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# The design and performance of a scintillating-fibre tracker for the cosmic-ray muon tomography of legacy nuclear waste containers

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ABSTRACT

Tomographic imaging techniques using the Coulomb scattering of cosmic-ray muons are increasingly being exploited for the non-destructive assay of shielded containers in a wide range of applications. One such application is the characterisation of legacy nuclear waste materials stored within industrial containers. The design, assembly and performance of a prototype muon tomography system developed for this purpose are detailed in this work. This muon tracker comprises four detection modules, each containing orthogonal layers of Saint-Gobain BCF-10 2 mm-pitch plastic scintillating fibres. Identification of the two struck fibres per module allows the reconstruction of a space point, and subsequently, the incoming and Coulomb-scattered muon trajectories. These allow the container content, with respect to the atomic number $Z$ of the scattering material, to be determined through reconstruction of the scattering location and magnitude. On each detection layer, the light emitted by the fibre is detected by a single Hamamatsu H8500 MAPMT with two fibres coupled to each pixel via dedicated pairing schemes developed to ensure the identification of the struck fibre. The PMT signals are read out to standard charge-to-digital converters and interpreted via custom data acquisition and analysis software.

The design and assembly of the detector system are detailed and presented alongside results from performance studies with data collected after construction. These results reveal high stability during extended collection periods with detection efficiencies in the region of 80% per layer. Minor misalignments of millimetre order have been identified and corrected in software. A first image reconstructed from a test configuration of materials has been obtained using software based on the Maximum Likelihood Expectation Maximisation algorithm. The results highlight the high spatial resolution provided by the detector system. Clear discrimination between the low, medium and high-$Z$ materials assayed is also observed.


## 1. Introduction

When high-energy cosmic rays bombard the Earth, muons are produced as part of particle showers within the upper atmosphere. These highly penetrating particles are observed at sea level with a flux of approximately one per square centimetre per minute and momenta of several GeV $c^{-1}$. As charged particles, they interact with matter primarily through ionising interactions with atomic electrons and via Coulomb scattering from nuclei. Both of these mechanisms have been exploited in recent years in the field of Muon Tomography (MT) to probe the internal composition of shielded structures which cannot be probed using conventional forms of imaging radiation *e.g.* X-rays. Since George measured the thickness of the ice burden above the Guthega-Munyang tunnel in Australia in the 1950s [1] and Alvarez conducted his search for hidden chambers in the Second Pyramid of Chephren in Egypt [2] a decade later, there has been a wealth of wide-ranging applications using cosmic-ray muons for imaging purposes, such as in the field of volcanology [3,4] and nuclear contraband detection for national security [5,6].

The seminal work outlined by Borozdin et al. in Ref. [5] revealed the potential to locate and characterise materials within shielded containers using the Coulomb scattering of cosmic-ray muons. This approach relies on precision reconstruction of the initial and scattered muon trajectories to determine the scattering location within the container and the scattering density, denoted $\lambda$. This scattering density is known to exhibit an inherent dependence

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on the atomic number $Z$ of the material [7] *i.e.* larger scattering angles are typically observed for objects with larger $Z$ values.

This work presents the design and fabrication processes of a small prototype MT system for use in the identification and characterisation of legacy nuclear waste materials stored in highly engineered industrial waste containment structures. For this purpose, a detector with high spatial resolution was required. It was essential that the design of the system, and the materials and fabrication processes used, be scalable to allow the future construction of an industrially deployable detector system. The requirement of industrial deployability mandated that the detection medium be radiation-hard, robust and capable of performing to a high degree of stability over prolonged periods of time for operation in the typical high radiation, high stress industrial environment found within a nuclear waste processing plant.

A modular design based on plastic scintillating fibres was chosen to satisfy these criteria. The individual components and modular construction are described in Section 2 with the assembly process outlined in Section 3. The readout electronics, data acquisition (DAQ) and complex fibre multiplexing requirements are described in Section 4. Results showing the performance of the constructed, commissioned system are presented in Section 5 and first results from the image reconstruction of a test configuration of low, medium and high-$Z$ materials are presented in Section 6.

## 2. Tracker module design and components

Each detector module comprised orthogonal detection planes of plastic scintillating fibres which were supported and positioned on a low-density rigid foam and aluminium structure. The two planes of fibres were bonded within this structure and further supported at the extremities by plastic polymer distribution blocks. Fibres were coupled to photon detectors (here, multi-anode photomultiplier tubes) housed within lightproof boxes. The active area of each module was encased within a lightproof vinyl film. The design of the individual detector modules and all components and materials used in the fabrication process are detailed in the following section.

### *2.1. Scintillating fibres and Hamamatsu H8500 PMTs*

Prior to the design and fabrication processes, dedicated Geant4 [8] simulation studies were performed to assess the fibre pitch required for this system with regard to the anticipated light output and reconstructed image resolution [9]. A design based on 2 mm-pitch plastic scintillating fibres was chosen. The fibres used in the production of this muon tracker were Saint-Gobain[2] BCF-10 round fibres comprising a polystyrene-based core (97% by cross-sectional width) with polymethylmethacrylate (PMMA) optical cladding (3%). The light emission output of this formulation, which peaked at 432 nm, provided excellent overlap with the sensitivity of the chosen photon detector, the Hamamatsu[3] H8500 MAPMT.

Feasibility studies (outlined in Section 4) revealed the potential to reduce the required number of readout channels by 50% through the coupling of two scintillating fibres to a single pixel on the 64-pixel segmented anode of the PMT. A single detection layer comprising 128 fibres coupled to a single PMT was therefore chosen for the final prototype design.

The design for the complete detector system comprised four modules, two situated above, and two below the volume under interrogation *i.e.* the assay volume. With this modular design and the identification of a space point in each module, the initial and scattered muon trajectories could be reconstructed allowing the determination of the scattering position and magnitude required for image reconstruction. Within each module, two orthogonal detection planes, comprising a single layer of 128 fibres, yielded an active area of 256 mm × 256 mm. To allow for minimal transmission losses and manageable strain as a result of the fibre bending required for PMT coupling, fibres of 860 mm length were used. In total, for eight detection layers, 1024 fibres and 8 PMTs were required.

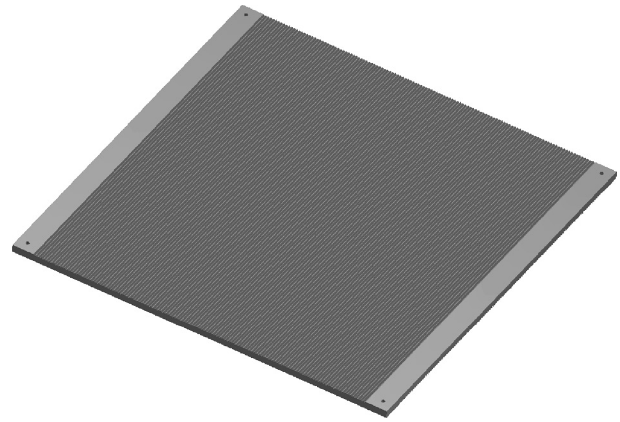

**Fig. 1.** A CAD schematic of a Rohacell® support sheet etched with 128 $V$ grooves (central region). The four holes on the smooth, non-grooved edges were used to secure the locating pins on the aluminium base plate described in Section 2.3.

### *2.2.* Rohacell® *support sheets*

For each fibre layer, accurate fibre positioning and support was provided by a low-$Z$, precision-machined structure of Rohacell® sheeting[4] a closed-cell rigid polymethacrylimide foam. This provided sufficiently high tensile strength in comparatively small thicknesses to support the individual fibre layers whilst providing only a negligible Coulomb scattering effect on transient muons. A layered configuration of Rohacell® support sheets of varying thicknesses and dimensions was fabricated to support the orthogonal layers of fibres. The assembly of this structure is described in detail in Section 3.2.

Shown in Fig. 1 and measuring 300 mm in length, the central square sheet that supported the fibres was machined with shallow, parallel $V$ grooves to position each of the 128 fibres per layer. Grooves were cut in the $x$ ($y$) direction on the top (bottom) side of the support sheet. On this central sheet, narrow non-grooved regions were located at the sides parallel to the fibre direction (shown in Fig. 1) to accommodate the holes which allowed the sheet to be fixed onto locating pins on the aluminium base plate (see Section 2.3). Each sheet of Rohacell® had locating holes in each corner to fix the sheet to these locating pins to ensure accurate alignment and uniformity across all four modules.

### *2.3. Aluminium base plate*

A 3 mm-thick flat sheet of aluminium was used to provide a robust support base for the multiple layers of Rohacell® and scintillating fibres which formed the active area of each module. This square sheet of aluminium, shown in Fig. 2, measured 460 mm with a central square region of 270 mm removed to minimise the material contributing towards Coulomb scattering

[2] http://www.saint-gobain.com
[3] http://www.hamamatsu.com
[4] Manufactured by Evonik Industries (www.rohacell.com).