Recent results of the technological prototypes of the CALICE highly granular calorimeters

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Recent results of the technological prototypes of the CALICE highly granular calorimeters

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On behalf of the CALICE Collaboration

Credits to K. Krüger, G. Grenier and Ch. de la Taille for helping preparing this talk

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Detector requirements in high energy e+e- collision

Examples:

- W Fusion with final state neutrinos requires reconstruction of H decays into jets
- Jet energy resolution of ~3% for a clean W/Z separation

Slide: F. Richard at International Linear Collider – A worldwide event
Detector systems – Linear e+e- colliders

e+e- detector concepts for linear colliders
Preferred solution Particle Flow Detectors

CLIC Detector

SiD

ILD

B= 4T

B= 5T

B= 3.5T

Highly granular calorimeters

Central tracking with silicon

Inner tracking with silicon

Central tracking with TPC
Particle Flow Detector

Jet energy measurement by measurement of **individual particles**
Maximal exploitation of precise tracking measurement

- large radius and length
  - to separate the particles
- large magnetic field
  - to sweep out charged tracks
- "no" material in front of calorimeters
  - stay inside coil
- small Molière radius of calorimeters
  - to minimize shower overlap
- **high granularity of calorimeters**
  - to separate overlapping showers

Particle flow as privileged solution for experimental challenges
=> Highly granular calorimeters!!!
Emphasis on tracking capabilities of calorimeters
Particle Flow Algorithms

Panda PFA jet energy resolution

Study within ILD Concept

- Design goal: $30\% / \sqrt{E}$ at 100 GeV
- $\sim 3-4\%$ over entire jet energy range

- At lower energies < 100 GeV resolution is dominated by intrinsic calorimeter resolution

- At higher energies have more particles and higher boost
  - Smaller distance between particles
  - More overlap between calorimeter showers
  - Pattern recognition becomes more challenging
  => Confusion

- Note particularly the gain by software compensation
  - i.e. exploiting the wealth of information available through high granularity

E_{\text{jet}} [GeV]

EPJ C77 (2017) 10, 698

PFA ARBOR is algorithm of choice for CEPC Detector with similar performance
Calorimeters for PFA

Mainly organised within the: Collaboration

\[\text{PFA Calorimeter} \rightarrow \text{ECAL} \rightarrow \text{Tungsten} \rightarrow \text{analog, digital} \rightarrow \text{Silicon, Scintillator, MAPS} \]

\[\text{PFA Calorimeter} \rightarrow \text{HCAL} \rightarrow \text{Tungsten} \rightarrow \text{analog, digital} \rightarrow \text{Scintillator, RPC, GEM, Micromegas} \]
Calorimeter R&D for the LHC... and beyond

~360 physicists/engineers from 60 institutes and 19 countries from 4 continents

• Integrated R&D effort

• Benefit/Accelerate detector development due to common approach

• Kicking since 2002
CALICE – History and Steps of R&D

**Physics Prototypes**

2003 - 2012

- Proof of principle of granular Calorimeters
- Large scale combined beam tests
- Validation of G4 Physics lists
- Main inspiration for CMS HGCAL Technology Choice

**Technological Prototypes**

2010 - ...

**Engineering challenges**

This talk

![Diagram](image)

- The goal
  - Typically $10^8$ calorimeter cells
- Compare:
  - ATLAS LAr $\sim 10^5$ cells
  - CMS HGCAL $\sim 10^7$ cells
Technological solutions for a final detector I

- Realistic dimensions
- Structures of up to 3m
- Integrated front end electronics

No drawback for precision measurements *NIM A 654 (2011) 97*

- Small power consumption (Power pulsed electronics)
Technological solutions for a final detector II

- Realistic dimensions
  - Structures of up to 3m
- Integrated front end electronic
  - No drawback for precision measurements *NIM A 654 (2011) 97*
- Small power consumption (Power pulsed electronics)

**SiW Ecal**

**Analogue Hcal and Scintillator Ecal**

**Semi-digital Hcal**

Optical readout

Gaseous readout

Details see poster by F. Magniette
ASICS – The “ROC Family”

**SKIROC**
(for SiW Ecal)
- SiGe 0.35μm AMS,
- Size 7.5 mm x 8.7 mm, 64 channels
- High integration level
- (variable gain charge amp, 12-bit Wilkinson ADC, digital logic)
- Large dynamic range (~2500 MIPS)
- Low noise (~1/10 of a MIP, 400 fC)
- Auto-trigger at ½ MIP
- Low Power: (25µW/ch) power pulsing

**SPIROC**
For optical readout, Tiles + SiPM
- Variant of SKIROC
- 36 channels, 15 bit readout
- Auto-trigger down to ½ p.e,
- 80 fC for $G=1\times10^6$
- Timing to ~ 1ns
- Low Power: (25µW/ch) power pulsing

**HARDROC**
For gaseous r/o - GRPC
- 64 Channels with three thresholds
- Power pulsing
- Variant for Micromegas: MICROROC

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VCI 2019
Intermezzo – Power pulsing

- Electronics switched on during $> \sim 1\text{ms}$ of ILC bunch train and data acquisition
- Bias currents shut down between bunch trains

Mastering of technology is essential for operation of ILC detectors

N.B. Final numbers may vary
SiW Ecal stack for beam tests

- Total ~15 layers constructed
- 1024 channels per layer
- Assembly chains in France and Japan
- Beam tests at DESY and CERN since 2016

PCB FEV12
with long adapter card
Wafer thickness
325 µm

PCB FEV13
with small adapter card
Wafer thickness
650 µm

R&D for thin PCB see backup
SiW Ecal – Performance at MIP Level I

Objectif: Trigger and readout of small signals, Design criterion: S/N ~ 10:1

- S/N ratio from relative position and width of threshold curves
- Result here S/N ~12.9±3.4
- Dedicated runs in 2018 TB, Analysis ongoing

Ability to trigger on small signals and to read them out for analysis
Trigger thresholds uniform at around 1/2 MIP

MIP Detection efficiency ~100%

PFA requires:
- a) Access to small signals -> Low trigger thresholds ✔
- b) Tracking in calorimeters -> High MIP detection efficiency ✔
AHCAL Beam test setup

- AHCAL with 39 active layers of 4 HBUs, 1.7cm steel absorber (4$\lambda_I$)
- Tail catcher: 12 layers with 5.4cm steel absorber (4$\lambda_I$)
- Commissioning and beam test in 2018, less than 0.1% dead channels
- Set-up of assembly and test infrastructure with contributions from Europe and Japan
  - Available to devices of similar purpose
AHCAL Event Display

- Large scale techno, prototypes can be successfully operated
- High granularity allows for efficient Particle Id
- Fine details of hadronic shower visible
• MIP signal: product of light yield (pixel/MIP) and gain (ADC/pixel)

• MIP value in ADC relevant for trigger threshold

• μ=228 ADC, RMS=31 ADC (14%)
  • uniform enough for same trigger threshold for all channels
  • stable between May and June runs
Performance of analogue HCAL

Response to electrons

Beam Tuning several energies

CALICE work in progress

muons

K. Krüger, LCWS2018
New feature: Hit time measurement

- ROCs are equipped with a TDC
- Design goal 1ns for SPIROC
  - Different operation mode
  - Testbeam 250 kHz, ILC 5MHz
  - => Different timing resolutions
- Results with SPIROC2B in Testbeam mode
  - ~5ns for muons
  - ~8ns for electrons
  - dependency of $\sigma_t$ on number of hits
- 1ns can be expected for ILC Mode (higher clock frequency)
  - Encouraging results on test bench
Power pulsing at work – Example AHCAL

- 2.5 Hz switched at 5 Hz
- 150µs settling time
  - Settling time also observed for other detectors
  - See further results in backup
  - (including results in a magnetic field)
DHCAL (until 2014)

- 1bit resolution (i.e. 1 threshold)
- Two m³ stacks with 40-50 layers
- About 500000 cells each

SDHCAL (since 2011)

- 2bit resolution (i.e. 3 thresholds, see above)
Response to $\pi^+$

- Larger electromagnetic fraction of hadron shower with increasing energy
- “Counting” calorimetry shows (expected) saturation
- Remedy by correction function with (for data) $a \sim 20$, $b \sim 0.9$ and $c \sim 15$
The thresholds weight evolution with the total number of hits obtained by minimizing a $\chi^2$:

$$\chi^2 = \frac{(E_{\text{beam}} - E_{\text{rec}})^2}{E_{\text{beam}}}$$

$$E_{\text{rec}} = \alpha (N_{\text{tot}}) N_1 + \beta (N_{\text{tot}}) N_2 + \gamma (N_{\text{tot}}) N_3$$

$N_1$, $N_2$, and $N_3$ : exclusive number of hits associated to first, second and third threshold.

$\alpha$, $\beta$, $\gamma$ are quadratic functions of the total number of hits ($N_{\text{tot}}$)

Weighting factors nearly independent of number of hits

Slight dependency for highest threshold

(y factor, sensitive to electromagnetic part of had. shower)
Semi-digital HCAL - Performance

- Linear response within 5-10%
- Consistent results for different run periods
=> stable performance

- Energy resolution reaches 7.7% at 80 GeV
  (even without electronics gain correction)
Different schemes of hadronic energy reconstruction I

Semi-digital readout allows for comparing to full binary mode with same detector and data sets

- Similar results are low energies
- Resolution curves deviate above 30 GeV
- Semi-digital mode shows improved resolution
- Supplementary information helps above ~30 GeV
Understanding the Performance of Highly Granular Calorimeters

- CALICE hadron calorimeters use different schemes for energy reconstruction - depending on readout technology:
  - scintillator: analog & software compensation
  - gas: digital (1 bit), semi-digital (2 bit)

N.B.: Semi-digital reconstruction and software compensation are related: both use optimised hit or energy dependent weighting factors

Simulations used to study 1 x 1 cm² granularity (scintillator)
Digital & fine granularity best at low energy:
Suppression of fluctuations SC & semi-digital comparable
NB: Sampling fraction matters: Semi-digital reconstruction in RPCs does not reach the same resolution

F. Simon, CALOR2018
Particle Separation

- A key figure of merit for PFA performance
  - At the example of SDHCAL
  - see JINST 6, P07005 (2011) and CALICE-CAN-2017-001 for other CALICE prototypes

ARBOR PFA: Separation of 10 GeV neutral particle from 10 (30) GeV charged particles

High separation power, plateau after 10cm of particle distance

From left to right
- Successful reconstruction of two Particle Flow Objects
- Correct association of second particle
- Successful energy measurement of neutral particle
CALICE spreads out

Similar idea

CMS HGC
Approved to be built 2015-2023

- 500 m² Si, 6M cells
- Detector design chosen to cope with and survive radiation doses of up to $10^{16}$ 1 MeV n/cm² at HL-LHC
- Operation at -30°C => active cooling

Also DUNE

Slide inspired by H. Zhang, IAS 2018
Challenges at Circular Colliders

Power pulsing at LC <-> No power pulsing at Circular Colliders => Strong heat dissipation

=> Active cooling

Material: C. Ochando, LLR

- CMS HGCAL integrates CO₂ Coolings pipes into layers
- Solution for e+e- colliders? Would reduce longitudinal sampling!
- Consistent R&D program needed that will of course benefit from CMS Experience
- Chinese CEPC groups have joined CALICE in recent years
The next decade – ps timing in calorimeters

Timing error:

The pulse *slew-rate (slope) dV/dt* is the critical parameter for timing consideration.
For signals of many MIPs, only jitter $\sigma_j = \text{Noise}/(\text{slope})$ is relevant if the time measuring circuit is under control.

Note that for $N$ concurrent MIPs, the jitter is $\sigma_j (N) = 1/N \times \sigma_j (\text{MIP})$ if an adequate TDC/digitisation is used.
The is the “root cause” for the good timing resolution in calorimeters.
Common beam tests

SiW ECAL/SDHCAL (2018)

CALICE meets CMS
Common beam tests since 2017

- Common beam tests benefit from common approach within CALICE
- But also from wider networking activities such as EUDAQ2 of AIDA2020
- More common beam tests to come after CERN shutdown
Common beam tests

SiW ECAL/SDHCAL (2018)

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Summary and conclusion

- **CALICE pioneered R&D on highly granular calorimeters**
  - Main target Linear Collider Detectors
  - R&D since 2002 starting with "physics prototype" phase
  - Large scale prototypes with rich set of results obtained in combined beam tests
  - Successful R&D inspired CMS to opt for a highly granular calorimeter for the LHC Phase 2 Upgrade
  - Further Spin-offs ALICE FOCAL, DUNE ND, Belle II CLAWS

- **Technological prototypes address technological challenges of highly granular calorimeters**
  - High level integration => dense detector layers
  - Proven stable operation of prototypes
  - Power pulsing is established but may need further scrutiny
  - Versatile mechanics to avoid inactive detector zones (sorry for having been short on this)
  - Timing capabilities studied and will be exploited further
  - Scale of prototypes will allow for producing new physics results to tune e.g. GEANT4

- **Ways forward (not mutually exclusive)**
  - Finalise R&D and accompany Linear Collider experiments during technology selection
  - Common beam tests
  - Address new challenges at Circular Colliders

- **Precious feedback from LHC Upgrades**
  - System integration, timing, active cooling
Backup
Power pulsing in action – SiW Ecal

Operation comparable to ILC mode, 1ms data taking and 99ms idle

Layers with different firmware settings

Continuous mode
Power Pulsing mode

Stable pedestal after around 600µs
Impact of ramp up time on overall consumption needs to be controlled

Measurement ok for power pulsing for “properly” connected ASICs
Encouraging results for SKIROC operation in power pulsed mode
Full system issue
Still more studies needed
Also pedestal measurements in magnetic field

Caveat: Result from 2013
To be validated again

ASIC M1
ASIC M2
ASIC M3
ASIC M4
Power pulsing in action – SDHCAL

Tests in 3T magnetic field
SiEcal – News from COB

- LAL/OMEGA collaboration with Korean Group of SKKU (EOS company for the PCB)
  - FEV11_COB: 10 boards of 1.2mm, good planarity and good electrical response.
  - SK2a wirebonded at CERN (Study by LPNHE and P2IO Platform CAPTINNOV)

- Successful debugging w/o sensors:
  - (≈4% of noisy channels, good response to injected signals)

- Debugging with sensors (baby wafers 3x3 px)
  - The system was not ready for test at DESY@2018.
  - New wafer testbench setup in LAL borrowed from LPNHE.
  - Duplication ongoing at LAL (using the CAPTINNOV platform)

- 3 baby wafers characterized, glued and tested with cosmosics. Test with radioactive sources are in preparation.

- Hit map with for cosmic runs.
  - (different mapping to BGA versions)

- Baby wafer tested in DESY. Some glue is spilled.