CaloCube and "Tracker In Calorimeter" projects for the direct measurement of high energy charged astro-particles and gamma rays.

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Abstract. Measurements of high energy cosmic rays in the "knee" region (about 10^{15} eV) are currently available only with ground detectors: new observations of cosmic particles up to these energies with direct measurements are one of the main goals of the next generation space experiments. To achieve those aims, a large acceptance, good energy resolution and particle identification are needed. CaloCube is the design of a space borne calorimeter which is capable to accept particles coming from any direction, increasing the acceptance with respect to traditional telescopes. A good performance for both hadronic and electromagnetic showers is achieved with a 3-D sampling capability: the basic picture of CaloCube is a cubic homogeneous calorimeter which consists of cubic scintillating crystals. MC simulations, concerning different materials and geometrical configurations, and several beam tests with different versions of the CaloCube prototype have been employed to optimize both the detector design and the data analysis method. Taking advantage of the CaloCube project, the space experiment HERD ("High Energy Cosmic Radiation Detection") will include a large acceptance cubic calorimeter with cubic LYSO crystals. It will be installed on-board of the Chinese space station around 2025.
Beside the charged particle observations, high energy gamma-rays provide direct information about the galactic cosmic ray sources. A new project named "Tracker In Calorimeter" (TIC) was approved by INFN in 2017 with the main purpose of the optimization of the calorimeter design for the reconstruction of the gamma-ray direction, without the requirement of additional not homogeneous pre-shower detector. A TIC prototype was recently assembled and tested at the PS-CERN and SPS-CERN accelerators.

1 Introduction

Accurate measurements of high energy astro-particles are needed to provide new information about the origin of cosmic rays (CR), but these are also relevant for the search of dark matter signatures. For example, the presence of possible CR sources nearby the Earth can be investigated observing the CR electron spectrum up to tens of TeV, while the models related to the CR acceleration and propagation can be tuned with new observation of proton and nuclei spectra up to the "knee" region, i.e. about 10^3 TeV per nucleon. Actually CR

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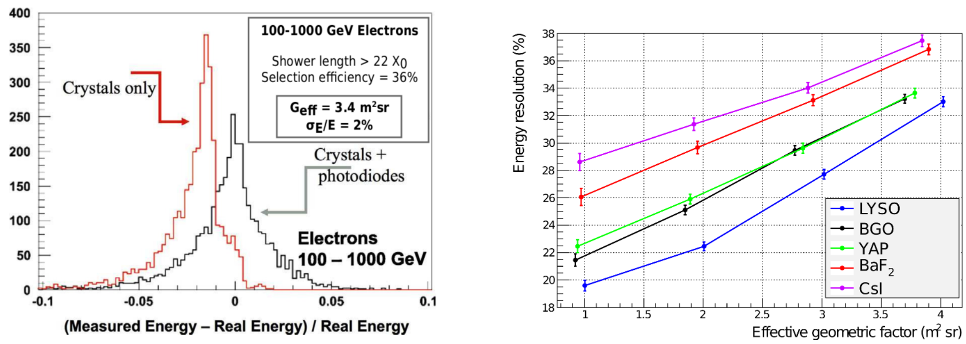

Figure 1. Left: fraction of energy deposited in the calorimeter by electrons from 100 GeV to 1 TeV, taking into account the energy deposited in crystals only (red histogram) or also the contribution of direct ionization on photodiodes (black histogram). Right: energy resolution for protons at 1 TeV by employing different materials and different event selections, corresponding to effective GFs.

observations in these energy ranges are available thanks to indirect measurements with ground detectors. These experiments exploit large geometrical factors (GF) but they are affected by large systematic errors due to the modeling of shower development in the atmosphere.
Space detectors are capable to provide precise direct measurements but they are limited by small acceptances with respect to ground experiments. A GF of about 3 m^2sr with an observation time of 5 years is required to measure protons up to the knee region. Furthermore an energy resolution for protons better than 40% and a good charge resolution, of about 0.3, for nuclei are needed. Finally an high dynamic range of about 10^7 is essential to measure the energy deposit from MIP particle to high energy shower.

2 The CaloCube project.

The goal of the CaloCube project[1] is the optimization of the design of a calorimeter which is capable to fulfill the requirements for next generation CR detectors. CaloCube is an homogeneous cubic calorimeter which detects of incoming particles from all the directions thanks to a 3-D segmentation: this design features a larger acceptance with respect to a typical CR telescope, which can detect particles hitting the detector on top surface only. The project base-line consists of 20x20x20 cubic CsI(Tl) scintillating crystals, with a total thickens of about 30 X_0. The crystal sides are equal to 1 Moliere radius, i.e. 3.6 cm, thus allowing for a good 3-D shower reconstruction. The scintillation light is read-out with a couple of photodiodes (PD) with different active area and connected to a double gain front-end electronics to extend the dynamic range of the detector.
By using the FLUKA package, accurate MC simulations[2] were developed to optimize the design. These take into account instrumental effects like electronic noise and direct ionization of the active area of the PDs. The left panel of figure 1 shows the energy deposited in the calorimeter by electrons simulated in the energy range between 100 GeV and 1 TeV. The red histogram takes into account the energy deposited in the crystals while the black one includes also the signals due to the direct ionization of the PDs. In both cases an energy resolution of about 2% is obtained. A simple event selection is employed in order to include only electrons

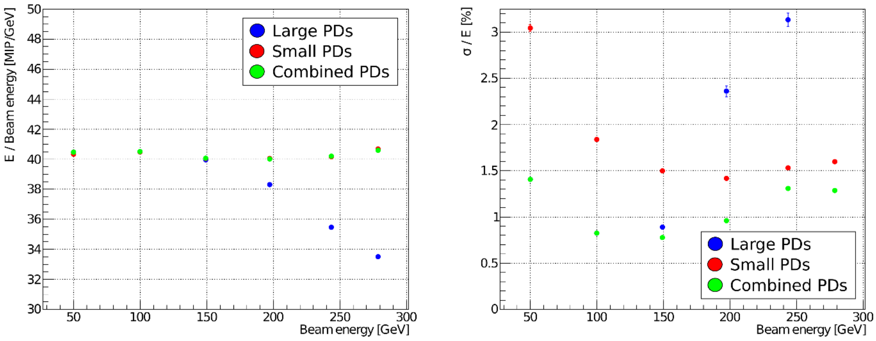

Figure 2. Fraction of the energy deposit in the calorimeter (left) and energy resolution (right) for electrons at different energies.

well contained in the calorimeter: the effective GF, which is the nominal GF multiplied by the selection efficiency, is 3.4 m^2sr for this analysis. The CaloCube performance for hadronic showers has been studied using different materials for the scintillating crystal (CsI(Tl), BaF_2, YAP(Yb), BGO, LYSO(Ce)). For each material, the number of crystals is adjusted in order to keep the total calorimeter weight equal to about 1.6 tons. The energy resolution for protons at 1 TeV obtained with different event selections, corresponding to different effective GFs, is shown in the right panel of figure 1. LYSO is the best candidate mainly thanks to its short hadronic interaction length.
To confirm the MC simulation results a prototype of CaloCube was developed and continuously upgraded[4]. The final version consists of 5x5x18 CsI(Tl) crystals, the scintillation light is read-out by two PDs (VTH2090 and VTP9421) with different active area. The front end-electronics consists of CASIS chips, which are low noise, low consumption, high dynamic range charge amplifiers developed by the INFN[3]. The performance of the prototype was studied with several tests at SPS-CERN by using electron and nuclei beams. Figure 2 shows the mean energy deposit in the calorimeter divided by the beam energy (left panel) and the energy resolution (right panel) obtained with electron beams from 50 GeV to 280 GeV using the large and the small PDs. The green points are obtained using the large PD where when its signal is not saturated and the small PD otherwise. The saturation of the large PDs starts at about 150 GeV but by using the combined information, a resolution better than 1.5% is achieved in the entire energy range, as expected from the FLUKA MC simulations of the prototype. Finally the energy resolution for protons obtained with beam test data is better than 40%.

3 The Tracker In Calorimeter project.

In parallel with observations of high energy charged particle, also gamma-rays detection is relevant: the direction of incoming photons points the CR sources, providing direct and unique information about these. The standard approach of a typical gamma-ray detectors is based on a named tracker-converter with silicon tracking layers interleaved by tungsten layers, e.g. the Fermi-LAT detector[5]. This design achieve a good angular resolution, since it exploits the photon conversion in tungsten, but it limits the acceptance of the detector with respect to the calorimeter GF, as shown in left panel of figure 3. Furthermore the tungsten layers are thick passive material, thus when using the same detector to detect charged CR,

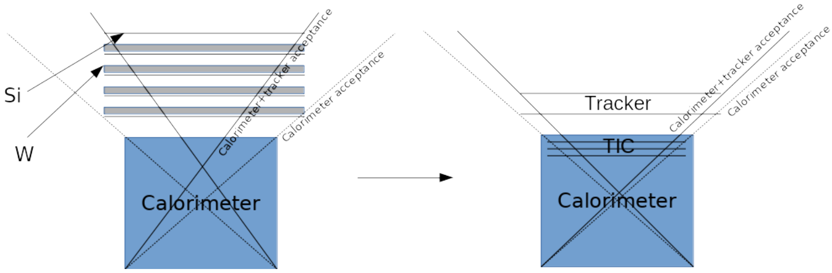

Figure 3. Schematic picture of the standard configuration of a tracker-converter (left) and the TIC basic idea (right). For simplicity only the top face of the instrument is considered in this illustration.

they degrade the energy resolution for low energy particles and the charge resolution for nuclei due to fragmentation in the passive material. Tracker In Calorimeter (TIC) is an *R&D* project approved by INFN in 2017; its main scientific goal is to adding to a detector for charged CRs the possibility to measure also gamma-rays, without compromising the performance for charged particles. The basic idea is to insert silicon micro-strip detectors inside CaloCube and make use of the scintillating crystals as an active converter. By combining the signals of the cubes and the silicon planes the early stage of the electromagnetic shower generated by gamma-rays can be precisely sampled, and the sampling can then be used to reconstruct the arrival direction of the primary photons giving origin to the shower. Some conventional tracking layers are needed outside of the calorimeter to track charged particles and measure the particle charge. This external tracking device can have a lower profile than that of a conventional tracker-converter; furthermore, tungsten is no longer needed. Preliminary MC simulations of several TIC configurations feature an angular resolution better than 0.5° for gamma-rays above 10 GeV. A TIC prototype have been realized integrating several silicon layers inside the CaloCube prototype: prototype has been tested in 2018 at PS-CERN and SPS-CERN accelerators with several electron beams from 1 GeV to 100 GeV. The data analysis is still ongoing.

4 Prospectives of the CaloCube and TIC projects

The idea of a 3-D deep isotropic calorimeter was investigated by the CaloCube collaboration and the good performance of this design is consistent with the one required for the next generation CR experiments. The future space experiment HERD ("High Energy Cosmic Radiation Detection") has chosen the 3-D large acceptance calorimeter design with cubic LYSO crystals. Furthermore if the ongoing data analysis of TIC beam test will confirm competitive performance with that of the tracker-converter design then it will be proposed for being used in HERD.

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