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CaloCube: an innovative homogeneous calorimeter for the next-generation space experiments

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Abstract.
The direct measurement of the cosmic-ray spectrum, up to the knee region, is one of the instrumental challenges for next generation space experiments. The main issue for these measurements is a steeply falling spectrum with increasing energy, so the physics performance of the space calorimeters are primarily determined by their geometrical acceptance and energy

resolution. CaloCube is a three-year R&D project, approved and financed by INFN in 2014, aiming to optimize the design of a space-born calorimeter. The peculiarity of the design of CaloCube is its capability of detecting particles coming from any direction, and not only those on its upper surface. To ensure that the quality of the measurement does not depend on the arrival direction of the particles, the calorimeter will be designed as homogeneous and isotropic as possible. In addition, to achieve a high discrimination power for hadrons and nuclei with respect to electrons, the sensitive elements of the calorimeter need to have a fine 3-D sampling capability. In order to optimize the detector performances with respect to the total mass of the apparatus, which is the most important constraint for a space launch, a comparative study of different scintillating materials has been performed using detailed Monte Carlo simulation based on the FLUKA package. In parallel to simulation studies, a prototype consisting in 14 layers of 3 x 3 CsI(Tl) crystals per layer has been assembled and tested with particle beams. An overview of the obtained results during the first two years of the project will be presented and the future of the detector will be discussed too.

1. Introduction

Precise measurements of the cosmic-ray (CR) spectrum and composition are essential to improve the constraints on the theoretical models of CR propagation and acceleration. Since the differential all-particle flux of CR is very steep, a large acceptance is required to achieve statistically significant measurements of high energy CR flux. Measurements of the CR all-particle spectrum with ground experiments show that it becomes suddenly steeper and the composition progressively heavier in the PeV region. This feature, known as the "knee", is believed to indicate the energetic limit of the galactic accelerators. A precise knowledge of the spectrum and composition in this region would address key items in the field of high-energy astrophysics. Furthermore, measurements of primary and secondary species is important in understanding CR propagation in the Galaxy. On the other hand, electrons and positrons suffer significant energy losses due to radiative emission along their path to Earth, so detailed measurement of the high energy electron spectrum and anisotropy could provide information about nearby CR sources.

Ground experiments achieve very large statistics for high energy CRs thanks to their large acceptance but are affected by large systematic errors due to modelling of the interaction of particles with the atmosphere. Direct observation of CR, by experiments installed on satellites and balloons, provides precise information of single-particle spectra. The main limitations of these experiments are due to the constraints on volume and mass. In order to extend nuclei spectra above 100 PeV, and electron+positron spectra up to 10 TeV, future space experiments need an acceptance of at least 2.5 $m^2sr \times 5$ yr, an energy resolution better than 40% for protons and nuclei and 2% for electrons, a good particle identification and a high dynamic range.

2. The CaloCube baseline and the expected performance

CaloCube [1] proposes an innovative solution for space experiments, based on a deep homogeneous isotropic calorimeter with three dimensional segmentation. The current space experiments (e.g. [2, 3, 4, 5]) accept particles only from the top surface while CaloCube can accept particles from almost all directions: only the bottom surface is unusable due to the mechanical structures and the Earth. The base line for such a detector is a cubic calorimeter consisting of $20\times20\times20$ cubes. The crystal side is 3.6 cm, approximately one Moliere radius. The spacing between crystals is 0.3 cm and the total depth for vertical particle is 39 X_0 (1.9 λ_I). Due to the five-faced detection, the total geometric factor (GF) is very large, 9.55 m^2sr. Scintillation light is detected by two photodiodes (PDs): a large area one and a small area one to achieve a very high dynamic range. The PDs are connected to an automatic double-gain front-end electronics by kapton cables as shown in Fig. 1.

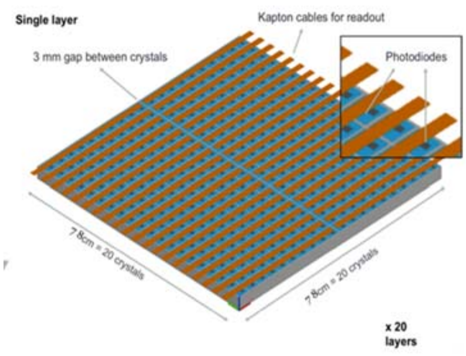

Figure 1. One layer of the CaloCube baseline geometry. The complete calorimeter consists of 20 identical layers.

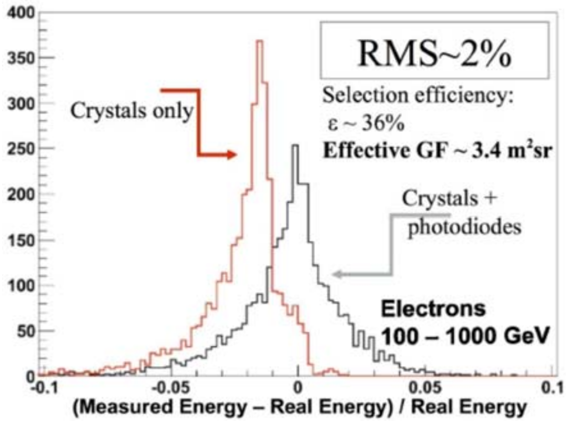

Figure 2. Measured energy in the calorimeter for electrons in the energy range 100 GeV - 1 TeV.

A Monte Carlo simulation based on the FLUKA package have been developed. The CaloCube baseline geometry is implemented and both the scintillation light and the energy deposit in the large area PD due to the direct ionization are converted into photo-electrons. Electrons from 100 GeV to 1 TeV are simulated with an isotropic generation on the top surface of the calorimeter. The distribution of energy measured in the calorimeter is shown in Fig. 2: the red line includes only the energy deposit in crystals and the black line includes the direct ionization on the PDs. The energy resolution is about 2%, and a very large effective GF[1] is achieved, 3.4 m^2sr.

Protons from 1 TeV to 1 PeV have been simulated. In order to get a good energy resolution for hadronic showers an off-line compensation method is required: the measured energy in such thin calorimeter strongly depends on the shower length[2]. As an example, the trend of the measured energy for protons at 1 TeV versus the shower length is shown in Fig. 3: the integral of a Gamma function is used in the fit. Event by event corrections of the longitudinal leakage based on the fitted function improve the energy resolution for protons: about 35% with an effective GF$\sim$ 2.5 m^2sr at 1 TeV. Simulations show that the energy resolution and the effective GF are weakly dependent on the proton energy, only $\sim$ 10% differences in the simulated range.

In order to optimize both the energy resolution and the effective GF, different materials for the scintillating crystal (CsI(Tl), BaF_2, YAP:Yb, BGO, LYSO:Ce) have been tested using MonteCarlo simulations. The geometric parameters have been defined by assuming about 1.6 *tons* of active material, 78% of active-volume fraction, and the size of the single element has been fixed to one Moliere radius. The energy resolution dependence on the GF for the tested materials applying a progressively lower limit on the shower containment are shown in fig. 4. As expected an increase in the shower containment translates into an improvement of the energy resolution while the GF gets worse. LYSO is found to be a promising material to maximize energy resolution and GF.

3. The prototype: beam test results

As a validation of the calorimeter simulations, a small-scale prototype has been assembled [6]. This calorimeter consists of 15 layers of 3×3 CsI(Tl) cubic crystals with a side equal to 3.6 cm. The spacing between crystals is 0.4 cm. A large area PD (VTH2090, Excelitas) is used for

[1] The *effective geometric factor* is defined as the geometric factor of five-faced detection multiplied by the event selection efficiency.

[2] The shower length is the distance from the shower starting point and the exit point from the calorimeter

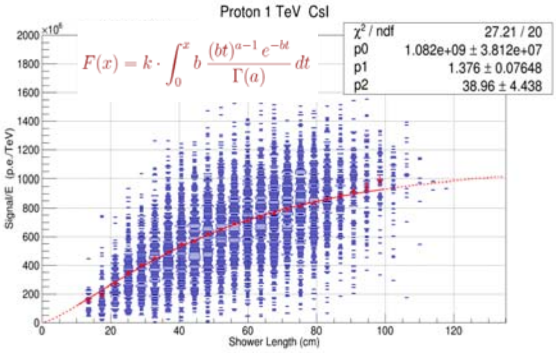

Figure 3. Measured energy in the calorimeter (CsI(Tl)) versus the shower length for protons at 1 TeV. The red curve is the integral of the gamma function used in the fit.

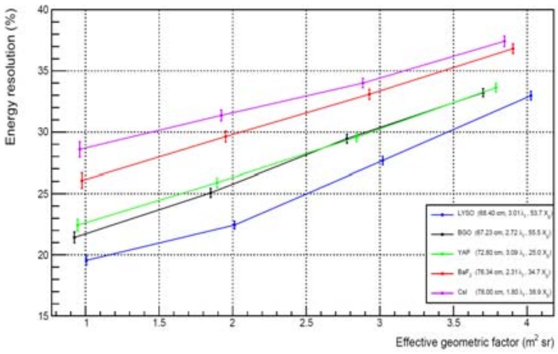

Figure 4. Energy resolution and effective geometric factor for protons at 1 TeV with different scintillating materials. LYSO is one of the best candidates for future hadronic calorimeters.

the read-out of the scintillating crystal. Nine CASIS ASICs developed by the INFN in Trieste [7] are the front-end electronics. The CASIS chip consists in 16 channels with a double-gain charge-amplifier with automatic gain selection circuitry and correlated double sampling filtering: thank to this design high dynamic range, up to 52.6 pC, low noise (ENC $\sim$ 3000 e^-) and low power consumption, 2.8 mW/ per channel, are achieved. Different wrapping materials of the crystals have been studied: laboratory measurements have shown that Vikuiti optimizes the light collection.

Beam tests with ions, from Deuterium to Iron at 12.8 GeV and 30 GeV per nucleon, were performed at CERN-SPS in 2013. The results are presented in [6]: a very good linearity up to ion kinetic energies of 1.6 TeV is shown. A Monte Carlo simulation based on the FLUKA package of the prototype has been developed and a good agreement between beam test data and simulation is found.

An upgraded version of the prototype has been tested with electron and muon beams at CERN-SPS in 2015. During this test, ADAMO [8], a tracking system based on a silicon micro-strip detector, was located in front of the calorimeter. Data with muon beam at 150 GeV and electron beam at energies from 50 GeV to 200 GeV were acquired. The muon dataset has been used for channel-by-channel calibration and for the reconstruction of the geometrical position of both the crystals and the PD active areas thanks to the direct ionization within the silicon, Fig. 5. This information is crucial to understand correctly the performance of the calorimeter for electrons; in a beam test configuration all the incident particles are almost perpendicular to the top face of the calorimeter, therefore an electron shower can intercept all the PD active areas. This difference with respect to the situation with real CR, where the flux is isotropic and the number of PDs directly hit is a stochastic variable, affects the expected energy resolution estimated by the simulation of an isotropic flux (sec. 2). The energy resolution for electrons at 50 GeV without selection on the incident position is $\sim 3\%$, but rejecting events directly interacting in the PDs results in a energy resolution of $\sim 1.5\%$, Fig. 6. A FLUKA based simulation of the beam test configuration has been developed: a good agreement with the beam test data is found and the estimated energy resolution is consistent with the one measured from beam test data for both unselected and the geometrical-selected events.

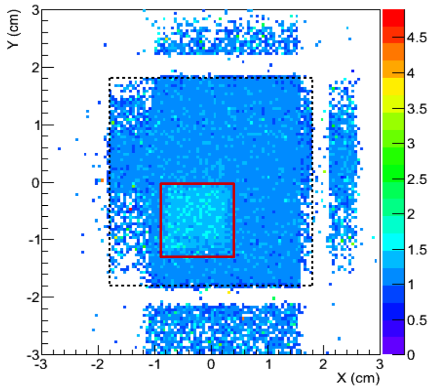

Figure 5. Measured energy for muons at 150 GeV in the central crystal of the central column of the calorimeter versus the position reconstructed by ADAMO. The crystal (black dashed line) and the PD active area (red line) are highlighted.

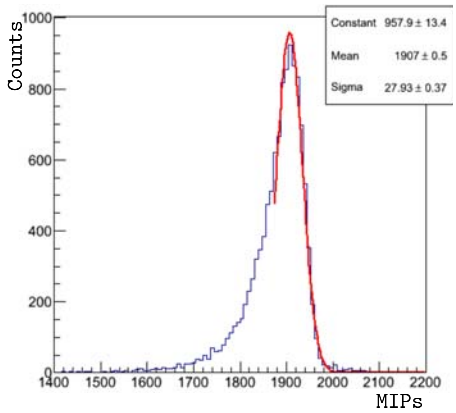

Figure 6. Measured energy for an electron beam at 50 GeV. Only events that do not intercept the PDs are taken into account. A good energy resolution, about 1.5% is achieved.

4. Conclusion

An innovative design for a space calorimeter is presented. Thanks to the five-faced acceptance and to the high granularity a good energy resolution and a very large effective geometric factor for both electrons and protons are achieved. Monte Carlo simulations of different scintillating crystals show that LYSO is one of the best candidates as active material of future space hadronic calorimeters. A small-scale prototype has been tested with ion and electron beams: a good agreement between simulations and data has been obtained.

An upgrade of the prototype is under construction: the new version will consist of 18 layers, each consisting of 6×6 CsI(Tl) crystals, and a small area photodiode will be added to each crystal to extend the current dynamic range (some TeV for hadronic showers) to the hundred TeV region.

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