Neutron Transport Analysis of the Processes Affecting the in situ Calibration of ITER In-Vessel Neutron Flux Monitors Equipped with a Micro-Fission Chamber System

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Neutron transport analysis is used to evaluate the effects of neutron calibration source position, support structure, and water coolant on the *in situ* calibration of the in-vessel neutron flux monitor using the micro-fission chamber (MFC) system by applying a Monte Carlo code for neutron and photon transport (MCNP). Results indicate that changing the position of a neutron calibration source leads to a longer calibration time of the MFC detectors. When positioned below the source, the supporting rail significantly affects the detection efficiency of the lower MFC detectors. On the other hand, though it has smaller impact when positioned adjacent to the neutron source, the analyses results suggest that the position and the size of the rail need to be optimized because the detection efficiency is sensitive to scattered neutrons by in-vessel components. Furthermore, water coolant can significantly affect the detection efficiency. This result indicates that when the *in situ* calibration is performed, the cooling water should be filled in the blanket module in the same manner as the ITER operations.

Keywords: neutron measurement, neutron flux monitor, in-situ calibration, neutron transport analysis, micro-fission chamber, fusion power

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1. Introduction

The temporal evolution of ITER fusion power, in terms of the total neutron emission rate, will be measured with neutron flux monitors (in-vessel [1], in-port [2], and diverter monitor [3]). Since the ITER fusion power evaluation requires accuracy of less than 10%, the relation between neutron flux monitor output and the total neutron emission rate must absolutely exceed this accuracy level. In ITER, a neutron *in situ* calibration procedure will be applied to determine the absolute neutron flux monitor calibration factors. For *in situ* calibration, a neutron source, i.e., a neutron generator and/or an isotope neutron source, will travel or be positioned at several points along a toroidal ring located on the plasma axis and/or on several poloidal coordinates. The basics of *in situ* calibration, for example, an optimum neutron source during an appropriate time frame, has been studied previously [4, 5]. However, the calibration factor or the detection efficiency of the neutron flux monitors, particularly the in-vessel neutron flux monitor using the micro-fission chamber (MFC) [1] is affected by the position of the neutron source. On the other hand, a supporting structure of the neutron source can affect the detection efficiency. Further, the difference in the ITER Tokamak condition between ITER operations and the *in-situ* calibration, for example the condition of cooling water in the blanket modules, can also be affected. Thus, a detailed analysis of the factors affecting *in situ* calibration is necessary. Therefore, via neutron transport analysis using MCNP, the various effects mentioned above on the calibration time and the detection efficiency of the MFC were evaluated. In this study, we present the analysis results for the in-vessel neutron flux monitor equipped with a MFC system. The MFC measurement setup is described in Sec. 2. In Sec. 3, the proposed calibration strategy for ITER neutron flux monitors is presented. The calculation model and method are described in Sec. 4. In Sec. 5, the time needed to conduct *in situ* calibration of the MFC is evaluated through neutron transport analyses. The effects of neutron source support structure and cooling water in the blanket module are presented in Secs. 6 and 7, respectively. Finally, a summary is presented in Sec. 8.

2. Micro-Fission Chamber

2.1 Structure

The MFC is a pencil-sized gas counter containing fissile material, which was developed as an in-core monitor for fission reactors [6]. Figure 1 shows a schematic view of a MFC designed for ITER. In the MFC, a coating of UO_2 as the fissile material covers the outer cylindrical electrode. The active length is 76 mm and the MFC contains a total amount of 10 mg of ^{235}U. Next, 14 atm of Ar gas is supplied to the MFC as an ionizing gas. The housing material is made of stainless steel 304 L, and the electric insula-

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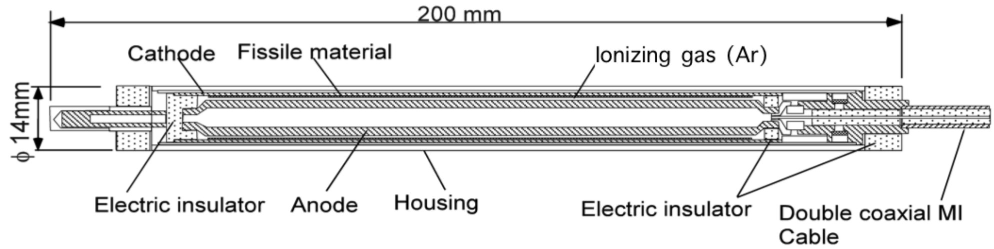

Fig. 1 MFC detector structure.

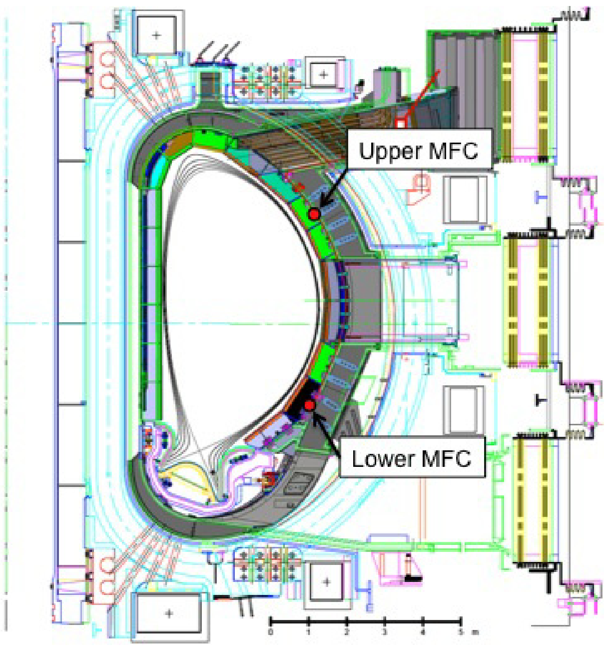

Fig. 2 Installation position of the MFC detector.

tor is made of alumina (Al_2O_3). The MFC measurement range covers total neutron emission rate from 10^{14} n/s to 7.5×10^{20} n/s, corresponding to fusion power from 100 kW to 1.5 GW, using both pulse counting and Campbelling (mean square voltage) modes [7] with a 1 ms temporal resolution and within 10% statistical error, which meets the ITER requirements for a neutron monitor.

2.2 Installation

The MFCs will be installed behind the upper and lower outboard positions of the blanket modules as shown in Fig. 2. The installation positions have been determined on the basis of the neutron transport calculation with MCNP, whereby the average MFC output at the upper and lower outboard positions is insensitive to changes in plasma shape and position [6]. At each proposed location, two MFCs and a dummy chamber, which has the same structure as an MFC, but without any uranium coating on the electrode, will be installed. Two MFCs are installed at the same position to ensure continuity in case one breaks down over the course of ITER operations. The dummy chamber is also installed to compensate for gamma-ray effects and electrical noise. In previous designs, the detailed location of the MFC installation behind the blanket modules was determined considering the interface with the vacuum vessel and other equipment [1].

3. Calibration Strategy of the Neutron Flux Monitors in ITER

Neutron flux monitor and MFC detection efficiencies are derived from several calibrations using a neutron generator/source. The planned calibration strategy at ITER will be based on four phases [4].

(1) Full characterization and absolute calibration of all the detectors at each factory.

(2) Detector calibration at the ITER Neutron Test Area site before installation on the Tokamak.

(3) *In situ* calibrations: DD and DT neutron generators, and ^{252}Cf neutron sources will be moved inside the ITER vacuum vessel and placed at different poloidal and toroidal positions.

(4) During ITER operations, detector calibrations and an inter-comparison will be made using well-characterized plasma reference shots.

Of the different phases listed, *in situ* calibration is most important for obtaining the absolute calibration factors (detection efficiency) of the neutron flux monitors for the ITER plasma. The ITER *in situ* calibrations will require sufficient time and planning. A preliminary scheme is under consideration, which includes having a short (approximately 2 weeks) *in situ* calibration campaign at first, either just before or during the first shutdown, after the first plasma, and then a complete *in situ* calibration (approximately 8 weeks) before the DD operation phase. In fact, *in situ* calibration of all neutron measurement systems, i.e., not only neutron flux monitors but also neutron cameras (vertical, radial) and the neutron activation system, must be conducted during the limited period. Therefore, a well-planned *in situ* calibration is necessary.

4. Calculation Model and Method

To evaluate an calibration calibration time the effect of a neutron source structure and cooling water in the blanket module on detection efficiency of the MFC, neutron trans-

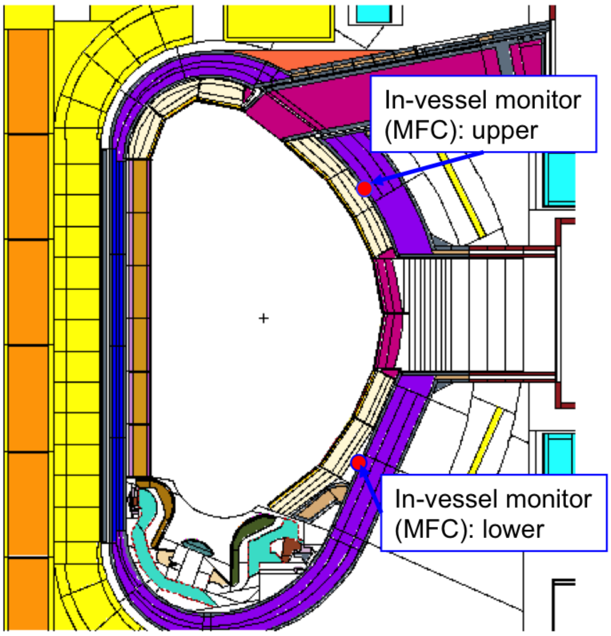

Fig. 3 Poloidal cross section of the Alite-ITER model and installation position of the in-vessel monitor (MFC).

port analyses using MCNP code (version of MCNP 5 [8]), combined with the nuclear data libraries, FENDL 2.1 and JENDL 3.3 [8], have been performed using the Alite-ITER model [1]. This was the MCNP input model with a detailed 40° ITER Tokamak, including the vacuum vessel, blanket module, divertor cassette, and other machine construction. Figure 3 shows the poloidal cross section of the Alite-ITER model along with the MFC detector installation position. We assume the neutron source is set as a 14 MeV toroidal ring source to simulate that a DT neutron generator circulates along the toroidal direction. In this analysis, the effect of a neutron generator such as the self-shadowing and scattering of the neutron generator on the detection efficiency is not taken in to account. The MFC detector fission material is ^{235}U. The MFC detection efficiency was derived from the neutron spectrum at the position of the MFC detectors and energy cross sections of ^{235}U fission reaction rate.

5. Total Calibration Time Evaluation

In the previous study, the time needed to obtain sufficient counts (1000 s–3% statistical error, 10000 s–1%) when the neutron source was set on the plasma axis was evaluated [4]. However, the neutron source is set on 5 – 9 toroidal rings along several poloidal positions to adequately correct for the effects of neutron emission profile changes, as shown in Fig. 4 [9]. Since detection efficiencies of the MFC detectors are dependent on the source position, the time needed for calibration could be different

[1] Developed as a collaborative effort between the FDS team of ASIPP China, ENEA Frascati, JAEA Naka, UKAEA, and the ITER Organization

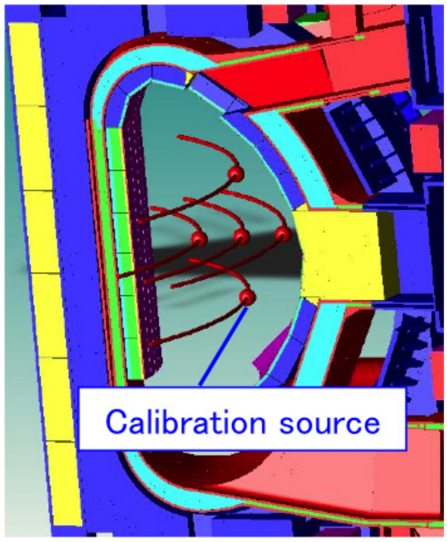

Fig. 4 CAD image [9] of *in situ* calibration with five ring sources.

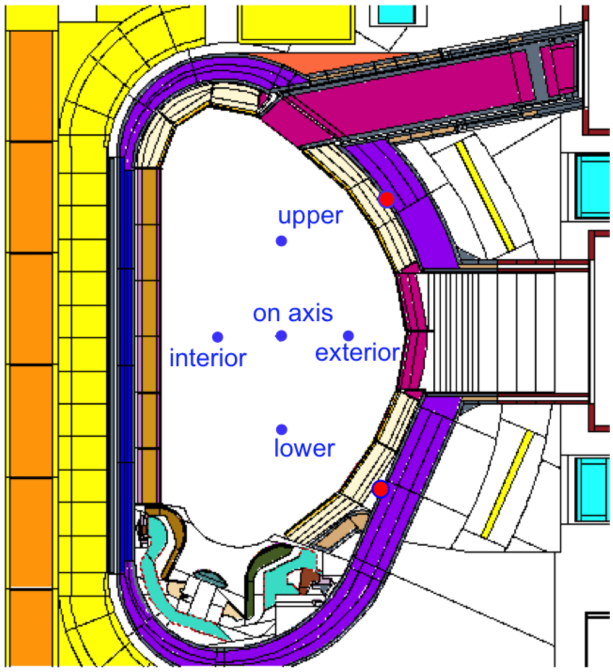

Fig. 5 Calculation model for evaluating the total calibration time with five ring sources.

at each source position. Next, the calibration time to obtain the necessary number of counts at each source position is evaluated for the upper and lower MFC detectors. In this calculation, when the neutron source is set to five poloidal positions (the plasma axis and the upper, bottom, interior, and exterior locations) as shown in the blue circles in Fig. 5. Table 1 shows the MFC calibration time at each position setting of the neutron source and the total calibration time, which are normalized for the calibration time of the upper MFC when the neutron source is set to

Table 1 Normalized calibration time of the upper and lower MFC detectors at each neutron source position, which is normalized to the upper MFC calibration time at the plasma axis.

generator position	Plasma Axis	upper (+150cm)	lower (-150cm)	interior (-100cm)	exterior (+100cm)	Total
upper MFC	1.0	0.7	1.9	1.1	1.2	5.6
lower MFC	0.9	1.8	0.7	0.9	1.0	5.3
Both MFCs	**1.0**	**1.8**	**1.9**	**1.1**	**1.2**	**7.0**

the plasma axis. When the source sits above the plasma axis, the lower MFC calibration time becomes longer than that at the plasma axis and the calibration time of the upper MFC becomes shorter. In contrast, when the source sits below the plasma axis, the calibration time of the upper MFC becomes longer than that at the plasma axis, and the lower MFC calibration time is shorter. Since the differences in calibration times for each MFC detector effectively cancel each other out, the total calibration time for each MFC detector is only five times longer when the source is set at the plasma axis. However, taking into account for the total MFC system, since a longer calibration time is necessary at each source position, the total calibration time to obtain the five toroidal rings for the MFC is not five times, but approximately seven times longer than when the source is set at the plasma axis. This is a result of the change in the detection efficiency as the distance between the neutron source and the MFC varies. Thus, the total calibration time is affected by the position of the supporting rail. An optimization of the supporting rail position, considering the total calibration time, is an important area for future research.

6. The Effect of the Supporting Rail on the Detection Efficiency of the MFC Detectors

The effect of the neutron source supporting rail on the *in situ* calibration was evaluated for the upper and lower MFC. Three cases, the bottom, inboard side and outboard side rails, are considered as the supporting rail, as shown in Fig. 6. The rail is set 10 cm away from the source and has a width of 20 cm in this analysis. The detection efficiencies drift for the upper and lower MFC due to the supporting rail, as a function of the supporting rail thickness, are shown in Fig. 7. Here the rails are assumed to be made of stainless steel (SUS) or aluminum (Al). If the supporting rail is located at the bottom of the source and the thickness of the SUS rail is 5 cm, the detection efficiency of the lower MFC is reduced by approximately 50% as shown in Fig. 7 (a). This is due to the support's location between the neutron source and the lower MFC. The lower MFC detection efficiency is also reduced if the bottom rail is made

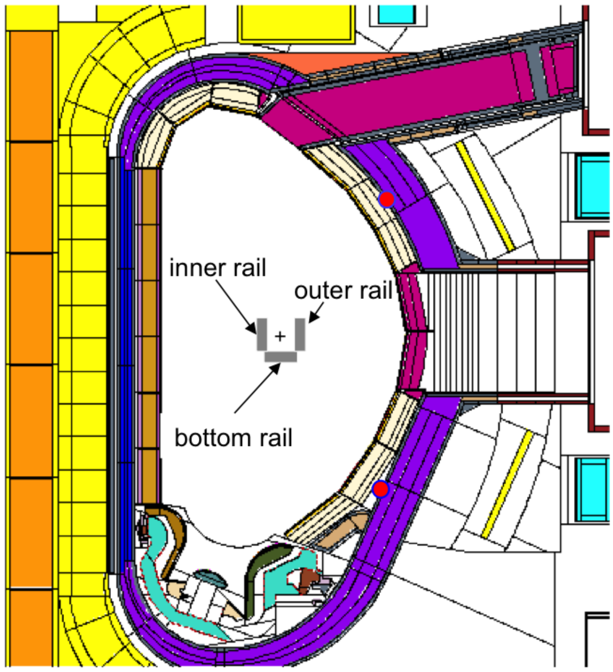

Fig. 6 Calculation model for investigating the effect of the supporting rail.

of Al, however, the reduction rate is smaller than the SUS rail. On the other hand, the upper MFC detection efficiency is slightly increased. It is considered that this is caused by scattering of neutrons due to the supporting rail. In contrast, if the supporting rail is located on the inboard and the outboard side of the source, the effect of the supporting rail on detection efficiency is less than 7% and much smaller than the bottom rail as shown in Figs. 7 (b) and (c). These results indicate that the supporting rail should not be placed between the neutron source and the MFC, and the supporting rail material should be optimized. Focusing on the position of the rail, the detection efficiencies are reduced for both MFCs if the supporting rail is located on the inboard side as shown in Fig. 7 (b), while the detection efficiencies are increased in the case of the outboard rail in Fig. 7 (c). Since the detection efficiency of the MFC, which is installed in the vacuum vessel, is sensitive to scattered neutrons due to in-vessel components, the position of the size of a supporting rail can affect the detection efficiency even though the rail is not positioned between a neutron source and the MFC. If a neutron generator is used as the neutron source during *in situ* calibration, a relatively large and heavy neutron generator support is necessary. Therefore, the supporting rail should be optimized such that the effect on the detection efficiency is minimized.

7. The Effect of Cooling Water in the Blanket Module

Water coolant is essential to cool the blanket module during ITER operation. However, the blanket module may

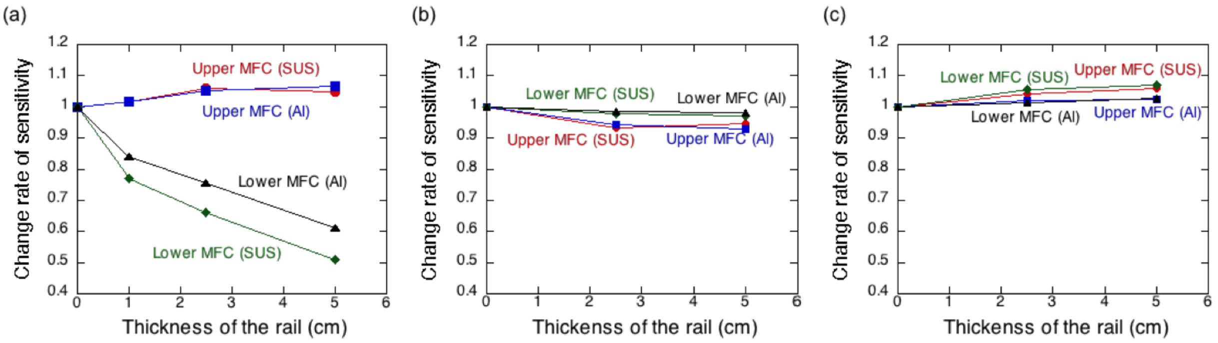

Fig. 7 Change in the rate of the MFC detector detection efficiency due to the support of the source: (a) bottom rail, (b) inboard rail and (c) outboard rail.

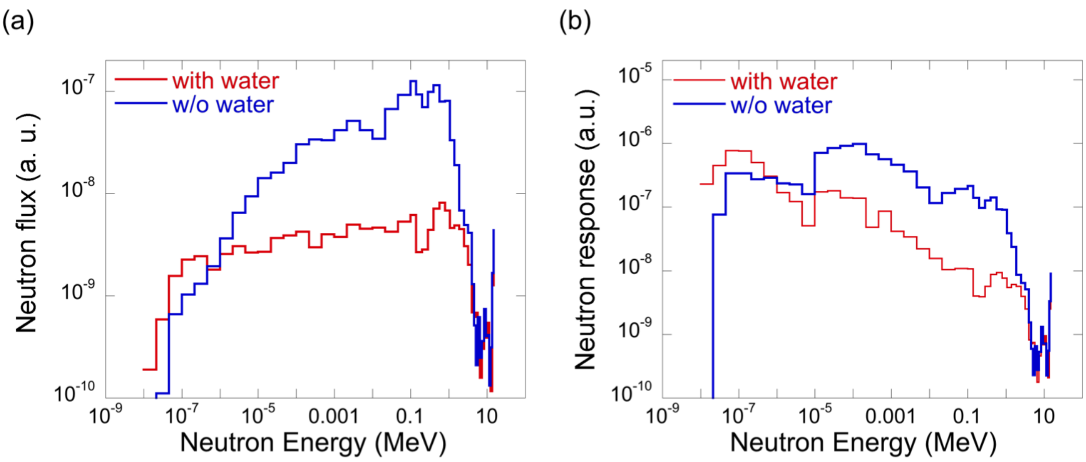

Fig. 8 (a) Neutron spectrum at the upper MFC detector position. (b) Energy dependence of the neutron response of the upper MFC detector.

not be filled with cooling water during *in situ* calibration. Since water slows down and scatters neutrons, it can affect *in situ* calibration. To investigate the effects of cooling water, the neutron flux at the MFC installation position is compared with those under the following two conditions: in the first case, the blanket module comprises 70% SUS316 + 30% water (with water) and in the second case, 70% SUS316+30% void (without water). Figures 8 (a) and (b) shows the neutron spectrum at the upper MFC detector position and the energy dependence of neutron response, defined as the product of the neutron flux and the fission reaction cross section of ^{235}U in a certain energy range, of the upper MFC detector, respectively. Without water, the neutron flux is approximately 10 times higher with water because attenuation of neutrons with over 10^{-5} MeV becomes much weaker due to lack of cooling water. Since the ^{235}U fission material in the MFC has a large cross section of fission reaction in the energy region of thermal neutrons ($<10^{-6}$ MeV), the effect of cooling water on the calibration factor becomes smaller than the neutron flux. However, without water, the total neutron response over the entire energy region is approximately twice as high compared with that with water. Thus, the results suggest that cooling water could significantly affect the *in situ* calibration. Therefore, cooling water should be filled in the blanket module in the same manner as the ITER operations when the *in situ* calibration is performed.

8. Summary

Several effects on *in situ* calibration of the in-vessel neutron flux monitor (MFC) are analyzed by neutron transport analysis using the MCNP. When the *in situ* calibration is performed at five poloidal positions, the total calibration time of the MFC is approximately seven times longer than the calibration time when the source is located at the center position, a result of the change in detection efficiency as the distance between the neutron source and the MFC changes. Thus, optimization between the number of source setting positions and total calibration time is necessary. Furthermore, we found that the bottom rail can strongly affect the lower MFC detector efficiency because the rail is positioned between the neutron source and the lower MFC. Conversely, the side rails have small effects on the detection efficiency of the MFC. However, the analysis results suggested that the supporting rail should be optimized such that the effect on the detection efficiency is minimized. Because the detection efficiency is sensitive to scattered neutrons by in-vessel components including the supporting rail. Cooling water can also significantly affect the *in situ* calibration. Hence, it is necessary that the blanket module be filled with cooling water during *in situ* calibration.

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