PAPER • **OPEN ACCESS**

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To cite this article: Gabriele Bigongiari and on behalf of theCaloCube collaboration 2020 *J. Phys.: Conf. Ser.* **1342** 012008

Journal of Physics: Conference Series **1342** (2020) 012008 doi:10.1088/1742-6596/1342/1/012008

Exploring calorimetry new dimensions: a novel approach to maximize the performances of space experiments for high-energy cosmic rays

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Abstract. Calorimeters are the key detectors for future space based experiments focused on high-energy cosmic rays spectra measurements. 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. A prototype, instrumented with CsI(Tl) cubic crystals, has been constructed and tested with particle beams.

1. Introduction
The direct measurement of cosmic ray (CR) spectrum in the PeV region is one of the instrumental challenge for the future CR experiments. Indirect measurements on ground show, around this energy region, a sudden steeping in the inclusive spectrum of particles and a progressively heavier composition, a feature known as the CR knee. So a precise knowledge of particle spectra and composition in this spectral region would allow to address fundamental issues in the field of high-energy CR physics. The direct CR detection can permit unambiguous elemental identification and a more precise energy measurement, but it suffers from low exposure due to the steepness of the CR spectrum. This limitation prevented the past experiments to go beyond 100 TeV/n for the nuclei and 1 TeV for electron+positron spectra. Direct measurements of cosmic ray proton and nuclei spectra up to 1 PeV/n and electron spectrum above 1 TeV require an acceptance of few m^2str, an energy resolution better than 40% for nuclei and 2% for electrons, a good charge identification and a high electron proton rejection power (at least 10^5).

2. A novel calorimeter
To achieve these performances, the major constraint comes from the limitation in weight for the detectors (few tons), which severely affects both the geometrical factor and the energy resolution. The R&D project CaloCube aims to optimize the design of a space-borne calorimeter to extend the range of direct CR measurements up to the PeV region in order to measure the knee of the lightest components [1]. The proposed solution consists of a segmented calorimeter made of a large number of cubic scintillating crystals, readout by photodiodes (PDs), arranged to form a cube (see figures 1 and 2). The cubic geometry and the homogeneity provides the possibility to

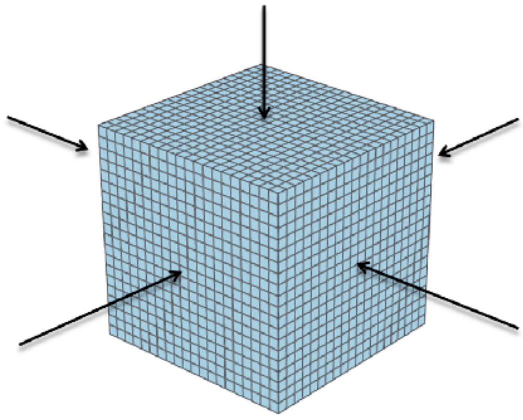

Figure 1. the CaloCube conceptual design.

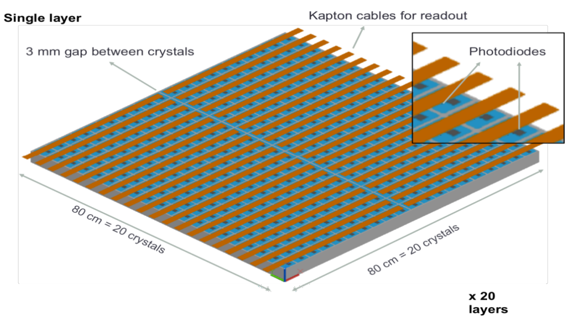

Figure 2. details of a single layer of the calorimeter.

collect particles from either the top or the lateral faces, thus allowing to maximize the geometrical acceptance for a fixed mass budget. The active material provides good energy resolution, while the high granularity allows shower imaging and provides criteria for both leakage correction and h/e separation [2].

3. The Montecarlo simulations

As a starting point for the optimization of the design of the detector, a FLUKA-based model of the calorimeter has been developed, in order to evaluate the expected performances and to optimize the design. A comparative study of different scintillating crystals has been done, among CsI(Tl), BaF 2, YAP(Yb), BGO and LYSO(Ce). For the hadron detection, the best choice is dictated by the balance between size (density of the absorber) and shower containment (interaction length), which determine energy resolution. The geometric parameters have been defined by assuming about 2 tons of active material in total; the size of the single cube has been fixed to one Moliere radius and the gap among adjacent elements has been rescaled to obtain the same active volume fraction (∼78%). 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 face, the size and the quantum efficiency of the PD at the emission peak. Direct ionization on the PD has been also considered. Isotropic fluxes of protons hitting one face of the calorimeter have been generated and the effective geometrical factor evaluated. All the five geometries satisfied the basic requirements, by providing an effective geometrical factor of at least 2.5 m^2sr with an energy resolution better than 40%. Further details about the Montecarlo studies can be found in ref.[3].

4. The prototype

To test the CaloCube concept, a prototype with 135 CsI(Tl doped) cubic crystals of 3.6 cm size, arranged in 15 planes of 3x3 cubes each, with a gap of 0.4 cm between them, has been constructed (see figures 3 and 4). CsI(Tl) has been chosen 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-photodiodes. This prototype results to have a lateral shower containment of about 1.5 Moliere radius and a total depth of 1.35 interaction lengths, corresponding to 28.4 radiation lengths. Signals are readout

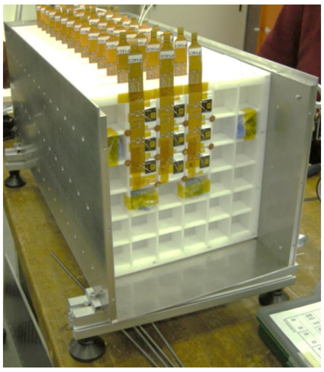

Figure 3. the first calorimeter prototype under construction: fourteen frames are visible, each equipped with a matrix of 3 3 crystals, 4 mm apart from each other.

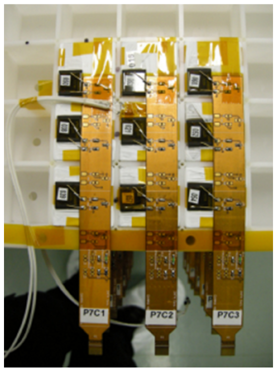

Figure 4. details of a single layer, showing the 9 large area photodiodes placed on the crystals, wrapped in white Teflon tape, and the kapton cables used to read out the signals.

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. The chosen PD is a large-area ($\sim$85 mm^2) sensor that, coupled to CsI(Tl) crystals and readout electronics, allows to clearly detect minimum-ionizing protons with a signal-to-noise ratio of about 15. One of the most challenging requirements is the very large dynamic range (10^7) ranging from 20 MeV for minimum ionizing protons to 10% of the energy of a PeV proton. This will be accomplished by using also a second small area PD ($\sim$1.6 mm^2).

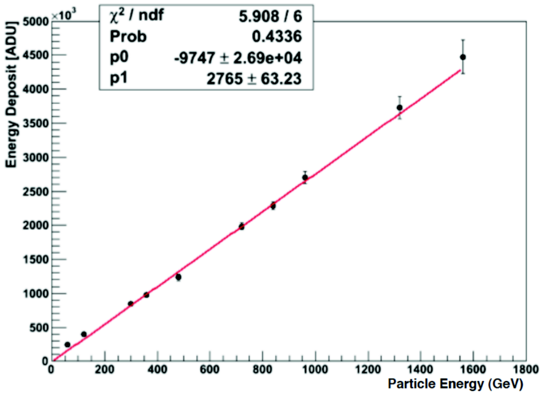

Figure 5. linearity of the response of the prototype to the 30 GeV/n beam as a function of the energy of the various ions.

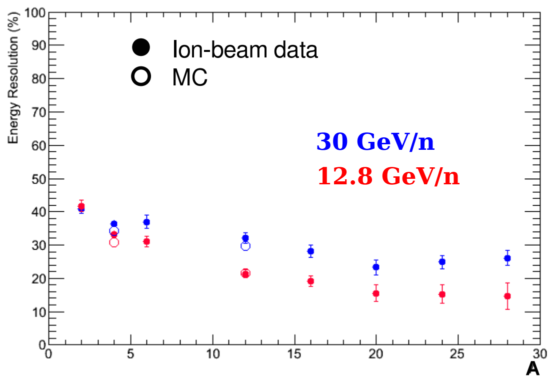

Figure 6. energy resolution as a function of the ion mass number and of the beam energy, for showers having the same containment.

5. Tests with particle beams

The first version of the prototype was tested at CERN with different particle beams (see table 1). In 2013 and 2015 it was exposed with ion beams extracted from the H8 line of CERN SPS. The beam contained A/Z=2 fragments produced by a primary (Pb/Ar) beam colliding with a target (Be/Poly). The experimental set-up included a Si tracking system in front of the calorimeter to provide tracking information and Z tagging. The single-crystal performances were studied, by selecting non-interacting ions. The responses were equalized by normalizing to the energy

Test	Beam	Energy
Feb 2013	ions Pb + Be	13-30 GeV
Mar 2015	ions Ar + Poly	19-30 GeV
Aug/Sep 2015	μ, π, e	50, 75, 150, 180 GeV

Table 1. Summary of beam tests.

deposit of non-interacting He nuclei, the most abundant fragments. The showers developing inside the calorimeter were classified on the basis of the starting point, which can determine the shower containment.

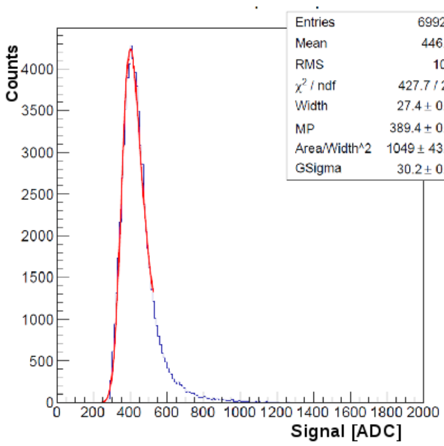

Figure 7. signal induced by minimum interacting particles (150 GeV muons) in a cube, used to equalize the crystal responses, fit to the expected distribution (red curve).

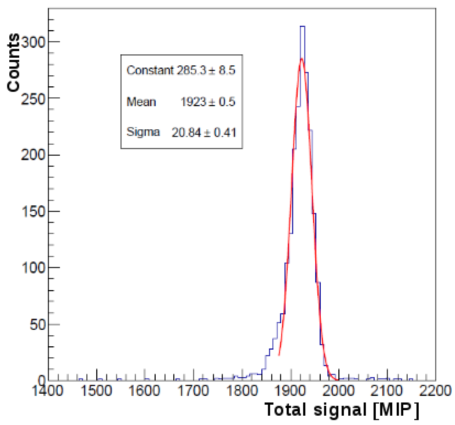

Figure 8. measured distribution of total energy (expressed in MIP units) released with a 50 GeV electrons beam, fit to the expected distribution (red curve).

The figure 5 shows the response of the calorimeter as a function of projectile energy for showers initiated before the fifth layer while the figure 6 shows the energy resolution for different ions at the same shower containment [4]. A Fluka-based model of the prototype has been developed and its predicted response is also shown in the left panel of figure 6 (open circles) in comparison with real data. A fine tuning of the MonteCarlo simulation 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. During the beam test at CERN in the summer 2015, the prototype was initially exposed to 150 GeV muon beams to equalize the response of all the cubes that compose the calorimeter (see figure 7). Then an estimate of the energy resolution has been determined exposing the calorimeter to electron beams of different energy and determining the total deposited energy. A preliminary result is shown in the figure 8 referring to a beam of 50 GeV electrons. The corresponding resolution is better than 1.5%, in good agreement with the expectation.

6. Recent developments

A new prototype has been constructed with a completely redesigned mechanics characterized by 18 layers, each equipped with a matrix of 5x5 crystals. The total depth of this new prototype is 1.6 interaction lengths, corresponding to 35 radiation lengths. In this prototype the light signal of each crystal is read out by two photodiodes, with different sensitive area, in order to cover the full expected dynamic range. This prototype was tested in 2016 with electron and hadron beams at the H4 line of CERN SPS. The figures 9 and 10 show a first glance at the performances of this improved prototype. The response of the calorimeter is linear as a function of beam energy. Using the large area photodiode the measured energy resolution for electromagnetic showers is better than 1.5% up to 200 GeV. Comparable performances above 200 GeV can be obtained also using small area photodiode. The analysis of data collected during the test is currently under way.

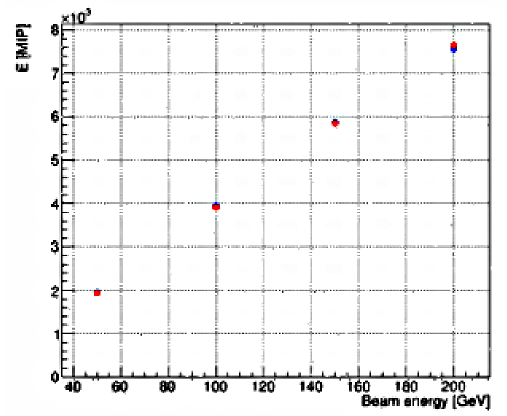

Figure 9. total energy deposit as a function of electron beam energy, measured with large PDs (blue dots) and small PD (red dots).

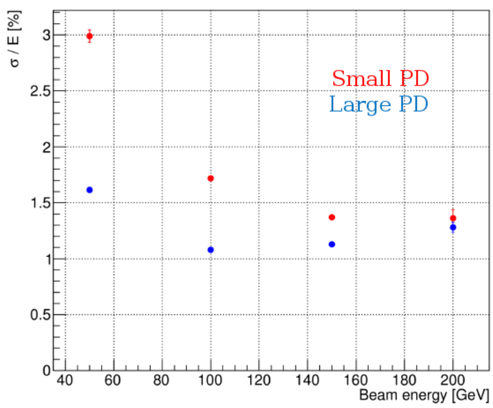

Figure 10. energy resolution as a function of electron beam energy, obtained with large PDs (blue dots) and small PD (red dots).

7. Conclusions

An innovative calorimeter for precise measurements of high-energy cosmic rays in space is being developed by the CaloCube collaboration. The basic, a large-acceptance, deep, homogeneous and isotropic cubic detector, composed of a 3-D lattice of small CsI(Tl) crystals able to detect particles from 5 sides, has been optimized. Monte Carlo simulations show that this design can reach the required acceptance and that its granularity, coupled with the large depth, will guarantee an excellent performance in the e/p separation, as well as in the energy resolution both for electromagnetic and hadronic particles. The present results from some beam tests with two prototypes of the apparatus show good performances in the energy measurements of electron and hadronic showers: an energy resolution better than 40% for ions up to 30 GeV/n and better than 1.5% for electrons up to 200 GeV, in the requirements of the project. The two-sensor readout system have been successfully tested obtaining a small-PD performances comparable with large-PD ones up to 200 GeV. Further beam tests are planned in the August and November 2017 at the CERN SPS.

Acknowledgments

This work was supported by the Istituto Nazionale di Fisica Nucleare (INFN), through the CaloCube project, and by the H2020 project AIDA-2020, GA no. 654168. The authors thank CERN for the allocation of beam time at the North Area test facility.

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