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Conceptual design of a charge identifier array for cosmic ray composition measurements in CALET

P. S. Marrocchesi[a], C. Avanzini[b], M. G. Bagliesi[a], A. Basti[b], K. Batkov[a,b],
G. Bigongiari[a], A. Caldarone[a], R. Cecchi[a], M. Y. Kim[a,b], T. Lomtatze[b],
P. Maestro[a], V. Millucci[a], F. Morsani[b], R. Zei[a].
[a]*Dept. of Physics, University of Siena and INFN, Via Roma 56, 53100 Siena, Italy*
[b]*University of Pisa and INFN sez. di Pisa, 2 v. F.Buonarroti, I-56127 Pisa, Italy*
marrocchesi@pi.infn.it

Abstract: The CALorimetric Electron Telescope (CALET) mission is proposed for the observation of high energy cosmic rays and gamma radiation for the JEM-EF attached payload on the International Space Station. The instrument, equipped with an imaging calorimeter of scintillating fibers (IMC) and a total absorption BGO calorimeter (TASC), is optimized for the measurement of cosmic ray electrons in the TeV energy range with the exciting possibility to identify individual nearby sources. The large collection power of CALET will also allow for precision studies of the elemental composition of charged cosmic rays and of their spectral features. The charge identification of the incoming particle will be performed by a two-layered array of pixelated silicon sensors, covering a seamless sensitive area of about 0.8 m^2, placed on top of the instrument. An innovative integrated design of the array and its front-end electronics is presented.

Introduction

An accurate measurement of the charge of the incident nucleus allows the identification of the chemical elements in the cosmic ray (CR) flux. This is a specific requirement for the present and the next generation of balloon-borne or space-based payloads designed to provide direct measurements of the elemental composition and of the individual energy spectra of cosmic rays.

Arrays of silicon detectors have been successfully operated as charge identifiers both in ATIC [1] and in CREAM [2, 3] balloon missions, where they achieved an adequate discrimination capability to tag individual elements, with excellent charge resolutions (for instance 0.3-0.4 electron charge units (e) for the elements from C to Si in ATIC [4]). On the basis of the preliminary results from the second flight of CREAM [5], equipped with a double-layered silicon detector array, resolutions of the order of $0.2e$ for the elements of the CNO group and $\sim 0.35e$ for Fe were achieved.

One of the major problems affecting instruments where, as in the case of CALET, a calorimeter provides an energy measurement, is the presence of "back-scattering" from the calorimeter itself. This background, which increases with energy, may strongly degrade the track reconstruction performance of the apparatus. The choice of a pixel segmentation reduces the complexity of the pattern recognition with respect to the case of silicon strip detectors, where this task is made more difficult by ambiguities in the coupling of coordinates measured on orthogonal views. With pixelated sensors, hits not originating from the incident particle track can be easily identified and eliminated. Also, the problem of the albedo from the calorimeter is greatly reduced if the granularity of the silicon array is optimized to achieve a single-hit occupancy per pixel. In order to provide a unique assignment of the pixel hit by the incoming cosmic ray, the detector segmentation has to match the track reconstruction accuracy of the instrument. Pixels with relatively large dimensions ("pads" with an area of order 1 cm^2) can be an adequate choice, if a sufficient lever arm is provided between the array and the imaging calorimeter.

An important requirement is to have at least two independent charge measurements of the same particle by means of a two-layered array. As in the case of second flight of CREAM [6], the request of a consistent charge measurement from the two layers, provides a great benefit in terms of background rejection and allows to increase the purity of the data sample when a single cosmic ray element is selected.

CALET is a proposed instrument to observe very high energy electrons and γ-rays on the Japanese Experiment Module Exposure Facility, JEM-EF, on the International Space Station (ISS). The main science goals of the CALET mission include a precise measurement of the electron spectrum up to several TeV, with the possibility to identify nearby sources of electron acceleration, the study of cosmic ray propagation in the galaxy and the search for dark matter signatures. The instrument will measure electrons from 1 GeV to $\sim$ 10 TeV and γ-rays from 20 MeV to several TeV, with excellent energy resolution beyond 100 GeV. Combining an imaging part and a total absorption part, the CALET calorimeter will have the required proton rejection capability to select electrons and γ-rays in the TeV region. With the addition of a charge-identifier detector (the Silicon Array described in this paper), CALET will also be able to study the elemental composition of CR with individual element resolution, up to the PeV scale.

The Silicon Array conceptual design

The Silicon Array (SIA) detector proposed for CALET consists of a mosaic of PIN diodes, covering a sensitive area of 896 mm × 896 mm with no dead regions. The sensors are pixelated on one-side with 64 pixels of dimension 11.25 × 11.25 mm^2, with inter-pixel distance of 0.1 mm.

The sensors (94.7 × 94.7 mm^2) have an active area of 90.7 × 90.7 mm^2 (100% fill factor). They are produced from 6" wafers of high resistivity (not less than 10 kOhm·cm) with 500 micron thickness. They are specified to have a full depletion voltage below 80 - 100 V and a dark current per pixel typically lower than 2 nA. Sensor prototypes with similar characteristics (with a slightly smaller pad size of 1 cm × 1 cm) have already been fabricated and successfully tested with atmospheric muons and particle beams [7, 8] achieving a S/N between 8 and 10 for Z = 1 ultra-relativistic particles.

The baseline configuration of the SIA consists of two layers of sensors for a total of 200 units. In order to achieve a seamless active region over the whole array, the sensors are overlapped in both dimensions (along the ladder and along the orthogonal direction). The active (geometrical) overlap region between adjacent sensors is 1.2 mm (3.2 mm).

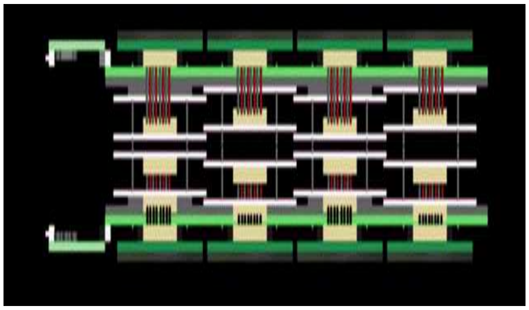

Figure 1: Detector concept: example of a 4 ladder prototype. View along the ladder axis (the detector mechanical structure is not shown).

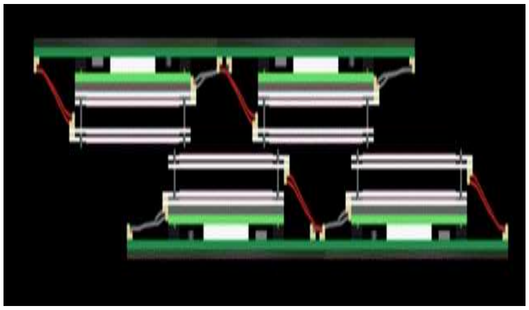

Figure 2: Detector concept: example of a 4 ladder prototype. View orthogonal to the ladder axis.

The two layers are mechanically arranged in one unit. An innovative design allows to achieve a complete overlap of all sensors, while providing two independent measurements of the charge of the incoming cosmic ray at all angles, within the acceptance of CALET. Along each ladder, sensors are mounted in pairs (one on top of each other) for a total of 20 sensors (an example is given in Figs.1-3 where only 4 ladders with 8 sensors per ladder are drawn). The mechanical arrangement of each pair of sensors allows an accurate knowledge of the relative position of the respective pixels.

The SIA is mechanically divided in two halves: a bottom section, where 5 (odd numbered) ladders are arranged, as shown in the example of Fig. 1, and an upper section which provides the mechanical support for the remaining 5 (even numbered) ladders.

The current design allows for assembly/disassembly operations of the silicon array to be carried out with sufficient precision and reproducibility in the sensors position, as well as the possibility to easily replace a given sensor and/or one or more readout cards, a feature of great value during the commissioning of the detector.

The readout of the two ladders is integrated with the mechanical structure. All the electronics cards are placed on the upper and lower surfaces of the detector in a symmetric way. This simplifies the design of the cooling system and allows for a minimization of temperature gradients across the instrument.

The readout of each pair of sensors (128 channels) is carried out by a dedicated board (VAB) hosting 4 chips of the VA family. The front-end chip: a sample-and-hold, low-power, large dynamic range ASIC with multiplexed readout of 32 channels, was first developed in collaboration with IDEAS (Norway) [9]. A later version HDR14.2, with epitaxial layer protection against SEE effects and optimized for positive charge inputs, was developed under the support of INFN [10]. The VAB board implements a sequencer for the readout of 4 VA chips with 16 bits digitization, using 4 independent ADC units.

Each ladder is readout by a Ladder Controller (LAC) which reads 10 VAB units (both layer). The LAC formats the event from a single ladder with no sparsification.

The global readout of the 10 ladders is done by a ReadOut Controller (ROC) interfaced to the main DAQ. Redundance will be implemented for the flight version. The ROC reads the LAC boards, assembles the event fragments and applies a sparsification threshold. A suitable scheme of event buffering is implemented in the ROC. A number of command and slow-control functions (e.g.: hold-delay control, readout of temperature sensors, charge-injection for gain calibration, etc.) is performed by the LAC under the control of the ROC.

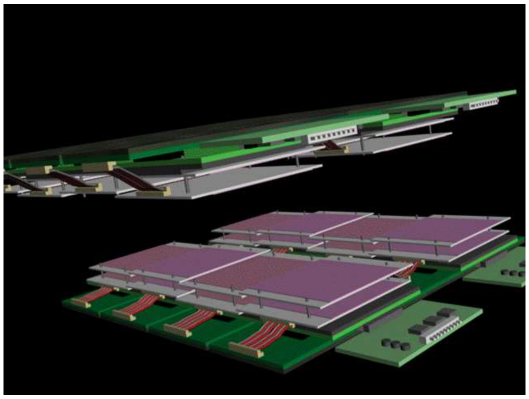

Figure 3: Detector concept : example of a 4 ladder prototype with 32 sensors (VAB and LAC boards are visible in an artist's view of the integrated assembly)

Preliminary estimates (weight, power, data size)

According to the baseline detector concept, the total number of readout channels is 12800 (6400 per layer). Due to the relatively low hit multiplicity per event, the maximum size of the sparsified data is expected to be reduced from about 25 kB of raw data per event to a few hundreds of bytes (or less) according to the value of the sparsification threshold versus the average system noise.

A preliminary estimate for the power requirement for the electronics (not including DC- DC conversion efficiency from main 28 V) and for sub-detector data readout is of order 120 W (not including the power budget for cooling).

A preliminary weight estimate (including: sensors, electronics, mechanics but excluding the sub-detector cooling interface to the main instrument) is at present around 50 kg.

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