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OVERVIEW OF NEUTRON MEASUREMENTS IN JET FUSION DEVICE

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The design and operation of ITER experimental fusion reactor requires the development of neutron measurement techniques and numerical tools to derive the fusion power and the radiation field in the device and in the surrounding areas. Nuclear analyses provide essential input to the conceptual design, optimization, engineering and safety case in ITER and power plant studies. The required radiation transport calculations are extremely challenging because of the large physical extent of the reactor plant, the complexity of the geometry, and the combination of deep penetration and streaming paths. This paper reports the experimental activities which are carried out at JET to validate the neutronics measurements methods and numerical tools used in ITER and power plant design. A new deuterium-tritium campaign is proposed in 2019 at JET: the unique 14 MeV neutron yields produced will be exploited as much as possible to validate measurement techniques, codes, procedures and data currently used in ITER design thus reducing the related uncertainties and the associated risks in the machine operation.

INTRODUCTION

With the construction and operation of ITER experimental reactor, fusion is entering in the nuclear phase. ITER will produce ~500 MW of fusion power, corresponding to $\sim 10^{20}$ neutrons/s for hundreds of seconds, orders of magnitude higher than any other existing fusion device. Several diagnostic systems have been designed to measure the total neutron yield in ITER with a target accuracy of ±10%. Nuclear analyses provide essential input to the conceptual design, optimization, engineering and safety case of in ITER devices and power plant studies. The required radiation transport calculations are extremely challenging because of the large physical extent of the reactor plant, the complexity of the geometry, and the combination of deep penetration and streaming geometries. Calculations are computer-intensive and require detailed geometry models of large components, and coupling of large and complex transport and activation codes and nuclear databases. The accuracy of the measurement methods and of neutronics calculations has been assessed so that remedial action or adequate margins can be taken.

JET is the largest operating fusion device, and can operate with tritium thus producing 14 MeV neutrons from deuterium-tritium (DT) plasmas. A new DT campaign is proposed in 2019: the unique 14 MeV neutron yields produced will be exploited as much as possible to validate codes, models, assumptions and methods currently adopted in ITER project thus reducing the related uncertainties and the associated risks in the machine operation. This paper presents an overview of the experimental activities which are currently carried out at JET in preparation of the DT experiments in support of ITER.

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CALIBRATION OF NEUTRON YIELD MONITORS

Several types of neutron detectors are usually employed in fusion reactors to provide a measurement of the fusion power and other plasma parameters, as well as of the Tritium burnt in fusion reactions, which must be known for Tritium accountancy. An accurate knowledge of the neutron yield is required also to evaluate the activation and radiation damage of irradiated materials as well as the resultant radiation dose loads to sensitive components, and the related biological dose rate distributions.

In ITER fission chambers and activation systems are used as neutron yield monitors [1]. The required accuracy is ±10% over the whole range of neutron emission rate, spanning several orders of magnitude from 10^{14} n/s (in deuterium operations, producing 2.5 MeV neutrons) up to almost 10^{21} n/s (in deuterium-tritium operations, producing 14 MeV neutrons). Achieving such accuracy is challenging in fusion devices because of the extent of the plasma neutron source, and because of the size and complexity of the reactor itself. The usual procedure adopted so far in fusion devices to calibrate neutron detectors is based on recording neutron detector signals when a calibrating neutron source of known intensity is deployed inside the machine at different toroidal and poloidal locations.

JET, the largest operating fusion device, like ITER employs both active detectors located around the machine (^{235}U, ^{238}U fission chambers) to monitor the time evolution of the neutron emission rate, and activation systems which allow for a transfer of activation samples inside the machine and their removal to provide the time integrated neutron yield. Usually, the ^{115}In(n,n')^{115m}In activation reaction is used for DD neutrons, and ^{28}Si(n,p)^{28}Al, ^{63}Cu(n,2n)^{62}Cu, ^{93}Nb(n,2n)^{92m}Nb reactions for DT neutrons.

Recently, a neutron yield calibration of both the fission chambers and the activation system has been carried out at JET based on the use of a ^{252}Cf source with intensity 2.62×10^{8} n/s deployed inside the vacuum vessel by means of the JET remote handling boom [2, 3]. In order to calibrate the fission chambers, the ^{252}Cf source has been positioned at more than 200 different poloidal and toroidal positions to simulate the extended plasma source. Forty positions were selected along the plasma toroidal axis (central ring), and along other four rings radially and vertically displaced by 50 cm around the central one. The signals recorded by the fission chambers are shown in Fig.1 as a function of the source toroidal position on the central ring inside the JET vessel. It was found that moving from the central to the off-axis rings caused a maximum change in the responses of fission chambers integrated over the rings of less than ~10%.

Neutronics analyses were also performed using the MCNP code to calculate the correction factors needed to derive the plasma calibration factors taking into account i) the presence of the massive robotic boom which deployed the neutron source inside the vessel, ii) the different energy spectrum and angular emission distribution of the calibrating (point) ^{252}Cf source as compared to DD plasmas, and iii) the ring integrals compared to the plasma volumetric source. The corresponding correction factors were i) <15%, ii) < 18% and iii) < 3%, respectively. In order to calibrate the activation system, the ^{252}Cf source was located at different positions close to one of the activation system irradiation ends. The resulting activity in the exposed Indium foils was measured and compared with that predicted by MCNP calculations. In this way, the MCNP model of the JET irradiation end was validated, and finally used to calculate the ^{115}In(n,n')^{115m}In reaction rate from a DD plasma source. After the calibration, the neutron yields from DD plasmas measured by the fission chambers agreed with that measured by the activation system within ±3%, i.e. within the combined uncertainty of ~10% [3] (Fig.2).

A new calibration at 14 MeV neutron energy is now being carried out to allow accurate measurements of the fusion power and of plasma ion parameters as a new Deuterium-Tritium campaign is planned at JET in 2019 [3]. The target accuracy of the new 14 MeV calibration at JET is ±10%, as required for ITER. In this new calibration, a 14 MeV neutron generator has been employed inside the JET vacuum vessel by means of the JET remote handling system. The first phase of the 14 MeV calibration has been completed with the characterization and calibration of the 14 MeV neutron generator carried out at the NPL Neutron Metrology Laboratory.

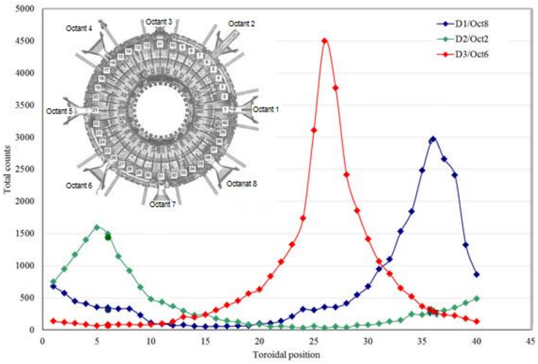

Figure 1. Fission chambers counts in 1200 s acquisition time as a function of the ^{252}Cf source position on central ring. The insert shows the toroidal positions of the source inside the JET vessel.

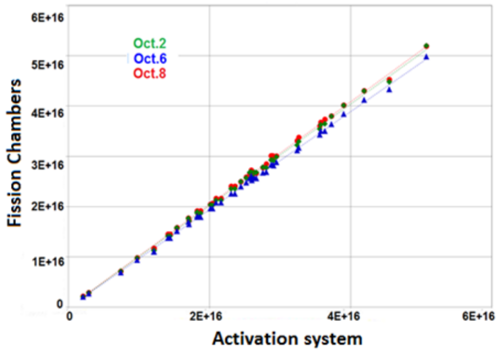

Figure 2. Comparison of neutron yields per shot as measured from DD plasmas during June – August 2014 campaign by the three fission chambers and the activation system on JET.

ACTIVE AND PASSIVE DOSIMETRY AT JET FUSION FACILITY

Neutronics benchmark experiments are conducted at JET to validate the codes used in ITER design to predict neutron flux along streaming paths and the shutdown dose rates [5,6,7]. Several measurements were carried-out during and at the end of last 2015-2016 DD campaign to characterize the radiation field with active and passive detectors inside and outside torus hall in preparation of future DT experiments [5].

Active detectors were used to measure the shutdown dose rate and decay gamma spectra in ex-vessel positions. Two spherical air-vented ionization chambers (ICs) were located at the side port of Octant 1 (IC#1) and on the top of Octant 2 port flange (IC#2) [7]. The positions are shown in figure 3.

The detectors were fixed on shelves made of low activation material. Low noise special cables (100 m long) connected the ICs to the electrometers located outside the torus hall. A dedicated software was developed for the real-time power control and acquisition. Dose rate measurements started on 18th October 2016, during the high performance DD campaign, and lasted more than four months after the end of the campaign. Air-kerma reate measured with both ICs versus time is shown in figure 4 [8].

The ICs have shown a good temporal stability without drifts and significant perturbations due to harsh radiation conditions. Not even relevant effects due to the intense electric and magnetic fields have been observed. The lack of a relevant signal degradation confirms that no damages were induced by neutrons. optimal stability. The dose measured with IC#1 is higher than IC #2 as expected, because in Octant 2 the IC is located in a better shield position.

High resolution decay gamma spectra were also collected during a survey performed in the first days after the JET shutdown (i.e. 16th and 17th November 2016) with portable High Purity Germanium gamma spectrometer located behind the ICs. Many radionuclides have been recognised and main contributions from vacuum vessel and mechanical structure activation products have been identified (i.e. ^{60}Co, ^{58}Co, ^{56}Mn, etc..). The measured data are used to validate the codes developed to predict the shutdown dose rates in ITER and fusion power plants [7].

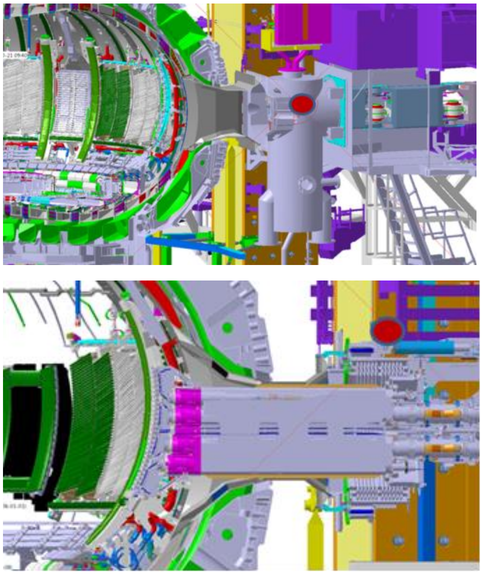

Figure 3 Positions of ICs marked by red circles for ex-vessel measurements of shutdown dose rate in Octant 1 (top) and Octant 2 (bottom).

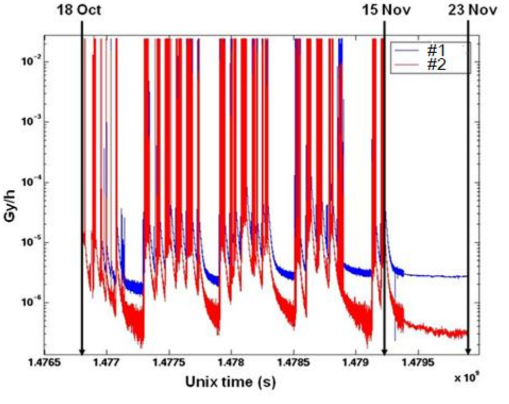

Figure 4. Air-kerma rate measured during the Deuterium campaign with ICs in position #1 and #2.

Neutron fluence measurements have been performed at JET inside and outside the biological shield in several positions up to about 40 meters distance from the plasma with thermoluminescent (TLDs) detectors during DD operations in 2015 and

2016 [6]. Highly sensitive ^{nat}LiF: Mg,Cu,P (MCP-N) and ^{7}LiF: Mg,Cu,P (MCP-7) TLDs detectors were located in at the centre of polyethylene moderators [5,9] in 22 positions inside and outside torus hall. The neutron fluence measurements with TLDs detectors were complemented with activation foils measurements in six positions close to TLDs' assembly for cross-calibration of the two methods. Co, Ag and Ta bare and Cd-covered (to discriminate between thermal and epithermal neutrons) foils were positioned in polyethylene moderators. In addition, in order to measure fast neutrons, aluminium holders containing Co, Ag, Ta and Ni foils, bare and Cd-covered, were used. Dedicated calibration campaigns under DD and DT neutrons have been performed for both TLDs and activation foils assemblies and are described in next paragraphs.

The experimental data are used to validated the calculations of 14 Mev neutron transport inside and outside the JET biological shield. An example of comparison between neutron fluence measuremens and calculations is given in Fig.5, where calculations are performed MCNP5/6 codes as well as with ADVANTG hybrid code [6 and references therein]. The comparison shows a very good agreement between measurements and calculation except for the positions close to the tokamak, as discussed in the next paragraph.

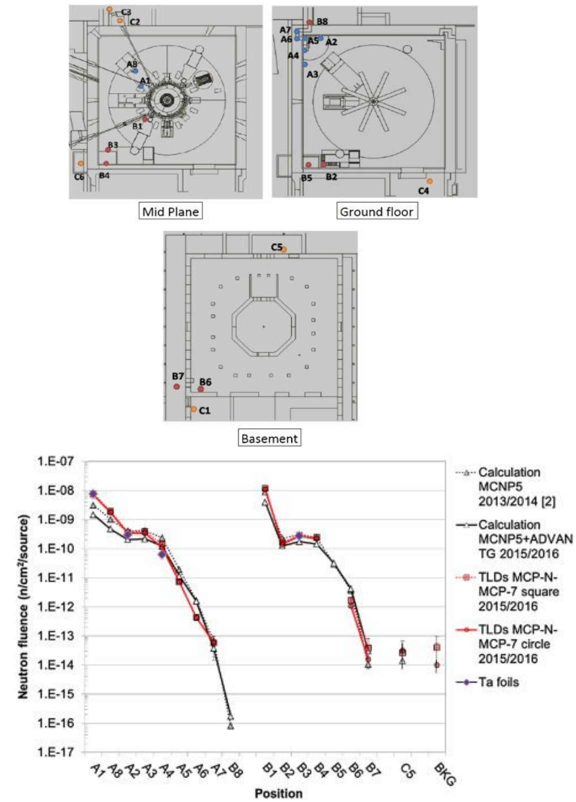

Figure 5. Calculated and measured neutron fluence with TLDs and Ta foils (from [7]).

Calibration of TLDs

The response of TLDs due to the neutron component is related to the neutron fluence in a well-defined neutron energy spectrum. In particular, the part of TLDs response due to neutron component of the radiation field can be related to the local neutron fluence taking into account LiF detectors' calibration at the PTB Thermal Neutron Reference Field at GeNF [10] performed in 2006 by Burgkhardt et al. [11]. The TLDs were calibrated at GeNF in a thermal neutron spectrum. In fact, in the case of JET measurements, although the neutron spectrum is not thermal in the Torus Hall, the large PE moderators ensures that the enclosed TLDs "see" a predominantly thermal neutron field. With this assumption the Burgkhardt et al. [11] calibration factors can be applied. It should be noted that in locations close to the tokamak, the neutron field inside the PE cylinder is not fully thermalized and the detectors are exposed to a significant fast neutrons component and the TLDs calibration factors from [11] are therefore not correct in these positions. Therefore, there was a need of more accurate TLDs calibration in real fusion radiation fields which will allow for more correct calculation of neutron fluence from TL measurements at JET [5,6,9].

In order to perform this task MCP-N and MCP-7 TLDs produced at the IFJ PAN were calibrated in the ENEA facilities of Frascati and Casaccia laboratories in November and December 2016.The TLDs' were irradiated under DD (2.5 MeV) and DT (14 MeV) neutrons at the Frascati Neutron Generator (FNG) in bare rectangular holders (positioned perpendicular to the beam), and inside moderators in both rectangular holders (perpendicular to the beam) and cylindrical holders (parallel to the beam) (same assembly as JET experiment). Bare irradiations were performed at 6 radial positions from 5.5 to 88.5 cm from FNG target. The positions and irradiation time were selected on the basis of pre-analysis carried out with MCNP5 to cover a range of neutron fluence spanning 2 orders of magnitude, relevant to the JET experiment. Bare irradiations lasted about 3 hours, DD, and 7 minutes, DT, with a neutron yield of ~2.23×10^{12} n and the fluence at detectors positions was in the range 3×10^{7}-10^{10} n/cm^2. A further 5 DD and 5 DT were performed in separate irradiations inside polyethylene moderators (cylindrical & rectangular holders in the plug assembly used during previous JET streaming experiments) at the same positions (except the first one) as bare. The irradiations lasted between 55 min and 106 min under DD and 3-6 min under DT, to provide to TLDs, inside the moderators, same level of fluence as bare. The other experiments have been performed at ENEA INMRI thermal neutron facility in Casaccia. This allows one to evaluate the moderator's body influence on the enhancement of thermal neutron signal registered by TLDs. The measurement results have been compared with MCNP simulations. The results will allow one to increase the accuracy of neutron fluence calculation at JET by replacing the calibration coefficients from [11] designated in the field of thermal neutrons with new coefficients which take into account the characteristics of neutron fields at fusion facilities. A summary of the results is presented in Fig. 6.

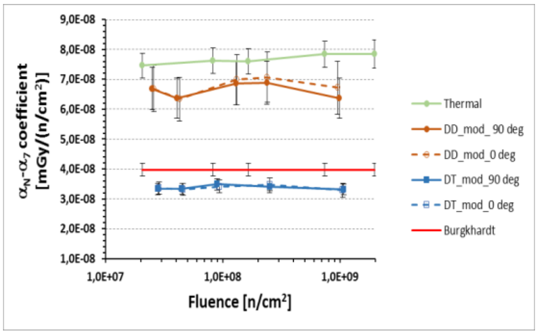

Figure 6. αN-α7 coefficients (kerma in air to neutron fluence) evaluated from response of MCP-N and MCP-7 detectors types with different Li-6 content for DD, DT and thermal neutron calibration experiments in comparison with Burgkhardt et al. [11] calibration factors.

The difference of about a factor 2 between thermal coefficients obtained in this work and Burgkhardt factors can be explained by the irradiation geometry. The GeNF thermal neutron radiation field was a plane parallel beam; the Burgkhardt coefficients were evaluated as mean value of results for three applied neutron fluences. In contrast, here we have applied thermal neutron field isotropically in the volume of irradiation chamber. In this approach we have exposed the entire surface of the detectors with thermal neutrons whilst at GeNF experiment only one side of detector absorbed neutrons.

Analyses of the results of calibration experiments and determination of new calibration factors and uncertainties were made. The new coefficients show a flat fluence response in all experiments and the variability of the values are caused by the differences in the applied neutron energy spectra. Their values depend on thermal neutron fluence obtained finally at the position of TLD dosemeters and one can observe that the moderation of DT neutrons is not as efficient as moderation of DD neutrons. The new calibration factors could reduce the discrepancies between calculations and measurements observed in past JET streaming experiment [5,6,9] and these will be applied to the past and to future JET measurements. In future work we intend to continue this interpretation and to conduct further calibration campaigns at other neutron facilities. Accurate MCNP simulations of the real experimental set-up are progressing to calculate the neutron and secondary gamma fluence spectra at the TLDs positions under DD and DT neutrons.

Calibration of activation foils

Activation foils provide a robust technique to determine neutron fluence in the environment of a fusion machine, where variable neutron and photon, as well as other electromagnetic fields are encountered. For this purpose, sets of Co, Ta and Ag foils (bare and Cd-covered) were positioned within polyethylene moderator cylinders of 25 cm in height and 25 cm in diameter. The moderators were chosen to be similar to those used for the TLD experiments for comparison. In order, to reduce uncertainties in the calculation of the neutron fluence levels a relative calibration technique was employed. Detector assemblies exactly similar to those irradiated at JET, were also irradiated at the Frascatti Neutron Generator facility providing D-D (up to 10^8 n/s) and D-T (up to 10^{11} n/s) neutron fields with an accurate knowledge of the neutron fluence level at ±3 % by utilization of the associated particle technique and minimum room scatter as well. The experiment was assisted by detailed Monte Carlo simulations performed using MCNP6 code in order to evaluate the neutron energy spectrum incident on each activation foil and their responses. The irradiations performed at FNG enabled experimental determination of the effective neutron cross-section of each foil under neutron irradiation conditions similar to that encountered at JET.

DOSIMETRY FOIL MEASUREMENTS WITHIN THE JET NUCLEAR ENVIRONMENT

During DD, TT and DT JET campaigns, samples of materials used in the manufacturing of main ITER tokamak components will be exposed to neutrons produced in the fusion reactions. Quantitative measurements of isotopic activation levels arising from these materials will be compared to test and, where needed, improve the predictions of neutron transport and activation simulation codes, and their underlying models and nuclear data. The ITER materials considered presently include Nb_3Sn, SS316L steels from a range of manufacturers, SS304B, Alloy 660, W, CuCrZr, OF-Cu, XM-19, Al bronze, NbTi and EUROFER. Progress has been made within this project, most recently on the experimental characterisation of irradiation locations within two long-term-irradiation stations (LTIS) assemblies, which are located close to the JET plasma-facing wall, and are thus exposed to large neutron fluxes relevant to ITER operations. Characterisation experiments have included exposing a range of dosimetry foils, including high purity elemental Ti, Mn, Co, Ni, Y, Fe, Co, Sc and Ta foils to these neutron fluxes. Fig. 7 shows the latest neutron activation simulations calculated using FISPACT-II using an MCNP6 calculated neutron spectrum. The simulations are performed on the complex neutron yield profile over time from JET between 27/08/2015 and 15/11/2016.

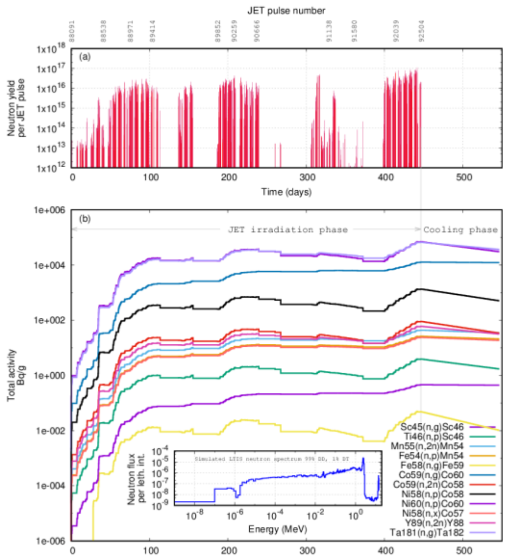

Figure 7: (a) JET neutron yield per pulse between 27/08/2015 and 15/11/2016; (b) Simulated specific activities calculated over time for dosimetry foils located within the long-term irradiation station assembly, exposed to JET experimental campaigns calculated using FISPACT-II.

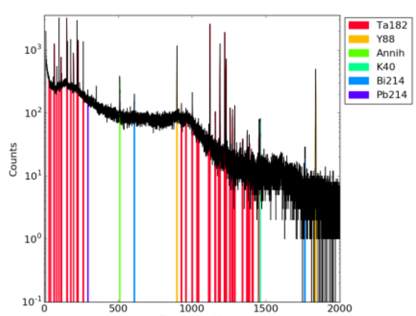

Figure 8: HPGe measurement taken from an Y foil 'CCFE1', showing the charactersitic lines from Y-88 and also Ta-182, the latter isotope being measured due to Ta impurities in the Y foil.

Fig. 8 shows an example gamma spectrometry measurement of a Y foil, exhibiting the characteristic lines from Y-88 and also lines from Ta-182 due to the small amount of Ta elemental impurity present within the foil. After the characterization experiments, the real ITER materials will be exposed to neutron in the LTIS in the next DD, TT and DT campaigns at JET.

CONCLUSIONS

Several experiments and analyses are carried out at JET fusion device for the development of nuclear experimental techniques capable to provide accurate neutron measurements in ITER, and to provide validation of the neutronics codes used in the design of ITER and fusion power plants. These experiments are currently carried out in DD campaigns in preparation of the planned TT, DT operations in the next few years.

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