3-D thermal and radiation-matter interaction simulations of a SiC solid-state detector for neutron flux measurements in JSI TRIGA Mark II research reactor

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Abstract*—Neutron detection is a relevant topic in the field of nuclear instrumentation. It is at the heart of the concerns for fusion applications (neutron diagnostics, measurements inside the Test Blanket Modules TBM) as well as for fission applications (in-core and ex-core monitoring, neutron mapping or safety applications in research reactors). Moreover, due to the even more harsh conditions of the future experimental reactors such as the Jules Horowitz Reactor (JHR) or International Thermonuclear Experimental Reactor (ITER), neutron detectors need to be adapted to high neutron and γ fluxes, high nuclear heating rates and high temperatures. Consequently, radiation and temperature hardened sensors with fast response, high energy resolution and stability in a mixed neutron and γ environment are required. All these requirements make wide-bandgap semiconductors and, more precisely, Silicon Carbide (SiC) serious candidates due to their intrinsic characteristics in such extreme environments. Thus, since the last decades, SiC-based detectors are developed and studied for neutron detection in various nuclear facilities. In this paper, a SiC-based neutron detector is 3-D designed and studied through thermal and radiation-matter interaction numerical simulations for a future irradiation campaign at the Jožef Stefan Institute TRIGA Mark II research reactor in Slovenia. Firstly, this paper presents the scientific background and issues of our SiC-based detectors. In a second part the 3-D geometry is shown. Thereafter, the 3-D numerical thermal simulation results are reported. Finally, the 3-D numerical radiation/matter interaction simulations results are presented.

***Keywords* —Neutron detection, silicon carbide, irradiation campaign, thermal, radiation-matter interaction, 3-D simulations.**

I. Introduction and Issues

In a nuclear reactor, either for fission or fusion applications, it is crucial to measure key parameters such as neutron and γ fluxes or nuclear heating rate for a better understanding of the behavior of nuclear fuels or materials subjected to nuclear radiation and for the monitoring of the nuclear facilities. All this places neutron detection and measurement at the heart of these scientific objectives. As the conditions in fusion and fission research reactors become more and more harsh, it is crucial to develop sensors adapted to such characteristics. For this reason, wide-bandgap semiconductors and more precisely 4H-SiC are interesting. Their main advantages are their fast response, their stability versus radiations, their high energy resolution, their ability to discriminate between neutrons and γ, their high thermal conductivity and their low semiconductor defect concentration. In addition, thermal and fast neutrons are able to be detected by adding Neutron Converter Layer (NCL) and /or by considering threshold energy reactions for this type of detectors [1-5].

At present, such SiC-based neutron detectors are studied within the framework of the LIMMEX laboratory (Laboratory of Instrumentation and Measurement Methods in EXtreme media, a joint laboratory between Aix-Marseille University and the CEA). This topic started, more precisely, with a previous joint European project, called I_SMART (Innovative Sensor for Material Ageing and Radiation Testing). The greatest achievement of this project was the development of SiC-based p^+n junction diodes with a thermal neutron converter layer with Boron-10 implantation in order to measure thermal and fast neutron fluxes.

Thermal neutron measurements with these SiC-based diodes have been achieved at MINERVE Zero Power Reactor at CEA Cadarache in France for a maximal neutron flux of around 9.4×10^{8} $n \cdot cm^{-2} \cdot s^{-1}$ including 31 % of thermal neutrons [2]. A fluence study in order to demonstrate the stability under radiation has been performed at the BR1 research reactor at Moll in Belgium for a maximum fluence of around 2.0×10^{13} $n \cdot cm^{-2}$ [3]. Afterwards, these detectors have been tested to detect 14.1 MeV fast neutrons at the Deuterium-Tritium generator of Technical University of Dresden in Germany. As a first step, the SiC-based diode signal stability has been studied to room temperature up to 500 °C with fast neutron fluxes of around 3.1×10^{7} $n \cdot cm^{-2} \cdot s^{-1}$ [4]. As a second step, the response and the energy resolution of the SiC-based diode were compared to those of a diamond-based detector purchased from CIVIDEC Instrumentation company for a neutron flux of 9.4 $\times 10^6$ $n\cdot cm^{-2}\cdot s^{-1}$ [5].

Consequently, there are three main objectives. The first aim corresponds to the increase of the measured total neutron flux: 5.5 $\times 10^{14}$ $n\cdot cm^{-2}\cdot s^{-1}$ for an energy > 1 MeV expected in the JHR core and from 10^9 $n\cdot cm^{-2}\cdot s^{-1}$ to 10^{14} $n\cdot cm^{-2}\cdot s^{-1}$ for an energy > 14.1 MeV expected in the ITER tokamak. The second aim is the increase in the irradiation duration as well as the adaptation of the housing of the detector for in-core measurements in a research reactor. The latter can be achieved by means of 3-D numerical thermal simulations and 3-D numerical simulations of radiation/matter interactions. The first kind of simulation can be used in order to evaluate the maximum temperature and the temperature fields. The second kind of simulation can provide neutron and γ fluxes and attenuation, nuclear heating rate values and other information such as the activation.

However, intermediate steps are necessary for the SiC-based detectors in order to reach these aims. A qualification of the SiC-based detector for measurements of increased neutron fluxes (especially higher than 10^{10} $n\cdot cm^{-2}\cdot s^{-1}$) with a new specific acquisition chain and nuclear-hardened instrumentation cables will be carried out during an irradiation campaign at the Jožef Stefan Institute TRIGA Mark II research reactor in Slovenia. The main characteristics of this reactor are its maximum thermal power (at steady state) i.e. 250 kW and its maximum neutron and γ fluxes at the center of the core i.e. 2.0 $\times 10^{13}$ $n\cdot cm^{-2}\cdot s^{-1}$ and 2.0 $\times 10^{13}$ $\gamma\cdot cm^{-2}\cdot s^{-1}$ respectively. The measurements will be carried out in a Triangular Irradiation Channel (TIC) which is an in-core dry air channel with natural convection (low heat transfer coefficient) and a maximum ambient temperature of around 40 °C. Another main feature of this channel is its size, as it measures almost 6 cm in diameter. The maximum total neutron flux (thermal and fast) is about 1.2 $\times 10^{13}$ $n\cdot cm^{-2}\cdot s^{-1}$, the maximum γ flux is about 1.2 $\times 10^{13}$ $\gamma\cdot cm^{-2}\cdot s^{-1}$ and an estimated nuclear heating rate through neutron and photon KERMA rate (Kinetic Energy Released per MAss unit) in Silicon lower than 0.055 $W\cdot g^{-1}$ [6]. Consequently, this paper focuses on 3-D numerical simulation studies dedicated to the definition of the most optimized device for this campaign.

In a first part, the 3-D detector geometry is shown and detailed. The latter consists of all the detector components (housing, base, diode placed on its support, connectors, screws and instrumentation cables).

In a second part, the 3-D thermal simulations realized by means of COMSOL Multiphysics finite element code are presented. The aim of these thermal simulations is to determine the maximum temperature and the temperature field inside the system and in particular in the SiC-based diode for various boundary conditions and the expected nuclear heating rate range.

In the last part, 3-D numerical simulations of interactions between nuclear radiations and matter are realized with the SiC detector inserted inside the MCNP computational model of the JSI TRIGA Mark II reactor. In order to reduce the calculation time, a simplified system as that implemented for 3-D numerical thermal simulations is used. The goal of these simulations is to estimate the neutron and γ fluxes expected inside the SiC-based diode and the KERMA rate in each part of the studied system at the vertical central position of the Triangular Irradiation Channel.

II. Detector 3-D Geometry

The studied SiC-based detector (cf. Fig. 1) is composed of three main parts. The first one is a machined housing made of Duralumin. Moreover, four fillets caused by the drill during the machining are positioned at the four inner corners of the housing. The latter induces an Air-gap located inside this housing. Finally, four Stainless Steel screws are placed on the top of the housing for the hood closing.

The second part is composed of the SiC-based diode placed on its Alumina support. Then, the latter is fixed on a base made of Duralumin and the whole assembly is maintained to the housing by means of two Stainless Steel screws in and two Alumina washers.

The last part consists in a connector made of Stainless Steel screwed on the housing by means of an inner part. Inside this connector, two sheaths pass through it corresponding to a k-type thermocouple and the two power and signal recovery wires of the SiC-based diode respectively.

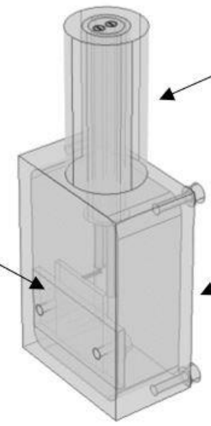

Fig. 1. 3-D schematic of the studied SiC-based detector and its three main parts.

The main dimensions are presented bellow in Table I.

TABLE I
GENERAL DIMENSIONS OF THE MAIN PARTS OF THE SiC-BASED DETECTOR

Geometrical part	Length (mm)	Width (mm)	Height (mm)	Diameter (mm)
Duralumin Housing	40	28	16.5	
Air-gap	37	25	13.5	
SiC-based diode	7	5	0.371	
Alumina support	16	14	1.0	
Duralumin base	12	25	1.5	
Stainless Steel connector (external part)	28			14
Stainless Steel connector (inner part)	36			8

The 3-D geometry given in Figure 1 is used for the 3-D thermal simulations. By against to reduce the calculation time in the case of the 3-D numerical radiation/matter interaction simulations, this 3-D geometry is simplified. The screws, washers, k-type thermocouple, SiC-based diode wires and the inner part of the connector are neglected.

III. 3-D Numerical Thermal Simulations

COMSOL Multiphysics finite element code coupled with a heat transfer module was used for this study. Regarding the considered 3-D thermal model, the heat equation is solved only by considering conductive heat transfers with thermal conductivity depending on temperature (convective and radiative exchanges are neglected inside the detector) and for the stationary state. Moreover, volumetric heat sources (Q) are applied in all parts of the detector. They depend on the material density (ρ_i) and the nuclear heating rate (E_n) value ($Q = \rho_i \cdot E_n$). The nuclear heating rate imposed is independent of the material nature. The nuclear heating rate range is considered from the literature, the range is from 0 $W \cdot g^{-1}$ to 0.055 $W \cdot g^{-1}$ [6] by steps of 0.0025 $W \cdot g^{-1}$. An extra-fine mesh was used with element sizes from 102 µm to 2380 µm. The applied boundary conditions correspond to external natural convection of dry air. The imposed temperatures of the coolant fluid (T_{fluid}) are 35 °C, 40 °C and 45 °C. The external heat transfer coefficient (h) is calculated and imposed by COMSOL Multiphysics finite element code by taking the geometry into account. Thus, four heat transfer coefficients are applied for the vertical housing walls, the lower housing wall, the upper housing wall, and the vertical cylinder of the connector. Finally, a constant heat transfer coefficient is applied on the upper surface of the connector and fixed at 2 $W \cdot m^{-2} \cdot K^{-1}$.

A. Boundary conditions influence

The nuclear heating rate influence on the external heat transfer coefficient has been studied for a dry air temperature equal to 40 °C for the complete 3-D detector (cf. Fig. 2). As shown, there is an increase in the heat transfer coefficient value with the nuclear heating rate. In fact, the increase in nuclear heating rate leads to higher wall temperatures which induce an increase of the thermal exchanges and thus the heat transfer coefficient values.

Moreover, as shown in Figure 2, the heat transfer coefficient values calculated by COMSOL Multiphysics code are coherent with those obtained by using correlations of the literature (from 5 $W \cdot m^{-2} \cdot K^{-1}$ to 25 $W \cdot m^{-2} \cdot K^{-1}$).

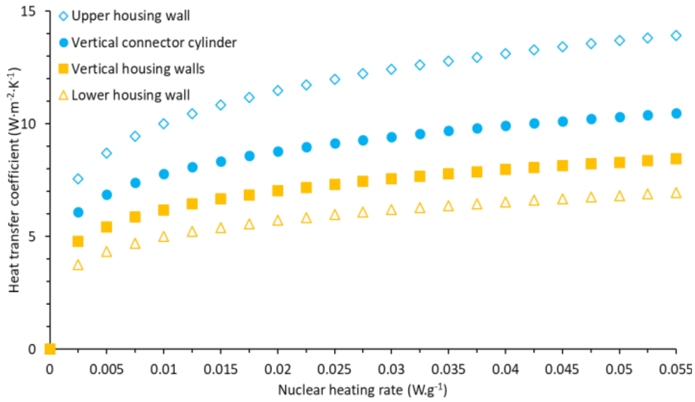

Fig. 2. Various heat transfer coefficient values calculated by COMSOL as a function of the nuclear heating rate for a fluid temperature of 40°C.

B. Nuclear heating rate influence on the maximum temperature

The nuclear heating rate influence on the maximum temperature and the temperature field has been studied in order to observe the thermal behavior of the complete SiC-based detector.

As expected, the maximum temperature is obtained under the highest extreme conditions: a nuclear heating rate value of 0.055 $W \cdot g^{-1}$ and a fluid temperature of 45 °C, giving rise to the maximal value of around 110 °C. For an expected fluid temperature of 40 °C and a maximum nuclear heating rate value, the maximum reached temperature is around 105 °C. These values are much lower than the Duralumin melting point i.e. around 600 °C. Concerning the SiC-based diode temperature, the obtained values are about 99 °C and 104 °C for fluid temperatures of 40 °C and 45 °C respectively. Thus, these obtained temperatures allow the use of standard Tin alloys welding for the SiC-based diode connection and wiring (melting point between 180 °C and 200 °C).

Regarding the thermal behavior of the SiC-based detector and as shown in Figure 3, the highest temperature is reached inside the connector. This behavior is confirmed whatever the imposed nuclear heating rate (cf. Fig. 3). In fact, the latter is induced by the low heat transfer coefficient value applied on the upper surface of the connector, and by a high energy deposited inside this part due to the high density of the used material i.e. Stainless Steel ($\rho = 7850$ $kg \cdot m^{-3}$).

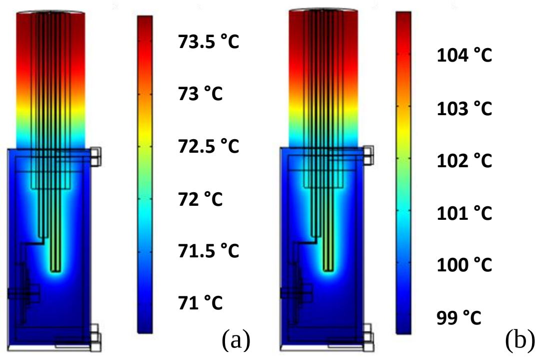

Fig. 3. Vertical cross section of the complete 3-D detector for nuclear heating rate values of 0.025 $W \cdot g^{-1}$ (a) and 0.055 $W \cdot g^{-1}$ (b) and a fluid temperature of 40 °C.

C. Comparison of the thermal behavior of the two geometries

As explained above, in order to gain time for the 3-D numerical radiation/matter interaction simulations, a simplified geometry has been designed. In order to check if any thermal differences are induced, a comparison with the same parameters than those used for the complete detector geometry was performed. The same thermal behavior was observed (cf. Fig. 4) for the two detectors and the most part of the heat is deposited in the connector. The geometry simplification leads to a very low difference of maximum temperature: -2.3 °C for a nuclear heating rate value of 0.055 W·g^{-1} and a fluid temperature of 40 °C. Moreover, the lower the condition values are, the lower the maximum temperature difference is. In fact, the geometry reduction leads to a lower mass of the SiC-based detector which induces a lower energy deposition and thus a lower temperature. As a conclusion, this simplified geometry can be used for the 3-D numerical radiation/matter interaction simulations since no significant thermal differences have been found.

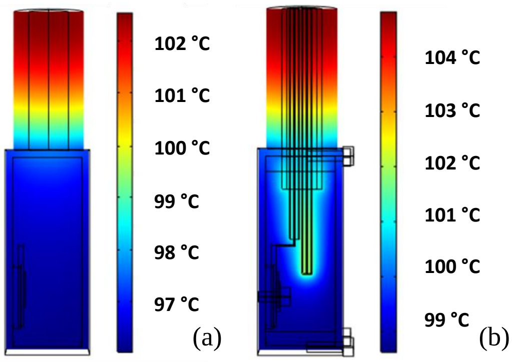

Fig. 4. Vertical cross section of the simplified 3-D detector (a) and the complete 3-D detector (b) for a nuclear heating rate value of 0.055 W·g^{-1} and a fluid temperature of 40°C.

IV. 3-D Numerical Radiation/Matter Interaction Simulations

Monte-Carlo N-Particle transport (MCNP) code [7] was used in order to estimate the prompt neutron and γ deposited energy with KERMA in all cells of the simplified geometry of the SiC-based detector (F6 tally in MeV·g^{-1}) and the prompt neutron and γ fluxes in the SiC-based diode (F4 tally in 1·cm^{2}) at different power level. Thus, this SiC-based detector geometry was built using MCNP6 code and then inserted inside the MCNP computational model of the JSI TRIGA Mark II reactor. More precisely, the detector was simulated inside the TIC at the center of the channel i.e. the middle axial position. For these simulations, the ENDF/B-VII.0 cross-section nuclear data library at 297.15 K was also used.

A. Prompt neutron and γ KERMA values

Nuclear heating rate can be estimated by the KERMA which is defined as the sum of the initial kinetic energies of all the charged particles liberated by the uncharged ionizing radiation i.e. the neutrons and photons. The track length F6 tally with a neutron–photon coupled mode (NP mode) was also used in order to obtain the sum of the KERMA induced by prompt neutrons and the one induced by prompt photons (γ). As projected, the maximal KERMA values are obtained at the maximal reactor thermal power i.e. 250 kW (cf. Table II). Moreover, the obtained values are coherent with the literature i.e. 0.055 W·g^{-1} [6]. The statistical uncertainties are lower than 0.3 %, except the one for SiC-based diode slightly higher and equal to 0.54 %. The small size of the latter and the low calculation time (1.51×10^{12} particles are considered) can explain this value which is not so high for this first study.

These values will be used for future more accurate 3-D thermal simulations by considering a nuclear heating rate value depending on the detector part.

Table II
Calculated KERMA Values For Various Reactor Thermal Powers

	Prompt Neutron and Photon KERMA Values (W·g^{-1})		
Geometrical part/Reactor power level	50 kW	150 kW	250 kW
Duralumin Housing	0.008	0.023	0.039
SiC-based diode	0.009	0.028	0.046
Alumina support	0.009	0.027	0.045
Duralumin base	0.008	0.025	0.042
Stainless Steel connector	0.010	0.029	0.048

B. Prompt neutron and γ fluxes in the SiC-based diode

In order to prepare our irradiation campaign, prompt neutron and γ fluxes in the SiC-based diode have been calculated in order to work on the writing of a first operating protocol. Indeed, as explain on the first section, the SiC-based diode has to be qualified for the measurement of increasing neutron fluxes, especially fluxes higher than 10^{10} n·cm^{-2}·s^{-1}. Thus, these results can provide interested information concerning the necessary reactor thermal power needed to measure a precise neutron flux or to calculate the measurement time in order to reach a targeted neutron fluence. As shown in Table III, the increase in the prompt particle flux varies constantly when the reactor thermal power increase. As expected, the maximal fluxes are obtained at full reactor thermal power i.e. 250 kW. Thus, the obtained maximum prompt neutron flux is 9.94×10^{12} n·cm^{-2}·s^{-1} and the obtained maximum prompt γ flux is 1.06×10^{13} γ·cm^{-2}·s^{-1}. Concerning the uncertainties, they are equal to 0.5 % for the prompt photons and 0.31 % for the prompt neutrons.

Table III
Calculated Neutron And γ Fluxes For Various Reactor Thermal Powers Inside The SiC-Based Diode

	Prompt Neutron and Photon Fluxes (particle·cm^{-2}·s^{-1})		
Kind of particle/Reactor power level	10 W	1 kW	100 kW
Prompt neutrons	3.98E+08	3.98E+10	3.98E+12
Prompt γ	4.25E+08	4.25E+10	4.25E+12

V. Conclusions and Outlooks

Thanks to the 3-D thermal simulations and 3-D radiation/matter interaction simulations, various conclusions were obtained for a future qualification of the SiC-based detector in the JSI TRIGA Mark II reactor. For the 3-D numerical thermal simulations, firstly the heat transfer coefficient values calculated by COMSOL are coherent with those estimated by using correlations of the literature. Moreover, the maximum SiC-based detector temperature is around 110 °C under the highest extreme boundary conditions (maximum nuclear heating rate and coolant fluid temperature). This value is much lower than Duralumin melting point even with a safety margin and permits the use of standard Tin alloys welding for the SiC-based diode connection (melting point between 180 °C and 200 °C). Afterwards, the most part of the heat is deposited in the connector and in order to reduce its temperature a material with a lower density could be used or a smaller connector could be designed. Finally, the low temperature difference of the SiC-based diode obtained between the two geometries has permitted the use of the simplified geometry for MCNP code simulations. Thus, the first preliminary results of the 3-D numerical simulations of radiation/matter interactions confirm the right nuclear heating rate range used for the 3-D thermal simulations. In spite of a short calculation time (due to a low number of particles considered), the maximum uncertainty is 0.54 % and majority are below 0.3 % and are satisfying for first results. Lastly, the estimation of the neutron flux for several reactor powers give us an idea of the future irradiation campaign conditions targeted to test our SiC-based detector.

Regarding the outlooks, about the 3-D numerical simulations of radiation/matter interactions, the key values will be calculated through the complete 3-D geometry of the detector for different axial positions inside the TIC, for various reactor powers or in another irradiation channel. Moreover, the integration of another estimator for nuclear heating rate calculations could be made. In fact, the electron energy deposition in matter (*F8:E pulse height tally with MCNP code) could be used in order to estimate the nuclear heating rate and not only the KERMA as performed in this paper. The neutron activation of the materials which compose the detector is another interesting parameter in particular for long time experiments. Afterwards, the use of the real detector geometry and assembly with the screws, washers, thermocouple, wires and maybe a new connector can be also interesting to study when considering a longer calculation time. For the 3-D numerical thermal simulations, new heat sources can be applied by considering the MCNP code results leading to a maximum temperature and temperature field comparison. The integration of radiative and convective heat transfers can be also a great opportunity in order to consider a more accurate model.
Furthermore, the optimized detector will be tested during an irradiation campaign at the JSI TRIGA Mark II reactor in the last quarter of 2021.

To conclude, within the framework of the LIMMEX laboratory, the great results previously obtained have led to study a new measurement device by coupling a non-adiabatic calorimeter to a SiC-based neutron detector for measuring nuclear heating rate and neutron fluxes (thermal and/or fast) in a research reactor core simultaneously [8-9].

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