Detailed reproduction of the neutron emission from the compact DT neutron generator used as an in-situ 14 MeV calibration neutron source at JET

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***Abstract*— A compact DT neutron generator (NG) based on the mixed-beam operation was used as a calibration neutron source in the latest in-situ calibration of neutron detectors at the Joint European Torus (JET). In order to meet the requirement for the total uncertainty of the neutron detector calibration below ±10 %, the neutron emission properties had to be experimentally characterized and reproduced through detailed modelling of the neutron source characteristics and geometry of the neutron generator.**

The detailed neutronics simulations were an essential part of both NG characterization and JET neutron detector calibration. The complex neutron emission properties of the NG were reproduced through a combination of simulations and high-resolution neutron spectroscopy measurements. This meant that six different DT neutron source components resulting from NG's mixed beam operation were explicitly simulated and their relative intensities scaled based on experimentally obtained neutron spectrum measurements. Furthermore, the detailed model of the NG's geometry was produced based on information from the supplier of the NG and images from a computer tomography (CT) scan. Finally, the positioning of the neutron source inside the JET tokamak during in-situ calibration was reproduced based on the information from the remote handling system (RHS) at JET, the system responsible for the positioning of the source during the calibration experiment.

The extensive effort presented in the paper significantly contributed to the total uncertainties of the calibration factors well within the target value of ±10 %.

***Index Terms*— DT neutron generator, neutron source characterization, neutron detectors, calibration**

I. Introduction

Neutron sources with well-known neutron emission characteristics and suitable neutron energies can be used as calibration neutron sources for in-situ calibration of neutron yield detectors in large tokamaks. Typically ^{252}Cf spontaneous fission sources [1] are used for calibrations to 2.5 MeV energy neutrons from a DD plasma and DT neutron generators for calibrations to 14 MeV neutrons from DT plasma. As neither simulations nor experiments alone can provide calibration factors with sufficient accuracy such calibration procedures typically consist of both measurements and simulations [2]. While in-situ measurements, i.e. measurements of detector responses to calibration neutron sources in positions inside the reactor, provide direct measurements of detector sensitivity neutronic simulations are used to relate the detector responses during calibration experiments to detector responses during plasma experiments. This is important in order to take into account the differences in reactor configuration during plasma operation and during calibration experiments as well as differences in the neutron source emission spectra between plasma neutron source and calibration neutron source [3].

In the latest calibration to DT neutrons at JET a portable DT neutron generator was used. Target uncertainty of the calibration factors was ±10 % meaning that accurate reproduction of the neutron source was essential. This was achieved through detailed modelling of the neutron emission properties and geometry while the validation of these models was performed through comparisons with measurements from the NG characterization [4].

The NG produces neutrons through DT reactions of nuclei from the ion beam impinging on the solid target. This means that its neutron emission properties depend on the ion beam composition, energy of ions, target composition, and the geometry of the NG. Highly detailed reproduction of the neutron source properties described in Section II was achieved by a combination of high-resolution neutron spectroscopy and simulations while the reconstruction of the geometry described in Section III is a result of the computed tomography (CT scan) of the NG which served as a basis for the neutronic model. Detailed reproduction of the NG was then compared to measurements from the characterizations presented in Section IV and used in simulations in support of the calibration procedure described in Section V.

II. Reproduction of the neutron source

A. Neutron source components

The neutron generator used as a calibration neutron source was the VNIIA supplied compact DT neutron generator model ING-17 [5]. Due to their "mixed-beam" mode of operation such neutron generators represent complex sources of neutrons. Deuterium (D) and tritium (T) are present both in the ion beam and in the target of the NG. Additionally, due to the lack of an analyzing magnet both ions (D^+, T^+) and ionized molecules (D_2^+, T_2^+, and $D_1T_1^+$) are expected in the beam. This means that for the acceleration energy E_{full} 6 DT reaction source components are expected, i.e. T(d, n)^{4}He at E_{full} (from D+), 1/2 E_{full} (from D_2^+), and 2/5 E_{full} (from $D_1T_1^+$) and D(t, n)^{4}He at E_{full} (from T^+), 1/2 E_{full} (from T_2^+), and 3/5 E_{full} (from $D_1T_1^+$). In addition, 3 DD and 3 TT source components are expected but their contribution can be neglected due to low intensity. This assumption is later tested and confirmed in Section II.E.

Due to the lack of detailed information on the beam and target properties, a combination of simulations and measurements was needed to determine NG's neutron emission spectrum. A high resolution measurement of the neutron emission spectrum directly in front of the NG (Figure 1) was performed to determine relative intensities of different DT source components. This spectrometer position was chosen due to the widest spread of the DT neutron emission peaks in such positions and thus the combination of the state of the art neutron spectrometer based on the diamond detector and simulations could be used to provide insight into the relative intensities of different DT neutron source components [6].

B. High resolution measurement of the neutron emission spectrum

A high resolution measurement of the neutron spectrum around 14 MeV was performed among other experiments during the NG characterization campaign at National Physical Laboratory, UK [4]. First, the acceleration voltage of the ion accelerator was determined based on the neutron spectrum measurement. This was needed as the values indicated by the NG control electronics do not directly indicate the acceleration voltage, e.g. at indicated operation voltage ~100 kV the neutron spectrum corresponded to 73 keV ions.

Figure 1: Experimental configuration for the determination of the neutron emission properties. NG tube is seen on the left side and the box containing the diamond detector is directly in front of it.

The measurement of the neutron spectrum was also used in the process of determination of the relative intensities of different neutron source components explained below.

C. Simulations of neutron source components

A state of the art Monte Carlo particle transport code MCNP [7] and its derivatives were used in all neutronic simulations presented in this paper. An ENEA-JSI subroutine [8] and MCUNED [9] extensions of the standard code were used to simulate the DT fusion reactions in the target.
Using the experimentally determined acceleration voltage of 73 keV, the individual neutron source components were simulated. This way their neutron emission spectra (Figure 2) and neutron yields (Table I), i.e. the probability for neutron production, were determined. Neutron spectra were determined using the ENEA-JSI source while the neutron yields were determined by MCUNED.

D. Combining simulations and measurements

The relative intensity of all expected DT source components in the NG was determined by fitting individual detector responses for each of the components to the measurement (Figure 3) [6]. The response function of the detector was applied to the calculated spectra for realistic fitting and the correlation of T(d, n)^{4}He and D(t, n)^{4}He were taken into account to decrease the amount of independent variables. The resulting relative intensities of neutron source components are presented in Table 1 together with neutron yields for different components expressed in neutrons being produced per ion from the beam.

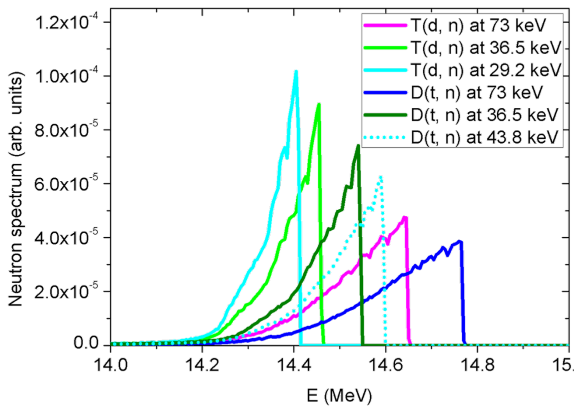

Figure 2: Neutron spectra of different DT source components in forward direction for a 73 keV beam.

TABLE I
NEUTRON YIELDS OF DT SOURCE COMPONENTS AND THEIR RELATIVE INTENSITIES BASED ON FITTING OF THE MEASURED SPECTRUM.

Source component	Neutron yield [n/ion]	Relative intensity [%]
T(d, n)^{4}He at 73 keV	3.85×10^{-6}	7.32
T(d, n)^{4}He at 36.5 keV	2.79×10^{-7}	15.14
D(t, n)^{4}He at 73 keV	1.37×10^{-6}	11.06
D(t, n)^{4}He at 36.5 keV	6.59×10^{-8}	2.93
T(d, n)^{4}He at 29.2 keV	1.02×10^{-7}	24.95
D(t, n)^{4}He at 43.8 keV	1.58×10^{-7}	38.61

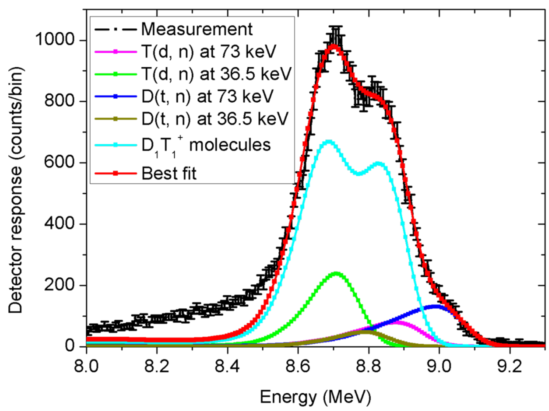

Figure 3: Measured detector response and the best fit of the DT source components from simulations.

Once the detailed source description was determined it was converted into format for use in MCNP simulations, i.e. into angular probabilities for neutron emission and its energy dependence for each angular bin (SDEF card in MCNP). To ensure high resolution reproduction of the source the description consisted of 400 angular bins and 10 keV energy resolution. Next, the ion beam composition presented in Table II was determined based on the relative intensities of the neutron source components and their neutron yields (Table I). The ion beam composition indicates that the majority of the particles in the beam are ionized D_1T_1 molecules which further demonstrates the importance of the neutron emission spectrum characterization effort as neutron emission spectrum from a DT generator with T(d, n)^{4}He reactions at energies defined by the acceleration voltage indicated by the control electronics would result in significantly different.

TABLE II
ION BEAM COMPOSITION BASED ON MEASUREMENTS AND SIMULATIONS.

Ion beam component	Relative intensity [%]
D^+	7.32
T^+	15.14
D_2^+	11.06
T_2^+	2.93
$D_1T_1^+$	24.95

E. Intensity of DD and TT components

Using the ion beam composition determined above, the intensity of the DD and TT neutron source components was evaluated to confirm whether they can really be neglected. MCUNED simulations were performed to assess the neutron yields of DD and TT reactions for the ion beam with composition from Table 2 and a TiH_2 target with hydrogen part consisting of a mixture of equal parts of D and T. The result show that 0.17 % and 0.96 % of neutrons are released resulting from DD and TT fusion reactions respectively. This means that around 99 % of neutrons are emitted due to DT fusion reactions (Figure 4) [10] which confirms the validity of our assumption that only DT components need to be taken into account. Additionally, due to scattering in NG materials about ¼ of neutrons originating from the DT reactions are already emitted from the generator at energies below the DT peak.

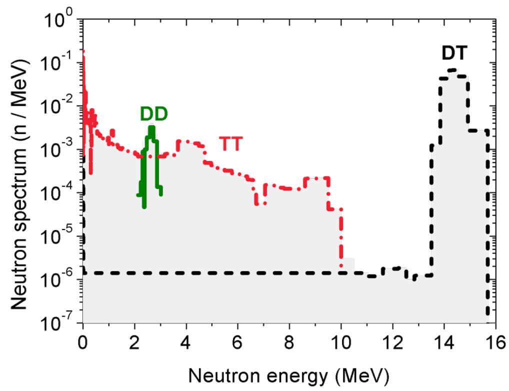

Figure 4: Neutron spectrum divided by components.

III. GEOMETRY OF THE NEUTRON GENERATOR

A. Geometry reproduction

In order to do simulations in support of the neutron emission spectrum determination we prepared a relatively simple model of the NG based on the sketch provided by the supplier (Figure 5 left). This model was also used in some first analyses intended to get first approximation of the anisotropy of the NG as a source of neutrons. However, once the neutron emission spectrum was reproduced in detail a more detailed model of the NG was required. To get accurate information about the internal structure of the NG a CT scan was made (Figure 5, right) and used as a basis for a detailed CAD model which was converted into MCNP model using SuperMC [11] (Figure 5, center). The material descriptions in this detailed model were based on information provided by the supplier. Furthermore, studies of sensitivities to uncertainties in material composition were performed and it was found that the results are mostly sensitive to details of the geometry, especially target position, and relatively insensitive to minor differences in materials of the components. The comparison of results from the generic and detailed models (Figure 6) revealed that while the general emission properties were captured by the simplified model there are some significant differences. The additional work invested into creation of the more detailed model thus significantly contributed to the accuracy of the reproduction of the neutron emission properties.

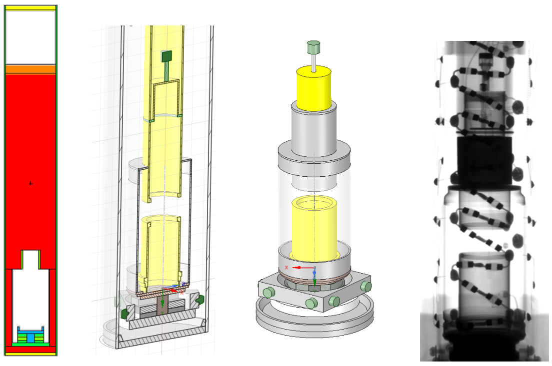

Figure 5: Generic model of the NG based on supplier-provided sketch (left), detailed model of the NG (center left and center right) and X-ray image used as a basis for the detailed model (right).

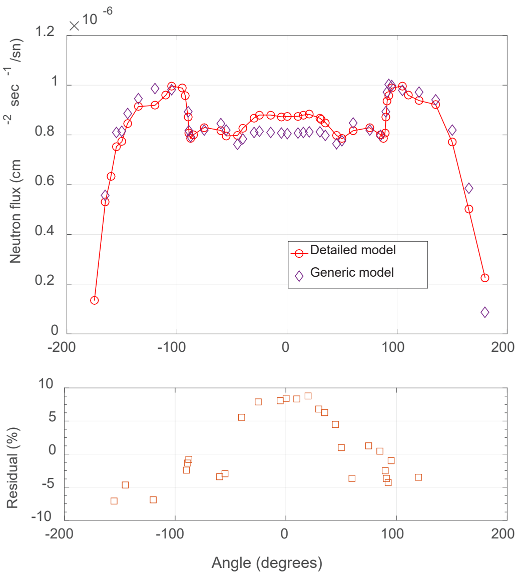

Figure 6: Comparison of the angular dependence of the neutron flux from a generic and detailed model of the neutron generator. Residual means the relative difference between neutron fluxes from generic and detailed models.

IV. COMPARISON TO CHARACTERIZATION EXPERIMENTS

The neutron emission of the NG was also compared to the measurements from the characterizations campaign to validate the MCNP model (Figure 7) [12]. The agreement between simulations and measurements was found to be within 2 % for all angles between 0° and 165°. While at grater angles the difference increases to ~6 % at the same time the neutron fluence significantly decreases for up to 5 times compared to the maximum which reduces the effect of this uncertainty.

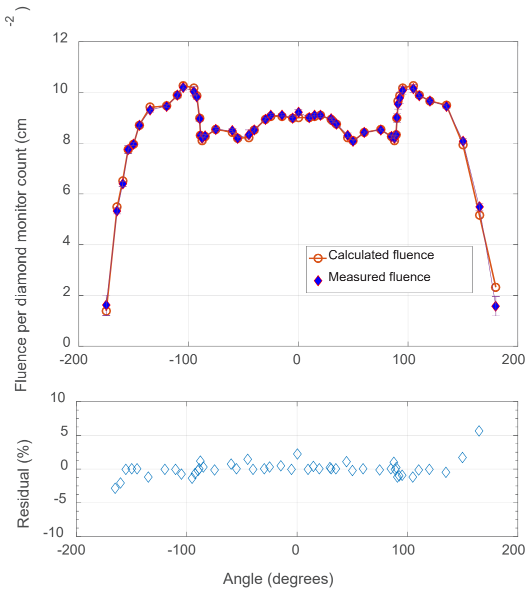

Figure 7: Comparison of the detector responses from simulations and NG characterizations measurements.

V. IN-SITU CALIBRATION OF NEUTRON DETECTORS AT JET

Once the model of the neutron generator was validated it was used in the simulations in support of the calibration of JET's neutron yield detectors. In these experiments the calibration neutron source was positioned in positions inside the tokamak by the RHS and detector response was measured. To simulate all the experimental configurations the RHS was modelled (Figure 8) and scripts were written to automate the process of the model preparation [13]. These scripts take the information about the configuration of components, e.g. angles and translations between components, and prepare the transformation cards used for geometry definition in MCNP. This model was then inserted into a model of JET (Figure 9) together with the detailed model of the neutron generator for simulations of detector responses in experimental conditions.

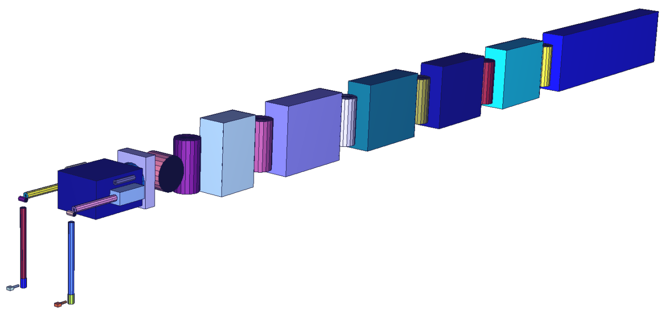

Figure 8: MCNP model of the remote handling system [13].

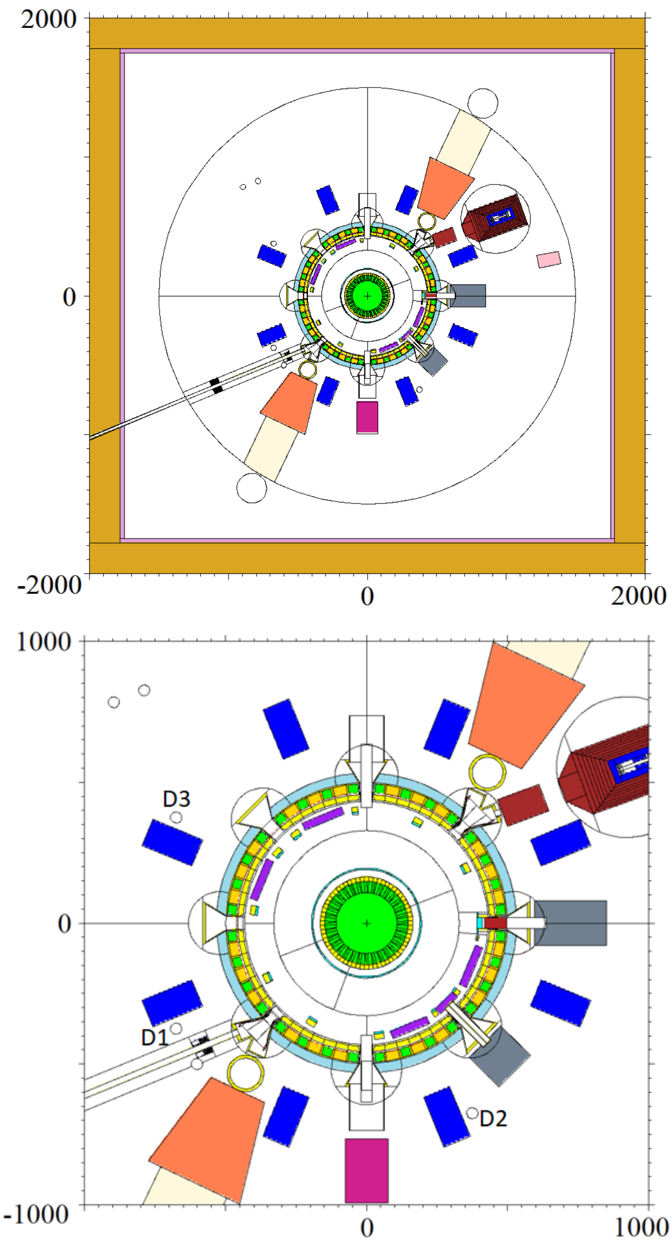

Figure 9: MCNP model of JET (XY view). Dimensions are annotated in cm. Walls of the tokamak hall important in ex-vessel detector response determination are visible in upper figure and the positions of the three fission chambers (D1, D2, D3) is annotated in bottom figure.

Main goal was to determine the calibration factors for in-vessel irradiation foils using geometry as close to experiment as possible and to determine relative changes in the response of ex-vessel fission chambers between experimental conditions in plasma experiments and calibration experiment, e.g. presence of RHS and NG in reactor during the calibration experiment. The relative changes described with correction factors (C) were divided into geometry related part ($C_{geometry}$) and differences caused by the differences in the neutron source (C_{source}). The former quantifies the difference in detector responses to a ring of 14 MeV neutron sources in JET configured as during plasma operation (R_{points}) and responses to a DT neutron generator carried by the RHS in JET in its calibration experiment configuration ($R_{calibration}$) while the latter quantify the difference between R_{points} and detector response to plasma neutron source in JET configured for plasma experiments (R_{plasma}). The correction factors $C_{geometry}$ and C_{source} are defined for each of the three fission chambers (i) as

$$C_{geometry,\,i} = \frac{R_{points,\,i}}{R_{calibration,\,i}}$$

$$C_{source,\,i} = \frac{R_{plasma,\,i}}{R_{points,\,i}}$$

and are used in calibration factor (F_i) determination as

$$F_i = F_{measured,\,i}\frac{1}{C_{geometry,\,i}}\frac{1}{C_{source,\,i}}$$

for experimentally determined calibration factor $F_{measured,\,i}$ in units of neutrons/count.

This process shows that in order to calibrate the fission chambers it is important that both experimental and computational parts are carefully planned and carried out. For example to further increase the accuracy of in-situ measurements, the neutron emission from the NG was monitored by two diamond detectors and irradiation foils attached to the NH. These neutron emission measurements were then used to normalize the values measured at JET's neutron yield monitors to account for the time dependence of NG's neutron emission. On the side of simulations the accurate modelling of the NG was important in determination of the $C_{geometry}$ correction factors. Capturing the NG's anisotropy, position and orientation inside the reactor was crucial to make sure correction factors are representative.

When it comes to the calibration of the in-vessel activation system the strategy was completely different. The calibration factors (in units or neutrons/reaction) for different irradiation foils were determined entirely through MCNP simulations and calibration measurements were used only to confirm the model works well. Accurate modeling of the NG was thus crucial both in calibration factor determination and in planning of measurements during calibration experiment.

Due to extensive simulations performed using methodology described above and in more detail in [14] we were able to determine the correction factors for both fission chambers and activation system well within the target accuracy of ±10 %. Final assessments of uncertainties in the calibration factors are ±5 % for fission chambers and 6 % to 8 % for the activation system [15].

VI. Conclusion

To use a DT neutron generator as a calibration neutron source its extensive characterization is required. A characterization campaign consists of a measurements using a range of detectors and simulations in their support. For the case of the DT neutron generator used as a calibration neutron source in the latest DT calibration campaign at JET the neutron generator was characterized and its neutron source characteristics reproduced with simulations. Both neutron emission and geometry description were produced in significant detail based on a combination of measurements and simulations. Later this model was used in simulations needed to determine the calibration factors and significantly contributed to the achievement of the calibration goal of uncertainty below ±10 %: ±5 % for ex-vessel fission chambers and ±6 % - 8 % for the in-vessel activation system.

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