Silicon carbide neutron detectors for reactor monitoring in subcritical conditions

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***Abstract*— Silicon carbide (SiC) semiconductor detectors offer key advantages for radiation detection, including a wide bandgap, high thermal conductivity and radiation hardness, making them ideal for applications in harsh environments. Engineering and optimization of dedicated neutron converter components can enable achieving high detection sensitivities, comparable to BF_3 or ^{3}He detectors of the same physical dimensions. This study explores the use of wide-area SiC Schottky Barrier Diodes (SBDs) for neutron flux measurements in a nuclear reactor in subcritical conditions. Two detectors, fabricated at the National Institutes for Quantum Science and Technology in Japan and equipped with ^{6}LiF converter layers, were tested at the Jožef Stefan Institute TRIGA reactor in Slovenia using the Libera MONACO 3 system, developed at the French Atomic and Alternative Energies Commission and manufactured by the Instrumentation Technologies company in Slovenia. Results showed excellent performance, in comparison to a Centronic FC165 fission chamber, routinely used for this purpose. SiC detectors and standalone neutron converter components also have a high educational value, allowing for visual and hands-on demonstrations of neutron detection aspects and phenomena. Such activities are implemented in the framework of the European Nuclear Experimental Educational Platform (ENEEP).**

***Keywords* —Silicon Carbide, Lithium-6, Neutron Detector, Nuclear Reactor, Criticality Measurements.**

I. Introduction

SILICON carbide (SiC) semiconductor radiation detectors are being researched in the field of radiation detection as a promising technology offering superior performance characteristics that address many limitations of traditional detector materials, thanks to inherent advantages of SiC. These are, for radiation detection in particular, its wide bandgap, high thermal conductivity and exceptional radiation hardness, which make SiC highly suitable for use in harsh environments. Several excellent review papers on the topic of radiation detection using SiC detectors have been published [1-5]. The development and deployment of SiC-based neutron detectors is opening new avenues in various applications, ranging from nuclear reactor monitoring, neutron detection in specific applications [6], as well as applications in homeland security [7].

Furthermore, SiC neutron detectors are finding applications in space exploration and high-energy physics experiments. Their ability to withstand extreme conditions such as high radiation levels and wide temperature variations makes them suitable for use in space missions, where reliable radiation detection is critical for both mission success and the protection of onboard electronics and human crew members. In high-energy physics, these detectors contribute to the study of fundamental particles and forces, providing precise measurements that are essential for advancing our understanding of the universe. As research and development continue to advance, these detectors are expected to play an increasingly vital role in ensuring safety, security, and scientific discovery.

This paper presents research into the application of SiC detectors for measurements of the neutron flux in a nuclear reactor in subcritical conditions, relevant for neutron measurements / monitoring of subcritical and zero power reactor facilities or spent fuel facilities. A first series of measurements was performed during a controlled approach to criticality to demonstrate the capability of such detectors to monitor criticality conditions. A second series of measurements was performed in which the axial neutron flux distribution was measured in steady-state subcritical conditions.

The application of SiC detectors for neutron measurements is also highly relevant in nuclear education, as was implemented at the JSI in the framework of hands-on education activities organized by the European Nuclear Experimental Educational Platform (ENEEP) [8].

II. Experimental

A. *SiC Schottky barrier diodes*

The detectors used in the present work were SiC-SBDs fabricated on 36 µm thick n-type 4H-SiC epitaxial layer grown on an n-type 4H-SiC substrate by Chemical Vapor Deposition (CVD) [9]. The donor concentration in the epitaxial layers were 1.7×10^{14}. Schottky contacts with 4 mm x 4 mm and and 5 mm × 5 mm were formed on the epitaxial layers using the deposition of Ni. For the ohmic contact on the backside, Ni deposition and sintering at 950 ^{o}C for 10 min in Ar were carried out. The contact quality was verified with I-V measurements. The detectors were surface-mounted onto chip carriers with wire bonded electrical contacts. The chip carriers were enclosed in 3D-printed plastic holders in order to isolate the electrical contacts under high voltage.

B. *Neutron converter*

A neutron converting layer based on ^{6}LiF was deposited onto the front contact of the SiC diodes. The target thickness for the ^{6}LiF deposit was 20 µm, based on our previous work [10], in order to maximize the detection efficiency for measurements in a low neutron flux corresponding to a subcritical configuration of the reactor. The converting layer was realized by dispersing 27.43 mg of ^{6}LiF powder, obtained from the Oak Ridge National Laboratory (USA) in 0.4821 g of ethanol (^{6}LiF mass fraction of approximately 5.4 %). Approximately one half of the ^{6}LiF material did not disperse and was present as precipitate. One drop of the liquid dispersion was deposited onto the diode surface, the deposit mass on the 5 mm × 5 mm diode was 14.6 mg, the deposit mass on the 4 mm × 4 mm diode was 24.8 mg. The estimated effective thickness of the deposit, assuming only half of the ^{6}LiF material dispersed, was 6 µm for the 5 mm × 5 mm diode and 17 µm for the 4 mm × 4 mm diode. Fig. 1 displays a close-up of the deposition of the converter solution onto the SiC diode surface.

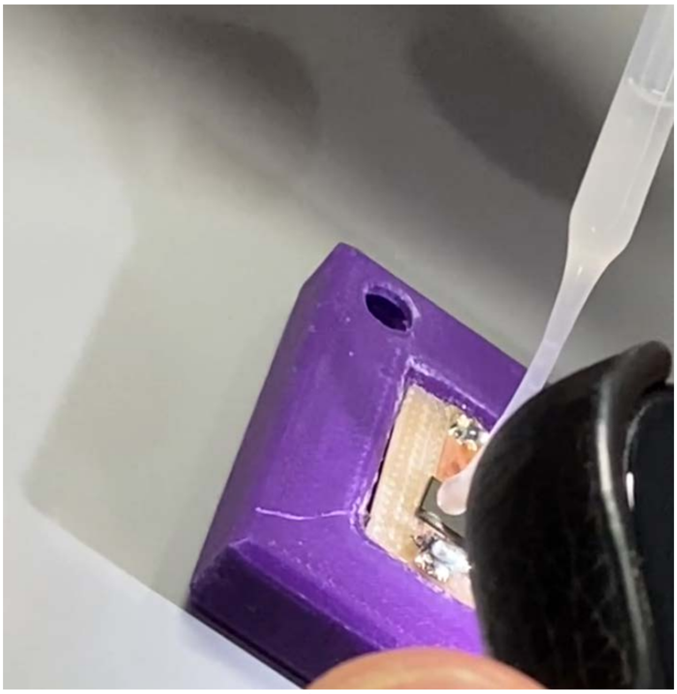

Fig. 1. Deposition of one drop of ^{6}LiF ethanol solution onto the surface of a SiC diode.

C. Measurement setup

The SiC diodes in their 3D-printed holders, equipped with the ^{6}LiF converting layers were mounted to a 3D-printed support, designed to prevent contact between the diodes and the interior surface of the irradiation channel used (and resulting damage to the diode). The detector assembly is displayed in Fig. 2. Additionally, a fission chamber (Centronic, model FC165 with a ^{235}U fissile deposit) was used in this work for comparison, also displayed in Fig. 2.

For the measurements during the approach to criticality, bottom spacers were present in both Triangular Irradiation Channels 1 and 2, designed to locate typical irradiation capsules in the core centre-line. The spacers were 238 mm in height and constructed from a top and bottom plate, shaped to fit the Triangular Irradiation Channel cross-section, joined by three aluminium tubes. A detailed description of the Triangular Irradiation Channels is given in [11]. The SiC detector assembly was lowered from the reactor platform level and rested on the spacer. For the axial profile measurements the spacer in TIC2 was removed, the SiC detector assembly was lowered to the bottom of the TIC2 and progressively raised by means of a steel cable. The assembly height was measured using a pneumatic system developed for accurate positioning of miniature fission chambers in the reactor core, used in [12] and other previous work. The system features a wheel with a rubber tread in contact with the cable, coupled to a rotary encoder. Fig. 3 displays a schematic view of the JSI TRIGA reactor core configuration and a drawing of the Triangular Irradiation Channel cross-section.

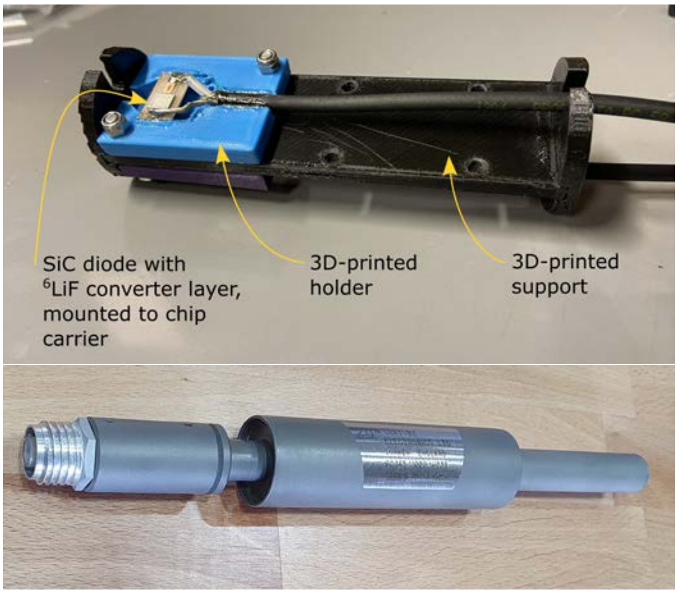

Fig. 2. Top: photograph of the SiC diode used in the present work with a ^{6}LiF converter layer, mounted to a chip carrier, enclosed in a 3D printed holder and support. Bottom: photograph of the FC165 fission chamber also used in the present work.

Pulse-height spectra resulting from the energy deposition of charge particles originating from ^{6}Li(n,t)^{4}He reactions in the coverter layer, and interacting in the active 4H-SiC material were acquired using the Libera Monaco 3 system, developed by the French Atomic and Alternative Energies Commission (CEA) [13] and industrialized by the Instrumentation Technologies company in Slovenia [14]. The system integrates high voltage, signal preamplification and processing stages, and incorporates three acquisition modes working in parallel: pulse mode, Cambpell (or variance) mode and current mode. The Monaco system was developed for acquisition of signals from fission chambers in nuclear reactors, but enables signal acquisition for different detector types as well, such as ionization chambers (current mode only) and self-powered neutron detectors (current mode only). In this work, its ability of signal acquisition from semiconductor detectors was tested with excellent results.

The JSI TRIGA reactor is equipped with four control rods, the Pulse rod (P), equipped with a pneumatic system used to eject the rod in pulse operation mode, the Safety rod (S), the

Compensating rod (C), and the regulating rod (R), equipped with an automatic system for operation in steady-state mode. The reactor core configuration including the locations of the control rods and the in-core irradiation channels is displayed in Fig. 3.

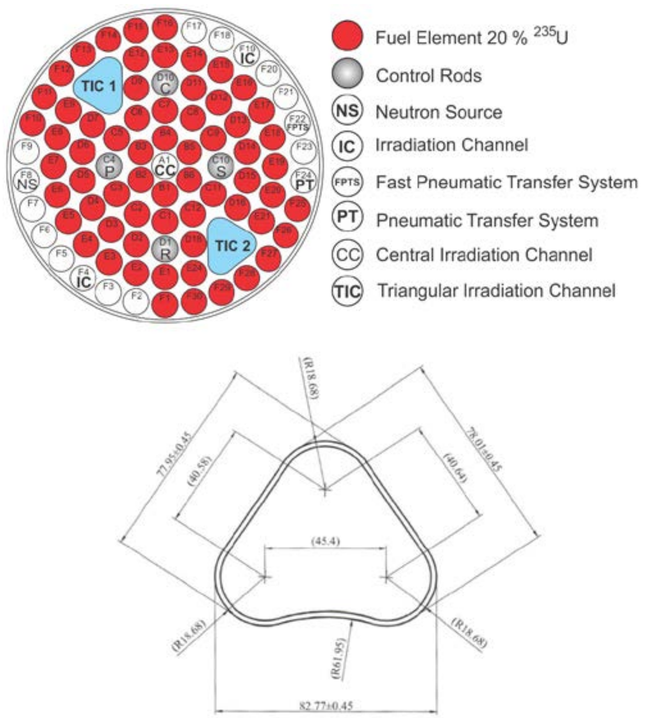

Fig. 3. Top: JSI TRIGA reactor core configuration (schematic). Bottom: cross-section of the Triangular Irradiation Channels (technical drawing).

D. Measurements

Measurements during the controlled approach to criticality were started with the reactor in a deeply subcritical state, with all rods inserted. Measurement steps were defined by progressive withdrawal of the control rods. Pulse height spectra from the SiC diode were recorded, displayed in Fig. 4. The spectra recorded from the SiC detectors, displayed in blue and green color in Fig. 4 appeared consistent for the measurement steps, as was the case for the spectra recorded from the FC165 fission chamber, displayed in red in Fig. 4. Detector count rates were determined by summation of the events in the shaded region of interest for the two SiC detectors as well as the FC165 fission chamber.

III. Results and Discussion

Tables I and II report the experimental data obtained during the controlled approach to criticality. Table 1 reports the control rod positions and the cumulative inserted reactivity for each measurement step. Table II reports the measured count rates on the two SiC detectors as well as the FC165 fission chamber, and the computed (inverse) subcritical multiplication factors.

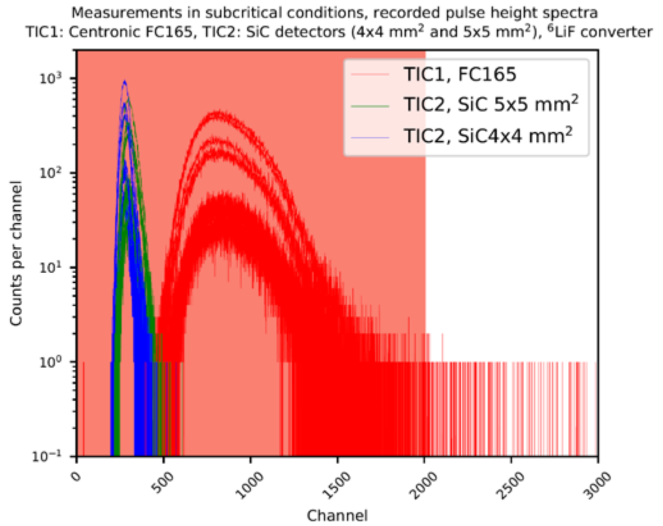

Fig. 4. Recorded pulse height spectra from the SiC diodes equipped with a ^{6}LiF converting layer and the FC165 fission chamber. The region shaded in color represents the signal considered in the present work, attributable to charged particles originating from neutron events. Spectra originating from the SiC detectors are displayed in blue and green, spectra originating from the FC165 fission chamber in red.

Table I
Approach to criticality – control rod positions and calculated inserted reactivity for each measurement step.

Meas. step (*i*)	T. rod position [step]	C. rod position [step]	S. rod position [step]	R. rod position [step]	Inserted reactivity [pcm]
0	901	900	900	901	0
1	451	900	900	901	1956.7
2	1	900	900	901	2962.2
3	1	900	450	901	5874.0
4	1	900	200	901	6740.3
5	1	700	200	901	7379.3
6	1	600	200	901	8007.2
7	1	500	200	901	8672.0
8	1	500	200	804	8845.5
9	1	500	200	751	9052.5
10	1	500	200	704	9275.1
11	1	500	200	675	9427.3
12	1	500	200	660	9510.1
13	1	500	200	642	9612.5
14	1	500	200	631	9676.6
15	1	500	200	620	9741.6
16	1	500	200	610	9801.3

The measurements performed give a good indication on the achievable detection sensitivity of SiC detectors. Observing the measured count rates in Table II, in particular during the last measurement steps, we see that they are of the same order of magnitude as the fission chamber count rates, despite the fact that there is a large difference in size in the active volume of the detector in favour of the fission chamber. This observation underscores the interest in researching SiC detectors for neutron applications, especially in case high detection efficiency is required.

TABLE II
APPROACH TO CRITICALITY – MEASURED COUNT RATES AND CALCULATED SUBCRITICAL MULTIPLICATION FACTORS FROM TE TWO SIC DETECTORS AND THE FC165 FISSION CHAMBER.

Meas. step (i)	**SiC 5x5 mm² [cps]**	**SiC 5x5 mm² I_0/I_i**	**SiC 4x4 mm² [cps]**	**SiC 4x4 mm² I_0/I_i**	**FC [cps]**	**FC I_0/I_i**
0	4.3	1	5.17	1	32.33	1
1	5.27	0.8165	6.56	0.7884	36.04	0.897
2	6.23	0.6914	7.59	0.6817	42.37	0.763
3	11.72	0.3672	13.59	0.3805	55.25	0.5851
4	14.47	0.2975	17.76	0.2912	65.52	0.4935
5	19.09	0.2256	23.25	0.2225	82.51	0.3919
6	25.27	0.1704	30.39	0.1702	110.17	0.2935
7	38.03	0.1132	47.18	0.1096	169.96	0.1902
8	44.65	0.0964	54.5	0.0949	188.71	0.1713
9	54.9	0.0784	65.11	0.0794	221	0.1463
10	70.12	0.0614	85.97	0.0602	269.31	0.1201
11	86.13	0.05	100.49	0.0515	322.44	0.1003
12	94.34	0.0456	111.32	0.0465	348.25	0.0928
13	114.31	0.0377	139.2	0.0371	416.88	0.0776
14	133.92	0.0321	161.85	0.032	480.22	0.0673
15	157.9	0.0273	190.29	0.0272	555.69	0.0582
16	185.75	0.0232	223.09	0.0232	654.14	0.0494

Fig. 5 displays the 1/M diagrams derived from the measurements performed with the two SiC diodes and the FC165 fission chamber. In subcritical conditions, the neutron population N in a nuclear reactor is proportional to the neutron source strength S (neutrons / s), in the present case a Ra-Be startup source, located in the core periphery, and the subcritical multiplication factor M:

$$N = SM = S\frac{1}{1-k_{eff}}, \quad (1)$$

where k_{eff} is the effective multiplication factor. If the measured signal I is proportional to the neutron population, the 1/M diagram is drawn by observing the ratio I_0/I_i, the indices 0 and i referring to the zero-th and i-th measurement step, as a function of the change made to the system, e.g. the progressive withdrawal of neutron absorbers [15]. The I_0/I_i ratios in Fig. 5 are displayed as a function of cumulative inserted reactivity, computed from the measured control rod reactivity worth tables. In theory, the ratio should depend linearly on the cumulative inserted reactivity, starting at the value 1 and approaching 0 as the reactor approaches criticality. As can be seen, the I_0/I_i diagrams from measurements using both SiC detectors are fully in line with expectations, whereas the I_0/I_i values from measurements using the fission chamber are more scattered initially, and appear to follow a linear dependence closer to criticality.

Similar measurements are performed routinely in the "Critical Experiment" exercise in the framework of education activities at the JSI TRIGA reactor. During the exercise, students / trainees observe the variation of the I_0/I_i ratio and make on-the-spot estimates on the amount of reactivity required to reach criticality. The indications obtained using the FC165 fission chamber in this work are qualitatively very similar to results from previous measurements, i.e. there are significant deviations from linearity far from criticality, and the resulting estimates on the amount of reactivity required to reach criticality are often unreliable. This can be explained by the position of the detectors used for the measurements. In principle, the closer a detector is located to the neutron source, the larger is the fraction of the signal originating from the neutron source and the lower is the sensitivity of the measurement setup to neutrons originating from the multiplication process in the fuel. Therefore, in deeply subcritical systems, more reliable indications on the criticality of a reactor are obtained by detectors located further away from the neutron source. Closer to criticality however, the neutron population increases significantly, and can become dominant over the contribution due to the neutron source. This is the reason why closer to criticality the reliability of the detector signals improves. Another important point to be considered during such measurements is the signal stabilization time. Equation (1) follows from a more general expression relating to successive neutron generations in the multiplication process:

$$N = S + k_{eff}S + k_{eff}^2\,S + k_{eff}^3 S + \cdots, \quad (2)$$

which converges for $k_{eff} < 1$. Each neutron generation is separated in time by the mean generation time Λ, of the order of several 10 μs, depending on the core configuration [16]. In a deeply subcritical system the higher order terms vanish quickly, meaning a short signal stabilization time after each successive change in the system. However, close to criticality, higher-order terms do become important, and in order to obtain reliable measurements, sufficient time for signal stabilization must be ensured. Stabilization times of the order of minutes are commonly observed.

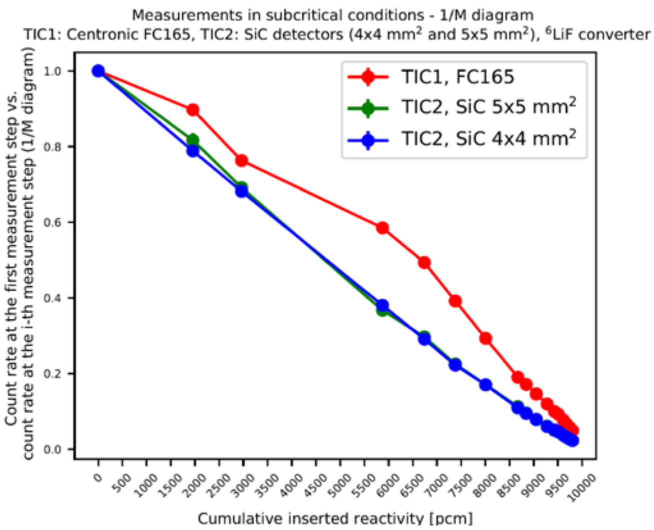

Fig. 5. 1/M diagrams from the measurements performed using the two SiC diodes and the FC165 fission chamber.

Table III reports the measured SiC detector count rates as a function of the height from the bottom of the TIC2 channel, Fig. 6 displays the measured axial distribution of the SiC detector signal in the TIC2 channel. Qualitatively, the observed distributions are consistent with previous measurements of fission rates using miniature fission chambers in collaboration with the French Atomic and Alternative Energies Commission (CEA), published as a benchmark case in the International Reactor Physics Benchmark Experiment Handbook [12]. The measured distributions display a central cosine-shaped maximum corresponding to the central fuel region, and tails corresponding to the top and bottom axial graphite reflectors.

TABLE III
MEASURED SIC DETECTOR COUNT RATES AS A FUNCTION OF HEIGHT FROM THE BOTTOM OF THE TIC2 CHANNEL.

Height above bottom in TIC2 [mm]	SiC 5×5 mm^2 signal [cps]	SiC 4×4 mm^2 signal [cps]
0	7.43	13.16
19.5	9.12	15.29
39.7	9.85	18.10
59.2	11.46	21.42
80.3	13.12	24.54
100.1	14.39	27.41
121.9	15.16	28.83
139.8	17.39	31.56
160.2	18.11	32.95
185.3	20.06	35.24
210	21.67	38.58
233.4	21.46	38.96
259.4	23.85	39.78
284.1	23.95	41.93
303.2	23.42	42.59
325.7	23.62	40.93
350.7	23.55	40.67
375.1	22.19	37.43
400.1	20.72	35.87
425.8	20.23	33.12
474.8	15.63	26.59
502.1	14.04	23.05
524.6	12.53	18.63
551.5	10.76	17.10
574.6	8.77	13.43
603.2	7.03	9.85

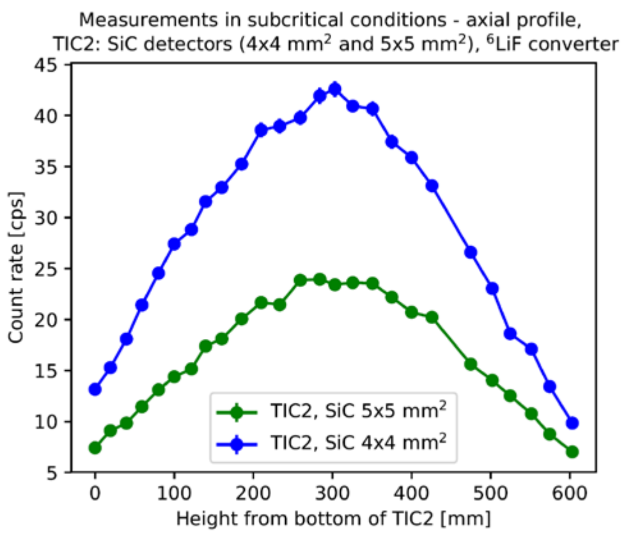

Fig. 6. Axial profiles measured using the two SiC diodes.

The measurements presented in this work clearly demonstrate the capability of SiC detectors to be used for measurements in a subcritical reactor, especially in the context of education activities, with several advantages. The detectors are less costly than typical neutron detectors, either fission chambers or gas detectors (^{3}He, BF_3) and do not introduce the need for handling radioactive materials as in the case of fission chambers. Additionally, they are of smaller dimensions compared to typical fission chambers or gas detectors, although miniaturized fission chambers are commonly being used. This enables achieving high spatial resolution, of the order of mm to cm, which is particularly important for neutron flux mapping experiments. Optical-fibre based neutron detectors equipped with a neutron-sensitive scintillating material, e.g. ZnS:^{6}LiF, as first developed by Mori et al. [17] and utilized e.g. in large numbers in a recent experiment at the CROCUS reactor at EPFL [18] are a comparable alternative with qualitatively similar characteristics.

For education purposes, SiC detectors equipped with standalone (removable) neutron converters introduce a series of possibilities, enabling observation and deeper understanding of a plurality of phenomena, e.g.

- measurement of I-V characteristics of SiC
- measurement of SiC detector response to α radiation, using e.g. ^{241}Am α sources
- demonstration / meaurement of the range of α radiation in air / vacuum, using a vacuum chamber and internal structures to locate the SiC detector and α source
- Energy calibration of the SiC detector setup using α sources, demonstration of α spectrometry
- Measurements of the energy(es) of secondary charged particles emitted in neutron interactions, using thin neutron converting layers containing ^{6}Li or ^{10}B isotopes
- Measurements of neutron detection efficiency, on the basis of information on the neutron flux.

IV. CONCLUSIONS

The results of this study demonstrate that silicon carbide (SiC) Schottky Barrier Diodes (SBDs) are highly effective for neutron flux monitoring in subcritical reactor conditions. Their robustness, wide bandgap, and radiation hardness enable reliable operation in environments where traditional detectors may fail or degrade over time. Measurements conducted at the Jožef Stefan Institute TRIGA reactor, using the Libera Monaco 3 data acquisition system, confirmed the capability of SiC detectors to track neutron population changes and provide spatial flux distribution data in low-power reactor scenarios. Their sensitivity and stability in subcritical conditions support their potential use in various nuclear facilities, including research reactors, zero-power systems, and spent fuel monitoring applications. These findings contribute to the growing body of evidence supporting SiC as a next-generation material for advanced radiation detectors.

In addition to their technical performance, SiC detectors offer unique benefits for nuclear education and training. The use of visible and detachable neutron converter layers allows for intuitive demonstrations of neutron interactions, particle attenuation, and (self)absorption effects, enhancing hands-on learning. Their visual accessibility and experimental flexibility make them well-suited for instructional settings, as already demonstrated through activities within the European Nuclear Experimental Educational Platform (ENEEP). This dual utility—operational and educational—positions SiC detectors as a valuable tool for both reactor monitoring and the advancement of nuclear science education.

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