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

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## Motivation

The growth of plasma volume, temperature and confinement time inevitably leads to the rise of neutron yield and fusion power. Fast neutrons carry approximately 80% of the power produced, as well as allow for breading of tritium in dedicated blanket modules and for hybrid reactor schemes. Assessment of neutron flux, fluence, source profile and spectrum proves useful for understanding of the expected dose rates and for measurements of ion temperature and fuel ratio. Therefore, it is imperative to implement as part of diagnostic setup several detectors intended to measure fusion neutrons. 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 and JET, featuring in situ calibration campaigns with isotope source ($^{252}$Cf) and compact neutron generators (D-T, sealed tube, up to $10^8$ $s^{-1}$). 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 exacerbated by increasing next-gen machine dimensions – BEST (R = 3.6 m), ITER (R = 6 m), CFETR (R = 7.2 m), EU-DEMO (R > 7.5 m) and others.

In present work the progress of neutron diagnostics development for the ITER machine 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, 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.

## ITER Divertor Neutron Flux Monitor (DNFM)

This section covers an example diagnostic system – ITER DNFM - necessary to reach the target requirements of measurements related to fusion power.

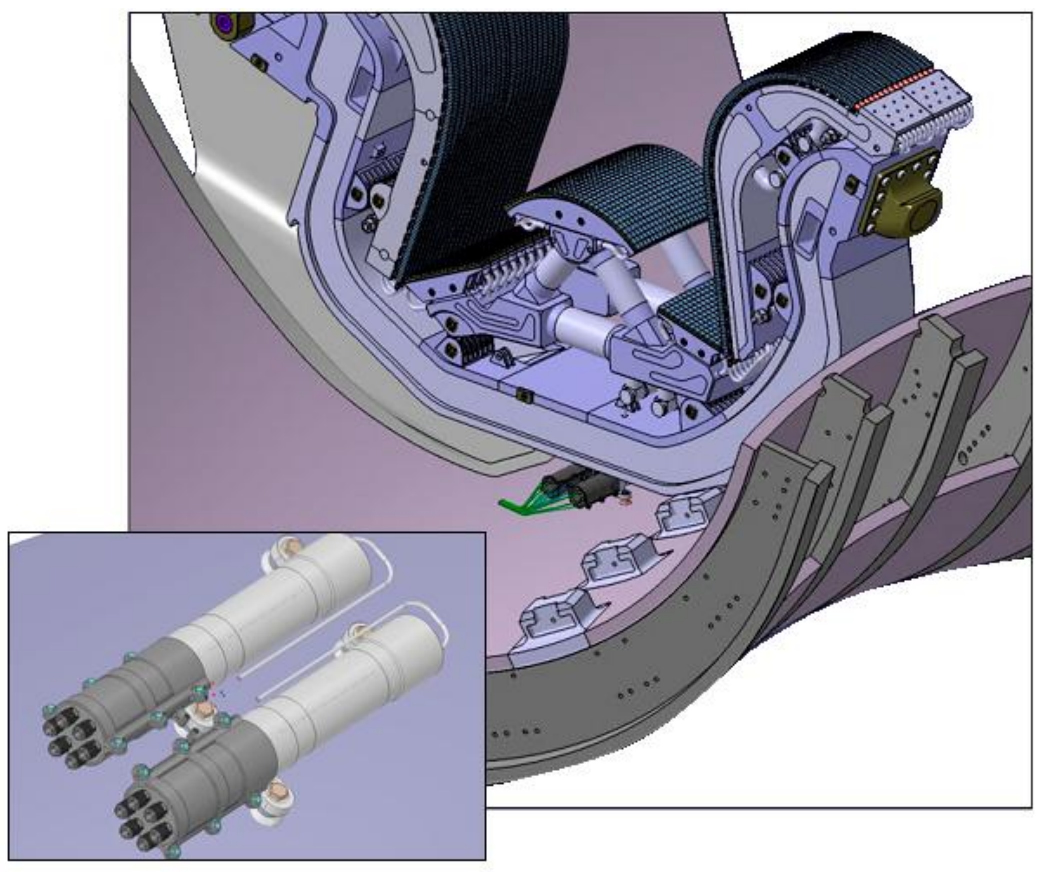
Aiming to locate sensors close to plasma, DNFM detector units are planned to be installed on the inner shell of the ITER vacuum vessel, with neutron flux reaching $2\times10^{12}$ $cm^{-2}s^{-1}$ during a 500 MW baseline discharge down to ~$10^6$ $cm^{-2}s^{-1}$ during the ohmic deuterium discharges.

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.

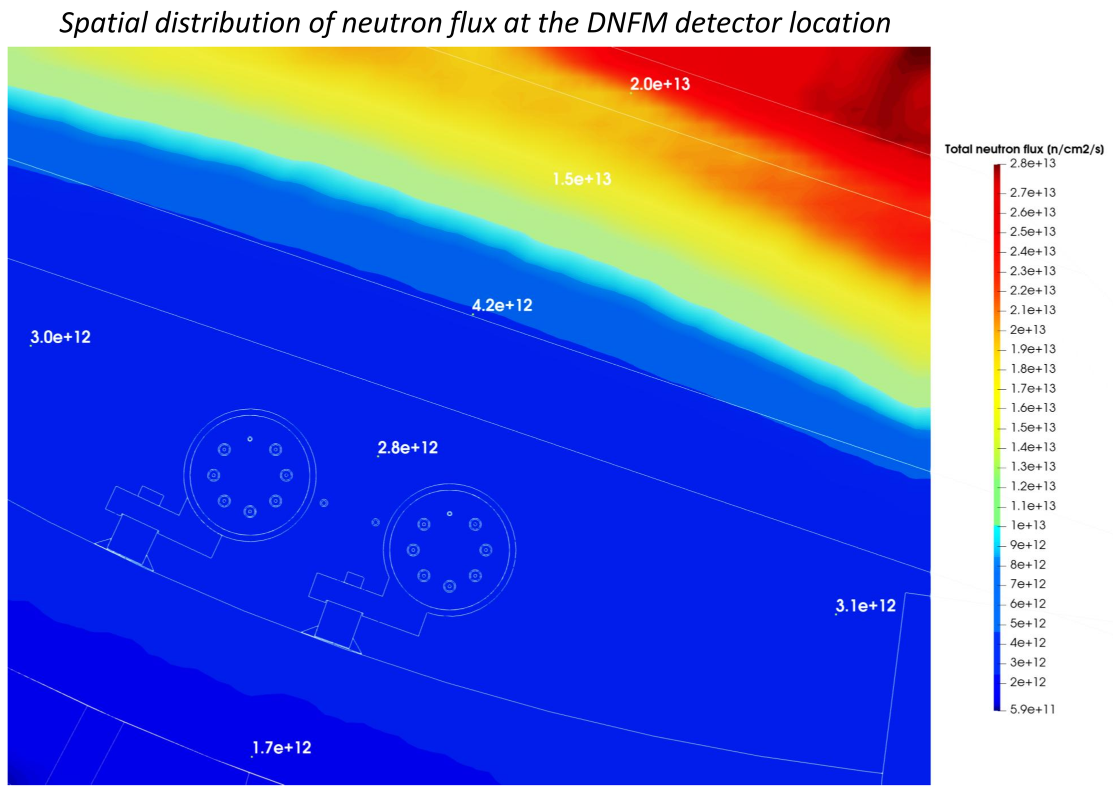
*DNFM requirements for neutron yield and fusion power measurements at ITER*

| Parameter | Units | Range | Designation | $t_{res}$, ms | Acc., % |
|---|---|---|---|---|---|
| Neutron yield | n/s | $10^{14}$ ~ $10^{18}$ | DD | 10 | 20 |
| | | $10^{18}$ ~ $3\times10^{20}$ | DT | | 10 |
| Fusion power | MW | 0.1 ~ 3.0 | DD | | 20 |
| | | 3.0 ~ 900 | DT | | 10 |

*DNFM detector location under the divertor cassette on VV inner shell*



*Spatial distribution of neutron flux at the DNFM detector location*



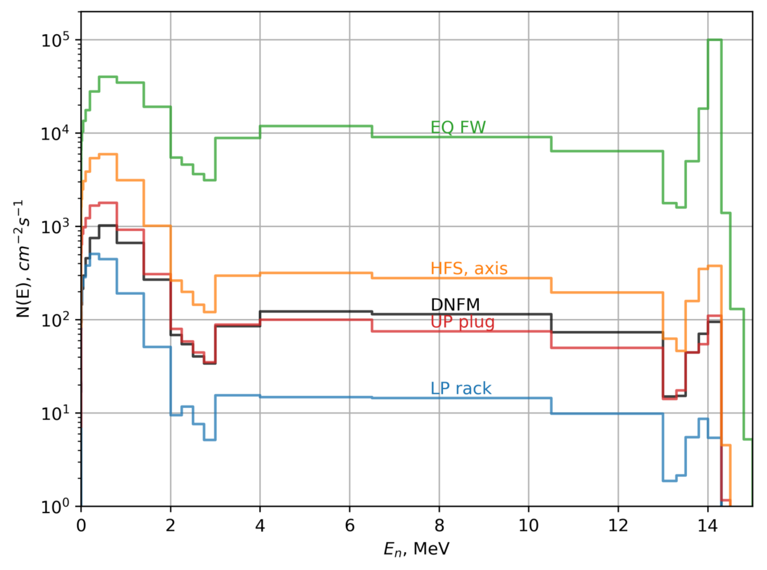

## Challenge of *in situ* calibration

- utilizing **multiple NG positions to emulate circular or 'ring' source** of fusion neutrons for absolute calibration of the permanent neutron detector set
- **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 more reference points for further model validation with the same (or less) calibration campaign duration.

Temporary detector locations will have to be done based on the accessibility to the desired in-vessel zones. Locating a detector at equatorial port level near first wall can provide up to $4\times10^5$ $cm^{-2}s^{-1}$ 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 ~$1.5\times10^4$ $cm^{-2}s^{-1}$ versus ~$5\times10^3$ $cm^{-2}s^{-1}$ for DNFM. Temporary detectors shielded by more material as the reference lower port diagnostic rack location provides similar neutron flux levels – up to $3.6\times10^3$ $cm^{-2}s^{-1}$, with significantly higher scattered fraction of neutron flux.

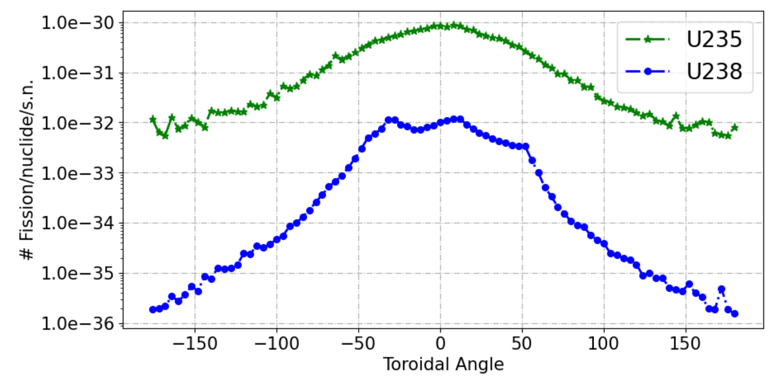
Based on this simplified assessment it is highly advisable to use said additional reference points, specifically in the equatorial port level. At a fraction of the cost of a complete diagnostic system **these temporary detectors can provide much needed reference points for model validation in MCNP/OpenMC**, with the optimal time for said calibration being before the start of machine operation after commissioning of the in-vessel systems.

*Group neutron flux at multiple temporary detector locations around poloidal cross-section of the ITER machine*




*Nishitani, T. et al. Fusion Engineering and Design 191, 113548 (2023).*

*Unit fission rate at DNFM location for the case of D-T NG in situ calibration*

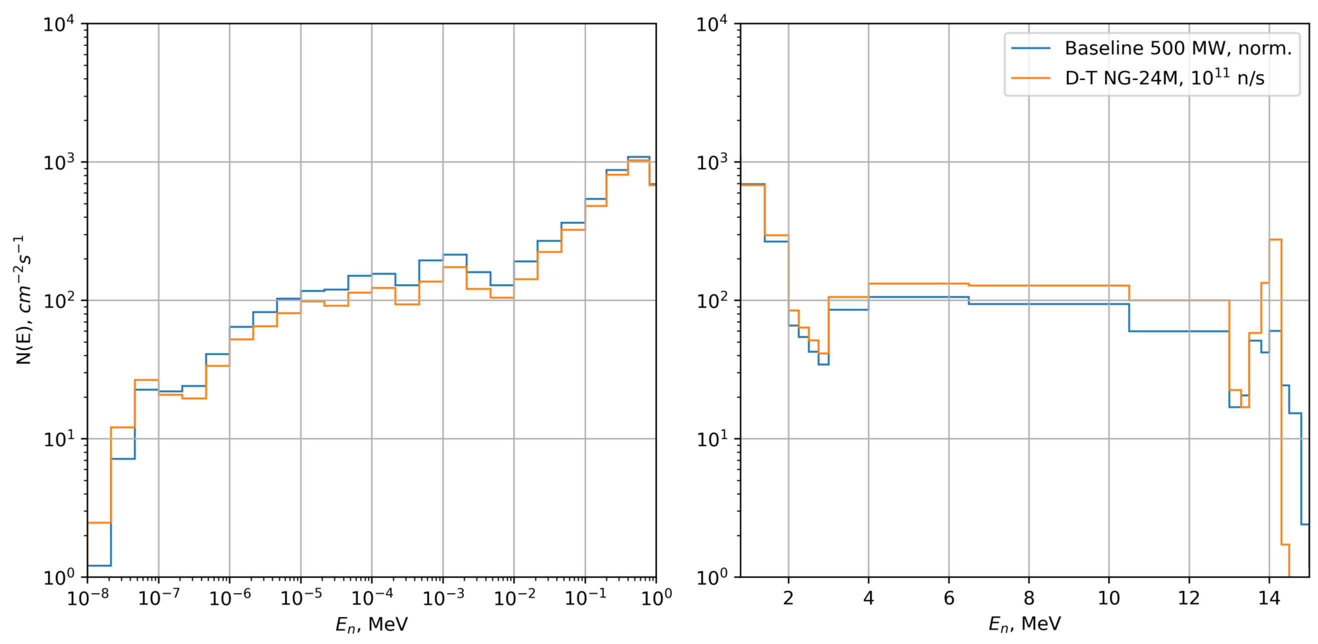



## Group flux during calibration vs. operation

Group neutron flux at DNFM location as illustrated on figure 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 for comparative analysis.

The relative contribution of the scattered component to the resulting count-rate appears dominant and consistent compared between the two 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%, with neutrons above 1 MeV 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.

*Group neutron flux at DNFM location during 500 MW scenario and in situ calibration with D-T NG*




## Factory calibration and model validation

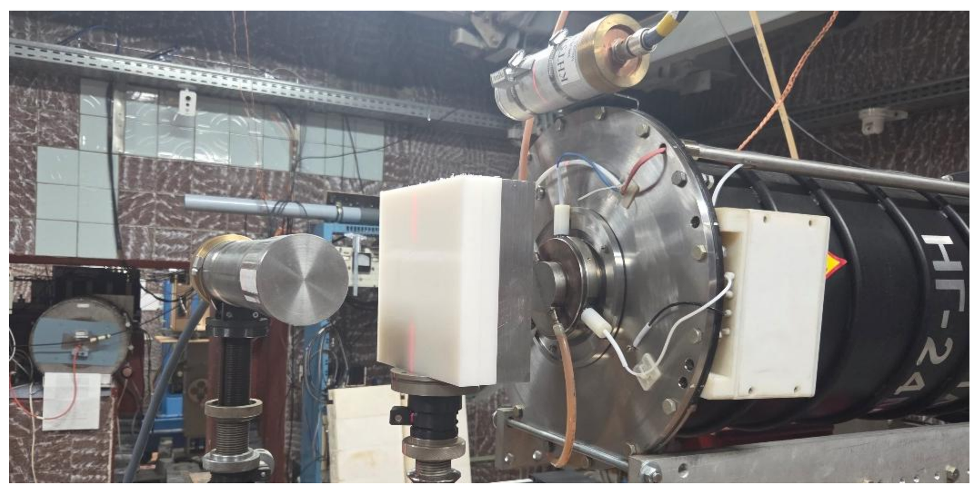
For further assessment, a realistic model of detector response was created using Geant4 software. The model was then benchmarked in laboratory conditions using isotope neutron sources, compact neutron generators, mock-up moderators of borated polyethylene and ITER-grade stainless steel (4 cm thickness of material layers). **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 complexity of in situ calibration procedure.

The model is 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 to D-T neutrons is estimated obtained using this model well correspond to the values obtained via neutron activation for the case of D-T source, and ranges from ~$3.7\times10^{-3}$ $cm^2$ (500 mg of $^{235}$U) down to ~$5.8\times10^{-6}$ $cm^2$ (5 mg of $^{238}$U).

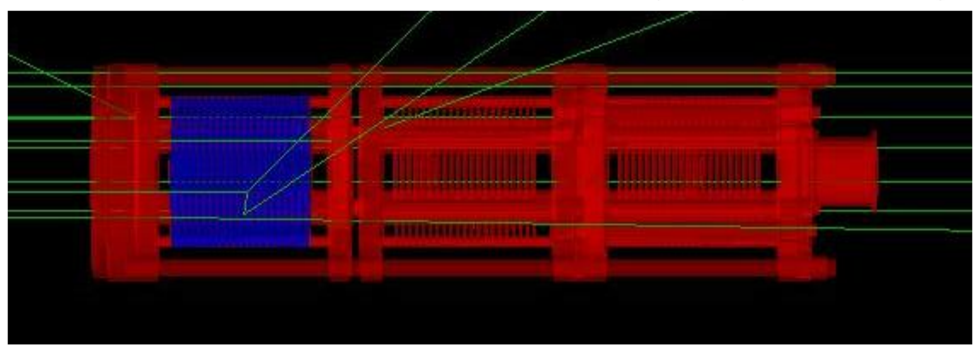
For the overall 10% target accuracy of fusion power measurement required in high-yield scenarios, this factor is critical and can be only precisely determined on a modern machine once the detector unit is tested in its final configuration with complete signal lines and surrounding materials. As an added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

*Allison, J. et al. (2016) Nuclear Instruments and Methods in Physics Research, Section A, 835, pp. 186–225.*

*Benchmark experiment with mock-up moderators under D-T NG irradiation*

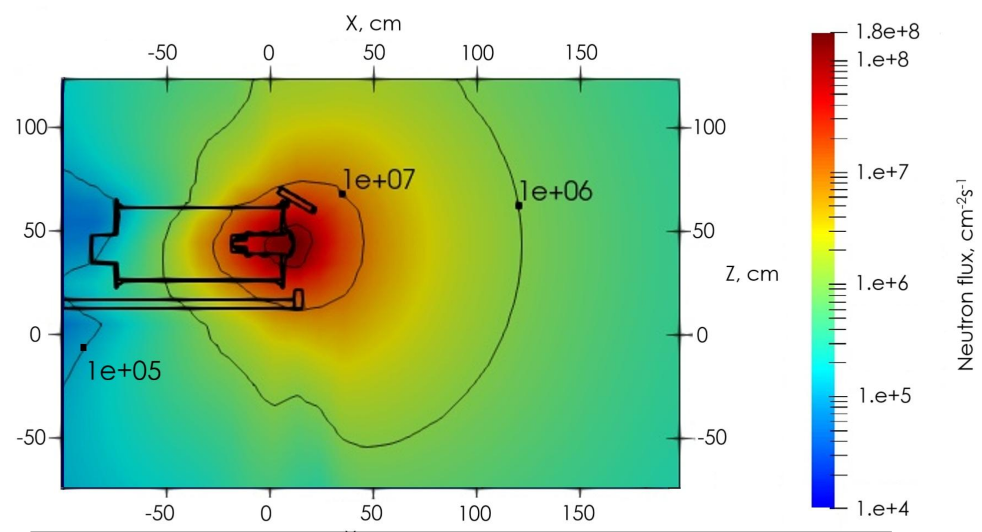


*DNFM detector CAD model translated to Geant4 for response modelling*



## Neutron source suitable for next-gen machines

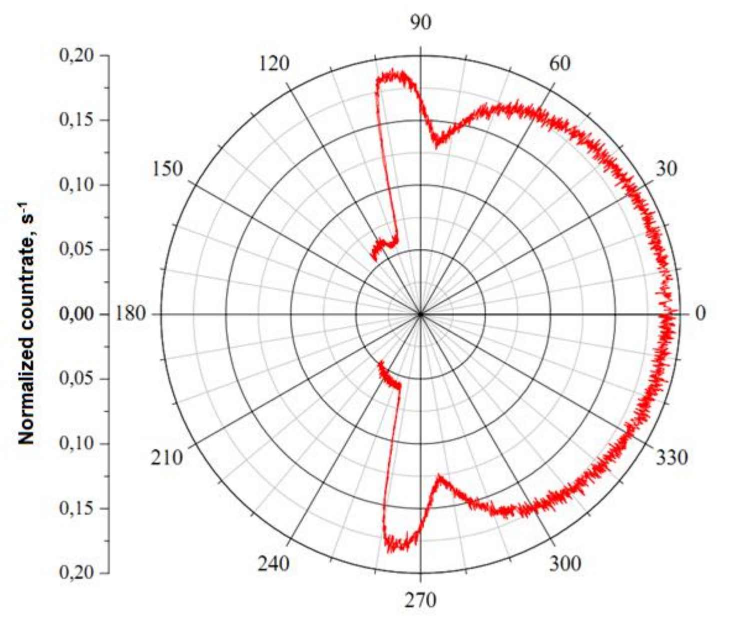
Results of the assessment show that the use of powerful (up to $10^{11}$ $s^{-1}$ D-T, $10^9$ $s^{-1}$ D-D) yet compact NGs with sealed tubes raises a challenge of source metrological assurance, especially when considering said sources for the task of in-situ calibration. A demonstration of D-T NG anisotropy was performed using uniformly moving $^{238}$U fission chamber mounted in direct view of the NG target. Results of the analysis of neutron flux attenuation by the NG body illustrate that a significant fast neutron flux attenuation occurs already around 85 degrees of line-of-sight incline with respect to NG axis.




*Neutron flux distribution around NG irradiation unit with realistic SDEF*

*Kormilitsyn, T. et al. EPJ Web of Conferences 288, 03002 (2023).*

*NG yield curve demonstrated using uniform movement of 238U fission chamber around NG target*




## Conclusion and outlook

This work clearly demonstrates the extensive nature of characterization efforts required to provide fusion power measurements for a next generation fusion power plant of reactor scale (ITER, CFETR, EU-DEMO, etc.). Given the realistic neutron flux and detector locations during the discharge, it is strictly necessary to characterize the detector at factory level. This characterization 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 $10^{11}$ $s^{-1}$) 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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The views and opinions expressed herein do not necessarily reflect those of the ITER Organization

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