Close Cathode Chamber technology for cosmic particle tracking

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Abstract. The Close Cathode Chamber (CCC) technology has been developed and found useful in a portable tracking system under harsh and varying environmental conditions due to their mechanical and operational stability. The muon flux have been measured on ground and at shallow depths underground (< 70 m.r.e.) which provides a good reference for other experiments. The multiple scattering in rock and the soft contamination of the track sample have been investigated experimentally and by GEANT4. The applicability of the sensor to detect underground rock density inhomogeneities has been demonstrated via reconstruction of an underground tunnel system. A modified muon tomograph has been built with sensitive area of 0.25 m² and angular resolution of 15 mrad which is useful for material discrimination via the measurement of multiple scattering and absorption of muons. The reliable tracking performance, low power consumption and fair angular resolution make the CCC technology useful also in large area tracking detectors.

1. Introduction

It has been long established both soft and hard components of cosmic rays reach the surface of Earth. The soft (or electromagnetic) component is largely absorbed after 10 radiation lengths of material. The hard component consists mostly of muons which are highly penetrating due to their small interaction cross-section and long lifetime. The flux of muons decreases by the transversed material. Muography (short for muon radiography) deduces the density length (integral of density as a function of length in a given direction) in the interior of the investigated object, such as a mountain or volcano, by the measurement of the muon absorption along different paths through the object. If path lengths (average densities) are measured, the average density (path length) can be deduced along the muon paths.

The first muography measurement has been performed by E. P. George, to determine the rock density above an Australian mine [1]. L. W. Alvarez et al. studied the inner structure of the Kephren pyramid by spark chambers to find hidden caverns [2]. Speleological application has also been demonstrated by measurements [3]. Muography has successfully been applied to the investigation of volcanoes from the reconstruction of their shape [4] to visualize and analyse the magma movements and modification patterns [5] by the measurement of the flux of near horizontal muons. The measurement of absorption and multiple scattering of muons allows to
make a 3-dimensional tomographic image of the investigated object, e.g. detect hidden smuggled nuclear materials [6, 7] or monitoring the fuel level in nuclear reactors [8, 9].

Since 2010, the REGARD group [10] is also focusing on the reconstruction of hidden caverns and rock densifications by cosmic muon tracking. We found that the cost efficient and lightweight gaseous detectors, the so called Close Cathode Chambers [11, 12] are applicable for underground measurements due to their mechanical and operational stability [13, 14, 15]. In present paper, we briefly present the Close Cathode Chamber technology and its application in tracking detectors. We will quantify the required detector parameters for muography and our measurements in an underground tunnel system. Furthermore, we present encouraging preliminary results on material discrimination by muon tomography.

2. Close Cathode Chamber technology
The Close Cathode Chamber (CCC) is an asymmetric multi-wire proportional chamber (MWPC) which does not involve heavy frames to hold the wire tension. The CCC is lightweight, easy to construct and tolerant to mechanical effects such as vibration, external tension or bulging by pressure. The scheme of the CCC is shown in the left panel of Fig. 1. The thickness of the CCC in our application is about 12 mm. There are 20-25 μm thick sense wires and 100 μm thick field wires 1.5 mm above the baseplate. The gas gain of the CCC is around $10^4$ in Ar + CO$_2$ 80:20 gas mixture with the field wire potential and the sense wire potentials are around -600 V and +1000 V respectively. Its material budget is less than 1 % radiation length, whereas its energy cut-off is a few MeV. The CCC concept, the key operational parameters and issues of large size construction (see right panel of Fig. 1) have also been presented in Refs. [11] and [12].

![Figure 1](image)

**Figure 1.** *Left panel:* the outline of the CCC detector. *Right panel:* CCC detector with the size of 0.5 m × 1 m (1 m long wires).

3. Portable tracking detectors for outdoor measurements
3.1. Detector structure
The surface of cosmic ray detectors needs to be as large as possible to acquire the largest statistics during the data taking. However, over-sized detectors are not appropriate to perform measurements inside unexplored underground caverns or artificial tunnels which may be difficult to access. These places require human handling of the equipments, which limits size and weight of a detector. In our case, the size of the detectors were designed to fit into caverns, described in Ref. [13], [14] and [15]. The mobile detector should be safely handled manually by a single person: the external size of the tracking system is 50 × 46 × 32 cm$^3$, and its weight is about
15 kg without additional power supplies and gas bottle. The left panel of Fig. 2 shows an installed station. The detector consists of a stack of five CCC layers. All these, including the DAQ and control, is housed inside a plexi-glass box which absorbs mechanical shocks during the deployment and isolates the detector from the humid environment. The CCC layers require low level continuous gas flow during the measurement of typically 0.5-1 L/h. A gas bottle with volume of 10 L and pressure of 150 bar is sufficient for 2 months.

**Figure 2.** Left panel: a portable detector with five tracking layers in a plexi-glass box and the additional power supply and gas system. Right panel: the elements of the Raspberry Pi-based DAQ system for mobile detectors.

### 3.2. Data Acquisition (DAQ) systems for mobile detectors

Our first portable detector was equipped with a PIC32 micro-controller based DAQ system [13, 14, 15]. It consists of three main modules: a processor board controls the data acquisition and includes a low-voltage power supply; a high-voltage module operates the chambers; and finally a Human-Machine Interface module is responsible for maintenance and data storage. The key advantage of this DAQ is the low total power consumption of 5 W, whereas its dead time is 9.8 ms.

An upgraded DAQ, based on Raspberry Pi computer [16] and a custom designed board, called MtRD (right panel of Fig. 2) allows a high level remote control, data management and analysis. The MtRD is responsible for processing of data from the CCC layers. It includes a coincidence unit with up to 10 trigger lines. The actual trigger inputs and the coincidence settings can be selected manually on the MtRD. The individual trigger signals and the number of missed triggers are also recorded. The duration of the data readout (dead time) is 100 μs, considerably less than for the previous PIC32 based one. The DAQ software runs on the Raspberry Pi exploiting its fast GPIO pins. For standard operation, a convenient graphical user interface has been developed, running on any remote computer with internet connection to the Raspberry Pi (common internet link, or one of them as AP host; wired or wireless).

The electrical power for the detector is supplied through a single line nominally at +12 V DC. An efficient power converter (∼ 80 %) supplies +5 V DC to the Raspberry Pi and the DAQ board. The power consumption of a complete detector system is 6 W at +12 V DC, thus it can operate for about one week with a standard 50 Ah battery.
4. Muography experiments at shallow depths underground

4.1. Data taking time estimation as a function of zenith angle

The muon flux is maximal from the zenith, however measurements at different zenith angle are necessary under general conditions. It is then relevant to quantify the required time of data taking at a given depth and a given object – a cavern in this example. The muon flux \( f(H) \) reduces as a function the density-length \( H \), therefore the change (derivative) of \( f(H) \) versus \( H \) allows one to detect the underground rock inhomogeneities. The relative error of the detection, directly related to the confidence level, for a \( 2R \) diameter cavern at the depth of \( H-h \) (see left panel of Fig. 3) is proportional to

\[
\frac{t(\theta)}{t(0)} = \frac{f^*(H)}{f^*(\frac{H}{\cos(\theta)})} \times \cos^{-2}(\theta) \times \cos^{-2}(\theta) \times A^{-1}(\theta)
\]

on the right side, the second factor is a reasonably good approximation of the angular distribution of cosmic muons, the third term is from the reduction of the angle of view if the cavern is located under the zenith angle of \( \theta \). Depending on detector geometry, an additional factor \( A(\theta) \) determines detector acceptance relative to \( \theta = 0 \).

![Diagram](image)

**Figure 3.** Left panel: The 2-dimensional view of the geometry of the simulations. Right panel: The relative duration of the data taking which is required to detect a cavern with level of significance of 3 sigma at the zenith angle of \( \theta \), with a horizontal detector.

The detector angle of view dependence has also been quantified by GEANT4 [18]. The simulation includes the penetration of atmospheric muons across a rock box with and without cavern (see in the left panel of Fig. 3). In our case, the CRY [19] cosmic ray generator provides the particle showers (\( \mu^\pm \) and \( e^\pm \)) as the input for the detector simulations. Muon and electron showers have been generated within a 100 m \( \times \) 100 m area at sea level. Standard rock (\( Z=11, A=22, \rho = 2.65 \text{ g cm}^{-3} \)) has been implemented with different thickness \( (H) \) and with different cavern diameters \( (R) \) as well as without any cavern. For simplicity, a “flat” detector model has been used with \( A(\theta) = \cos(\theta) \); however this term can be set to \( A(\theta) = 1 \) if the detector is turned towards the object of interest. The time ratio of data taking to detect the cavern with 3 sigma confidence level has been calculated. Figure 3 shows the results of the GEANT4 simulation with different rock thickness \( (H) \) and cavern diameters \( (R) \) as well as the above detailed estimation which is used the muon flux versus density-length curve, measured
by Barboutit et al. [17]. Both of the estimation and simulation results show the same trend. One can conclude that detectors with the angle of view greater than \( \pm 45^\circ \) for reconstruction of underground caverns require increased data taking time by an order of magnitude to collect sufficient statistics.

4.2. Angular resolution for cavern detection

Atmospheric muons suffer multiple scattering from the nuclei of the traversed material. The distribution of the scattering angles is approximately Gaussian with the following standard deviation:

\[
\sigma = \frac{13.6 \text{ MeV}}{\beta pc} \sqrt{\frac{X}{X_0}} \left[ 1 + 0.038 \ln \left( \frac{X}{X_0} \right) \right]
\]  

where \( p \) is the momentum of the muon, \( X \) is the rock thickness, and \( X_0 = 10 \text{ cm} \) is the radiation length of standard rock. Equation 2 is only true in the approximation that the muon momentum \( p \) does not change significantly between the entry and exit point, which is not fulfilled during muography applications: multiple scattering will increase towards the end of the muon’s trajectory. Hence it is also not correct to conclude, that deeper detector will suffer from less multiple scattering.

![Figure 4. Left panel: The scheme of the muon multiple scattering of muons in rock. Right panel: The evolution of multiple scattering of cosmic particles which are stopped at the depth of 20 m (empty rectangles), 30 m (filled triangles) and 50 m (empty circles).](image)

To quantify the effect, CRY and GEANT4 have been applied to generate atmospheric muons and simulate their penetration across the rock. Particle showers have been generated within a 300 m \( \times \) 300 m area at sea level. Standard rock has been implemented with the thickness of 100 m. The angular scattering has been calculated at each half meter for those muons which could penetrate a certain thickness (penetration depth).

An interesting result arises if we measure the mean scattering angle as a function of the difference between the detector depth and the real penetration depth (see the left panel of Fig. 4). This actually corresponds to the observed cavity size: in case of a cavity (void), the increase of the muon flux happens because of those muons which penetrate more by the cavity size. The right panel of Fig. 4 shows the evolution of multiple scattering for those particles which are stopped at the depth of 20 m, 30 m and 50 m. The values fall on a universal curve. The angular resolution of the detector should be compatible with the smearing effect of multiple scattering to adequately detect rock inhomogeneities: 40 mrad smearing corresponds to 2 meter in difference between detector depth and penetration depth; in other words, a 2 m diameter
A cavity will appear with this smearing (because of multiple scattering) on the cosmic muon flux map independently of its depth. This is counter-intuitive: the multiple scattering smearing is indeed the same for larger depths at a given cavity (or other object) size.

4.3. Muon flux measurements in underground tunnel systems

The Jánossy Pit in the campus of the Wigner RCP is an underground tunnel system with three parallel tunnels under each other at 10 m, 20 m and 30 m depth with the size of $11 \times 2.5 \times 2.6 \text{m}^3$, $9.5 \times 2.5 \times 2.6 \text{m}^3$ and $23 \times 2.5 \times 2.6 \text{m}^3$ respectively. Furthermore, there are two additional tunnels at the level of 30 meter with the orientation of $\pm 60$ deg from main tunnel. The soil density is $2.2 \pm 0.2 \text{g cm}^{-3}$ and tunnels are built from concrete with the density of $2.4 \text{g cm}^{-3}$. It is an excellent place to test the capabilities of the presented detector on muography at shallow depth.

Figure 5. Muon flux measurements (right panels) have been compared with the GEANT4 simulation (left panels): the tunnels and the building structures are well reproduced by the measurements [20]. Grayscale shows the flux values divided with $\cos^2(\theta)$. 

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The geometry of the Jánossy Pit has been implemented into GEANT4 with the above parameters. The expected angular dependent muon flux have been calculated from the empirical formulae of vertical muon flux versus depth [17] and the combination of the angular distribution of cosmic muons.

Figure 5 shows the expected (left panels) and measured (right panels) flux values divided with \( \cos^2(\theta) \). Specifically, the upper panels show the pit entrance dome of the tunnel system towards South and the building edge at the North-East corner from 10 meter depth. In the middle panels, two parallel tunnels are observed in the North-South orientation from 30 meter depth. In the lower panels, a tunnel at 20 meter depth has been observed in the North-East - South-West orientation from 30 meter depth.

5. CCC technology for material discrimination

As shown by Eq. (2), the high-Z materials (e.g. U, Pb) are particularly effective scatterers. Tracking devices placed around an object of interest (even vehicle or cargo container) can be used to obtain tomographic images about the high density regions inside the object [6, 7]. To demonstrate the applicability of CCC technology for such transmission muon tomography, an adequate tracking station has been built. The detector (see in the left panel of Fig. 6) consists of six tracking layers with the sensitive area of 0.5 m by 0.5 m and angular resolution of about 10 mrad. The right panel of Fig. 3 shows a 2-dimensional image of the scattering powers for different materials (Pb, Fe and Al). The data taking time to make an image with this precision was few hours without applicable advanced analysis methods. These presented results are encouraging in the direction that the CCC technology is useful for tomographic imaging.

**Figure 6.** Left panel: Left: A cosmic setup for muon tomography with the investigated objects inside the middle CCC layers. Right panel: A photo and a 2-dimensional image of scattering strength in arbitrary units for Pb, Fe and Al absorbers.
6. Summary
The Close Cathode Chamber technology and its application in portable tracking detectors as well as their new data acquisition system have been presented. The detector parameters have been optimized for muography at shallow depth and also verified by GEANT4 simulation. The smearing effect in the angular distribution of muons due to their multiple scattering has been quantified, showing that the smearing only depends on the size of the object in study, and not on the detector depth. The angular resolution should be compatible with the smearing effect, e.g. the angular resolution of 40 mrad (2.3°) is sufficient to detect a cavern with the diameter of 2 meters. Muon flux measurements are ongoing in underground tunnels (< 100 meter-rock-equivalent), showing good agreement with the expected muon flux. The results demonstrate the applicability of CCC-based portable tracking detectors to perform muography measurements. Furthermore, encouraging ground level studies have been performed as well: material discrimination is achievable by the measurement of multiple scattering of cosmic particles on the investigated materials, especially those of high Z. The reliable tracking performance, low power consumption, fair spatial and angular resolution and cost-efficiency make the CCC technology competitive also in large area tracking detectors for cosmic ray research.

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