Progress towards large ultra-granular Silicon-Tungsten electromagnetic calorimeters

Roman Pöschl

On behalf of the Collaboration

LCWS 2023 – SLAC May 2023

Supported by
Calorimeters for PFA

Mainly organised within the Collaboration

All projects of current future high energy colliders propose highly granular calorimeters

- $X_0 \sim 3\,\text{mm}$, $\rho_M \sim 9\,\text{mm}$
- $X_0 \sim 20\,\text{mm}$, $\rho_M \sim 30\,\text{mm}$
Steps of R&D

Physics Prototype
2005 - 2011

Proof of principle of granular calorimeters
Large scale combined beam tests

Technological Prototype
2010 - ...

Engineering challenges
Higher granularity
Lower noise

LC detector

The goal
• Typically $10^8$ calorimeter cells

Compare:
• ATLAS LAr ~$10^5$ cells
• CMS HGCAL ~$10^7$ cells
Silicon Tungsten electromagnetic calorimeter

Optimized for Particle Flow: Jet energy resolution 3-4%, Excellent photon-hadron separation

Basic Requirements:
- Extreme high granularity
- Compact and hermetic
- (inside magnetic coil)

Basic Choices:
- Tungsten as absorber material
  - $X_0=3.5\text{mm}$, $R_M=9\text{mm}$, $l=96\text{mm}$
- Narrow showers
- Assures compact design
- Silicon as active material
  - Support compact design
  - Allows for pixelisation
  - Robust technology
  - Excellent signal/noise ratio: 10 as design value

All future e+e- collider projects feature at least one detector concept with this technology
- Decision for CMS HGCAL based on CALICE/ILD prototypes

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Ecal alveolar structure

Sandwich calorimeter
26 layers (+/- 4)
Thickness: ~20cm, 24 $X_0/1\lambda_i$
Pixel size ~5x5 mm$^2$
Expected elm. energy resolution 15-20%/$\sqrt{E}$

- Two layers within 13mm max.
- Key feature: Embedded electronics
SiW Ecal Technological prototype – Elements of (long) layer

**ASIC+PCB+SiWafer = ASU**
- **Size 18x18 cm²** (IJCLab, Kyushu, OMEGA, LLR, SKKU)

**ASIC SKIROC2(a)** (OMEGA)
- **Wire Bonded or In BGA package** (IJCLab, Kyushu, LLR)

**Interconnection** (IJCLab)
- **HV Supply** (IJCLab, LLR)

**Digital readout**
- **SL-Board (IJCLab)**

**Si Sensors glued onto PCB**
- **Pixel size 5.5x5.5 mm²** (LPNHE, IFIC)

The beam test set ups comprised mainly **short layers** consisting of one ASU and a readout card each.
Requirements on compactness

- Successful application of PFA requires calorimeters to be inside the magnetic coil
  => Tight lateral and longitudinal space constraints

Calorimeter has to be conceived as one device with electromagnetic and hadronic sections

40-70mm for services as readout, cooling and power

~200mm for up to 30 layers with 10-20 kcells each
“Dead space free” granular calorimeters put tight demands on compactness
• Current developments in for SiW ECAL meet these requirements
System allows to read column of 15 layers <-> to be expected in ILD
• Important that full readout system goes through scrutiny in beam tests
Readout piloted by performant firmware

Deliverable of AIDA-2020 and HIGHTEC
SiW ECAL Technological Prototype – Development phases

≤ 2018

Up to 7 short layers (18x18x0.5cm³)
  • Up ~10 \( X_0 \)

1024 channels per layer => 7186 cells

Technical tests at “MIP level”

First version of r/o system

> 2018

15 short layers equivalent to 15360 readout cells
  • Partially by `recycling` of ASUs from earlier stacks
  • Up to 21 \( X_0 \)

Overall size 640x304x246mm³

Flexible mechanical structure to adapt to beam conditions

Commissioned 2020-2022
  • ~450000 calibration constants for one ASIC feedback capa setting

Testbeams (finally) in November 2021 and during 2022

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# Detector Setup

Detector in beam position

<table>
<thead>
<tr>
<th>Beam spot in 15 layers</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Beam spot in 15 layers" /></td>
</tr>
</tbody>
</table>
SiW-ECAL Beam test – Online Monitoring

Jihane Maalmi, CALICE Meeting Valencia

Online Hit Maps and shower profiles
Allow for real time beam and detector tuning
e.g. Adaptation of beam rates or thresholds

Further online tools
Pedestal measurement and subtraction
Charge measurement and histogramming
MIP gain correction

These are just a few examples from the powerful online suite
SiW-ECAL + AHCAL DAQ test @ DESY in March 2022

Common setup at CERN June 2022

15360 + 22000 (full analogue) readout cells
Successful synchronisation of data recorded with SIW-ECAL and AHCAL
• First step of knowledge transfer on compact readout system to AHCAL
Common running makes full use of EUDAQ tools (developed within European projects)
Common data analysis ongoing

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Correlation

Fig. Difference between BXID in the readout cycle.
Clear showers measured during beam test campaigns
  • Requires full event reconstruction
  • These (and more) “high level” views are available already while a run is going on

“Particle separation continued”
  • Two electrons “seen” in 20 GeV e- run at CERN
After proper filtering energy resolution in right ballpark for current prototype
Convergence in agreement data/MC

Hot news - First results from DESY beam test 03/22

J. Kunath, F. Jimenez-Morales, SiW Ecal Analysis Meeting, 22/09/22
We have good layers ...

- Homogeneous response to MIPs over layer surface
- > 90% efficiency for MIPs
- Here white cells are masked cells due to PCB routing
  - understood and will be corrected

... and not so good layers

Inhomogeneous response to MIPs

- Partially even no response at all, in particular at the wafer boundaries
- Not seen in 2017, degradation observed during 2018/19
- To be understood, will require dedicated aging studies

Since Summer 2022 access to the different stages of the ASICs

- => analogue probes, major debugging tool
Metrology and PCB Deformation

- Setup of a device to measure the flatness of the PCB at different stages
- PCBs will be out into cabling machine and dimensions will be monitored before and afterwards

Glue – Alternative agents and procedures

- After discussion with Astronomy Institute of Paris and Epotek
- Test glue of type H20E as alternative to Epotek J2189
  - Should have higher mechanical stability
- Use EPOTEK 301-2 as underfill for mechanical stabilisation (proposal of Epotek)
  - This underfill has low viscosity that ensures mechanical stability by capillary effect
  - First tests carried out – Stay tuned for results
- Alternative proposal EPOTEK 353ND-T
  - Epoxy for gluing electrical component, could be used to stabilise glued sensor at sensor boundaries
  - Data sheet in backup
- Further alternatives will be studied

Pull tests

- IJCLab will prepare pull tests in order to get a quantitative picture of the mechanical stability of the glue
- Maybe in combination with C2N – A CNRS Institute specialised for materials
PCB Mechanical Monitoring – Planned Steps

**Uncabled PCB**
- Measurement before cabling

**Cabled PCB**
- Measurement after cabling

- Control and measure the PCB before and after cabling for deformations
- Shipping to e.g. IFIC for sensor gluing
- ==> Set up of a logistics chain
New FE boards

Improvements:

- Power distributions
  - Local power regulation
  - Local High Voltage filtering & Supply
- Signal distribution (buffering), data paths
- Monitoring (single ID, temp, probe analogue line)
- ASIC shielding/routing

Status:

- pre-version 2.0 tested, minor corrections needed
  - Noise uniformity dramatically improved (ex: outliers in thr. / 20 !)
- version 2.1 produced, … in metrology
  - before cabling, 2\textsuperscript{nd} metrology, gluing, …
  - All material available : ASICs being tested

Goal: build 15 layer stack for 2024 based on these Boards
(One of) Next step(s) – Slab long

Chain of 8 detection elements ~2m

Encouraging results in first beam test in 2018
  • Issues with signal drop towards extremities
  • Long slab studies vital for all future applications

Beam test at DESY June 2018

May 2023
Timing?

- Timing is a wide field
- A look to 2030 make resolutions between 20ps and 100ps at system level realistic assumptions
- At which level: 1 MIP or Multi-MIP?
  - For which purpose?
    - Mitigation of pile-up (basically all high rate experiments)
    - Support of PFA – unchartered territory
    - Calorimeters with ToF functionality in first layers?
      - Might be needed if no other PiD detectors are available (rate, technology or space requirements)
      - In this case 20ps (at MIP level) would be maybe not enough
    - Longitudinally unsegmented fibre calorimeters
  - A topic on which calorimetry has to make up it's mind
    - Remember also that time resolution comes at a price -> High(er) power consumption and (maybe) higher noise levels
Features that emerge in the time domain can help distinguish particle types and, with GNNs, enhance $\sigma(E)/E$.
New Trends Timing

Pioneered by LHC Experiments, timing detectors may require adaptation for LC Experiments

- Better dV/dt by “active” Si diodes ? => Low Gain Avalanche Detectors
  - LGADs applied for ATLAS HGTD and CMS ETD
  - Expect time resolution $\sigma_t \sim 30$-50ps
- Integration of LGADs into calorimeter volume may be one of the roads to follow

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High energy e+e- colliders:

- Physics rate is governed by strong variation of cross section and instantaneous luminosity
- Ranges from 100 kHz at Z-Pole (FCC-ee) to few Hz above Z-Pole
- (Extreme) rates at pole may require other solutions than rates above pole

- Event and data rates have to be looked at differentially
  - In terms of running scenarios and differential cross sections
  - Optimisation is more challenging for collider with strongly varying event rates
  - Z-pole running must not compromise precision Higgs physics
Operation mode- pulsed or continuous

- Linear Colliders operate in bunch trains
  - CLIC: $\Delta t_b \sim 0.5$ns, $f_{\text{rep}} = 50$Hz
  - ILC: $\Delta t_b \sim 550$ns, $f_{\text{rep}} = 5$ Hz (base line)

- Power Pulsing reduces dramatically the power consumption of detectors
  - e.g. ILD SiECAL: Total average power consumption 20 kW for a calorimeter system with $10^8$ cells

- Power Pulsing has considerable consequences for detector design
  - Little to no active cooling
  - => Supports compact and hermetic detector design
  - Have to avoid large peak currents
  - Have to ensure stable operation in pulsed mode

- Upshot: Pulsed detectors face other R&D challenges than those that will be operated in “continuous” mode
  - Tendency: Avoid/minimise active cooling in also continuous mode
Active cooling?

Cooling needs may be enhanced due to precision timing and will most likely be unavoidable at circular colliders.
“Early Applications” of CALICE Technologies - LUXE

Laser Und Xfel Experiment – QED in extreme fields

Granular calorimeters in positron and electron arms of spectrometer

- Our focus ECAL-E
- Main application electron measurement of Breit-Wheeler process in γ-laser setup
- Could also be used in early LUXE phase in case of delays of ECAL-P
  - Dark photon search next to γ dump could be further option
  - Ideal application(s) of CALICE SiW Ecal technological prototype

Further interest by dark photon experiments
EBES (KEK) and Lohengrin (Uni Bonn)
“Early Applications” of CALICE Technologies - EBES

EBES (Eletron Beam-dump Experiment at SY3)

- Sub-GeV ALP (Axion-Like Particle) produced at beam dump of KEK Linac switching-yard (SY) 3 (7 GeV e⁻ / 4 GeV e⁺) decaying to 2 photons
- Combination of 5 SiW-ECAL layers and PbO Cherenkov calorimeters

- ALP production
- Decay volume (ALP to 2 photons)
- T(Lead)
- 80 cm
- 500 cm
- Detector
- 2 photon clusters should be seen as ALP signal

Pilot run at SY3 in July 2022

Huge background from upstream seen shielding being developed

Second run later 2023
Summary and conclusion

- Two beam tests campaigns in 2021 and 2022
  - ... partially in combination with CALICE AHCAL
  - Data analysis is still ongoing
  - See also Adrian's talk on Chip-On-board PCBs

- CALICE SiW ECAL is about to reply to conclusions from 2021/22 beam test campaigns

- Understanding and remedying of observed sensor delamination
  - Independent of application in future projects
  - One study ongoing with underfill agent and epoxy with better mechanical properties
  - Further solutions will have to be studied and evaluated
  - Need a conclusion this year in order to move on

- New PCB designed and meanwhile manufactured
  - Basis for revised 15 layers stack => Gearing up for next beam test campaign in 2024
  - Will be important step towards readiness for linear collider detector construction

- Precious feedback from LHC Upgrades for future steps
  - System integration, timing, active cooling

- Application in small scale experiments (BES, LUXE, Lohengrin)
Backup
The roadmap document(s)

- ECFA R&D Roadmap
  - CERN-ESU-017 https://cds.cern.ch/record/2784893
  - 248 pages full text and 8 page synopsis

- Endorsed by ECFA and presented to CERN Council in December 2021

The Roadmap has identified
- General Strategic Recommendations (GSR)
- Detector R&D Themes (DRDT) for each of the taskforce topics
- Concrete R&D Tasks

- Timescale of projects as approved by European Lab Director Group (LDG)

Guiding principle: Project realisation must not be delayed by detectors
Toward DRD Calorimetry

Proposed organisation scheme:

Endorsed by CERN Council in Sept. 2022

Research themes calorimetry:

**Calorimetry**

- **DRDT 6.1** Develop radiation-hard calorimeters with enhanced electromagnetic energy and timing resolution
- **DRDT 6.2** Develop high-granular calorimeters with multi-dimensional readout for optimised use of particle flow methods
- **DRDT 6.3** Develop calorimeters for extreme radiation, rate and pile-up environments
• The developments in CALICE have paved the way for a number of applications of highly granular calorimeters and related technologies in HEP

Central contributions by groups very active in CALICE, including CERN, DESY, LLR, OMEGA.

Most prominent: The CMS Endcap Calorimeter Upgrade HGCal
The CALICE Collaboration

Calorimeter R&D for large imaging calorimeters

~270 physicists/engineers from 62 institutes and 18 countries from 4 continents

- Integrated R&D effort
- Acceleration of detector development due to \textit{coordinated} approach
- MOU 2005
  - IN2P3 among founding members, first Spokesperson Jean-Claude Brient
**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=1x10^6  
- Timing to ~ 1ns  
- Low Power: (25µW/ch) power pulsing

**HARDROC**  
For gaseous r/o - GRPC  
- Variant of SKIROC  
- 36 channels, 15 bit readout  
- Auto-trigger down to ½ p.e,  
  80 fC for G=1x10^6  
- Timing to ~ 1ns  
- Low Power: (25µW/ch) power pulsing  
- 64 Channels with three thresholds

**Seminar CPPM April 2023**
Towards Implementation of DRD Calorimetry

- Entry point, “DRD Calo indico page”: https://indico.cern.ch/event/1213733/
  - Information on important events and access to relevant documents
  - Note also the Q&A Doc
  - 227 people from four regions registered so far

- 1\textsuperscript{st} Community Meeting 12/1/23
  - https://indico.cern.ch/event/1212696/

- Proposal phase until 1\textsuperscript{st} of July 2023
  - Input-proposals until latest 1\textsuperscript{st} of April 2023
  - 2\textsuperscript{nd} Community Meeting 20\textsuperscript{th} April at CERN
    - https://indico.cern.ch/event/1246381/
    - Summary of input-proposals (w/o disclosing confidential information)
    - Presentation/discussion of organisation of DRD Calorimetry (with focus on scientific aspects)
      - Guidance by existing R&D collaborations

- Input-proposals will be condensed into a DRD on Calorimetry proposal until (around) 1\textsuperscript{st} of June 2023
  - Further iteration with stakeholders, community and higher level bodies
# CALICE (Technological) Prototypes

<table>
<thead>
<tr>
<th>Name</th>
<th>Sensitive Material</th>
<th>Absorber Material</th>
<th>Resolution</th>
<th>Pixel size/mm$^3$</th>
<th>~Layer size**/cm$^3$</th>
<th>~Layer depth/$X_0$</th>
<th>~Layer depth/$\lambda$</th>
<th># of Pixels/layer</th>
<th># of layers</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>ScECAL</td>
<td>Scintillator</td>
<td>W-Cu Alloy</td>
<td>Analogue, 12bit</td>
<td>5x45x2</td>
<td>23x22x0.5</td>
<td>0.73</td>
<td>0.03</td>
<td>210</td>
<td>32</td>
<td>2x16 x and y strips</td>
</tr>
<tr>
<td>SiECAL</td>
<td>Si</td>
<td>W</td>
<td>Analogue, 12bit</td>
<td>5.5x5.5x0.3 (0.5, 0.65)</td>
<td>18x18x0.24 (-0.63)</td>
<td>0.6-1.6</td>
<td>0.02-0.06</td>
<td>1024</td>
<td>$\geq$22</td>
<td>Can be run in different configs.</td>
</tr>
<tr>
<td>AHCAL</td>
<td>Scintillator</td>
<td>Fe*/W</td>
<td>Analogue, 12bit</td>
<td>30x30x3</td>
<td>72x72x2/1.4</td>
<td>1/2.9</td>
<td>0.11</td>
<td>576</td>
<td>38</td>
<td>Running with Fe and W</td>
</tr>
<tr>
<td>SDHCAL</td>
<td>Gas</td>
<td>Fe*</td>
<td>Semi-digital 2bit</td>
<td>10x10x6</td>
<td>100x100x2.6</td>
<td>1.1</td>
<td>0.12</td>
<td>9216</td>
<td>48</td>
<td></td>
</tr>
</tbody>
</table>

*Stainless Steel

**Only absorber + sensitive material for z direction, air gaps, electronics discarded here (would add 5-10%)
ILD concept and highly granular calorimeters

- **ILD is particle flow detector**
  - Implies goal to measure every particle of hadronic final state
  - Key components for PFA are highly granular calorimeters

- **Calorimeter options in ILD**
  - **Silicon-Tungsten Ecal**
    - 26-30 layers
    - Cell size 5.5x5.5mm$^2$, layer depth 0.6-1.6 $X_0$
  - **Scintillator-Tungsten Ecal**
    - 30 layers
    - Strip size 5x45 mm$^2$, layer depth 0.7 $X_0$
  - **Analogue Hcal**
    - 48 layers
    - Scintillating tiles: 30x30mm$^2$, layer depth 0.11$\lambda$
    - Absorber stainless steel
  - **Semi-Digital Hcal**
    - 48 layers
    - GRPC: 10x10mm$^2$, layer depth 0.12 $\lambda$
    - Absorber stainless steel
Improved Layout

- Better shielding of AVDD and AVDD PA plans and minimisation of cross-talk between inputs and digital signals.

Power Pulsing Mode: new philosophy

- Limiting the current through a layer (current limiter present on the SL Board) to:
  - Avoid driving high currents through the connectors and makes the current peaks local around the SKIROCs chips
  - Avoid voltage drop along the slab
  - Ensure temperature uniformity
- Large capacitors with low ESR for local energy storage (around each SKIROC chip)
- Generate local power supply with LDO (Low Drop Out) to avoid voltage variations

- 25 PCBs delivered beginning of March 2023

This board will enable us to finish the ongoing R&D, join the LUXE Experiment (see later) and be ready in case of ...
Beam Structure and Detector Operation

- Linear collider beams come in bunch trains
  - CLIC: repetition frequency 50 Hz, ILC: repetition frequency 5 Hz (minimum)

- Power pulsing of electronics:
  - Electronics switched on during > ~1ms of bunch train and data acquisition
  - Bias currents shut down between bunch trains

Exploiting beam structure can/will lead to power economic operation of linear collider detectors
Detector requirements

Track momentum: $\sigma_{1/p} < 5 \times 10^{-5}/\text{GeV} \ (1/10 \times \text{LEP})$

(e.g. Measurement of Z boson mass in Higgs Recoil)

Impact parameter: $\sigma_{d_0} < [5 \oplus 10/(p[\text{GeV}]/\sin^{3/2}\theta)] \ \mu\text{m} \ (1/3 \times \text{SLD})$

(Quark tagging c/b)

Jet energy resolution: $dE/E = 0.3/(E[\text{GeV}])^{1/2} \ (1/2 \times \text{LEP})$

(W/Z masses with jets)

Hermeticity: $\theta_{\text{min}} = 5 \ \text{mrad}$

(for events with missing energy e.g. SUSY)

Final state will comprise events with a large number of charged tracks and jets(6+)

- High granularity
- Excellent momentum measurement
- High separation power for particles

Particle Flow Detectors

Detector Concepts: ILD, SiD and CLICdp
### Efficiency of selection for $e^+_i e^-_j \to X$ [%]

<table>
<thead>
<tr>
<th>Cut</th>
<th>$X = q\bar{q}$ ($E_T &lt; 35$ GeV)</th>
<th>$X = q\bar{q}$ ($E_T &gt; 35$ GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$bb$</td>
<td>$c\bar{c}$</td>
</tr>
<tr>
<td>No cuts</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>Cut 1</td>
<td>84.5%</td>
<td>84.9%</td>
</tr>
<tr>
<td>+ Cut 2</td>
<td>82.8%</td>
<td>82.0%</td>
</tr>
<tr>
<td>+ Cut 3</td>
<td>72.1%</td>
<td>71.7%</td>
</tr>
<tr>
<td>+ Cut 4</td>
<td>71.5%</td>
<td>71.1%</td>
</tr>
</tbody>
</table>

### Efficiency of selection for $e^+_R e^-_\ell \to X$ [%]

<table>
<thead>
<tr>
<th>Cut</th>
<th>$X = q\bar{q}$ ($E_T &lt; 35$ GeV)</th>
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<td>No cuts</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>+ Cut 1</td>
<td>84.1%</td>
<td>85.2%</td>
</tr>
<tr>
<td>+ Cut 2</td>
<td>82.6%</td>
<td>82.2%</td>
</tr>
<tr>
<td>+ Cut 3</td>
<td>71.6%</td>
<td>72.3%</td>
</tr>
<tr>
<td>+ Cut 4</td>
<td>71.1%</td>
<td>71.6%</td>
</tr>
</tbody>
</table>

Table 3: Cut flow for the signal and background events.

- Cut 1: Photon veto based on acolinearity
- Cut 2: Photon veto based on ISR photon reconstruction in detector volume
ILD concept and highly granular calorimeters

Concepts currently studies differ mainly in **SIZE** and **aspect ratio**

Relevant: inner radius of ECAL: defines the overall scale

- **Figure of merit (ECAL):**
  - Barrel: \( B \frac{R_{in}^2}{R_m^{effective}} \)
  - Endcap: "B" \( \frac{Z^2}{R_m^{effective}} \)
  
  \( R_{in} \): Inner radius of Barrel ECAL
  \( Z \): Z of EC ECAL front face

- **Different approaches**
  - **SiD**: \( B \left( \frac{R_{in}^2}{R_m^{effective}} \right) \)
  - **LDC**: \( B \left( \frac{R_{in}^2}{R_m^{effective}} \right) \)
  - **GLD**: \( B \left( \frac{R_{in}^2}{R_m^{effective}} \right) \)