Beam Test Studies of an Analog Hadron Calorimeter with APD Readout

G. Eigen
Dept. of Physics, University of Bergen, Bergen, Norway,
Representing the Calice collaboration

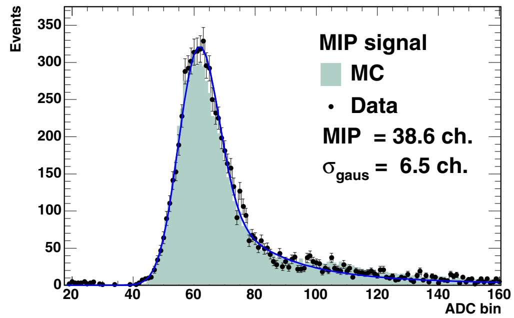
The performance of an analog hadron calorimeter prototype is presented, where plastic scintillator tiles are read out with wavelength-shifting fibers coupled to APDs. The tests were performed in a positron beam at DESY with energies between $1-6$ GeV.

The physics goals at the International Linear Collider (ILC) require high-granularity calorimeters [1]. One option for the hadron calorimeter consists of small (3×3 cm^2 wide and 0.5 cm thick) plastic scintillator tiles sandwiched between 2 cm thick stainless-steel plates [2]. The light of each tile is collected by a wavelength-shifting fiber inserted into a groove that is coupled to a photodetector, such as an avalanche photodiode (APD) or a Silicon photomultiplier (SiPM). The amount of material per layer corresponds to 1.15 X_0 or 0.12 λ.

At DESY, we have tested a twelve-layer prototype in a positron test beam with energies between 1 GeV and 6 GeV [3]. The stainless steel plates were stacked with a 9 mm gap, into which thin-walled aluminum cassettes were inserted, each housing nine 5×5 cm^2 wide and 0.5 cm thick plastic scintillator tiles (BC408 from Bicron) that were wrapped with a super reflector foil (Radiant Mirror film from 3M). The scintillation light was collected with a 60 cm long wavelength-shifting (WLS) fiber (double clad Y11-300 from Kuraray) that was inserted into a quarter circle groove in the tile guiding about 5% of the scintillation light after being shifted into the visible green spectrum onto an APD. To reduce systematic effects in the readout system the WLS fibers were coupled to the APD via an air gap. Center tiles (having four neighbors) were read out individually, since they record more than 90%(95%) of the energy of a 6(1) GeV shower. For edge tiles (having three neighbors) and corner tiles (having two neighbors) the WLS fibers of three consecutive longitudinal layers were coupled to one APD. Due to a limited number of 33 APDs, we could read out only one corner amounting to an energy loss of < 1.5 %. Each APD was also coupled to one of four LEDs to monitor gain stability and temperature effects.

The APD's were specially produced photodetectors from Hamamatsu (S 8664-55 special) with a thin photosensitive area of 3×3 mm^2 surrounded by a guard ring. They were operated either at gains of ~ 100 when coupled to charge-sensitive preamplifiers from Minsk that produced typical gains of $\sim 10^4$ or with gains of ~ 250 when coupled to voltage-sensitive preamplifiers from Prague that produced typical gains of 2×10^3. The analog signal was digitized using an 11-bit charge-sensitive ADC (Le Croy 2249W). For data collection and storage a CAMAC-based data acquisition served. The beam trigger was defined by a coincidence between two scintillator finger counter signals located in front of the prototype. Noise and LED events were collected in addition by producing a trigger with a pulse generator at a rate of 1 Hz. The stability of the LED signal itself was monitored by a special temperature-stable PIN photodiode. The prototype was mounted inside an electrically shielded light-tight box placed on a moving table that allowed to steer the beam at any transverse position in the cassette. The temperature inside the box was monitored by three temperature sensors that were read out by a slow control system independently from data taking.

For calibration all cassettes were moved outside of the steel absorber. A 3 GeV positron beam was aimed at the center of one row of twelve tiles at normal incidence, thus calibrating the entire prototype with nine beam positions. The energy loss in the tiles is expected to follow a Landau distribution. Though the probability of secondary-particle productions is reduced since 12 cassettes have a total thickness of 0.4 X_0, we require the shower deposition in the last layer to be consistent with that of a minimum-ionizing particle. Since the most probable value of the Landau distribution is a stable observable, we characterize each readout channel in terms of the distance of the peak position ($A_{\rm sig}$) from the pedestal ($A_{\rm ped}$), called the MIP peak, $MIP = A_{\rm sig} - A_{\rm ped}$. To study the performance of the prototype,



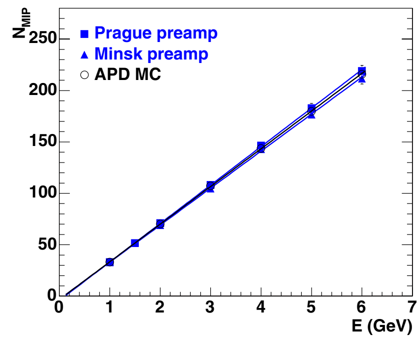


Figure 1: (left) Comparison of measured and simulated MIP spectrum from a single-tile channel recorded with an APD. The data are represented by points with error bars and the MC simulation by the shaded histogram. The solid line shows a fit with a Gaussian distribution for the MIP peak plus a Landau distribution for the tail.

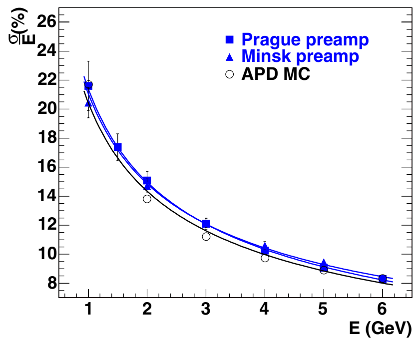
Figure 2: (right) Linearity measured with the Minsk preamplifier (triangles) and with the Prague preamplifier (squares), respectively. Open points show MC prediction for APD measurement.

we have performed energy measurements from 1.0 GeV to 6.0 GeV. Since both calibration and energy measurements were accomplished in a few hours, gain changes due to temperature variations were within 1%.

The electron shower evolution was simulated for the prototype geometry using the GEANT4 [5] framework. The individual physics processes of the readout chain were implemented in three steps. First, we determined the ratio of energy deposited in a tile to the most probable energy deposition of a minimum ionizing particle, E_{dep}/MIP, where MIP corresponds to a value of 810 keV. Next, we divided result this by the number of photoelectrons per MIP, N_{pe}/MIP, extracted from the MIP signal width in the data. Finally after adjusting the simulated MIP position by comparing it to that in the data, we multiplied this by N_{ADC}/N_{pe}. Here, we also accounted for electronic noise by applying Gaussian smearing using the width of the measured pedestal distribution (for details see [3]). This procedure which yields the energy deposition in ADC bins was performed for each channel individually in order to account for differences in light collection efficiencies. The conversion of ADC channels back into MIPs was achieved with the same method used in our calibration procedure. Figure 1 shows a comparison of measured and simulated MIP spectra, demonstrating that our simulation reproduces our measured spectra rather well. To obtain the entire energy of the positron shower, we summed the individual MIP contributions of all tiles. The energy spread of the beam was taken into account as well as fluctuations in the signal detection. The simulation of the longitudinal shower evolution and the lateral shower shape show reasonable agreement with the measured distributions.

The ratio of the MIP amplitude S and the noise N, specified by the Gaussian width of the pedestal distribution characterizes the performance of different readout systems. We obtain $S/N = 9.7 \pm 2.0$ for the measurements with the Minsk preamplifier and $S/N = 3.4 \pm 0.7$ for measurements with the Prague preamplifier. Due to the APD excess noise and an increased pickup noise caused by a reduced intrinsic gain of APD, the S/N values were worse for APD readout than for SiPM readout. To set a minimum requirement on the threshold for separability of the MIP position from the pedestal we determined the quantity $S/\sigma_{\rm gauss}$, where $\sigma_{\rm gaus}$ represents the Gaussian width of the MIP signal. The results for the two preamplifiers are 5.1 ± 0.5 and 2.5 ± 0.4, respectively, which are comparable to SiPM results of $S/\sigma_{\rm gaus} = 3.7 \pm 0.1$.

The summed shower energy was fitted with a Gaussian shape. For compatibility with the SiPM results [4], the central tile of the twelfth layer was omitted. Figure 2 shows the measured shower energies in units of MIPs as a function of the positron beam energy in the 1 GeV to 6 GeV range for data measured with the Minsk preamplifier (triangles), the Prague preamplifier (squares), and for the Monte Carlo prediction (open points). A linear fit to the data yields consistent results for the two measurements. The fitted slopes agree at the level of 3%, which lies within the considered systematic uncertainties. By constraining the intercept of the fit to zero changes the slope by 2% (3%)



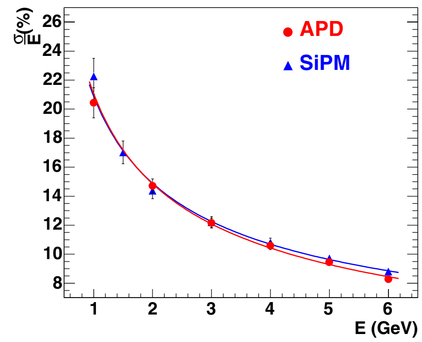


Figure 3: (left) Energy resolution measured with the Minsk preamplifier (triangles) and with the Prague preamplifier (squares), respectively. Open points show the MC prediction for APD measurement. The fit functions comprises of the stochastic term and a constant term added in quadrature.

Figure 4: (right) Measured energy resolution for test beam data of the prototype read out with APDs (points) and SiPMs (triangles).

for the measurements with the Minsk (Prague) preamplifier with respect to the unconstrained fit. The predicted values from the APD Monte Carlo simulation are in good agreement with the measured results. Figure 3 shows the measured energy resolutions, σ_E/E, for the two data sets in comparison to that of the simulation. The stochastic terms of the energy resolution for both data sets are in excellent agreement, yielding values of the order of 21%. This is also reproduced in the simulation. The measured energy resolutions are not very sensitive to the constant terms which are zero within errors.

The statistical errors in our measurements are typically of the order of 1.0–1.5%. They are added in quadrature with the systematic errors that vary from 8% for 1 GeV to 3.6% for 6 GeV and that include contributions of $\sim 1\%$ from different calibration methods, $6\% - 1\%$ from electronic noise, $2\% - 1\%$ from low-energy thresholds, 3% from calibration stability and $4\% - 1\%$ from the non-linearity of the ADC. Uncertainties due to the beam energy spread are of the order of 6% at 1 GeV decreasing to 2% above 3 GeV. Figure 4 shows a comparison of the energy resolution of our prototype measured with APDs to that measured with SiPMs. Both results are in good agreement with each other and are consistent with the expectation from our Monte Carlo simulations.

We have demonstrated that for a plastic-scintillator tile calorimeter APDs provide an alternative readout option to SiPMs. Future R&D will have to prove, if small APDs are practical for a full-size calorimeter. The next step requires a test of the analog scintillator tile calorimeter in a hadron test beam. Presently, a 1 m^3 large analog hadron calorimeter prototype with plastic-scintillator tiles read out by SiPMs is under construction. The goal is to take data in a hadron beam in 2006/2007 together with an electromagnetic calorimeter prototype and a tail catcher.

Acknowledgments

I would like to thank the members of the analog hadron calorimeter group of the Calice collaboration. This work was in part supportrd by the Norwegian Research Council.

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