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Report

Calibration of ITER neutron diagnostics

Final Report

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CALIBRATION OF ITER NEUTRON DIAGNOSTICS

Contents

Executive Summary

Neutron Diagnostics are essential for the accurate measurement of neutron emission and fusion power in ITER. These parameters play a key role in machine protection as well as plasma optimisation and physics understanding. Demonstrating confidence in the accuracy and reliability of the measurement of fusion power will be important in gaining approval for ITER to operate with tritium. The required measurement accuracy is 10% and experience in TFTR and JET shows that this is possible but very demanding. Statistical errors in the neutron measurements are relatively small (typically 1%) and the main limitation on the overall accuracy is due to systematic errors in the calibration.

A Neutron Calibration Task Team with representatives from the ITER Organisation and the Domestic Agencies was set up in March 2013 to advise IO on the calibration requirements for neutron diagnostics. The main motivation for the study was the need to clarify the requirements for neutron calibration facilities on the ITER site and to refine the planning for the in-vessel calibrations. The study also looked at the requirements for calibration of the neutron diagnostics by the DAs before delivery to the ITER site and the requirements and priorities for neutron transport calculations in support of the diagnostic design and calibration. It is convenient to divide the calibration of the neutron diagnostics into the following steps:

1. The calibration and characterisation of individual neutron diagnostic systems and detectors by DAs before delivery to the ITER site. Different DAs will be responsible for the detailed design and manufacture of the neutron diagnostics. The requirements and specifications for the calibration procedures by the DAs (and/or by their suppliers) need clarification to specify the required calibration accuracy and neutron energies etc., and to ensure overall consistency in the calibration standards for the neutron diagnostics.

2. The pre-delivery calibration of the neutron diagnostics by the DAs should be sufficient that further calibration or re-calibration of the neutron diagnostics is not required at ITER. However, functional checks will be required before integration into the machine assembly and at various stages during the installation of the neutron diagnostics into the ITER machine. There is a large number of neutron detectors (including some spare detectors) to be checked. Some of the functional tests will require dedicated and shielded areas at (or close to) the ITER site. In general, these tests will involve the use of relatively weak radioactive sources, although some stronger sources may be required for functional tests of the less sensitive detectors. There will also be a requirement for the safe and secure storage of fission chambers (containing ^{235}U and ^{238}U regulated materials), for storage casks for the radioactive and neutron calibration sources used for the functional tests, for the storage of the more powerful ^{252}Cf sources and for functional testing of the neutron generator tubes required for the in-vessel calibration. These activities require a dedicated area on the ITER site. It may be possible to use the Hot Cell, provided it is available at a sufficiently early stage. There will also be a requirement for some less frequent but more sophisticated calibration procedures using the "CEZANE" and "AMANDE" facilities operated by IRSN on the adjacent Cadarache site. These options need further study.

3. Extensive numerical computations of neutron transport are required to support the design of the neutron diagnostics and their calibration. Numerical calculations of the neutron transport combined with the absolute calibration and characterisation of the neutron detectors by the DAs will be an essential part of the calibration process, but this will not be sufficient to guarantee the 10% accuracy required for the neutron flux and fusion power measurements.

4. In-vessel calibration using relatively powerful neutron sources will be required when the machine assembly is fully complete and immediately before the start of operation in deuterium and tritium. The in-vessel calibration is an essential step to ensure the required accuracy in the neutron measurements. It will always be under pressure to take as short a time as possible and, without careful planning and preparation, the calibration of the neutron diagnostics could involve an extensive, and unacceptably long, period of in-vessel work. The calibration sources need to be compact in order to avoid complications due to self-shielding and there are non-trivial problems of deploying and supporting the sources inside the ITER vacuum vessel. The in-vessel calibration of the ITER neutron diagnostics requires two distinct campaigns. The first campaign (for d-d neutrons) will use a radioactive ^{252}Cf source for simplicity and reliability and should take place at the end of Assembly Phase II (i.e. towards the end of year 2 of the current ITER Research Plan). The second in-vessel calibration campaign (for d-t neutrons) will use a 14 MeV neutron generator tube and should take place at the end of the Pre-nuclear Shutdown (end of year 6 of the current ITER Research Plan). A provisional estimate is that each campaign will take approximately two weeks (assuming 2 shifts/day, 7 days/week) – but further study and detailed planning is required to confirm these estimates.

5. The neutron emission in ITER will span a range of seven orders of magnitude – from 10^{14} up to 10^{21} neutrons per second and this wide range requires detectors with different sensitivities. The most sensitive detectors will be calibrated directly with the in-vessel neutron sources before the start-up of d-d and d-t plasma operation. The less sensitive detectors will be cross-calibrated in situ as the neutron emission in ITER progressively increases. The Neutron Activation System will play a key role in maintaining accuracy and confidence in the calibration throughout the operating life of ITER.

Recommendations and Actions

1. Specify and agree with the DAs the calibration standards for the neutron diagnostics before delivery to ITER – in particular the required calibration accuracy and neutron energies.
2. Specify and agree with the DAs the neutron source strengths and energies that will be required for functional testing after delivery to the ITER site.
3. Clarify the requirements for functional testing, source storage etc. and other neutron testing facilities at the ITER site and identify suitable areas.
4. Discuss using the "CEZANE" and "AMANDE" metrology facilities on the Cadarache site for more sophisticated but less frequent requirements.
5. Re-design and optimise the position of the irradiation ends of the Neutron Activation System to improve the calibration accuracy and long-term robustness.
6. Agree priorities for the neutron transport calculations to support the neutron calibration.
7. Define source strengths and procurement times for the in-vessel calibrations.
8. Identify remote handling facilities and procedures for the in-vessel calibration. Design and procure any special equipment.
9. Include the in-vessel calibrations in the ITER Research Plan.

Introduction

Neutron Diagnostics are essential for the accurate measurement of the neutron emission and the fusion power in ITER – parameters that play a key role in machine protection as well as plasma optimisation and physics understanding. The neutron diagnostics will also be required for measuring various other important parameters including fusion power density, neutron and alpha source profiles, deuterium and tritium densities in the plasma core, ion temperatures, and the neutron fluence at the first wall, etc. The neutron emission in ITER will span a range of seven orders of magnitude, from 10^{14} up to 10^{21} neutrons per second. This wide range requires a series of detectors with a range of sensitivities. The accuracy specified for the measurement of the neutron emission is 10% with temporal resolution of 10^{-3} seconds and (where appropriate) spatial resolution of 20 cm (corresponding to one tenth of the plasma radius).

The full set of neutron diagnostic systems for ITER consists of:

1. Neutron Flux Monitors (NFM) installed in radial diagnostic ports – CN DA,
2. Divertor Neutron Flux Monitors (DNFM) installed under the dome of the divertor – RF DA,
3. Micro Fission Chambers (MFC) located between the blanket modules and the inner shell of the vacuum vessel – JA DA,
4. Neutron Activation System (NAS) with irradiation ends at various locations inside the vacuum vessel – KO DA,
5. Radial (RNC) Neutron Cameras (with in-port and ex-port lines of sight) – EU DA,
6. Vertical (VNC) Neutron Camera – RF DA,
7. High Resolution Neutron Spectrometer (HRNS) – EU DA.

The primary role of the Neutron Flux Monitors, Divertor Neutron Flux Monitors, Micro Fission Chambers and the Neutron Activation System is the measurement of the total neutron flux and the fusion power. The Radial and Vertical Neutron Cameras measure the spatial distribution of the neutron emission and the fusion power. The High Resolution Neutron Spectrometer measures the fuel ratio and the ion temperature. Accurate and reliable calibration of the neutron diagnostic systems is clearly very important to achieve the required accuracy of 10% for measurement of the neutron emission and fusion power. Statistical errors are relatively small (typically about 1%) and the main source of the overall error in the neutron measurements are systematic errors in the calibration. Experience in TFTR and JET shows that it is possible to achieve this degree of accuracy – but it will not be easy and requires very considerable care and effort. The fusion neutrons with initial energies of 2.5 or 14 MeV have to pass through the ITER shielding structure (diagnostic first wall, blanket, divertor modules etc.) before they reach the neutron diagnostic detectors – on the way the neutrons are scattered, attenuated and degraded in energy. The calibration is required to be able to relate the measured flux of degraded and scattered neutrons to the initial source of fusion neutrons.

In 2010, the Neutron Working Group of the ITPA Topical Group on Diagnostics carried out a preliminary study of the in vessel calibration requirements for ITER neutron diagnostics. The ITPA study estimated that the in-vessel calibration of the Neutron Flux Monitors, Neutron Cameras and the Neutron Activation System would take a minimum of 8 weeks dedicated access inside the Vacuum Vessel and would require neutron generators with source strength greater than 10^8 neutrons per second for d-d and greater than 10^{10} neutrons per second for d-t.

Following discussions with the Domestic Agencies, a small Neutron Calibration Task Team with experts from the DAs and IO was set up in March 2013 to take these studies a stage further and to advise the ITER Organisation on the calibration requirements for neutron diagnostics. The main motivation for the study was the need to clarify the requirements for neutron calibration facilities on the ITER site and to refine the requirements for in-vessel calibrations. The study also considered the requirements for calibration of the neutron diagnostics by DAs before delivery to the ITER site and the requirements and priorities for neutron transport calculations in support of the diagnostic design and calibration. The study, which was conducted mainly by remote participation, included a Workshop held at the ITER site on 14 & 15 October 2013 that served both as a plenary meeting of the Calibration Task Team and as an opportunity to open the discussion to independent experts.

Calibration Requirements at the Domestic Agencies

It is very important that the neutron diagnostics are fully characterised and calibrated by the DAs and/or their suppliers before delivery to ITER. The calibration requirements will depend on the specific type of detector and the application. The DAs and IO should agree the details for each diagnostic system as soon as possible with particular attention given to:

1. The range of neutron energies and calibration points.
2. Sensitivity to operating temperature and to magnetic fields.
3. How to include or simulate the effect of cables, connectors and electronics.
4. Provision of calibration reference point(s) so that simple functional checks on performance can be made after delivery to the ITER site.

Requirements for Testing after Delivery to ITER

As outlined in the previous section, the neutron diagnostics will undergo rigorous performance checks and will be fully calibrated, according to procedures approved by the IO, by the DAs before being shipped to ITER. The facilities on the ITER site will not provide for extensive calibration or re-calibration of the neutron diagnostics – testing after delivery should be limited to checking detector performance. Functional checks will be required before installation and there is a large number of detectors (including some spare detectors) to be checked. It is essential that the DAs should specify as soon as possible the energies and strengths of the sources that will be required for the functional testing at ITER. Some detectors will be embedded inside complex shielding structures (e.g. the port-plug section of the Radial Neutron Camera) and require suitable access holes for inserting neutron sources close to the detectors. There may be a limited requirement for more detailed measurements on a small number of diagnostic systems or individual detectors in cases, for example, where the functional tests show some disagreement with the calibration data supplied by the DAs. The testing requirements for the Neutron Activation System will be different from the other neutron diagnostics. Functional testing of the foil transfer systems will be necessary and the gamma detectors should be tested in the counting room facility assigned for the measurement of the activation foils.

The following table gives an overview of the pre-installation tests foreseen for each of the seven neutron diagnostic systems. The table shows the number of detectors at the current stage of design but this is a provisional number and may change during the detailed design. A simple minimum requirement for functional testing and characterization for each system is also indicated. These testing requirements are different depending on the type of detector involved.

Requirements for Pre-installation Functional Tests at IO

Diagnostic	DA	Number of Detectors	Functional Check	Characterization	Calibration issues
Micro Fission Chambers	JA	12	Alpha-particle signals / neutron response	Weak neutron source	Intrinsic background
Neutron Flux Monitors	CN	13	Alpha-particle signals / neutron response	Weak neutron source	Intrinsic background
Divertor Neutron Flux Monitors	RF	18	Alpha-particle signals / neutron response	Weak neutron source	Intrinsic background
Radial Neutron Camera	EU	104	Alpha-particle signals/ neutron and gamma responses	Detector dependent sources	Intrinsic background in fission chambers
Vertical Neutron Camera	RF	45	Alpha-particle signals/ neutron and gamma responses	Weak neutron source	Intrinsic background in fission chambers
Neutron Activation System	KO	4	Mechanical operation/gamma response	Dosimetry calibration sources	Background shielding assessment for counting room
High Resolution Neutron Spectrometer	EU	About 100	Neutron, gamma and alpha-particle responses	Pulse-height analysis/timing checks	

Some neutron diagnostics will require further functional tests at specified stages during the installation in order to check the correct installation and continuity of cables etc. All detectors will need to be tested end-to-end after installation is complete and, in the case of the Micro Fission Chambers, before installing the blanket modules. The objective is to confirm the discriminator settings for the fission chamber electronics. This requires placing a neutron source (typically a relatively weak Am-Be neutron source) adjacent to the detector and obtaining a gated pulse-height spectrum or taking a bias curve.

Requirements for Neutron Diagnostic Test Facilities at ITER

The following activities are expected:

1. Functional checks of neutron detector systems and individual detectors prior to their installation on ITER (i.e. checking that the performance still meets that determined by manufacturers).
2. Check on characterization of these detectors after reconstitution of complete systems after delivery.
3. Routine checks during installation to confirm continuity of cables, connectors etc.
4. Storage of fission chambers (containing ^{235}U and ^{238}U regulated materials) before installation and longer-term storage of some spare chambers.
5. Storage casks for low-level calibration sources for neutron tests and gamma-sensitivity.
6. Storage of powerful ^{252}Cf in-vessel calibration sources.
7. Operation of a low-strength accelerator-based neutron source (~1×10^7 n/s) for calibration and characterization purposes.
8. Final check of the high flux 14 MeV neutron generator ($\geq 1 \times 10^9$ n/s) to be used in the in-vessel calibration (the generator, with its support structure, will have been fully characterized before delivery).
9. Checks of practical issues with mock-ups for perceived issues due to temperature changes, etc., in alignments and material movements in ITER. These mock-up tests will require a working area where neutron scattering will be negligible.
10. Testing developments in the diagnostics for improving the measurement capability.
11. The neutron test facility might also be required to check the sensitivity of other diagnostic systems and detectors (i.e. non-neutron diagnostics) to radiation backgrounds.

The neutron calibration facilities under discussion here will not need to handle highly activated components removed from ITER after operational campaigns. Some of the equipment to be checked will be quite large (in particular, the Neutron Flux Monitors already integrated into Port Plugs, the Radial Neutron Camera and the Vertical Neutron Camera). Clearly, it would be most convenient for some of these requirements (in particular items 1 through 7 above) to have a facility on the ITER site. One option could be to use a dedicated part of the Hot Cell, provided it can be available sufficiently early before the installation of the diagnostics on the machine assembly. Another option might be the Port Plug Assembly area under discussion with CEA Cadarache. Some of the more sophisticated but less frequent requirements (items 8 through 10) could use the "CEZANE" and "AMANDE" metrology facilities on the Cadarache site.

Neutron Transport Calculations

Neutron transport calculations play an important role in the design and calibration of the neutron diagnostics. They help to determine the strategy of in-situ calibration, to assess the perturbation in the neutron source and activation of remote-handling tools, to calculate neutron and gamma spectra at detector locations, to estimate the effect of environment (temperature and magnetic field) on detector sensitivities, to evaluate the scattering from collimating channels etc. The most advanced and widely used 3D neutron transport tools are the Monte-Carlo codes (MCNP, MCNPX) and the deterministic code Attila. This report summarises the transport calculations needed for calibration of neutron diagnostics in ITER and allocates priorities.

In principle, there would be no need for in-vessel calibration of the neutron diagnostics if the neutron transport calculations were accurate enough and if the spatial profile of the plasma neutron source and the detector sensitivities were sufficiently well known. The crucial question is whether transport calculations can replace the in-situ calibration of the Neutron Flux Monitors and other neutron diagnostics. The major uncertainty factors in transport calculations using the Monte-Carlo method are:

- Approximations in modelling the geometry and components of ITER
- Uncertainty in the neutron emissivity profile
- Uncertainty in the amount of Uranium in the fission chambers
- Uncertainty in cross-section data
- Finite computing time - limited number of particle histories (statistical error)
- Neutron physics models applied in the code

It is difficult to quantify the uncertainty due to approximations in modelling the ITER geometry and hence this is the major factor for the inaccuracy of the calibration determined through transport calculations. The amount of uranium in the fission chambers is another uncertainty – this depends on the manufacturing process and has to be determined as accurate as possible. The uncertainties in the cross-section data used for the transport of neutrons are typically less than 5% for ITER relevant materials. Neutron physics models in MCNP are very well applied. The availability of super-computers has allowed the number of source particle histories to be increased substantially, but still it is a limitation for a deep penetration problem like the ex-vessel Neutron Flux Monitors. Considering all factors, transport calculations cannot replace the need for in-situ calibration – but they can help in optimising and reducing the time required for in-vessel calibrations. The following list of calculations required to support the calibration of neutron diagnostics is arranged in approximate order of priority:

1. **Calculations to determine temperature effects on cross-sections**: The in-vessel NFMs based on ^{235}U fission chambers will use neutron moderators such as water, graphite, beryllium etc., which will be at elevated temperatures during ITER operation but will be at room temperature during the in-situ calibration. The nuclei of these materials moderate the neutron energy by elastic scattering and this process is temperature dependent. Preliminary transport calculations using temperature dependent scattering cross-sections using a simplified spherical geometry indicate that there is a significant effect on detector sensitivity (typically 11% for beryllium and 5% for water) between a moderator at 127 C and at room temperature.
2. **Calculations to optimize functional testing of detectors:** Calculations to support the functional testing of detectors.
3. **Investigation of thermal expansion and mechanical movements:** Neutrons reach the detectors after passing through the massive material structures (port plugs, divertor cassettes, blanket modules etc.) surrounding the plasma. Some neutrons will reach the detectors by streaming through gaps between components and this effect can be very sensitive to small changes in the dimensions of the gaps due to thermal expansion and mechanical movement during ITER operation. The importance of these effects need quantifying by transport calculations.
4. **Background counts from γ-rays:** Fission chambers are sensitive to gamma rays as well as neutrons. Although the signals from gammas and neutrons can be distinguished electronically, there are problems due to pulse pile-up and it is very important to quantify the gamma background with the help of transport calculations.
5. **Time and source strength estimates for in-situ calibration:** Preliminary estimates suggest that an in-vessel neutron source of 10^9 n/s is sufficient to complete the in-situ calibration within two weeks. However, more detailed transport calculations are required to confirm these estimates and to optimize the planning of the calibration campaigns.
6. **Estimation of neutron scattering from the in-vessel calibration source, its support structure and RH components:** The effect of the support structure for the neutron source and the Remote Handling manipulator on the in-vessel calibration source will be modelled with transport calculations.

7. **Activation of the neutron tube, support structure, RH equipment etc.:** Estimates of the activation of components used during in-vessel calibration are important for the safe handling of these components after the in-situ calibration exercise is completed.
8. **Validation of transport calculations against JET in-situ calibration: T**he recent in-situ calibration on JET offers an excellent opportunity to bench mark the quality and uncertainty in the transport calculations in complex geometries,

Strategies for the in-vessel calibration

The calibration strategy proposed for ITER is guided by the extensive experience gained in TFTR and JET where confidence in the calibration of the neutron diagnostics has evolved over several decades. JET has recently (2013) carried out a careful re-calibration of the neutron diagnostics using an in-vessel ^{252}Cf neutron source and is planning a further in-vessel calibration with a 14 MeV neutron generator source in 2015 before the next operation in d-t.

The in-vessel calibration of the ITER neutron diagnostics should be planned as two distinct campaigns. The first in-vessel calibration campaign should take place at the end of Assembly Phase II (i.e. towards the end of year 2 of the current ITER Research Plan) and, for simplicity and reliability, will use a radioactive ^{252}Cf source (ideally 10^9 n/s) to simulate d-d neutrons. It is important to stress that the machine assembly must be complete with water in the blanket modules and in all cooling circuits before starting the in-vessel calibration. For the calibration of the Neutron Flux Monitors located in the equatorial ports (in particular EP 1 & 7), it is important also that the port plug assemblies are complete with all neighbouring diagnostics installed. The second in-vessel calibration campaign should take place a few years later at the end of the Pre-nuclear Shutdown (end of year 6 of the current ITER Research Plan) before operation in tritium and will use a 14 MeV neutron generator tube – in the range 10^9 to 10^{10} n/s.

This strategy allows time for careful evaluation of the data from the first calibration with the ^{252}Cf source and it has to be stressed that this evaluation will be time consuming. In addition, there will be an opportunity to gain experience during the subsequent operation of the neutron diagnostics with plasma (albeit mainly in H and He but possibly with some trace deuterium), before conducting the definitive in-vessel calibration with the 14 MeV neutron source before the start of operations in d-d and d-t. The first in-vessel calibration campaign will also provide experience in conducting the calibration exercise and in the remote handling of the calibration sources. This two-campaign strategy will most certainly reduce the time and risks that would be associated with a single in-vessel calibration exercise. In the event that machine assembly is incomplete at the end of Assembly Phase II, there should be contingency planning for an additional calibration campaign (with ^{252}Cf) during the short shutdown planned midway during year 4 of the ITER Research Plan. Contingency planning should allow a repeat of the 14 MeV calibration if required (for example if plasma operation in d-d shows significant inconsistencies in the neutron measurements or if there have been significant changes to the machine) during the scheduled shutdown in year 8. This would require operating the neutron calibration source inside the activated and Be-contaminated vacuum vessel.

Neutron sources for the in-vessel calibration

The in-vessel calibration requires neutron sources in the range 10^9 to 10^{10} n/s that are sufficiently compact and light in weight to be positioned accurately and moved around the interior of the vacuum vessel. The choice lies between a radioactive Californium source (^{252}Cf) and a neutron generator tube – either d-d for 2.5 MeV neutrons or d-t for 14 MeV neutrons. There are significant advantages and disadvantages with both types of source.

The most convenient neutron source for in-vessel work is ^{252}Cf – it is compact, light in weight, readily deployable and it simulates an isotropic point source with minimum need for corrections due to support structure, cables etc. For ITER, a source strength of 10^9 n/s would be desirable, but two weaker sources of around $5x10^8$ n/s could be used if a single more powerful source is not available. The neutron spectrum from ^{252}Cf is relatively close to 2.5 MeV but it is not an accurate simulation of 14 MeV neutrons. However, the difference in the response of the ^{235}U fission detectors should not be too large and these relatively small differences can be corrected using neutron transport calculations. An obvious problem with ^{252}Cf is that it has a relatively short half-life (2.6 years) – so the procurement of the source needs careful planning to fit in with the calibration schedule and there must be an option to delay procurement if there are delays in the ITER programme. The ^{252}Cf source needs to be stored in a heavily shielded flask. The source needs careful handling and the transport to and from the vacuum vessel needs careful planning to comply with safety requirements.

Neutron generator tubes have the advantage that they provide sources of 2.5 MeV and 14 MeV neutrons – but they are not true isotropic point sources and the neutrons are scattered and screened by the generator itself and by its support structure. These effects have to be corrected by neutron transport calculations which add to the systematic errors in the calibration. The 2.5-MeV neutron strength from available d-d generators is limited to about 10^8 n/s and this is too small for ITER. Even if a more powerful d-d source could be developed, it would be very bulky and heavy and the difficulties accompanying its use would far transcend those for a ^{252}Cf source, which seems the better option for the first (d-d) calibration campaign.

There are suitable d-t generator tubes for 14 MeV neutrons with source strengths in the range 10^9 to 10^{10} n/s. Tubes that are even more powerful may be available (or could be developed) but they are likely to prove inconveniently massive. For a neutron generator to be considered for ITER, it should be compact, easily portable, have minimal mass to reduce scattering, preferably not require cooling, have few trailing cables, be very stable, preferably be continuous as opposed to pulsed and have a long life-time (hundreds of hours). There is an obvious trade-off in selecting the optimum source. A more powerful source will reduce the time for the calibration but the increased bulk and mass will be more difficult to handle and will cause more screening and distortion of the neutron source. A weaker source will reduce these problems but will require a longer calibration time. The Russian VNIIA in-vitro generator NG-20 (10^9 n/s) appears well suited to the ITER task, particularly if the drift tube length could be extended from 15 to 50 cm to further reduce the effect of scattering. There are other contenders and the choice of 14 MeV neutron tube needs further study.

The neutron tube will require detailed calibration and characterisation at an expert off-site metrology facility after procurement from the manufacturer. This characterisation should include tests with the neutron tube mounted on the actual close support structure (or a realistic mock up) that will be used for the in-vessel calibration. After delivery, the tube will have to be tested functionally in a suitable area on the ITER site prior to deployment in the vacuum vessel. A suitable method (e.g. a high-resolution silicon or diamond detector) for monitoring the source strength during the in-vessel calibration will be needed and its response should not be sensitive to the environment in which the source is employed.

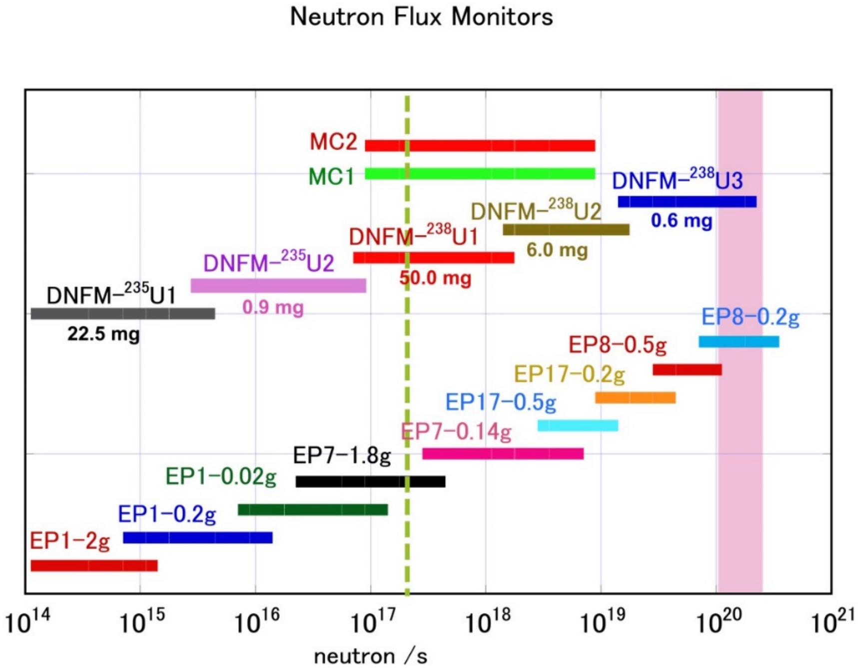
A manipulator system is required for moving the neutron source around the torus, in order to map out the plasma volume and to simulate a distributed source of plasma neutrons. The manipulator needs to be able to move and position the source accurately (typically within ± 1 cm) around the full toroidal extent both on the horizontal mid plane and at a number of selected other positions above and below the mid plane. For the radioactive ^{252}Cf source, there needs to be provision to remove and replace the source safely in its transport cask – and provision to recover safely the radioactive source from inside the vacuum vessel in the event that the source is accidently dropped or there is a failure of the manipulator. For the neutron tube, transport and handling outside the vacuum vessel is simplified – but it has trailing electrical cables and water cooling pipes.

One of the ITER remote-handling devices such as the Multi-Purpose Deployer (MPD) or the Divertor Trolley could be suitable but this will need careful study. If the existing ITER remote handling systems are found not to be suitable, a purpose-built system will be needed. A typical arrangement would have a trolley running all around the torus around along a pair of support rails set well below the mid-plane and it would have provision to support and accurately position the calibration source. The structure has to be strong enough to support not only the ^{252}Cf source but also the 14 MeV neutron generator, which will have trailing electric cables and water pipes. The source transport system will introduce a significant perturbation of the neutron field from the neutron sources that will need to be studied and corrected using transport codes.

Calibrating the Neutron Flux monitors

In-vessel calibration of the Neutron Flux Monitors is required to achieve 10% measurement accuracy. There are three independent types of Neutron Flux Monitors and together they will have the dynamic range to measure the time-resolved neutron yield over all phases of ITER operation. The figure on the following page shows their dynamic range and the range covered by the in-vessel calibration.

The Neutron Flux Monitors will be in modules located in Equatorial Ports #1, 7, 8 and 17 with each module containing several fission chambers with different fissile content and correspondingly different sensitivities. The most sensitive detectors will be calibrated directly with the in-vessel sources – these are the three fission chambers in EP1 and one of the chambers in EP7. The Divertor Neutron Flux Monitors will be installed under the dome in divertor cassettes at three different toroidal locations 120° apart. Each module will have 6 fission chambers, two with U^{235}, three with U^{238} and one dummy. The in-vessel sources will calibrate the three most sensitive chambers in each of the three locations. The Micro Fission Chambers will be installed on the inside wall of the vacuum vessel and they will be shielded from the plasma by the blanket modules. These are the least sensitive of the neutron flux monitors to be calibrated with the in-vessel calibration sources.



The figure shows the overall dynamic range of the Neutron Flux Monitors (EP1 to EP8), Divertor Neutron Flux Monitors (DNFM) and Micro Fission Chambers (MC1 & MC2) in counting mode for a 1 ms response time. The pink shaded area corresponds to 500 MW fusion power. The in-vessel calibration (5 hours with a 10^{10} neutrons/s source or 50 hours with a 10^{9} source) will calibrate all the detectors to the left of the vertical broken line.

Calibrating the Neutron Activation System

The Neutron Activation System will play a fundamental role in maintaining the ITER Neutron Calibration during subsequent plasma operation. The required accuracy of 10% for the activation system is achievable through computation using neutron transport codes only when the irradiated sample has a relatively unimpeded view of the plasma that is not restricted by the immediately surrounding material. The presently proposed positions for the irradiation ends between the blanket modules appear not to meet these requirements because of the depth (10 cm to 15 cm) behind the first wall of the irradiation ends, thus constraining the view of the plasma to a narrow ill-defined sector. The 10 to 15 cm depth amplifies the uncertainties due to installation tolerances, thermal expansion of the blanket modules and the possible movements that would take place over several decades of operation. The upper and lower irradiation end positions within the diagnostic ports should be more suitable, although the detailed information needed to provide this assurance is presently lacking. Improvements to the design are being considered.

The purpose of the in-vessel calibration is to provide a test of the accuracy of neutron transport modelling, primarily of the irradiation end itself and of the immediately surrounding sector of the machine. For a few well-chosen positions of the neutron source, the computed induced activities of the irradiated samples will be compared with experimental measurements.

Calibrating the Neutron Cameras

The external radial neutron camera will have weak internal neutron sources that will enable the setting up of the electronics prior to plasma operations commencing. However, the upper and lower neutron cameras will lack these internal neutron sources and will therefore rely on the in-vessel calibration campaign for setting the electronics associated with their fission chambers.

Calibration Campaign #1 – Measurements with the ^{252}Cf Source

As noted already, this first in-vessel calibration campaign using a ^{252}Cf calibration source should be at the end of Assembly Phase II when the machine assembly is 100% complete and with water in all cooling circuits. If the machine assembly is not complete at this stage, contingency planning should allow the ^{252}Cf calibration to be delayed until (or to be repeated during) the short shutdown planned midway during year 4 of the ITER Research Plan. However, it should be noted that this might delay regulatory approval to start operations in d-d.

For reference purposes, we assume a 10^9 n/s ^{252}Cf neutron source and the estimates of the time requirements are extrapolated from a study (Ishikawa *et al*) for calibrating the Micro Fission Chambers using a 10^{10} n/s 14 MeV neutron source. The Ishikawa calculations estimate that a 10^{10} n/s neutron source moved continuously around the torus mid-plane would take 5 hours to accumulate 10^4 counts (corresponding to a statistical accuracy of 1%) on the Micro Fission Chambers. The equivalent time using a 10^9 n/s ^{252}Cf source would be about 50 hours. In addition to the mid-plane scan, several off-axis scans are needed to simulate the distributed emission profile of fusion neutrons. The number of scans can be optimised with neutron transport calculations. Assuming five complete toroidal scans, the total time for mapping out the whole plasma using a 10^9 n/s source to reach 10^4 counts on each scan would take 250 hours. This can be reduced to 50 hours overall with the 10^9 n/s ^{252}Cf source by accepting 1% statistics *overall* for modelling the plasma – i.e. a total of 10^4 counts accumulated on the Micro Fission Chambers over all 5 toroidal scans.

There are various ways whereby the calibration of a diagnostic at a specific toroidal location could be optimised by concentrating the calibration points close to the diagnostic and avoiding time with the source in regions of the torus far from the detector where the response is effectively zero. The response falls roughly as the inverse square of the distance separating the source from the detector and falls off completely when the source disappears behind the central column. However, the full benefit of the above approach cannot be realised in practice because there are flux monitors to be calibrated in many different toroidal locations. The proposed calibration campaign would execute a single on-axis and 4 off-axis scans at a range of suitable (typically 36) azimuthal points to obtain 10^4 counts in total on the least sensitive detectors (i.e. the Micro Fission Chambers). The more sensitive Fission Chambers in EP1 and EP7 and those in the Divertor Neutron Flux Monitors (at three Toroidal locations) would of course accumulate many more counts during this time with correspondingly lower statistical errors. The total time allocated for the measurement phase of the calibration of the flux monitors would be about 50 hours (plus the time spent moving the source).

One concern is that the average count-rate on the Micro Fission Chambers with a 10^9 n/s source would be 3.3 counts per minute and this could well be comparable with the intrinsic background count-rate. This could constitute an important issue for the Micro Fission Chambers and the effect on the systematic calibration error needs further study. Counting statistics will not be an issue for the more sensitive Divertor Neutron Flux Monitors and the Neutron Flux Monitors.

For the in-vessel calibration of the Neutron Activation System, a preliminary study shows that it is possible to make useful measurements with a 10^9 n/s source placed on the plasma axis and 3 m from the irradiation end (this distance could be somewhat reduced, if necessary). Measurements should be made for a number of source positions. Obliquely viewing positions are necessary to explore blanket shielding effectiveness, keeping constant the distance between source and irradiation end. Much depends on the details of the chosen irradiation position. To calibrate the activation system with a ^{252}Cf source requires the low-threshold $^{115}In(n,n')^{115}In$ reaction. The alternative would be delayed neutron counting using fissile materials – but such a system is not proposed for ITER. A 10^9 n/s source with a source to sample distance of 3 m requires 4.5 hour for the irradiation and counting to achieve 3% statistics. To prove consistency, several repeat measurements will be needed. Provisionally two days are estimated for this activity, assuming that only one irradiation position is calibrated.

There are three Neutron Cameras to be calibrated, with varying detector types. Their detection efficiencies should be well known prior to installation. NE213 scintillators and similar detectors in the radial neutron camera can be set up using inbuilt gamma-ray and neutron sources. It would be almost too easy to elaborate an extensive series of measurements but it should be remembered that the shielding effectiveness of the collimators will be better for 2.5 MeV neutrons than for 14 MeV neutrons so the key tests should be deferred until the second in-vessel calibration campaign. As discussed earlier, the main use of the in-vessel source is to set up the electronics in the upper and lower neutron cameras. A two-day allocation appears necessary given the large number of channels.

Calibration Campaign #2 – Measurements with the 14 MeV Neutron Generator

The second in-vessel calibration campaign should be scheduled the end of the Pre-nuclear Shutdown (end of year 6 of the current ITER Research Plan) and will use a 14 MeV neutron generator tube – in the range 10^9 to 10^{10} n/s. As in the first campaign, it is important that the ITER machine assembly is fully complete with water in all blanket modules and cooling circuits before starting the calibration. By this stage, the data from the first in-vessel calibration campaign will have been carefully evaluated and there will be experience of the neutron diagnostics with plasma operation (albeit in H and He with possibly some trace d-d plasmas). This will help to guide the priorities for the second in-vessel calibration. Contingency planning should allow for a repeat of the 14 MeV calibration if required (for example if subsequent operation in d-d shows significant inconsistencies in the neutron measurements or if there are any significant changes in the machine components) during the scheduled shutdown in year 8, although this would require operating the neutron calibration source inside the activated vacuum vessel.

The in-vessel calibration of the Neutron Flux Monitors, Divertor Neutron Flux Monitors and Micro Fission Chambers with the 14 MeV generator would proceed broadly along the lines already outlined for the first in-vessel campaign using the ^{252}Cf source. A 10^9 n/s 14 MeV source is used as the reference for estimating the time requirements. A stronger source would reduce the actual measurement time – but the overall time saving would not be so dramatic taking into account the overheads such as source installation, commission and removal, as can be seen in the table on the next page.

High threshold energy reactions should be chosen to calibrate the Neutron Activation System with 14 MeV neutrons. There are several likely candidate materials using a source strength of 10^9 n/s and a separation of 3 m between generator and irradiation end. Maximum periods of eight-hours are considered for both irradiation and counting times unless the half-life is smaller, in which case the half-life is the preferred time interval. The $^{27}Al(n,p)^{27}Mg$, $^{28}Si(n,p)^{28}Al$ and $^{63}Cu(n,2n)^{62}Cu$ reactions all have very short half-lives (minutes, rather than hours); for the first two examples, repeated irradiations will be needed to build up statistics. With a 10^{10} n/s generator or with the irradiation end to neutron generator separation reduced to 1 m or even less, further reactions can be considered, including $^{65}Cu(n,2n)^{64}Cu$, $^{27}Al(n,\alpha)^{24}Na$ and $^{93}Nb(n,2n)^{92}Nb$ all of which would then provide better statistics. With gamma-ray energies above about 1 MeV, it is expedient to use a NaI(Tl) scintillator instead of the germanium high-resolution detector assumed in making the above assessment, thereby gaining an order-of-magnitude improvement in counting statistics. Depending on the reactions chosen, the activation system calibration, with possibly more than one irradiation position being calibrated, could take as little as a day or two or extend up to several weeks. We assume a compromise and propose allocating a maximum of 4 days to these calibrations.

For the Neutron Cameras, many of the assessments of the shielding effectiveness, examination of cross-talk issues and determinations of the collimation viewing solid angles can be carried out more effectively using neutron transport codes than with the neutron generator. Exhaustive testing of all of the collimator channels with the 14 MeV source would be very time consuming. However, adequate time, provisionally 2 days, should be allowed for the most important experimental tests and calibrations of collimators and detectors.

Time requirements for the in-vessel calibrations

Preliminary Estimates of Time Requirements for in-vessel calibrations.

Calibration campaign	Assembly Phase II	Pre-nuclear Shutdown	
Source	^{252}Cf	14 MeV neutron generator	
Source strength	10^9 n/s	10^9 n/s	10^{10} n/s
Installing and testing the support structure	3	3	3
Preliminary work – meeting safety requirements, testing the generator, setting discriminator levels etc.	1	1	1
Toroidal scans to calibrate the Neutron Flux Monitors	4	4	2
Neutron Activation System	2	4	3
Radial & Vertical Neutron Cameras	2	2	2
Removal of support structure	1	1	1
Total time (days) Assuming 2 shifts per day	13	15	12

The time needed for the in-vessel calibrations of the neutron diagnostics will depend on the degree of automation – and speed of repositioning – of the remote handling devices for moving the neutron source around the torus. It is assumed that the same manipulator system would be used for the ^{252}Cf source and for the 14 MeV neutron generator. The table gives a preliminary estimate of the time needed for the in-vessel calibrations. These estimates require a more detailed study and planning, but it is worth noting that the time estimates are broadly in line with the time taken recently (two weeks) for the in-vessel calibration exercise at JET with a ^{252}Cf source using JET's Mascot remote handling tool.

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