



Article

Detector Response and Energy-Threshold Optimization for Imaging with Cosmic-Ray Muon-Induced Secondary Radiation

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Abstract

Imaging with cosmic-ray muon-induced secondary radiation complements muon transmission radiography and muon scattering tomography by exploiting the electrons and bremsstrahlung photons created along the muon track inside the target. Because these secondaries are produced predominantly at low energies, the performance of such a system depends critically on parameters that are usually treated as routine: the uniformity of the response of the surrounding scintillator array and the energy threshold applied during acquisition. This contribution reports the instrumental characterization of the muon camera (MUCA) setup operated at the University of Novi Sad, comprising a five-layer Close Cathode Chamber tracker and four large-area plastic scintillation detectors. Over a continuous run of about 24 h, the combined tracking efficiency was about 0.96 and stable at the percent level. Single-detector and joint spectra recorded with ¹³⁷Cs and a bulk KCl source were used to equalize the high voltage across the array, and the acquisition threshold was set to approximately 230 keV. A direct comparison of images of a copper cylinder reconstructed with a 250 keV and with a 1 MeV analysis cut shows that the conventional MeV-level threshold discards the majority of the target-related signal. The corresponding limitation of the geometrical acceptance is also discussed. The design of the COMIS upgrade, which extends the scintillator coverage to the forward region and introduces a compact multi-channel readout, is outlined together with a first map of the light collection uniformity of its large-area scintillators.

Keywords: muography; muon-induced secondary particles; plastic scintillation detectors; energy threshold; detector calibration; Close Cathode Chamber



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1. Introduction

Cosmic-ray muons are an omnipresent and highly penetrating probe. At sea level their integral flux is about $1 \text{ cm}^{-2} \text{ min}^{-1}$ with a mean energy of approximately 4 GeV, and their angular distribution follows a $\cos^2\theta$ law [1,2]. Two approaches dominate applied muography. Muon transmission radiography measures flux attenuation and is suited to geological and architectural volumes [3,4], whereas muon scattering tomography exploits multiple Coulomb scattering and is exceptionally sensitive to high-Z materials in cargo- and cask-sized objects [5,6]. Neither modality performs well for compact, low-Z and low-density targets: the attenuation of the muon flux is negligible, and the scattering angles fall below the intrinsic angular resolution of practical tracker arrays.

The complementary approach used in this study forms the image from the secondary radiation generated by the muon inside the target itself. Knock-on electrons produced

by direct ionization, together with the bremsstrahlung photons, are emitted, and their escape probability is governed by the self-absorption of the matrix, so that the detected secondary signal carries information on both the effective atomic number and the density of the traversed material [7–10]. In this sense, the technique probes the properties of the condensed matter of the target itself: the yield and the energy spectrum of the escaping secondaries are determined by the density, the effective atomic number and the self-absorption of the material in which they are generated. Our group has developed this modality through a series of setups, including the characterization of the low-energy continuum produced in pure low-Z materials and images obtained with a dual muon tracker combined with plastic scintillation detectors [11].

The present contribution is deliberately restricted to the instrumental side of the technique. This study reports the calibration and response equalization of the scintillator array of the muon camera (MUCA) setup, the determination of the acquisition energy threshold together with its practical consequences for image quality, and the efficiency, angular uniformity and stability of the muon tracker. Additionally, the design rationale of the COMIS (COsmic Muon Induced Secondaries) upgrade is discussed, and the light collection efficiency map of a $50 \times 50 \times 5 \text{ cm}^3$ scintillator is presented.

The two setups considered here are successive stages of the same development and are complementary. MUCA, operated in Novi Sad, combines a five-layer CCC tracker of $25 \text{ cm} \times 25 \text{ cm}$, placed above the imaging volume, with four large-area plastic scintillators covering its vertical faces; the scintillator signals and the tracker time stamps are recorded independently, and the coincidence is formed offline. This makes MUCA well suited to a systematic study of the acquisition parameters (detector equalization, energy threshold and coincidence window) on one and the same data set, which is the main subject of this work. Its limitations, namely the missing coverage of the forward region below the target and the offline matching of large raw data sets, motivated the construction of COMIS at the Wigner Research Centre for Physics in Budapest. COMIS keeps the same imaging volume and side detectors, but adds four segmented scintillators below the target, uses a larger $51 \text{ cm} \times 51 \text{ cm}$ tracker placed below the target, and employs a common, hardware-triggered data acquisition. Both setups are included in this paper because the conclusions drawn from the characterization of MUCA define the design choices of COMIS, whose first performance checks are reported in Section 4.

The quantitative analysis of material discrimination obtained with these setups will be the subject of a separate, more extensive publication.

2. Materials and Methods

2.1. The MUCA Setup

The MUCA setup (Figure 1a; schematic in Figure 1b) has been in operation at the Faculty of Sciences, University of Novi Sad, Serbia. The muon trajectory is reconstructed by a tracker built from five Close Cathode Chamber (CCC) layers of $25 \text{ cm} \times 25 \text{ cm}$ active area, segmented into $4 \text{ mm} \times 4 \text{ mm}$ pixels [12,13]. The CCC is an asymmetric multiwire proportional chamber; each layer provides two-dimensional position information with projective geometry, typically with better than 95% efficiency (Section 3.1 with the values obtained in this work) and with less than one noise cluster per layer, which makes the pattern recognition unambiguous. The tracker is mounted directly above the imaging volume. In the following, the five tracker layers are numbered from 1 (top) to 5 (bottom).

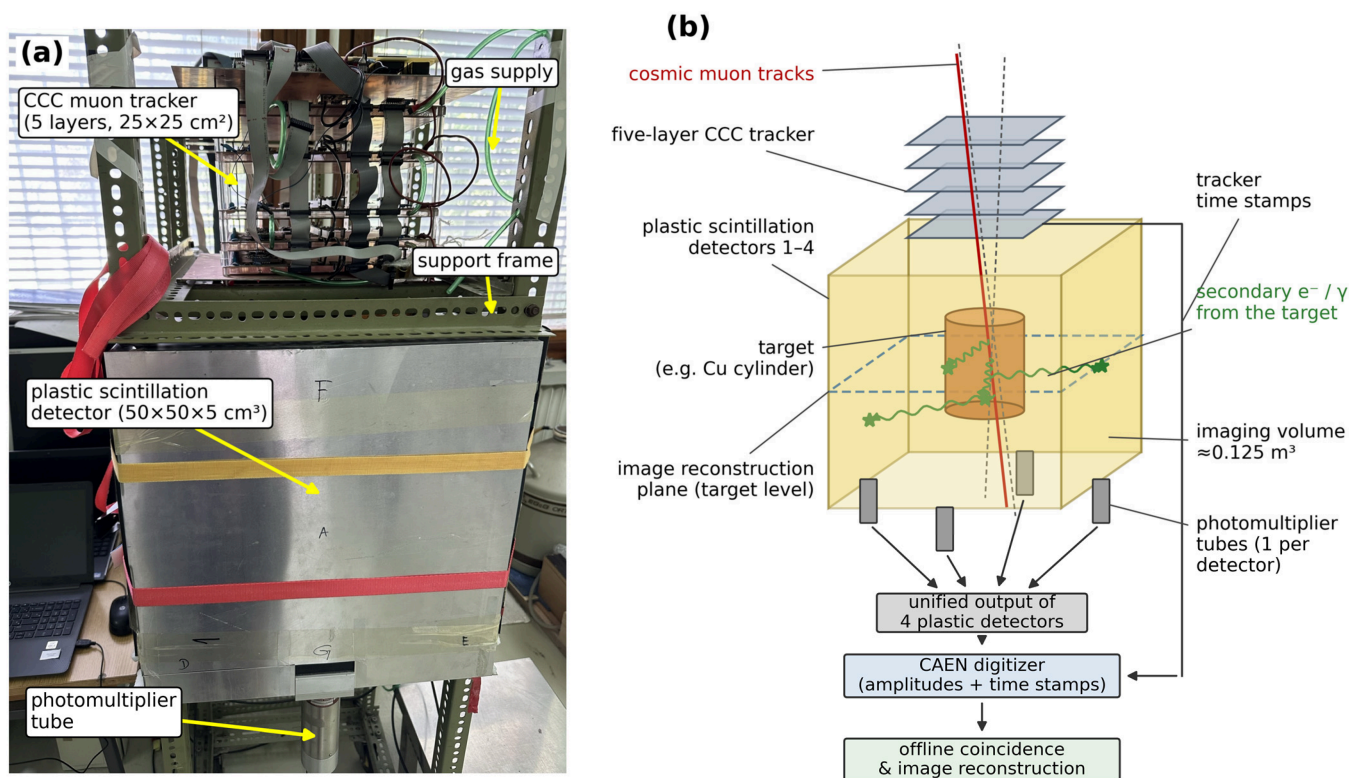


Figure 1. The MUCA setup at the University of Novi Sad: (a) photograph of the setup with the main components indicated; (b) schematic drawing (not to scale) of the five-layer CCC muon tracker ($25\text{ cm} \times 25\text{ cm}$ active area) mounted above the box formed by the four $50\text{ cm} \times 50\text{ cm} \times 5\text{ cm}$ plastic scintillation detectors that enclose the imaging volume. A muon track crossing the target (red) and the secondary electrons and photons escaping towards the scintillators (green) are indicated, together with the image reconstruction plane at the target level (dashed) and the readout chain.

The secondary radiation escaping the target is registered by four plastic scintillation detectors of $50\text{ cm} \times 50\text{ cm} \times 5\text{ cm}$, arranged as a box and thus enclosing an imaging volume of about 0.125 m^3 . The detectors are unshielded and therefore continuously exposed to the ambient gamma background of the laboratory. Each scintillator is read out by its own photomultiplier tube (PMT). Signal amplitudes and time stamps from the scintillators, together with the time stamps of the tracker, are recorded by a CAEN digitizer (CAEN S.p.A., Viareggio, Italy), and the coincidence between a reconstructed muon track and a scintillator signal is formed offline.

2.2. Calibration and Response Equalization

Because the image is built from the coincident response of four independent detectors, any difference in their gain translates directly into a spatially dependent detection probability and hence into an artifact in the reconstructed image. The energy calibration was therefore performed for each detector separately, using a standard ^{137}Cs source and a bulk potassium chloride (KCl) sample, the latter providing an extended, low-activity reference rather than a point source. The high voltage of each PMT was then adjusted iteratively: after each step, the single-detector ^{137}Cs spectra were recorded and compared with each other, and the voltages were changed until the positions of the Compton edges and the shapes of the four spectra coincided over the full energy range. The result was finally cross-checked with the KCl sample and with the joint spectrum of the array. Uniformity within a single scintillator is discussed in Section 4.

2.3. Track Reconstruction and Coincidence

In each CCC layer, all sense wires are connected, so that a crossing muon produces a signal in the layer irrespective of the crossing point, while the segmented cathode and the field wires provide the position. The hit coordinates are combined by a combinatorial tracking algorithm applied independently to the two orthogonal projections of the chambers; straight lines are fitted to all hit combinations, and the trajectory with the best reduced chi-squared is retained. A track is reconstructed when at least four of the five layers provide a hit.

The reconstructed trajectory is extrapolated to the horizontal plane of the target, giving the coordinates at which the muon entered the imaging volume. If a scintillator signal exceeding the acquisition threshold falls within the coincidence window of the corresponding detected muon, the event is accepted as a secondary-particle detection associated with that trajectory, and the intersection point is entered into the image. Because the coincidence is formed offline from the recorded time stamps, the window and the energy cut can be varied on the same data set (see Section 3.3).

3. Results and Discussion

3.1. Tracker Performance

The performance of the muon tracker was evaluated on a continuous run of approximately 24 h. Figure 2a shows the tracking efficiency as a function of the direction of the incident muon, parameterized by the tangents of the projected zenith angles; the corresponding angles are given on the secondary axes. The efficiency exceeds 0.9 over the whole central region and degrades only towards the extreme corners of the angular acceptance, where the path length through the chamber stack is longest, and the geometrical overlap of the five layers is smallest. Figure 2b shows the corresponding angular distribution of the acceptance-corrected muon flux, which peaks at the vertical and falls off with increasing zenith angle, as expected for the sea-level cosmic-ray flux. Its projection onto the zenith angle θ , obtained by averaging the flux map in 4° wide intervals of θ , is shown in Figure 2c.

A fit of the form $I(\theta) = I_0 \cos^n \theta$ up to $\theta = 45^\circ$ gives $n = 1.71 \pm 0.04$ (statistical uncertainty only), somewhat lower than the value $n \approx 2$ commonly quoted for the sea-level muon flux [1]. The difference is attributed mainly to the systematic uncertainty of the acceptance correction towards the edge of the angular acceptance, which is not included in the quoted error.

Figure 3 shows the time evolution of the tracking efficiency over the same run, separately for the five layers and for the tracker as a whole; the dashed horizontal lines indicate the mean value of each curve. At the operating point of this run, the individual layer efficiencies range from 0.878 (layer 1) to 0.969 (layer 3), while the tracking efficiency of the tracker is 0.965. The latter is higher than that of the weakest layer because a track is reconstructed whenever at least four of the five layers register a hit (Section 2.3): assuming independent layers, the probability of this condition calculated from the five mean layer efficiencies is 0.965, in agreement with the measured value. What matters for imaging, however, is not only the absolute value but also the stability of the system: each curve is flat over the full day, with fluctuations at the percent level that are compatible with the statistical uncertainties of the individual points, and without drift, so that the exposure accumulated in different parts of a multi-day acquisition can be compared directly without a time-dependent correction. Figure 4 shows the corresponding distributions of the residuals of the fitted tracks for each layer, in the two orthogonal projections x and y . The distributions are centered to within 0.1 pad widths (0.4 mm), and their root-mean-square widths range from 0.4 to 0.7 pad widths (1.6–2.8 mm), confirming the millimeter-scale position resolution assumed in the reconstruction.

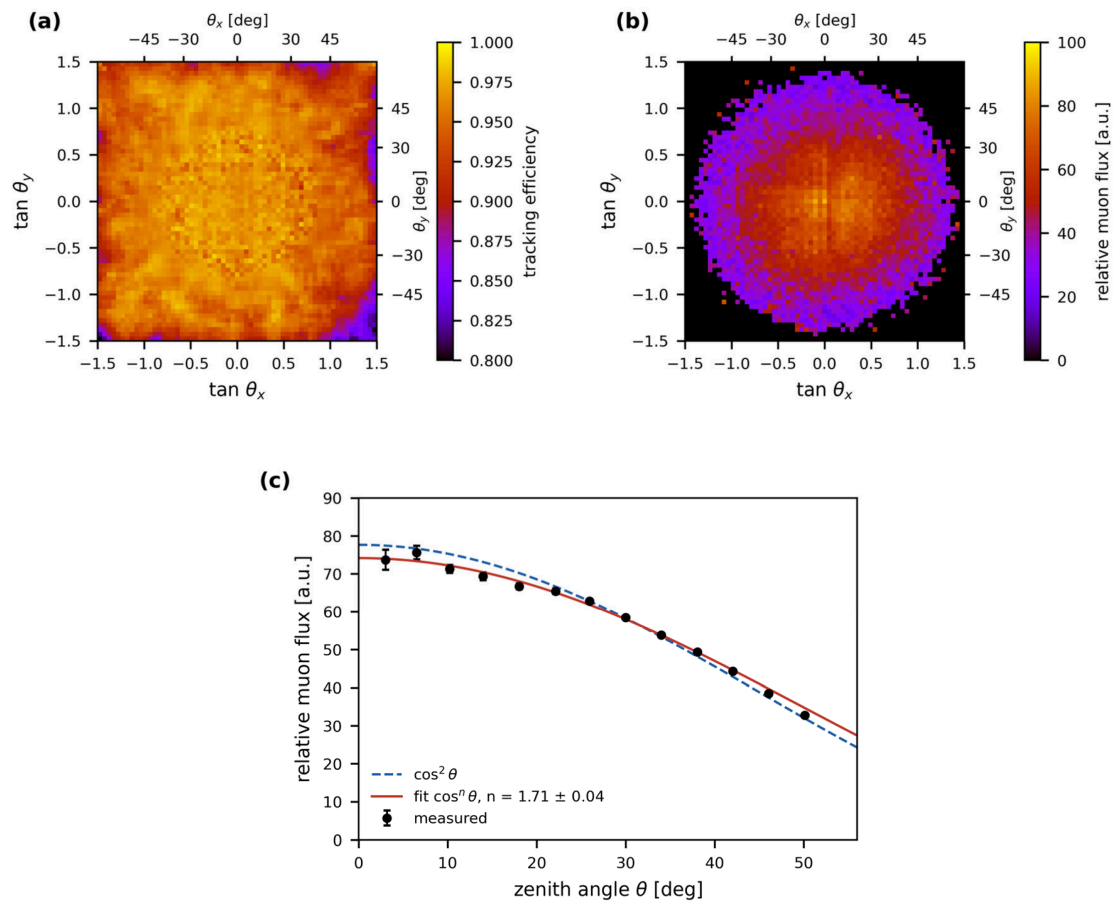


Figure 2. Angular dependence of the tracker response for a continuous 24 h run: (a) tracking efficiency as a function of the tangents of the projected zenith angles θ_x and θ_y (the corresponding angles in degrees are given on the top and right axes); (b) angular distribution of the acceptance-corrected muon flux; (c) projection of the flux onto the zenith angle θ , compared with a $\cos^2\theta$ dependence and with a fit of the form $\cos^n\theta$.

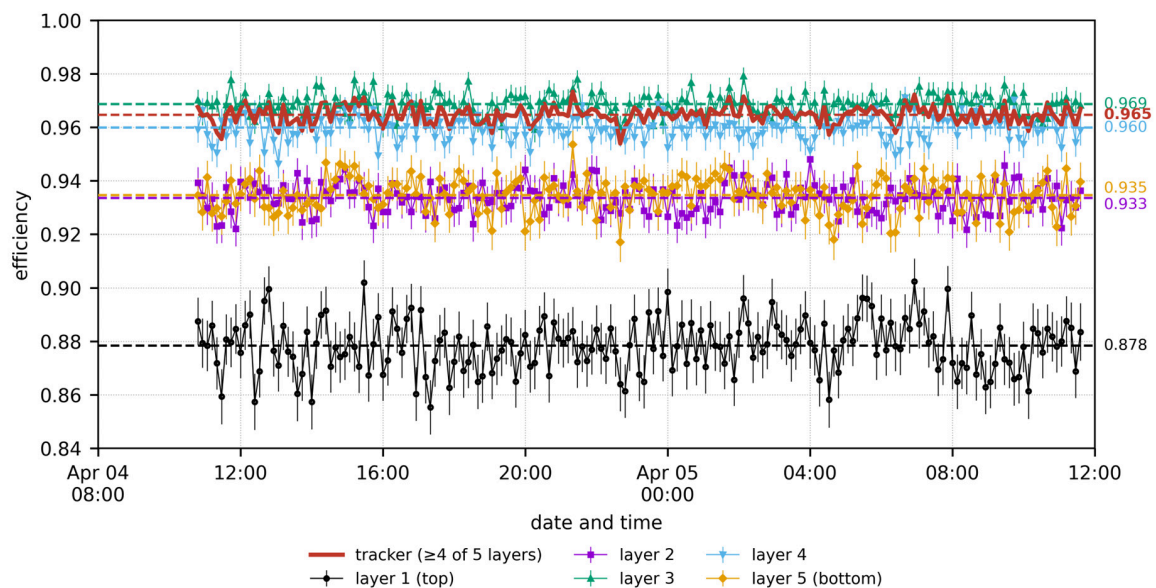


Figure 3. Stability of the tracker over the same run: time evolution of the tracking efficiency of the five individual CCC layers, numbered from 1 (top) to 5 (bottom), and of the tracker as a whole (thick red line). Each point corresponds to 8 min of data taking; the dashed lines and the numbers on the right indicate the mean values.

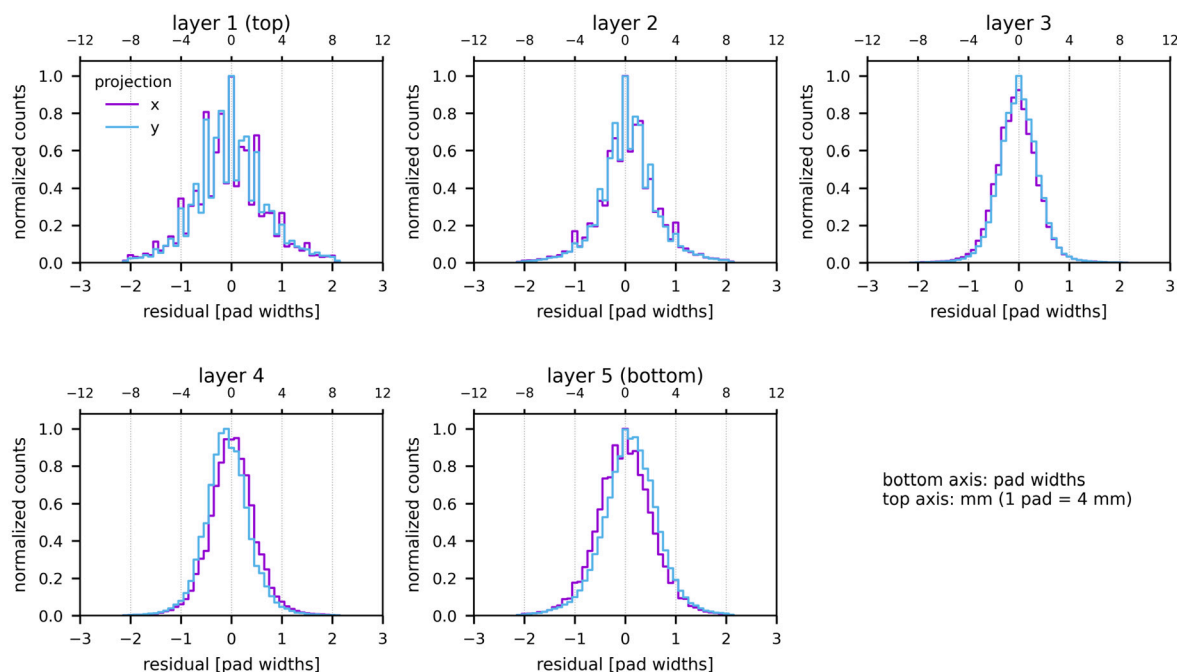


Figure 4. Residual distributions of the fitted tracks for the five CCC layers over the same run, for the two orthogonal projections x (purple) and y (blue). The residuals are given in units of the pad width (bottom axis; 1 pad width = 4 mm) and in millimeters (top axis); the histograms are normalized to their maximum.

3.2. Uniformity of the Scintillator Array

Figure 5a shows the four single-detector spectra acquired with the ^{137}Cs source after the high-voltage adjustment, while 5b shows the same spectra acquired with the bulk KCl sample. The spectra are shown separately because the equalization can only be verified detector by detector; the energy range is limited to about 14 MeV, which covers the gamma-induced distributions and the region relevant for the secondary particles. On the logarithmic scale, the four distributions closely overlap over the whole range, indicating that the array responds uniformly and that no geometrical weighting has to be applied to compensate for detector-to-detector differences. This qualitative agreement was considered sufficient for the purpose of the present measurements; a quantitative channel-by-channel comparison of the four spectra has not been performed at this stage. Figure 5c shows the joint background spectrum of the array, displayed up to 45 MeV in order to include the full muon contribution. The joint spectrum extends far beyond the endpoint of the individual gamma-induced distributions, up to several tens of MeV, because it contains the energy deposited by muons crossing the scintillator slabs; the Landau-type muon contribution near 10 MeV per slab is thus clearly separated from the low-energy region in which the secondary particles are expected.

3.3. Choice of the Acquisition Threshold

Portal monitors and scattering-tomography systems commonly operate with a hardware threshold of the order of 1 MeV, chosen to suppress environmental gamma rays. For secondary-radiation imaging, this choice is counterproductive, as shown below. The differential cross-section for the production of a knock-on electron of kinetic energy E_k by a relativistic charged particle scales approximately as $1/E_k^2$ [2], so that most of the secondaries generated in the target, and of the bremsstrahlung photons they subsequently emit, appear well below 1 MeV.

The joint spectrum of the array is shown in Figure 6, with the applied cut indicated. The acquisition threshold was set at the tenth channel of the CAEN digitizer, corresponding to approximately 230 keV, which is as low as the system can be operated without the noise rate of the photomultipliers becoming the dominant trigger source; a slightly more conservative cut of 250 keV was then applied in the offline analysis. This limit was determined empirically by lowering the threshold until the trigger rate started to increase steeply; a systematic measurement of the dark-count and random-coincidence rates as a function of the threshold has not been performed at this stage. Random coincidences with the ambient gamma background are, in any case, strongly suppressed by the narrow time window of the offline coincidence with the reconstructed muon track [8,11].

The practical consequence of this choice is illustrated in Figure 7, which compares two reconstructions of the same data set recorded with a copper cylinder placed in the imaging volume, the only difference being the energy cut applied to the scintillator signals. With the 250 keV cut, the wall of the cylinder is clearly outlined against the surrounding background. With a 1 MeV cut, the same structure is barely recognizable: the majority of the target-related coincidences are rejected, the statistical fluctuations of the remaining sample dominate, and the contrast between the target and its surroundings collapses. Acquiring the low-energy part of the spectrum is therefore not an optimization but a prerequisite for this imaging modality. The comparison presented here is qualitative; a quantitative evaluation of the image quality (signal-to-noise and contrast-to-noise ratios, line profiles across the object) requires a dedicated set of reference measurements and is planned within the forthcoming study of material discrimination.

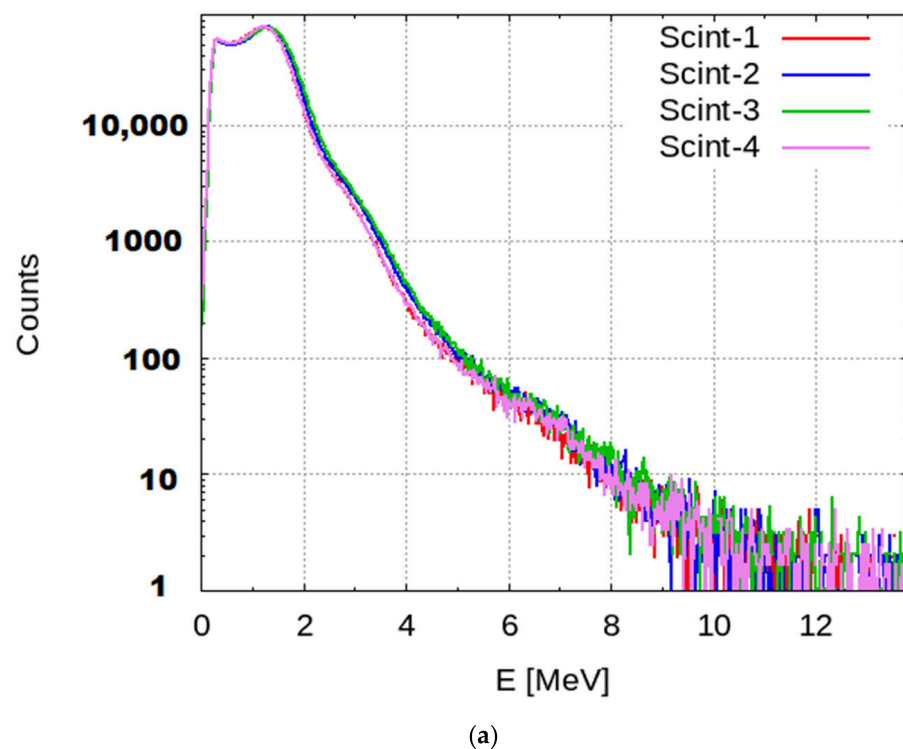
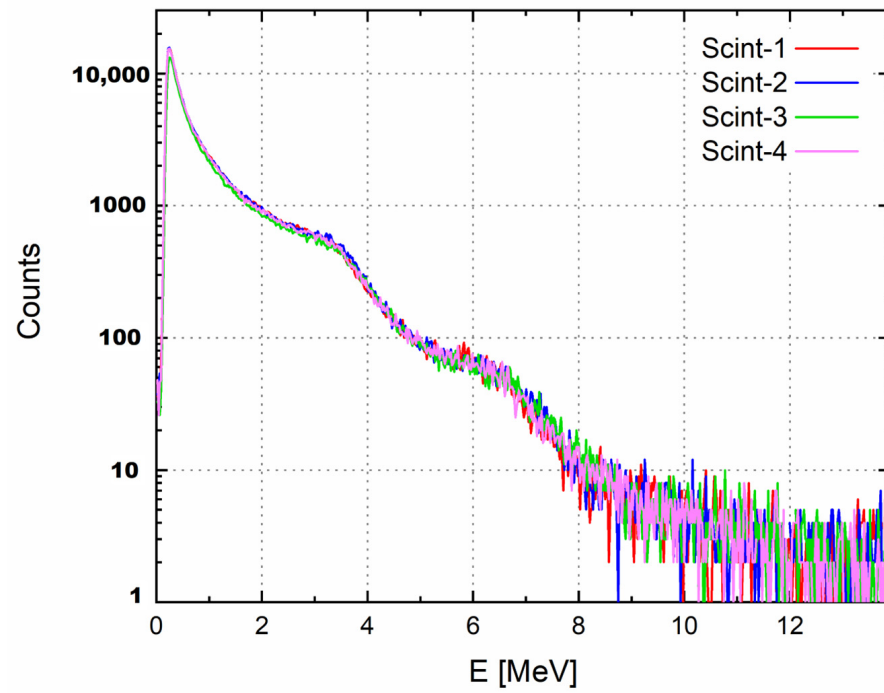
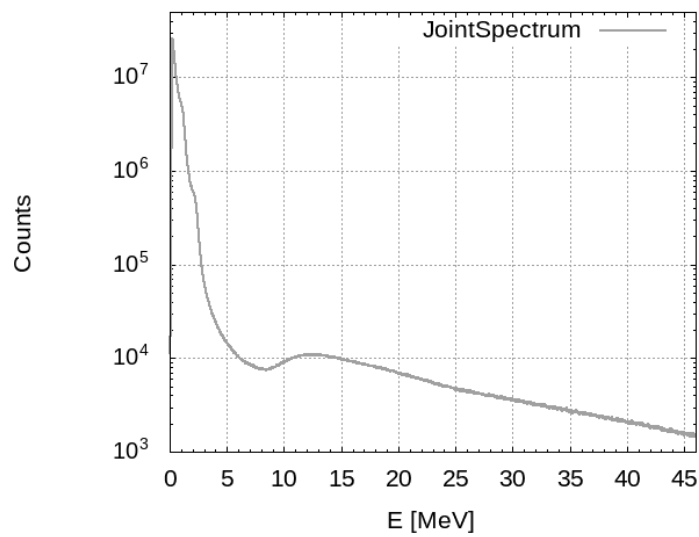


Figure 5. Cont.



(b)



(c)

Figure 5. Response of the four plastic scintillation detectors after high-voltage equalization: (a) single-detector spectra (Scint-1 to Scint-4) acquired with a ^{137}Cs source; (b) single-detector spectra (Scint-1 to Scint-4) acquired with a bulk KCl sample; (c) joint background spectrum of the array, shown up to 45 MeV to include the Landau-type contribution of the muons crossing the slabs.

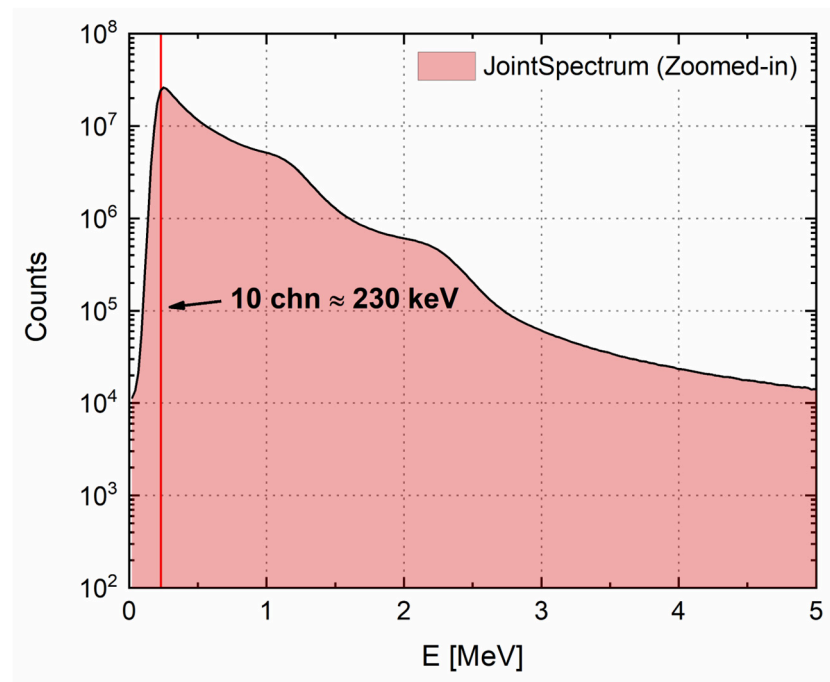


Figure 6. Joint spectrum of the four plastic scintillation detectors with the low-energy cut used for data acquisition marked. The threshold corresponds to the tenth digitizer channel, i.e., approximately 230 keV.

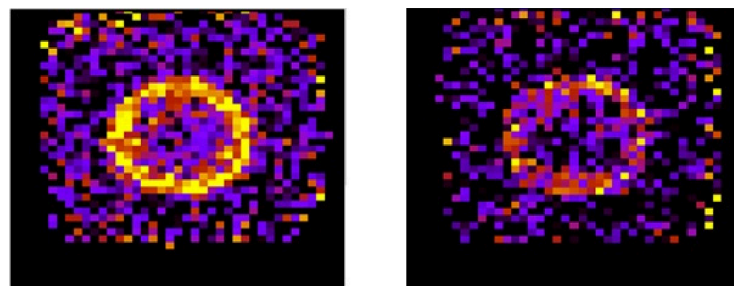


Figure 7. Images of a copper cylinder reconstructed from the same acquisition with two different energy cuts applied to the scintillator signals: 250 keV (**left**) and 1 MeV (**right**). The measured two-dimensional yield maps are shown, with a color scale for the eye (ranging from 0 to 3%). The single-tracker MUCA configuration described in Section 2.1 was used; images obtained with the dual-tracker configuration are reported in [11].

3.4. Consequences for the Detector Geometry

The threshold is not the only acceptance-limiting parameter of the MUCA geometry. The scintillators cover the vertical faces of the imaging volume, so that only the secondaries leaving the target sideways are registered, whereas GEANT4 simulations of the muon interaction show that their emission is markedly forward-peaked and that the region directly below the target carries a comparable share of the escaping flux [10]. Instrumenting that region is not simply a matter of adding detectors: a muon that has traversed the target also crosses any forward scintillator and deposits there an energy of the order of 10 MeV, far above the secondary signal, so the forward detector has to be segmented and read out channel by channel for the muon itself to be vetoed while the neighboring segments remain sensitive. The successor COMIS setup, which implements this geometry together with a compact multi-channel acquisition system and electron tagging, has been described in [14].

4. COMIS Detector System Upgrade

The COsmic Muon Induced Secondaries setup (COMIS), assembled at the Wigner Research Centre for Physics (Budapest, Hungary), was designed to improve the critical elements of the experimental setup. The sensitive volume is kept the same, while the scintillator arrangement has been expanded: the four 50 cm side detectors are retained, and four $25 \times 25 \times 5 \text{ cm}^3$ plastic scintillators are added underneath the target to cover the forward region (Figure 8). The scintillators are read out separately, so that the crossing muon can easily be excluded and the individual gains can be adjusted. The upgraded setup uses a common data acquisition system, so that no offline matching is required: triggering on the coincidence of any lower scintillator with the muon tracker selects the relevant events with an extremely low background, while the raw data size is reduced by two orders of magnitude. The DAQ is based on earlier muograph systems of similar design, using a Raspberry Pi microcomputer and several custom-designed boards, and allows tracker layers and external detector inputs to be incorporated with simple user access. For muon tracking, five CCC layers of $51 \times 51 \text{ cm}^2$ area have been chosen to increase the acceptance of the setup, reduce the acquisition time and provide the basis for a vertical segmentation of the target.

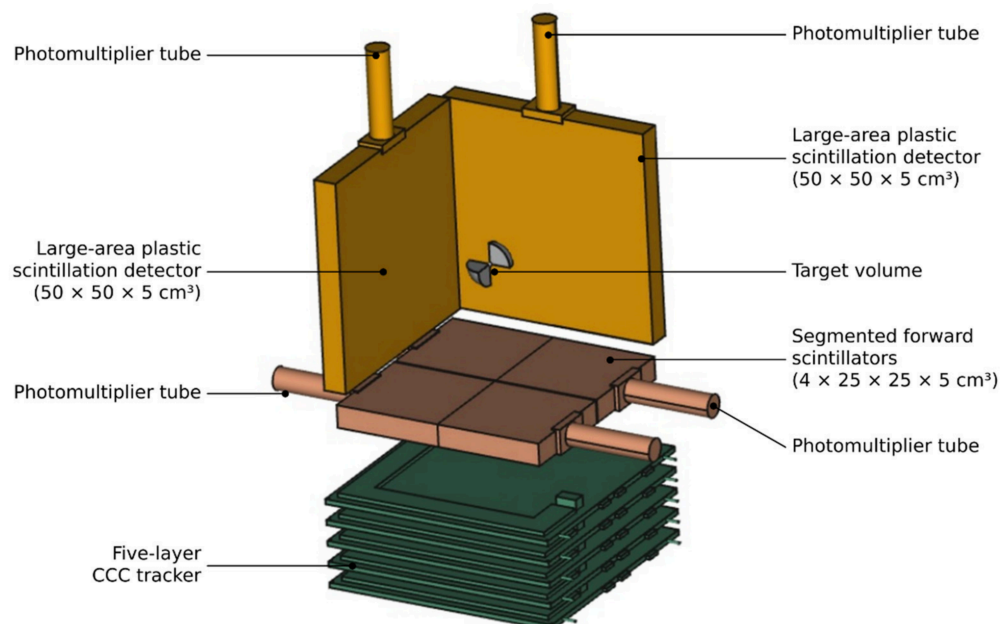


Figure 8. Schematic of the COMIS setup: the large-area plastic scintillation detectors surrounding the target volume (yellow; two of the four are drawn for clarity), the four segmented $25 \times 25 \times 5 \text{ cm}^3$ scintillators covering the forward region below it (brown), the photomultiplier tubes, and the five-layer CCC tracker at the bottom (green).

For the calibration of the scintillators, a COMIS-like arrangement was used to evaluate the uniformity of the individual $50 \times 50 \times 5 \text{ cm}^3$ plastic scintillators: the scintillators were stacked on top of each other underneath the muon tracker, so that a traversing muon crosses all of them. One scintillator was selected, and its gain was reduced by lowering the high voltage of its PMT, so that the full energy deposited by the muon remained within the dynamic range of the readout, while the trigger was formed by the tracker in coincidence with the remaining scintillators. For every triggered event, the reconstructed track was extrapolated to the plane of the selected scintillator and the pulse height was recorded as a function of the crossing point. Averaging the pulse heights in each spatial bin and normalizing them to the maximum yields a quantitative map of the light collection efficiency of the chosen scintillator. Figure 9 shows a typical uniformity map, in which

three regions can be clearly distinguished: high gain near the PMT, two darker corners next to the PMT, and a roughly flat response over most of the area.

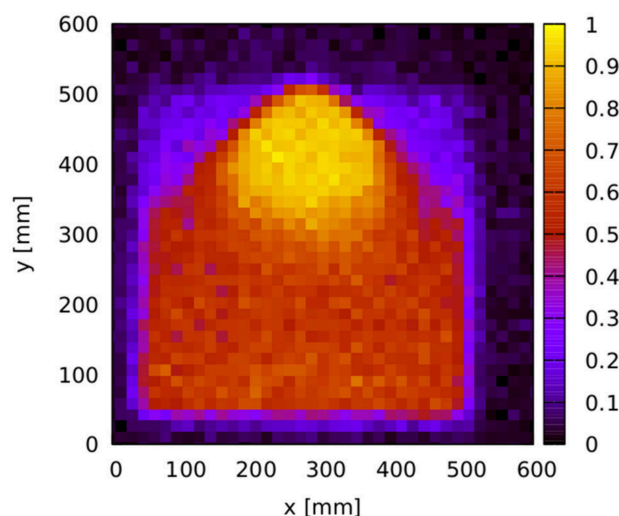


Figure 9. Measured light collection efficiency map of a $50 \times 50 \times 5 \text{ cm}^3$ scintillator; the color indicates the average normalized pulse height of the crossing muons. The PMT was mounted at the top edge; the three regions described in the text are clearly visible.

The map serves two purposes. First, it quantifies the position dependence of the scintillator response: a secondary particle that deposits a given energy close to the PMT produces a larger signal than one that deposits the same energy in the darker corners, so that the effective energy threshold varies across the detector surface. Second, it can serve as the input for a position-dependent gain correction in the COMIS analysis. Since the secondaries emitted from a given point of the target are registered over a large part of the surfaces of the four side detectors, the local non-uniformity is largely averaged out in the image, but it contributes to the systematic uncertainty of the image intensity; its quantitative effect on the reconstructed images will be addressed together with the material discrimination analysis.

Data taking with the new setup has started, and the detector performance has been verified, while detailed analyses regarding material identification are ongoing and will be described in a dedicated article. The purpose of this section is to show how the limitations identified with MUCA are addressed in the design of COMIS.

5. Conclusions

The instrumental parameters of a secondary-radiation muon imaging system determine what can subsequently be extracted from its data. Equalizing the response of the four plastic scintillation detectors with a ^{137}Cs source and a bulk KCl sample removes a spatially dependent bias from the reconstructed images, and the joint spectrum confirms the separation of the muon energy deposit from the low-energy region relevant for the secondaries. The acquisition threshold proved to be the most consequential setting: lowering it to approximately 230 keV, compared with the MeV-level values customary in portal monitoring, preserves the target-related signal, as the direct comparison of two reconstructions of the same copper cylinder demonstrates. The geometrical acceptance is a nontrivial issue, since a comparable fraction of the secondaries leaves the target in the forward direction and can only be recovered by a segmented forward detector with channel-by-channel muon rejection, as realized in the successor setup. The tracker itself was shown to operate at a combined efficiency of about 96%, obtained by requiring hits in at least four of the five layers, uniform over the central angular acceptance and stable at

the percent level over a full day of continuous running, so that exposures accumulated at different times can be compared. The overall detection probability of an image element is the product of the tracking efficiency and the probability that a secondary particle is registered above the threshold; the latter depends on the light collection uniformity of the scintillators, which was mapped for the large-area detectors and will be taken into account in future analyses. The COMIS experiment was designed to address the highlighted issues within a compact and flexible setup that has already started acquiring data. The quantitative material discrimination capability of the setup will be analyzed further and described in a dedicated article.

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