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Simulation of a small muon tomography station system based on RPCs

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ABSTRACT: In this work, Monte Carlo simulations were used to study the performance of a small muon Tomography Station based on four glass resistive plate chambers(RPCs) with a spatial resolution of approximately 1.0mm (FWHM). We developed a simulation code to generate cosmic ray muons with the appropriate distribution of energies and angles. PoCA and EM algorithm were used to rebuild the objects for comparison. We compared Z discrimination time with and without muon momentum measurement. The relation between Z discrimination time and spatial resolution was also studied. Simulation results suggest that mean scattering angle is a better Z indicator and upgrading to larger RPCs will improve reconstruction image quality.

KEYWORDS: Gaseous imaging and tracking detectors; Detector modelling and simulations I (interaction of radiation with matter, interaction of photons with matter, interaction of hadrons with matter, etc); Interaction of radiation with matter

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Contents

1 Introduction

Muon tomography(MT) is an advanced technology using muons from cosmic ray to detect high Z material [1, 2]. To measure the incoming and outgoing angles of the cosmic-ray muons precisely, the applied tracking detectors should have a sub-millimeter spatial resolution. Drift tubes [1], drift chambers [3] , gas electron multiplier detectors [4] and MRPCs [5] were used to construct MT systems.

In the previous work, we have developed a very simple and cost-effective type of glass Resistive Plate Chambers (RPCs) with LC delay-line readout. The spatial resolution of these glass RPCs is less than 1.0mm (FWHM) [6, 7]. Our RPC offers high efficiency, good spatial resolution, and stable operation. Therefore it is an ideal detector for muon tomography system. Peking University Small MUon TOmography station(PUSMUTO) based on the RPCs described above has already been built in our laboratory, and several tests have been performed to examine its work ability. However, its performances in three-dimensional object reconstruction and material identification remain unknown. Further tests are required.

PUSMUTO is a relatively small and simple muon tomography prototype. Compared with a typical RPC MT System built by AWE of U.K. which bases on 12 RPCs ($50cm \times 50cm$) with 0.50mm (Sigma) spatial resolution [8, 9], the eight RPCs we use have a smaller sensitive area of $20cm \times 20cm$, while the spatial resolution of our detector can reach 0.38mm (Sigma). Because of the small sensitive area of our detector, the acceptance of muons is limited to small zenith angle, which lead to long testing time in real experiment. Simulation works are needed at first to predict the tomography station's performance, which is helpful to guide our next experiment and other experiments alike.

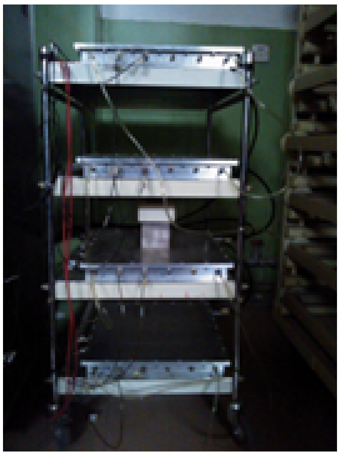

Figure 1. Muon tomography station.

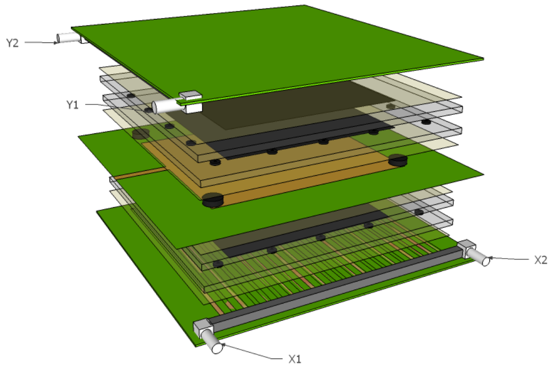

Figure 2. Structure of RPC detector.

This paper describes in detail the simulation of our small system, together with object reconstruction and material discrimination based on the simulated data.

2 Simulation

GEANT4 was used to implement the Monte Carlo simulation. The first step is to construct our muon tomography station in GEANT4. Then we generate muons which conform to the distribution of energies and angles of cosmic ray at sea level, and propagate them through our station. The station will record the positions of muons passing through every detector.

2.1 Simulation of the system

Our tomography station is shown in figure 1. It consists of four evenly spaced RPC detectors, which have the same structure inside. The object measurement area is between the two inner detectors. Two floating-glass plates formed the gas chamber of the RPC, each with a 2.6mm thickness. The gas gap in between of the plates is 2mm thick, fixed by spacers. Every detector contains two RPCs (see figure 2), each of them measures position of hitting muon in one dimension, which means the detected X and Y coordinates are not in the same plane. By measuring two points in the incoming

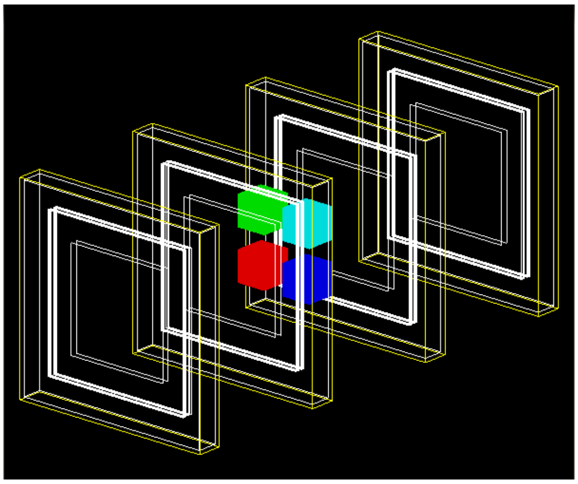

Figure 3. Simulated tomography system.

and outgoing tracks, respectively, and using the space information between each two RPCs, we can extrapolate the coordinates into the same plane. As a prototype, the sensitive area of each RPCs is only $20\times20\text{cm}^2$. These RPCs can be easily upgraded to larger size.

To examine the imaging performance of PUSMUTO, the size of detectors and positions of simulated system are consistent with the reality. Figure 3 shows the simulated system in GEANT4. Some objects of different materials represented by different colors are placed in the object measurement area.

2.2 Simulation detail of the cosmic ray muon

Muons in cosmic ray cover a broad energy range, from a few MeV to hundreds of GeV, coming from different directions. We use Gaisser's formula to approach the distribution of cosmic-ray muons at sea level [10, 11].

Then we generate 2,000,000 cosmic-ray muons on the surface of the top detector in the range of $40\times40\text{cm}^2$, which covers all muons can be recorded by the station. In consideration of the cosmic-ray muon rate, which is approximately $1\text{s}^{-1}\text{cm}^{-2}$ at sea level, the time to accumulate such number of muons in reality is about 21h. Approximately 17,000 events are detected passing through all four detectors' sensitive area, equal to $\sim13.6\text{min}^{-1}$ which is a really low rate. Considering that the acceptance angle is very limited because of the small sensitive range, it seems to be understandable.

3 Object reconstruction

Using the data from simulation, we performed object reconstruction. Two situations have been considered:

Situation 1: four same-sized objects ($6\times6\times6\text{cm}^3$ blocks), Al (purple), Fe (blue), Pb (green), W (black), are placed in a plane vertical to Z direction (see figure 4(a) & figure 4(d)). The distance between two adjacent objects is 4cm.

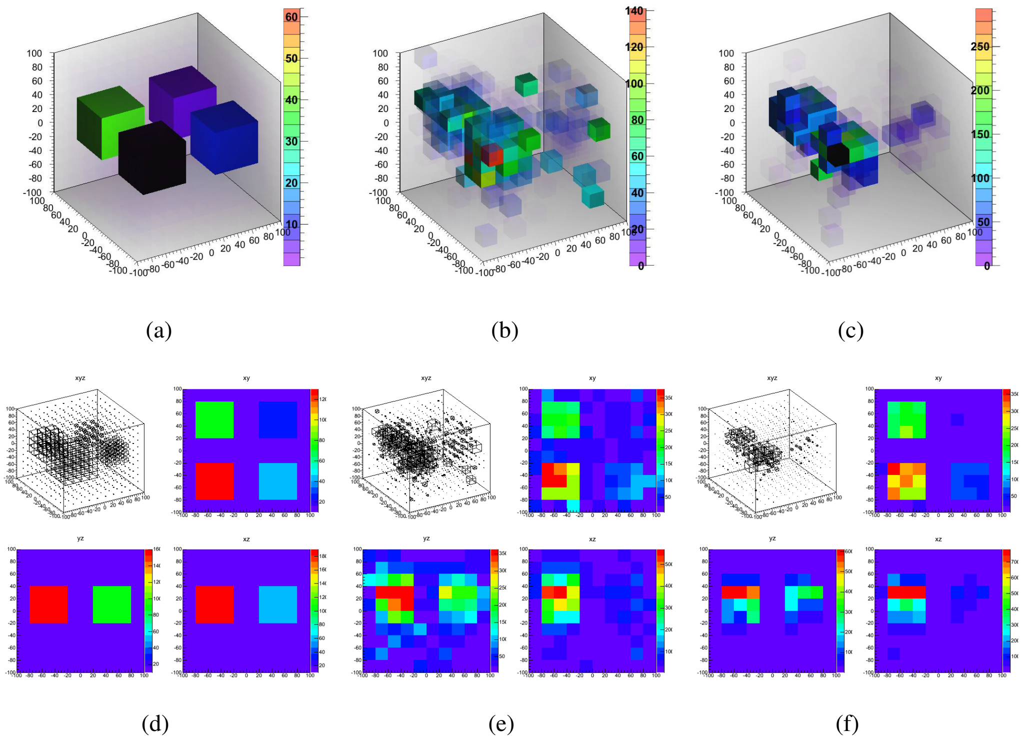

Figure 4. 3-D reconstructed images and projections in three directions of situation 1. (a)(d) objects placement of situation 1. (b)(e) reconstruction using PoCA algorithm. (c)(f) reconstruction using EM algorithm.

Situation 2: two objects ($8\times8\times6$cm^3 blocks), Fe (blue), Pb (black), are placed along Z direction (see figure 5(a) & figure 5(d)). The distance between the two objects is 8cm.

Each situation has performed reconstruction using two algorithms: PoCA algorithm and EM algorithm, both developed by Los Alamos [2, 12, 13]. The results are shown in figure 4 and figure 5. The whole detected area is a $20cm \times 20cm \times 20cm$ box, divided into $10 \times 10 \times 10$ voxels. Each voxel is a $2cm \times 2cm \times 2cm$ cube. We present two pictures for each algorithm in each situation: the 3-D reconstructed image and projections from three directions.In 3-D reconstructed images, every voxel is assigned a value for scattering density, whose unit is mrad^2/cm. Colors are filled in voxels to represent scattering density. It closes to red side as the density goes higher. While in the projected image, the value in each pixel is the sum of the 10 voxels that project on the pixel, also represented by colors.

3.1 Reconstruction using PoCA algorithm

Point of Closest Approach(PoCA) is a simple algorithm that can rapidly reconstruct image of muon tomography. It assumes that the scattering occurred due to one single scattering event located at the PoCA point. The 3-D reconstructed results and projections in three directions are shown at figure 4(b) & figure 5(e) and figure 5(b) & figure 5(e).

In the result of situation 1, four objects are separated with clear edges in XY projection. While in the result of situation 2, two objects are ambiguous to a mess. It is obvious that reconstruction in XY projection is better than in other directions, which is not difficult to be understood, since cosmic-ray muons tend to probe the volume vertically.

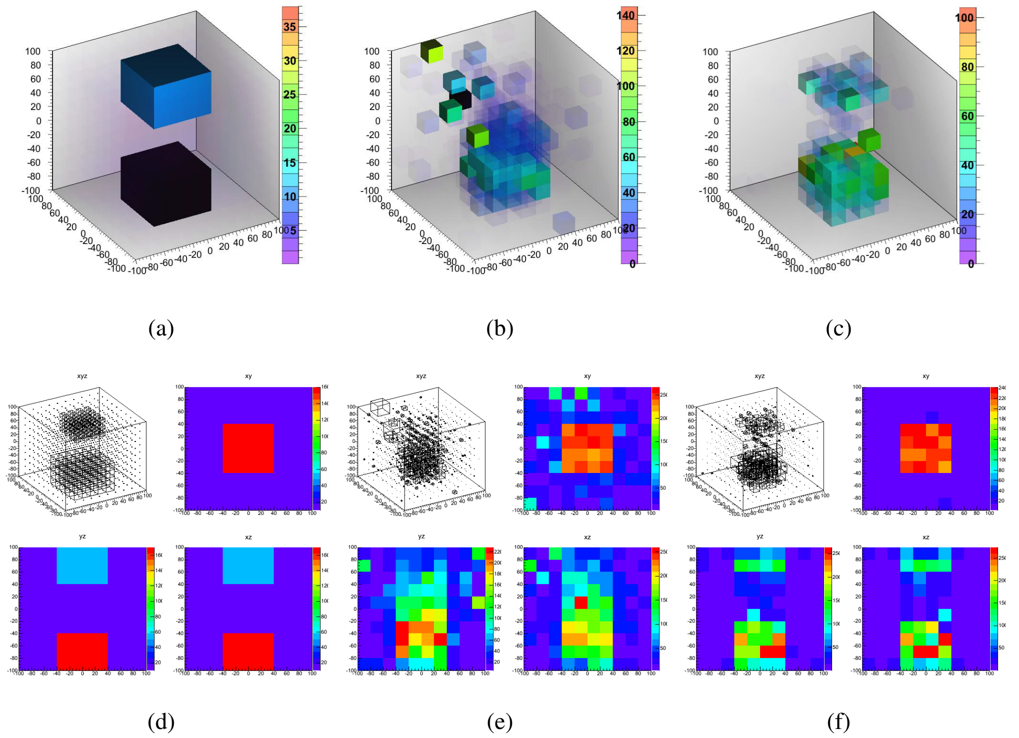

Figure 5. 3-D reconstructed images and projections in three directions of situation 2. (a)(d) objects placement of situation 2. (b)(e) reconstruction using PoCA algorithm. (c)(f) reconstruction using EM algorithm.

3.2 Reconstruction using EM algorithm

In order to acquire more delicate reconstructed image, a complicated algorithm has been developed in Los Alamos. EM, which represents Expectation maximization, is an algorithm using iteration technique to find maximum likelihood estimates of density profiles of objects, thus can improve the quality of reconstructed image. Correspondingly, EM algorithm will cost a much longer time than PoCA to get the better image. It is worth noting that to use EM algorithm, we need to know the muon's momentum, at least some information about the momentum, which is unable to get from the present system. We are planning to improve our system and add momentum measuring device.

Figure 4(c) & figure 4(f) shows the 3-D reconstructed image and projections in three directions of situation 1 using EM algorithm, and figure 5(c) & Figure 5(f) of situation 2. There are less discrete spots around the object block, leading to more clear edges. In situation 2, the two objects are separated this time, indicating a better performance in object reconstruction.

4 Material discrimination

Another application of the tomography station is to discriminate different materials. In image reconstruction, every voxel is assigned a value related to scattering angle. The mean scattering angle for a given material depth and the Z number of material are correlated. Therefore, we can use the value of each voxel gotten from reconstruction to identify the material in the voxel. In

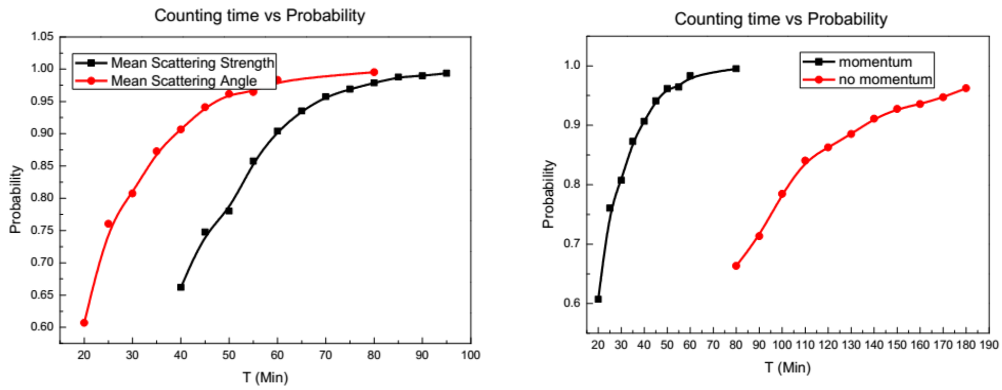

Figure 6. Material discrimination: probability means the possibility to find Pb from Fe. (Left) using two quantities. (Right)with and without momentum knowledge.

this paper, we use PoCA algorithm to discriminate different materials in situation 1. Our aim is to discriminate Pb (high-Z) from Fe (medium-Z) with zero false positive.

There are two parameters can be used to reflect the Z number of material, mean scattering strength, expressed as:

$$\widehat{\lambda} = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{p_i^2}{p_0^2}\cdot\frac{\theta_i^2}{2L_i}\right) \tag{4.1}$$

and mean scattering angle:

$$\widehat{\theta} = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{p_i}{p_0}\cdot\frac{\theta_i}{\sqrt{L_i/L_0}}\right) \tag{4.2}$$

We test these two parameters with simulated data. As plotted in figure 6 left, discrimination using mean scattering angle requires less counting time than using mean scattering strength to reach the same probability, suggesting mean scattering angle to be a better quantity in our system.

As we not yet build momentum measuring device in PUSMUTO, there are no momentum information of muons can be used in reality.In consideration of this, we plot two curves (see figure 6 right), using precise momentum and using no momentum information, respectively. The curve of real experiment using partly information of muon's momentum is expected to locate between them. In most cases, the probability is required to be not lower than 90%, which will cost ∼40min using precise momentum value, and ∼135min if not any momentum information can be used.

5 Improvement

All the performances of reconstruction and discrimination discussed above are based on the simulation of the already built station. However, as we mentioned at the beginning, the sensitive range of RPCs can be easily extended, making the system more efficient in muon tomography.

Here, we simulated a larger station consisted of RPCs with sensitive range of $1\times1\text{m}^2$. All other parameters in the simulation remain unchanged. To cover all muons accepted by the station, cosmic-ray muons are generated on the surface of the top detector in range of $1.2\times1.2\text{m}^2$. Totally 500,000 muons are generated, which equals to ∼35min in real experiment. Comparing with

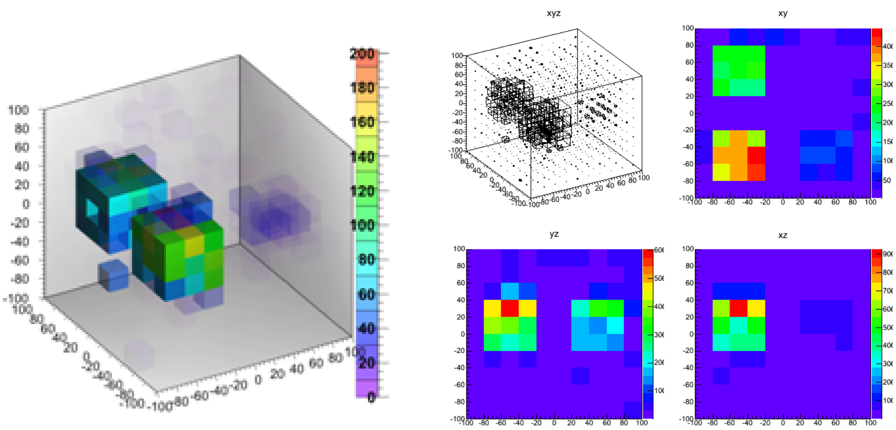

Figure 7. Reconstruction of situation 1 using EM algorithm.

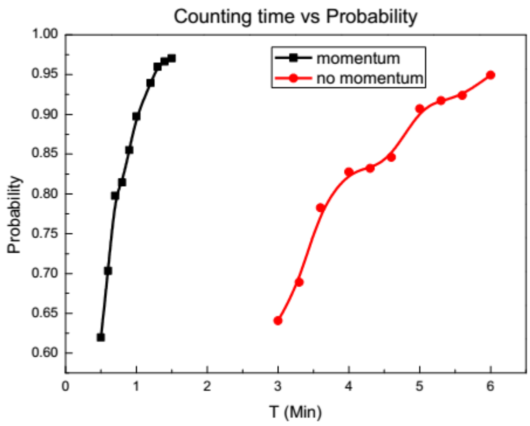

Figure 8. Material discrimination of large station.

the small RPC, the useful events of the large RPC, which are the events can be used to perform reconstruction and discrimination, is almost 26 times higher.

Similarly, the data gotten from simulation are used to perform reconstruction and discrimination. Figure 7 shows reconstructed image of situation 1 using EM algorithm. Perfect cubes of lead and tungsten can be seen in the 3D image. The reconstruction result of large station is much better than the small one. It is owing to the extended acceptance angle. More muons from various directions improved the quality of reconstruction. The performance in material discrimination is also improved. The time cost of discriminating Pb from Fe with 90% probability decreases to ∼1min using precise momentum value, and ∼5min using no momentum information.

6 Conclusions

In this work we presented the simulation of our small muon tomography station. Using the data from simulation, we performed object reconstruction and material discrimination, and estimated our station's performance in both aspects. The results indicated that our station suit for MT reconstruction using PoCA algorithm and performs better when EM algorithm is deployed, which of course needs to build a momentum measuring device at first. To have 90% chance to discriminate lead from iron with zero false positives requires ∼40min with precise momentum value and ∼135min with no momentum information. We also simulated a larger station with sensitive range extended to $1\times1\text{m}^2$. The performance in reconstruction and discrimination are both obviously improved.

Acknowledgments

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