Chapter 5

Applicability of the Neutron Spectrometer to ITER

This chapter describes the optimization of the design configurations of the neutron spectrometer for the fuel ratio monitoring in the burning plasma presented for an application to ITER. The system characteristics such as measurement accuracy and time resolution depend on the installation site as well as the design parameters that are represented in Fig. 4.1. The installation site and system configurations have been considered according to the Monte Carlo simulations. The expected performances and applicable range in the ITER experiments are also discussed.

5.1 Measurement accuracy and time resolution of fuel ratio monitoring

The counting statistical uncertainty of the intensity ratio for DD/DT neutron r is derived from

$$\frac{\sigma_r}{r} = \sqrt{\left(\frac{\sigma_{S_{\mathrm{DD}}}}{S_{\mathrm{DD}}}\right)^2 + \left(\frac{\sigma_{S_{\mathrm{DT}}}}{S_{\mathrm{DT}}}\right)^2} \quad , \tag{5.1}$$

$$r = \frac{S_{\mathrm{DD}}}{S_{\mathrm{DT}}} , \tag{5.2}$$

where $\sigma_{S_{\mathrm{DD}}}$ and $\sigma_{S_{\mathrm{DT}}}$ are counting statistical uncertainties of the DD neutrons and DT neutrons, S_{DD} and S_{DT} are signal counts of the DD neutrons and DT neutrons, respectively. In a statistically poor situation for the DD neutrons,

$$\frac{\sigma_r}{r} = \frac{\sigma_{S_{\mathrm{DD}}}}{S_{\mathrm{DD}}} \quad , \tag{5.3}$$

can be used to estimate counting statistical uncertainty of r, because $\frac{\sigma_{S_{\mathrm{DT}}}}{S_{\mathrm{DT}}}$ is much smaller than $\frac{\sigma_{S_{\mathrm{DD}}}}{S_{\mathrm{DD}}}$. Signal ($S_{\mathrm{DD}}$) is derived from Equation (5.4) with a gross count (C_{G}) and a background count (C_{B}) for measurement time of Δt.

$$S_{\mathrm{DD}} = C_{\mathrm{G}} - C_{\mathrm{B}}, \tag{5.4}$$

C_{G} is a total count involving C_{B}, which will be obtained over the energy region of DD neutron. C_{B} is given by the following two factors. The first factor is the down scattering component of neutron spectrum B_{d} due to the Wall Emission. The second is an accidental count B_{a} that is expected in the actual ITER measurement. Radiation intensity at the detector site strongly depends on peripheral devices and a beam dump structure. The radiation field behind the ITER RNC is roughly mocked up by the accelerator DT neutron source with a thick neutron collimator made of stainless steel in the Fusion Neutronics Source (FNS) facility, JAEA. The accidental count B_{a} in the ITER site would be preliminary predicted by a linear extrapolation of the accidental count obtained in the FNS facility. The FNS, however, has much less backscattered radiations than those expected in ITER experiments, because the ITER plasma is a volume neutron source not a point source, and the ITER machine will be surrounded by large devices and thick biological shields by which a lot of secondary γ-rays would be induced. The estimation of B_{a} needs any further compensation considering the intensity of backscattered radiations in the ITER machine. Therefore, C_{B} is written as follow.

$$C_{\mathrm{B}} = B_{\mathrm{d}} + kB_{\mathrm{a}}. \tag{5.5}$$

Here, k is a correction factor, which compensates the differences of the intensity of scattered radiations between the ITER machine and the FNS facility.

The ultimate accuracy of the fuel ratio monitoring R with time resolution of Δt is given by

$$R = \sqrt{\left(\frac{\sigma_{S_{\mathrm{DD}}}}{S_{\mathrm{DD}}}\right)^2}$$
$$= \sqrt{\frac{C_{\mathrm{G}} + C_{\mathrm{B}}}{\left(C_{\mathrm{G}} - C_{\mathrm{B}}\right)^2}}$$
$$= \sqrt{\frac{C_{\mathrm{G}} + (B_{\mathrm{d}} + kB_{\mathrm{a}})}{\left(C_{\mathrm{G}} - (B_{\mathrm{d}} + kB_{\mathrm{a}})\right)^2}} \quad . \tag{5.6}$$

Time resolution under the required accuracy of 20% is the most interesting parameter for the design consideration of the present system. Equation (5.7) preliminarily predicts the expected time resolution of the fuel ratio monitoring with 20% accuracy and has been used as a figure of merit for the design consideration discussed in section **5.3**.

$$\Delta t = \frac{c_{\mathrm{G}} + (b_{\mathrm{d}} + kb_{\mathrm{a}})}{0.04\left(c_{\mathrm{G}} - (b_{\mathrm{d}} + kb_{\mathrm{a}})\right)^2} \quad , \tag{5.7}$$

where c_{G} is the gross count rate, b_{d} and b_{a} are the count rates of the background due to down scattering of the DT neutron and the accidental counts, respectively.

5.2 Installation position of this system and neutron spectrum

This system will be installed in the center chord of the ITER RNC [1]. The neutron flux coming from the center chord of the RNC has been calculated by a Monte Carlo simulation cord MCNP-4C2 [2] with the ENDF/B-VI neutron data library. The MCNP model is shown in Fig. 5.1. This model has a full torus shape, which includes a Vacuum vessel, First wall, Blanket, Toroidal field coils, Poroidal field coils, Central solenoid coil, Equatorial ports, Upper port plug, Lower port plug and Biological shield. A neutron source with Gaussian energy distribution (FWHM 420 keV for 14.1 MeV and FWHM 195 keV for 2.45 MeV) is distributed with a parabolic profile at the torus center in front of the aperture of the RNC center chord, diameter of the aperture is 5 cm. The source profile was assumed as Equation (5.8).

$$S=\left(1-\frac{r^2}{a^2}\right)^m , \tag{5.8}$$

where a stands for the plasma minor radius and m is power of the parabolic profile. The poroidal cross section of this source profile is a circle, whereas the actual ITER plasma has an elliptic profile. This calculation employed a = 2.0 m and m = 0.8. The neutron flux along with the line of sight of the collimator decreases as shown in Fig. 5.2.

The installation position was determined according to the discussions and circumstances in the research activities on the ITER plasma diagnostics. The report on a neutron transport analysis based on Monte Carlo simulations was submitted, and it claims that intensity of down-scattered neutron, which is a significant obstacle of the DD neutron detection, is relatively low at a position 10 m or more away from the plasma core [3]. Because of its poor detection efficiency, a higher neutron flux is preferable to make the time resolution as good as possible, which means the present system should be incorporated as close to the plasma as possible, as far as event rate of the scintillators is acceptable for the signal processing circuit. The spatial restriction in the ITER machine and RNC practically dominates the installation position, and it has been decided that this system will be placed 10 m away from the plasma core in the center chord of the RNC.

The estimation of the applicability to ITER needs the actual neutron spectrum at the center chord of the ITER RNC in the DT phase. The energy spectrum of neutrons at this position has also been calculated by MCNP-4C2 with ENDF/B-VI neutron data library. Figure 5.3 shows a typical neutron spectrum in the ITER full power operation. The generation ratio of DD/DT neutron at the plasma is 0.50%, which corresponds to a fuel ratio n_D/n_T equal to 1. The neutron spectra with other generation ratios of DD/DT neutron have been prepared in order to estimate an applicable range of the present system.

5.3 Design consideration of this system and performance evaluation

5.3.1 Design consideration

As shown in Fig. 4.1, this system consists of a radiator, a first detector and roundly distributed a few tens of second detectors. Scattering angles θ_1 and θ_2 of around 40 degree are appropriate for this system as described in section **4.4.1**. The design parameters of this system to be considered here are radiator thickness d_1, the first flight path FL_1 and the second flight path FL_2. The results of consideration are described below.

I Radiator

Figure 5.4 shows the calculated results of the intensity ratios of DD/DT neutron that enter the first detector after scattering by the radiator. The neutron intensity ratio decreases as d_1 increases, while the efficiency of the DD neutron that comes into the first detector increases. An efficiency of the DD neutron at the first detector more than 10^{-4} is preferable for this system to have a sufficient counting efficiency for realization of the required accuracy. Therefore, a 2 cm-thick and 3 cm-diameter water cell has been employed for the radiator.

II Flight paths

The energy spectra of neutrons that come to the first detector after scattering with the radiator are presented in Fig. 5.5, these spectra has been calculated by MCNP-4C2 with ENDF/B-VI neutron data library based on the original incident spectrum calculated in section **5.2**. The candidates that were taken for FL_1 are 10, 15, 20, 25 and 30 cm, while the survey range on FL_2 is 130 to 220 cm. A much longer flight passes lead to a lack of detection efficiency, and shorter ones results in a poor energy resolution or SNR. As mentioned in section **5.1**, the expected time resolution of the fuel ratio monitoring Δt given by Equation (5.7) was used as a figure of merit that indicates the expected system performance for each design parameter. Figures 5.6 and 5.7 present the simulated results on Δt for flight passes FL_1 and FL_2, respectively. It has been found that FL_1 of 15 cm and FL_2 of 170 cm are suitable.

5.3.2 Evaluation of detector response

The results of considerations on design parameters are listed in Table 5.1, the system configuration obtained here is shown in Fig. 5.8. The intrinsic energy resolution of this system is 34% for DD neutron, 37% for DT neutron. The detection efficiencies of $(6.79\pm0.03)\times10^{-5}$ cm^2 and $(6.11\pm0.06)\times10^{-6}$ cm^2 are expected for DD and DT neutron, respectively. Figure 5.9 presents the calculated time spectrum, which is expected for the proposed system in the full-power ITER operation. The generation rate of DD/DT neutron in the calculation is 0.50%, which corresponds to a fuel ratio of $n_D/n_T=1$ and is a typical condition in the ITER full power. A contribution of DD neutron can be observed in 120-150 ns region.

5.4 Applicability to ITER

5.4.1 Time resolution

The expected time resolution in the full power ITER operation (500 MW) has been evaluated by Monte Carlo calculations in Fig. 5.10 according to Equation (5.7). In this calculation, the generation ratio of DD/DT neutron is fixed at 0.50%, which corresponds to $n_D/n_T=1$ in the plasma. As mentioned in section **5.1**, the accidental count rate in the actual measurement depends on a beam dump structure, and is predicted with the correction factor *k* based on the accidental count rate that has been encountered in the basic experiment at the FNS facility. The time resolution of 8.5 s will be realized at most for *k*=1, which is acceptable for the compensation of the fuel ratio at the plasma core, because the ITER plasma shot is a few hundred seconds or longer [4]. In the situation with the larger *k*, a longer sampling time will be needed, because the monitoring system will be exposed to a lot of backscattered radiations. In other words, control of backscattered radiation flux at the actual detector position must be important to satisfy the required accuracy or sufficient time resolution.

5.4.2 Dynamic range

The expected time resolution in the reactor power region of 50-500 MW, has been evaluated in Fig. 5.11 using Equation (5.7) under the required measurement accuracy of 20%. This system is not applicable to the region of 50 MW power, because a time resolution of a few hundred seconds is needed at present. The dynamic range of this system mostly depends on the neutron generation rate or the intensity of the neutron beam. Therefore improvement of detection efficiency is the most promising way to extend the applicable range of this system. Another way for the extension of the applicable range is optimization of the beam dump structure that crucially affects the intensity of backscattered radiation at the detector position.

A carefully designed beam dump would decrease the intensity of background radiation well.

Detector responses to neutron beams with DD neutrons of lower intensities have been estimated in Fig. 5.12. The necessary time resolutions to achieve a measurement accuracy of 20% have been calculated with a Monte Carlo method. The energy spectra of the incident neutron with the different generation ratios of DD/DT neutron other than 0.50%, which were calculated in section **5.2,** have been used for this calculation. As the generation ratio of DD/DT neutron decreases, this means that the fuel ratio n_D/n_T in the plasma decreases, a longer sampling time will be required to keep an accuracy of 20%. If $k \leq 2$ can be sustained, a time resolution of better than 100 s will be secured for the situation with the generation ratio of DD/DT neutron 0.30%. For the much larger *k*, the expected time resolution will be a few hundred seconds in the same situation. Reduction of backscattered radiations is also important here at a situation with a poor DD neutron intensity.

5.5 Summary

Design consideration on the proposed TOF neutron spectrometer for the fuel ratio monitoring in the ITER plasma core has been made through the Monte Carlo simulations. The applicability of this system to the ITER upper-power region is also estimated. This system will be placed 10 m away from the plasma core in the center chord of the ITER RNC. The expected neutron energy spectrum at this position has been calculated by the MCNP-4C2 and ENDF/B-VI neutron cross section data library and used for the design consideration on this system to optimize the system configurations. The measurement accuracy and time resolution depend on the signal count of the DD neutron and background count mainly due to the down scattered DT neutron. In addition, the accidental count of the TOF method, which will be caused by other radiations as well as neutrons, is another background factor. The accidental count in the actual detector location has been predicted based on that of the basic experiment at the FNS facility. Through the survey calculations on the design parameters of this system that dominate energy resolution and detection efficiency, the system configuration has been optimized in terms of time resolution under the required measurement accuracy of 20%. The proposed system is expected to achieve the required 20% accuracy with a time resolution of 8.5 s at most in a measurement of DD neutron with the intensity ratio of 0.50% at the ITER full power operation. This system has promising potential as a monitoring system of the fuel ratio in the ITER high-power-operation phase. At the 1-order-lower-power phase, because of the lack of signal count due to a poor incident neutron flux, the time resolution of a few hundred seconds will be necessary to secure the 20% accuracy.

References

[1] L. C. Johnson, Cris W. Barnes, P. Batistoni, C. Fiore, G. Janeschitz, V. Khripunov, A. Krasilnikov, F. B. Marcus, T. Nishitani, G. Sadler, M. Sasao, V. Zaveriaev and the ITER Joint Central Team and Home Teams, "Analysis of neutron cameras for ITER", Rev. Sci. Instrum. **70**, 1145 (1999).

[2] J. F. Briesmeister, Ed., MCNP-A general Monte Carlo code for neutron and photon transport version 4C, LANL Report, Los Alamos National Laboratory, LA-13709-M (2000).

[3] K.Okada, K. Kondo, S. Sato, T. Nishitani, K. Nomura, A. Okamoto, T. Iwasaki, S. Kitajima and M. Sasao "Development of neutron measurement system for n_d/n_t fuel ratio measurement in ITER experiments", Rev. Sci. Instrum. **77**, 10E726 (2006).

[4] ITER-Final Design Report, IAEA (2001) (unpublished).

Figures and tables

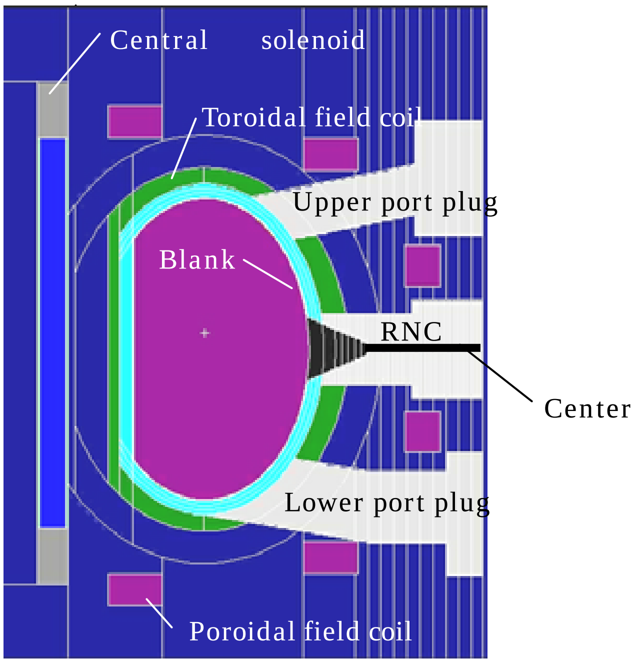

Fig. 5.1 MCNP model to calculate neutron spectra coming from the center cord of RNC.

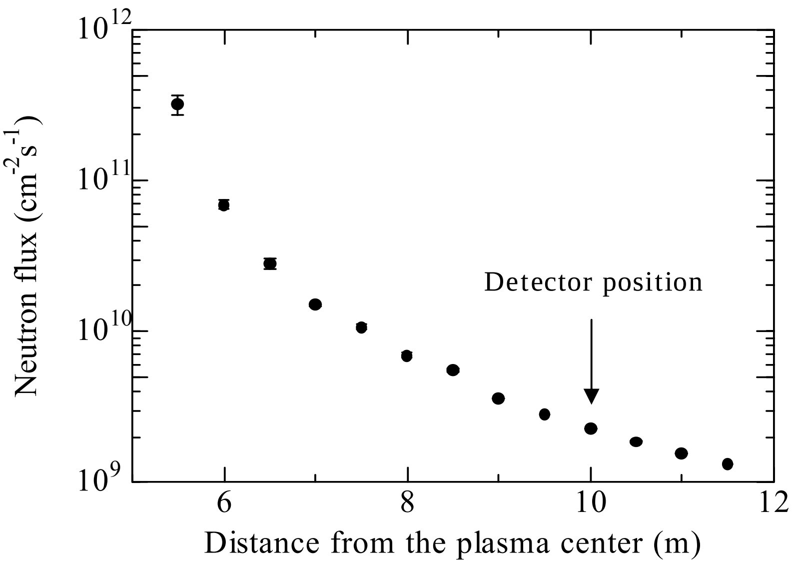

Fig. 5.2 Neutron flux in the line of sight of the RNC center chord (500 MW).

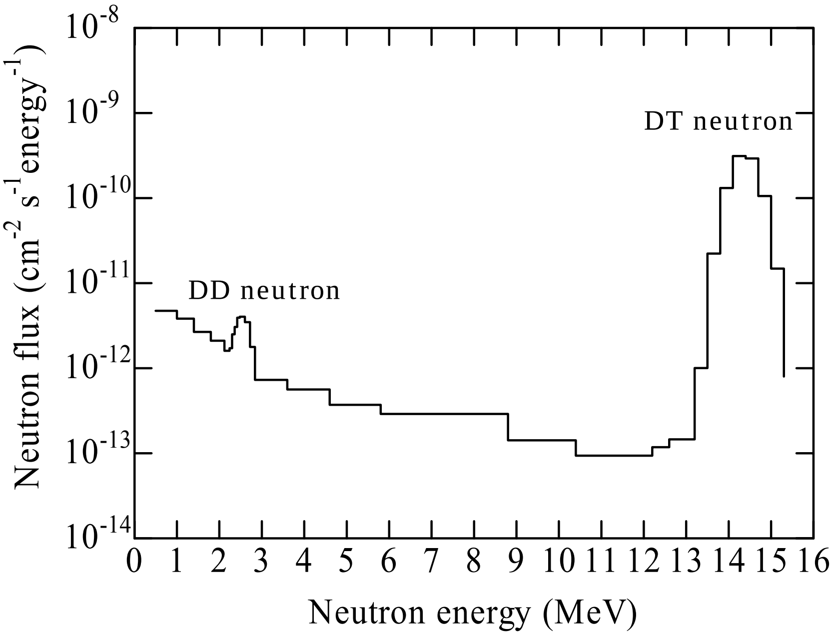

Fig. 5.3 Calculated energy spectrum at 10 m away from the plasma core in the line of sight of RNC center chord (500 MW).

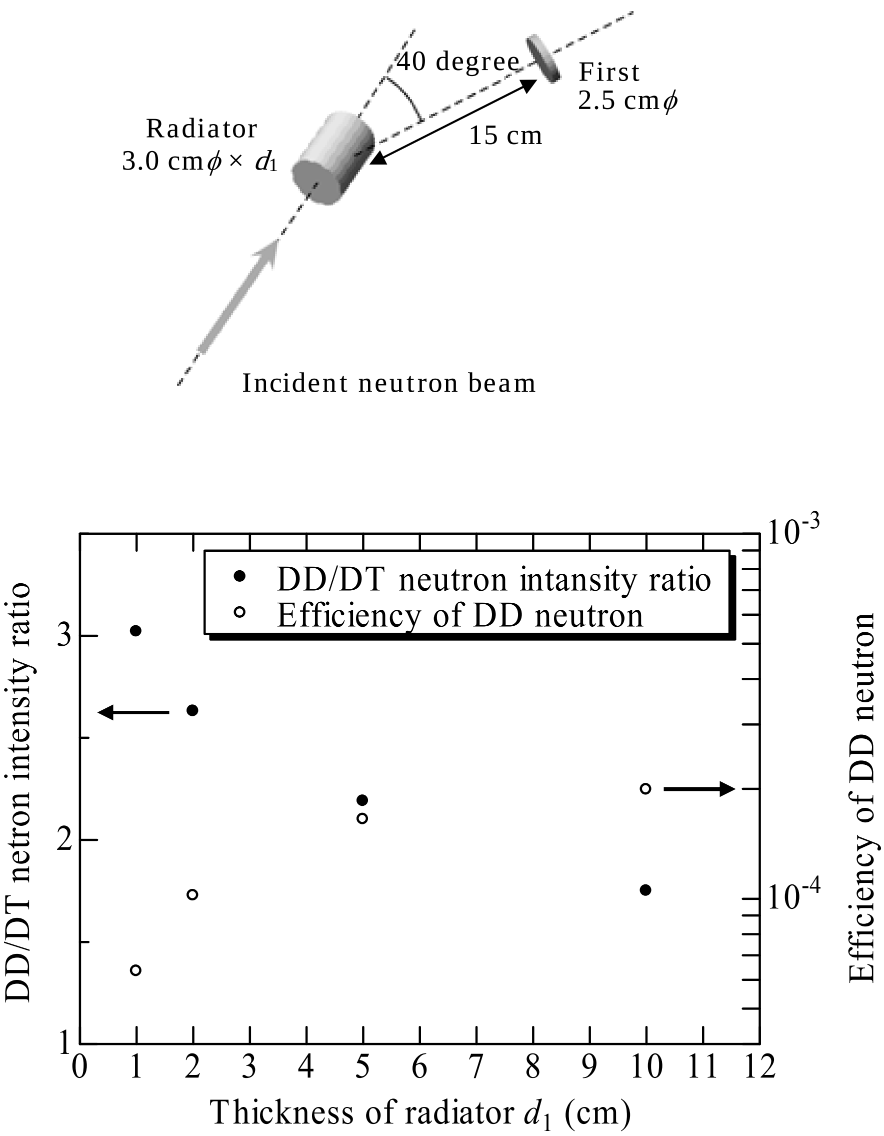

Fig. 5.4 DD/DT intensity ratio of scattered neutrons incoming to the first detector and width of DD neutron peak (FWHM) calculated by MCNP-4C2 with ENDF/B-VI neutron data library.

Diameter of the water cell is 3.0 cmϕ. The calculation point is 15 cm behind the water cell in a direction of 40 degree from the incident beam line.

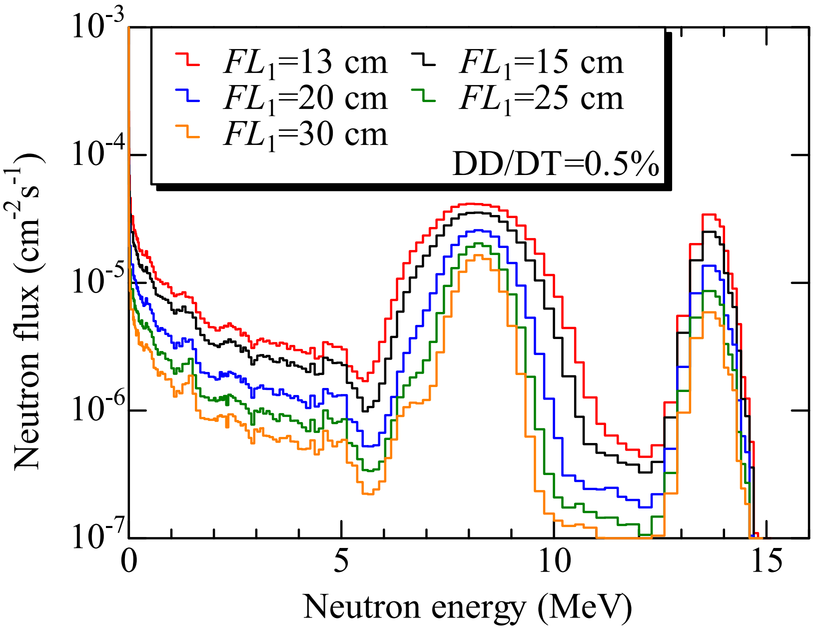

Fig. 5.5 Energy spectra of the scattered neutrons incoming to the first detector after scattering with the radiator. The diameter and the thickness of the radiator are 3.0 cmϕ and 2.0 cmt, respectively.

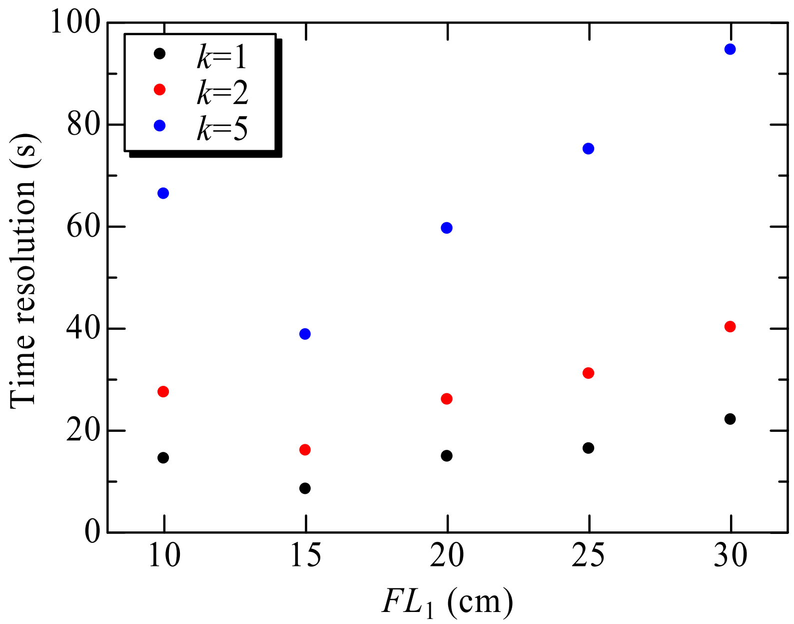

Fig. 5.6 Consideration on the first flight path FL_1.

The vertical axis is the expected time resolution for a measurement of the intensity ratio of DD/DT neutron, which has been derived from Equation (5.7). FL_1=15 cm is appropriate.

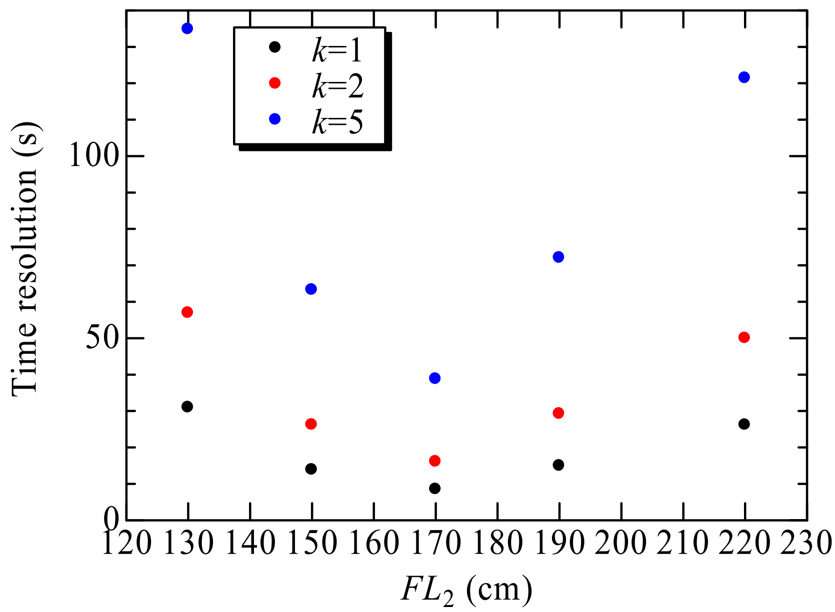

Fig. 5.7 Consideration on the second flight path (FL_2).

The vertical axis is the expected time resolution for measurement of the intensity ratio of DD/DT neutron, which has been derived from Equation (5.7). FL_2=170 cm is appropriate.

Table 5.1 Design results of this system.

Design Parameter		
Detector location from the plasma core		10 m
Radiator	ϕ	3.0 cm
	d_1	2.0 cm
First detector		
Distance from the radiator	FL_1	15 cm
First scattering angle	θ_1	40 degree
Schintillator size	ϕ_1	2.5 cm
	t_1	2.5 cm
Second detector		
Distance from the first detector	FL_2	170 cm
Second scattering angle	θ_2	40 degree
Schintillator size	ϕ_2	12 cm
	t_2	10 cm
Total number of the second detectors		50

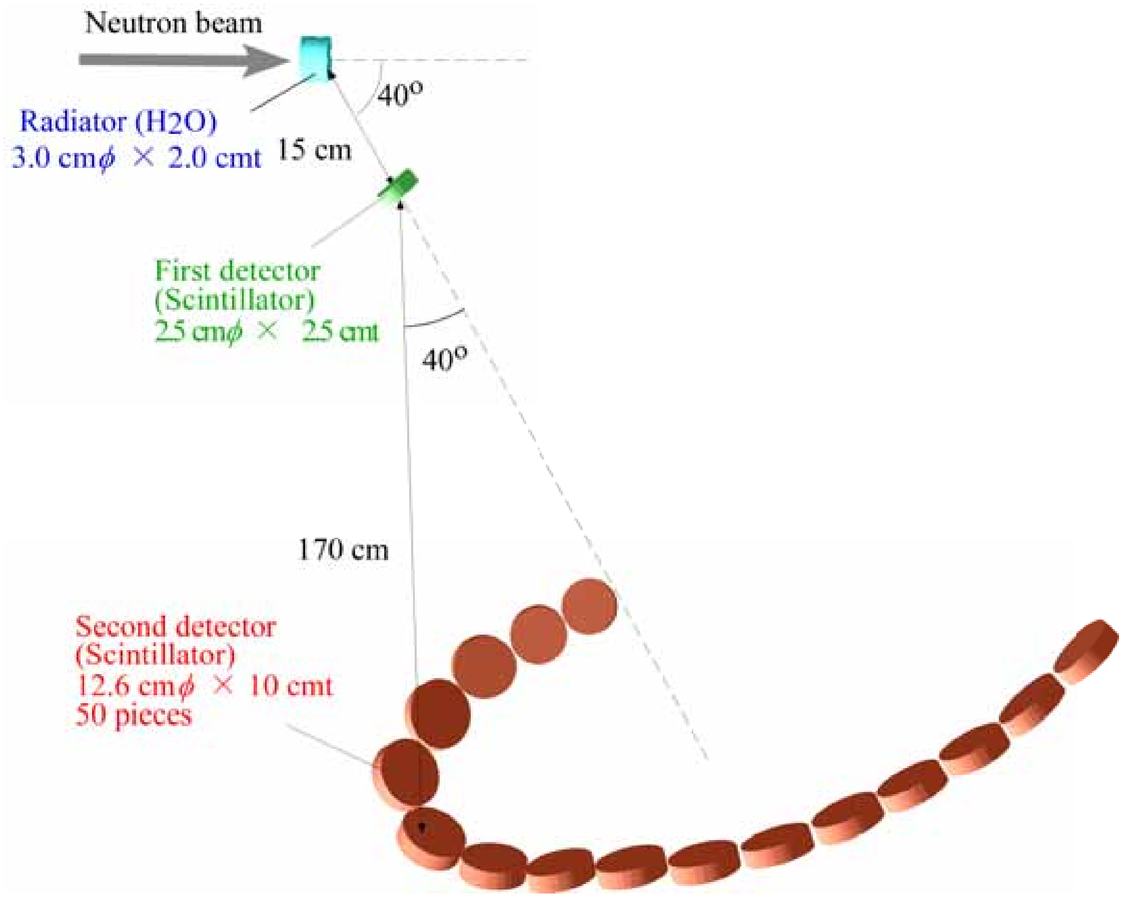

Fig. 5.8 Optimized system configuration for an application to ITER.

50 pieces of second detectors are distributed roundly.

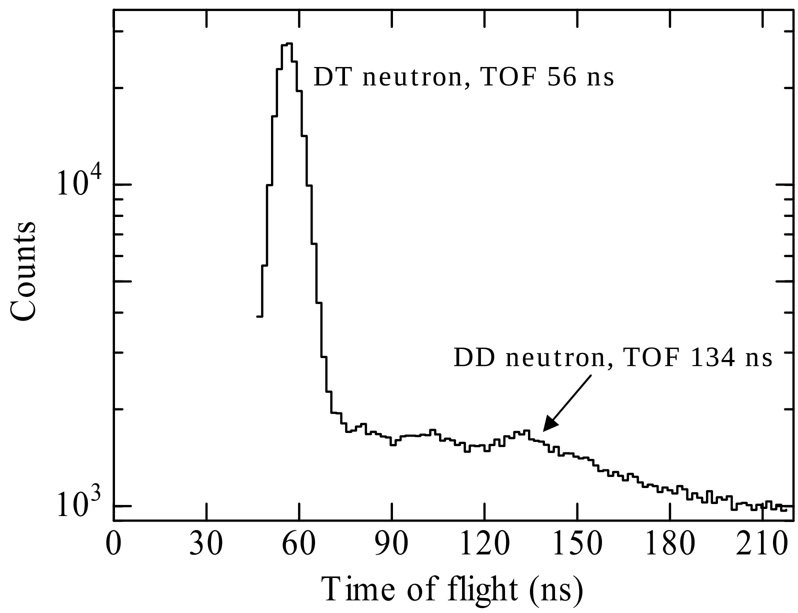

Fig. 5.9 Calculated detector response of this system with the optimized configuration presented in Fig. 5.8.

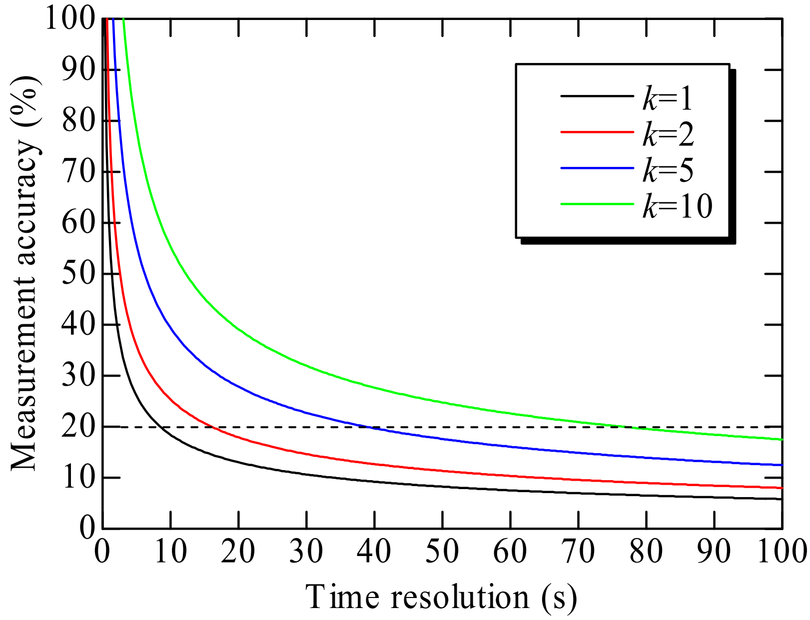

Fig. 5.10 The expected time resolution at the full power operation (500 MW).
The vertical axis has been derived from Equation (5.6). The original neutron generation ratio (DD/DT) is fixed at 0.50% throughout this evaluation.

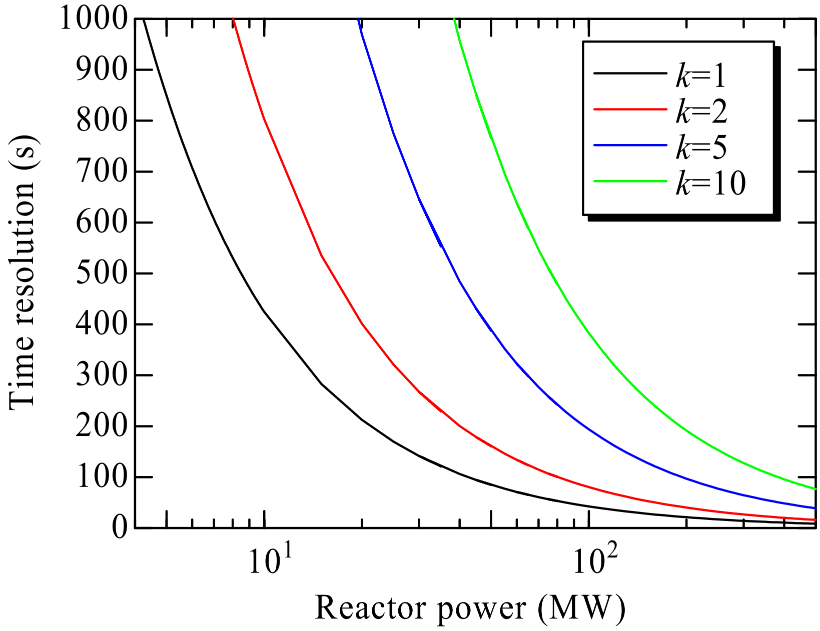

Fig. 5.11 The expected dynamic range of this system.

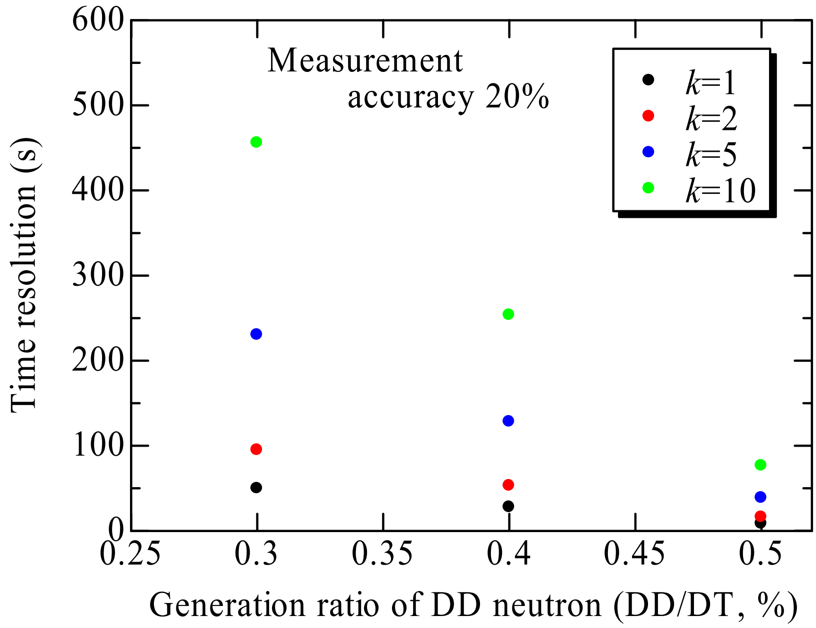

Fig. 5.12 Detector response for neutron beam involving the lower-intense DD neutron (500 MW). The total neutron yield is fixed at 2×10^{20} n/s for this estimation.