Low-energy beam test results of a calorimeter prototype for the CREAM experiment

M.G. Bagliesi[a], T. Lomtadze[b], P. Maestro[a*], P.S. Marrocchesi[a], M. Meucci[a], V. Millucci[a], F. Morsani[b], G. Valle[a]

[a] Physics Dept., University of Siena and INFN, 55 v.Banchi di Sotto, 53100 Siena , Italy

[b] INFN sez. di Pisa, 1291 v.Livornese S.Piero a Grado, 56010 Pisa, Italy

H. S. Ahn[c], O. Ganel[c], K.C. Kim[c], M.H. Lee[c], L. Lutz[c], E.S. Seo[c]

[c]Inst. for Phys. Sci. and Tech., University of Maryland, College Park, MD 20742, USA

CREAM (Cosmic Ray Energetics And Mass) is an experiment under construction for a direct measurement of high energy cosmic rays (10^{12} to $> 5 \cdot 10^{14}$ eV) over the elemental range from proton to iron. The first flight of CREAM is intended to demonstrate the new Ultra Long Duration Balloon (ULDB) capability under development by NASA. A prototype of a tungsten-SciFi imaging calorimeter designed for CREAM has been tested at CERN with electron beam energies ranging from 5 to 100 GeV. Although the calorimeter module is optimized for cosmic-ray spectral measurements in the multi-TeV region, the response of its electromagnetic section to low energy electrons has been studied with this dedicated prototype. Results show good agreement with the expected behaviour in terms of linearity and energy resolution.

1. Introduction

A new series of balloon-borne direct measurements of primary cosmic ray energy spectra and of their elemental composition in the multi-TeV energy range are in progress or scheduled for flight in the near future [1–3]. With an energy reach typically limited by statistics, the range of energies explored by direct measurements is expected to improve along with the accumulated flight time and to slowly approach the lower end of the transition region where the all-particle spectral index increases from ∼2.7 below 10^{14} eV to approximately 3.3 above 10^{16} eV, a feature of the spectrum known as "knee". The main science objectives are the understanding of the mechanism of acceleration of primary cosmic rays of very high energy, the possible identification of their sources and the clarification of their interactions with the inter-stellar medium. The CREAM (Cosmic Ray Energetics And Mass) experiment [3–9], designed for a direct measurement of cosmic nuclei over the elemental range from proton to iron at energies 10^{12} eV to $> 5 \cdot 10^{14}$ eV, is currently under preparation for its first Ultra Long Duration Balloon (ULDB) flight. It will take advantage of this new capability under development by NASA in a series of flights designed to last from 60 to 100 days each. According to the current development schedule, the first launch will take place in December 2003. The CREAM energy measurement relies on two complementary techniques based on a sampling Tungsten/Scintillating fiber calorimeter, preceded by a graphite target with scintillator layers for track reconstruction and supplemental charge measurement, and on a Transition Radiation detector (TRD). Simultaneous measurements of the energy of a subset of nuclei, by the calorimeter and TRD, will allow in-flight intercalibration of their energy scales. Dual charge measurements using a segmented timing-based particle-charge detector (TCD) and a pixellated Silicon detector (SCD) will allow excellent charge

*Corresponding author: paolo.maestro@pi.infn.it

identification. Physics beyond 100 TeV will be an opportunity for CREAM which is designed to reach 500 TeV after a series of 3 flights and to collect almost twice the current world total of direct high-energy cosmic ray events in a single ULDB flight. The instrument layout and expected performance are described elsewhere [3–9]. A protoflight calorimeter module was tested at CERN in 2001 [7]. The calorimeter flight model for the first CREAM mission was completed in 2002. It was then shipped to CERN where it was calibrated with high-energy electron and hadron beams in July 2002 [7,9]. In this paper we discuss the beam test results of a reduced-scale prototype of the calorimeter which was built to investigate its response to low-energy e.m. showers below 100 GeV.

2. The CREAM calorimeter module

The baseline CREAM configuration includes a tungsten scintillating-fibers calorimeter with an active area of 50×50 cm^2 preceded by a Carbon target of approximately 0.5 interation lengths and thickness equivalent to about 1 radiation length. The target must force at least one hadronic interaction to provide an energy measurement. The primary cosmic nucleus interacts inelastically and generates secondary particles, mostly charged and neutral pions. The latter decay almost immediately, initiating an electromagnetic shower whose energy and direction is reconstructed by the finely segmented imaging calorimeter with :

- a longitudinal segmentation in layers of 1 X_0 thickness;
- a lateral segmentation of 1 cm (close to one Moliere radius $\rho_M \sim 9$ mm) in order to sample with sufficient accuracy the lateral shower development

The calorimeter is constructed as a stack of 20 tungsten plates, each 3.5 mm thick (1 X_0), a bottom aluminum plate and 20 interleaved scintillator layers. Each scintillator layer is made up of 1 cm wide, 0.5 mm thick scintillating fiber ribbons. Each ribbon is read out, through an acrylic light-mixer and a bundle of thin clear fibers, by a multi-pixel Hybrid PhotoDiode (HPD). For mechanical reasons, alternate ribbons are read out on opposite ends. Non-readout ends are aluminized by vacuum sputtering to increase the light-yield and effective attenuation length, thereby increasing the S/N ratio and improving response uniformity over the active area. The light-mixer is interfaced to a bundle of 265 μm diameter round clear fibers. Each bundle of 48 fibers is split into three sub-bundles to create low-, mid- and high-energy readouts. Optical splitting of the light from the scintillator, together with the use of neutral density filters, allows to divide the calorimeter dynamic range into 3 sub-ranges optimized to match the dynamic range of the front-end electronics. The CREAM design goal requires the calorimeter to measure, with an almost energy independent resolution, particle energies in the range 1 to 1000 TeV. However, the calorimeter threshold allows accurate energy measurements also in the sub-TeV region. The energy scale of the flight-model was calibrated using electron beams (up to 200 GeV) as well as proton and pions beams (up to 350 GeV) at CERN [8].

3. The reduced-scale prototype

In order to verify the expected performance of the electromagnetic section of the calorimeter module (i.e.: calorimeter alone with no target) with respect to the Monte Carlo simulation, a special prototype was built in Italy by the INFN group of Siena/Pisa to be operated at a lower energy threshold (Fig.1). The prototype followed the baseline CREAM design, with minor differences. However, the photon detection was carried out by multi-anode photomultipliers instead of HPDs. The larger gain in photoelectron statistics allowed to operate the calorimeter at beam energies of a few GeV. Further gain in collected light was achieved by using all (48) available clear fibers for light transmission between the light mixer and the photodetector, thus implementing only one out of the three read-out subranges. Minor differences were on the total number of tungsten layers (16 instead of 20) and on the calorimeter mechanics. The tungsten plates were cut into a square shape with size increasing from 11×11 cm^2 on the front layers to 20×20 cm^2

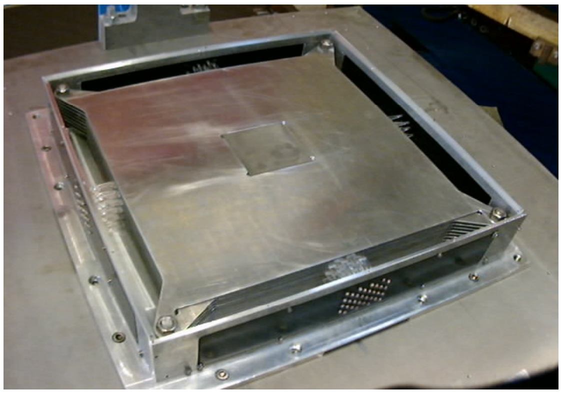


Figure 1. The prototype during the early assembly phase.

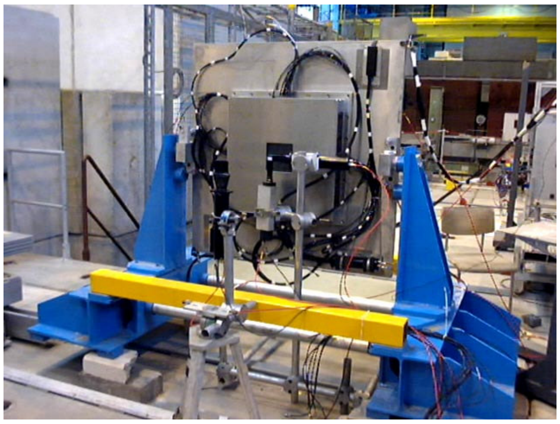


Figure 2. The calorimeter prototype after installation in the X7 beam line.

on the downstream layers. Dimensions were chosen to allow for a complete lateral containment of the shower, given the expected beam profile. Each tungsten plate was glued, as an insert, in a 4 mm thick Al plate. The latter had the same shape and size as any of the full-size tungsten plates of the flight module except for the larger thickness. A groove in the Al (8 cm$\times$0.5 mm) allowed the insertion of the fiber ribbons. The 16 layers were instrumented with a total of 96 fiber ribbons, each with an active length of 50 cm. The number of ribbons per layer ranged from 4 to 8 increasing along the calorimeter depth. Due to the limited total number of photomultiplier pixels available, only 8 layers had individual fiber ribbons read-out by a total of 2 multi-anode photomultipliers with 16 anodes each (Hamamatsu H6568). The first 2 and last 6 layers of the calorimeter had their light output summed up into one (single anode) photomultiplier (ETL-9814A). Individual analog signals were fed into a charge integrating gated ADC (CAEN V792) with a charge resolution of 100 fC. Digital read-out was carried out via a VME-to-PCI interface (SBS-620).

4. Channel equalization and energy calibration

The prototype was mounted on a rotating fixture (Fig.2) and tested respectively with electrons, hadrons and muons in the X7 beam line at CERN in August 2002. Signals from individual ribbons were equalized by steering a narrow electron beam (as defined by the triple coincidence of the beam trigger counters to an area of approximately 1 cm^2) into the centre of each ribbon. Taking advantage of the fact that 95% of the shower is contained in one Moliere diameter, fine tuning of the beam alignment was performed, on-line, by monitoring the lateral tails of the shower in the pulse height distributions of the two nearby ribbons, one on each side. Once all ribbons in a layer had been equalized to their average response, a second pass was performed, whenever necessary, to calibrate the relative energy response among the layers by fitting the longitudinal distribution of the shower at one given beam energy (Fig.3) . A single set of constants turned out to fit all longitudinal distributions taken at different energies and provide the correct absolute energy scale. An independent calibration procedure had to be performed on the single anode photomultiplier based on the ratio of its measurement with the energy sum from each of the two pixellated PMTs at different beam energies.

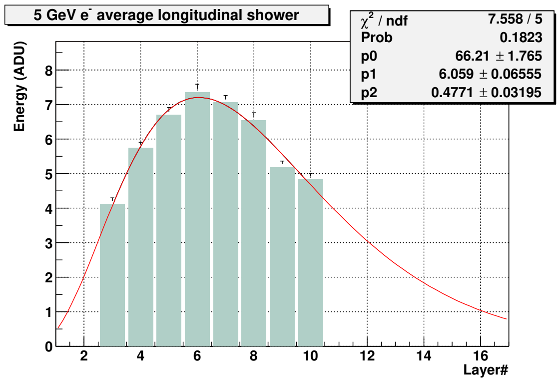


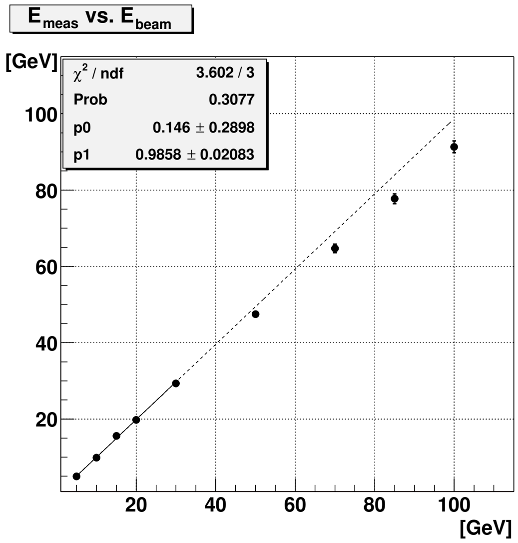
Figure 3. Fitted longitudinal distribution with a 5 GeV electron beam.

5. Beam test results

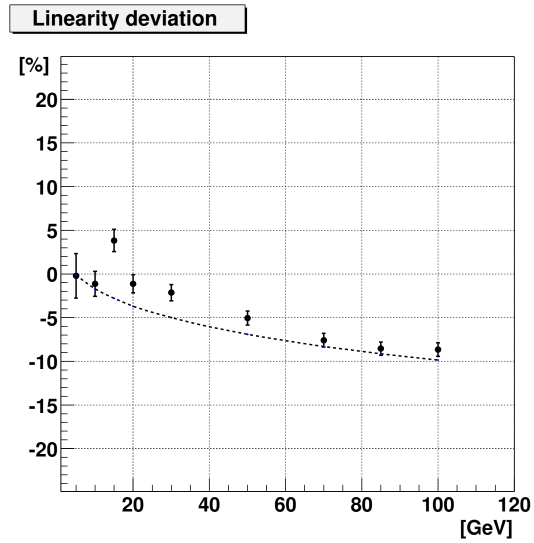
An energy scan was carried out with electron beams of energies ranging from 5 to 100 GeV. The energy response of the calorimeter is plotted in Fig.4(a) as a function of beam momentum. The observed non-linearity, shown in Fig.4(b), is in complete agreement with our expectations (dotted line) and was found to be entirely due to the longitudinal energy leakage as predicted for a calorimeter with a thickness of 16 X_0. The energy resolution was extracted from the data, plotted in Fig.5 as a function of beam momentum and fitted to:

$$\frac{\sigma(E)}{E} = \frac{(2.31 \pm 0.02)\%}{\sqrt{E[TeV]}} \oplus (3.8 \pm 0.6)\% \qquad (1)$$

where the constant term is summed in quadrature with the energy dependent coefficient which reflects the contribution due to the photon statistics. As the calorimeter is designed for operation in the multi-TeV range, the sampling fraction has to be of the order of a fraction of 1% in order for a calorimeter element to provide signals within the available dynamic range of the system. Therefore, a quite large contribution to the uncertainy on the energy measurement is to be expected at energies below 100 GeV due to the large fluctuations in the shower energy sampling. Such a term becomes negligible at the TeV energy scale. Our result is compatible with the



(a)



(b)

Figure 4. (a) Measured energy vs. beam energy. (b) Linearity residuals (dotted line : expected non-linearity from longitudinal leakage).

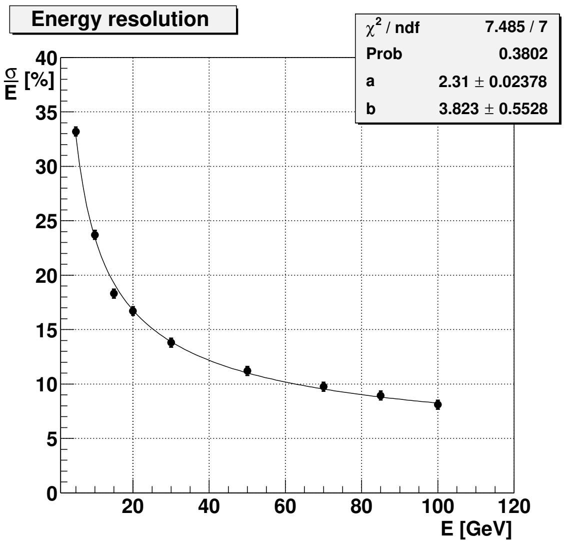


Figure 5. Energy resolution vs. beam momentum.

parametrization of [10] where the observed energy resolution of a sampling calorimeter is corrected for the threshold effect caused by a nonzero value for the minimum visible energy detectable in a single calorimeter cell. Our fitted value is compatible with a minimum visible energy threshold of order 10 MeV in a single ribbon.

6. Conclusions

The low-energy (5 to 100 GeV) response to electromagnetic showers of a tungsten-SciFi imaging calorimeter prototype for the CREAM experiment was studied during a beam test at CERN. The results were found in good agreement with the expectations in terms of linearity and energy resolution given the limited prototype depth and the low beam energies spanned during the tests reported.

7. Acknowledgements

This work is supported by the *R&D* program WCAL of INFN (Gruppo 5). The authors greatly appreciated the support of dr. A. Basti for the mechanical design of the calorimeter and the skilful technical support of C. Stanghini, A. Orsini, A. Tazioli, S. Tolaini.

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