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Mixed n–γ fields dosimetry at low doses by means of different solid state dosimeters

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ABSTRACT

A Mock-up of the inboard shield of the ITER International nuclear fusion reactor was realized at the Frascati Neutron Generator (FNG) at ENEA Frascati with the scope to measure the nuclear heating (total dose) in the superconducting coils. High sensitivity MCP-6 and MCP-7 dosimeters were used to measure the low (<150 μGy) expected doses. A dedicated calibration effort was devoted to calibrate the detectors in reference gamma and thermal neutrons secondary standards fields. The TLD's reading cycle was also optimized for the expected low dose to minimize the signal to noise ratio. The neutron and gamma separation was obtained by the "pair detectors" method. The experimental results (gamma air-kerma and neutron fluence) are compared with the results of Monte Carlo simulations performed with the MCNP-5.2 code and the FENDL-2.1 nuclear data library.

1. Introduction

The simultaneous and accurate measurement of the dosimetric quantities for neutrons and gammas in mixed neutron-gamma fields is a complex task, especially when the doses are below few hundreds of μGy.

The ITER international project (www.ITER.org) has the goal to build and operate the largest fusion tokamak. One of the main issues of the design is the accurate determination of the dose on the superconducting magnets which, producing the magnetic field necessary for the tokamak operation, are crucial for the proper operation of the machine. The magnets are heavily shielded since the shield must attenuate the huge radiation (neutrons and gamma) fluxes produced by the plasma so that the total dose absorbed by the magnet will not excide the safety level.

Experiments were carried out in past years to check whether the used calculation tools were able to properly calculate the doses in the magnets, however, the experimental uncertainty on the measured total absorbed dose in the magnet was about ±30% (M. Angelone et al., 1997). A much lower uncertainty is now requested by the design (≤±10%) to reduce the magnets' operational uncertainty margin.

An experiment was designed and performed at the 14 MeV Frascati Neutron Generator (FNG) of ENEA Frascati (Martone et al., 1993) in which a mock-up of the inboard shield of the ITER thermonuclear reactor was realized. The mixed fields in the ITER magnet were accurately calculated using the Monte Carlo code MCNP-5.2 (Pelowitz, 2005) and the FENDL-2.1 data library (Aldama and Trkov, 2004).

The objective of the FNG's experiment was the measurement of the photon and neutron fluxes and absorbed doses in the magnet coils (E) using several different detectors (activation foils, TLDs, CR-39) and the comparison with the calculation (C). The goal was to validate the calculation of nuclear heating with accuracy on the C/E comparison ≤± 10%.

This paper reports about the neutron flux and absorbed dose measurements performed using high sensitivity thermoluminescent (TLD) detectors, and discusses the C/E comparison.

2. The experimental mock-up

The experimental mock-up (Fig. 1) was realized on the basis of the present ITER design. The mock-up includes all the most relevant features and materials of the inboard shield of ITER (radial dimensions, materials composition, volumetric ratio etc.). It is realized by a series of stainless steel (SS) plates (AISI SS-316 type), 5 cm thick and of Perspex plates, 2 cm thick. Perspex is used instead of water since it simulates water from a neutronics point of view. The block has 1 m × 1 m side and about 80 cm thickness. This large (main) block is attached to a second smaller block (0.4 m × 0.4 m × 0.4 m) reproducing the superconducting magnet. This small block is made of Cu and SS-316 plates, 2 cm thick each.

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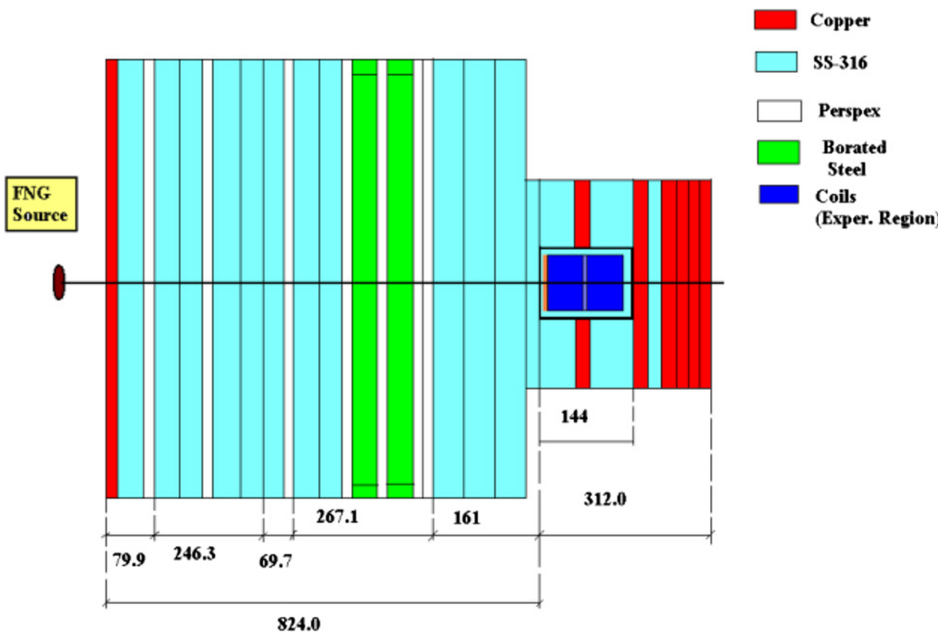

Fig. 1. The mock-up of the ITER inboard shield assembled at FNG.

Some pieces of the real ITER superconducting coil cable were located at the center of the second small block. This is to better reproduce the real structure of ITER and represents the so-called "*coil region*" which is the main experimental region for the purpose of the present paper.

An experimental channel of 3 cm diameter crosses the mid-plane of the main block for detectors location. Other detectors are located in selected positions inside or around the "coil region" (see Section 3).

Neutron fluxes and absorbed doses were measured inside the mock-up using activation foils (Nb, Al, Ni, Au and W) and lithium fluoride (LiF) thermoluminescent dosimeters (TLD) respectively.

3. Monte Carlo calculation

A detailed MCNP geometry (Fig. 2) was produced to simulate the mock-up. Accurate importance maps (at many energy groups) were produced to speed-up the calculation and to reduce to lower than ±5.0% the uncertainty for all of the various nuclear responses even in the deepest positions (up to about 1 m from the FNG source).

Fig. 3 reports a detail of the superconducting coils region, as modeled by MCNP. This is made by four pieces of ITER superconducting coils (Nb/Sn alloy) surrounded by 10–15 mm of insulator (vetronite) and enclosed in a casing made of Stainless Steel AISI-316 (SS-316). The experimental positions are evidenced in Fig. 3 too.

To directly compare the MCNP calculations with the measurements, the calibration of TLDs was made in terms of air-kerma. The air-kerma in the TLD has been calculated with MCNP using both F4 flux tally multiplied by an energy-dependent multiplier (FM card), and track length cell energy deposition tally for neutron and photons with TLDs as air (F6 tally). In the first case the material used for transport is LiF while air is used only for tally. In the second case the actual TLD material (e.g. LiF) is replaced by air.

The F6 heating tally is a special case of the F4 track length estimate of cell flux with energy-dependent multipliers. For the photon results to be identical in the two F4 and F6 cases, both electron transport and the thick-target bremsstrahlung approximation (PHYS:P j 1) must be turned-off.

In the F6:P tally, if a photon produces an electron that in turn generates another photon, the second photon is not accounted for since it is already tallied in the first photon heating. In the F4:P tally,

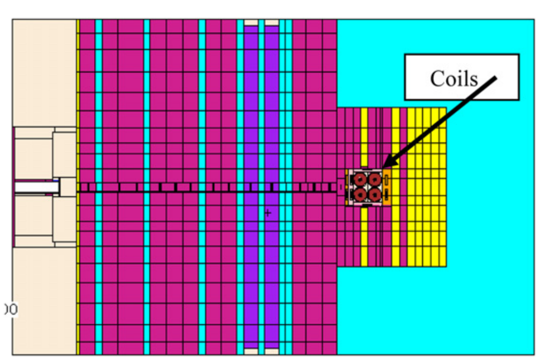

Fig. 2. : MCNP model of the experimental mock-up. For dimensions and materials see Fig. 1.

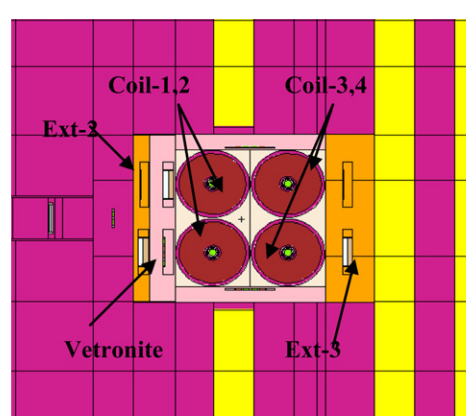

Fig. 3. Detail of the "coils region" as simulated by the MCNP code. The experimental positions are reported too as indicated by the arrows. The colors meaning is: the purple region is steel, yellow is copper, orange is the casing (steel), orange is vetronite while brown is the superconducting coil. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the second photon track is counted for, so the F4 tally will slightly over predict the F6 tally. To avoid this problem the PHYS:P j 1 card is used.

The effect of turning-off bremsstrahlung has been evaluated. It was found that the latter option increases the calculated value of few percent.

The air-kerma and doses calculated in each experimental position inside the TF coil region with both F4 and F6 tallies agree within ±6% at maximum.

4. TLD measurement and n-γ dose separation

The mock-up is irradiated at FNG which produces up to 10^11 n/s. The expected absorbed dose in the coils (after 15h of irradiation) is of the order of 100–130 μGy or lower. The dose of interest for the purpose of the experiment is that due to prompt gammas produced during the neutron irradiation. Longer irradiations should last two or more days and face the problem of subtracting a not negligible amount of "background" signal produced during the shut-down phase (e.g. overnight) and due to the activation of the structure surrounding the TLD (decay-heat). This background signal has to be measured independently and to be subtracted from the measured total signal.

High sensitivity MCP-7 and MCP-6 TLDs were used to measure these low doses (Bedogni et al., 2006). An accurate study of the reading cycle was performed in order to optimize the ratio between the measured signal and the background signal (S/B), under the expected working condition (dose and working time). The used cycle has a pre-heat at 160 °C per 10 s followed by a heating ramp of 5 °C/s up to 240 °C. Annealing at 240 °C per 15 min in a oven with electronic controlled heating/cooling ramp rate was used too.

The TLDs were individually calibrated in secondary standard photon and thermal neutron fields available at the Radioprotection Institute of ENEA (IRP). Only TLDs whose sensitivity varies less than ±3% where used in the experiment. The gamma calibration was performed at low air-kerma (<150 μGy) using a Co-60 source absolutely calibrated at ±2% by a ionization chamber, while a fluence of 2.07 × 10^8 n*cm^{-2} (±5%) was delivered to both type of TLDs to calibrate them in the reference thermal neutron field (Burn and Gualdrini, 2002; Gualdrini et al., 2004).

The gamma and neutron sensitivities were also derived and are reported in Table 1. In Table 1, S_{th}/S_{th6} is the thermal neutron sensitivity relative to MCP-6 and $S_\gamma/S_{\gamma6}$ is the gamma sensitivity respect to MCNP-6 (measured TL-light ratio for n and gamma calibration); S_{th}/S_γ is ratio between thermal neutron and gamma sensitivity for each TLD.

The relative neutron and gamma sensitivities (η_n, η_γ), defined as the TLD response (e.g. the TL-signal) due to n and gamma calibration air-kerma respect to the delivered neutron and gamma air-kerma (see Gibson, 1985), were also derived for MCP-6 and MCP-7. The $k_{6,7}$= $(\eta_n/\eta_\gamma)_{6,7}$ ratio is reported in the last column of Table 1.

The experimental air-kerma measured by MCP-7 are compared in Tables 2 and 3 with the results of the MCNP simulation (F4 and F6 tally respectively). As already discussed in sect. 3, the use of the air-kerma allows for direct comparison with the results of the MCNP simulation. Here we recall that MCNP provides the dose normalized to one source neutron (Gy/neut), thus the experimental data for the dose (Gy) are normalized to the total neutron yield measured by the standard neutron monitor available at FNG. This monitor provides the absolute neutron emission at ±3%.

Table 1
Measured neutron and gamma sensitivity for MCP-6 and MCP-7. (Symbols are explained in the text).

TLD	S_{th}/S_{th6}	$S_\gamma/S_{\gamma6}$	S_{th}/S_γ(pGycm^2)	$K_{6,7}$
MCP-6	1.00 ± 0.07	1.00 ± 0.04	96.5 ± 9.0	17.65 ± 0.18
MCP-7	0.064 ± 0.008	1.19 ± 0.06	5.2 ± 0.6	1.00 ± 0.10

Table 2
Comparison between measured and calculated (F4 Tally) air-kerma (Gy/neut).

Exp. position	MCNP Tally F4	Exper.	C/E	Error% on C/E
Ext1	1.42E-19 ± 4.0%	1.33E−19 ± 7.4%	1.06	±8.4
Ext2	1.11E-19 ± 2.0%	1.03E-19 ± 8.4%	1.08	±8.6
Coil1-2	7.71E-20 ± 2.1%	7.76E-20 ± 7.0%	0.99	±7.3
Coil 3-4	5.27E-20 ± 3.6%	5.17E-20 ± 7.2%	1.02	±8.0
Ext3	3.41E-20 ± 6.0%	3.43E-20 ± 7.5%	0.99	±9.6

Table 3
Comparison between measured and calculated (F6 tally) air-kerma (Gy/neut).

Exp. position	MCNP Tally F6	Exper.	C/E	Error % on C/E
Ext1	1.34E-19 ± 1.8	1.33E-19 ± 7.4	1.01	±7.6
Ext2	1.11E-19 ± 1.4	1.03E-19 ± 8.4	1.08	±8.5
Coil1-2	7.84E-20 ± 1.6	7.76E-20 ± 7.0	1.01	±7.2
Coil 3-4	5.59E-20 ± 3.3	5.17E-20 ± 7.2	1.08	±7.9
Ext3	3.62E-20 ± 6.6	3.43E-20 ± 7.5	1.05	±10.0

As far as the experimental uncertainties are concerned, the uncertainty on the measured air-kerma is calculated by applying the quadratic propagation law. The main contributions arise from calibration (±2.0%), counting statistics (<±5.0%) and for the case of the C/E comparison also the ±3.0% uncertainty due to the FNG absolute neutron source calibration.

In a mixed n-γ field, the measured response of a TLD is given by the contribution of the neutron and gammas components. From the measured MCP-6 and MCP-7 responses (R_6 or R_7, respectively) the neutron fluence (or dose) and the gamma absorbed dose can be derived using the well known pair method (Attix, 1986).

A system of two equations, one for MCP-6 and the other one for MCP-7 respectively, can be written:

$$R_6 = D_\gamma + k_6 D^*_n$$

$$R_7 = D_\gamma + k_7 D^*_n$$

Here $k_{6,7}$ are the relative thermal neutron sensitivities ($k_{6,7}$ in Table 1), while D_γ and D^*_n are the gamma dose and the thermal fluence in the TLD, respectively. Solving the system both D_γ and D^*_n are obtained. Table 4 reports the experimental results for D_γ and comparison with the MCNP simulation.

Since the TLDs were calibrated in terms of thermal neutron fluence, the output of the separation was the thermal neutron fluence D^*_n rather than neutron dose.

The thermal fluence measured in the coils by the TLDs was thus compared with the same quantity obtained by activation techniques measuring the activation reaction $^{197}Au(n,\gamma)^{198}Au$. The activated gold foils were measured by the absolute radiometric technique using an HPGe detector absolutely calibrated at ±3.5%. Gold foils 30 μm thick and 20 mm diameter were used. They were

Table 4
Comparison between calculated and measured (derived from the pair-detectors method) gamma air-kerma.

Position	MCNP (Gy/n)	Experim. (Gy/n)	C/E
Ext-2	5.65E-20 ± 2.8%	4.75E-20 ± 15.0%	1.19 ± 0.19
Coil 1-2	4.23E-20 ± 2.8%	4.34E-20 ± 15.0%	0.97 ± 0.15
Coil 3-4	2.91E-20 ± 4.8%	3.11E-20 ± 15.0%	0.94 ± 0.14
Ext-3	1.62E-20 ± 8.7%	1.63E-20 ± 15.0%	1.00 ± 0.16

Table 5
Comparison between thermal neutron fluences measured by TLDs and gold foils.

Position	TLD-fluence	Gold Fluence	Ratio	Error %
EXT-2 SS-316	1.92E + 07	1.76E + 07	1.09	±15.8
INT-1 (vetronite)	2.09E + 07	1.80E + 07	1.16	±15.8
EXT-3 SS-316	6.56E + 06	5.90E + 06	1.11	±15.8
INT-2 vetronite	1.43E + 07	1.31E + 07	1.09	±15.8

located in some of the experimental positions used for the TLD, but were irradiated in a separate run to avoid self-shielding effects.

The thermal fluence comparison is reported in Table 5. As far as the quoted uncertainties are concerned, the gold fluence was measured with an overall uncertainty of±5.0%, while the uncertainty to be associated to the thermal neutron fluence measured by MCP-6 is ±15.0. This large uncertainty is due to the uncertainty propagation in the pair-detectors method.

5. Conclusion

The experimental procedure adopted allowed to get high accuracy for the TLD measurements. The accurate selection of each detector coupled with their single calibration and a proper heating cycle which optimizes the signal to noise ratio, allow to reduce the standard deviation of responses of the irradiated dosimeters and the experimental results are provided with an uncertainty $< \pm 8\%$ (see Table 2, 3).

The C/E results indicate that the present simulation tool composed by the MCNP code and the FENDEL-2.1 data library is able to predict the heating of the ITER magnet within an accuracy of ±10%. This fulfils the design request.

One major point of concern is however due to the fact that methods to measure the absorbed dose in materials such us stainless steel or copper or other materials of interest for a fusion tokamak are missing. The use of TLD of LiF type is suitable but it is not the best from a dosimetric point of view since their atomic number is low compared with that of the surrounding medium. To overcame this problem in the past TLD-300 (CaF_2:Tm) were used (Angelone et al., 1997), however these dosimeters do not have enough sensitivity to low dose and the experimental results were affected by large uncertainty.

Effort is ongoing to try to find new thermoluminescent materials which can match the request of high atomic number to that of high sensitivity. An alternative can be the use of small active detectors with high sensitivity (e.g. ionization chambers) and capable to separate neutron and gamma response.

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