibrations. Additional installation places are demanded as close to the plasma as possible to achieve a much higher efficiency. Since many kinds of devices such as other diagnostic tools are supposed to be installed in the Equatorial ports near the plasma, the sizes of those devices are restricted. Because of the spatial constraint, the detector module that will be placed near the plasma should be as small as possible. Therefore, BMDM has been employed for this purpose and will be used near the plasma. The BMDM has a beryllium layer of 50 mm without lead layer and the size of which is $900 \times 570 \times 130$ mm, it can be mounted in the small place near the plasma.

2.3 Summary

This chapter has described the basic designs of detector modules for the ex-vessel neutron yield monitor in ITER. The detector modules have several ^{235}U fission chambers surrounded by graphite or beryllium moderator, lead and cadmium have been employed for γ -ray and thermal neutron shield, respectively. The moderating regions of the detector module have been optimized to make the energy dependences of the detection efficiencies as flat as possible. The GMDM ($1,000 \times 800 \times 500$ mm) has a 550 mm-thick graphite layer and a flat energy response within $\pm 14.4\%$ over a wide energy region from thermal region to 14.1 MeV. The detector modules will be incorporated in the Equatorial port plugs of the ITER machine. Since the DD phase of ITER and the *in-situ* calibration need a detector with a much higher sensitivity, one of the detector modules should be mounted near

the plasma. Because of the spatial constraint near the plasma, the size of devices that will be incorporated near the plasma is as small as possible. A down-sized module with beryllium moderator, $900 \times 570 \times 130$ mm, has also been designed for this purpose. It has an energy response within $\pm 40.8\%$. The fission chambers will be used under a pulse-Campbell combined operation mode, which can extend the dynamic range of single detector up to 9 orders. Detector modules that have several fission chambers with different amounts of fissile material achieve a further expansion of dynamic range, which is helpful for securing the required range of 11 orders.

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Figures and tables

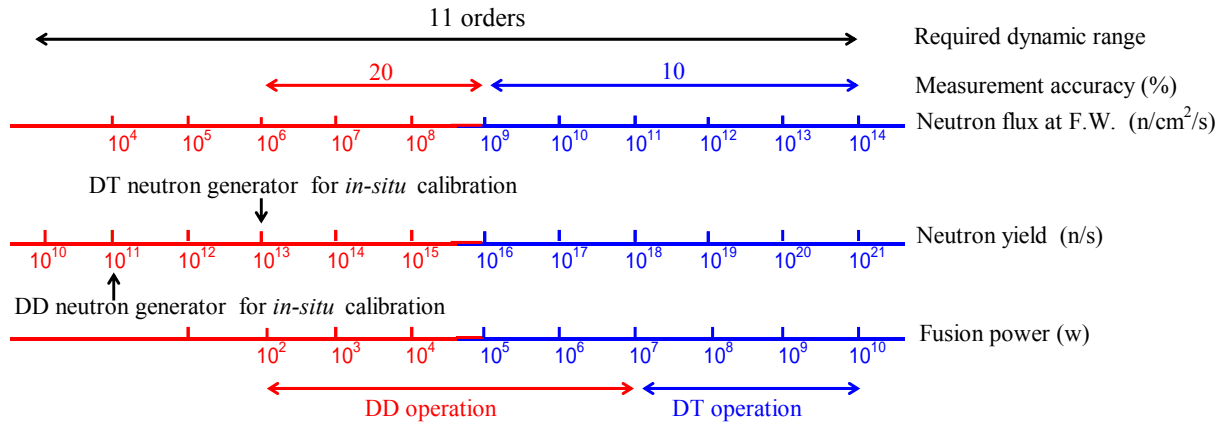


Fig. 2.1 Required dynamic range of this system.

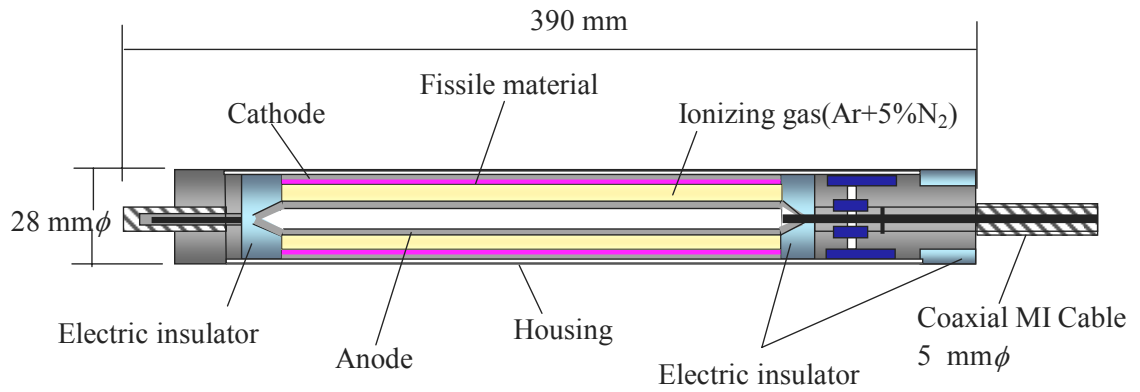


Fig. 2.2 Schematic diagram of the fission chamber with specification for JT-60U (Tokamak machine, Japan Atomic Energy Agency).

Detector size: 28 mm ϕ \times 390 mm

Fissile material : 90% enriched ²³⁵UO₂

Counting gas: 8 atm Ar + 5% N₂

Operative temperature: up to 673 K

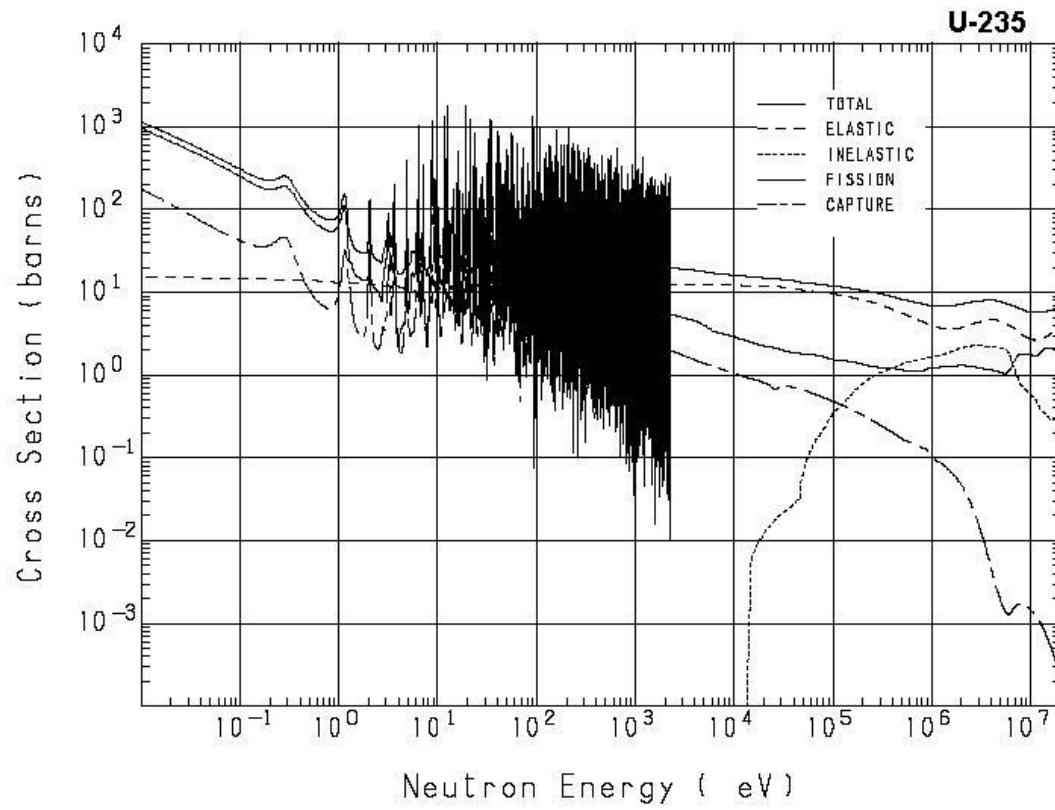


Fig. 2.3 Neutron cross section of ^{235}U [JENDL-3.3].

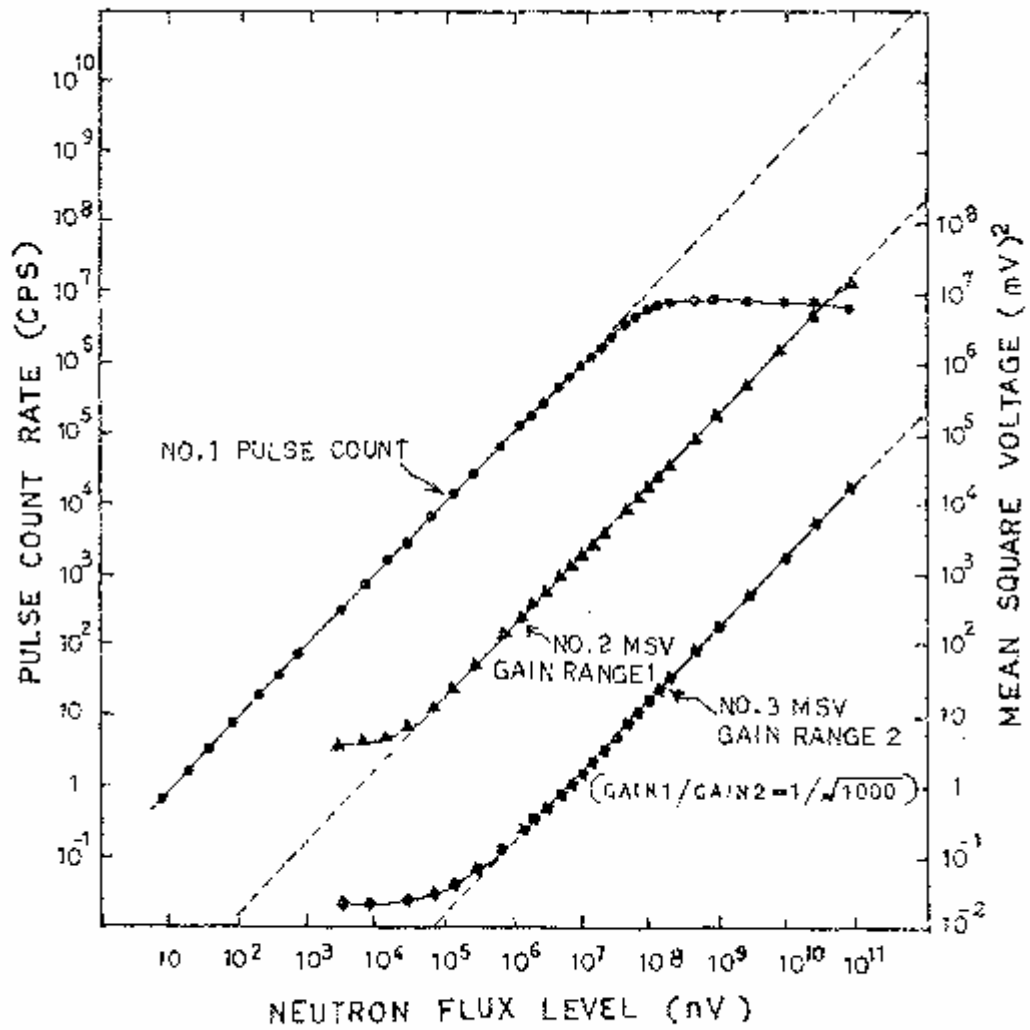


Fig. 2.4 Overlap of dynamic range between pulse counting mode and Campbell mode [9].

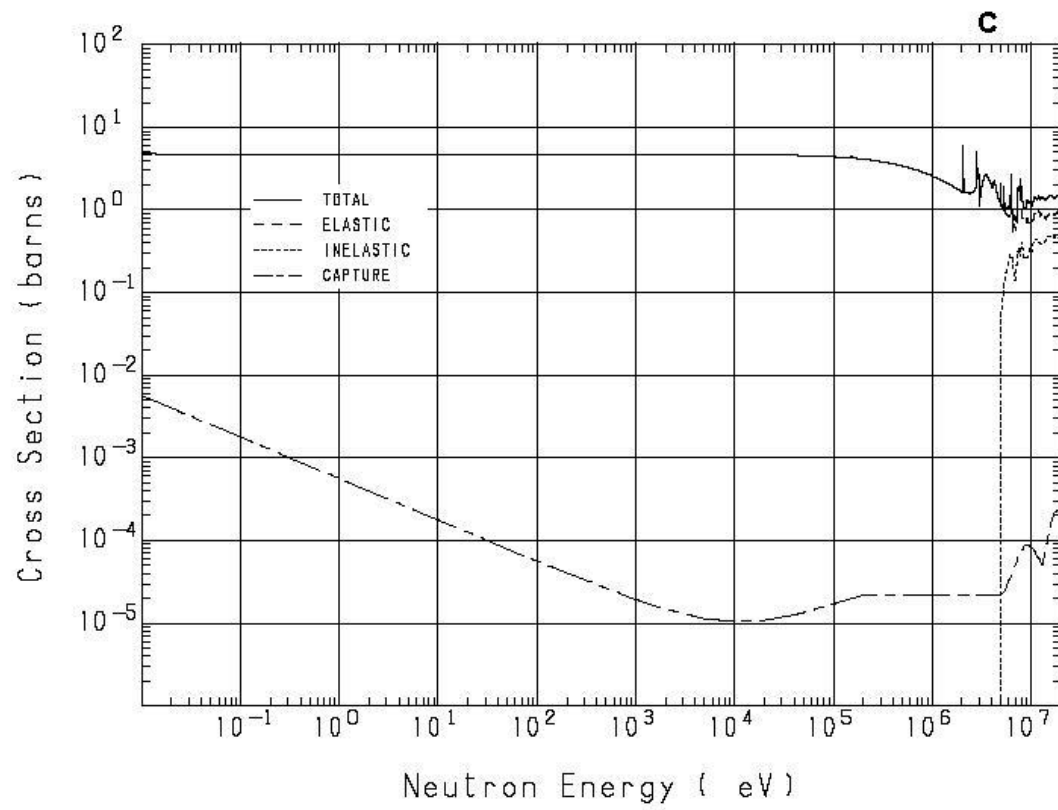


Fig. 2.5 Neutron cross section of ^{12}C [JENDL-3.3].

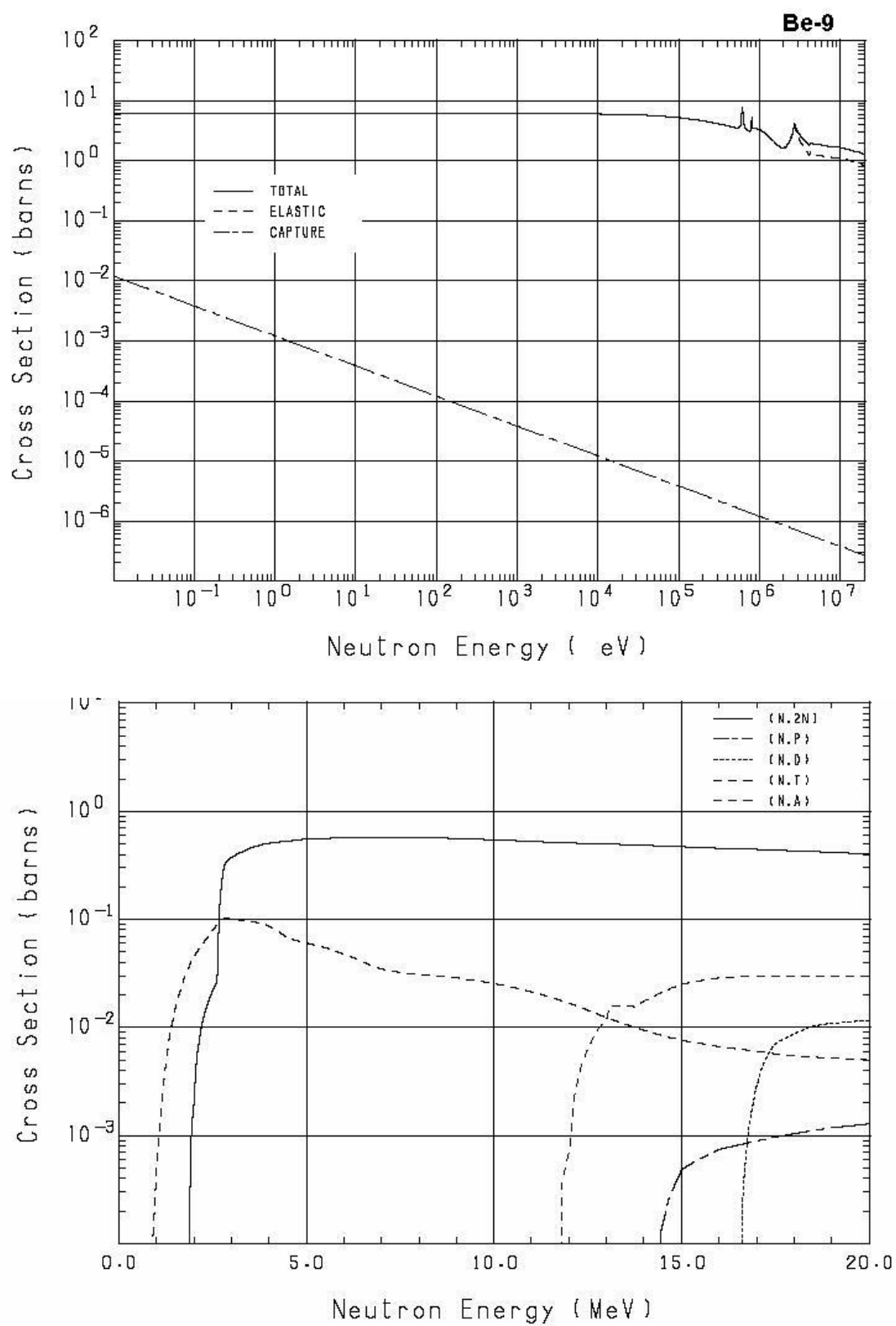


Fig. 2.6 Neutron cross section of ^9Be [JENDL-3.3].

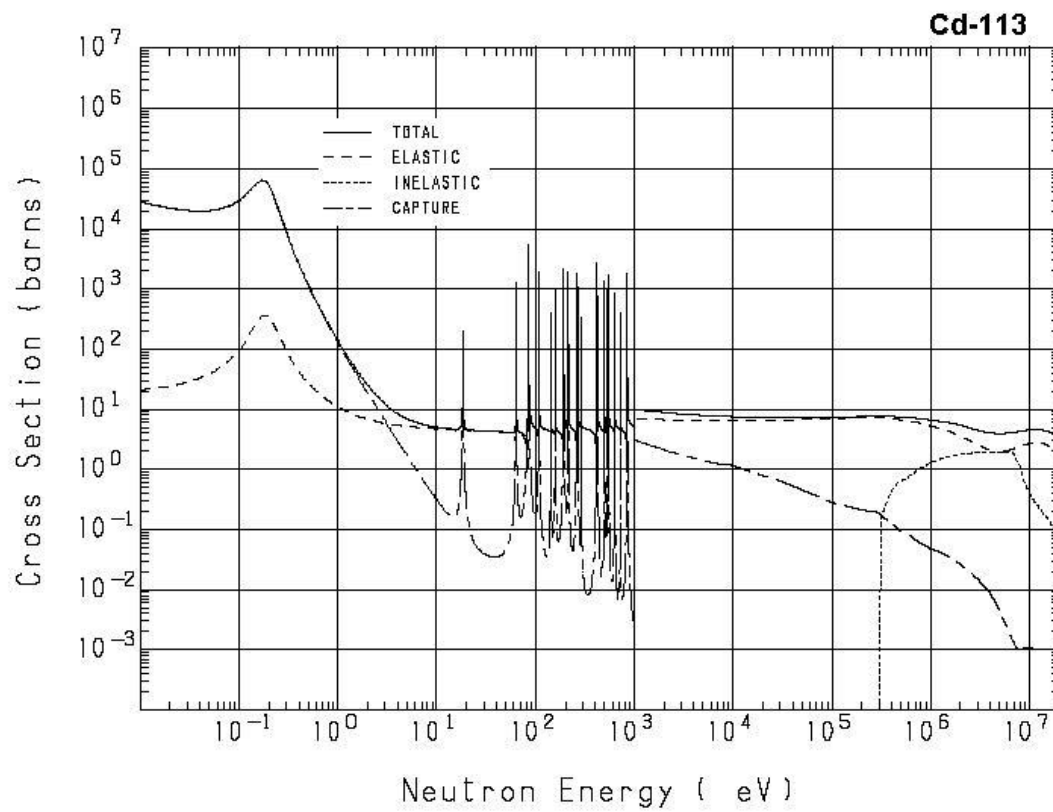


Fig. 2.7 Neutron cross section of ^{113}Cd [JENDL-3.3].

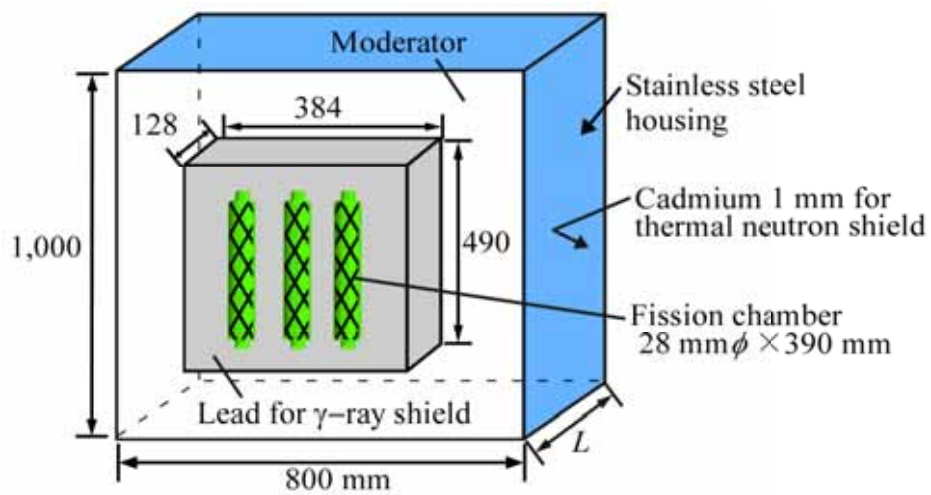


Fig. 2.8 Basic structure of the detector module.

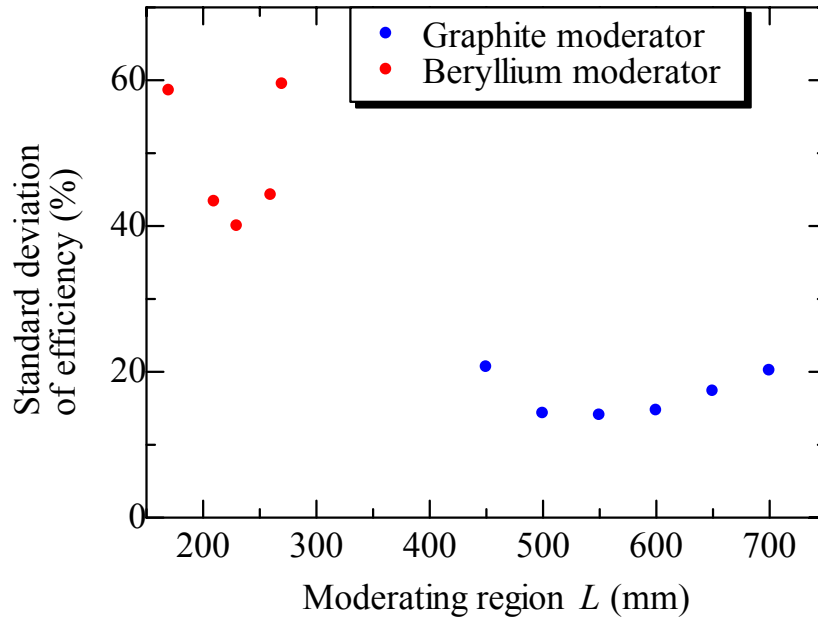


Fig. 2.9 Optimization of the moderating regions.

Vertical axis indicates standard deviation of detection efficiencies for each energy group.

The standard deviation of 14.1% for 550 mm-Graphite moderator means that energy dependence of detection efficiency is within $\pm 14.1\%$ (1σ).

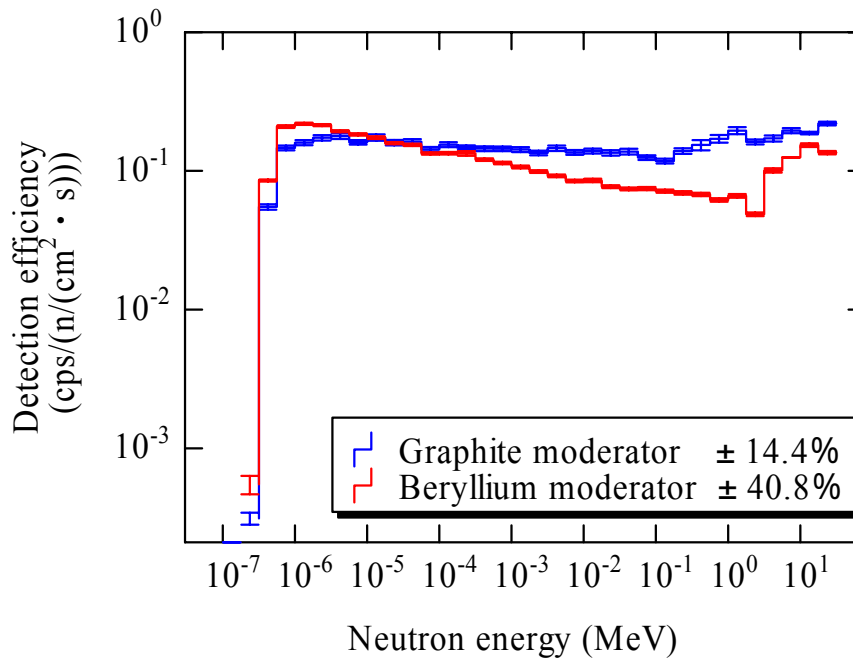
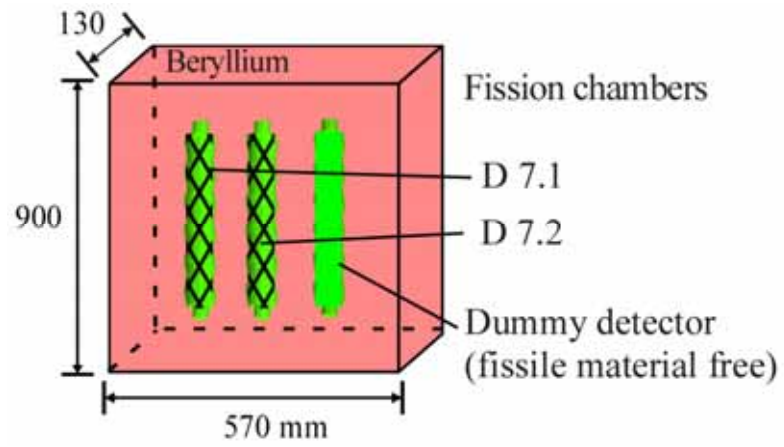
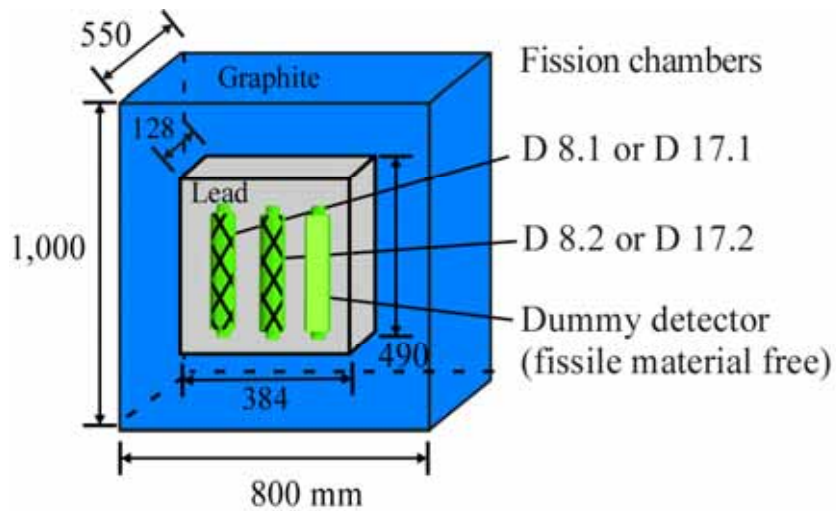


Fig. 2.10 Response function of the detector module with the optimized-thickness moderator computed by MCNP-4C2 with ENDF/B-VI neutron data library.



(b)



(a)

Fig. 2.11 Detector module designs.

(a) Graphite Moderated Detector Module (GMDM).

(b) Beryllium Moderated Detector Module (BMDM).

The small-size detector module with beryllium moderator has been designed for the *in-situ* calibration and the DD phase in the ITER experiments.

Table 2.1 Requirements of the neutron yield monitoring system in ITER.

Parameter	Parameter range	Spatial resolution	Time resolution	Accuracy
Total neutron yield	1×10^{13} - 1×10^{16} n/s	Integral	1 ms	20%
	1×10^{16} - 5×10^{20} n/s	Integral	1 ms	10%
Fusion power	100 W - 10 kW	Integral	1 ms	20%
	10 kW - 1 GW	Integral	1 ms	10%

Table 2.2 Candidates of the neutron detector for this system.

		BF ₃ counter	³ He counter	¹⁰ B counter	Fission chamber
Operating temperature range	(°C)	< 100	< 250	< 150	< 500
Sensitivity	(cps/nv)	0.1-20	1-100	0.25-10	0.1-1
neutron/γ-ray discrimination		Inferior at high γ-ray flux	Possible	Inferior	Superior
Operating voltage range	(V)	1,000-2,000	500-5,000	700-1,000	200-500