Chapter 1
Introduction

1.1 Plasma burn control

Tokamak fusion reactor that uses deuterium (D) and tritium (T) as its fuel is one of several types of magnetic confinement devices and a leading candidate for producing fusion energy. Fusion energy is produced by the following reactions. In this thesis, the 14.1 MeV and 2.45 MeV neutrons from the DT and DD reactions are called DT neutron and DD neutron, respectively. The DT and DD plasma discharges that involve the following two kinds of fusion reactions are named as "DT phase" and "DD phase".

$$\mathrm{D+T} \rightarrow {}^{4}\mathrm{He}\ (3.54\ \mathrm{MeV}) + \mathrm{n}\ (14.1\ \mathrm{MeV}) \tag{1.1}$$

$$\mathrm{D+D} \underset{50\,\%}{\rightarrow} \mathrm{T}\ (1.01\ \mathrm{MeV}) + \mathrm{p}\ (3.03\ \mathrm{MeV}) \tag{1.2}$$

$$\underset{50\,\%}{\rightarrow} {}^{3}\mathrm{He}\ (0.82\ \mathrm{MeV}) + \mathrm{n}\ (2.45\ \mathrm{MeV}) \tag{1.3}$$

The International Thermonuclear Experimental Reactor (ITER) project is in progress, and the primary purposes of this project are demonstrations of controlled ignition, long-pulse burning with steady-state, comprehensive technologies for blanket, superconductive coil and plasma facing wall. The DT burn control is one of the key issues for the ITER tasks.

Several types of algorithm for the plasma control were developed, and the performances and applicability of them have been considered [1-13]. Figure 1.1 shows an example of a basic algorithm for the DT burn control [5, 11 and 13]. The most fundamental input factors are external heating power for maintaining H-mode state and fueling rate to control the fusion power and plasma density. The total fueling rate will be controlled by Proportional-Integral-Derivative (PID) control method [13], which is the most reliable and widely-used automatic control technique, using some relevant plasma parameters as its error signals. Neutron measurement system, magnetic probes, bolometer, electron cyclotron emission spectrometer, interferometer and spectroscopy techniques are required as real-time diagnostic tools for the burning plasma. Table 1.1 summarizes the respective candidates for diagnostic systems and their monitoring parameters.

1.2 Plasma diagnostic system for the DT burn control in fusion experimental reactor

Plasma diagnostics using quantum particle, including quantitative measurement of fusion products such as neutrons and γ-rays, will be more important than other diagnostic tools in future fusion power plants. The DT burn control of fusion plasma requires reliable techniques of plasma diagnostics, and they have been considered as a key issue for realization of a fusion power plant since the fusion research was launched. The main diagnostic tools that have been developed are reflectometer and interferometer using electro-magnetic wave, magnetic probes, X(γ)-ray measurement, spectroscopy and particle measurement system. Real-time monitoring indicated in Table 1.1 is mainly required for the DT burn control. Figure 1.2 schematically shows the arrangement of plasma diagnostic tools in ITER [18]. The difficulties in development of the diagnostic tools for the DT burn control are reviewed in references 19 and 20. Neutron yield monitoring is one of the diagnostic technique with fusion products, and the primary candidate for monitoring of fusion power P_{f} and α particle heating power P_{α} , details are described in section **1.3**.

The fuel ratio n_D/n_T in plasma should be controlled to maintain high power fusion plasma with steady state. Here n_D and n_T represent deuterium and tritium ion densities. Some kinds of fueling techniques have been considered for the ITER plasma control such as pellet injections, gas puff injections and a compact troid injection [14]. Successful combination of these techniques is preferable for effective fueling in the actual fusion power plant. Isotopic control of fueling or each injection rate of D and T needs real-time information of the actual fuel ratio in the plasma. Besides, a fuel injection without any certain information of the fuel ratio inside the reactor, especially on tritium inventory, is dangerous and not preferable for radiation safety. The fuel ratio monitoring in the burning plasma is classified into the edge plasma region and the plasma core. The feedback control of fueling and density is supposed to relay on real-time information of the fuel ratio in the edge plasma [15]. The primary candidate of monitoring system for the fuel ratio in the edge plasma is a spectroscopy technique of H_α , D_α and T_α [16, 17]. The fuel ratio monitoring in the plasma core will play a complementary role in the DT burn control such as the isotopic fuelling as described in section **1.3**. Several kinds of techniques have been proposed for fuel ratio monitoring in plasma core such as γ-ray spectroscopy [21], fast Alfvén wave interferometer and reflectometer [22], collective Thomson scattering [23-25], neutral particle analysis [26, 27] and neutron spectroscopy [28-33]. Because of their poor Signal-to-Noise Ratios (SNR), it has been considered difficult to realize the required time resolution of 100 ms with 20% accuracy. Each technique is still under development and has a long way to realize in actual fusion reactors.

1.3 Nuclear instrumentation for the DT burn control

Neutron measurement can directly provide information on the fusion reactions themselves without any plasma disturbance by the high-penetrating power of neutron, and it has much contribution to the DT burn control. Neutron diagnostic system consists of neutron yield measurement, neutron emission profile measurement and neutron energy spectrum measurement. The information of the burning plasma obtained from these systems is presented in Table 1.2. Plasma diagnostics based on neutron measurement, which is superior to other tools for a high-density plasma, especially in α particle emission rate and its profile, distributions of ion energy and density as well as Q-value. Because of the high-penetrating power of neutron, a spectroscopic technique of fusion neutron has been considered a candidate for monitoring the fuel ratio in the plasma core [28-33]. Based on the technical achievements in the existing large Tokamaks, several kinds of fusion neutron diagnostic systems for ITER were proposed and developed. The brief summaries of them were reported in references 34-37.

Neutron energy accounts for 80% of the total DT fusion power, while the rest of 20% is given to α particle. A large part of neutron energy is deposited in the Blanket modules. On the other hand, α particles deposit their energies in the plasma and contribute to the plasma heating. Neutron yield monitoring is the most suitable for P_f measurement obviously. Because α particle losses almost all of its energy in plasma core, direct measurement of P_α is difficult. As can been seen in Equation (1.1), neutron yield monitoring can provide an emission rate of α particles as well, and P_α is given by $P_\alpha = P_f/5$. Thus the external heating power control, which requires monitoring of P_α, P_f, P_{oh}, P_b and P_s, considerably depends on neutron yield measurement.

Neutron spectroscopy technique can directly give the information of the fuel ratio that practically contributes to each fusion reaction, DD and DT, by detecting the corresponding neutrons. Besides, the information of the fuel ratio in the plasma core where plasma burns most effectively can be an important indicator for isotopic fueling, which means tailoring an isotope ratio D/T of the fuel to be injected [38]. Thus, neutron yield monitoring system and neutron spectrometer to measure the fuel ratio in plasma core is the key technologies for the DT burn control.

1.4 Neutron yield monitoring

Neutron yield monitoring system significantly contributes to high-energy particle physics in burning plasma as well as plasma burn control. Activation foil is the most promising method for total neutron yield measurement, because it is robust and insensitive to γ-ray, electro-magnetic noise and radiation damage. In Tokamak devices, activation foils are put near the plasma through a pneumatic tube system. Cross-section, half life and threshold energy should be considered to select the materials to be irradiated. ^{115}In(n, n'), ^{27}Al(n, p), ^{64}Zn(n, p), ^{63}Cu(n, 2n), ^{28}Si(n, p), ^{27}Al(n, α) and ^{58}Ni(n, 2n)^{57}Ni are widely used in neutron activation systems [39-41]. Since the response time of actuators for plasma heating is 10-100 ms, time resolution of 10 ms is required for neutron yield monitoring for burn control [12]. However, activation method does not have time resolution in principle, it can provide only an integrated neutron yield every a few hundreds seconds at most, and hardly serve the real-time feedback control of plasma burning. In recent years, new type of activation system using water as an irradiation material has been proposed. Intensity of a specific γ-ray from ^{16}N that is produced by neutron reaction with oxygen in water is related to the irradiated neutron fluence. The water flows through a circulation tube passing by near the plasma, being expected to secure a time resolution of 100 ms or better [42, 43].

BF_3 counter, ^3He counter and fission chamber are usually used for neutron monitors that can give time-resolved yield information. The neutron yield monitor using fission chamber is the most established method for fission reactors, and also has been used in other large Tokamaks such as JET [44], TFTR [45] and JT-60U [46]. Fission chamber is a simple ionization chamber that has a thin coating of 90% enriched $^{235}UO_2$ or $^{238}UO_2$ outside the chamber containing counting gas. Wide dynamic range over 10 orders of magnitude and high count-rate capability are required in ITER. Three kinds of approaches were proposed for ITER neutron yield monitoring system. The first one is called “in-vessel monitor”, which uses micro-fission chambers (pencil-size, 14 mmϕ × 200 mm) and will be placed just behind the Blanket modules [47-49]. Second is “ex-vessel monitor”. This system uses fission chambers surrounded by moderator and will be incorporated outside the Vacuum vessel in the ITER machine [50]. The other is “divertor monitor”, which also uses moderated fission chambers located inside the divertor cassette [51] (see Fig. 1.3). Table 1.3 shows a comparison of characteristics the three systems. The ex-vessel monitor is superior to the other system in dynamic range. The in-vessel monitor and divertor monitor are able to have a good time response, but their dynamic ranges are not as wide as that of the ex-vessel monitor.

In-situ calibration of the neutron yield monitor will be implemented to relate the detected neutron counts to the actual neutron yield. Measured neutron counts $C_n(X_D)$ is theoretically represented as follows

$$C_{\mathrm{n}}(X_{\mathrm{D}}) = \int Y(\mathrm{v})\eta(\mathrm{v}, X_{\mathrm{D}})\mathrm{dv}, \tag{1.4}$$

where, $\eta(\mathrm{v}, X_D)$ is detection efficiency, X_D is detector position and $Y(\mathrm{v})$ represents neutron yield per unit volume. The conversion factor, which means the ratio of detector counts and the actual neutron generation rate, should be determined experimentally with a DD and/or DT neutron generator, because Tokamak device itself and peripheral devices that affect neutron behavior are too complicatedly mounted to establish an accurate calculation model. The *in-situ* calibration dominates the measurement accuracy of the monitoring system, and its strategy can affect the system design itself. Therefore, a calibration strategy needs to be considered well before the system integration in ITER.

1.5 Fuel ratio monitoring based on neutron spectroscopy

As can be seen in Equation (1.1) and (1.3), the ratio of DD and DT neutrons, which is directly related to the fuel ratio n_D/n_T in the plasma core, can be derived from spectroscopic measurement of neutron beam coming from the burning plasma. Here n_D and n_T are deuterium and tritium densities in plasma, respectively. Fuel ratio monitoring based on neutron spectroscopy has not practically demonstrated in actual Tokamaks. Several types of neutron spectrometers were developed for fusion plasma diagnostics, such as organic scintillators [52, 53], diamond detectors [54-56], Si detectors [57], magnetic proton recoil spectrometers [58, 59], proton recoil telescopes [60, 61], time-of-flight spectrometers [62-65] and associated particle coincidence counting and/or time-of-flight method [66, 67]. These spectrometers were developed for an application to a measurement of fuel ion temperature that needs a high energy resolution better than 3% [68-70]. As described in section **1.3**, several proposals were presented on neutron spectrometer for fuel ratio monitoring in burning plasma [28-33]. Foil activation system that uses a few materials with appropriate energy thresholds for distinction of DD and DT neutrons is mentioned in reference 32. Though the applicability of the proposed neutron spectrometers to the fuel ratio monitoring have been discussed, specific techniques or designs for this purpose have not presented yet.

For neutron spectroscopy and a neutron emission profile measurement in the ITER, Radial Neutron Camera (RNC) with horizontal views and/or vertical views will be mounted outside the Vacuum vessel of the ITER [71]. As shown in Fig. 1.3, the RNC consists of fan-shaped arrays of neutron collimators. Neutron spectrometer for fuel ratio monitoring at the plasma core will be installed in the line of sight of the RNC center chord. DD neutron generation rate in DT burning plasma is considerably poor, typically 0.5%, compared to that of DT neutron due to the difference of cross-sections between the two reactions. Down scattering of overwhelming amount of DT neutrons by the ITER machine structure and RNC, which is called “Wall Emission”, becomes a background signal that prevents DD neutron detection [32, 72 and 73].

Double Crystal Time-Of-Flight method (DC-TOF) is the most promising technique out of other neutron spectrometers for this purpose. It is generally simple and can easily discriminate neutron energy without complicated process such as a spectrum unfolding method, and generally has higher detection efficiency than other methods that are based on recoil proton detection. On the other hand, DC-TOF method in which the first detector is placed in a beam line of the incident neutron has a disadvantage under a high-flux of neutron beam. In ITER experiments, the radiation intensities change as the reactor power increases. In a high reactor power region, thickness of the first scintillator and/or an aperture of the neutron collimator must be adjusted; otherwise the first scintillator of the TOF system would suffer from considerable accidental count due to the high radiation fluxes. This accidental count can be another cause of background for DD neutron detection. Since measurement accuracy of fuel ratio directly depends on the background level under statistically poor situation for DD neutron, the system design and development should be concerned mostly with improvement of the Signal-to-Noise Ratio (SNR) for DD neutron.

1.6 Motivation and contexture

Fusion power plants demand a high power and cost-effective burning plasma with steady state. The DT burn control is necessary for the realization of fusion power, and neutron yield monitoring and fuel ratio monitoring are the key technologies for the DT burn control described in section **1.3**. The motivation of this study is nuclear design of an advanced version of neutron yield and fuel ratio monitoring systems for ITER, based on the experience and/or difficulties that have been encountered in the existing large Tokamak devices.

As mentioned in section **1.4**, three kinds of neutron yield monitoring system was proposed for ITER. It has not been confirmed, in terms of neutronic considerations, if they can satisfy the ITER requirements such as dynamic range and measurement accuracy. Neutronic design consideration of a neutron yield monitoring system for ITER and its *in-situ* calibration strategy are presented in this study following the former proposals. The fuel ratio monitoring based on neutron spectroscopy has not been an established technique in the existing large Tokamaks, and any system has not been proposed in detail for the monitoring of plasma core in ITER. A new approach to neutron spectrometer for the fuel ratio monitoring in the DT plasma discharge in ITER is proposed and discussed in this thesis.

Applicability of them to ITER has also been discussed through detailed Monte Carlo simulations. The following is contexture of this thesis.

Because the ex-vessel neutron yield monitor is relatively far from the plasma, the measurement accuracy of it is not negatively affected by variances of plasma parameters compared to the in-vessel monitor and divertor monitor. Besides, it has an advantage over the other systems in realization of the required dynamic range. This study employs the ex-vessel method for a neutron yield monitor in ITER. Chapter **2** describes the basic designs of the detector modules that have several fission chambers surrounded by a neutron moderator. The installation of the modules in the ITER machine and the *in-situ* calibration techniques using DD/DT neutron generators are discussed in Chapter **3**. The ultimate measurement accuracy to be expected in the ITER operations is also presented.

New concept of the fuel ratio monitoring in ITER is proposed in Chapter **4**, which is characterized for improvement of SNR for DD neutron detection in the high power DT burning plasma. This system is based on a DC-TOF method placing a neutron scattering material in front of the crystal pair. The inserted material enhances DD/DT neutron intensity ratio by the difference of its neutron cross section before entering the TOF crystals. This enhancement expects an improvement of SNR by decreasing the intensity of DT neutron and γ-ray of no interest that enters the TOF crystal. Chapter **5** describes design considerations and applicability of this neutron spectrometer to ITER. The consideration results on its installation site and the expected performances such as measurement accuracy, time resolution and dynamic range in ITER are also discussed.

Chapter **6** concludes this thesis with perspectives of the DT burn control and nuclear instrumentation systems in fusion reactors.

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Figures and tables

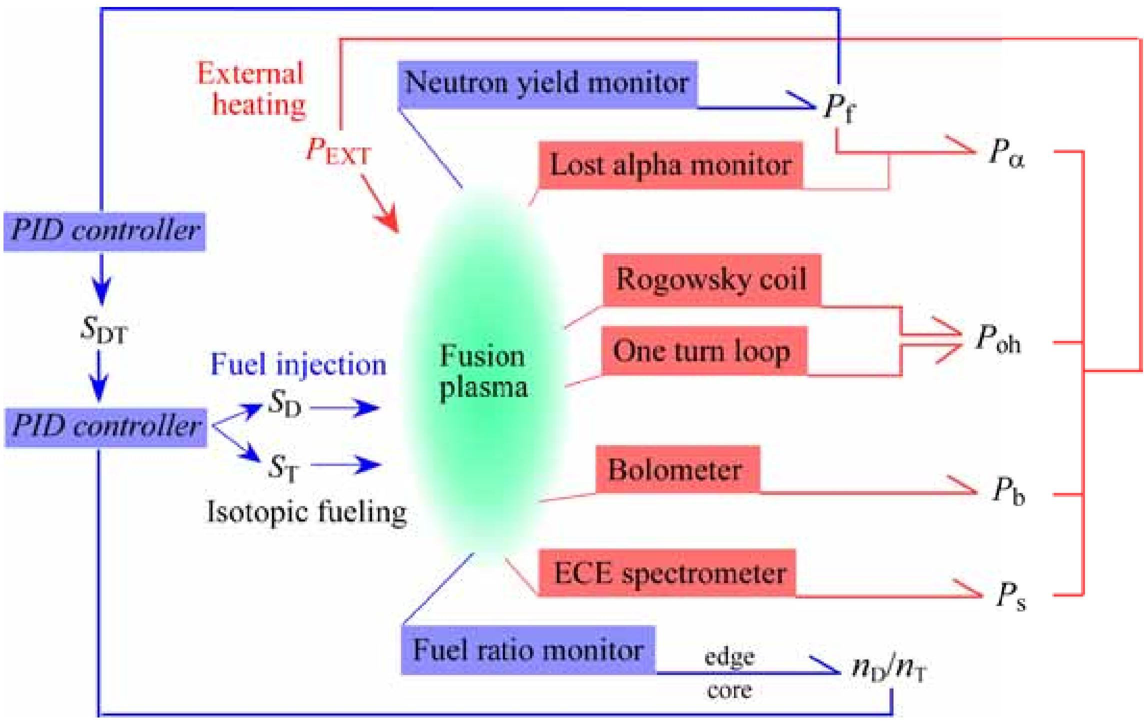

Fig. 1.1 Simplified conceptual diagram for the DT burn control [5, 11].

The relevant part was cited from the original diagram in references 5 and 11. The most fundamental input factors are external heating power for maintaining H-mode state and fueling rate to control the fusion power and plasma density. Neutron yield monitoring and fuel ratio monitoring play an important role for the DT burn control.

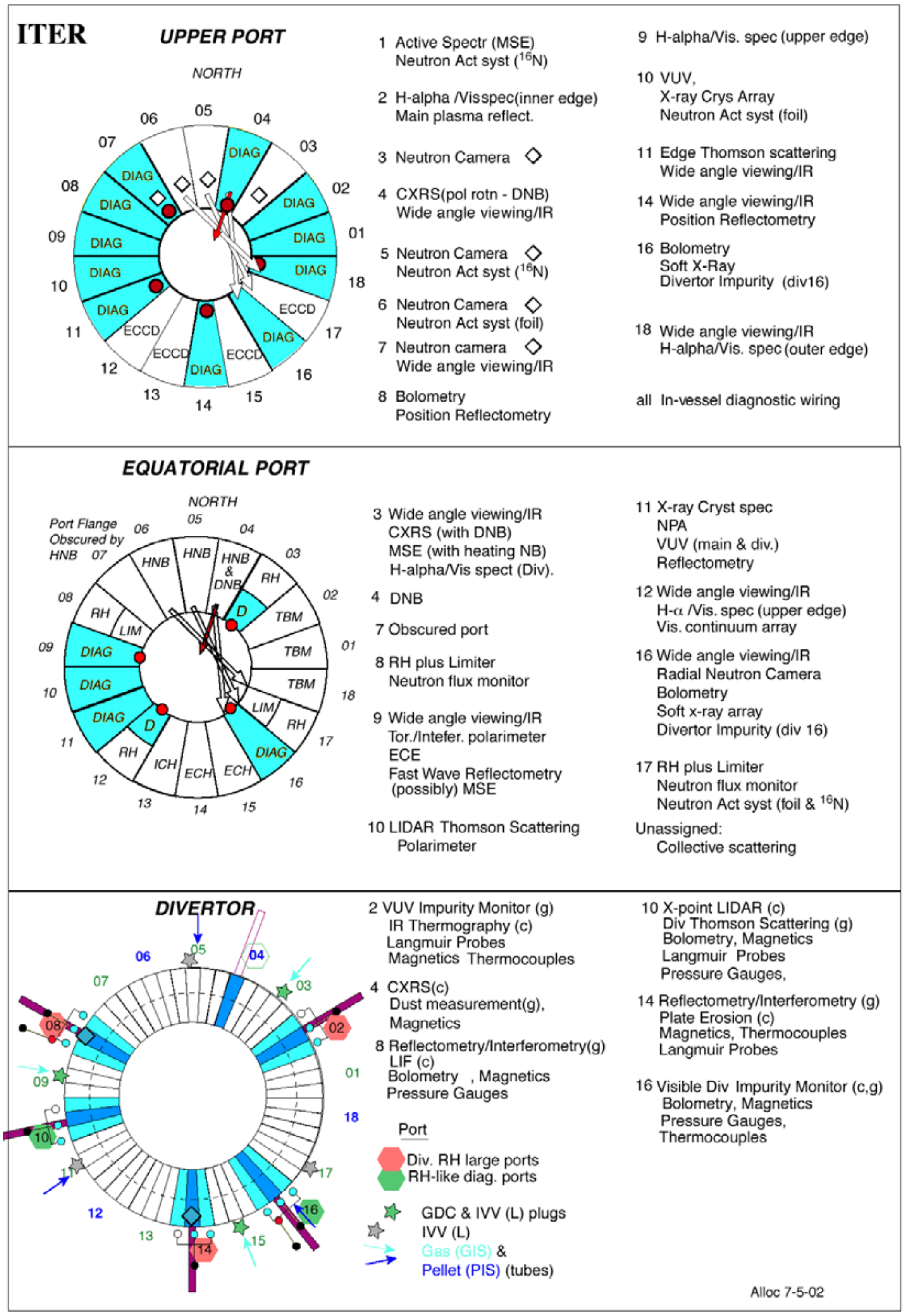

Fig. 1.2 Integrations of the plasma diagnostics system in ITER [18].

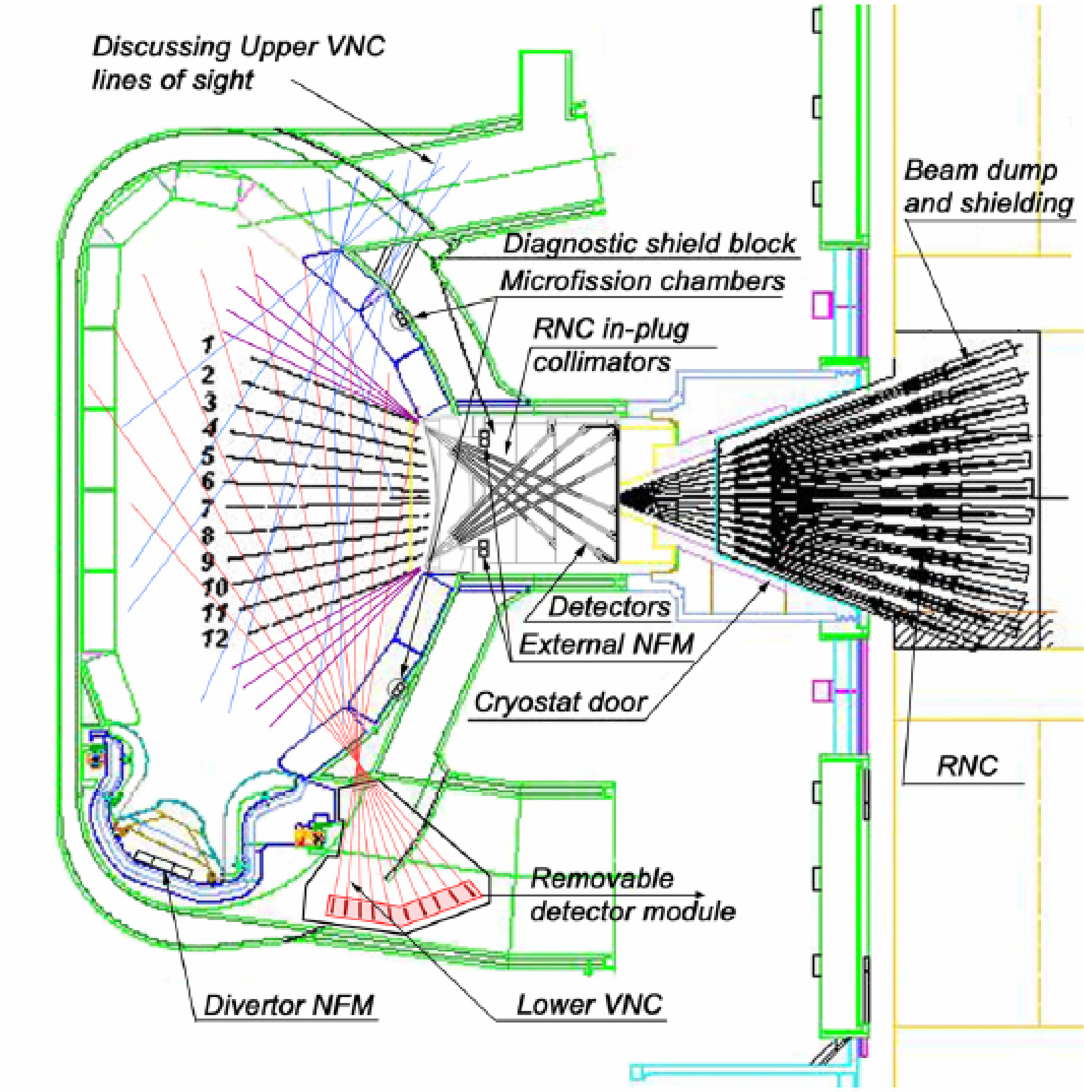

Fig. 1.3 ITER Radial Neutron Camera (RNC) and neutron yield monitoring system [36]. The "Microfission chambers" indicates the in-vessel neutron yield monitor, and the ex-vessel monitor is described as "External NFM" in this figure. "The Diverter NFM" represents the diverter monitor.

Table 1.1 Plasma diagnostics tools for the DT burn control.

Measurement system	Plasma parameter		Purpose
Neutron flux monitor	Fusion power α particle heating power	: P_f : P_α	Fueling rate Ignition access, H-mode sate
Magnetic probe	Ohmic heating power	: P_{oh}	Ignition access, H-mode sate
Bolometer	Bremsstrahlung loss	: P_b	Ignition access, H-mode sate
ECE spectrometer	Cyclotoron radiation loss	: P_s	Ignition access, H-mode sate
Interferometer	Plasma density	: n	Fueling rate, Ignition access, H-mode sate
Spectroscopy	Fuel ratio in edge plasma	: n_D/n_T	Optimization of fueling rate, Plasma dillution
Neutron spectroscopy Fast wave reflectometry	Fuel ratio in core plasma	: n_D/n_T	Optimization of fueling rate, Plasma dillution

Table 1.2 Neutron measurement systems and plasma parameters.

Mesurement system	Plasma parameter
Neutron yield measurement	Fusion power Q-value α particle heating power
Neutron emission profile mesurement	Neutron spatial distribution Ion density distribution Ion temperautre profile
Neutron energy spectrum mesurement	Ion temperature α knock-on tail Fuel ratio

Table 1.3 Characteristics of the three kinds of neutron yield monitoring system in ITER.

System	Dynamic range	Time resolution	Accuracy	Maintenance
Ex-vessel	Superior	Good	Good	Easier to access
In-vessel	Good (superior for the lower reactor power)	Superior	Inferior (sensitive to plasma profile)	Difficult
Divertor	Good (superior for the lower reactor power)	Superior	Inferior (sensitive to plasma profile)	Difficult
Activation	Superior	Poor	Superior	Unnecessary