A novel design for a highly granular hadron calorimeter scintillator-SiPM tile

Erika Garutti, Sebastian Laurien, Marco Ramilli

***Abstract*—Silicon Photomultipliers are the photosensor of choice for many future high energy particle detectors, among which the hadronic calorimeters designed for Particle Flow application [1]. The Hamburg group has elaborated a novel design for the single channel of a highly granular analog hadronic calorimeter, proposed by F. Simon and C. Soldner in [2], based on the direct coupling of SiPMs with a plastic scintillator tile. In the present study the details of the design are reported, together with the tile characterization performed in Hamburg University laboratories.**

***Index Terms*—Silicon photomultiplier, MPPC, Calorimetry.**

I. Introduction

THE CALICE collaboration is developing new calorimeter systems for a future linear collider (ILC) [1] optimized for particle flow algorithms [2]. The aim is a jet energy resolution of 3-4 % at 100 GeV. One of the calorimeter systems under investigation is the analogue hadron calorimeter (AHCAL), a $5-6\,\lambda$ deep sampling calorimeter with a 2 cm thick iron absorber. The sensitive layer consists of $3\times3\times0.3\,\mathrm{cm}^3$ plastic scintillator tiles, that are read out via silicon photo multipliers (SiPM). Their high current signal due to the Geiger-mode operation, low power consumption, compactness and operability in magnetic fields makes them the photo-detector of choice. The parameters characterizing the performances of the detection system are the gain, dark count rate (DCR), optical cross talk, temperature dependence of the SiPM, as well as the SiPM-tile system response to minimal ionizing particles (MIP) and the noise over threshold. For a full AHCAL system for the international large detector (ILD) 10^7 single channels [3] will have to be produced and characterized. A good SiPM-tile system will feature a simple design for cost opimization and fast production, as well as minimal spread of operation parameters. The dynamic range of the single channel should cover the main energy deposited by a 100 GeV π shower in one tile without going into saturation. Every 10^{-3} hits has an energy exeeding 200 MIP. Given a response between 15 - 20 fired pixel per Minimal Ionising Particles (MIP) the signal without saturation correction around $\approx$100 MIP will be well outside the saturation region. A design with maximum tile-to-tile homogeneity already in production will ensure fast characterization and a reliable pre-calibration of the detector. A new design for the single channels has been finalized at the University of Hamburg. An extensive calibration in the laboratory with dedicated setups before mounting on the detector provides a rich data set to predict and understand the detector behavior in detail.

E. Garutti, S. Laurien, M. Ramilli are with the Institute of Experimental Physics, University of Hamburg, Luruper Chaussee 149, D-22761 Hamburg, Germany,

E.Garutti is the corresponding author, and can be reached by *Email: Erika.Garutti@physik.uni-hamburg.de*

Version - Printing date: November 28, 2014

II. Tile design

A. The AHCAL project and design requirements

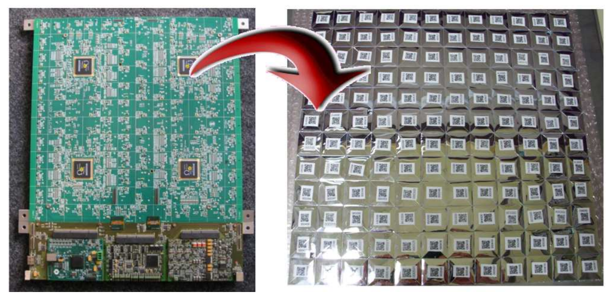

Fig. 1. HBU with four Spiroc2b and 144 channels on the rear side.

THE basic building block of the analogue hadronic calorimeter (AHCAL) is the $36\times36\,\mathrm{cm}^2$ HCAL base unit (HBU). The PCB hosts four custom made readout ASICs which read out 144 channels mounted on the other side of the PCB. The Spiroc2b [4] ASIC has been designed by OMEGA IN2P3 - Ecole polytechnique for SiPM operation as an intermediate step towards the final ILC readout. It features a channel-wise SiPM bias voltage adjustment, preamplifier adjustment (4 bit range), auto-trigger with adjustable threshold, shaping, integration, buffering with 16 cell deep analog memory and digitization for 36 channels. Every single feature of the ASIC would need to be calibrated in time consuming procedures before use. For a detector with thousands of chips such a calibration is not be feasible.

The goal of a good tile design is to homogenize the detector response and the precision level on which it can be calibrated. With every tile having the same behavior and the same response to particles, the detector commissioning, like setting thresholds, is simple and calibration of every single channel may not be necessary. To equalize the response of the tiles it is necessary to adjust the voltage of each SiPM independently. The bias voltage to the ASICs is produced by a power supply with a precision of 10 mV. The Spiroc2b channel-wise voltage adjustment has an uncertainty on the set voltage, depending on the range used up to 200 mV. So using a wider range of bias voltages to equalize the detector response worsens the precision with which the single channels can be calibrated. This uncertainty is directly responsible for the constant term of the calorimeter energy resolution.

B. Single channel design

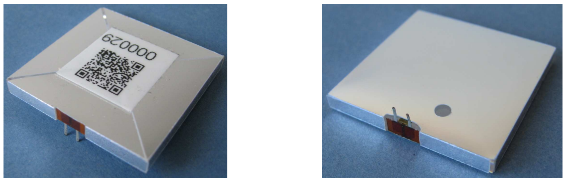

Fig. 2. *Left*: Wrapped scintillator tile with SiPM. *Right*: Hole in the reflector foil for LED calibration.

EACH active calorimeter channel consists of a plastic scintillator ($30\times30\times3\,\mathrm{mm}^3$) read out via a SiPM. The plastic scintillator (Eljen EJ-200 (BC-408)) tile is machined from a large plate with a size of $500 \times 500\,\mathrm{mm}^2$ and $30 \pm 0.2\,\mathrm{mm}$ thickness. The plate is cut with a hard metal (Widia) diamond blade at low RPM into strips of $320 \times 500\,\mathrm{mm}^2$. The strips are placed on a vacuum holding table and milled down with a 60 mm two head diamond reamer (2000 RPM) with a industrial diamond head for pre-milling and a natural diamond head for polishing to a thickness of $30\,\mathrm{mm}^{+0.001\,\mathrm{mm}}_{-0.2\,\mathrm{mm}}$ in order to fit the detector tolerances. The strips are cut to $320\times320\,\mathrm{mm}^2$ using the hard metal blade. A FP4 router with a fast-running Widia milling head and the polishing head of the diamond reamer as second step are used to perform the final cut to dimension of $29.8 \times 29.8\,\mathrm{mm}^2$ with a precision at the $50\,\mu\mathrm{m}$ level. A pack of 10 raw cut tiles are pressed together in a custom made rotateable holder. The two opposing sides are milled down and polished to 29.8 mm. The high precision turn of the holder by 90 °C guarantees perpendicular angles of the tiles. In all steps of the procedure high pressured air has to be applied to cool the scintillator material and remove chip from the tools. A cut out in front of the SiPM where the light collection is largest ensures a homogeneous response to MIP. The optimization of the cut out dimensions is based on a study performed by C. Soldner et.al [5], but simplified for faster machining. The step structure to hold the SiPM-capton unit displayed in figure 3 on the left panel is milled via a CNC-router with a hard metal (Widia) end-mill. For the cut out in front of the SiPM a 2 mm ball-nose end-mill is used. The cut is left unpolished. High pressured air has to be applied in those step as well to prevent melting of the scintillator. The SiPM is glued to the tile using its capton holder and the coupling in the cut out is through air. To minimize the optical crosstalk the tile is wrapped by a semiautomatic process with reflecting plastic foil (3M Vikuiti$^{\mathrm{TM}}$Enhanced Specular Reflector (ESR), $65\,\mu\mathrm{m}$ thick, 98 % reflectivity). Bragg reflexion at the air scintillator boundary has a higher reflectivity than the foil and ensures the highest light collection efficiency. The few photons leaving the tile are stopped by the foil and mostly re-injected into the tile or absorbed in reflections between air and foil. A hole for LED calibration on the HBU is cut into the foil. The photosensor is a SMD Ketek PM1125 with 2304 $25\times25\,\mu\mathrm{m}^2$ pixels and a total area of $1.4\,\mathrm{mm}^2$. Due to the peak sensitivity at $\lambda = 420\,\mathrm{nm}$ it can be coupled directly to the scintillator tile with an emission maximum at $423\,\mathrm{nm}$. The SiPM is soldered on a custom made capton holder to be compatible with the current HBU design. Fig.(3) shows a scan with a ^{90}Sr source of the deviation from the mean response of the tile design with micro-metric resolution by MPI Munich. Only 5.9 % of the total area of the tile deviates more than 10 % from the mean value. The small area directly in front of the SiPM (right side of the figure) shows a higher response to particles. The source is place above a 1 mm diameter collimator. This implies a resolution of 1.25 mm on the edge of the tile. The scanned surface in the picture is thus reduced to $27.5 \times 27.5\,\mathrm{mm}^2$. For more details see [5].

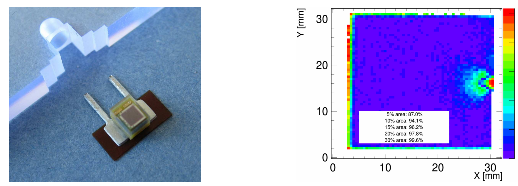

Fig. 3. *Left*: Ketek PM1125 mounted on capton holder in front of the cut-out on the plastic tile. *Right*: Response scan to a ^{90}Sr source.

III. Measurements and Analysis

A precise laboratory calibration before assembly is required to predict the behavior of the detector and to set initial bias voltage and threshold. In a dedicated 6 channels,

Fig. 4. *Left*: 6 Tiles on motorized sled. On the leftmost the cylinder containing the source is visible. *Right*: UV LED fiber system under each tile.

temperature controlled (accuracy 0.2 K) characterization setup the SiPM gain, dark count rate (DCR), pixel crosstalk (XT_{px}) and the tile response (R) to a ^{90}Sr source are measured at varying voltages and temperatures. The UV LED system enables also inter-tile crosstalk (XT_{Tile}) measurements. All measurements except the response are performed for 6 tiles in parallel. A motorized sled moves each tile between the ^{90}Sr source and the trigger. The fully automated data acquisition and analysis for 6 tiles takes around 20 min.

A. Gain and Breakdown

A Gain spectrum is obtained with a charge to digital converter (QDC) integrating the pulse over 142 ns (Shaping time of the Spiroc2b). The single peaks correspond to the amounts of fired pixel of the SiPM, see the red curve in figure 5 left, the first peak being no pixel fired (electronic pedestal). Gain spectra at several voltages and temperatures are fitted with a multi-gaussian function to extract the peak-to-peak distance (gain). The voltage and temperature dependency of the gain can be parametrised as

$$G(V,T) = \frac{dG}{dV} \cdot (V - V_{bd}(T)) \,. \qquad (1)$$

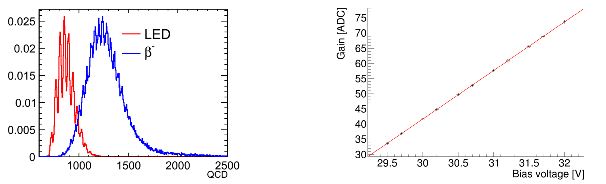

Fig. 5. *Left*: Low light intensity spectrum for gain measurement (red), ^{90}Sr spectrum for response evaluation (blue). *Right*: Gain versus reverse bias voltage.

Extrapolation of the gain versus bias voltage to zero yields the breakdown voltage V_{bd} with an accuracy of 30 mV.

B. Response

The response, defined as the most probable value (MPV) of the spectrum induced by MIP divided by the gain,

$$R(V,T) \;=\; \frac{MPV(V,T) - P(V,T)}{G(V,T)} \tag{2}$$

is measured by placing a collimated ^{90}Sr source above the tile, where $P(V,T)$ is the value of the noise pedestal obtained as the mean value of the noise distribution without source. The data acquisition is triggered by the coincidence of two scintillators below the tile.

C. Inter-tile Crosstalk

The inter-tile crosstalk XT_{Tile} is defined as the fraction of the total energy that is induced into the four neigbouring tiles.

$$XT_{Tile} \;=\; \frac{I_2}{I_1 + 4 \cdot I_2}; \qquad \begin{array}{l} I_1 = \text{Signal in illuminated tile} \\ I_2 = \text{Signal in neighbouring tile} \end{array} \tag{3}$$

One tile is illuminated by a UV LED source as can be seen in the left panel of figure 6. The neighboring ones are in the dark. The light leaking from the first tile into the second (dark) tile is quantified. The induced signals by the source have a relatively low amplitude hence the UV LED is used with high amplitudes to observe a measurable crosstalk. In order to exclude effects of saturation on the SiPMs this measurement is repeated at four different UV light intensities. Due to the extremely low signals induced by inter-tile crosstalk this measurement is time consuming and highly sensitive to small temperature variations.

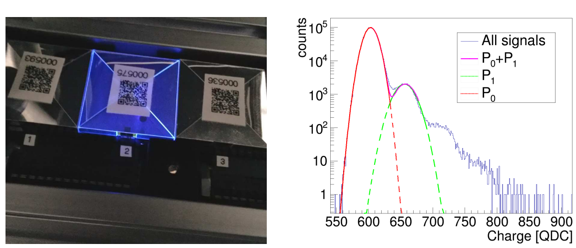

Fig. 6. *Left*: High intensity setting for inter tile crosstalk determination. *Right*: High statistics pedestal spectra with P_0 (red, no pixel fired) and P_1 (green, one pixel fired).

D. DCR and Pixel Crosstalk

For the determination of the dark count rate and the inter-pixel crosstalk a high statistics pedestal spectrum is taken at different voltages with the LED switched off and a random trigger window of 142 ns. The dark-count rate for a given gate length Δt is obtained from P_0, the fraction of events with pulse charges corresponding to no pixel fired. Assuming that the occurrence of dark counts can be described by Poisson statistics, $P_0(\Delta t)$ is given by

$$P_0(\Delta t) \;=\; e^{-DCR\cdot\Delta t} \rightarrow DCR = -\frac{ln(P_0(\Delta t))}{\Delta t}. \tag{4}$$

Due to the low DCR of the SiPM and the high dynamic range of the setup the electronics pedestal can not be separated well from the remaining spectrum. A Gaussian function is fitted to the first peak within $-3\sigma/+0.2\sigma$ as shown in the right panel of figure 6. The inter-pixel crosstalk probability is obtained from

$$XT_{px} = \frac{P - (P_0 + P_1)}{P_1}; \qquad \begin{array}{l} P = \text{All events} \\ P_0 = \text{Events with no pixel fired} \\ P_1 = \text{Events with one pixel fired} \end{array} \tag{5}$$

as the ratio of events with more than one pixel fired to one pixel fired. The electronic pedestal and the one pixel fired distribution is fitted with the sum of two Gaussian functions at a peak to peak distance determined by the gain measurement (III-A). P_0 and P_1 are respectively the integral of the first and second Gaussian function from the fit.

IV. Production and Results

THREE batches of different scintillating tiles with the KETEK PM1125 where produced.

1	Bicron (BC-408) scintillator	300 pc
2	Eljen EJ-200 scintillator	276 pc
3	Eljen EJ-200 dried SiPM	576 pc

TABLE I
SiPM / Tile batches produced

During assembly of batch 1 and 2 we experienced soldering problems due to the so called popcorn effect. The transparent epoxy enclosing the SiPM absorbs humidity from the air. When soldered the vaporising water can rip the bonding off. Drying the SiPM at high temperature diffuses the water out of the epoxy for a safer soldering. The SiPMs for batch 3 had to be dried in 80 °C for four days before mounting on the tile. This procedure changes the SiPMs casing opacity and thus the response is reduced and larger spreads are introduced.

A. SiPM Performance

The 1200 SiPMs characterised in the setup show a narrow spread in breakdown voltage (table II) of only 170 mV and a spread of the gain versus excess bias voltage slope on the order of the measurement precision. The combination of a small temperature dependency and a moderate gain slope lead to negligible sensitivity to temperature changes during operation. When operating the SiPMs at the same excess bias

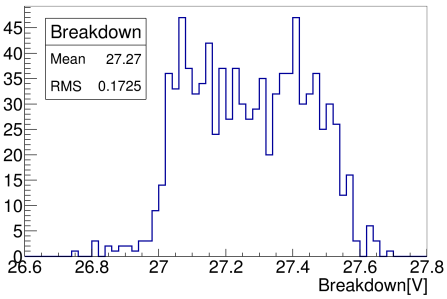

Fig. 7. Breakdown voltage of 1200 Ketek SiPMs

	Breakdown	Temp. dep.	Gain slope
Value	27.3 V	17 $\frac{mV}{°C}$	$253 \times 10^3 \ \frac{1}{V}$
RMS	170 mV	30 %	0.8 %

TABLE II
SiPM FIGURES OF MERIT AND SPREAD AT 22 °C

@ 2.5 V	Gain	DCR	Crosstalk
Value	613×10^3	2×10^5 cps	0.03
RMS	1.4 %	16 %	43 %

TABLE III
SiPMs FIGURES OF MERIT AND SPREAD AT 2.5 V EXCESS BIAS VOLTAGE AND 22 °C

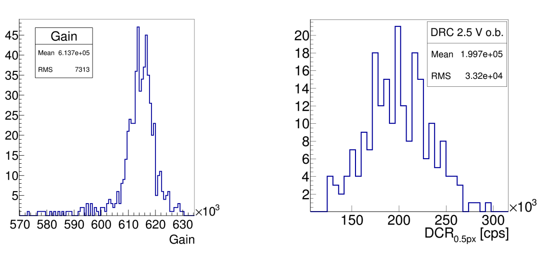

Fig. 8. SiPM Gain and DCR spectra @ 2.5 V excess bias voltage.

voltage the spread in gain, DCR and pixel crosstalk are also on the order of the measurement precision. The values for an operation voltage of ΔV 2.5 V above breakdown are reported in table III. The low DCR in combination with the small inter-pixel crosstalk will enable a nearly noise-free operation for thresholds of 5 fired pixels.

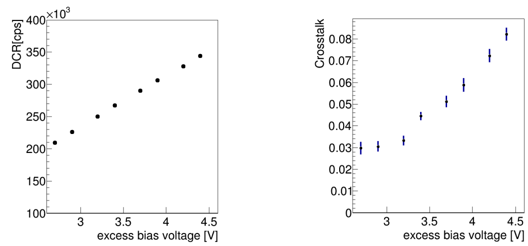

Fig. 9. SiPM performance: *Left*: DCR versus excess bias voltage. *Right*: Inter pixel crosstalk versus excess bias voltage.

B. Tile Performance and Detector Operation

The wide range of voltages in which the SiPMs can be operated makes it possible to choose a voltage for each batch at which the desired pixel per MIP response can be achieved, see values in table IV. The blue line in Figure 10 shows the desired 18 pixels per MIP that have been chosen to accommodate for outliers with lower response. The operation voltage of each batch has to be adjusted accordingly. All SiPMs in one batch

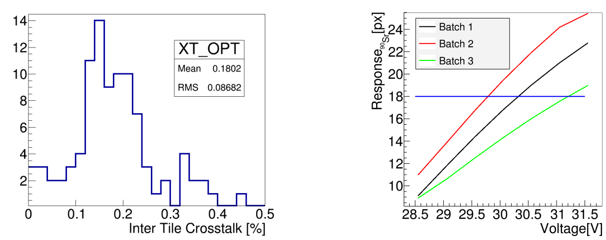

Fig. 10. *Left*: Inter tile crosstalk. *Right*: Response of the three batches at different bias voltages.

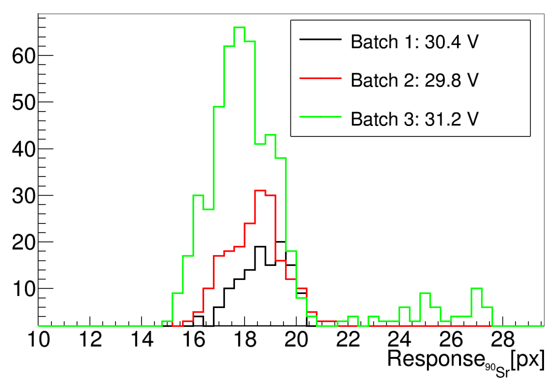

Fig. 11. Response of the three batches to ^{90}Sr at operational voltages

can be operated at the same bias voltage thanks to the low spread in parameters. 144 SiPMs are mounted on each HBU ordered by batch so an individual base voltage for each HBU can easily be set with a high precision. The ASICs voltage setting is not used, which results in a better precision on calibration and no time consuming calibration of the ASIC is necessary. With a gain spread of 5 % no further adjustment of the preamplifier settings of the ASIC is needed to operate the detector. The spread in response on the order of 10 %

makes a separate channel-by-channel auto-trigger threshold adjustment unnecessary. Operated with a threshold of 0.3 MIP

Batch	Bias	Response	RMS	Gain	RMS
1	30.4 V	18.6 px	7.9 %	766×10^3	5.4 %
2	29.8 V	18.4 px	7.4 %	595×10^3	5.5 %
3	31.2 V	18.2 px	15 %	993×10^3	3.5 %

TABLE IV
OPERATIONAL PARAMETERS FOR THE DIFFERENT BATCHES

@ op. Voltage	Inter tile crosstalk	Noise 0.3MIP	Efficiency
Value	0.0018	0.03 cps	0.996
RMS	40 %	0.1 cps	0.2 %

TABLE V
OPERATIONAL PARAMETERS (ALL BATCHES)

this readout option combines high MIP efficiency with an almost noise free auto-triggered detector, see values in table V. The data taking efficiency in low rate environments like test beams is greatly enhanced.

V. CONCLUSIONS AND OUTLOOK

THE manuscript presents the tile design realized at Hamburg University. It shows a low spread in operational parameters, demonstrating the possibility for an easy and fast commissioning of an analogue hadron calorimeter with a large number of channels only introducing a spread of 10% in response when operating all channels at the same bias voltage. In 2014 a prototype has been commissioned for test beam at the PS, CERN, to be tested with pions from 3 GeV to 15 GeV. The goal is a high level electronics test and proof of the scalability of the AHCAL technology as well as a rich physics program focusing on the timing of hadronic showers. Eight HBUs with 1200 channels are equipped with the design discussed here while eight more of the same design are produced in cooperation with the University of Heidelberg to be equipped with SensL SiPMs, which show a similar small spread in operation parameters.

ACKNOWLEDGMENT

The authors would like to thank P.Buhmann and M.Matysek for helping in the development of the tile design, automated procedure and in the realization the large tile production. We are grateful to the KETEK company, in particular to F. Wiest for the kind collaboration and the valuable information.

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