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A large-area array-type muon radiography detector μ Sight-1

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Abstract

Compared with conventional radiation-based radiography methods such as X/ γ rays and neutrons, muon absorption radiography offers distinctive advantages, including the absence of artificial radiation sources and strong penetrating capability. It is typically employed for imaging concealed structures inside large-scale objects. Nonetheless, muon radiography still faces challenges such as low counting rates and random incidence angles. The development of high-performance muon detectors is one of the effective approaches to mitigating these limitations.

Plastic scintillator-based muon radiography detectors provide the advantages of low cost and strong environmental adaptability. In this work, a large-area planar muon radiography device, μ Sight-1, based on a plastic scintillator array, is developed. The detector system reconstructs muon tracks using three layers of two-dimensional position-sensitive detectors composed of scintillator bars with triangular cross-sections. The scintillation light is collected by wavelength-shifting (WLS) fibers and subsequently converted into electrical signals by SiPMs. A fully customized DAQ system is implemented, capable of simultaneously acquiring signals from 384 scintillator units. The detector has an effective area of 1.3 m², achieves a detection efficiency greater than 98.5%, and attains a position resolution of 1.9 mm.

Full Text

Preamble

A Large-Area Array-Style Cosmic-Ray Muon Radiography Detector μ Sight-1

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Muon absorption radiography technology offers unique advantages compared to conventional radiation-based techniques (e.g., X/ γ -ray and neutron radiography), including inherent source-free operation and high penetration capability. This method is typically employed for imaging obscured internal structures within large-scale objects. However, muon radiography also faces challenges due to low flux rates and non-directional incidence. Advanced muon detection systems represent one effective approach to mitigating these limitations. Due to their low cost and high environmental adaptability, plastic scintillator detectors are widely employed in muon absorption radiography. In this work, we developed μ Sight-1, a large-area planar muon radiography system based on plastic scintillator arrays. The detector employs three layers of position-sensitive tracking modules composed of triangular-cross-section scintillator units. Scintillation photons are wavelength-shifted through wavelength-shifting fibers and subsequently converted to electrical signals by silicon photomultipliers. A custom-developed data acquisition system concurrently processes signals from all 384 scintillator channels. The effective area of the detector is 1.3 m², the detection efficiency exceeds 98.5%, and the position resolution reaches 1.9 mm.

Keywords: muon absorption radiography; plastic scintillator

INTRODUCTION

Muons at sea level are primarily generated by the decay of pions (π mesons) and kaons (K mesons) produced through interactions of primary cosmic rays with atoms in the upper atmosphere [1, 2]. Muons carry a unit of negative

charge and have a rest mass approximately 207 times that of an electron [3, 4]. Compared to electrons, muons experience lower radiation losses and primarily lose energy through Coulomb interactions, enabling them to penetrate hundreds to thousands of meters of rock [5, 6]. The muon flux at sea level is stable at approximately $1 \text{ cm}^{-2} \cdot \text{min}^{-1}$ [7] and follows a zenith angle distribution roughly proportional to $\cos^2\theta$ [8].

Based on the characteristics of muon interactions with target materials, muon radiography methods are primarily divided into two categories: muon absorption radiography and muon scattering radiography. Muon absorption radiography reconstructs the density distribution inside objects by measuring the attenuation of muon flux passing through the target, making it suitable for internal imaging of large-scale objects. Muon scattering radiography identifies materials by tracking changes in muon trajectories before and after penetration. Due to its heightened sensitivity to high-atomic-number materials, the latter technique is generally employed for detecting nuclear materials with higher atomic numbers.

The application of muon absorption radiography technology dates back to 1955, when E.P. George used a Geiger counter in a mine tunnel to verify the feasibility of using cosmic rays to measure the thickness of rock overburden [9]. In 2017, Morishima et al. discovered a hidden chamber inside Khufu's Pyramid by comparing experimental data with simulation results [10]. This discovery attracted widespread attention and promoted the development of muon absorption radiography technology globally. The Tanaka team in Japan has dedicated efforts to muon radiography of volcanic internal structures and achieved continuous monitoring of volcanic activity and structural changes [11-14]. They imaged the Athabasca uranium mine in Canada, and their experimental results were consistent with drill hole data, demonstrating the huge potential of this technology in mineral exploration [15]. Regarding muon scattering radiography, the Los Alamos National Laboratory (LANL) in the United States successfully applied muon radiography technology for the first time in 2003 [16]. The experiment successfully distinguished between tungsten and steel—two materials with different atomic numbers—by measuring the scattering angles of muons passing through them [17]. Since then, research institutions worldwide have conducted extensive technical exploration and applied research in muon scattering radiography. Overall, muon radiography technology has broad application prospects across various fields. The continued development of muon radiography technology will enhance the precision and reliability of material detection and radiography, particularly for high-density and thick objects, offering unique advantages [18, 19].

However, as application scenarios continue to expand, selecting and designing appropriate radiography detectors becomes critical [20]. Large-area muon imaging detectors not only enhance the muon counting rate and reduce imaging time but also expand the scanning range to enable comprehensive imaging of large-scale target objects. High-sensitivity muon imaging detectors can accurately reconstruct incident muon trajectories, improving the utilization efficiency of

muon events, thereby enhancing imaging quality and reducing the time required for object information reconstruction. Common muon radiography detectors include gas detectors, scintillator detectors, and nuclear emulsion detectors. Gas detectors offer good position resolution (typically on the order of hundreds of microns) but require high voltage and a flowing gas environment, and are subject to stability issues [21–23]. Nuclear emulsion detectors have high radiography accuracy but are complex to analyze and difficult to process data in real-time [24]. In contrast, scintillator detectors, while having lower position resolution, are stable, robust, and easy to process over large areas, making them widely used in muon radiography technology [25]. Selecting the appropriate detector for specific application scenarios is particularly crucial for imaging [26]. Additionally, with the development of silicon photomultiplier (SiPM) technology, SiPMs have replaced traditional photomultiplier tubes (PMTs) in many scenarios due to their high flexibility in design and excellent timing resolution [27], which has further advanced the development of scintillator-based muon radiography detectors [28].

As an archetypal example of scintillator-based muon radiography detectors, the INFN in Italy has developed two generations of muon radiography devices based on scintillators, namely MU-RAY and MIMA [29, 30]. Both generations of detectors utilize triangular-cross-section scintillator units to optimize muon track reconstruction. The MU-RAY system boasts an area of 1 m^2 with a position resolution of 2.3 mm. The MIMA, on the other hand, has a detection area of 0.16 m^2 and offers a position resolution of 3.3 mm.

In recent years, cosmic-ray muon absorption radiography technology has developed rapidly in China [31, 32]. For example, Lanzhou University has deployed a triangular-cross-section plastic-scintillator-based muon radiography system achieving a position resolution of 2.5 mm and a detection area of 0.25 m^2 , which has been applied in various scenarios [33]. The performance and application scenarios of the above detectors are shown in .

Summary of domestic and foreign triangular-cross-section plastic scintillation muon imaging detectors

Experimental group	INFN(MU-RAY)	INFN(MIMA)	Lanzhou University
Effective area	0.16 m^2	0.25 m^2	1 m^2
Position resolution	2.5 mm	3.3 mm	2.5 mm

This paper introduces μ Sight-1, a large-area muon absorption radiography detector based on plastic scintillators, developed by the Muon Radiography Group from Beijing Normal University [34–36]. Section 2 delineates the principle of muon absorption radiography and the specific structural design of the detector, including the overall detector architecture, the scintillator units and packaging,

and the method of light signal extraction. Section 3 elaborates on the front-end electronics for silicon photomultiplier (SiPM) signal readout and the data acquisition (DAQ) system implementation. Section 4 presents the performance test experiments and measurement results of the open-sky muon flux, including the detector position resolution and trigger efficiency. Section 5 summarizes the overall design and performance of the detector and offers suggestions for future improvements.

II. THE MUON ABSORPTION RADIOGRAPHY DETECTOR STRUCTURAL DESIGN

A. The Principles of Muon Absorption Radiography

Muon absorption radiography principles are analogous to those of X-ray radiography [37], relying on analyzing changes in muon flux passing through targets of varying densities and thicknesses, as illustrated in [FIGURE:1].

[FIGURE:1] The principle diagram of muon absorption radiography shows the muon flux in different directions. Only muons that are incident in the forward direction can be used for reconstructing the internal structure of the object.

The ionization energy loss of muons while traversing through objects can be described by the Bethe-Bloch formula [38]. Ideally, the muon transmission rate, T , varies with zenith angle, θ , and azimuth angle, ϕ . This variation can be expressed as follows [39]:

$$T(\theta, \phi) = \frac{N(\theta, \phi)}{N_{\text{sky}}(\theta, \phi)} = \frac{\int_{E_{\text{min}}}^{+\infty} \Phi(E) dE}{\int_0^{+\infty} \Phi(E) dE}$$

where $N(\theta, \phi)$ represents the actual measured muon flux passing through the target, while $N_{\text{sky}}(\theta, \phi)$ denotes the muon flux measured in open sky conditions. E denotes the energy of incident muons, and E_{min} represents the minimum energy required for muons to penetrate the object along their path. Density length refers to the product of a material's density (g/cm^3). Defining X_0 as the density length traversed by muons through the object under investigation, we derive:

$$E_{\text{min}} = \int_0^{X_0} \left\langle \frac{dE}{dx} \right\rangle dx$$

By combining Equations (1) and (2), the mass thickness distribution of the target object can be reconstructed from the muon flux distribution. This inversion process yields a two-dimensional projection map of the object's mass thickness.

In the application of muon absorption radiography, the ratio of measured flux to expected flux is often used to search for structural anomalies. The expected

muon flux $N_{\text{exp}}(\theta, \phi)$ can be obtained through Monte Carlo simulation. During the simulation process, a computational model is typically constructed based on the known structure and density of the target, from which the expected muon flux is derived. By comparing the measured flux with the projected values, structural anomalies within the target can be determined. Furthermore, muon absorption radiography technology can be used in conjunction with other techniques, such as seismic tomography (ST), electrical resistivity tomography (ERT), or gravity tomography [40, 41]. These supplementary methods can be used to correct the data, leading to better radiography results.

B. Design of Detector Structure

The muon radiography detector $\mu\text{Sight-1}$ uses three two-dimensional position detectors, forming a six-layer scintillator array (three layers in the X direction and three layers in the Y direction), to achieve precise measurement of muon trajectories. The overall structural design of the detector is shown in [FIGURE:2].

[FIGURE:2] The schematic diagram of the detector structure. Armor plates are on the 2nd and 4th layers, while muon position detectors are positioned on the 1st, 3rd, and 5th layers of the detector frame.

Three muon position detector boxes and two armor shielding layers are placed on the rectangular frame. Each position detector box contains two layers of orthogonally arranged scintillator arrays. The central detector box is fixed at the center of the frame. The distances between the other two detector boxes and the central box can be adjusted in the range of 0 to 1.1 m, which allows for adjustment of the muon acceptance angle between 60° and 180° . The six-layer scintillator setup effectively reduces the accidental coincidence rate. The armor shielding layer is composed of a 5 cm thick steel plate, which can shield low-energy muons with energy less than 150 MeV [42] and shower electrons with initial energy less than 0.1 GeV [43].

The rectangular frame is mounted on a triangular support frame and placed on a hexagonal base, whose leveling can be adjusted. The elevation angle of the detector can be adjusted between 0° and 90° , and the detector assembly is mechanically designed to execute 360° full rotation about the central axis of its base within the horizontal plane to adjust its azimuthal orientation. Due to the large size and number of the scintillators, the detector itself is quite heavy. To achieve detector weight reduction, the outer casing of the position detector boxes is made of aluminum and reinforced with aluminum profiles and steel fasteners to prevent deformation. The rectangular frame and the triangular support frame are made of standard aluminum profiles. The hexagonal base is made of steel. The modular design or multi-component design allows for flexible assembly and disassembly of the overall system, making it easier to transport to the detection site.

The internal structure of a single detector box is shown in

Figure 3

Figure 1: Figure 3

Figure 3

Figure 2: Figure 3

The interior of the two-dimensional position detector box features orthogonally arranged scintillator arrays in the X and Y directions. Within each direction, the scintillator units are staggered, with each scintillator unit alternating between upper and lower positions. Additionally, there are fasteners inside the box to secure the positions of the scintillator units.

It consists mainly of two layers of plastic scintillator arrays, one in the X direction and the other in the Y direction. Each layer contains 64 scintillator units. The structure of one scintillator unit is shown in

Schematic diagram of the structure of a single plastic scintillator unit.

The unit is 112 cm in length, with a cross-section of an isosceles right triangle with a base length of 3.4 cm and a height of 1.7 cm. The plastic-scintillator-based detection units are configured in a vertically staggered arrangement to form a rectangular active area. The energy deposited by a muon as it passes through the scintillator unit is proportional to the distance the muon travels through the scintillator [44]. By measuring the light signal detected in adjacent scintillator units, the incident position of a muon can be accurately calculated.

The scintillator units have a light yield approximately 60% that of anthracene crystals, with a light attenuation length of 2 m, making them suitable for large-area muon radiography detectors. Each scintillator unit uses a combination of scintillator material and optical wavelength-shifting (WLS) fiber BCF-92 to extract the scintillation light [45]. WLS fiber is a single clad fiber with a diameter of 1.5 mm. The bottom of each scintillator unit is mechanically grooved, and optical coupling agents are used between the scintillator and the optical fiber to enhance the number of scintillation photons entering the optical fiber. The entire scintillator unit is wrapped with a double-sided ESR reflective film to reflect scintillation photons and prevent interference between adjacent scintillator units. The two ends of the fiber are manually polished, with one end sealed with an aluminum film to minimize photon loss from the fiber, and the other end is used

Figure 4

Figure 3: Figure 4

Figure 4

Figure 4: Figure 4

Figure 5

Figure 5: Figure 5

for light signal extraction.

C. Plastic Scintillator Signal Readout

μ Sight-1 uses Hamamatsu's C series 3 mm \times 3 mm SiPMs to read out scintillator signals [46]. This series of SiPMs is well-matched with the output light wavelength after WLS fiber conversion and has the advantages of low operating voltage and high photon detection efficiency. The detection efficiency at the peak absorption wavelength of 460 nm is close to 50%. The optical fiber end face is polished and connected to the SiPM using the same optical coupling agent.

The entire system consists of 384 scintillator units, with each unit corresponding to one SiPM. Each optical fiber extends 10 cm from the scintillator and is coupled to the SiPM through a collimating plate. The collimating plate has fiber coupling holes aligned with the center of each scintillator unit's end face, as shown in

.

Schematic diagram of connection between WLS fiber and SiPM readout board.

The SiPM readout board is fixed on the outer side of the collimating plate, and the optical fibers are secured to each SiPM through these collimating holes. Due to the high manufacturing cost and fragility of overly long SiPM readout boards, the 64 SiPMs for each layer of scintillator array are divided into two groups. Each readout board is equipped with 32 SiPMs and has a length of 55 cm. In total, 12 SiPM readout boards are used to read the scintillator signals, with each pair of boards reading the signals from one layer of scintillator. The SiPMs are powered by Hamamatsu's power supply chips, each of which can simultaneously provide voltage for 64 SiPMs [47].

The operating state of the SiPM is influenced by the ambient temperature. When the temperature changes, the SiPM operating voltage needs to be adjusted to maintain gain stability. The front-end electronics can tune the SiPM supply voltage in response to changes in the ambient temperature. The change

Figure 5

Figure 6: Figure 5

in temperature is detected by a thermistor, which signals the power supply chip to adjust its output voltage. The temperature compensation coefficient is designed to be 34 mV/°C. The ambient temperature during SiPM operation is monitored using a PT-100 temperature measurement module mounted on the SiPM readout board. The temperature data is read by the host computer every second.

III. DETECTOR ELECTRONICS SYSTEM

A. Overall Design of Electronics

The DAQ system of μ Sight-1 consists of two modules: the front-end board and the main control board, as shown in [FIGURE:6].

[FIGURE:6] The schematic diagram of the DAQ system illustrates a structure comprising three X-plane detectors and three Y-plane detections. The main control board is utilized to process logical signals and receive data.

The entire system has a total of 384 signal inputs, with 12 front-end boards used to read out the signals from all the scintillator units, with each front-end board corresponding to one SiPM board. The main control board manages the operation of the 12 front-end boards and receives the data. The design and calibration details of the hardware circuitry are thoroughly explained in other articles [48]. Here, we will only introduce the composition and working principles of the hardware system.

B. Design of Front-End Board

The core component of the front-end board is a CITIROC chip [49]. This chip is specifically designed for SiPM signal acquisition, with a large dynamic input range (1-2500 photoelectrons), and each integrates 32 front-end channels. Each channel has two parallel, independent amplification and shaping paths: one for high gain and the other for low gain. Each channel is also equipped with a 4.5 V/8-bit DAC to adjust the operating voltage of the SiPM. The CITIROC chip has two operating modes: peak output mode and photon counting mode. In the peak output mode, the chip detects and latches the peak value of each signal that exceeds a predefined threshold. This is crucial for this study, as the peak values of muon event signals are needed for position reconstruction. Therefore, the peak output mode is employed.

When a signal arrives, the peak detector inside the CITIROC chip latches the peak value for any channel where the signal exceeds the threshold and waits for the readout command. 32 analog signals are serially output to two 12-bit ADCs (AD9220) for digital conversion of the high-gain and low-gain channels. The control of the acquisition chip is managed by an FPGA (EP4CE55) [50]. When the scintillator signal arrives, the CITIROC chip outputs a standard TTL trigger level. The FPGA receives this trigger signal and controls the CITIROC chip to serially output the 32 peak values and temperature data to the ADCs.

To improve the accuracy of measurements, both the high- and low-gain channels of the CITIROC chip are measured simultaneously.

The ADC sampling frequency can be adjusted between 1 MHz and 5 MHz. At a sampling frequency of 5 MHz, the data collection for a single event takes approximately 8 μ s. In normal operating mode, the power consumption of each front-end board is about 3.5 W.

C. Design of Main Control Board

The main functions of the control board include coincidence determination, time-of-flight (ToF) measurement, and data reception and transmission. Communication between the front-end board and the control board uses 12 parallel 422 serial ports (up to 10 Mbps). The trigger signals generated by the CITIROC chips on the 12 front-end boards are ORed together into a single signal and fed into the control board for logical evaluation. These 12 trigger signals are grouped into six pairs, representing the X-direction and Y-direction detector layers for the three position detectors. The coincidence time window for the six trigger signal pairs is set to 1 μ s. The trigger signals participating in the coincidence can be freely combined.

When the coincidence conditions are met, the control board instructs the front-end boards to parallelly transmit data to the FIFO memory of the control board. Upon receipt of the trigger, the TDC module within the FPGA on the control board precisely measures the time at which each trigger signal is received. Communication between the control board and the host computer is carried out using a 100 Mbps Ethernet connection. This high-speed communication ensures efficient data transfer and real-time monitoring of the system's performance.

The entire system has a low power consumption of only about 50 W, making it convenient for deployment in various application scenarios. With the addition of remote control software, it enables remote control of the experimental apparatus and data transmission. A 12 V DC regulated power supply provides power to the main control board and the 12 front-end boards. The control software can configure parameters, control operation, and switch the DC power supply on/off via dedicated software.

D. Host Computer Software Control

The host computer software is developed using Python based on QT5.12. It directly controls the main control board to issue all commands and collect detection data. Before detector operation, the software needs to configure the working states of each front-end board, including parameters such as channel gain, signal shaping time, and channel trigger thresholds. The six trigger signal groups used for coincidence can be set to different trigger states via the control software. The operating voltage can be adjusted between 20–80 V for SiPMs.

During the detector's operation, the control software receives the 384 signals

from a single event uploaded by the main control board, as well as the timing information of the trigger signals, and saves them as human-readable files for subsequent offline analysis. The software also displays the positions of the scintillator units that triggered the signal in each coincidence event, as shown in [FIGURE:7].

[FIGURE:7] The depiction of plastic scintillator units hit by a muon event as the muon traverses the detector, with the intersection of the X and Y directions indicating the hit position. The depth of color represents the amplitude of the muon signal in the plastic scintillator unit. Figure (a) represents a single muon event, while Figure (b) represents a high-energy particle cluster event.

IV. DETECTOR TESTING AND PERFORMANCE ANALYSIS

The data analysis section of the article primarily includes three parts: detector response uniformity, position resolution capability, and open-sky measurements. The impact of detector response uniformity involves two aspects. On one hand, the non-uniformity of each scintillator unit affects the accuracy of two-dimensional position coordinate reconstruction, which is caused by the use of the centroid method for incident position correction. On the other hand, the non-uniformity of the detector plane response leads to inconsistencies in detection efficiency for muons incident at different angles, ultimately affecting the measured muon flux distribution. Position resolution capability directly influences the quality of muon absorption radiography. The higher the resolution, the more detailed the radiography of the density distribution of the object under investigation. These two parameters directly affect the accuracy of muon flux reconstruction. By comparing GEANT4 simulation results using a standard muon flux model with actual experimental measurements, the accuracy of the muon radiography system can be validated.

A. Detector Response Uniformity

Set the overvoltage of the SiPM to 3 V, with a low-gain channel amplification factor of 30. Utilize the analog probe function of the CITIROC chip to output the raw waveform after single-channel amplification and shaping. The results of the cosmic ray spectrum for a single scintillator unit are shown in [FIGURE:8].

[FIGURE:8] The results of the cosmic ray spectrum test for a single scintillator unit.

We can determine the system's trigger threshold based on the electronics calibration results. The analog probe is used to collect the energy spectrum because, in peak detection mode, the CITIROC chip only outputs radiation signals that exceed the set threshold. If the threshold is set too low, continuous triggering can cause baseline drift in the chip.

Because data from both high and low gain channels were collected simultaneously, the maximum acquisition value for the 12-bit ADC is 4096. As shown in FIGURE:9, the high gain portion has reached saturation. These saturated signals lose their energy information. As shown in FIGURE:9, prior to the saturation point Q, the peak values from both the high and low gain channels are linearly related to the input charge. A linear relationship between the high and low gain channels can thus be fitted for either channel.

[FIGURE:9] The high-gain saturation correction results, based on the fitted relationship, effectively improved the experimental accuracy. Panel (a) shows the correspondence between the high and low gain channels. Panel (b) presents the cosmic ray energy spectra for both high and low gains, along with the corrected high-gain energy spectrum.

$$V_H = 3.273V_L - 144.7509$$

where V_H and V_L represent the signal peak amplitudes for the high and low gain channels, respectively. As shown in the formula, due to the presence of the SiPM inter-electrode capacitance, the linear equation does not pass through the origin. This formula was used to correct the high gain saturation portion, effectively merging the values from both the high and low gain channels. The combined data allows for more accurate position resolution calculations. The blue line in FIGURE:9 represents the amplitude correlation between high-gain and low-gain channels after saturation correction. This formula provides a unified representation of the energy deposited by muons in the scintillator.

Based on the cosmic ray spectrum test results and electronics calibration results, a threshold of 5 photoelectrons is adopted. Cosmic ray signals are collected under the conditions of a low gain of 50 and a high gain of 20. The average deposited energy values for the 384 scintillator units, after packaging in the detector box, are shown in FIGURE:10.

[FIGURE:10] The average deposited energy in low-gain channels of the 384 plastic scintillators are shown in (a). Panel (b) is two-dimensional distribution of average signal amplitudes across the detector plane.

The average output amplitudes of the 384 scintillator units exhibit overall uniformity, though isolated channels demonstrate relatively lower outputs. In addition, the responsivity to muons varies across different positions on its planar surface. By reconstructing muon trajectories, we obtained the two-dimensional distribution of average signal amplitudes across the detector plane, as presented in FIGURE:10. The results show the signal nonuniformity within a scintillator unit, which is larger the closer to the SiPM. This response non-uniformity directly impacts muon flux measurements. Quantitative assessment of its effect requires comparative validation in subsequent experiments.

Although we strive to ensure that all scintillator units have consistent detection performance, there are still some variations in their performance. Signal ampli-

tude correction can reduce the impact of these differences on the consistency of the detector. When calculating the actual deposited energy E_{dep} , it is adopted that:

$$E_{\text{dep}} = \frac{V_i}{V_{i-\text{Avg}}}$$

where V_i represents the signal amplitude of the scintillator in a single event. $V_{i-\text{Avg}}$ is the average signal amplitude of the 64 scintillator units in that layer. The reason for selecting 64 units is that the SiPMs reading out the signals from every 64 scintillators are powered by the same power supply.

B. Muon Track Reconstruction

The core of muon radiography is the precise measurement of the muon trajectory. When a muon passes through the detector, it can be considered to propagate in a straight line. Each position detector can provide the coordinates of the muon impact location. As shown in [FIGURE:11], taking a single layer as an example, assume that the incident muon generates signals greater than the threshold on two adjacent scintillator units. The true impact position of the muon is denoted as (x, z) . The energy deposited on the adjacent scintillator units are E_1 and E_2 .

[FIGURE:11] Schematic illustration of muon hit position calculation in a plastic scintillator array.

Since the thickness of the reflective film packaging is greater than zero, the spacing between adjacent scintillator units cannot be exactly zero. To standardize the real positions of the scintillator under this packaging, during the actual assembly process, the distance between the top corners of adjacent scintillator units at the bottom is controlled to be 1 mm. This ensures that the actual position of each scintillator unit aligns strictly with its theoretical position. The energy deposited by the muon is proportional to the distance it travels through the scintillator. The true impact position can be described as:

$$x = x_0 + 1.8 \frac{E_1}{E_1 + E_2}, \quad z = z_0 + 1.7 \frac{E_1}{E_1 + E_2}$$

The six-layer detector reconstructs three (x, z) coordinates on the XOZ plane and three (y, z) coordinates on the YOZ plane, as shown in [FIGURE:12]. The intersection line of these two reconstructed planes represents the incident trajectory of the muon.

[FIGURE:12] Schematic of muon track reconstruction.

C. The Position Resolution and Muon Detection Efficiency

Position resolution testing requires precise measurement of the incident muon trajectory. In the absence of detectors with higher position resolution for test-

ing, we constructed a 6-layer position resolution measurement system using 384 scintillator units. Each layer consists of 64 scintillator units arranged parallel in one direction. The experimental setup is shown in [FIGURE:13].

[FIGURE:13] The schematic for position resolution test. The physical layout of six detection planes is on the right-hand side.

The vertical distance between adjacent layers is 40 cm, and the positions of the scintillator units within each layer are aligned vertically. During the testing process, the lighting condition is set to a darkroom. The muon trajectories can be reconstructed using the position calculation method mentioned in Section IV.B.

For the position resolution test, the 3rd layer of the 6 layers is intentionally set not to participate in the muon event coincidence, serving as a test layer, while the remaining 5 layers are used to reconstruct the muon trajectory. The linear fitting equation can be described as $x = f(z)$, and the residuals of the five layers participating in the fit are calculated as:

$$\Delta x_{\text{fit},i} = x_{\text{measure},i} - x_{\text{fit},i} = x_{\text{measure},i} - f(z_{\text{measure},i}) \quad i = 1, 2, 4, 5, 6$$

The chi-square (χ^2) for the fitted straight line is given by:

$$\chi^2 = \sum_{i=1,2,4,5,6} \frac{(x_{\text{measure},i} - x_{\text{fit},i})^2}{\hat{\sigma}^2}$$

where $\hat{\sigma}$ represents the position resolution of each layer. However, since the position resolution is the quantity to be determined, we adopt an iterative straight-line selection method. Initially, set $\hat{\sigma}_0 = 10$ mm and substitute this value into the chi-square expression to compute the chi-square of the fitted straight line. The selection criterion for the straight line is $\chi^2 < 7.82$, which corresponds to 3 degrees of freedom and a significance level of 0.05. For those that meet the straight-line criterion, we estimate the position resolution $\hat{\sigma}$ using:

$$\hat{\sigma}_k = \sqrt{\frac{1}{5} \sum_{i=1,2,4,5,6} \sigma_i^2} \quad i = 1, 2, 4, 5, 6$$

where k is the number of iterations. Substitute the computed value of $\hat{\sigma}_k$ into the chi-square formula in the next iteration to re-calculate the chi-square value. Once the value of $\hat{\sigma}$ converges, the straight lines are selected based on this value. The value of $\hat{\sigma}$ is not changing at this point. The residual distribution of the test layer can then be calculated as:

$$\Delta x_{\text{fit},3} = x_{\text{measure},3} - x_{\text{fit},3} = x_{\text{measure},3} - f(z_{\text{measure},3})$$

A Gaussian fit is performed on the residual distribution of the test layer to estimate the apparent position resolution σ_3 . Assuming that the position resolutions of all six layers are identical, the error propagation relationship can be derived to estimate the single-layer position resolution:

$$\sigma = c \cdot \sigma_{3,\text{fit}}$$

where $\sigma = 1.9$ mm, c is the error propagation factor, with $c = 1.105$. As shown in [FIGURE:14], this is due to the least squares method. Among the five layers involved in the linear fit, the σ_i values at cap layers are lower. Although the position resolution can be obtained with the 5 fitting layers, we still retain an independent test layer to calculate the position resolution. If the position resolution calculated using the test layer is close to that obtained from the five-layer fit, this further supports the validity of our assumptions and method.

[FIGURE:14] Standard deviation results of the 5-layer linear fit and the test layer fit.

The detection efficiency of muons is critical for the detector system. To determine the muon trigger efficiency of the detector, the position resolution test was conducted by comparing the total counts of the test layer (Layer 3, which does not participate in triggering) with the total counts from the remaining five layers. Using the test results from the third layer, the final muon-induced trigger efficiency of the 3rd detector was found to be 98.5%, as shown in . The counts in the table are directly printed out through the RS232 serial port of the main control board. During the muon detection process, the number of events uploaded by each preamplifier board is counted. The number of uploads from the detectors involved in the coincidence is consistent with the number of triggers. However, the detectors in the layer to be tested do not participate in the coincidence. Their upload counts can be used to calculate the muon detection efficiency (where 5-layer coincidence events are considered muon events). Both the position resolution experiment and the trigger efficiency experiment used a threshold of 5 p.e.

The counts are directly printed out through the RS232 serial port of the main control board

Total count	Count of layers to be tested	Detection efficiency
		98.5%

Generally, under conditions where the overvoltage of the SiPM and the gain of the front-end amplifier remain constant, a higher threshold leads to lower position resolution of the detector. The muon detection efficiency is effectively a superposition of the actual efficiency of detecting muons and the efficiency of other triggering events. If the threshold is set too low (below the SiPM's

dark noise level), the event rate in the detection layer will far exceed the muon count rate, resulting in an overestimated calculated value of muon detection efficiency. Therefore, striking a balance between position resolution and muon detection efficiency is crucial for the successful application of muon absorption radiography technology. By precisely reconstructing muon trajectories while maximizing detection rates, researchers can obtain detailed and reliable data for applications such as geological and archaeological surveys, infrastructure assessment, and more.

D. Open-Sky Measurements

To obtain the mass thickness distribution of a measured object based on muon absorption radiography principles, accurate open-sky muon flux measurements are essential. The experimental setup ([FIGURE:15]) was configured with a detector spacing of 1 m and zenith angle of 12° for open-sky muon measurements. The open-sky measurement was conducted over 10 days without any modification to the detector's parameter configuration during this period.

[FIGURE:15] The panel shows the assembled muon radiography detector with its elevation angle adjusted to 12° .

We use GEANT4 simulations to obtain the open-sky muon zenith angle distribution [51]. The muon source was generated by sampling from the empirical differential cosmic-ray muon energy spectrum formula (Reyna) at sea level. The sampling range was from a zenith angle of 43° to 90° and energy from 0.1 GeV to 2000 GeV.

The results are shown in [FIGURE:16]. The measured open-sky muon zenith angle distribution is consistent with that obtained from simulation. The high consistency between the measured open-sky muon flux at different angles and the simulation results forms the basis for the reliability of the muon absorption radiography results.

[FIGURE:16] Panel (a) is the distribution of the zenith angle θ compared with the GEANT4 simulation results. Panel (b) is open-sky rates with the detector placed with an elevation angle of 15° .

V. CONCLUSION

The muon radiography device μ Sight-1 is based on plastic scintillators and uses triangular cross-section scintillator units. It employs WLS fiber to extract scintillation light signals, which are then converted to electrical signals by SiPMs. The system is based on the CITIROC integrated chip, offering a 384-channel signal readout capability. Tests show that the detector achieves a muon detection efficiency of 98.5% and a position resolution of 1.9 mm. This device can be widely applied in muon absorption radiography research for the detection of the internal structures of large objects.

In addition, as the first-generation muon radiography device independently developed by the group, some aspects of the design can be further improved. For example, the actual position deviation caused by the lack of limit devices in the scintillator unit and the inaccurate output accuracy and temperature compensation coefficient of the SiPM power supply system. Addressing these issues and adapting to different experimental scenarios, our group will continue to improve and upgrade the detector system to meet the evolving needs of muon absorption radiography technology. Modular, user-friendly, and environmentally adaptable muon radiography devices are currently in our plans.

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