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# DESIGN OF RADIAL NEUTRON SPECTROMETER FOR ITER

September 1996

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# Design of Radial Neutron Spectrometer for ITER

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We designed the radial neutron spectrometer using a new type DT neutron spectrometer base on a recoil proton counter-telescope technique aiming ion temperature measurement for ITER. The neutron spectrometer will be installed on the well-collimated neutron beam line. A large-area recoil proton emitter is placed in parallel to the incident neutron beam and a micro-channel collimating plates are inserted between the radiator and the recoil proton detectors away from the neutron beam in order to limit the scattering angle of protons to the proton detectors. Here a very thin polyethylene film and a silicon surface barrier detector are employed as the radiator and proton detector, respectively. The energy resolution and detection efficiency are estimated to be 2.5% and $1\times10^{-5}$counts/(n/cm$^2$), respectively for DT neutron through Monte Carlo calculations. Five units of the spectrometers will be installed just out side the bio-shield and consist a fun array using penetrations inside the bio-shield and a pre-collimator in the horizontal port. The life time of the proton detectors is estimated to be about one year in the Basic Performance Phase of ITER by neutron transport calculations using MCNP Monte Carlo code. The necessary R&D items and the design work were identified.

Keywords: Neutron Spectrometor, ITER, Recoil Proton Counter-Telescope, Ion temperature, Silicon Surface Barrier Detector, MCNP

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This work is conducted as an ITER Engineering Design Activities and this report corresponds to 1995 ITER Design Task Agreement on "Diagnostics Design Task"(S91 TD 21 95-01-20 FJ).

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# ＩＴＥＲ用径方向中性子スペクトロメータの設計

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（１９９６年8月６日受理）

ＩＴＥＲにおけるイオン温度測定を目的とし、反跳陽子カウンターテレスコープ法に基づく新たなＤＴ中性子用スペクトロメータの設計を行った。この中性子スペクトロメータは良くコリメートされた中性子ビーム上に設置される。中性子ビームに平行に配置した反跳陽子放出用薄膜（ポリエチレンフィルム）と陽子検出器（表面障壁型検出器）の間にマイクロチャンネルコリメータを挟むことにより、ある放出角の反跳陽子のみを選択的に測定する。この中性子スペクトロメータのエネルギー分解能及び検出効率をモンテカルロ計算によって評価したところそれぞれ、ＤＴ中性子に対し2.5％及び$1\times10^{-5}$counts/(n/cm$^2$)であった。ＩＴＥＲでは、生体遮蔽に貫通したコリメータにより扇状のアレイを形成し、イオン温度分布を測定する。この中性子スペクトロメータで最も大きな問題の一つである表面障壁型検出器の照射損傷について中性子のモンテカルロコードＭＣＮＰで評価したところ、ＩＴＥＲの運転環境において約１年の寿命があることが解った。また今後必要な設計・開発項目の摘出を行った。

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本研究はＩＴＥＲ工学設計活動の一環として実施したもので、本報告は1995年設計タスク協定（S91 TD21 95-01-20 FJ）に基づくものである。
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# 1. Introduction

Neutron spectroscopy was proposed[1] early on in the fusion research as a direct method of ion temperature measurement in deuterium or deuterium-tritium plasmas. If the ion velocity distribution is Maxwellian, the neutron energy spectrum is centered at 14 MeV for the d(t,n)$\alpha$ reaction with a full width at half-maximum $\Delta E_n$ (in keV) represented by

$$\Delta E_n \approx 177 T_i^{1/2} \qquad (2.1)$$

where $T_i$ is the ion temperature in keV. The ion temperature can be derived from the broadening of the neutrons spectrum using this relation.

In present large tokamaks such as JET, TFTR or JT-60U, ion temperature measurements have been tried using a $^3$He neutron spectrometer[2-4] and a time-of-flight neutron spectrometer[5,6] for ohmically heated discharges. In those tokamaks, main experiments are carried out with intense auxiliary heating of neutral beam (NB) injections or ICRF heating, where the ion velocity distribution is no longer Maxwellian and consequently it is difficult to derive the ion temperature from the neutron spectrum. The competing diagnostic, Charge Exchange Recombination Spectroscopy (CXRS), is employed as a reliable method of the ion temperature measurement with high temporal and space resolutions. The International Thermonuclear Experimental Reactor (ITER) aims to demonstrate a 1000 sec ignited plasma, where the ion velocity distribution is expected to be Maxwellian. Although CXRS has a difficulty that a diagnostics neutral beam with suitable energy for CXRS (~100 keV) could not reach the core region of the ITER plasma. Furthermore more, CXRS has problem with the radiation damages of optical components such as fiber optics or windows. Therefore we believe the neutron spectroscopy is the most promising $T_i$ measurement technique for ITER.

The neutron emission spectrum of a DT plasma consists of the 2.5 MeV and 14 MeV peaks, which are from d(d,n) $^3$He and d(t,n)$\alpha$ reactions, respectively. The 14 MeV neutron emission is ~100 times larger than 2.5 MeV neutrons. The broader component of neutrons centered at 14 MeV is predicted to be produced by super-thermal ions generated by knock-on collision with fast alpha particles. The neutron spectroscopy is useful not only for the ion temperature measurement but also the ion density from 2.5 MeV and 14 MeV neutron intensities, the fast alpha particle population from the broader spectrum of 14 MeV neutrons and the plasma toroidal rotation measurements from the shift of the 14 MeV peak in the tangential measurement. Several types of the 14 MeV neutron spectrometer have been proposed or developed. The proton recoil counter telescope (COTETRA) [7] and the diamond detector[8] have been demonstrated in the TFTR DT experiments. The tandem-radiator spectrometer[9], the associated-particle time-of-flight spectrometer (TANSY)[10] and the magnetic proton recoil spectrometer(MPR)[11] are or will be installed on JET for the DT experiments to be carried out in 1996. Those neutron spectrometers are too large to install in the limited space of ITER except the diamond detector. We are developing a relatively compact neutron spectrometer[12] based on a recoil proton counter-telescope technique to consist the radial neutron spectrometer array concentrating on the ion temperature profile measurement.

## 2. Development of the prototype spectrometer unit

### 2.1 Requirements for neutron spectrometer

The ion temperature profile measurement aiming the burn optimization and transport studies is categorized in the measurements for the performance evaluation and the optimization (Category II) [13] in ITER. The physics requirements for the ion temperature measurement are listed in Table 2.1.

Table 2.1. Requirement for ion temperature profile measurement

| Temperature range | Spatial resolution | Time resolution | Accuracy |
|---|---|---|---|
| 0.5-50 keV | 30 cm | 100 ms | 10% |

In order to measure the ion temperature from the neutron spectrum, a high-energy-resolution spectrometer should be employed. To be useful, the intrinsic energy resolution of the spectrometer, $\Delta E_{det}$ needs to be less than the thermal broadening represented by equation (2.1). Thus, for an ion temperature of 5 keV, $\Delta E_{det}$ should be better than 2.8% which is achievable. The accuracy of the ion temperature is related to the total counts of 14 MeV neutron peak, N, by

$$\frac{\Delta T_i}{T_i} = \sqrt{\frac{2}{N}\left[1 + \left(\frac{\Delta E_{det}}{\Delta E_n}\right)^2\right]} \qquad (2.2)$$

When $\Delta E_{det} \leq \Delta E_n$, 400 counts will satisfy the 10% accuracy of the ion temperature. So the detection efficiency should be high enough to obtain a counting rate of 4000 cps to result in 100 ms time resolution.

Concerning of the spatial resolution, approximately 20 channels of the spectrometer are needed to satisfy the ITER requirement shown in Table 1. If the port space for two or three arrays of the spectrometer is available, it is possible to satisfy the requirement for medium size spectrometer proposed here, however, which is very difficult due to tight space for diagnostics. Only the diamond detectors can satisfy the spatial resolution because it is very compact (2-3 $cm^3$) and can share the collimator with the neutron profile monitor. But the diamond detector has a disadvantage of the radiation damage which degrade the spectrometer performance such as an energy resolution. So the combination of the relatively reliable neutron spectrometer (medium or large size spectrometer) and the diamond detectors to keep the redundancy of $T_i$ measurement. The former spectrometer will calibrate the diamond detector performance so that several channels of the former spectrometer might be enough. We listed the design target for the radial neutron spectrometers in Table 2.2.

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Table 2.2. Design target for radial neutron spectrometers

| Energy resolution | Detection efficiency | Spatial resolution | Time resolution |
|---|---|---|---|
| 2.5 % at 14 MeV | $1 \times 10^{-5}$ counts/(n/cm$^2$) | ~ 1.0m | 100 ms |

## 2.2 Basic concept of the spectrometer

Figure 2.1 shows the schematics of the compact neutron spectrometer based on a recoil proton counter-telescope technique. The neutron spectrometer will be installed on a well-collimated neutron beam line, where a rectangular cross-section with 3 cm height × 20 cm length dimension is considered. A large-area recoil proton emitter(radiator) is placed in parallel to the incident neutron beam and a micro-channel collimating plates are inserted between the radiator and the recoil proton detectors away from the neutron beam in order to limit the scattering angle of protons to the recoil proton detectors. Here a very thin polyethylene film and a silicon surface barrier detector(SBD) are employed as the radiator and proton detector, respectively. Recoil proton energy is measured with the SBDs using conventional pulse height analysis electronics. Incident neutron energy $E_n$ is related to the recoil proton energy $E_p$ by

$$E_n = E_p / \cos^2\Theta \qquad (2.3)$$

where $\Theta$ is the tilting angle of the channel in the micro-channel collimating plate against the neutron incident direction. The advantage of this spectrometer is the compatibility of high energy resolution and high detection efficiency. The high energy resolution characteristic can be realized by the use of a very thin radiator to reduce the energy loss of recoil protons inside the radiator and a recoil proton collimator to subtend the small solid angle of recoil protons incidence to the SBDs. While the detection efficiency can be freely controlled by adjusting the detection area under the high energy resolution geometry.

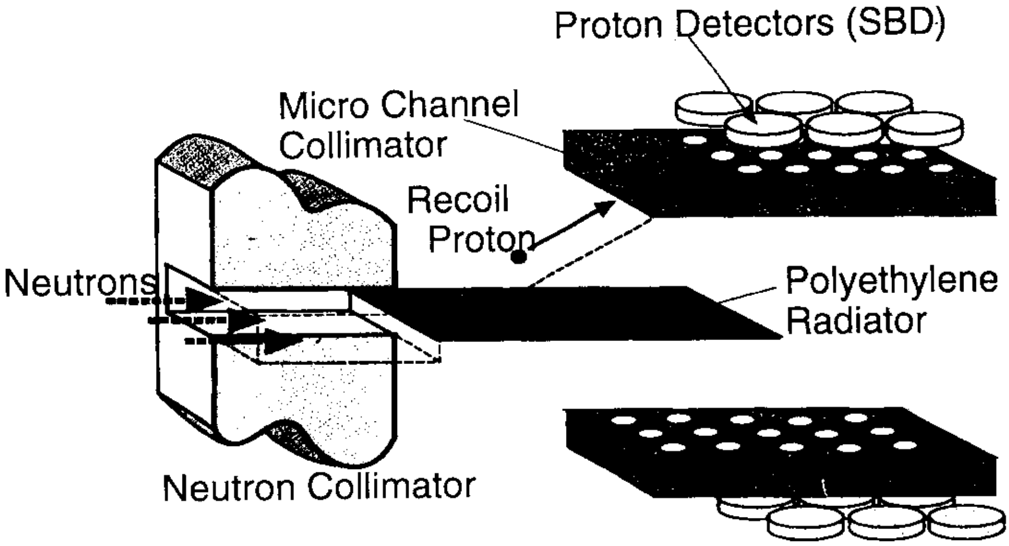


Fig.2.1 Concept of the new 14 MeV neutron spectrometer based on a recoil proton counter-telescope technique.

## 2.3 Numerical calculation of detector response

To meet a very severe requirement for the trade-off between energy resolution and the detection efficiency, the design parameters were widely surveyed on the radiator thickness, the diameter of a recoil proton collimator and the incident angle of the recoil protons against the neutron incident direction, using simple Monte Carlo calculations. In this calculation, we considered only the loss of the recoil proton energy in the radiator but not the multi-collision of the neutrons in the radiator, the small angle scattering of the recoil proton in the collimator nor the energy loss of the recoil proton inside the collimator material when it is transmitting through the collimator edge.

The radiator thickness dependence of the detection efficiency and the energy resolution is shown in figure 2.2, where the detection efficiency is defined as the counts for single collimator channel. We can see that the detection efficiency and the energy resolution are strongly trade-off. Also both the detection efficiency and the energy resolution increase with increasing collimator radius as shown in figure 2.3. Figure 2.4 shows the calculated recoil proton spectrum for the micro channel collimator with 0.1 mm diameter and 10 mm thick polyethylene radiator, where 1% of the SBD's energy resolution is assumed. The calculation shows 2.3 % of the energy resolution and $1.2 \times 10^{-7}$ counts/(n/cm$^2$) for the single SBD with an active area of 2000 mm$^2$. So we need 80-90 SBDs to satisfy the required detection efficiency of $1 \times 10^{-5}$ counts/(n/cm$^2$).

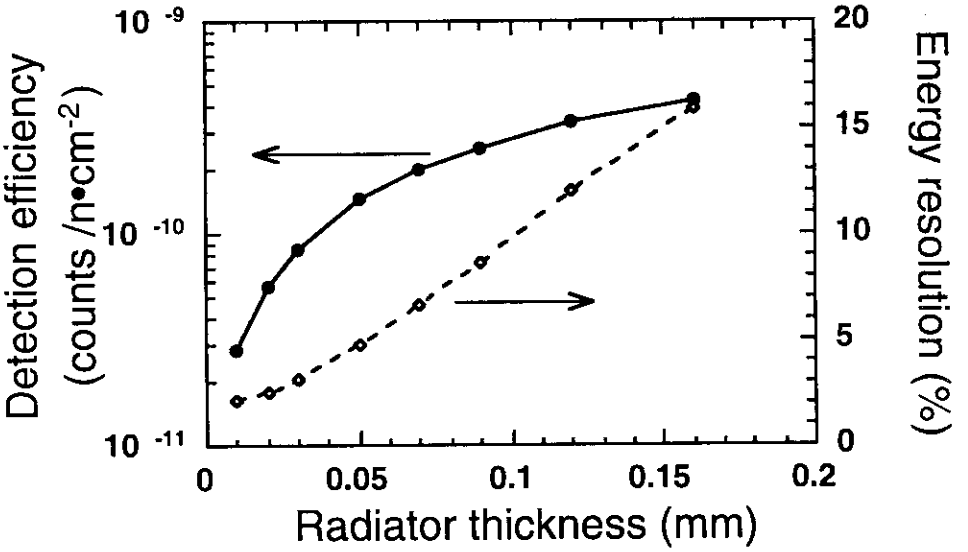


Fig.2.2 Detection efficiency and energy resolution of the spectrometer as a function of the radiator thickness.

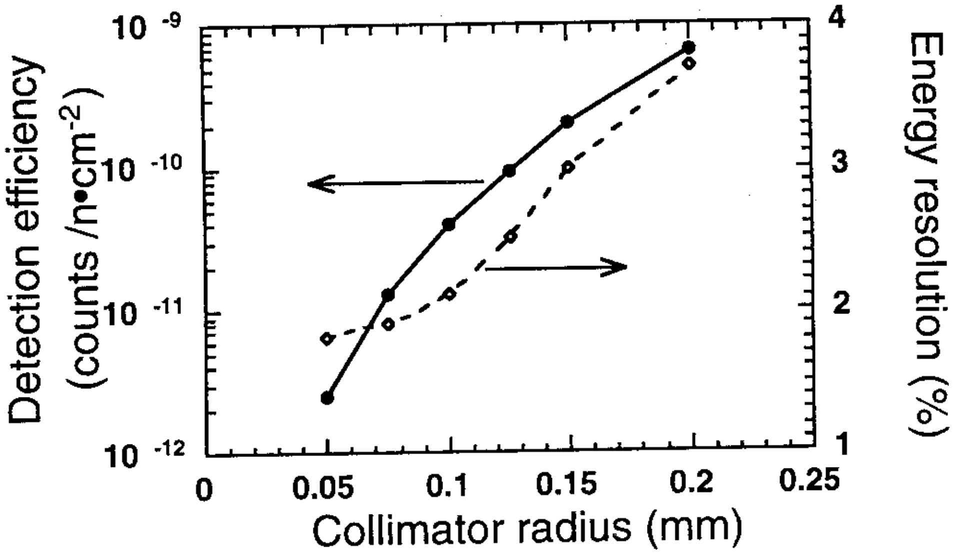


Fig.2.3 Detection efficiency and energy resolution of the spectrometer as a function of the collimator radius.

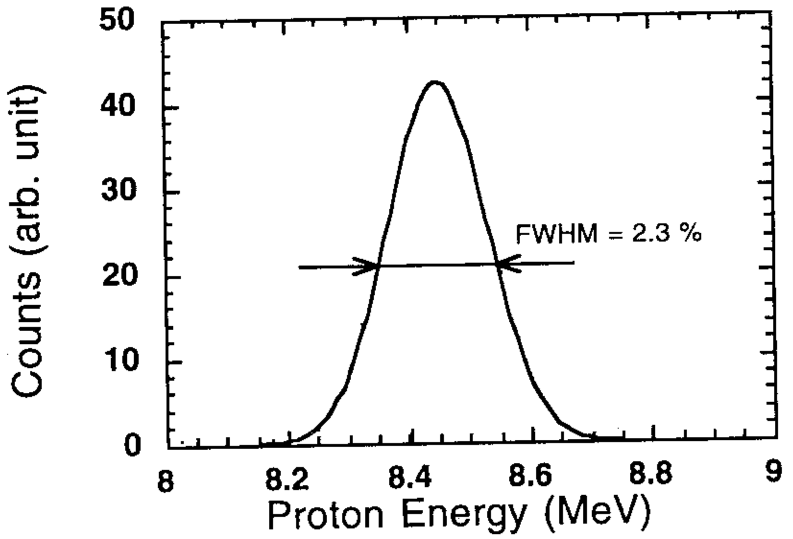


Fig2.4 Calculated recoil proton spectrum for the micro channel collimator with 0.1 mm diameter and 10 µm thick polyethylene radiator.

### 2.4. Performance of Prototype Spectrometer

The prototype of this spectrometer has been tested its performance at the FNS 14 MeV neutron generator[14]. Figure 2.5 shows the schematics of the experimental arrangement of the prototype spectrometer at FNS. The spectrometer unit consists of a polyethylene radiator film and micro channel collimator plate and the SBD with an active area of 2000 mm$^2$ and a depletion depth of 0.5 mm. The axis of the system is tilted 100° against the deuteron beam line, where the spread of the source neutron energy is almost minimum. We employed new type micro channel collimator made of a 10 mm thick lead glass plate with the holes of 200 μm diameter and 620 μm pitch tilted 30°, capillary plate made by HAMAMATSU (see Fig. 2.6). The proton recoiled for 30° by the 14 MeV neutron has a energy of 10.6 MeV. The range of the 10.6 MeV proton in a silicon is about 0.7 mm so that the 30° tilted SBD with 0.5 mm depletion depth is enough to stop the recoil proton. The energy resolution of both SBDs are calibrated using $^{241}$Am source to be 47 keV for 5.5 MeV alphas.

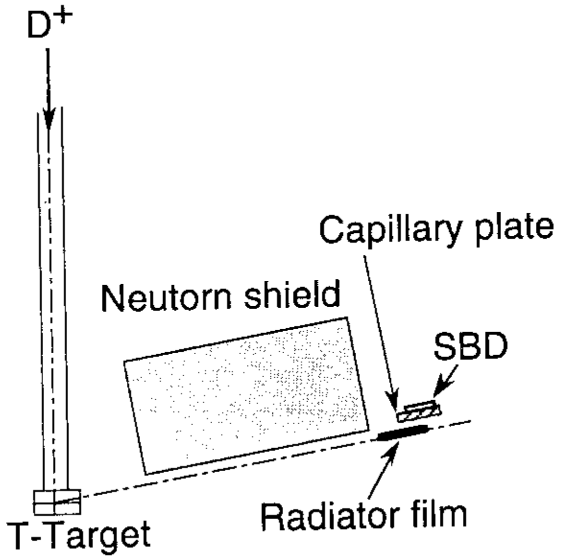


Fig2.5 Schematics of the experimental arrangement of the prototype spectrometer at FNS.

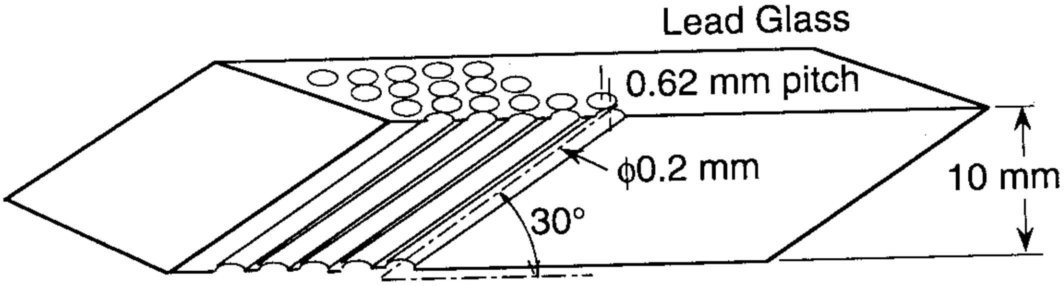


Fig2.6 Schematics of the capillary plate for the micro channel collimator.

Figure 2.7 shows the recoil proton spectra comparing with numerical calculations assuming 1% of the SBD energy resolution. The statistics of the measured data is rather poor, but we can see that the measured spectrum with a thick radiator has relatively good agreement with the calculation. Also The measured and calculated performances are listed in Table 2.3.

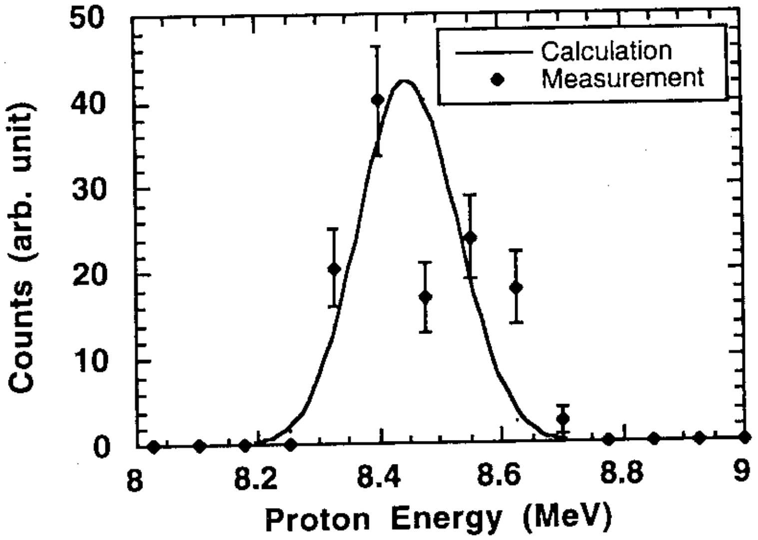


Fig2.7 Measured and calculated recoil proton spectrum for the micro channel collimator.

Table 2.3 Measured and calculated performances of the prototype spectrometer for 14 MeV neutron.

| | Energy resolution | Detection efficiency/one SBD |
|---|---|---|
| Calculation | 2.3 % | $2.4 \times 10^{-7}$ counts/(n/cm$^2$) |
| Measurement | 2.5 % | $2.0 \times 10^{-7}$ counts/(n/cm$^2$) |

# 3. Design of the radial neutron spectrometer

## 3.1 Concept of radial neutron spectrometer

Previously, we proposed radial neutron spectrometer to be installed inside the cryostat. From the maintenance and the radiation damage of SBDs the point of view, we changed mind that the spectrometer will be outside the biological shield (bio-shield). This radial neutron spectrometer system consists of;

- Pre-collimator
- Collimator
- Neutron spectrometer units
- Post-shield and neutron beam dump
- Electronics and data acquisition system

Figure 3.1 shows the conceptual schematics of the radial neutron spectrometer, where five channels of the spectrometer consist a fun array using penetrations inside the bio-shield and a large pre-collimator in the horizontal port. The spectrometers are surrounded by the post-shield and the neutron beam dump. The electronics and the data acquisition system will be installed outside of the post-shield in the pit and the diagnostics room. Drawing of the neutron spectrometer is shown in Figure 3.2.

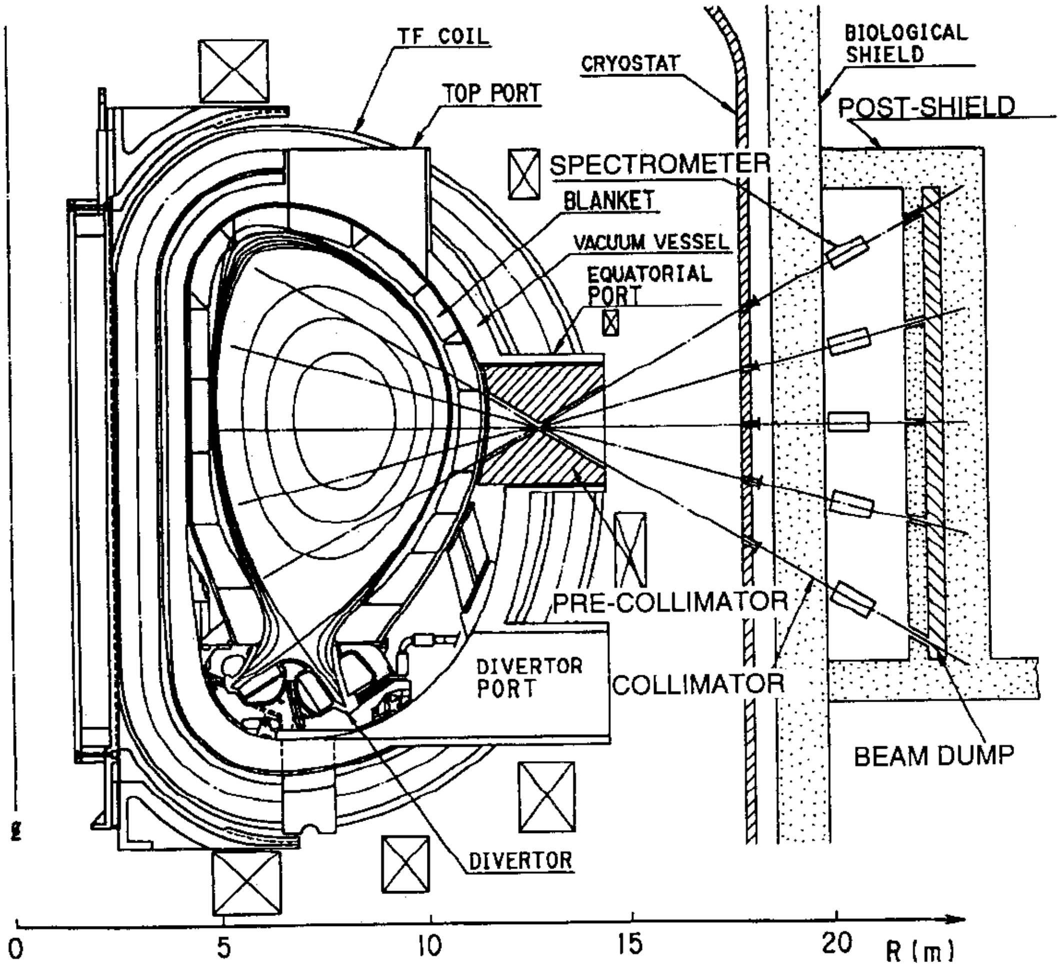
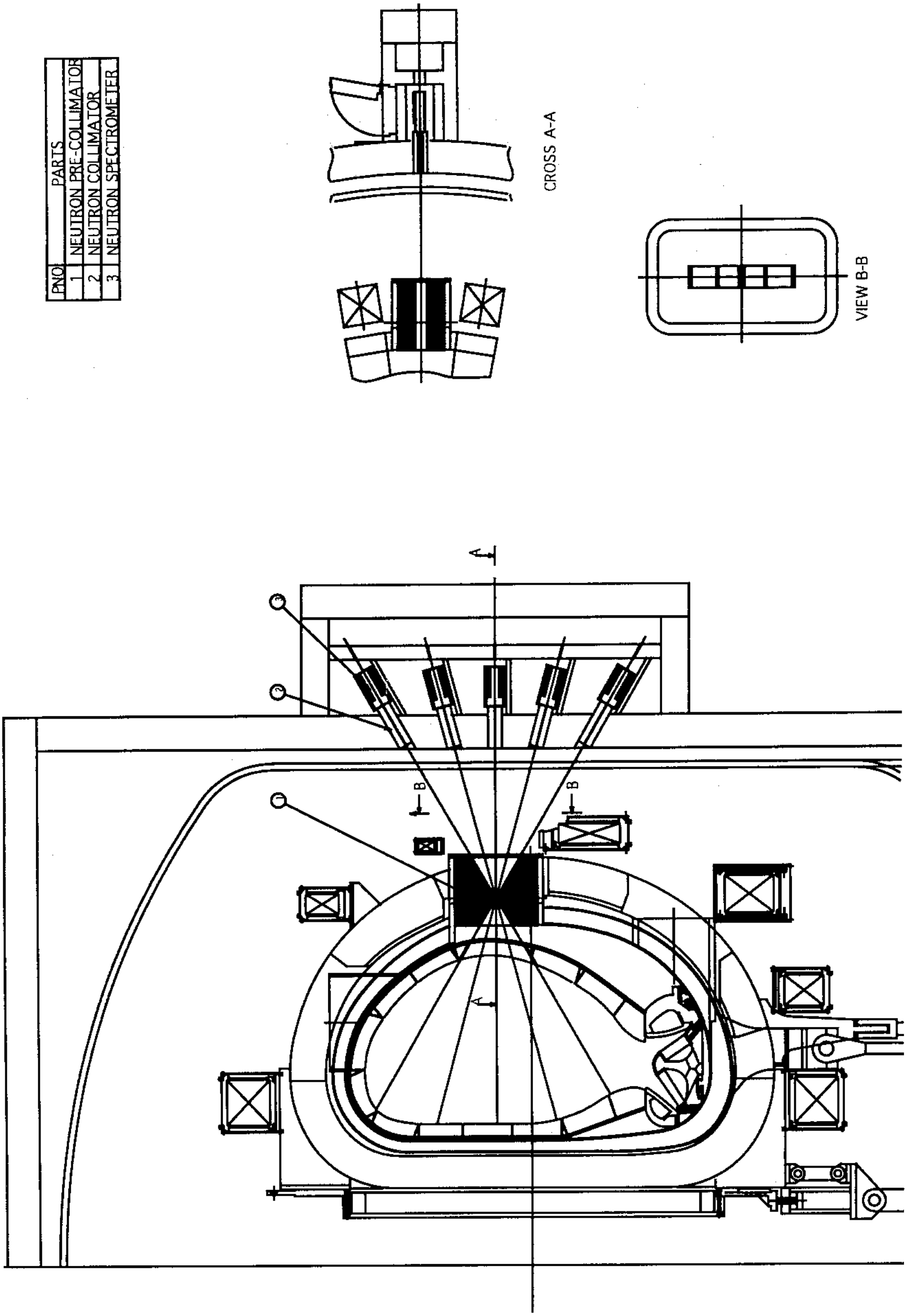


Fig.3.1 Conceptual schematics of the radial neutron spectrometer.



| PNO | PARTS |
|---|---|
| 1 | NEUTRON PRE-COLLIMATOR |
| 2 | NEUTRON COLLIMATOR |
| 3 | NEUTRON SPECTROMETER |

Fig.3.2 Arrangement of the radial neutron spectrometer on ITER.

## 3.2 Pre-collimator

### 3.2.1 Structure of the pre-collimator

Large pre-collimator will be inserted into the horizontal port to make the pin-hole camera for the fun array of the neutron spectrometer. The drawing of the pre-collimator is shown in Figure 3.3. Mechanical parameters are as follows;

- Outline size : 2500D × 1700W × 3000H (mm)
- Material and Weight
  - Stainless steel 316 : 61,000 kg
  - Water (coolant) : 3,850 kg

We expect that the pre-collimator can be supported by the horizontal port. The cooing of nuclear heating is very important issue for this pre-collimator because the radiation circumstances are almost same as that of the shielding blanket. We need special blanket to cover the front of the pre-collimator except the collimator hole to reduce the neutron flux incident into to the pre-collimator. Evaluation of nuclear heating and the cooling is described in Sections 3.2.1.

The coolant inlets and outlets are arranged in front of the pre-collimator (ϕ 200 mm × 8). We consider that the coolant will be supplied same way as the shielding blanket. The flow channel of the coolant is very complicate inside the pre-collimator in order to reduce the eddy current on disruptions.

This pre-collimator will be connected to the horizontal port by welding. The back plate of the pre-collimator with thin metal windows on the lines of sight will become the first vacuum boundary. Also we want to introduce thin metal windows on the cryostat, which will be second vacuum boundary.

The electro-magnetic stress in disruptions is another big issue, which is described in 3.2.2.

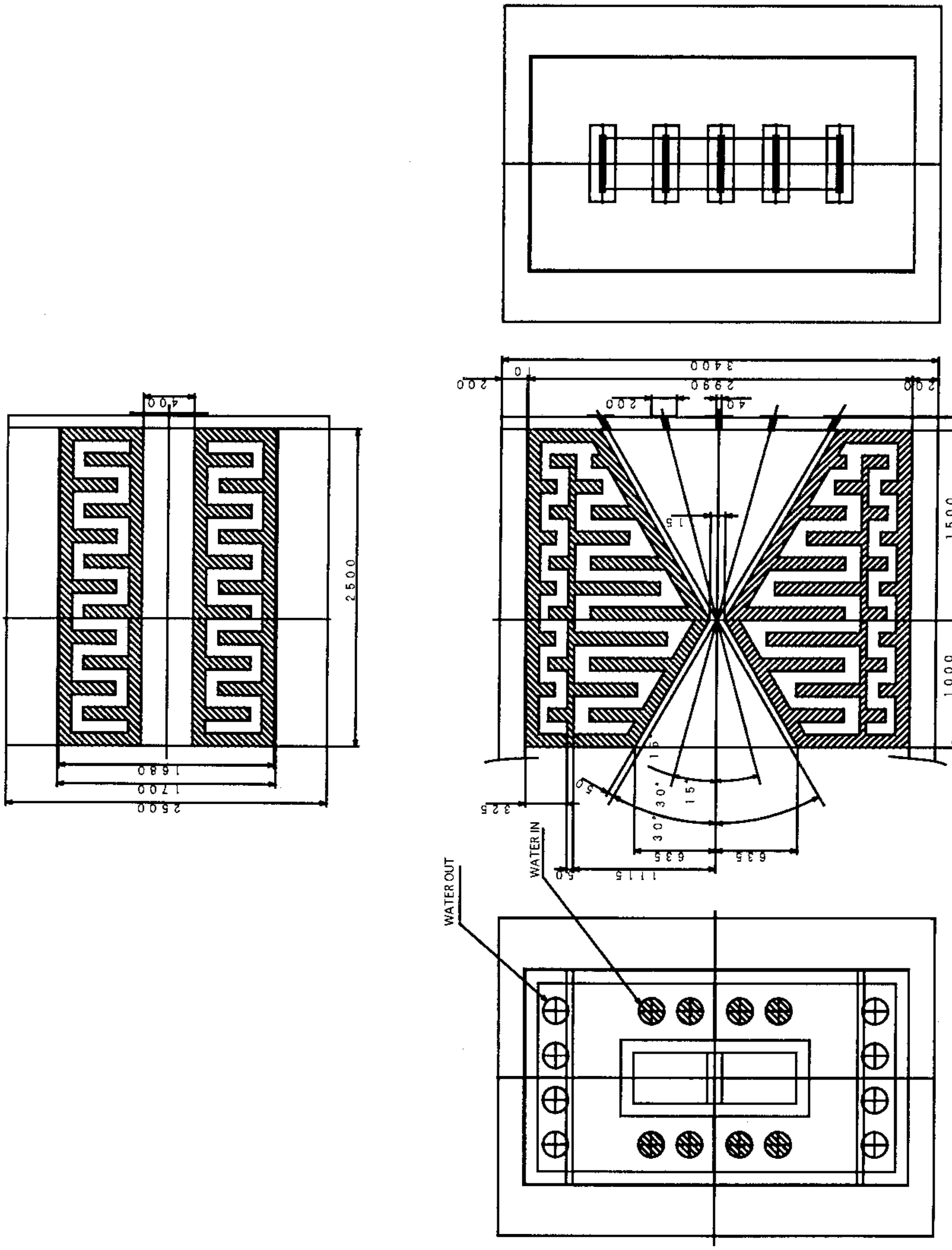


Fig.3.3 Structure of the pre-collimator.

### 3.2.2 Nuclear heating and the cooling

Nuclear heating of the pre-collimator are estimated by the model shown in Fig. 3.4.

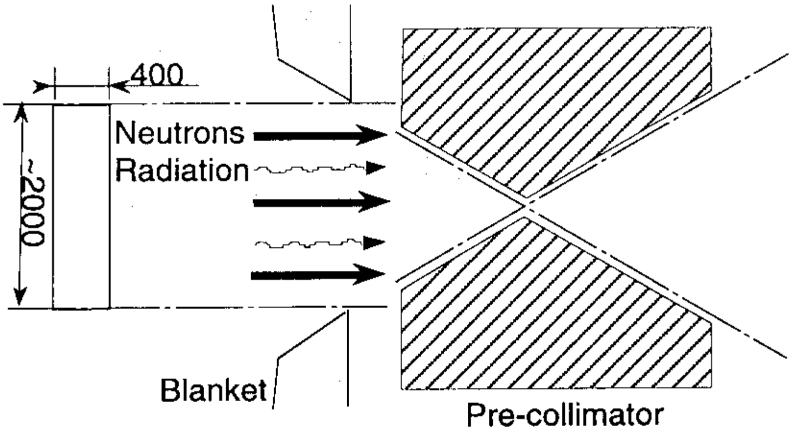


Fig.3.4 Model for the nuclear heating estimation of the pre-collimator.

Vertical cross-section of the pre-collimator is $1.7 \times 3 = 5.1$ m$^2$. Area of the pre-collimator facing to plasma and covered by blankets are

| | |
|---|---|
| Area facing to plasma | : $2 \times 0.4 = 0.8$ m$^2$ |
| Area covered by blanket | : 4.3 m$^2$ |

The pre-collimator will be heated by both of the nuclear heating and the plasma heating. The neutron flux on the front of the pre-collimator is evaluated to be 70% of that on the first wall (see Section 4.1). The neutron flux behind blanket is roughly estimated to 10% of that on the first wall.

| | |
|---|---|
| Nuclear heating | : 0.7 MW/m$^2$ (facing to plasma) |
| | : 0.1 MW/m$^2$ (behind blanket) |
| Plasma radiation | : 0.25 MW/m$^2$ |

Pre-collimator is thick enough to absorb those radiation. So the total heating rate of the pre-collimator is estimated to be

$$\text{Total heating rate} = (0.7 + 0.25) \times 0.8\ \text{m}^2 + 0.1 \times 4.3\ \text{m}^2 = 1.2\ \text{MW}$$

Assuming inlet and outlet coolant water temperatures are 100°C and 150°C, respectively, the flow rate of the coolant (V) is evaluated to be

$$V = Q/\delta\,\theta\,\Delta T$$
$$= 6\ l/\text{sec}$$
$$= 0.36\ \text{m}^3/\text{min}.$$

where, $\delta$ is the density of water at 100°C (0.958 g/cm$^3$) and q is the specific heat at constant pressure of water (4.22 j/g•k).
This flow rate is realizable from the technical point of view.

### 3.2.3 Electro-magnetic stress

The electro-magnetic stress in disruptions is an important issue. We estimated the electro-magnetic stress of the pre-collimator using simple rectangular pipe model shown in Fig. 3.5.

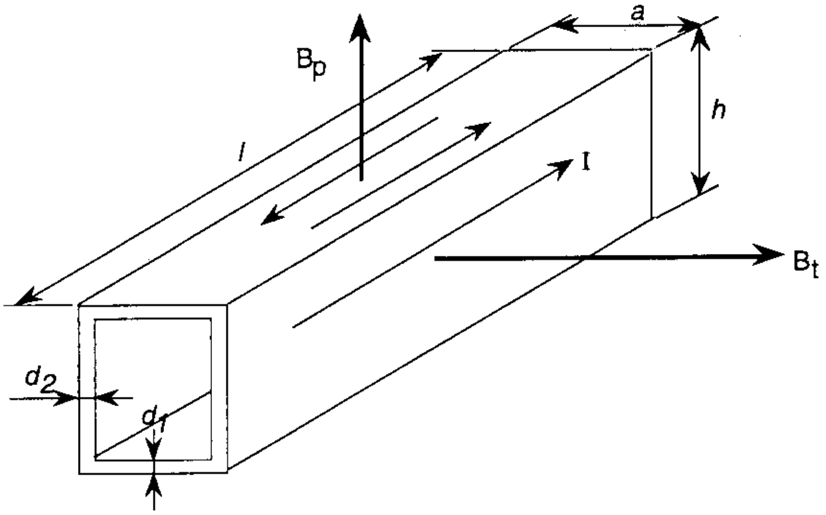


Fig.3.5 simple rectangular pipe model for the electro-magnetic stress estimation.

Condition of the calculation is as follows;

- Material : Stainless steel
- Resistivity : $\rho$ ( 8.00 × 10-7 $\Omega \bullet$m)
- External magnetic field ;
  Toroidal magnetic field: $B_t$ (3.07 T)
  Poloidal magnetic field: $B_{p0} \bullet \exp(-t/\tau_{ex})$
- Plasma current decay time : $\tau_{ex}$

where the toroidal magnetic field at the pre-collimator was derived from

$B_t$ (at pre-coll.) = $B_{t0}$ (plasma center)$\bullet$R(pre-coll.)/$R_p$

$B_{t0}$ = 5.1 T, R(pre-coll.) = 13.53 m, $R_p$ = 8.14 m

Here we used following formulae

- Initial current; $I_0 = \pi B_{p0} ((ad_1 + 2hd_2) / 4m_0) \bullet (d_1 - hd_1 / a \bullet \tan^{-1}(a/h) + d_2 \tan^{-1}(h/a))^{-1}$
- Current; $I = I_0 (\tau_c/(\tau_{ex}-\tau_c) (\exp(-t/\tau_{ex}) - \exp(-t/\tau))$
  $\tau_c = \mu_0 a/\pi\rho(d_1 - hd_1/a \bullet \tan^{-1}(a/h) + d_2 \tan^{-1}(h/a))$
- Force; $F = I B_t l$
- Moment; $M = 2(ad_1 + 3hd_2)/(3(ad_1 + 2hd_2)) \bullet F a$

Figure 3.6 shows the moment as a function of current decay time $\tau_{ex}$ in the case of $B_{p0}$ = 0.8 T (Ip = 21 MA), and $d_1 = d_2$ = 0.5 m. For the typical disruption of ITER with = 2.5 ms, the moment is estimated to be 2.8 × $10^7$ Nm.

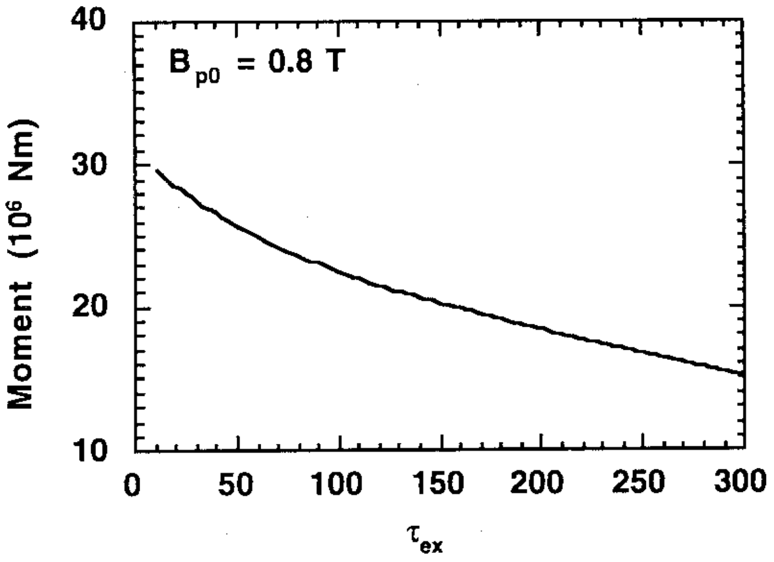


Fig.3.6 Moment as a function of current decay time $\tau_{ex}$.

Also figure 3.7 shows the moment as a function of wall thickness *d* in the case of $B_{p0}$ = 0.8 T (Ip = 21 MA), and $\tau_{ex}$ = 25 ms. If we reduce the wall thickness to be 20 cm or 10 cm from 50 cm, the moment can be reduced 20 % or 35 %, respectively.

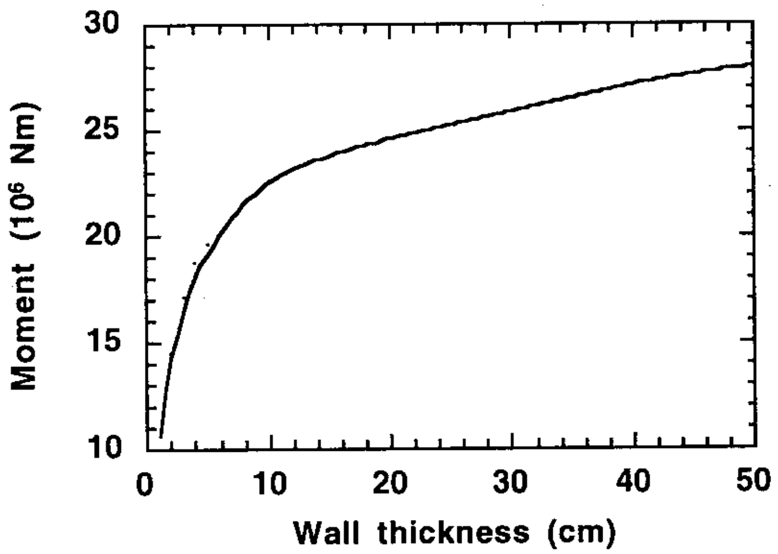


Fig.3.7 Moment as a function of wall thickness.

### 3.3 Collimator, post-shield and neutron beam dump

Figure 3.8 shows the arrangement of the collimator, post-shield and neutron beam dump. The neutron collimator plugs are indebted in the bio-shield. The drawing of the collimator plug itself is shown in Fig. 3.9. Mechanical parameters are as follows;

| | |
|---|---|
| • Outline size | : 500W × 500H × 1500L (mm) |
| • Collimator channel size | : 200W × 20H × 1500L (mm) |
| • Material and Weight | : Stainless steel 316 , 2,800 kg |

Alignment mechanism is thought to be necessary, because the vacuum vessel will expand to major radius direction during the baking and nuclear heating. However it has not been designed yet in this design work.

Mechanical parameters of the post-shield and neutron beam bump are as follows;

| | |
|---|---|
| • Outline size | : 2700W × 14000H × 4700L (mm) |
| • Room size for spectrometer units | : 1700W × 12000H × 2000L (mm) |
| • Cavity size in neutron beam bump | : 1700W × 12000H × 1000L (mm) |
| • Material | : Concrete |
| • Location | : In the pit |

We can access the spectrometer units via shielding door installed on the side of the post shield. The neutron beam dump has large cavity. the wall between the cavity and the spectrometer room has rectangular penetrations sized 400W × 20H (mm) on the axis of each spectrometer unit. Those penetrations are filled by polyethylene to thermalize the incident neutrons. Neutrons passed into the cavity through the penetration will be scattered and slowing down, and absorbed finally within the cavity.

We have not calculated the radiation dose outside of the post-shield, however, we expect that the post-shield can play the roll of the extended bio-shield.

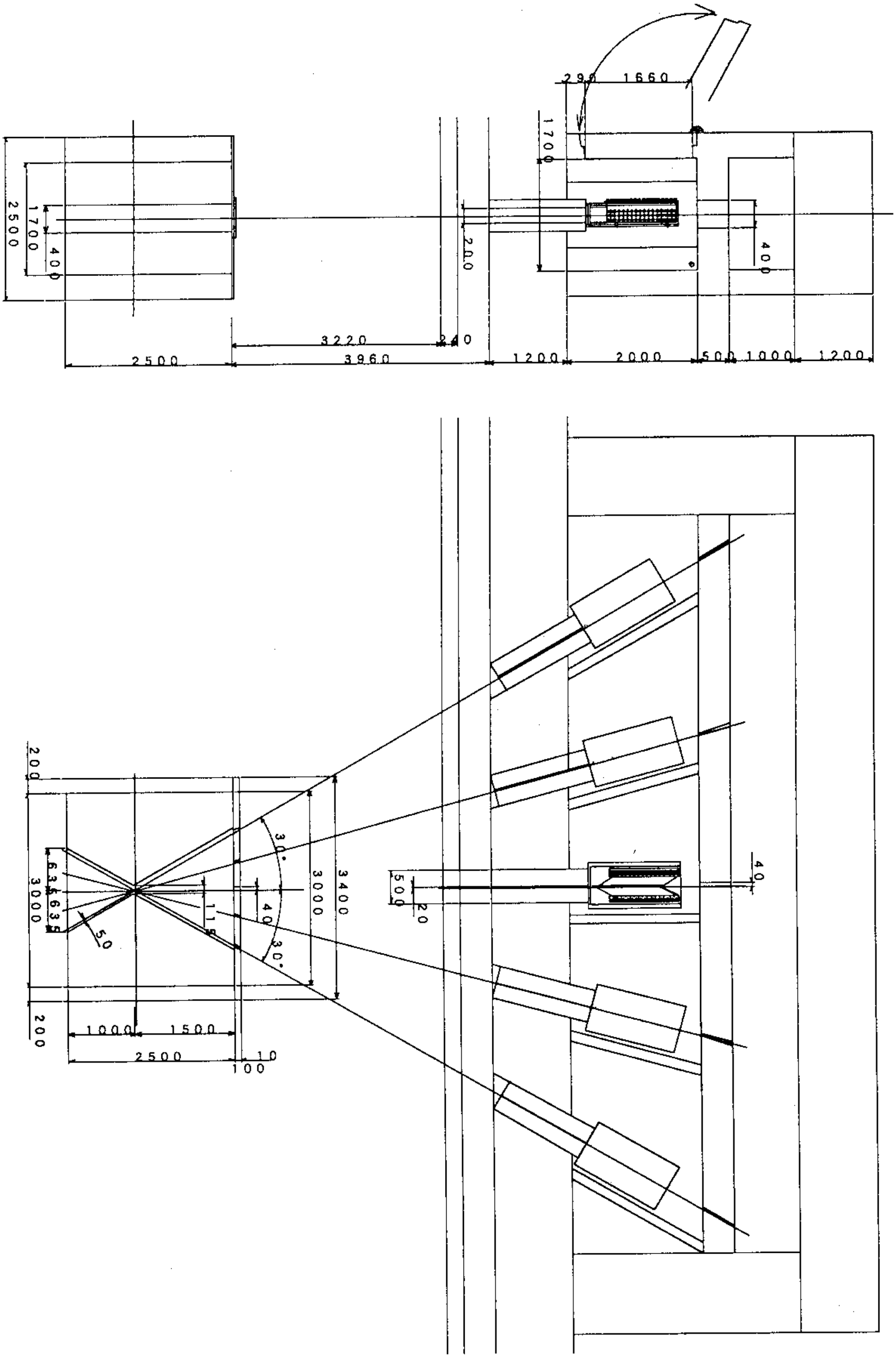


Fig.3.8 Arrangement of the collimator, post-shield and neutron beam dump.

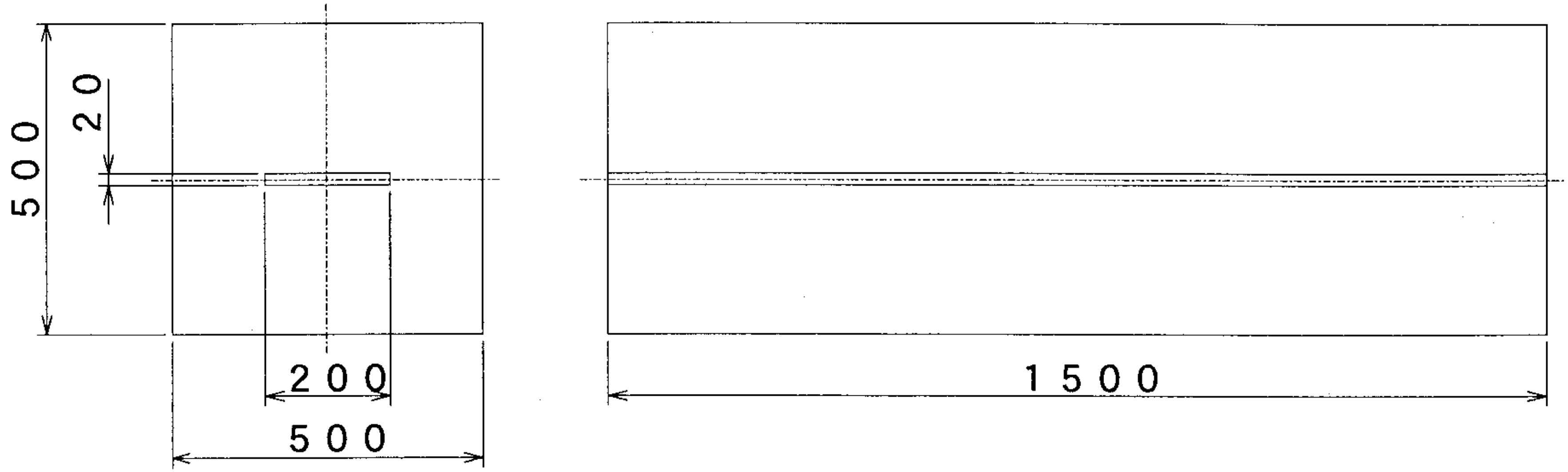


Fig.3.9 Structure of the collimator plug.

### 3.4 Spectrometer unit

We designed the neutron spectrometer unit to satisfy the ITER requirement listed in Table 2.2. We will realize the following performance by employing 96 SBDs as the proton detectors and very thin capillary plates as the micro channel collimator;

- Energy resolution : 2.5 % for 14 MeV neutrons
- Detection efficiency : $1 \times 10^{-5}$ counts/(n/cm$^2$)

Figure 3.10 shows the drawing of the spectrometer unit. One radiator cassette and two detector cassettes are mounted in the vacuum chamber. Mechanical parameters are as follows;

- Outline size : 380W × 740H × 1430L (mm)
- Material and Weight : Stainless steel 316 , 610 kg

Figure 3.11 shows the drawing of the radiator cassette. The cassette is mounted in the vacuum chamber by lock lever, which makes the replacement easy. The precise positioning is made by guide pins. Mechanical parameters are as follows;

- Outline size : 350W × 110H × 1190L (mm)
- Radiator size : 250 mm W × 1080 mm L (mm) × 16 μm thick
- Radiator material : Polyethylene ($CH_2$ density 0.92 g/cm$^3$)
- Flame material : Stainless steel 316
- Total weight : 41 kg

Figure 3.12 shows the drawing of the detector cassette. The cassette contains 48 SBDs and micro channel collimators. The detectors are 15 cm away from the radiator film. The cassette is mounted in the vacuum chamber by lock lever same as the radiator cassette. Mechanical parameters are as follows;

- Outline size : 322W × 240H × 1076L (mm)
- Number of detectors : 48
- Flame material : Stainless steel 316
- Total weight : 65 kg

The performance of the proton detector is

- Detector type : Partial depletion silicon surface barrier diode
- Depletion layer thickness : 500 μm
- Sensitive area : 2000 mm$^2$

Mechanical parameters are as follows;

- Type : Capillary plate (Lead glass)
- Outline size : 1.0 mm thick × 65 mm diam.
- Diameter of capillary area : 60 mm
- Capillary diameter : 40 μm
- Capillary pitch : 45 μm
- Oblique angle : 30°

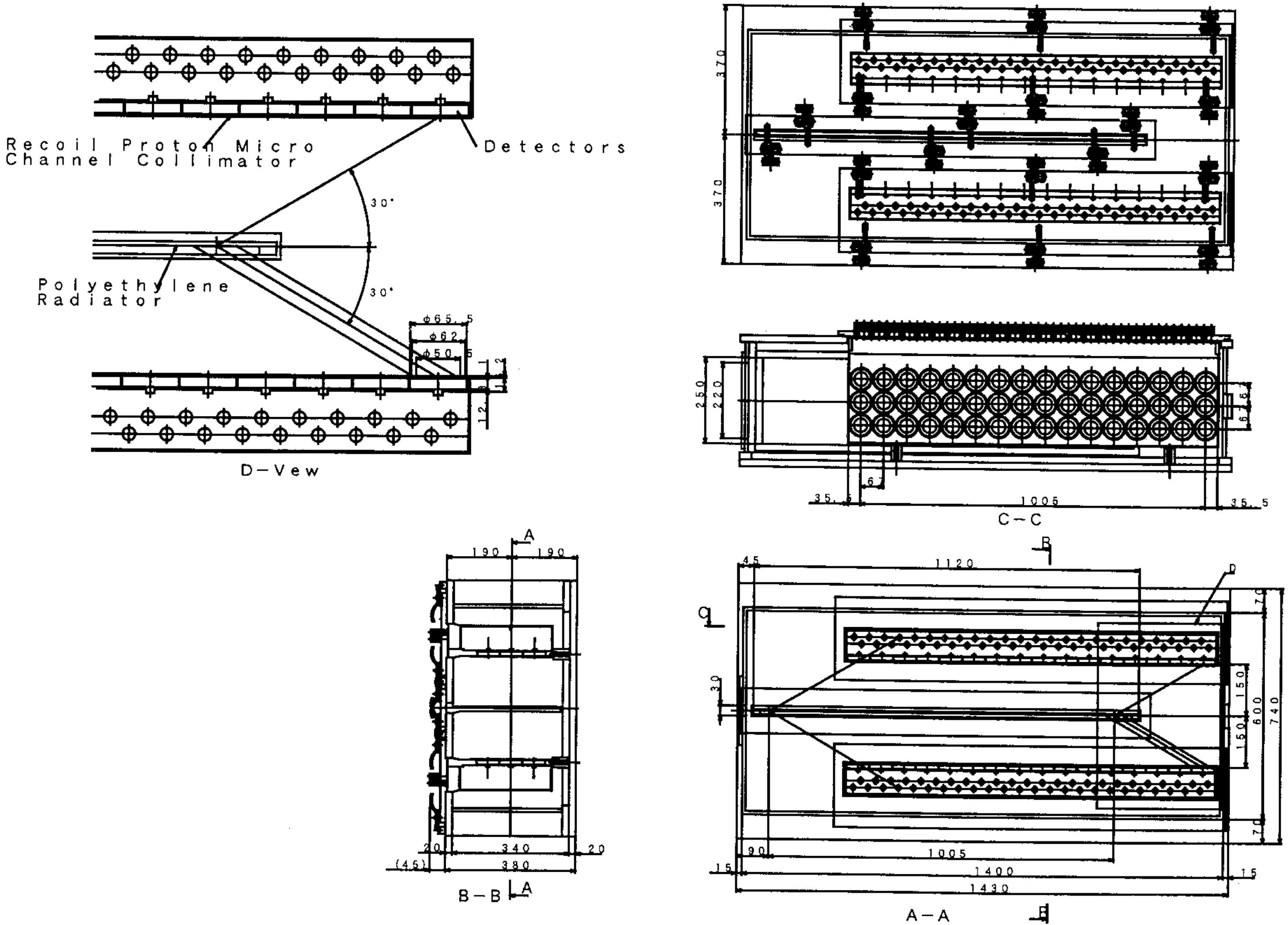


Fig.3.10 Structure of the spectrometer unit.

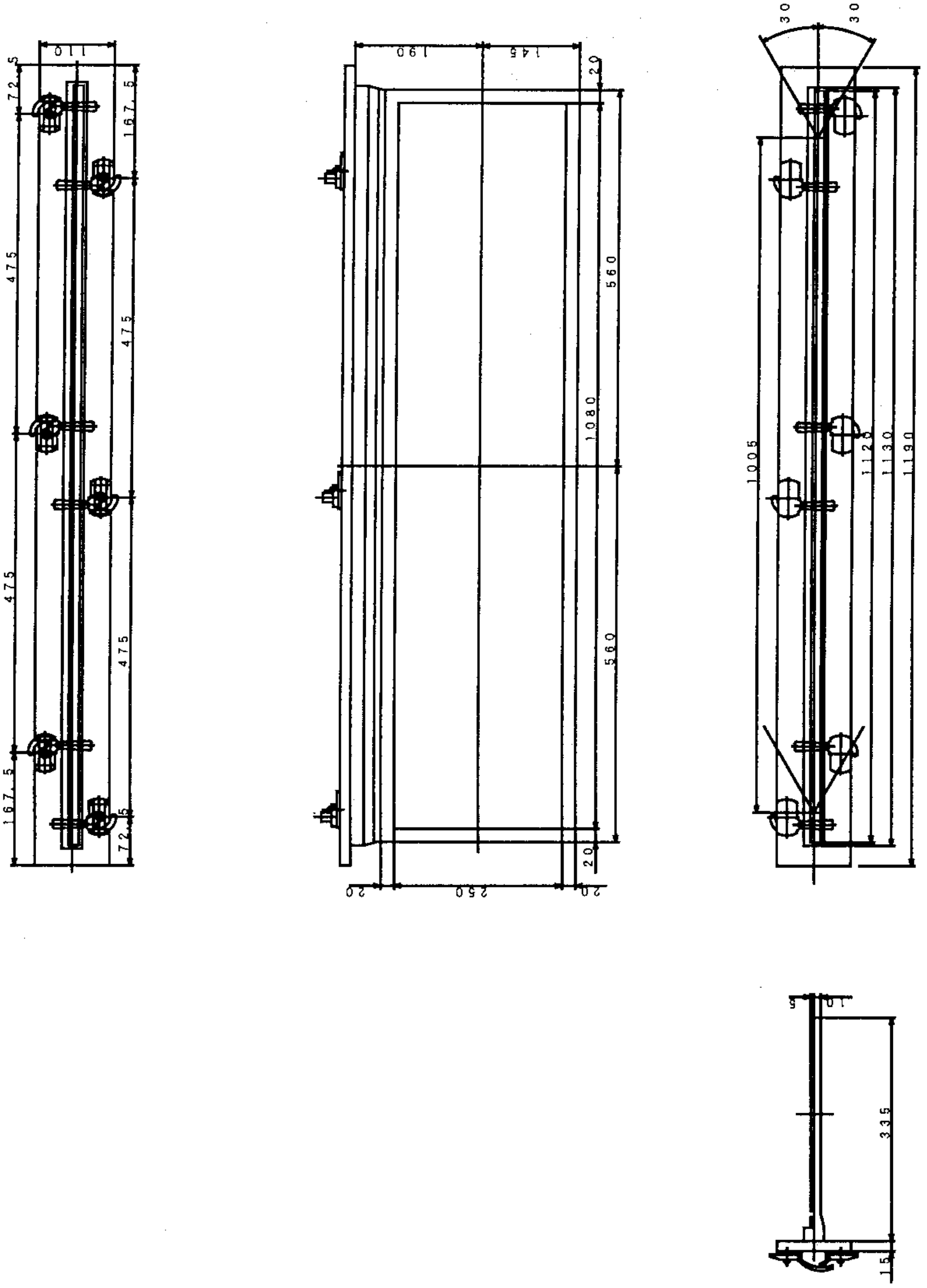


Fig.3.11 Structure of the radiator cassette.

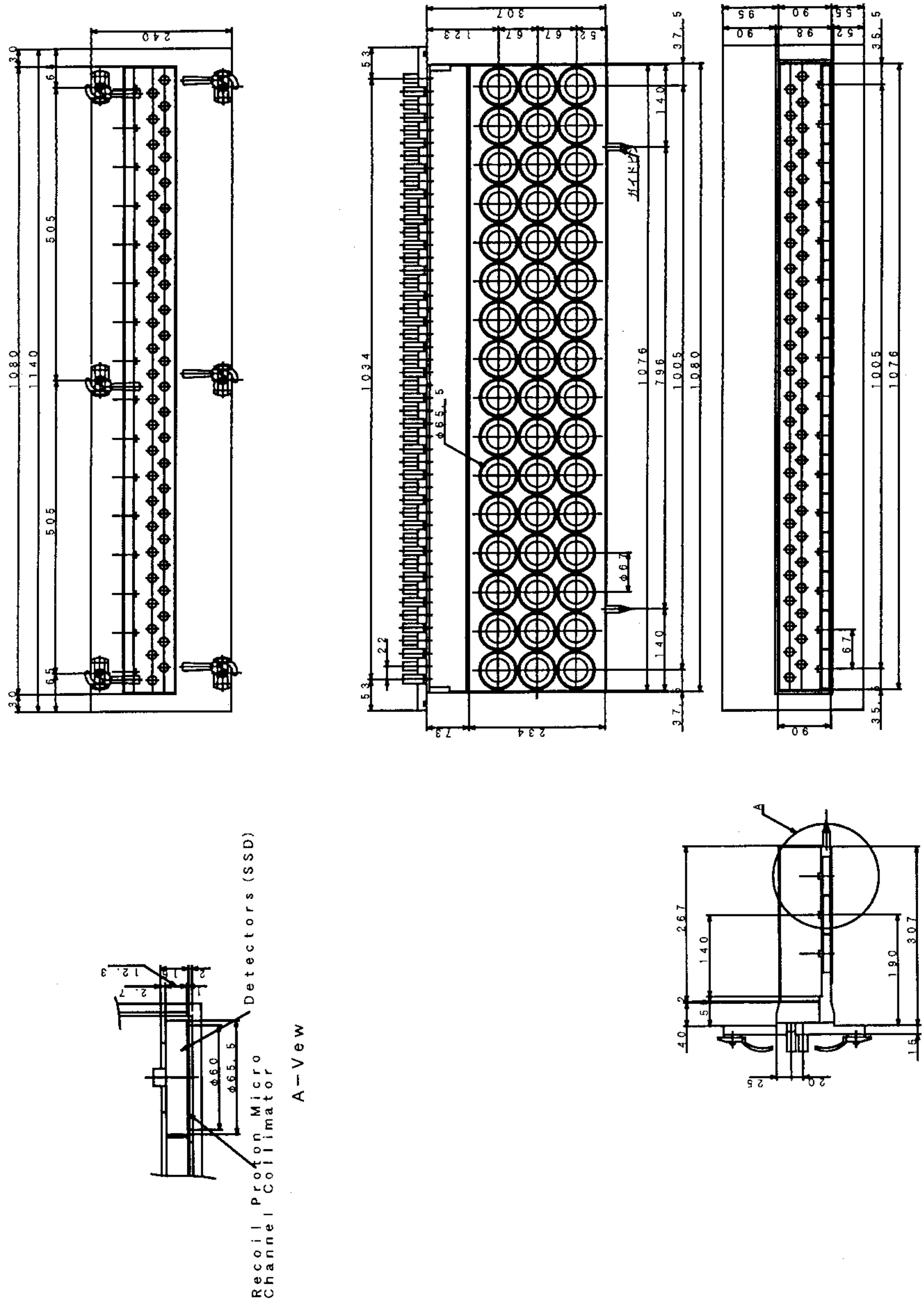


Fig.3.12 Structure of the detector cassette

### 3.5 Electronics and data acquisition system

The concept of the electronics and the data acquisition system is shown in Fig. 3.13. The signals of the SBD detectors are measured by conventional pulse height analysis technique. Those data is collected by a workstation via CAMACs, and transferred to the data processing system. The block diagram is shown in Fig.3.14. The content of the electronics and the data acquisition system is listed in Table 3.1.

Pre-amplifiers should be located as close as possible to the SBD detectors. So the box including 96 pre-amplifiers will be installed in the post-shield or just outside of post-shield in the pit.

Amplifiers, ADCs and other CAMACs will be located in the diagnostics room. Five racks are needed to mount those modules for one spectrometer unit. The outline size of the rack is

- Outline size : 800W × 1200D × 1800H (mm)

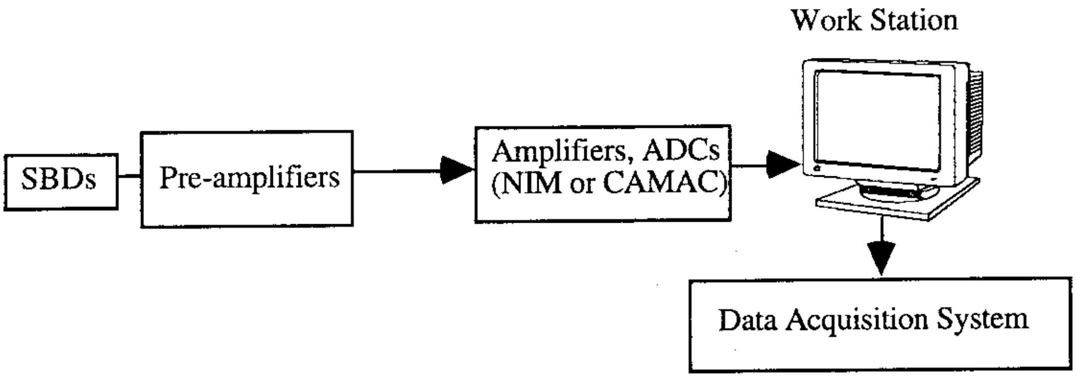


Fig.3.13 Concept of the electronics and data acquisition system.

Table 3.1 Content of the electronics and the data acquisition system including proton detectors for one spectrometer unit.

| Item | Company | Type | The number |
|---|---|---|---|
| Proton detector (SBD) | ORTEC | R-050-2000-500 | 96 |
| Pre-amplifier | CANBERRA | 2003BT | 96 |
| Linear amplifier | CANBERRA | 2022 | 96 |
| A/D converter (ADC) | LeCroy | 3351 | 12 |
| ADC interface | TOYO | 623E | 6 |
| Histogram memory | CES | 2126 | 6 |
| Crete controller | TOYO | CC/7700 | 2 |
| High voltage power supply | LeCroy | 1461P | 8 |
| High voltage controller | LeCroy | 1454 | 2 |
| NIM BIN power supply | TOYO | NB-4100 | 8 |
| CAMAC crate | TOYO | PS-7500 | 2 |
| Pre-amplifier box | | | 1 |
| Rack | | | 4 |

We designed the electronics and the data acquisition system by assembling commercially available electronics in this report, however, integrated electronics modules should be developed for too many detectors in order to save the cost and the space.

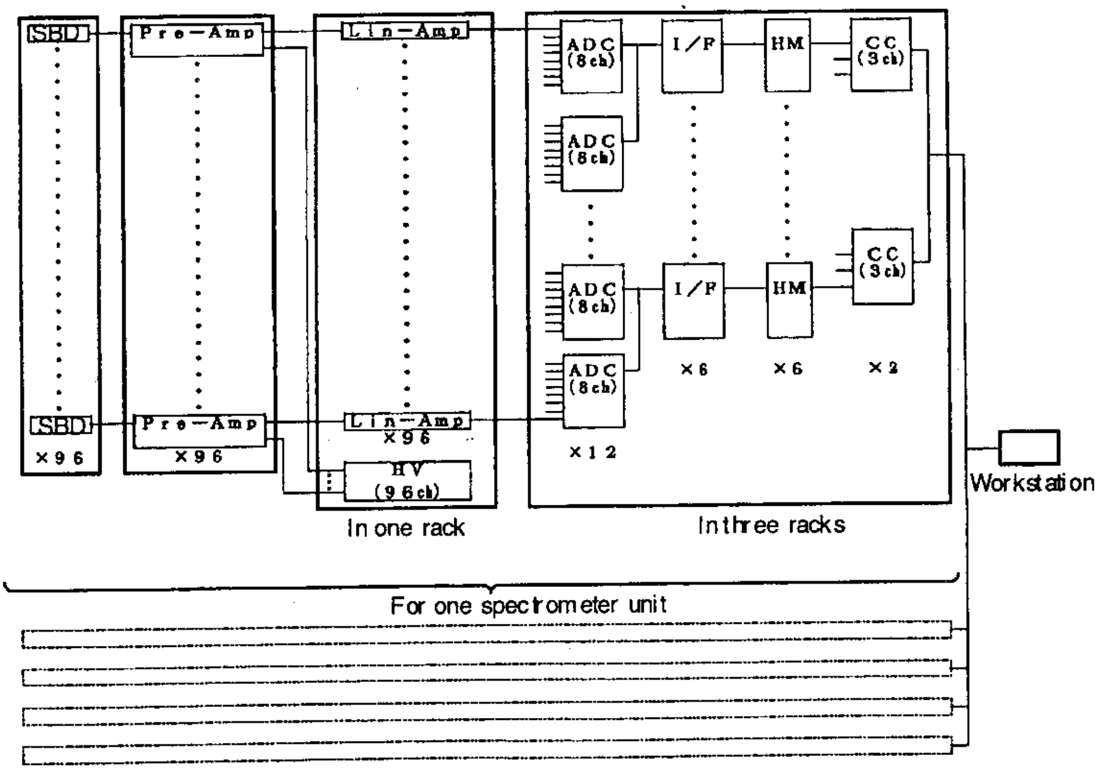


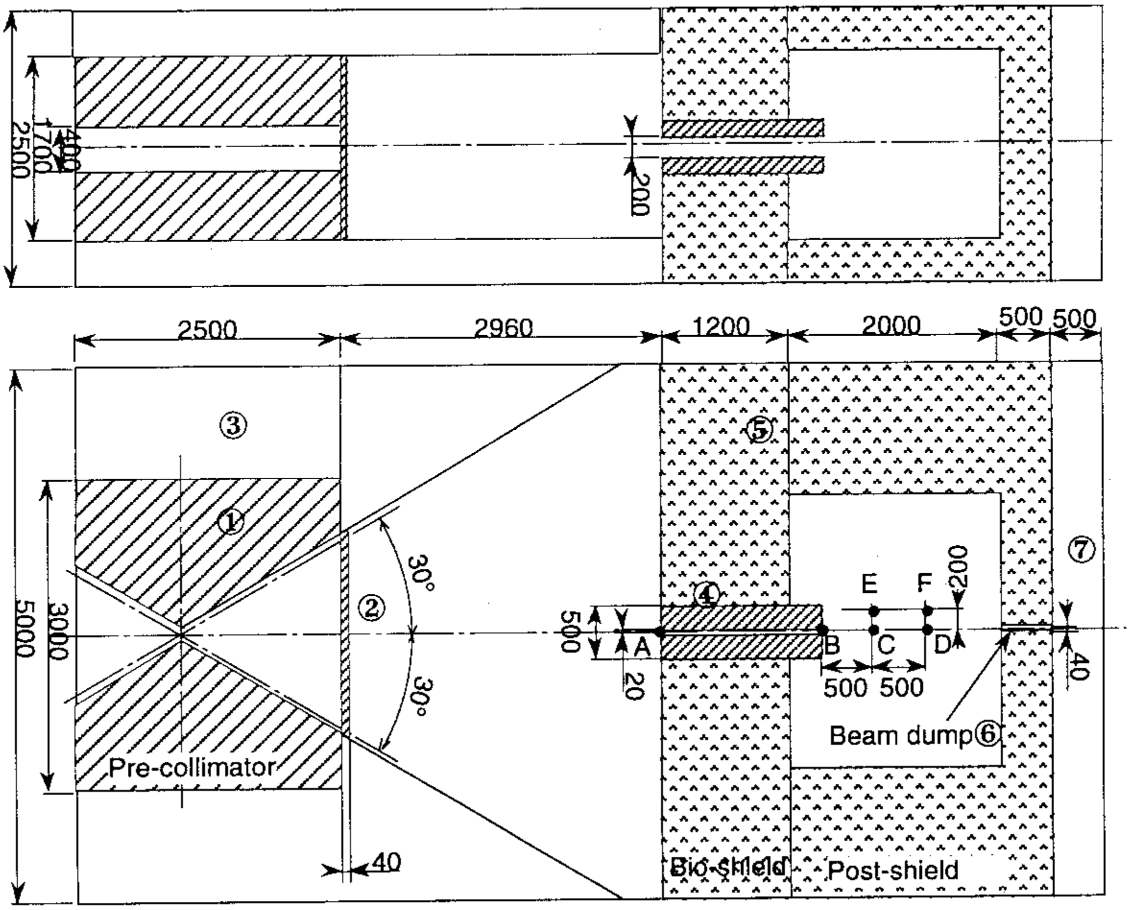
Fig.3.14 Block diagram of the electronics and data acquisition system.

# 4. Neutron transport calculations

In this spectrometer, radiation damaged of the SBDs is most serious problem. because the SBD is sensitive to the radiation induced noises and damages. We expect that the radiation resistance will be ensured by placing the detector at sufficient long distance from the incident neutron beam plane. The shielding performance of a neutron collimator with rectangular cross-section was calculated using the Monte Carlo code MCNP[15] with the neutron cross-section library JENDL-3[16].

## 4.1 Three-dimensional modeling

We made a simplified model for one channel of the neutron spectrometer in order to save the time of the calculation.



| Number | Item | Material |
|---|---|---|
| ① | Pre-collimator | Stainless steel 316 (70%) + Water (30%) |
| ② | Vacuum seal + Cryostat | Stainless steel 316 |
| ③ | Port | Stainless steel 316 |
| ④ | Collimator | Stainless steel 316 |
| ⑤ | Biological shield, Post -shield | Concrete |
| ⑥ | Neutron beam bump | 10% borated polyethylene |
| ⑦ | Air | Air |

Fig.4.1 Three dimensional modeling for MCNP calculation.

Figure 4.1 shows three dimensional modeling for MCNP calculation including Pre-collimator, cryostat, bio-shield, spectrometer and post-shield. The plane neutron source in placed in front of the pre-collimator. Figure 4.2 shows the souse neutron and gamma spectrum calculated by two dimensional neutron transport code DOT 3.5 with the modeling of the plasma, first wall, blankets and diagnostics port. The neutron flux on the front of the pre-collimator is about 70% of that on the first wall.

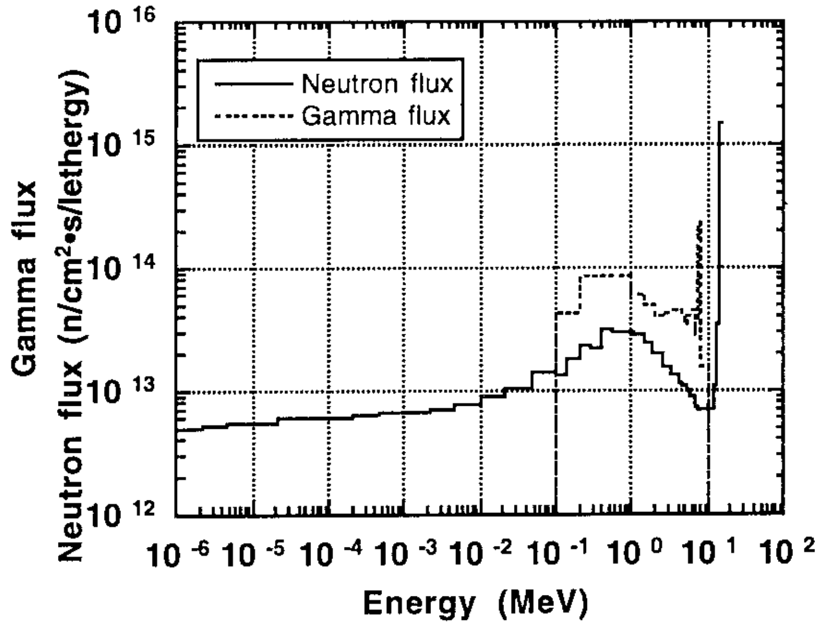


Fig.4.2 Neutron and gamma energy spectra on the front of the pre-collimator.

## 4.2 Neutron flux and spectrum

Figures 4.3 and 4.4 show the neutron and gamma spectrum around the neutron spectrometer. Also Table 4.1 summarizes the neutron flux.

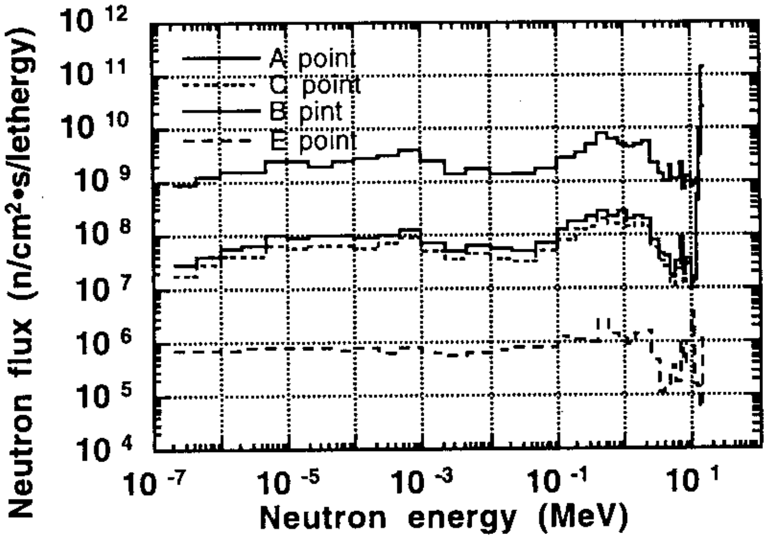


Fig.4.3 Neutron energy spectrum around the neutron spectrometer.

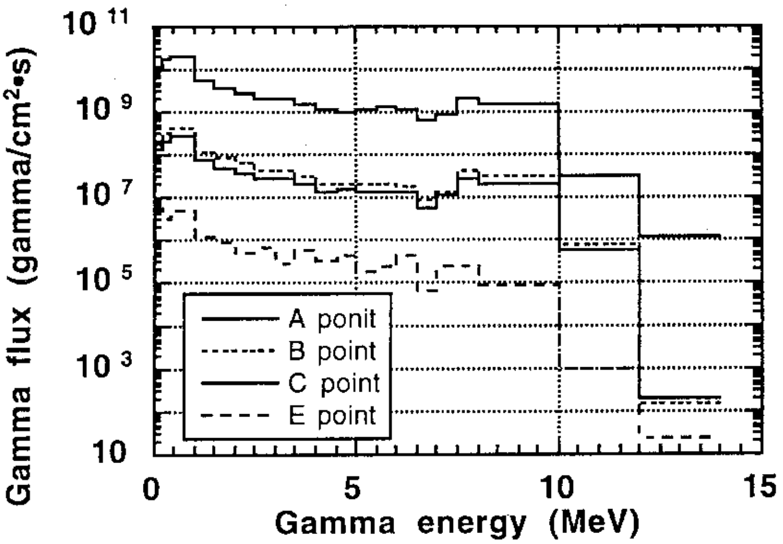


Fig.4.4 Gamma energy spectrum around the neutron spectrometer.

Table 4.1 Neutron flux around the neutron spectrometer.

| | Front of collimator Point A | Back of collimator Point B | On radiator film Point C | At SBD Point E |
|---|---|---|---|---|
| Total neutron | $5.43 \times 10^{10}$ | $4.11 \times 10^{9}$ | $2.83 \times 10^{9}$ | $2.50 \times 10^{7}$ |
| 14 MeV neutron | $1.24 \times 10^{10}$ | $2.29 \times 10^{9}$ | $1.61 \times 10^{9}$ | $1.01 \times 10^{5}$ |
| En > 3 MeV | $1.98 \times 10^{10}$ | $3.55 \times 10^{9}$ | $2.36 \times 10^{9}$ | $1.68 \times 10^{6}$ |
| Total gamma | $8.06 \times 10^{10}$ | $3.50 \times 10^{9}$ | $2.35 \times 10^{9}$ | $4.63 \times 10^{7}$ |

Unit is ($n/cm^2 \bullet s$) for neutron flux and ($photon/cm^2 \bullet s$) for gamma flux.

### 4.3 Estimation of the proton detector life time

When the detector behind the collimator is placed at a distance of 15 cm from the neutron beam plane, the scattered neutron flux above 4 MeV is estimated to be $1.7 \times 10^6$ neutrons $/cm^2 \bullet s$ for the 1 MW $m^{-2}$ neutron wall load operation. Noise of the SBD is produced mainly by Si(n,p) and Si(n,$\alpha$) reactions inside the silicon plate. Threshold energy of those reactions are 4.0 MeV and 2.8 MeV, respectively. We evaluated the Signal to Noise ratio (S/N ratio) from the ratio of the recoil proton counts to Si(n,p) and Si(n,$\alpha$) reaction rate inside the SBD using the calculated neutron spectra at point E. So we obtained,

$$S/N \text{ ratio} \approx 28 \qquad (4.1)$$

The SBD will be damaged mainly by Si(n,p) and Si(n,$\alpha$) reactions, and elastics and inelastic scattering. Those reactions are important for fast neutrons higher than 3 MeV. The operation limit of the SBD is reported to be ~ $10^{12}$ n/cm2 of fast neutron fluence. So the life time of the SBD in this spectrometer is estimated roughly as;

$$\begin{aligned}\text{Life time of SBD} &\approx 10^{12}/1.68\times10^{6} \\ &= 6.0\times10^{5}\ \text{sec} \\ &\approx 2000\ \text{shots of 1 MW m}^{-2}\ \text{neutron wall load operation} \\ &\approx 1\ \text{year in Basic Performance Phase}\end{aligned} \tag{4.2}$$

We found that the SBD can survive about 1 year in the Basic Performance Phase (BPP) of ITER. However, we have to replace SBDs only each three or four months in Extended Performance Phase (EPP). So this spectrometer is rather difficult to use in EPP.

## 5. Maintenance

- The pre-collimator is maintenance free, except coolant leak.
- The collimators in the bio-shield is also maintenance free.
- We can access the spectrometer unit from the pit after operation. Radiation dose rate is expected to be not so high in the pit after operation.
- The detector cassette is replaced each year in BPP and each three or four months in EPP of ITER.
- The radiator cassette is also replaced when it is damaged.
- The pre-amplifier is also replaced when it is damaged. We do not wary about the radiation damages of pre-amplifiers because those will be installed outside of the post-shield of the neutron spectrometer in the pit. Other electronics will be installed in the diagnostics room so that the maintenance of those equipment is easy.

## 6. Space requirement

The space requirement of the radial neutron spectrometer is summarized in Table 6.1.

Table 6.1 Space requirement of the radial neutron spectrometer

| Item | Location | Space size (mm) | The number |
|---|---|---|---|
| Pre-collimator | Horizontal port | 1700W × 2500L × 3000H | 1 |
| Collimator | Bio-shield | 500W × 1500L × 500H | 5 |
| Spectrometer unit | Post-shield | 380W × 1430L × 740H | 5 |
| Post-shield | Pit | 2700W × 4700L × 14000H | 1 |
| Electronics | Diagnostics room | 800W × 1200L × 1800H | 20 |

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## 7. Necessary design work during EDA, and necessary R & D items

- The prototype spectrometer using same components as for ITER should be developed to confirm the performance.

- S/N of ~28 is not so good, we need optimization of the collimator and the beam dump.

- Alignment method of the pre-collimator, collimator and spectrometer including alignment mechanism the collimator should be developed.

- Automatic calibration methods of the proton detector performance should be developed. For example, a standard alpha source will scan all SBDs to check those energy resolution.

- Calibration methods of the viewing field, energy resolution, absolute detection efficiency should be developed.

## Acknowledgments

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