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Overview of neutron and confined/escaping alpha diagnostics planned for ITER

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Abstract

Fusion product measurements planned for ITER are reviewed from the viewpoint of alpha particle-related physics studies. Recent advances in fusion plasma physics have extended the desirable measurement requirements to the megahertz region for neutron emission rate, better resolution of neutron profiles for the study of internal transport barriers (ITBs), etc. Employing threshold counters and/or scintillation detectors confers megahertz capability on neutron emission rate measurement. The changes in the neutron/alpha particle birth profile due to the formation of ITB and its deviation from uniformity on the magnetic flux surface can be measured by addition of eight viewing chords in an equatorial port plug and seven viewing chords from the divertor to the original radial neutron camera. On the other hand, it is still difficult to measure the distributions of confined and escaping alpha particles. Several proposals to resolve these difficulties are currently under investigation.

1. Introduction

Neutron measurement has been considered to be one of the major diagnostic methods used since the initiation of the ITER design phase [1]. Its principal role is to allow evaluation of fusion output, with consequent machine protection. To date, seven sub-systems have been considered, some of which are well designed and are now ready for construction. In the meantime neutron diagnostics have supplied a variety of both spatially and time-resolved information to facilitate our understanding of physics, especially with regard to the behaviours of energetic particles in the two decades of DD and DT tokamak experiments [2–4].

Physics related to energetic particles, i.e. alpha particles, will become more important in the next-stage burning plasma experiments. Self-heating of a DT plasma by fusion-produced alpha particles is the key to realize a self-sustainable thermonuclear plasma in a fusion reactor. Recent progress in tokamak physics has revealed the importance of profile control of the plasma current, $I_p(\rho)$, temperatures, $T_i(\rho)$, $T_e(\rho)$, the temperature gradient, $\nabla T_i(\rho)$, $\nabla T_e(\rho)$, plasma pressure, $\beta(\rho)$, and pressure gradient, $\nabla \beta(\rho)$ [5]. Self-heating by alpha particles will complicate the control of these profiles, because it has a positive feedback feature (local power input increases on a magnetic flux surface (MFS) with higher reaction rate).

The next issue to be studied is the energetic ion-driven collective instabilities, such as various Alfvén eigenmodes. A DT burning plasma produces significant amounts of alpha particles, resulting in a steep spatial gradient of the fast ion pressure, which will trigger energetic ion-driven collective instabilities. The alpha particle birth velocity is close to, or above the Alfvén velocity, and the initial velocity distribution of an inverse gradient, $\partial f(v)/\partial v < 0$, has the potential to make the instability growth rate larger. On the other hand, some damping mechanisms are closely related to the profiles of $I_p(\rho)$, $q(\rho)$, $\nabla T_{i,e}(\rho)$, $\nabla \beta(\rho)$, etc. These instabilities interact with energetic particles, perturb and kick alpha particles, and consequently might change the alpha particle population in space and pitch angles. Because the initial pitch angle distribution of alpha particles is uncontrollable, the perturbation has the potential to induce selective loss of alpha particles. All of these processes are correlated with each other and complicate the problem significantly. In recent experiments, the frequency ranges of various Alfvén eigenmodes, such as global Alfvén eigenmodes (GAE) or compressional Alfvén eigenmodes, were extended into the megahertz region [7], although it is not yet known whether these modes couple with energetic particles.

In consideration of these recent advances, the neutron diagnostic set for ITER is reviewed here with particular emphasis on the following questions:

1. Can the neutron emission rate be measured with microsecond time resolution?
2. Can the change of neutron profile due to the formation of the internal transport barrier (ITB) be detected? Is the non-axisymmetric neutron emission profile caused by loss of trapped particles or MHD activities detectable?
3. Are the local alpha particle distribution and/or velocity distribution measurable?
4. Are the losses of alpha particles measurable with sufficient time resolution?

This paper presents a brief overview of nine neutron sub-systems for ITER, followed by discussion of the above four issues.

2. Requirements and sub-systems of fusion product measurement

The measurements required in ITER are categorized into three groups according to their role: (A) machine protection and basic control, (B) measurement for advance control,

Table 1. Measurement Requirement of ITER [6].

Category	Parameter	Parameter range	Time resolution	Spatial resolution	Accuracy (%)
(A)	Fusion power	$\leqslant 1$ GW	1 ms	Integral	10
	(Total neutron source strength)	1×10^{14}–5×10^{20} n s^{-1}			
(B)	Neutron and α-source profile	1×10^{14}–4×10^{18} n s^{-1} m^{-3}	1 ms	$a/10$	10
	Ion temperature profile (core) ($r/a < 0.9$)	0.5–50 keV	100 ms	$a/10$	20
	α-particle loss	$\leqslant 2$ MW m^{-3}	100 ms	$a/10$ (along poloidal direction)	20
	Neutron fluence on the first wall	0.1–1 MWa m^{-2}	10 s	$\sim$10 locations	10
(C)	Confined α-particles	0.1–2×10^{18} m^3	100 ms	$a/10$	20

and (C) performance evaluation and physics. Group (A) has the highest priority. Those related to fusion product measurement and their requirements are listed in table 1.

To meet these requirements, seven sub-systems were originally considered, as outlined in table 2. These systems are described in the design document [8], but problems and difficulties were encountered during the design process by the ITER joint central team (JCT) and performance study by the Topical group of Diagnostics in International Tokamak Physics Activities (ITPA TGD). The present statuses of these sub-systems are summarized in table 2.

The requirements for fusion power measurement and neutron fluence on the first wall listed in table 1 will be met by appropriate choice of detectors and careful calibration combined with neutron transport calculation, such as MCNP. The choice of detectors and the expected frequency range are discussed in the following section. Cross-checking among sub-systems, and comparison with activation systems, which avoid contamination of radiation induced electric noise, will improve reliability. Two kinds of activation systems are planned: one uses encapsulated foils pneumatically transferred from the irradiation stations between blanket modules to the gamma-ray measurement station, while the other uses activation of circulating water. It has a time resolution of about 50 ms with a time delay of about 1 s, and is expected to be used as a fusion output monitor in future fusion reactors. These measurements supply global space-integrated information. The effect of the emission profile is not negligible if better than 10% accuracy is required [7]. The radial neutron camera (RNC) covers only the core region of $r/a \leqslant 0.5$, while the vertical neutron camera (VNC) provides coverage of the outer region. However, there is a serious problem due to the relative movement of the first and second collimators of the VNC.

For the same reason, the neutron emission profile and the ion temperature in the outer region of $r/a \geqslant 0.5$ may not be obtained without VNC. The importance of the VNC will be discussed in section 4.

3. Frequency range of neutron emission rate

Fast time-resolved measurements of global neutron source strength and fusion power will be provided by micro-fission chambers and flux monitors (see table 2). In the ITER design report of 2001 [8], it was proposed that micro-fission chambers should be installed inside the vacuum vessel, with flux monitors placed in remote handling ports. Further analyses of their optimal locations and number of detectors are still ongoing.

Table 2. Sub-systems of fusion product measurement of ITER.

#	Name of sub-system	Purpose	Present status and comment
B.01	Radial neutron camera	Total neutron source strength	This system has sensitivity in the region of $r/a < 0.5$ [9], but provides accurate information regarding the source. It is relatively insensitive to the surrounding materials. The requirement will be met by appropriate choice of detectors, cross-checking with other sub-systems (B.03, 04), and careful calibration
		Neutron/alpha source profile	The profile will be obtained by assuming a function of magnetic flux surface. The reliable measurement will be provided only for $r/a < 0.5$
		Ion temperature profile	The requirement will be met by appropriate choice of detectors in a limited parameter range. The reliable measurement will be provided only for $r/a < 0.5$
		Neutron fluence on the first wall	The requirement will be met by appropriate choice of detectors
B.02	Vertical neutron camera	Total neutron source strength Neutron/alpha source profile Ion temperature profile Neutron fluence on the first wall	The original design is now reconsidered because a severe relative movement of the first and the second collimators is anticipated. Divertor VNC is under consideration
B.03	Microfission chambers	Total neutron source strength Neutron fluence on the first wall	The requirement will be met by appropriate choice of detectors, cross-checking with other sub-systems (B.01, 04, 08), and careful calibration
B.04	Neutron flux monitors	Total neutron source strength Neutron fluence on the first wall	The requirement will be met by appropriate choice of detectors, cross-checking with other sub-systems (B.01, 03, 08), and careful calibration
B.07	Gamma-ray spectrometers	Confined alpha density profile	Shield design and background estimation should be performed. Other sources for 4.44 MeV gamma production should be assessed. Beryllium density should be measured
		$n_{\mathrm{T}}/n_{\mathrm{D}}$	Shield design and background estimation should be performed. Further assessment is needed
B.08	Neutron activation systems	Total neutron source strength Neutron fluence on the first wall	The foil activation system will provide absolute values and information on the neutron scattering effect. Water activation system, which is expected to be used as a fusion output monitor in future reactors, has a time resolution of about 50 ms
B.09	Lost alpha detectors	Escaping alpha flux (steady state) Escaping alpha flux (transient)	Expected performance for each proposal is currently under investigation

Detectors of both sub-systems use fissile materials, such as ^{235}U and ^{238}U. These materials have one of two types of neutron cross-section, the $1/v$ type or the threshold type. ^{235}U is of the former type and the cross-section increases with decreasing incoming neutron velocity. In contrast, ^{238}U is of the latter type and fission reactions occur only for neutrons with energy
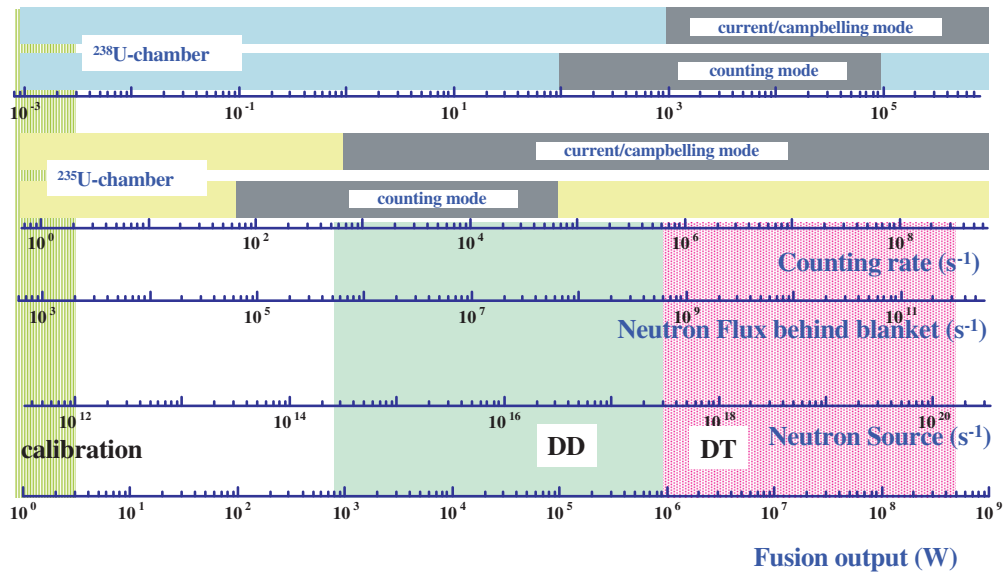
Figure 1. Frequency range of neutron flux monitors. The number of neutron signals from 10 mg ^{235}U or ^{238}U fission chambers placed behind the blanket is estimated. The campbelling mode is a current mode coupled with an input-square electronics for suppression of low height pulses.

above a threshold ($\sim$0.8 MeV for ^{238}U). Therefore, the detection efficiency depends markedly on the detector fissile materials, neutron moderator surrounding the detector, and the neutron energy spectrum at the detector location. The materials, especially those between the neutron source and detection position, affect the neutron spectrum. This is the reason why *in situ* calibration and neutron transport calculation are necessary, and why multiple detectors should be installed not only outside but also within the vessel. The fission reaction rates in 1 g of ^{235}U and ^{238}U for neutron flux with a typical spectrum behind the ITER blanket are 0.1 per neutron cm^{-2} and 1.5×10^{-04} per neutron cm^{-2}, respectively. If the location is away from the plasma, that of ^{235}U becomes slightly larger and that of ^{238}U becomes less [10]. Typical amounts of fissile materials used in a detector are in the range of 10–100 mg. To subtract contamination of spurious signals, such as those induced by gamma radiation, a fissile-free 'blank detector' will be prepared and used at the same positions as fission chambers.

The neutron source strength from DD or DT plasma in ITER is expected to be in the range from 10^{14} to over 10^{20} n s^{-1}, while the calibration source will be at most 10^{12} n s^{-1}. This illustrates an essential difficulty with ITER neutron detector *in situ* absolute calibration related to the huge differences in neutron flux on the detectors during ITER operation and calibration procedures. Arrangement of internal neutron flux monitors with the allocation of the ^{235}U micro-fission chamber inside the ITER vacuum chamber behind the blanket was proposed by Nishitani *et al* [10]. Typical total neutron flux behind the blanket is shown in figure 1. The number of neutron signals from 10 mg ^{235}U and ^{238}U fission chambers placed behind the blanket can be estimated by multiplying this neutron flux by the sensitivities proportional to the fission reaction rates mentioned above (figure 1). With a maximum counting rate capability of fission chambers of $\sim$10^6 s^{-1}, the dynamic range of seven orders of magnitude during ITER operation will be covered by employing both pulse counting mode and current/Campbelling mode in the electronics. During the calibration experiment, sufficient statistics from ^{235}U will be obtained by accumulation over a period of 10^2–10^3 s in pulse counting mode. The counting

rate will be 10-fold higher than that in figure 1 when the calibration source moves close to the detector section, but 10-fold less when the source is behind the centre column [11].

Although officially a time resolution of 1 ms is required (see table 1), recent studies of MHD have indicated the importance of coupling between their activities and energetic particles. Occasionally, reduction of neutron emission during energetic-ion-driven MHD is observed in various tokamaks. The reduction is thought to be mostly induced by redistribution of either bulk ions or energetic fuel ions, or both. It would be interesting and important to study how the neutron emission behaves under alpha heating. The frequency of such activities reaches up to the megahertz range, which may not by the covered by the counting mode. A ^{235}U chamber combined with the Campbelling mode may produce a sufficient number of neutron events during the DT phase. The Campbelling mode is a current mode coupled with an input-square electronics for suppression of low height pulses. It is more resilient to gamma-induced noise than the current mode, and linearity has now been tested up to 100 kHz. Another concern related to high frequency measurement using ^{235}U fission chambers is the time delay required for thermalization of DT neutrons. It is anticipated to be of the order of tens of microseconds and the delay time distribution may smear out the MHD activities. A detailed study has been carried out by using a Monte-Carlo simulation [12].

One solution to this problem is the employment of a threshold type detector. As shown in figure 1, the number of events produced in a 10 mg ^{238}U chamber behind the blanket might not be sufficient even during a high performance DT shot. A better location, such as inside the divertor cassette where 2×10^{12} ($E_n > 13.8$ MeV), 10^{13} (1 MeV $< E_n < 13.8$ MeV), and 2×10^{12} (thermal) n cm^{-2} s^{-1}) neutron flux is expected, was proposed recently by Krasilnikov *et al* [13].

Under these conditions, several R&D activities have been carried out. An in-vacuum type micro-fission chamber has been designed specifically for use in the ITER and various test experiments, including radiation tests, have been performed [14]. A high performance ^{238}U fission chamber with 1.5 g of ^{238}U was also developed [13]. A 1.5 g ^{238}U chamber combined with current or Campbelling mode electronics may provide a megahertz response during a DT shot of fusion output higher than 10 MW if installed inside the divertor cassette.

Another solution is the employment of scintillation detectors. Some scintillation detectors have the capability to discriminate gamma-ray background from neutron signals, while most of the fast scintillation detectors do not. Calculated neutron fluxes at detectors of central channels in the neutron cameras, which are mentioned later, range at (1–3) $\times 10^9$ n cm^{-2} s^{-1} at the maximum neutron rate of 2.2×10^{20} n s^{-1}. Considering typical detection efficiency and detector sizes, the neutron fluxes are high enough for the megahertz time resolution. However, scintillation detectors with n-gamma discrimination are usually slow in scintillation quenching and electronics for n-gamma discrimination do not have megahertz capability. At the moment, fast scintillation detectors without n-gamma discrimination and ^{238}U chambers are being considered for installation in collimators.

4. Measurement of neutron emission profile

The neutron emission profile is equivalent to the alpha birth profile and provides information regarding the source power profile for transport study. In the original plan, it was measured by a combination of RNC and VNC. As there are problems with the engineering design of VNC, the accuracy of the profile measurement is determined by the plasma coverage of RNC. A detailed RNC design has been carried out and 12 viewing chords cover the plasma of $|Z - Z_0| < 0.5b$. The pivot point is located inside the port plug and the detector box is outside the biological shield. The fraction of neutrons not seen by the camera can be as large as 10–20%. Each chord
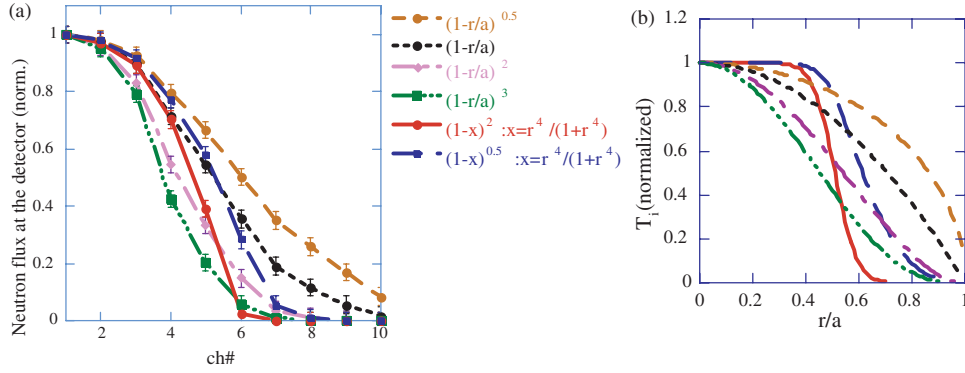
Figure 2. (*a*) Neutron flux at the detectors in lower half chords of RNC (#1–#6), when four parabolic ion temperature profiles with different peaking factors, and two types of ITB are assumed as shown in (*b*). Additional viewing chords (#7–#10) are proposed by NWG (Krasilnikov *et al*). The formation of ITB is clearly observed by the addition of chords.

in RNC will be equipped with total flux detectors and compact spectrometers. A combination of different detectors is needed to cover the wide range in the expected level of the flux.

As only line-integrated neutron emission is measured by each chord, the alpha particle birth profile can be obtained by assuming a simple analytical form as a function of the MFS [9]. This might raise the question of whether the changes in alpha birth profile due to ITB can be observed by the 12 viewing chords of RNC. Figure 2 shows the neutron flux at the detectors (*a*) in the lower half-chords of RNC (#1–#6), assuming four parabolic ion temperature profiles with different peaking factors, and two types of ITBs (*b*). The errors might be dominantly from changes in back-scattered neutrons and gamma particles, and changes in detector efficiency. If ambiguity of 2% of neutron flux at the centre chord is taken into account for every channel, the profile parameter can be obtained within limited accuracy, but a moderate ITB cannot be recognized.

Additional viewing chords (#7–#10) were proposed recently by Krasilnikov *et al* [13]. As the outer region can only be seen by detectors much closer to the plasma, the pivot points should be near the plasma edge and the detectors should be installed inside the port plug. For this reason, the proposed collimators (#7–#10 and four others viewed symmetrically on the other vertical side of the plasma) were arranged in a compact in-plug neutron camera placed inside the ITER equatorial port. Although further engineering work is needed, figure 2 shows substantial improvement of the accuracy of the profile parameter and that of the determination of the ITB structure. In addition, up-down asymmetry and vertical movement can be clearly detected by channels of the RNC and the compact in-plug neutron camera (housing channels, #7–#10).

However, the analysis is based on the assumption of uniform neutron emission on an MFS. There are several reasons why uniformity cannot be assumed. Non-uniformity on the MFS, caused by trapped particles, has been observed in JET [2]. Other interesting phenomena, such as selective production of trapped particles by ICRF, selective loss of energetic ions in a $\chi-\rho$ space induced by MHD, and redistribution of ions during sawtooth oscillation have also been reported. If these phenomena occur in ITER, it cannot be distinguished by 20 chords of RNC and a compact in-plug neutron camera.

To obtain the two-dimensional tomography of the neutron/alpha birth profile, and to distinguish the non-uniformity on the MFS, the divertor vertical neutron camera (DVNC) was proposed by Krasilnikov, Walker *et al* [13, 15]. The concept of DVNC is shown in figure 3.
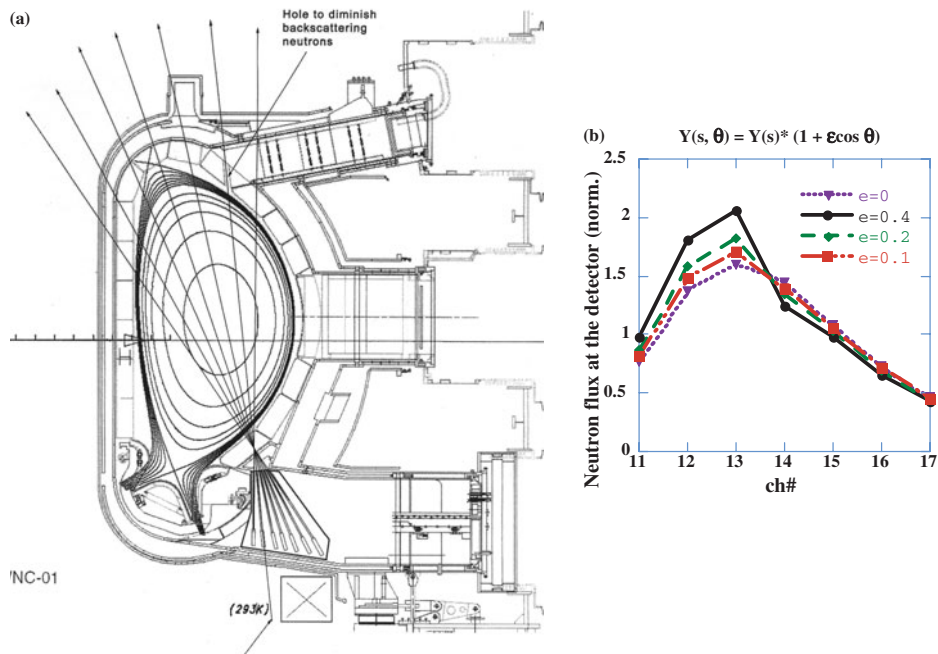
Figure 3. (*a*) Additional viewings (DNC) are proposed by NWG (Krasilnikov *et al*). (*b*) Neutron flux at the detectors in DNC. Non-uniformity on the MFS, caused by trapped particles, can be distinguished by seven additional chords of the divertor camera.

The concept of the DVNC is currently under study. There are several issues to be addressed. It is necessary to show that there will be significant asymmetries under ITER conditions and that the camera can measure them. There are also several difficult interface issues that have to be resolved. In addition, the tomography analysis technique should be further developed. The JET KN3 profile monitor uses two-dimensional tomography employing a hybrid pixel/analytic algorithm [2], which involves poloidal Fourier analysis and radial Abel inversion, starting from the outside and working inward.

Figure 3 shows neutron flux at the detector positions of the additional seven chords of DVNC when non-uniformity on the MFS of the form of $Y(s, \theta) = Y(s) (1 + \varepsilon \cos \theta)$, where $\varepsilon = 0.1, 0.2, 0.3$, and 0.4, is assumed. Local emissivity of 10% enhancement in poloidal distribution can be identified. It can be resolved with a poloidal angle resolution of 45° if the enhancement is higher than 40%.

5. Confined alpha measurement

Measurement of confined alpha particles is a large challenge in ITER. Several measurement methods have been proposed and their feasibilities were studied, but as yet none of these methods are satisfactory. As alpha particles are confined in the plasma, an active method should be used to obtain spatial information, which has attracted a great deal of attention from the viewpoints of transport studies, ITB studies, and alpha particle-driven and/or pressure-driven instabilities. Velocity distribution is also important for analyses of Alfvén instabilities.

One of the active methods currently in use is collective thomson scattering (CTS). Several approaches have been proposed. Kondoh *et al* [16] proposed use of a CO_2 high power laser (50 J, 10 Hz) with a scattering angle of 0.5° injected from the divertor port. The main difficulties

arise due to stray beams. An experimental study of the feasibility of this method is currently in progress at JT-60U. Bindslev proposed launching of 50–65 GHz radiation from a tuneable gyrotron and receiving from the top and bottom of a single equatorial port. This approach has already shown actual results in JET and TEXTOR [17]. Although further advanced studies on the operational window are required, it probably will meet the requirements. Launching 1–2 MW at 170 GHz in the O-mode from an equatorial port and collecting the scattered radiation from the upper port was proposed by Tartari. In this method, the ECE background might cause problems. In CTS measurement, the velocity distribution of ions is obtained. The major concern is whether it is possible to discriminate alpha particles from the heating beam particles with similar velocity. The discrimination may be possible by measuring their characteristics in pitch angle distribution.

There have been several proposals based on charge exchange recombination spectroscopy (CHERS). A method that uses a heating beam (Krasilnikov, von Hellermann) [18] could be applied for measurement of high energy (0.8–2.4 MeV) alpha particles moving in the direction close to the heating beam because the charge exchange cross-section decreases rapidly as the energy of relative motion of beam deuterons and alpha particles increases above 100 keV. Application of this method in ITER looks questionable due to the expected low signal-to-background ratio. This method is more promising for fast beam deuteron measurement [18]. The method that uses the diagnostic neutral beam (DNB) (von Hellermann, Tugarinov *et al*) might be used for thermalized alpha particle measurements. Due to the strong beam attenuation, the measurable region is limited to $r/a > 0.6$. A method that uses a gas jet for measurement of the outer region has also been proposed. In this method, plasma perturbation should be studied carefully. Charge exchange neutralization with high-energy neutral beams was proposed by Sasao *et al* [19]. This method uses a tangential ^{3}He beam with energy of 0.8–1.5 MeV injected from port 6. This method can only be realized when this port is available. In addition, activity on intense beam development is required.

Alpha knock-on measurements are an indirect method using elastic scattering between alpha particles and fuel ions producing energetic deuterons or tritons. One proposal is to measure knock-on ions neutralized by the 1 MeV D^0 beams (Fisher *et al*) or by electron capture from intrinsic impurities (Petrov *et al*). In both methods, fast neutrals are analysed by NPA. Stripping foils can be used to separate energetic D^+ from He^{2+}. Calculations for ITER show NPA count rates up to $10^4 \, s^{-1}$ for deuterons of $E > 1$ MeV.

Another approach, which is actually the origin of this method, is to measure the neutron high-energy tail produced by alpha knock-on energetic ions [20]. The neutron high-energy tail can potentially be measured using a high count rate neutron spectrometer, such as a magnetic proton recoil (MPR) spectrometer or bubble detectors. Other concepts of high count rate neutron spectrometers are also under investigation. One potential way to install MPR on ITER is alongside the neutron camera. Actually, alpha knock-on neutrons were measured successfully at JET by MPR [20]. Again, the discrimination of alpha knock-on from beam particle knock-on should be studied carefully.

Alpha particle measurements by means of gamma-ray spectroscopy using ^{9}Be$(\alpha, n\gamma)^{12}$C and ^{10}B$(\alpha, p\gamma)^{13}$C reactions was proposed by Kiptily *et al* [21]. This is a passive method. It is necessary to know the radial distribution of Beryllium ions to obtain spatial information, and velocity information will not be obtained.

6. Lost alpha measurement

Localization of alpha particle bombardment on the first wall surface was reported by Konovalov [22] in 2000. The loss location is about 200° in poloidal angle with toroidally enhanced
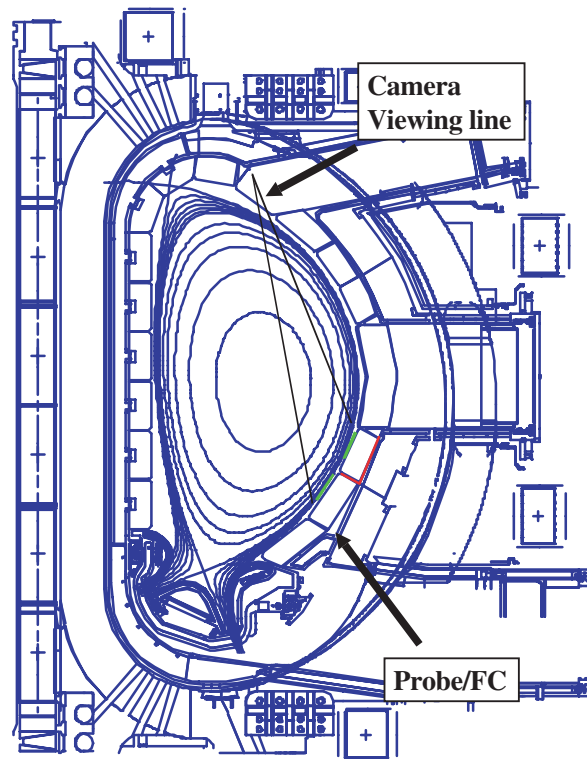
Figure 4. Geometry of lost alpha measurement.

bombardment between adjacent TF coils. However, there are several factors that perturb the alpha deposition profiles on the wall, such as change of q-profiles, the electric field, MHDs, etc. Therefore, it is important to monitor the bombardment location (loss imaging) not only for machine protection, but also for the study of loss mechanism. Measurement of the pitch angle and energy distribution of lost alphas and their temporal behaviour during MHD is essential to understand the underlying physics.

An IR camera can be used to monitor loss imaging. The possible geometry of this slow but robust method is shown in figure 4. Note that there is no discrimination of alpha signals from other ions. Camera imaging of scintillators fixed on the FW, as proposed by Sasao *et al*, will provide a bombardment image enhanced by alpha particles. Ceramic scintillators might be used to enhance alpha particle signals from background. A tilted surface will also help to discriminate alpha signals.

Candidate measurement tools for time-resolved pitch angle and energy measurement of lost alphas include Faraday-cup and scintillator probes. As shown in figure 4, a suitable position for these probes is between the blanket gap. Working models are currently in preparation for examination at JET. Neutron-induced noise on the Faraday-cup probe has been examined theoretically and is about 2% against maximum loss. Dummy probes are necessary. RIC and RIEMF might be problems for current measurement in the nanoamphere range. Twisted cables should be tested. In addition, a cooling system should be designed for the scintillator, because they will be exposed to temperatures above 300°C.

Gamma-ray spectroscopy placed on the first wall using the ^{10}B$(\alpha, p\gamma)^{13}$C reaction was proposed by Kiptily *et al*. The geometry for detection has not yet been examined.

7. Summary

For fusion product measurement on ITER, seven sub-systems are designed: a RNC, a VNC, in-vessel neutron flux monitors, ex-vessel neutron flux monitors, neutron and gamma spectrometers, neutron activation methods, and lost alpha detectors. As to the total neutron source strength and neutron fluence on the first wall, the measurement requirement of ITER will be met by appropriate choice of detectors, cross-checking among sub-systems, and careful calibration. The neutron emission profile will be obtained by assuming that it is a function of the MFS. Further investigations to improve performance are currently underway.

Neutron emission rate (time response) measurement for burn control and MHD studies will have the 10 MHz capability, achieved by using specially developed high-performance ^{238}U chambers.

The neutron/alpha birth profile can be obtained with the assumption of its uniformity on MFS by the addition of eight viewing chords of the compact in-plug neutron camera. Deviation of neutron source from uniformity on MFS can be detected with a poloidal angle resolution of $45°$ by the addition of seven neutron collimators viewing plasma from the divertor region.

The measurements of confined alpha particle distributions and escaping alpha diagnostics are still difficult, and several proposals to overcome this problem are currently under examination.

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