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To cite this article: E Berti *et al* 2019 *J. Phys.: Conf. Ser.* **1162** 012042

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Abstract. Given the good performances in terms of geometrical acceptance and energy resolution, calorimeters are the best suited detectors to measure high energy cosmic rays directly in space. However, in order to exploit this potential, the design of calorimeters must be carefully optimized to take into account all limitations related to space missions, due mainly to the mass of the experimental apparatus. CaloCube is a three years R&D project, approved and financed by INFN in 2014, aiming to optimize the design of a space-borne calorimeter by the use of a cubic, homogeneous and isotropic geometry. In order to maximize detector performances with respect to the total mass of the apparatus, comparative studies on different scintillating materials, different sizes of crystals and different spacings among them have been performed making use of Monte Carlo simulations. In parallel to this activity, several prototypes instrumented with CsI:Tl cubic crystals have been constructed and tested with particle beams (muons, electrons, protons and ions). Both simulations and prototypes showed that the CaloCube design leads to a good particle energy resolution (< 2% for electromagnetic showers, < 40% for hadronic showers) and a good effective geometric factor (> 3.5 m^2 sr for electromagnetic showers, > 2.5 m^2 sr for hadronic showers). Thanks to these performances, in 5 years of operation it would be possible to measure the flux of electrons+positrons up to some tens of TeV and the fluxes of protons and nuclei up to some units of PeV/nucleon, hence extending these measurements by at least one order of magnitude in energy compared to the experiments currently operating in space.

1. Introduction

Precise measurements of flux and composition of cosmic rays are needed to understand the mechanisms responsible for their production, acceleration and propagation. These measurements can be performed directly in space or indirectly at ground. In the former case, the highest energy achievable is limited by the typical constraints in terms of mass ($\sim 1-5$ t) and life time ($\sim 5-10$ y) of a payload: being the cosmic rays flux very steep, it is difficult to collect enough statistics at high energy (this is for example the case of protons above the *knee* region, located between 10^{15} and 10^{16} eV). In the latter case, it is possible to collect enough statistics up to the endpoint of the spectrum, but the properties of the cosmic rays must be reconstructed indirectly from the air showers detected at ground: because the hadronic interaction models used for this purpose have large systematics, these measurements of flux and, in particular, composition are also affected by large uncertainties. Thus, extending direct measurements in space up to high energy is crucial in order to get precise indications on cosmic ray physics. Calorimetry is the best suited detection technique to achieve this goal, because the energy resolution improves as a function of energy and the geometry of the detector can be designed in order to maximize the geometric factor. The largest experiment currently operating in space is DAMPE [1] that is expected to measure the flux of electrons+positrons up to $\sim$ 10 TeV and the fluxes of protons and nuclei up to $\sim$ 100 TeV/n. Future space satellite experiments must be carefully designed in order to extend these measurements of about one order of magnitude in energy (up to some tens of TeV for electrons+positrons, up to some units of PeV/nucleon for protons and nuclei). In particular, assuming 5 years of operations, they must have a good energy resolution σ_E/E (< 2% for electromagnetic showers, < 40% for hadronic showers) and a good effective geometric factor G_{eff}[1] (> 3.5 m^{2}sr for electromagnetic showers, > 2.5 m^{2}sr for hadronic showers).

2. The CaloCube project

CaloCube [2] is a three years R&D project, approved and financed by INFN (Italy) in 2014. The basic idea is to develop and optimize a cubic calorimeter made of $\mathrm{N} \times \mathrm{N} \times \mathrm{N}$ scintillating crystals, each one having cubic geometry of 1 Molière radius ($\mathrm{R_M}$) side and equipped with a system of two photodiodes (PDs). For example, assuming a CsI:Tl calorimeter of 2 t (including both crystals and support), each scintillator has a 3.6 cm side with a gap between scintillators of 0.3 cm, for a total number of crystals of $20 \times 20 \times 20$. In this way, the total depth of the calorimeter is 78 cm, corresponding to 39 radiation length ($\mathrm{X_0}$) and 1.9 nuclear interaction length (λ_I) for vertical particles. This design, schematically shown in Fig.1, has three main advantages. First of all, being as most homogeneous as possible, it has a good energy resolution, especially in the case of electromagnetic showers. Secondly, being as most isotropic as possible, it has a good geometric factor because, assuming to employ a face for mechanical support, the detector can

[1] Effective geometric factor G_{eff} is defined as the product between the geometric factor G and the analysis selection efficiency ϵ: hence it depends both on the design geometry and the shower containment of the detector.

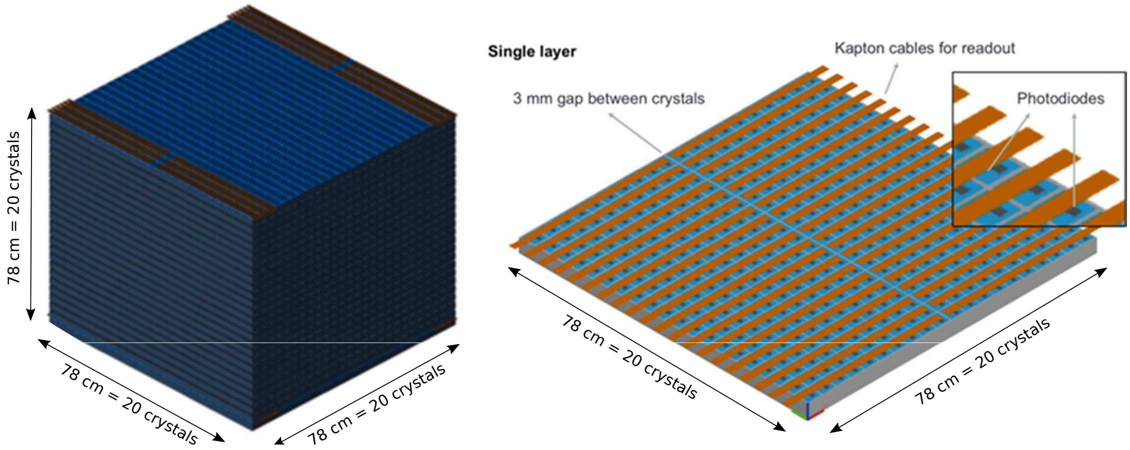

Figure 1. Conceptual design of the CaloCube 3D highly-segmented calorimeter: on the left, the complete cubic detector; on the right, one of the 20 layers.

accept particles entering from five faces without any difference in reconstruction performances: for example, in case of a CsI:Tl calorimeter, this solution increases G from 1.91 m^{2}sr (single face) to 9.55 m^{2}sr (five faces). Lastly, the fine segmentation allows us to reconstruct the 3D profile of the shower, useful for energy reconstruction and for e/p discrimination. In order to measure an energy deposit going from the minimum ionizing particle (MIP) signal necessary for channels calibration ($\sim$ 10 MeV) to the one released in a single crystal from a shower of a proton near the knee region ($\sim$ 100 TeV), a 10^7 dynamic range is required. This is achieved employing a simple and compact readout scheme obtained equipping each crystal with two photodiodes (PD): a large area PD for small signals and a small area PD for large signals.

3. Simulation

In order to satisfy the requirements described in Sec.1, the design of the detector was optimized making use of several simulation studies [3, 4], all based on the FLUKA package [5, 6]. For this purpose, three kinds of energy release were simulated: the photoelectron signal generated by the PDs, obtained scaling the energy deposit in the crystal to take into account light yield, collection efficiency and quantum efficiency; the signal due to direct ionization in the active volume of PDs; the loss of signal due to the energy deposit in the passive layers used for mechanical support, assumed to be made of carbon fiber. The geometry of the calorimeter was defined by the following parameters: 2 t mass, cubic shape, 1 R_M crystal side and 0.3 cm crystal spacing (the value of this last parameter refers to CsI:Tl only). The performances of the detector in terms of σ_E/E and G_{eff} were then investigated injecting an isotropic flux of 100-1000 GeV electrons, 1-1000 TeV protons and 1 TeV nuclei on a single face. Because the containment of hadronic showers is complicated by leakage, the analysis selection criteria have been divided in two groups: the first group performs a preselection (with an efficiency $\epsilon_{ps} = 45 - 55\%$) requiring that (1) the number of crystals having dE $>$ 0.85 MIP is higher than 100, (2) there is a crystal having dE $>$ 15 MIP that can be identified as the shower starting point and (3) the crystal having the maximum dE is not on the edges of the calorimeter; the second group performs an additional selection based on the minimum acceptable value of the shower length (once decided the scintillating material, we fixed four different values in order to correspond to a selection efficiency ϵ_{sl} of 25, 50, 75 and 100%, respectively). The final effective geometric factor is therefore given by $G_{eff} = G \times \epsilon_{ps} \times \epsilon_{sl}$. In the case of hadronic showers, the main goal of this study is to understand how σ_E/E and G_{eff} depend on the change of several parameters

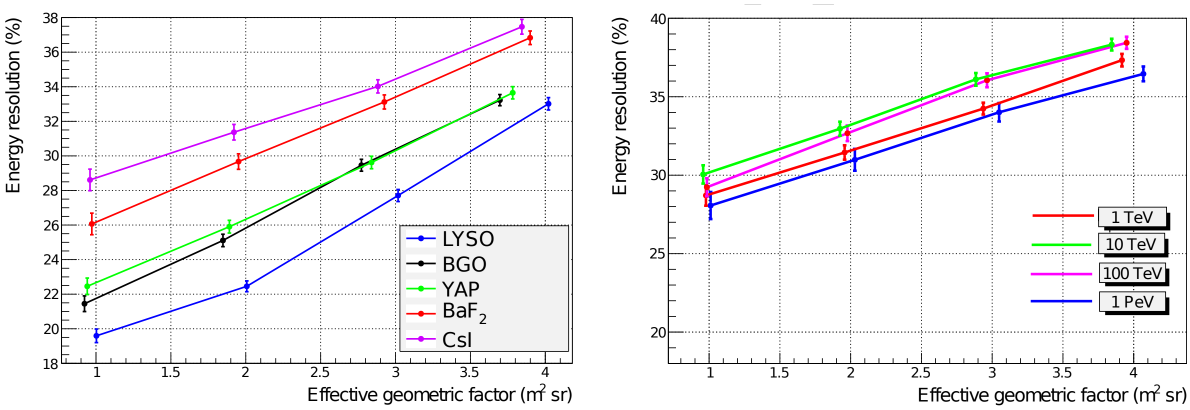

Figure 2. Average energy resolution as a function of the effective geometric factor, obtained by applying a progressively looser cut on the shower length: the two figures represents the dependence of the performances on the scintillator crystal used to build the calorimeter in the case of 1 TeV protons (left) and the dependence of the performances of a CsI calorimeter on the proton incident energy in the range between 1 TeV and 1 PeV (right).

relative to detector geometry. To give an idea, two results obtained simulating incident protons are discussed in the following. At first, we investigated the dependence of the performances on the choice of the scintillating crystal, testing five different materials - CsI:Tl (CsI), BaF_2 (BaF_2), $YAlO_3$:Yb (YAP), $(Bi_2O_3)_2(GeO_2)_3$ (BGO), $Lu_{1.8}Y_{0.2}SiO_5$:Ce (LYSO) -, while keeping the side of the cube to 1 R_M and scaling the gap according to the crystal side. This is shown in Fig.2 left in the case of 1 TeV protons, where we can see that all scintillators satisfy the requirements defined in Sec.1, but the best ones are the crystals having a low value of λ_I. This is because, even if the size of the calorimeter is smaller in this case, the better shower containment leads to a higher ϵ_{ps} and, therefore, to a larger G_{eff}, as well as to a better σ_E/E. In particular, LYSO is the best candidate for future space satellite experiments, leading to $\sigma_E/E \sim 32.5\%$ and $G_{eff} \sim 4$ m^2sr, in case ϵ_{sl} is set to 100%. Another interesting study is to investigate the dependence of this result on the incident proton energy. In order to do that, protons from 1 TeV to 1 PeV were injected in a calorimeter made of CsI scintillator cubes. This is shown in Fig.2 right, where we can see that the performances of the detector depends only slightly on the incident energy. The performances of the calorimeter for electrons in the energy range between 100 and 1000 GeV were also investigated. As depicted in Fig.3, in this case σ_E/E and G_{eff} are respectively 2% and 3.4 m^2sr, if we select only events with a shower length longer than 22 X_0. It is important to note that the additional release in PDs due to direct ionization does not spoil the performances of the calorimeter, because it changes the average energy deposit of about 1.7% without affecting the energy resolution.

4. Prototype

Starting from 2012, several prototypes of the CaloCube detector have been built [7, 8] in order to optimize the design from the hardware point of view and to verify the performances expected from simulation studies. Version by version, the detector was improved both increasing the total size of the calorimeter and adopting new hardware solutions based on what we learned from the previous prototype. A schematic view of the latest version, assembled in 2016, is shown in Fig.4. It is made of 18 layers, each layer made of a matrix of 5 × 5 CsI:Tl crystals of 3.6 cm side spaced by 0.3 cm, for a total longitudinal size of 35 X_0 (1.7 λ_I) and a lateral size of 2.5 R_M from the center. The CsI:Tl crystal has two main advantages. The first one,

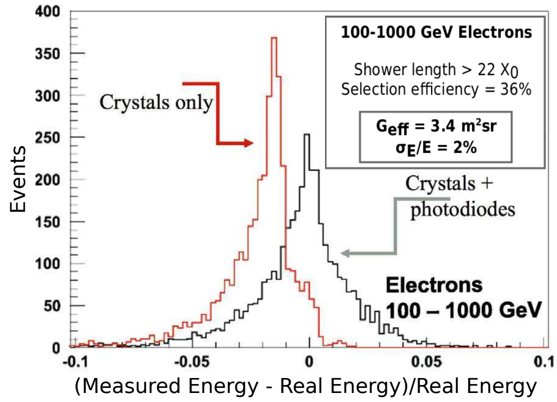

Figure 3. Energy resolution of the detector for 100-1000 GeV incident electrons, in case of the energy deposit in crystals only (red) or in both crystals and photodiodes (black).

as discussed in Sec.3, is the fact that its density leads to a good compromise between energy resolution and geometric factor. The second one is that the signal can be easily read by a photodiode, both because of the high light yield ($\sim$ 54 photons/keV) and because of the peak emission wavelength ($\sim$ 550 nm), located in a region where PDs quantum efficiency is large[2]. Each crystal is wrapped using Vikuiti, a reflective material with a high light collection efficiency: a property that is particularly important to eliminate optical cross talk between adjacent cubes. On each scintillator, two photodiodes are mounted: a large PD (VTH2090 with an active area of 84.6 mm^2) and a small PD (VTP9421H with an active area of 1.6 mm^2), that are expected to saturate the electronics in case the energy deposit inside a single crystal is larger than $\sim$ 25 and $\sim$ 2500 GeV, respectively. Both PDs are mounted on a kapton cable that brings the signals to the front-end electronics. The front-end electronics is based on the HiDRa chip (previously CASIS chip [9]), made of 28 channels, each one connected to a charge sensitive amplifier followed by a correlated double sampling circuit. The amplifier has two different gain regimes available (ratio 1:20) and a real-time control feedback network to select the gain, depending on the amplitude of the input signal. The high dynamic range (52.6 pC), the low noise (2280 e + 7.6 e/pF) and the low consumption (2.8 mW/channel) make this chip ideal for space application.

The present version of the prototype was tested making use of different particles beams (muons, electrons, protons and ions) acquired at the Super Proton Synchrotron (SPS) at CERN. While the analysis of this data is still ongoing, some preliminary result will be discussed in the following. The performances of the prototype for electromagnetic showers have been investigated using electrons beam between 50 and 280 GeV. Fig.5 shows linearity and resolution in the case the energy is reconstructed in three different ways: using large PDs only (blue), using small PDs only (red), combining the two information (green) so that small PDs are used for the cubes where large PDs saturate and large PDs are used in all other cases where small PDs have low signal. As expected, in case of large PDs only, saturation starts to significantly spoils the performances between 150 and 200 GeV, whereas, in case of small PDs only, σ_E/E is quite large below this energy because of the small amount of the detected signal. Anyway, the combined result leads to a non linearity below 1% and an energy resolution better than 1.5% in all the energy range.

[2] As the discussed in Sec.3, the LYSO crystal would have led to better performances respect to CsI crystal, even if the collected signal would have been reduced by the lower light yield ($\sim$ 27 photons/keV) and the different peak emission wavelength ($\sim$ 420 nm). However, in order to demonstrate the operating principle of the CaloCube idea, it is important to build a large prototype able to maximize the shower containment: this reason, considering the different cost of the materials, led to the choice of CsI crystal instead of LYSO crystal.

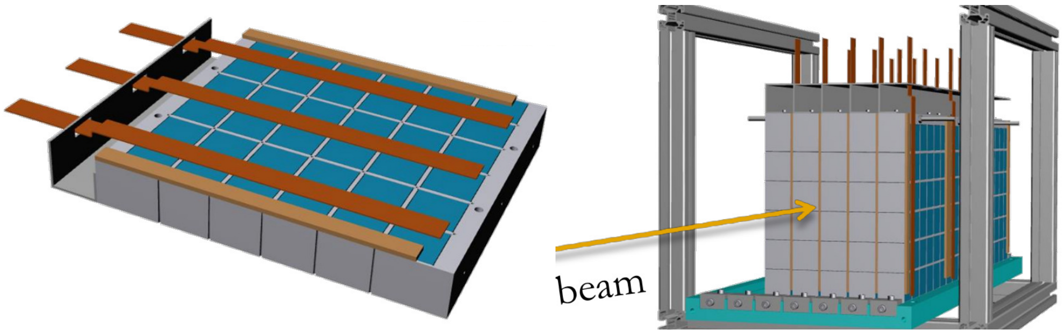

Figure 4. Conceptual design of the latest version of the CaloCube prototype built in 2016: on the left, one of the 18 layers; on the right, the complete detector.

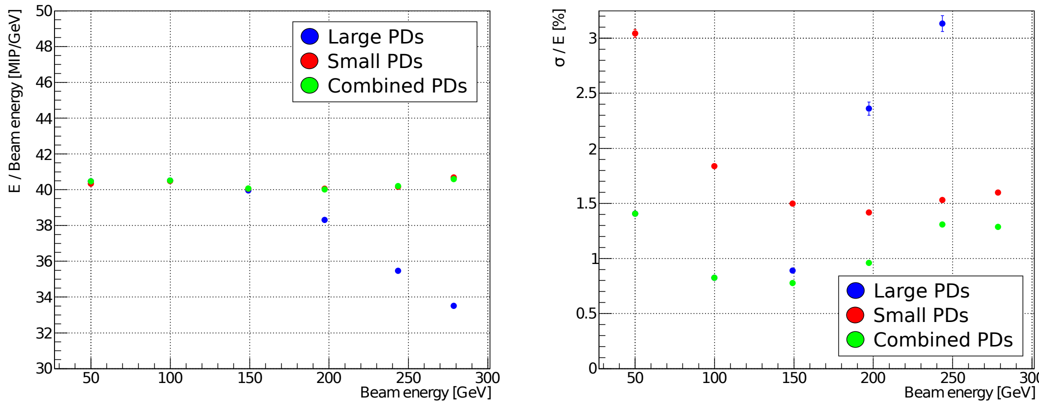

Figure 5. Prototype performances for incident electrons in the energy range between 50 and 280 GeV: average deposit/beam energy (left) and energy resolution (right). Energy is reconstructed using large PDs only (blue), small PDs only (red) or combining the two information (green).

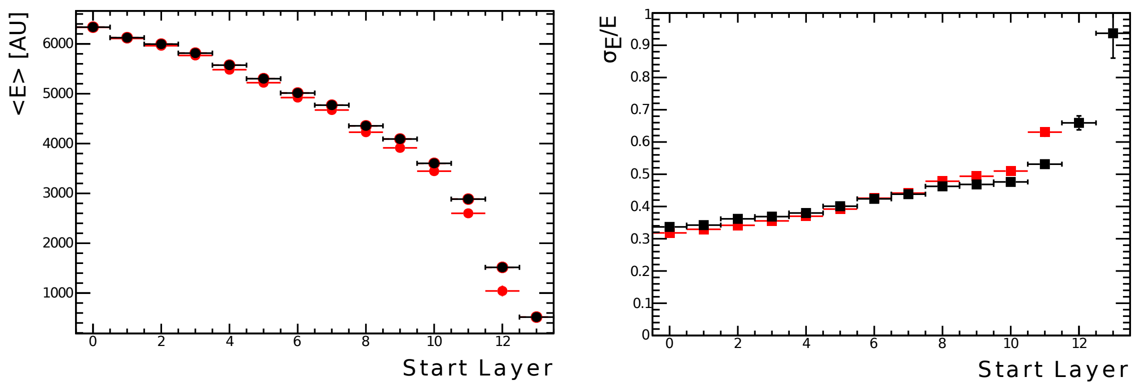

Figure 6. Prototype performances for incident 350 GeV protons: average deposit (left) and energy resolution (right). The mean and the standard deviation of the distributions was derived both from histogram statistics (black) and from gaussian fit (red).

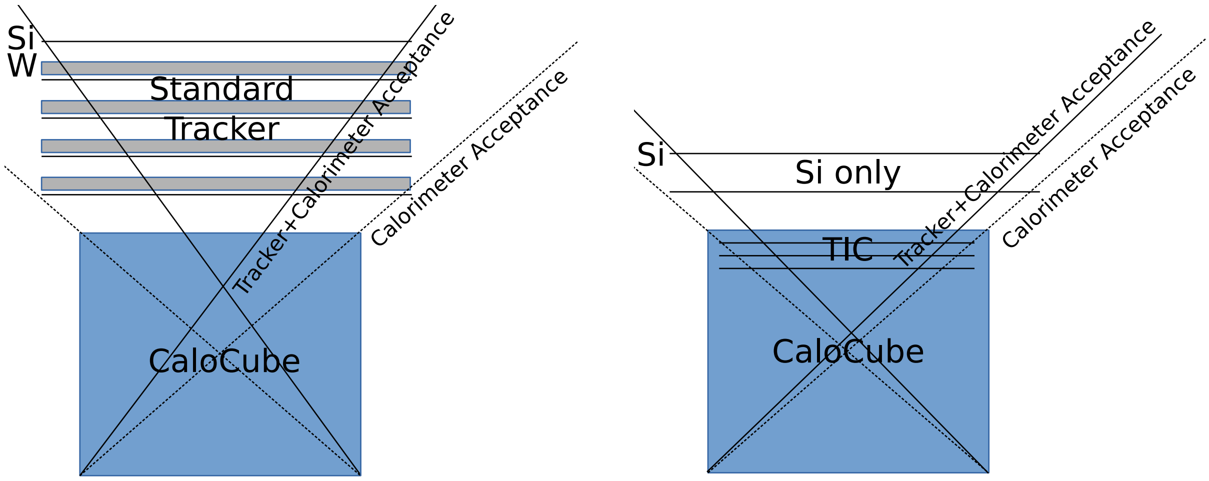

Figure 7. Schematic design of the two different methods for angle reconstruction: on the left, the standard approach of a Si+W tracker external to the calorimeter and, on the right, the TIC approach of a Si tracker inside (and a couple of Si layers outside) the calorimeter.

The performances of the prototype for hadronic showers have been investigated using protons beam between 100 and 350 GeV. Fig.6 shows the total deposit and the energy resolution as a function of the shower starting layer, defined as the first layer having dE > 15 MIP. As we can see, if we select shower started before the fifth layer, the energy resolution is better than 40%, consistently with the expectations. All the results discussed in this section are comparable or better than the ones relative to the previous version of the prototype [10], confirming that the current implementation of the detector satisfies the energy resolution requirements for future space satellite experiments, discussed in Sec.1.

5. Future development

The CaloCube project is focused on the optimization of a calorimeter for the detection of charged cosmic rays, but, in a general multipurpose experiment in space, the detection of γ rays plays also an important role. An important requirement for γ rays astronomy is to have a good angular resolution in order to allow precise identification of astrophysical sources in space. This is generally obtained placing a tracker external to the calorimeter, but, as discussed in the following, this solution decreases the geometric factor of the apparatus. The optimization of the detector in order to have a good angular resolution, needed for γ rays, and a good geometric factor, needed for charged particles, is the main purpose of the Tracker In Calorimeter (TIC) project. TIC is a one year R&D project, approved and financed by INFN (Italy) in 2017. In cosmic rays experiments, like Fermi-LAT [11], the direction of the incident particle is reconstructed using an external tracker made of passive layers (like tungsten) and active position sensitive layers (like silicon microstrip detector). In this case, the angle of the γ rays is indirectly measured from the tracks of the electron-positron pair formed by conversion in passive layers. The main disadvantage of this configuration is that the acceptance is limited by the large level arm between silicon layers needed to have good track reconstruction performances. In addition, tungsten layers require an additional allocation of a fraction of the mass budget that could instead be used to increase the size of the calorimeter. Passive layers induce fragmentation of nuclei as well, thus worsening charge reconstruction performances. All these drawbacks are solved by the TIC approach, where silicon detectors are moved inside the calorimeter, except a couple of external layers dedicated mainly to charge and track reconstruction of charged particles. This solution exploits the scintillator layers to develop the shower and the silicon detectors to measure the lateral profile. In this case, the angle of the γ rays is reconstructed indirectly from the lateral profile of the shower sampled at different depths in the calorimeter, in a similar approach to the one adopted by the LHCf experiment [12]. The two different methods just described are depicted in Fig.7. The development and the optimization of the TIC design are still under study. However, even if the details are not yet defined, preliminary studies showed that the idea is promising. Different TIC geometries have been investigated using simulations, leading to an angular resolution of the order of 0.5° for vertical γ rays above 10 GeV. A prototype has been built inserting several spare silicon layers from the DAMPE experiment inside the latest version of the CaloCube prototype. The detector was tested at the CERN accelerators using electrons with 1-200 GeV incident energy and 0-20° incident angle. The analysis of data is ongoing.

6. Conclusion

In order to extend direct measurements of cosmic rays fluxes of at least one order of magnitude in energy respect to the maximum value currently achievable, the CaloCube project proposed a cubic calorimeter made of cubic scintillator crystals equipped with photodiodes. Being as most homogeneous and isotropic as possible and having five faces usable for particles detection, this design ensures a good particle energy resolution ($< 2\%$ for electromagnetic showers, $< 40\%$ for hadronic showers) and a good effective geometric factor (> 3.5 m^{2}sr for electromagnetic showers, > 2.5 m^{2}sr for hadronic showers), as confirmed by FLUKA simulations. These performances are consistent with experimental tests on a large prototype made of 18 layers, each layer composed by a 5×5 matrix of CsI:Tl scintillator cubes, each cube equipped with large and small area photodiodes. In order to optimize the detector not only for the detection of charged particles, but also for the detection γ rays, a new approach of integrating a silicon tracker inside the calorimeter is under study by the TIC project, thought as the natural development of the CaloCube project.

Acknowledgments

This project has received founding from the European Union's Horizon 2020 research and innovation program under grant agreement No. 654168.

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