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CaloCube: a novel calorimeter for high-energy cosmic rays in space

The Calocube collaboration

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2017 JINST 12 C06004

Abstract: In order to extend the direct observation of high-energy cosmic rays up to the PeV region, highly performing calorimeters with large geometrical acceptance and high energy resolution are required. Within the constraint of the total mass of the apparatus, crucial for a space mission, the calorimeters must be optimized with respect to their geometrical acceptance, granularity and absorption depth. CaloCube is a homogeneous calorimeter with cubic geometry, to maximise the acceptance being sensitive to particles from every direction in space; granularity is obtained by relying on small cubic scintillating crystals as active elements. Different scintillating materials have been studied. The crystal sizes and spacing among them have been optimized with respect to the energy resolution. A prototype, based on CsI(Tl) cubic crystals, has been constructed and tested with particle beams. Some results of tests with different beams at CERN are presented.

Keywords: Calorimeter methods; Calorimeters; Space instrumentation; Scintillators and scintillating fibres and light guides

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2017 JINST 12 C06004

Contents

1 **Introduction** 1

2 **The CaloCube concept** 1

3 **The Monte Carlo simulations and the expected performances** 2

4 **The prototype** 3

5 **Beam test and results** 4

2017 JINST 12 C06004

1 Introduction

The scientific rational driving CaloCube[1] [1] requirements is the direct measurement of the charges cosmic rays close to the 'knee', the PeV region where the inclusive spectrum of cosmic rays changes slope becoming steeper and the composition progressively heavier. So far this region has been accessible only with ground based experiments detecting induced air-showers. This indirect measurements have large acceptance but result in large systematic errors due to model dependence for what concerns energy resolution and composition studies. Direct CR detection overcomes those limitations, but suffers from limited exposure, due to constraint in the apparatus mass in space mission. This constraint have limited the measurement of H and He spectra to 100 TeV and heavier nuclei to no more than 1 TeV. The detection of the knees of the H and He spectra requires an acceptance of at least 2.5 m^2 sr×5 yr while the energy resolution is less constrained, being sufficient ~ 40%. A possible detector design satisfying these requirements is a charge measuring device followed by a calorimeter.

Additionally this calorimeter can measure the cosmic rays electrons and, if coupled to a tracker-converter system and an anticoincidence shield, the high-energy gamma radiation. This possibility requires an energy resolution better than 2% and a high h/e rejection factor above 1 TeV.

2 The CaloCube concept

The goal of CaloCube is to achieve the above discussed performance with a space-borne calorimeter, within the constraint dictated by the limitation in weight (~ 2 tons).

The proposed solution consists in a 3D array of cubic scintillating crystals, optically isolated from each other, readout by one or more photodiodes (PDs), arranged to form a cube (see figure 1). The homogeneous detector geometry provides the possibility to collect particles from five faces out of six (bottom is excluded), so the geometrical acceptance for a fixed mass budget is maximised. The

[1]CaloCube is an R&D project financed by INFN for 3 + 1 years (end 2017).

cubic crystals, acting as active absorber, provides good energy resolution, while the high granularity provides 3D shower imaging, providing information for leakage correction and h/e separation.

Such stringent requirements can be obtained using a calorimeter in conjunction with a dE/dx detector, and for this purpose the CaloCube project was created, with the aim of designing and optimising of a calorimeter for measurements of high-energy cosmic rays in space [2, 3].

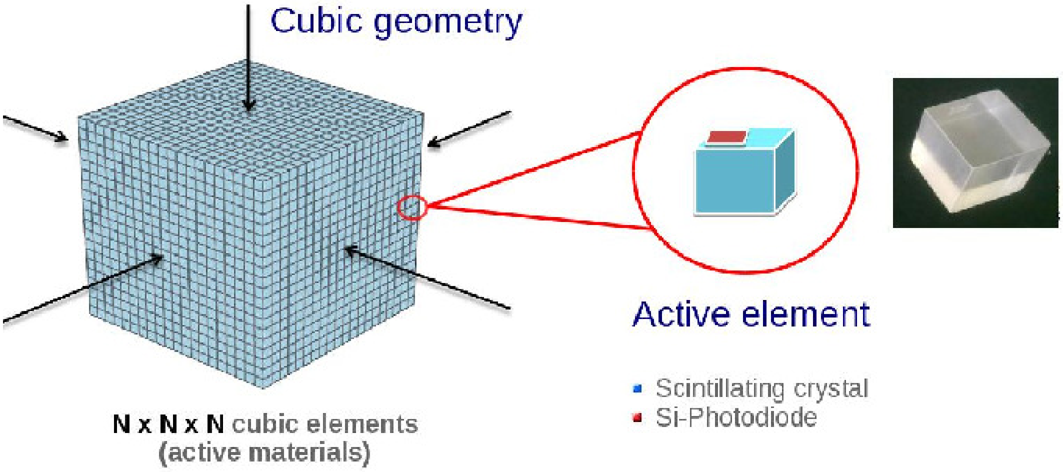

Figure 1. The CaloCube layout is based on a quasi-isotropic geometry with cubic symmetry, where the active volume is made of NxNxN small cubic scintillator crystals, optically isolated from each other, read from one or more solid state detectors (Si-Photodiode).

3 The Monte Carlo simulations and the expected performances

The calorimeter response depends on the adopted geometry and on the material used for the single scintillating crystals. For this reason, an accurate Monte Carlo, based on the FLUKA package, has been developed to carefully study the calorimeter operation in different configurations.

A NxNxN cubic geometry, with cubes of about 1 Molière radius size each, has been studied with different scintillating materials, sizes and gaps (distance between the adjacent cubes). Different configurations, comparable in terms of total weight ($W_{tot} \simeq 2$ tons) and active volume fraction (about 78%) are shown in table 1. Among the five materials, LYSO ($Lu_{1.8}Y_{0.2}SiO_5$(Ce)) is the best one

Table 1. Main parameters of the simulated calorimeter geometries (see section 3 for explanation).

	CsI(Tl)	**BaF_2**	**YAP(Yb)**	**BGO**	**LYSO(Ce)**
l (cm)	3.60	3.20	2.40	2.30	2.10
Gap (cm)	0.30	0.27	0.20	0.19	0.18
N cubes	$20 \times 20 \times 20$	$22 \times 22 \times 22$	$28 \times 28 \times 28$	$27 \times 27 \times 27$	$30 \times 30 \times 30$
L (cm)	78.0	76.3	72.8	67.2	68.2
L_{int} (λ_{int})	1.80	2.31	3.09	2.72	3.01
L_{rad} (X_0)	38.88	34.73	24.96	55.54	53.75
GF (m^2 sr)	9.56	9.15	8.32	7.10	7.35

2017 JINST 12 C06004

for protons, due to the better shower containment, which compensates for the smaller volume (due to its high density of 7.1 g/cm^3).

The collection efficiency of the scintillation light depends on the type of coating used to reflect the light and isolate each crystal from the adjacent ones. Several different materials have been tested measuring the signal induced by a 5.5 MeV α emitted by a ^{241}Am source, and the results (in terms of signal amplitude) are shown in figure 2.

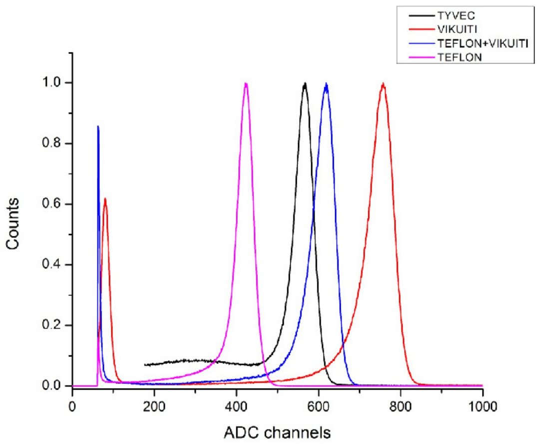

Figure 2. Signal amplitude due to 5.5 MeV α particles of a single CsI(Tl) scintillator crystal (36 mm)^2 with different coating materials.

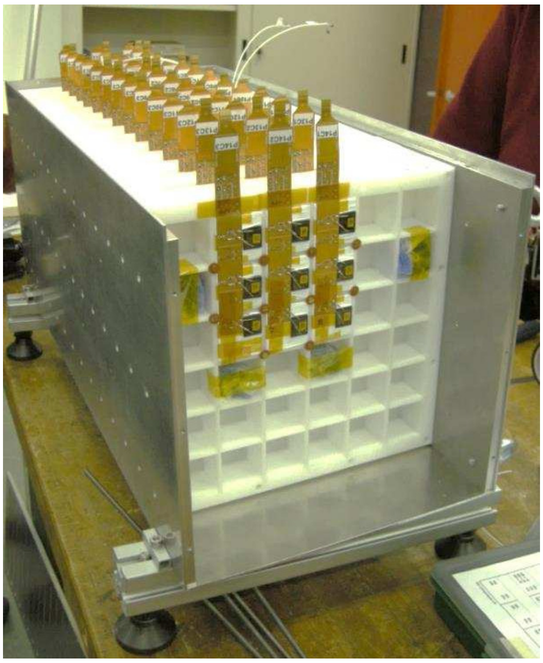

Figure 3. The prototype with $3 \times 3 \times 15$ CsI(Tl) crystals tested under beam at CERN in 2015.

4 The prototype

A small mechanical structure has been built, to allow the test of different geometric configurations on an accelerator beam. A prototype with 135 CsI(Tl) cubic crystals of 3.6 cm size, arranged in 15 planes of 3×3 cubes each, with a gap of 0.4 cm between them, has been built (figure 3) and tested on accelerator beams.

This prototype has a shower containment of about 1.5 Molière radius (R_M) and an active depth of 28.4 X_0 and 1.35 λ_{int}, and has been tested at CERN with different particle beams, summarised in table 2. Each crystal is wrapped with few layers of Teflon tape and optically coupled to a single PD, VTH2090H from Excelitas, a large-area ($\sim$ 100 mm^2) sensor that allows to clearly detect minimum-ionising protons with a signal-to-noise ratio of $\sim$ 15. One of the most challenging requirements is the very large dynamic range (10^7) ranging from 20 MeV for minimum ionising protons to 10% of the energy of a PeV proton. This will be accomplished by using also a second small area PD ($\sim$ 1 mm^2). The front-end electronics is based on a custom designed high dynamic-range, low-noise ASIC, characterised by a dynamic range of 52.2 pC and an ENC $\sim$ 0.5 fC at 70 pF input capacitance.

2017 JINST 12 C06004

Table 2. Parameters of the beam tests.

Test	Beam	Energy
Feb. 2013	ions from Pb + Be $A/Z = 2$	13–30 GeV
Mar. 2015	Ions from Ar + Poly	19–30 GeV
Aug./Sep. 2015	μ, π, e	50, 75, 150, 180 GeV

5 Beam test and results

During the beam test at CERN in summer 2015, the prototype was exposed to $\mu^{\pm}$ beams, to obtain the response of each crystal to a minimum ionising particles (m.i.p.), thus determining the individual conversion factors between the deposited energy and the photodiode signal (figure 4). These factors were later used to equalise the response of all the cubes.

Then an estimate of the energy resolution has been determined, exposing the calorimeter to $e^{\pm}$ beams of different energy, and determining the total deposited energy, given by the sum of the equalised signals of all the cubes. A preliminary result is shown in figure 5, referring to a beam of 50 GeV electrons. In this case the measured total energy (expressed in m.i.p) is in good agreement with the expectation, and the corresponding resolution is at level of 1%. In the 2013 beam test the prototype was exposed to ion beams of 12.8 and 30 GeV/n, containing $A/Z = 2$ fragments produced by a primary Pb beam colliding with a Be target.

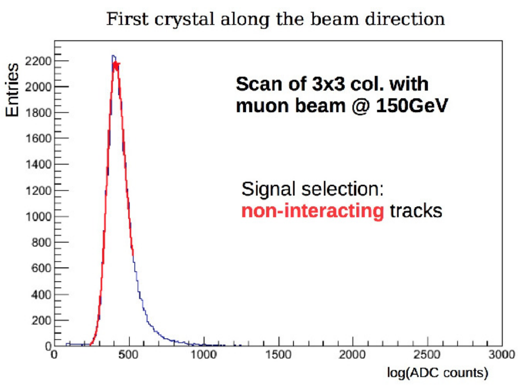

Figure 4. Response of a single crystal to a non-interacting track at 150 GeV (mainly μ). The distribution is well fit with a Landau distribution (red).

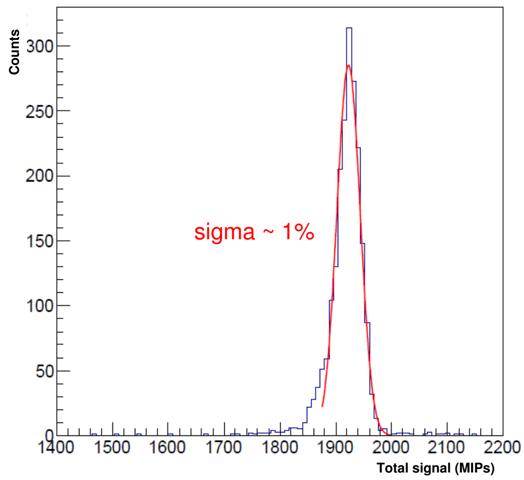

Figure 5. Measured distribution of total energy (expressed in m.i.p.) released with a 50 GeV electrons beam, fit with with the expected distribution (red). The resulting energy resolution is about 1%.

The single-crystal performances were studied, by selecting non-interacting ions. The observed dispersion among crystal responses was about 15%, with an average signal-to-noise ratio for deuterons of ~ 10. The single-crystal responses were equalised by normalising to the energy deposit of non-interacting He nuclei (set by definition to 4 MIP), the most abundant fragments. Showers were classified on the basis of the starting point, which in the beam-test set-up univocally determines the shower containment. Figure 6 shows the energy deposit (left) and its relative fluctuations (right) for He induced showers, versus the shower starting layer; in spite of the significant leakage for showers starting progressively deeper inside the calorimeter, the energy resolution is almost constant and better than 40% down to the fifth layer.

A Monte Carlo model of the prototype has been developed in Fluka and its predicted response is shown in figure 7 in comparison with real data. A fine tuning of the Monte Carlo was necessary in order to reproduce the beam-test data. In particular, an additional spread of 4.5% on the single-crystal responses and an optical cross-talk of 14% were introduced.

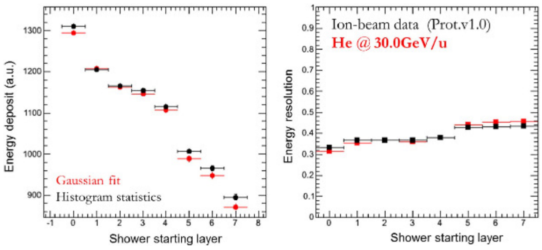

Figure 6. Energy deposit (left), in MIP, and energy resolution (right) measured for He nuclei, as a function of the layer where the shower starts.

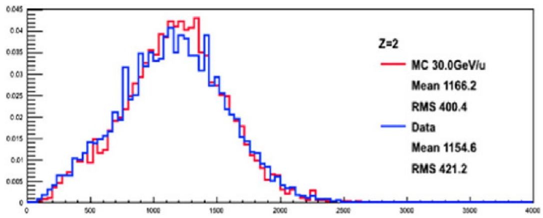

Figure 7. Distribution of the energy deposit (in MIP) of 30 GeV/n He ions for data (blue) and MC (red).

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2017 JINST 12 C06004