A Highly Granular SiPM-on-Tile Calorimeter Prototype

Construction and Commissioning

CALOR 2018
Eugene, OR, May 22, 2018

Felix Sefkow - On Behalf of the CALICE Collaboration
DESY
Outline

This Talk.

Design overview
  • particle-flow driven

Construction and Quality Assurance
  • automation and scalability

Commissioning and first experience
  • DESY and CERN test beams (as we speak)
Design Principles
Particle Flow Paradigm

Tackle the jet energy challenge.

In $e^+e^-$ physics every event counts - exclusive reconstruction possible

- Heavy objects - multi-jet final states

$W$ / $Z$ mass splitting dictates required jet energy resolution of 3-4%

- Cannot be archived with classical calorimeters (e.g. ZEUS: 6%)

Reconstruct each particle individually and use optimal detector

- 60% charged, 20% photons, 10% neutral hadrons

Requires fine 3D segmentation of and sophisticated software

- ECAL few 10 mm$^2$, HCAL 1-10 cm$^2$ - millions of channels

Today all linear collider detector concepts follow particle flow concept

\[
E_{\text{Jet}} = E_{\text{ECAL}} + E_{\text{HCAL}}
\]

\[
E_{\text{Jet}} = E_{\text{Track}} + E_\gamma + E_n
\]
Particle Flow Paradigm

Tackle the jet energy challenge.
Particle Flow Paradigm
Tackle the jet energy challenge.
Technologies for Highly Granular Calorimeters

Because we can.

Large area silicon arrays
- silicon calorimetry grows out of the domain of small plug devices

New segmented gas amplification structures (RPC, GEM, μMs)

Silicon photomultipliers on scintillator tiles or strips

- small, B-insensitive, cheap, robust
SiPM-on-Tile Evolution
A long way

2003: MiniCal
SiPM-on-Tile Evolution

A long way

2006: Physics Prototype
SiPM-on-Tile Evolution

A long way
The Next Step: Scalability
Technological prototypes.

- 1000’s of channels per m²
- 1000’s of m²
- must embed electronics and go digital as early as possible; power pulsing
- Integrate SiPMs in read-out board, too
The Next Step: Scalability

Technological prototypes.

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SPIROC2E (OMEGA, F)
MPPCS13360-5PE (Hamamatsu, JP)
(un)wrapped tiles
MPPCs on HBU
polystyrene tiles (Uniplast, RU) with ESR film
Goals of a New Prototype

**LC and beyond**

**Technology:**
- establish the scalability of SiPM technology
- high granularity at the scale of a collider detector
- validate the automated construction and QA procedures
- establish operation with
  - active temperature compensation
  - on-detector zero-suppression
  - power pulsing
- re-establish calorimeter performance

**Physics:**
- study shower evolution in 5 dimensions
  - add timing capabilities (ns level) to electronics
- validate Geant4 in time domain
- study use of timing for particle flow
- use different absorber materials (Fe and W)
Construction and Quality Assurance
Tile Wrapping

Custom-made machine

• University of Hamburg

start in October
Tile Wrapping
Custom-made machine

- University of Hamburg
  start in October
Pick & Place
Standard Machine

- University of Mainz

start in November
Pick & Place
Standard Machine

• University of Mainz

start in November
Automated Production and Quality Assurance

Establishing the concept.

In addition test infrastructures:
- Multi-channel SiPM tests
- Automated ASIC tests
- PCB tests using LEDs
- Cosmic tests after tile assembly

Injection-moulded tiles

Reflector wrapping machine

Camera system with flash light

Pick-and-place head

Tile-board assembly

LED tests

AHCAL: latest mass assembly activities

Surface-mount tile design
- Baseline design for the tech. prototype
- 6 new SMD-HBUs assembled in 2016
- New SiPMs with updated tile design
- 2017: ~170 new boards will be fully assembled and tested
- New generation of SiPMs
- Reduced DCR and low inter-pixel crosstalk
- Noise free in AHCAL
- Improved uniformity (SiPM- and pixel-wise)

Camera system with flash light

Pick-and-place head

Tray for tiles to be placed

1.3% Low crosstalk SiPM

Tile position

SMD-SiPM LED

Custom made reels (56 mm)
- 420 tiles stored in a reel
- Feeder for the pick and place machine.
- Test for placing the tiles stored in the reels in progress

Injection-moulded tiles

Reflector wrapping machine

Camera system with flash light

Pick-and-place head

Tile-board assembly

LED tests

AHCAL Overview, TIPP17 (yong.liu@uni-mainz.de)
Quality Assurance at Each Step

Tiles:
- spot checked for mechanical tolerances
- some deviations affected automatic wrapping

SiPMs:
- spot checked for break-down voltage gain, noise, cross-talk
- all samples passed, excellent uniformity

ASICs:
- semi-automated tests on dedicated board, yield ~ 80-90%

HBUs (bare):
- tested with integrated LED system before mounting tiles (see previous page)
- 158 out of 160 boards OK

HBUs with tiles:
- Cosmics tests
- Most boards: very good light yield uniformity

σ_G = 2.6%
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Active Layers: Cosmics and Beam

Cosmics and Beam Tests

Layer integration:
- one set of interface modules serves up to 18 HBUs
  - DIF: DAQ interface, data concentration,
  - CALIB: LED control
  - POWER regulators, distribution, cycling capacitances

Commissioning with cosmic muons:
- strip hodoscope for central area
- light yield and DAQ stability

Commissioning with DESY electron test beam:
- 5 layers at a time in “air stack”
- automatic scan for all channels
  - movable stage controlled by DAQ
- initial MIP calibration
  - active temperature compensation ensures portability

8 dead channels out of 21’888 total

January - March
Active Layers: Cosmics and Beam

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MIP MPV from DESY electrons

January - March
Stack integration and Cosmic Test

Stack services dimensioned for full collider detector module

- Data concentration
  - output via single ethernet line
- Power distribution
  - 3 voltages per layer
- Cooling
  - pipe cross-sections suitable for “leak-less” operation

Commissioning with cosmics

- benefit from self-triggering capabilities
- test the full software chain
Stack integration and Cosmic Test

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First impressions from Test Beam
Muon Calibration at CERN SPS

- in principle only a cross-check
- full scan high statistics takes 24 h
  - sufficient for memory-cell dependent corrections
Muon Calibration at CERN SPS

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Hit Energy Distribution, 120GeV Muons

![Hit Energy Distribution](chart.png)

<table>
<thead>
<tr>
<th>Hit Energy [MIP]</th>
<th># Entries</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>30000</td>
</tr>
<tr>
<td>0.5</td>
<td>25000</td>
</tr>
<tr>
<td>1</td>
<td>20000</td>
</tr>
<tr>
<td>1.5</td>
<td>15000</td>
</tr>
<tr>
<td>2</td>
<td>10000</td>
</tr>
<tr>
<td>2.5</td>
<td>5000</td>
</tr>
<tr>
<td>3</td>
<td>2000</td>
</tr>
<tr>
<td>3.5</td>
<td>1000</td>
</tr>
<tr>
<td>4</td>
<td>500</td>
</tr>
<tr>
<td>4.5</td>
<td>200</td>
</tr>
<tr>
<td>5</td>
<td>100</td>
</tr>
</tbody>
</table>

Entries: 172763
Mean: 26.45
RMS: 18.39
Muon Calibration at CERN SPS

- in principle only a cross-check
- full scan high statistics takes 24 h
  - sufficient for memory-cell dependent corrections

Hit Energy Distribution, 120GeV Muons

- Mean
- RMS

Entries
- Mean
- RMS

NProf 0.50MIP
- Entries
- Mean
- RMS
- RMS $\gamma$
Electrons and Hadrons

Mixed Beams

- Electron data 10 - 100 GeV
- Hadron data 10 - 160 GeV
Electrons and Hadrons

Mixed Beams

- Electron data 10 - 100 GeV
- Hadron data 10 - 160 GeV
Electrons and Hadrons

Mixed Beams

- Electron data 10 - 100 GeV
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Conclusions and Outlook

CALICE SiPM-on-tile HCAL prototype with 22'000 channels built and successfully commissioned

Design and procedures for construction and QA are scalable to a full collider detector

Beam test at CERN SPS is on-going, more in June
  • include layer with large (6x6cm²) tiles

Combined test with CMS High Granularity silicon prototype this fall
  • representing SiPM-on-Tile section of endcap hadron calorimeter
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HBU with 6x6cm² tiles, U Tokyo
Back-up
Detector Requirements for LC and LHC

Accelerator environment.

Compared to LHC, LC radiation tolerance and bandwidth requirements are benign

Precision requirements are more demanding for LC:
• 2x for jet energies, 10x for track momenta, 5-10x for material budgets, 2x for strip and pixel dimensions

At LC, bunch train structure allows power cycled operation (~1%)
• simplifies powering and cooling: thinner trackers, denser calorimeters

Backgrounds from beamstrahlung and hadronic 2-photon interactions
• more relevant for CLIC, higher E and smaller beam spot (5x1nm²)
• somewhat higher emphasis on fine granularity and precise timing

Shifted focus and unwanted long time span led to development of new detector concepts up to TDR readiness level
• Imaging calorimeters
• Other examples: MAPS / ALICE ITS, …
High Granularity and Pile-up
Particle flow with harsher backgrounds.

Studied intensively for CLIC: backgrounds from $\gamma\gamma \rightarrow \text{hadrons}$ and short BX 0.5 ns

- Overlay $\gamma\gamma$ events from 60 BX, take sub-detector specific integration times, multi-hit capability and timestamping accuracy into account
- Apply combination of topological, pt and timing cuts on cluster level (sub-ns accuracy)

High granularity essential for pile-up rejection capabilities

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**Figure 7**: Energy (left) and mass (right) distributions of reconstructed W at an energy of 500 GeV. Separate distributions are shown for events without background and for events with 60 BX of background before and after application of Tight PFO selection cuts.

- The energy and mass resolutions were studied by calculating the RMS and mean for the distributions of jet energy and jet mass. With the overlay of 60 BX of background, the energy and mass distributions were distorted and the tails became more prominent. The RMS method to calculate the resolution is robust against these changes, whilst considering all features of the distribution, not just the main part of the peak. The resolutions given in this section are therefore purely a measure of peak quality, but cannot be used directly to assess the power to distinguish between W and Z particles. This is addressed in Section 7.2.

**Figure 8** shows the energy and mass resolution of the reconstructed W as a function of the W energy. Separate distributions are shown for the samples without background, for the samples with 60 BX of background and for the samples with $2 \times 60$ BX of background. Without background, the resolutions are comparable to those obtained in the study described in Section 6, without jet reconstruction. In the presence of background, the degradation of the energy resolution at lower energies is significant. With increasing W energy, the impact of the background on the energy resolution becomes rather small. As the mass resolution is more sensitive to the jet quality, the background still leads to appreciable degradation of the mass resolution, even at higher energies. The additional degradation upon moving from 60 BX to $2 \times 60$ BX of background is rather small.

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7.2. W and Z Separation
A key requirement for the physics programme at CLIC is the ability to separate hadronic W and Z decays. For this purpose, the di-jet mass distributions obtained from the simulated W decays were compared to those obtained from Z decays using simulated $e^+e^-$ events. As for the W datasets, fully simulated and reconstructed events were available with Z energies of 125, 250, 500 and 1000 GeV. Samples were produced without background and with 60 BX and $2 \times 60$ BX of overlaid hadrons background. The same reconstruction and selection procedure was used and the reconstruction performance was found to be very similar to that obtained for the Ws. Figure 9 shows the reconstructed mass peaks for W and Z particles with an energy of 500 GeV. Without background, there is clear separation between the peaks. With 60 BX of background, the separation is somewhat degraded.
High Granularity and Pile-up

Particle flow with harsher backgrounds.

Studied intensively for CLIC: backgrounds from $\gamma \gamma \rightarrow$ hadrons and short BX 0.5 ns
- Overlay $\gamma \gamma$ events from 60 BX, take sub-detector specific integration times, multi-hit capability and time-stamping accuracy into account
- Apply combination of topological, pt and timing cuts on cluster level (sub-ns accuracy)

High granularity essential for pile-up rejection capabilities

![Image](https://example.com/image.png)
CALICE Test Beam Experiments

Large prototypes, complex systems.

- SiW ECAL
- ScintW ECAL
- Scint AHCAL, Fe & W
- RPC DHCAL, Fe & W
- RPC SDHCAL, Fe

plus tests with small numbers of layers:

- ECAL, AHCAL with integrated electronics
- Micromegas and GEMs
CALICE Test Beam Experiments

Large prototypes, complex systems.
Proof-of-Principle

Validation of performances, simulations and algorithms.

- 38 layers, 7608 channels - first large-scale application of SiPMs
  - 6 years of data taking at DESY, CERN, Fermilab
- 12 journal papers (from SiPM-on-tile phototype alone)
  - resolution for electrons and hadrons, shower shapes and shower separation, different particle types and absorber materials,…
- All CALICE results
  - https://twiki.cern.ch/twiki/bin/view/CALICE/CalicePapers

\[ \sigma/E = 45.1\%/\sqrt{E} \oplus 1.7\% \oplus 0.18/E \]

software compensation now implemented in Particle Flow


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