Proceedings of ICRC 2001: 2151 © Copernicus Gesellschaft 2001

ICRC 2001

Čerenkov-assisted readout of ionization calorimeters for space-based and balloon-borne cosmic ray studies

A. F. Sill, V. Nagaslaev, and R. Wigmans

Texas Tech University, Lubbock TX 79409-1051 USA

Abstract. Calorimeters for energy measurement of cosmic rays are quite limited in the amount of mass that can be used when these devices are deployed in space-based and balloon-borne missions. Therefore it is of primary importance to achieve the physics goals of these experiments that the maximum amount of information is extracted from each event that occurs in the detector. We describe a technique that distinguishes the electromagnetic energy fraction of each shower by detection of Čerenkov light in quartz fibers in addition to the usual ionization readout. The combination of these two readout methods allows event-by-event correction for leakage in thin calorimeters with improvements to resolution that are so far only limited by the amount of light obtained in the quartz, a restriction that should become less important at high particle energies. Results of ground-based beam tests with accelerators and plans for future flight testing of this technique are summarized.

1 Introduction

The origin and dynamics of the production of high energy cosmic rays present open questions of great practical and theoretical interest. Knowledge of variations in composition of the elemental spectra of cosmic rays over the energy range up to and including the “knee” (5×10^{15} eV) would provide crucial information needed to test current supernova acceleration models and help establish the lifecycle of cosmic rays. Our present ability to explore this range experimentally, however, is limited by significant restrictions on the mass and consequently the collecting power of the detectors used for direct measurement of cosmic rays.

Calorimeters are presently the most effective instruments for the measurement of the elements (primarily protons and helium nuclei) that dominate cosmic ray composition in this energy regime. Space-based or balloon-borne instruments are needed to reduce the complications associated with the primary particles interacting in the material (for example, the atmosphere) above the detector. Such platforms carry with them stringent power, weight and data rate limitations that constrain the geometrical acceptance of these instruments.

The goal of this investigation is to pursue a promising calorimeter concept to maximize the scientific return of missions under the above constraints. A recent set of studies funded by NASA allowed us to produce a thin calorimeter with intriguing properties by combining quartz fibers and conventional scintillating fiber ionization readout. The relative and absolute signals from these two readout methods were studied with test beam exposures at CERN with favorable results. However, the range of energies available in the test beams for calibration and for measuring the physical properties of these detectors was limited to well below what could be studied in even a short set of limited test flights. For this program we will continue development of these ideas and will extend the energy range of the testing dramatically through a set of balloon flights from Fort Sumner, NM.

Correspondence to: A. F. Sill (Alan.Sill@ttu.edu)

2 Detector design and physical motivation

In general, deeper calorimeters, in terms of interaction lengths (λ_I), have better energy resolution. For a given weight, deeper calorimeters have a smaller geometrical acceptance. Weight constraints and the relatively low flux of high energy cosmic rays tend to favor calorimeter designs that are shallow ($\approx few\ \lambda_I$) with a larger geometrical acceptance. In this configuration the energy of the primary particle is determined by the energy released during the first interaction. Fluctuations in the number and type of pions produced in the first interaction dominate the energy resolution of the instrument. The electromagnetic energy fraction of each shower can be quantified by measuring Čerenkov light produced by these particles as they travel through quartz fibers and comparing the resulting signal to the results of a traditional ionization readout. This information from the fibers can be used to categorize the fluctuation and improve the energy resolution.

3 Application to thin calorimetry

When high-energy hadrons develop showers in a 1–2 $\lambda_{\rm int}$ deep calorimeter, the response function is completely determined by leakage fluctuations. These fluctuations are very likely correlated with the fraction of energy spent on π^0 production inside the detector. In general, π^0s produced in the first nuclear interaction develop electromagnetic (em) showers that are contained in the detector, while charged pions typically escape. Therefore, events in which a large fraction of the initial energy is converted into π^0s in the first interaction will exhibit little leakage (a large detector signal), while events in which a small fraction of the energy has been transferred to π^0s will be characterized by large leakage (small detector signals).

Most of the energy in the *non*-electromagnetic component of the signal is deposited by non-relativistic shower particles, which do not emit Čerenkov light (Wigmans, 2000). Calorimeters using quartz fibers as active material are therefore sensitive to the π^0 component of hadron showers. This feature has been confirmed experimentally in detectors that rely only on Čerenkov readout (Akchurin *et al.*, 1997).

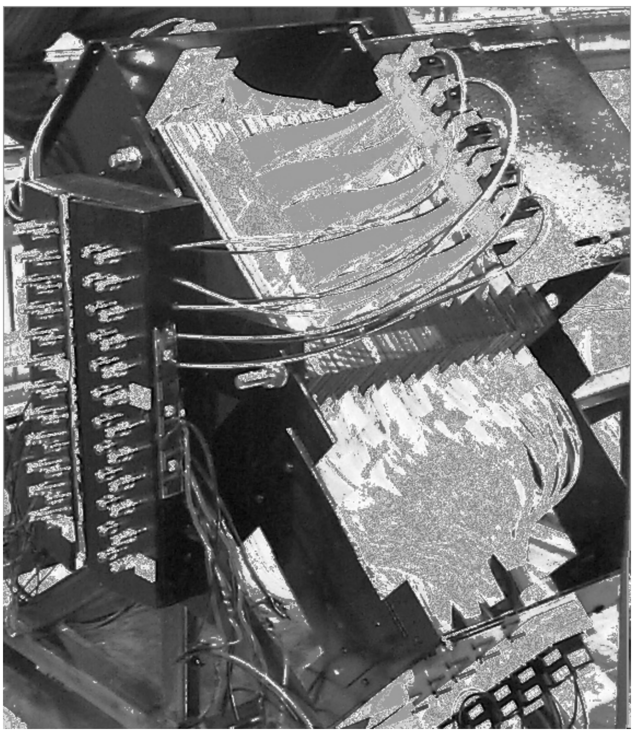

Fig. 1. Photograph of the TTU test beam prototype of a dual-readout Čerenkov+ionization calorimeter. The beam entered from the right and produced signals in crossed ribbons of scintillationg fibers and in another set of crossed ribbons of quartz fibers oriented at right angles to the beam direction. Signals from these crossed sets of x and y fibers were gathered in towers for comparison with each other and with the incident beam energy.

Use of a dual-readout technique combining ionization and quartz signals in thin calorimeters should therefore allow application of cuts and correction factors to distinguish between events with relatively small and large shower leakage. A relatively large Čerenkov signal would indicate relatively little shower leakage, while a small Čerenkov signal (compared to the dE/dx signal) should be correlated with conditions in which a large fraction of the shower energy escapes from the detector.

4 Construction of dual-readout test beam prototype

The calorimeter consisted of 39 lead plates (with a thickness of 6.4 mm each, for a total depth of 1.4 $\lambda_{\rm int}$ or 46 X_0). These plates were interleaved with alternating ribbons of scintillating and quartz fibers, providing x, y-readout and an effective tower structure for particles entering perpendicular to the absorber plates, for both types of light (Figure 1).

The scintillating fibers[1] were 500 μm thick and had a numerical aperture of 0.72. The quartz fibers[2] were 270 μm thick and their numerical aperture was 0.40. The showering particles generated scintillation light in the plastic fibers and Čerenkov light in the quartz fibers. Photons emitted within the numerical aperture of the fibers were captured and transported through internal reflection to the fiber ends, where they were converted into photoelectrons in the photocathode of a photomultiplier tube (PMT)[3]. The calorimeter is further described in Nagaslaev *et al.* (2001).

Because of the way the signals were read out, the calorimeter had a tower structure for particles entering it perpendicular to its front surface. In total, there were 25 towers, each with a cross section of 4×4 cm^2, both for the scintillating-fiber and the quartz-fiber signal readout.

This detector was tested in the H2 beam line of the SPS at CERN. It was mounted on a platform that could be moved vertically and laterally, so that the center of each tower could be moved into the beam, as needed for calibration purposes. Usually, the angle (θ) between the beam and the calorimeter's front face was 0°. However, we also performed some measurements in which the detector was rotated, at angles up to $\theta = 90^\circ$.

Upstream of the calorimeter, a trigger counter telescope was installed that allowed a choice of the beam spot size for the recorded events. Downstream of the calorimeter, a large scintillation counter served as the "tail catcher". The hadron measurements were carried out with a $0.25\lambda_{\rm int}$ carbon target installed directly in front of the calorimeter. Scintillation counters placed upstream and downstream of this target allowed offline selection of events in which the beam particle had interacted in it. In the electron measurements, this target was replaced by a Preshower Detector, consisting of a 5 mm thick lead plate, followed by a scintillation counter. This device was very useful for eliminating hadron and muon contamination at very high energies.

[1] SCSN-81, a polystyrene-based product manufactured by Kuraray Inc., Japan

[2] Manufactured by Fiberguide Industries, USA

[3] Hamamatsu R5900U, 10-stage

5 Results of beam tests

All individual calorimeter cells were calibrated with 150 GeV electrons incident on the cell center. Data were then taken with a wide variety of energies for both protons and pions, varying the location and angle of incidence of the beam with respect to the detector.

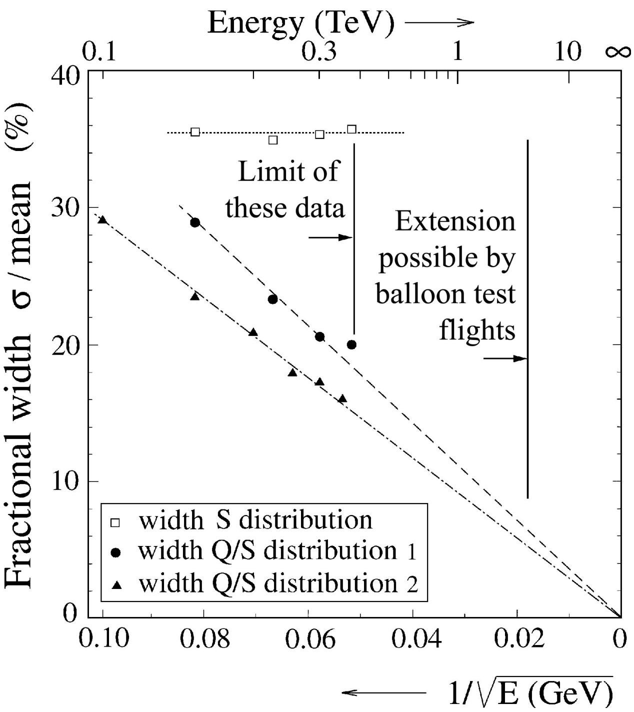

Fig. 2. The fractional width of the distributions of the signals from the scintillating fibers S) and of the ratio of the signals from the quartz and the scintillating fibers (Q/S) as a function of the energy. The resolution in the Q/S distribution is given for two different configurations in the amount of quartz (solid circles and solid triangles), and shows that this resolution in these tests is so far limited only by photostatistics in the amount of Čerenkov light.

Figure 2 shows the fractional width of the distribution of the ratio of the signals from quartz and scintillating fibers, represented by the black dots, as a function of the energy of incoming test beam pions. This energy is plotted on a scale linear in $E^{-1/2}$, so that a straight line through the bottom right corner of this plot corresponds to resolution that improves in a way that scales directly with $\left[\sqrt{E}\right]^{-1}$. The experimental data cover an energy range of 150 – 375 GeV and are well described within this range by such a line. This means that the width of the Čerenkov-to-ionization signal distribution in this energy range is completely determined by fluctuations governed by Poisson statistics, *i.e.,* fluctuations in the number of photoelectrons produced by Čerenkov light from the quartz fibers.

Figure3 shows the resulting improvement in energy resolution over the range of energies studied when cuts and correction factors based on the simultaneous use of the two readout methods are applied. A crucial parameter in these results turned out to be the ratio of the signals from the two types of fibers, Q/S. This relationship is shown for a particular incident particle energy in Figure 4. Events in which a large fraction of the energy of the incoming particle was spent on π^0 production, which were thus well contained in the calorimeter, were characterized by a large Q/S value, whereas a small Q/S ratio was indicative for relatively large shower leakage. The beneficial effects of the dual-readout method are independent of the type of ionization signal used and were limited by the small light yield of the quartz fibers.

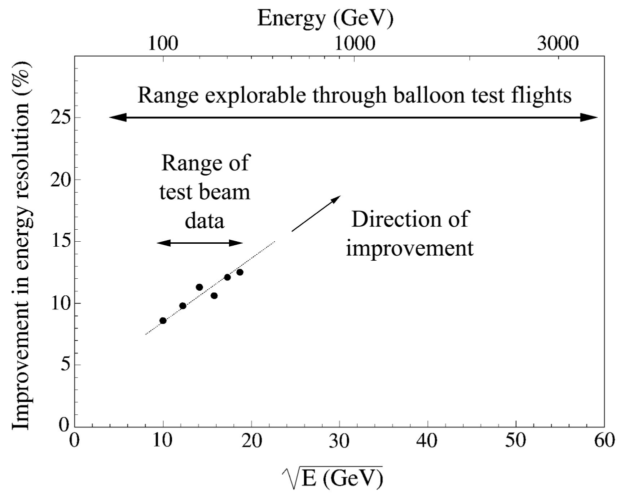

Fig. 3. Experimental improvement in overall energy resolution when cuts and correction factors based on the dual-readout method are applied. Results from the beam tests show a continuous trend of improvement over the range of energies studied, limited only by the photostatistics of the production and collection of Čerenkov light. These results are encouraging, but higher energy data from balloon test flights will be required in order to extend the range of data into the region of interest to cosmic-ray astrophysics experiments.

These studies also showed the underlying relationship between the Čerenkov and ionization signals to be independent of energy over the energy range accessible in the test beams. It is extremely important to test this relationship over a broad range of energies and particle incidence angles, which is the focus of the series of test flights proposed here. Should this relationship continue to hold true at higher energies, very substantial benefits of this method may be expected in the multi-TeV energy range.

6 Angular Dependence

In many cases in the reconstruction of cosmic ray particle energies, tracking of the particle trajectory through the detector turns out to be of significant importance to avoid confusion by misidentification of the incoming particle type and in the reconstruction of its energy. Increasing the segmentation and number of readout layers in the active portion of the detector is possible, but comes at the expense of an increased number of readout channels and a corresponding increase in the

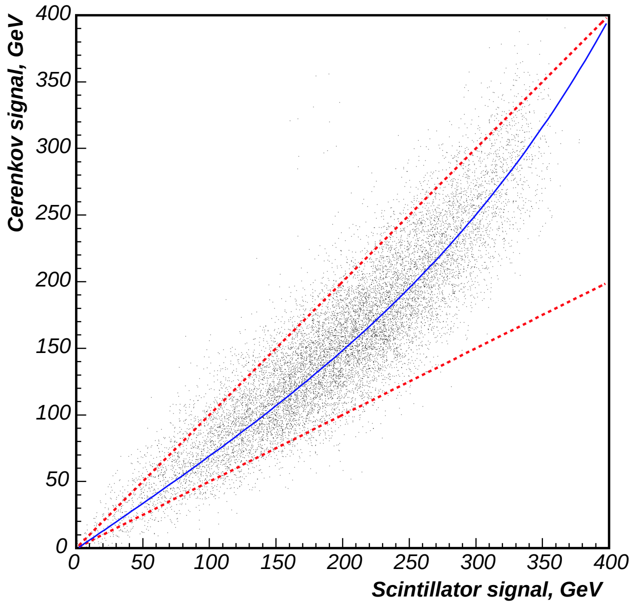

Fig. 4. Experimental relation between the quartz and scintillating fiber signals for 350 GeV incident pions using the test bema prototype described in the text. The correlation between the ratio of these signals and energy leakage allows cuts and correction factors to be applied to improve energy resolution and reduce non-gaussian tails.

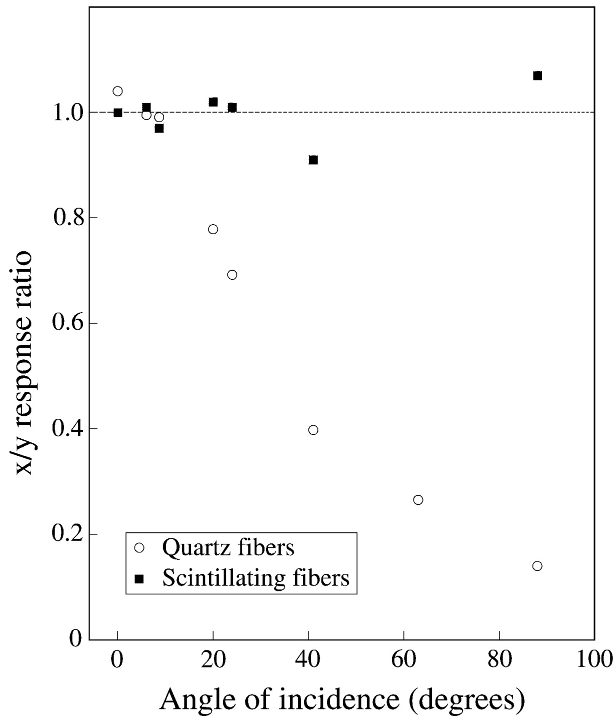

Fig. 5. Ratio of the signals measured in fibers oriented in the x and y directions, as a function of the angle of incidence of the showering electrons (200 GeV). Results are shown separately for the response of the quartz fibers and scintillating fibers.

cost and complexity of the detector. Consequently, an unexpected benefit that showed up in the test beam studies of the dual-readout technique has proven to be of great interest.

Our studies showed that the angular direction of incidence of the shower could be reconstructed to within a four-fold ambiguity *entirely on the basis of the quartz fiber signals themselves.* This relationship, shown in Figure 5, demonstrates the differences between the two types of signals produced by the shower particles. In the test beam device, scintillation light was emitted isotropically when excited molecules in the scintillating fibers returned to their ground state.

On the other hand, the Čerenkov light in the quartz fibers is emitted in a characteristic cone with a 46° opening angle centered around the direction of each of the relativistic shower particles. The ratio of the signals in the x and y scintillating fibers stayed essentially constant as the angle of the incident electron test beam was changed, but the ratio of the signals from the x and y quartz fibers strongly depended on the direction of the incoming particles. The latter effect is in good agreement with results measured in other quartz fiber calorimeters (Anzivino *et al.*, 1995; Ganel and Wigmans, 1995).

While observation of this effect in the controlled environment of a test beam is interesting and was important, we believe it is important to verify and to extend the energy range and range of particle types in observing this effect with real cosmic rays in test flights. This set of measurements can be made over a broad range of energies in data obtained from ballon flights, and will allow us to evaluate whether in the future a simpler calorimeter with fewer readout channels and fewer readout planes can be proposed by implementation of this technique. The natural range of incident particle energies, interaction locations, and initial directions available with cosmic rays in flight would also allow us to study the response of the detector as a function of each of these parameters separately through offline event analysis and selection.

7 Conclusions

We have demonstrated a dual-readout calorimeter that measures both the ionization losses (dE/dx) and the production of Čerenkov light. The combination of these two readout methods allows event-by-event correction for leakage in thin calorimeters. The resulting improvements to resolution are so far only limited by the amount of light obtained in the quartz, a restriction that should become less important at high particle energies. Future balloon tests should allow extension of this technique.

References

R. Wigmans, *Calorimetry – Energy Measurement in Particle Physics*, International Series of Monographs on Physics, Volume 107, Oxford University Press, Oxford (2000).

N. Akchurin *et al.*, Nucl. Instr. and Meth. **A399** (1997) 202.

V. Nagaslaev *et al.*, Nucl. Instr. and Meth. **A 462** (3) (2001) 411.

G. Anzivino *et al.*, Nucl. Instr. and Meth. **A360** (1995) 237.

O. Ganel and R. Wigmans, Nucl. Instr. and Meth. **A365** (1995) 104.