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Report

Calibration of ITER neutron diagnostics - Workshop II

Final Report

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Report and Recommendations of the Second ITER Neutron Calibration Workshop

(23 to 25 November 2015)

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1 Introduction

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

The full set of ITER neutron diagnostic systems consists of:

1. Neutron Flux Monitors (NFM) installed in several 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 Neutron Flux Monitors, Divertor Neutron Flux Monitors and Micro Fission Chambers will measure the neutron flux. The Neutron Activation System will play a key role in maintaining accuracy and confidence in the calibration throughout the operating life of ITER. The Radial and Vertical Neutron Cameras will provide spatial resolution of the neutron emission profile and the High Resolution Neutron Spectrometer will measure the neutron energy spectrum. The calibration of each system has some common issues and some specific differences.

The first Neutron Calibration Workshop was held at the ITER site on 14 & 15 October 2013. Five key steps in the calibration procedure were discussed:

1. Calibration and characterisation of neutron diagnostic systems and individual detectors by the responsible DAs before delivery to the ITER site.
2. Functional checks after delivery to the ITER site, before integration into the machine assembly and at various stages during the installation of the neutron diagnostics into the ITER machine.
3. MCNP computations of neutron transport to support the design of the neutron diagnostics and their calibration.
4. In-vessel calibration using 2.4 and 14 MeV neutron sources when the machine assembly is fully complete and immediately before the start of operation in deuterium and tritium.
5. Cross-calibration, as the neutron emission in ITER progressively increases, to demonstrate consistency between the various neutron systems and to extend the calibration to the less sensitive detectors which cannot be calibrated with the in-vessel sources.

The First Calibration Workshop emphasised that calibration of the ITER neutron diagnostics using in-vessel sources will be essential to reach the required level of accuracy and recommended that it should be planned as two distinct campaigns. The first calibration campaign, using a radioactive ^{252}Cf source (typically 10^9 n/s), will be at the end of *Assembly Phase II* (towards the end of year 2 of the current ITER Research Plan). The second in-vessel calibration campaign using a 14 MeV neutron generator tube (in the range 10^9 to 10^{10} n/s) will be at the end of the *Pre-Nuclear Shutdown* (end of year 6 of the current ITER Research Plan) before starting operation in tritium. 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 these in-vessel calibrations. 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. A

preliminary study of possible manipulators for the in-vessel sources has been carried out since the first Workshop.
The Second Workshop on Calibration Standards was held on 23 to 25 November 2015 with the specific aim of bringing experts from Neutron Metrology Institutes together with the scientists and engineers working on Neutron Diagnostics in the IO-CT and in the DAs. The meeting was well-attended by experts from both areas. The main emphasis of the Second Workshop was to review 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 (i.e. step 1 of the procedure outlined above). The requirements for functional checks after delivery to the ITER site (i.e. step 2) and the in-vessel calibration (i.e. step 4) were also discussed. A Panel of Experts was invited to make recommendations for the calibration standards and requirements of ITER neutron measurements.

2 Recommandations from NMI participants (NPL, IRSN, PTB, NIST)

ITER would like to obtain a 10% or better uncertainty on the yield of neutrons from the plasma. The calibration factors of the different neutron detector assemblies available for measurement of this quantity cannot be determined experimentally, but will be the result of a complex calibration procedure which needs several intermediate steps.

Due to the intermediate steps in the calibration chain, 10% uncertainty in the determination of the neutron yield from the plasma can be translated to about 3% uncertainty on the calibration of the neutron fluence response of the individual detectors used within the various detector assemblies and this is the level of uncertainty achieved by the best metrology labs, i.e. by the national metrological institutes (NMIs). It means that NMIs have to be involved at the first step of the chain.

NMIs recommendations for neutron calibration of ITER neutron diagnostics are the following:

1. All the calibration processes have a single objective that is the experimental validation of the performance of the neutron diagnostic systems as derived from MCNP simulation of the whole tokamak.
2. The calibration process has to be done in several steps with increasing level of complexity:
    i. Calibration of individual detectors, e.g. fission chambers, diamond detectors, scintillators, etc.
    ii. Calibration of detector assemblies to be delivered to ITER (including moderators, cabling, etc.)
    iii. In-vessel calibration of the detector assembly inside the tokamak

2.1 Calibration of the individual detectors

1. Determination of the physical properties of individual detectors (e.g. $^{235}U/^{238}U$ ratio and amount, hydrogen content in scintillators, light output function in scintillators, conversion factor between energy and charge in diamond detectors, etc.). All the unknown or not 100% reliable properties have to be determined. These data are the basis for step 2.
2. MCNP simulations of the detector response function or functions on the basis of step 1.
3. Verification of the MCNP simulations and adjustment of data from step 1 if needed. Because this is the first step in a chain during which uncertainties will increase, this verification, which needs to cover the whole energy range of interest, has to be performed with the lowest achievable uncertainty, i.e. with direct traceability to NMI standards, by: calibration at NMIs, use of a transfer instrument, or use of radionuclide sources calibrated at NMIs. The kind of neutron field will depend on the nature of the detector.

2.2 Calibration of detector assembly to be delivered to ITER

The main objectives are to provide:

1. The detector assembly.
2. A correct and validated MCNP model for the detector assembly that can be plugged into the whole tokamak model geometry for calculation of the in-vessel calibration situation. This will involve using data from the calibrations of the individual detectors.
3. A sensitivity study of the assembly for temperature and Electromagnetic fields conditions at ITER.

The MCNP model of the detector assembly has to be verified using a reference neutron field, i.e. with well-known angular and energy distributions of the neutron fluence with low uncertainty. From our point of view, it is necessary to have a traceability of this field to standards of NMIs to avoid too much uncertainty coming from knowledge of the neutron source that otherwise would limit the benefit of this benchmark test.

The very best option would be to use an existing "realistic neutron field" at an NMI, with energy distribution close to the neutron field seen by the assembly at the tokamak, to test all the relevant parts of the assembly. That means that this field at the assembly position has to be calculated first. Irradiations with different orientations of the assembly should be also performed. However, the use of calibrated radionuclide neutron sources (^{241}AmBe or ^{252}Cf) or accelerator-produced mono-energetic neutron reference fields (e.g. 14 MeV), at several orientations of the detector assembly, could be sufficient for certain assemblies to validate the MCNP model. The use of D-D or D-T neutron generators at this stage is also a possibility although uncertainties in output, calibration procedures, calibration environment, etc. might mean that the uncertainties would not be sufficiently low to achieve the desired validation. If this option is adopted, however, the involvement of NMIs in advising or participating in the calibrations is highly recommended.

Ideally tests of sensitivity to ITER environmental conditions (temperature, electromagnetic fields, photon fields, mechanical stress, etc.) should be performed in parallel.

2.3 Functional check of the detector assembly

To check that the detector assembly has not been damaged during transportation, a neutron irradiation in the same conditions has to be performed before shipment and after reception at the ITER site (neutron test facility NTF). The same kind of calibrated radionuclide source with traceability to NMI standards has to be used at the two places (DA and ITER) at the same distance and using if possible shadow cone method to subtract most of the scattered neutrons. This will be however only possible for the most sensitive detectors.

2.4 In-vessel calibration

At present this is planned with a ^{252}Cf source and a D-T neutron generator. These should be calibrated in terms of emission rate, anisotropy and in the case of the neutron generator the spectrum as a function of emission angle, with traceability to national standards. Stability in time and in spectral distribution will be vital. These calibrations need to be performed on the source and the generator in the configuration in which they will be used inside the tokamak, for example including any carrying baton used with the ^{252}Cf source. Accurate monitoring of emission rate is absolutely essential in the case of the neutron generator.

As the plasma volume and neutron energy distribution can only be approximated with calibrated neutron sources (^{252}Cf, 14 MeV generator), the differences in the calibration factors of detector assemblies in going from the situation during the calibration with these sources to the real plasma have to be calculated with neutron transport codes. These calculations of the differences cannot be validated directly; however, agreement between calculation of the calibration factors for the calibrations with the ^{252}Cf and 14 MeV generator and experiment will provide confidence in the accuracy of the neutron transport codes calculation with the complex geometry of the fully equipped Tokomak. .

Finally, the scanning scheme should be relevant to irradiate all the part of the assembly with sufficient statistics to validate the MCNP modelling of the Tokamak.

2.5 The Neutron Activation System

The Neutron Activation System will play a key role in maintaining accuracy and confidence in the calibration throughout the operating life of ITER. One of the recommendations of the First Workshop was to improve the field of view of some of the irradiation ends and this has been achieved. The Neutron Activation System (NAS) will be the main reference for fusion power determination. However, the very low sensitivity of NAS makes difficult a proper calibration during the in-vessel calibration phase. Indeed, the neutron source has to be put very near the activation foils, i.e. the foils will see mainly direct neutrons from a point like source instead of a volume source, lot of scattered neutron and edge effects. In that aim, the source could be moved up and down, further and closer, but this will be difficult within the limited time that will be allowed for testing neutron diagnostics in the tokamak. It is noted that the JET NAS system experienced systematic deviations due to some mechanical issues. That is why ITER wants to use the other neutron diagnostics as an independent system to determine the plasma neutron emission. In that aim, the NMIs propose the calibration procedures discussed above, that can also, at some extent, be adapted to the NAS.

3 Recommendations by Participants from the Fusion Community

3.1 Calibration of Neutron yield monitors

A strategy for calibrating the neutron yield monitors should include:

3.1.1 Experimental measurement by the responsible DAs of the response functions of each single detector in the range of neutron energies from 14 MeV down to thermal energy using reference fields. Response function using either a realistic neutron source or suitable series of mono-energetic sources to accurately represent the calculated neutron spectrum at detector location in ITER.

3.1.2 MCNP calculations of the neutron spectrum at the specific locations inside the machine where the detectors will be located (it is important to use accurate and detailed models of the machine components especially in the vicinity of the detectors as streaming channels/voids and water cooling channels have significant effects).

3.1.3 Realistic neutron filed

Create a realistic neutron field and measure the detectors' responses in these fields. The realistic neutron field should be a reference field experimentally characterized (known energy and angular spectrum). Operation of the detector in a neutron spectrum close to the one occurring in the machine where the detector will have to work. This requires an assembly of suitable materials and size around the detector and to irradiate it at a 14 MeV neutron source. The measured signal would be compared with the calculated one using the detector response function and the calculated spectrum in the assembly. The objective of this "validation integral experiment" would be to validate the response function in the relevant neutron spectrum, and also the cabling/electronics. The detector could be tested at different temperatures and also in the presence of a magnetic field.

3.1.4 Calculation of the calibration factor for detector installed in the machine using a full MCNP model of the machine and the validated response function.

3.1.5 Perform the in-vessel calibration with the source(s) at some points on the plasma axis in front of the detector. Compare the measure signal to the calculated one using the MCNP model of the machine and the validated response function. This would validate the MCNP and response function needed to calculate the "calibration factor" relative to the plasma neutron source (this step is necessary in any case).

3.1.6 Perform sensitivity analyses to understand the impact of variation on relevant parameters (magnetic field, temperature …).

3.2 Potential issues for fission chambers

A very large number of fission chambers are proposed to be inserted inside the vacuum vessel. These chambers will be operated in high magnetic fields, at relatively high temperatures and in vacuum with long electrical connecting mineral-insulated cables. Three potential issues for them were noted at the Workshop:

a. Uncertainty of the quantity of Uranium isotope in the detector,
b. Potential for out-gassing during operational life of ITER,
c. Potential for directionality depending on the deposition of the U-isotope.

It is wholly unacceptable for there to be any doubt as to the quantity of U235 in the fission chambers. That quantity can be easily determined through the use of a neutron die-way chamber, a relatively simple apparatus used by the nuclear safeguards fraternity. Alternatively, a determination can be made by placing the bare fission chamber at a suitable distance (1 metre or so) from an accelerator-based standard neutron source (either 2.5 MeV or 14 MeV neutrons) provided with associated-particle detection to determine the absolute neutron yield. For this work, the room scatter contribution would need to be assessed and, possibly, modelled – along with the structure of the fission chamber itself. A shadow cone could be employed for an experimental determination of the room contribution.

An international advisory committee, involving members of the NMI community, is proposed to advise on the design, construction and testing of the detectors. Funding should be made available for prototyping and testing if thought advisable.

3.3 Cabling and I&C

Another concern is the quality of the pulse-height spectrum provided by the fission chambers. They really should exhibit a clear separation between noise and alpha-particle signals and fission events. If this is not the case the bias curve instead of having a flat plateau region, will slope down more or less gradually and the setting of the electronic discriminator will need to be set and maintained precisely. For chambers exhibiting a sloping plateau region, it will be necessary to assess the signal degradation in the cable layout as proposed for installation in ITER, where there will be several different types of cable for in-vessel and ex-vessel operation as well several interconnectors of differing types. It may be necessary to employ a mock-up of this cabling for the laboratory calibration.

3.4 Functional test at IO

We need to distinguish between the full pre-delivery calibration by the DA (i.e. the measurement of the response function of the detectors over the full range of neutron energies) and the pre-delivery check at some specified energies that will be reproduced later at the ITER site.

3.4.1 The neutron source energies and strengths for the pre-delivery check need to be agreed quickly by the DAs and IO-CT so that the neutron test area and the sources required at the ITER site can be specified.

3.4.2 Electronics - It is important to agree the detailed conditions, including cables and electronics, for the full pre-delivery calibration and the pre-delivery check. These should be, so far as possible, the same as will be used in the final assembly on ITER.

3.5 In-vessel calibration

3.5.1 Source transporter

Strong arguments were made against using the main ITER manipulator for carrying out the in-vessel calibration by moving sources inside the vessel. One argument was the length of time in preparation and dismounting, another was the relatively large beam which would support the calibration sources.

The new concept of equipment introduced through upper ports has a lot of attraction but is particularly limited in its source positional stability and its ability to support and point the 14 MeV source, as well as its being able to provide a full spatial coverage of the necessary detectors. The alternative strategies need to be studied in more detail.

3.5.2 Detailed MCNP modeling is required to determine the number of calibration locations necessary to achieve the required overall uncertainty of 10%.

3.5.3 In-vessel calibration using a ^{252}Cf source has benefits as the self-shadow effect is low and the source size is small.

3.5.4 It would also be good to develop estimates of the impact of the temperature change during operation on the sensitivity of the detectors.

3.5.5 JET Calibration Campaign

Every effort should be made to benefit from the in-vessel calibration to be done at JET in September 2016. The JET team has done a very detailed characterization of their 14 MeV accelerator-based source and will also use a Californium source. Such actions as careful modeling and small source movements close to the neutron activation system heads, comparison of the need for use of both a 14 MeV and a Californium source in some cases, sketching out the sensitivity of the radial and vertical cameras might be considered. However, it is clear that the JET calibrators will be under intense time pressure to complete their work and ITER, and possible external advisors, will need very good arguments to extend their access.

3.5.6 It is not clear if calibration of the neutron cameras is necessary or feasible with an in-vessel source. The EU & RF DAs should indicate the requirements as soon as possible.

3.6 Tangential Neutron Spectrometer:

There are two significant issues affecting the value of the installation of the proposed tangential neutron spectrometer.

3.6.1 The first is what the new physics information is to be learned. Any directional effects will appear as very slight distortions of the Gaussian shape difficult to distinguish with a strong background. In DD, there might be more distinctive features but the signals will be small.

3.6.2 The second is the background scattered neutron component in the signals observed by the diamond detectors. The MCNP results presented for the vertical neutron camera suggest strongly that the signals in the locations selected for the diamond detectors will be dominated by scattered neutrons. Spectral information will be more difficult to unfold than positional information. The purpose of the fission chambers is not clear.

4 Summary and Actions

The IO Neutron calibration team suggests the following strategy in support with NMI and Fusion committee remarks:-

1. Proposal by DAs for Home-based calibration strategy in the design reviews including:-
   a) DAs have to contact their NMI in for Detector Response function using reference fields(see section 2.1, 3.1.1)
   b) Effect of magnetic field & temperature on detector sensitivity (see section 2.2)
   c) Detector assembly calibration for validation of MCNP model with direct traceability to NMI standards (see section 2.2, 3.1.3)
2. Fission chambers are operated in high magnetic fields, at relatively high temperatures and in vacuum with long electrical connecting mineral-insulated cables. Three potential issues for them were noted at the Workshop (See section 3.2) :
   a) Potential for out-gassing during the operational life of ITER.
   b) Potential for directionality depending on the deposition of the U-isotope.
   c) Uncertainty of the quantity of Uranium isotope in the detector.

   Precise measurement of quantity of uranium 235 & U-238 in the fission chambers (for example by neutron die-way chamber method).

   An international advisory committee, if any, should advise on all detection systems and not only fission chamber. Temperature and electromagnetic field experts from NMIs should be involved to advise on the design, construction and testing of the detectors.

3. The pulse-height spectrum provided by the fission chambers should exhibit a clear separation between noise and alpha-particle signals and fission events. For chambers exhibiting a sloping plateau region, it will be necessary to assess the signal degradation in the cable layout as proposed for installation in ITER. (See section 3.3).
4. The alternative strategies for the source transporter to be used for in-vessel calibration need to be studied in more detail taking into account the amount of time in preparation and dismounting; source positional stability and ability to provide a full spatial coverage of the necessary detectors (see section 3.5.1).
5. Every effort should be made to benefit from the in-vessel calibration to be done at JET. It will be a good learning experience (see section 3.5.5).

Acknowledgements

This report contains contributions from the members of the expert panel, the NMI participants and from the participants of the neutron calibration workshop, in particular Neil Jarvis, Kenneth Young, Mamiko Sasao, Paola Batistoni, Sergey Popovichev, Vincent Gressier and Ralf Nolte.

Appendix A – References

The links to various documents of the workshop are mentioned below:

a) Workshop Presentations ITER_D_S94VC7
b) Book of Abstracts for the Neutron calibration workshop - II (ITER_D_RVML4V v1.0)
c) Minutes of the workshop (ITER_D_SDNK32 v1.0)
d) Final report of first workshop on calibration of ITER neutron diagnostics ITER_D_NFGLTZ

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Appendix C – Agenda of the workshop

	Day 1 - 23 November 2015	Presenter	Time (hh:mm)	Discussion (hh:mm)	Start	End
1	Welcome	Michael Walsh	00:10	00:00	09:15	09:25
2	Introduction and Background to the Neutron Calibration Challenge	Peter Stott	00:15	00:10	09:25	09:50
3	Overview of ITER Neutron Diagnostics and calibration	Luciano Bertalot	00:15	00:10	09:50	10:15
4	Overview of Neutron Calibration Standards & Metrology	Vincent Gressier	00:15	00:10	10:15	10:40
	Coffee break		**00:25**		**10:40**	**11:05**
5	Neutron metrology at CIAE and NIM	Vincent Gressier on behalf of Zhang Hui	00:15	00:05	11:05	11:25
6	Neutron calibrations at the National Metrology Institute of Japan	Vincent Gressier on behalf of Tetsuro Matsumoto	00:15	00:05	11:25	11:45
7	VNIIM Neutron Laboratory - Equipment and measurement capability	Vincent Gressier on behalf of Nikolay Moiseev	00:15	00:05	11:45	12:05
	Lunch		**01:30**		**12:05**	**13:35**
9	Calibration of JET neutron monitors at 14-MeV neutron energy	Paola Batistoni (remotely) & Sergey Popovichev	00:15	00:25	13:35	14:15
10	IRSN Facilities and realistic case calibration	Véronique Lacoste	00:15	00:05	14:15	14:35
11	Fast neutron source GENEPI at LPSC, Grenoble	Francesca Villa	00:15	00:05	14:35	14:55
12	Neutron Reference Fields at the PTB Ion Accelerator Facility PIAF, Germany	Ralf Nolte / Andreas Zimbal	00:15	00:05	14:55	15:15
	Coffee break		**00:25**		**15:15**	**15:40**
13	Neutron Metrology at NIST, USA	J.S. Nico (remotely)	00:15	00:05	15:40	16:00
14	Neutron Metrology at NPL, UK	David Thomas	00:15	00:05	16:00	16:20
15	General discussion & setting the tasks for the Expert Panel	All	01:00		16:20	17:20
	End of day 1					17:20

	Day 2 - 24 November 2015	Presenter	Time (hh:mm)	Discussion (hh:mm)	Start	End
1	Opening and overview of Day 1	Peter Stott	00:15	00:00	09:00	09:15
2	Neutron Flux Monitors - NFM (with realistic case calibration)	Luciano Bertalot on behalf of Qingwei Yang	00:25	00:10	09:15	09:50
3	Strategy for Calibration of ITER Microfission Chamber System	Ishikawa Masao	00:25	00:10	09:50	10:25
	Coffee break		**00:20**		**10:25**	**10:45**
4	Divertor Neutron Flux Monitors - DNFM	Yuri Kashchuck	00:25	00:10	10:45	11:20
5	Calibration plan of Neutron Activation System	MunSeong Cheon	00:25	00:10	11:20	11:55
	Lunch		**01:30**		**11:55**	**13:25**
6	Requirements for neutron flux measurements from Nuclear Safety perspective	Miguel Dapena	00:15	00:05	13:25	13:45
7	Tangential Neutron Spectroscopy - TNS	Vitaly Krasilnikov	00:25	00:10	13:45	14:20
8	Radial Neutron Camera (RNC) & Radial Gamma ray Spectroscopy (RGRS) Calibration plan	Ryszard Miklazewski	00:25	00:10	14:20	14:55
	Coffee break		**00:20**		**14:55**	**15:15**
9	Calibration strategy on Vertical Neutron Camera - VNC	Grigory Nemtsev	00:25	00:10	15:15	15:50
10	Expert Panel Session	Expert Panel	01:40		15:50	17:30
	End of day 2					17:30

	Day 3 - 25 November 2015	Presenter	Time (hh:mm)	Discussion (hh:mm)	Start	End
1	In-vessel calibration overview and discussion	Edward McCarron (remotely) / Otto Bede	00:30	01:00	09:00	10:30
	Coffee break		**00:20**		**10:30**	**10:50**
2	Preliminary recommendations of the Expert Panel and Open Discussion	All	01:15		10:50	12:05
	Lunch		**01:30**		**12:05**	**13:35**
3	Expert Panel Session and Report Preparation	Expert Panel	01:45		13:35	15:20
	Coffee break		**00:20**		**15:20**	**15:40**
4	Open discussion for all	All	01:45		15:40	17:25
	End of day 3					17:25