Beam tests for CMS High Granularity Calorimeter Prototypes at CERN and DESY 2018

Thorben Quast

for the CMS HGCal System Test Group
The CMS HGCal upgrade in a nutshell

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

**Key parameters:**
- $1.5 < |\eta| < 3.0$
- $\sim 600 \text{ m}^2$ **silicon**
- $\sim 6 \text{ M Si-channels, 0.5 and } 1\text{cm}^2$ cell-size
- 50ps timing
- $\sim 500 \text{ m}^2$ scintillator

**Radiation hardness**

**Increased pileup**

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

HL-LHC: $10^{35} \text{ cm}^2 \text{ s}^{-1}$
Shower sampling: HGCal prototype modules

Modules assembled as glued stack of baseplate, Kapton®, Si sensor and PCB:

- **baseplate**
  - CuW
  - Cu

- **Kapton®**
  - Gold plated

- **Si sensor**
  - 6" silicon sensors:
    - n-type, 128 cells
    - 1 cm² cell-size
    - depletion: 200 & 300μm

- **PCB**
  - Skiroc2-CMS ASIC, 64 ch., 4 chips/module
  - Developed for CALICE (Skiroc2) & adjusted for HGCal requirements

- **Copper cooling plate**

- **1-module layer in CE-E**

- **7-module “daisy” layer in CE-H-Si**

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Passive material

- **CE-E:**
  - material: Pb, W, Cu
  - thickness: 5-6 mm
- **CE-H-Si:**
  - material: Fe
  - thickness: 4 cm
  - weight: O(1000kg)

Hanging file design for flexible insertion:

October 2018 - Configuration #2

CE-H-Si

CE-E

42 cm, 26 X₀, 1 λ

70-80 cm, 3-4 λ

few hours!

October 2018 - Configuration #3

CE-H-Si

CE-E

42 cm, 26 X₀, 1 λ

70-80 cm, 3-4 λ
Busy 2018: Three CMS HGCal test beams

First tests with **Skiroc2-CMS** ASIC

- @ **DESY**
  - 3 modules
- @ CERN’s **SPS**
  - full CE-E: 28 modules
- @ CERN’s **SPS**
  - full prototype: 94 modules

**N. Akchurin et al 2018 JINST 13 P10023**

Begin of “serious” beam tests with Skiroc2-CMS ASIC

- March 2018
- June 2018
- October 2018
First HGCal beam test at DESY in March 2018

- 1.6-6 GeV positrons
- Only 1+2 HGCal modules
- DATURA beam telescope for precise tracking with O(μm) resolution
  - 1 module: mounted on moving pi-stage
  - 2 modules: 2-layer “calorimeter” (W absorbers in front)
- Trigger: 2x scintillators
- Synchronisation: EUDET TLU

Positive experience: First HGCal beam test at DESY
Double-sided cassettes with two modules on CuW baseplate on Cu plate and integrated cooling
Second beam test at CERN’s SPS in June 2018

- Double-sided cassettes with two modules on CuW baseplate on Cu plate and integrated cooling
- Full 28-layer CE-E only setup

- e, μ up to 150 GeV
- Trigger: 2x scintillators in front of CE-E
Second beam test at CERN’s SPS in June 2018

- **Double-sided cassettes** with two modules on CuW baseplate on Cu plate and integrated cooling
- **Full 28-layer CE-E only setup**
- e, μ up to 150 GeV
- Trigger: 2x scintillators in front of CE-E
- Active temperature control by chiller
- Nitrogen flux to dry setup
- Temperature & humidity sensors
- HV/LV currents monitored
- Delay wire chambers

▶ **System getting serious and mature**

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Difficult electron beam conditions in June 2018

- Especially at higher energies:
  - 99% purity < 80 GeV;
  - 10% for 150 GeV

- Also seen by CALICE AHCAL before
- Requires cleaning of data
- Provides interesting data set for pattern recognition/clustering
Third beam test at CERN’s SPS in October 2018

- **28-layer CE-E setup from June**
- **+12-layer CE-H-Si setup (94 modules)**
  - 3 configurations tested
  - environmental control as in June
  - Delay Wire chambers
  - Threshold Cherenkov counters
  - MCPs
  - CALICE - AHCAL

- **e, μ, hadrons up to 300 GeV**
  - Trigger: 2x scintillators in front of CE-E
  + 1x additional (veto) behind CE-H-Si

➡ **First large-scale test of 0(100) HGCal modules**
HGCAL = Imaging calorimeter

October 2018 run 517 - event 1:

250 GeV π⁻
Variety of hadron shower signatures

October 2018 run 517 - event 1:
250 GeV π⁻

October 2018 run 517 - event 2:
250 GeV π⁻

October 2018 run 517 - event 3:
250 GeV π⁻

October 2018 run 517 - event 101:
250 GeV π⁻
Electron “MIPs” at different bias voltages

Energy sum [MIPs]

Number of hits in HGCal

Synchronisation with CALICE-AHCAL

October 2018 run 517 - event 30:
250 GeV π⁻
Main objectives for beam tests:

- Technological **prototyping** of the detector modules
- **First experience** with a FE ASIC with components of the ultimate (HGC)ROC in beam conditions: ADC, ToT, ToA
- **Physics performance** of the CE-E and CE-H silicon / scintillator parts
- Check **agreement** with **simulation**
Main objectives for beam tests:

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Lesson learnt: Beam characterisation helpful
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Rest of this talk
MIMOSA26 chips

- 576 x 1152 pixels
- 10.6 x 21.2 mm$^2$
- 18.4 $\mu$m pitch
- 100 $\mu$s rolling shutter

✓ EUDAQ1 readout provided

Reconstruction:

Corryvreckan (v0.6)
Telescope plane

Material: e.g. bare PCB

Cluster

kink angle & impact position
PCB tomography

Tomography of selected areas on the PCB

Tomography of the full PCB

- PCB thickness = 1 mm Aluminium = 1% $X_0$
- ASIC thickness = 3 mm Aluminium = 3% $X_0$

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Tracking with DWCs @ CERN

DWCs in CERN’s North Area H2 for the October 2018 test

ext. A B C D E

2.6m 0.4m 2.0m 18.2m 7.2m 1.6m

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Sub-mm pointing resolution with these DWCs

Tracking with DWCs @ CERN

DWCs in CERN’s North Area H2 for the October 2018 test

Unbiased residuals at DWC D

before alignment

after alignment

CMS work in progress
CERN H2 October 2018
200 GeV μ

width ~ 640μm

500μm pointing resolution
DWC-tracking helpful for our analyses

Hit selection for MIP calibration

Search for “holes” in the modules

Pre-showering filtering

October 2018 run 722 - event 2: 200 GeV μ⁻

CMS work in progress

October 2018 run 722 - event 2: 200 GeV μ⁻

noisy hits

DWC track

CMS work in progress

10 GeV e⁻

4 DWCs&chi²<10, 32%

4 DWCs, 54%

no selection, 100%

pre-showered electrons
Summary

HGCal beam tests in 2018
1. March, DESY: First HGCal beam test at DESY
2. June, CERN: Towards a mature system
3. October, CERN: First large-scale tests, O(100) modules

Beam characterising detectors incorporated
✓ DATURA telescope: precise tracking
✓ Delay wire chambers: tracking
✓ Cherenkov detectors: hadron ID
✓ MCP: O(10ps) t₀ reference

★Good data quality
➡ Datasets to be analysed now...
Challenge:
Experimental condition: π-beam != 100% π
+ calorimeter response depends on hadron type

≈ 300 GeV beam = pions

≈ 300 GeV beam = protons
**Challenge:**

Experimental condition: $\pi$-beam $\neq$ 100% $\pi$  
+ calorimeter response depends on hadron type

Hadron ID with 2 upstream XCETs

- Good:
  ~0% fake-rate below threshold

- Not so good:
  Tubes only 2m long  
  average #photo-electrons < 1

- we saw low efficiency:  
  ~2-10% @ $\Delta P=0.3$ bar

- Not yet clear if and how to be used for our analyses...
Use of MCPs for $t_0$ measurement

**Skiroc2-CMS** designed to provide timing resolution of 50ps

- 2 MCPs for O(10ps) $t_0$ measurement installed in front of CE-E

**Digitised MCP Waveform**

- waveform analysis for many events

- **MCP-t$_0$ correlation to HGCal ASIC timing**

- **Correlation:** good

- **Facilitated:** Timing calibration
- **Possible:** Unbiased measurement of timing resolution

**CMS work in progress**

CERN H2 October 2018
Backup
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- Check **agreement** with **simulation**
- *(what ever challenges we encounter!)*

High noise level in 2017 prototypes
Tomography calibration

Reference:
- Aluminium plates of various thicknesses
- one tungsten plate (=53.4 mm Al)
DATURA Telescope - HGCal correlation

Module 53, chip 0, ch. 18

DESY TB March 2018:
run 1174, 6GeV e⁺, 200V

Module 53, chip 0, ch. 24

DESY TB March 2018:
run 1174, 6GeV e⁺, 200V

Module 53, chip 1, ch. 44

DESY TB March 2018:
run 1174, 6GeV e⁺, 200V

Module 53, chip 2, ch. 36

DESY TB March 2018:
run 1174, 6GeV e⁺, 200V
Delay wire chambers @ CERN’s North Area

Tracking

Tracking with DWCs @ CERN

![Delay wire chamber image]

10cm

10cm

CATHODE

impinging particle

up

down

T_{Down}

Straight-forward position reconstruction:

Y-Position = (T_{Down} - T_{Up}) \times \text{slope}_y + \text{offset}_y

X-Position = (T_{Left} - T_{Right}) \times \text{slope}_x + \text{offset}_x

Readout via TDCs

<table>
<thead>
<tr>
<th>PC</th>
<th>VME Crate</th>
<th>NIM Crate</th>
<th>Delay Wire Chambers</th>
</tr>
</thead>
<tbody>
<tr>
<td>TDC-EUDAQ producer</td>
<td>VX2718 controller</td>
<td>LEMO cables</td>
<td>DWC E</td>
</tr>
<tr>
<td></td>
<td>VME Bus</td>
<td>coaxial cables</td>
<td>DWC A</td>
</tr>
<tr>
<td></td>
<td>v1290 TDC</td>
<td></td>
<td>DWC D</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>DWC ext.</td>
</tr>
</tbody>
</table>

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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).

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.*
**Gain calibration**

High Gain $\rightarrow$ Low Gain $\rightarrow$ TOT
- May use LG directly (MIPs in LG)
- TOT Pedestal must be taken into account

**Time calibration**

TOA [ADC] $\rightarrow$ time [ps]
- Data driven approach (exploits: asynchronous beam wrt to clock)
  - promising first results!

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**Data**

- **rechit_energy_noHG**
  - 0, 200, 400, 600

- **rechit_amplitudeLow**
  - 0, 500, 1000, 1500, 2000

- **reconstructed energy (no HG) [MIPs]**
  - 100 GeV $e^-$
  - module #32, ASIC 1

- **LG-TOT transition continuous**

- **70 ps cell-cell time resolution**

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**Graphs**

- **LG-TOT transition**
  - Continuous transition

- **Calibrated time of arrival between neighbouring cells [ns]**
  - CMS work in progress
  - CERN H2 June 2018

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TOA measurement principle

- Early arrival: TOA high
- Late arrival: TOA low

ASIC-level

Clock Pulse exceeds a threshold ➔ Trigger

Global Counter

N

N+1

TOA Ramp ➔

TOA ADC

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VME DAQ during the beam test

- **2x TDC**: CAEN v1290
  - 24 input channels = up to 6 DWCs
  - 2 input channels = 2 XCET
  - 2 input channels = veto & coincidence of scintillators

- **1x digitiser**: CAEN v1742
  - 1024 samples up to 5GHz
  - fast trigger with low latency (40ns)
Event synchronisation

\[ \Delta t := \text{time between two events} \]

Data streams are synchronised \( \rightarrow (\Delta t_1 - \Delta t_2) \sim 0 \)

HGCal vs. DWC (etc.): offset at beginning of each run

Example: HGCal - DWC synchronisation

Run 1033 with wrong offset

CERN H2 October 2018

CMS work in progress

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“Calorimeter” configuration at DESY 2018

Config 4.3: 28 March

ORM DATA

124.2 cm 122.7 cm 120.3 cm 118.7 cm

PCB Module 55
0.28X₀ CuW

Module 64

12-22mm W

15mm 15mm 15mm

PCB Module 53
0.08X₀ Cu

36.8 cm

ORM DATA

95.3 cm 80.0 cm 64.8 cm

30.5 cm 15.3 cm 0 cm

10μm @3GeV/c
Exemplary MIP Energy spectra

**Module 78 Chip 1 Channel 36**

- **No selection**
- **HGCal-track selection**
- **DWC selection**

 CMS work in progress  
 CERN H2 October 2018

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17 January 2019