CHEF Conference in Lyon 2017

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

On behalf of the CMS Collaboration

Thorben Quast

06 Oct 2017
Endcap calorimeters must be upgraded for HL-LHC

Calorimeters designed for radiation dose equivalent to $500\text{fb}^{-1}$.

- Replacement of CMS’ complete endcap calorimeter during HL-LHC upgrade.

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**HL-LHC Conditions**

Current design: $10^{34} \text{cm}^{-2} \text{s}^{-1}$

- Increased pileup

Current design: $10^{34} \text{cm}^{-2} \text{s}^{-1}$

HL-LHC: $10^{35} \text{cm}^{-2} \text{s}^{-1}$

- Radiation hardness

Thorben Quast - 06 Oct 2017
Key parameters:
- $1.5 < |\eta| < 3.0$
- $\sim 600 \text{ m}^2$ silicon
- $\sim 500 \text{ m}^2$ scintillator
- $\sim 6 \text{ M Si-channels, } 0.5$ and $1 \text{ cm}^2$ cell-size

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The other four HGCal related talks at CHEF 2017

3. “Large-Area Silicon Detectors for the CMS High Granularity Calorimeter”, Elias Pree (06 Oct at 10:00).
Key parameters:
- $1.5 < |\eta| < 3.0$
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→ This talk: HGCal beam tests

✓ Successful series of beam test of CE-E part prototype at FNAL and CERN in 2016.

_extended setup including CE-H (Si) parts and CALICE AHCAL under test this year.

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3. “Large-Area Silicon Detectors for the CMS High Granularity Calorimeter”, Elias Pree (06 Oct at 10:00).
Module construction for the beam tests

- Module assembled as glued stack of **baseplate**, **Kapton**, **Si sensor** and **PCB**.

**Si sensor**
- 6” silicon sensors:
  - n-type, 128 cells.
  - 1 cm² cell-size.
  - 300 μm depleted region.

**baseplate**
- EM: CuW
- Hadronic: Cu

**Kapton**
- Gold plated.

**PCB**
- **Skiroc2-CMS** ASIC, 64 ch., 4 chips/module
- Developed for CALICE and adjusted for CMS requirements.
- Skiroc2 ASIC in 2016, 2 chips/module.
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Thorben Quast - 06 Oct 2017
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Hanging file design for flexible insertion:
- Structure for CE-H(Si)
- Module screwed to Cu cooling plate

Copper cooling plate

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Tests of silicon sensors at CERN

- Perform IV and CV measurements on probe station at FNAL and CERN to characterise sensors used in test beam.

Probe-card measurement in probe station @CERN

- Contact all cells with spring-loaded pins.
- All neighbour cells biased.
- Automatic switching between cells through custom designed switching unit.

Average full-cell leakage current

! More on the HGCAL sensors by Elias Pree in his talk “Large-Area Silicon Detectors for the CMS High Granularity Calorimeter” today at 10:00.
Setup and results with the CE-E prototype in 2016
Tests of CE-E with beam setups at FNAL and CERN

- Common effort between CERN and FNAL in test beams 2016 to test a CE-E prototype.

**Fermilab**
- Up to **16 HGC modules** tested.
- **Electron** beam with **4-32 GeV**.
- **0.6-15 X₀ tungsten** absorber configuration.
- 120 GeV protons.

**CERN**
- Up to **8 HGC modules** tested.
- **Electron** beam with **20-250 GeV**.
- **6-15 X₀ & 5-27 X₀ tungsten** absorber configurations.
- 125 GeV muons and pions.
Main goals for test beams 2016:

1. Proof of concept of the proposed design with a preliminary chip (Skiroc2).
2. Comparison of results to simulation.

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- 125 GeV muons and pions.

+ detailed GEANT IV based simulations for both setups
Electron induced showers visualised in 2016

**Fermilab:** 32 GeV electron passing through 15 $X_0$.

**CERN:** 250 GeV electron passing through 27 $X_0$. 
Main results from 2016 are documented for the technical design report and are targeted for publication in NIM/JINST:

- Calibration, linearity, shower shapes and energy resolution of 8-16 modules.
- Position resolution of incident electrons as a function of their energy.
- Precision timing results of the full module at CERN.

![Energy resolution](image1.png)

![Longitudinal shower shape](image2.png)

![Precision timing results](image3.png)
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Overall agreement between data and simulation within ~percents.
➡ Basic validation of the simulation of the CE-E part.
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Towards the extended setup in 2017
High ambitions for beam tests in 2017

Goal as defined at beginning of 2017: Prototype with 112 6”-modules
• 28 layers with one module in CE-E, 12 layers with 7 modules in CE-H (Si).
• Gradual upscaling of the system towards a full CE- E+H (Si)+H (scint.) prototype.

➡ Extend and consolidate measurements from 2016.
➡ Measurements on hadron-induced showers with HGC modules.
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Revised strategy:
- Period 1: 8-15 May
  - One CE-E Module.
- Period 2: 31 May-7 June
  - As many modules as possible.
- Period 3: 12 July-19 July
  - CE-E + CE-H (Si) + AHCAL

• Less layers.
• Less modules per layer.

Original ambition: CE-E, CE-H (Si), CE-H (scint. +SiPM) (CALICE AHCAL prototype)
Realised prototype:
Skiroc2-CMS is the new readout chip in 2017

- Skiroc2-CMS is based on the CALICE Skiroc2.
- Shapes, amplifies and digitises signals from the silicon sensors.
- 64 channels.
- **13 SCA rolling analog memory** with 40MHz clock.
  - Overwrites every 13x25ns.
- Four quantities read out: Low- and High gain, “Time over Threshold” (ToT) and “Time of Arrival” (ToA).
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- 13 SCA rolling analog memory with 40MHz clock.
  - Overwrites every 13x25ns.
- Four quantities read out: Low- and High gain, “Time over Threshold” (ToT) and “Time of Arrival” (ToA).
- Larger pulses stay longer over some threshold.
  - ToT is a measure of the signal pulse amplitude.
  - ToT can be used for energy reconstruction when low gain is saturated (left plot).

*left: Relation of HG-LG and LG-TOT with test pulses in the lab.*
New DAQ hard- and software in 2017

HGCAL Data Flow

- **Readout boards** control hexaboard and read data.
- Multiple hexaboard are connected to one readout board.
New DAQ hard- and software in 2017

**HGCAL Data Flow**

- Network switch
- Ethernet 5m cat 6a 10 Gbps
- PC
- Temporary data storage
- For DQM
- Ethernet 5m cat 6 1 Gbps
- RPI3
- Master ORM
- Slave ORM
- Slave ORM
- Slave ORM
- Slave ORM
- Readout board
- BV distribution (LEMO)
- HDMI cable ~2m (signal & SV)
- AGW28 or 26
- Bias voltage (LEMO ~2m)
- Interposer board
- Bias voltage (wires)
- MAX10
- Hexboard
- BV input (SMA)

**DAQ software** based on EUDAQ1 and IPBUS.

- Producers for:
  - HGCAL
  - AHCAL
  - Wire Chambers
- Built-in **DQM**.

**Readout boards** control hexaboard and read data.

- Multiple hexaboard are connected to one readout board.

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New DAQ hard- and software in 2017

**DAQ software** based on EUDAQ1 and IPBUS.

- Producers for
  ✓ HGCAL
  ✓ AHCAL
  ✓ Wire Chambers
- Built-in **DQM**.

### Positive aspects:
- The DAQ is cheap and scalable.
- Reuses existing components from CMS: The Optical Readout Modules (ORMs).
- Simple Raspberry PIs as interface to computers.
- Readout using IPBUS protocol works well and reliably.

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**HGCAL Data Flow**

- **Readout boards** control hexaboard and read data.
- Multiple hexaboard are connected to one readout board.
Multi-module setup with CALICE AHCAL in July

- CE-E part: Hanging file structure with lead absorber.
- CE-H (Si) part: Hanging file structure with iron absorber.
- Data taking together with CALICE AHCAL prototype as CE-H (scint.+SiPM) part.

Total detector: ~9.4 $\lambda_0$

July 2017 Setup at CERN SPS

"Prototype tests for a highly granular scintillator-based hadron calorimeter" by Felix Sefkow.
Multi-module setup with CALICE AHCAL in July

- CE-E part: Hanging file structure with **lead** absorber.
- CE-H (Si) part: Hanging file structure with **iron** absorber.
- Data taking together with CALICE AHCAL prototype as CE-H (scint.+SiPM) part.

![Image](image_url)

- 2 or 3 modules in the **CE-E** part.
- Limited number of layers: 4 instead of 12 in **CE-H (Si)**.
- Only 1 or 3 modules per layer instead of 7.
Hadron and electron showers are seen

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O(10^6) events are simulated

- GEANT4 based simulation of the prototype using CMSSW.
  - “FTFP_BERT_EMM” physics list.
- CE-E section: 14 layers of Pb absorber and 2 sensitive silicon layers.
- CE-H (Si) section: 12 layers of Fe absorber and 4 sensitive silicon layers.
+ Simulation of AHCAL.
Analysis of the HGCal July Data

First results are shown for:

- MIP signals
- Energy sums
- Shower shapes
Full HGCal reconstruction workflow

ORM data
~10GB/22k events

UnpackRaw

Skiroc2CMS
~1.6 GB/22k events

Pedestals

RawHits
~0.9 GB/22k events

Common Mode Noise

Skiroc2CMS
~1.6 GB/22k events

UnpackRaw

ProduceRawHits

ProduceRecHits

HG/LG/TOT Correlations

RecHits
~0.1 GB/22k events

GainCalibration

RecHits data format (~100MB/22k events):

- Pedestals and common mode noise is subtracted.
- CMS Preshower Pulse fit is performed to the time samples.
- Switches between HG/LG/TOT —> one energy per hit.
- Location of each hit in the detector.

Input files
Reconstructed files
Meta files

Reconstruction tasks
Meta tasks
Visualisation/Analysis tasks

Inspection of output by analyst

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MIP signals are seen despite high noise

- MIPs from parasitic muons from experiments further upstream in the area.
- Large spread $\rightarrow$ Large amplitude of noise peak.
  + Width smears into the expected MIP signal for most channels!
  - Event selection with wire chamber information.

- Procedure similarly successful for other channels.
  - Different data streams can be synchronised & MIP signal $\sim$50 ADC counts.

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Energy sums - We do have a calorimeter

- Pedestal and common mode noise are subtracted.
- Sum of fitted pulse amplitudes over all cells in all layers. No weighting.
- Preliminary LG-TOT is included.

Simple cuts:

- Electron suppression: \( \frac{E_{CE-E}}{E_{CE-H(Si)}} < 0.03 \)
- Inhibit noise contribution: 4 MIP cut on cells prior to summing.

Much room for improvement:

- Smarter selection of cells (clustering)
- \( \frac{dE}{dX} \) weights per layer

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Transverse shower size - Data vs. sim.

Definitions:
• E7: Sum of reconstructed energies of cell with most energy plus of one ring around it.
• E19: Sum of reconstructed energies of cell with most energy plus of two rings around it.

E7/E19 ~ transverse spread of the shower at a given sampling depth. E7/E19 is computed for each layer in an event.

**E7/E19 in data and compared to simulation** \((E_{CE-E}/E_{CE-H(Si)} < 0.03)\)

- No obvious disagreement for most layers “out-of-the-box”.
- Discrepancies to simulations are under investigation.
Outlook: Combination with the AHCAL data

• Beam hits AHCAL centrally.

• AHCAL has operated well.
  ➡ Good data quality.

Offline analysis combined with HGCal data soon.

300 GeV π

AHCAL Online Analysis:
• minimal selection: =>3 hits
• very preliminary calibration
Summary

- CMS-HGCal TB related results with the CE-E prototype with data recorded in 2016 are summarised for publication.

- The upgraded CMS-HGCal prototype including FH-part and CALICE AHCAL has been tested with electrons and pions at CERN this year.

- Setup had to be reduced compared to the initial plan for the 2017 tests.

- Data taking in 2017 has been successful. Calibration is ongoing. Good quality of data. Comparison to simulation has started.

- Now, prototype is continuously extended and more tests are coming!
Additional material
Hanging file design for flexible insertion of absorbers and modules on cooling plates.
Purpose of a good timing resolution:
Use precision timing of EM shower for pileup energy removal.

- Reduction of impact of pileup.

Timing test with 300 μm HGC layer with fast readout:

Results with 32 GeV e⁻ test beam:

- Precision around 16ps.
- Scaling with S/N.

Energies up to 250 GeV at CERN last November:

- Analysis ongoing.
- Expect better resolution with higher S/N, usage of multiple cells.
A machine learning based energy reconstruction

- Explore full content of features in the data in terms of energy reconstruction with a convolutional neural network (CNN).

Training on simulated data with 1-300 GeV electrons.
Evaluation on simulated and real test beam energy binned electron samples.

- Implementation in Tensorflow v1.0.1
- Minimisation of \( \chi^2 \) cost function

**2016 CE-E Prototype Energy Resolution**

**Simulation**

- CNN with best resolution
- Benchmark reconstruction
- CNN based reconstruction

**TB 2016**

- CNN performance not recovered in data.
One module test in May 2017

- One module mounted on Cu cooling plate and mounted on plexiglas support.
  - Two scintillators as triggers.
  - 8 $X_0$ upstream Pb absorber.

Electron signals seen in the module on the 1st day.

Contamination with pions this May.

Comprehensive C++ based analysis framework was implemented.
Analysis of one module May 2017 data

- Comprehensive C++ based analysis framework is developed.
- Allows for a variety of studies with the data.

Energy reconstruction:
Low gain becomes non-linear above 50 GeV.
Longitudinal shower size - Data vs. sim.

Definitions:
• ELayer: Sum of reconstructed energies in a given layer.
• Evis: Total sum of reconstructed energies over all cells in the calorimeter.

ELayer/Evis for many layers —> Longitudinal shower profile.

- No obvious disagreement for most layers “out-of-the-box”.
- Discrepancies to simulation, especially for EE-2, are under investigation.

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