CaloCube: A new-concept calorimeter for the detection of high-energy cosmic rays in space☆

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A R T I C L E I N F O

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A B S T R A C T

The direct observation of high-energy cosmic rays, up to the PeV region, will increasingly rely on highly performing calorimeters, and the physics performance will be primarily determined by their geometrical acceptance and energy resolution. Thus, it is extremely important to optimize their geometrical design, granularity, and absorption depth, with respect to the total mass of the apparatus, which is among the most important constraints for a space mission. Calocube is a homogeneous calorimeter whose basic geometry is cubic and isotropic, so as to detect particles arriving from every direction in space, thus maximizing the acceptance; granularity is obtained by filling the cubic volume with small cubic scintillating crystals. This design forms the basis of a three-year R &D activity which has been approved and financed by INFN. A comparative study of different scintillating materials has been performed. Optimal values for the size of the crystals and spacing among them have been studied. Different geometries, besides the cubic one, and the possibility to implement dual-readout techniques have been investigated. A prototype, instrumented with CsI(Tl) cubic crystals, has been constructed and tested with particle beams. An overview of the obtained results will be presented and the perspectives for future space experiments will be discussed.

☆ Fully documented templates are available in the elsarticle package on CTAN.
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1. Introduction

The science: The direct measurement of individual particle spectra in the PeV region of cosmic-ray (CR) spectrum is one of the instrumental challenge for next-generation CR experiments. Indirect measurements, performed by detecting on ground the extensive air showers produced by primary CRs in the atmosphere, show that, around this energy region, the inclusive spectrum of particles becomes suddenly steeper and the composition progressively heavier. This feature, known as the CR "knee", is believed to indicate the energetic limit of the galactic accelerators. A precise knowledge of particle spectra and composition in this spectral region would allow to address key items in the field of high-energy CR physics, such as the unambiguous identification of the acceleration sites, the clear understanding of the acceleration mechanisms, as well as an accurate modeling of particle propagation and confinement within the Galaxy.

In spite of the improvements achieved by indirect techniques, composition studies are still very difficult. Only the spectra of groups of elements are measured and the results are considerably model dependent, for what concerns both the energy reconstruction and the element identification (see e.g. [1,2]). Direct CR detection permits unambiguous elemental identification and a more precise energy measurement, but suffers from limited exposure, which, due to the steepness of the CR spectra, practically prevented the past missions to go beyond 100 TeV in the measurement of H and He spectra [4]. Even more severe limitations affect the less-abundant heavier nuclei and in particular the rare secondary B component, whose abundance provides the most stringent constraint to propagation models and is measured only up to 1 TeV/n [3]. In order to clearly detect the "knees" of the H and He spectra, an acceptance of at least 2.5 m^2 sr ×5 yr is necessary. No strict constraints on the energy resolution are instead required, an upper limit being 40%. In order to satisfy these requirements, a possible instrumental setup is a calorimeter coupled to a charge measuring device.

An additional scientific item in the reach of this type of calorimeter is the measurement of the inclusive electron CR component (electrons +positrons) and, if the calorimeter is coupled to a tracker-converter system and an anticounter shield, of the high-energy gamma radiation (see e.g. [5]).

The possibility to study the em component of the cosmic radiation poses further requirements on the instrument, which should have an excellent energy resolution (better than 2%) and a high h/e rejection power (better than 10^5).

The basic idea: To achieve the above discussed performance with a space-borne calorimeter is definitely a challenge. The major constraint comes from the limitation in weight for the apparatus (few tons), which severely affects both the geometrical factor and the energy resolution.

CaloCube [6,7] is an R &D project aiming to optimize the design of a space-borne calorimeter that could extend the range of direct CR measurements up to the PeV region, in order to measure the "knee" of the lightest components. The proposed solution consists in a 3D mesh of cubic scintillating crystals, readout by photodiodes (PDs), arranged to form a cube (see the insert in Fig. 1). The cubic geometry and the homogeneity provides the possibility to collect particles from either the top or the lateral facets, thus allowing to maximize the geometrical acceptance for a fixed mass budget. The active absorber provides good energy resolution, while the high granularity allows shower imaging, thus providing criteria for both leakage correction and h/e separation.

We focus here on the CaloCube performances for the detection of protons and nuclei, while the detection of electrons is discussed elsewhere [7].

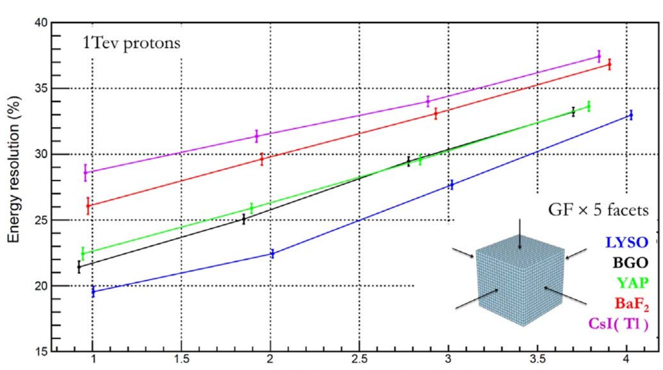

Fig. 1. Average energy resolution, for different scintillating materials, as a function of the effective geometrical factor, obtained by applying a progressively lower limit on the shower containment.

2. Monte Carlo studies and expected performances

A FLUKA-based model of the calorimeter has been developed, in order to evaluate the expected performances and to optimize the design. The full geometry has been implemented, including scintillating crystals and readout PDs, as active media, and carbon fibers, as passive support structures.

The scintillating material: A comparative study of different scintillating crystals has been done, among CsI(Tl), BaF_2, YAP(Yb), BGO and LYSO(Ce). For the detection of hadrons, the best choice for the active material is dictated by the balance between the whole size, which is related to the density of the absorber, and the shower containment, which is related to its total interaction length and affects both the energy resolution and the detection efficiency. The geometric parameters have been defined by assuming about 2 tons of active material in total; the size of the single element has been fixed to one Moliere radius and the gap among adjacent elements has been scaled to keep the same active-volume fraction (78% for the benchmark geometries illustrated in Table 1). The signal induced in the PDs by the scintillation light has been evaluated by accounting for the light yield of the scintillators, the light collection efficiency on one facet (about 80%, from ray-tracing calculations with diffusive surface), the size and the quantum efficiency of the PD (Excelitas VTH2090, see Section 3) at the emission peak. Direct ionization on the PD has been also considered. Isotropic fluxes of protons hitting one facet of the calorimeter have been generated and the effective geometrical factor evaluated, depending on the selection cuts applied, by multiplying the geometrical factor

Table 1
Main parameters of the simulated calorimeter geometries (see Section 2 for explanation).

Parameter	CsI:Tl	BaF_2	YAP:Yb	BGO	LYSO:Ce
Crystal size (cm)	3.60	3.20	2.40	2.30	2.10
Gap (cm)	0.30	0.27	0.20	0.19	0.18
N° crystals	20 × 20 × 20	22 × 22 × 22	28 × 28 × 28	27 × 27 × 27	30 × 30 × 30
Total size (cm)	78.00	76.34	72.80	67.23	68.40
Total depth (λ_I)	1.80	2.31	3.09	2.72	3.01
Total depth (X_0)	38.88	34.73	24.96	55.54	53.75
Geometric factor (m^2 sr)	9.56	9.15	8.32	7.10	7.35

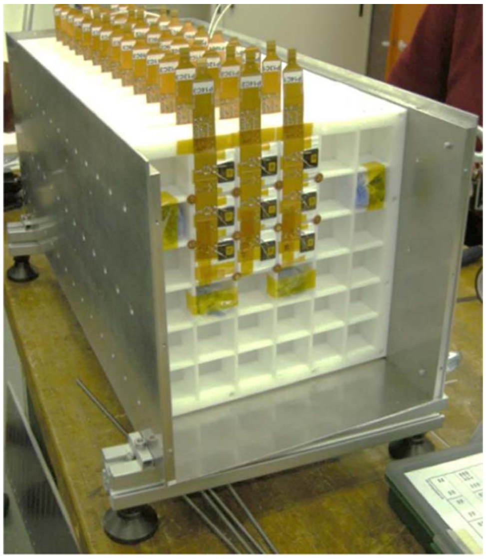

Fig. 2. The partially completed prototype used for tests at CERN.

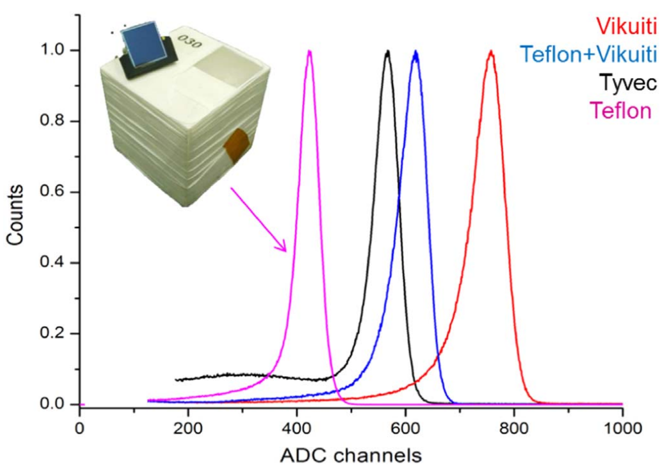

Fig. 3. Signal induced by 5.5 MeV α particles, for a different crystal wrapping.

of the generation surface with the fraction of selected events.

The major issue for energy reconstruction is the determination of the shower containment; first, the shower axis is determined by fitting the hit distribution in 3 dimensions, then the shower starting-point along the axis is found and the shower length evaluated. The measured energy deposit strongly depends on the shower length (about 60% effect, passing from 80 to 40 cm containment in CsI). Response curves are derived, for different initial hadron energies, and iteratively applied on a event-by-event basis to determine the incident particle energy.

The energy resolution of the calorimeter depends on the required shower containment, which in turn affects the selection efficiency. Fig. 1 shows the average energy resolution as a function of the effective geometrical factor, obtained by imposing a progressively weaker constraint on the containment of the showers, for different scintillating

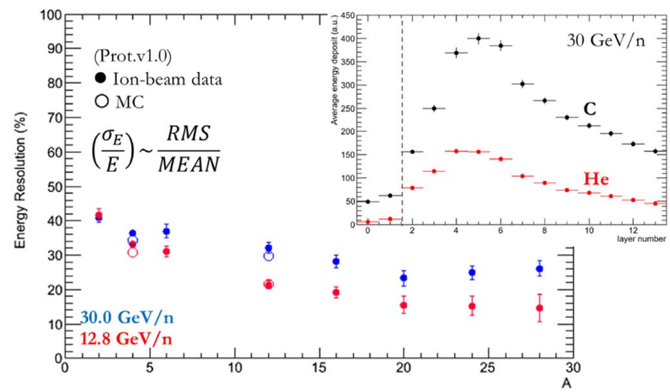

Fig. 5. Energy resolution as a function of the ion mass number and of the beam energy, for showers having the same containment. In the insert, the average shower profile of He and C ions at 30 GeV/n.

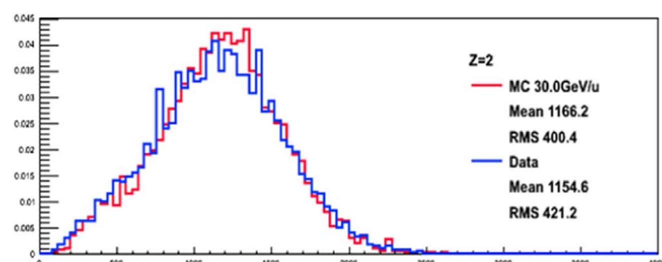

Fig. 6. Distribution of the energy deposit (in MIP) of 30 GeV/n He ions.

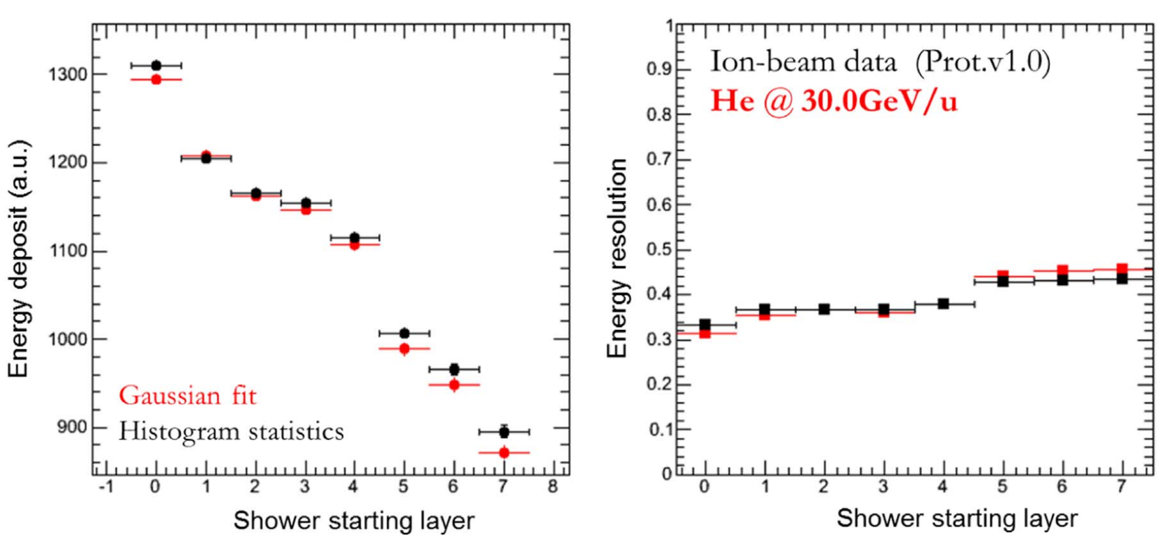

Fig. 4. Energy deposit (left), in MIP, and energy resolution (right) measured for He nuclei, as a function of the layer where the shower starts.

materials. The general trend is, as expected, an increase of the geometrical factor at the expense of the energy resolution. Among the five materials, LYSO is the best one for protons, due to the better shower containment, which compensates for the smaller volume. It has to be noticed, however, that all the five geometries satisfy the basic requirements, by providing an effective geometrical factor of at least 2.5 m^2 sr with an energy resolution better than 40%.

3. The prototype

As a proof principle of the CaloCube concept, we have constructed a small-scale prototype made of CsI(Tl). In spite of the considerations reported in Section 2, CsI(Tl) has been chosen for the prototype for practical reasons; it is widely available on the market at an affordable price, it has a very high light yield and its emission spectrum matches very well the spectral response of a large variety of Si PDs. In addition, the relatively low density of the material permits to construct a calorimeter with a reasonably large area, with small dead volumes and suitable also for the detection of electrons and gamma rays. Fig. 2 shows a picture of the prototype taken during its preparation for the first beam test. Fourteen frames, made of Delrin ®, are visible in the picture, each equipped with a matrix of 3 ×3 crystals, 4 mm apart from each other. The total depth of the prototype is 1.3 interaction lengths, corresponding to 27 radiation lengths. In this version of the prototype, each crystal is wrapped with few layers of Teflon™ tape and optically coupled to a single PD. Signals are readout by means of polyimide flexible printed circuit boards and routed to the front-end board, placed on the side of the calorimeter. The front-end electronics is based on a high dynamic-range, low-noise ASIC, developed by members of the CaloCube collaboration and specifically designed for Si-calorimetry in space [8]. The version used in the first prototype is CASIS v1.1, which is characterized by a dynamic range of 52.2 pC and an ENC~0.5 fC at 70 pF input capacitance.

The chosen PD, the VTH2090H from Excelitas, is a large-area (~100 mm^2) sensor that, coupled to our CsI(Tl) crystals and readout electronics, allows to clearly detect minimum-ionizing protons with a signal-to-noise ratio of about 15. One of the most challenging requirements for the instrument is the very large dynamic range needed to detect PeV protons. According to simulation, an interacting proton can deposit up to 10% of its kinetic energy in a single CsI(Tl) crystal of 3.6 cm size. Considering that non-interacting minimum ionizing protons deposit about 20 MeV, the needed dynamic range is of the order of 10^7. This will be accomplished by using also a second PD of small area (~1 mm^2).

Many tests have been performed in laboratory, in order to optimize the light collection efficiency, to compare and characterize various PD responses and to test system readout. Fig. 3 shows the results of a test, carried out with 5.5 MeV α particles from Am source, to compare different wrapping materials, both diffusive (Teflon™ and Tedlar®) and reflective (Vikuiti™). The latter resulted as the best choice and has been used for the prototype upgrade.

4. Test with ion beams

The first version of the prototype was tested in 2013 with ion beams, of 12.8 and 30 GeV/n, extracted from the H8 line of CERN SPS. The beam contained A/Z=2 fragments produced by a primary Pb beam colliding with a Be target. The experimental set-up included a Si tracking system [9], placed in front of the calorimeter and providing both tracking information and Z tagging.

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, lower than expected due to the not-optimized light collection. The single-crystal responses were equalized by normalizing to the energy deposit of non-interacting He nuclei (set by definition to 4 MIP), the most abundant fragments.

Following the approach discussed in Section 2, showers were classified on the basis of the starting point, which in the beam-test set-up univocally determines the shower containment. Fig. 4 shows the energy deposit (left) and its relative fluctuations (right) for He-induced showers, as a function of 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. Fig. 5 shows the energy resolution for different ions, at fixed shower containment. In a first approximation, the shower generated by a nucleus can be described as a superposition of independent showers generated by A nucleons, where A is the mass number. The ions in the beam have the same kinetic energy per nucleon; thus, while the total energy deposit scales as A (see the insert in Fig. 5) , the energy resolution scales approximately as $1/\sqrt{A}$, due to progressively reduced shower fluctuations.

A Fluka-based model of the prototype has been developed and its predicted response is shown in Fig. 5 (open symbols) and Fig. 6 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. Both effects are consistent with the non-optimized light collection observed in the first version of the prototype (see Fig. 3) and some instrumental issues related to the readout set-up. Both problems were fixed in the successive prototype upgrades. The analysis of the results obtained with the upgraded prototype is currently under way.

Acknowledgments

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