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Construction, Commissioning and First Results of a Highly Granular Hadron Calorimeter with SiPM-on-Tile Read-out

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***Abstract*—The CALICE collaboration is developing a highly granular Analogue Hadron sampling CALorimeter (AHCAL) for a future electron-positron collider. Very small detection units are required for the AHCAL due to an optimized design for the Particle Flow Algorithm. This is realized with scintillator tiles each wrapped in reflector foil and individually read out by a silicon photomultiplier (SiPM). These scintillator tiles and SiPMs are assembled on readout boards (HCAL Base Unit, HBU) which are integrated later on in the AHCAL detector stack. With this design a higher energy resolution is achievable, but also a large quantity of components (around 8,000,000 scintillator tiles and SiPMs) are needed to cover the detection area. To lessen the assembly time and also to assure a proper quality check and control of the final AHCAL an optimized assembly and testing chain is essential. With a large technological prototype both scalability of this project and a reliable operation of a larger number of channels, can be demonstrated. Also, several relevant quantities can be measured in an electron / hadron test beam like energy linearity and resolution for electrons and pions up to 100 GeV including shower profiles and separation. This document recaps the joint efforts of the AHCAL groups to install such an assembly and testing chain in different institutes for the large AHCAL technological prototype with around 22,000 channels. First promising results of the test beams at CERN SPS in summer 2018 are shown.**

I. INTRODUCTION

Future electron-positron collider experiments for precision measurements of the Standard Model and searches for new physics beyond it require a jet energy resolution of better than 4% for an exact jet energy reconstruction [1]. Such a resolution can be reached with an optimization of the subdetectors for Particle Flow Algorithm (PFA) [2]. For a PFA optimized hadronic calorimeter design millions of small detection channels are required, also the calorimeter needs to be placed inside the detector magnet. Due to this compact design, the read-out electronics is fully integrated in the calorimeter. The AHCAL, one of the hadronic calorimeter concepts of CALICE, is using $\sim 30 \times 30 \times 3\,mm^3$ scintillator tiles with a SiPM readout [3]. In total, there are about 8 million channels, which makes the design dependent of automated production, assembly and testing chains.

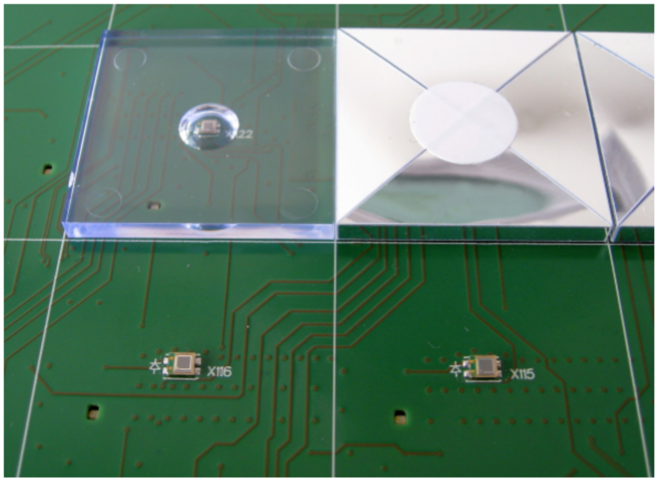

Fig. 1. SiPM-on-Tile Design [5]

The SiPM-on-Tile design was developed at the Johannes Gutenberg University Mainz (JGU Mainz) (s. Fig. 1). The SiPMs in this design are directly mounted on top of the HBUs. A scintillator with a round cavity in the center is placed on top of each SiPM. The scintillator tile is wrapped by 3M ESR reflector foil at the University of Hamburg [10]. The first prototype HBU board showed very good performances and due to the advantage of an easier mass assembly this design was chosen as the new baseline for all upcoming HBUs [4].

A scalability demonstration of the production, assembly and testing of the SiPM-on-Tile design was needed, therefore the plan was developed to build a large technological prototype with 38 layers and in total ~22,000 channels. With this dimensions and very different working steps, that needed to be carried out, a joint effort of several institutes was required to succeed in this goal. This document will recap the production, assembly and testing chain and conclude with first physics performance tests at the CERN SPS [5][17].

II. COMPONENT PRODUCTION AND TESTING CHAIN

The scintillator tiles were produced at LPI and Mephi Moscow via injection molding. The surfaces of these

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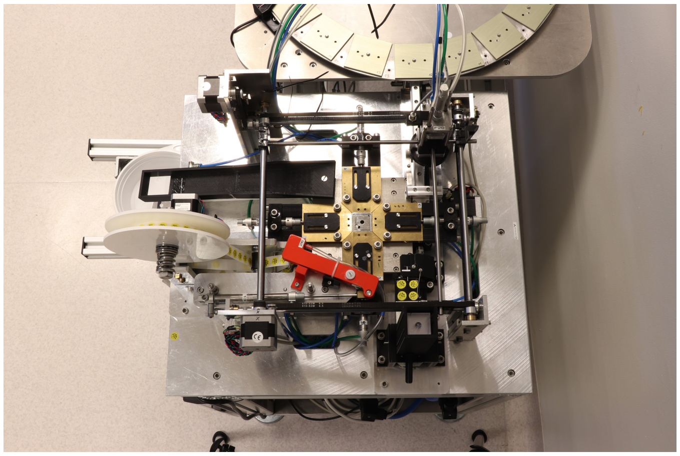

Fig. 2. Automatic wrapping machine of Hamburg University [11]

polystyrene tiles are very smooth, therefore a surface polishing was not necessary. Samples of each tile batch were tested by the Hamburg University group in terms of size. The requirements on tolerances were for the sides $29.65 + 0.00/-0.10\,mm$ and for the thickness $2.98+0.00/-0.03\,mm$. The average of the measured tiles were satisfactory concerning their lateral size ($29.63 \pm 0.04\,mm$), the horizontal size was slightly too thick ($3.03 \pm 0.06\,mm$) [6]. The wrapping was performed via a self-designed semi-automatic foil cutting and wrapping chain also by the Hamburg group. At first a sheet of 3M ESR reflector foil was fixed in a CO_2 laser cutter machine. Then the laser transected the outer edges. The bending edges were only cut through halfway, so that at these edges the foil was still connected and stable, but folding of straight creases was also possible. Out of one ESR sheet 25 individual wrappings each suitable for one tile could be produced. These individual foils were fixed on the carousel of the wrapping machine (s. Fig. 2). A pick-and-place head took one piece of foil and put it precisely in the wrapping position. After that, the pick-and-place head grabbed a scintillator tile and placed it centered on top of the foil. Both foil and scintillator tile were fixed with a vacuum suction system. Mechanical sliders were bending the foil around the tile and kept them tightly fixed until a labeling machine put a sticker on top for fixation of the foil.

For these different sets of movements a complex controlling circuit was needed. The user interface of the automatic wrapping machine was programmed via Labview [7]. The Labview program controls relais-cards, an Arduino Uno [8] and a LabJack U12 [9]. The LabJack detected the state of switches and its digitized analog signals (i.e. for pressure sensors). The relais-cards controlled the pneumatic cylinders and the Arduino the stepper-motors, which were necessary to fulfil these complex movements.

In total ∼25,000 tiles were wrapped in this production chain. Before sending the wrapped scintillator tiles for further treatment, one sample of 50 tiles each was checked by an edge recognizing algorithm on a recorded image [10].

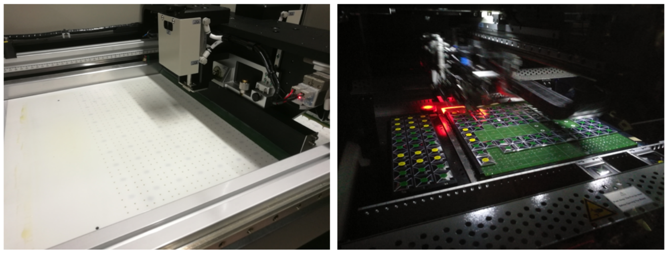

Fig. 3. Screen printer and pick-and-place machine of JGU Mainz

TABLE I
RESULTS OF THE HEIDELBERG UNIVERSITY SIPM TESTS [14]

Breakdown Voltage min - max [mV]	Crosstalk [%]	Gain spread [%]	dV/dT [mV/K]	DCR [kHz]
152 ± 40	4.0 ± 0.8	2.5	54.6	74 ± 13

A characterization of the main electronics component of the HBU board was absolutely necessary, some samples of each SiPM batch were calibrated in the Heidelberg SiPM characterization bench. SiPMs (MPPC S13360-1325PE [12]) were fixed with a silicone mask on top of a PCB with KLauS-readout chips [13]. A movable head with twelve mounted fibers connected to a laser was positioned above the SiPMs. Injecting light through the fibers breakdown voltage, dark count rate, gain and crosstalk were measured with this test stand (s. Table I). Some sub-samples where also checked for temperature correlation with increasing bias voltage [14].

Each HBU was equipped with four Spiroc2E Chips [15] (BGA-ASICs), which are performing signal preamplification, digitization and storing of the events. All ASICs were calibrated and tested before assembly. For this purpose the University of Wuppertal together with DESY had designed a test board. The BGA-ASICs were mounted in a socket holding system that interconnects the pads of the chip and PCB to each other by pressing them together. With this test board the functionality of TDC, ADC, bias voltage and preamplifier were tested [16].

III. ASSEMBLY CHAIN UND HBU PERFORMANCE TESTS

After having the ASIC and SiPM checked, the DESY group took care of the electronic components assembly. After performing a smoke and functionality test, the HBU boards were sent to the JGU Mainz for further assembly.

The wrapped tiles were sent to a company for placing them on tape, a format which is necessary to feed the pick-and-place machine with these large quantities. The tapes were mounted on reels suitable for 56 mm feeders and sent to Mainz.

Screen printer and pick-and-place machine (s. Fig. 3) were extended with a compatible carrier system to assure a proper work flow. A tray for individual tile feeding was integrated in the pick-and-place machine.

The first step was to deposit glue on the HBU boards. This was carried out by an automatic screen printer equipped with a

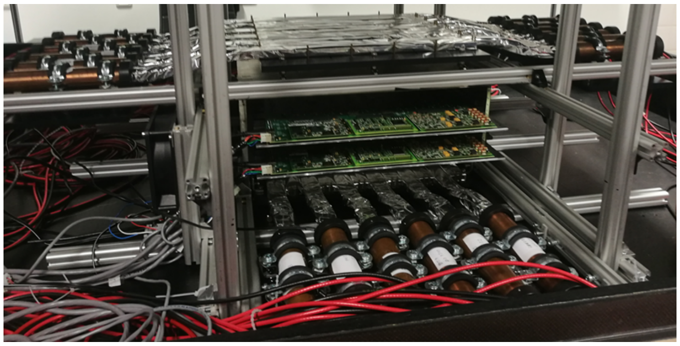

Fig. 4. Performance test stand at JGU Mainz

PumpPrint screen, consisting of 3 mm thick plastic with drilled holes and small cavities. At first, the screen was pressed on top of the PCB. Then the 2-component glue (Araldite 2011) was deposited on top of the screen. After this, the motorized scraper of the screen printer distributed the glue over the complete screen, the holes were filled with glue during this process. The diameter of these holes defined the amount of glue that was remaining after separation of screen and PCB. The cavities were necessary because of the non-flat surface of the HBU (SiPMs were already mounted on top of the HBUs). The parameters of this procedure were optimized after several test runs (number of scraper movement, height of the screen over HBU board, amount of glue on top).

After glue deposition, the board was mounted in the pick-and-place machine on the carrier system. During preparation of the assembly line proper positioning of the tiles was programmed in the machine, so that a recognition of the fiducials, well defined positioning marking spots on top of the HBU, was enough for the machine to know where to place the tiles. The reels, equipped with 420 tiles each, were mounted on the feeders before assembly. So after a simple teach-in process the mounted HBU was ready for assembly. One HBU board needed roughly seven minutes until a complete assembly run was finished. The curing time of the distributed glue was around 20 hours. Usually four HBUs were assembled per day to assure a proper work flow.

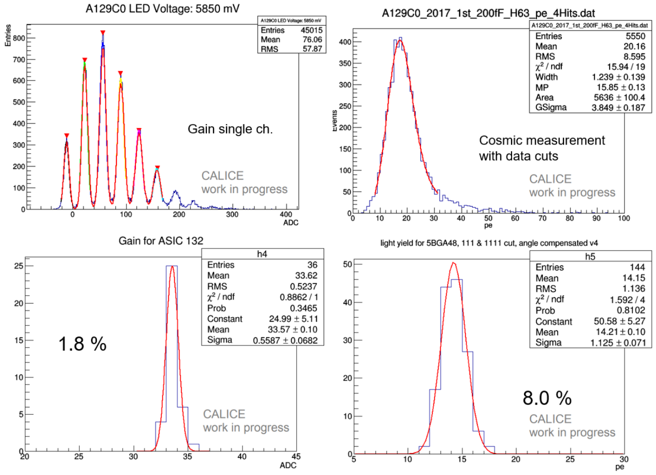

Fig. 6. Gain and light yield measurements of one channel (top row) and ASIC/HBU wise (bottom row) distribution

After curing usually four HBU boards were mounted in a cosmic ray test stand (s. Fig. 4). The test stand was equipped with a mechanical stack with ten equidistant slots. To reduce

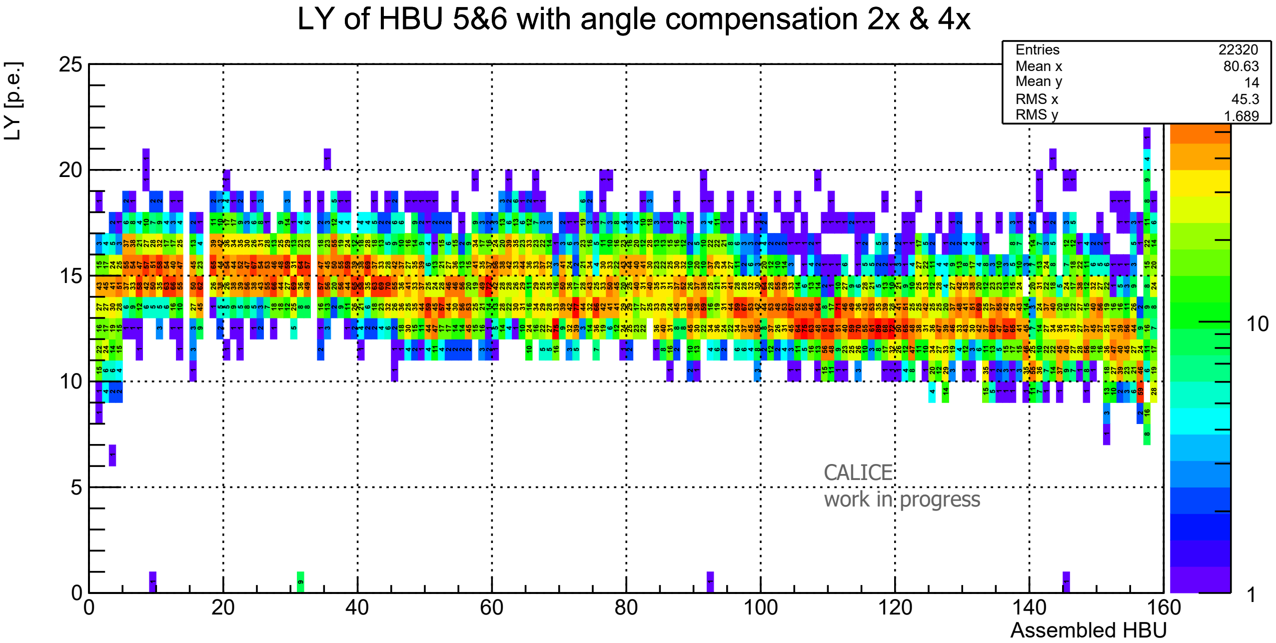

Fig. 5. 2D Plot of light yield measurements over assembly sequence

Fig. 7. Technological Prototype in test beam [5]

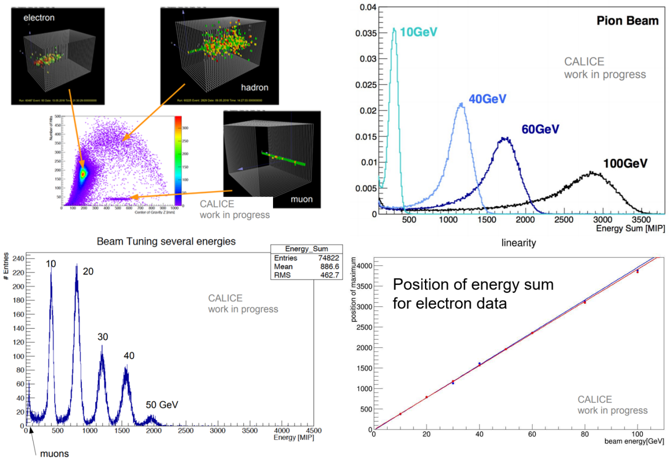

Fig. 8. Electron and pion data recorded at SPS with AHCAL technological prototype [17] [18]

heating of each layer, the HBUs were inserted while skipping one slot in between each other and with an alternating rotation, so that there were three empty slots between the interface boards (main heating source). The test stand was placed in a dark box to ensure light tightness, also an air circulation system was installed, so that the temperature remained stable. Special cables with shared voltage lines were created to save roughly 2/3 of the powering channels. The test stand was equipped with a total of 24 scintillator strips, 12 above the stack and 12 below, each strip read out by a photomultiplier. Each layer of strips was connected to discriminator with an OR output. Top and bottom OR outputs were connected to a logic AND unit and later on transformed to the correct trigger threshold of the Clock and Control Card (CCC) validation trigger input. So if a cosmic muon crossed the top and bottom trigger layer, a signal would be sent to the DAQ system and the events were recorded.

At first the cosmic ray runs were performed. Due to a slow heating up to operation temperature of the HBU boards (2-3 hours) a long term measurement was more useful to start with. A data cut on temperature stability was applied in the data analysis (max 1°C of difference between fluctuation and plateau value). Afterwards, a gain calibration using the embedded LED system of each HBU board and a pedestal run were started. The first step of the analysis was a pedestal estimation for each memory cell of each single channel due to its individual charge fluctuation. Then a channel wise gain calculation was applied using a multi gaussian fit over the single photon spectrum with pedestal correction (s. Fig. 6, top left. Bottom left shows the gain spread over one ASIC).

Only trigger validated events were used for the light yield analysis. Additionally the condition of exactly one hit on at least three HBUs was required to ensure a proper noise cancellation. Then the hit positions on each HBU board were used to calculate the incidence angle. With this result, a correction factor was calculated and applied to the recorded ADC values of each channel within this event. A proper translation to photo-electrons was computed with the pedestal correction and gain factor division.

In total 155 HBUs were measured in the cosmic ray test stand, 147 of which were classified as fully operational (all channels working), seven as acceptable (six with one strange behaving channel each, one with broken temperature sensors) and one HBU was rejected (eight strange behaving channels).

Observing the light yield's RMS value (12%) over all channels, it became apparent that this value is slightly higher than the usual light yield RMS of channels of one corresponding HBU (8-10%). Plotting the HBU light yield in order of assembly sequence (s. Fig 5), a negative slope is observed. Currently this trend is also investigated by the DESY group using test beam data.

After the boards were tested in Mainz they were sent to DESY for layer integration. Four boards were put in a 2 x 2 matrix cassette and they were connected to a set of readout boards. First tests with this layer configuration were performed with a second cosmic ray test stand built by the University of Tokyo and based at DESY. After that a test beam at DESY with 3 GeV electrons used as MIPs was performed. The mounting system was a so called "air-stack" (no absorber in between) and four layers were calibrated in parallel. This air stack was mounted on an automatic movable stage, so that the beam was directed sequentially in the center of each tile in the first layer. Due to the small radiation length of the material one could assume that most electron were going straight through the detector. One calibration run for four layers took around one day. After the data were recorded and checked, the layers were mounted at DESY in the detector stack (s. Fig. 7) [17].

IV. TEST BEAM ACTIVITIES AT SPS H2

The complete detector stack was moved to the CERN SPS H2 beam line and mounted on a movable platform. There were 2 test beam periods in 2018 for the technological prototype. The first one was in May with 38 Layers with 1.7 cm steel absorber ($\sim 4\,\lambda$) and wire chambers, trigger scintillators and Cherenkov detectors were used as beam instrumentation. In June an additional layer with larger tiles of 6 x 6 cm was included. The CMS HGCAL thick stack prototype [17] with twelve layers of one HBU each and 7.4 cm steel absorbers was implemented as a tail catcher. In addition to this, a single HBU was placed in front of the absorber stack as "pre-shower" detector.

The data taking ran very stably with an active temperature compensation. The test beam measurements confirmed that the number of dead channels was below one per mille. Data were taken with and without power pulsing. Muon data were recorded for calibration and electron data were taken in energy steps between 10 and 100 GeV, each with statistics between 200,000 and 400,000 events. Also, negative pion data were recorded with energies between 10 and 350 GeV and larger statistics (400,000 to 600,000 events per energy). In total tens of millions of events were recorded. Additionally further technical tests were performed.

The complete analysis of these test beam data is still ongoing, so all plots shown for this topic are preliminary (s. Fig 8). The beam composition is recognizable if all recorded electron beam events of one energy are plotted over the center of gravity in z (s. Fig 8 top left).

The energy sum distributions for different pion (s. Fig. 8 top right) and electron (s. Fig. 8 bottom left) energies show a good resolution. For electrons, the maximum of the peak positions of the energy sum shows a good linearity and just a small difference with and without power pulsing is visible (s. Fig. 8 bottom right) [17].

V. CONCLUSION

In summary, construction, commissioning and testing of the AHCAL technological prototype with 38 active layers were very successful. The quality assurance worked very well as shown by the total number of dead channels. Each HBU board was operational after the complete assembly and testing chain, so the yield of used resources was optimal. The production and testing was optimized for a constant and reliable work flow, so everything was handled in time and a successful data taking at the SPS was possible. The data look already quite promising and further analysis is ongoing.

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