Tests for a new concept of EAS detector for UHE neutrinos

M Iori¹, E Arslan², H Denizli², F Ferrarotto¹, M Kaya³, A Yilmaz² and J Russ⁴

¹ “Sapienza” University of Rome, Piazzale A. Moro 5 00185 Rome, Italy and INFN Roma1
² Abant Izzet Baysal University, 14280 Bolu,Turkey
³ University of Kafkas, 36100 Kars,Turkey
⁴ Carnegie-Mellon University, Pittsburgh, PA 15213, U.S.A.

E-mail: maurizio.iori@roma1.infn.it

Abstract. We present results from tests performed at Karlsruhe Institute of Technology (KIT) and at FermiLab Meson Test Beam Facility (FNAL) to study electron-muon separation, time of flight resolution and the acceptance for a new EAS detector concept. The very good time resolution and adjustable orientation of the detector permit to separate upward-moving tracks from downward tracks at any orientation with high efficiency. With these performances the detector can measure interaction products from cosmic neutrinos with zenith angles > 90 degrees, defining a chord through the earth as the interaction path. This kind of detector using SiPM will be a part of a large area array (several square kilometer) designed to measure UHE neutrinos (0.01-100 EeV).

1. Introduction

The interest in Ultra High Energy Cosmic Rays (UHECR) has spawned a large variety of 2d (surface) or 3d (volumetric) detector arrays using different detection techniques (Cherenkov [1],[2], air fluorescence [3] and radio waves [4]). Almost all applications concentrate on cosmic ray shower particles moving downward or possible sideways toward the detection elements. While timing information is often used to obtain shower angular information, none of the present detectors uses precision time measurements to separate upward- or downward-moving particles by Time Of Flight (TOF). Such discrimination is essential to experiments that seek to identify cosmic ray or cosmic neutrino interactions at zenith angles greater than 90°. In this paper we show the test results made in coincidence with KASCADE-GRANDE experiment (KGE) of e/µ separation capabilities of a prototype element intended for deployment in an array, named TAUWER, capable of measuring large zenith angle cosmic rays as well detecting the signature of Ultra High Energy τ neutrino interactions using the Earth ‘skimming strategy’ [5, 6, 7, 8]. Electron-muon separation is an important part of identifying τ hadronic showers. Our method was tested at Fermilab Meson Beam Facility and cosmic ray EAS results from eight stations installed in a cluster of KGE at KIT are also presented.
2. The performance of working prototype

For the experimental application the module was designed to recognize single particles and determine the direction of motion (up/down). It uses two pairs of scintillator counters, named towers, each composed by two tiles ($20 \times 20 \text{ cm}^2$, 1.4 cm thick), separated by 160 cm. Each tile is read by one low voltage R5783 Hamamatsu photomultiplier (PMT). Two PMT boxes are attached to a metal structure as shown in figure 1. Each tile is embedded in a PVC box which also contains the PMT. The PMT has excellent time resolution ($\approx 400 \text{ ps}$). However, the TOF precision is limited by light collection dispersion. The precision is improved by using two photodectors set on opposite sides of each tile. Recently we have studied replacing the PMT by a pair of Silicon Photomultipliers (SiPM). Results from laboratory studies, beam tests at the FTFB and long-term studies with detectors in the KGE array indicate that these SiPM devices will function well in the TAUWER setup and similar Cosmic Ray applications.

![Figure 1. Station installed at HFSJG to test upward/downward particles separation.](image1)

![Figure 2. Station set vertically at KIT to study electron-muon separation. The bottom tiles are covered by a layer of 1.5 cm lead.](image2)

The hadronic showers produced by sea-level decays into multipion final states of very high energy $\tau$ leptons produce a high local density of electromagnetic particles in a small cone around the $\tau$ axis and a muon density about 0.1% as large spread over an area 1000 times larger. To detect this pattern of particles from an upward-moving $\tau$-induced shower and to reject cosmic ray interactions, we use an array of 640 stations spread over a 2.5 km$^2$ area on a mountain slope. The solid angle of a single tower is about $1.4 \times 10^{-2}$ sr and its zenith angle range is $\pm 7.5^\circ$ around the axis and a geometrical acceptance of 5.6 cm$^2$sr. To increase the solid angle coverage we mount two towers with their axes parallel, separated by $\sim 60$ cm. This increases the acceptance to $\pm 20^\circ$ along the azimuthal angle and the covered solid angle increases almost by a factor 3. This behaviour is particularly important in situations like a large array whose target are rare events (i.e. UHE neutrino flux). With a TOF resolution of the order of 1 ns it is possible to reject vertical air showers, even at large zenith angles, without need of shielding. We can select upward- and downward-moving particles passing through the detector with negligible intrinsic contamination.

The performance of a prototype, shown in figure 1, was tested at the High Altitude Research Station Jungfraujoch (HFSJG), located in Switzerland at $\approx 3600$ m. The module has shown a good upward/downward discrimination capability in all our tests. Performance details are given in [9]. Figure 2 shows a tower set up vertically in the KASCADE-GRANDE array to study electron-muon separation. The DAQ is based on waveform sampling, initially using a MATACQ board [10] and currently using the DRS4-PSI board [11]. These boards digitize the
scintillator waveform at 2GS/s, covering a 2.5 µs window. The time of flight for determining whether the track is moving up or down is refined offline from the waveform output, using an algorithm based on the linear fit of the leading edge of the photodetector signal. In order to maximize upward-downward TOF separation the light collection technique has been optimized for time resolution at the expense of energy resolution. The definition of a minimum-ionizing particle (MIP) in our system is made by calibration on vertical downward cosmic ray muons, to set proper charge cuts to obtain good time resolution. Because of poorer light collection efficiency in the corners near the photodetector, this slightly reduces the effective area per tower, but the effect is small and stable (1%). Using a pair of photodetectors essentially removes the effect.

The time resolution as shown in figure 3 is ≈ 1.2 ns, comparable to the PMT transit time spread. This is achieved by minimizing the role of reflections in defining the leading edge of the light signal. The 1 cm² PMT window is directly coupled by a silicone rubber pad to the scintillator. The scintillator is wrapped with Tyvek for diffuse reflection. This configuration lets the first light arriving at the PMT window dominate for the leading edge of the phototube signal, optimizing time resolution.

2.1. Electron-muon identification

Electron identification is obtained using a layer of lead to produce an electromagnetic shower in front of a tile. Geant4 studies optimized the thickness for the energies of electrons expected from hadronic τ showers. In the test made at KGE we set up our module vertically and a layer of 1.5 cm lead (3X₀), covered the bottom tile (B). The downwarding tracks that cross the top (T) and B tile of same (vertical) tower or different tower (diagonal) are selected by TOF.

![Figure 3. The distribution of time of flight between the two 20 × 20 cm² tiles 160 cm apart, for downward vertical cosmic ray events (left) and diagonal (right) in data with a 1.5 cm lead of layer. The towers are apart 60 cm. In this figure we performed two gaussian fit to cover a tail as well. For vertical and diagonal tracks sigma is about 1.3 and 1.7 ns, respectively. That shows we are in around 2σ level since good events are defined as TOF of 5 ± 3 ns.](image)

The TOF was evaluated by an algorithm that extrapolates the front of the signal to zero voltage after we applied a threshold cut of 6 mV (the average amplitude of signal is 60 mV after cable attenuation). The TOF distribution for vertical and diagonal tracks is shown in figure 3. The spread in time between vertical and diagonal tracks is consistent with the geometrical acceptance.
In this analysis we use a sample of 5792 and 2520 good tracks with TOF in the interval \(5 \pm 3\) ns taken with a 1.5 cm lead layer and no lead. When we cover the B tile with a layer of lead more light is generated in the scintillating tile by electrons or gammas due to electromagnetic processes such as pair production or Compton effect than without lead. In case of muon tracks we do not expect a different amount of light deposited in T and B tile. That suggests the ratio \((R)\) of the charge in B tile \((q_B)\) to the charge deposited in T tile, \((q_T)\) is a good variable to separate the electromagnetic component from muons.

![Figure 4. Ratio distributions for 200K generated gammas, electrons and muons at energies 50, 100, 150, 200 and 500 MeV. Upper graphs are generated without lead, the lower graphs with lead. While gammas have a distribution with a tail, the electron and muon R distributions are close to one for no lead.](image)

The KGE experiment has separate detectors for electrons and muons. Their reconstructed EAS shower profile gives us a particle density map with which we can predict the electron and muon detection probabilities in each of our counters, shower by shower. To predict the fraction of gammas, electrons and muons in our event sample, we use our Geant4 simulation of normally incident tracks of each type passing through the scintillating T tile at a specific momentum. In the simulation we generated gammas, electrons and muons at energies 50, 100, 150, 200 and 500 MeV with and without lead layer in front of B tile. We then evaluated the ratio \(R\), defined in Geant4 as the energy deposited in the B tile divided by that in the T tile. We required at least 1 MeV energy energy loss in the scintillating tile for a simulated particle to have been called detected. Figure 4 shows the ratio \(R\) of gammas, electrons and muons at different energies without lead (upper row) and with lead (lower row). The gamma and electron \(R\) distributions show a clear difference of slope between the run with lead due to more energy deposited in the B tiles as shown in the figure 4. In the case without lead the electron \(R\) distribution is clustered near unity close to 1, quite similar to the muons. The muon \(R\) value is always close to one except for 50 MeV muons where the Coulumb effect in the lead layer produces electrons that spread the \(R\) distribution. The broad \(R\) distribution for 500 MeV gammas and electrons is due to the relativistic rise in the energy loss.

Experimentally the \(R\) distribution can be influenced by different PMT gain and by light collection differences. To evaluate these effects we use the no-lead run and select a sample of
tracks with a single peak signal in both tiles. Because there is very little energy loss in the air between the two tiles, the same particle traversing the two scintillators should produce a narrow charge distribution close to a mean value of total charge collected by photomultiplier. Comparing the mean values of charge distribution between T and B tiles we evaluate the ratio correction factor. The correction factors, $k$, are $0.89 \pm 0.09$ and $0.82 \pm 0.08$ for each tower respectively. To quantify the effect of the lead we compare $R$ to the inverse ratio $R^* = \frac{q_T}{q_B}$. In the absence of lead the $R$ and $R^*$ distributions should be almost equal. Figure 5 shows the corrected ratio $R^*$ (solid line) and $R$ (broken line) of the good tracks in the data for no lead (left) and with lead (right). The slope is very similar. Exact symmetry can be broken if downward-moving tracks interact in the T tile and produce reaction products that count in the B tile. This effect can be reproduced in the Geant4 simulation and accounts for the slight shape differences of $R$ and $R^*$ in the left (no lead) plot in figure 5.

For the data with lead the $R$ distribution in figure 5 (right) shows a clear increment of events at $R$ bigger than one due to more charge released in the B tile by the production of electromagnetic component in the lead layer.

![Figure 5. The corrected ratio $R^*$ (solid line) and $R$ (broken line) of the good tracks from run without (left) and with lead (right).](image)

In order to quantify the contributions coming from electromagnetic components in $R$ distributions, we fit by Minuit code the experimental data to the Geant4 simulations weighting the gammas, electrons and muons by momentum density obtained by vertical shower simulation by CORSIKA, [12]. The best result corresponds to a detected track sample that is 83% electrons, 12% gammas and 5% of muons.

To check the Geant4 simulations, we took data using a 500 MeV electron beam from the Fermilab Meson Test Beam Facility. Electrons were identified by a gas Cerenkov counter. They traversed two scintillator tiles spaced 6 cm apart, with 1.5 cm of Pb covering the downstream tile. We took data in samples over the entire tile area. The left 10% of the downstream scintillator was not covered by the Pb. We used events in this region to normalize the pulse height distributions between the two scintillator tiles. The measured pulse height ratio for the counter after the Pb to that before was $3.56 \pm 0.14$, in good agreement with the Geant4 prediction shown in figure 4. We also wrote a simple ray-tracing program to predict the variation of the ratio across the face of the scintillator, to compare to the test beam data. The agreement was good to 10%, showing that there are no surprises in the light collection from a TAUWER-type scintillator with the photodetector sampling a small fraction of the total edge area.
2.2. Mini array studies in coincidence with KGE

To study the acceptance and background of an array of the detectors described in section 2, four stations, labeled T in figure 6, were installed at the corners of an outer square of side 40 m and four more on an inner square of side 13 m in a sector of KGE with 16 EAS stations, as shown in figure 6 (left). The detectors in this test were set vertically and selected the reconstructed showers in coincidence with KGE events detected within a 600 ms time window. Figure 6 (right) shows TAUWER detector signals that are in time with an EAS of $5.2 \times 10^{14}$ eV detected by KGE. The TAUWER detectors reconstruct 8 tracks by TOF distributed between five of the eight stations in the array.

Also using the KGE triggered events with KGE energy reconstruction, we can look in the TAUWER events to find cases in which TAUWER observes one or more tracks in time with a KGE EAS measured to have its center within our array and to have a zenith angle less than 8 degrees. Figure 7 shows the fraction of EAS events that have one or more tracks detected by the TAUWER array in coincidence with KGE as function of the energy shower.

![Figure 6](image)

**Figure 6.** Left : KIT array cluster (K) where 8 TAUWER stations (T) have been installed to study the background and the acceptance; Right : $5.2 \times 10^{14}$ eV event in coincidence of KGE shower. Eight tracks have been reconstructed by TOF using five stations whose signals are shown with station number.

2.3. Track acceptance and TOF improvement using Silicon Photomultipliers

To improve the acceptance of tracks reconstructed by TOF we have started to test by cosmic rays and particle beam at FNAL a readout of the tile by using with 3 mm x 3 mm Silicon photomultipliers (SiPM) produced by IRST-FBK-Trento and SensL. Both devices have a maximum PDE at 420 nm and a breakdown voltage of 29 V. The SiPM have been set on opposite side of the tiles. The TOF time resolution is 250 ps. By using the SiPM the thickness of the tile can be reduced to 7 mm due to high photon efficiency.

Acknowledgments

We express our gratitude to the KASCADE-Grande Collaboration for hosting our detector at Forschungszentrum Karlsruhe/Karlsruhe Institute of Technology and making their airshower triggers available to us; these measurements would not have been possible otherwise. In particular we thank Harald Schieler, Andreas Weindl, Vitor de Souza, and Bernd Hofmann for their technical help. We thank the National Science Foundation and the INFN for financial aid and data taking support, Dr. E. Delagnes (CEA-Saclay) and Dr. D. Breton (IN2P3-Orsay).
Figure 7. Fraction of reconstructed showers in coincidence with KGE as function of energy of the shower requiring at least two TAUWER stations fired.

for the modification of the MATACQ board. Thanks are due to the Director of the International Foundation High Altitude Research Stations Jungfraujoch and Gornergrat, the Technical Staff working in Jungfraujoch Station and to Dr. Rolf Butikofer. We also thank Giacomo Chiodi and Riccardo Lunadei of INFN-Rome1-Labe and Mauro Ciaccafia for technical support, the Scientific Research Projects Unit (BAP-2009.03.02.324) for partial support by Abant Izzet Baysal University.

References

[1] Antokhonov B A et al Nucl. Instrum. Meth. A in press
[2] Aharonian F et al Astronomy and Astrophysics 2002 39 390
[3] Abbasi R U et al 2010 Astrophys. J. Lett. 713 L64
[4] Apel W D et al 2010 Astrophys. J. 32 294
[5] Fargion D et al 2004 Astrophys. J. 613 1285
[6] Feng J L et al 2002 Phys. Rev. Lett. 88 161102
[7] Beacom J F et al 2003 Phys. Rev. D 68 093005
[8] Zas E 2005 New J. Phys. 7 130
[9] Iori M and Sergi A 2008 Nucl. Instrum. Meth. A 588 151
[10] Delagnes E and Breton D Echantillonneur analogique rapide grande profondeur memoire. French patent n01-05607 April 26th 2001. US patent 6,859,375 Feb 22nd 2005: fast analog sampler with great memory depth
[11] Ritt S DRS4 Evaluation board, Paul Scherre Institute Villigen Switzerland
[12] Knapp J and Heck D 1993 Report KfK 5196B