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Performance of tracking stations of the underground cosmic-ray detector array EMMA

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ABSTRACT

The new cosmic-ray experiment EMMA operates at the depth of 75 m (50 GeV cutoff energy for vertical muons; 210 m.w.e.) in the Pyhäsalmi mine, Finland. The underground infrastructure consists of a network of eleven stations equipped with multi-layer, position-sensitive detectors. EMMA is designed for cosmic-ray composition studies around the energy range of the knee, i.e., for primary particles with energies between 1 and 10 PeV. In order to yield significant new results EMMA must be able to record data in the full configuration for about three years. The key to the success of the experiment is the performance of its tracking stations. In this paper we describe the layout of EMMA and construction of the two main detector types used for muon tracking: the high-resolution drift chambers and fast scintillation detector arrays. We also show the measured tracking efficiencies, position and angular resolutions, and sensitivity of drift chambers to the air pressure. The measured angular muon distributions are well reproduced by CORSIKA simulations folded with the known density distribution of the overburden. The single muon flux at the depth of 210 m.w.e. is (1.29 ± 0.06) $m^{-2}s^{-1}$. This value was determined from the reconstructed tracks registered by a six-layer array of position-sensitive drift chambers.

1. Introduction

The EMMA (Experiment with Multi-Muon Array) underground cosmic-ray detector array has been designed to study cosmic-ray composition around the knee energy that is for the primary cosmic-ray energies in the range from 1 to 10 PeV. When such an energetic particle encounters a nucleus in the upper layers of the Earth's atmosphere it generates an extensive air shower (EAS). The profile, density, and energy distribution of the secondary particles produced in an EAS are used to reconstruct the mass and energy of the primary cosmic-ray particle. This has been exploited by several ground-based cosmic-ray measurements, like the successful KASCADE-Grande experiment (see, for example, Refs. [1] and [2], and Refs. therein).

EMMA implements a different approach. It is based on the outcome of CORSIKA [3] and QGSJET01 [4] simulations (cross-check with EPOS 1.99 [5]) predicting that by introducing a moderate energy cut-off the lateral density distribution of muons is indicative to the mass of the primary particle while the density around the shower axis (core) contains information on the energy. Consequently, it seems sufficient to measure only the muon component and still get the full information on the primary particle.

It is achieved by using a suitable overburden to filter out all the secondaries with the exception of energetic muons (and neutrinos). This approach has several experimental advantages. For example, due to the reaction kinematics energetic muons are concentrated around the shower axis. Therefore, a relevant part of EAS can be detected using an underground array with a smaller footprint. Furthermore, the particle flux is significantly reduced because of the particle rejection and a clear energy cutoff.

The key scientific reason for the construction of EMMA is to provide a significant contribution towards a better understanding of the knee region by yielding an independent and qualitatively different data set at the energy range that is already outside of the direct measurements and not yet in the full sensitivity domain of the large, indirect (air-shower) experiments.

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Fig. 1. EMMA detector stations are placed 75 m below ground in the Pyhäsalmi mine. Stations C (right) and G (left) are shown in the photograph, see Fig. 2 for the layout.

In particular, we attempt to search for additional evidence of the expected light/heavy switch in the composition around the knee. The proposed systematic study of the energetic muons should also shed light on the possible energy dependence of the muon excess in EAS and thus provide an independent verification of air-shower propagation models. In addition, by placing neutron detectors within the tracking volume of EMMA, we could investigate correlations between energetic muons and neutron bursts. Finally, in parallel to the above-mentioned measurements, the collected single-muon data will be used as a test and verification of muon tomography approach to the known profile of the mine section located within the acceptance range of EMMA. If successful, similar methods could also be employed for geological applications.

Over the past decade the construction and testing phase of the EMMA experiment has been completed. EMMA is entering the data acquisition phase. Considering the size of the array and the known particle fluxes it will require three years to yield significant new results on the composition. During that phase the stability and quality of the operation must be guaranteed. The key parameter needed to judge the setup and to prove that the obtained data are trustworthy is the tracking performance. One standard test for this is the ability to detect the Moon shadow in the data (see, for example, Refs. [6], [7] and Refs. therein). However, EMMA is located in the Pyhäsalmi mine at the latitude of 63° North and therefore the Moon never properly enters the field of view of EMMA. Instead, we show the outcome of series of dedicated tests aimed at the determination and monitoring of the tracking abilities of our detector setup.

2. Layout

The layout of EMMA is determined to a great extent by the shape and location of the vacant caverns at a suitable depth in the Pyhäsalmi mine. The second restricting factor is the limited coverage that can be provided by available detectors. Ideally we would like to fully instrument a circular area with a diameter of 50 m or more protected by a uniform overburden of around 210 m.w.e. The actual realization is shown in Figs. 1 and 2. Instead of a full coverage at a fixed depth the detectors are installed in 11 detector stations placed on two different levels: Nine at the average depth of 75 m (210 m.w.e.) and two at 35 m below the ground (120 m.w.e.). The centre-to-centre distance between the detector stations is approximately 10 m. The spacing is based on detailed simulations of cosmic-ray induced showers and muon propagation in the rock (see [8] for details).

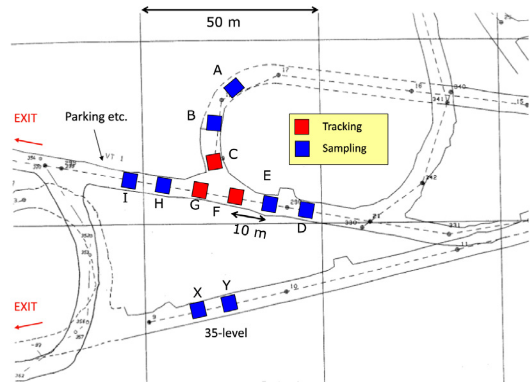

Fig. 2. Layout of EMMA in the mine caverns 75 m below ground (the two stations X and Y are 35 m below ground).

The three central stations are called tracking stations and are marked red in Fig. 2. The tracking stations have a double distance between the top and the bottom layer of the detectors compared to the other stations. In addition, the tracking stations are equipped with a third detector plane located half way between the top and bottom layer. The cross section of a tracking station is shown in Fig. 11. As explained below such an arrangement enables accurate determination of the muon arrival direction and hence the primary cosmic-ray direction. This determination is done independently by each tracking station (for tools concerning tracking, see for example [9]).

The addition of a layer of fast scintillation detectors in the tracking stations serves multiple purposes. It provides an independent verification of tracking efficiency, event multiplicity and, for multi-muon events, derives the arrival angle from the time of flight (TOF) differences which can be used as an initial guess for the tracking angles and to reject possible misinterpretations in the arrival angles.

3. Detectors

EMMA employs two detector types: drift chambers [10] and plastic scintillation detectors [11]. The former is the primary detector of the experimental setup providing the total active area of approximately 240 m^2. The drift chambers used by EMMA have been recovered from the decommissioned DELPHI experiment [10] at CERN LEP collider. They were explicitly designed and built for muon tracking and referred to as Barrel muon chambers (B-MU). The plastic scintillation detectors with the total coverage of approximately 24 m^2 were designed as ancillary detectors for EMMA and for the use in underground measurements (see [12]). In the future the coverage of EMMA will be extended by Limited Streamer Tubes [13] which have the total area of 180 m^2 (60 modules, 3 m^2 each).

3.1. Drift chambers - Calibration procedures

The drift chambers operate in the proportional mode at the anode voltage of approximately 6 kV. Instead of the original gas mixture of Ar(85.5%):CH_4(8.5%):CO_2(6%) we chose to use an Ar(92%):CO_2(8%)-mixture to avoid the use of methane gas in the mine environment even if that slightly hampers the detector performance. However, as shown below the difference is not significant.

The drift chambers are arranged into detector modules called planks. Each plank consists of seven position sensitive drift chambers (365 × 20 cm^2, 20 mm thick) arranged in lengthwise half-overlapping groups of 3 + 4 (area of 2.9 m^2 each). The