The ScIDEP Project at the Egyptian Pyramid of Khafre

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Abstract

The ScIDEP (Scintillator Imaging Detector for the Egyptian Pyramids) Collaboration is constructing a new scintillator-based muon telescope to investigate the internal structure of the Pyramid of Khafre at the Giza Plateau in Egypt. This pyramid is only slightly smaller than the Great Pyramid of Khufu; however, its known internal structure seems much simpler compared to the latter and hence raises the question if there are any hidden rooms or structures that have yet to be discovered. The previous and very first muography campaign performed at this pyramid conducted by Alvarez et al. in the 1970s yielded no indications of any hidden structures. The current project aims to install a new muon telescope inside the king's burial chamber which is located near ground level at the bottom of the pyramid, slightly off-center from the central axis. The base muon detector that has been developed consists of two $61 \times 61 \times 2\,\mathrm{cm}^3$ plastic scintillator planes with wavelength shifting fibers embedded in orthogonal orientations in both faces of each scintillator, to retrieve 2D hit information from each plane for muon tracking. The scintillation light is read out by SiPMs connected to each individual fiber. The data acquisition system is based on commercial CAEN PETIROC ASIC-based digitizer modules. The detector construction is being completed, and commissioning of the setup in the lab is currently ongoing. In parallel to the detector commissioning, a detailed simulation package for the full setup is being developed. For the simulation, the cosmic-ray spectrum is taken from the CRY generator, while the particle transport through the pyramid and the detector is modeled in both the Geant4 and MCNP simulation packages.

Keywords: muography, muons, plastic scintillator, pyramids, archaeology
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1. INTRODUCTION

Muon radiography is a method of imaging that utilizes the detection of cosmic-ray-produced muons to map density and structures within buildings, environments, or containers. The term "tomography" can imply a three-dimensional imaging method while "radiography" is a two-dimensional projection that may be used to create a three-dimensional reconstruction of a volume above the muon detectors. A number of research fields have used muon imaging measurements of density variation in ground-level or subsurface environments, including, but not limited to, archaeology [1, 2, 3], tunneling activities [4, 5], carbon sequestration [6, 7], nonproliferation and treaty verification [8, 9], nuclear smuggling [10, 11], oil and gas exploration and storage [4], mineral exploration [12], and volcano studies [13].

Muons with a broad range of energies, from MeV to TeV, generated in the Earth's atmosphere impinge on the Earth's surface at sea level with about 160 muons $\mathrm{s}^{-1} \cdot \mathrm{m}^{-2}$ with an angular distribution that follows closely a $\cos^2$ law with respect to the vertical [14]. At these energies, muons are minimally ionizing particles. Muons undergo small-angle scattering, and the muon flux is attenuated proportionally to the atomic number and density of the material through which it passes. This provides the opportunity to determine the density of the material that muons traverse before reaching a detector.

2. PLANNED KHAFRE PYRAMID APPLICATION

One application for a muon detector is to search for undiscovered cavities, including possibly hidden voids, within the great pyramids of Giza. The first muography application to investigate Khafre's pyramid was in 1970 by the Physics Nobel Laureate L. W. Alvarez, looking for hidden chambers inside it using 4 m^2 spark chambers, but nothing was found [3]. In 2017, a large void was discovered above the Grand Gallery in the Great Pyramid of Khufu [15]. Three different muon detectors were used for the pyramid scan: nuclear emulsions, scintillators, and micromegas. In 2023, ScanPyramids provided detailed data on the North Face Corridor behind the North Face of Khafre.

The ScIDEP Project

The ScIDEP (Scintillator Imaging Detector for the Egyptian Pyramids) Collaboration is constructing a new scintillator-based muon telescope to investigate the internal structure of the Pyramid of Khafre at the Giza Plateau in Egypt. The Khafre pyramid is only slightly smaller than the Great Pyramid; however, its known internal structure seems much simpler compared to the latter and hence raises the question if there are any hidden rooms or structures that have yet to be discovered. The current project intends to install a new muon telescope inside the king's burial chamber, which is located at the bottom of the pyramid, slightly off-center from the central axis. The Khafre pyramid's actual height [16] is 136.4 m, with a base length of 215.3 m, and is built out of limestone blocks weighing over 2 tons each. The pyramid slope rises at a $53^\circ 10'$ angle.

3. MUON DETECTOR

A new muon detector has been developed based on polyvinyl toluene (PVT) plastic scintillator with wavelength shifting fiber readout intended for making radiography measurements in the Khafre pyramid located in Giza, Egypt, as described previously in [17, 18].

For muon radiography, the detector consists of several planes of detector material, each of which determines the X-Y coordinates of a muon's passage, thus determining the muon's trajectory. Figure 1 shows one of the PVT plates with the wavelength-shifting fibers that make up the new detector. The printed circuit boards (PCBs), manufactured by Nalu Scientific, that hold the silicon photomultipliers (SiPMs) to the fibers are also shown on two sides of the plate. The initial version of the full detector consists of two of these PVT planes housed in individual cases that can be stacked to allow measurement of the muon direction. More planes can be added to improve the muon tracking.

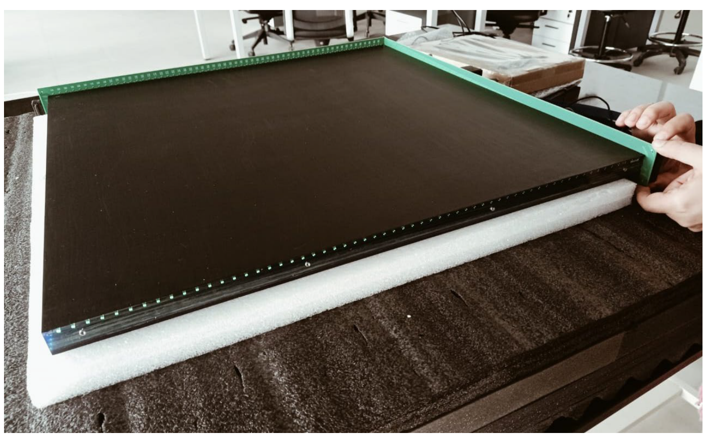

FIGURE 1: One of the detector PVT planes with embedded wavelength shifting fibers and the PCB readout boards holding the SiPMs coupled directly to the fibers.

The initial readout system of the detector, as shown in Figure 2, is based on the CAEN DT5550W data acquisition platform that is equipped with A55PET4 electronics boards containing 32-channel PETIROC ASICs for the readout of the SiPM signals. A total of 120 fibers are read out by the system, and the data is stored in an ASCI file for later analysis. The analysis looks for coincident SiPM events and extrapolates the interaction position in both the x and y coordinates for both PVT plates.

4. SIMULATIONS

Simulations for the muon radiography measurements of the Khafre pyramid have been carried out with both Geant4 [19] and MCNP [20]. While the MCNP simulation is being used with a simplified detector and pyramid model to provide initial estimates, a full simulation framework is being developed in Geant4 which should eventually include several cosmic-ray muon generators, a detailed description of the detector geometry and particle interactions inside the detector, and a model for the detector noise and detector signal digitization.

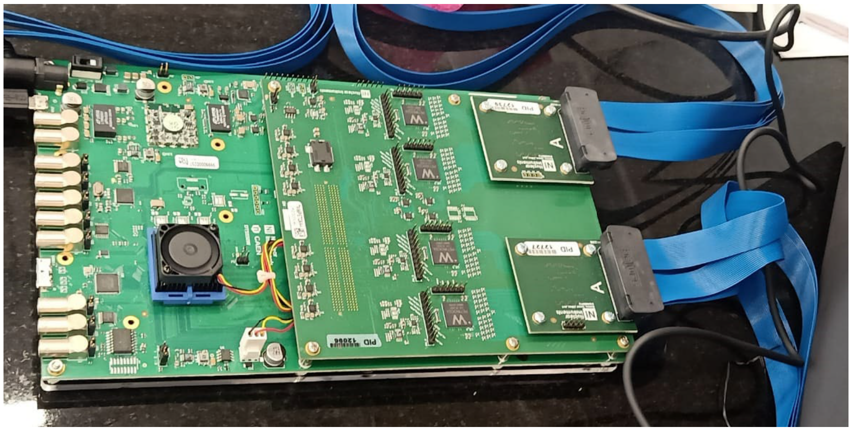

FIGURE 2: The data acquisition system consisting of the CAEN DT5550 and A55PET4 PETIROC electronics boards.

4.1. MCNP Simulations

The Monte Carlo n-particle (MCNP) version 6 simulation package was used in several iterations to build a model of the Khafre pyramid with the detector at its center at ground level. The detector was modeled as two PVT plates separated by 50 cm and supported by four legs (Figure 3).

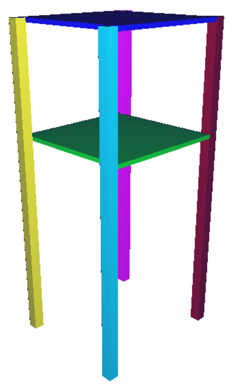

FIGURE 3: Simplistic model of the two PVT plates of the initial detector separated by 50 cm and supported by four legs.

The pyramid was modeled (Figure 4) in a simplified manner as a solid calcium carbonate structure of the correct dimensions with the detector placed in the burial chamber (14.15 m $\times$ 5 m $\times$ 6.83 m high) at ground level. A “hidden void” (10 m $\times$ 10 m $\times$ 10 m high off-center at 50 m up from the ground) was added in some simulations to determine the sensitivity of the model to such features.

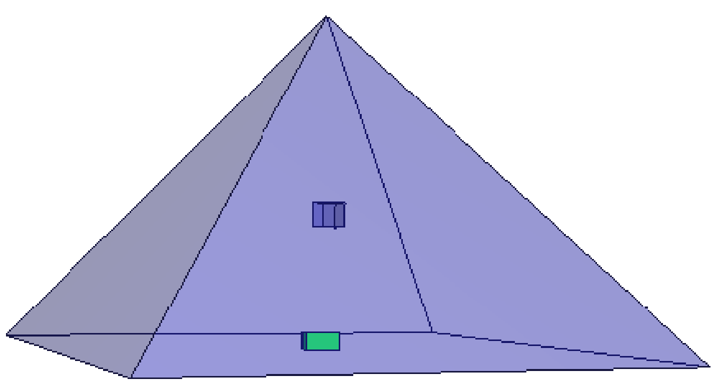

FIGURE 4: Simplified model of the Khafre pyramid, with the known burial chamber (green) and a “hidden room”.

The muon source was modeled as a hemispherical dome of radius 155 m that emitted muons inward with a bias of 2000 so that all muons were directed toward the detector region. A "bias" in MCNP is a parameter that can limit the angle of emission of the muons so that only those that would impact the detector are computed, thus not wasting computing time for muons that could not reach the detector. The source was limited to the angular region of 45 degrees from the vertical because muons at larger angles could not pass through both PVT detector planes. For simplicity, the angular distribution was taken as uniform rather than a $\cos^2$ distribution. For this simulation, the muon energy spectrum was taken from the distribution shown in the CRY manual [20] but was limited to muons with energies above 50 GeV since lower-energy muons would not penetrate the pyramid to the detector. This approximation of the muon distribution is adequate for this simplistic model and should be within a factor of about 2 of the actual distribution. Figure 5 shows some muon tracks in the simulation (with no "hidden chamber"). Muons of all energies (green) are seen leaving the source hemisphere and interacting in the pyramid, with a few reaching the burial chamber at ground level.

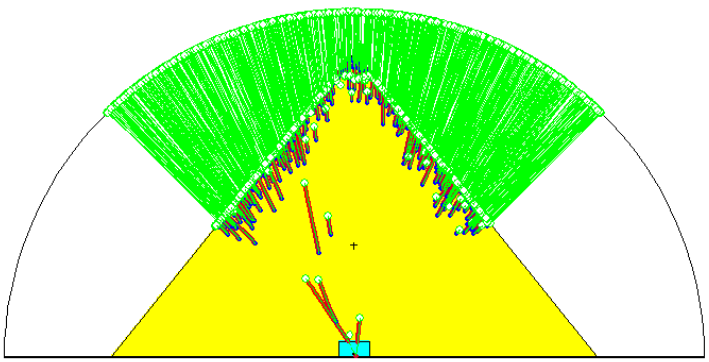

FIGURE 5: The simplified MCNP model showing muon tracks simulated on a hemisphere around the pyramid that contains the burial chamber at ground level.

The results of further simulations showed that the modeled "hidden room" could be observed with an arbitrary, but adequate, number of 108 emitted muons.

4.2. *Geant4 Simulations*

Simulations were performed in Geant4 to observe the amount of energy that is expected to be deposited by muons of different energies in the detector material. For these simulations, isotropic muon sources were placed at varying heights above the PVT plates (Figure 6). This example consisted of a 1 GeV isotropic muon source placed above two vertically stacked PVT plates each with a 61 cm $\times$ 61 cm face, with a thickness of 2 cm. For muons interacting with the PVT plates, the total energy deposited was tallied. An example of these results can be seen in Figure 7 for the geometry shown.

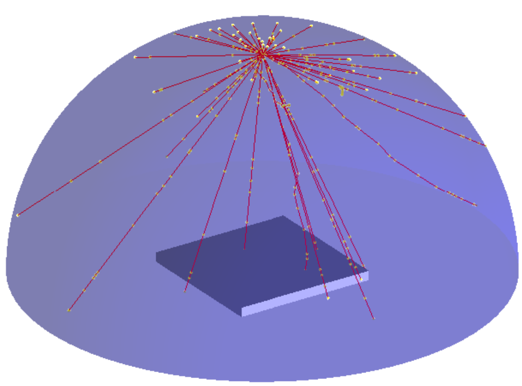

FIGURE 6: Muon emission from a point source above PVT plates in a Geant4 model.

Further simulations were performed to estimate the expected muon flux at the site where measurements are to be performed. The Cosmic-ray Shower Library (CRY) [21], developed by Lawrence Livermore National Laboratory, was coupled with Geant4 to simulate the natural muon flux rate and energy spectrum near Cairo, Egypt. The Geant4 simulated energy spectrum, up to 500 GeV for 10 million source particles, is shown in Figure 8. Using the particle generation times provided by CRY, the muon flux in Cairo

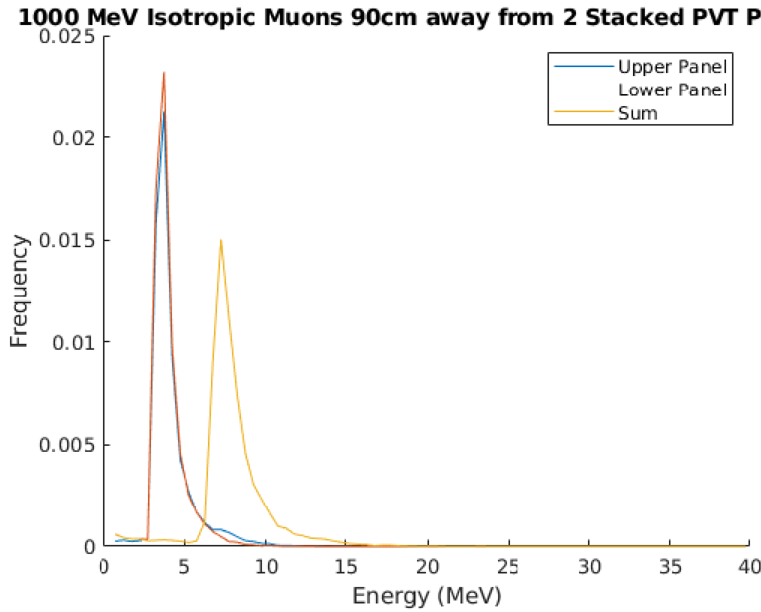

FIGURE 7: Simulated energy deposition by 1 GeV muons in the two PVT plates.

was approximately 109 muons $s^{-1} \cdot m^{-2}$. Of this, only 1.44 muons $s^{-1} \cdot m^{-2}$ are above 50 GeV and have sufficient energy to be observed after interacting with large portions of the pyramid.

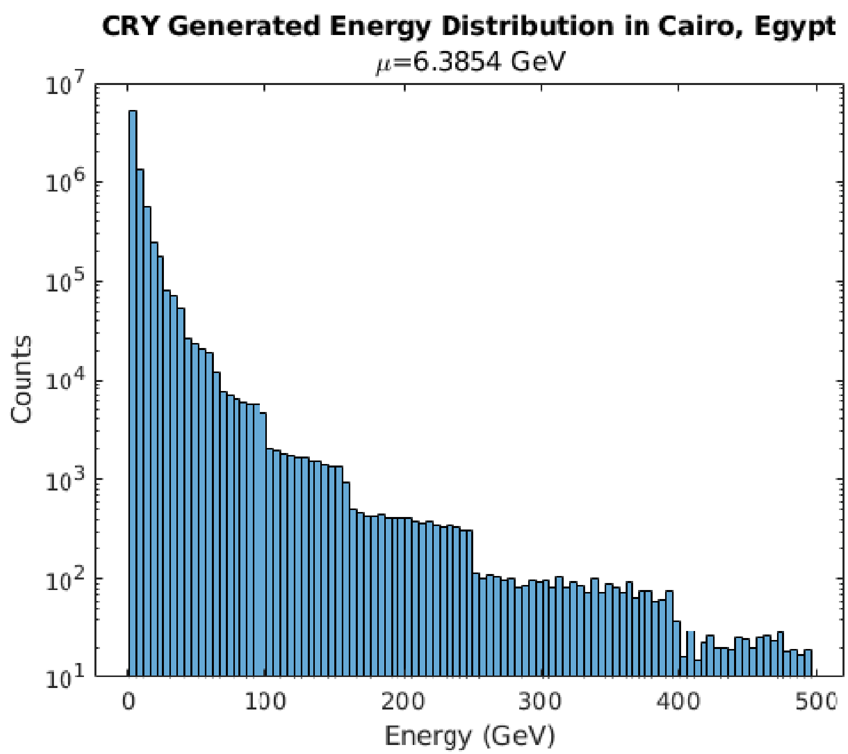

FIGURE 8: Simulated cosmic muon spectrum in Cairo, Egypt.

5. EXPERIMENTAL WORK

5.1. Data Acquisition System

The CAEN SCI-5550W readout software was used to set different parameters for the muon detector's operation (e.g., the bias voltage of each SiPM, thresholds, delay, etc.). The output is displayed as a real-time plot during the run where the charge value of each channel corresponds to each SiPM on the muon board (Figure 9). This display is provided by CAEN's software. The two peaks in the figure represent the energy response of two data channels. Several parameters such as the energy spectrum, ASIC number, counts per channel, the dark current, and SiPM temperature are also monitored.

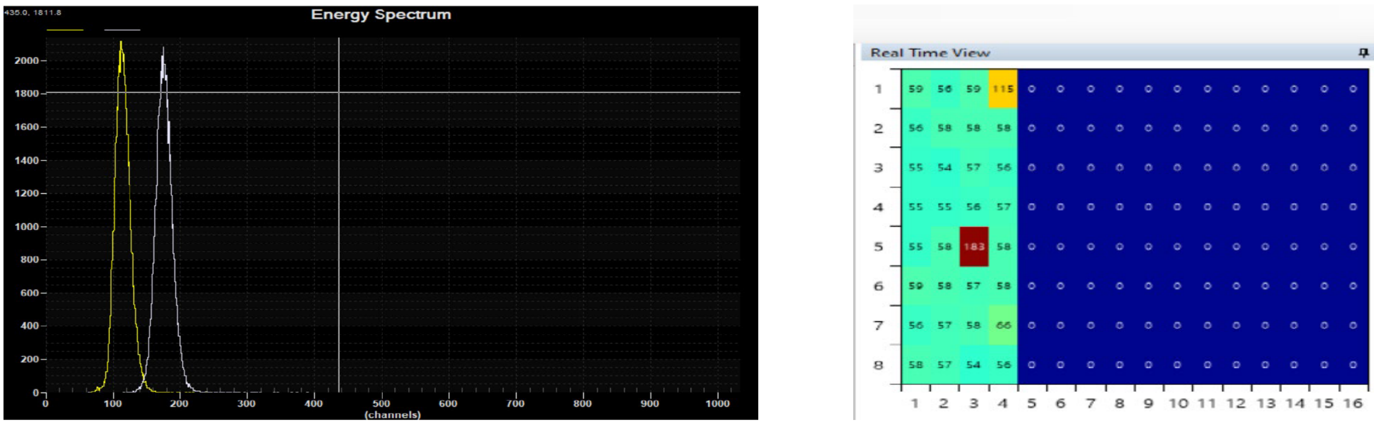

FIGURE 9: *Left*: The graphical interface of the CAEN DAQ shows the energy spectrum per channel; the yellow and white graphs show the energy spectrum of two channels corresponding to two SiPM. *right*: The real-time view during data taking shows the channel numbers that contain hits (red and yellow squares).

5.2. Muon Board Mapping

The Channels of the DT5550W system correspond to the SiPMs on the muon board. Each SiPM was individually tested using an RGB LED (Figure 10). The corresponding channel is identified on the real-time plot with the highest charge value (Figure 11).

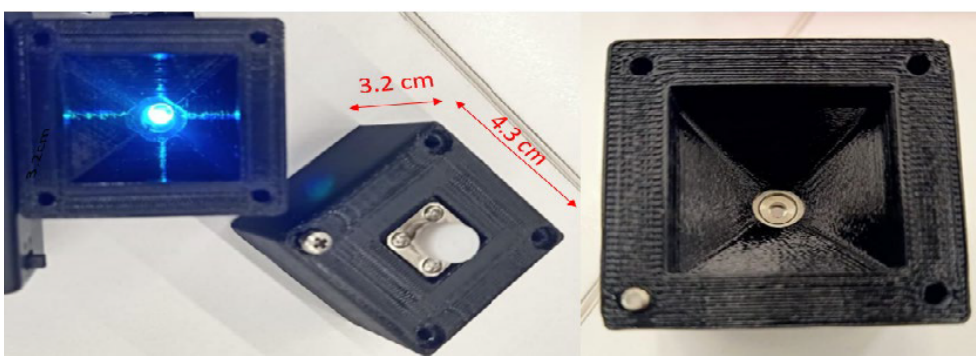

FIGURE 10: The RGB LED mounted into a small black box for better light collimation.

5.3. Scintillator Localization Test

A ^{60}Co gamma source of $\sim$1 μCurie was used for the localization test of each scintillator fiber. The source was positioned $\sim$6 cm from the SiPMs (Figure 12).

The charge values accumulated in the real-time plot refer to the nearest four SiPMs to where the radiation source was located. The bias voltage of the SiPMs was 41 V with an internal trigger delay of 8 ns (Figure 13).

6. CONCLUSION

The ScIDEP Collaboration intends to install a new muon radiography telescope inside the burial chamber of the Pyramid of Khafre at the Giza Plateau near Cairo, Egypt. The initial version of the telescope consists of PVT scintillator plates with wavelength-shifting fibers in X-Y orientations, connected to SiPMs. The SiPM signal readout is based on a CAEN DT5550W data acquisition platform

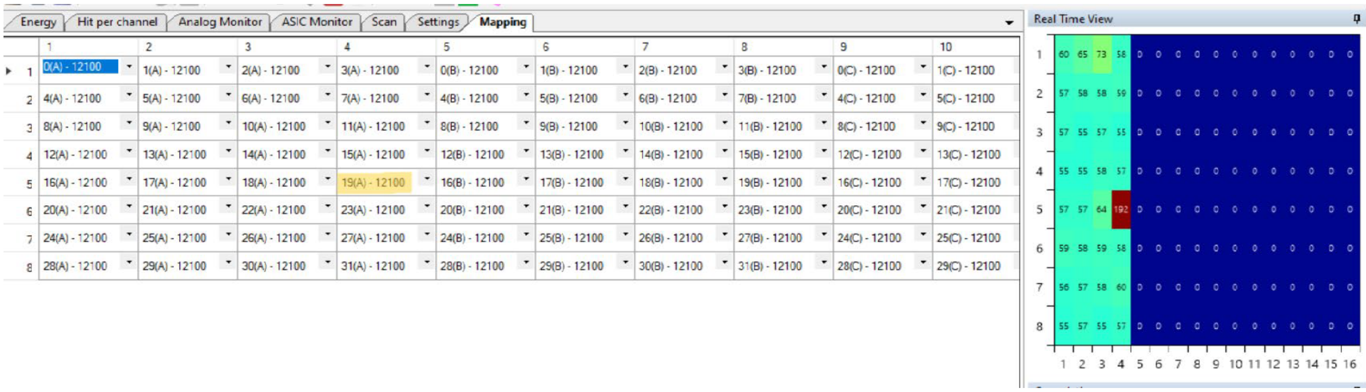

FIGURE 11: The red square refers to the highest charge value of channel 19(A), which corresponds to SiPM number 12 which was exposed to the RGB LED.

FIGURE 12: The ^{60}Co gamma source placed at 6 cm from both ends of the muon boards.

equipped with PETIROC front-end ASICs. The construction of the detector components and electronics has been completed, and the detector assembly and commissioning are ongoing at E-JUST in Alexandria, Egypt.

Initial test measurements are presented as part of the ongoing detector commissioning effort. Using a LED, the SiPMs were mapped successfully to their corresponding channels of the CAEN electronics system. A localization test was performed using a ^{60}Co source confirming the position of the source via the measured charge values of the nearby detector channels.

Simulation studies of the setup are under development using the MCNP and Geant4 packages. A simplified model of the Khafre pyramid and the detector was implemented in MCNP to perform a number of basic studies. An energy threshold of at least 50 GeV was derived for cosmic muons to be able to reach the detector placed inside the nearly centered burial chamber at the ground level inside the pyramid. Meanwhile, a detailed modeling of the detector geometry, including the wavelength shifting fibers and SiPMs, and the detector response to cosmic particles is being implemented in Geant4. This simulation also contains a detailed CAD model of the Khafre pyramid and its known internal structure. The CRY generator was coupled to Geant4 to simulate the cosmic muon energy spectrum. Our Geant4 simulation framework was so far used to study the energy deposited by incident muons in the detectors and to estimate the expected muon flux of $\sim$1.44 muons $s^{-1} \cdot m^{-2}$ with muon energies above 50 GeV which could interact effectively with the detector system.

CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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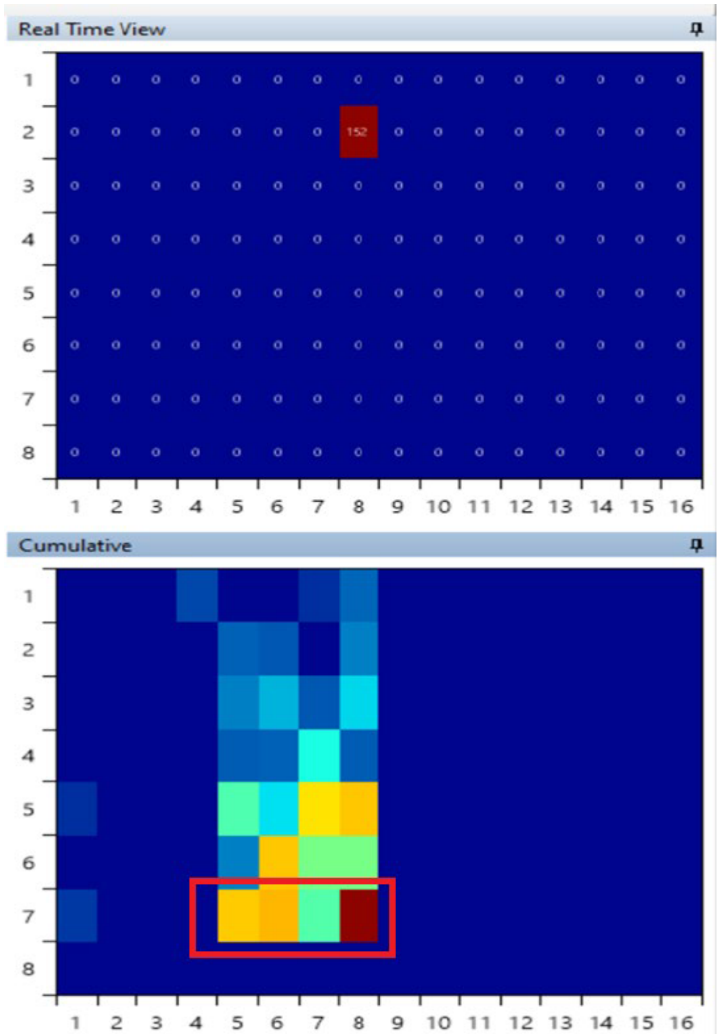

FIGURE 13: The four SiPMs nearest to the radiation source have the highest charge value and are shown as four different colors at the bottom of the cumulative plot, marked with a red rectangle.

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