The Compact Muon Solenoid Experiment

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Construction and first beam-tests of silicon-tungsten prototype modules for the CMS High Granularity Calorimeter for HL-LHC

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Abstract

The High Granularity Calorimeter (HGCAL) is the technology choice of the CMS collaboration for the endcap calorimetry upgrade planned to cope with the harsh radiation and pileup environment at the High Luminosity-LHC. The HGCAL is realized as a sampling calorimeter, including an electromagnetic compartment comprising 28 layers of silicon pad detectors with pad areas of $0.5 - 1.0 \text{ cm}^2$ interspersed with absorbers made from tungsten and copper to form a highly compact and granular device. Prototype modules, based on hexagonal silicon pad sensors, with 128 channels, have been constructed and tested in beams at FNAL and at CERN. The modules include many of the features required for this challenging detector, including a PCB glued directly to the sensor, using through-hole wire-bonding for signal readout and 5 mm spacing between layers - including the front-end electronics and all services. Tests in 2016 have used an existing front-end chip - Skiroc2 (designed for the CALICE experiment for ILC). We present results from first tests of these modules both in the laboratory and with beams of electrons, pions and protons, including noise performance, calibration with mips and electron signals.

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Construction and first beam-tests of silicon-tungsten prototype modules for the CMS High Granularity Calorimeter for HL-LHC

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ABSTRACT: The High Granularity Calorimeter (HGCAL) is the technology choice of the CMS collaboration for the endcap calorimetry upgrade planned to cope with the harsh radiation and pileup environment at the High Luminosity-LHC. The HGCAL is realized as a sampling calorimeter, including an electromagnetic compartment comprising 28 layers of silicon pad detectors with pad areas of $0.5 - 1.0 \text{ cm}^2$ interspersed with absorbers made from tungsten and copper to form a highly compact and granular device. Prototype modules, based on hexagonal silicon pad sensors, with 128 channels, have been constructed and tested in beams at FNAL and at CERN. The modules include many of the features required for this challenging detector, including a PCB glued directly to the sensor, using through-hole wire-bonding for signal readout and 5 mm spacing between layers - including the front-end electronics and all services. Tests in 2016 have used an existing front-end chip - Skiroc2 (designed for the CALICE experiment for ILC). We present results from first tests of these modules both in the laboratory and with beams of electrons, pions and protons, including noise performance, calibration with mips and electron signals.

KEYWORDS: Calorimeters, Detector design and construction technologies and materials, Data analysis

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1 Introduction

The CMS electromagnetic and hadronic endcap calorimeters will suffer irrecoverable radiation damage by the end LHC running in year 2023. To sustain much higher radiation and mitigate the extreme pile-up environment during operation at the High Luminosity-LHC (HL-LHC, 2025+), the CMS collaboration has decided to replace its current endcap calorimeters with a new High Granularity Calorimeter (HGCAL) [1]. This detector is a sampling calorimeter with silicon as the main active material. It includes both an electromagnetic (EE) section (28 silicon-tungsten layers) and a front hadronic (FH) section (12 silicon-steel layers), followed by a backing hadronic calorimeter (BH) with steel as the absorber and scintillating plastic as the active medium.

Prototype EE modules with hexagonal silicon pad sensors have been built and tested in beams at both FNAL and CERN. One of the primary goals of these beam-tests was to evaluate the basic module concept, featuring deep wire-bonding through holes in the PCBs to the silicon beneath. At the same time, the performance of these modules was studied, looking at the signal-to-noise ratio and the energy response, including linearity. In the beam-tests at FNAL, various configurations were built, culminating in a $15.3 X_0$ 16-layer system that was tested with incident 120 GeV protons (for calibration) and electrons with energies between 4 – 32 GeV. At CERN the largest system constructed used 8 layers, with up to $27 X_0$. Both pions and muons were used for calibration purposes, with electrons between 20 and 250 GeV incident to explore the calorimetric performance.

2 The HGCal EE prototype

2.1 Sensors

Fig. 1 shows one of the sensors used during the test beam campaign. These sensors are 128-channel hexagonal silicon devices made from 6" p-in-n silicon wafers manufactured by HPK¹. The physical

¹Hamamatsu Photonics, Hamamatsu, Japan

thickness of these sensors is $320\text{ }\mu\text{m}$ with a depleted thickness of $200\text{ }\mu\text{m}$. The cells on the sensor, except those on the edges², are hexagonal with an area of $\sim 1.1\text{ cm}^2$. There are two cells on the sensor known as calibration pads, that have an area of about 1/9th of the area of the full hexagonal cell. These cells facilitate MIP calibration after extreme irradiation, when the S/N of a standard cell may be too small to detect single MIPs efficiently. Since noise is proportional to the area of the cell (due to the cell capacitance), it will still be possible to see MIP signals in these calibration pads even at the end of HL-LHC operation.

Figure 1. A 128-cell silicon sensor used in the beam tests.

2.2 Modules

For the construction of the HGCal EE prototype, the silicon sensors and readout electronics were assembled into detector modules. Each module is a glued stack comprising a CuW (25% – 75%) base plate, a Kapton sheet, the silicon sensor and a PCB to host the wire bonds down to the sensor. A second PCB was plugged into connectors on this first PCB.

Figure 2. Module assembly for the test beam prototype

²Due to the overall hexagonal geometry, cells around the edges are either half-hexagons or other shapes

The function of the copper-tungsten plate is threefold: it supplies the mechanical rigidity to the module; it provides a thermal pathway to the copper cooling plate that supports the module, and it is part of the calorimeter absorber. It has a coefficient of thermal expansion close to that of silicon. The Kapton sheet provides the bias voltage to the back of sensor through wire bonds from the PCB. Fig. 2 shows the various stages of this assembly, starting from the CuW baseplate glued to the Kapton and then to the sensor. A passive PCB is glued to the silicon sensor and electrical connections are made through wire bonding. These connections are routed through the two connectors on this PCB to the top board. This top board has two 64-channel SKIROC2 ASICs [2], which are used to amplify, digitise and readout the signals from the cells. A complete assembled module is shown in Fig. 3 with double layer PCB readout. This design has been chosen for flexibility so that the top board can be changed to evaluate different ASIC designs. These SKIROC2 chips have been developed by the OMEGA group for the CALICE experiment for the ILC [3] with a shaping time of 200 ns and two 12-bit ADCs with programmable (high and low) gains. This ASIC is an intermediate step towards the final front-end design for the CMS HGCAL. The overall thickness of a module depends on the thickness of the CuW plate and is between 5 and 6 mm.

Figure 3. Complete assembled module with double PCB layer readout.

2.3 Mechanics

The HGC EE modules are attached to 6 mm ($0.4X_0$) thick copper plates as shown in Fig. 4. These plates have embedded channels to allow the flow of a cooling fluid, although this feature was not used in 2016. The cooling plates can support two modules at a time on either side. This feature has been used at FNAL test beam where the double sided structure of the modules placed on each side of the Cu plate was repeated eight times to obtain a 16-layer configuration. A flexible mechanical support system was built, incorporating a "hanging file" design for easy insertion of modules attached to cooling plates and absorber plates. The copper plates, with modules attached, were interspersed with tungsten absorber plates to form the calorimeter stack. Given the flexibility of the support structure, various configurations have been checked to sample electromagnetic showers at different longitudinal depths. At FNAL, the 16-layer calorimeter had a total depth of $15 X_0$. The thicknesses of the W/Cu and tungsten plates were chosen so that the detector modules were

Figure 4. Module attached to the copper cooling plate. It also shows the cables that carry data, control and low voltage along with the high voltage connections.

at depths in radiation lengths of 0.6, 1.4, 2.0, 2.8, 3.4, 4.3, 5.1, 6.1, 6.9, 7.9, 8.7, 10.1, 11.3, 12.7, 13.9 and 15.3 X_0 , for a normally incident particle. Similarly, at CERN two 8-layer configurations were constructed, to sample the shower maximum (6-15 X_0) and full (5-27 X_0) shower. Fig. 5 is a photograph of the 8-layer stack of modules and absorbers placed inside the support structure in the 27 X_0 configuration at CERN. Also shown is a schematic representation of the system. The beam enters from the left.

Figure 5. 27 X_0 configuration with 8-layer system at CERN. Top: photograph of the hanging-file structure, with the copper cooling planes (mounted with modules) and tungsten plates evident. The schematic shows that some modules were mounted upstream of the cooling plates, whilst most were downstream.

3 The Data Acquisition System

The Data Acquisition system (DAQ) has been designed to be scaleable and affordable, using commercially available components mounted on custom PCBs. During a so-called "beam spill"³ data from each sensor module are transferred, via an "elbow board" (to make a 90 degree transition with Kapton cables) to an "FMCIO" incorporating an Artix FPGA. A pair of FMCIOs are mounted

³a period of several seconds every minute when beam particles are incident on the detector

on "DDCs" (dual daughterboard carriers), which also provides power to the front-end electronics through Kapton cables (which also carry the control and data signals). Between beam spills the DDCs transfer the data stored in the FMCIOs to a commercial Zedboard⁴ via HDMI cables and a custom "ZEDIO" PCB that allows the Zedboard to take data from up to 14 DDCs, i.e. 28 modules. The Zedboard then transfers the complete set of data from one spill from all modules to a PC through a standard ethernet connection. The full DAQ chain is shown in the photograph in Fig 6.

Figure 6. The DAQ hardware components for the 2016 HGCAL beam tests. The yellow arrows show the data flow.

4 Results

Calibration was performed using incident 120 GeV protons (FNAL) or 125 GeV pions (CERN). These provided effective "MIPs" (minimum ionising particles) in the modules. MIP signals have also been seen from muons passing through the detector, as demonstrated in Fig. 7, where a muon traverses the 8 layer configuration of the module stack at CERN.

Figure 7. Event display showing the passage of a muon through the 8-layer system at CERN.

⁴<http://zedboard.org>

The MIP signal has been modelled with a Gaussian convoluted with a Landau distribution; the pedestal distribution is modelled with a simple Gaussian function. Fig. 8 shows the number of ADC counts observed in the central channel being hit by a pion beam, giving a most-probable value (MPV) of ~ 17.9 ADC counts with a noise of ~ 2.4 ADC counts, leading to a signal-to-noise ratio of about 7.5 for single particles. This calibration procedure was performed for all cells struck by particles (defined by upstream trigger scintillators.). ADC counts per MIP was found to be dependent on the SKIROC2 chips but stable within a SKIROC2 chip. A systematic uncertainty of 1.1% was found due to the change in range of the fit performed. A conservative systematic error of 5% has been considered on ADC counts per MIP from a given SKIROC2 chip.

Figure 8. ADC-count distribution of the central channel in the first layer seen by the pion beam.

Using the ADC-to-MIP calibration values, the response of the signals from electrons can be expressed as a number of MIPs. Fig. 9 is an event display showing the evolution of a 250 GeV electron shower through the 8-layer stack at CERN, showing the shower development with depth. It can be clearly seen how the transverse size of the shower increases until the shower maximum and how it dies out as the depth goes beyond the shower maximum. Various algorithms are being developed to reconstruct the energy deposited by the particle as it passes through each layer and produces the shower. An initial study is being done to look at how dynamic clustering algorithm performs over the clustering that seeds from highest energy cell.

The energy deposited in each layer from incident electrons is summed for all cells above 2 MIPs in order to obtain the total energy. Then, a Gaussian function is fit to the core of this distribution. Fig. 10 shows the fitted mean as a function of depth for the various configurations and electron energies explored at FNAL and CERN. This effectively shows the longitudinal shower profile; the shower maximum position can be seen to increase as the electron energy increases, as expected. Here, a flat offset of $\sim 15\%$ has been observed between data and simulation. In simulation, the beam line elements upto ~ 20 m have been included. The beam is simulated with the same momentum spread and with the same vertex smearing as in the data. The arrangements have been simulated as close as possible to the original setups at FNAL and CERN. Distances between various elements

Figure 9. Event display of a 250 GeV electron passing through the 8-layer stack at CERN.

have been measured to a precision of 1 mm. Thickness of various elements were measured with high precision, especially the tungsten absorbers, which are uniform to better than 0.05mm.

Figure 10. The energy deposited by electrons in all cells is plotted as a function of depth at a) FNAL (15 X_0), b) CERN (15 X_0) and c) CERN (27 X_0) configurations.

From the energy deposited in a given layer, the total energy of the incident particle is reconstructed using the sampling fractions for the different configurations and a comparison is then made with respect to the incident beam energy. Fig. 11 shows the electron response from the detector as a function of beam energy and its comparison between data and simulation. Simulation has been tested with three different shower models described by three different physics lists (FTFP_BERT_EMM, QGSP_FTFP_BERT and QGSP_FTFP_BERT_EML)⁵ in GEANT4 [4]. FTFP_BERT_EMM has been found to give the best resolution agreement with data with a flat 15% discrepancy in energy scale. QGSP_FTFP_BERT_EML gave the best agreement in overall energy scale whereas QGSP_FTFP_BERT has been found to give intermediate results between the above two mentioned

⁵http://geant4.cern.ch/support/proc_mod_catalog/physics_lists/referencePL.shtml

physics lists. More studies are ongoing to study shower shape comparisons between data and MC to better understand and tune the simulation.

Figure 11. Electron response as a function of beam energy compared with the simulation (staggered here to show the points clearly)

5 Summary

The construction and operations with first 16 HGC EE prototype modules has been successful. Many lessons have been learnt through the test beam activities. The proposed design of closely stacked modules with the deep wire bonding through holes has worked well. Since the copper cooling plates on which these modules are mounted can hold two modules at a time on either side, this was used to build a 16 layer configuration at FNAL. Given the flexibility of the support system built with "hanging file" design, it gave access to configure and test electro-magnetic shower development at various depths with different configurations in the system. This is the feature that was used at CERN to test 8-layer calorimeter stack with two different configurations of the absorber plates, one to sample the shower maximum ($6-15X_0$) and another to sample the tail of the shower ($5-27X_0$).

Concerning the performance of these modules, MIP signals have been observed in all the layers well separated from the noise. For calibration, protons of 120 GeV (FNAL) and pions of 125 GeV were used. ADC counts per MIP were found to be dependent on the SKIROC2 chip but stable within the chip. Electron response has been studied as a function of depth and beam energy and comparisons have been made between data and simulation. Simulation has been tested with three different shower models, wherein FTFP_BERT_EMM gives the best resolution agreement with data with a flat 15% discrepancy in energy scale. More detailed analyses of both sets of test beam data at CERN and FNAL are still ongoing to validate the best simulation with shower shape comparisons.

Since the tests in 2016 involved double layer PCB readout with SKIROC2 chips, the next step is to test variant versions of these chips (SKIROC2-CMS) better matched to CMS needs with a

shaping time of 25 ns on a single PCB as a stepping stone toward the final ASIC for HGCal. The complete test beam prototype is planned to be tested next year in 2017 with 28 layer EE (6" silicon modules), 12 layer FH (7×6" silicon modules) and a CALICE AHCAL [5] prototype for BH in order to study the performance of the full system that is proposed for the HL-LHC upgrade.

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