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First results on material identification and imaging with a large-volume muon tomography prototype

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ABSTRACT

The muon tomography technique, based on the Multiple Coulomb Scattering of cosmic ray muons, has been proposed recently as a tool to perform non-destructive assays of large-volume objects without any radiation hazard. In this paper we discuss experimental results obtained with a scanning system prototype, assembled using two large-area CMS Muon Barrel drift chambers. The capability of the apparatus to produce 3D images of objects and to classify them according to their density is presented. We show that the absorption of low-momentum muons in the scanned objects produces an underestimate of their scattering density, making the discrimination of materials heavier than lead more difficult.

1. Introduction

Penetrating cosmic-ray muons are a natural radiation background. When they travel through a material, muons are slowed down, deviated from their original trajectory and eventually stopped, the extent of the effect depending on the material composition and thickness and on the particle momentum. The first use of these particles to inspect large volumes dates back to 1955, when the depth of rock above an underground tunnel was measured by George [1]. A more spectacular experiment took place in 1970, when Nobel Prize Alvarez [2] inspected the Chefren pyramid searching for hollow vaults. In both cases muon absorption was used to estimate the thickness of the material crossed by cosmic-ray particles. Other applications such as inspection of volcanoes followed [3,4].

More recently, a novel muon tomography technique has been proposed [5], exploiting the multiple scattering through an object to generate its image. A prototype able to inspect volume of about $10^{-1}\,\mathrm{m}^3$ provided the proof of principle that such technique can be used to scan large objects.

The underlying physics of muon tomography is Multiple Coulomb Scattering (MCS) [6,7] of the muons crossing a given material. The deviation angle, projected on a plane, has approximately a Gaussian distribution with zero mean value and root mean square σ that depends on radiation length X_0 and thickness x of the material and on the inverse of the muon momentum p according to the well-known formulae:

$$\sigma = \frac{13.6\,\mathrm{MeV}}{\beta pc}\sqrt{\frac{x}{X_0}}[1 + 0.038\,\log(x/X_0)] \approx \frac{13.6\,\mathrm{MeV}/c}{p}\sqrt{\frac{x}{X_0}} \qquad (1)$$

$$X_0 = \frac{716.4\,(\mathrm{g/cm^2})}{\rho}\frac{A}{Z(Z+1)\,\log(287/\sqrt{Z})} \qquad (2)$$

where ρ, Z and A are the density, atomic number and mass number of the material, respectively. As an example, for muons of 1 GeV/c momentum traversing a 10 cm thickness, σ is 14 mrad for aluminum, 35 mrad for iron, 64 mrad for lead and 86 mrad for uranium (see also Table 1). Cosmic-ray muons exhibit a wide momentum distribution (see, for example, Ref. [8] for a world survey of cosmic-ray experimental data). Nonetheless, using a sophisticated reconstruction technique, the shape and the composition of materials crossed by muons can be deduced from a high statistics measurement of the cosmic-rays deflection angles even in the absence of any measurement of the muon momentum.

Following the first proof of principle of the technique, the development of sophisticated reconstruction algorithms and of Monte Carlo simulations was reported [9–11].

In this paper we present our tomographic prototype, located at the INFN National Laboratories of Legnaro (Padova, Italy), and the experimental results obtained so far. The system can inspect a volume of about $11\,\mathrm{m}^3$, thus allowing one to characterize the

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technique on volumes comparable to the size of some real-life applications, such as cargo inspection. A part of this work is devoted to the study of material recognition. It is shown that, due to the broad energy spectrum of cosmic-ray muons at sea level and to the ignorance of the incoming particle energy, the density of high-*Z* materials is underestimated to an extent that depends on the thickness and radiation length of the object.

2. The experimental setup

The muon tomography technique requires that the impact position and direction of each cosmic-ray muon be measured by two detectors, one placed above and one below the volume under investigation. Consequently, the use of large-area detectors with excellent tracking capability is mandatory. The Muon Barrel drift chambers, built for the CMS experiment [12] at CERN, satisfy such requirements, having an active area of several square meters and a position resolution of about 200 μm. We used two such chambers in the setup shown in Fig. 1. The chambers are supported by a concrete and iron structure, leaving a gap of 160 cm in between.

Two additional drift chambers have been placed underneath the lower detector and will be used in the future, together with iron absorbers, as a momentum filter.

2.1. The CMS Muon Barrel drift chambers

The CMS Muon Barrel drift chambers are described in detail elsewhere [12,13]. Here we recall their main features.

The chambers used in this study have dimensions of $300 \times 250\,\text{cm}^2$ and are 29 cm thick. Each chamber consists of three independent units, called Super Layers (SL), structurally connected to an aluminum honeycomb panel, as shown in Fig. 2. Each SL is composed of four planes, called layers, of parallel drift tubes with $43 \times 13\,\text{mm}^2$ cross-section, filled with an Ar (85%)+CO_2 (15%) gas mixture at atmospheric pressure. Each layer is staggered by half a cell with respect to the contiguous ones. The two external SLs (called Φ_1 and Φ_2 in Fig. 2) have wires in the same direction and measure the muon trajectory in the x–y plane (so-called Φ view), y being the vertical axis. The central SL, called Θ, has wires perpendicular to the Φ SLs and measures the trajectory in the z–y plane (Θ-view). Each Φ SL contains 286 drift tubes, each Θ SL 227 tubes, for a total of 799 channels per chamber.

Table 1
Most relevant properties of the materials used in the test.

	Density (g/cm^3)	X_0 (cm)	λ_0 (cm^{-1})	$\sigma_{\Delta\Phi}$ (mrad)
Al	2.7	8.9	0.11	14
Fe	7.9	1.76	0.57	35
Brass	8.5	1.49	0.67	38
Cu	8.9	1.43	0.70	39
Pb	11.3	0.56	1.8	64
W (sintered)	18.1	0.37	2.7	79

The last column gives the r.m.s. value of the scattering angle of 1.0 GeV/c muons traversing a 10 cm thickness of material, computed using Eq. (1).

In the Φ view, the muon track is measured by 8 points, while in the Θ-view only 4 points are available. Linear fits of the measured points provide the projected angles Φ and Θ of the reconstructed muon trajectory.

The signal from each wire is fed to the front-end electronics and then delivered both to the TDC system, which measures the signal arrival time, and to the custom-made trigger electronics [14]. The trigger electronics looks for track segments in each SL, verifying the alignment of hits in the four layers. In addition, it checks whether segments found in the two Φ SLs can belong to the same track. If the alignment conditions are fulfilled, the track angle and position are computed and a trigger signal is produced at a fixed time with respect to the passage of the particle. Therefore each chamber has the capability to trigger itself in a standalone mode, not requiring any external detector. Moreover, the trigger can be easily configured with different acceptance angles and alignment quality.

We typically used the upper chamber to trigger the whole apparatus. To reduce the amount of useless events, the chamber trigger was configured in order to accept only tracks that were approximately pointing to the lower chamber. In such conditions, the trigger rate is about 350 Hz.

The TDC is used in common stop mode, the stop signal being the trigger signal after an appropriate delay. All signals within a time window of a few μs centered on the trigger time are accepted. The information from the TDCs is sent to the Data Acquisition System, which collects and formats the events to be stored on disk.

The intrinsic single hit resolution of the CMS drift chambers, σ_{hit}, has been measured with high-energy muon beams ($p \approx 200$–$300\,\text{GeV}/c$) at CERN [15] studying the residuals of the

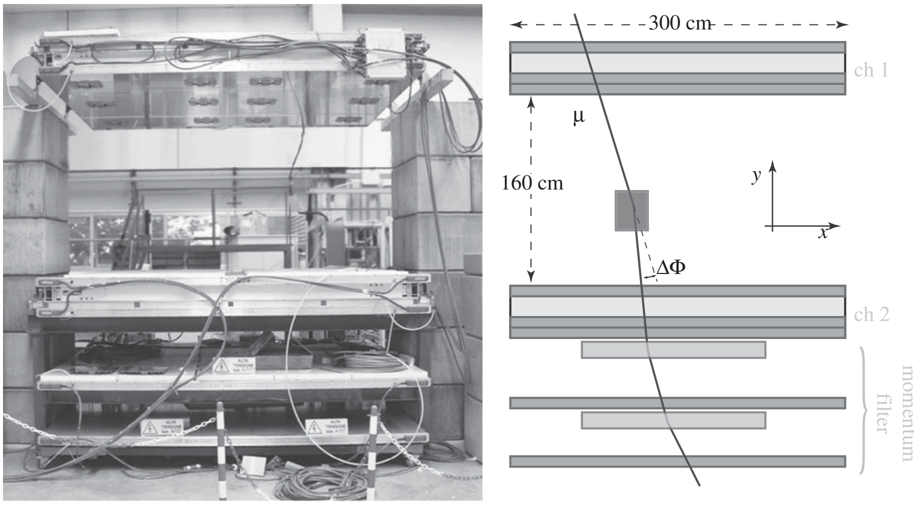

Fig. 1. The prototype of the muon tomography system. The sketch on the right shows, not in scale, in the so-called Φ-view (see text) the main elements of the setup. The z-axis is perpendicular to the drawing plane.