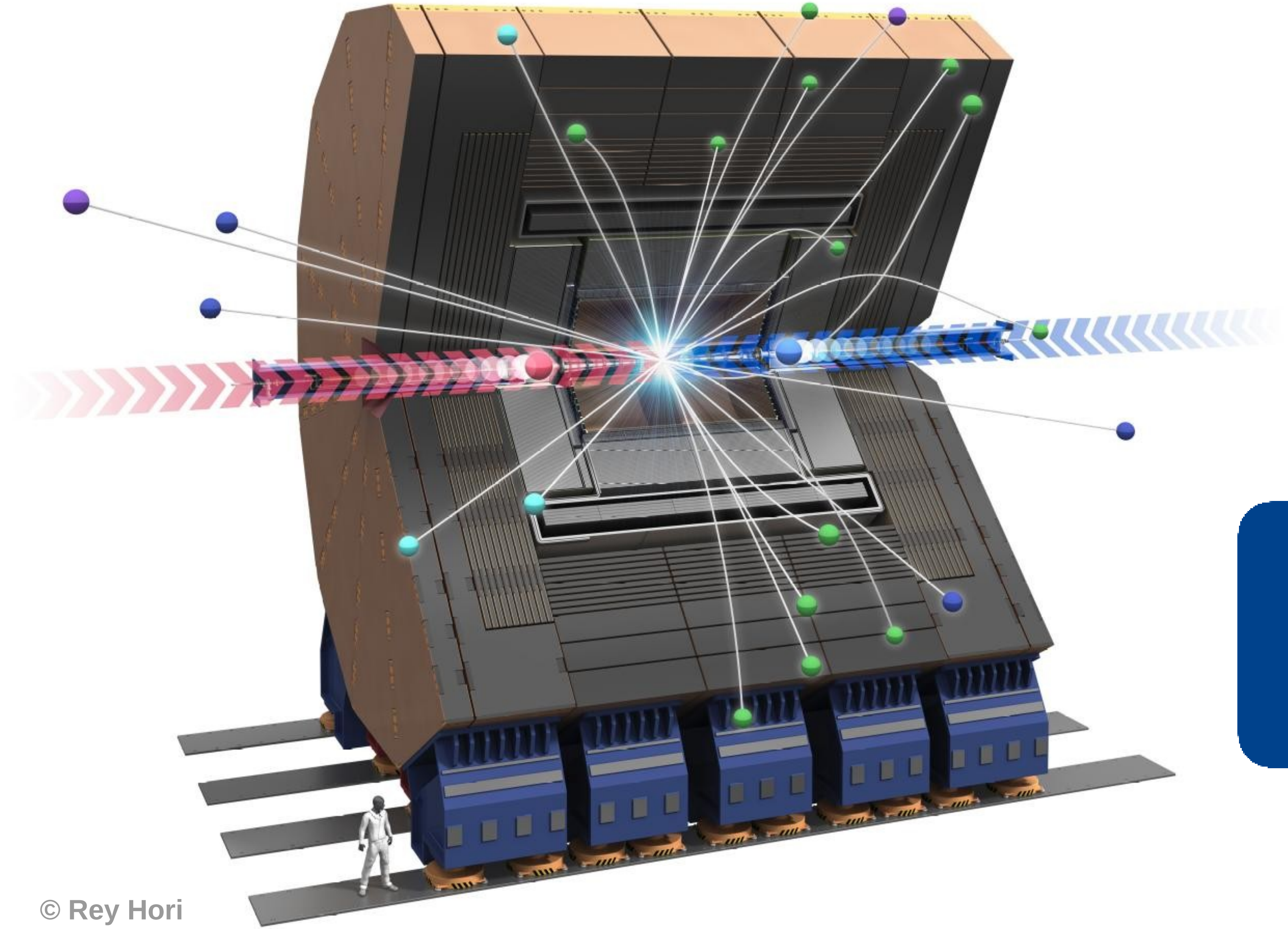
Spanish Highly Segmented Calorimetry Activities for Future Colliders

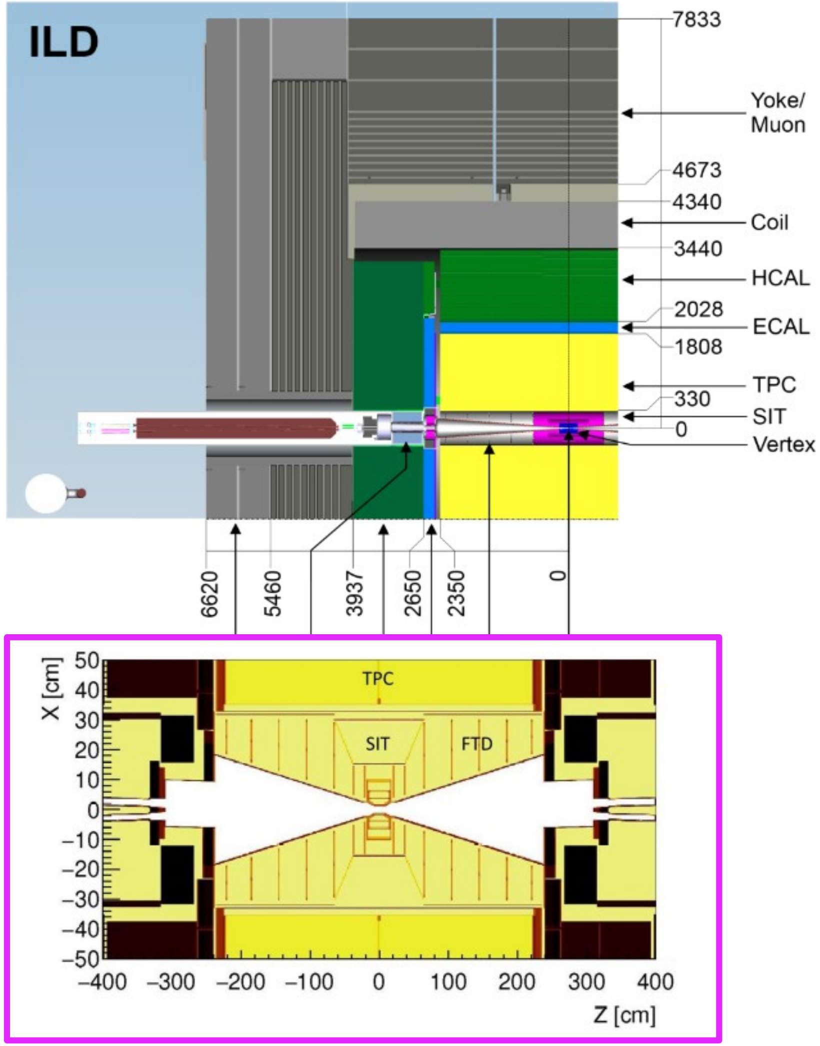
A. Irles

AITANA group at IFIC – CSIC/UV



© Rey Hori

Design of a PF detector



▷ **Holistic** approach:

- Tracking, vertexing, PID detectors, calorimeters, coils, etc.. all systems are at the service of the event reconstruction

▷ Maximal **acceptance** minimizing cracks, dead material, endcap-barrel transitions…

- Forward calos as close as possible to the IP.

▷ **Minimum material** in front of the calorimeters,

- Low material budget tracking systems.
- Calorimeters **inside a large magnetic field** (no coil between trackers and calos)

▷ **Highly compact calorimeters** (cost and physics)

- **Readout is highly integrated**: data processing done “in” the detector

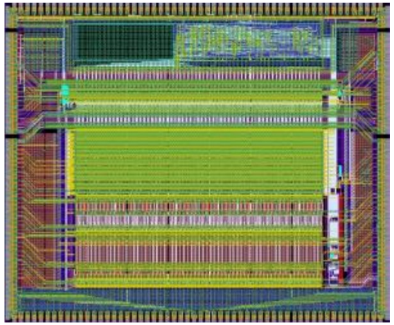
▷ **Highly Granular calorimeters**

- Between 10^6-10^8 channels (barrel)

High-Granular Calo: Technological premises

Highly integrated (very) front end electronics

e.g. SKIROC (for SiW Ecal)

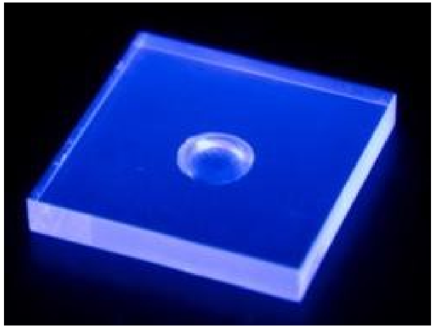


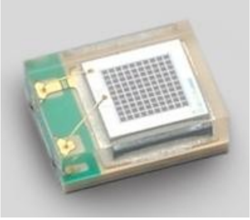
Size 7.5 mm x 8.7 mm, 64 channels

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

- **Common developments on different CALICE projects**

Miniaturisation of r/o devices





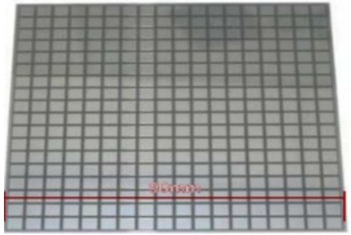
- Small scinitllating tiles
- (Low noise) SiPMs

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

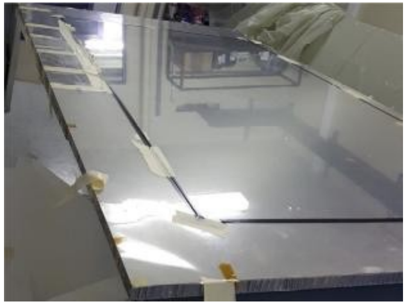
Self trigger of individual cells below MIP level

Large surface detectors

Si Wafer



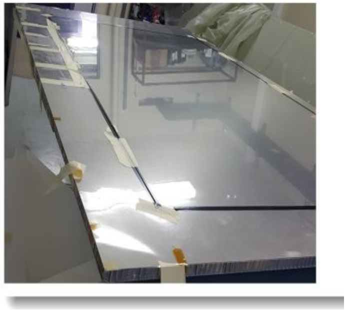
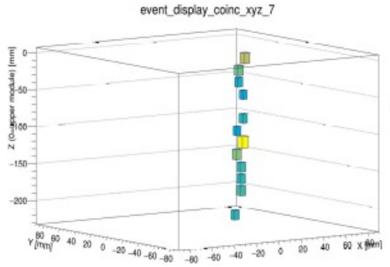
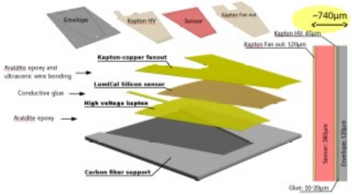
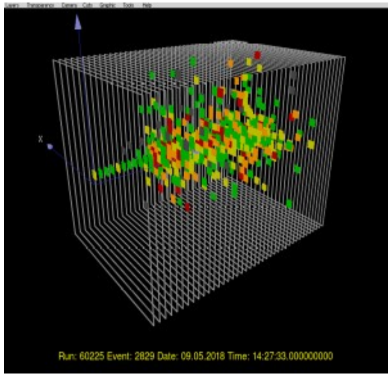
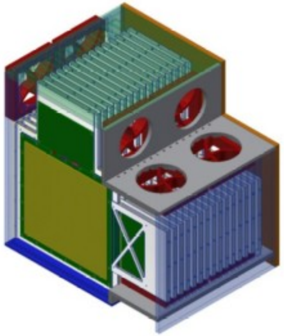
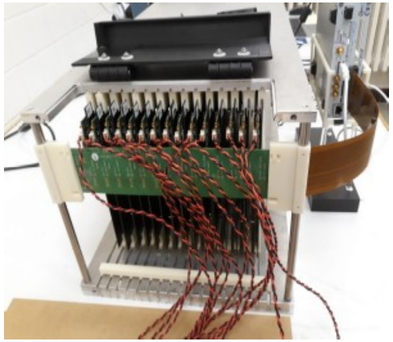
RPC layers



Calorimeter for ILC

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

Prototyping + intensive TB phase

AHCAL	Sc-ECAL	SDHCAL	SiW-ECAL	Lumi-CAL
		2 m^2 RPC assembled 		
				

All calorimeter options built large size prototypes → linear and/or circular colliders
Tested at DESY/CERN in common beam tests including telescope synchron.

Prototyping + intensive TB phase

AHCAL

Sc-ECAL

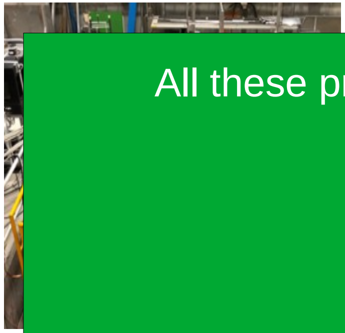
SDHCAL

SiW-ECAL

Lumi-CAL

2 m^2 RPC assembled

event_display_coinc_xyz_7

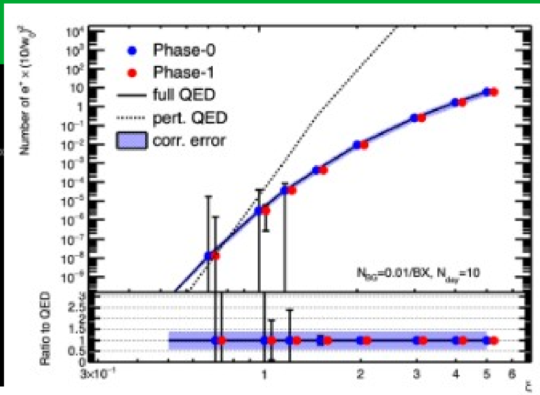


All these prototypes are **tailored for ILD-Linear Collider** but also adopted for other concepts:

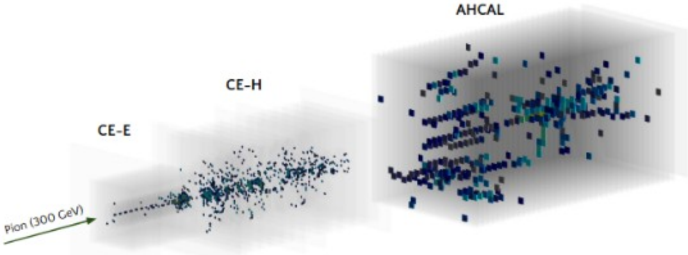
Linear and Circular Higgs Factories:
CLICd, SiD (ILD), C3, CLD (FCCee), CepC detectors

Other experiments:
LUXE, EBBES, Lohengrin…

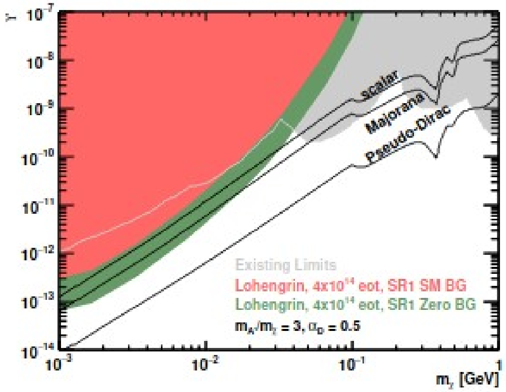
AND have been instrumental for **HL-LHC upgrades**
CMS-HGCAL



LUXE and LUXE-NPOD
https://arxiv.org/pdf/2308.00515



CMS-HGCAL prototyiping and test
https://arxiv.org/pdf/2211.04740



Lohengrin https://arxiv.org/pdf/2410.10956

Silicon ECALs

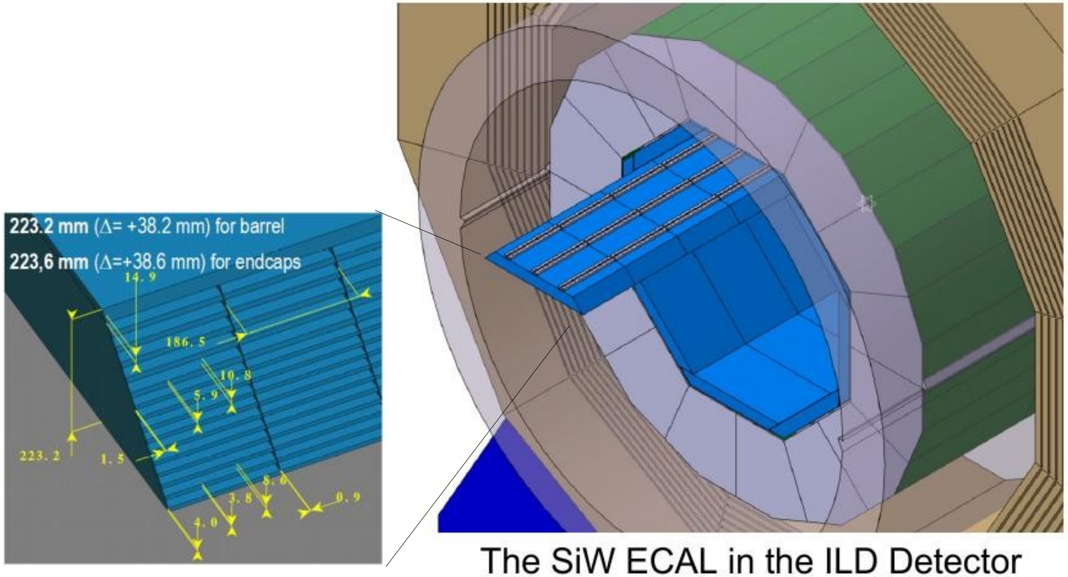
SiW-ECAL for future LC

▷ **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

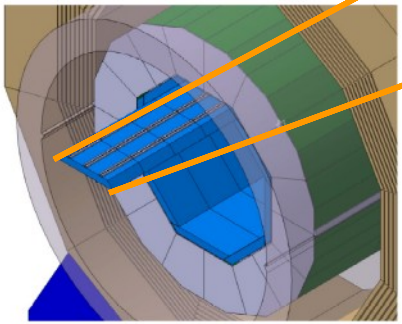
- Support **compact** designs
- Allows **pixelisation**
- **Robust technology**
- **Excellent signal/noise** ratio

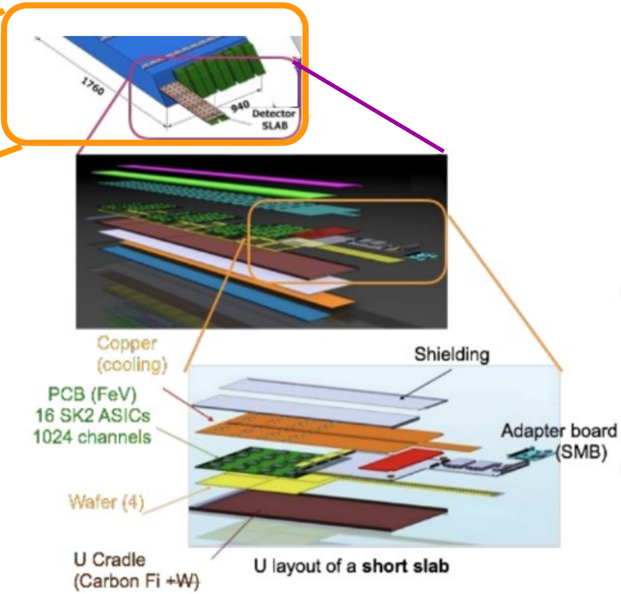


The SiW ECAL in the ILD Detector

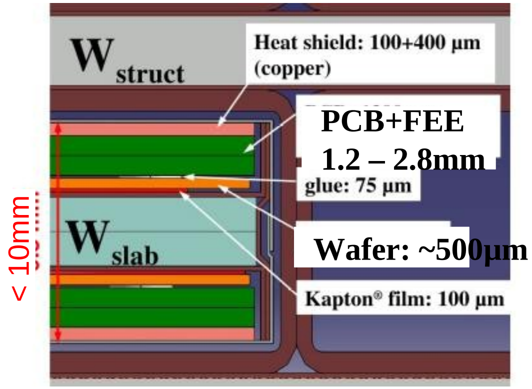
The **SiW ECAL R&D** is tailored to meet the specifications for the **ILD** ECAL **baseline** proposal

Requirements: highly integrated

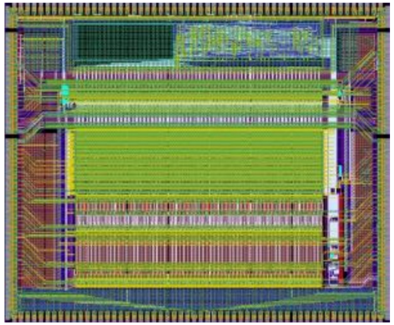

The SiW ECAL in the ILD Detector



SiW Ecal



e.g. SKIROC (for SiW Ecal)



Barrel

- ▷ O(10^4) slabs
- ▷ O(10^5) ASUs (PCB+wafer+ASIC+DigReadout)
- ▷ O(10^{6-7}) ASICS
- ▷ O(10^8) cells
  - 2000 m² of Si
- ▷ 130 T of tungsten

Cell size of 5x5 mm → all cells are self triggered + zero suppression

Size 7.5 mm x 8.7 mm,

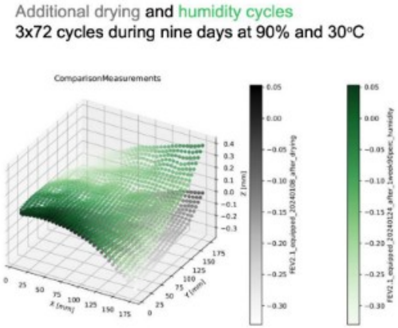
64 channels

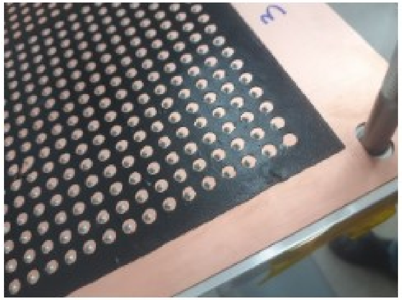
Dual gain, autotrigger, powerpulsed

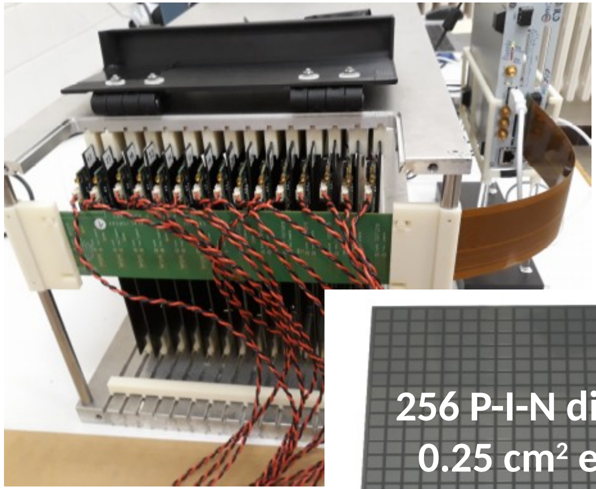
(goal of 25uW / chn)

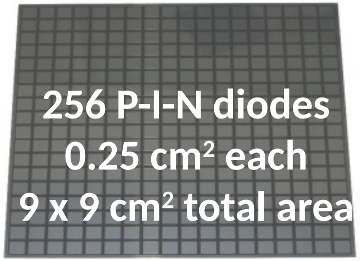
SiW-ECAL

SiW-ECAL (<2020)
- **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**
- **Sensor delamination issues**





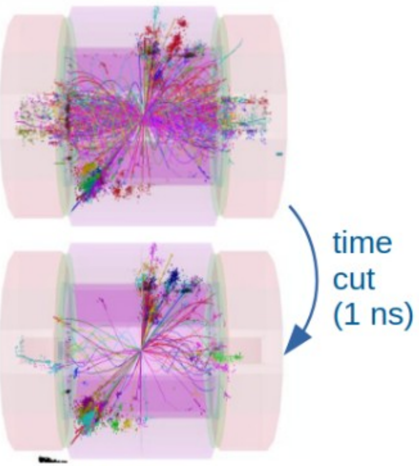




EUDET layout
Prototype from Hamamatsu

SiW-ECAL (ongoing)
- Goal 15 layers 18×18 cm²
- **New PCB generation & ASICs**
- **R&D on optmized hybridization**
- **Ongoing studies on requirements for Circular Colliders:**
  - - high fluxes
  - - cooling
- **5d calorimetry**

Cleaning of Events

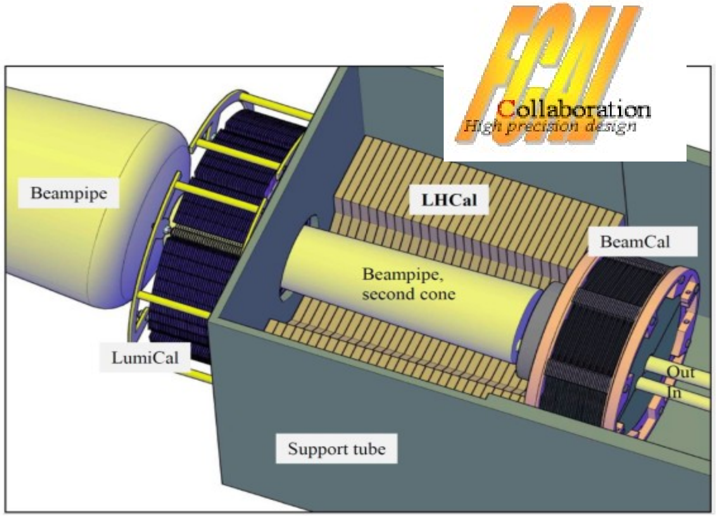


[CLIC CDR: 1202.5940]
adapted from L. Emberger

Forward Calorimetry (extreme compactness)

- ▷LumiCal for precise luminosity measurement (Counting Bhabhas)
- ▷BeamCal for fast luminosity measurement (using beamstrahlung)
- ▷Technology choice: Si or GaAs/W sandwich calorimeters
- ▷1 X0 absorber thickness per layer, 20 (30) layers in ILC (CLIC)
  - Optimal geometries for FCC being studied
- ▷Recent progress:
  - investigation of new GaAs sensors with integrated signal routing → similar signal size to silicon sensor
  - **FLAMe and FLAXE ASICS** development and production

    (ongoing)



Slide from K. Krueger

Requirements: highly compact

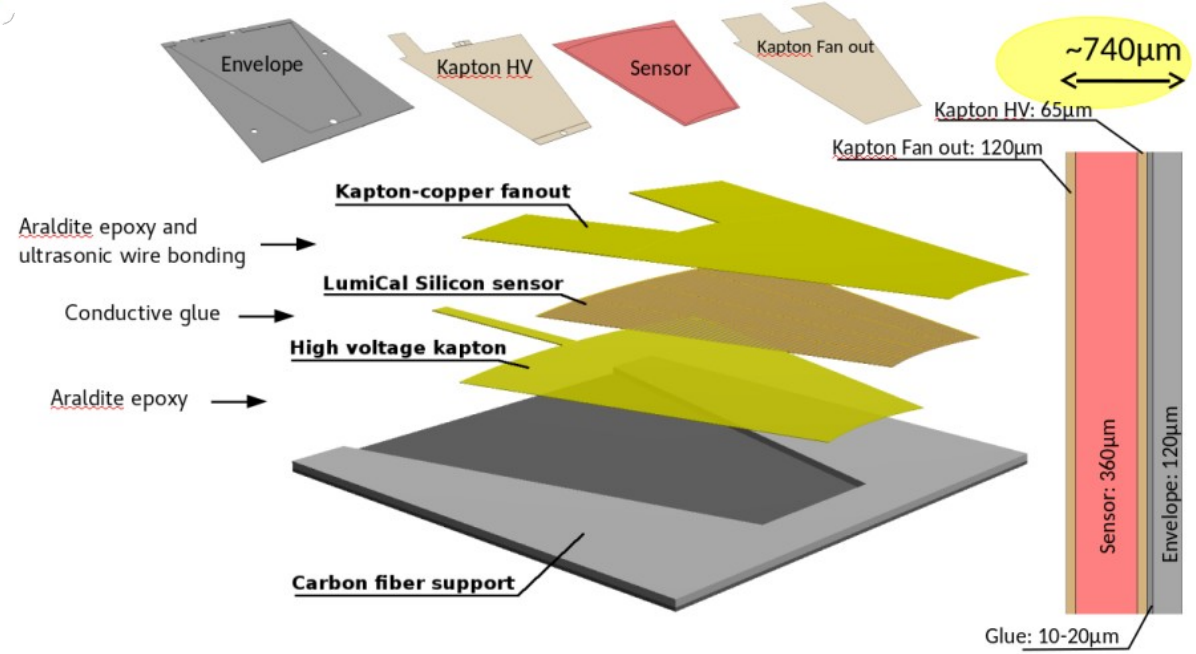


Figure 5.13. Structure of a sensitive layer of the LumiCAL calorimeter.

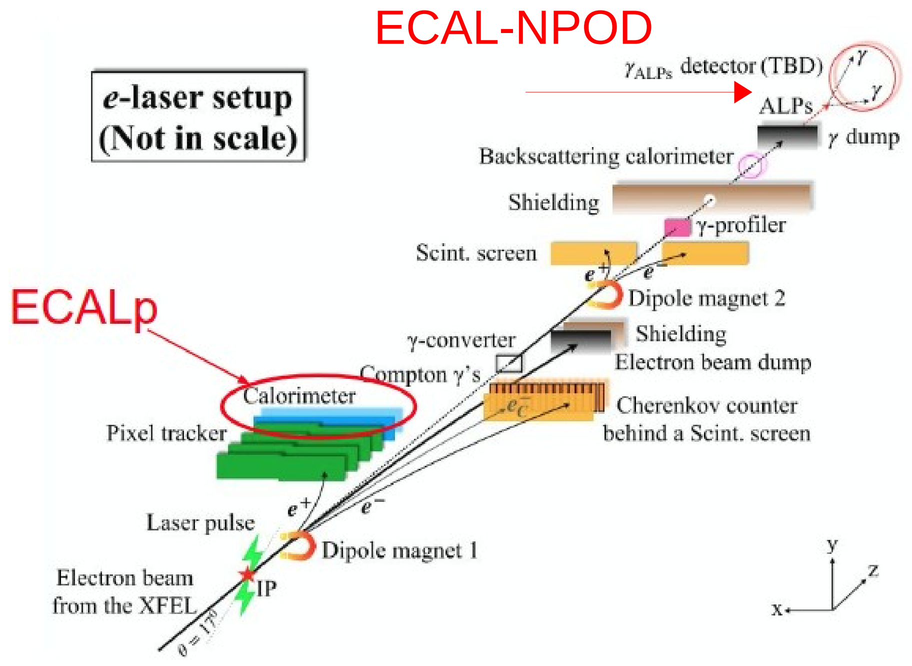
Forward region (LUMICAL)

- Ultra thin layers <1mm for minimal Moliere Radius
- Not embedded electronics
- Higher radiation levels

The LUXE ECAL systems

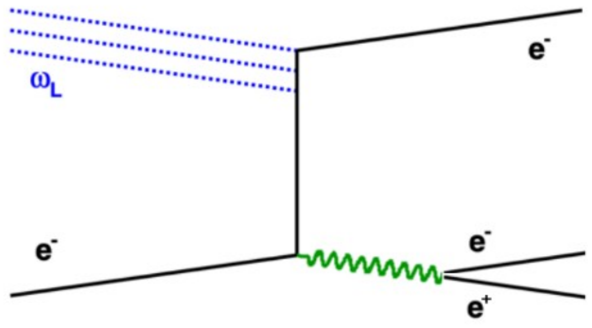
▷ LXUE Dedicated to Strong Fields Quantum Electrodynamic studies

- Makes use of 17.5 GeV Eu.XFEL electron beam colliding with intense optical laser pulses
- Dedicated searches of BSM profiting from intense gamma beam (non-linear compton)



Layout optimization for the LUXE-NPOD experiment (Quispe, Trevisani et al) https://arxiv.org/abs/2507.17716

$$e^- + n\omega_L \rightarrow e^- + e^- + e^+$$

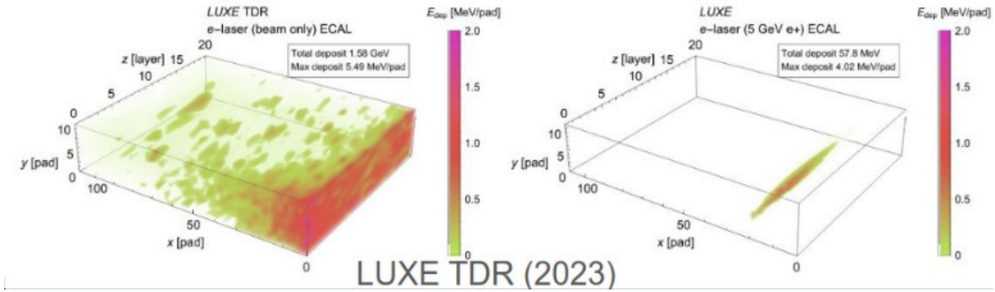


Positron-electron pair production not accessible in “standard” QED...
⇒ “smoking gun” for non-linear processes...

Challenges – proposed solutions

▷(main) **Challenges SF-QED**

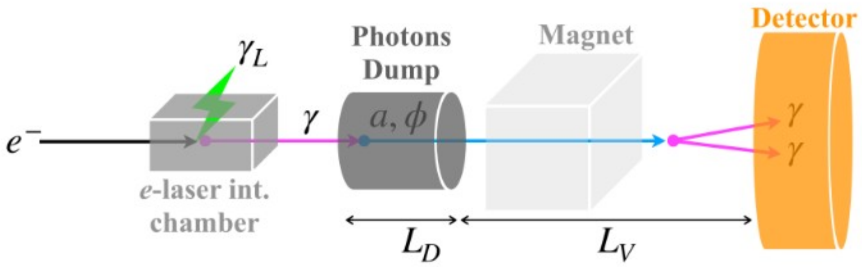
- Two modes with expected number of positrons varying from 10^{-4} 10^{7}
- EM shower overlap at high multiplicity
- Low multiplicity showers immersed in low energy widely spread background



LUXE TDR (2023)

▷(main) **Challenges BSM searches**

- Very low multiplicity of events,
- Low mass ALPs decaying into two photons (E~1-3GeV)
- Background rejection capabilities



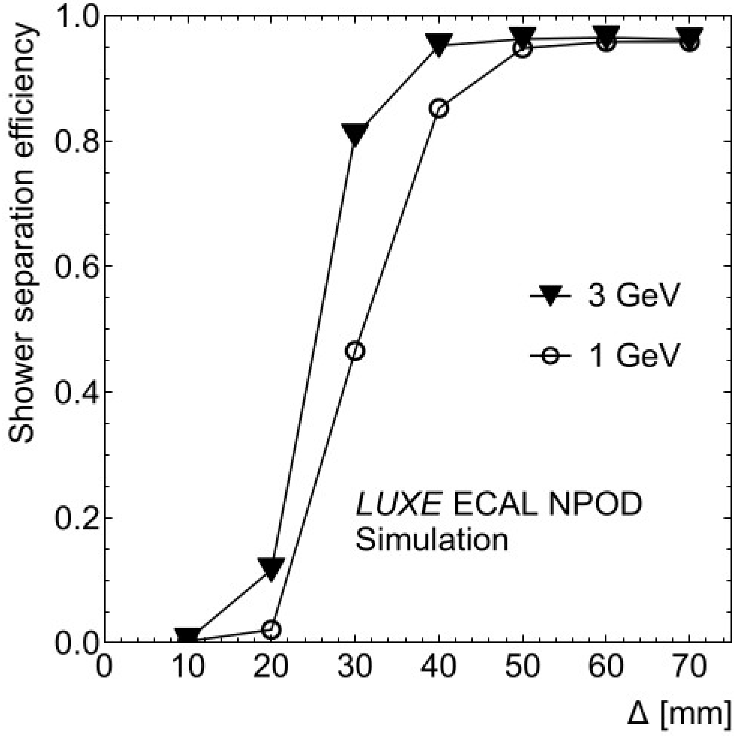
▷**Similar solutions for both**

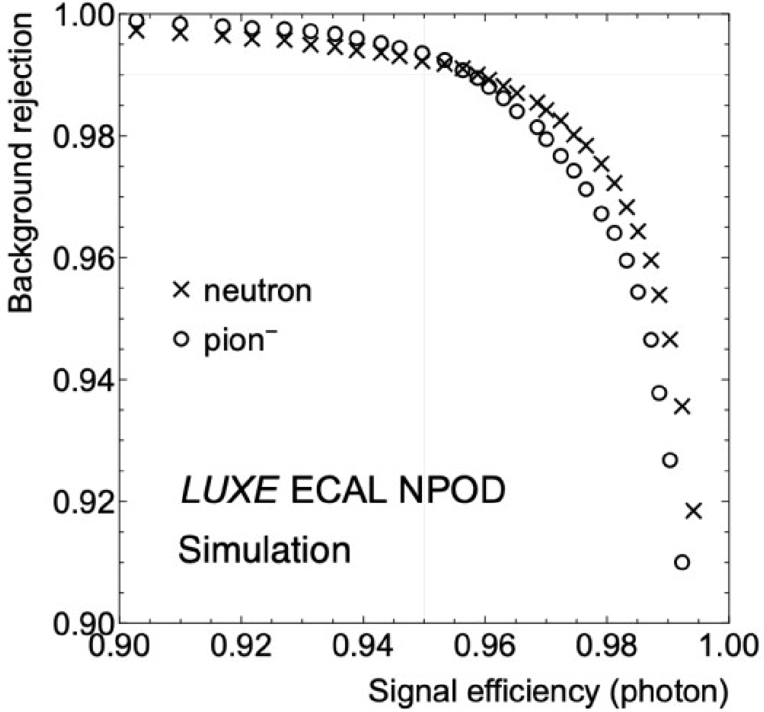
- Compact sampling calorimeter
- Small Molière radius
- High granularity

ECALe = proposed by FCAL group
ECAL-NPOD = proposed by SiWECAL group

ECAL-NPOD (aka SiWECAL)

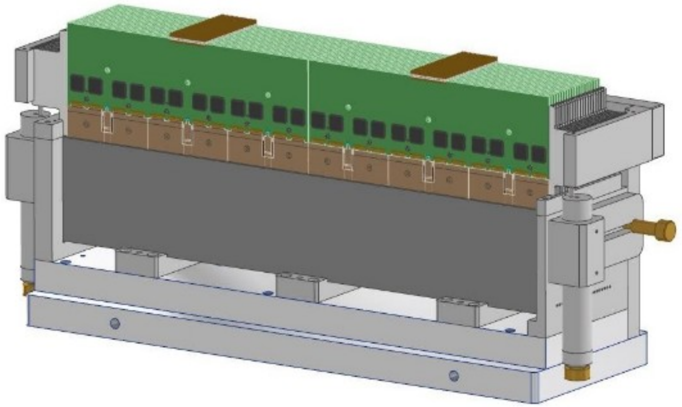
Layout optimization for the LUXE-NPOD experiment https://arxiv.org/abs/2507.17716v1





ECALp (aka. HighCompactCalo - FCAL)

- ▷ Positron calorimeter
- ▷ Highly compact and modular calorimeter to minimize the Molière radius.
- ▷ Design based on the concept considered by the FCAL collaboration for compact calorimeters
  - 21 tungsten plates of 1 X0
  - 1 mm sensor gaps between
  - 20 active planes with 6 sensors per plane
  - Front-End-Boards (FEB) above the sensors
  - Requires dedicated sensor sandwich design (designed and produced at IFIC)
  - dedicated FEB, readout scheme and mechanics.
- ▷ Realistic design presented in LUXE TDR.
- ▷ Tests of the first prototype took place in June 2025.



ECALp (aka. HighCompactCalo - FCAL)

▷ Positron calorimeter

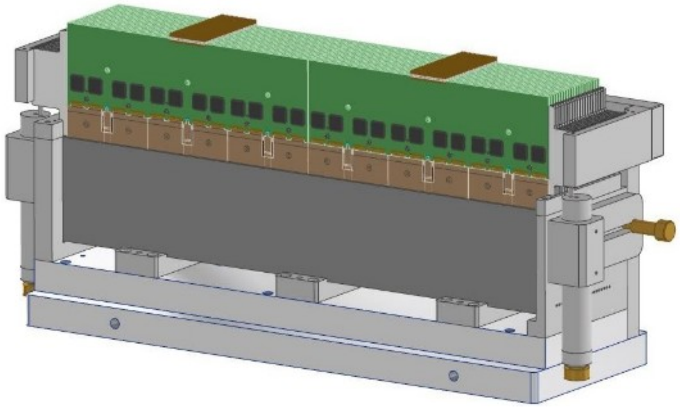
▷ Highly compact and modular calorimeter to minimize the Molière radius.

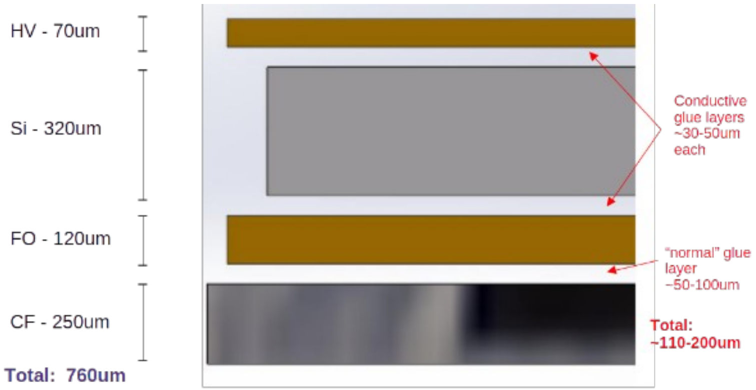
▷ Design based on the concept considered by the FCAL collaboration for compact calorimeters

- 21 tungsten plates of 1 X0
- 1 mm sensor gaps between
- 20 active planes with 6 sensors per plane
- Front-End-Boards (FEB) above the sensors
- Requires dedicated sensor sandwich design (designed and produced at IFIC)
- dedicated FEB, readout scheme and mechanics.

▷ Realistic design presented in LUXE TDR.

▷ Tests of the first prototype took place in June 2025.

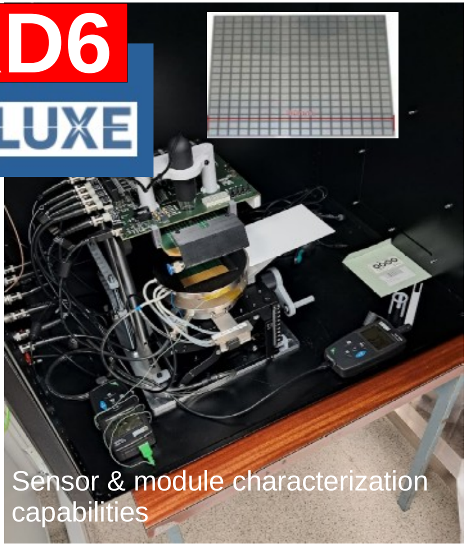




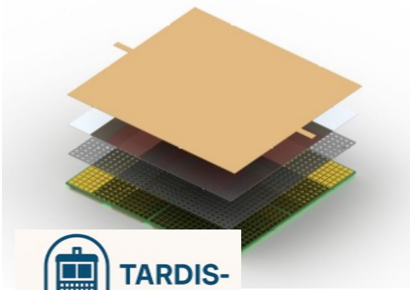
TARDIS-Lab for ECAL hybridization

- **New facility and capabilities at IFIC**
- **IFIC is the the hub** for module hybridization R&D / production / commissioning for DRD6 Si-ECALs and for the LUXE experiment
- Hybridization of large surface sensors (PiN Hamamatsu) in rigid and flex PCBs
  - For high integration (barrel detectors)
  - Or for high compactness (forward calorimetry, strong-field qed calorimeters)

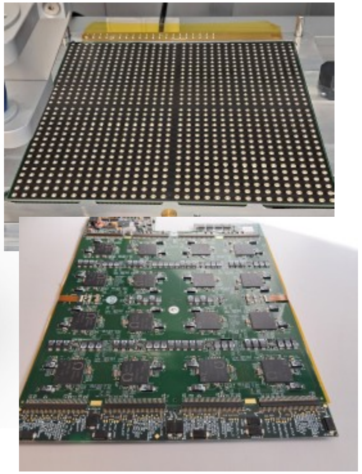
New installation at IFIC

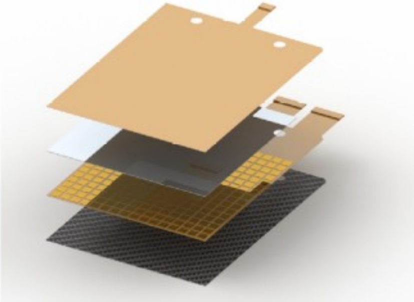

Sensor & module characterization capabilities

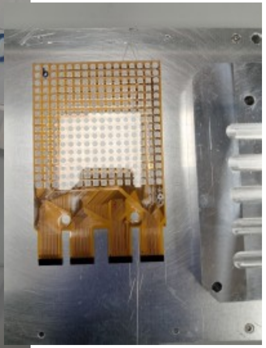
DRD6 ILD LUXE



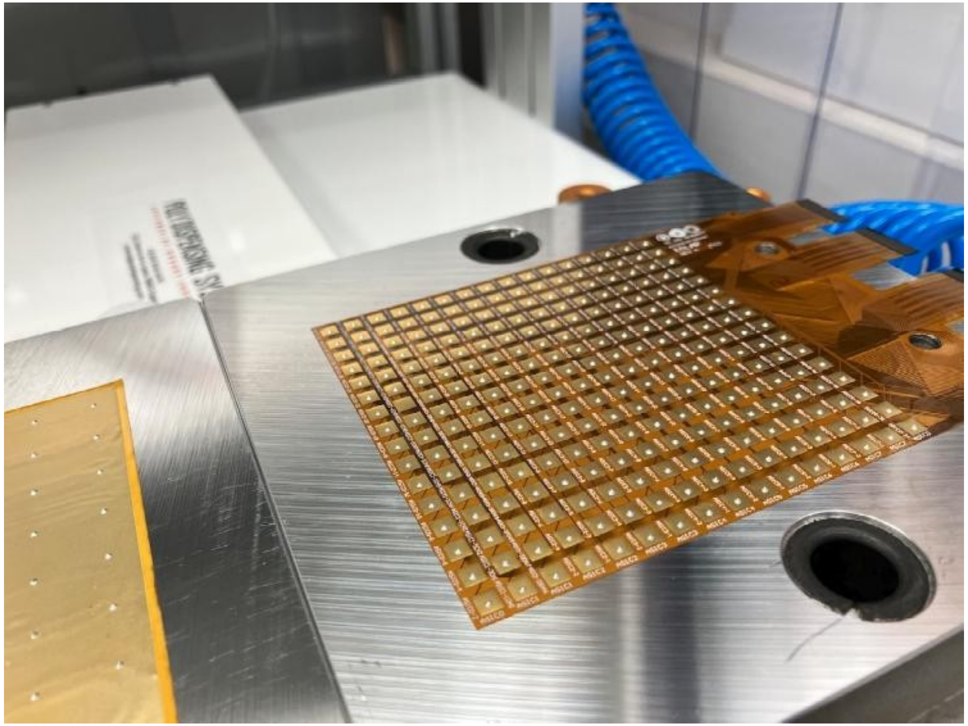
TARDIS-Lab

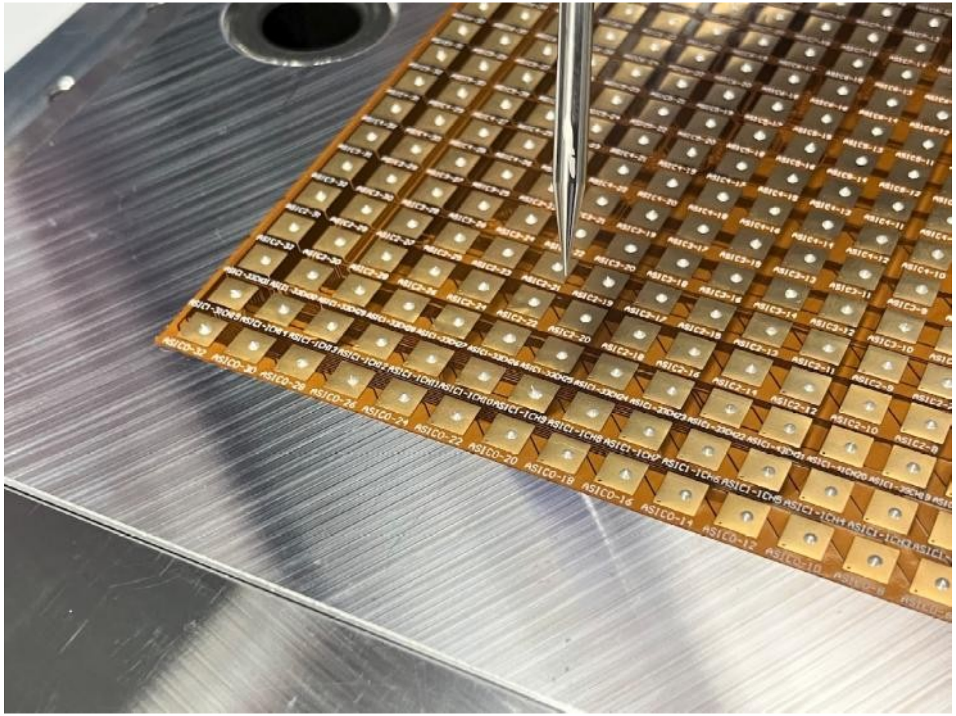




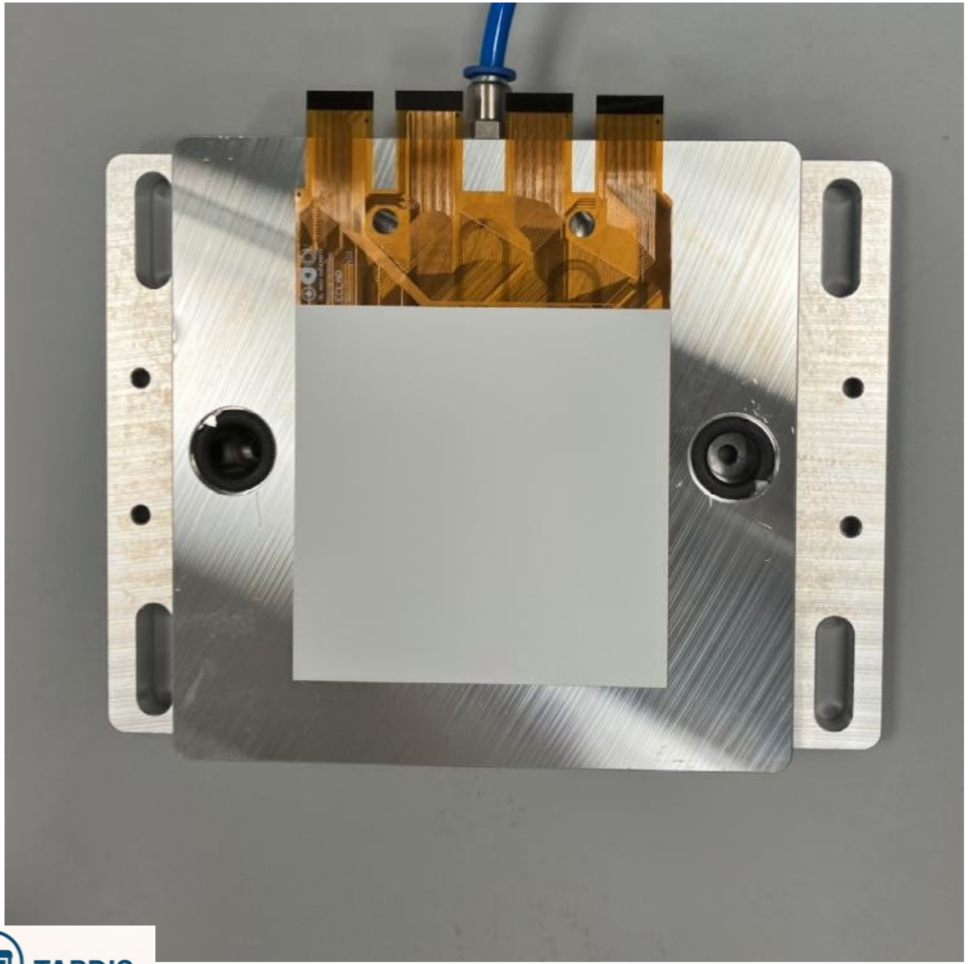


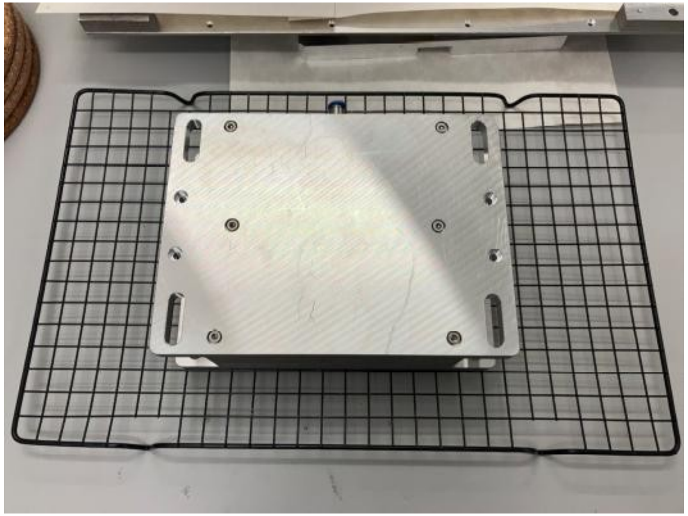
TARDIS-Lab for ECAL hybridization

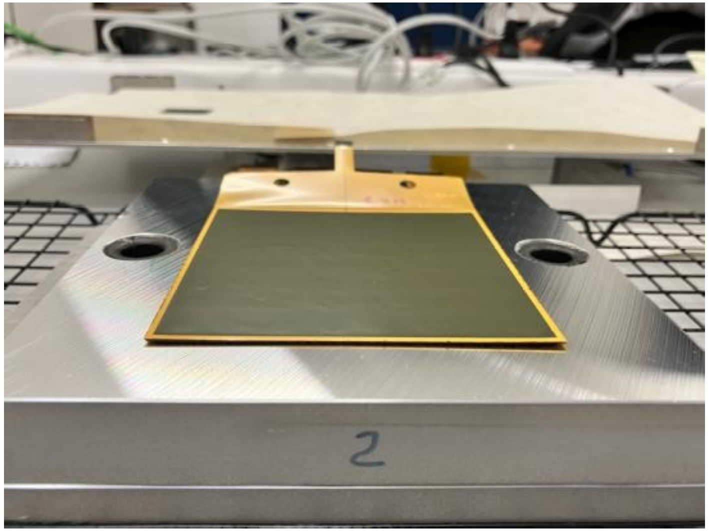




TARDIS-Lab for ECAL hybridization

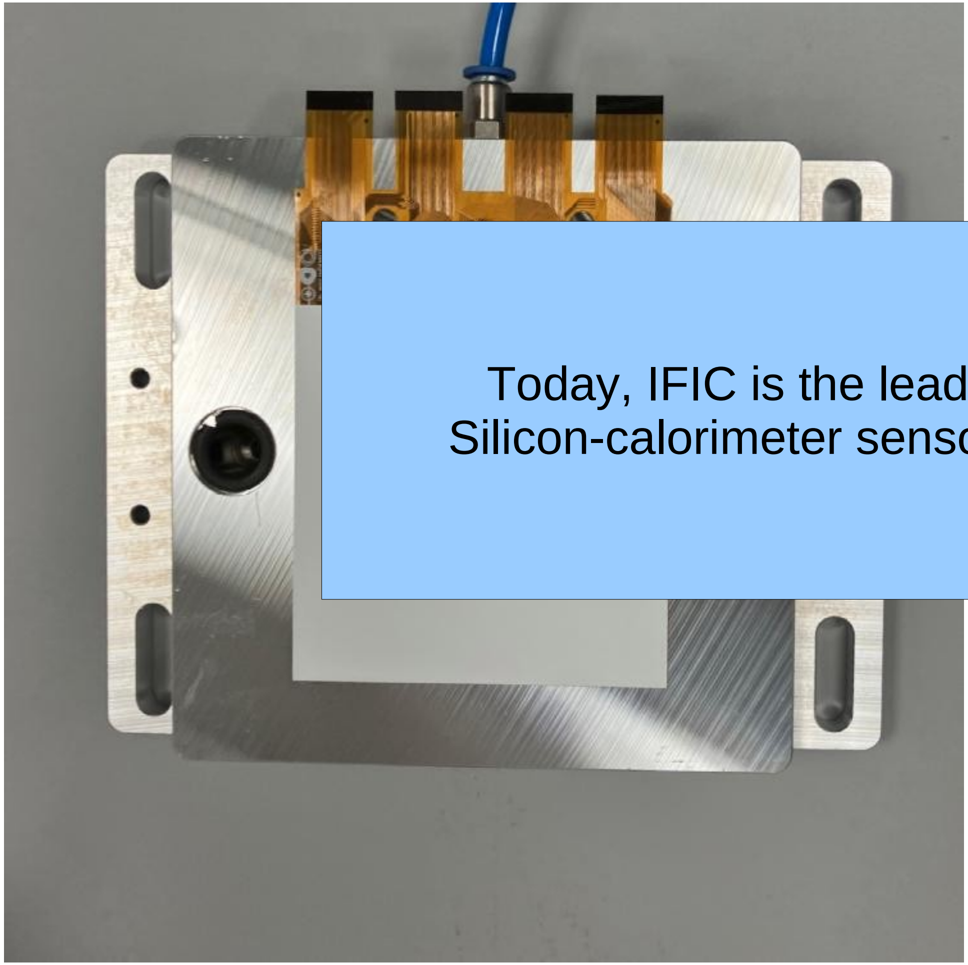




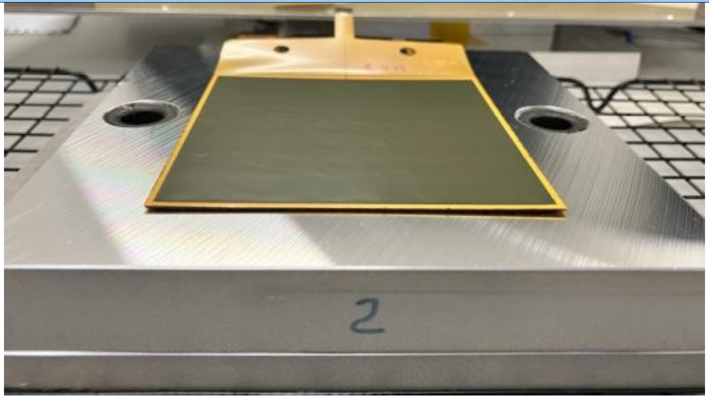


TARDIS-Lab

TARDIS-Lab for ECAL hybridization

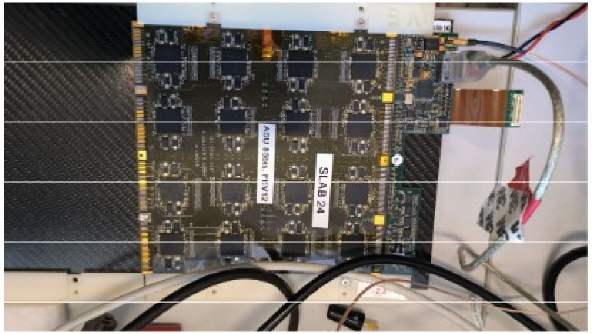


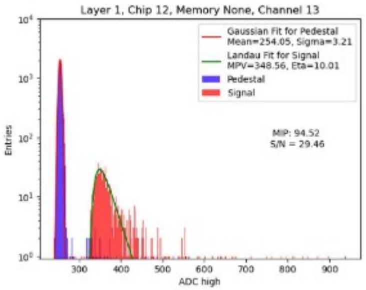
Today, IFIC is the leading center in the DRD-Calo on Silicon-calorimeter sensor assembly and characterization



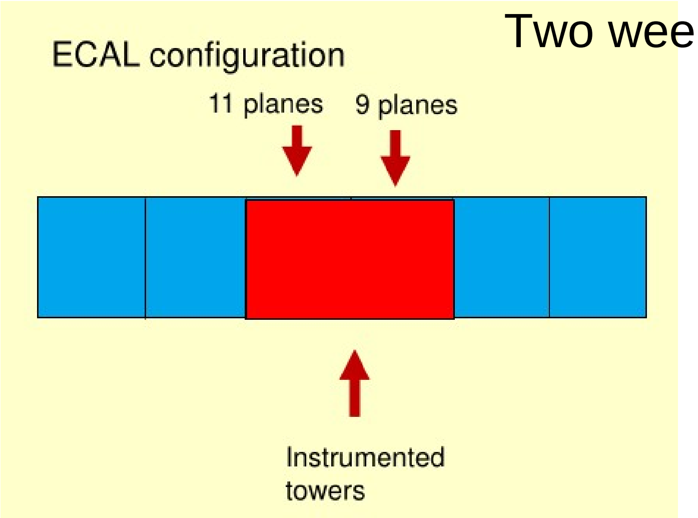
SiW-ECAL beam test at DESY

- ▷3 layers (1-chip on board, 2 new FEV2.1 boards optimized for power-pulsing)
  - New hybridization techniques → developped by CNRS/IFIC
  - 32x32 cells of 5.5 x 5.5mm²
- ▷Two weeks of data taking
  - ECAL standalone MIP calibration (and TDC calibration)
  - ECAL+HCAL → common data taking using AIDA TLU + EUDAQ

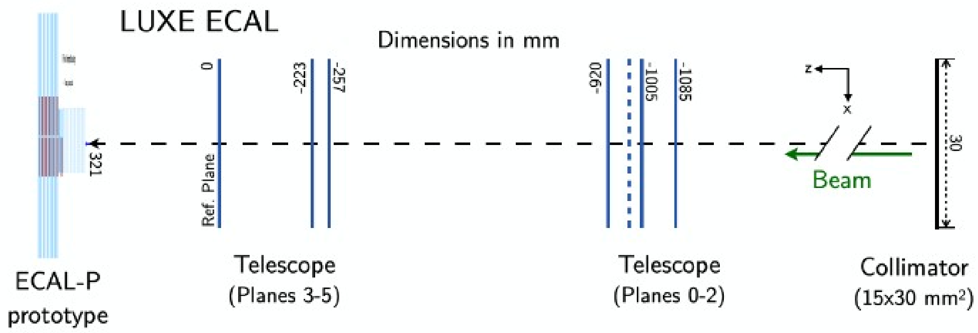




ECALp Beam test setup



Two weeks of beam test at DESY – around 250M triggers (TLU)



▷**Tracker mode**

▷Initial runs with 3 layers

- **Area Scan** but mostly debugging

▷**Ful stack**, with 11 layers

- ~10 M at two positions (3 GeV)
- **Area scan** with ~1 M per position (5GeV, **35** positions)

▷**Calorimeter mode**

▷**Position scan**, 11X0 & 9X0 (5GeV)

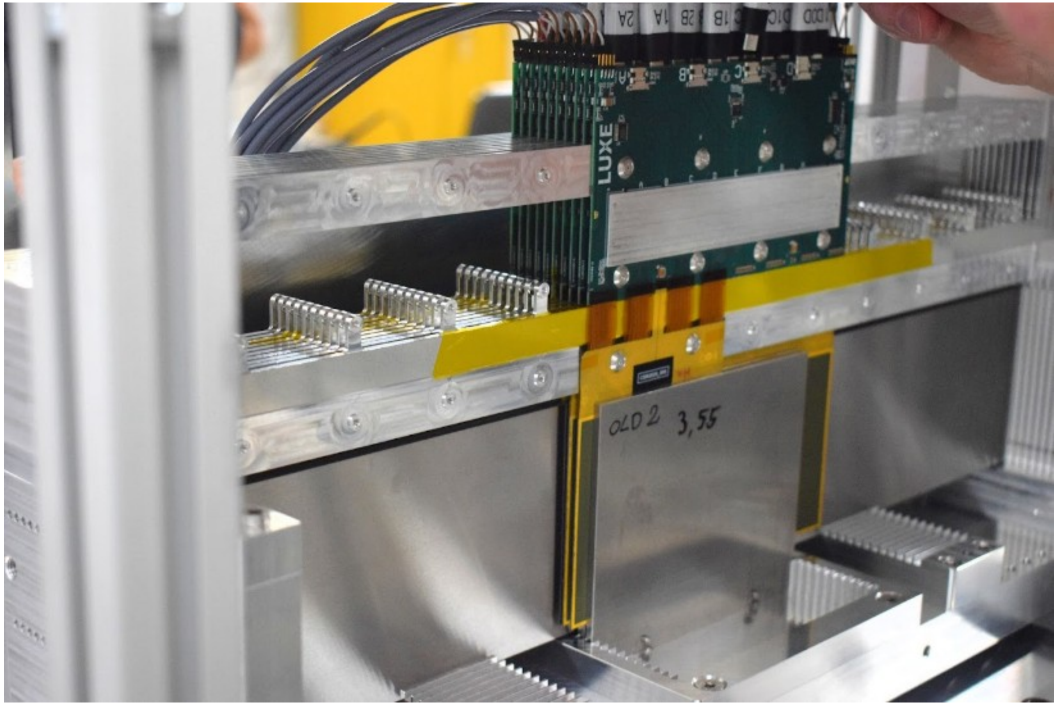
▷**Angular scan** – energies and incidence angles matching LUXE scenarios

- Performance study with real gaps between sensors

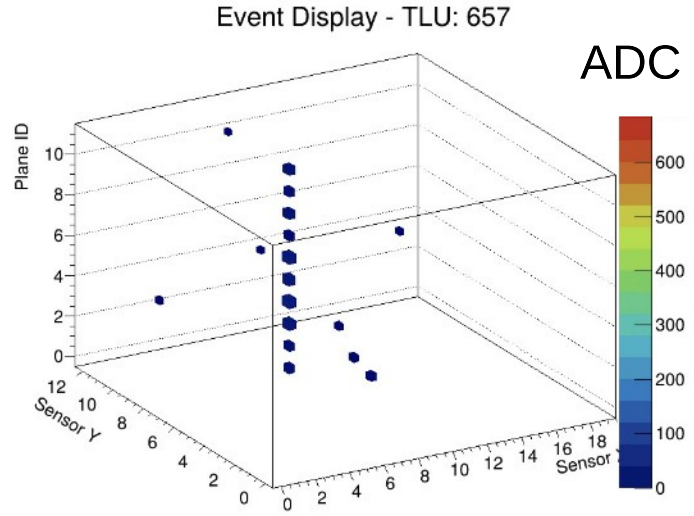
▷**Energy scan** from 1-5.6GeV in two positions

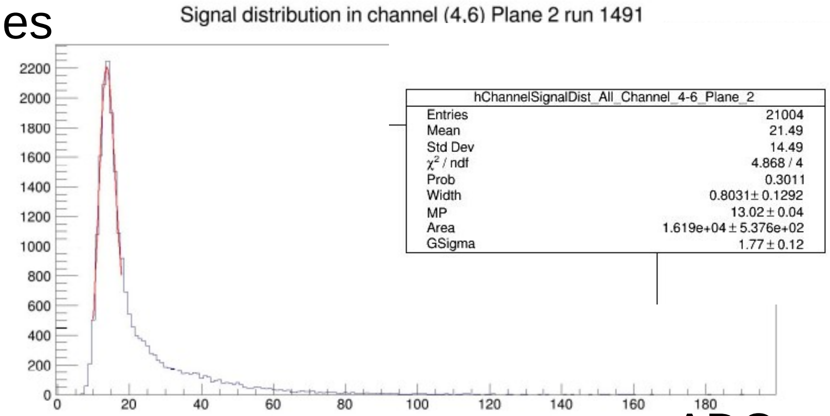
▷**Depth scan** 11 X0, 15 X0, 18 X0, 21 X0

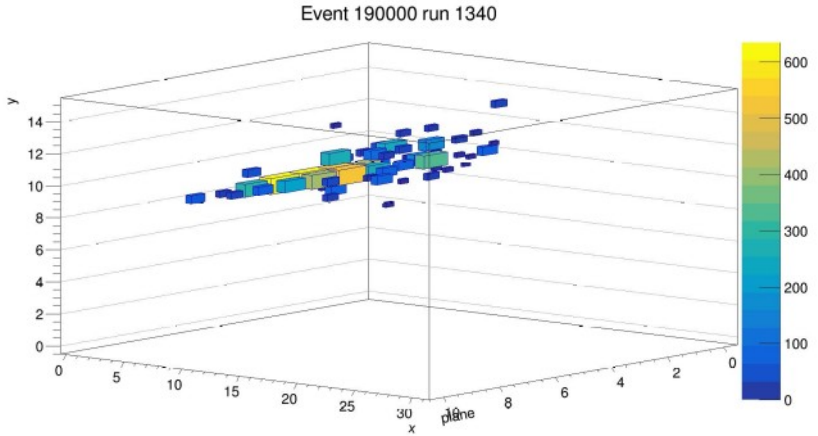
Beam test fun

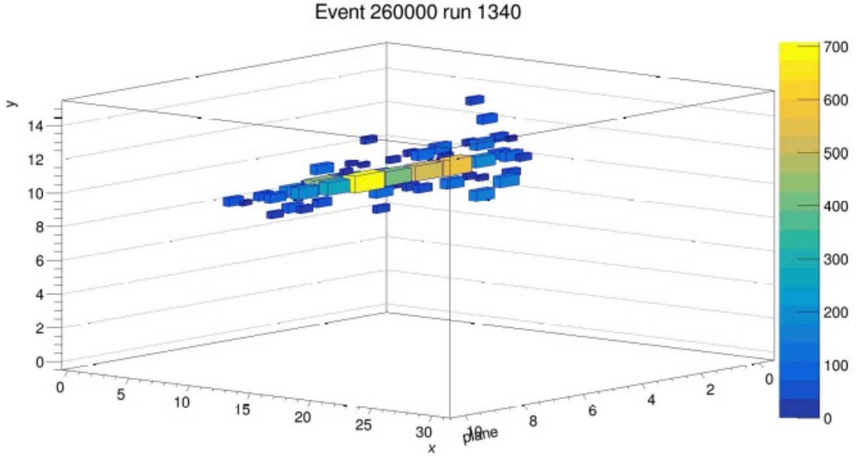


Beam test fun









5 GeV showers

Beam test fun

AGH

UNIVERSITY OF WARSAW

TEL AVIV UNIVERSITY

DESY.

INSTITUTE OF SPACE SCIENCE INFLPR SUBSIDIARY

Outlook - ECALs

- IFIC has positioned itself as reference center for detector assembly and testing for silicon-ecals
- We will take care of the hybridization for:
  - SiW-ECAL 15 layer production planned for 2026-2027
  - FCAL (High Compact Calo) production of 15 layers (90 sensors) 2026-2027
  - Both concepts are key in the R&D for future Higgs Factories detectors... but also baseline detectors for LUXE.
  - Other applications under discussion: Lohengrin, EBBES, SHIP

Outlook – ECALs - FCCee

Circular colliders :

- Continuous readout
- (Much) Higher data flux
- Lower CMS energy wrt LC's
  - PFA with lower granulatity ?

Timing:

- "Centrimetric timing" ➞ 30 ps, achievable ?
  - Exp'd : PiD, simplier and more performant PFA

CALOROC1C

- Capitalising on SKIROC2A ➞ HGCROC ➞ HKROC

  See pres. from Aimie and Christophe this morning

- **New FE boards :**
  - I2C, data concentrator (lpGBT), cont. data flux, improved timing performances
  - 1st prototype based on HKROC (~ pin-2-pin compatible CALOROCs)

Work just starts…

Implementation for CC's, …

… SHiP and Lohengrin experiments

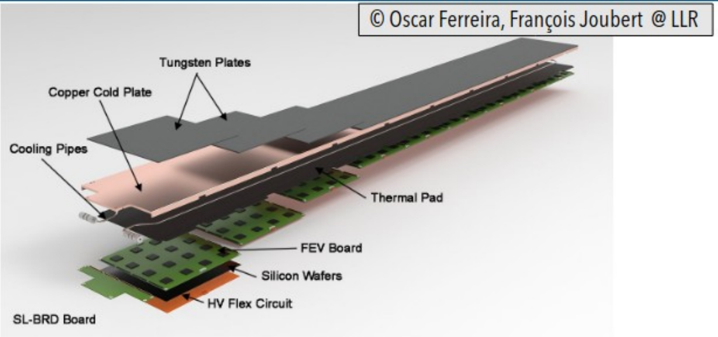
"Boosted Standard Slab"

- ➞ 210W (30W/ASU) : ASICs + Concentrators + PS…
  - (ILC like in CC ~ 130W)

Active cooling:

- 4 mm Cu plate with 1/8" Stainless Steel Tubing
- 0.2 ℓ/min of water @ 15°C

Simulations [See François pres. In WP1 session]
Adiabatic, but for heat bridge at the end, $t = \infty$



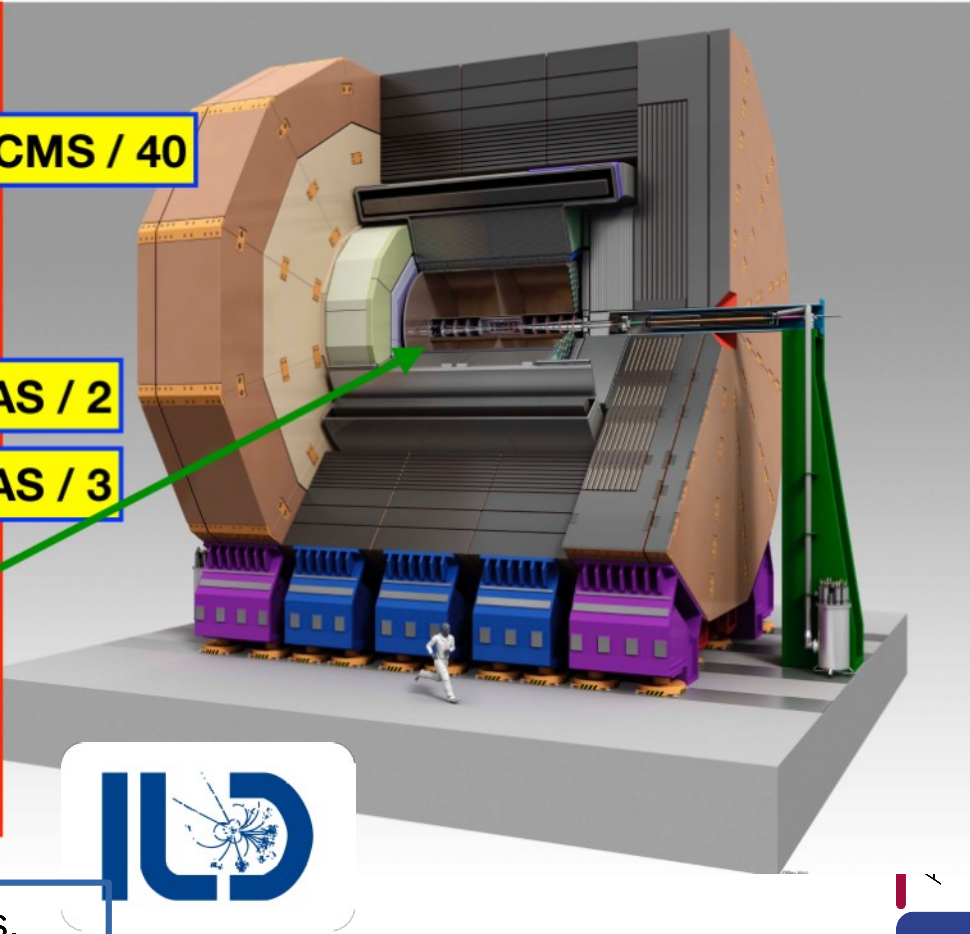
Optimized layout Particle Flow Detector

From key requirements from physics:

- **p_t resolution** (total ZH x-section)
  $\sigma(1/p_t) = 2 \times 10^{-5}\ \mathrm{GeV}^{-1} \oplus 1 \times 10^{-3} / (p_t \sin^{1/2}\theta)$
- **vertexing** ($H \rightarrow bb/cc/\tau\tau$)
  $\sigma(d_0) < 5 \oplus 10 / (p[\mathrm{GeV}] \sin^{3/2}\theta)\ \mu m$
- **jet energy resolution** ($H \rightarrow$ invisible) 3-4%
- **hermeticity** ($H \rightarrow$ invis, BSM) $\theta_{min} = 5$ mrad

To key features of the detector:

- **low mass tracker:**
  - main device: **Time Projection Chamber** (dE/dx !)
  - add. silicon: eg VTX: 0.15% rad. length / layer)
- **high granularity calorimeters**
  optimised for particle flow

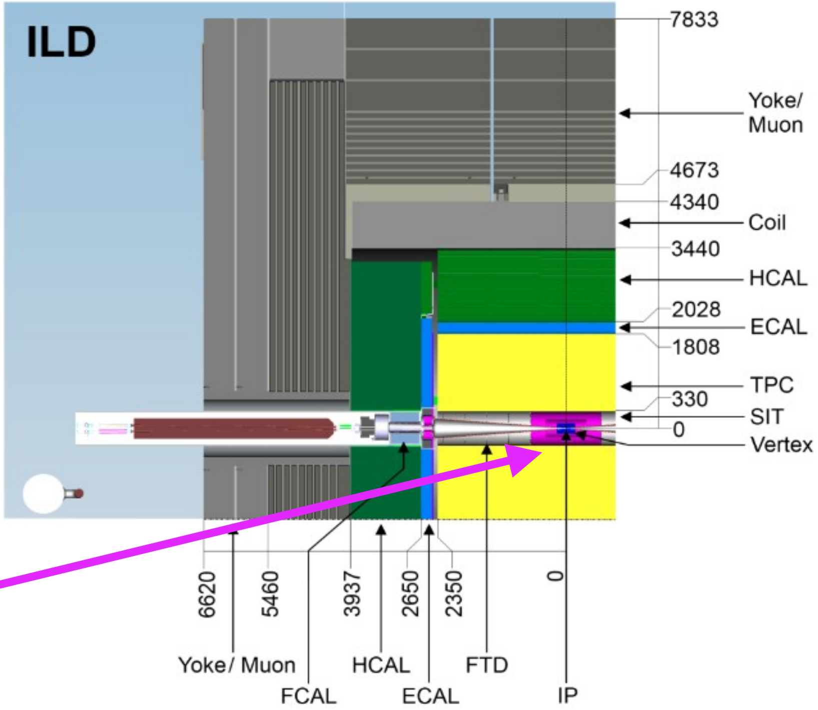


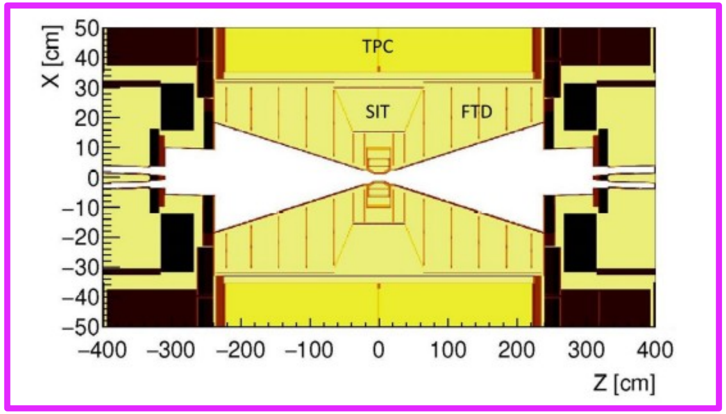
~x1000 more ro cells than LHC exps.
~x10-100 more than HL-LHC exps.

The ILD layout

Main features of the ILD

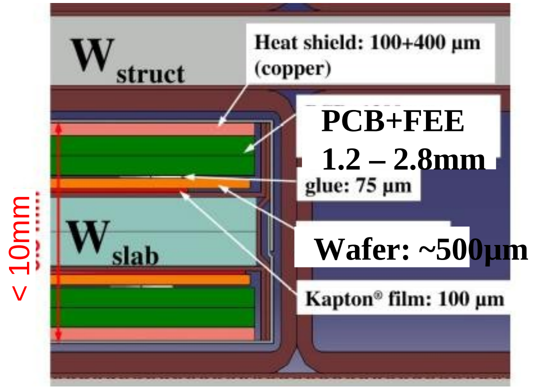
- ▶ **Particle flow** as the key design driver
- ▷ **Excellent vertexing very close to the IP (~1cm)**
- ▷ **Hybrid tracking system** optimized for excellent resolution at high energies and ultimate efficiency over a broad momentum range
- ▷ **High granular calorimetry**
- ▷ Up to and including the HCAL, **all inside solenoidal coil of 3-4 T**





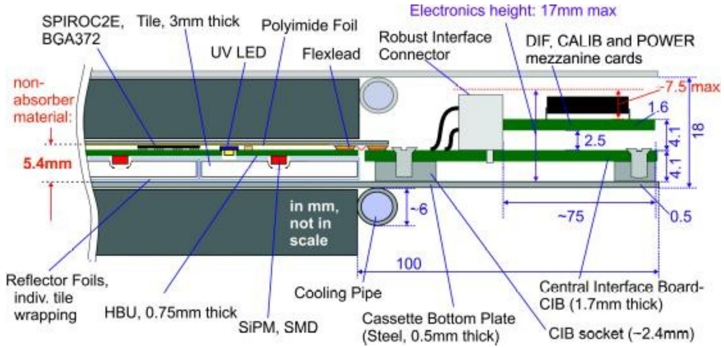
Technological solutions for final detector I

SiW Ecal



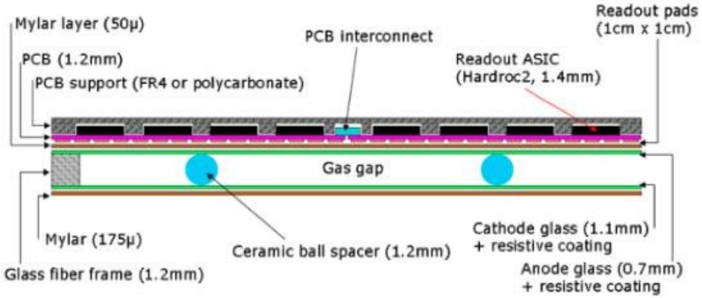
Semi-conductor readout
Typical segmentation: 0.5x0.5 cm^2

Analogue Scintillator HCAL and ECAL



Optical readout
Typical segmentation: 3x3cm^2

Semi Digital HCAL

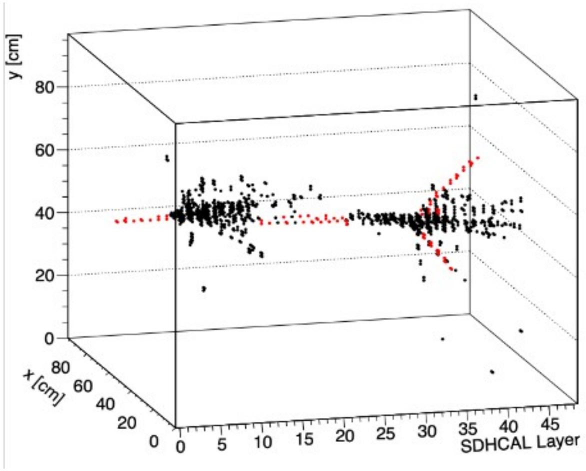


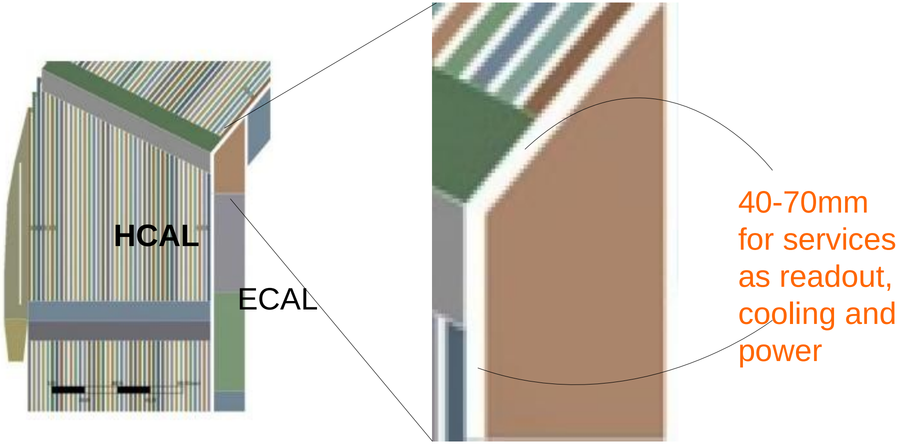
Gaseous readout
Typical segmentation: 1x1cm^2

Integrated front end electronics

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

Premises





To reconstruct the full shower development

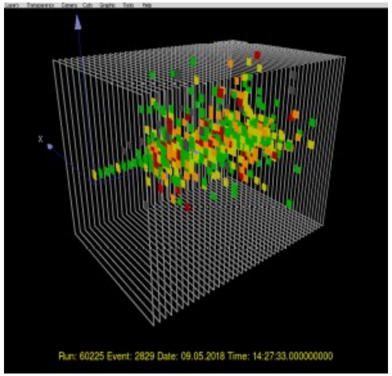
- ▷Sub-MIP self-trigger & high gain / large dynamic range
- ▷At least 4D granularity (5D welcome)

In a real detector: PF requires an **holistic** approach with all systems having maximal efficiency and coverage

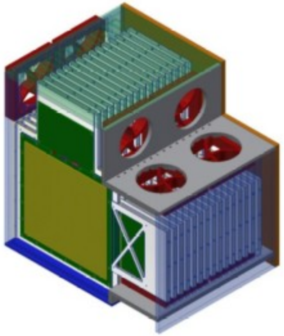
- ▷Hermetic & compact design / no cracks / no dead areas
- ▷Low power consumption – no active cooling (or minimal)
- ▷Highly integrated electronics → only digital data, after ZS is sent outside.

Prototyping + intensive TB phase

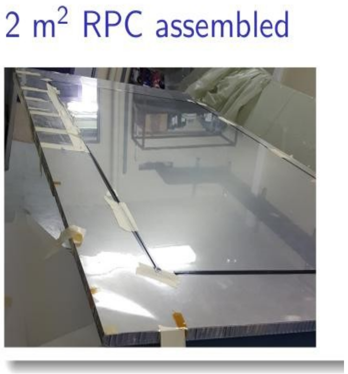
AHCAL



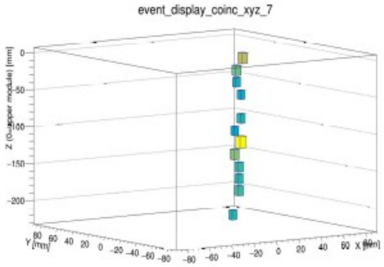
Sc-ECAL

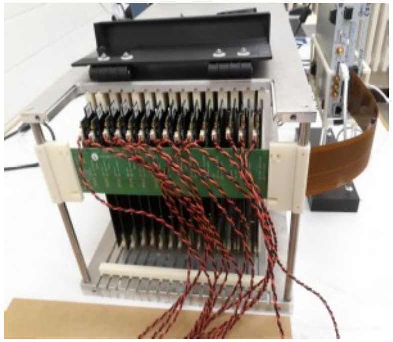


SDHCAL

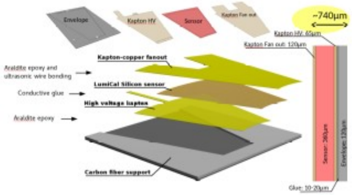


SiW-ECAL





Lumi-CAL

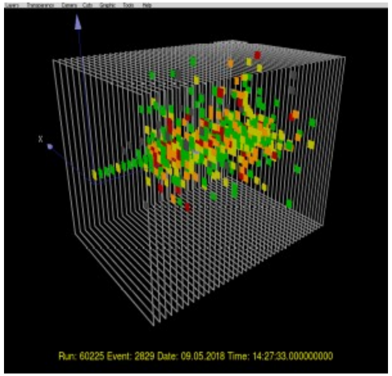


FCAL Collaboration High precision design — CALICE Calorimeter for ILC → Now part of **DRD Calo**

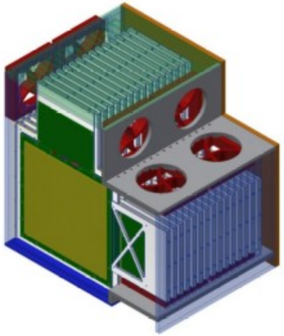
Prototyping + intensive TB phase

AHCAL	Sc-ECAL	SDHCAL	SiW-ECAL	Lumi-CAL

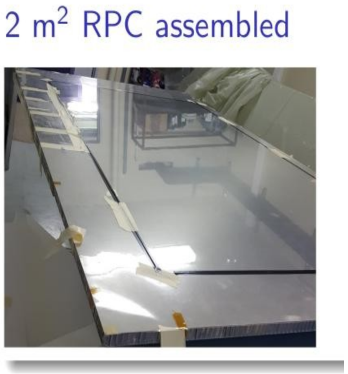
AHCAL



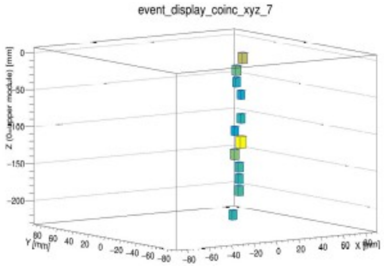
Sc-ECAL

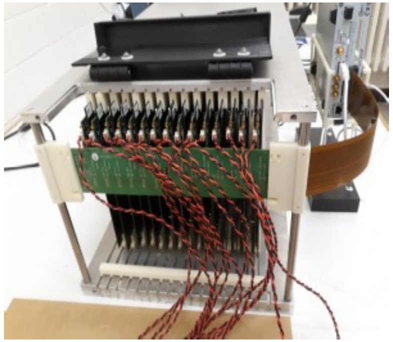


SDHCAL

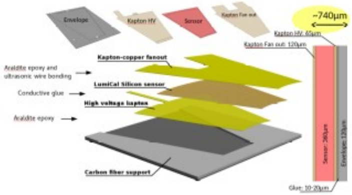


SiW-ECAL





Lumi-CAL



Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

IFIC
INSTITUT DE FÍSICA CORPUSCULAR

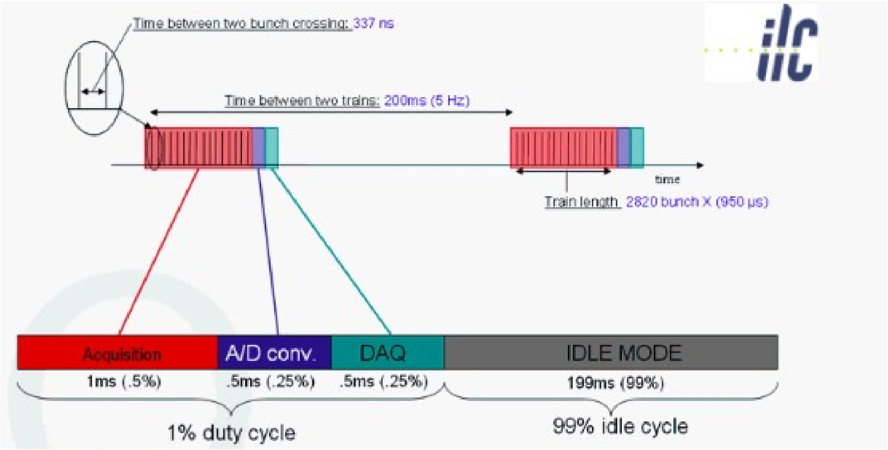
Lepton colliders: a kind experimental framework

Lepton Colliders favor fully optimized PFA detectors

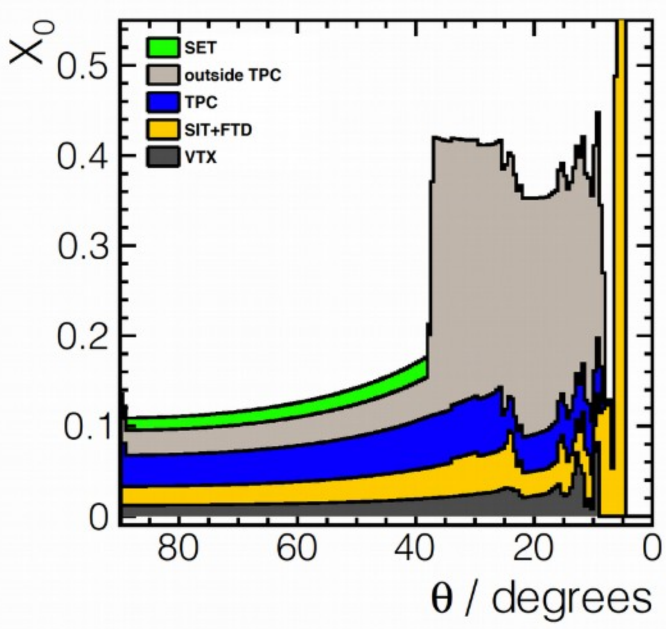
▷ Possible since experimental environment at Lepton Coll. very different from LHC/LEP:

- much smaller beam spot and beam pipe (first tracking layer at ~1cm of the IP)
- much lower backgrounds
- much less radiation
- **Pulsed beam structure (LC)**

Power pulsed electronics → low material budget !
triggerless operation ! –> ALL events are recorded



N.B. Final numbers may vary



DRD6 – high granular silicon ECALs

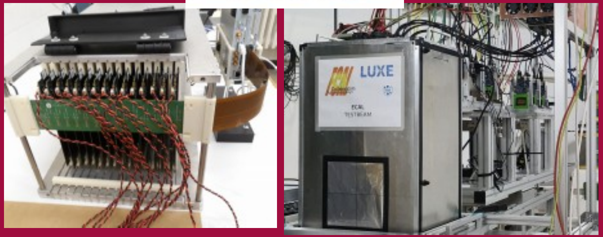
Barrel ECAL:
Similar design in:

(linear collider)
CLICdetector, ILD, SiD

(circular collider)
CLD, ILD, CepC

Electron Calo for LUXE

LUXE



CALICE -type calorimeter

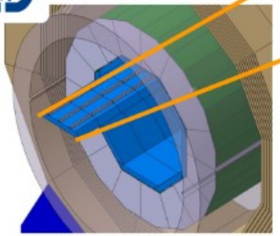
FCAL-type calorimeter

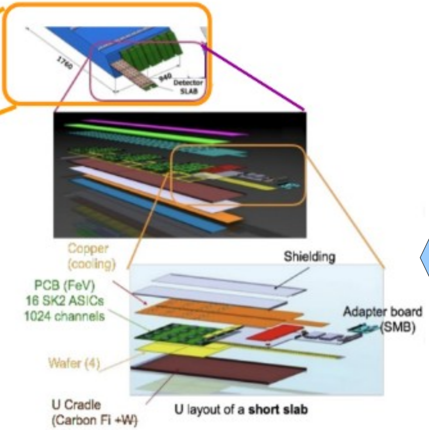
Froward LumiCAL:
Similar design in:

(linear collider)
CLICdetector, ILD, SiD

(circular collider – with adaptations)
ILD, CEPC,..

Positron Calo for LUXE

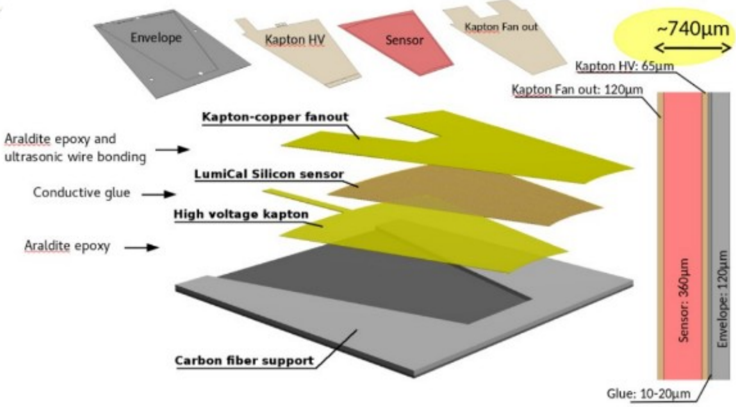

The SiW ECAL in the ILD Detector



SiW Ecal

R&D on sensor hybridization

IFIC
INSTITUT DE FÍSICA CORPUSCULAR



Future collider activities. Present/short/medium term goals

New t-SDHCAL Calorimeter

CIEMAT ACTIVITIES

New National Plan project granted from Sep. 2026 to Aug. 29 (Provisional resolution)

- **New mechanical cassettes to host the new MultiGap RPC prototypes**
- **Contribution to the readout electronics (if person power available)**
- **Beam tests & data analysis + Monte Carlo simulation**

Includes the development of new simulation and algorithms integrating timing measurements in the energy reconstruction, using both traditional and AI-based methods

- **Contribution to design and production of the cooling system - Only if the OTELLO project, submitted last week to the HORIZON-INFRA-2025-01-TECH-02 EU call is granted**

Future collider activities. Present/short/medium term goals

New t-SDHCAL Calorimeter

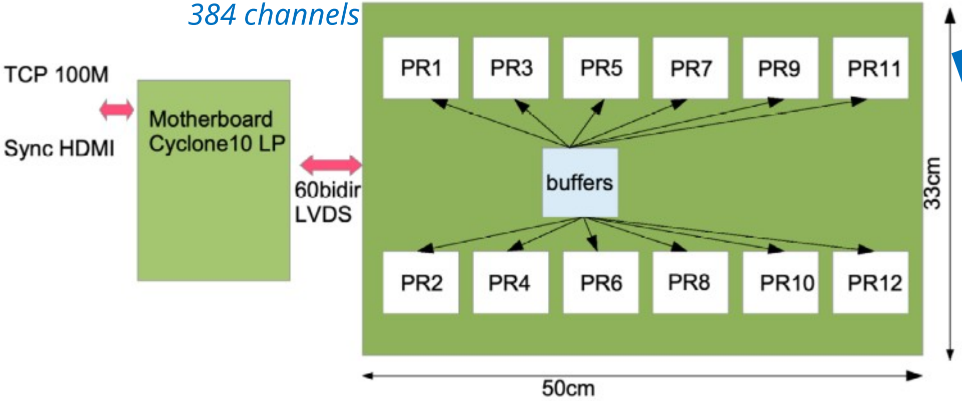
New detectors: Multi-gap RPCs will improve the intrinsic timing of the detector

New FE Electronics & DAQ with precise timing capabilities (<100 ps)

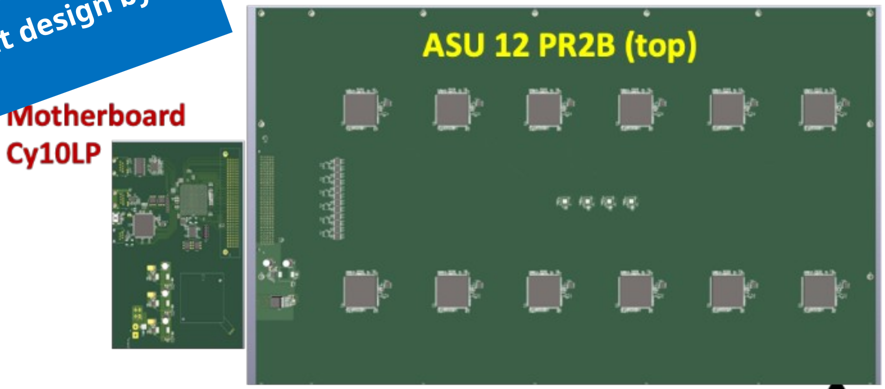
- PETIROCv2B ASIC (~50ps) as first step (difficult to chain, limited digital logic, deadtime) before a better new ASIC is available (under development at OMEGA- Paris)
- Also developments using LIROC (Weeroc, 2022) ongoing at GWNU (South Korea)

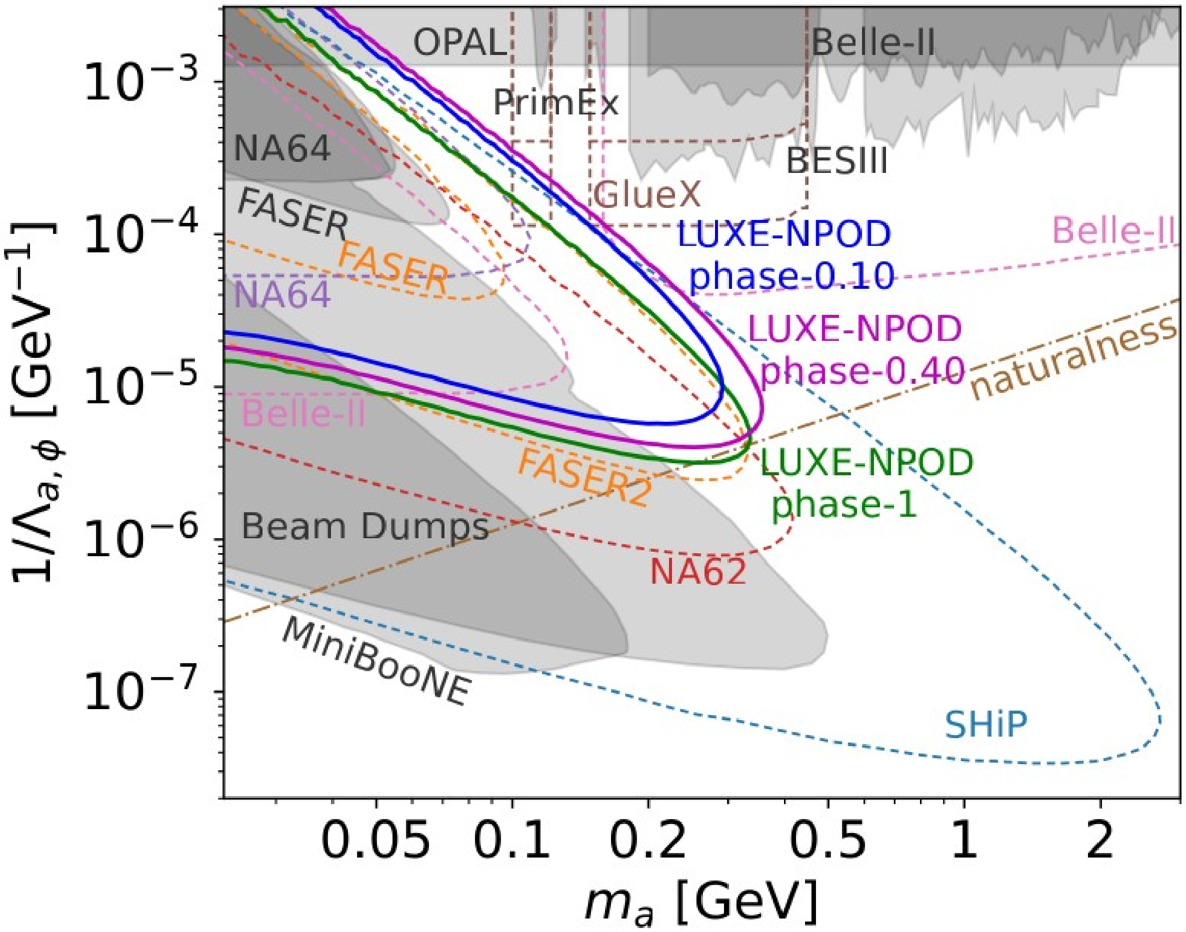
Cooling to be design (needed for FCCee)

12 Petiroc2B ASICs, 384 channels



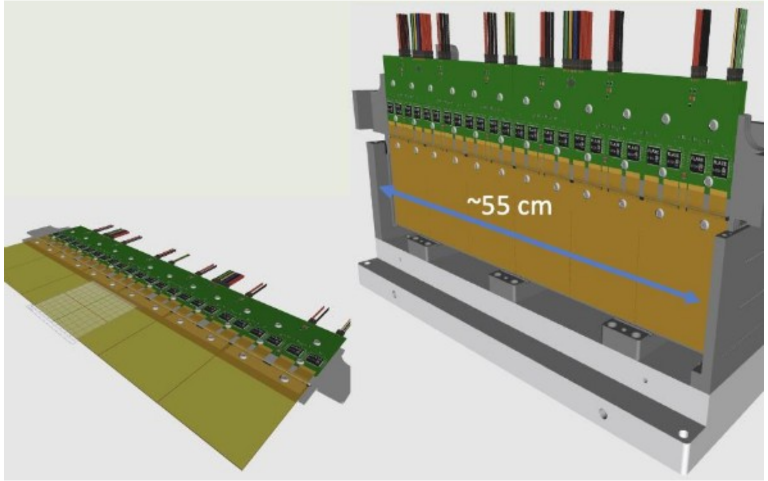
Present design by I2PI

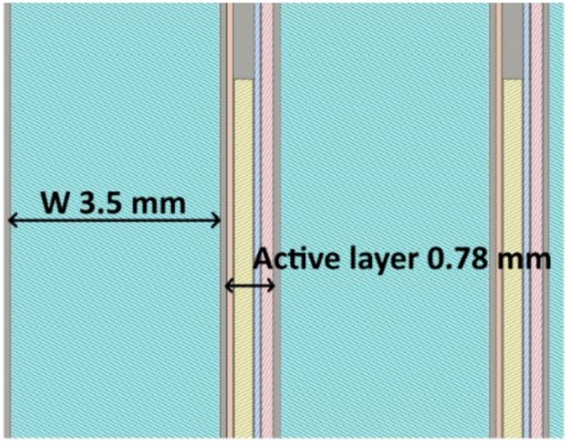



OPAL
Belle-II
PrimEx
NA64
BESIII
GlueX
FASER
LUXE-NPOD phase-0.10
Belle-II
FASER
NA64
LUXE-NPOD phase-0.40
naturalness
Belle-II
FASER2
LUXE-NPOD phase-1
Beam Dumps
NA62
MiniBooNE
SHiP
$1/\Lambda_{a,\phi}$ [GeV^{-1}]
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
0.05
0.1
0.2
0.5
1
2
m_a [GeV]

ECALp design

- ▷ Design tailored for LUXE
- ▷ Highly compact calorimeter and modular
- ▷ Silicon – tungsten planes
- ▷ Six sensors per plane (~55cm)
- ▷ 20 active planes
- ▷ Distance between tungsten plates : 1mm
  - Minimal Molière radius – to enhance the shower-shower separation
- ▷ Front End Boards above the sensors : readout and HV
- ▷ Dedicated electronics (FLAXE) developed for LUXE
- ▷ **Test beam with single sensors (Si, GaAs) in 2022**
  - Eur.Phys.J.C 85 (2025) 6, 684
- ▷ **Test beam with 20 sensors in June 2025**
  - Discussed today





Maximal compact ness goal

ECALp readout - FLAXE

▷Based on previous developments FLAME ASIC: developed for the luminosity detector at future e+e- accelerators.

- **FLAME has been extensively tested → including in the last beam test in 2025**

▷Main features

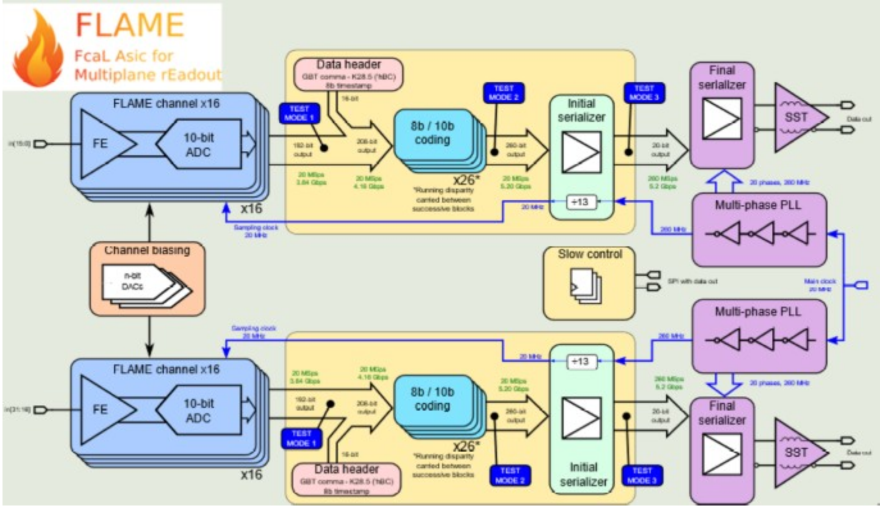
- 32 channels
- 10 bit ADC at 20 MHz **in each channel**
- Analog front end in each channel. CR-RC shaper of 50 ns
- High speed serialize

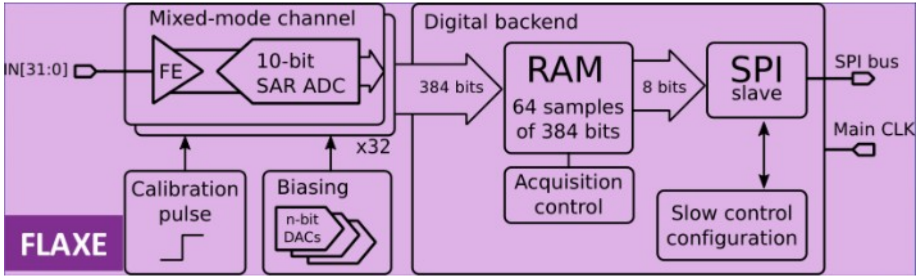
▷FLAXE is similar but w/o the high speed serializer

- Acquisition at LUXE frequency (10 Hz)

▷Production failure in 2024.

- New production in 2025-2026 (MORE INFO in the backup)





https://iopscience.iop.org/article/10.1088/1748-0221/20/01/C01026/pdf

Developments from AGH Krakow

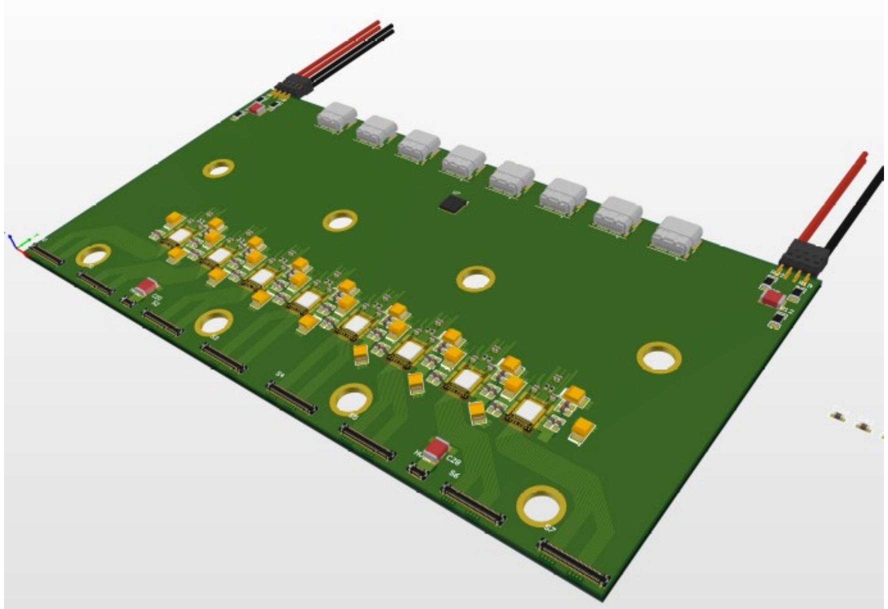
ECALp readout – FPGA & Synch

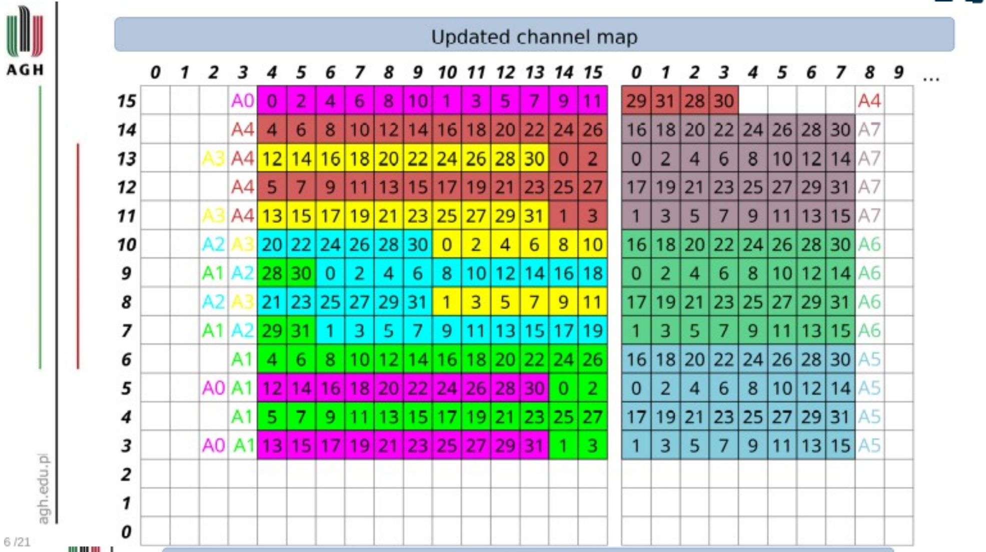
- The FLAXE production failure forced us to go back to FLAME
- Advantages&Disadvantages:
  - We factorize developments (new mechanics, sensors, hybridization process but “old&known” electronics)
  - Limited amount of available FLAME ASICs. & FPGA for the readout.
  - Double work… now for FLAME later for FLAXE

ECALp readout - FEB

▷ "Funny" mapping to enable the fabrication of a 10-11 layer prototype with 2 sensors per layer.

- With the available number of ASICS

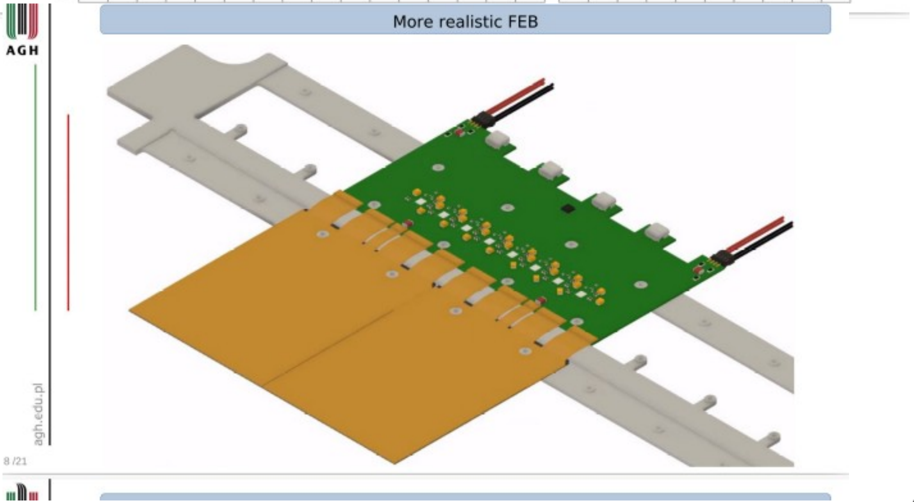




Updated channel map

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
15				A0	0	2	4	6	8	10	1	3	5	7	9	11
14				A4	4	6	8	10	12	14	16	18	20	22	24	26
13			A3	A4	12	14	16	18	20	22	24	26	28	30	0	2
12				A4	5	7	9	11	13	15	17	19	21	23	25	27
11			A3	A4	13	15	17	19	21	23	25	27	29	31	1	3
10			A2	A3	20	22	24	26	28	30	0	2	4	6	8	10
9			A1	A2	28	30	0	2	4	6	8	10	12	14	16	18
8			A2	A3	21	23	25	27	29	31	1	3	5	7	9	11
7			A1	A2	29	31	1	3	5	7	9	11	13	15	17	19
6				A1	4	6	8	10	12	14	16	18	20	22	24	26
5			A0	A1	12	14	16	18	20	22	24	26	28	30	0	2
4				A1	5	7	9	11	13	15	17	19	21	23	25	27
3			A0	A1	13	15	17	19	21	23	25	27	29	31	1	3
2																
1																
0																

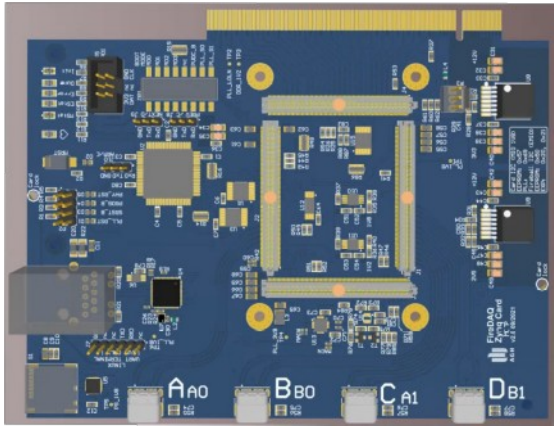
	0	1	2	3	4	5	6	7	8	9	...
15	29	31	28	30					A4		
14	16	18	20	22	24	26	28	30	A7		
13	0	2	4	6	8	10	12	14	A7		
12	17	19	21	23	25	27	29	31	A7		
11	1	3	5	7	9	11	13	15	A7		
10	16	18	20	22	24	26	28	30	A6		
9	0	2	4	6	8	10	12	14	A6		
8	17	19	21	23	25	27	29	31	A6		
7	1	3	5	7	9	11	13	15	A6		
6	16	18	20	22	24	26	28	30	A5		
5	0	2	4	6	8	10	12	14	A5		
4	17	19	21	23	25	27	29	31	A5		
3	1	3	5	7	9	11	13	15	A5		
2											
1											
0											



ECALp readout – FPGA & Synch

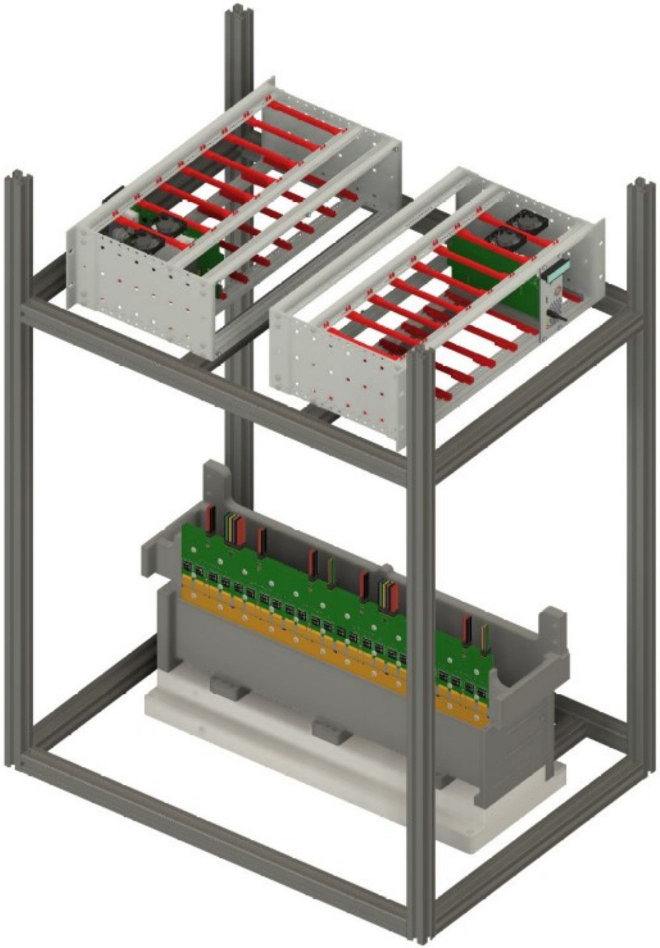
▷Commercial Trenz TE0808 FPGA modules were used FLAME (we kept same design)

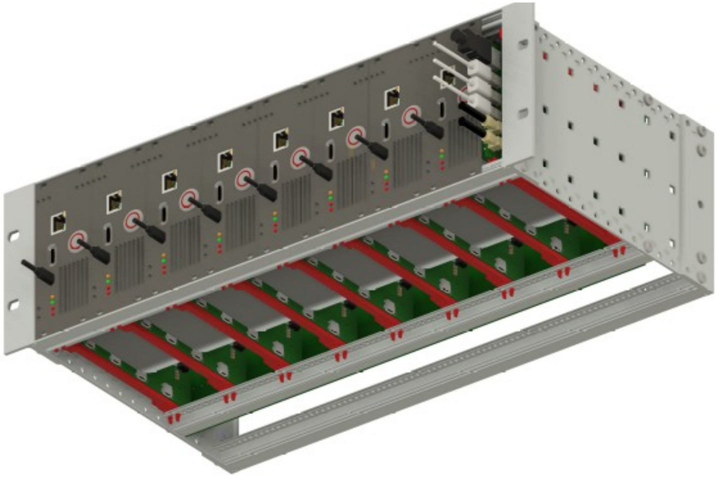
- Baseboard was based on custom made solution for FCAL. Required optimization of power suply control (simplification) and synchronization



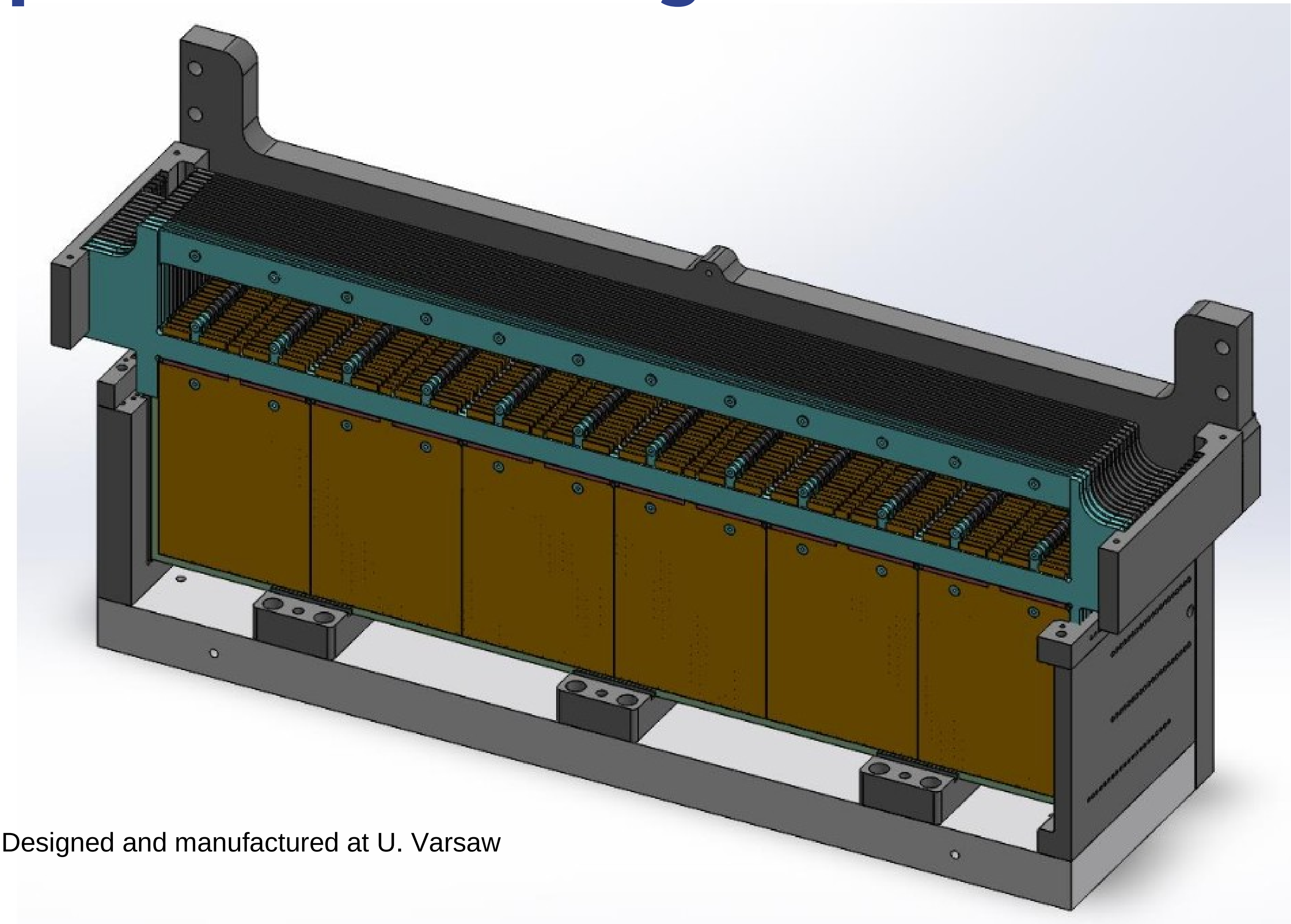
AGH

ECALp Mechnical housing





ECALp Mechnical housing



Designed and manufactured at U. Varsaw

ECALp Mechnical housing

▷ Mainframe and combs

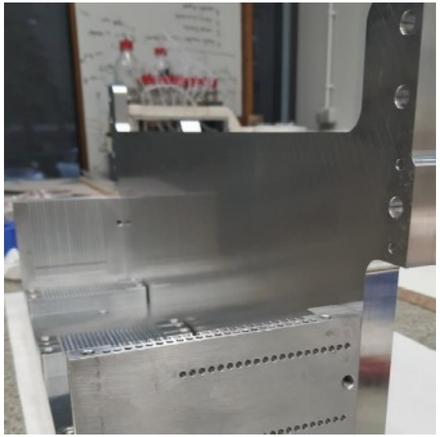
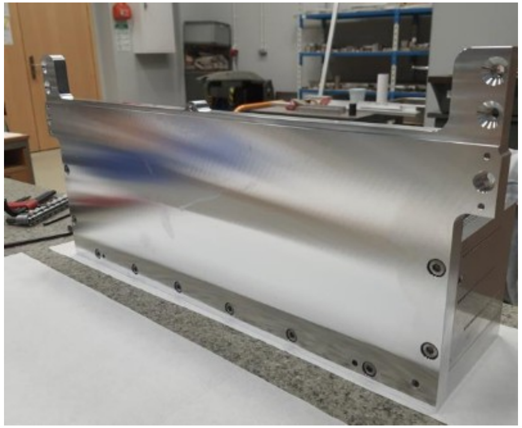
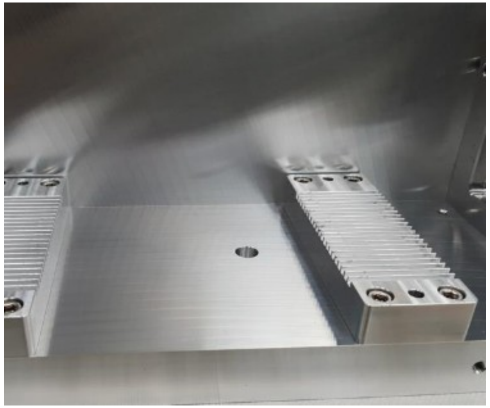
- Aluminum : bottom (30mm), backplane (20mm), combs (20mm and 10 mm)
- Overall machining assembly ~10 um
- Connection to the Front-End Board frame
- Technical holes for future lowering mechanics

▷ Compact calorimeter for LUXE:

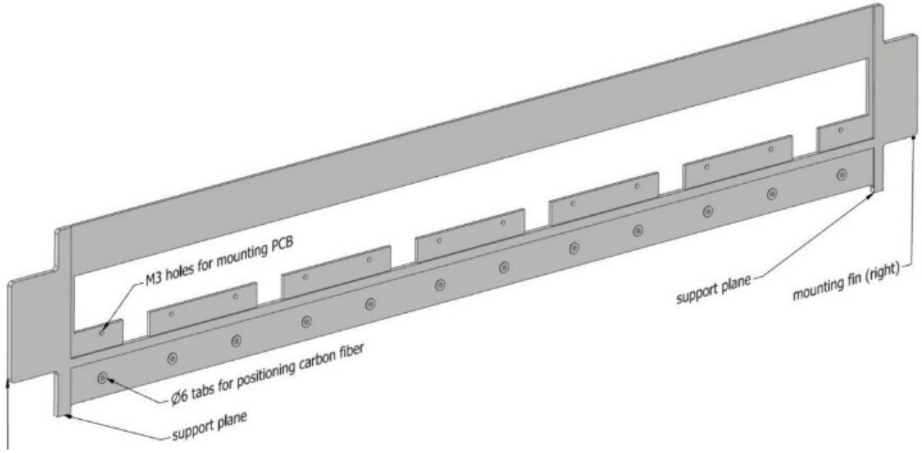
- Combs pitch : 4.5 mm (tungsten: 3.5 mm +detector: 1 mm)
- Comb gaps : 3.5 + 0.08 mm (bottom combs), 3.5 + 0.08 (side combs)

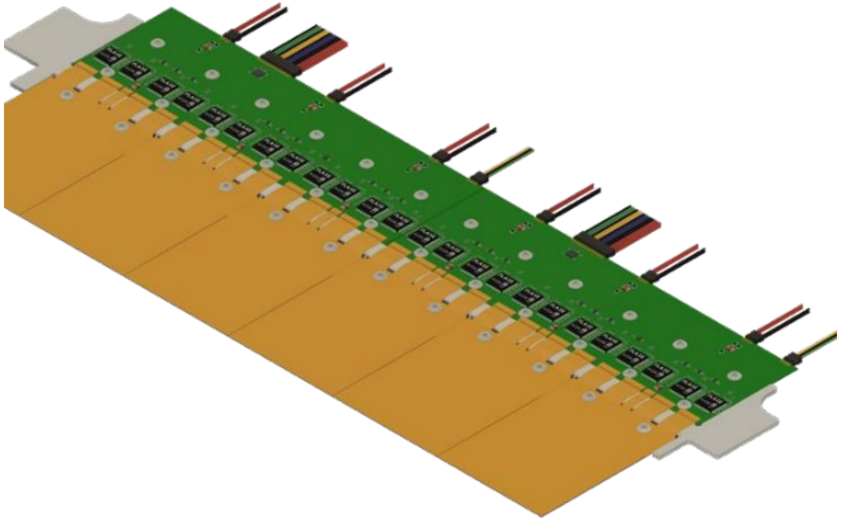
▷ Prototyping phase

- Gap of 1.2 mm (instead of 1mm)


ECALp Mechnical housing



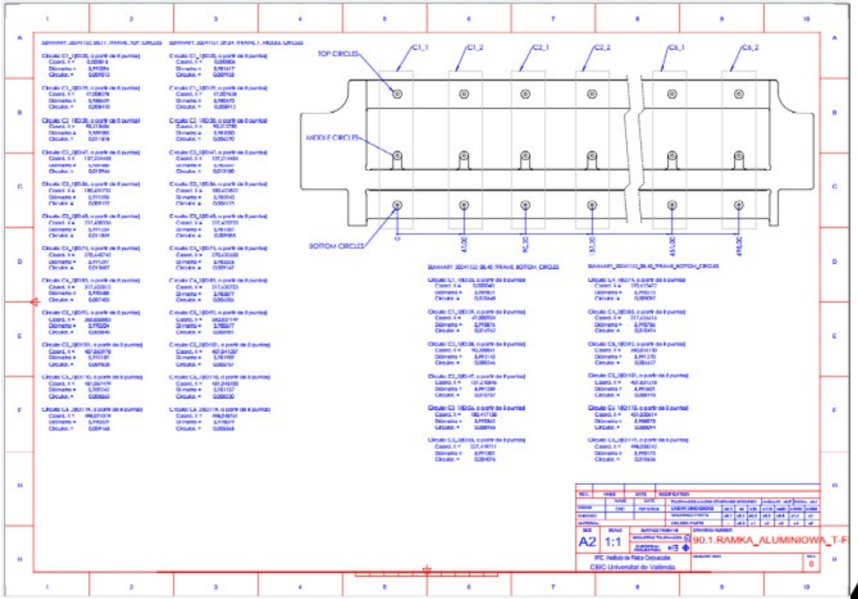


▷T-Frames

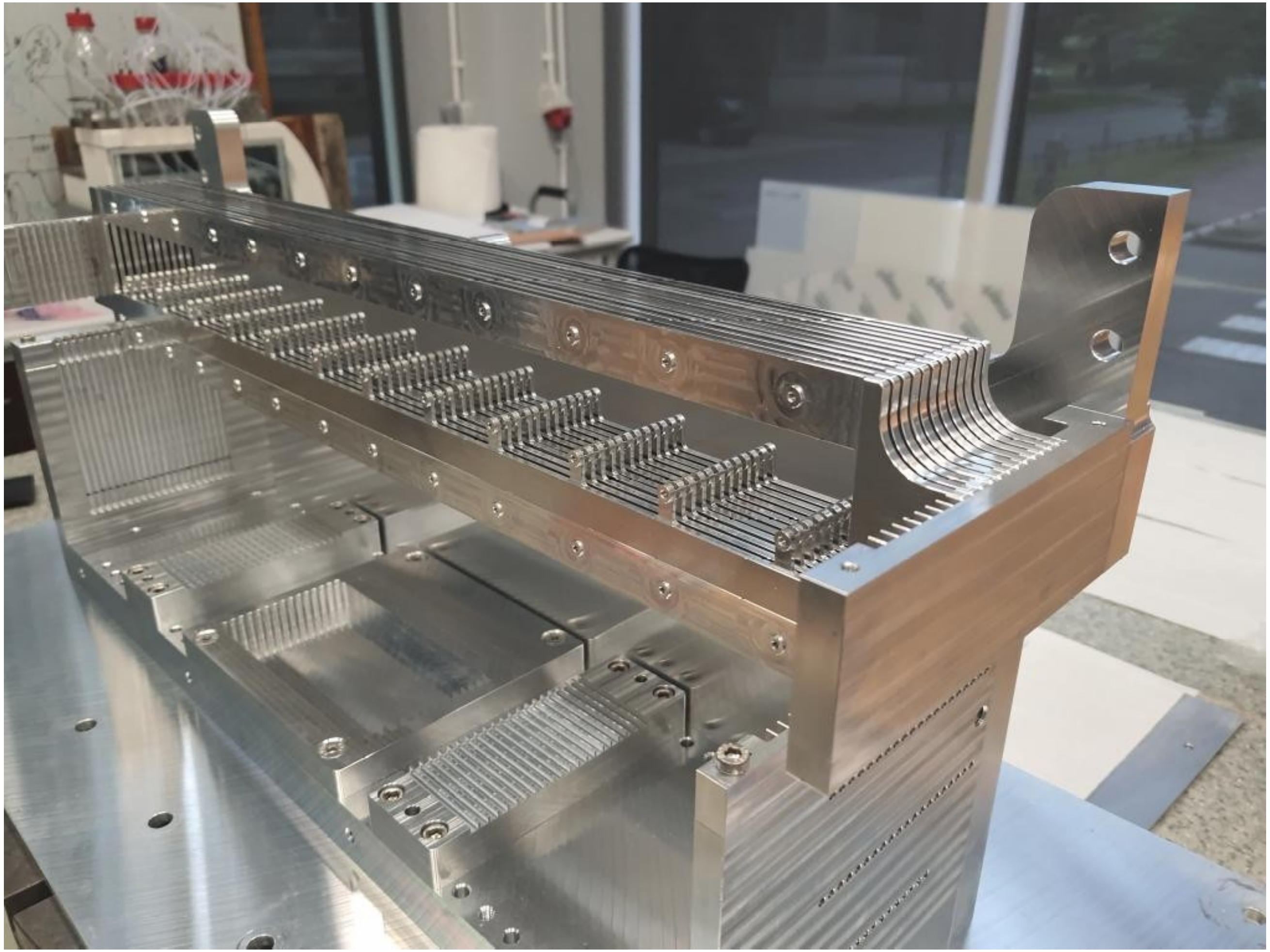
- The sensors are hanging from it
- The FEB is supported by it.

▷The sensors position in the detector is defined wrt the Ø6mm tabs

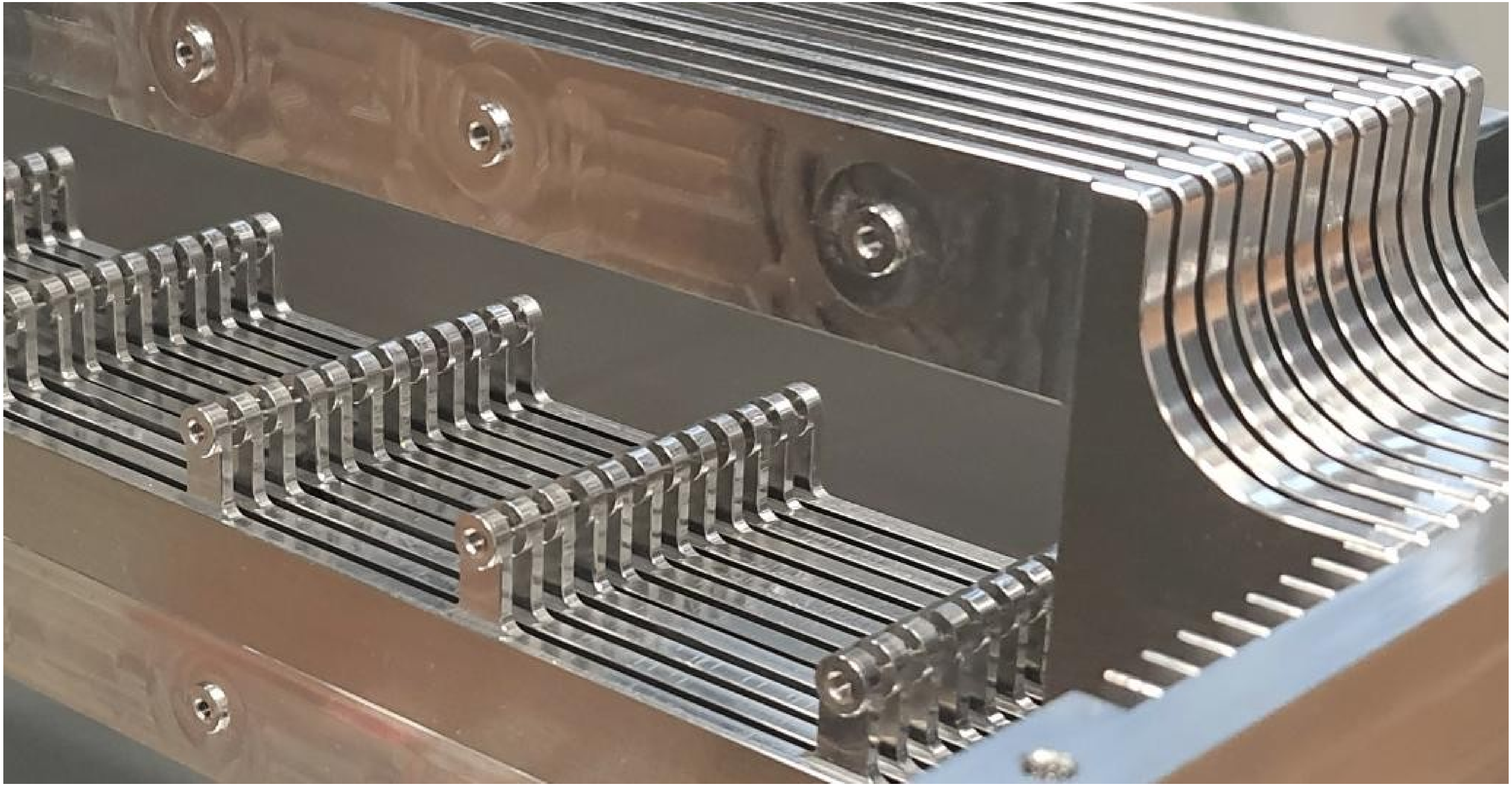
- 10um precision seek and reached!



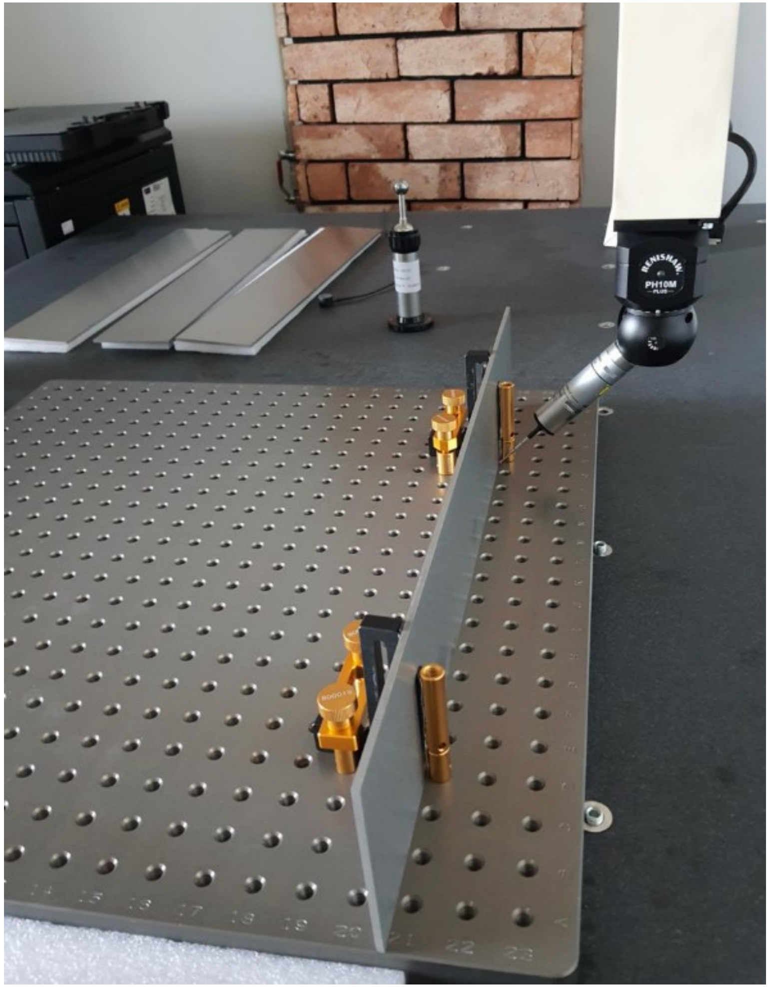
ECALp Mechnical housing



ECALp Mechnical housing



ECALp tungsten plates - 2024



▷ Long and thin tungsten plates (1X0)

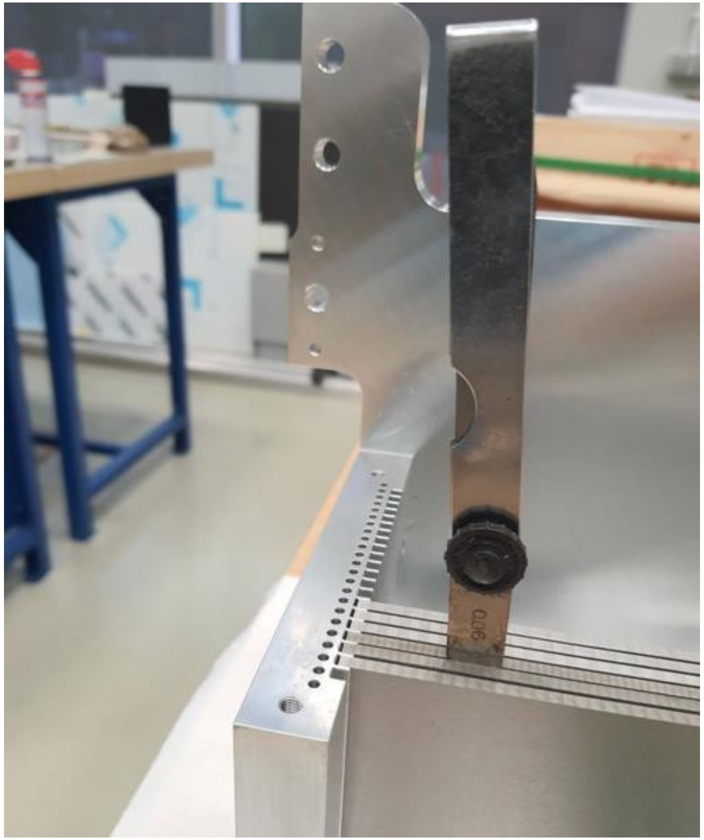
- 55cm x 10xm x 0.35 cm → With requested tolerances on planarity better than 100um

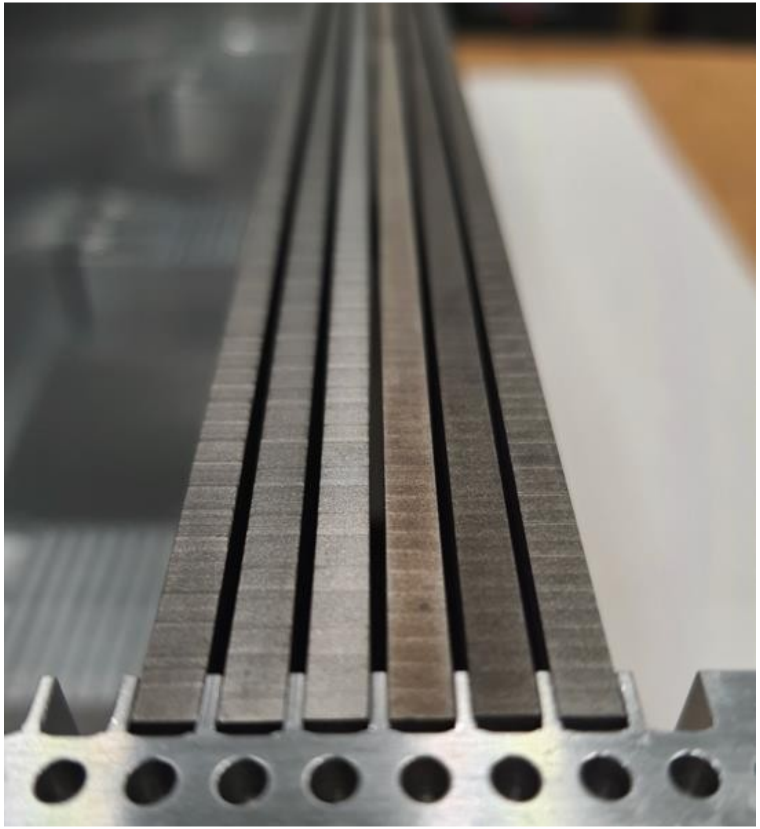
▷ 6 plates purchased in 2024 from two different Chinese companies

- "Requested 3.55+-0.05mm and 50um planarity
- Slightly worst planarity than expected (up to 150um) → measurements in vertical. Compensated with the combs
- Slightly thicker than expected → due to mismatch in communication with the company (they provided 3.55 $^{+0,0}_{-0,1}$ mm)

XYZ dimensions (mm)			
Plate	X	Y	Z
X1	555.1039	100.0907	3.5593
X2	555.1047	100.0864	3.5429
X3	555.1388	100.0964	3.5407
B1	555.0785	100.0640	3.5451
B2	555.0654	100.0458	3.5547
B3	555.0637	100.0366	3.5701
Nom	555.00±0.20	100.00±0.20	3.50±0.05

ECALp tungsten plates - 2024





ECALp tungsten plates – 2025 (and from the past)

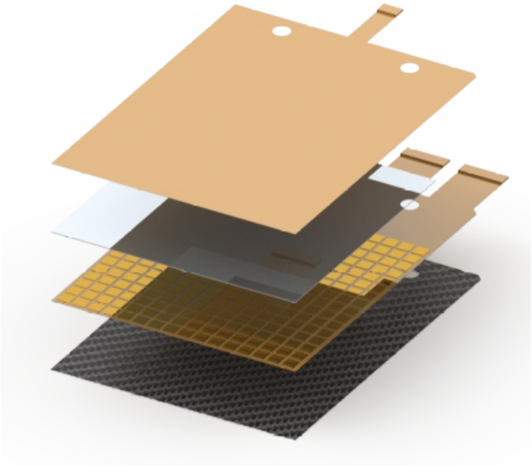
- New purchase to german company
  - 6 plates with 55cm x 10xm x 0.355 cm dimensions
  - Arrived directly to DESY the day of the beam test start.
- In addition, we took 6 “old FCAL” plates which were also 1X0 thick but different size
  - They were cut to fit in front of the detector
  - A new comb designed and manufactured

ECALp Compact Silicon Sandwich - CSIS

▷ CSIS = entity of Carbon fiber support, signal fanout, silicon sensor, HV delivery kapton

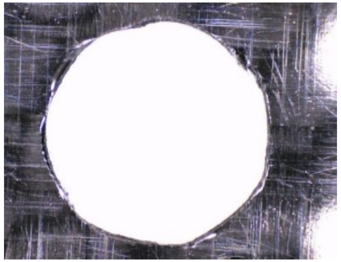
▷ Designed to match the **tight mechanical** precision requirements from the mechanical housing (physics driven)

- Thickness bellow 1mm (relaxed to 1.2 mm for the testbeam 2025)
- Precision in the lateral separation between sensors to be better than 100 um (relaxed to 200um for beam test 2025)



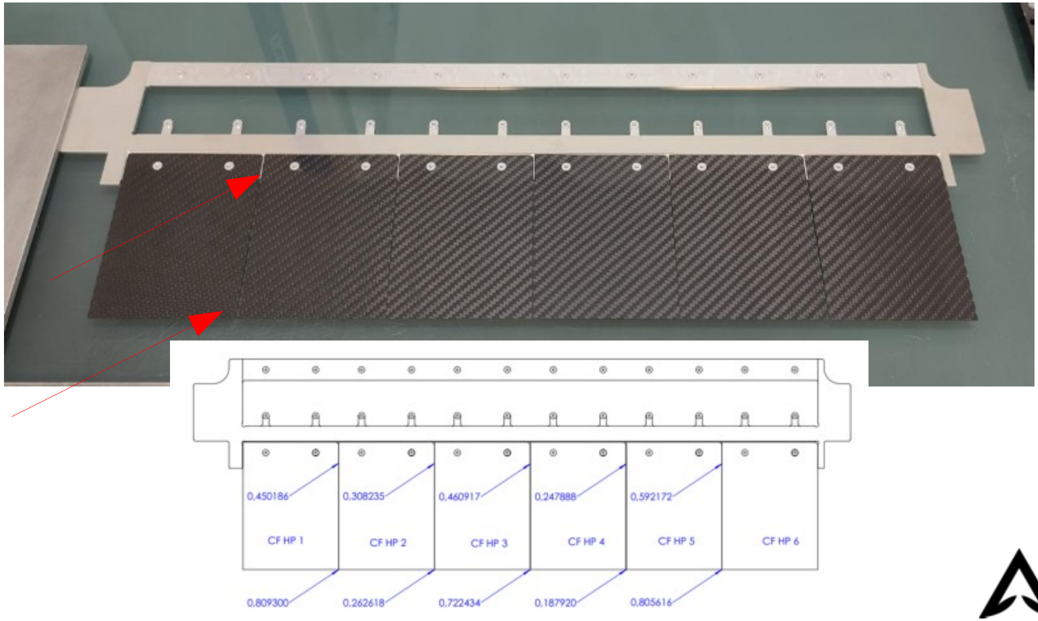
ECALp Compact Silicon Sandwich - CSIS

- ▷ Carbon-fibber sheet, 250um thick
  - Manufactured by a small Spanish company (ClipCarbono): good thickness but with improvable machining results
  - Machined by a French company (Workshape)
  - Overall size slightly bellow specs (obtained 89.7-89.8mm !)
- ▷ Si Sensors – 320um (not measured after production)
- ▷ Kaptons (measured after production)
  - 120um (fanout)
  - 70um (HV)



ClipCarbono

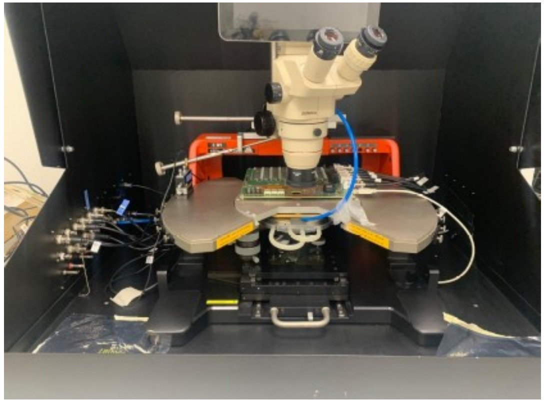
Workshape

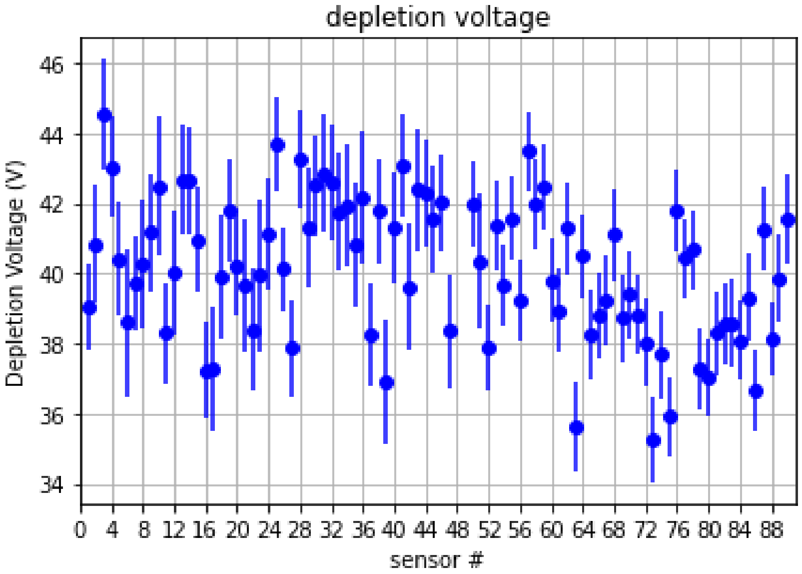


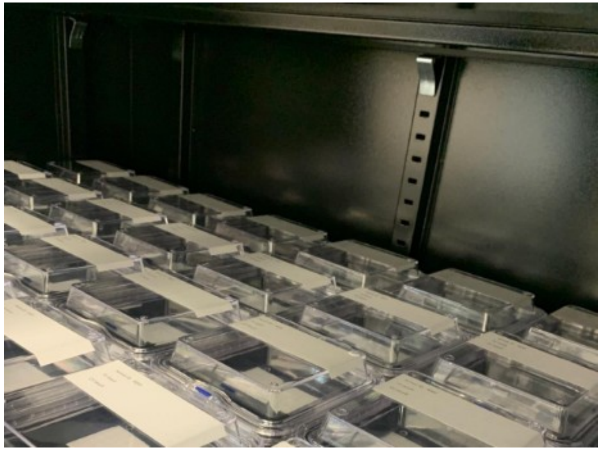
ECALp CSIS – sensors

▷ 110 sensors purchased to Hamamtsu

- 16x16 pads of 5.52 x 5.52 mm^2
- 320 um thickness
- 90 tested and fully characterized by **Tel Aviv University**
- 20 used in Test Beam at DESY 2025

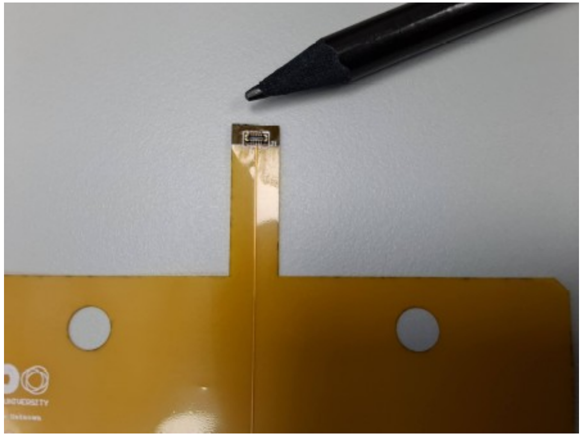


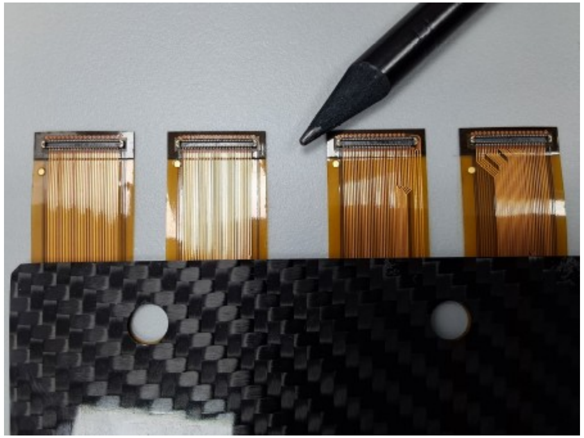


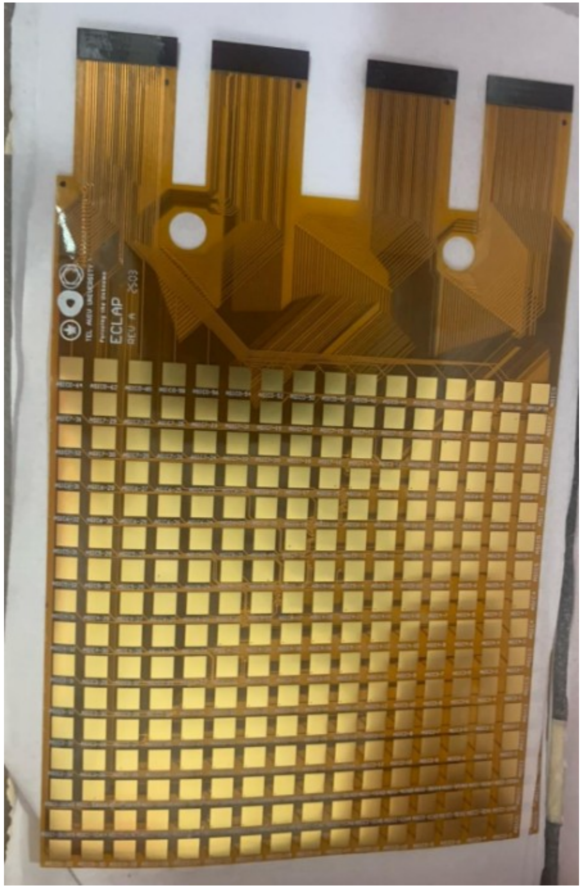


ECALp Compact Silicon Sandwich - Kaptons

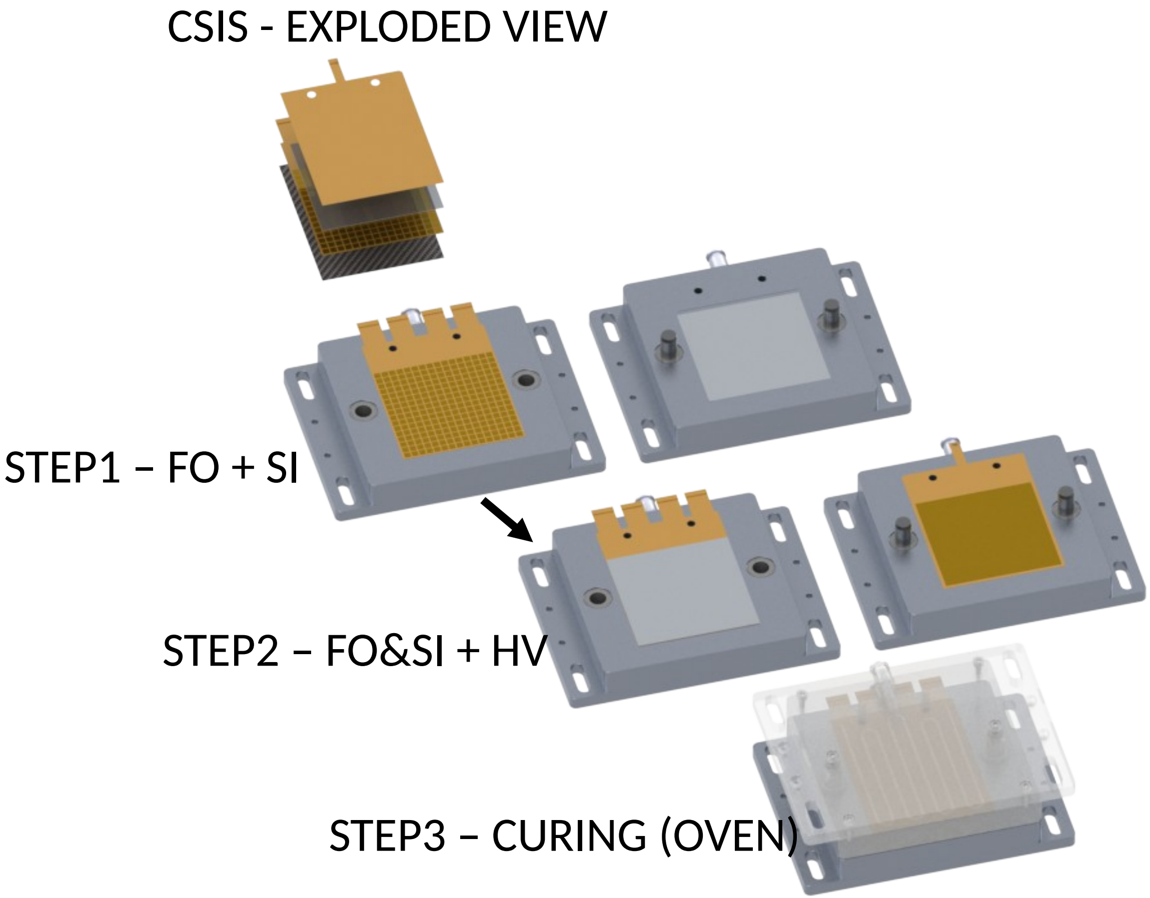
▷ Designed and produced by Tel Aviv U.

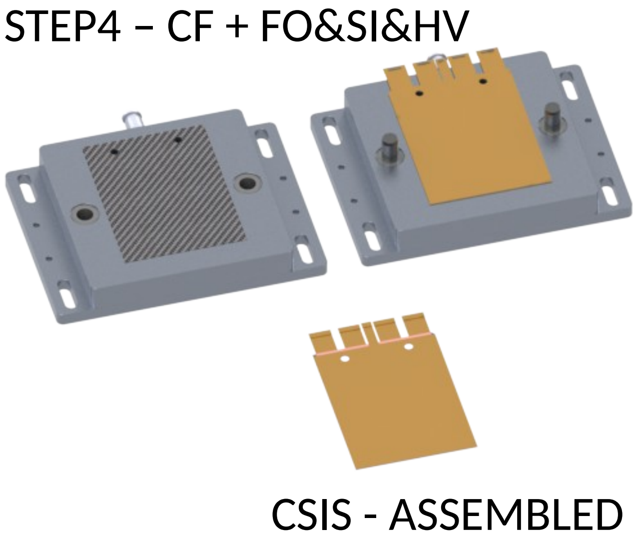






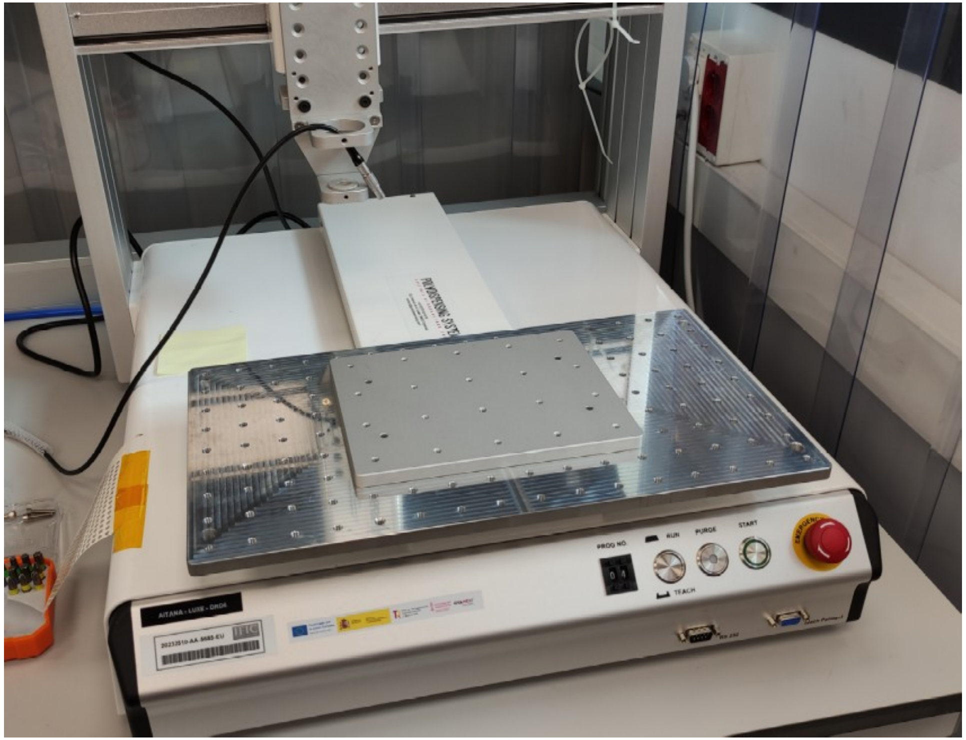
ECALp CSIS Assembly





ECALp CSIS Assembly

Glue mixing tooling



3d programmable robot - PDS400

ECALp CSIS Assembly

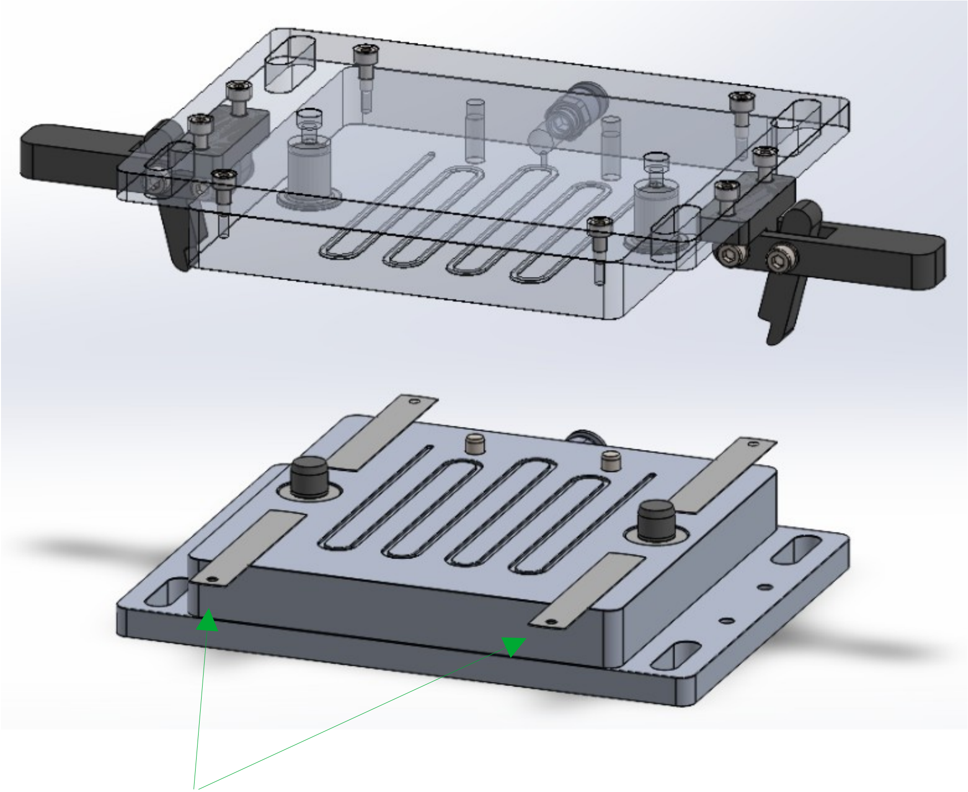
Glue preparation (of small doses!) is an crafting work – mastered by the full group now.

▷ Two types of glue tested (datasheets in the backup)

- H20E – from EPOTEK (Standard recommended solution for hybrid micro-electronics)
- TDS-9410 – from MG-Chemicals. Mono component solution, cheaper, less performant… but enough for us?

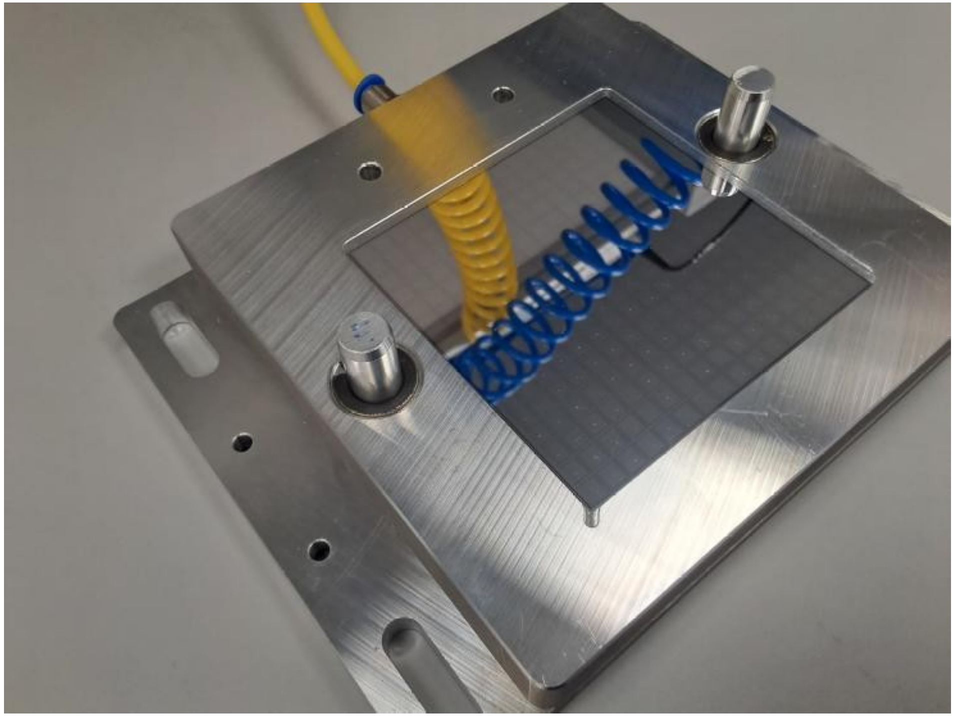
ECALp CSIS Assembly

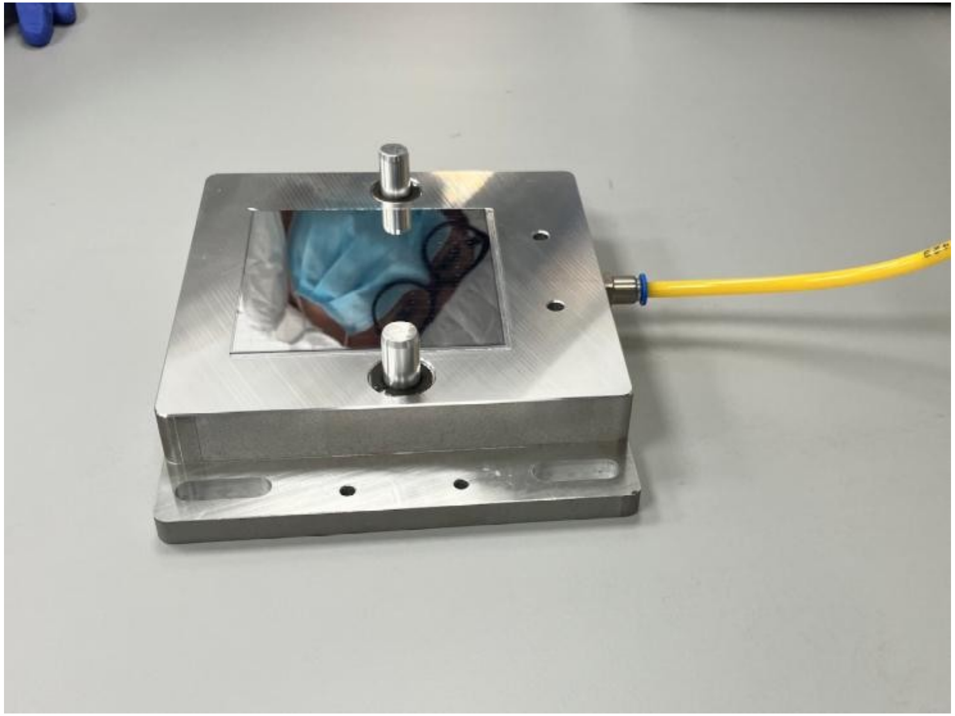
▷Jigs and tooling manufactured at IFIC



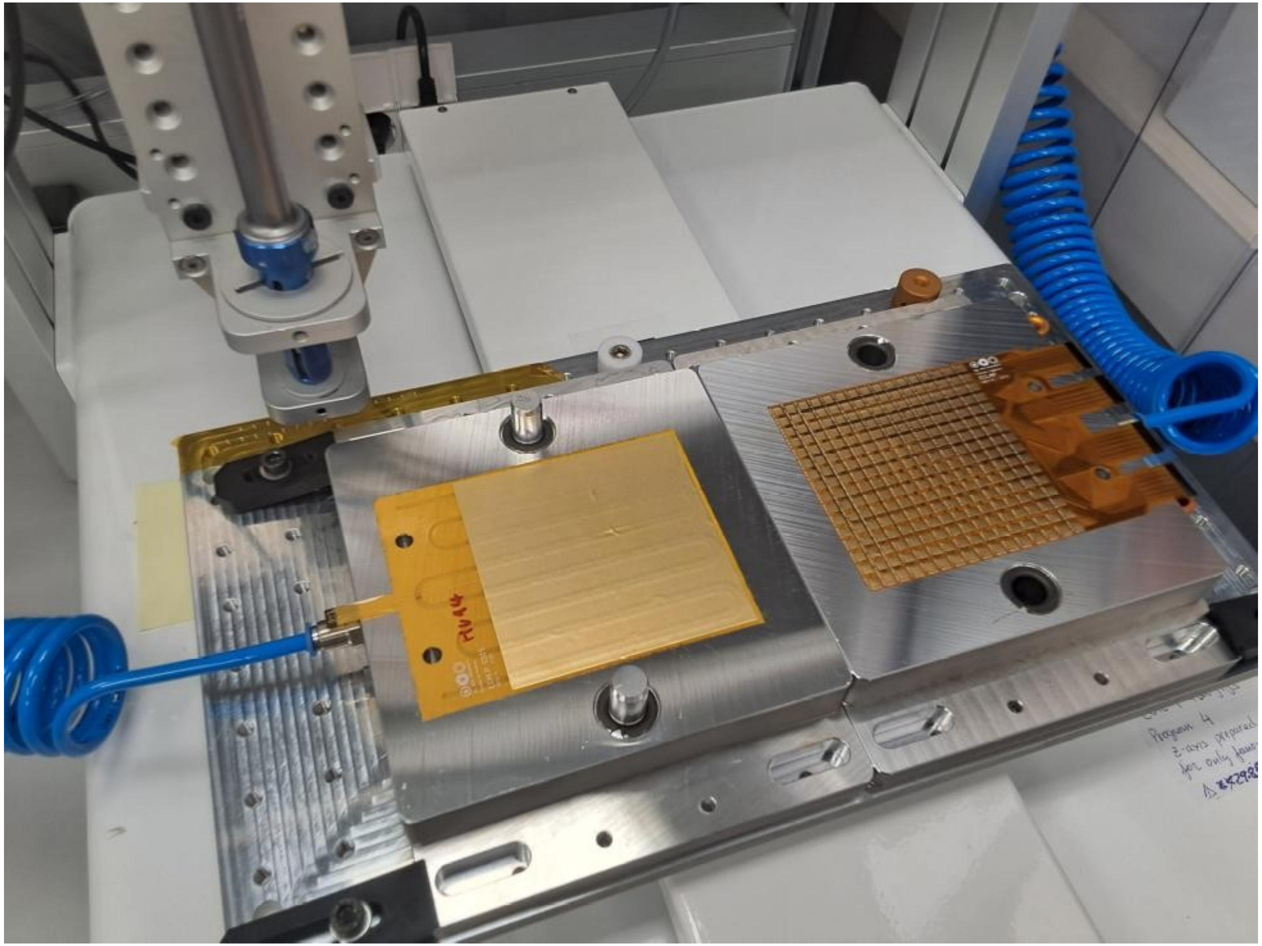
No feeler gauges used for current production → only the weight of the jigs

ECALp CSIS Assembly

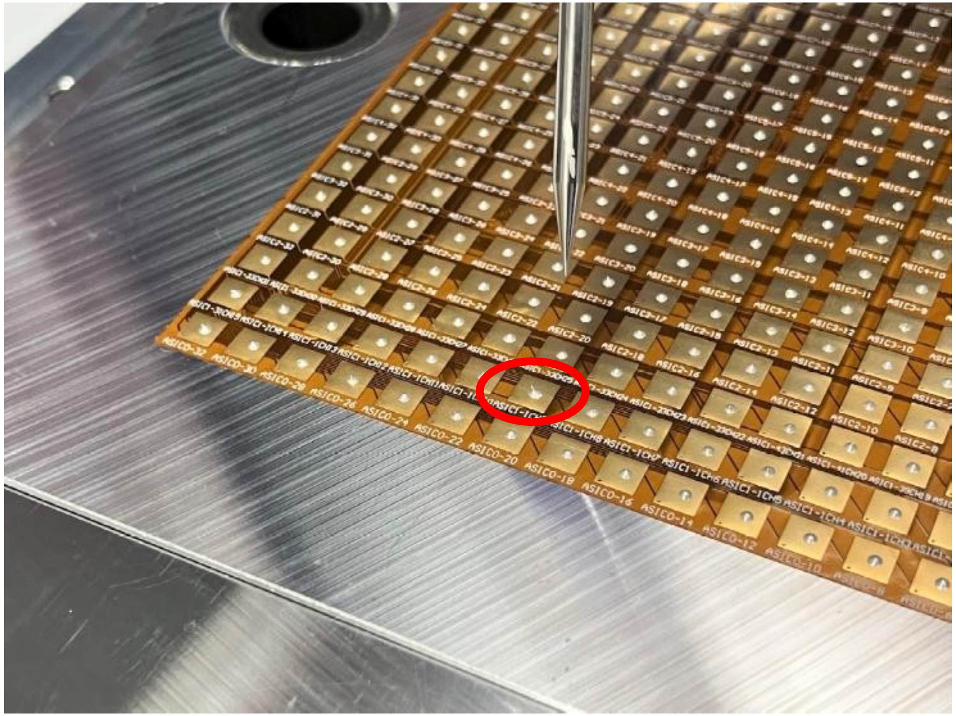




ECALp CSIS Assembly

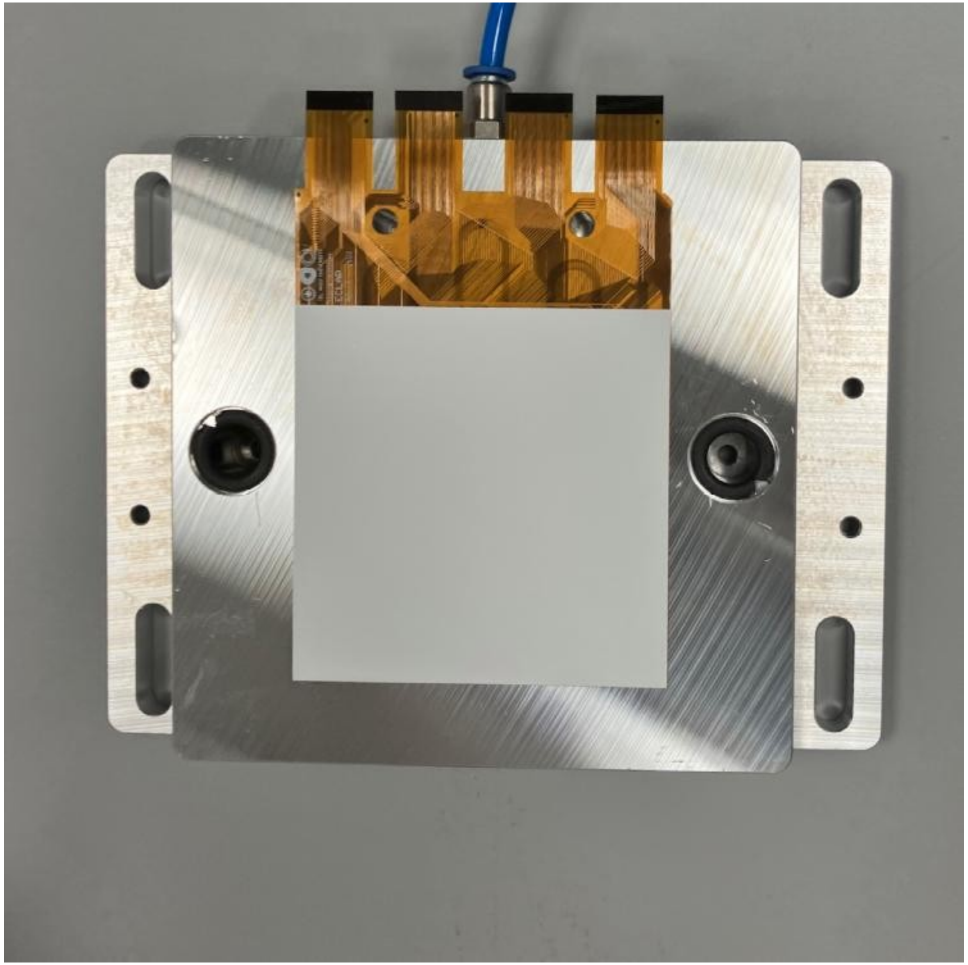


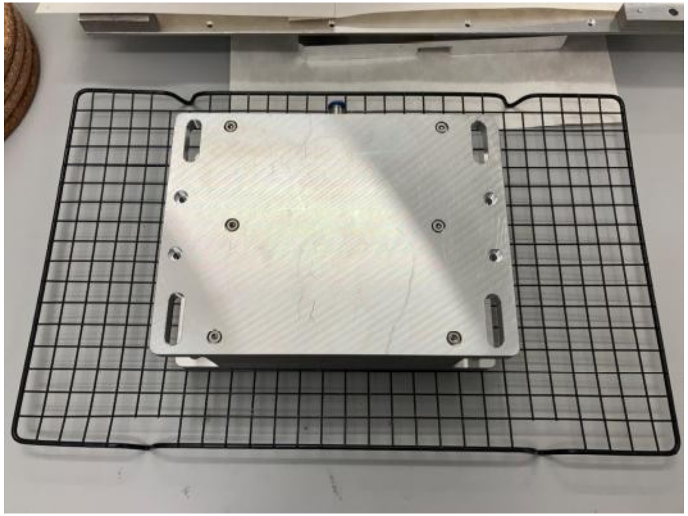
ECALp CSIS Assembly

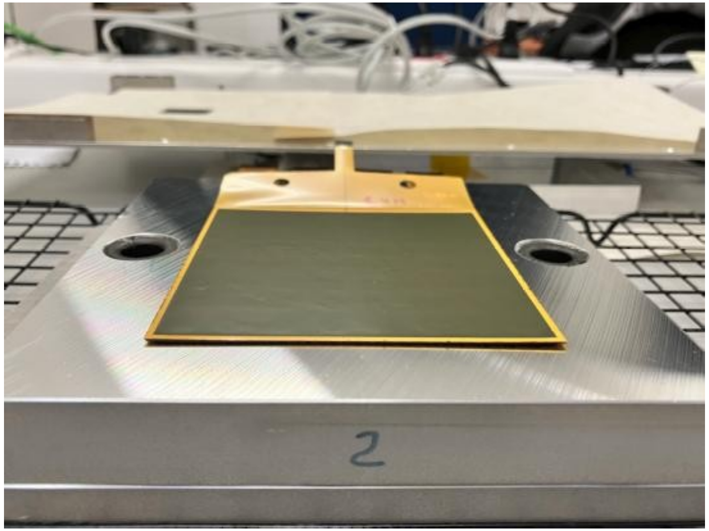


- We deposited more than 2112 glue dots → only 4 were missing.
  - Manually corrected with a needle and profiting from capillarity effects to deposit.

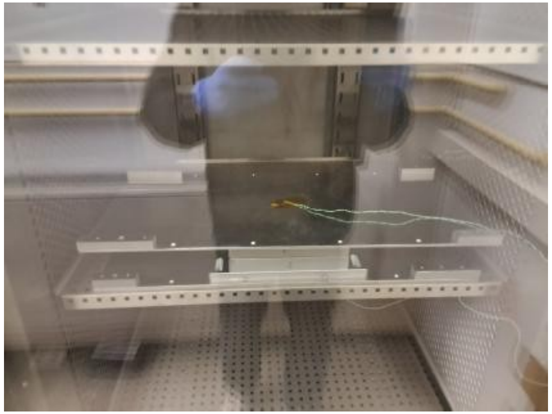
ECALp CSIS Assembly

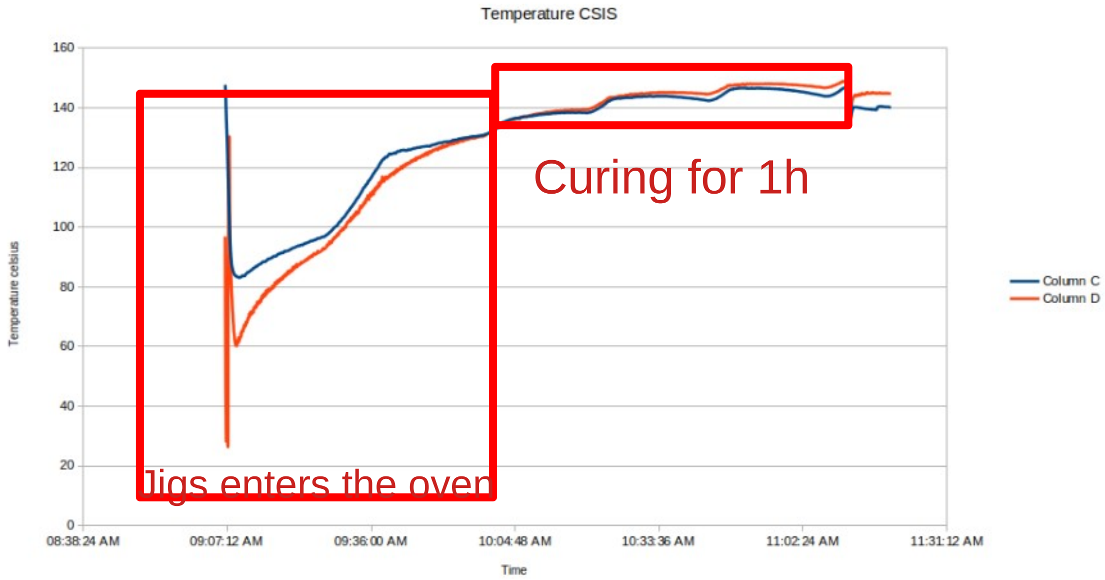






ECALp CSIS Assembly & storage



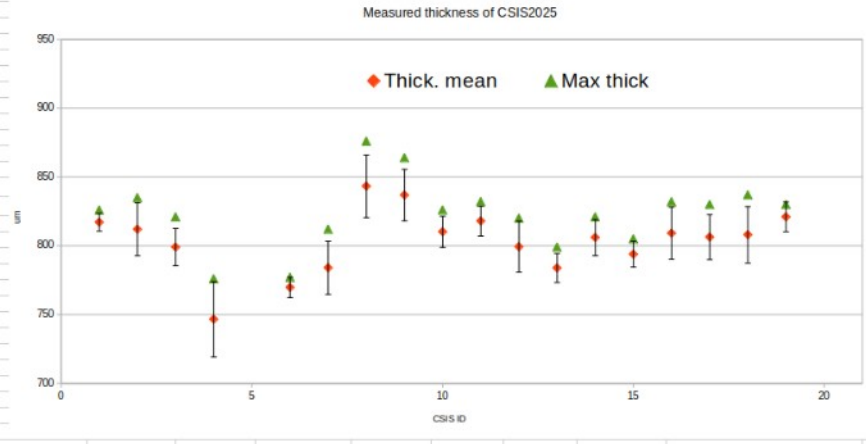


ECALp CSIS validation

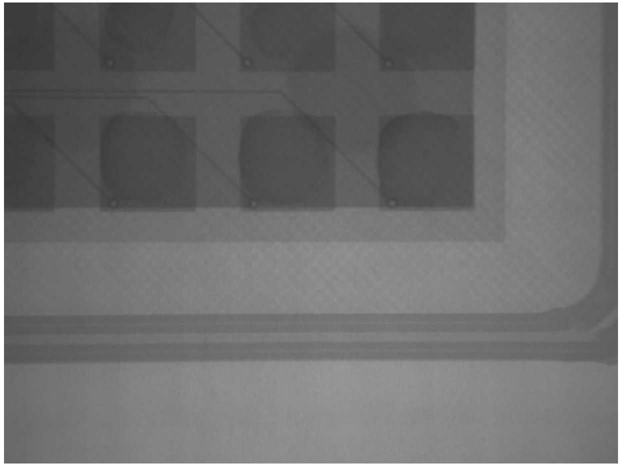
X-ray inspection of glue dots.

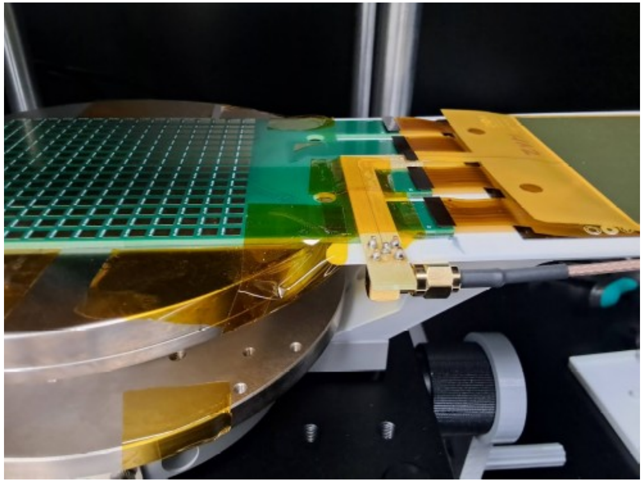
CMM measurements: All bellow 900um

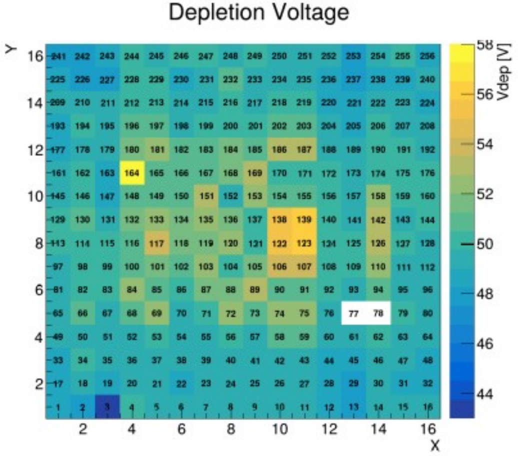
Electrical in probe station: All operative



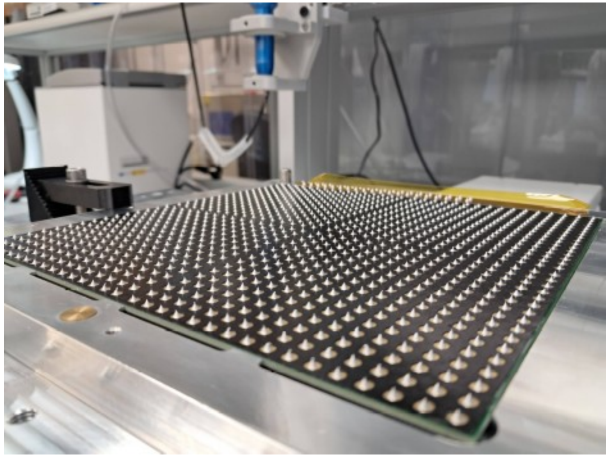
2025_001	DOWSIL+H20E
2025_002	DOWSIL+H20E
2025_003	DOWSIL+H20E
2025_004	3MDST+H20E
2025_005	3MDST+H20E
2025_006	3MDST+H20E
2025_007	3MDST+MG9410
2025_008	DOWSIL+MG9410
2025_009	DOWSIL+MG9410
2025_010	DOWSIL+H20E
2025_011	DOWSIL+H20E
2025_012	DOWSIL+H20E
2025_013	DOWSIL+H20E
2025_014	DOWSIL+H20E
2025_015	DOWSIL+H20E
2025_016	DOWSIL+H20E
2025_017	DOWSIL+H20E
2025_018	DOWSIL+H20E
2025_019	DOWSIL+H20E
2025_020	DOWSIL+H20E







TARDIS-Lab for LUXE ECAL(s) module assembly

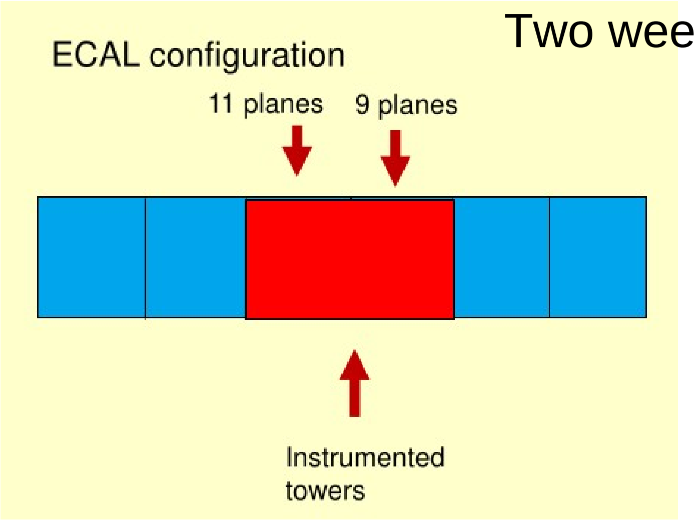


- ▷ The hybridization process is done in the new clean room (ISO4-5) of IFIC (TARDIS-Lab*)
  - For sensor characterization
  - Module assembly
  - Module characterization
- ▷ Same technologies used for ECALp and ECALe.
  - First two modules with upgraded Front-End-Board electronics (FEV2.1) of ECALe were assembled at IFIC in March
  - Tested at DESY in March too.

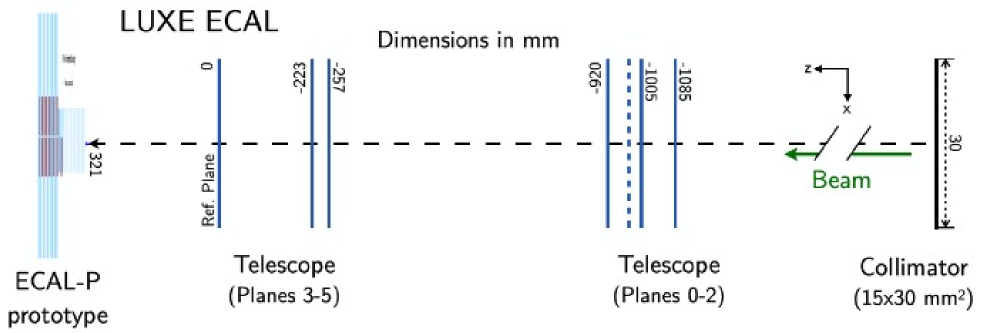
TARDIS-Lab

*(because it is larger on the inside)

ECALp Beam test setup



Two weeks of beam test at DESY – around 250M triggers (TLU)



▷ **Tracker mode**

▷ Initial runs with 3 layers

- **Area Scan** but mostly debugging

▷ **Ful stack**, with 11 layers

- ~10 M at two positions (3 GeV)
- **Area scan** with ~1 M per position (5GeV, **35** positions)

▷ **Calorimeter mode**

▷ **Position scan**, 11X0 & 9X0 (5GeV)

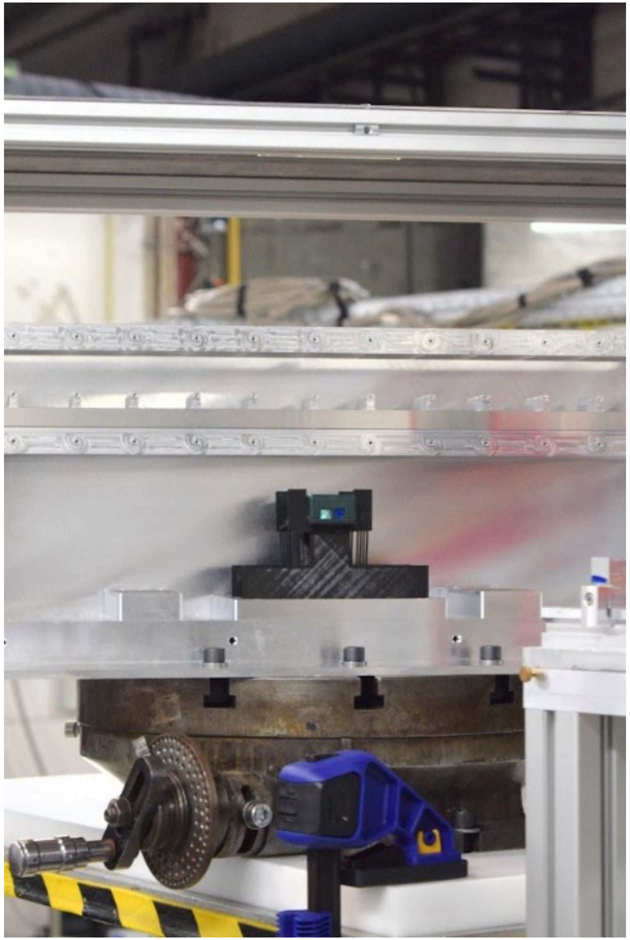
▷ **Angular scan** – energies and incidence angles matching LUXE scenarios

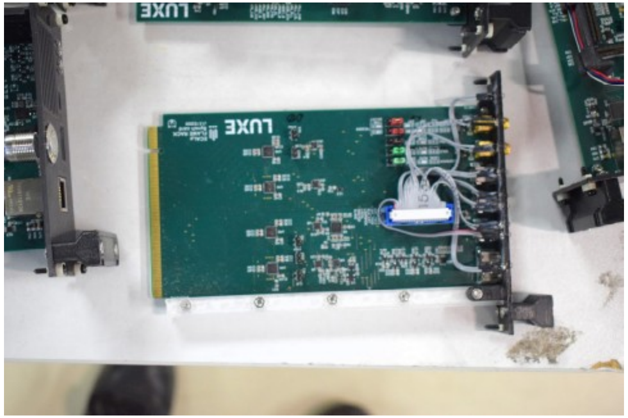
- Performance study with real gaps between sensors

▷ **Energy scan** from 1-5.6GeV in two positions

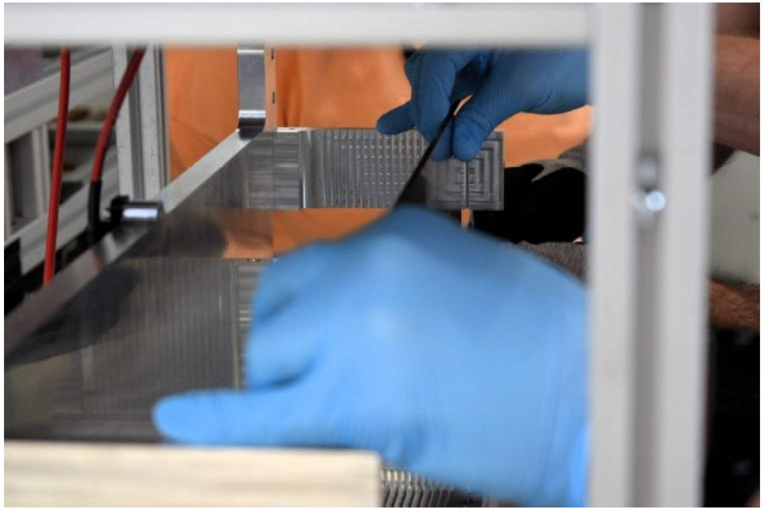
▷ **Depth scan** 11 X0, 15 X0, 18 X0, 21 X0

Beam test fun

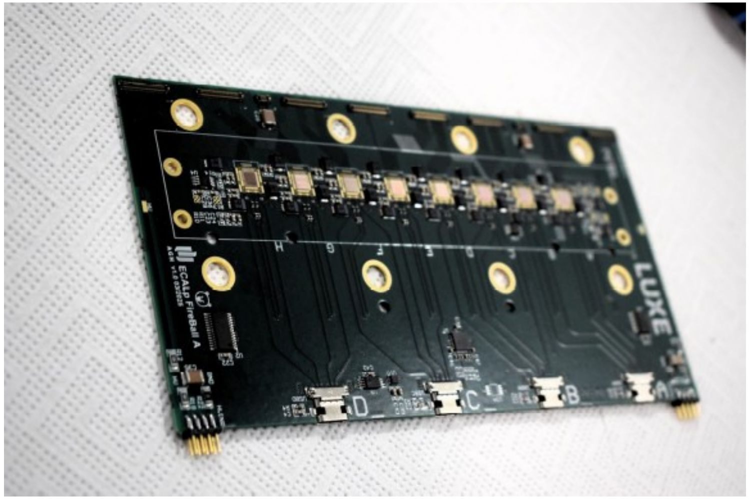


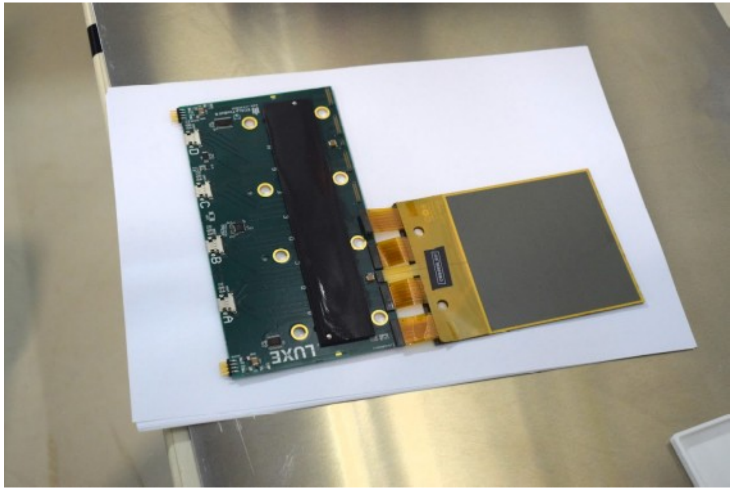


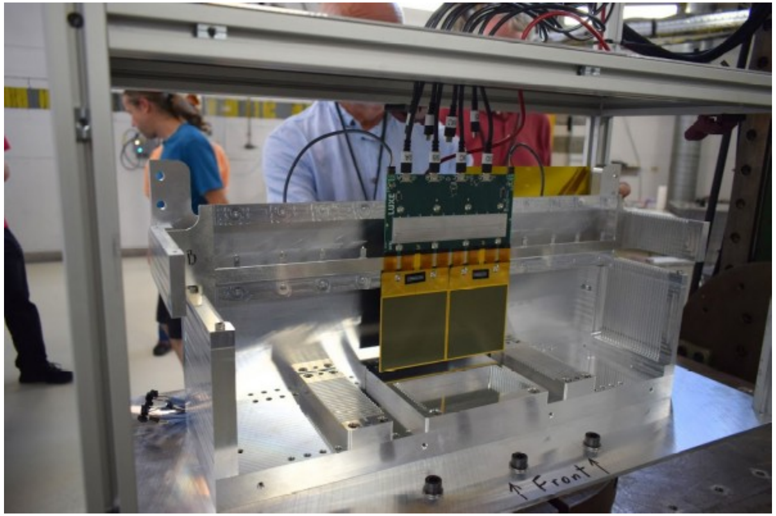
Beam test fun



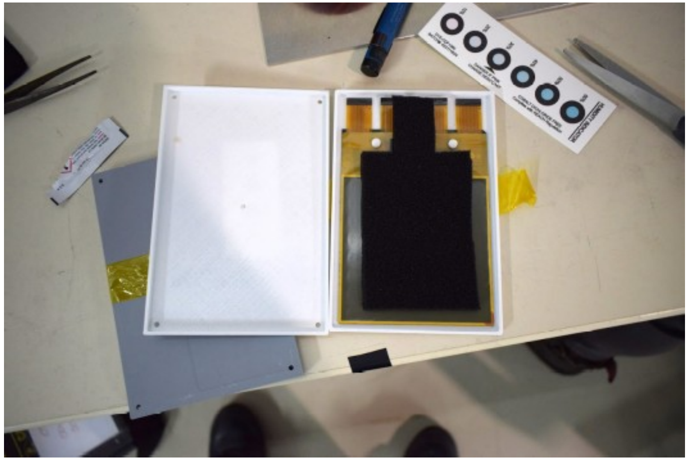
Beam test fun

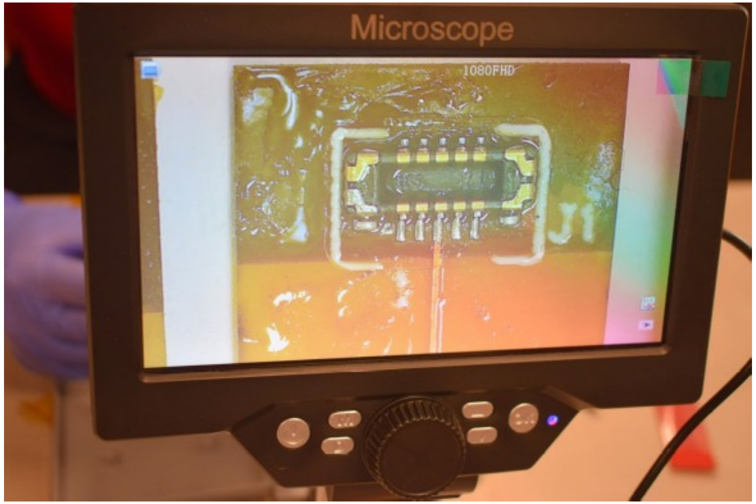


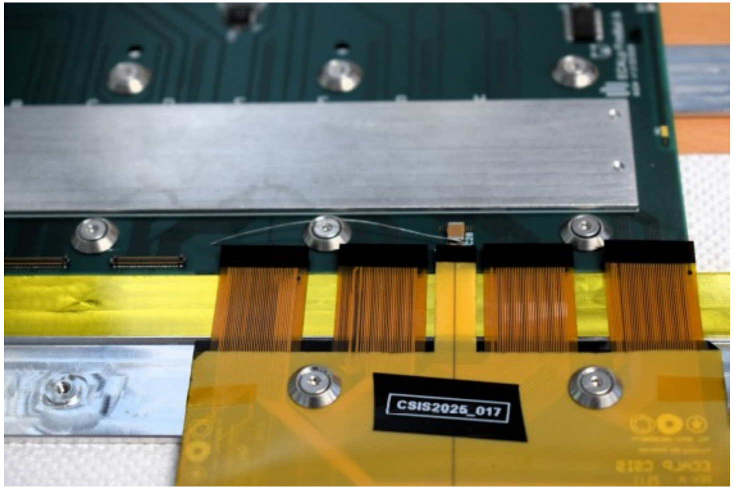


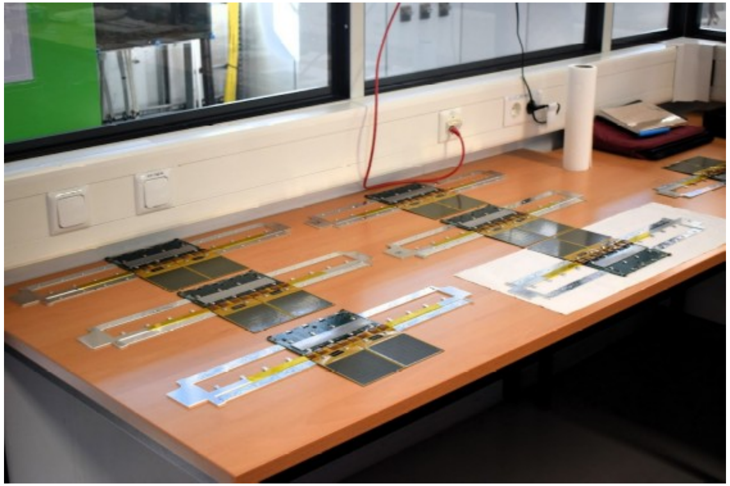


Beam test fun

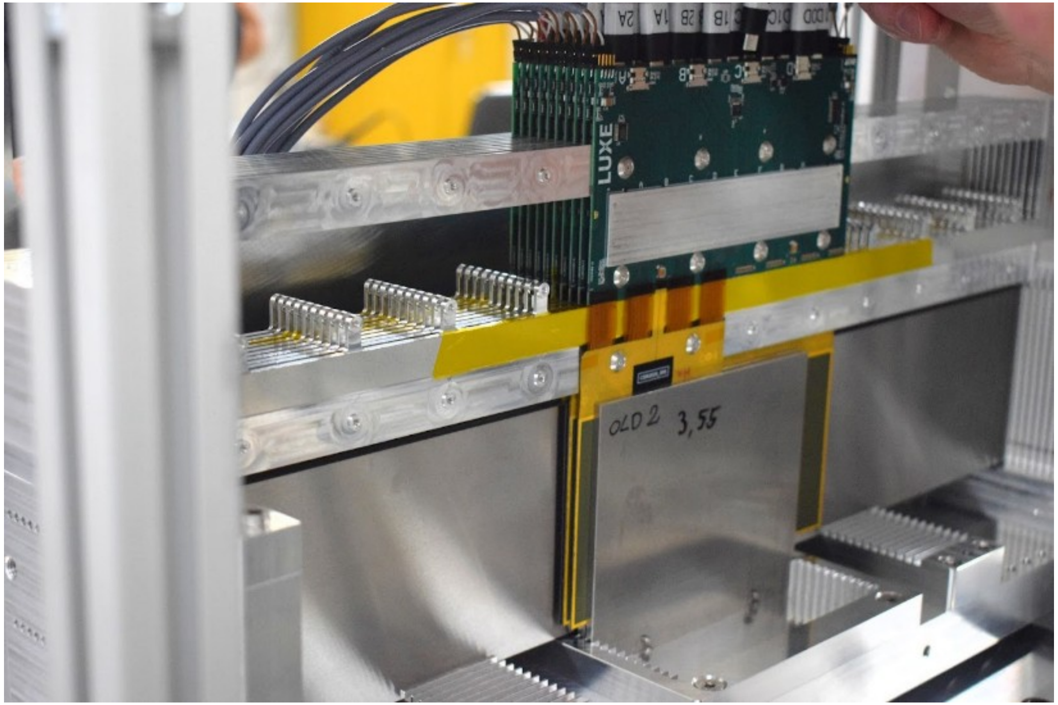




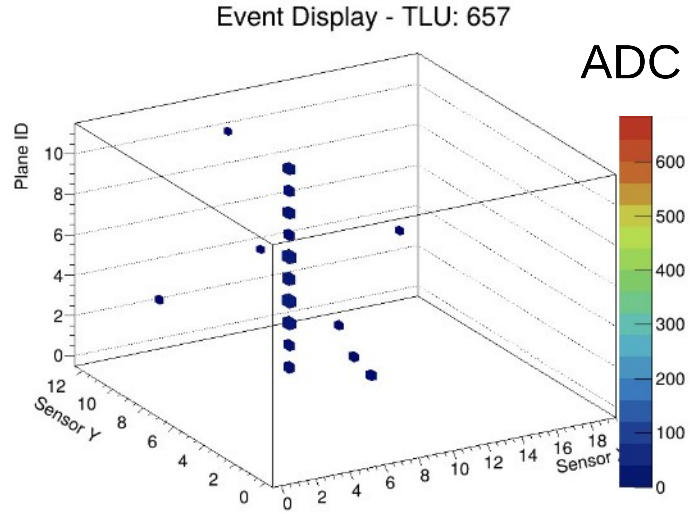


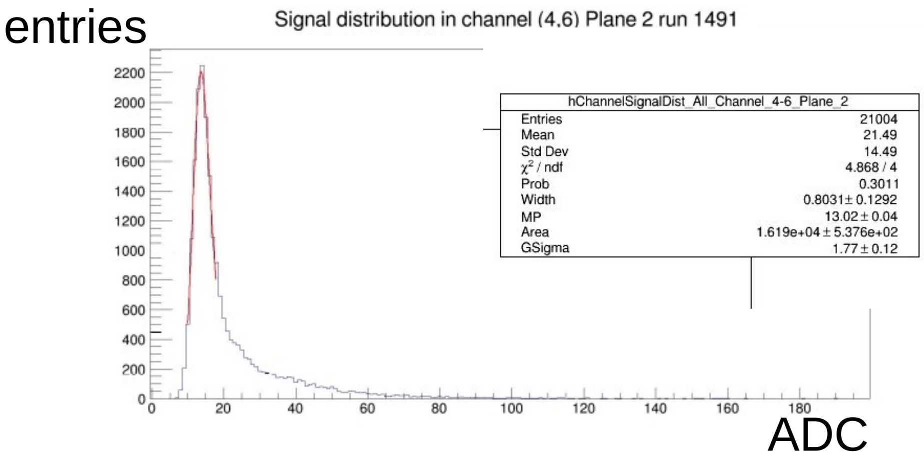


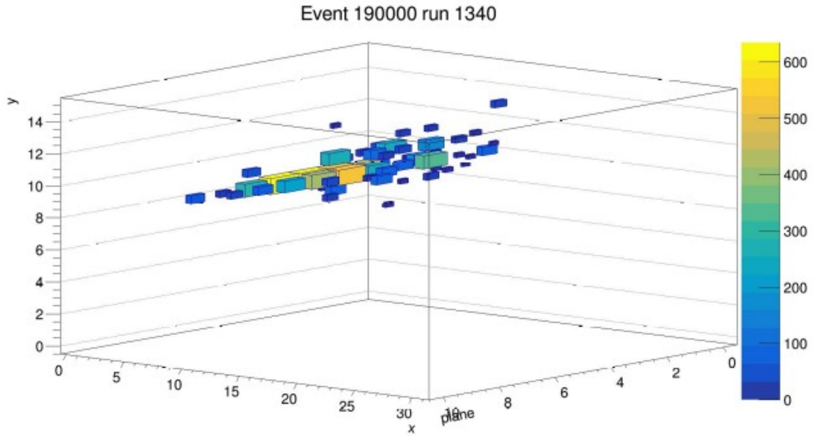
Beam test fun

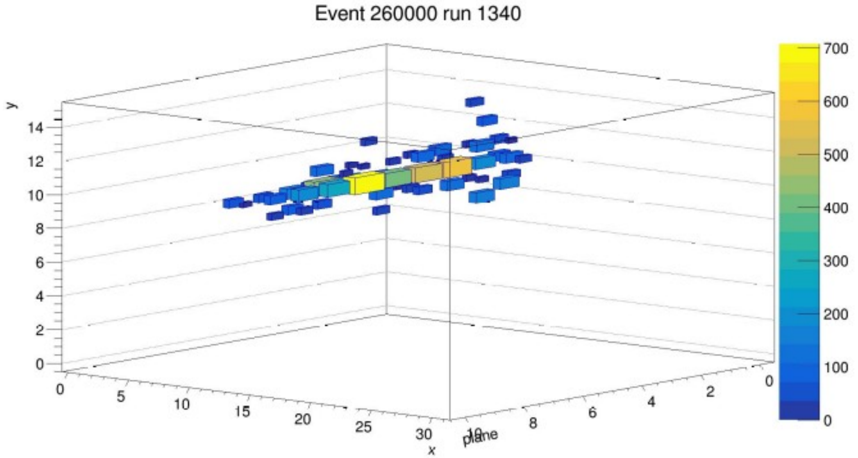


And even data… (more in Dawid's talk)







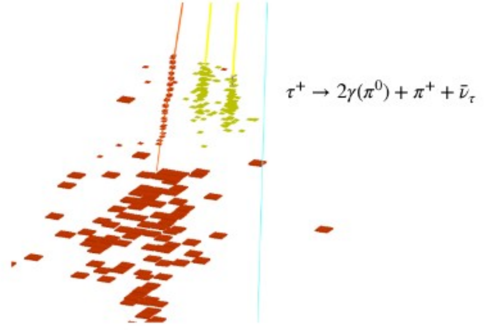


5 GeV showers

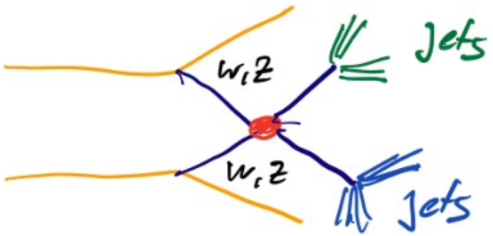
Back-up slides

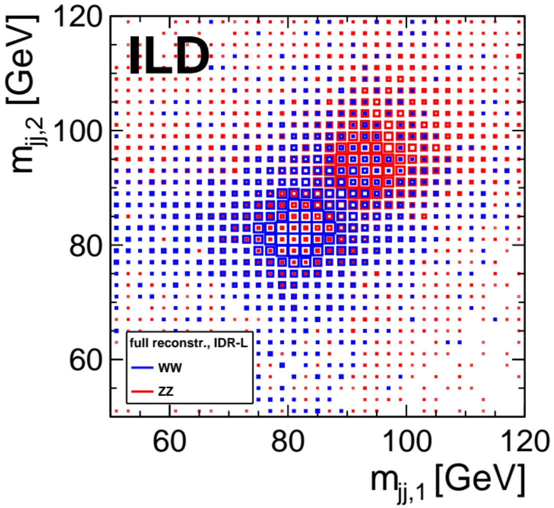
Detector Requirements

- A comprehensive test of the SM and BSM (specially in the Higgs sector) requires unprecedented performance of the detector and reconstruction techniques
- Excellent tracking + flavour tagging + Particle Identification
- Single particle separation
- Excellent energy resolution of ~3%



- Results in close-by / overlapping electromagnetic and hadronic showers



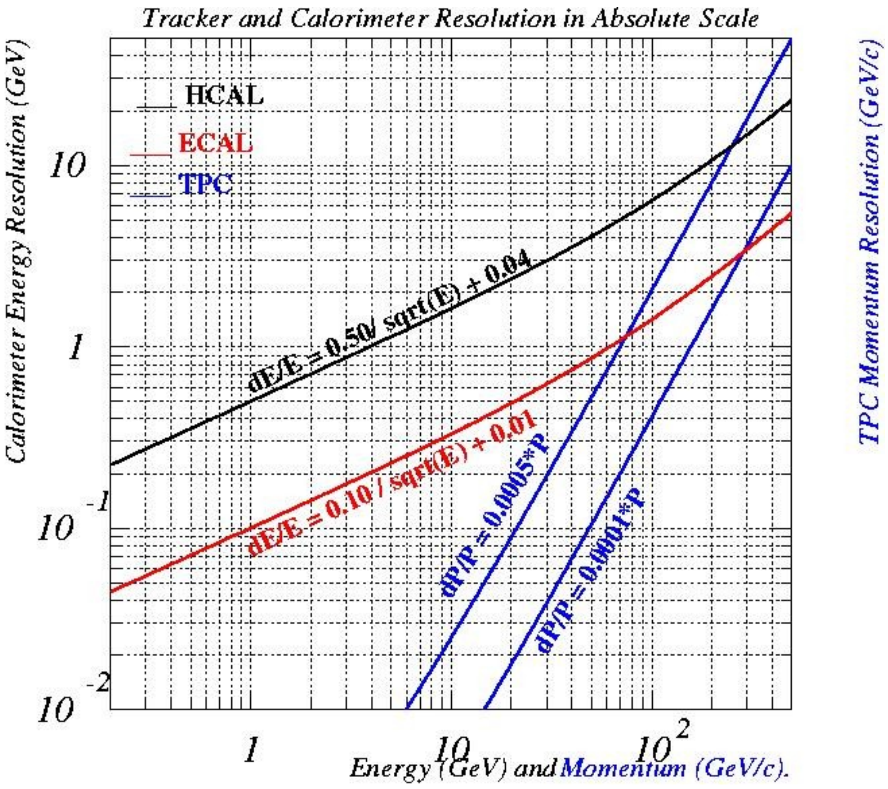


How ?

By designing a

Particle Flow Detector

Particle Flow Algorithms



In a “typical jet” the energy is carried by

▷ **Charged particles ($e^{\pm}$, $h^{\pm}$,$\mu^{\pm}$): 65%**

- Most precise measurement by **Tracker**

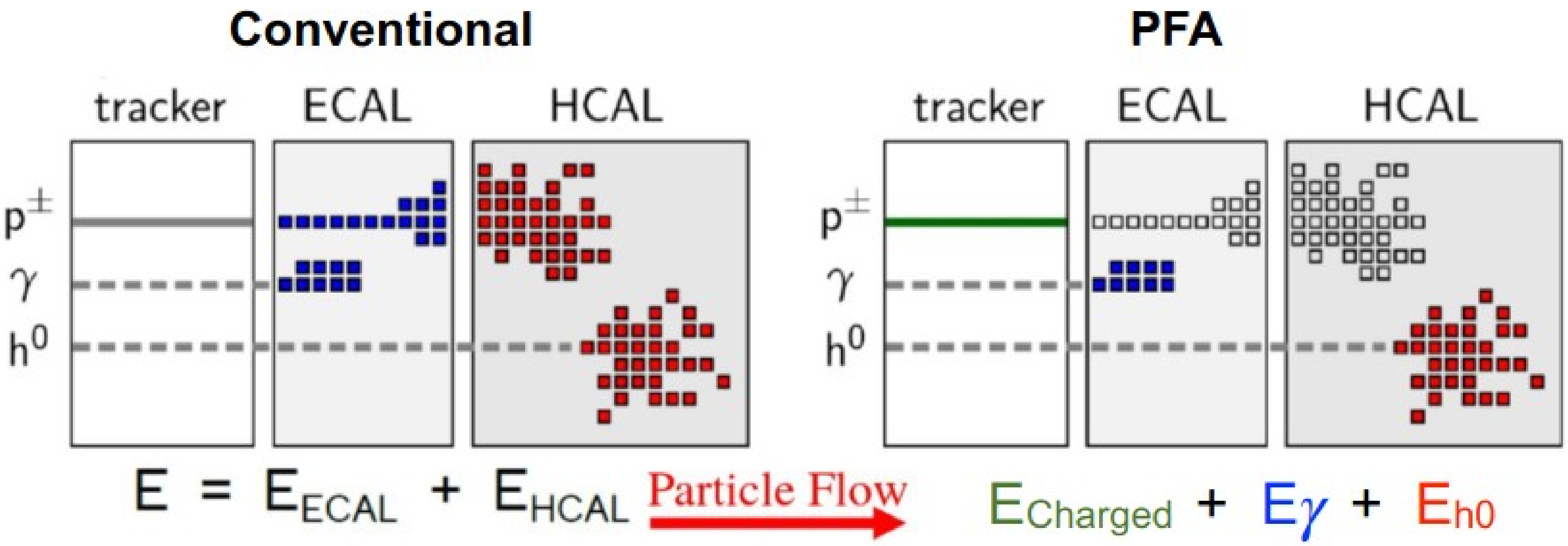
▷ **Photons: 25%**

- Measurement by Electromagnetic Calorimeter **(ECAL)**

▷ **Neutral Hadrons: 10%**

- Measurement by Hadronic Calorimeter **HCAL** and ECAL

Particle Flow Algorithms

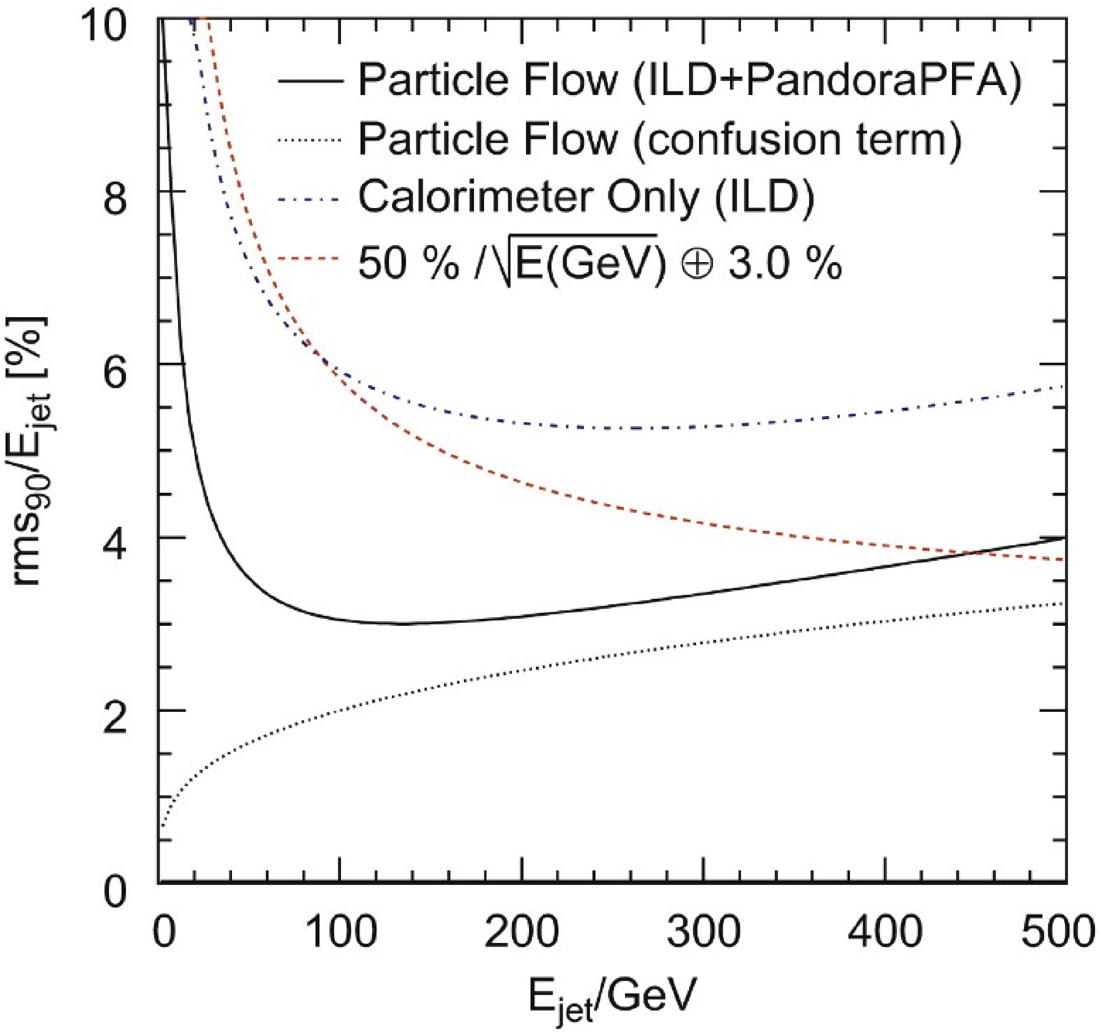


Example: jet created by a proton

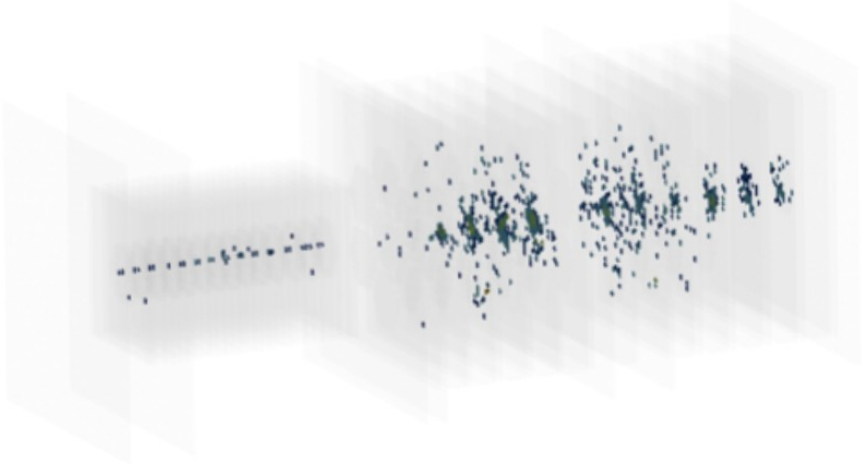
"traditional" detector : $E = E_{ECAL} + E_{HCAL}$

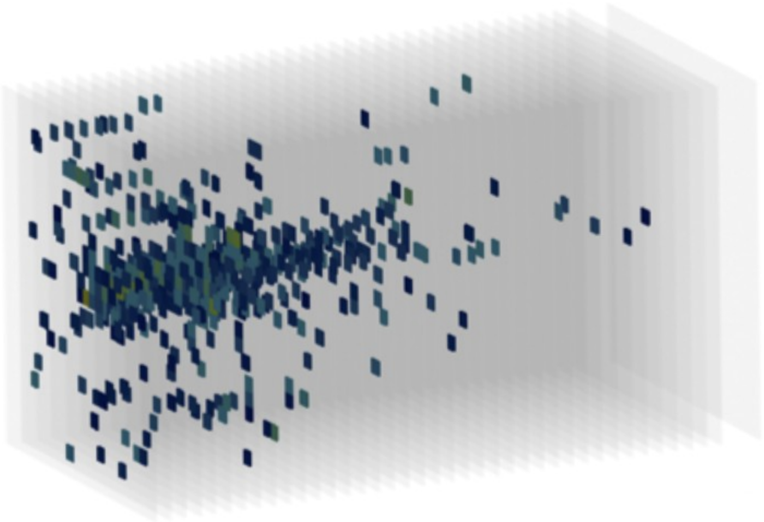
Particle Flow detector: $E = E_{track}$

High granular calorimetry

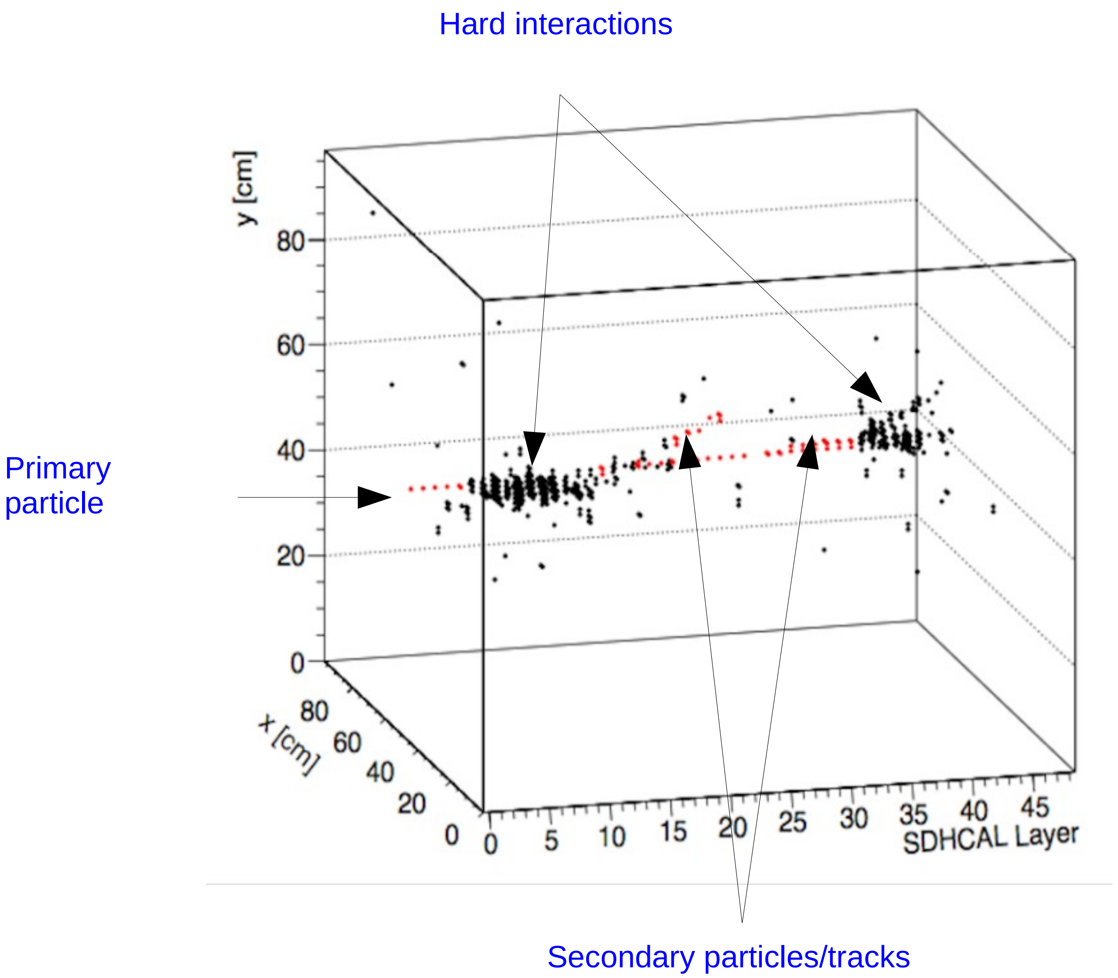


High granularity calorimeters: not only JER

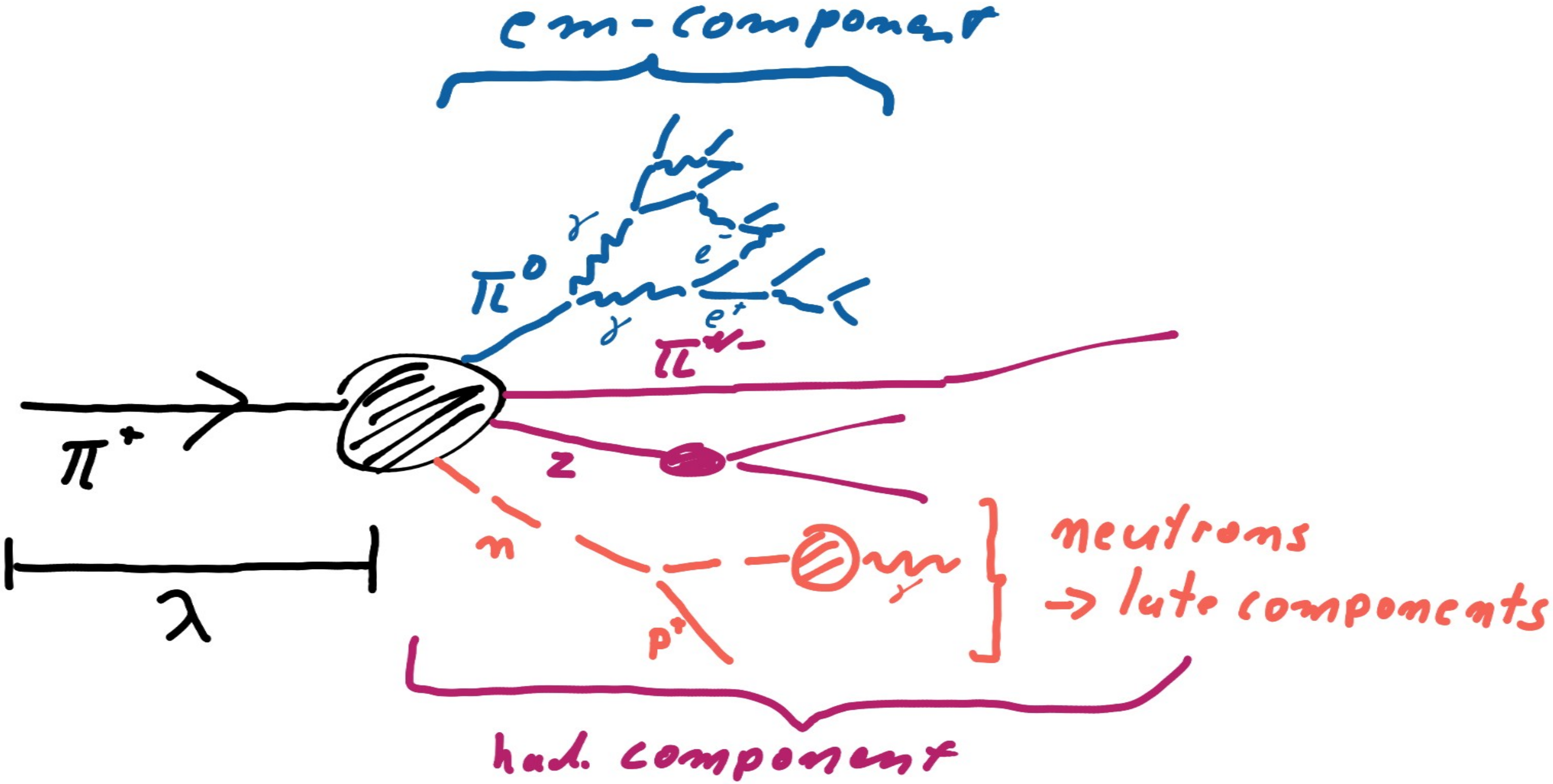




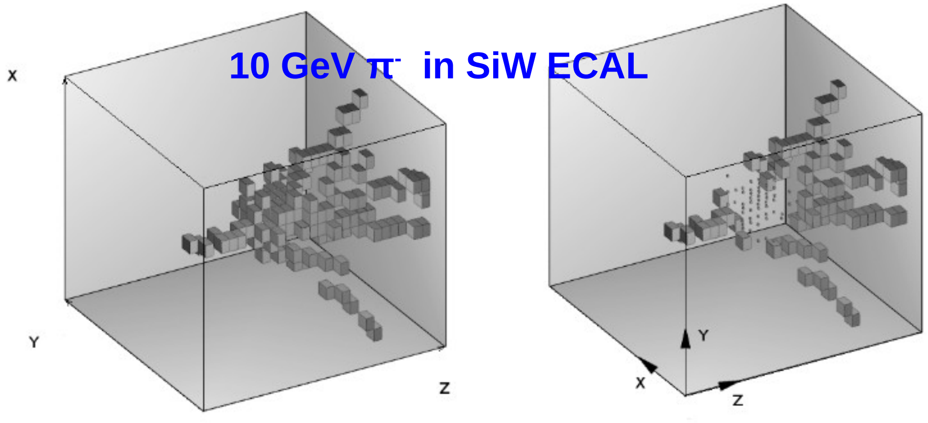
High granularity calorimeters: not only JER

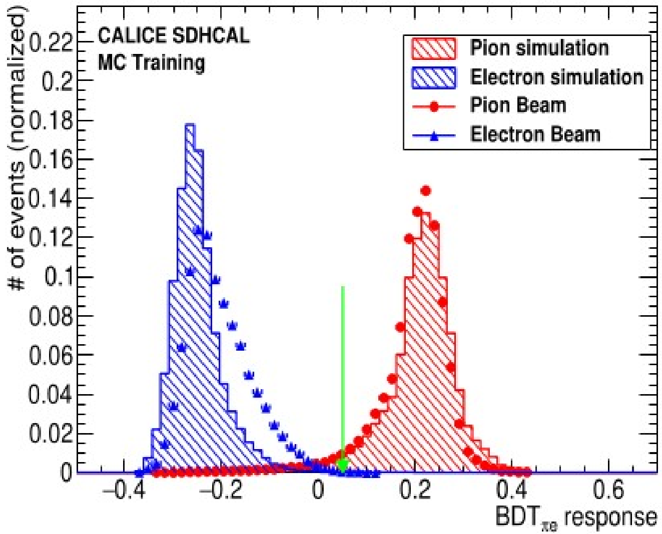


High granularity calorimeters: not only JER



High granularity calorimeters: not only JER





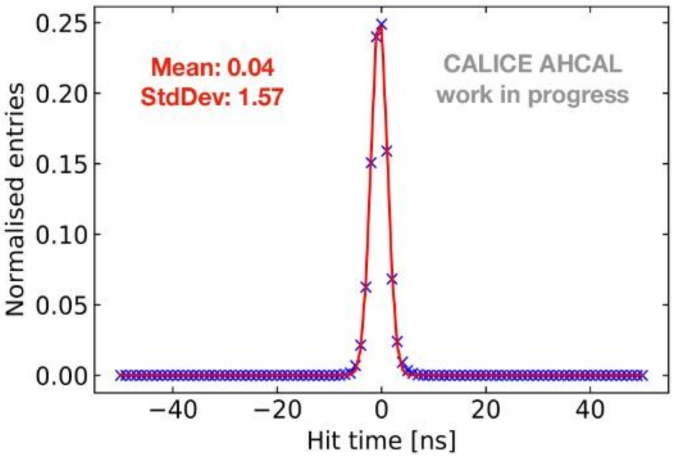
- **study of first hadronic interaction in the SiW-ECAL** (physics prototype)
  - NIM A 937 (219) 41-52

- **SDHCAL** using 6 variable discriminnating **BDT for Particle Identification** [JINST 15 (2020) P10009]

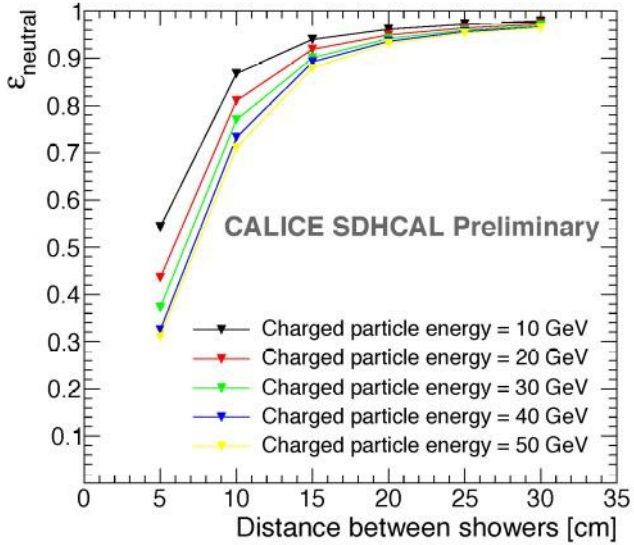
The unprecedented granularity of the proposed calorimeters offers also unprecedented capabilities to study the development of showers

High granularity calorimeters: not only JER

Clock frequency 5 MHz,
Powering pulsing



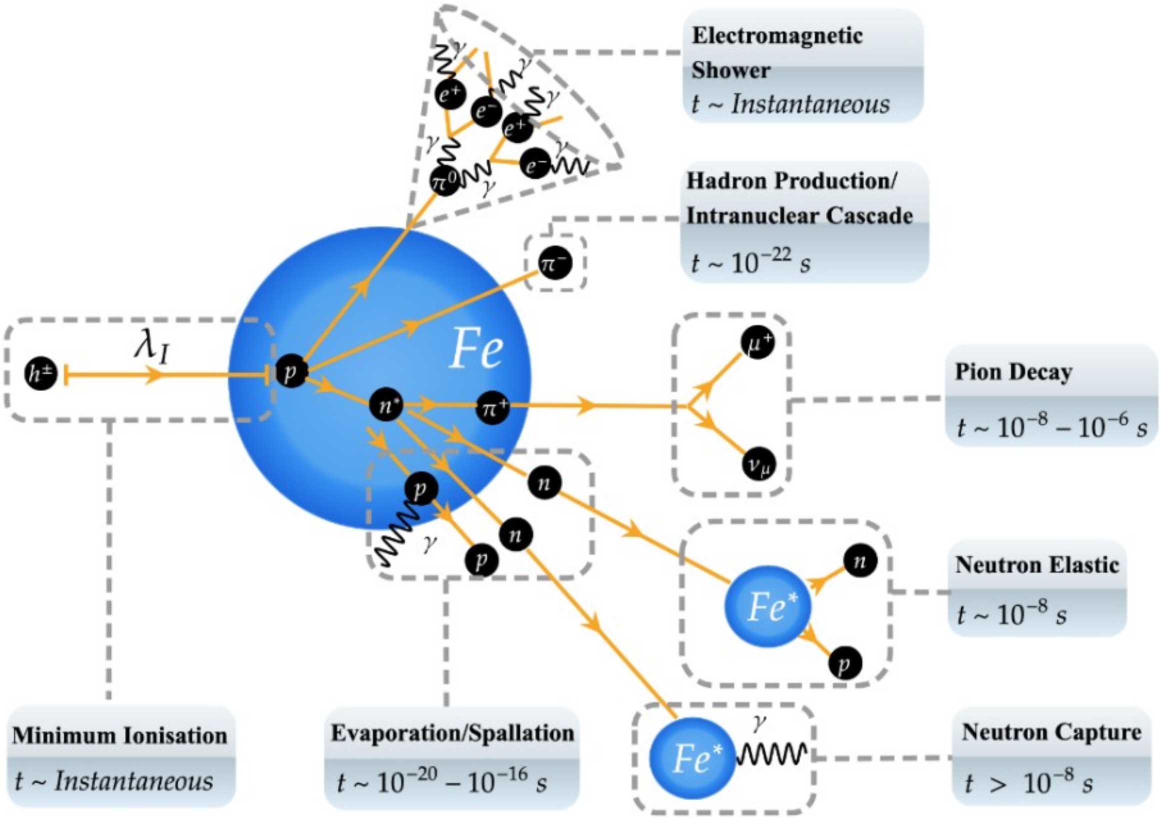
- Hit time resolution: Results from **2018 beam test** of **AHCAL** with muons
  - Encouraging results (1-2 ns resolution)
  - Distinction between slow and fast components in the showers (neutral vs charged)



- **SDHCAL**: Separation of 10 GeV between neutral hadron and charged hadron [CALICE-CAN-2015-001]
  - More than 90% efficiency and purity for distances ≥ 15 cm

The unprecedented granularity of the proposed calorimeters offers also unprecedented capabilities to study the development of showers

High granularity calorimeters: timing granularity



Timing measurements for shower developments

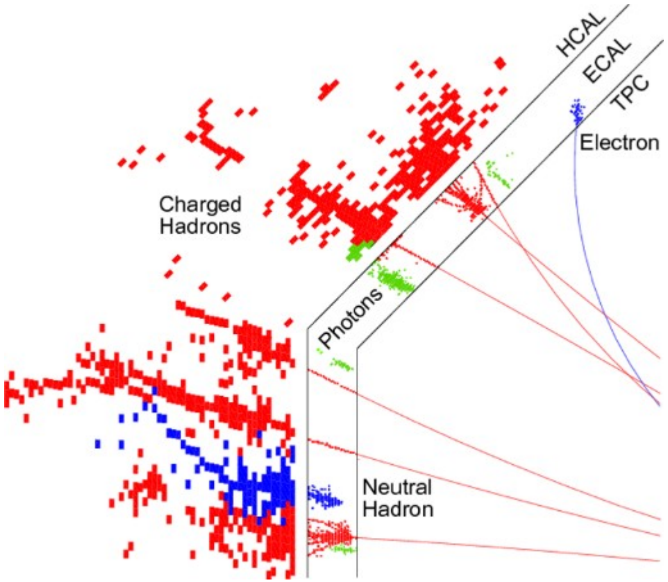
▷ Neutral and slow components

- Require ~ns precision
- Reachable today with "standard" silicon, scintillators calorimeters

▷ ~0.1 ns scale: near the corner

- with "standard" silicon sensors (HGCAL)
- GRPC (20ps)

Particle Flow Concept

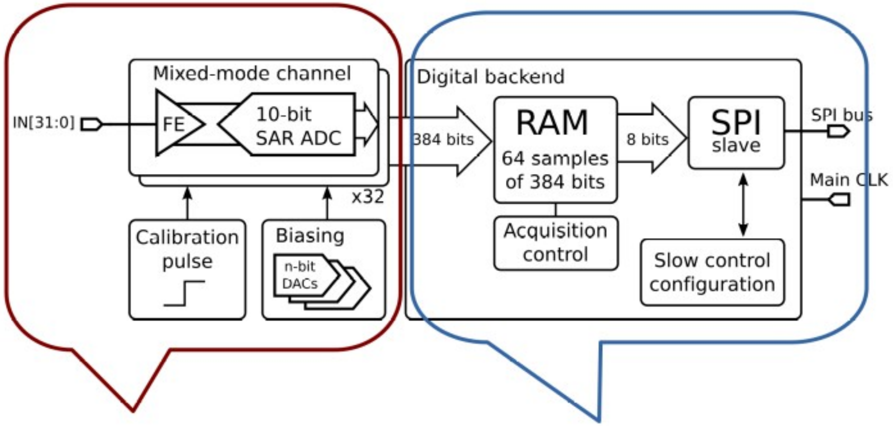


(some) Technological Challenges

- Need **extremely granular calorimeters** (100 of millions of cells…!)
- Require **very low material budget** in front of the calorimeters and **excellent tracking systems**

FLAXE

FLAXE architecture

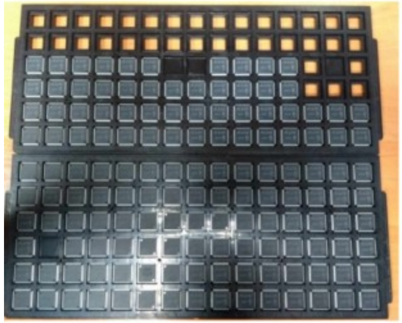


Copied from FLAME

New “simple” slow readout with memory

FLAXE – Qualification tests

Out of ~1000 fabricated chips, 142 were packaged and tested



Test	Good	Acceptable	Bad	Failed
Overall ASIC yield	0 [0%]	6 [4.2%]	5 [3.5%]	131 [92.3%]
Supply shorts	92 [64.8%]	0 [0%]	0 [0%]	50 [35.2%]
Power consumption in sleep mode	7 [7.6%]	9 [9.8%]	30 [32.6%]	46 [50%]
Power consumption in always on	6 [12.8%]	9 [19.1%]	25 [53.2%]	7 [14.9%]
SPI SC register default read	33 [35.9%]	10 [10.9%]	46 [50%]	3 [3.3%]
SPI SC register write	10 [10.9%]	16 [17.4%]	21 [22.8%]	45 [48.9%]
Datapath RAM error map	0 [0%]	18 [38.3%]	3 [6.4%]	26 [55.3%]
Datapath RAM input sample	41 [87.2%]	3 [6.4%]	2 [4.3%]	1 [2.1%]
Biasing DAC's	17 [36.2%]	15 [31.9%]	1 [2.1%]	14 [29.8%]
Channel data readability	5 [10.6%]	12 [25.5%]	4 [8.5%]	26 [55.3%]
Channel trimDAC	0 [0%]	19 [90.5%]	1 [4.8%]	1 [4.8%]
FE response and pulse shape	0 [0%]	7 [33.3%]	4 [19%]	10 [47.6%]
FE gain	0 [0%]	7 [33.3%]	4 [19%]	10 [47.6%]

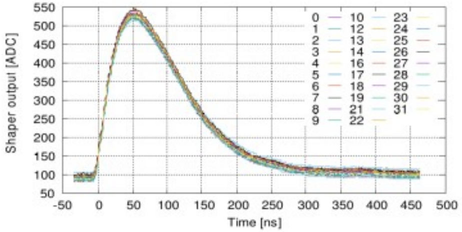
Our conclusion is that there was a production failure

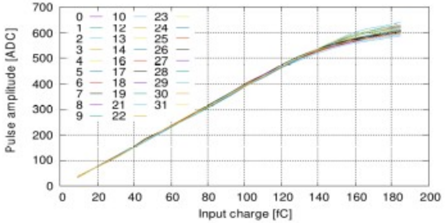
FLAXE

AGH

FLAXE – Tests
6 chips got "acceptable" status

Chip Number	No. of working channels	No. of correct trimDAC's	No. of correct shapes	No. of correct gains
25	19	20	11	16
32	26	25	25	26
76	22	23	19	20
84	27	28	16	27
136	30	30	28	29
139	27	27	25	26





Performance of working channels in very good agreement with simulations

AGH

JINST — Published by IOP Publishing for Sissa Medialab

Received: October 31, 2024
Accepted: December 18, 2024
Published: January 22, 2025

Topical Workshop on Electronics for Particle Physics
University of Glasgow, Scotland, U.K.
30 September–4 October 2024

FLAXE, a SoC readout ASIC for electromagnetic calorimeter at LUXE experiment

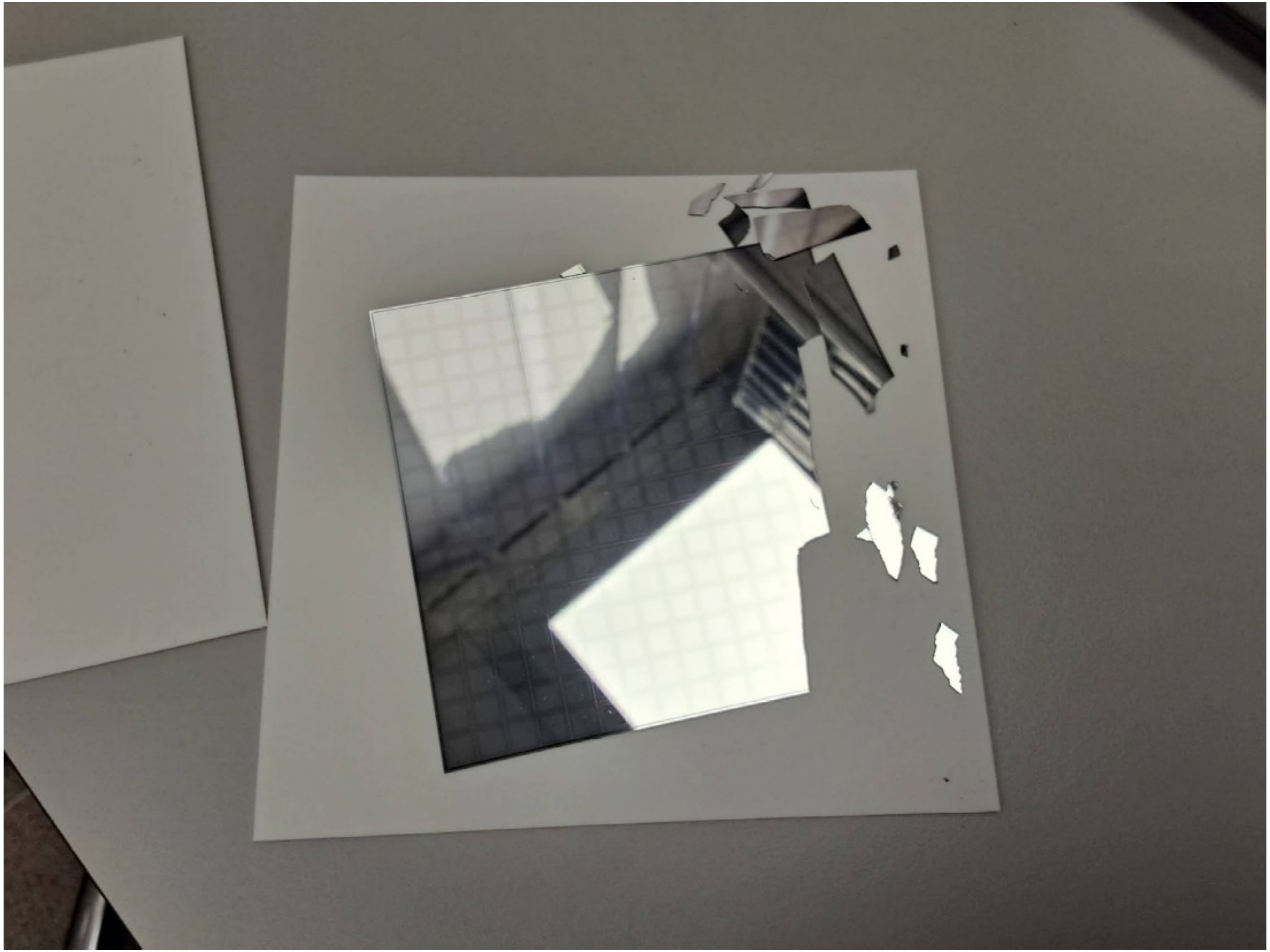
Jakub Moroń,* Mirosław Firlej, Tomasz Fiutowski, Marek Idzik and Krzysztof Świentek

Faculty of Physics and Applied Computer Science, AGH University of Krakow, Al. Mickiewicza 30, 30-059 Kraków, Poland

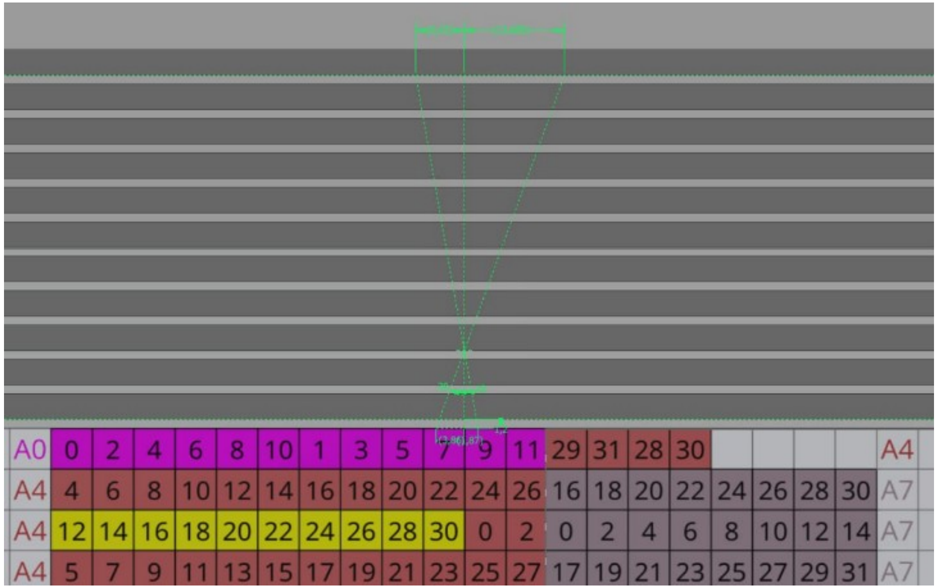
E-mail: jmoron@agh.edu.pl

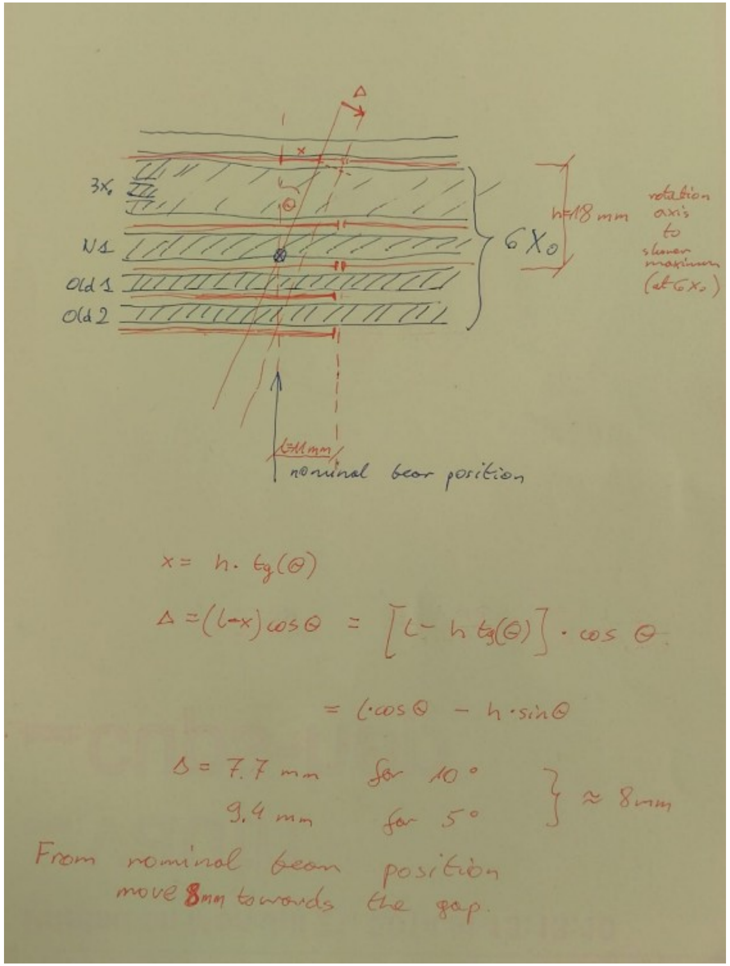
Abstract: The design and qualification results of a System on Chip (SoC) Application-Specific Integrated Circuit (ASIC), called FLAXE, fabricated in 130 nm CMOS technology are presented. FLAXE is a readout ASIC designed for ECAL-p, a compact electromagnetic calorimeter being a part of a detector system for Laser Und XFEL Experiment (LUXE) proposed at DESY, Hamburg, as an extension to the European X-ray Free Electron Laser (XFEL) facility. ECAL-p is a sampling calorimeter with a very compact design targeting small Molière radius, comprising 16 (up to 20) layers composed of 3.5 mm (1 X_0) thick tungsten absorber plates interspersed with silicon sensors. Sensor signal is read and shaped by the analogue readout channel, comprising a Charge Sensitive Amplifier (CSA) and a fully differential CR-RC shaper with 50 ns peaking time, which output is digitized in each channel by a 10-bit Successive Approximation Register (SAR) Analog-to-Digital Converter (ADC). Data from ADC are collected into the ASIC internal memory and read out by the Data Acquisition (DAQ) system between Bunch Crossings (BXs). Around 1000 ASICs have been fabricated and a first batch of 142 ASICs has been packaged and tested. The results of the qualification procedure,

2025 JINST 20 C01026

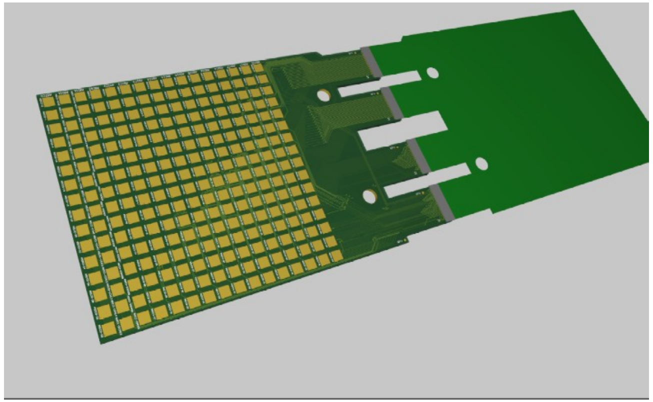


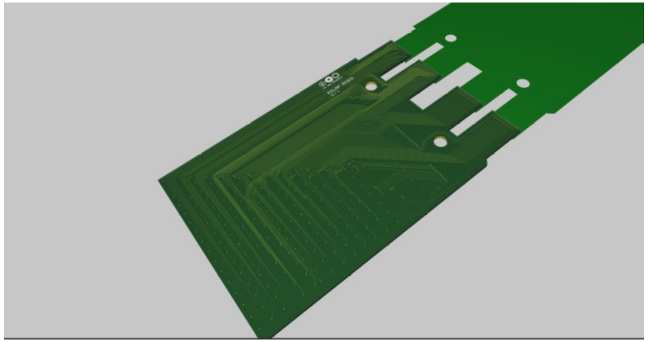
Beam test setup

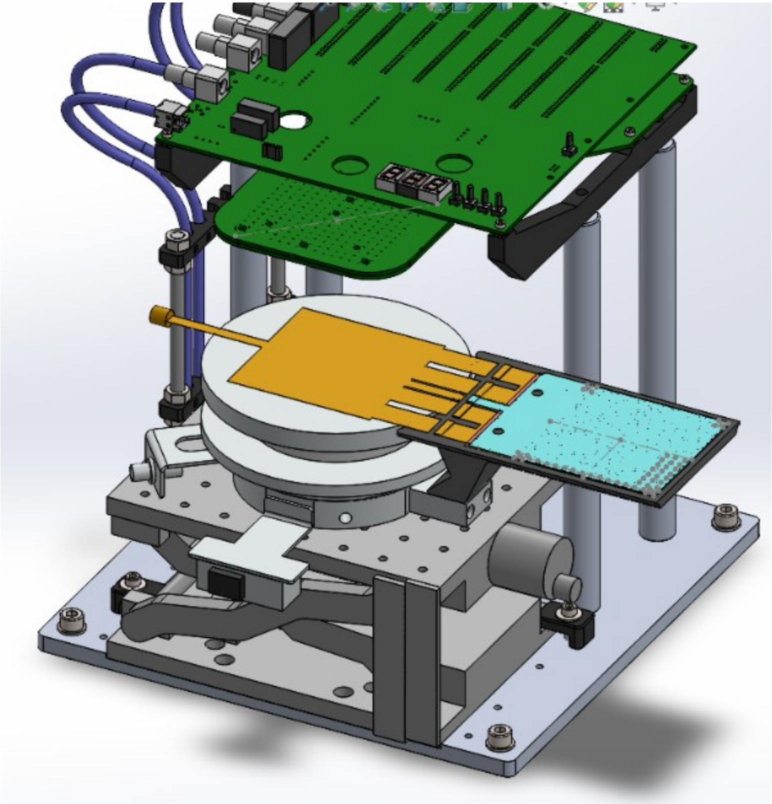




Testing the connectivity







9410

MG Chemicals

1-Part Epoxy, Electrically Conductive Adhesive, High T_g

9410 is a 1-part electrically conductive epoxy adhesive that can be stored at room temperature. It bonds well to a wide variety of substrates, and offers strong chemical resistance.

9410 is designed for semi-conductor flip chip packaging as well as die attach for small chips, LEDs and diodes. It provides excellent EMI/RFI shielding and is very effective at filling in seams between metal plates. It can be readily used in manual, pneumatic and robotic dispensing processes.

Features and Benefits

- Creates strong permanent electrical connections
- No mixing required
- Low cure temperature of 90 °C
- Room temperature storage (≤22 °C)
- Suitable for automated dispensing

Available Packaging

Cat. No.	Packaging	Net Vol.	Net Wt.
9410-3ML	Syringe	3 mL	7.00 g
9410-30ML	Cartridge	30 mL	70.0 g
9410-180ML	Cartridge	180 mL	378 g

Contact Information

MG Chemicals, 1210 Corporate Drive
Burlington, Ontario, Canada L7L 5R6

Email: support@mgchemicals.com

Phone: North America: +(1)800-340-0772
International: +(1) 905-331-1396
Europe: +(44)1663 362888

Cured Properties

Resistivity	1.8×10^{-3} Ω·cm
Hardness	70 D
Compressive Strength	26 N/mm²
Lap Shear (stainless steel)	2.6 N/mm²
(aluminum)	2.8 N/mm²
Glass Transition Temperature (T_g)	96 °C
CTE Prior T_g	42 ppm/°C
CTE After T_g	150 ppm/°C
Thermal Conductivity @ 25 °C	1.1 W/(m·K)
Service Temperature Range	-65–145 °C

Uncured Properties

Viscosity @ 25 °C	Thixotropic paste
Thixotropic Index @ 25 °C	3
Density	2.3 g/mL

EPOXY TECHNOLOGY

EPO-TEK® H20E

Technical Data Sheet
For Reference Only
Electrically Conductive, Silver Epoxy

Date:	November 2019
Rev:	XVII
No. of Components:	Two
Mix Ratio by Weight:	1 : 1
Specific Gravity:	Part A: 2.03 Part B: 3.07 Syringe: 2.67
Pot Life:	2.5 Days
Shelf Life- Bulk:	One year at room temperature
Shelf Life- Syringe:	One year at -40°C

Recommended Cure: 150°C / 1 Hour

Minimum Alternative Cure(s):
May not achieve performance properties below
150°C / 5 Minutes
120°C / 15 Minutes
80°C / 3 Hours

NOTES:
- Container(s) should be kept closed when not in use.
- Filled systems should be stirred thoroughly before mixing and prior to use.
- Performance properties (rheology, conductivity, others) of the product may vary from those stated on the data sheet when bi-pak/syringe packaging or post-processing of any kind is performed. Epoxy's warranties shall not apply to any products that have been reprocessed or repackaged from Epoxy's delivered status/container into any other containers of any kind, including but not limited to syringes, bi-paks, cartridges, pouches, tubes, capsules, films or other packages.

Product Description: EPO-TEK® H20E is a two component, 100% solids silver-filled epoxy system designed specifically for chip bonding in microelectronic and optoelectronic applications. It is also used extensively for thermal management applications due to its high thermal conductivity. It has proven itself to be extremely reliable over many years of service and is still the conductive adhesive of choice for new applications. Also available in a single component frozen syringe.

Typical Properties: Cure condition: 150°C / 1 Hour Different batches, conditions & applications yield differing results.
Data below is not guaranteed. To be used as a guide only, not as a specification. * denotes test on lot acceptance basis

PHYSICAL PROPERTIES:				
* Color (before cure):	Part A: Silver		Part B: Silver	
* Consistency:	Smooth thixotropic paste			
* Viscosity (23°C) @ 100 rpm:		2,200 - 3,200	cPs	
Thixotropic Index:		4.6		
* Glass Transition Temp:		≥ 80	°C (Dynamic Cure: 20-200°C/ISO 25 Min; Ramp -10-200°C @20°C/Min)	
Coefficient of Thermal Expansion (CTE):				
Below Tg:		31	$\times 10^{-6}$ in/in°C	
Above Tg:		158	$\times 10^{-6}$ in/in°C	
Shore D Hardness:		75		
Lap Shear @ 23°C:		1,475	psi	
Die Shear @ 23°C:		≥ 10	Kg	3,556 psi
Degradation Temp:		425	°C	
Weight Loss:				
@ 200°C:		0.59	%	
@ 250°C:		1.09	%	
@ 300°C:		1.67	%	
Suggested Operating Temperature:		< 300	°C (Intermittent)	
Storage Modulus:		808,700	psi	
Ion Content	Cl^-:	73 ppm	Na^+:	2 ppm
	NH_4^+:	98 ppm	K^+:	3 ppm
* Particle Size:		≤ 45	microns	

ELECTRICAL AND THERMAL PROPERTIES:		
Thermal Conductivity:	2.5	W/mK *based on standard method: Laser Flash*
Thermal Conductivity:	29	W/mK *based on Thermal Resistance Data: $R = L \times K^{-1} \times A^{-1}$)*
Thermal Resistance (Junction to Case):		TO-18 package with nickel-gold metallized 20 x 20 mil chips and bonded with H20E (2mils thick) *EPO-TEK® H20E:* 6.7 to 7.0°C/W *Solder:* 4.0 to 5.0°C/W
* Volume Resistivity @ 23°C:	≤ 0.0004	Ohm-cm

Epoxies and Adhesives for Demanding Applications™

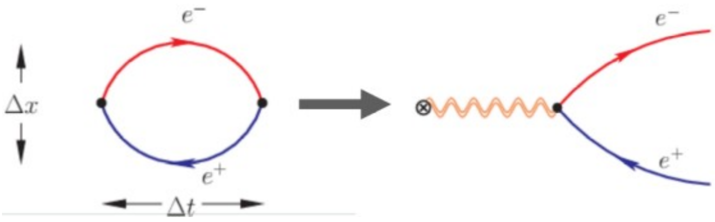
This information is based on data and tests believed to be accurate. Epoxy Technology, Inc. makes no warranties (expressed or implied) as to its accuracy and assumes no liability in connection with any use of this product.

EPOXY TECHNOLOGY, INC.
14 FORTUNE DRIVE, BILLERICA, MA 01821 (978) 667-3805, FAX (978) 663-9782
www.epotek.com

QED in strong fields: SFQED

▷For large values of EM field **ε** → the **Schwinger critical** field is surpassed and **the vacuum becomes unstable** to pair production

- during the fluctuation, *E>2m*$_e$ is supplied



$$\mathcal{E}_{crit} = \frac{m_e^2 c^3}{\hbar e} = 1.32 \times 10^{18} V/m.$$

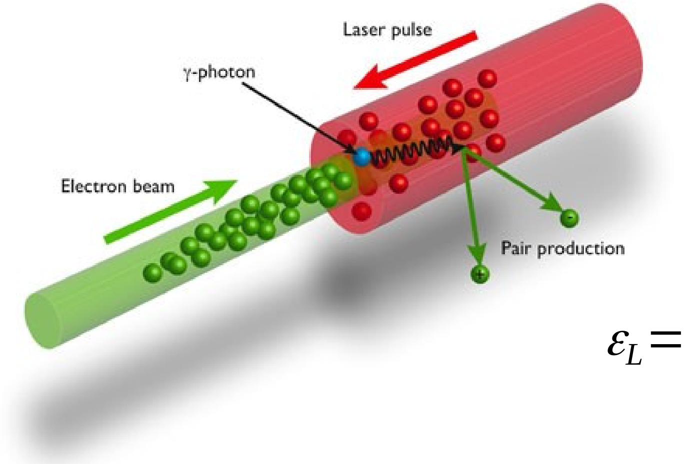
▷Perturbative **QED breaks down** in the presence of **strong fields**

▷**Such fields have not been reached experimentally** in laboratories although they are expected to exist:

- On surface of neutron stars
- In bunches of **future linear e+e− colliders**.

▷**Can be reached** by colliding high intensity laser beams with a high-energy electron beam

- Lasers powerful enough don’t exist yet
- A high energy e- beam is required: The EM field strength is boosted

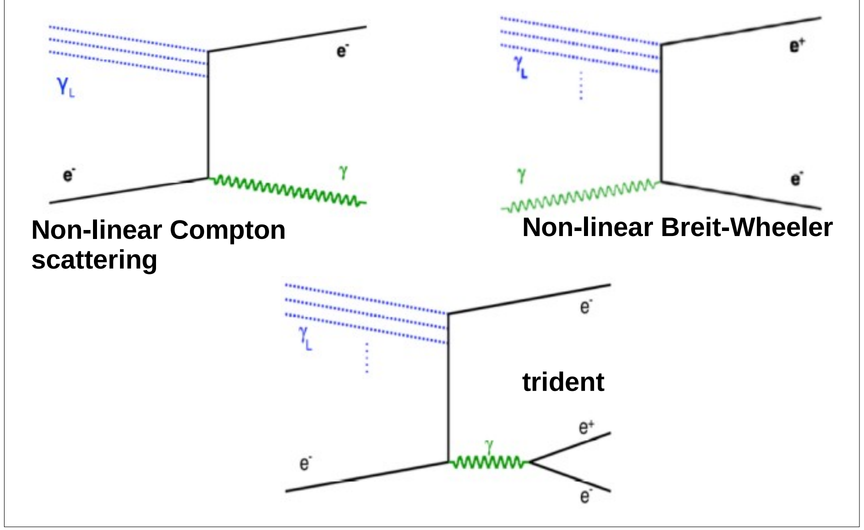


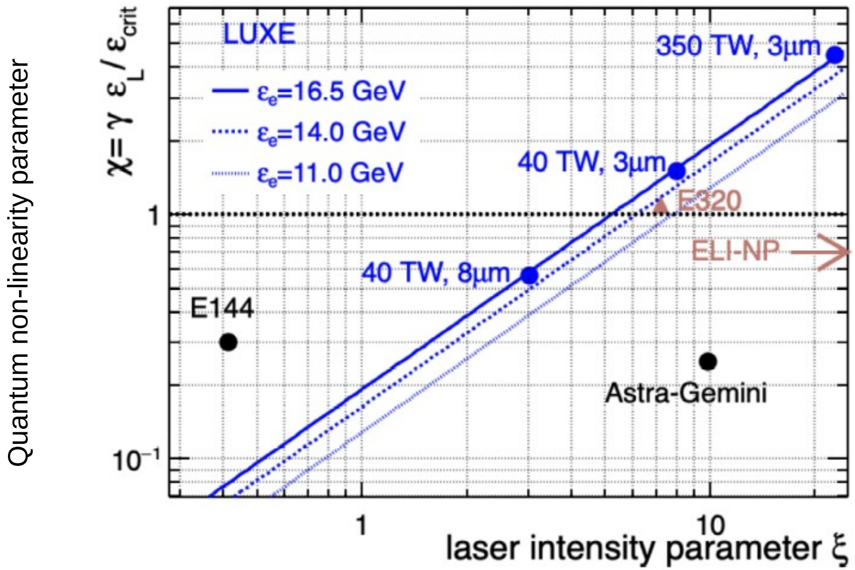
$$\varepsilon_L = \gamma\, \varepsilon (1+\cos\theta)$$

LUXE: Laser Und XFEL Experiment

- ▷ Experiment based at **DESY-XFEL**
- ▷ **Strong EM field**: 30-350TW laser & 16.5 GeV e- beam
  - e- / laser interaction mode and γ /laser interaction mode
- ▷ **Ambitious time-scale** (start data taking in 2027)
  - CDR published, TDR in arxiv since 2023

Physics processes



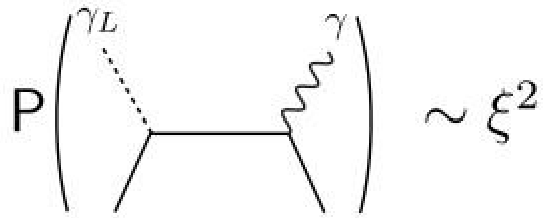


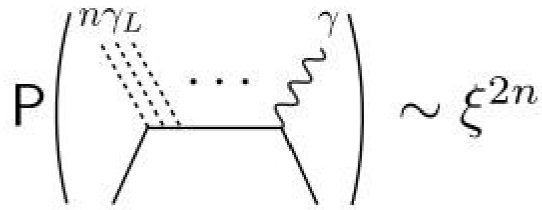
First experiment to try this E144 @ SLAC in 1990s.
Nowadays experiments : SLAC-E320 (US), Astra Gemini (UK), ELI-NP (RO)

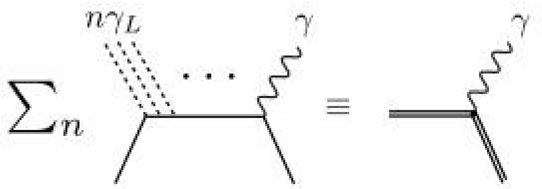
Field intensity parameter

$$\xi = \sqrt{4\pi\alpha}\left(\frac{\varepsilon_L}{\omega_L m_e}\right) = \frac{m_e \varepsilon_L}{\omega_L \varepsilon_{cr}}$$

non-linear Compton Scattering







$\xi < 1$

The probability to produce one Compton photon is proportional to the laser photon density

Still the electron can collide with n laser photons (non-linear compton).
The process is still perturbative if $\xi < 1$

$\xi > 1$
There are no more leading order processes and we are require to resum all higher order contributions in ξ

The non-perturbative resulting expression can be expressed as an effective larger electron mass:

$$m_e(eff) = m_e\sqrt{1+\xi^2}$$

SFQED at LUXE

Charge field coupling
→ work done by the EM field over electron Compton wavelenght in units of EM field

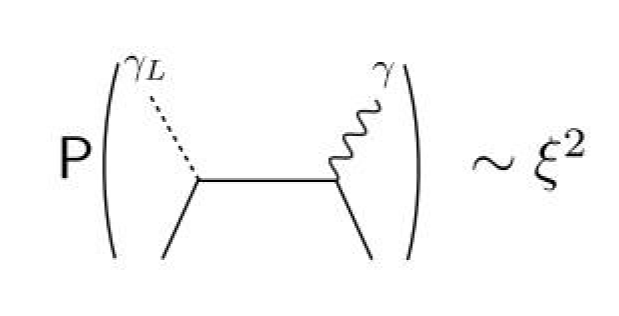
~ number of laser photons interacting with the electron beam at a given time

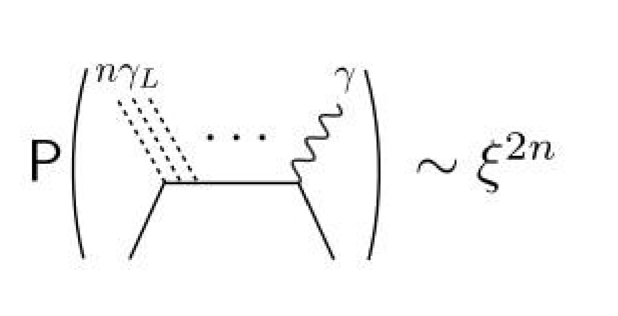
Laser photon density ~ ξ^2

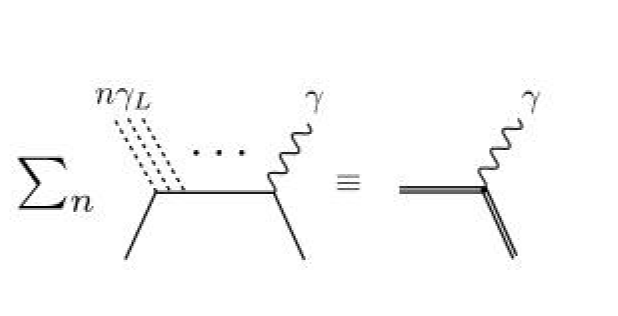
Theory Parameter		Definition	Range accessed in LUXE phase-0	phase-1
ξ	Classical non-linearity parameter	$\xi = \frac{m_e}{\omega_L}\frac{\mathscr{E}_L}{\mathscr{E}_{cr}}$	≤ 6	≤ 19
η_i	Energy parameter	$\eta_i = \frac{\omega_L \varepsilon_i}{m_e^2}(1+\beta\cos\theta)$	$\eta_i \leq 0.2$	
χ_i	Quantum non-linearity parameter	$\chi_i = \frac{\varepsilon_i}{m_e}\frac{\mathscr{E}_L}{\mathscr{E}_{cr}}(1+\beta\cos\theta)$	≤ 1	≤ 3

How much the QED deviates from the classical limit

non-linear Compton Scattering







$\xi < 1$

The probability to produce one Compton photon is proportional to the laser photon density

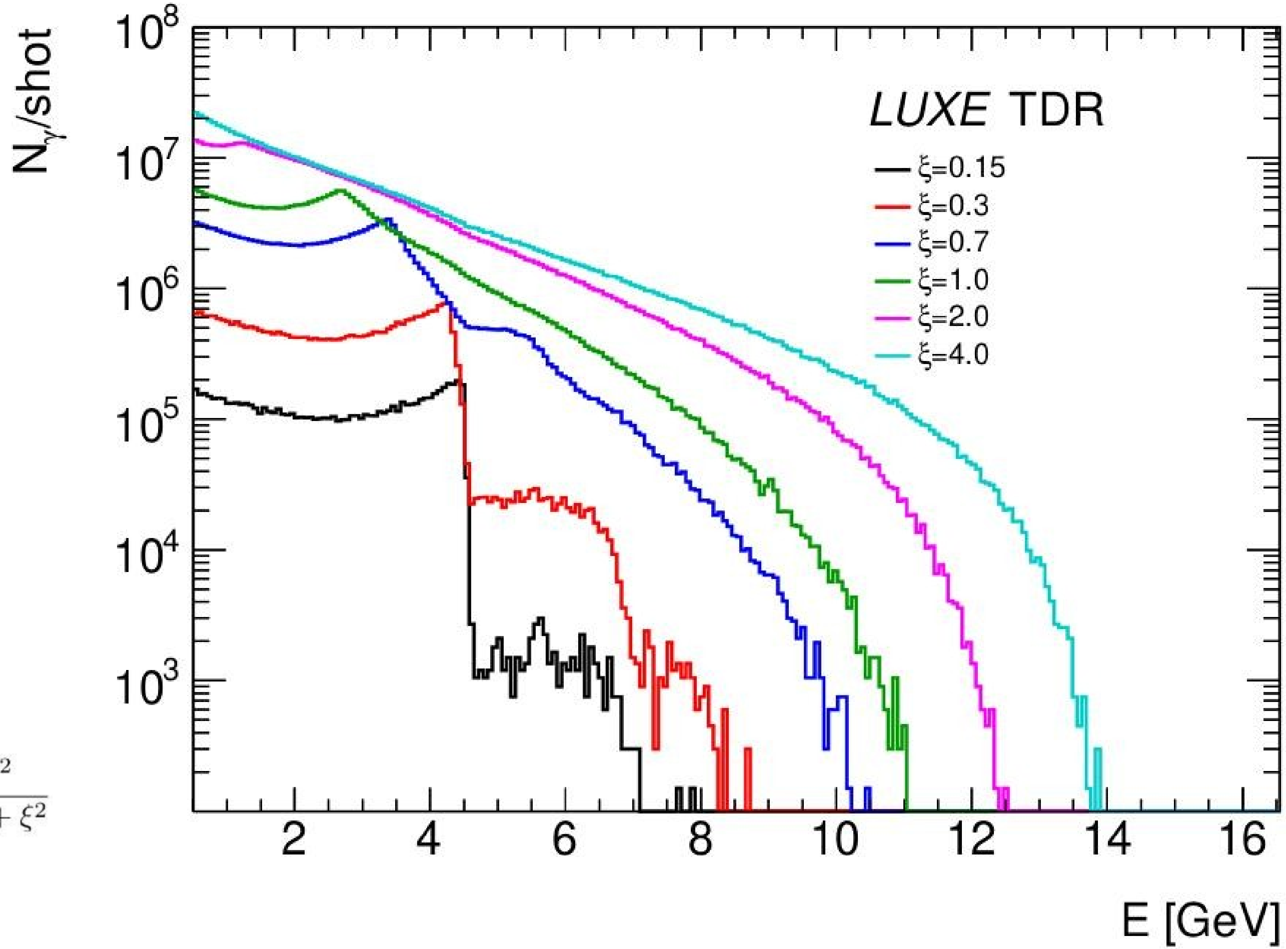
Still the electron can collide with n laser photons (non-linear compton).
The process is still perturbative if $\xi < 1$

$\xi > 1$
There are no more leading order processes and we are require to resum all higher order contributions in ξ

The non-perturbative resulting expression can be expressed as an effective larger electron mass:

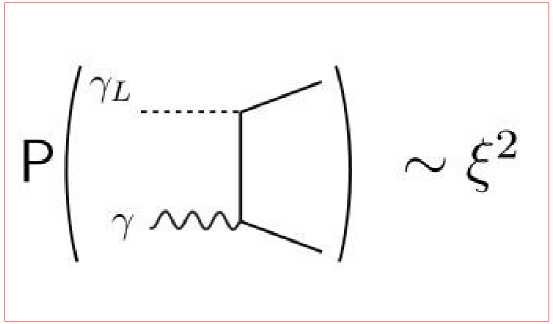
$$m_e(eff) = m_e\sqrt{1+\xi^2}$$

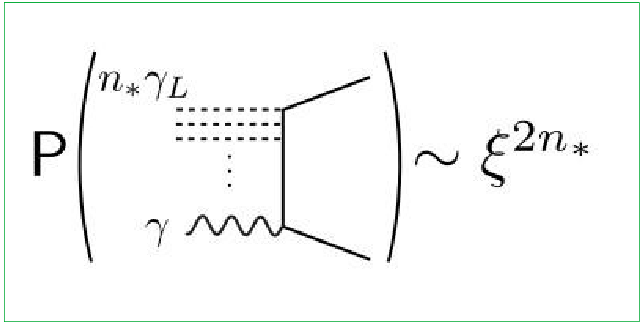
non-linear Compton Scattering

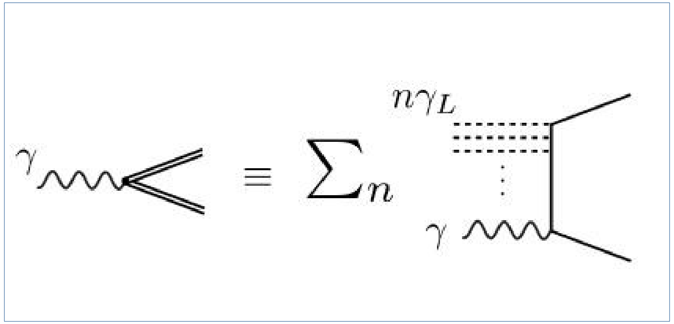


$$E^e_{edge}(\xi) = E_e \frac{1+\xi^2}{2\eta + 1 + \xi^2}$$

non-linear Breit-Wheeler







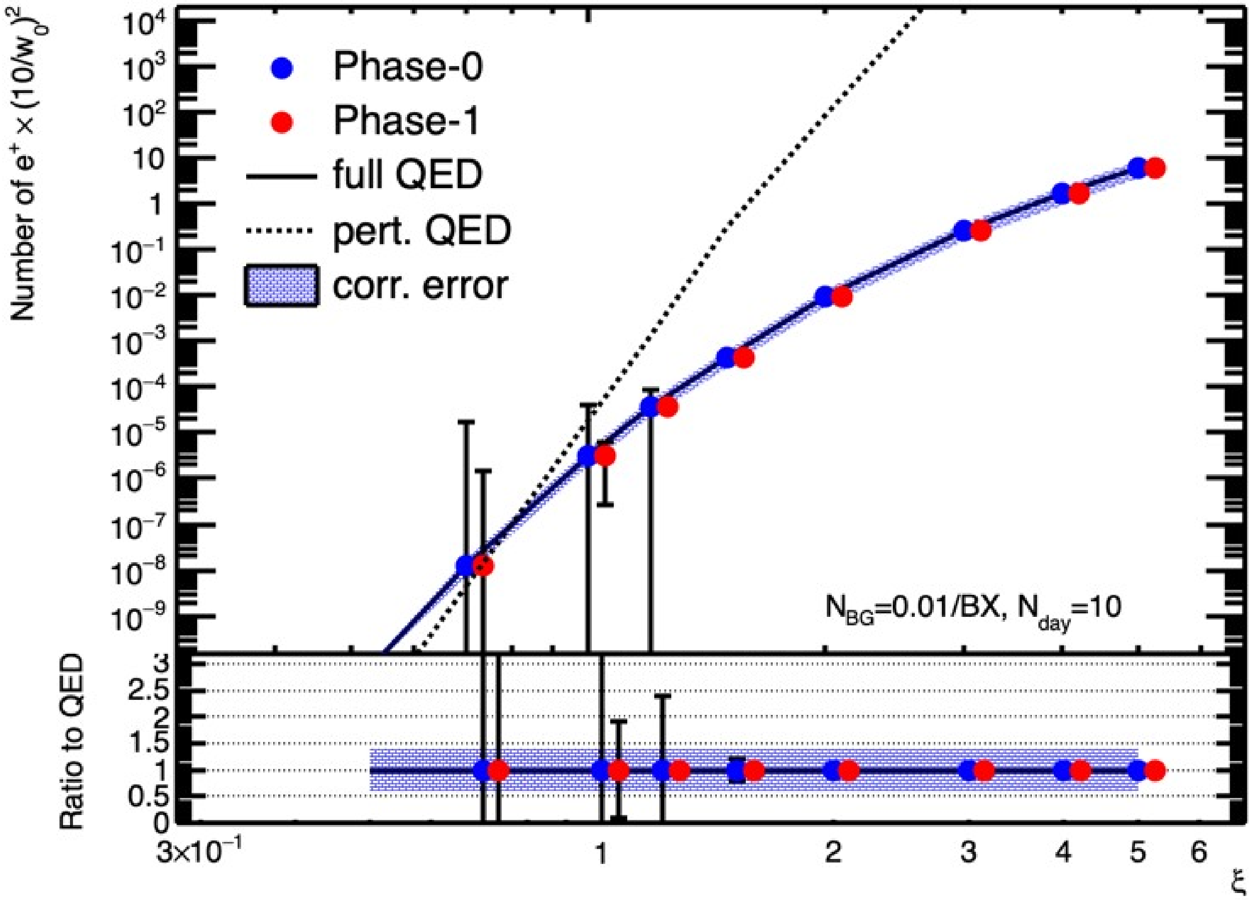
$\xi < 1$

One photon colliding with one laser photon (linear)

Still the photon can collide with n* laser photons (non-linear BW).
The process is still perturbative if $\xi < 1$

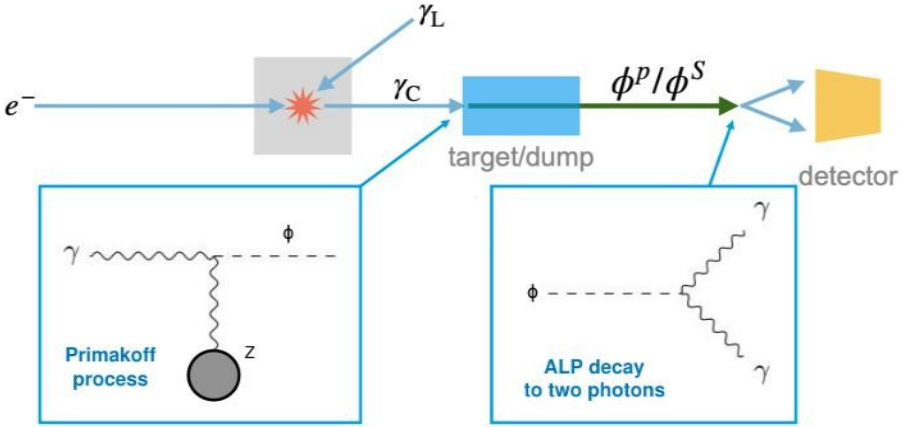
$\xi > 1$
Sum of all orders of ξ resulting in a non-linear non-perturbative BW process

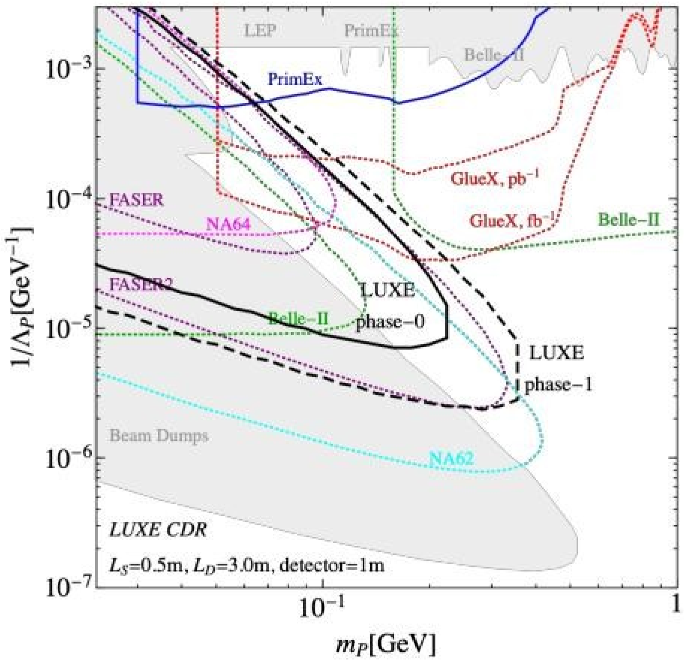
non-linear Breit-Wheeler



BSM direct searches with LUXE

▷ High intensyt photon beam produced → dumped in a wall



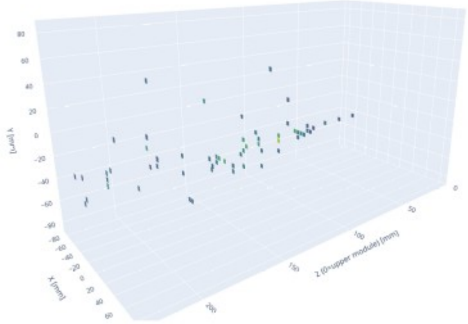


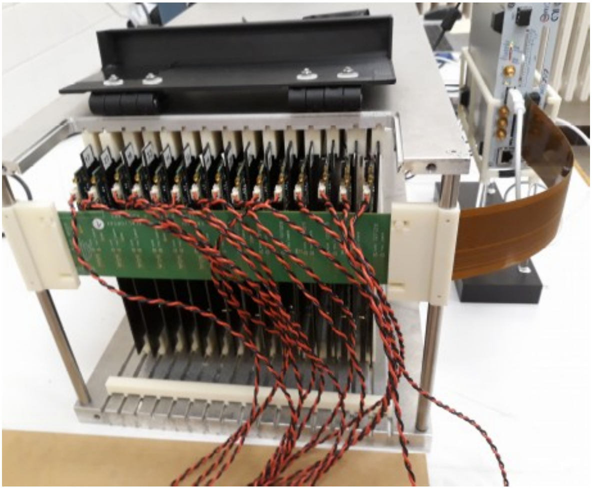
▷ Could be competitive with other experiments

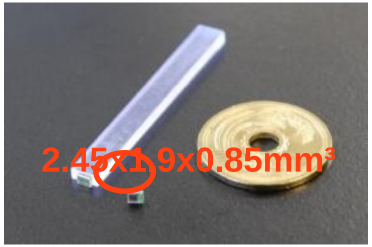
- Estimations for 1 year of data taking with no background

Sc-ECAL and SiW-ECAL CALICE prototypes

SiW-ECAL
- **15 layers 18×18 cm^2**
- 0.5×0.5 cm^2 Si cells
- 2.8+5.6 mm W (21 X_0)
- 100 kg, 0.4×0.4×80 cm^3
- **15k channels**







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

The sensitive layer is composed of **210 plastic scintillator strips**. The strip size is 5 mm x 45 mm x 2 mm^3.
Each scintillator is coupled with a SiPM at the bottom

Effective granularity of 5x5mm^2
(but with x10 less channels) → relevant for power consumption control

Large scale prototypes and common beam tests

- ▷ Common ECAL+AHCAL beam tests with **high energy beams** are mandatory
  - At Europe, only at CERN. Available during LS3 ?
- ▷ **Test 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

2

Constructing large scale PF ECAL calorimeters: **R&D challenges ahead us**

*Disclaimer: for lack of time and personal bias I will emphasize the SiW-ECAL wherever the SiW-ECAL and Sc-ECAL share commonalities

What for?

- ▷ **HL-LHC Upgrade** of existing detectors
  - ALICE FoCAL pixel calorimeter
  - HGCAL with high granular Si and SC calorimeter systems
- ▷ **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)
- ▷ 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)
- ▷ **Longer term**
  - **Muon** colliders and/or **Hadron-hadron** machines (high rates and high **radiation** environments)

The path to Large Scale prototypes

- ▷ **Ongoing R&D** phase with the goal of **the construction of multilayer scale ECAL (and HCAL) PF prototypes**
  - With **high granularity** (up to 5x5mm^2)
  - **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**

Readout Modules

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

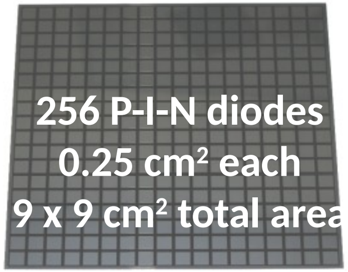
▷ **VFE** (ASICS, common developments within CALICE)

▷ **PCBs**

- Very dense PCBs with up to 1024 channels + extra components for power pulsing and noise filtering in 18x18cm^2

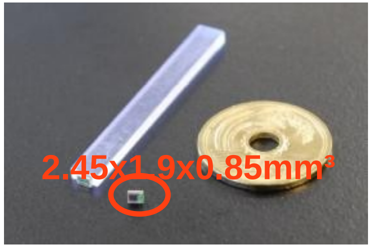
▷ **Active material**

- **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

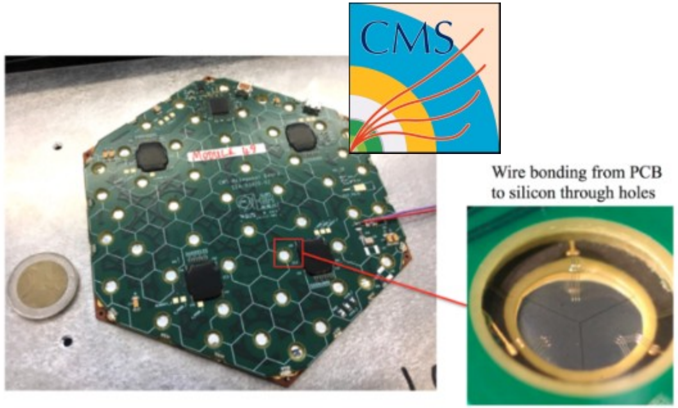
Prototype from Hamamatsu



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

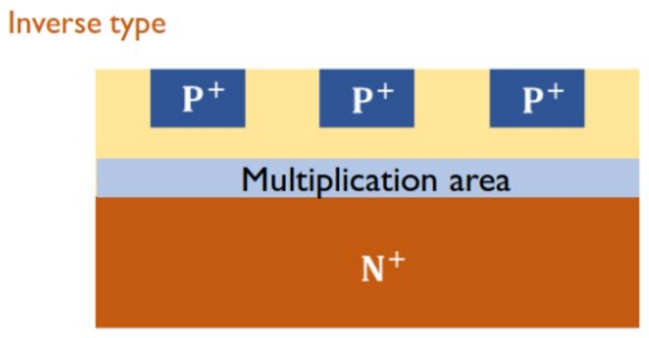
▶ **Thicker** sensor → **larger charge S/N**

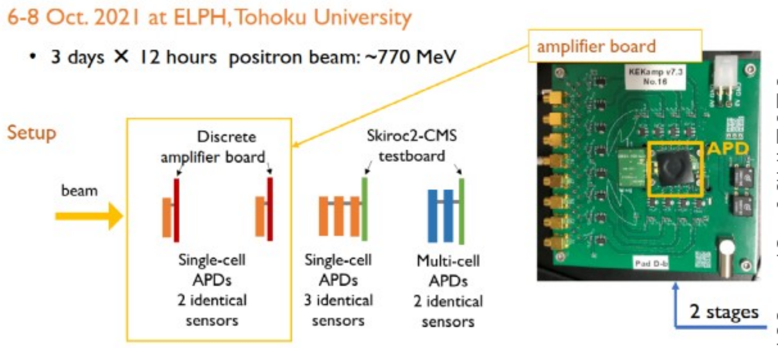
▷ Integration of larger surface **8" sensors**

- Experience from **HGCAL**

▷ Strengthen synergies with industry.

LGAD (Low Gain Avalanche Detector)



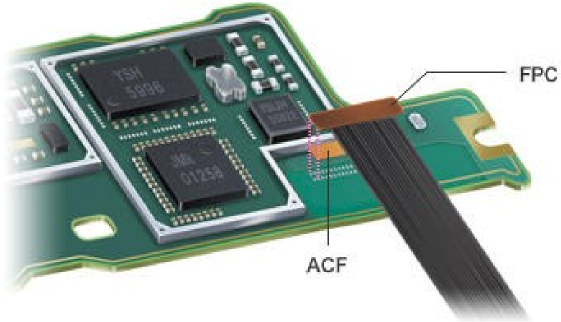


Open challenges (Silicon-PCB integration)

Near Future (~5 years)

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

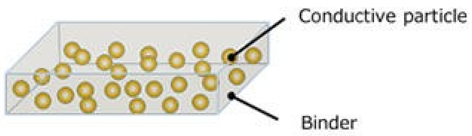
- Mechanical strength, industrialization, durability… to be studied.
- Silver → may be an issue on high radiation environments



▷ 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

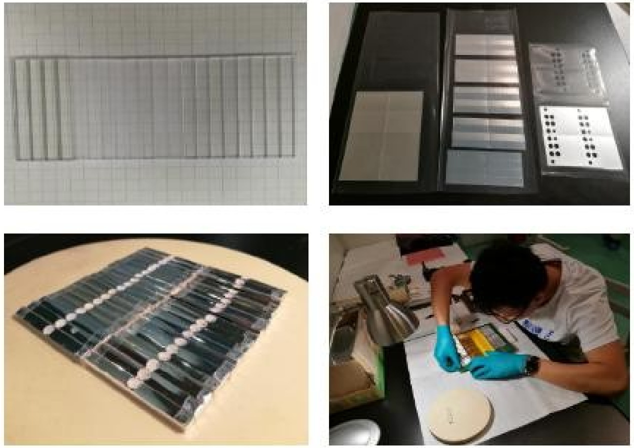
▶ **Improvement of timing** performance with **dedicated timing layers** ~10ps

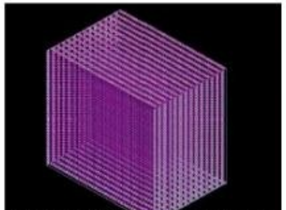
- Scintillator tile + larger SiPM with high light yield → better time resolution
- Cherenkov detector based on RPC-GasPM (New R&D)

▶ **R&D on new materials:**

- High Granular Crystal Calorimetry

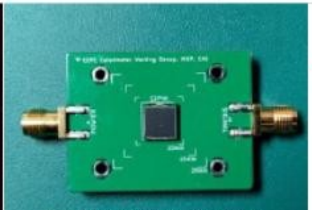
Strip wrapping and assembly on EBU was done by hand (Shanghai Institute of Ceramic)





Long bar configuration in Geant4

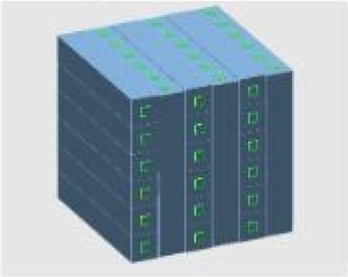
BGO crystal and wrapping foil



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

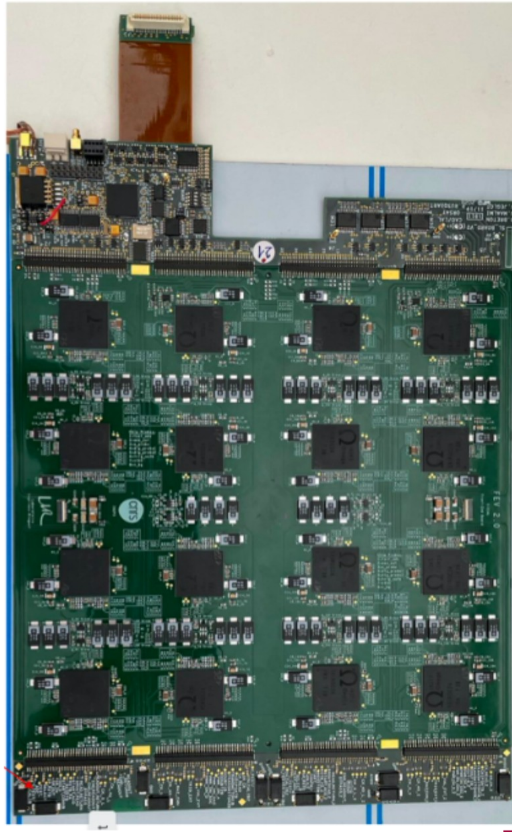
Near Future (~1-3years)

- ▷ **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

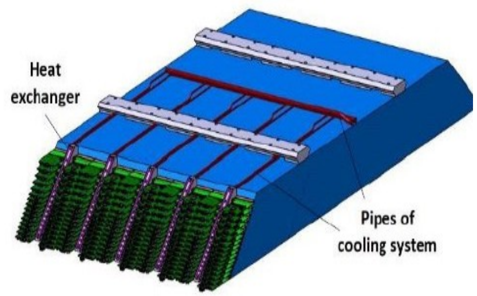
- Very little space for services / DAQ
- Cooling system developed for ILD → SiW-ECAL readout electronics designed accordingly

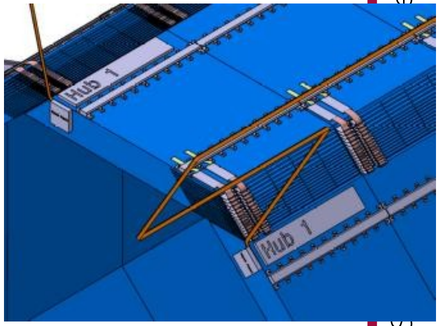
Near Future (1-5years)

▷**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