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Muon tomography with multiplexed Micromegas detectors using compact telecopes for societal applications

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Muon tomography has emerged as a powerful technique for non-invasive imaging in various fields, including nuclear security, geology, and archaeology. For ten years, genetic multiplexed resistive Micromegas (MultiGen) detectors, invented at CEA/Irfu, have been developed for muon tomography, aiming to enhance imaging resolution and efficiency. MultiGen detectors provide telescopes with high spatial resolution, and a low number of electronic channels, making them suitable for deployment in various experimental environments, including those encountered in projects like ScanPyramids and nuclear dismantling.

After describing our effort to optimize the MultiGen-based telescopes, our contribution in ScanPyramids project and the first three-dimensional muon tomography of a nuclear reactor will be presented. A sustained effort was also made to produce MultiGen detectors in a Frencg PCB company.

Future projects on nuclear dismantling for non-destructive inspection and imaging will be presented.

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1. Introduction

Muon tomography uses the detection and tracking of atmospheric muons (produced by cosmic rays in the Earth's atmosphere) to scan the internal structure of large objects [1]. Muons may be stopped, attenuated or deviated along their path, which can reach hundreds of meters up to kilometers through matter. This attenuation mainly depends on the opacity ζ of the material traversed, which is defined as the product of the path length L and the material's mean density ρ (ζ [g/cm^2] = L [cm] $\times\rho$ [g/cm^3]) [2]. Based on these principles, several methods exist for obtaining images using muon tomography, with the main techniques being transmission, absorption, and deviation. More detailed descriptions of each method can be found in [3, 4].

The instruments and analysis techniques used in muon tomography are typically derived from nuclear and particle physics. In recent years, there have been significant advancements in these methods, particularly in muon detection devices (commonly referred to as muon telescopes). Consequently, the number of projects and publications related to muon tomography has increased considerably.

Since the CEA/Irfu team conducted the first outdoors muon tomography measurement [5], there has been continuous progress in both the instrumentation of muon telescopes (which consistently use Micromegas detectors) and the associated analysis techniques. This evolution has enabled projects in diverse fields such as archaeology and the nuclear domain.

2. Compact telescope with resistive multiplexed Micromegas

The Micromegas detector, invented at CEA in 1996 [6, 7], has two main components: a micromesh and an anode plane. The micromesh separates a drift region, where primary ionization occurs, from an amplification region, where gas multiplication takes place, producing an amplified signal. The resistive Micromegas design incorporates a resistive layer between the amplification structure and the readout plane, which helps distribute charge and prevent sparks from high-energy particle events, providing a more stable and durable detector.

The CEA/Irfu telescope is based on four resistive genetic multiplexed Micromegas detectors, called MultiGen detector [8, 9] readout by front-end unit board developed for the CLAS12 Micromegas Vertex Tracker [10]. Each detector is an assembly of two square printed-circuit board (PCB) of 54.6×54.6 cm^2 : a resistive Micromegas bulk on the first one for the signal amplification and the readout, and the second one for the cathode electrode. The active area is 50×50 cm^2 and the drift distance is 8 or 10 mm.

The multiplexed readout is designed to group multiple readout strips (or pads) to one electronic channel. This significantly reduces costs and complexity, particularly in applications involving large detection surfaces.

The MultiGen detector maintains the high precision and fine spatial resolution of standard Micromegas while simplifying the readout, making it especially useful for relative large-area and compact muon telescopes.

3. Societal applications

Examples in two domains of application (archaeology and nuclear dismantling) with muon tomography telescopes from our laboratory are described here.

3.1 Archaeology

The CEA telescopes, operating outdoors and indoors, were used in the ScanPyramid mission [11] to contribute to recent discoveries inside the Khufu Pyramid. Several hidden chambers have been revealed. In collaboration with two Japanese laboratories (KEK and Nagoya University), muon tomography images or muographies in transmission have been performed and compared.

In 2017, the detection of a large void above the Grand Gallery of the pyramid, measuring about 100 feet (30 meters) long, were performed by two CEA telescopes and two Japanese teams, operating respectively, outside facing the North side and inside the Queen's Chamber [12].

In 2023, a hidden corridor located near the main entrance on the northern face was also found by operating 3 compact telescopes (two, *Degennes* and *Charpak*, of 1/2 m^2 of active area each and *Joliot* of 1/4 m^2) inside the pyramid. This corridor of about 9 meters long was filmed with an endoscope on March 2, 2023 (see pictures on Fig. 1) [13].

The detection sensitivity of the muographies has been obtained with the help of Geant4 simulation with and without the NFC (see Fig. 2).

3.2 Nuclear dismantling

The G2/G3 and IZEN (*Installation Zone d'Entreposage Nord*) installations are key facilities at CEA Marcoule, each was built for specific activities in the nuclear domain:

- G2/G3 installations: G2 and G3 reactors are historical nuclear reactors using graphite moderator and located at CEA Marcoule. These reactors, built in the 1950s, were part of the early French nuclear energy program and were the first industrial-scale reactors for producing plutonium. They were shut down in the 1980s and are currently undergoing decommissioning.

- IZEN (*Installation Zone d'Entreposage Nord*): This facility is used for the safe interim storage of nuclear materials and radioactive waste. It primarily handles low- and intermediate-level radioactive waste, storing it securely until it can be disposed of or processed further.

At G2/G3 installation, the first 3D structure of a whole large nuclear reactor have been obtained by muon tomography in transmission with four telescopes in a year [14] (see Fig. 3).

At IZEN installation, a bench has being commissioned in the facility with the aim of obtaining muon absorption tomography using a 0.25 m^2 telescope at 2 m above the package and a veto system above it (see Fig. 4). The telescope reconstructs the trajectories of the muons while the veto system discriminates between muons that have passed through the package and those that have stopped. This configuration avoids blurring of the image which would be obtained by transmission.

4. Technological transfer

The Micromegas detector technology, originally developed at the CEA and CERN, was transferred to the French company ELVIA-PCB [16], which specializes in printed circuit boards. This

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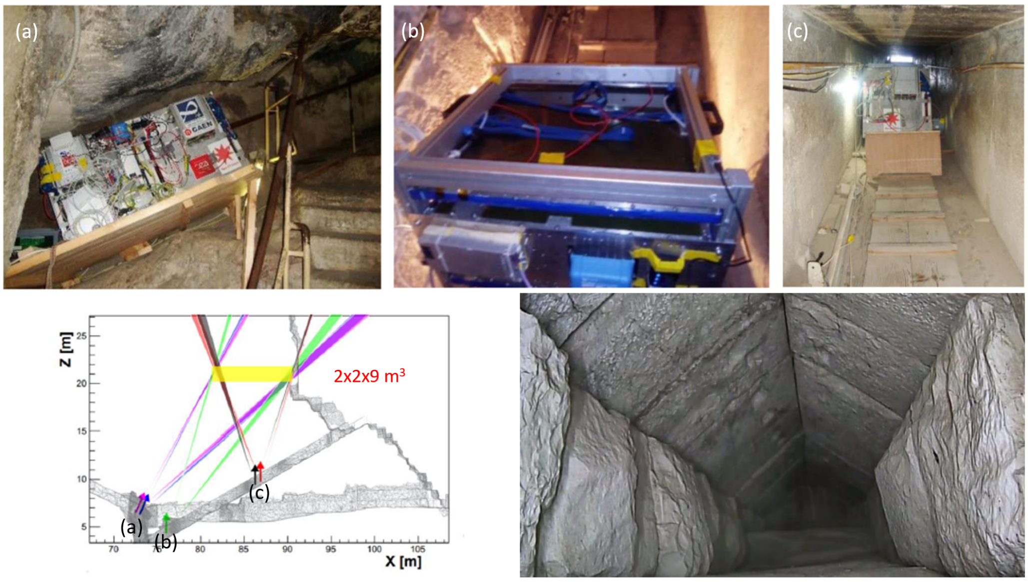

Figure 1: Kufhu pyramid configurations. Top: pictures of the three telescopes during operation: *Degennes* (a), *Joliot* (b) and *Charpak* (c). Bottom left: triangulation of the NFC, where each cone represents the extremity of the NFC found in one data set taken from the positions of the telescopes. Bottom right: image of the endoscopic investigation of the north face corridor on March 2, 2023.

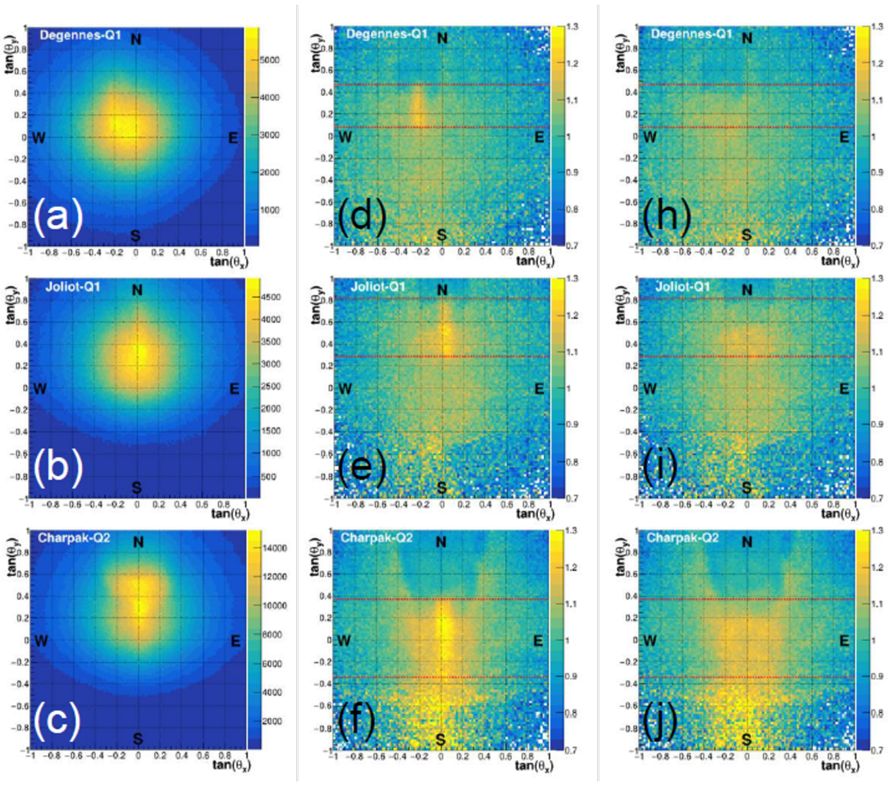

Figure 2: Left: raw muographies from the telescope in position (a), (b) and (c) shown on Fig. 1. Middle: ratio between data and simulation for these three corresponding positions. The horizontal, dashed red lines indicate the limit of the NFC obtained by slicing each image. Right: same ratio as in (d), (e) & (f), obtained with a simulation containing a void representing the NFC (h), i() & (j) [13].

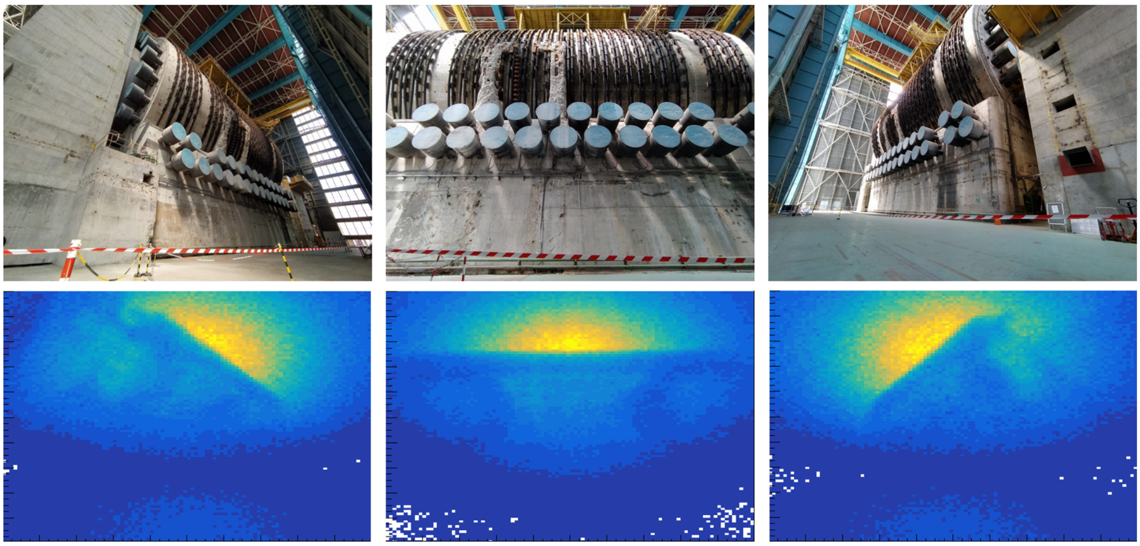

Figure 3: Muographies from three telescope positions at the G2 reactor at CEA-Marcoule

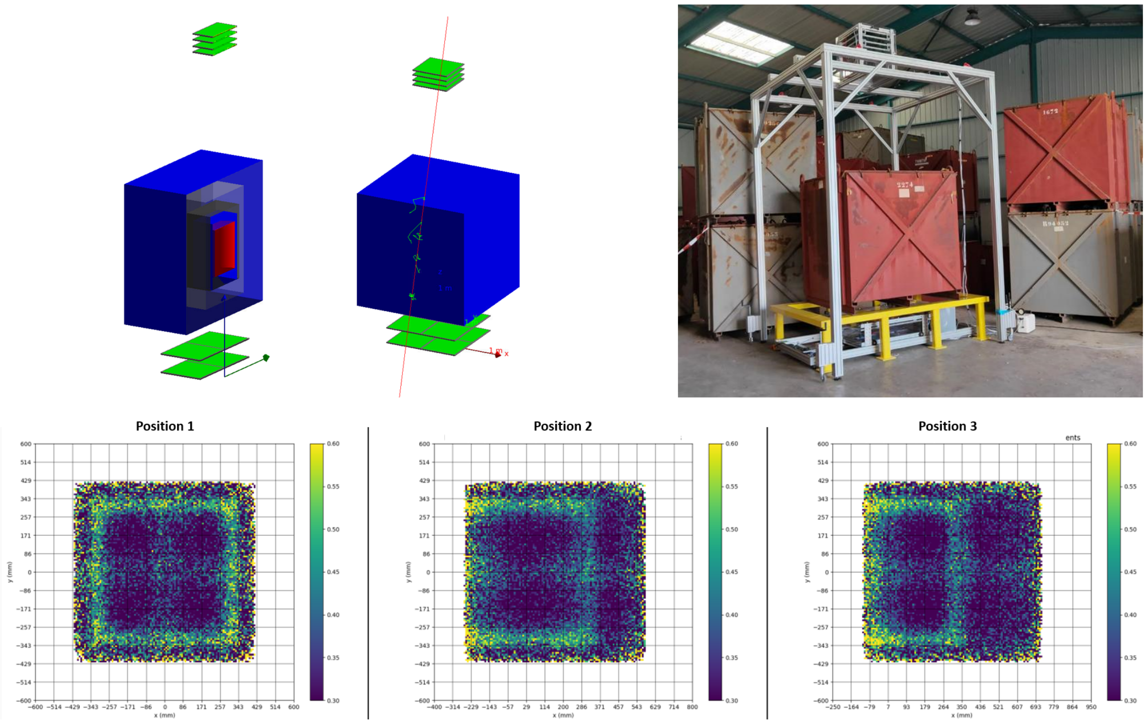

Figure 4: Top leff: Geant4 simulations of the nuclear waste package. Bottom: muographies obtained by simulation at three different positions of the 1 m² Veto. Top right: picture of the setup showing a telescope, a Veto and nuclear waste package.

collaboration has allowed ELVIA-PCB to adapt their production processes to manufacture Micromegas detectors, used in particle physics experiments and muon tomography applications.

MultiGen detectors are made with resistive Micromegas detectors. These detectors require a large readout board with high-precision (100 μm) and processes similar to what is needed for printed circuit boards. ELVIA-PCB's expertise in PCB manufacturing makes them an ideal partner for this technology transfer. Since 2012, by adapting the technology for industrial production, ELVIA-PCB is the only company to build large resistive bulk Micromegas detectors. This successful technology transfer, combined with applications of muon tomography, enabled the manufacture of around a hundred MultiGen detectors.

5. Conclusions and prospects

Although a late starter in muon tomography, the French laboratory has become a key partner in the community by providing high-resolution images and demonstrating proof of concept in various applications, including archaeology and nuclear decommissioning. Further proofs of concept, particularly in the nuclear field, are currently underway. The nuclear industry is looking forward to results in the coming years.

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