The first prototype of an MWPC-based borehole-detector and its application for muography of an underground pillar

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ABSTRACT

Muography is an emerging visualization technique for inspection of large-sized objects with the measurement of the absorption rate of cosmic-ray muons. Present paper introduces the first prototype of a Multi-Wire-Proportional-Camber (MWPC)-based borehole detector. The designed tracking system is based on the so-called Close Cathode Chamber (CCC) concept, which provides easily handling and robust detectors. The 18-cm-length detector is covering a sensitive area of 20 cm × 32 cm and an angular acceptance up to 60 deg with close to full tracking efficiency (99 %), reasonable position resolution of 1.8 mm and angular resolution of 10 mrad. The detector has been tested inside a shallow shaft and an underground iron pillar with concrete basement has successfully been imaged with the resolution of 15 cm within 15 days, which indicates the future industrial usage of MWPC detectors and encourages the application oriented development of this technology for borehole-based muography.

Keywords: Muography, Gaseous tracking detectors, MWPC, borehole, civil engineering

1. Introduction

Muography is an emerging technique for imaging of large-sized (from few meters to few kilometers) objects with the measurement of the absorption rate of cosmic-ray muons across the investigated bodies (Alvarez et al., 1970; George, 1955), similarly to radiography of small-sized bodies. The muons are produced in upper (typically 10-15 km ASL) atmosphere in particle physics processes generated by the collisions of primary cosmic-rays with the atmospheric nuclei. The directional dependent flux of muons has been measured in the Earth's atmosphere, at sea level (Tsuji et al., 1998) and different parametrization of muon spectra have also been developed, e.g. see in the model of (Guam et al., 2015). The interaction of muons with the transversed media can also be parametrized or simulated, thus the expected flux of muons can be determined after a known amount of material. Consequently, the amount of material (average density × path-length) can be deduced with the comparison of modeled and measured fluxes and the density (path-length) of the transversed material can be determined with the knowledge of the path-length (density).

The idea of muography is originated from E. P. George, who aimed to measure the thickness of overburden material of an Australian mine in the middle of last century (George, 1955). The next pioneering measurement has been performed in the second Egyptian Pyramid, called Chephren, to explore its internal structure and search for hidden chambers (Alvarez et al., 1970). Thanks to the development of detector technologies, particle physics instrumentation could be applied for cosmic-ray muon imaging in harsh and varying environment from the middle of 1990's (Caffau et al., 1997; Nagamine et al., 1995) and the first breakthroughs have been achieved from the 2000's: the applicability of muography has been demonstrated for the investigation of various natural formations, e. g. volcanoes (Ambrosino et al., 2015; Carbone et al., 2013; Lesparre et al., 2012; Oláh et al., 2018; Tanaka et al. 2007; 2010; 2014; 2016), underground soil structure...
and cavities (Bryman et al., 2015; Guardincieri et al., 2017; Lesparre et al., 2017; Oláh et al., 2012; 2013; 2015; Saracino et al., 2017; Tanaka, 2015), glaciers (Nishiyama et al., 2017), and for exploration and inspection of various human made objects, such as pyramids (Morishima et al., 2017), or nuclear reactors (Perry et al., 2013).

The accessibility of the investigated objects were an important prerequisite to perform successful measurement in all of the above experiments. The development of borehole-based muography would be the next step to access non-approachable sites and extend the scope of cosmic-ray muon imaging for mineral, gas or water exploration, monitoring of deep underground CO₂ storage sites (Kudryavtsev et al., 2012), exploration of geothermal reservoirs (Tanaka et al., 2013), inspection of abandoned places under urban area (NEC Corporation, 2017) or monitoring of building structures, such as dams, bridges, or tunnels. The boreholes can be drilled into to ground with the typical diameter of 10 cm and depth from few tens of meters to few kilometers. The borehole environment requires small-sized, compact, robust and low-power detectors which can operate autonomously. Due to the high cost of the drilling, the detector needs to be maintenance-free for long periods of many months, and needs to endure the insertion procedure. The development of borehole detectors is ongoing all around the world using different detector technologies, such as plastic scintillators (Saracino et al., 2017), drift chambers (Bonneville et al., 2017), Micro-MEsh Gaseous Structures (Bouteille et al., 2016; Hivert et al., 2014), Resistive Plate Chambers (Wuyckens et al., 2018), or Multi-Wire Proportional Chambers (Varga et al., 2011; 2013; 2015; 2016).

In this paper we present the first prototype of a new borehole detector which is based on the Close Cathode Camber concept, the design of the so-called MWPC-based Muographic Observation System (MMOS) (Varga et al., 2017) and developed in the cooperation of the Earthquake Research Institute of The University of Tokyo, Wigner Research Centre for Physics of the Hungarian Academy of Sciences, and NEC Corporation. The paper is organized as follows. Sections 2 presents the structure of the MWPC-based borehole detector. Section 3 describes the test experiment performed in a shallow shaft. Section 4 focuses on the imaging of an underground iron pillar. Section 5 summarizes the results and discuss the future perspectives of borehole-based muography with MWPCs.

2. The First Prototype of MWPC-based Tracking Detector for Borehole-based Muography

The combination of portability, high imaging resolution, real-time measurement (monitoring) capability and low cost motivates the application oriented development of gaseous detectors for borehole-based muography. The operation of gaseous detectors in nutshell is the following (Sauli, 1977): they localize the electron avalanche created via ionization of gas medium by the penetrated charged particles. Each segment is individually read out after the amplification and digitization of analogue signals, and transferred to a data acquisition and detector control system for analysis and visualization.

For the basement technology of our borehole detector we have chosen the so called Close Cathode Chamber (CCC) concept (Varga et al., 2011; 2013), which provides high tolerance against mechanical inaccuracies and deformation of detectors suffered from mechanical stress in borehole environment. Thus the CCC provides a robust and easily handle detector which is a good candidate for borehole-based muography. Fig. 1A shows the inner structure of the CCC detector. There are two 2 mm-thick copper plates placed parallelly under each other at a distance of 1 cm, and the gas volume is closed with 1 cm-thick glass-epoxy walls. In case of large-sized detectors the support pillar can also be installed inside the CCC. The upper copper plate serves as a cathode and the lower printed-circuit-board (PCB) plate is etched to 4-mm-wide pads. Perpendicularly to the pads, a wire plane is placed close to the lower PCB plate at a distance of 0.7-1.5 mm. The wire plane consists of 100 micrometer-thick copper wires (Field-wires) and 25 micrometer-thick gold-plated tungsten wires (sense-wires or anode wires), which are alternately placed equidistantly, typically with the wire-pitch of 4 mm. A non-toxic, non-flammable Ar-CO₂ gas mixture (80:20) is flushed across the gas volume with the flow of about 0.5-1 liter per hour. For efficient signal production the high-voltage of +1300 V is applied on the anode wires and the other electrodes are kept on ground potential. The typical electron amplification is about few thousands in the CCCs. The signals are amplified with a factor of ten and digitized by custom-designed, 16-channel front-end electronics which are based on commercial integrated circuits (see the photograph of CCC in Fig. 1B). Each detector layer localize the penetrated charged particles and together measure the particle's trajectory.

The first prototype of MWPC-based borehole detector is based on the concept of MMOS. Fig. 1C shows the photograph of the first prototype, which consists of four vertically placed, 20×32-cm²-sized CCCs. The length of the tracking system is 18 cm, thus MWPC-based MMOS can provide an angular resolution of about 10 milliradian with the positional resolution of about 1.8 mm. The data acquisition and control system is placed parallely with the detector layers. For the first test measurements three 2-cm-thick lead shielding plates have also been installed between the tracking layers
for suppression of background particles. The electronics cables connected to the CCCs on the top and the gas tubes are connected to CCCs on the bottom of the detectors. Each detector element is housed inside a box made from stainless steel with a plexi window to access the detector interface. The total weight of the detector is about 10 kilograms including the detector layers and the box, as well as about 75 kilograms including the lead plates. Fig. 1D shows the first prototype of the MWPC-based borehole detector during its installation inside a shallow shaft.

The data acquisition and detector control system is operated by a micro-computer and a custom-designed board (Hamar, 2015). The data taking is triggered by the coincidence of the detector layers and the sequential stream of data bits is shifted to the DAQ. The electronics are placed on the back of the detectors to minimize the size of detector. During the readout the trigger is blocked for about 100 microseconds. The data is collected and stored into ASCII file with the typical size of few hundreds kBytes per event. The data can be accessed on the mini-computer via its wireless Internet access point or Ethernet cable, which allows online-analysis and data monitoring. The detector is operated by +12 V DC which can be derived from alternating current or batteries. The high-voltage supply is based on AHV box which converts the +12 V DC to the +2,000 V output. The variation of environmental parameters (atmospheric pressure and temperature) affect the gas quality and detection efficiency of gaseous detectors. To reduce this effect the real-time compensation of high-voltage is applied. The total power consumption of the prototype is about 6 W including all the detector layers, electronics, data acquisition and control systems as well as low- and high-voltage power supplies. Practically, the borehole detector can be operated for about 4 days from a standard 12 V and 50 Ah car battery.

3. Detector Tests in a Shallow Shaft at NEC Tamagawa Plant

The first outdoor tests of the MWPC-based borehole detector have been performed at NEC Tamagawa Plant, Kanagawa, Japan. A 3-meter-high mound with the basement area of 20 m × 10 m has been chosen for the test experiment. The mound was made up from a mixture of local soil and construction waste with unknown density. A 3-meter-deep shaft with the diameter of 40 cm has been constructed inside the mound and a 90-cm-diameter iron pillar with cylindrical-shape concrete basement has been installed inside the mound. Fig. 2 shows the geometrical arrangement of the test measurement (A) with a photograph about the surface of the mound with the shaft and the upper part of the iron pillar.

The MWPC-based borehole detector has been installed at the bottom of shaft at the depth of 3 meters to image the shape and bottom of the pillar. The tracking system was supplied by +110 V AC and Ar-CO₂ (80-20) gas mixture with the flow of 1 liter per hour. The power and gas suppliers were installed
in a closed cabin next to the shaft on the surface of the hill. The data have been downloaded from the detector's micro-computer via its wireless access point and off-line analysis have been performed to determine the detector performance parameters and produce the image of the pillar.

The data analysis is performed on event-by-event: the clusters on each CCCs have been reconstructed and particle trajectories have been selected by a combinatorial algorithm in 1+1 dimension. The tracking efficiencies have also been calculated with the extrapolation of tracklets to the investigated detector layers, and efficiency values were given by the ratio of the number of found clusters and the number of extrapolations for each CCC. Finally, the flux of muons has been calculated as a function of the slopes of track projections with taken into account the detector acceptance, efficiency and measurement time.

The detector was operated for 15 days during the first test measurement. Fig. 3 shows the variation of detector performance parameters with 1σ statistical errors for this measurement. The rate of triggers, i.e. the double coincidences of four CCCs, and the rate of tracks with clusters on at least three different CCCs were found stable within 3% during the measurement period (see in Fig. 3A). The tracking efficiencies, i.e. the probability to find cluster on...
the fourth detector if clusters were found on the other three, were also determined and found above 93 % for all of the CCCs (see in Fig. 3B). The combination of these efficiencies provides the tracking efficiency of 99 % to detect tracks with clusters at least on three different CCCs. The observed results demonstrate that the MWPC-based borehole detector served data with excellent quality at shallow depth for the imaging of the pillar.

4. Muography of an Underground Iron Pillar with Concrete Basement

To produce the image of the pillar, the so-called muographic density imaging procedure has been applied for each direction determined by the slopes of track projections, \( m_x \) and \( m_y \), respectively. The expected fluxes, \( F(m_x, m_y)_{\text{expected}} \), have been determined for different average densities from 1 gcm\(^{-3}\) to 6 gcm\(^{-3}\) with the density step of 0.1 gcm\(^{-3}\) for each \((m_x, m_y)\) bin with known muon path-length. Finally, the density values has been extracted for the matching calculated and measured fluxes.

To calculate the expected fluxes, first of all the muon path-lengths were determined. The shape of the mound was measured by laser-based distance meter and the path-lengths were calculated from the detector point of view. We note that it was not possible to take into account the surrounding buildings which could bias the measurement with the absorption of muons. The path-lengths across the mound ranges between 3 meters and 16 meters from near-vertical direction to horizontal direction. Thereafter, the modeled muon energy spectra (Guam et al., 2015) were integrated from the detector point of view. The density imaging procedure has been applied for each direction because the pillar was installed above it.

The average density maps around the pillar are shown in Figs. 5A, 5B, 5C and 5D for the durations of 1 day, 3 days, 7 days and 15 days, respectively. Here the depth and horizontal distance are calculated in the plane after the pillar (at 3.35 m horizontal distance from the detector) and angular bin size corresponds to 15 cm. With the imaging resolution of 15 cm, the pillar (middle black patch with the average density above 3 gcm\(^{-3}\)) could be distinguished from the surrounding soil after 7 days and the lower part of the pillar and its bottom has

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F(m_x, m_y)_{\text{expected}} = \int \frac{dF(E, m_x)}{dE} dE,
\]

where \( p_0 = 2298.2 \) meter-water-equivalent, \( p_1 = 0.00192 \) GeV\(^{-1}\) and \( p_2 = 0.99809 \) are parameters. Fig. 4 illustrates the applied muographic density imaging procedure. Fig. 4A shows the flux measured during 15 days around the pillar in which two horizontal flux slices across the pillar (B and C) and one flux slice below the pillar (D) are denoted. Figs. 4B, 4C and 4D show the comparison of these measured flux slices with 1\( \sigma \) statistical errors to the expected fluxes calculated for various densities. Fig. 4A hints the presence of a higher density object, but it can not visualize the the pillar. In Figs. 4B and 4C the flux slices show that the measured and expected fluxes are matching at relatively larger densities between the horizontal slopes from −0.4 to 0. As it was expected, Fig. 4D shows the lack of any significant signal in this horizontal region because the pillar was installed above it.
visualized within its expected position (black dashed lines) after 15 days. We note that the upper part of the iron pillar could not be imaged because of the multiple scattering of low energy muons which are blurring the upper part of the image. The observed density images demonstrate the applicability of MWPC-based detector for small-scale imaging of dense structures on few meter scale.

5. Summary and Outlook

The first prototype of an MWPC-based borehole detector has been developed based on the so-called Close Cathode Chamber technology and the design of MWPC-based Muographic Observation System with low power consumption (~ 6 W), reasonable position resolution of about 1.8 mm and angular resolution of about 10 mrad. The borehole detector has been tested in a 3-meter-deep shaft in which its excellent operational stability and tracking efficiency (~ 99 %) have been demonstrated. To test the muographic imaging capabilities of the tracking system, an iron pillar with concrete basement has been installed inside the mound and it has successfully been imaged with a reduced resolution of 15 cm. The observed density image visualized the lower part of the pillar and demonstrated the applicability of the our technology for underground muography.

Concerning the applications of the MWPC-based detectors inside a standard borehole with a diameter below 10 cm, the robustness against mechanical shocks, high humidity and temperature variation, the low power consumption and the reasonable resolution makes a good candidate this technology. The adaptation of the size of MWPCs to a typical borehole detector house (cylindrical shape steel tube with a diameter of maximum 10 cm) is possible, as it was demonstrated by the construction of small-sized and high-resolution MWPCs in Ref. (Varga et al., 2013). To solve this task the optimization of chamber outer mechanics is ongoing. The application of lead plates in the design of the next prototype is under investigation to suppress the underground soft component (Oláh and Varga, 2017) and low-energy scattered muons (Gómez et al., 2017; Nishiyama et al., 2016). The disadvantage of the application of gaseous detectors inside boreholes is the need of continuous gas supplying. One solution is the construction of gas tight detectors, see e. g. Ref. (Wuyckens, 2018) about Resistive Plate Chambers, however that solution is challenge in case of light-weight and thin printed-circuit-boards which applied for MWPCs. In our case the application of a gas-circulation system is expected a better solution for this technical issue.

Concerning muographic density imaging at small-scale (from 1 meter to few ten meters), the extension of data sets of low-energy muons spectra and refinement of muon flux models are required to improve the accuracy of expected flux determination used for this procedure. For this aim, an MWPC-based muon spectrometer (an alternating series of MWPCs and lead absorber plates similarly to MMOS) has been constructed in the joint laboratory of NEC, Wigner RCP, CRIEPI, and The University of Tokyo, called NEWCUT.
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