Development of a 3-D cubic crystal calorimeter for space: CaloCube

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An innovative calorimetric solution for direct measurements of high-energy cosmic rays in space is described in this paper. The basic idea is to build a large acceptance, very deep, homogeneous and isotropic calorimeter (CaloCube), to be placed in orbit around the Earth for direct measurements of the cosmic-ray spectrum up to the PeV region. The large acceptance will be achieved by accepting particles coming from every direction in space; the fine 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. An overall description of the system, as well as some preliminary test beam data of a medium-size prototype will be described.

Calorimetry for High Energy Frontiers - CHEF 2013,
April 22-25, 2013
Paris, France

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1. Introduction and physics motivations

The overall flux of primary cosmic rays can be nicely described by a rapidly decreasing power law spectrum in the energy range where the solar modulation effects can be neglected, from few GeV up to 10^{15} eV. A dramatic reduction of the flux by ~ 15 orders of magnitude is observed in this range. The PeV region is then characterized by a softening of the spectrum, which can be parametrized by a change in the slope (normally referred to as "cosmic-ray Knee"). The origin of the knee is still strongly debated in the cosmic-ray community [1, 2]: it could probably be related to the acceleration or to the propagation mechanisms of the cosmic rays in the galaxy. Detailed measurements with good energy resolution of the elemental composition of the high energy cosmic rays are really necessary to shed some light on this fundamental topic.
These measurements represent however a real challenge from the experimental point of view, since the small flux of cosmic ray particles in this energy region requires a detector with a very large acceptance. This is normally accomplished by using the Earth's atmosphere as passive absorber, and measuring on ground the distribution of the secondary particles with large area detectors arrays [3, 4, 5]. This technique, however, does not allow to obtain neither the very good energy resolution nor the excellent charge identification capabilities that are necessary to precisely understand the origin of the knee.
Direct measurements with a detector in orbit around the Earth with large acceptance and long exposure are hence really necessary. In this paper we will describe a proposal for such a type of detector, based on the development of a completely symmetric and very deep 3D cubic calorimeter, allowing direct measurements of high energy cosmic rays with

- large acceptance ($\sim$ few m^2sr)
- long exposure ($\sim$ few years)
- excellent energy resolutions both for electrons/positrons ($\sim$ few %) and hadronic particles ($\sim$ 30-40%)
- very large e/p rejection power ($\sim 10^5$)
- precise charge identification of atomic nuclei from hydrogen up to iron.

2. The basic idea

The basic idea behind this proposal (originally described in [6]) is the development of a completely symmetric 3D homogeneous calorimeter (**CaloCube**), with cubic external envelope, assembled by using small-sized cubic scintillating crystals, schematically shown in Fig. 1.

Thanks to the complete symmetry of the system, the detector is able to reconstruct in an optimal way particles coming not only from the zenith, but also from the lateral sides, assuming that the bottom face is used for the mechanical connections to the satellite structure. In this way the geometrical factor GF is 5 times larger than the one-face standard configuration, allowing to reach a nominal value of ~ 10 m^2 sr.

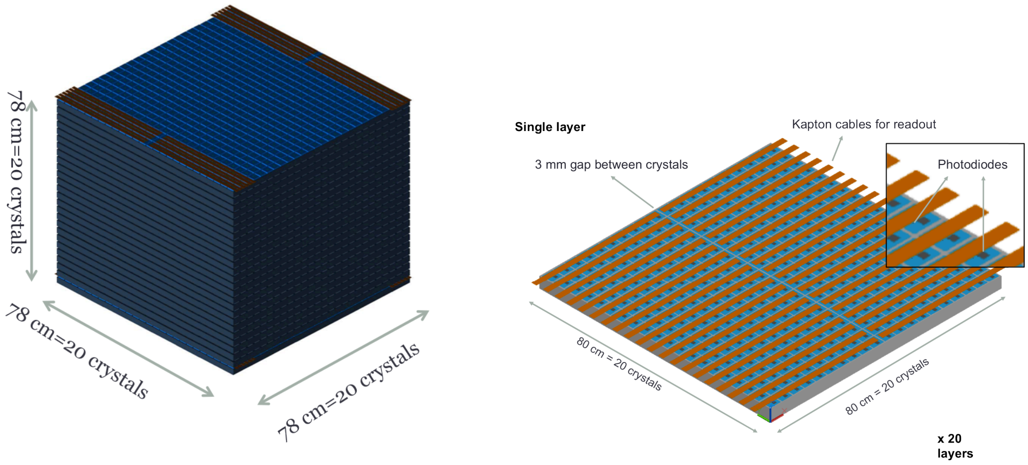

Figure 1: Schematic drawings of the 3D cubic calorimeter. Left panel shows the overall calorimeter assembly, while right panel describes in more details the structure of one single plane.

2.1 The overall structure

The overall structure is composed by 20 planes (80x80x4 cm^3), each consisting of 20x20 cubic CsI(Tl) scintillating crystals. The dimensions of every crystal (3.6x3.6x3.6 cm^3) are defined to match the Molière radius for the electromagnetic showers development in the calorimeter, to optimize the e/h rejection power. The CsI(Tl) has been selected because of the very high light yield (54000 ph/MeV) and because of its intermediate density (4.5 g/cm^3), which allows to reach a very large GF with an acceptable overall mass (1683 kg of active material). 4 mm gaps are left on each side of each crystal, maximizing the GF without any significant degradation of the calorimeter's performance. The very large depth of the calorimeter (39 X_0, 1.8 λ_I for vertically incident particles) allows a complete containment of the electromagnetic showers up to the highest energies, and the measurement with high efficiency of the hadronic particles up the PeV region. A total of 8000 crystals will be used for the whole calorimeter assembly.

2.2 Photodetectors and front end chip

To cover the huge required dynamic range (from ≤ 1 MIP for non interacting protons, useful for calibration purposes, up to 10^7 MIPs in one single crystal for PeV interacting hadrons) the photosensors and the readout electronics must be carefully chosen and designed. In this proposal the scintillation light produced in one crystal is read out with 2 different photodiodes, one with large area for the low energy particles, and one with small area for the highest energy particles. The large area photodiode that we have selected and used for the assembly of the prototype (described in the next section) is the VTH2090 device, from Excelitas [7], with a 9.2x9.2 mm^2 active surface, large quantum efficiency ($\sim 75\%$) and good spectral response (~ 0.35 A/W) for the 560 nm photons emitted by the CsI(Tl) scintillator. For the small area photodiode we are planning to use a 0.5x0.5 mm^2 device, to be inserted in the same package of the large area one; both devices should be housed

in a low profile package, with total thickness < 1 mm, to be inserted in the small gap between 2 consecutive detection planes.
To make optimal use of the excellent linearity of the photodiodes, the use of a large dynamic range front-end chip is mandatory. In our proposal we have selected the CASIS chip [8], that has been specifically developed by INFN Trieste for calorimetric space applications. Every chip consists in 16 independent channels, with a charge sensitive amplifier and a correlated double sampling system, with automatic switching between 2 different gains (Low and High), depending on the injected charge. The small power consumption of a single channel (2.8 mW), associated with the low noise (3000 e^- for 100 pF input capacitance) and the large maximum input charge (53 pC) are perfectly suited for the CaloCube design; by properly combining the dual gain of the chip and the pair of photodiodes connected with a single crystal, we can efficiently cover the whole required dynamic range.

2.3 The expected performance

The performance estimated from a detailed FLUKA based simulations have already been reported in ref. [6]. Here we want only to remind that a electromagnetic energy resolution better than 2% for TeV particles and $\sim 35\%$ hadronic energy resolution for 1-100 TeV protons can be expected, with an effective GF $\sim$ 3-4 m^2 sr.

3. The CaloCube prototype and SPS beam test

To really understand the CaloCube performance and to validate the simulation results, a medium size prototype was built by a collaboration involving the Florence, Pisa/Siena and Trieste sections of INFN. The prototype was assembled using 126 CsI(Tl) crystals, arranged in 14 layers with 9 crystals each (see Fig. 2), in a mechanical structure that will allow simple extensions of the prototype; each crystal was coupled with a large area photodiode only. A total of 9 CASIS chips have been used for the readout.

Figure 2: The assembled prototype. Left side: a detail of a single plane, where the crystals with large area photodiodes and the readout kapton cables can be observed. Right side: the overall assembly of the prototype.

The prototype has been exposed to high energy ion beams at CERN SPS accelerator in February 2013. Ions with A/Z=2 and 30 GeV/n and 12.8 GeV/n have been used to characterize the detector and the front end electronics. The excellent low-noise performance obtained can be seen from Fig. 3, that shows an impressive clear separation of the ^{2}H and ^{4}He peaks observed in the first layer of the prototype, as well as a clear separation of the 1 MIP signal from the pedestal value. The non-interacting deuterium peak can be resolved with a S/N$\sim$ 14.

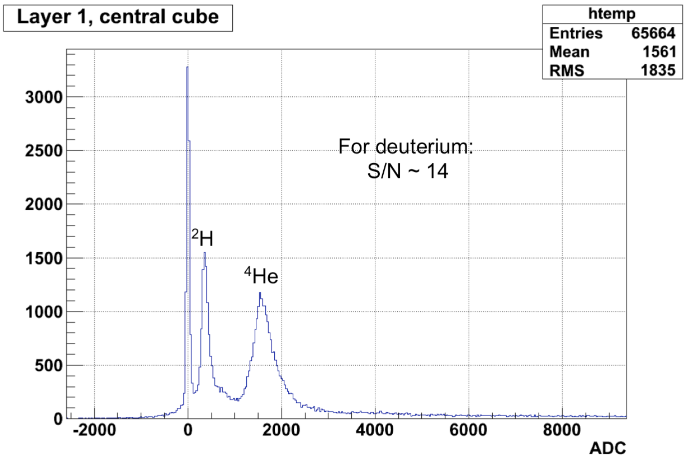

Figure 3: Non-interacting 30 GeV/n ^{2}H and ^{4}He observed in the first layer of the prototype.

A first glance at the performance in the large energy release region can be obtained from Fig. 4, which shows a good linearity in the prototype's response from the low Z particles (^{2}H) up to the high Z particles (Fe).

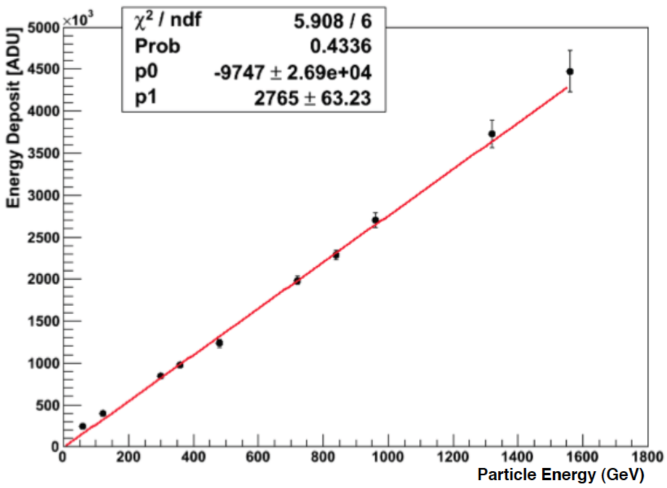

Figure 4: Linearity of the prototype's response for the various ion species, for the SPS ion beam with A/Z=2 and 30 GeV/n (preliminary). D, He, B, C, O, Mg, SI, S, Ti and Fe nuclei have been selected by a precise low-thickness silicon tracker located upstream of the prototype, providing a high purity charge tagging by means of 12 independent dE/dx measurements of the incoming beam particle.

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