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Silicon carbide detectors for particle therapy within the SAMOTHRACE ecosystem

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Abstract: A goal of the nowadays cancer radiotherapy treatment would be to reduce the healthy tissue damage, while maximizing the cancer disruption. Among the different possibilities, X-rays have been widely used during the irradiation for tumor cells killing, but they have manifested to damage healthy tissue. On the other hand, it was shown that the irradiation with charged particles (such as protons, alphas, carbon ions) allows a more precise definition of the deposited energy in the tumor cells, saving the healthy tissues. Promising could be also ions, as the Carbon-11, coming from radioactive ion beams. The use of Carbon-11 particles, in fact, would allow the use in both hadron therapy and medical imaging. In this context, SiC detectors are being characterized within the SAMOTHRACE ecosystem [1] for their employment as dosimeter, micro-dosimeter and tagging for RIBs such as the Carbon-11. In this contribution the characterization of two Silicon Carbide devices, will be discussed: a detector with a surface of 1 cm^2 and 10 µm thick, intended to be used as a dosimeter and micro-dosimeter; and a 100 µm thick detector, with the same surface area, to be used as beam tagging.

Keywords: Detector modelling and simulations I (interaction of radiation with matter, interaction of photons with matter, interaction of hadrons with matter, etc); Radiation-hard detectors; Solid state detectors

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1 Introduction

The development of semiconductor detectors for medical and nuclear applications has progressed significantly in the last decade, with silicon detectors gaining popularity for their integration capabilities, reuse, and real-time performance [2]. Advances in epitaxial growth [3] have enabled high-quality silicon carbide (SiC) devices, which offer superior radiation hardness, a wide band gap for better signal-to-noise ratio, and high temperature resistance [4–6]. In medicine, radioactive ion beams — such as Carbon-11 — show great promise for cancer treatment by combining hadron therapy with real-time imaging, enhancing both precision and effectiveness. Meanwhile, in the nuclear field, high-intensity radioactive ion beams [7, 8] are opening new research frontiers. To address the challenges of higher intensities, advanced diagnostics and tagging systems are being developed, with SiC devices playing a key role. The project aims to characterize and optimize SiC devices, both single and 2D arrays, for real-time beam monitoring and dosimetry. In this respect, the devices are characterized by a surface area of 1 cm^2, and thicknesses of 10 µm for dosimetry and micro-dosimetry, and 100 µm for beam tagging. In this work, we present the progress achieved in the energy resolution estimation and simulations that have been performed in GEANT4 toolkit and Synopsys Sentaurus.

2 Data analysis and simulations

2.1 Characterization of SiC with alpha source

The first detector investigated is a 100 µm thick SiC, with a surface of 1 cm^2 and divided into four pixels (figure 1, right). The detector was tested under a 400 V bias, and the resulting waveform was processed using a trapezoidal filter to extract the signal amplitude, as pictured in figure 1 (left). The waveform maximum provides the energy estimate; the start time is defined as the point where the signal reaches 10% of this maximum, and the rise time is measured between 30% and 80% of it. The experimental setup used for this device consists of a Mesytec preamplifier MPR [9], and a CAEN digitizer DT5742, 1 GHz. To test the SiC detector and to extract the energy resolution a ^{239}Pu-^{241}Am-^{244}Cm radioactive source has been used. Analysis of the energy spectra yielded an initial resolution estimate of 1%, as shown in figure 2 (left). Concurrently, the energy vs. rise time

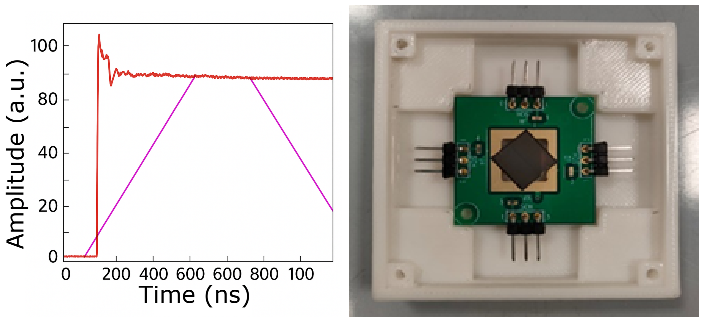


Figure 1. Left: waveform of 100 µm thick SiC detector (red) and the signal after the application of the trapezoidal filter (pink). Right: 100 µm thick-SiC used.

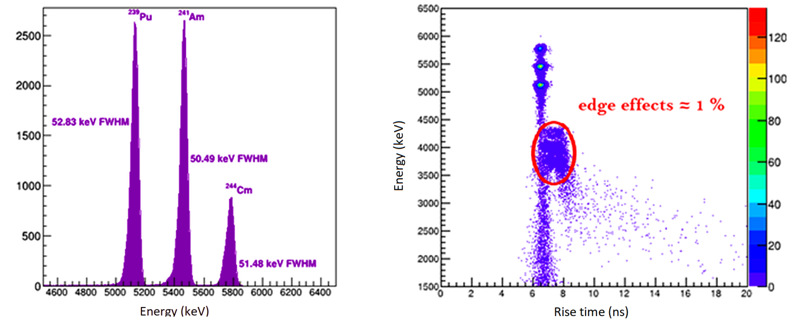


Figure 2. Left: energy spectra of the triple α source measured by SiC device. Right: energy vs rise time plot obtained for one pixel using the triple α source.

plot revealed a subset of events (1%, marked in red in figure 2) attributed to edge effects, as discussed in [10, 11]. The next step would be the optimization of the electronics, tailoring it for these devices in order to achieve better energy resolution. A comparative test was conducted between the SiC detector and a silicon detector of similar capacitance (1.77 cm^2 area, 99.7 µm thickness). A detailed analysis can be found in [12], where the same electronic setup was used for both devices. A first test was carried out on the 10 µm thick-SiC device. The electronic chain consisted of Mesytec preamplifier (MPR 16 channels) and CAEN digitizer (1 GHz, 14 Bit). The SiC detector was irradiated with a $^{148}Gd\ \alpha$ source, and an energy versus rise time plot was produced. The results of the data analysis are discussed in more detail in [13, 14]. In particular, edge effects were identified, and by using a collimator, we were able to suppress them effectively.

2.2 Neutron detection performances

A test with a primary beam of protons impinging on a LiF target at 5.5 MeV was performed at INFN-LNL. The resulting secondary neutron beam was directed onto the 100 µm thick SiC detector positioned at 12° relative to the beam axis. Preliminary results on the experimental energy spectrum have been extracted for all the four pixels, as presented in [13, 14]. Then, the experimental energy spectra were compared with those obtained with GEANT4 simulations, under the same experimental conditions. In particular, the simulation considered the two neutron energies expected from the ^{7}Li(p,n)^{7}Be* and ^{7}Li(p,n)^{7}Be reactions at a proton energy of 5.5 MeV. Table 1 presents the neutron energy values taken from [15]. The simulated and experimental spectra show good agreement, confirming the reliability

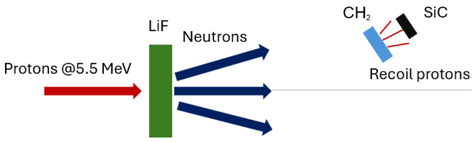


Figure 3. Experimental setup used at INFN-LNL.

Table 1. Neutrons energy obtained from the ^{7}Li(p,n)^{7}Be* and ^{7}Li(p,n)^{7}Be reactions at 5.5 MeV [15].

Reaction	E_n (MeV)
^{7}Li(p,n)^{7}Be*	3.356
^{7}Li(p,n)^{7}Be	3.802

of the experimental setup and analysis procedure. However, further refinement is needed to fully optimize the simulation parameters and improve the accuracy of the model.

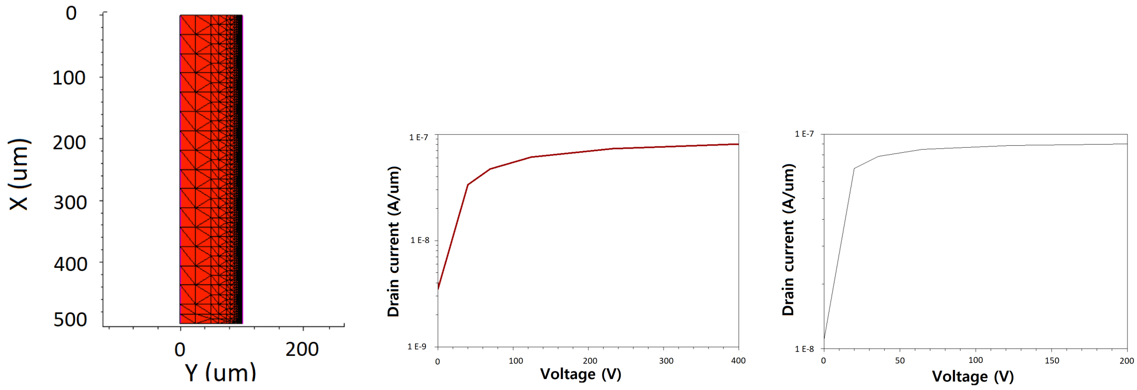
In front of the SiC detector a CH_2 plastic, 200 μm thick was used to convert neutrons to protons. The experiment setup is summarized in figure 3. The electronic consisted of a Mesytec Preamplifier and Caen Digitizer (1 GHz-16 channels), the experiment was performed in air.

2.3 Sentaurus simulations

Initial simulations of SiC devices were performed using the Sentaurus TCAD toolkit [16], a multidimensional platform for modeling electrical, thermal, and optical behavior in semiconductor devices. These simulations aimed to replicate the device structure and assess its response under applied bias conditions. Dopant types and concentrations used are summarized in table 2. A 100 μm-thick SiC device was first modeled in two dimensions (figure 4,a), including the creation of its simulation mesh. In Sentaurus, mesh design is critical, as it defines the spatial discretization required for numerically solving semiconductor equations. Fine meshing in regions with sharp gradients ensures accuracy while balancing computational efficiency and precision. Then, a bias voltage of 400 V (typical operating voltage) was applied to the 100 μm thick SiC sample, while a higher-than-typical voltage (~40 V) of 200 V was applied to the 10 μm thick SiC sample. A current-voltage (IV) plot was then generated for the two devices, as shown in figures 4, (b,c). Due to its wide band-gap, the SiC device exhibits low leakage current, making it well-suited for high-voltage applications. It also demonstrates a stable response under high bias, which is a promising characteristic for detector performance. Sentaurus simulations predict IV characteristics consistent with high energy and timing performance. The simulated IV characteristics indicate that comparable current levels can be achieved in both 100 μm and 10 μm thick SiC devices, although at significantly different bias voltages. This behavior is consistent with electric field scaling and reflects the influence of device thickness on charge transport. These findings demonstrate that device thickness can be optimized based on voltage and material constraints.

Table 2. Doping concentration parameters used in Sentaurus simulation.

	Material	Concentration
p+	Aluminum	$10 \cdot 10^{18}/\mathrm{cm}^3$
n-	Nitrogen	$8 \cdot 10^{13}/\mathrm{cm}^3$



(a) Mesh of 100 µm SiC (b) 100 µm SiC IV simulation (c) 10 µm SiC IV simulation

Figure 4. (a) Mesh layout of the 100 µm-thick SiC detector. (b) IV simulation results for the 100 µm SiC device. (c) IV simulation results for the 10 µm SiC device.

3 Results and conclusions

In this contribution two sets of SiC detectors with a surface of 1 cm^2 and divided into four pixels have been investigated. A 100 µm thick device was tested with a triple α-source, with the aim to optimize the electronics and achieve good energy resolution. It was also exposed to a neutron beam to detect recoil protons coming with the interaction with a CH_2 plastic. Preliminary energy spectra were extracted and compared with GEANT4 simulations. Initial simulations using the Sentaurus toolkit were conducted to model the detector response. The simulations show that both 100 µm and 10 µm thick SiC devices exhibit similar current characteristics at different bias voltages, indicating that device thickness can optimize charge transport and voltage handling. The SiC material's wide band-gap and low leakage current make it ideal for high-voltage applications, with stable performance under high bias.

4 Perspectives

More work is required to optimize the timing performance [17, 18]. To address this, an experimental campaign is currently underway at INFN-Labec in Florence involving beam tests. Subsequently, it will be necessary to refine the Sentaurus simulation, including modeling the oscillation of the electric field within the device. Following these steps, we plan to conduct a test using the ^{12}C+^{12}C reaction to evaluate the time resolution as a function of the fragment energy.

Acknowledgments

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