Improved neutron activation dosimetry for fusion

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ABSTRACT

Neutron activation technique has been widely used for the monitoring of neutron fluence at the Joint European Torus (JET) whereas it is foreseen to be employed at future fusion plants, such as ITER and DEMO. Neutron activation provides a robust tool for the measurement of neutron fluence in the complex environment encountered in a tokamak. However, activation experiments previously performed at JET showed that the activation foils used need to be calibrated in a real fusion environment in order to provide accurate neutron fluence data. Triggered by this challenge, an improved neutron activation method for the evaluation of neutron fluence at fusion devices has been developed. Activation assemblies similar to those used at JET were irradiated under 14MeV neutrons at the Frascati Neutron Generator (FNG) reference neutron field. The data obtained from the calibration experiment were applied for the analysis of activation foil measurements performed during the implemented JET Deuterium-Deuterium (D-D) campaign. The activation results were compared against thermoluminescence measurements and a satisfactory agreement was observed. The proposed method provides confidence on the use of activation technique for the precise estimation of neutron fluence at fusion devices and enables its successful implementation in the forthcoming JET Deuterium-Tritium (D-T) campaign.

Keywords: neutron activation, neutron dosimetry, JET, fusion

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1. INTRODUCTION

The Joint European Torus (JET) is the world's largest operational magnetically confined plasma physics experiment and the only fusion device able to operate with Deuterium-Tritium (D-T) fuel. JET has the important role to serve as the main risk-mitigation element for the preparation of its successor ITER, the nuclear fusion reactor experiment that is expected to pave the way for future fusion power plants [1]. In particular, the scientific and technological exploitation of the planned JET D-T plasma campaign is of outmost importance for ITER and future fusion power plants design. The JET D-T campaign is expected to produce large yields of up to 1.7×10^{21} neutrons and therefore will provide a unique opportunity to obtain high quality data to validate the computational methods, codes, data and assumptions adopted in ITER analyses [2-4]. Such experiments are almost certain that are not going to be repeated in the foreseeable future, until the full operation of ITER.

Neutron measurements in a fusion device need to be performed both near and at larger distances from the plasma source. In particular, the precise knowledge of neutron streaming along shielding penetrations far from the plasma source enables the estimation of the activation of ex vessel materials and components and the assessment of shut-down dose rates. Therefore, the accurate knowledge of the neutron fluence far from the plasma source is important for the optimization of the radiation protection of personnel involved in maintenance procedures, as well as for radioactive material recycling and waste management purposes [5]. Nevertheless, studies have shown that a theoretical evaluation of neutron fluence along large shielding penetrations in a fusion device is difficult due to the very complex geometries and long neutron paths encountered, as well as due to the uncertainties in the source, material and cross-section data [6-9].

Neutron activation provides a robust and unbiased technique for the determination of neutron fluence in the complex environment of a fusion device, where variable neutron, photon and other electromagnetic fields are encountered. It can be used in a wide range of neutron energies, fluence rates, mixed neutron and gamma ray fields, without mechanical, electro-magnetic and temperature interferences. The neutron activation dosimetry technique has been used to measure neutron fluence at positions inside the machine [5, 10] as well as in the torus hall and along streaming paths [11, 12]. However, in order to reduce uncertainties and provide reliable data, the activation foil detectors need to be calibrated in known neutron fields that realistically represent the actual conditions of the measurement.

In the present work, an improved neutron activation method for the measurement of neutron fluence at JET is discussed. The detector responses were derived after irradiation in a reference 14 MeV neutron field at the ENEA Frascati Neutron Generator (FNG). Neutron spectrum correction factors were then applied to account for the differences between the actual neutron field at the position of the measurement and the reference one. These corrections factors were derived by Monte Carlo simulations taking into account estimations of the neutron spectra at JET and FNG. The methodology was applied on neutron measurement data obtained during the JET 2015-2016 Deuterium-Deuterium (D-D) experimental campaign using activation foils. The activation foil results were compared against thermoluminescence measurements and a satisfactory agreement between the two techniques was observed.

The distinct advantage offered by the activation foil technique is the robustness and capability to accurately measure neutron fluence at locations in and around the JET vessel where high gamma ray background as well as other non-ionizing radiation fields are present. Therefore, the present study improves the neutron measurement capabilities at JET, allowing high quality neutron fluence data to be obtained and contributes towards the validation of other measurement techniques and simulations.

2. EXPERIMENT AT FNG

FNG uses a deuteron beam accelerated up to 300 keV impinging on a tritium target to produce a nearly isotropic 14 MeV neutron output via the T(d,n)α fusion reaction [13, 14]. FNG operates either in steady state or pulse mode. The neutron intensity is 1×10^{11} n/s (4π), while the absolute uncertainty of the neutron source is ± 3% (1σ). To monitor neutron output, the associated particle technique is used, employing an α-detector, a fission chamber and a scintillation counter.

Sets of foils comprised of cobalt, tantalum, silver and gold were positioned near the centre of two polyethylene (PE) moderator cylinders of 25.0 cm in height and 25.5 cm in diameter. The dimensions of the discs were 14.9 mm in diameter and 0.5 mm in thickness. The PE density was of $0.96\ g\cdot cm^{-3}$. The first moderator (moderator A) contained both bare and cadmium-covered foils, while in the second one (moderator B) only bare foils were used. It is noted that the activation assemblies irradiated at FNG were similar to those used for neutron measurements performed by our group at the JET Hall [11, 12].

Moderator cylinders A and B were irradiated for 24480 s & 25714 s, respectively. They were both placed exactly in front of the source, along the main axis, with the centre of the PE cylinder at a distance of 15.5 cm from the FNG target (Fig. 1). The total yield from the source during the irradiation of moderator A and B was, according to the monitors, 2.35E+14 and 1.83E+14 neutrons, respectively.

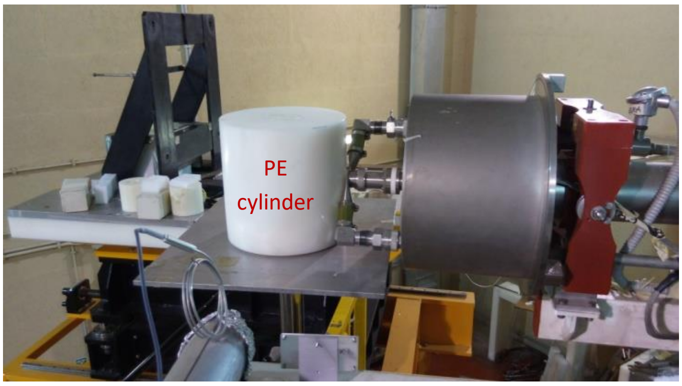

Fig. 1 The irradiation configuration showing the position of the PE moderator

After irradiation, the detectors were disassembled and the activation foils were measured to determine their activity. The gamma-ray spectrometry system used was based on a high-purity coaxial germanium semiconductor detector of 85% relative efficiency, 1.67 keV energy resolution (Full Width at Half Maximum) at the 1332 keV and a peak-to-Compton ratio of 93:1. All foils were measured at a sample to detector distance of 1 cm.

The nuclear reactions used for analysis, the corresponding target isotopic abundances, product nuclide half-lives, gamma ray energies and gammas per disintegration are shown in Table 1. It is stressed that in the cases of isotopes with multiple photo-peaks, the gamma lines selected for analysis were the ones with the highest gammas per decay ratios.

Table 1 Nuclear data used for analysis

Foil	Nuclear Reaction	Target Isotopic Abundance (%)	Product Half-life (d)	Gamma Energy (keV)	Gammas per disintegration (%)
Co	$^{59}Co(n,\gamma)\,^{60}Co$	100.00	1925 ± 20	1173.2 1332.5	99.0 100.0
Ta	$^{181}Ta(n,\gamma)\,^{182}Ta$	99.99	114 ± 3	1121.3 1189.0 1221.4 1231.0	35.0 16.4 27.4 11.6
Ag	$^{109}Ag(n,\gamma)\,^{110m}Ag$	48.16	250 ± 24	657.8 884.7 937.5 1384.3	94.7 72.9 34.3 24.3
Au	$^{197}Au(n,\gamma)^{198}Au$	100.00	2.70 ± 0.02	411.8	95.5

3. FNG SIMULATIONS

Monte Carlo calculations were used to predict the neutron spectra and fluence at the irradiation positions as well as to determine the reaction rates and fluence within the volume of each activation foil. Simulations were performed using Monte Carlo codes MCNP5 and MCNPX [15, 16] and cross section data from the Joint Evaluated Fission and Fusion (JEFF 3.1.2) and the International Reactor Dosimetry and Fusion File (IRDFF v.1.05) libraries [17-19].

A two-stage simulation approach was used. In the first stage, a detailed model of the FNG configuration developed by ENEA (Fig. 2) was modified in order to simulate the source, PE cylinder and activation foil configuration. This model was used in order to calculate the neutron fluence and energy spectrum at the exact positions of the activation foils, namely near at the centre of the PE moderator (at a distance of 15.5 cm from the FNG target). Subsequently, the neutron spectrum defined at the first stage was used to predict the reaction rates and fluence within each one of the activation foils. It is noted that in the developed MCNP models the neutron generator and activation assemblies were described in detail, taking into account the material and dimensions of the PE moderator, the activation foils and the cadmium covers. In Figure 3, the MCNP calculated neutron fluence at the centre of the PE moderator (per source neutron) using the VITAMIN-J 175 energy group structure is plotted as a function of energy for both D-D & D-T sources.

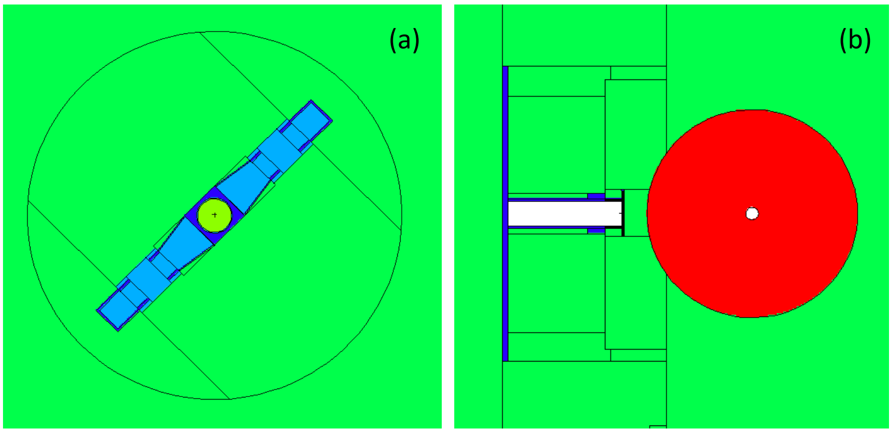

Fig. 2 MCNP model of the FNG configuration (a) vertical & (b) horizontal cross-section

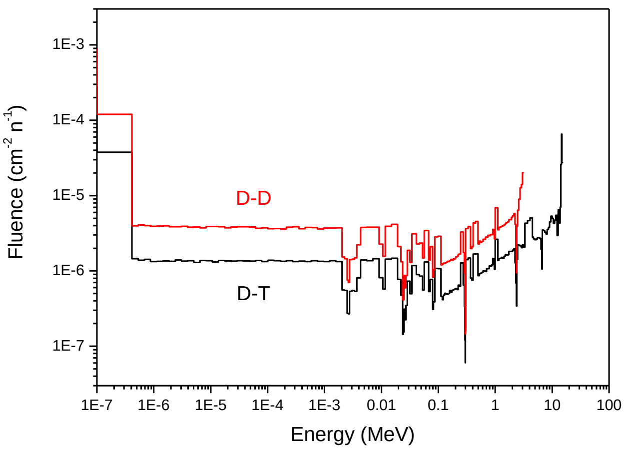

Fig. 3 MCNP calculated fluence at the centre of the PE moderator for the FNG D-D & D-T sources (normalization per source neutron)

4. CALIBRATION

Foil saturation activity, A_{sat}, is related to neutron fluence $\Phi(E)$ through the relationship

$$A_{sat} = \lambda\, N_t \int \sigma(E)\,\Phi(E)\,dE \qquad (1)$$

where λ is the decay constant for the product radionuclide, N_t is the number of target nuclei, $\sigma(E)$ is the microscopic cross-section for the reaction of interest at energy E and $\Phi(E)$ is the neutron fluence at energy E. Equation (1) can be re-written as

$$A_{sat} = \lambda N_t\, \Phi_{PE} \frac{\int \sigma(E)\,\varphi(E)\,dE}{\int \varphi(E)\,dE} \qquad (2)$$

where Φ_{PE} is the total neutron fluence at the position of the foil (in the centre of the PE moderator).

Introducing a spectrum averaged cross section (σ_{av}) defined as

$$\sigma_{av} = \frac{\int_0^{E_{\max}} \sigma(E)\,\phi(E)\,dE}{\int_0^{E_{\max}} \phi(E)\,dE} \qquad (3)$$

equation (2) is simplified to

$$A_{sat} = \lambda\, \mathrm{N}_t\, \Phi_{PE}\, \sigma_{av} \qquad (4)$$

The saturation activity, A_{sat}, is related to the activity at end of irradiation, A_0, through the expression

$$\mathrm{A}_{sat} = A_0 \times \frac{1}{(1-e^{-\lambda t_{irr}})} \qquad (5)$$

Taken into account that the activity at end of irradiation, A_0, can be experimentally determined through the relationship

$$\mathrm{A}_0 = \frac{C}{\varepsilon_\gamma\, f_\gamma\, G_\gamma\, f_{TCC}} \times \frac{\lambda}{(1-e^{-\lambda t_c})\,e^{-\lambda t_d}} \qquad (6)$$

equation (5) can be re-written as

$$\mathrm{A}_{sat} = \frac{C}{\varepsilon_\gamma\, f_\gamma\, G_\gamma\, f_{TCC}} \times \frac{\lambda}{(1-e^{-\lambda t_c})\,e^{-\lambda t_d}} \times \frac{1}{(1-e^{-\lambda t_{irr}})} \qquad (7)$$

where *C* are the net counts registered during the counting time, ε_γ is the Full Energy Peak Efficiency (FEPE) for the gamma-ray energy of interest, f_γ is the gamma-ray abundance i.e. the number of gammas emitted per disintegration, G_γ is the gamma self-attenuation correction factor, f_{TCC} is the true coincidence summing correction factor, t_{irr} is the irradiation time, t_c is the counting time and t_d is the decay (cooling) time.

Correction factor f_{TCC} accounts for the true coincidence effect due to the cascade emission of photons by the measured radionuclides. Correction factors f_{TCC} were calculated for the isotopes of interest using the "TrueCoinc" programme [20, 21]. Correction factor G_γ, defined as the ratio of the detector FEPE for a given foil shape, material and photon energy, to the detector FEPE for a point source in air (without foil), was calculated using a detailed MCNP model of the germanium detector and foil configuration for the photo-peak energies and foil materials examined in this study.

Combining equations (4) & (7) one takes the expression for the neutron fluence at the position of the foil (in the centre of the PE moderator)

$$\Phi_{PE} = \frac{C}{\varepsilon_\gamma\ f_\gamma\ f_{tcc}\, G_\gamma}\ \frac{1}{(1-e^{-\lambda t_{irr}})e^{-\lambda t_d}\, 1-e^{-\lambda t_c}}\ \frac{1}{N_t}\frac{1}{\sigma_{av}} \quad (8)$$

Using eq. (8), neutron fluence can be experimentally determined provided that the spectrum averaged cross section is known, i.e., under the assumption that the neutron energy spectrum at the measurement position is known. This "absolute" method is simple and straightforward; nevertheless, the uncertainties in the result may be large due to the combination of several factors [22].

In order to reduce uncertainties, neutron fluence can be estimated using a relative technique against a reference neutron field. Provided that identical activation foils and moderator assemblies are used in the irradiation experiments performed at the unknown and reference neutron fields, foil parameters such as N_t, ε_γ, f_γ, f_{TCC} and G_γ, can be cancelled out, allowing lower uncertainties and higher quality of results to be achieved. Dividing the two equations, one takes

$$\frac{\Phi_{PE,FNG}}{\Phi_{PE,un}} = \frac{C_{FNG}}{C_{un}}\ \frac{(1-e^{-\lambda t_{irr,un}})e^{-\lambda t_{d,un}}(1-e^{-\lambda t_{c,un}})}{(1-e^{-\lambda t_{irr,FNG}})e^{-\lambda t_{d,FNG}}(1-e^{-\lambda t_{c,FNG}})}\ \frac{\sigma_{av,un}}{\sigma_{av,FNG}} \quad (9)$$

where indices *FNG* and *un* are used to denote magnitudes corresponding to the reference (FNG) and the unknown fields and $\Phi_{PE,FNG}$ and $\Phi_{PE,un}$ is the neutron fluence in the centre of the PE moderator irradiated at the reference (FNG) and the unknown neutron field, respectively.

In the case of the reference field, the neutron fluence at the centre of the moderator, $\Phi_{PE,FNG}$, can be derived from the measured FNG neutron yield (number of neutrons emitted from the source), Y_{FNG}, and the MCNP calculated neutron fluence at the centre of the moderator per source emitted neutron, Φ_{MCNP}, as follows

$$\Phi_{PE,FNG} = Y_{FNG} \times \Phi_{MCNP} \quad (10)$$

Combining equations (9) & (10) one obtains the general expression for the neutron fluence in the centre of the PE moderator irradiated at the unknown field

$$\Phi_{PE,un} = \frac{C_{un}}{C_{FNG}}\ \frac{\sigma_{av,FNG}}{\sigma_{av,un}}\ \frac{(1-e^{-\lambda t_{irr,FNG}})e^{-\lambda t_{d,FNG}}(1-e^{-\lambda t_{c,FNG}})}{(1-e^{-\lambda t_{irr,un}})e^{-\lambda t_{d,un}}(1-e^{-\lambda t_{c,un}})}\ Y_{FNG} \times \Phi_{MCNP} \quad (11)$$

If the neutron energy spectra at the reference (FNG) and the unknown measurement positions were similar, then the spectrum averaged cross section is equal to one and equation (11) is further simplified. However, in the general case of an unknown and probably quite different neutron field, the differences in the spectrum shape need to be taken into account and thus, the ratio of the spectrum averaged cross sections needs to be estimated.

In any case, both the accuracy and precision of the relative method are expected to be much better than those of the respective "absolute" measurement. This is due to the fact that the introduction of the reference configuration removes the dependency of the neutron fluence on parameters that are usually evaluated with larger errors, such as the detector efficiency (with a rel. uncertainty in the order of ~5-10%). Furthermore, due to the use of identical foil detectors, several parameters simply cancel out in calculations while the elimination of mass reduces the complexity of experiments and increases the quality and reliability of the procedure [22].

5. APPLICATION ON JET

The FNG calibration results were applied on neutron fluence measurements performed during the JET 2015-2016 D-D campaign using activation foils. Activation measurements at JET had been performed with cobalt, tantalum and silver foils positioned within PE moderators, namely using assemblies similar to those irradiated at FNG. The neutron spectra at the centre of the PE moderator at the various JET measurement positions are shown in Fig. 4.

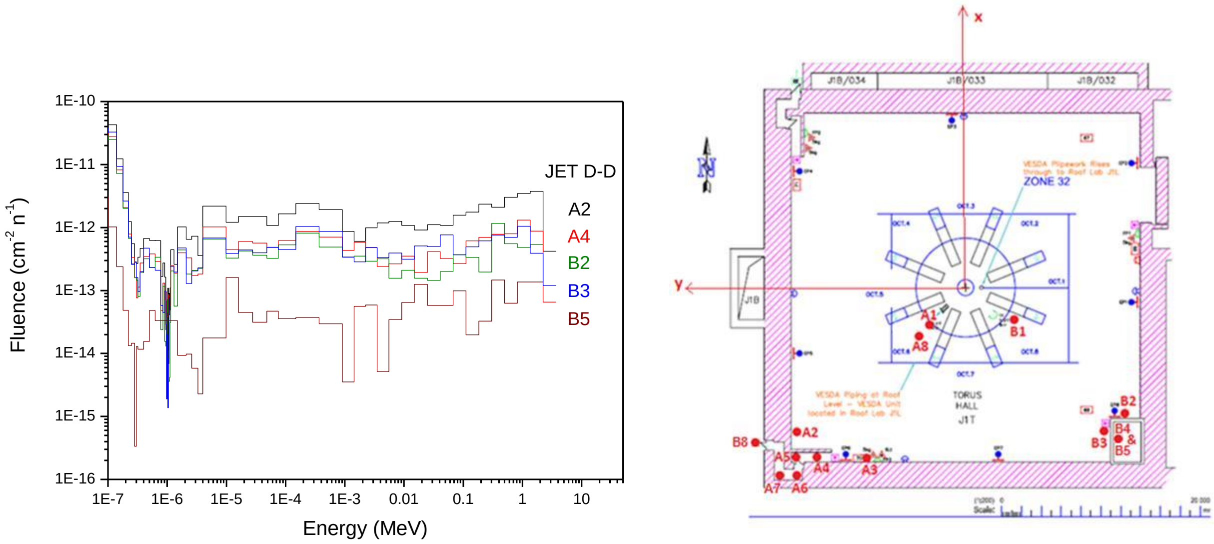

Fig. 4 MCNP calculated fluence at the centre of the PE moderators (left) positioned at several locations in the JET Hall (right)

Due to the differences between the calibration and JET neutron spectra, the ratios of the spectrum averaged cross sections were calculated using Monte Carlo simulations. In particular, the spectrum averaged cross sections for the foils irradiated at the two experiments were calculated as the ratios of the reaction rate to the fluence within the foil using the MCNP cards FM4 and F4, respectively. In both cases, the simulations were performed in two stages, namely the neutron spectrum defined at the first stage at the exact position of each detector assembly (at FNG and JET) was used at the second stage to predict the fluence and reaction rate within each activation foil.

It is stressed that the statistical uncertainties of the MCNP simulations were kept below 0.1% for all tallies. Nevertheless, the overall uncertainties of the calculations were much higher due to the neutron spectrum uncertainties which were estimated to be approximately 10%. The spectrum uncertainty expresses the overall uncertainty related to the estimation of the neutron spectrum at each of the experimental positions studied, namely, depicts the trueness of the model. This magnitude includes uncertainties related to the description of the source, the determination of the experimental positions as well as the simplifications and adjustments of the model used to describe the extremely complex geometry of the tokamak. If combined with the statistical uncertainty of the MCNP runs, it gives the overall uncertainty of the calculations.

More details on the JET streaming simulations can be found elsewhere [9]. In Figure 5, the MCNP predicted spectrum averaged cross section ratios are shown for the foils and positions studied.

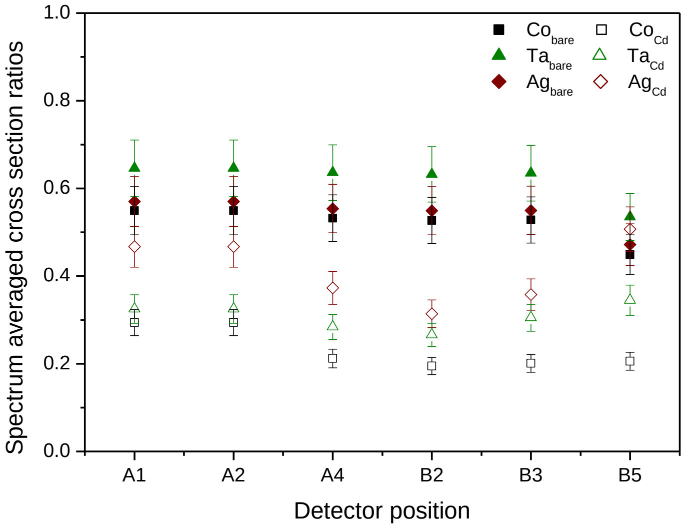

Fig. 5 MCNP calculated spectrum averaged cross section ratios

In equation (11) the irradiation is considered to be continuous. However, the activation foils were irradiated at JET under a pulsed irradiation scheme. In particular, during the specific irradiation period (9/11/2015-29/1/2016) a total neutron budget of 3.52E+18 neutrons was produced at the source and was delivered in 740 shots, as shown in Figure 6.

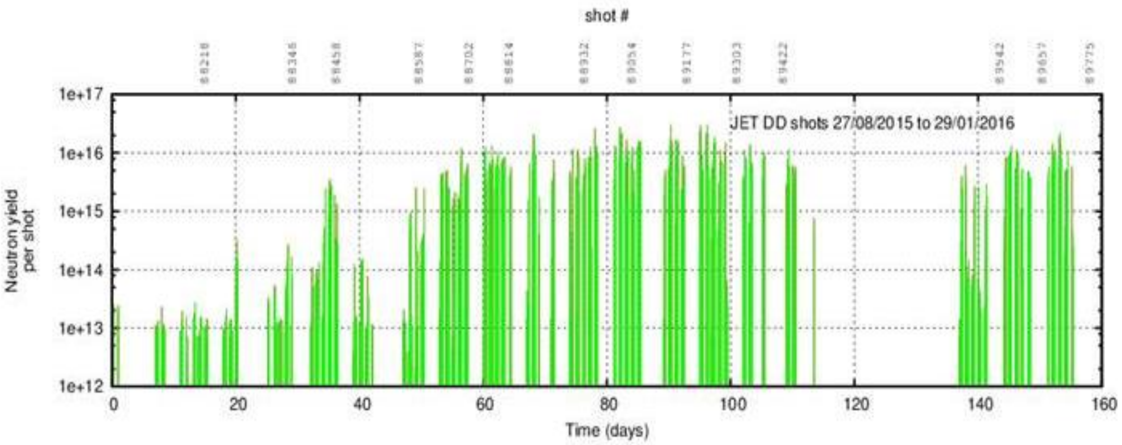

Fig. 6 Neutron yield history of JET 2015-2016 D-D campaign (data from [10])

Therefore, an additional correction factor, F_{irr}, needs to be introduced to account for the actual irradiation scheme that corresponds to 740 pulses of different magnitude and time duration. Factor F_{irr} is calculated using the inventory code FISPACT-II [23] as the ratio of the activity produced at a certain foil at the end of pulsed irradiation to the activity at the end of a continuous irradiation with the same total neutron fluence. Finally, equation (11) is formulated as follows

$$\Phi_{PE,JET} = \frac{C_{JET}}{C_{FNG}} \frac{\sigma_{av,FNG}}{\sigma_{av,JET}} \frac{(1-e^{-\lambda t_{irr,FNG}})e^{-\lambda t_{d,FNG}}(1-e^{-\lambda t_{c,FNG}})}{(1-e^{-\lambda t_{irr,JET}})e^{-\lambda t_{d,JET}}(1-e^{-\lambda t_{c,JET}})} \frac{1}{F_{irr}} Y_{FNG} \times \Phi_{MCNP} \qquad (12)$$

6. RESULTS AND DISCUSSION

6.1 Neutron fluence results

Combining the MCNP calculated spectrum averaged cross section ratios and the experimental data for the foils irradiated at FNG and at JET, the neutron fluence was calculated through equation (12) for all JET detectors. In Figure 7 the neutron fluences for the cobalt, tantalum and silver foils in the PE moderators are shown along with their relative uncertainties for the 6 JET positions studied (A1, A2, A4, B2, B3 & B5). It is noted that the presented relative uncertainties include also the spectrum uncertainty, which was assessed to be approximately 10%.

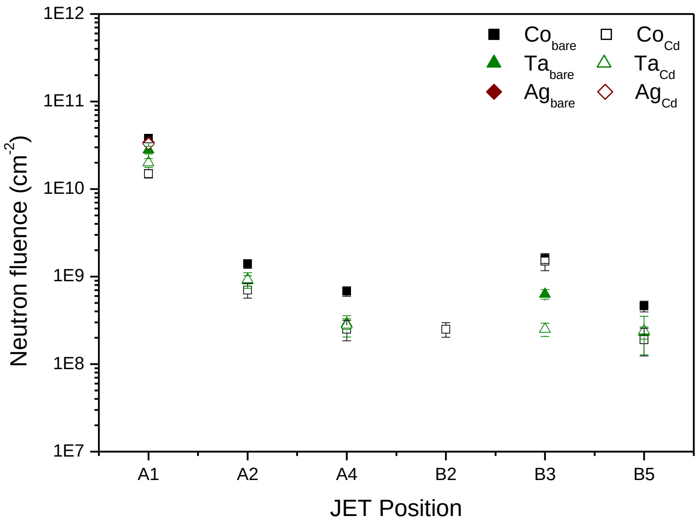

Fig. 7 Neutron fluence for the foils in the PE moderators irradiated at JET

As it can be seen in Figure 7, a satisfactory agreement is observed among the fluence values determined by the foils for all positions apart from B3, where the fluences derived from the tantalum foils are significantly lower than the ones of the cobalt foils (2-5 times lower). This discrepancy could be attributed to the fact that cobalt and tantalum have different responses in the resonance region, therefore, an overestimation or underestimation of the epithermal flux component in the neutron spectrum of the specific experimental position would have different impact on each foil. Therefore, the difference between cobalt and tantalum results could be taken to suggest an underestimation of the epithermal region of the neutron spectrum in the MCNP calculated spectra at B3 position (by the chimney at the south east corner of the JET hall).

In fact, as previous studies have revealed, the spectrum shape in the slow neutrons energy region has been estimated with large uncertainties while significant deviations were observed in this region among the spectra produced from the different models used. The reason for these deviations lies in the great complexity of the studied geometry and the inevitable approximations and simplifications used for its description [6, 7, 24].

Furthermore, similar or even larger discrepancies among the neutron fluence values derived from different foils have been observed in previous neutron activation experiments performed at JET [25, 26].

6.2 Comparison against thermoluminescence measurements

The neutron fluence values derived from the activation foils were compared against measurements performed with thermoluminescence detectors (TLDs), produced and measured by the Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland [11, 12]. Highly sensitive ^{nat}LiF: Mg, Cu, P (MCP-N) and ^{7}LiF: Mg, Cu, P (MCP-7) TLDs were placed within large cylindrical PE moderators similar to the ones containing the foils. TLDs were arranged in circular and rectangular containers which were mounted in the moderators in horizontal and vertical orientation, respectively. To produce results comparable to those obtained by the activation measurements, the PE moderators with the TLDs were positioned relatively close to those with the activation foils and were irradiated under exactly the same conditions [11, 12]. More details on the production, readout and calibration of TLDs can be found elsewhere [6, 7, 11, 12].

In Figure 8 the average neutron fluence values derived from the calibrated activation foils and the TLDs are shown for the JET positions studied. In particular, the average fluence derived by activation foils and TLDs is given.

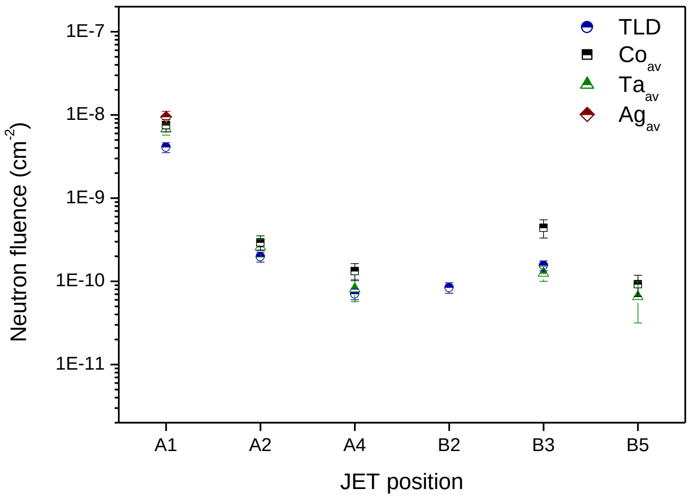

Fig. 8 Average neutron fluence for foils and TLDs in the PE moderators irradiated at JET

To further compare the results, the ratios of neutron fluence values derived from the bare and Cd-covered activation foils to the fluences obtained by the TLDs are plotted in Figure 9 for the JET positions studied. It is noted that in position B5 TLDs didn't provide results due to displacement of the respective PE moderator, therefore B5 is not included in the comparison.

As it can be seen, the ratios of the neutron fluence values derived from the calibrated activation foils to the fluences obtained by the TLDs are within 0.5-2.9 for all positions studied. In particular, a very good agreement is observed between the values derived from the TLDs and the Cd-covered cobalt foils (ratios within 0.9-1.0), with the exception of the Cd-covered cobalt foil in position B3 (ratio of 2.7). A satisfactory agreement is also observed for the tantalum foils with the respective ratios being within 1.2-1.9 for the bare and 1.1-1.4 for the Cd-covered tantalum foils. Again, the only exception is the Cd-covered tantalum foil in position B3 with a neutron fluence ratio of 0.5. Nevertheless, larger discrepancies are observed for the bare cobalt foils (ratios within 2.0-2.9) as well as for the two silver foils (ratios ~2.3).

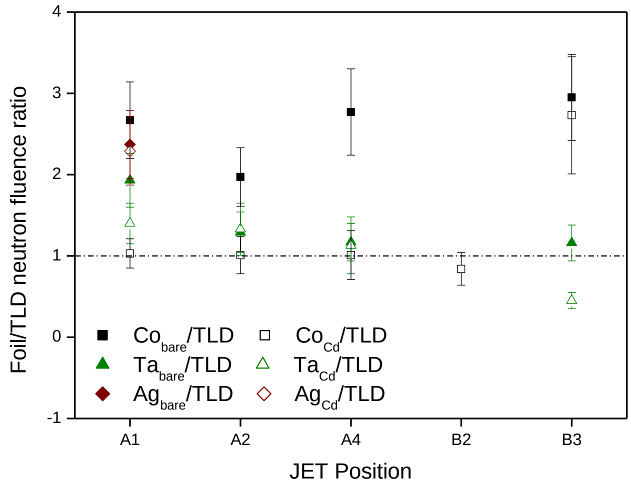

Fig. 9 Comparison of fluence results obtained by activation foils and TLDs

It is noted that position A1 is very close to the tokamak (in front of a port on JET octant 6) while position B3 is far from the plasma source (by the chimney in the south east corner of the JET hall) (Fig. 4). Therefore, detectors located at these positions may experience significantly different neutron energy spectra, since in areas close to the machine the fast neutron component of the flux is much higher whereas before the torus hall walls the thermal neutron flux component is dominant due to the scattered slow neutrons [3].

A more detailed modeling of the torus hall outside the machine and before the wall, including the numerous substantial structures and equipments present, would probably provide a better representation of the neutron flux in JET hall. Nevertheless, taken into account the overall complexity of the studied geometry, the agreement between the neutron fluence values derived from activation foils and thermoluminescence measurements is considered to be satisfactory.

Further studies and activation experiments are planned to be performed in the forthcoming JET D-D, T-T and D-T campaigns using optimized detector assemblies based on the experience acquired so far.

7. CONCLUSIONS

The activation foil detector assemblies used for neutron fluence measurements at JET were calibrated using the reference D-T neutron field of the FNG facility. The results of the calibration experiment were applied to evaluate neutron streaming measurements performed in the 2015-2016 JET experimental campaign. The neutron fluence values derived for the activation foils using the relative calibration technique were compared against experimental measurements performed at JET using TLDs and a satisfactory agreement was observed. In particular, the ratios were within 0.5-2.9 for all positions studied.

The discussed work provides data that will allow the implementation of accurate neutron fluence measurements in the forthcoming JET plasma campaigns. This is essential for JET operations, especially in the case of the high neutron fluxes expected in and around the JET machine during the planned D-T experiment. Moreover, the results of the present study enable the benchmarking of the experimental techniques and computational tools used for neutron streaming and material activation studies at JET and therefore contribute to the validation of computational methods, codes, data and assumptions adopted in the design and nuclear analyses of ITER and future burning plasma devices.

Acknowledgments

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