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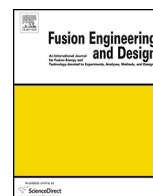
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The preparation of the Shutdown Dose Rate experiment for the next JET Deuterium-Tritium campaign

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HIGHLIGHTS

- The assessment of the shutdown dose rate is a major safety issue for fusion devices.The future DTE2 campaign at JET will provide a unique opportunity to check the capabilities of the numerical tools for SDR predictions.
- Detectors for SDR experiment are characterized by excellent reproducibility, long-term stability and flat energy response.
- Different ENEA facilities and laboratories have been used for calibrating and testing the dosimetry equipment selected for the experiment.
- Flat energy response in terms of air kerma within 4.1% has been observed for both the ionization chambers.

ARTICLE INFO

ABSTRACT

The assessment of the Shutdown Dose Rate (SDR) due to neutron activation is a major safety issue for fusion devices and in the last decade several benchmark experiments have been conducted at JET during Deuterium-Deuterium experiments for the validation of the numerical tools used in ITER nuclear analyses. The future Deuterium-Tritium campaign at JET (DTE2) will provide a unique opportunity to validate the codes under ITER-relevant conditions through the comparison between numerical predictions and measured quantities (C/E). For this purpose, a novel SDR experiment, described in the present work, is in preparation in the frame of the WPJET3-NEXP subproject within EUROfusion Consortium. The experimental setup has been accurately designed to reduce measurement uncertainties; spherical air-vented ionization chambers (ICs) will be used for on-line ex-vessel decay gamma dose measurements during JET shutdown following DT operations and activation foils have been selected for measuring the neutron fluence near ICs during operations. Active dosimeters (based on ICs) have been calibrated over a broad energy range (from about 30 keV to 1.3 MeV) with X and gamma reference beam qualities. Neutron irradiation tests confirmed the capability of active dosimeters of performing on-line decay gamma dose rate measurements, to follow gamma dose decay at the end of neutron irradiation as well as insignificant activation of the ICs.

1. Introduction

Neutrons produced during Deuterium-Deuterium (DD) and Deuterium-Tritium (DT) plasma operations induce the activation of the materials constituting the fusion machine components.

The assessment of the shutdown dose rate (SDR) is a major safety issue for fusion devices, to guarantee the respect of dose limits to external exposure during maintenance and interventions. Radiation dose limits are based on protection quantities that are not directly measurable and the need for readily measurable quantities that can be related to effective dose and equivalent dose [1] has led

to the development of operational quantities for the assessment of external exposure. For area monitoring, the operational quantity for strongly penetrating radiation as gamma rays due to neutron activation, is the ambient dose equivalent at a 10 mm depth of the ICRU sphere H*(10) [1,2].

SDR experiments represent also a key issue for the design and for planning the maintenance operations of future fusion devices, in particular for ITER. In order to ensure the reliability of SDR predictions for ITER, the use of qualified and validated codes and nuclear data is fundamental. The future Deuterium-Tritium campaign (DTE2) at JET will provide a unique opportunity to check the capabilities of the numerical tools for SDR predictions [3–6] in a complex fusion device and to validate the codes under ITER-relevant conditions, exploiting the significant 14 MeV neutron production (up to $1.7 \cdot 10^{21}$ neutrons) [7].

The present work summarizes the main experimental activities in preparation of the SDR experiment during the next DTE2: the selected measuring equipment to be installed at JET is described in Section 2, calibration of active dosimeters and neutron irradiation tests, respectively, in Sections 3 and 4. Conclusions are given in Section 5.

2. Experimental assembly

The measuring equipment at JET consists of three active dosimeters, for measuring the dose rate at the shut down and during some inter-shots, and a passive system for measuring neutron fluence (i.e., two activation foil assemblies) during JET pulses near active dosimeters [8]. Thermo-luminescent detectors (TLDs) for passive in-vessel measurements and a portable High-Purity Germanium spectrometer (HPGe) for gamma-ray spectra measurements at the shutdown (when the human access to the torus hall is allowed), complete the equipment.

The active gamma dosimeters are based on two 140 mm diameter air-vented spherical ionization chambers (ICs), PTW model 32002, and on one smaller IC, 44 mm diameter, PTW model 32005 [9]. ICs 32002 have been procured by ENEA and KIT (henceforth, named respectively ENEA IC 32002 and KIT IC 32002); the smaller IC has been procured by ENEA (here labeled ENEA IC 32005). ICs 32002 and 32005 are designed for radiation protection and are characterized by excellent reproducibility, long-term stability of the sensitive volume and above all, flat energy response (in terms of air kerma [1]), which is essential in this application. The spherical construction ensures a nearly uniform response to gamma radiation from every direction. These detectors have been selected to cover a dose rate range from background to 30 mSv/h, as predicted by calculations reported in [10].

ICs are operated in current mode and the output signal is analyzed by two suitable electrometers for dosimetry, one for both ENEA ICs and the other one for the KIT IC. These electrometers, model PTW UNIDOS [9], are equipped with an Ethernet interface for integrating them in the laboratory local network (LAN) for remote access. A user written software has been implemented for remote control of electrometers and data acquisition. High quality triaxial cables, 100 m long, serve as low noise connection of radiation detectors, located near the tokamak, to electrometers, located outside the torus hall for limiting radiation damage. The selected cables, designed for precise current measurements down to 10^{-15} A and with a low leakage caused by irradiation, provide insulated potentials for the measuring signal, the guard electrode, and high voltage (i.e., 400 V) to ICs.

The two activation foil assemblies consist of an aluminum holder (100 mm × 50 mm × 4.5 mm) with 7 foils (Co, Ta, Ag and Ni foils, 4 bare + 3 Cd-covered) [8].

Two ex-vessel positions, close to the JET horizontal ports of Octants 1 and 2, have been chosen for the location of ICs and activation foil assemblies, on the basis of calculations reported in [8]. The position in Octant 1 is close to the Radial Neutron Camera and the position in Octant 2 is on the top of the ITER-like Antenna. ENEA ICs 32002 and 32005, together with an activation foil assembly, will be located on a dedicated support in Octant 1; KIT IC 32002 and the other set of activation foils, on a dedicated support in Octant 2. The in-vessel position for TLDs is the same as in the previous benchmark experiment described in [10].

3. Calibration of active dosimeters

3.1. ENEA dosimeters

The two dosimetry systems, respectively based on the ENEA ICs 32002 and 32005, connected to the associated PTW electrometer, have been calibrated at ENEA-INMRI [11] in terms of air kerma, using the selected X and gamma reference beam qualities at low doses (the range of interest is < 40 mSv/h) reported in Table 1 and according to ISO 4037 [12]. N qualities represent filtered X-rays produced with an accelerated electron beam (voltage of vacuum tube and added filters are indicated in the same table), while S qualities are gamma-emitters.

Air kerma at the reference measuring point (K_{air}) was determined with INMRI national standard reference ionization chambers (parallel plate and cylindrical chambers), each dedicated to a specific radiation quality. The air kerma calibration factor N_{Kair} at a specified radiation quality, is then calculated as the ratio between K_{air} and the dosimetry system reading M. A calibration in terms of H*(10) would be useless, since the detector response for this operational quantity is strongly energy-dependent and the decay gamma energy spectrum at the detectors is variable during measurements. For these reasons, a weighted integration of calibration coefficients at different beam qualities over the gamma energy spectrum, for determining the mean calibration coefficient to be used for converting instrument reading M into H*(10), is precluded. An energy-independent response is needed in this case and, as earlier mentioned, the selected ICs show a flat energy response when measuring air kerma. Ambient dose equivalent H*(10) can be then calculated from air kerma by means of ICRP conversion coefficients [13].

Results of the calibrations are reported in Table 1 and shown in Fig. 1, where diamond-shaped dots are N_{Kair} for the different beam qualities; circular dots in correspondence of the Co-60 are the calibration factors measured by PTW, consistent with the INMRI ones. Expanded measurement uncertainty U (coverage factor k = 2), which gives a level of confidence of approximately 95% and calculated according to the ISO recommendations [12] is also indicated. Calibrations have been carried out under controlled reference ambient conditions (i.e., T = 20 °C, P = 1013.25 hPa and relative humidity = 50%, without significant variations), since variations of air density and humidity affect the response of air vented ICs. Air density and humidity will be monitored during SDR experiment and departures from the reference conditions must be considered in order to apply appropriate correction factors to the electrometers readout. To convert the instrument readout (Coulomb) into air kerma (Gray), an 'equivalent' calibration factor ($N_K{}^{cal}$) is needed; under the hypothesis of perfect flat energy response of the dosimeters, y = $N_K{}^{cal}$, the measured calibration factors N_{Kair} can be considered energy independent. In particular, if

Table 1
Radiation qualities used for the calibration of ENEA ICs.

| Radiation Quality	High Voltage (kV)	Added Filtration (mm)	Average Energy (KeV)	Air kerma rate (Gy/s)		IC 32002		IC 32005	
				IC 32002	IC 32005	N_{Kair} (Gy/C)	U (%)	N_{Kair} (Gy/C)	U (%)
N-40	40	4 Al + 0.21 Cu	32.5	–	$2.0 \cdot 10^{-4}$	–	–	$1.145 \cdot 10^6$	1.0
N-150	150	4 Al + 2.5 Sn	116.6	$5.6 \cdot 10^{-5}$	$2.6 \cdot 10^{-5}$	$2.442 \cdot 10^4$	2.4	$1.090 \cdot 10^6$	2.3
N-300	300	4 Al + 3 Sn + 5 Pb	249.6	$2.8 \cdot 10^{-5}$	$2.8 \cdot 10^{-5}$	$2.526 \cdot 10^4$	2.5	$1.113 \cdot 10^6$	2.4
S-Am			59.0	$4.2 \cdot 10^{-6}$	$2.8 \cdot 10^{-5}$	$2.462 \cdot 10^4$	2.4	$1.098 \cdot 10^6$	2.4
S-Cs			662.0	$1.9 \cdot 10^{-6}$	$1.9 \cdot 10^{-6}$	$2.506 \cdot 10^4$	2.4	$1.107 \cdot 10^6$	2.4
S-Co	ENEA lab.		1253.0	$1.3 \cdot 10^{-4}$	$1.3 \cdot 10^{-4}$	$2.402 \cdot 10^4$	1.4	$1.087 \cdot 10^6$	1.1
	PTW lab.			min $1.7 \cdot 10^{-7}$/max $5.0 \cdot 10^{-3}$		$2.487 \cdot 10^4$	2.5	$1.099 \cdot 10^6$	2.5
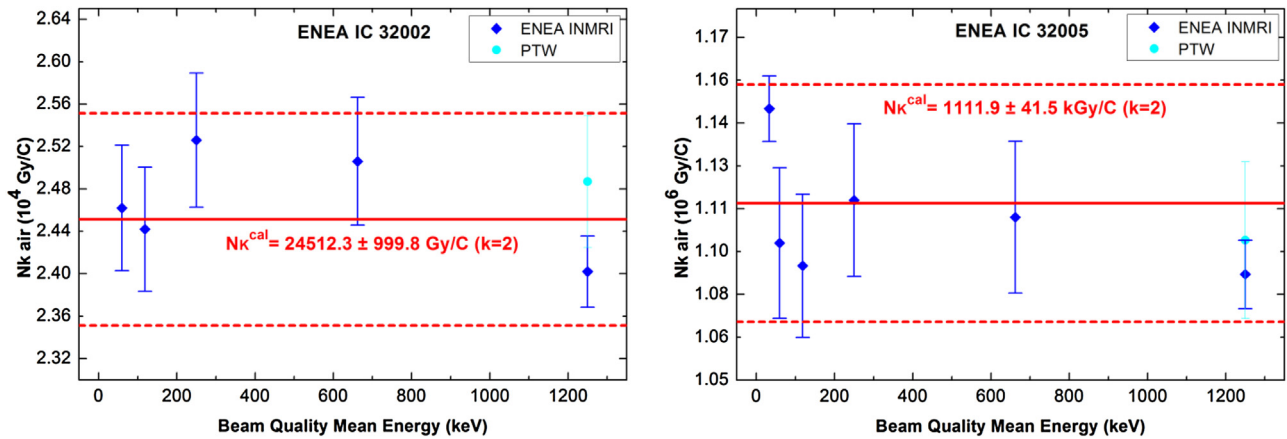
Fig. 1. N_{Kair} factors for the ENEA ICs 32002 (left) and 32005 (right) resulting from the INMRI (diamond-shaped points) and PTW (circle-shaped points) calibration. Error bars represent the expanded measurement uncertainty (coverage factor k = 2). The 'equivalent' calibration factor N_K^{cal} is plotted as solid line; dashed lines represent the limits of the expanded uncertainty (k = 2) associated to N_K^{cal}.

their distribution about N_K^{cal} follows a Gaussian function, the most probable value of N_K^{cal} is the weighted least squares estimator [14]:

$$N_K^{cal} = \frac{\sum_{i=1}^{n} N_{Kair}(i) \cdot \sigma(i)^{-2}}{\sum_{i=1}^{n} \sigma(i)^{-2}} \qquad (1)$$

In Eq. (1), summations are over the n calibration points and each N_{Kair} value is weighted with the inverse square of the associated uncertainty. Finally, the uncertainty associated to N_K^{cal} is calculated as the square root of the sample variance:

$$\sigma_{cal}^2 = \frac{\sum_{i=1}^{n} \left(N_K(i) - N_K^{cal} \right)^2}{n - 1} \qquad (2)$$

Where $n-1$ is the number of degrees of freedom of the sample (i.e., 5 for IC 32002 and 6 for IC 32005).

N_K^{cal} values are indicated in Fig. 1 for the two dosimeters and plotted as solid horizontal lines; in the same figure, dashed lines represent the limits of the 95% confidence interval. Both dosimeters show flat energy response in terms of air kerma within 4.1%.

3.2. KIT dosimeter

To compare the response of the KIT dosimetry system (IC 32002 + PTW UNIDOS electrometer) with the ENEA identical system calibrated at INMRI, a cross-calibration has been performed at the gamma calibration laboratory of ENEA-INMRI. The two ionization chambers were alternatively exposed to 3 different standard

Cs–137 gamma sources. A scheme of the experimental setup is in Fig. 2.

The dose rate at the sphere position for the 3 standard gamma sources was respectively 0.2, 1.7 and 3.6 mGy/h. The detectors had been preventively exposed for 5 min to the gamma source before the measurements started. During measurements, temperature (18.4 °C–18.8 °C), pressure (1011.1–1011.3 hPa) and relative humidity (42%) did not undergo significant variations.

The collected charge was recorded every 60 s and measurements lasted 900 s each. The slope of the linear fit of the collected charge vs. acquisition time shown in Fig. 3 (bottom) is the ionization current measured with the ENEA dosimetry system, proportional (through the calibration factor) to the air kerma rate. Normalized differences between measurements of collected charge performed with the KIT (C_{KIT}) and the ENEA (C_{ENEA}) systems, with respect to C_{KIT}, are shown in the upper graph of Fig. 3. A systematic overestimation of about 0.5% of the KIT dosimeter is observed. The maximum difference is within 1%.

4. Irradiation tests at FNG

A preliminary test of the ENEA IC 32002 was carried out at FNG (Frascati Neutron Generator), the ENEA 14 MeV neutron source facility, with the aim of assessing the correct functioning of the detector after neutron irradiation. This test showed that the dosimetry system correctly measures the background dose rate in the laboratory at the neutron source shutdown, after a run of irradiation experiment [8]. A further test was performed to check for self-activation of the detector induced by neutrons. The detector was positioned 1 m from the FNG target (where neutrons are produced) and irradiated for about 3 h. The 14 MeV neutron fluence
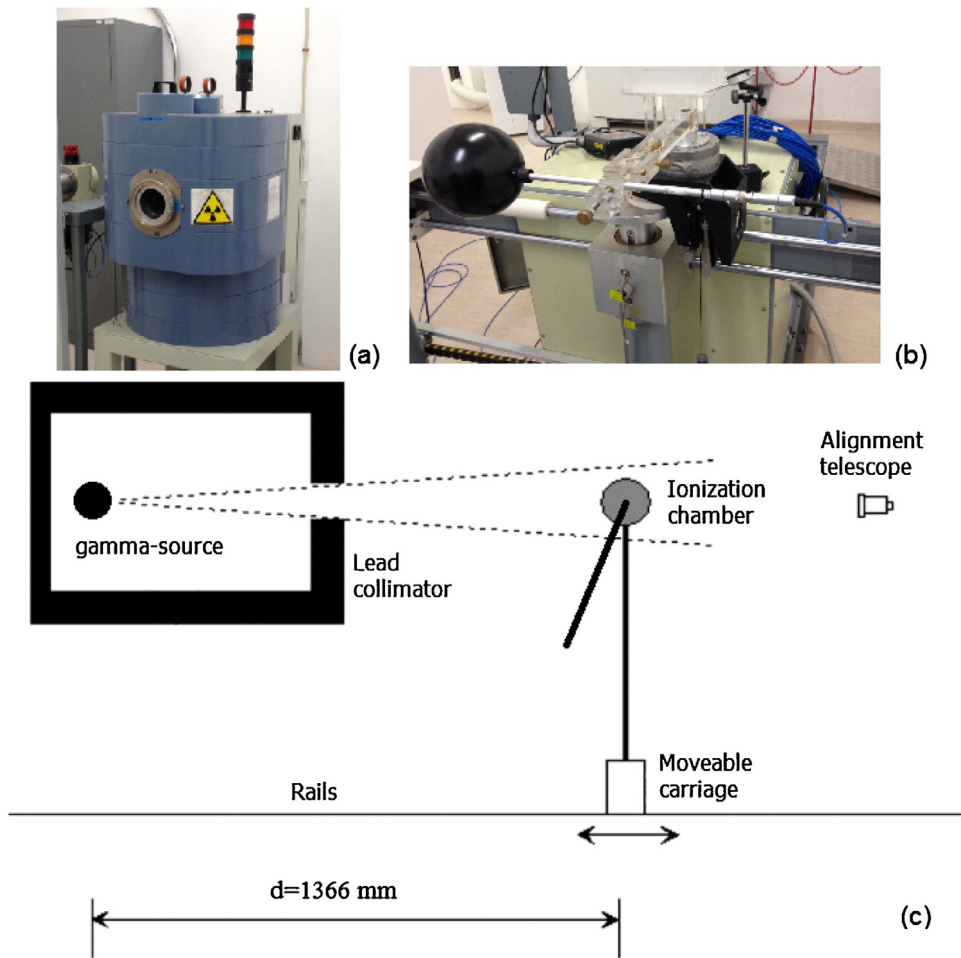
Fig. 2. Source lead collimator (a) and ionization chamber located on the movable carriage (b) at ENEA INMRI gamma calibration laboratory; (c) scheme of the experimental setup.
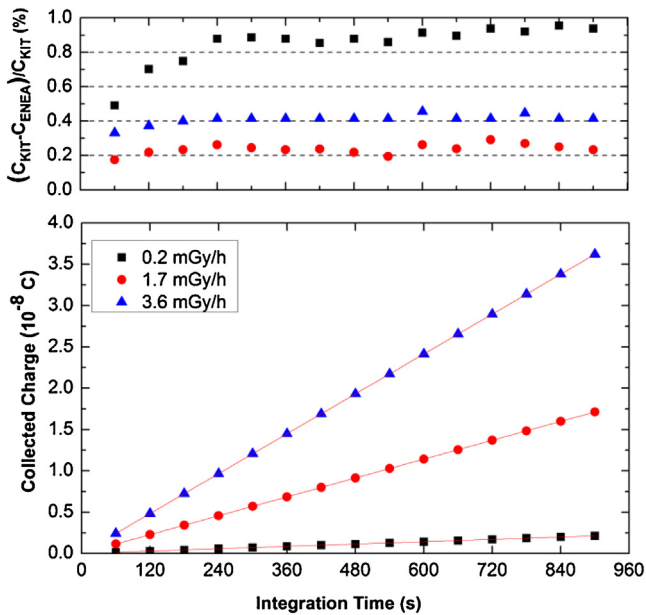

Fig. 3. Bottom: Collected charge measured with the ENEA dosimetry system at different dose rates (0.2, 1.7 and 3.6 mGy/h). Top: normalized difference of collected charge measured with the KIT and ENEA systems.
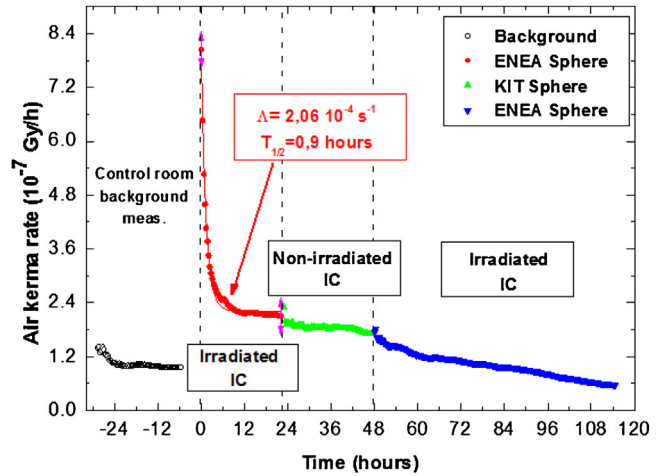

Fig. 4. Air kerma rate measured after the second irradiation test at FNG with the irradiated IC (i.e., ENEA IC 32002) and the non-irradiated IC (i.e., KIT IC 32002).

(at the sphere position) was $8.2 \cdot 10^8 \, cm^{-2}$. The ionization chamber, after being irradiated, was immediately moved to the control room and then switched on. Measured air kerma rate is shown in Fig. 4 during the different phases of the test. The background dose rate in control room, previously measured, is also reported. Background in the FNG control room is not constant and strongly dependent on the Rn-222 concentration in air.

The acquisition with the irradiated detector in the control room lasted 22 h. An exponential decrease (see Fig. 4) is observable in this phase with a decay constant $\lambda \approx 2.06 \cdot 10^{-4}\,s^{-1}$ and half-life $T_{1/2} \approx 0.9$ h. This indicates that only short-term activation is observed and it is related to the activation of air inside the IC. Subsequently, the KIT IC 32002, identical to the ENEA chamber but never exposed to neutrons, was connected to the electrometer, in place of the irradiated detector, for 24 h. The background dose rate measurements in the control room with the two detectors show that after about one day the two ICs measure the same current; after this period, no residual current due to the self-activation is detectable. It also confirms that no damages were induced in the irradiated ionization chamber.

5. Conclusions

The preparation of the Shutdown Dose Rate (SDR) experiment at JET required the choice of suitable detectors for radiation protection, characterized by excellent reproducibility, long-term stability and flat energy response. Different ENEA facilities and laboratories have been used for calibrating and testing the dosimetry equipment selected for the experiment. In particular, the two dosimetry systems, respectively based on the ENEA IC 32002 and 32005, have been calibrated at ENEA-INMRI in terms of air kerma with X and gamma sources at low doses. Flat energy response in terms of air kerma within 4.1% has been observed for both the ionization chambers. Irradiation tests of the ENEA IC 32002 were carried out at FNG with the aim of assessing

the correct functioning of the detector after neutron irradiation and for checking the self-activation of the detector induced by neutrons. These tests have shown that after the irradiation of the detector, the dosimetry system measures correctly the characteristic dose rate trend in the FNG laboratory at the neutron source shutdown. After about one day, no residual current signal due to the self-activation is detectable and no damages were induced in the irradiated ionization chamber.

Acknowledgments

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