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Particle physics detector development and application for muography

PhD Booklet of Thesis Statements

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Introduction

Muography is a novel imaging method that utilizes the muon particles created by the cosmic rays. These naturally occurring high energy muons are able to penetrate even kilometers of rock. The principle of imaging that the denser matter absorbs more muons, similar to X-ray imaging of bones. To a first approximation, the detected muon flux (normalized count rate) depends only on the zenith angle of the arriving particles and the material density integrated along the muon path (density-length). The strictly monotonic relationship between the muon flux and density-length is the core of absorption muography, thus providing a powerful tool to image the average densities of 10–1000 m rock layers. The muon trajectories in a given direction unit can be measured with tracking detectors known from high energy physics. The geometric constraint of muography is that the altitude of the particle tracking detector must be lower than the examined object level: no muons come from or below the horizon. However, if the geometric constraint can be overcome, then muography can provide superior imaging resolution in certain cases compared to other non-destructive geophysical techniques (such as gravimetry, seismic, or electric resistivity survey). Applications arise in multiple disciplinaries, including volcanology, mining, archeology, or civil engineering. The result of the muographic measurements are the localization of density anomalies like unknown cavities, erosion zones, high-density ore bodies, or even dynamic density changes. In some cases, if multiple detector viewpoints overlap the examined space, even 3D density reconstruction is possible.

The research field is interdisciplinary by nature, which has been one of the main challenge to the development in recent decades. From the measurement technology side, different muon tracking detector technology trends have emerged for muography, starting from high energy particle physics experiments, and since these are typically very complex systems, the experimental groups clearly focus on one or a few technologies.

In the Wigner Research Centre for Physics, the Innovative Gaseous Detector Development Research Group, which I am a member of, deals with gaseous tracking detectors, and mainly the MWPC (Multi-Wire Proportional Chamber) gaseous detector type proved to be the most efficient choice for muography. The MWPC is a robust, low consumption, inexpensive design with sufficient tracking resolution (below 10 mm). However, the detectors also have to meet further challenges due to fact that muographic data collection typically takes months in the harsh environment of a remote field.

My research group is also involved in developments for the cutting-edge tracking technology of Micro-Pattern Gaseous Detector (MPGD), such as the GEM (Gas Electron Multiplier), which enjoys widespread popularity in high energy particle physics. The MPGD can also be a promising choice for specific muography applications, especially if high resolution and monitoring is required, yet detectorphysical challenges can arise in terms of signal gain homogeneity or production defects.

In my PhD thesis, I present my gaseous detector research and development works and data evaluation efforts for muography applications in the detector physics group of Wigner Research Centre for Physics.

Objectives

The motivation of this PhD dissertation is to show my research and developments on gaseous detectors and the application for muography, aiming to meet the requirements described in the Introduction, furthermore elaborate on the research results of muographic data evaluation processes, ultimately leading to radiographic or tomographic imaging.

I will elaborate on my research and developments for the advanced MWPC for the applicability in a wide range of muography situations (thesis statement 1), which sets the following requirements for the detectors: long-term stability in underground or surface measurements, withstand ambient temperature, pressure, and humidity variations, mobility and robustness against transportation stresses, in addition to the cost efficiency, safety, and autonomous operation.

I will present the research of low gas consumption in order to significantly reduce the detector maintenance (thesis statement 2). The autonomy of the detector, and hence the low gas consumption to reduce maintenance, is crucial in specific muography applications, since the remote data allocation can take months, thus if frequent maintenance required then the muography survey would be unfeasible in some cases (usually when infrastructure is not available). I objective was to investigated how to operate the gaseous detectors with the lowest possible gas flow, keeping in mind the simplicity, which still results safe detector performance.

I will introduce our "Leopard" nicknamed GEM scanner and my developments on it, with the aim of an exclusive MPGD diagnostic examination (thesis statement 3). My developments were aimed to enhance the system resolution so not just Thick GEMs (300–400 µm hole diameter) but standard GEM foils (50–70 µm hole diameter) could be scanned, furthermore not just gold plated surfaces but the widespread copper-plated ones (much lower quantum efficiency, thus lower photoelectron yield) could be measured. As a result of the developments, my motivation was to investigate the gain-homogeneity of GEMs and the effect of manufacturing defects in order to optimize the technology and quality control.

In the final sections of the dissertation, I will describe my efforts to produce muographic images to reconstruct density distributions (thesis statement 4): here, in addition to muographic data processing, my goal was to develop a tomographic inversion method for determining the spatial location of density anomalies, and to use the method on experimental data to determine the three-dimensional structure of an underground rock layer containing a complex density anomaly system, identifying the essential experimental conditions that make this possible (measurements quality, quantity, knowledge of local geometry, and methodological issues).

Research methods

I developed 3D printed detector components and supplementary instruments (support stands, high durability and multifunctional casings, production equipments), construction procedure, chamber size and detector module variations, and a direct measurement of angular resolution for the advanced MWPC detectors.

My second thesis statement concludes that adding a non-outgassing buffer tube at the end of the gas line, which has a sufficiently large volume and at the same time long enough to restrict axial diffusion of gas degrading contaminations, the advanced MWPC detectors can be operated with an order of magnitude lower gas input flow as applied before. The research methods I developed, included the following: intrinsic detector outgassing measurement (signal gain drop in "sealed mode"), tubing radial diffusion estimation of contaminations, axial diffusion determination from the open end of the gas system, and working gas volume contraction ("breathing effect") measurement due to ambient temperature or pressure variation.

I examined the stability of the developed MWPC detectors against the above mentioned challenges (long-term outdoor test of low flow operation, signal gain calibrations, chamber stress tests). In addition to development and data analysis, I contributed to the investigations with the application of detectors through field installations and maintenance, for example at the MWPC-based muograph observatory established at the Sakurajima volcano in Japan, the muography research in Hungarian caves and the Buda Castle, the survey of Mussomeli Castle in Italy, and mining applications in Finland and Germany.

I upgraded the optical system of the Leopard UV scanner for a uniquely detailed research and development of GEM detectors. I designed adjustable 3D printed optical elements, I fine-tuned the optimal object-image distances, equipped aspheric lens and smaller pinhole, I used focused and deuterium UV sources, and I covered the aluminum elements which can blur the imaging due to reflection. I demonstrated, that the Leopard system can scan standard GEMs in 30 µm resolution which allows the examination of local detectorphysical phenomena such as edge-effect or the effect of production defects, therefore the system can contribute to the optimization of the GEM technology.

I developed a muographic data processing software, which generates rock lengths from DEM data in given directions, calculates muon flux from an expected density-length, or computes the density-length from the measured muon flux. Possible systematic uncertainties and error propagation is also included.

I investigated methods for spatial density reconstruction from the muon flux data. We adapted a maximum likelihood inversion, based on linearization and weighted least squares fitting, which reconstructs density in a discretized space with the combination of geologically relevant Bayesian constrains for the multi-view muographic measurements. The method includes uncertainty propagation, quantifications for focus zone determination, a simplified "2+1D" reconstruction for stability and convergence, and synthetic data test. I validated the 3D density estimation on a high resolution muography survey of a karstic underground crack zone at shallow depth (40–60 m) by suggesting core drill locations, and the drill samples verified the existence of density anomalies.

Thesis statements

1. MWPC detector design and construction for muography purposes

I participated in the development of the first advanced MWPC prototypes [1]. Based on this, I developed underground detector systems, which meet the conditions of long-term autonomous muographic data collection (portability, viewing alignment, dust and water droplet protection). I participated in the geophysical applications of these detectors [9, 18-20], and I developed a method for the direct determination of the angular resolution of a detector module.

With field applications, I showed that large-surface MWPC-based detectors can be produced with the 3D printed elements and designed construction processes for producing detectors that can perform stable operation in outdoor conditions for long-term remote field surveys. The detectors are able to withstand large natural daily temperature fluctuations (Δ20 °C) and rapid temperature changes, high absolute temperature (40 °C) and high humidity (90% RH), as well as significant mechanical stresses occurring during transportation [2, 5, 6, 15, 17]. The developments significantly contributed to the application of the advanced MWPC detector chambers in the muographic observatory of the Sakurajima volcano in Japan [4-6, 10-13, 15, 16].

2. Low gas consumption for MWPC detectors

I showed that gas consumption can be minimized (even below 3 l/day) in the field application of MWPC-based detectors with an open gas system if a buffer tube is attached at the end of the gas line with a non-outgassing material, a volume corresponding to the air backflow resulting from daily temperature fluctuations, and a length to restrict air diffusion [2, 8, 15, 17]. Diffusion can be further reduced with chokes installed in the buffer tube [8].

3. High resolution UV scan of micro-pattern detectors

I showed that with the Leopard detector scanner the gain-homogeneity of GEM (Gas Electron Multiplier) detectors can be examined with a resolution of down to 30 µm and that the local detector physical properties can also be measured (e.g., edge-effect, effect of production defects) [7, 14]. I have demonstrated that Leopard is capable of industrial quality control of large-scale GEMs [14]. I presented the possibilities and limits of using micro-pattern detectors in muography.

4. Muographic data processing and density reconstruction

I investigated the conversion methods between muon flux and density-length. These are necessary for the evaluation of muographic data. Furthermore, I developed a software for the application of these calculations. I took part in the muography survey for cavity research in the Királylaki Reservoir in the Buda Mountains, and by processing high-resolution and multi-viewpoint data, I showed that the spatial location of density anomalies can be determined. Based on my preliminary calculations, I planned drilling points for validation, and the drilling validated the location of low-density crack zones underground. Based on the muographic data, I tested the determination of the spatial density distribution using a maximum likelihood-based tomographic inversion method and showed that the 3D muographic density inversion can be performed after appropriate linearizations in 2+1 dimensions in the case of linear measurement positions, i.e., instead of spatial meshing, it is sufficient to perform a two-dimensional inversion in the planes intersecting the lines of the measurement points for more stable convergence [3, 18].

Applications

The first application of the advanced MWPC detectors was at the Sakurajima volcano, Kyushu, Japan, in collaboration between Wigner Research Centre for Physics, the University of Tokyo, and the NEC corporation starting from 2016. The joint Hungarian-Japanese Sakurajima Muography Observatory (SMO) facility has been developing ever since, and the number of MWPC modules reached 11 in the SMO in 2022 (8.7 m^2 sensitive area), resulting the largest muograph monitoring system in the world and numerous geoscientific findings so far. For volcanological applications, muography measurement is also initiated at Mount Etna, Italy.

Some of the ongoing or completed muography campaigns (awaiting for publication), which rely also on my thesis statements and my contribution, are presented in the Outlook chapter of the dissertation. This includes a quantification and demonstration of the muographic imaging resolution by a unique topography setup (Fairy Rock), furthermore archaeological, civil engineering, and mining applications presented (Buda and Mussomeli Castle, Kemi and Saxore mines).

Further applications of the MWPC modules are dedicated for the Horizon Europe projects of “AGEMERA” and “Mine.io”.

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