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To cite this article: Matteo Hakeem Kushoro *et al* 2025 *Meas. Sci. Technol.* **36** 125901

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Measurement Science and Technology
Meas. Sci. Technol. **36** (2025) 125901 (9pp)
https://doi.org/10.1088/1361-6501/ae2536

Fast neutron spectroscopy with 4H-SiC solid-state detectors up to 500 °C for nuclear fusion applications

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Received 29 August 2025, revised 12 November 2025
Accepted for publication 27 November 2025
Published 9 December 2025

Abstract

Silicon carbide (SiC)-based detectors offer exceptional radiation hardness and thermal stability, making them suitable for neutron spectroscopy in fusion reactor environments, which are characterized by high temperatures and intense neutron fluxes. In this study we demonstrate a 250 μm-thick 4 H-SiC p–n junction detector that maintains stable deuterium–tritium neutron detection performance across the full temperature range from 25 °C to 500 °C, thereby overcoming the limitations commonly encountered with diamond-based detectors. These results highlight the potential of thick SiC detectors for monitoring neutron flux and performing neutron spectroscopy in harsh environments, such as the breeding blanket of fusion reactors.

Keywords: silicon carbide, neutron detectors, neutron spectroscopy, high-temperature radiation detectors, tokamak technologies, fusion diagnostics

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1. Introduction

The advancement of fusion technologies, driven both by public and private initiatives, is generating increasing interest in neutron diagnostics capable of operating under the extreme conditions typical of fusion machines. In the view of a fusion power plant, particular attention is given to the breeding blanket (BB), designed to produce the tritium required to fuel the fusion plasma. Tritium is generated through interactions between plasma-emitted neutrons and lithium isotopes, via nuclear reactions as ^{6}Li(n,α)T or ^{7}Li($n,\alpha + n$)T. Accurate monitoring of neutron flux and energy inside the BB is therefore crucial for assessing the tritium production rate, validating numerical models, optimizing the tritium breeding cycle, and ensuring the safe operation and maintenance of fusion reactors. To meet these requirements, compact neutron detectors are needed that can fit within tight geometrical constraints, while withstanding neutron fluxes up to $10^{14}\,\frac{n}{s\cdot cm^2}$ at operating temperatures of 300 °C–500 °C [1–3]. Exceptional thermal stability and radiation hardness are therefore essential for neutron detectors in industrial fusion reactors.

Diamond detectors currently represent the state of art for neutron spectroscopy in fusion-relevant conditions. They feature solid and compact active volumes with excellent radiation hardness and low sensitivity to gamma radiation, making them suitable for neutron measurements in both fusion and particle physics applications [4, 5]. Their effectiveness as neutron spectrometers has been demonstrated in deuterium–tritium (DT)-dominated environments [6–10]. However, diamond detectors suffer from significant performance degradation at high temperatures (250 °C–300 °C), primarily due to thermal effects such as increased leakage current and reduced charge collection efficiency [11–13], which severely limits their applicability in high-temperature environments.

In recent years, 4 H silicon carbide (SiC) detectors have emerged as a promising, cost-effective alternative to diamond detectors for operations in harsh nuclear environments [4, 5]. This is due to their high displacement threshold energy (20–35 eV) and wide bandgap (3.27 eV) [14]. Their suitability as neutron flux monitors has been demonstrated in multiple experimental campaigns [15–18], and their radiation hardness has been verified under both heavy ions [19, 20] and neutron irradiation [21, 22]. SiC detectors have also shown potential for spectroscopic applications, with successful demonstrations involving both neutron and other radiation sources [23–28], including prospective applications on tokamak devices [29]. High temperature operation was also achieved [27, 28, 30–34], although a loss in detection quality was observed with thin active volumes (<100 μm).

In a previous work we demonstrated that 250 μm-thick SiC detectors can maintain stable detection performance up to 250 °C [35]. Building on this work, the present study extends the investigation to evaluate the spectroscopic performance of a 250 μm-thick 4 H-SiC p–n junction detector, developed within the framework of the 'Ettore Majorana' Eni-CNR Joint Research Centre, at temperatures up to 500 °C.

The paper is structured as follows: section 2 describes the sensor and experimental setup. DT neutron spectroscopy, carried out at the Frascati neutron generator (FNG) facility, is detailed in section 3. Final considerations and perspectives on the application of SiC detectors in harsh environments are discussed in section 4.

2. Experimental setup

2.1. Sensor design and fabrication process

The 4 H-SiC p^+–n^- detector considered in this work was fabricated by the CNR Institute for Microelectronics and Microsystems [36, 37], as part of the 'Ettore Majorana' Eni-CNR Joint Research Centre. The device structure consists of a 250 μm thick active epitaxial layer grown on a commercially available, 350 μm-thick, $< 0001 > 4°$ off-axis n^{++} 4 H-SiC epitaxial wafer. A 5 μm thick n^+ buffer layer was included to mitigate defects originating from the substrate. The low-doped n-type epilayer has a 250 μm thickness and a doping concentration of $n_D = 7 \times 10^{13}$ cm^{-3}. It was deposited by chemical vapor deposition using a horizontal hot-wall reactor (ASM PE106), Ethylene as carbon source, trichlorosilane as a chlorinated silicon source, and nitrogen as n-type dopant. The deposition was carried out at a temperature of 1650 °C under a chamber pressure of 100 mbar. The highly doped ($n_p = 2 \times 10^{18}$ cm^{-3}) 0.3 μm-thick p^+ layer was formed via ion implantation. The p^- and n^+ implanted regions were designed to implement a junction termination extension and a field stop structure, respectively. Nickel was deposited and subjected to a silicidation process, forming a nickel silicide in the contact regions to reduce contact resistance. Unreacted nickel on the oxide was then removed by etching. The cathode contact was completed by depositing 1 μm thick aluminum (Al) layer. A silicon dioxide (SiO_2) layer was deposited on top of the device to provide electrical insulation. Finally, the device was passivated with a 7 μm thick polyimide layer, capable of withstanding temperatures up to 350 °C. A picture of the devices, along with a technical drawing of its structure, is reported in figure 1. The device used in this paper had an area of 25 mm^2 and was manufactured from the same wafer as the device used in [35].

2.2. Electronics and heating system

Neutron spectroscopy was performed adapting the setup originally described by Angelone *et al* [11] and subsequently employed in [35]. Electrical connection to the SiC device was achieved via mechanical contact, using a stainless-steel support to press the detector against a mineral-insulated (MI) cable, which served both as the high-voltage supply and signal transmission line. The low-noise MI cable, manufactured by Thermocoax, was rated for operation up to 1200 °C. A schematic of the setup with pictures of the MI cable, support and oven are shown in figure 2.

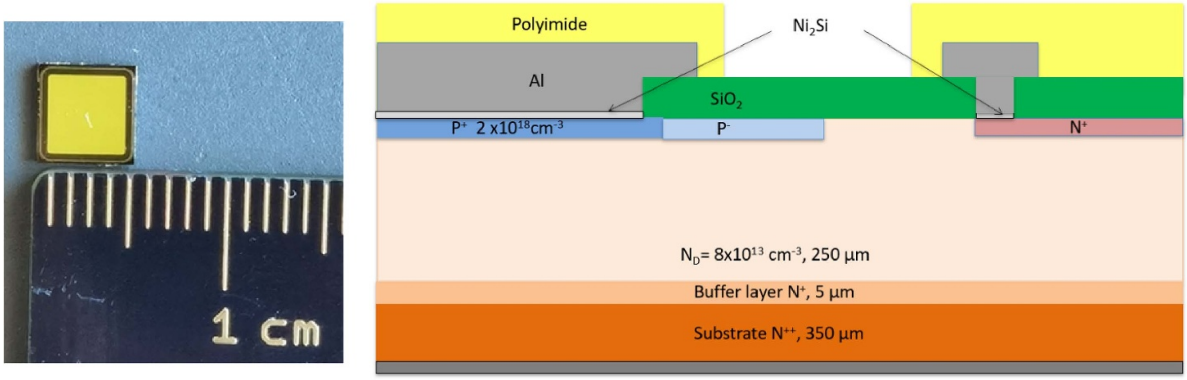

Figure 1. (Left) macroscopic image of the 4 H-SiC p^{+}–n^{-} detector, fabricated by the CNR institute for microelectronics and microsystems in the framework of the 'Ettore Majorana' Eni-CNR Joint Research Centre The area of the device is 25 mm^2.The device is presented with a reference scale. (Right) Schematic (not-to-scale) technical representation of the sensor structure.

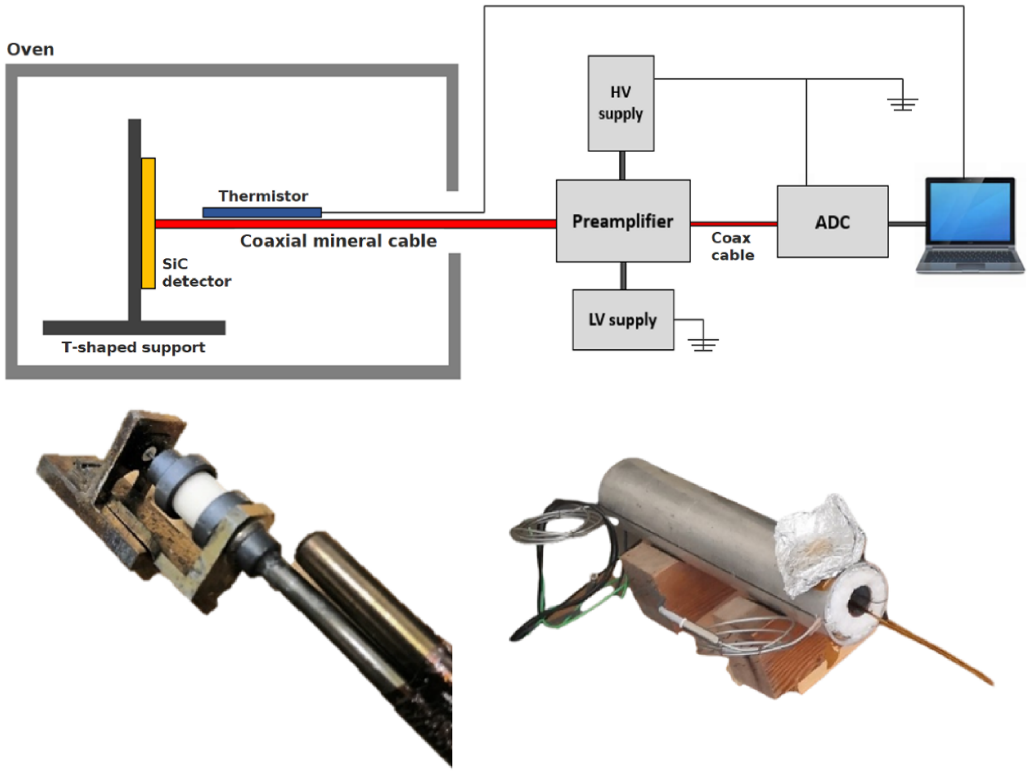

Figure 2. Top: schematic representation of the experimental setup for high temperature spectroscopy. Bottom left: SiC active volume mounted on the T-shaped support, secured by the tip at the end of the mineral cable. The T-shaped support was connected to the ground voltage, while the thermistor monitored the temperature inside the oven in figure 2(a). The entire apparatus was enclosed in a copper envelope to act as a Faraday cage, shielding the SiC detector from electromagnetic noise. A secondary Kapton envelope was used to insulate the copper envelope from the metallic components of the oven, preventing electrical contact. Bottom right: picture of the cylindrical heating system. The mineral cable and the thermistor cable are inserted into the opening in the right face of the cylinder. The insulating material is shown in white.

Neutron irradiations were carried out at the FNG, using a customized Cividec CX-L preamplifier. The preamplifier features an AC coupled bipolar input and a ± 1 V output with a shaping time of 107 ns (FWHM). The amplified signal was digitized with a 500 MHz, 14-channel CAEN 5730 analog-to-digital converter. A 200 V voltage was chosen as an input bias as a compromise between achieving a substantial depletion and avoiding detection instabilities demonstrated at higher voltages in the past [38], resulting in relatively small currents (<5 µA) at all temperatures.

Temperature control was provided by an insulated cylindrical ohmic heating system operating in air, equipped with

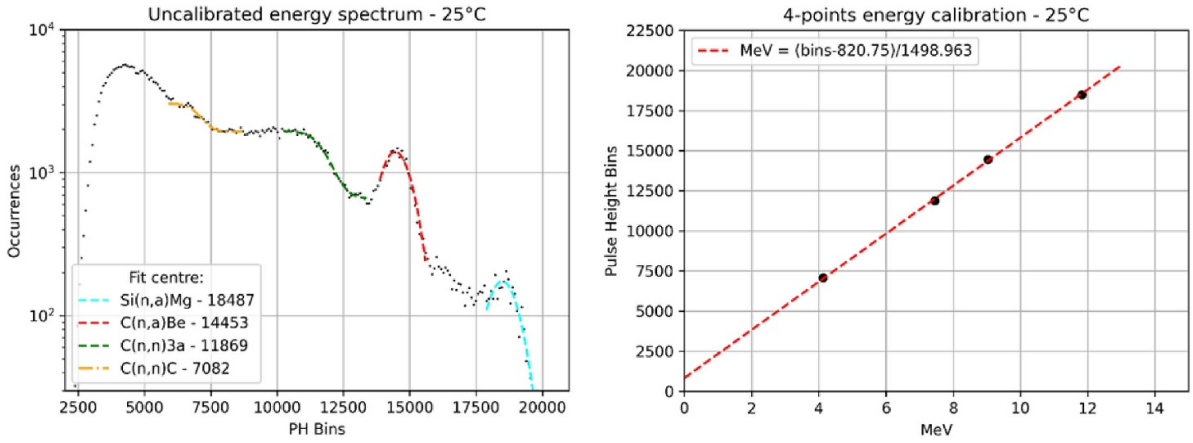

Figure 3. Exemplificative calibration process of a PH spectrum. The four most important spectral features are identified in the uncalibrated spectrum (left image) and fitted with a Gaussian (in the case of ^{28}Si(n,α)^{25}Mg and ^{12}C(n,α)^{9}Be) or a step function convoluted to a Gaussian (in the case of ^{12}C(n,3α) and elastic scattering on carbon ^{12}C(n,n)^{12}C). The center of the fit is then compared with the expected E_d value, obtained as a difference between E_n and the Q_{value} of the specific reaction. From the comparison a linear correlation between the PH value and the correspondent E_d is obtained (right image).

a thermistor and a PID feedback temperature controller, ensuring stability within ± 1.0 °C throughout the measurements.

3. Experiment: HT neutron irradiation

The effect of temperature on neutron detection properties has been investigated by performing DT neutron spectroscopy at the FNG [39]. The DT source produced neutrons on the entire solid angle with a rate between $5 \cdot 10^9$ and $4 \cdot 10^{10}$ n s^{-1}. The neutron rate was measured by FNG by measuring the 3.6 MeV α particle generated by the D(T,α)n fusion reaction, providing a reading with $\pm 3\%$ uncertainty [40]. The flux of neutrons through the detector volume was then estimated by taking into account the 20 cm distance between the source and the detector, resulting in a mean intensity between $2.5 \cdot 10^4$ and 10^5 n s^{-1}. Since the detector was positioned at 30° relative to the deuterium beam, the neutron spectrum was centered at $E_n = 14.73$ MeV with a full width half-maximum (FWHM) of 0.49 MeV [41]. In order to compare the spectra, the duration of most irradiations was set to achieve the same number of neutrons produced by the source ($=10^{13}$), resulting in irradiations being between 10 and 30 min long. Two irradiations (the one at RT and the one at 500 °C) were an exception to this: to correct this, the number of counts of the two spectra were multiplied by a normalizing factor equal to the ratio between the standard fluence ($=10^{13}$) and the fluence measured by the alpha detector for the irradiation.

The detector was tested from room temperature (RT) up to the heating system's operational limit of 500 °C. The detected events were recorded as pulse height spectra (PHS). Each PHS was calibrated in energy by identifying the characteristic peaks of known nuclear reactions on SiC (^{28}Si(n,α)^{25}Mg, ^{12}C(n,α)^{9}Be, ^{12}C(n,n)3α and the elastic scattering on carbon), as shown in figure 3. This allowed the conversion of PHS into deposited energy (E_d) spectra [42]. The calibrated spectra are shown in figure 4.

The stability of the SiC detector's spectroscopic performance to 14 MeV neutrons was quantified by evaluating the variation of its response function (PHS), energy resolution (ϵ) and efficiency (e). The response function, describing the relationship between pulse height and deposited energy E_d, was obtained from the calibration process, while ϵ and e were derived from the standard deviation (σ) and amplitude of the ^{12}C(n,α)^{9}Be peak modeled with a Gaussian function. The Gaussian[11] fit was performed through a Markov Chain Monte Carlo (MCMC) method. In particular:

- The response function was monitored via the uncalibrated centroid position of the Gaussian fitting the ^{12}C(n,α)^{9}Be peak.
- The energy resolution ϵ was calculated as the ratio between the FWHM of the fit and the neutron energy E_n [43]:

$$\epsilon = \frac{\text{FWHM}}{E_n} = \frac{\sqrt{2 \cdot \ln(2) \cdot \sigma}}{E_n}.$$

- The efficiency e was derived from the area A_f:

$$A_f = \sqrt{2\pi} \cdot a \cdot \sigma.$$

With a being the amplitude of the Gaussian.

For each spectrum, the MCMC Gaussian fits were performed over a variable channel range centered around the peak data maximum ($E_{\text{peak, max}}$), covering all energy-equivalent channel combinations within the interval ($E_{\text{peak, max}} \pm 1.5$ MeV),

[11] The trade-off between data fitting and model complexity, assessed through AIC and BIC criteria, identified the Gaussian model as the most suitable for fitting the ^{12}C(n,α)^{9}Be peak. Nevertheless, MCMC fits were also performed using Lorentzian e Voigt profiles (two commonly adopted alternatives in spectroscopy), to ensure the selection of the most appropriate model to capture the specific characteristics of the experimental peak.

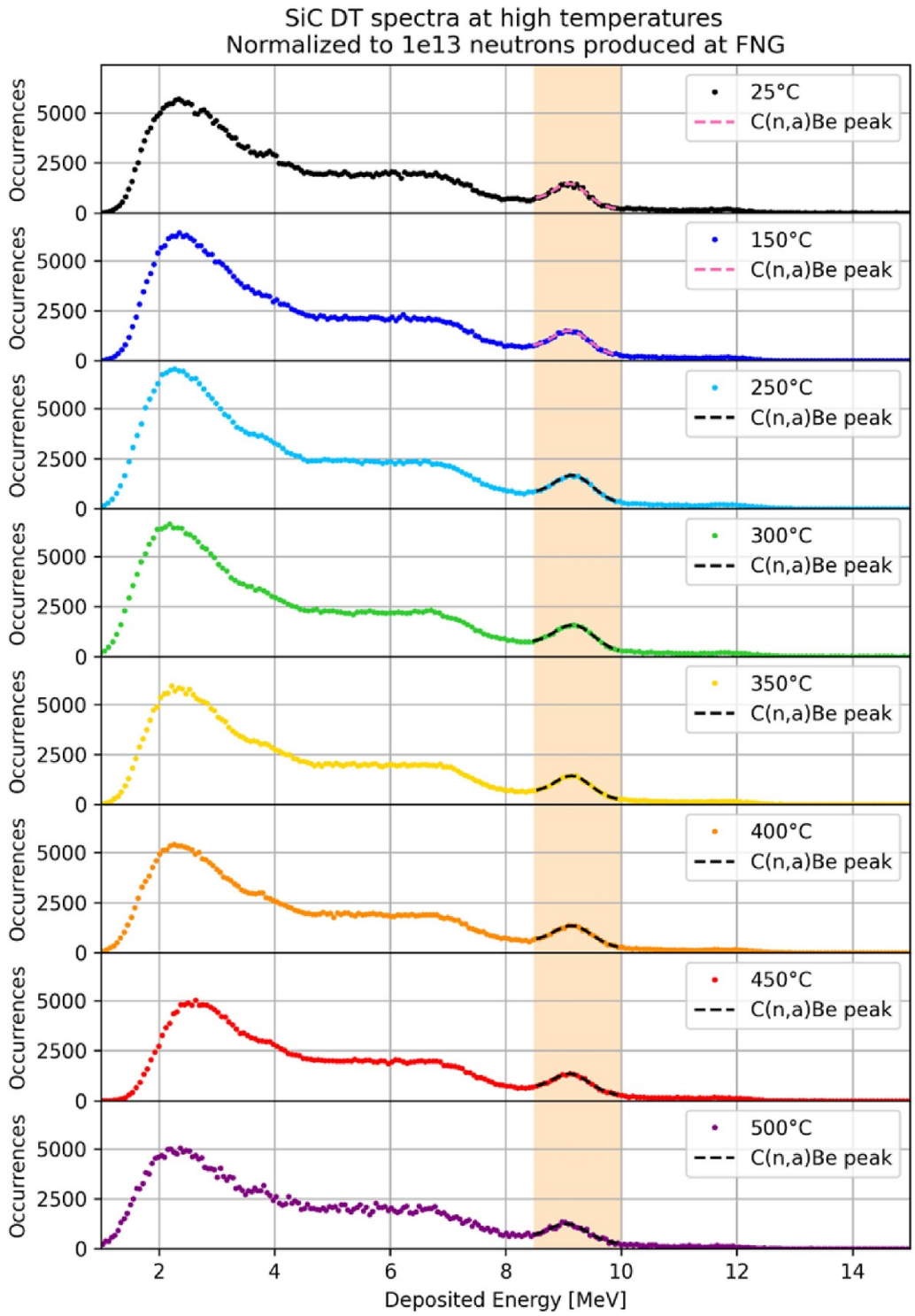

Figure 4. Calibrated E_d spectra of SiC irradiated at FNG by 14.73 MeV DT neutrons at various temperatures between 25 °C and 500 °C. The $^{12}C(n,\alpha)^{9}Be$ peak is highlighted in figure, along with its Gaussian fit. The amplitude and standard deviation of such fit are then used to measure the detection properties of the detector in figure 5.

with a step size of 0.1 MeV. The final values of the spectroscopic parameters for each temperature were then calculated as weighted means of the results obtained across all the spectra analyzed in the interval, with weights based on the statistical significance of each fit. Uncertainties on the number of counts (N) were estimated as the Poissonian term $\sqrt{N}$ plus a systematic 3% contribution, accounting for the intrinsic neutron emission uncertainty of the FNG facility [41].

The temperature dependence of the SiC detector characteristics, along with their associated uncertainties, is shown in figure 5. Data were fitted using a linear model, and both

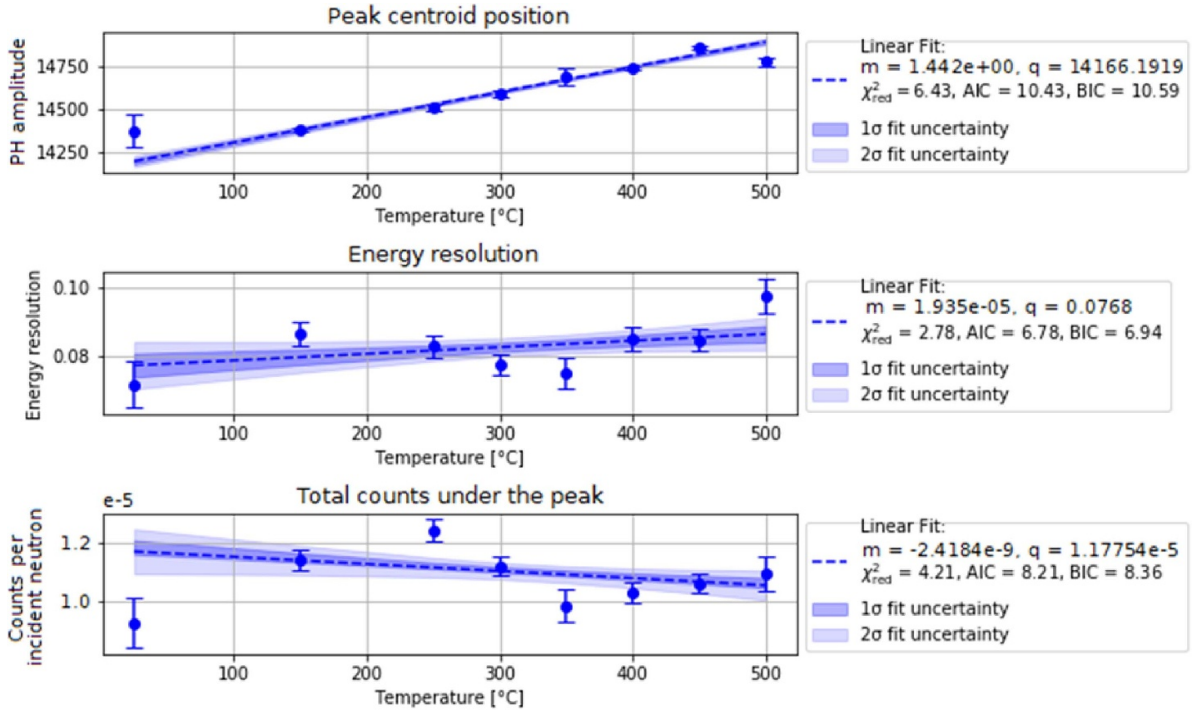

Figure 5. Analysis of dependence of spectroscopic parameters on the working temperature, obtained by MCMC Gaussian fitting.

1σ and 2σ confidence intervals are reported. As shown in the figure, both energy resolution and total counts for the $^{12}C(n,\alpha)^9Be$ peak remain constant across the investigated temperature range. This behavior was confirmed by a statistical hypothesis testing, using the null hypothesis $m = 0$ (i.e. no temperature dependence). Some data points measuring the total number of counts under the peak (more specifically, RT and 250 °C) show significant deviation from the fitting, being more than 2σ away from the fit value. Such deviations do not match with the experiment performed in the past [35], thus suggesting that the source of the deviation is due to an underestimation of the setup errors rather than some property of the SiC itself. More experiment in the future with a different setup should be conducted to assess the nature and eliminate the large dispersion in the data.

It should be noted that the measured energy resolution value (7%, 3% at RT) is much higher than the energy resolution achieved in the past on other similar SiC detectors (ranging from 2% to 3% for 14 MeV neutrons [23, 27, 44]). This is due to the setup not being optimized for energy resolution: the non-monochromatic neutron flux at the detector position, the presence of the oven very near the detector, the absence of welding and the electrical contacts not optimized for high temperature all contributing all contributed to worsen the energy resolution. As such, the value of the energy resolution should not be interpreted as an accurate prediction of a future SiC spectrometer, but rather as a mean to study the dependence of the energy resolution to temperature.

The centroid position, instead, exhibits a slightly positive linear trend which is incompatible with the null hypothesis $m = 0$, indicating an increase in pulse-height signal with temperature for a fixed deposited energy. This behavior is attributed to the temperature-dependent reduction in the average electron–hole pair creation energy in 4 H-SiC, as previously reported in [27, 28].

The maximum observed centroid shift, obtained from the difference between the highest and lowest Gaussian centroid values (at 450 °C and 25 °C), corresponds to an E_d variation of 300 ±35 KeV. This represents 2.0% of the nominal neutron energy ($E_n = 14.7$ MeV), a value comparable to the best reported SiC detectors energy resolution values (∼2% @14 MeV) [27, 44]. Nevertheless, the linearity of the centroid shift, together with the characteristic spectral shape, enables straightforward calibration adjustment to compensate for the response function drift.

4. Conclusions and outline

This study, conducted within the framework of Eni-CNR Joint Research Centre 'Ettore Majorana', investigated the performance of a 4 H-SiC-based fast neutron detector under high-temperature conditions, extending previous work [35] to fusion power plant relevant temperatures up to 500 °C.

A 250 μm-thick SiC detector was tested with DT neutrons from the FNG across a temperature range of 25 °C–500°C. The results show that, when coupled with MI cables and heat-resistant junctions, the detector maintains stable neutron detection performance up to 500 °C. Both the peak area and energy resolution remain constant with temperature, while

the response function exhibits a small linear drift (corresponding to a 318 keV shift in the main spectral feature from RT to 500 °C) which can be compensated to preserve detection accuracy. Data (especially those linked to the number of counted neutrons) also presents significant dispersions around the mean, suggesting that the measurement setup should be improved in the future. In response, an optimized 250 µm 4 H-SiC device is currently under development within the ongoing research activities at the Eni-CNR Joint Research Centre. The new design includes improved doping profiles, edge structures and enhanced high-temperature-compatible components.

The results presented here represent a significant step forward in high-temperature neutron detection. The robust observed detection properties indicate that, when coupled with suitable electronics, SiC detector can operate effectively under harsh thermal conditions, reinforcing the potential for SiC detectors as a promising solution to fill the current technological gap in high-temperature neutron spectroscopy. Applications may include test blanket modules (TBMs) and future tokamak BBs, where operational temperatures exceed 300 °C. Before the SiC could prove to be a definitive solution for TBMs neutron detection, though, more studied should be conducted on the SiC-especially for evaluating the performance of the detector under the unprecedentedly high levels of fast neutron irradiation, which might alter the performance of it due to neutron damage. A comparative study with diamond detectors and other means of neutron detection should be performed in the future combining extreme fluencies (10^{14} n cm^{-2} and more) and high temperatures (300 °C–500 °C) to obtain a final assessment on the performance of the SiC in fusion near-plasma environments.

Beyond nuclear fusion, SiC detectors may also prove valuable in other fields requiring fast particle detection in extreme environments, such as spent nuclear fuel monitoring [45, 46], aerospace industry and high-energy physics experiments.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Acknowledgment

This study was conducted as part of the Joint Research Agreement between Eni and CNR (Linea 5). The authors gratefully acknowledge ENEA Frascati for providing access to the FNG facility which was instrumental in carrying out this research. Special thanks are extended to Antonio Trotta, Miriam Parisi and Laura Meda (ENI/TECH/DE-R&D/NOLAB/C) for their invaluable support and contributions to the 'Linea 5' activities. The authors also wish Laura Meda all the best in her retirement and express their deep appreciation for her dedication over the years. Authors Daniele Torsello and Francesco Laviano also acknowledge support from Eni SpA.

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References

[1] Giancarli L M *et al* 2014 Tritium and heat management in ITER test blanket systems port cell for maintenance operations *Fusion Eng. Des.* **89** 2088–92
[2] Federici G, Boccaccini L, Cismondi F, Gasparotto M, Poitevin Y and Ricapito I 2019 An overview of the EU breeding blanket design strategy as an integral part of the DEMO design effort *Fusion Eng. Des.* **141** 30–42
[3] Giancarli L M *et al* 2012 Overview of the ITER TBM program *Fusion Eng. Des.* **87** 395–402
[4] Angelone M and Verona C 2021 Properties of diamond-based neutron detectors operated in harsh environments *J. Nucl. Eng.* **2** 422–70
[5] Griffin S M, Hochberg Y, Inzani K, Kurinsky N, Lin T and Yu T C 2021 Silicon carbide detectors for sub-GeV dark matter *Phys. Rev. D* **103** 075002
[6] Rigamonti D *et al* 2018 Neutron spectroscopy measurements of 14 MeV neutrons at unprecedented energy resolution and implications for deuterium-tritium fusion plasma diagnostics *Meas. Sci. Technol.* **29** 045502
[7] Rebai M, Giacomelli L, Milocco A and Gorini G 2016 Neutron emission spectroscopy of DT plasmas at enhanced energy resolution with diamond detectors *Rev. Sci. Instrum.* **87** 11D822
[8] Cazzaniga C *et al* 2014 A diamond based neutron spectrometer for diagnostics of deuterium-tritium fusion plasmas *Rev. Sci. Instrum.* **85** 11E101
[9] Rigamonti D *et al* 2024 The single crystal diamond-based diagnostic suite of the JET tokamak for 14 MeV neutron counting and spectroscopy measurements in DT plasmas *Nucl. Fusion* **64** 016016
[10] Tardocchi M *et al* 2022 A high-resolution neutron spectroscopic camera for the SPARC tokamak based on the jet European torus deuterium-tritium experience *Rev. Sci. Instrum.* **93** 113512
[11] Angelone M *et al* 2020 Systematic study of the response of single crystal diamond neutron detectors at high temperature *J. Instrum.* **15** P03031
[12] Kumar A, Kumar A, Topkar A and Das D 2017 Prototyping and performance study of a single crystal diamond detector for operation at high temperatures *Nucl. Instrum. Methods Phys. Res. Sect. A* **858** 12–17
[13] Steinegger M *et al* 2015 High-temperature characteristics of charge collection efficiency using single CVD diamond detectors *Nucl. Instrum. Methods Phys. Res. A* **789** 50
[14] De Napoli M *et al* 2022 SiC detectors: a review on the use of silicon carbide as radiation detection material *Front. Phys.* **10** 898833
[15] Obraztsova O, Ottaviani L, Klix A, Döring T, Palais O and Lyoussi A 2018 Comparison between silicon-carbide and diamond for fast neutron detection at room temperature *EPJ Web Conf.* **170** 08006
[16] Flaspoehler T and Petrovic B 2020 Radiation environment in the I2S-LWR concept: part I—Radial distribution and its impact on vessel fluence, neutron detectors placement, and radial reflector gamma heating *Ann. Nucl. Energy* **145** 106272
[17] Ruddy F H, Dulloo A R and Seidel J G 1999 Demonstration of an SiC neutron detector for high-radiation environments *IEEE Trans. Electron Devices* **46** 567-71
[18] Kandlakunta P, Tan C, Smith N, Xue S, Taylor N, Downing R G, Hlinka V and Cao L R 2020 Silicon carbide detectors for high flux neutron monitoring at near-core locations *Nucl. Instrum. Methods Phys. Res. A* **953** 163110
[19] Hrubčín L, Gurov Y B, Zaťko B, Ivanov O M, Mitrofanov S V, Rozov S V, Sandukovsky V G, Semin V A and Skuratov V A 2018 A study of the radiation hardness of Si and SiC detectors using a Xe ion beam *Instrum. Exp. Tech.* **61** 769–71
[20] Altana C *et al* 2023 Radiation damage by heavy ions in silicon and silicon carbide detectors *Sensors* **23** 6522
[21] Kushoro M H *et al* 2021 Detector response to D-D neutrons and stability measurements with 4H silicon carbide detectors *Materials* **14** 568
[22] Dulloo A R, Ruddy F H, Seidel J G, Adams J M, Nico J S and Gilliam D M 2003 The thermal neutron response of miniature silicon carbide semiconductor detectors *Nucl. Instrum. Methods Phys. Res. A* **498** 415–23
[23] Kushoro M H *et al* 2020 Silicon carbide characterization at the n_TOF spallation source with quasi-monoenergetic fast neutrons *Nucl. Instrum. Methods Phys. Res. A* **983** 164578
[24] Rebai M *et al* 2019 New thick silicon carbide detectors: response to 14 MeV neutrons and comparison with single-crystal diamonds *Nucl. Instrum. Methods Phys. Res. A* **946** 162637
[25] Bertuccio G and Casiraghi R 2003 Study of silicon carbide for x-ray detection and spectroscopy *IEEE Trans. Nucl. Sci.* **50** 175–85
[26] Ruddy F H, Seidel J G, Chen H, Dulloo A R and Ryu S-H 2006 High-resolution alpha-particle spectrometry using 4H silicon carbide semiconductor detectors *IEEE Trans. Nucl. Sci.* **53** 1713–8
[27] Jiménez-Ramos M C, García Osuna A, Rodriguez-Ramos M, Viezzer E, Pellegrini G, Godignon P, Rafí J M, Rius G and García López J 2024 Spectrometric performance of SiC radiation detectors at high temperature *Radiat. Phys. Chem.* **214** 111283
[28] Garcia T R, Kumar A, Reinke B, Blue T E and Windl W 2013 Electron-hole pair generation in SiC high-temperature alpha particle detectors *Appl. Phys. Lett.* **103** 152108
[29] Kushoro M H *et al* 2025 SiC detector response to tokamak neutron spectra mock-up validated on experimental results *Fusion Eng. Des.* **214** 114875
[30] Szalkai D *et al* 2015 Detection of 14 MeV neutrons in high temperature environment up to 500 °C using 4H-SiC based diode detector *IEEE, 4th Int. Conf. Advancements in Nuclear Instrumentation Measurement Methods and Their Applications (ANIMMA)* (https://doi.org/10.1109/ANIMMA.2015.7465610)
[31] Szalkai D, Ferone R, Issa F, Klix A, Lazar M, Lyoussi A, Ottaviani L, Tutto P and Vervisch V 2016 Fast neutron detection with 4H-SiC based diode detector up to 500 °C ambient temperature *IEEE Trans. Nucl. Sci.* **63** 1491–8
[32] Ruddy F H *et al* 2003 Fast neutron spectrometry using Silicon Carbide detectors *Reactor Dosimetry in the 21st Century* (World Scientific) pp 347–55
[33] Ruddy F H, Ottaviani L, Lyoussi A, Destouches C, Palais O and Reynard-Carette C 2021 Performance and applications of silicon carbide neutron detectors in harsh nuclear environments *EPJ Web Conf.* **253** 11003

[34] Bertuccio G, Casiraghi R, Cetronio A, Lanzieri C and Nava F 2004 Silicon carbide for high resolution x-ray detectors operating up to 100 °C *Nucl. Instrum. Methods Phys. Res. A* **522** 413–9
[35] Kushoro M H *et al* 2024 Operation of a 250 μm-thick SiC detector with DT neutrons at high temperatures *Fusion Eng. Des.* **204** 114486
[36] Trovato G *et al* 2024 250 mm thick detectors for neutron detection: design, electrical characteristics, and detector performances *Key Eng. Mater.* **22** 35-40
[37] Mancuso A S *et al* 2025 Defects induced by high-temperature neutron irradiation in 250 μm-Thick 4H-SiC pn junction detector *Materials* **18** 2413
[38] Kushoro M H, Angelone M, Bozzi D, Gorini G, La Via F, Perelli Cippo E, Pillon M, Tardocchi M and Rebai M 2024 Partially depleted operation of 250 μm-thick silicon carbide neutron detectors *Nucl. Instrum. Methods Phys. Res. A* **1058** 168918
[39] Martone M, Angelone M and Pillon M 1994 The 14 MeV Frascati neutron generator *J. Nucl. Mater.* **212** 1661–4
[40] Angelone M, Pillon M, Batistoni P, Martini M, Martone M and Rado V 1996 Absolute experimental and numerical calibration of the 14 MeV neutron source at the Frascati neutron generator *Rev. Sci. Instrum.* **67** 2189–96
[41] Pietropaolo A *et al* 2018 The Frascati neutron generator: a multipurpose facility for physics and engineering *J. Phys.: Conf. Ser.* **1021** 012004
[42] Pillon M, Angelone M, Krása A, Plompen A J M, Schillebeeckx P and Sergi M L 2011 Experimental response functions of a single-crystal diamond detector for 5–20.5 MeV neutrons *Nucl. Instrum. Methods Phys. Res. A* **640** 185–91
[43] Knoll G F 2010 *Radiation Detection and Measurement* (John Wiley & Sons)
[44] Kushoro M H *et al* 2023 Performance of a thick 250 μm silicon carbide detector: stability and energy resolution *J. Instrum.* **640** 185-91
[45] Dulloo A R *et al* Neutron and gamma ray dosimetry in spent-fuel radiation environments using silicon carbide semiconductor radiation detectors *ASTM International STP1398-EB* (https://doi.org/10.1520/STP13657S)
[46] Natsume T, Doi H, Ruddy F H, Seidel J G and Dulloo A R 2006 Spent fuel monitoring with silicon carbide semiconductor neutron/gamma detectors *J. ASTM Int.* **3** 1–8