DRD6 plans for sandwich ECALs

ECFA WG3: Topical workshop on calorimetry, PID and photodetectors

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CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

GOBIERNO DE ESPAÑA MINISTERIO DE CIENCIA E INNOVACIÓN

Plan de Recuperación, Transformación y Resiliencia

GENERALITAT VALENCIANA Conselleria d'Innovació, Universitats, Ciència i Societat Digital

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Gen—T

AITANA MATTER AND TECHNOLOGY

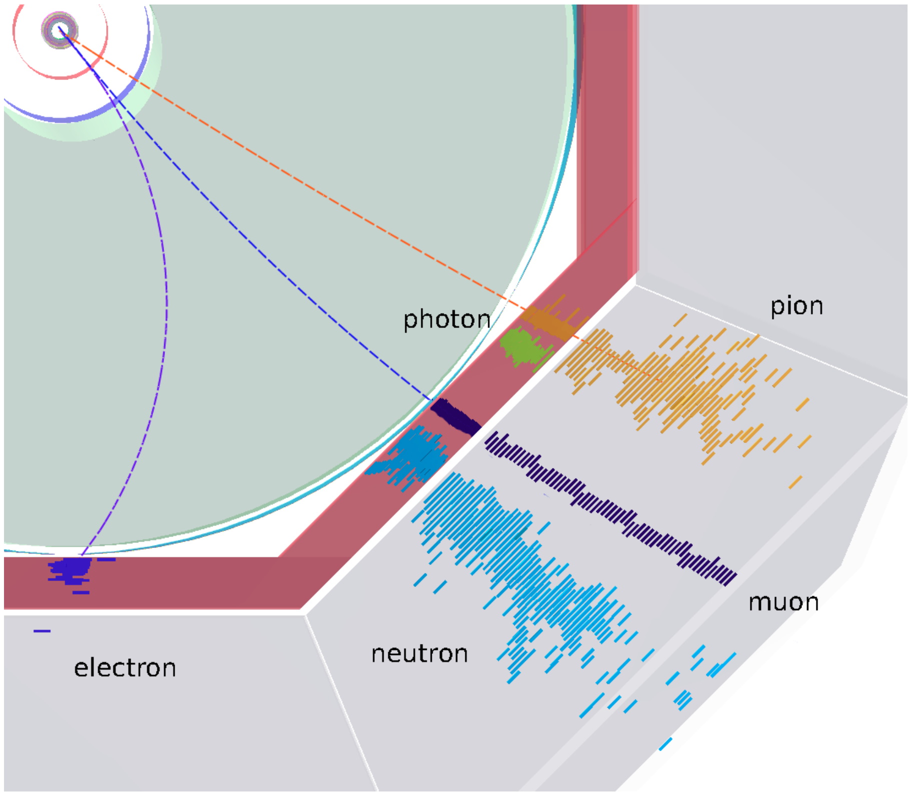
Outline

1 Sandwich ECALs: technological premises and objectives

2 The DRD-TF6: ECAL input proposals

Thanks to F. Simon, Y. Benhamou, V. Boudry, J. Liu, Y. Liu, W. Ootani, R. Poeschl, T. Suehara, and more for the material in these slides.
Mistakes and/or omissions are on me.

Particle Flow Calorimetry



Concept

- ▶ Base the measurement on the subsystem with best resolution for a given particle type (and energy)
- ▶ Separation of signals by charge and neutral particles in the calorimeters
- ▶ **Maximal exploitation** of precise **tracking** measurement
  - **“no” material in front of calorimeters → very low material budget for trackers**
- ▶ Single particle separation

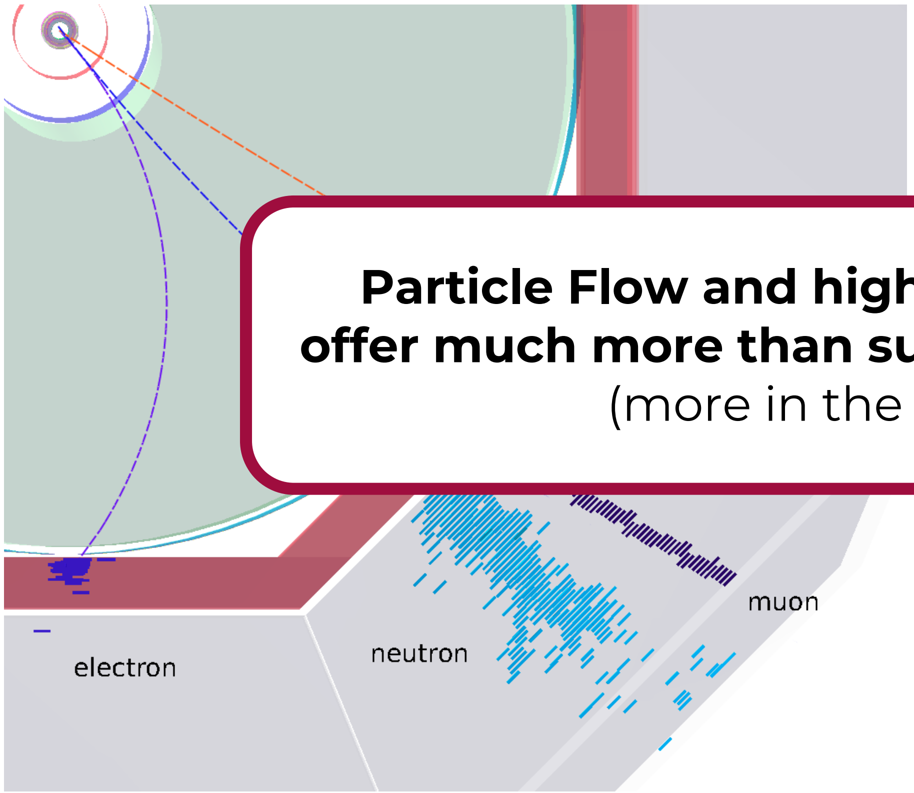
Calorimetry requirements

Ultracompactness: small Molière radius of calorimeters to minimize shower overlap

Maximal Hermicitiy

Extreme high granularity

Particle Flow Calorimetry



Concept

- ▶ Base the measurement on the subsystem with best resolution for a given particle type (and energy)
- ▶ Separation of signals by charge and neutral particles in the calorimeters

king measurement

ters → very low

Particle Flow and high granularity calorimetry offer much more than superb jet energy resolution
(more in the F. Simon's talk)

Calorimetry requirements

Ultracompactness: small Molière radius of calorimeters to minimize shower overlap

Maximal Hermicitiy

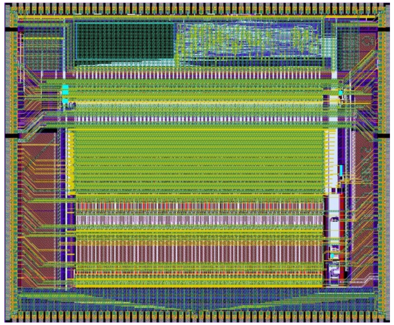
Extreme high granularity

Technological premises

à la CALICE

Highly integrated (very) front end electronics

e.g. SKIROC (for SiW Ecal)

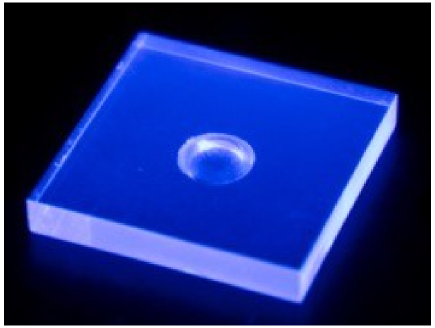


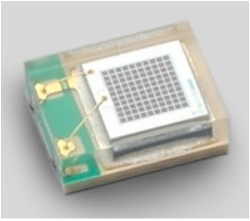
Size 7.5 mm x 8.7 mm, 64 channels

- **Analogue measurement**
- **On-chip self-triggering**
- **Data buffering**
- **Digitisation**
  ... all within one ASIC

- **Common developments on different CALICE projects**

Miniaturisation of r/o devices





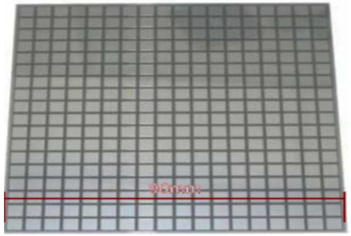
- Small scinitllating tiles
- (Low noise) SiPMs

Power pulsed electronics
to reduce power consumption…
Compactness –> no space left for active cooling systems

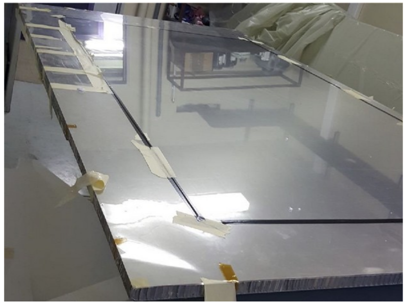
Self trigger of individual cells below MIP level

Large surface detectors

Si Wafer



RPC layers



Many things that look familiar to you today were/are pioneered/driven by CALICE

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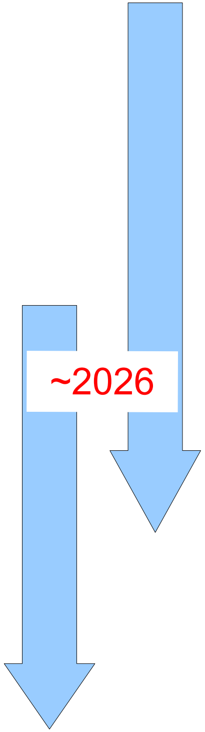
What for?

- **HL-LHC Upgrade** of existing detectors
  - ALICE FoCAL pixel calorimeter
  - HGCAL with high granular Si and SC calorimeter systems
- Mid-term: **Higgs Factories – Particle Flow** Calorimeters
  - **PF calorimetry**: up to about **$O(10^8)$ readout cells** for barrel calorimeters (SiW-ECAL case)
  - **Linear** colliders (**low rates** favoring self-trigger and low consumption electronics through **power-pulsing**)
  - **Circular** colliders (**higher rates**, specially running at Z-pole, challenging the power consumption budgets and/or the cooling needs)
- **Other applications** in the short term (i.e. 2025-2026)
  - For example: **LUXE** (featuring two silicon-tungsten highly granular and compact ECALs (CALICE and FCAL adaptations). XFEL pulsed electron beam (as ILC)
- **Longer term**
  - **Muon** colliders and/or **Hadron-hadron** machines (high rates and high **radiation** environments)

More in V. Boudry's talk

R&D path



▶ **Ongoing R&D** phase with the goal of **the construction of multilayer scale ECAL (and HCAL) PF prototypes**

- With **high granularity**
- **Extreme compactness** to ensure the smallest moliere radius
- Fully implementing **power pulsing**!
- To be tested in **beam facilities** in order to ensure a proper integration/interplay of the two sections (ECAL+HCAL) which is **crucial for PFA**

▶ **Adaptation** of the concepts to **different projects**

- Lineal-vs-circular → low or high rates → Power pulsing or not, self trigger or not
- e+e- vs hadron → no strict radiation hardness requirement vs the opposite
- First phase of simulation studies required.

▶ Application of **new ideas**

▶ **Calorimeters for Higgs Factories**

Towards DRD6 - Calorimetry

- 1^{st} Community meeting (12.1.2023)
  https://indico.cern.ch/event/1212696/
- Launch of Input proposal collection
  - mid February – April 1^{st}
  - Scientific proposal of what need to be built and tested in the next 3 (2024-2026) - 6 (2027-2029) years
  - Description and timeline
  - Objectives:
    - Milestones
    - Deliverables
  - List of participating Institutes/Labs with short description
  - Confidential information on resources
    - **they won't be disclosed!**

The Proposal Team

Track 1: Sandwich calorimeters with fully embedded Electronics – Main and forward calorimeters
Track conveners:
Adrian Irles (IFIC), **Frank Simon** (KIT), **Jim Brau** (U. of Oregon), **Wataru Ootani** (U. of Tokyo)

Track 2: Liquified Noble Gas Calorimeters
Track Conveners:
Martin Aleksa (CERN), **Nicolas Morange** (IJCLab), **Marc-André Pleier** (BNL)

Track 3: Optical calorimeters: Scintillating based sampling and homogenous calorimeters
Track Conveners:
Etiennette Auffray (CERN), **Gabriella Gaudio** (INFN-Pavia), **Macro Lucchini** (U. and INFN Milano-Bicocca), **Philipp Roloff** (CERN), **Sarah Eno** (U. of Maryland), **Hwidong Yoo** (Yonsei Univ.)

Track 4: Transversal Activities
Christophe de La Taille (Lab. Omega)

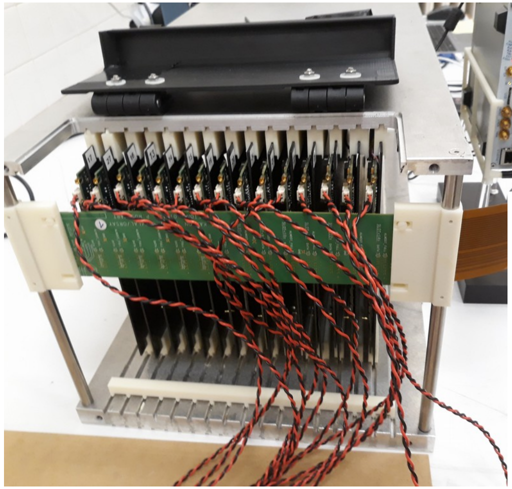
Overview of Input proposals

- Most of the material is from F. Simon's talk
  - 2nd Calorimetry Community Meeting (ECFA DRD-TF6) https://indico.cern.ch/event/1246381/contributions/5353454/attachments/2632111/4552924/DRD6_Track1_CommuityMeeting2023_04.pdf

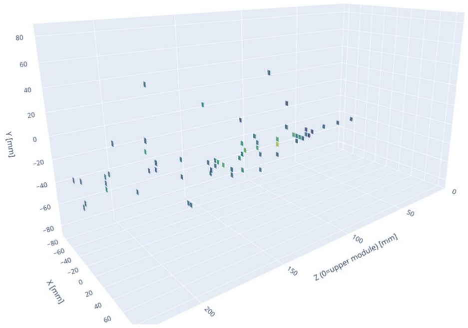
- Overview of each sandwich ECAL proposal to the DRD TF6 (track 1)
  - timelines/goals as in the input proposals
- **SiW-ECAL** (building on CALICE prototype)
  - LLR, IJCLab, LPNHE, OMEGA, IFIC, Kyushu U, KEK, CERN
- **Highly Granular Scintillator-strip** Calorimeter (building on CALICE prototype)
  - U Tokyo, USTC, IHEP, Shinshu U, SJTU
- **DECAL** (MAPS)
  - HU Berlin, U B'ham, DESY-Z, HEPHY & NTU Athens, IC, Frankfurt, Rutherford, Sussex, Utrecht
- **Highly Compact ECAL** (building on FCAL prototype)
  - TAU, AGH Cracow, U Warsaw, IFIC, ISS Romania

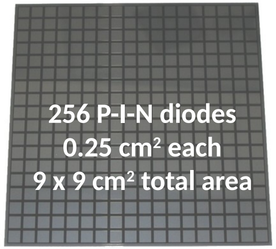
SiW-ECAL: LLR, IJCLab, LPNHE, OMEGA, IFIC, Kyushu U, KEK, CERN

- ▶ Primary experimental context: Higgs Factories, possible near-term applications in LUXE and others
- ▶ A SiW-ECAL using silicon pad sensors with analog readout
- ▶ Builds on CALICE SiW ECAL technological prototype
  - 15 single-ASU prototype in beam in 2024 (current technology)



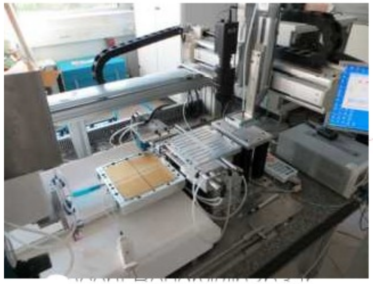
SiW-ECAL
- **15 layers 18×18 cm²**
- 0.5×0.5 cm² Si cells
- 2.8+5.6 mm W (21 X_0)
- 100 kg, 0.4×0.4×80 cm³
- **15k channels**

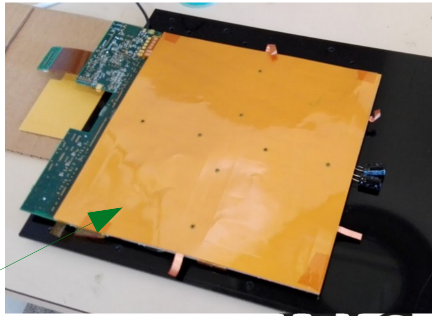




Prototype from Hamamatsu

Wafers are glued to PCB (robot at LPNHE & Kyushu U. & IFIC 2023-2024)

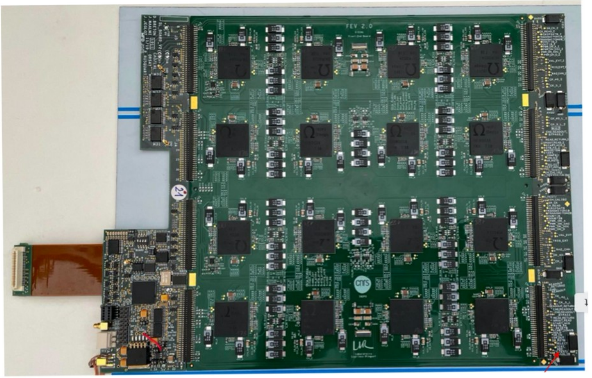


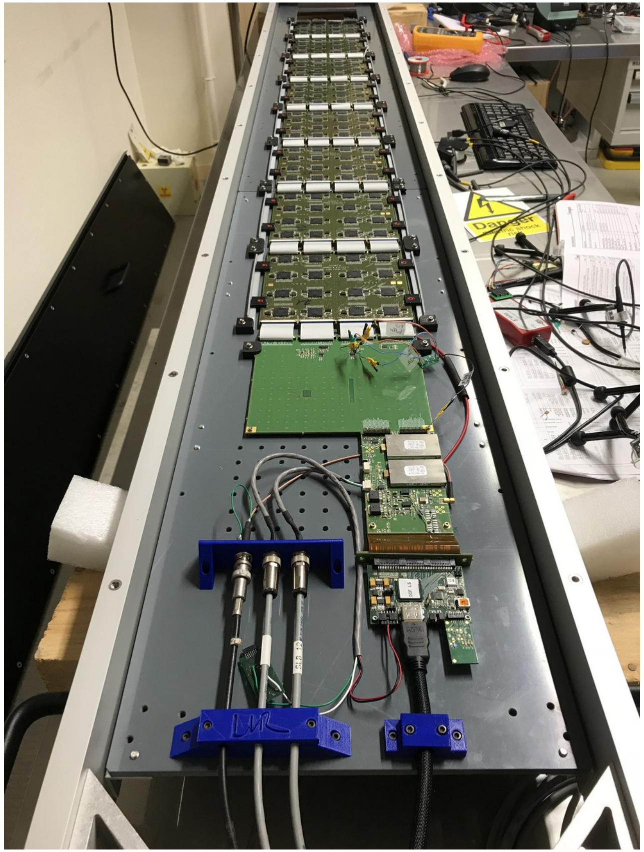


Sensor polarization through HV deliver via a copper/kapton sheet

SiW-ECAL: LLR, IJCLab, LPNHE, OMEGA, IFIC, Kyushu U, KEK, CERN

- Main R&D topics
  - Extension of current prototype based on power pulsing to continuous operations: reduction of power consumption, of cooling
  - Study of the addition of timing, either dedicated layers or volume timing
- Design for HF pilot module in 2025

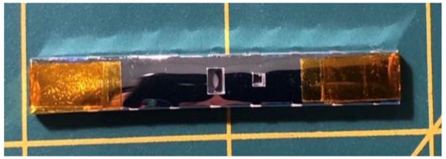


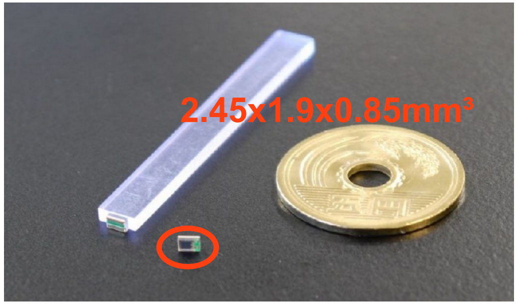


Highly Granular Scintillator-strip Calorimeter

U Tokyo, USTC, IHEP, Shinshu U, SJTU

- Primary experimental context: Higgs Factories
  - A tungsten-scintillator-strip (with SiPM readout) calorimeter
  - Building on CALICE technological prototype



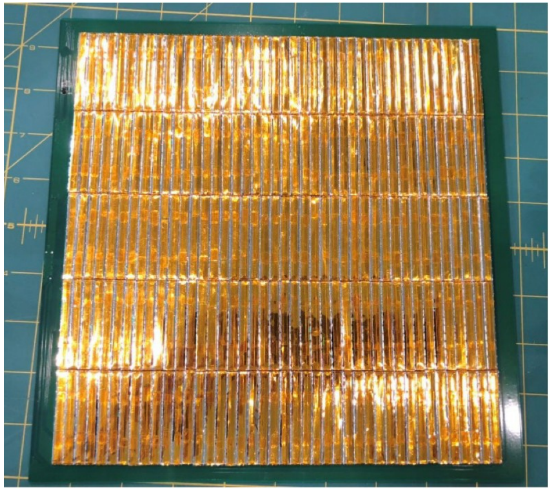


- 30 layers, 22cm*22cm
- 22X0
- 300 kg
- 6300 channels

Highly Granular Scintillator-strip Calorimeter

U Tokyo, USTC, IHEP, Shinshu U, SJTU

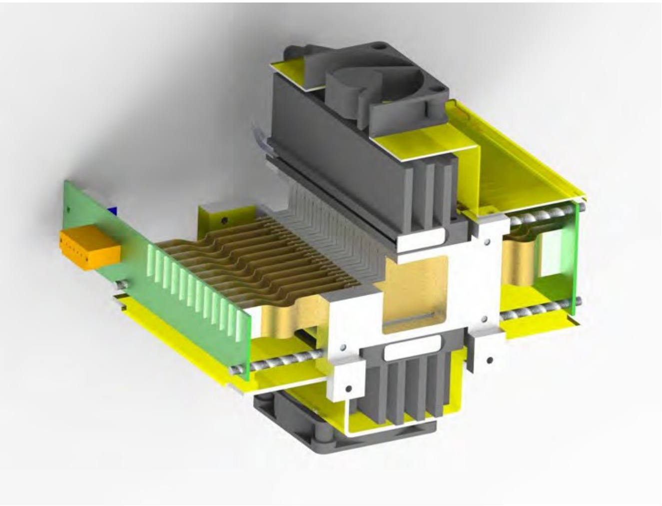
- Main R&D goals for next period:
  - Engineering study for large-scale production
  - Timing performance - possibly by introducing dedicated timing layer(s)
  - Scintillator material - also extending to new ideas such as quantum dot material
  - Scintillator strip design
  - Active cooling system
  - Mechanical structure and services
  - Electronics - including low-power readout ASIC
  - Trigger-DAQ system - studied for Circular Colliders
- Construction of a new prototype as main deliverable

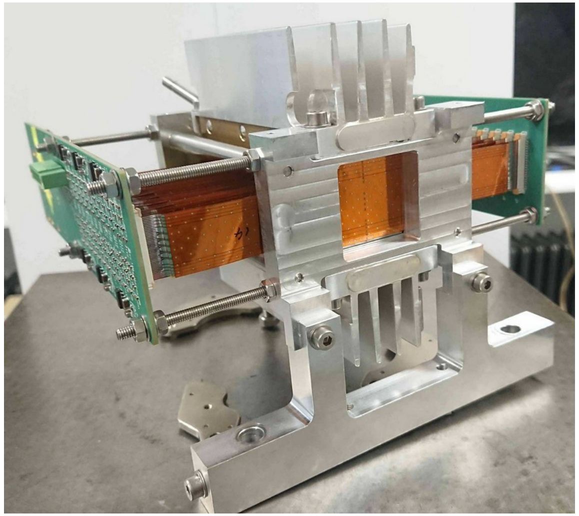


DECAL - Digital ECAL based on MAPS

HU Berlin, U B'ham, DESY-Z, HEPHY & NTU Athens, IC, Frankfurt, Rutherford, Sussex, Utrecht

- Primary experimental context: ALICE FOCAL, Higgs Factories
- A MAPS-based digital Silicon-Tungsten ECAL,
  - building on current DECAL and EPICAL projects, partially integrated in CALICE
  - Also relevant activities (and interest) at SLAC, U Oregon with connections to CERN





24 layers with each
- 3 mm W absorber
- 2 ALPIDE CMOS sensors
(NIM A, 845:583–587, 2017)

29.24 x 26.88 μm² pixel size

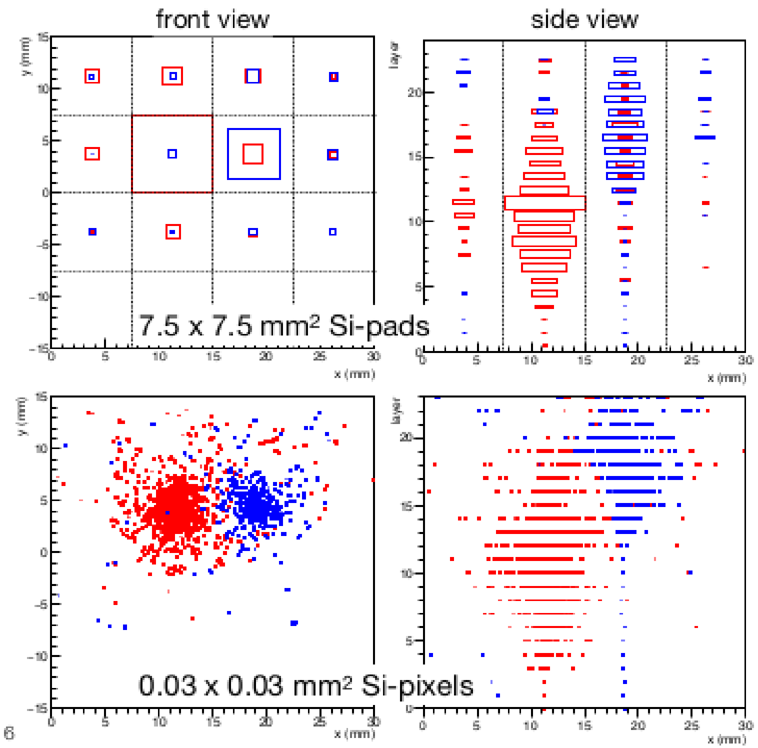
active cross section 3 x 3 cm²

compact design: expect $R_M \approx 11$ mm

DECAL - Digital ECAL based on MAPS

HU Berlin, U B'ham, DESY-Z, HEPHY & NTU Athens, IC, Frankfurt, Rutherford, Sussex, Utrecht

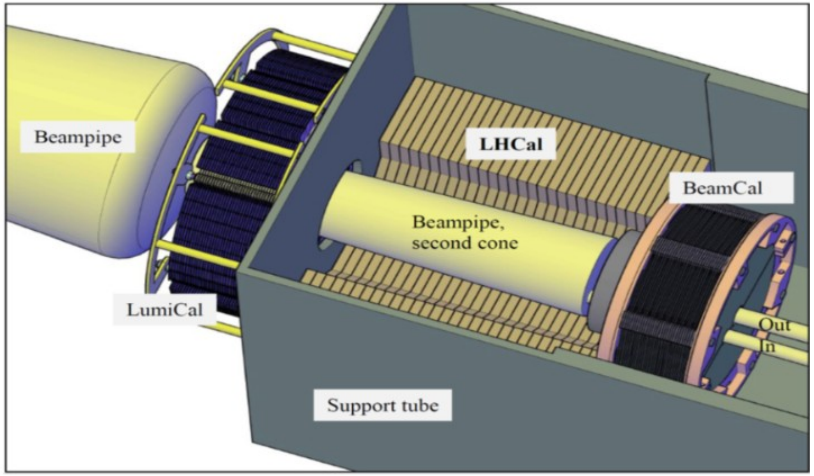
- Main R&D topics:
  - Full exploitation of existing EPICAL-2 prototype to evaluate performance
  - Establish requirements of a sensor dedicated for digital calorimetry
  - Design of next-generation sensor with calorimeter-specific optimisation (overlaps with DRDs 3, 7), and evaluation of sensor design
- Small-scale digital ECAL prototype in 2026, sensor submission early 2025

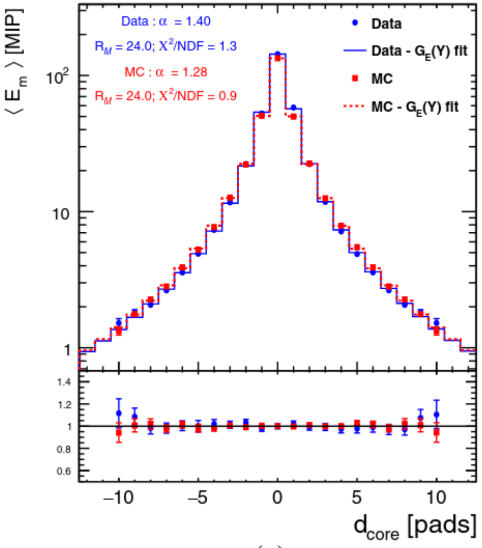


Highly Compact ECAL

TAU, AGH Cracow, U Warsaw, IFIC, ISS Romania

- ▶ Primary experimental context: Higgs Factories, possible near-term applications in LUXE
- ▶ Highly compact electromagnetic calorimeter with semiconductor sensors
  - Builds on developments in FCAL





(a)

Fig. 25 **a** The shower transverse profile $< E_m >$, as a function of d_{core} in units of pads, of the joint distribution of all three configuration from beam-test data and the MC simulation, after symmetry corrections and fit. The lower part of the figure shows the ratio of the distributions to the

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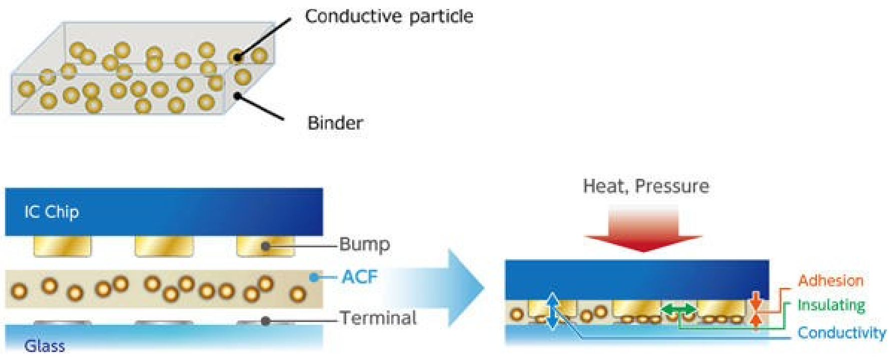
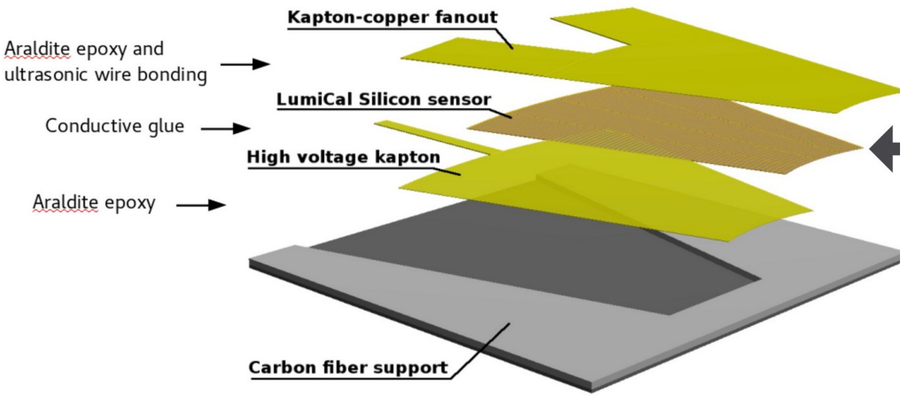
Highly Compact ECAL

TAU, AGH Cracow, U Warsaw, IFIC, ISS Romania

- Main R&D topics:
  - R&D on Si and GaAs sensors, including optimisation of readout integration
  - Development of thin conductive gluing
  - Development of readout electronics: Readout of FLAME ASICs; development of FLAXE variant for LUXE; Wireless data transmission, joining WADAPT program
  - Mechanics with minimal tolerances
  - Simulation studies
- Design of prototype in 2024, construction & performance studies in 2026
- Design for HF calorimeter in 2026





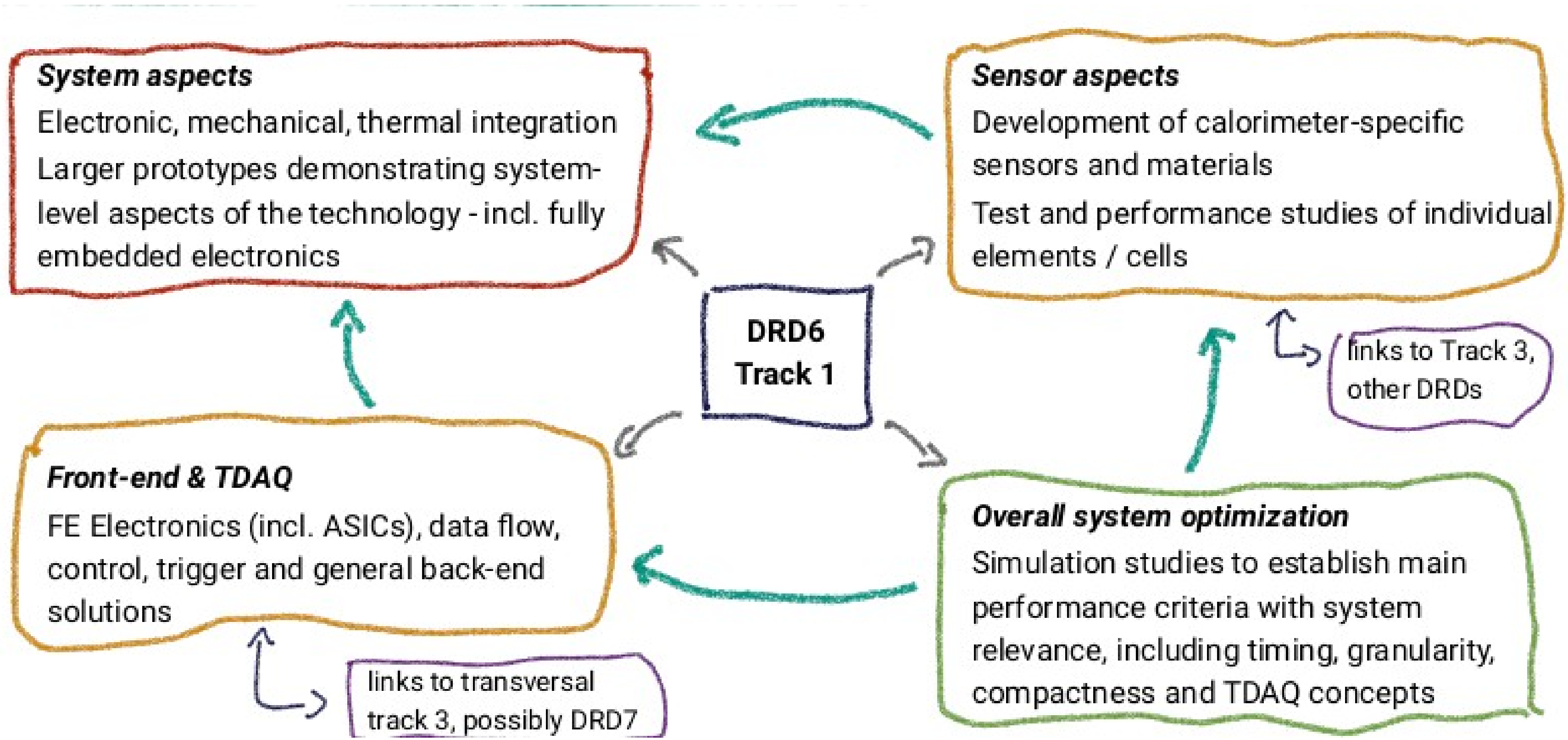
Extra comments

- ECAL+ACAL (two sectors of the same detector)
- Common beam tests with **high energy beams** are mandatory
  - At Europe, only at CERN. Available during LS3 ?
- **Building full scale prototypes for testing of the technology & study of the PFA performance** and deep understanding of shower developments
- Requires also **common developments** on **software**: common DAQ, simulations, Geant4 , event model, high level reconstruction tools
  - Not covered in this talk

Test-beams ≈ small experiments
leading to physics and R&D papers

- **Optimisation studies are needed:**
  - Timing benefits (& costs).
  - Granularity needs, acceptance, etc integration aspects
  - Adaptation to different beam conditions (higher rates, low or high energy, etc)

Summary



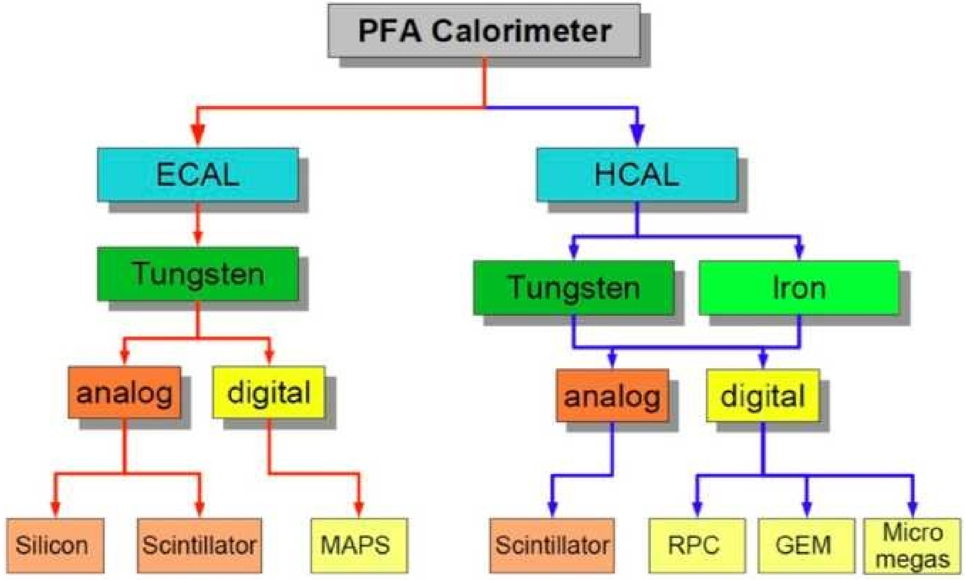
HCALs are needed for the full picture

Thanks to F. Simon, Y. Benhamou, V. Boudry, J. Liu, Y. Liu, W. Ootani, R. Poeschl, T. Suehara, and more for the material in these slides

Back-up slides

The CALICE Collaboration

High Granular Calorimetry for Particle Flow: Pioneered by the CALICE Collaboration

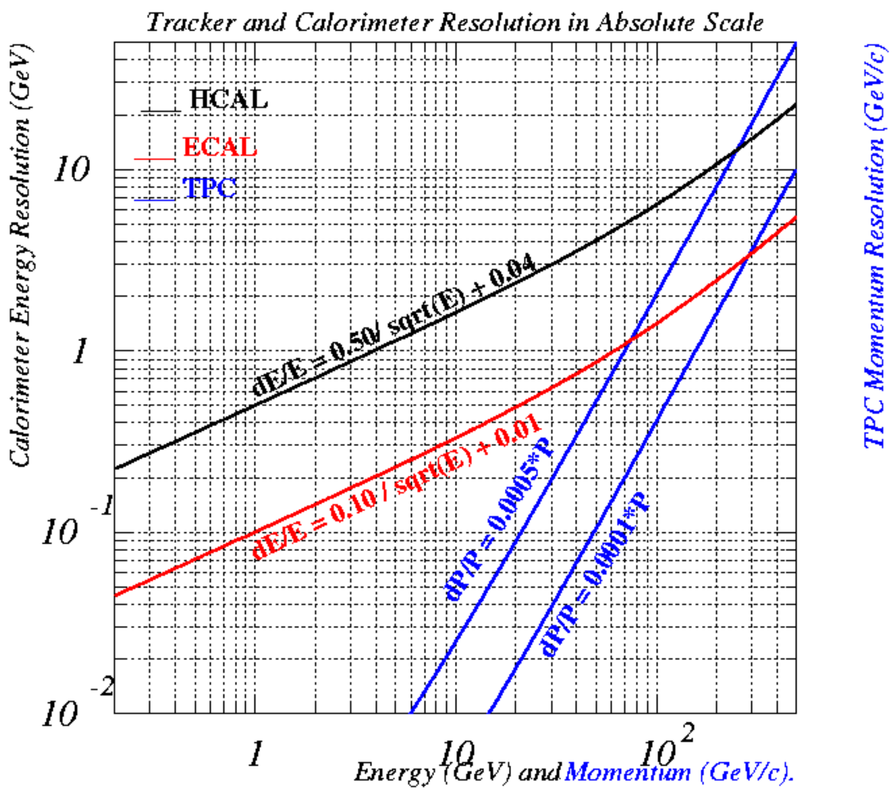


More than 300 physicists/engineers from ~60 institutes and 19 countries coming from the 4 regions (Africa, America, Asia and Europe)

Most projects of current and future high energy colliders propose highly granular calorimeters

PFA calorimetry is not only a quest on high jet energy resolution but on a deep understanding of shower developments

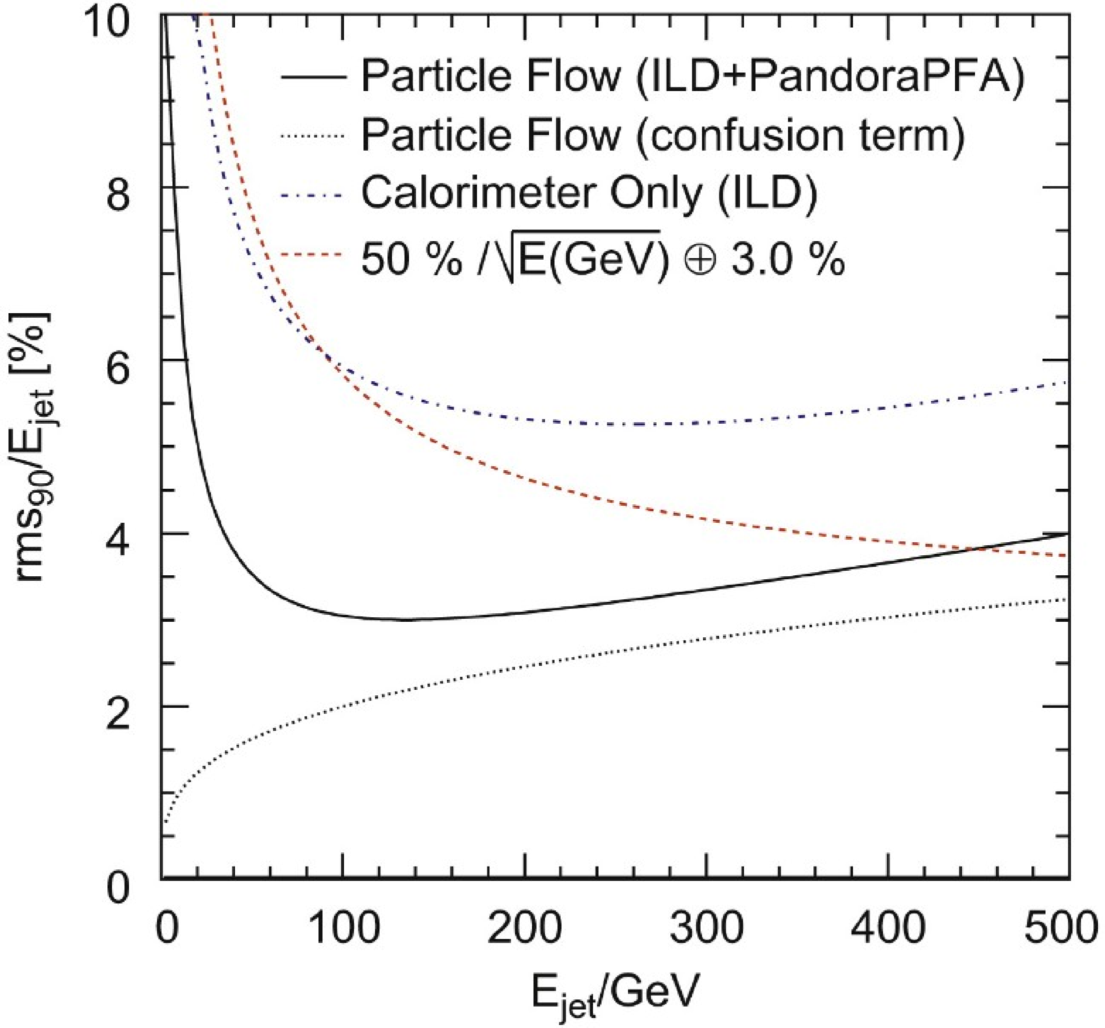
Jet energy resolution: how to improve it?



In a "typical jet" the energy is carried by

- **Charged particles ($e^{\pm}$, $h^{\pm}$, $\mu^{\pm}$): 65%**
  - Most precise measurement by **Tracker**
- **Photons: 25%**
  - Measurement by Electromagnetic Calorimeter **(ECAL)**
- **Neutral Hadrons: 10%**
  - Measurement by Hadronic Calorimeter **HCAL** and ECAL

Jet Energy Resolution



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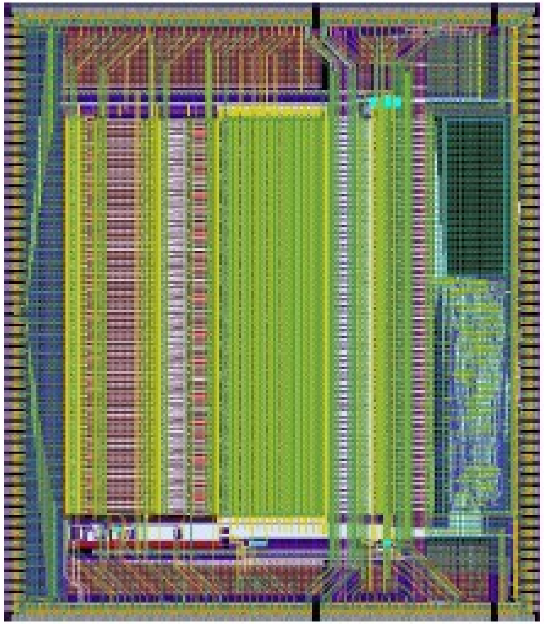
Very Front End electronics

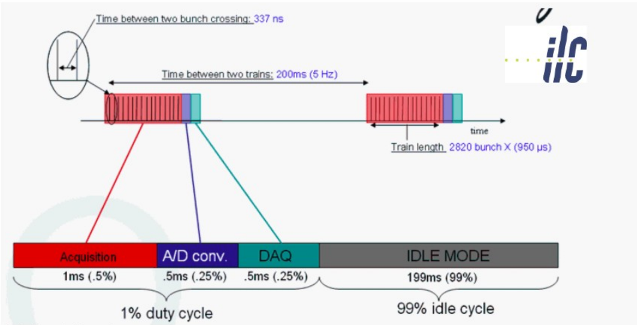
▶ **SKIROC and SPIROC** (SiW-ECAL and SC-ECAL)

- **Large dynamic range and low noise**
- **Dual readout: high and low gain plus TDC**
- **Auto-trigger at ~0.5 MIP**
- Low Power: (25μW/ch) **power pulsing:** switch off electronics bias currents during bunch trains

▶ **Common efforts in CALICE**

- Designs by Omega of ASICs for AHCAL, SDHCAL, ECAL with same readout scheme and basic features
- Also other independent developments (KlauS – for AHCAL)





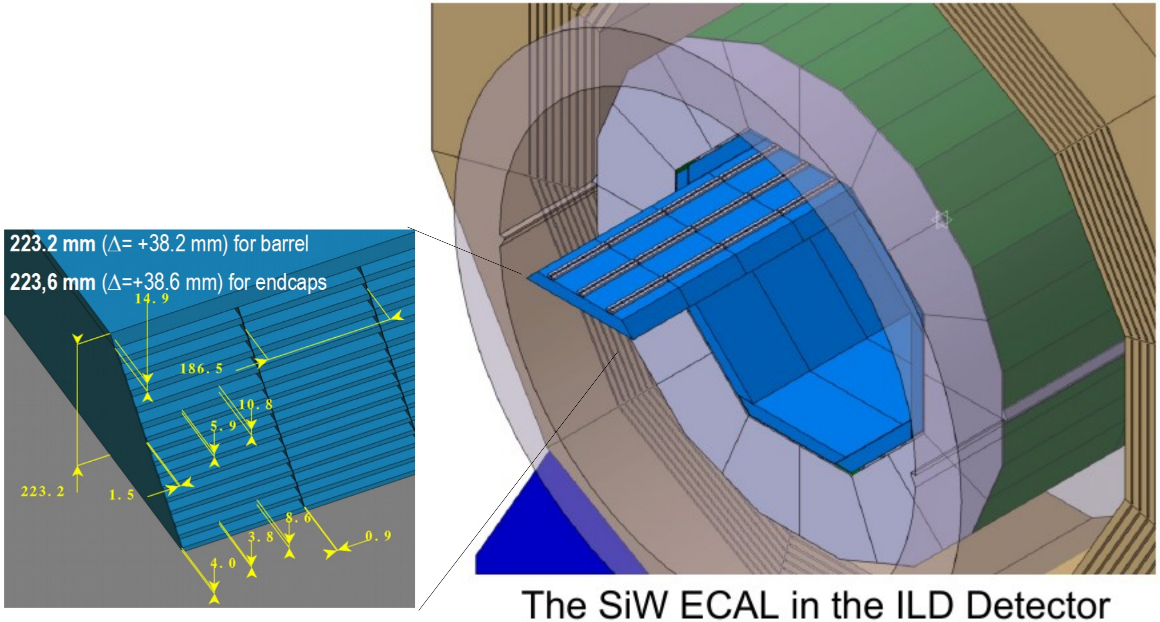
N.B. Final numbers may vary

Microelectronics

SiW-ECAL for future LC

- **Tungsten** as absorber material
  - **Narrow showers**
  - Assures **compact** design
  - Low radiation levels forseen at LC
  - X_0=3.5 mm, R_M=9mm, I_L=96mm

- **Silicon** as active material
  - Support **compact** designs
  - Allows **pixelisation**
  - **Robust technology**
  - **Excellent signal/noise** ratio



The SiW ECAL in the ILD Detector

The **SiW ECAL R&D** is tailored to meet the specifications for the **ILD** ECAL **baseline** proposal

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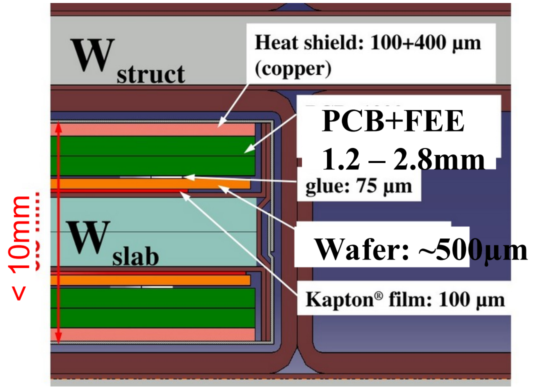
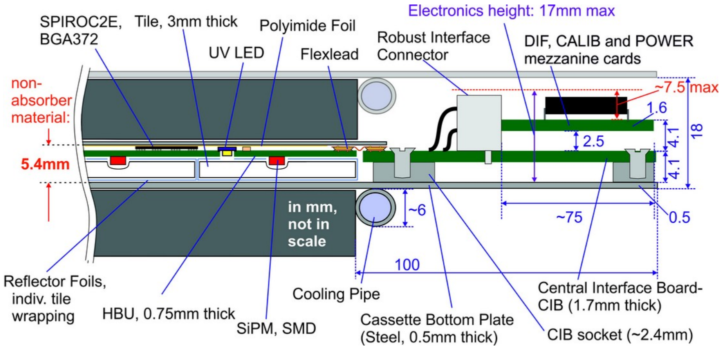
Technological solutions for final detector I

SiW Ecal



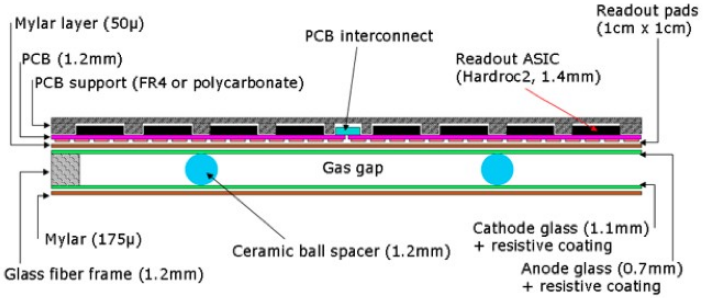
Semi-conductor readout
Typical segmentation: 0.5x0.5 cm^2

Analogue Scintillator HCAL and ECAL



Optical readout
Typical segmentation: 3x3cm^2

Semi Digital HCAL



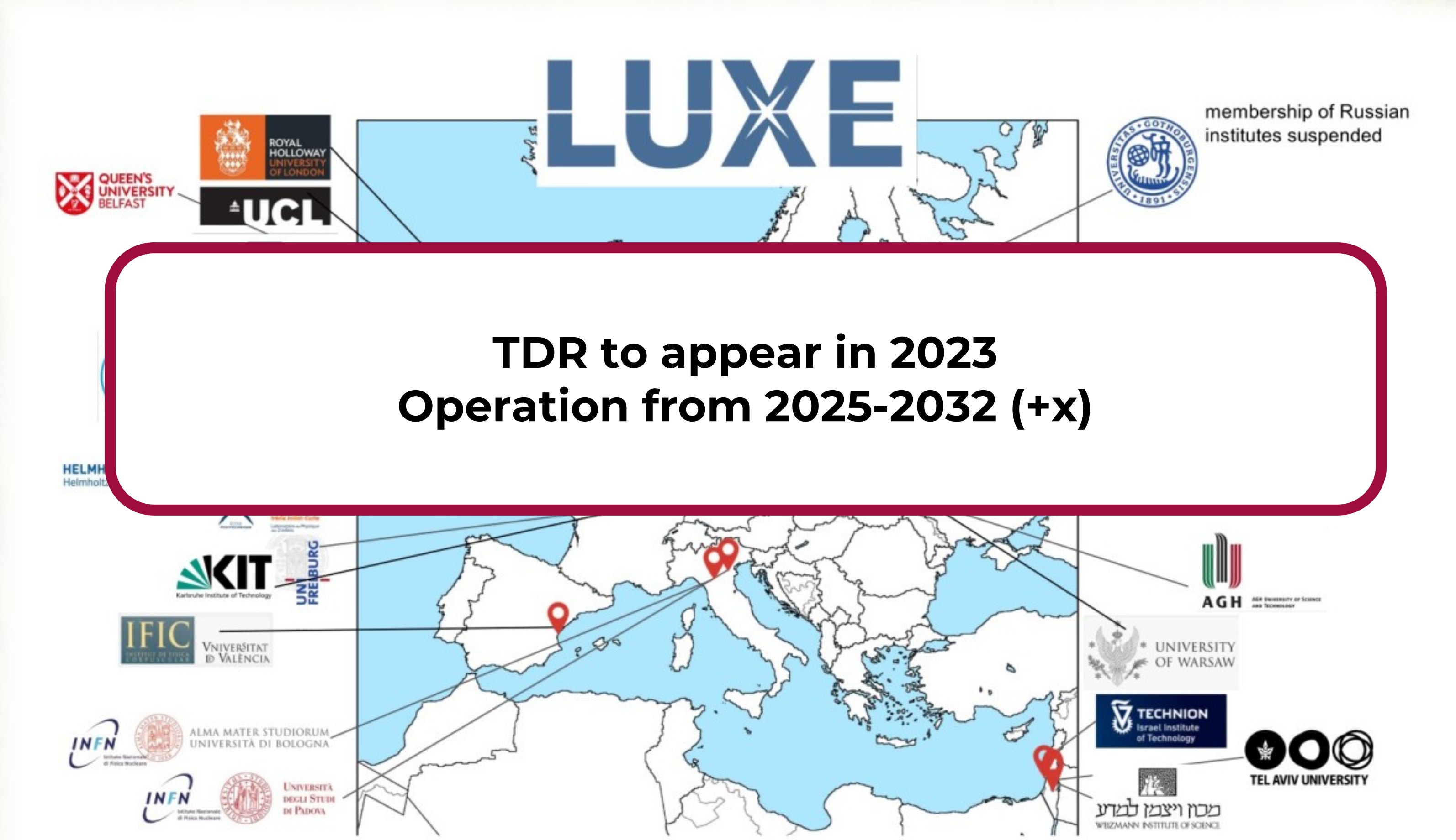
Gaseous readout
Typical segmentation: 1x1cm^2

Integrated front end electronics

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

LUXE (Laser Und XFEL Experiment)

LUXE (Laser Und XFEL Experiment)



TDR to appear in 2023
Operation from 2025-2032 (+x)

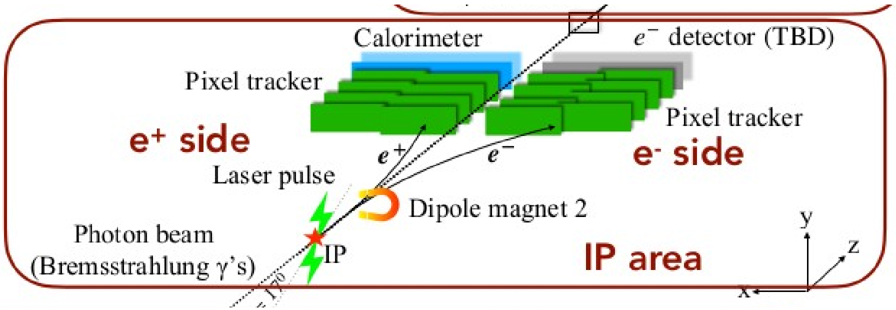
Positron and electron detection systems

Positron detection system proposal
Based on a pixel tracker + ECAL-p based on FCAL prototypes of LumiCal

But using CALICE-Hammatsu sensors

High Granular Calorimetry

Electron detection system proposal
Based on a pixel tracker + SiW-ECAL of CALICE (15 layers with modified/extended geometry)



Positron and electron detection systems

Positron detection system proposal
Based on a pixel tracker + ECAL-p based on FCAL prototypes of LumiCal

using "CALICE sensors"

High Granular Calorimetry

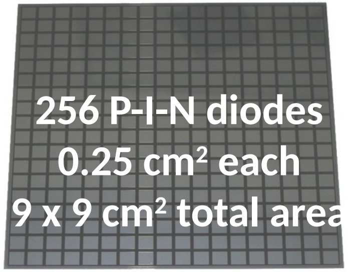
Electron detection system proposal
Based on a pixel tracker + SiW-ECAL of CALICE (15 layers with modified/extended geometry)

Two detectors of the **scale of CALICE prototypes** running in **real experiment conditions.**
Integration challenge: Very thigh compactness requirements

Readout Modules

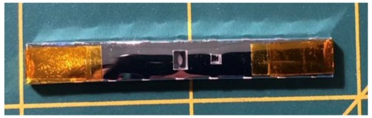
The core of the prototypes are the readout modules entities, consisting of:

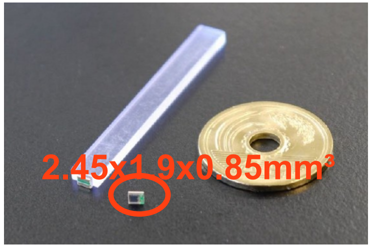
- **VFE** (ASICS, common developments within CALICE)
- **PCBs**
  - Very dense PCBs with up to 1024 channels + extra components for power pulsing and noise filtering in 18x18cm^2
- **Active material**
  - **Large surface silicon sensors** (9x9cm² directly **glued** to the back of the PCB) → **SiW-ECAL (CALICE)**
  - Large surface silicon sensors (8" wafers wire-bonded through PCB holes) → **CMS-HGCAL**
  - **Scintillator** strips individually wrapped connected to **SiPM** → **Sc-ECAL (CALICE)**



EUDET layout

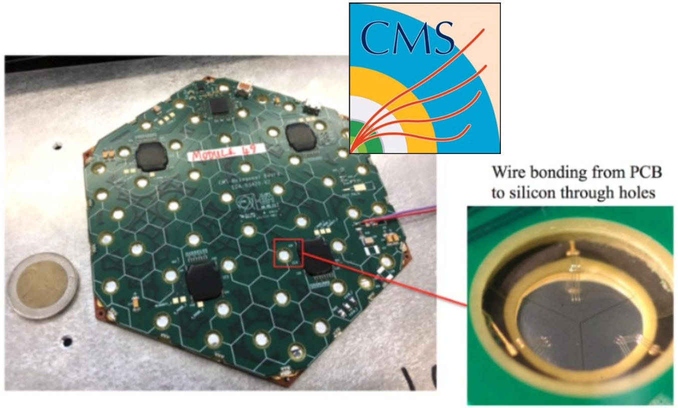
Prototype from Hamamatsu





PCBs

- Very dense **PCBs:**
  - i.e. at SiW-ECAL they are known as featuring 1024 readout channels (with digital, analogue, clock signals) in a 18x18 cm^2 board



CMS HGCAL Hexaboard

Wire bonding from PCB to silicon through holes

SiW-ECAL current prototype solution.

Meets industry requirements → bulky components **compromise compactness**

Chip-On-Board solution (R&D phase, tested recently in beam test)

The **most compact solution**… but no space for required components (i.e. for power pulsing)

Open challenges (very-front-end)

- ASICs for prototyping are already available

Near Future (~1-5years):

- Plans: how to implement high precision timing? (keeping low power budget)
  - Current TDC allows for ~ns timing measurements → to be further characterized and tested in beam test
  - New ideas associated to R&D on sensors

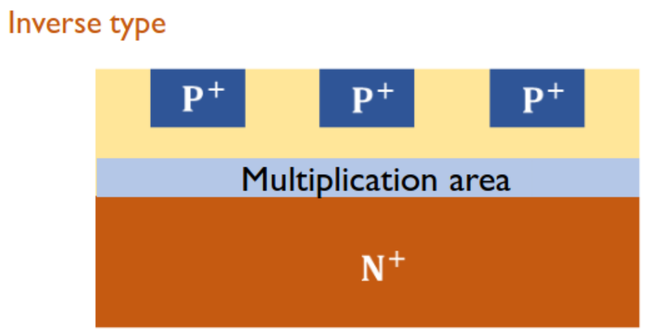
Mid/Long Term → Next Generation ASICs

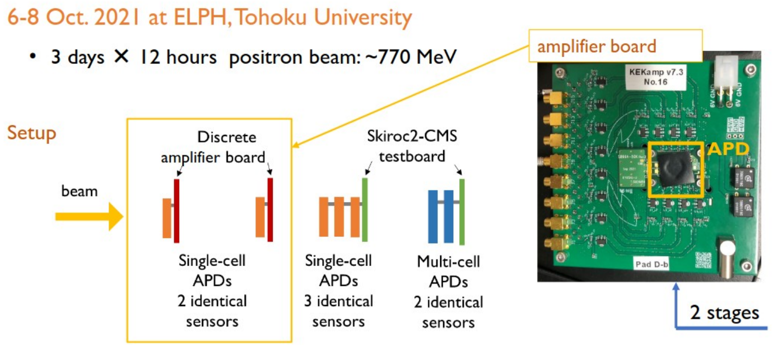
- design / performance goals are highly **experiment dependent**
  - However, **low consumption** is seek for all of them (even if active cooling systems are foreseen).
- **Adaptation to circular e+e-** machines with higher rates:
  - Interplay with forward calorimetry developments (where the rates are relatively high even at linear colliders)
  - Externally trigger? Low consumption without powerpulsing?
- For **hadron** machines, **radiation** issues become relevant again: **where can we irradiate large surface detectors?**
- High processing speed, high data compression, etc.
  - “adding software” into the front end (neural networks)

Open challenges (silicon sensors)

- ▶ **Highly integrated silicon sensors** → CMOS, ultragranular option, fully digital (see **T. Peitzmann talk**)
- ▶ How to implement **timing**?
  - **APD**, **LGADs**, (**thin** sensors with **gain**)
  - Newer options SPAD (avalanche diode with geiger-mode gain, can be monolithic)
  - Require **dedicated electronics** → **challenge** on the **power** management
- ▶ **Thicker** sensor → **larger charge S/N**
- ▶ Integration of larger surface **8" sensors**
  - Experience from **HGCAL**
- ▶ Strengthen synergies with industry.

LGAD (Low Gain Avalanche Detector)



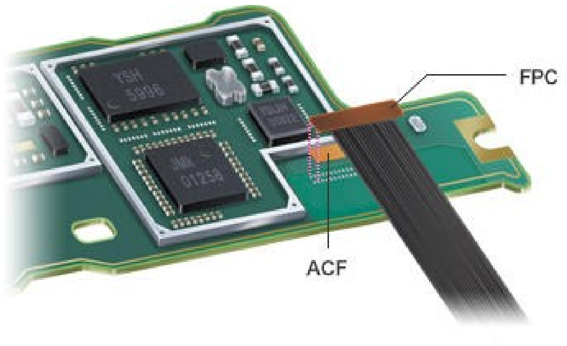


Open challenges (Silicon-PCB integration)

Near Future (~5 years)

▶ Current technological prototype solution for sensor-PCB connection is based on epoxy-silver glue.

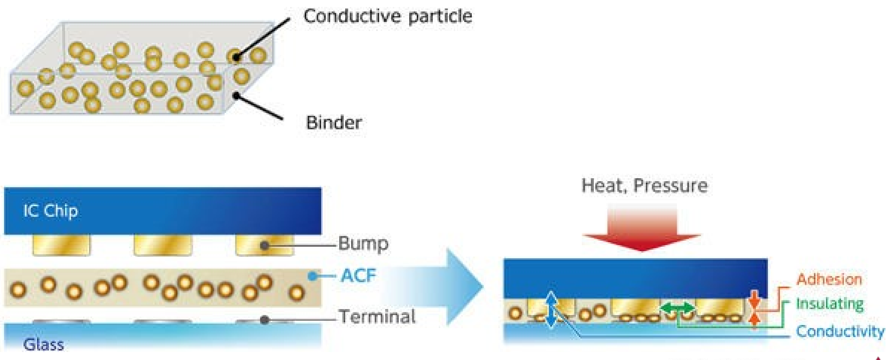
- Mechanical strength, industrialization, durability… to be studied.
- Silver → may be an issue on high radiation environments



▶ R&D Alternative solutions:

- through-hole wire bonding (à la HGCAL → could limit the extreme high granularity goals of PF ECALs)
- Check what the industry is doing (smartphones, LCD screens, etc)

  → Anysotropic Conductive Films, Micropearls… (investigated also in the context of LUXE)



▶ Similar issues are to be investigated about the interconnection of the (PCB+Silicon) to absorber/mechanics

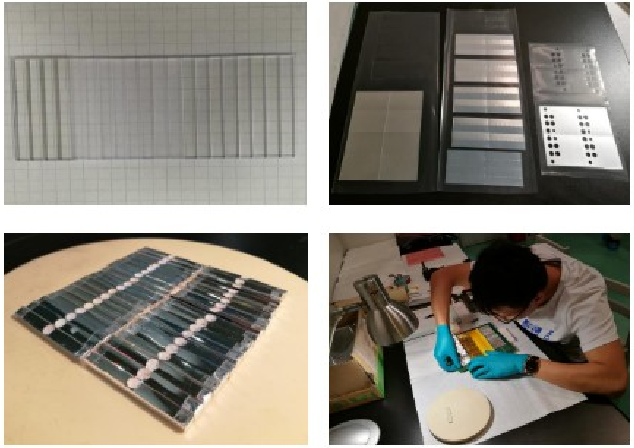
- Independently of the active material (Si or Sc)

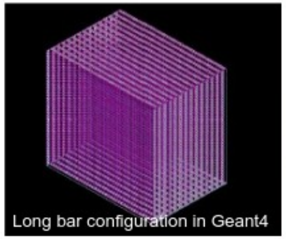
Open challenges (Scintillators/SiPMs)

Ongoing and Near Future (~5 years)

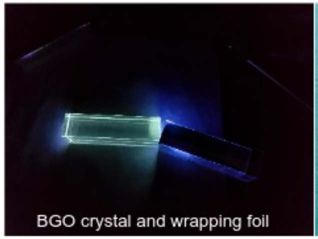
- ▶ Engineering work for **large scale production**
  - Injection moulding, automated assembly, system for QC/QA
- ▶ **Improvement of timing** performance with **dedicated timing layers** ~10ps
  - Scintillator tile + larger SiPM with high light yield → better time resolution
  - Cherenkov detector based on RPC-GasPM (New R&D)
- ▶ **R&D on new materials:**
  - High Granular Crystal Calorimetry

Strip wrapping and assembly on EBU was done by hand (Shanghai Institute of Ceramic)

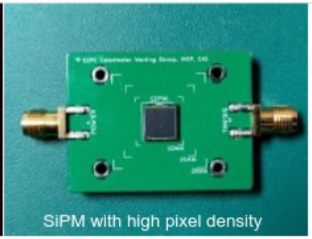




Long bar configuration in Geant4



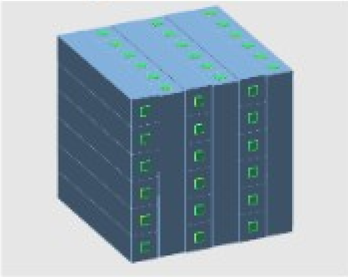
BGO crystal and wrapping foil

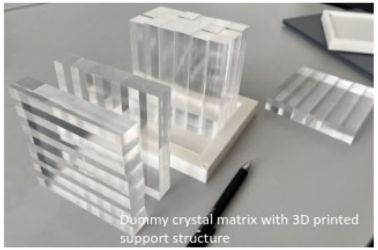


SiPM with high pixel density

SiPM readout electronics

Single EM module





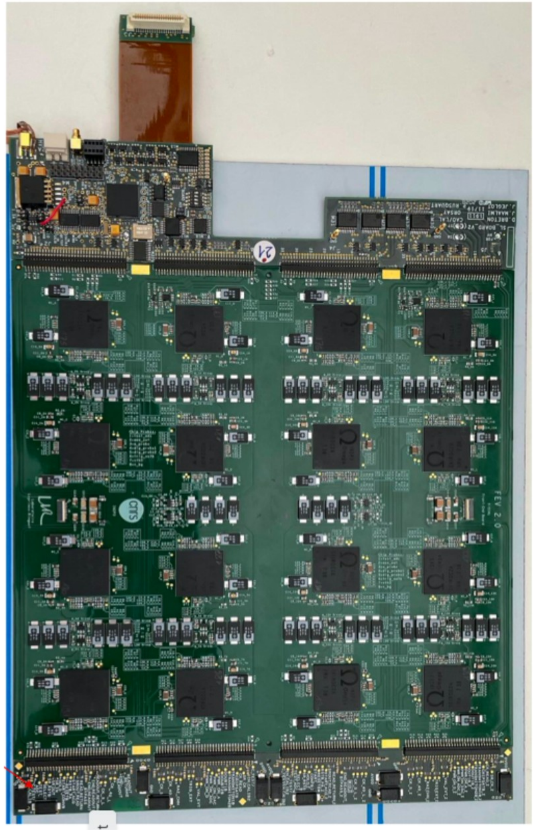
Dummy crystal matrix with 3D printed support structure

Open challenges (PCBs)

R&D happens in close communication with concept groups

Near Future (~1-3years)

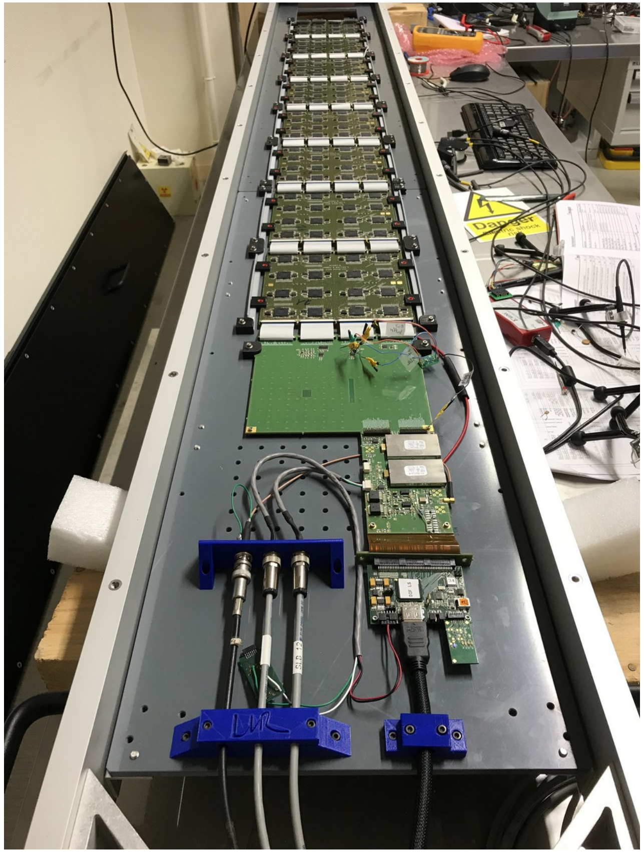
- **R&D iterations** for PCB design optimization for **testbeam** and other applications
- **Compactness** requirements:
  - Going **thinner** → challenge for very complex PCBs
  - **Thinner passive components** → needed for all, but key for power pulsing operation
- R&D on high **reliability** connectors/components → its importance is sometimes underestimated



Mid/Long Term Future

- **Adaptation** to different experiments (higher rates, higher radiation damage)
- **Industrialization**, mass production.
- Obtain **Quality Assurance** competences → in synergy with industry and other DRD
- For **hadron machines**, radiation issues become relevant again: where can we **irradiate large surface** detectors?

Full length modules & Open challenges



- Already an **existing prototype** (2m) for SiW-ECAL
  - Non compact mechanics
  - Not optimized for power pulsing
  - New prototype to be built with the new design of **PCB optimized for power pulsing** (with local storage of power)
- **Power pulsing is a particular challenge for long layers**
  - Build long layers as exercise to solve other issues for this type of detectors (connectors, signal processing)
- What about for **high rate circular colliders**?
  - These machines **require**, in the next 2-3 years, dedicated **simulation studies** before **hardware requirements** can really be formulated (CEPC may accelerate this process)

Mechanics / Cooling & Open challenges

▶ **Compactness** requirements on ECAL for PFA are very strict

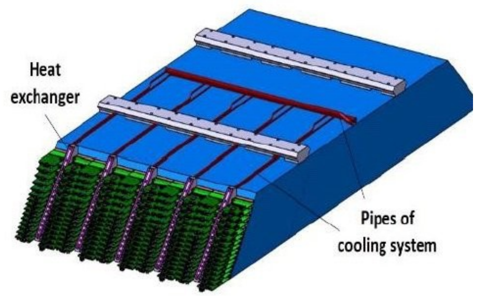
- Very little space for services / DAQ
- Cooling system developed for ILD → SiW-ECAL readout electronics designed accordingly

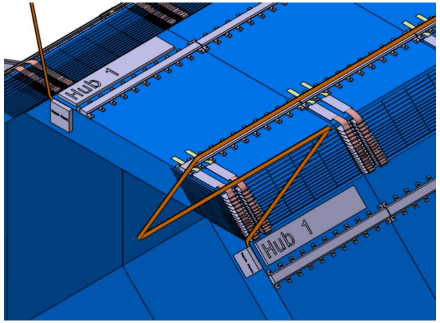
Near Future (1-5years)

▶ **Study** the impact of **"extra" cooling to cope** with **high rates** from other experiments (or with very demanding timing requirements).

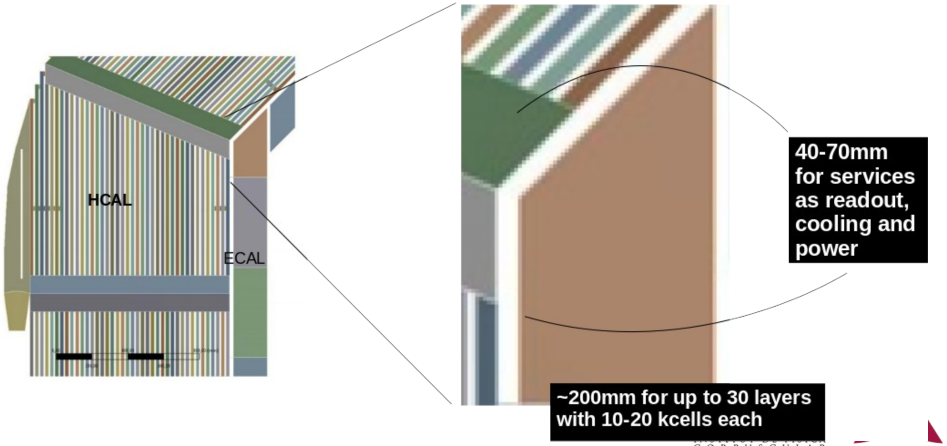
- **Simulation** and **integration studies**
- still, the goal should be to perform R&D on low consumption electronics

Zoom into ILD Ecal barrel





- Total average power consumption 20 kW for a calorimeter
- system with 10^8 cells*
  - Only possible through PP



R&D Steps: Medium-Long Term

- On chip processing on CMOS sensors allows compact design
- Achieved in prototype: $R_M \approx 11\,\mathrm{mm}$
  - Ultra-thin flex cables for all connections
  - Cooling via tungsten plates (possible for small dimensions only?)
  - No dead area due to overlapping sensors
- Need to scale up integration to realistic detector size
  - Compactness (small Moliere radius) scalable?
  - Cooling solutions (e.g. micro channels)?
    - Requirements depend on sensor power consumption
  - First experience to be obtained in ALICE-FoCal for single pixel layers, to be extended to full pixel detector design

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hardware/engineering R&D

T. Peitzmann, Utrecht University/Nikhef
ECFA Detector R&D Roadmap Task Force 6: Calorimetry Community Meeting

R&D Steps: Long Term

- Develop dedicated pixel sensor for calorimeter (connection to DRD3)
  - Enhance rate capability
  - Move from binary to few bits
  - Add timing information?
  - More intelligent on-chip processing
    - Data reduction, reconfigurable pixel-arrays? Compromise on position accuracy?
    - Consider optimal threshold strategy
    - Trigger information?
  - Power consumption?
- Investigate alternative sensor technology (LGADs, …)?

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hardware/CMOS sensor R&D

T. Peitzmann, Utrecht University/Nikhef
ECFA Detector R&D Roadmap Task Force 6: Calorimetry Community Meeting


TOUTES DIRECTIONS
AUTRES DIRECTIONS