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FEATURES OF FUSION POWER MEASUREMENTS IN THE NEXT GENERATION MAGNETIC PLASMA CONFINEMENT EXPERIMENTS

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Abstract

Fusion power measurements provide one of the key benchmarks for every successful reactor-scale magnetic confinement fusion facility. Neutrons carry outside of the plasma volume 4/5 of the produced fusion power in case of deuterium-tritium fuel mix. Thus, measurement of 14-MeV neutron yield is the primary direct measurement of the fusion power of the machine. The challenge of determining the uncertainty of the total neutron yield measurement is solved using several strategies: detailed detector assessment in the metrological neutron laboratory, in-situ calibration using a mobile neutron source (typically - ^{252}Cf) and cross-calibration using a well characterized detector in well-known discharge. Transition to reactor-scale devices such as BEST, ITER, DEMO, etc. will require the use of neutron sources with yields of 10^{10}-10^{11} s^{-1} and above. Multiple diagnostics systems fall in the scope - neutron counters, neutron activation system and multi-collimator systems. Together they provide fusion power measurement with up to 10% accuracy and 1 ms time resolution for the case of ITER, in a broad dynamic range of fusion power. Two methods for in situ calibration are considered: 1) utilizing multiple NG positions to emulate circular or 'ring' source of fusion neutrons for calibration of the permanent detector set, and 2) making use of multiple temporary detectors located in numerous locations inside the vacuum vessel for the period of the calibration, thus allowing to obtain more reference points for further Monte-Carlo model validation with the same (or less) irradiation duration. The work details results of neutron detector characterization activity in laboratory conditions with the use of compact NGs, showing that the use of powerful (up to 10^{11} s^{-1} D-T, 10^{9} s^{-1} D-D) yet compact NGs with sealed tubes raises a challenge of a steady source metrological assurance, especially when considering said sources for the task of in-situ calibration.

1. INTRODUCTION

The growth of plasma volume, temperature and confinement time inevitably leads to the rise of neutron yield and fusion power. Fast neutrons provide an indisputable evidence of the achieved fusion rate, they carry approximately 80% of the power produced, as well as allow for breading of tritium in dedicated blanket modules [1] and for hybrid reactor schemes [2]. Assessment of neutron flux, fluence, source profile and spectrum proves useful for understanding of the expected dose rates [3] and for measurements of ion temperature and fuel ratio [4]. Therefore, it is imperative to implement as part of diagnostic setup several detectors intended to measure fusion neutrons. Placement of these detectors as close as reasonably achievable allows for measurements with good time resolution and low uncertainty, at the same time imposing severe design requirements. Locating detectors at a fair distance from plasma leads to lowered overall sensitivity of the diagnostic system, increasing the time resolution required to obtain reasonable number of events. Successful operation of neutron diagnostics requires thorough preparatory work and generally includes the following steps, accompanied by detailed neutronics assessment at every stage:

- Assessment of detector assembly at metrological neutron laboratory
- *In situ* calibration with a mobile neutron source
- Cross-calibration with other detectors during a well-known discharge

The most prominent experience of D-T discharges was obtained at TFTR [5] and JET [6], featuring *in situ* calibration campaigns with isotope source (^{252}Cf) [7] and compact neutron generators (D-T, sealed tube, up to 10^8 s^{-1}) [8, 9]. For given dimensions of the machines, this already presented a challenge of irradiation duration up to multiple weeks, source stability and reliability, while still obtaining a rather low number of events at monitor location. These problems are undoubtedly exacerbated by increasing next-gen machine dimensions – BEST (R = 3.6 m) [10], ITER (R = 6 m) [11], CFETR (R = 7.2 m) [12], EU-DEMO (R > 7.5 m) [13] and others.

In present work the progress of neutron diagnostics development for the ITER machine in Russian Federation Domestic Agency is discussed, as well as the strategy developed for these diagnostics to facilitate fusion power measurements at ITER. This includes several recent achievements in design and testing of neutron diagnostic detectors, overall uncertainty minimization plan with particular focus on *in situ* calibration based on high-yield D-T neutron generator (NG, up to 10^{11} s^{-1}). Multiple diagnostics systems fall in the scope of this work including neutron counters (i.e. fission chambers), neutron spectrometers and multi-collimator systems. Together they allow for comprehensive measurement of total neutron fluence, time resolved yield and neutron source shape, thus providing fusion power measurement with high accuracy and time resolution (up to 10% and 1 ms for the case of ITER) in a broad range of fusion power form tenths of a MW up to hundreds. Similar set of systems is employed for neutron source control at JET [14], EAST [15], and other devices.

2. NEUTRON DIAGNOSTICS FOR FUSION POWER MEASUREMENT AT ITER

This section covers an example diagnostic system necessary to reach the target requirements of measurements related to fusion power as listed in table 1. The requirements listed in this table are only excerpts relevant to fusion power measurements covered by ITER Divertor Neutron Flux Monitor (DNFM), but are representative of other similar diagnostic systems. Aiming to locate sensors close to plasma, DNFM detector units are planned to be installed on the inner shell of the ITER vacuum vessel as illustrated on figure 1, with neutron flux reaching 2×10^{12} $cm^{-2}s^{-1}$ during a 500 MW baseline discharge (see figure 2) down to $\sim10^6$ $cm^{-2}s^{-1}$ during the ohmic deuterium discharges. Achieving this dynamic range of measurements is done using multiple electrode systems with various content of uranium-235 and uranium-238 oxides and independent signal readouts through MI cables, with preamplifiers located at ~30 m of cable length and over 5 welded and triaxial connectors.

TABLE 1. Neutron yield and fusion power measurement requirements for ITER DNFM

Parameter	Units	Range	Designation	Time resolution, ms	Accuracy, %
Neutron yield	n/s	$10^{14} \sim 10^{18}$	DD	10	20
		$10^{18} \sim 3\times10^{20}$	DT		10
Fusion power	MW	$0.1 \sim 3.0$	DD		20
		$3.0 \sim 900$	DT		10

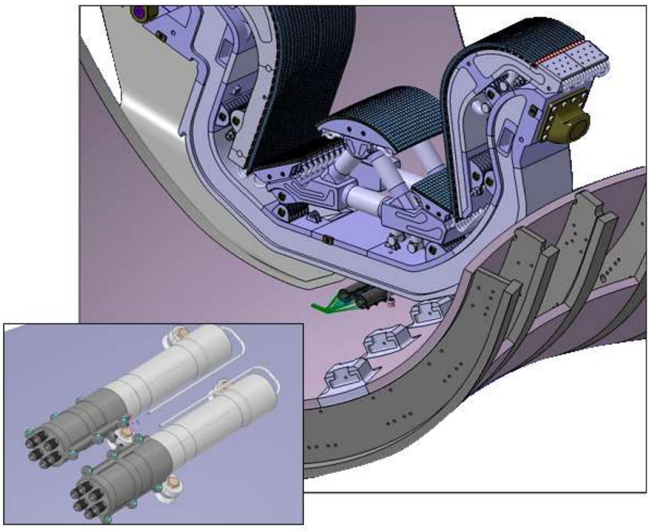

FIG. 1. Divertor Neutron Flux Monitors located on the inner vacuum vessel shell of ITER.

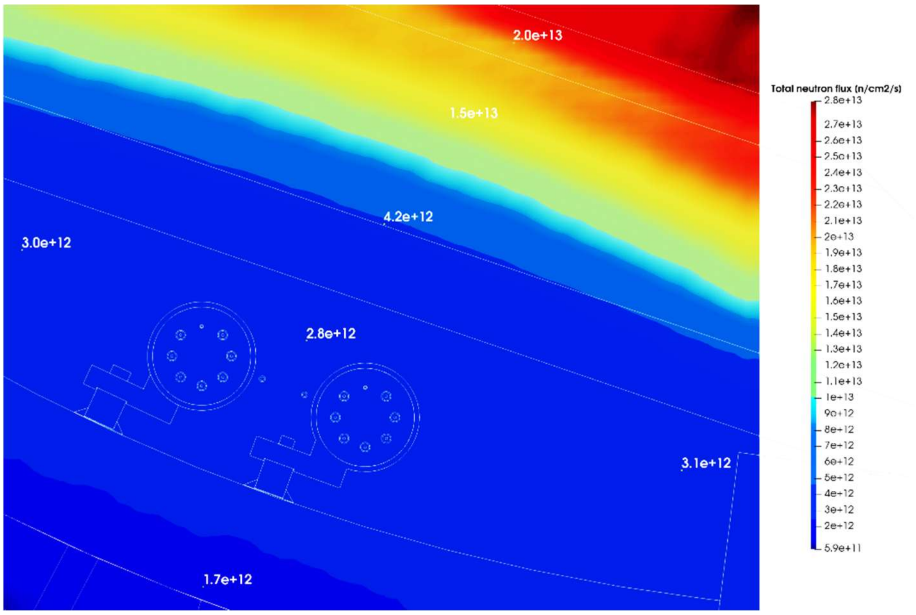

FIG. 2. Spatial distribution of neutron flux at the DNFM detector location calculated using OpenMC code

Group neutron flux at DNFM location as illustrated on figure 3 clearly shows a significant part of scattered neutrons contributing to the expected detector count-rate, group neutron flux obtained for 500 MW baseline discharge is normalized to match the neutron flux expected during *in situ* calibration. The scattered part is dependent on the surrounding parts of the machine, especially on the divertor configuration, replicating this part of the spectrum in laboratory conditions appears to be impractical. At the same time, the relative contribution of the scattered component to the resulting count-rate appears dominant and consistent compared between the two irradiation scenarios. The discrepancy of total neutron group flux between the normalized value at 500 MW and the calibration case below 1 MeV reaches 6.5% (figure 3, left), with neutrons above 1 MeV (figure 3, right) accounting for only 4.5%. The group neutron flux during in situ calibration was obtained by neutron transport analysis for the case of the NG-24 D-T neutron generator located with its target on plasma axis, and so that the NG target plane coincides with poloidal machine cross-section.

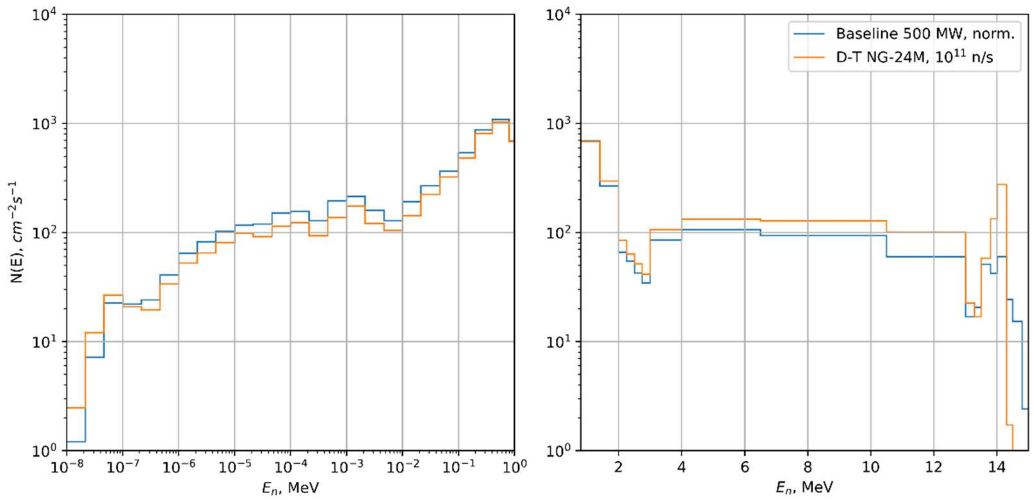

FIG. 3. Group neutron flux at DNFM location during baseline 500 MW scenario and in situ calibration with D-T NG

For further assessment, a realistic model of detector response was created using GEANT4 [16] software as illustrated on figure 4. The model was then benchmarked in laboratory conditions using isotope neutron sources, compact neutron generators, mock-up moderators of borated polyethylene and ITER-grade stainless steel (4 cm thickness of material layers), as illustrated on figure 5. It is evident that replicating tokamak environment and realistic cabling in our laboratory is not feasible, the length of cables, number of connectors, temperature gradients and other impacting factors underline the necessity of in situ calibration procedure. The model is nevertheless necessary for experiment support, allowing the assessment of detector pulse-height spectrum and analysis of count-rate decrease due to fission fragments lost in materials surrounding the charge-collecting gas volume, it is estimated that this loss accounts to 8.5% to 2.5% fission events depending on uranium oxide content and layer thickness. The sensitivity of DNFM detector units estimated obtained using this model well correspond to the values obtained via neutron activation for the case of D-T source, and ranges from ~3.7×10^{-3} cm^2 (500 mg of ^{235}U) down to ~5.8×10^{-6} cm^2 (5 mg of ^{238}U).

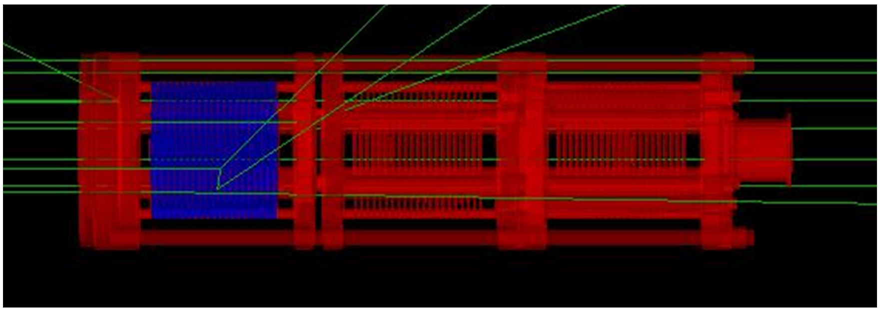

FIG. 4. Geant4-model of the intrinsic DNFM detector unit structure, blue colour highlights the gas mix surrounding one of the three electrode systems of a single DNFM detector unit.

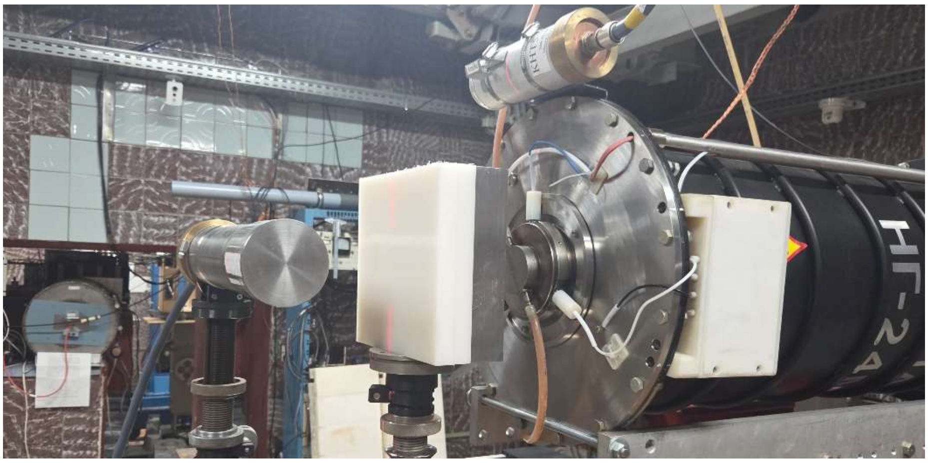

FIG. 5. Benchmark experiment setup of the DNFM detector unit under D-T neutron irradiation with polyethylene and stainless-steel composition moderator mock-up.

For the overall 10% target accuracy of fusion power measurement required in high-yield scenarios, this factor is critical and can be only precisely determined on a modern machine once the detector unit is tested in its final configuration with complete signal lines and surrounding materials. As an added value, this developed model allows the group-by-group assessment of the neutrons of various energies to the resulting count-rate.

From the engineering standpoint locating a detector unit at ~5 meters from plasma core on a next-generation device will impose significant load combinations during both operation and accident events. For the case of in-vessel detector, as for most conducting components in the vicinity of the plasma, EM-loads are a critical contributing factor [17], raising the need for electrical insulation of detector mounts to the conducting components [18]. The risk of detector leakage also is to be mitigated by external connection to a residual gas monitoring system. Locating detector further away in ex-vessel zone may allow for an easier integration and for less EM-noise, but at a price of lower neutron flux, which is especially critical during calibration of these diagnostics.

3. CHALLENGE OF IN SITU CALIBRATION

As an example, detector located under divertor in ITER machine during calibration is irradiated with ~5×10^3 cm^{-2}s^{-1} of total neutron flux, for the source yield of ~10^{11} s^{-1}, D-T. Only a substantially smaller machine (i.e. BEST) can be calibrated in reasonable time with the source with a lower neutron yield of ~10^{10} s-1 (D-T NG-14 neutron generator model). This neutron flux value is comparable with detector sensitivity, and is therefore contributing to the lower limit for the duration of a single *in situ* calibration campaign exposition. In current section key solutions of the in-situ neutron calibration problem are discussed, with both methods revolving around compact neutron generators being deployed inside the fusion machine vacuum vessel:

1) utilizing multiple NG positions to emulate circular or 'ring' source of fusion neutrons [19, 20] for calibration of the permanent detector set, with characteristic unit fission rate per source neutron of illustrated on figure 6, with ~95% of count-rate occurring within ±60 degrees and ±100 degrees for ^{238}U and ^{235}U DNFM fission chambers respectively;
2) making use of multiple temporary (low-cost and/or high-sensitivity) detector units located in various locations inside the vacuum vessel strictly for the period of the calibration, thus allowing to obtain more reference points for further model validation with the same (or less) calibration campaign duration.

Both methods are nevertheless to be augmented using the cross-calibration during reference discharges, preferably low fusion power, minimal-to-zero auxiliary heating, in essence – the ohmic discharges.

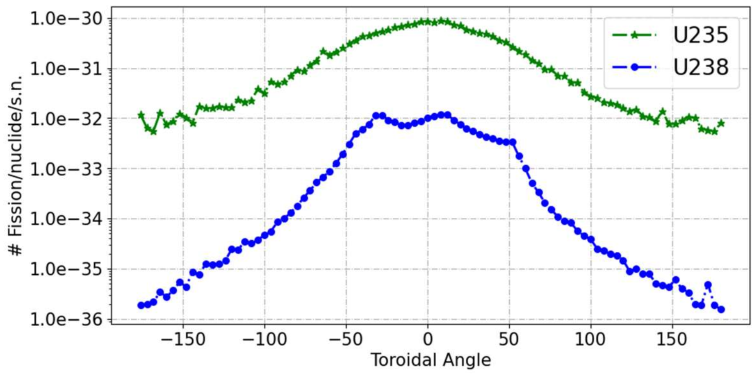

FIG. 6. Unit fission rate of DNFM ^{235}U and ^{238}U detector units versus toroidal angle under D-T neutron irradiation (isotropic point source) [21].

The structural integrity requirements for these temporary detector units, with locations proposed as shown on figure 7 (left) are quite limited (if any), as they are not intended for use during the actual machine operation. It is evident that given the constraints on the neutron source strength and calibration campaign duration, the use of temporary detector set with low price-per-unit and high sensitivity may facilitate greatly the validation process of the quite detailed tokamak models for Monte-Carlo modelling of the neutron transport.

The calculated group neutron flux at virtual detectors are shown on figure 7 (right), optimization of these virtual detector locations will have to be done based on the accessibility to the desired in-vessel zones. The primary candidate for such a calibration approach is the initial irradiation campaign to be conducted before the start of research operation. Locating a detector at equatorial port level near first wall can provide up to 4×10^5 cm^{-2}s^{-1} neutron flux, almost 2 orders of magnitude more than for reference DNFM location. Adding a temporary detector in the upper port plug amounts to an additional reference point quite similar in metrological power as DNFM with a slightly higher scattered neutron fraction – total flux is ~1.5×10^4 cm^{-2}s^{-1} versus ~5×10^3 cm^{-2}s^{-1} for DNFM. Temporary detectors shielded by more material as the reference lower port diagnostic rack location provides similar neutron flux levels – up to 3.6×10^3 cm^{-2}s^{-1}, with significantly higher scattered fraction.

Based on this simplified assessment it is highly advisable to use said additional reference points, specifically in the equatorial port level. At a fraction of the cost of a complete diagnostic system compatible with high vacuum, EM and thermal structural loads (and at least 100-fold decrease of price when comparing an regular detector unit and a single neutron sensitized particle track detector [22]) and respective data acquisition / etching and imaging systems, the latter option scales greatly (also allowing for toroidal scan coverage, instead of being limited to the

VV sectors with diagnostics installed) whilst having some neutron spectrometry capacity, a low sensitivity (~10^{-5} cm^2) and a fairly sophisticated processing station necessary to etch the detector and count particle tracks. The organic scintillator option allows for a more high-sensitivity measurements (up to ~1 cm^2) necessary to anchor the model with low statistical uncertainty of the fast neutron fraction.

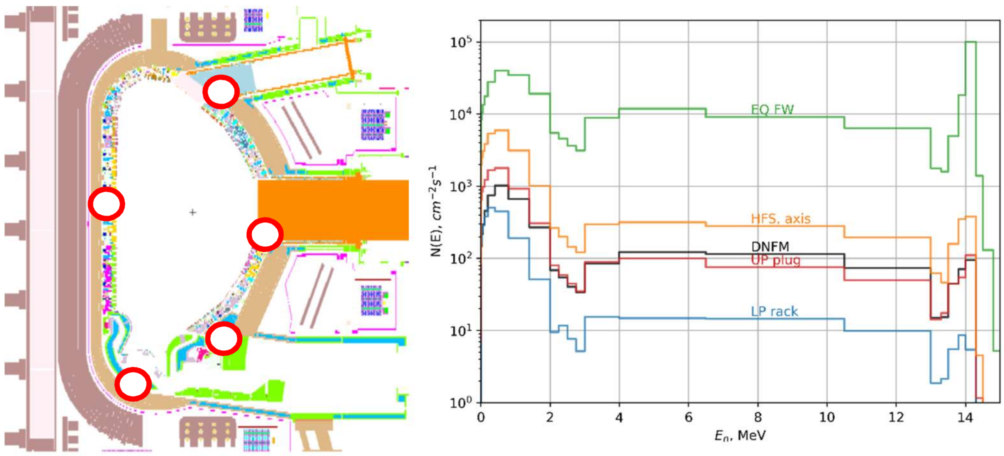

FIG. 7. Additional temporary detector locations (left) and group neutron fluxes during in situ calibration with D-T NG (right), red – inside upper port plug, green – equatorial port first wall, black – under divertor cassette, blue – lower port on top of diagnostic rack, orange – high-field side, plasma core level.

This 2nd method of *in situ* calibration is therefore beneficial for lowering the uncertainty of the neutron measurements and fusion power assessment of the reactor-scale tokamaks (ITER, CFETR, DEMO, etc.) with both parameters being critical from the regulatory standpoint. The proposed approach scaled toroidally may complement the existing ITER neutron activation system irradiation ends, present in upper, equatorial and lower ports in a couple of VV sectors.

4. NEUTRON SOURCE SUITABLE FOR NEXT GEN MACHINES

Current section discusses in detail the results of neutron detector characterization activity in laboratory conditions with the use of compact NGs. Results of the assessment show that the use of powerful (up to 10^{11} n/s D-T, 10^9 n/s D-D) yet compact NGs with sealed tubes raises a challenge of source metrological assurance, especially when considering said sources for the task of in-situ calibration. These NGs are to be supplied with monitoring systems, preliminary characterized at metrological facilities, with Monte-Carlo models built and verified in terms of both materials, geometry, and neutron source anisotropy. A detailed assessment of the D-T version of the neutron generator manufactured by FSUE VNIIA [23] has been conducted using diamond detectors. The measurements of the direct neutron spectra performed with RF DA detectors developed in house are consistent with the neutron source model, that considers various beam ion fractions (D+, D_2+, etc.), target thickness and angular dependence of the cross-section of the D-T reaction [24]. Additional demonstration of D-T NG anisotropy was performed using uniformly moving ^{238}U fission chamber mounted in direct view of the NG target, with resulting count-rate demonstrated on figure 8. Results of the analysis of neutron flux attenuation by the NG body are shown on figure 9. It is evident from the figures 8 and 9 that significant fast neutron flux attenuation occurs already around 85 degrees of line-of-sight incline with respect to NG axis.

At 175 kg of irradiation unit weight, tube lifetime confirmed operation up to 300 hours, and a modest reactor-compatible dimensions (Ø430×1150), the NG-24 yield of 10^{11} n/s proves barely suitable for the tokamak reactors of ITER-like dimensions. At current parameters, it is estimated that calibration campaign duration of multiple weeks would be required, without considering the downtime in case of component failure.

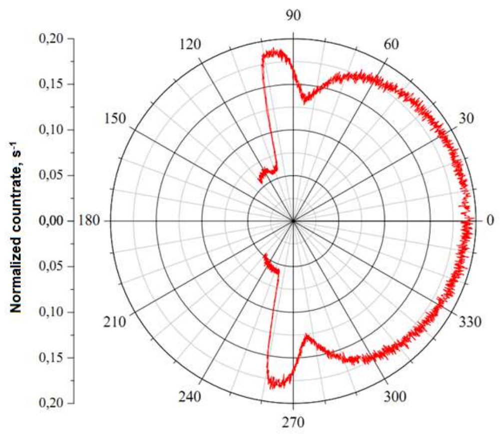

FIG. 8. ^{238}U fission chamber count-rate versus irradiation angle between line of sight and D-T NG-24 axis

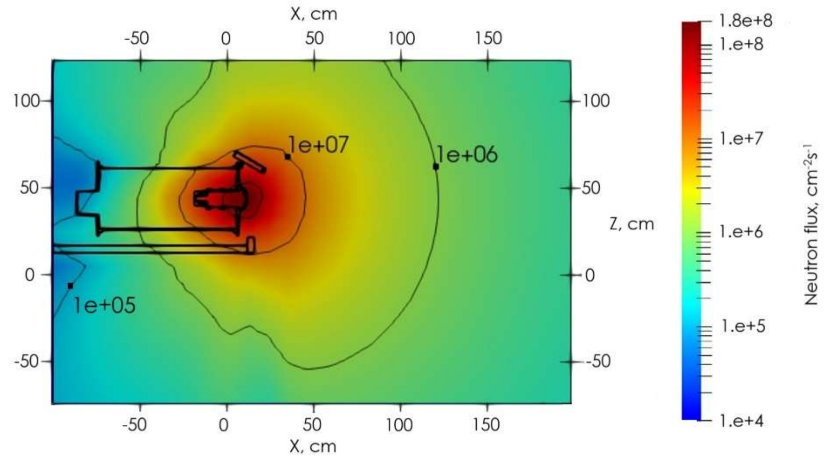

FIG. 9. Neutron flux distribution around the D-T NG irradiation unit, one of the neutron flux monitors is mounted on the NG front flange as shown

The metrological assurance of a neutron source of this scale requires a facility of large dimensions, allowing to mitigate any backscatter flux and extensive irradiation campaigns (see NPL facility [25]). Planning for such a facility to be available near the site of a next gen fusion reactor is crucial for demonstration of the machine performance with desired measurement accuracy.

5. SUMMARY AND OUTLOOK

This work clearly demonstrates the extensive nature of characterisation efforts required to provide fusion power measurements for a next generation fusion power plant of reactor scale (ITER, CFETR, EU-DEMO, etc.), showing that with the example of the ITER Divertor Neutron Flux Monitor. Given the realistic neutron flux and detector locations during the discharge, it is strictly necessary to characterise the detector at factory level. This characterisation will have to be followed by the tests on site with final I&C configuration, which could be too complicated to replicate elsewhere. Before the operation campaign, the final step would be the *in situ* calibration, given the realistic (up to 10^{11} n/s) neutron yield, only the most sensitive detectors will achieve sufficient number of events for the analysis. At this level, any additional temporary detectors of small size that only serve the purpose of adding reference points for Monte-Carlo model validation, provide the much-desired accuracy increase. The remaining neutron diagnostics will have to be cross-calibrated using a well described model of both the plasma neutron source in a reference discharge and the machine surroundings.

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