Status of ITER Neutron Diagnostic Development

M. Sasao 2), A.V. Krasilnikov 1), Yu.A. Kaschuck 1), T. Nishitani 3), P. Batistoni 4), V.S. Zaveryaev 5), S. Popovichev 6), T. Iguchi 7), O.N. Jarvis 6), J. Källne 8), C.L. Fiore 9), A.L. Roquemore 10), W.W. Heidbrink 11), R. Fisher 12), G. Gorini 13), A.J.H. Donné 14), A.E. Costley 15), and C.I. Walker 16)

1) SRC RF TRINITI, Troitsk, Russian Federation;
2) Tohoku University, Sendai, Japan;
3) JAERI, Tokai-mura, Japan;
4) FERC, Frascati, Italy;
5) RRC “Kurchatov Institute.”, Moscow, Russian Federation;
6) Euratom/UKAEA Fusion Association, Culham Science Center, Abingdon, UK;
7) Nagoya University, Nagoya, Japan;
8) Uppsala University., Uppsala, Sweden;
9) PPL, MIT, Cambridge, USA;
10) PPPL, Princeton, USA;
11) UC Irvine, Los Angeles, USA;
12) GA, San Diego, USA;
13) Milan University, Milan, Italy;
14) FOM-Rijnhuizen, Netherlands;
15) ITER IT, Naka Joint Work Site, Naka, Japan;
16) ITER IT, Garching Joint Work Site, Garching, Germany.

e-mail contact of main author: anatoli@triniti.ru

Abstract. Due to the high neutron yield and the large plasma size many ITER plasma parameters such as fusion power, power density, ion temperature, fast ion energy and their spatial distributions in the plasma core can be well measured by various neutron diagnostics. Neutron diagnostic systems under consideration and development for ITER include: radial and vertical neutron cameras (RNC and VNC), internal and external neutron flux monitors, neutron activation systems and neutron spectrometers. The two-dimensional neutron source strength and spectral measurements can be provided by the combined RNC and VNC. The neutron flux monitors need to meet the ITER requirement of time-resolved measurements of the neutron source strength and can provide the signals necessary for real-time control of the ITER fusion power. Compact and high throughput neutron spectrometers are under development. A concept for the absolute calibration of neutron diagnostic systems is proposed. The development, testing in existing experiments and the engineering integration of all neutron diagnostic systems into ITER are in progress and the main results are presented.

1. Introduction

ITER will be the first burning plasma experiment with collective behaviour of the alpha particles and other fast and thermal ions. A wide range of plasma parameters must be measured to reach the ITER programmatic goals [1]. Due to the high neutron yield and the large plasma size many ITER plasma parameters, such as fusion power, power density, ion temperature, fast ion energy and their spatial distributions in the plasma core, can be well measured by means of neutron diagnostics. A set of neutron diagnostics is planned for ITER to meet the specified measurement requirements [2]. In comparison with present-day experiments, the neutron diagnostics in ITER will be applied in a much more severe nuclear environment. The necessity to use a massive radiation shielding strongly influences the diagnostic designs, determines angular fields of view of the neutron cameras and spectrometers and gives rise to unavoidable difficulties in the absolute calibration [3,4].

Neutron diagnostic systems under consideration and development for ITER include: radial (RNC) [5,6] and vertical (VNC) [7] neutron cameras, internal (INFM)[8,9], external (ENFM) [10-12] and divertor [11] neutron flux monitors, neutron activation systems [13-15] and neutron spectrometers [16-21].

2. Neutron diagnostic subsystems and measurement requirements

The plasma parameters to be measured in ITER with the required accuracies, ranges of measurements and resolutions have been determined. All parameters to be measured are categorized into three groups according their role: (1a) measurements for machine protection and basic control, (1b) for advanced control, and (2) for performance evaluation and physics. The measurement specifications related to neutron diagnostics are shown in Table 1. The detailed requirements for the fast ion energy and two-dimensional (2D) spatial distribution measurements in the plasma core, especially during Alfvén eigenmodes (AE), fishbones and other MHD activity, are still under discussions [22]. The systems currently considered or included in the ITER neutron diagnostics set are presented in Table 2.

Table 1. ITER measurement requirements for parameters measured by neutron diagnostics

	Category	Parameter	Parameter range	Spatial resolution	Time resolution	Accuracy
1	1a	Fusion power or Total neutron flux	≤ 1 GW 10^{14} - 5×10^{20} n s^{-1}	integral	1 ms	10 %
2	1b	Neutron/α source profile	10^{14}-4×10^{18}ns^{-1}m^{-3}	a / 10	1 ms	10 %
3	1b	Ion temperature profile	0.5 – 40 keV	a / 10	100 ms	10 %
4	1a	n_T / n_D in plasma core	0.1 – 10	a / 10	100 ms	20 %
5	1b	Neutron fluence on the first wall	0.1 – 1 MW y m^{-2}	~ 10 locations	10 s	10 %
6	2	Confined α-particles energy and spatial distributions	0.1 – 4 MeV (0.1–2)$\times10^{18}$ m^{-3}	a /10	100 ms	20 %
7	2	Fast ion energy and spatial distribution	TBD	TBD	TBD	TBD

Table 2. ITER neutron diagnostic systems

	System	Parameters
1	Radial Neutron Camera (RNC)	1,2,3,5,6,7
2	Vertical Neutron Camera (VNC)	1,2,3,5,6,7
3	Micro-fission chambers (MFC, INFM)	1, 5
4	External Neutron Flux Monitor (ENFM)	1
5	Neutron Activation System (NAS)	1, 5
6	Divertor Neutron Flux Monitor (DNFM)	1, 5
7	Large Neutron Spectrometer (LNS)	1, 4, 6, 7
8	Compact Neutron Spectrometers (CNS)	1,2,3,5,6,7
9	Knock-on Tail Neutron Spectrometer (KNS)	6, 7

Prototypes of almost all the neutron diagnostic systems envisaged for ITER have been successfully applied in experiments on large tokamaks: TFTR (VNC, NFM, CNS), JET (RNC, VNC, NFM, LNS, CNS, KNS), and JT-60U (VNC, NFM, CNS, MFC). However, in ITER the design of the neutron diagnostic systems must accommodate their long time operation in much higher neutron fluxes and fluences (5 and 10^4 times higher respectively than in JET), and overcome the constraints caused by the necessity to use massive radiation shielding. The requirement for a large thickness of radiation shielding around the plasma and the available port opening restricts the possible plasma coverage by the RNC and possible VNC lines of sight. This has a large effect on the accuracy of the fusion power calibration and on the spatial resolution of the neutron source profile measurements and requires that special measures are taken. Absolute calibration of the neutron flux monitors will also be a difficult task in ITER due to the thick shielding between them and the plasma. More detailed discussions about the status and development issues of individual neutron diagnostic systems are included in the following sections .

3. Radial and Vertical Neutron Cameras

The necessity of 2D neutron profile measurements in ITER arises from the fact that, due to fast ion components, the neutron source profile may not be a constant on magnetic surfaces, especially during ion cyclotron resonance heating, neutral beam injection, sawteeth oscillations, AE modes and in advanced tokamak regimes with strongly negative magnetic shear. The JET results [23,24] have clearly demonstrated the influence of fast particle populations on the 2D neutron emission profile. The 2D neutron source strength and spectral measurements in ITER with the required temporal and spatial resolutions can be made by joint application of RNC [2,5,6], compact in-plug CRNC [7] and VNC [2,7].

The principal RNC design was proposed for ITER-98 [5]. There were no major changes in the RNC design [6] for the reduced size ITER (Fig. 1). The RNC consist of 12×3 fan-shaped arrays of neutron collimators viewing the plasma through a special shielding plug in an equatorial port. All channels penetrate through the vacuum vessel, cryostat and biological shield and cross through a single point**.** Stainless steel windows are used as vacuum barrier. Three separate collimator flight tubes (with different diameter in the range 10 - 40 mm) and detector housing for each poloidal angle offer a variety of choices of collimator/detector combinations to increase the dynamic range of RNC measurements. The 12 lines of sight of the RNC are equally spaced (by 30 cm at the plasma centre), symmetrically with respect to plasma equatorial plane. The vertical extension of the plasma coverage by the RNC is 3.3 m (from –0.5×b to 0.5×b, where b is the minor plasma radius in the vertical direction). Due to the limited plasma coverage by the RNC the fraction of neutrons not seen by the camera, because they are emitted from $\rho>0.5$ magnetic surfaces, could reach 10–20% depending upon the neutron source profile. As a result the channels of the RNC directed to the port cell cannot provide the fusion power or total neutron source strength measurements with accuracy 10% in the case of rather flat emission profiles [6].

To provide full plasma coverage in the vertical direction, additional channels placed inside equatorial port plug #1 (same port as standard RNC) are required [7]. These channels consists of a stainless steel plus water shielding block containing nine collimators with length ~140 cm and diameter 4 cm. Four collimators view the plasma above the main external RNC fan of view and another four –view below (see Fig.1). In this way, the additional channels will provide the plasma coverage for $0.5<\rho<0.9$ in the upper and lower parts of the plasma. A ninth collimator viewing the plasma center will be used for cross calibration of the external channels and the additional channels. The detector modules of the additional channels will be placed behind the collimators inside an in-plug shielding block. They will be ~35 cm long and have a diameter of 6 cm. Due to the strong restriction in maintenance the most robust and radiation resistant detectors are under consideration for this application.

Several possible arrangements of the vertical neutron camera have been studied. A conceptual design with all VNC flight tubes viewing the plasma through a single vertical port was proposed for ITER-98 [2]. Unfortunately, the existing ITER design does not have vertical ports, so first a VNC concept with neutron collimators distributed over four different poloidal cross sections viewing the plasma from the top was proposed. This VNC design had interfaces with several tokamak systems including the blanket, vacuum vessel, inter-coil structure, correction coils, cryostat thermal shield, ribs and bridge structure. One of the major problems of this VNC design is related to the expected uncontrollable changes of the effective collimator cross sections, and hence the calibration coefficients, due to relative movement of the ITER components interfacing with VNC flight tubes during tokamak operation.

The possibility to arrange VNC collimators inside the upper port plugs (UVNC) is under analysis. Unfortunately, the space is limited and so the lengths of UVNC in-plug collimators will be short, and it will probably not be possible to achieve the required collimation. In order to increase the effective length of the collimators the possibility to arrange collimating openings in blanket modules #11 and 12 and in the vacuum vessel is under consideration. The concept of a UVNC arrangement in two separate upper ports is shown in Fig.1 by indicating the possible lines of sight that might be achieved.

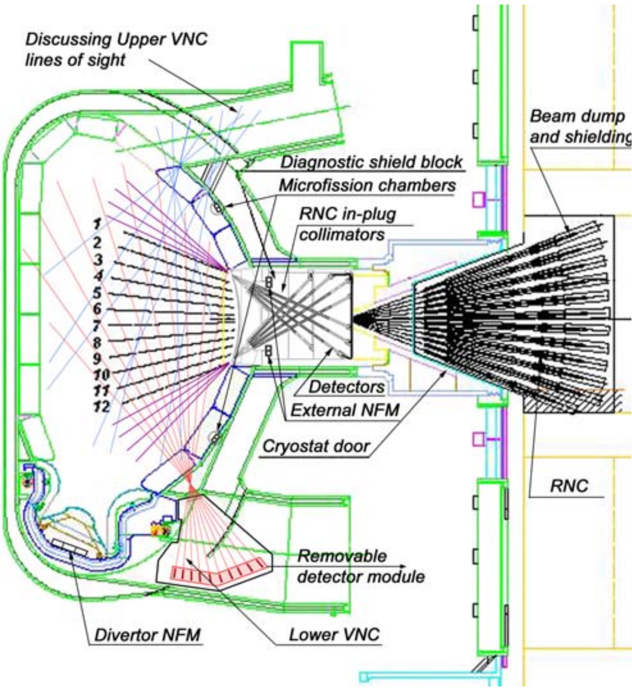

Fig 1 Arrangement of ITER neutron diagnostic systems integrated from several toroidal plans.

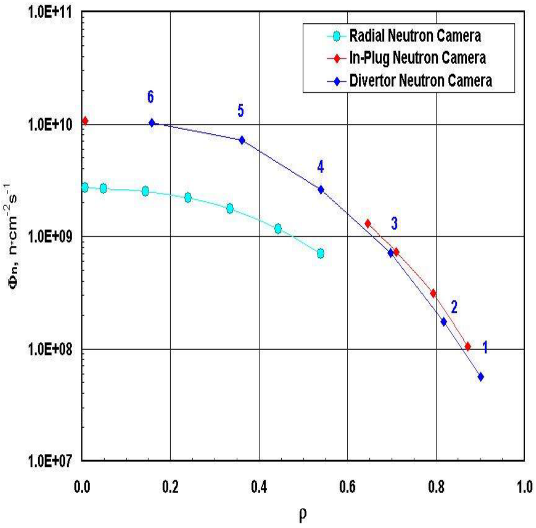

Fig.2 Un-scattered neutron fluxes in detector locations for $P_{fus} = 400$ MW and RNC collimators ∅ 25 mm, In-plug RNC and LVNC collimators ∅ 35 mm. Arrangement is shown on Fig.1

Taking into account the expected performance difficulties of a distributed VNC and the issues of the UVNC performance, a concept for a Lower VNC is now being studied. The main concept of the LVNC arrangement is to place the VNC shielding module inside a divertor port [7] with collimators viewing the plasma through the gaps in the divertor cassettes, the blanket modules and the triangular support. The LVNC version shown in Fig.1 has 10 collimators with diameter 35 mm and length ~150 cm. The detector block is placed behind the collimators and is removable for maintenance.

Neutron fluxes at the detector positions integrated over the respective viewing cones of the external and internal channels of the RNC and the LVNC collimators [25] are shown in Fig.2. These data were obtained for a neutron source profile calculated by a 1.5D transport ASTRA code [26] for ITER reference scenario #2 (Q=10, P_{fus}=400 MW, I_p=15 MA). Detectors that are under consideration for application in the ITER neutron cameras are presented in Table 3 along with their performance characteristics.

Table.3 Detectors considering for application in ITER neutron cameras

Detector	Housing $\varnothing \times l$, cm^3	Sensitivity, cm^2/n	Dynamic range for 1 ms time window.	Life time	Neutron Camera
			For maximum flux 5×10^9 n/cm^2/s		
Natural Diamond Detector (NDD) [17] – compact spectrometer	∅1×2	2×10^{-5} for single NDD	20 (for 100 ms time window)	10^4 full power seconds	RNC ext RNC int LVNC
NDD – flux monitor [17, 27]	∅1×2	10^{-3} for single NDD $2n\times10^{-3}$ for n NDD+radiator	50 100 × n	2×10^6 full power seconds ~10^6 full power seconds	RNC ext RNC int VNC
CVD diamond detector [28]	∅3×3	2×10^{-2} for detector ∅25×0.2 mm^3	1000	2×10^6 full power seconds	RNC ext RNC int VNC
Stilbene / NE-213 compact spectrometer [18,19] /monitor [29]	∅5×40	10^{-3}-1	10 (Digital spectrometer for 100 ms) 100 (Digital monitor)	?	RNC ext
U-238 fission chamber [30]	∅3×35	3×10^{-4}	20	forever	RNC int VNC
ZnS	∅5×30	10^{-3}-10^{-1}	1	?	RNC ext
Fast Plastic Scintillator.	∅5×30	10^{-3}-1	100-300	?	RNC ext

4. Neutron Flux Monitors

The ITER neutron flux monitors system will include Internal NFM, External NFM and Divertor NFM. The INFM will consists of set of detector blocks containing an ^{235}U micro-fission chamber (MFC) and a complete similar fissile-material-free “blank” detector and will be installed inside the vacuum vessel behind the blanket modules #11 and #16 (see Fig.1) in two toroidal cross section for redundancy [8,9]. The poloidal positions were selected on the basis of Monte Carlo N-particle (MCNP) transport calculations to make the INFM almost insensitive to changes in plasma position and peaking factor. The “blank’ detector will be used to eliminate γ-rays and electrical noise. Pencil size commercially available MFCs with 10 mg of ^{235}U yielding a fission reaction rate of ~3×10^{8} s^{-1} in a total neutron flux of ~3×10^{11} s^{-1} at maximum fusion power will be used in counting mode up to a count rate of 10^6 s^{-1} and in Campbelling mode from a count rate of 10^5 s^{-1}. So the ITER requirements of fusion power measurements with 1 ms time resolution and 10% accuracy will be fulfilled in a dynamic range of 3×10^3. The dynamic range could be increased by the application of FC with a larger amount of ^{235}U material. A set of MFC prototypes were tested for vacuum leak rate of the chamber with the mineral insulated cable, resistances and mechanical strength up to 50 g acceleration to meet design criteria. On the basis of an MFC test at a ^{60}Co γ-ray facility it was estimated that the γ-ray influence will be less than 0.1% of the neutron signal in current mode. The MFC linearity in a neutron flux dynamic range of 10^7 was demonstrated on a fission reactor [8] and during tests on JT-60U [31]. The MFC linearity was also confirmed in the temperature range 20-250^0 C in DT neutron fluxes of the Fusion Neutronic Source [9].

A number of ENFM conceptual designs were developed [10-12]. The integration of NFM detector blocks consisting of a set of ^{235}U and ^{238}U FCs of different sensitivity into the stainless steel + water shielding modules of the limiter moving mechanism inside equatorial ports #8 and #17 was performed, taking into account the neutron transport calculations with a MCNP code [11]. ENFM detector blocks based on a set of ^{235}U FCs of different sensitivities surrounded by beryllium and graphite moderators were also proposed for integration into limiter port (equatorial #8 and #17) plugs and equatorial port #1 [12]. Prototypes of detectors consisting of two FCs containing 1.5 g and 2 mg of ^{235}U and having sensitivity to thermal neutrons of ~1.3 cm^{-2} and ~1.6×10^{-3} cm^{-2} and two FCs containing 1.5 g and 2 mg of ^{238}U and having sensitivity to fast neutrons of ~10^{-3} cm^{-2} and ~10^{-6} cm^{-2} were manufactured [11, 30]. To provide as large as possible a dynamic range of the measurement of the neutron source strength and its absolute calibration it has been suggested [11] to locate also a detector module of a NFM inside a divertor cassette (see Fig.1), where the neutron flux will be ~20 times higher than in other possible NFM positions. The design of this DNFM detector module is based on combined application of two ^{238}U and two ^{235}U FCs. The amount of ^{235}U and ^{238}U fissile material will be in the range of a few mg – few grams to provide an adequate overlap of the linear operation ranges and allow for the FC cross calibration to one another. The FCs will operate in counting, Campbelling and current modes. The ^{235}U FCs will be surrounded by a water moderator to provide a flat energy response. The ^{238}U FCs will be surrounded by a B_4C screen of thermal neutrons. "Blank" detectors will be included into the detector module to identify gamma-ray and noise related signals. Three detector modules will be installed in two toroidal cross sections for redundancy. The DNFMs will meet the ITER requirements of time-resolved neutron source strength measurements in the dynamic range 10^{14}-5×10^{20} n/sec with 1ms temporal resolution and 10% accuracy and can provide the signals necessary for real time control of the ITER fusion power.

5. Neutron activation system

The neutron activation system will be dedicated to the robust fusion energy measurements for all plasma conditions and to obtain an absolute calibration for all other neutron diagnostics. One planned system [13] is similar to those successfully used at JET and TFTR and is based on the pneumatic transfer of a set of encapsulated activation samples from the irradiation station to remote counting stations, where the sample activation will be measured. The irradiation stations will be located inside some of the permanent filler modules and view the plasma from the outside wall, inside wall, top and bottom through gaps between blanket modules. Transfer lines driven with He gas at ~0.06 MPa will be arranged in upper ports #6 and 11, equatorial ports #7 and 17 and divertor ports #6, 12 and 18. A neutron activation system based on flowing water which will provide a time resolution of ~50 ms with ~1 s delay time of the measurements is also being designed [14]. Water pipes with ∅20 mm will be arranged in upper ports #1 and 5 and equatorial ports #7 and 17. A detailed MCNP analysis will be used to establish the relation between the total neutron yield and the neutron fluence and spectrum in the point of irradiation.

6. Neutron spectrometers

Compact neutron spectrometers (diamond [17], stilbene [18] and NE-213 [19] detectors) placed inside the collimators of the RNC and VNC will provide the measurements of ion temperature in the range T_i>5 keV, fast deuteron and triton energy distribution and poloidal rotation profiles. Neutron spectrometry using the magnetic proton recoil technique [16] is also under consideration for n_T/n_D ratio, plasma toroidal rotation and fast ion energy distribution measurements. Possible approaches to neutron knock-on tail measurements, which should provide information about the confined-alpha-particle density and energy distribution, include an MPR [16], bubble chamber neutron spectrometers [20], and recoil tracks in nuclear emulsions [21]

7. Neutron diagnostic calibration

A strategy for the absolute calibration of the neutron diagnostic systems [3,4] is being developed. It includes absolute calibration of all detectors at the manufacturer and calibration on site in a purpose built laboratory. Several different methods will be used for absolute *in-situ* calibration of the fusion power and power density measurements.

The first of them will be based on the absolute *in-situ* calibration of the most sensitive RNC, VNC and NFM detectors after their installation on ITER, using a radionuclide neutron source and a DT neutron generator having a neutron output of about 5×10^{10}-10^{11} neutrons/s. The source will be moved inside vacuum vessel in toroidal and poloidal directions. The application of an additional neutron source based on a target irradiated by the ITER deuterium neutral beam has also been proposed [4]. The most suitable period for in-situ calibration will be the end of Hydrogen Plasma Phase, when the in-vessel system characterization and tests will be completed. Careful characterization of the neutron generator emission strength, directionality, and the energy spectrum must be made before the calibration. This method also involves a detailed MCNP analysis of the neutron fluxes and spectra in the RNC, VNC and NFM detector positions and cross calibration of the least sensitive detectors against more sensitive calibrated detectors using the plasma as the source. The cross calibration is necessary because it is impossible to make an absolute calibration over the full dynamic range. In addition, some of the calibrated neutron detectors and ITER construction elements that have an influence on the calibration coefficients maybe changed or modified during tokamak operation and a new *in-situ* calibration will not be possible.

The second method to absolutely calibrate the RNC and VNC could be based on a characterization and detailed MCNP calculations for the compact spectrometers. The compact spectrometers must be characterized on accelerator facilities and/or 2.5 and 14 MeV neutron generators in terms of absolute efficiency and neutron response function for different neutron and gamma energies. The MCNP calculations will provide the neutron flux and spectrum at the detector locations. In such a way the calibration factor can be determined for all compact spectrometers. Gamma sources, 2.5 and 14 MeV neutron generators and/or AmBe n/γ sources should be build in the detector or should be periodically applied during maintenance for energy calibration and stability control of the compact spectrometers.

Another independent method to absolutely calibrate the fusion power will be based on the foil activation system. The advantages of this method are the intrinsic linearity and time stability. Its main weakness is the necessity of the essential MCNP calculations, especially for the region close to the irradiation stations. At ITER the irradiation station cannot be located close to the first wall, so the MCNP calculations will be time consuming and their accuracy will depend strongly on the machine components and detailed modeling around the irradiation stations. Using activation foil materials with a range of threshold energies will increase the confidence of the MCNP calculations. The neutron activation system will be used to check any change of calibration during ITER operation. In addition, it will provide the linearity and stability of the NFMs and the neutron cameras.

8. Conclusions

The ITER neutron diagnostic systems have been selected, conceptually designed and integrated into the machine design. The main characteristics of the systems are well determined and the ITER measurement requirements for parameters accessible with neutron diagnostics can be largely met: fusion power, neutron/α source profile, neutron fluence on the first wall and ion temperature profile in the range $T_i>5$ keV. Neutron cameras will provide a measurement of the 2D spatial distribution of the neutron emission and in particular the fast ion energy and 2D spatial distributions. Methods of neutron spectrometry for the n_T/n_D ratio and for the energy and spatial distribution of confined α-particles are under study.

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