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EMMA – an underground cosmic-ray experiment

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A new cosmic-ray experiment is under construction in the Pyhäsalmi mine, Finland. It aims to study the (mass) composition of cosmic rays at and above the *knee* region. The array, called EMMA (Experiment with MultiMuon Array), will cover approximately 130 m^2 of detector area at a depth of 75 metres (∼210 mwe). It is able to locate shower cores in an area of approximately 400 m^2 with an accuracy better than 6 metres. The array detects underground muons and the muon multiplicity, their lateral distribution and the arrival direction of the air shower can be determined. First scientific measurements can be started during the spring 2009 with a partial-size array. The full-size array is expected to be ready by autumn 2010. The full-size array consist of two type of detectors: drift chambers and plastic scintillation detectors. Besides the composition study, it is also expected that the array contributes on the study of high-multiplicity muon bundles that were observed at the cosmic-ray experiments at the LEP detectors.

1. Introduction

EMMA (Experiment with MultiMuon Array) uses a new experimental approach to the investigation of cosmic rays at the *knee* region. It is not the first underground cosmic-ray experiment (see, for example, Refs. [1–5]), but it differs significantly from previous underground experiments with its ability to measure the lateral distribution function of high-energy muons. The rock overburden filters out all other charged particles of the air shower except the high-energy muons. The overburden of 75 metres (corresponding to 210 m.w.e) sets an energy cutoff of approximately 45 GeV for vertical muons. Muons detected by EMMA are thus generated in the upper part of the air shower close to the primary interaction.

Another interesting research topic that can be carried out with EMMA is the so called muon bundles (see, for example, Ref. [6]) observed in the LEP cosmic-ray experiments. EMMA has good potential to study this phenomenon at long-time basis and composition analysis included.

Cosmic rays at the knee region have been studied already for decades, with sophistigated experiments and instruments (see, for example, Ref. [7] and references therein). Their conclusions, however, have been diverse, implying the need for further studies, especially using different approaches.

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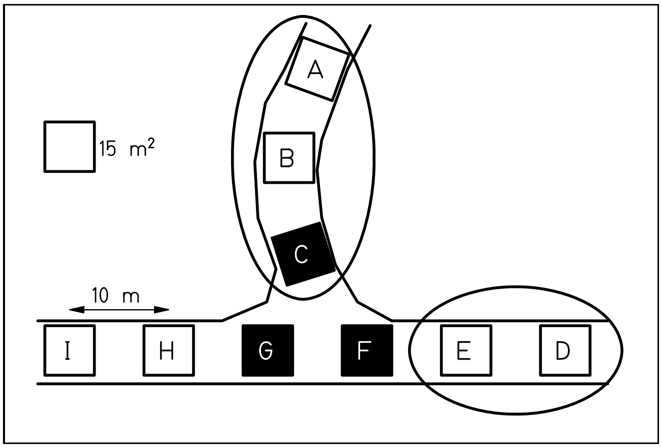

Figure 1. Schematic layout (top view) of the EMMA array in the underground site at a depth of 75 metres. The array consists of nine separate detector stations, called *cottages* and named from A to I (in the order of construction). Each cottage has an area of approximately 15 m^2 and the separation from cottage to cottage (centre to centre) is approximately 10 m. Cottages in black are called *tracking units*. There are three layers of drift chambers in each of those cottages. Also small-size plastic scintillation detectors are placed on those cottages. In other cottages one detector layer is used. Cottages inside the ellipses are ready and the measurement with angular information can be started during the spring 2009.

2. Experimental details

The present experiment will be carried out at the depth of 75 metres in the Pyhäsalmi mine (owned by the Inmet Mining Corporation Ltd., Canada) situated in the central Finland.

A layout of the array is shown in Fig. 1. The array consists of nine units (called *cottages*) each having an area of approximately 15 m^2. Two type of detectors are used: drift chambers in all cottages and small-size plastic scintillation detectors in central-area cottages. The total detector area is approximately 130 m^2.

The acceptance of the array, assuming an area in which the shower axis can be located with an accuracy better than 6 metres (see Fig. 2), was estimated to be approximately 300 m^2·sr for a 4-PeV proton-initiated shower.

2.1. Detectors

The drift chambers were previously used in the LEP–DELPHI experiments at CERN [8]. One drift chamber has an active volume of 365×20×1.6 cm^3. Seven partly overlapping chambers form a plank having an area of approximately 2.9 m^2. They operate in the proportional mode, with Ar:CO_2 (92:8) nonflammable gas mixture. Due to the safety issues, the gas mixture does not contain the formerly used CH_4.

The position resolution and efficiency calibration measurements of the drift chambers are undergoing. As preliminary results, position accuracies of better than 3 cm and efficiency better than 90 % have been obtained. Drift chambers are able to measure muon multiplicity, their lateral distribution and arrival direction by tracking.

The plastic scintillation detectors have been especially designed for the EMMA array to improve the muon measurement at high multiplicities. The drift chambers may saturate at very high multiplicities. The scintillators are small in size (12×12 cm^2 and 3 cm thick) and equipped with avalanche photo diode. There will be over 1500 such detectors in the EMMA array.

2.2. Gas system

The total gas flow needed by the drift chambers is approximately 8 ℓ/min. This cannot be carried out by gas bottles any more, which were used in the testing phase, and the new gas handling system will be in use in February/March 2009.

The gas control and monitoring system is situated at the surface and the mixed gas flows underground in an acid-proof metal pipe in a 94-metres long drilled hole. The liquid argon tank of 230 ℓ is used. Carbondioxide is taken from the bottle.

3. Simulation results

3.1. Muon tracking

The array uses muon tracking for the air-shower direction determination and in the tracking units also for the multiplicity determination. The tracking, according to simulations and first test measurements at the surface, is very accurate. The arrival direction of the air shower can be determined with an accuracy better than 2 degrees. Multiple scattering contributes approximately 1 degree to the accuracy.

The first tracking unit (cottage C in Fig. 1) will start measuring in spring 2009. This allows also to start muon bundle measurements.

3.2. Locating the shower axis

The reconstruction accuracy of the shower axis depends on the hit position in the array. An average accuracy of better than 6 metres can be achieved in a large collection area. This is illustrated in Fig. 2, where 300 proton-initiated showers at 4 PeV have been dropped into each cluster. In this example, the collection area is approximately 300 m^2 in which the shower-axis reconstruction is, on average, better than 6 metres.

In order to locate the shower axis, a two-dimensional fit routine was developed. The density distribution of the hit coordinates of muons (bin size 1×1 m^2) is used as an input for the routine (together with the assumption of the shape). The output values of the fitting routine are the shower axis location, total number of muons in the shower (above the threshold energy), and a parameter related to the gradient of the lateral distribution function.

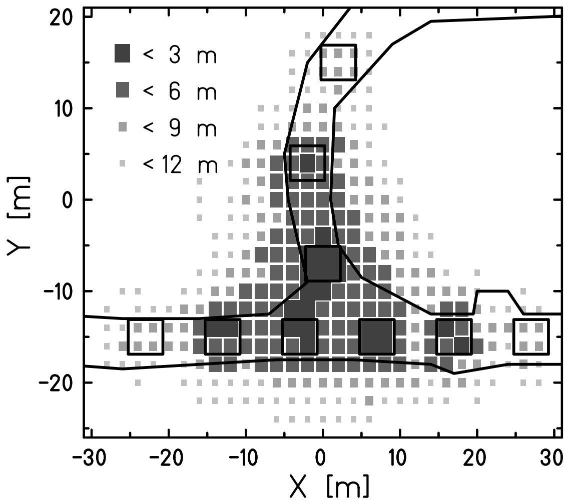

Figure 2. The accuracy of the reconstructed shower axis is shown as a cluster plot for a 4-PeV proton shower. The symbols represent the average shower axis uncertainty. The area where the shower axis can be determined with an average accuracy better than 6 metres is approximately 300 m^2. Each cluster contains 300 showers.

3.3. Composition extraction

The idea of extracting primary cosmic-ray mass composition is based on the fact that the lateral distribution of high-energy muons is sensitive to primary particles and their energies. The number of muons at the shower axis can be used as an indicator for the primary energy. The energy resolution of EMMA according to this preliminary analysis is somewhat moderate.

The composition reconstruction simulations have been performed with a realistic energy spectrum and various proton-iron fractions were assumed for. The energy interval of 0.8−20 PeV was selected and the spectral index of −2.7 was used. The shower axes were distributed uniformly in an area of 160 × 160 m^2. The simulated sample consisted of 2×10^6 showers. The outcome of the method is illustrated in Fig. 3.

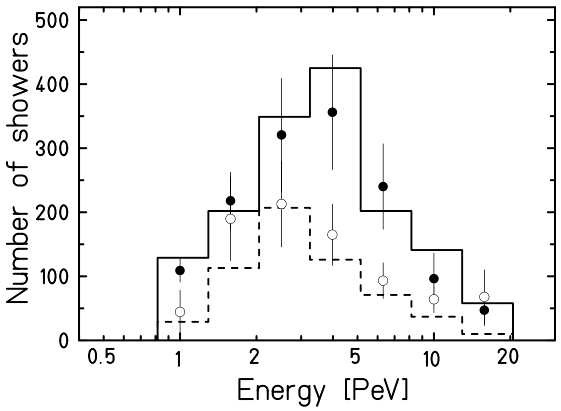

Figure 3. Reconstructed compositions for the initial condition of 80% proton (full symbols) and 20% iron (open symbols). Full histogram shows simulated proton composition and dashed histogram simulated iron composition.

4. High muon multiplicities

In the cosmic-ray experiments at LEP (DELPHI, CosmoALEPH, and L3+C) [3,6,9,10] events with high muon multiplicities were observed. While the small and medium muon bundles seem to fit into the model predictions, the production of the high multiplicities is not yet clear. These cosmic-ray experiments at LEP were short in time, effective running times of only about a month or two each.

The LEP experiments were not able to extract information on the lateral distribution of high-energy muons, and thus not directly on the primary particle producing the muon bundle.

EMMA is able to study the high-multiplicity events, already with a partial-size array. It is expected that EMMA can make a significant contribution to clarify the reason for the highest multiplicities. First, EMMA can measure the lateral distribution and thus obtain good information on the primary particle. In addition, this phenomena can now be studied systematically for several years.

5. Summary

The new underground cosmic-ray experiment EMMA is under construction. The first measurements can start during spring 2009. The analysis of simulated air showers shows that the primary cosmic-ray composition could be resolved at and above the knee energies. It is also expected that the anomaly of high-multiplicity muon bundles observed at CERN can be studied systematically with EMMA.

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