# ALLEGRO ECAL Overview

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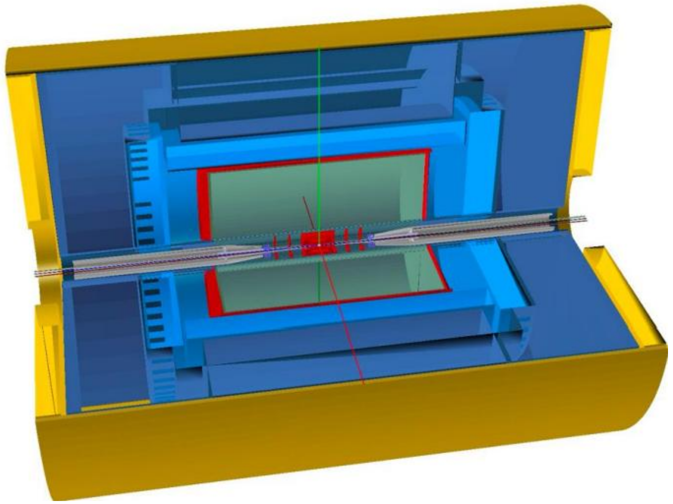
# ALLEGRO detector concept

**A L**epton co**L**ider **E**xperiment with **G**ranular calorimetry **R**ead-**O**ut: a general-purpose detector for FCC-ee ($\sqrt{s}$=90-360 GeV).

- Key feature: High granularity noble liquid EM calorimeter (ECAL) and tile hadronic calorimeter (HCAL).
  - ➢ LAr or LKr with Pb or W.
  - ➢ Multi-layer PCB as read-out electrode.
  - ➢ ECAL inside the 2 T solenoid sharing the cryostat.
- Other sub-detector systems: vertex detector, drift chamber and muon tagger.
- Designed for full FCC-ee physics program and focusing on particle identification with particle-flow.

The study of ALLEGRO ECAL belongs to DRD6 Collaboration as Work Package 2.


Layout of ALLEGRO



3D-view of ALLEGRO

https://allegro.web.cern.ch/



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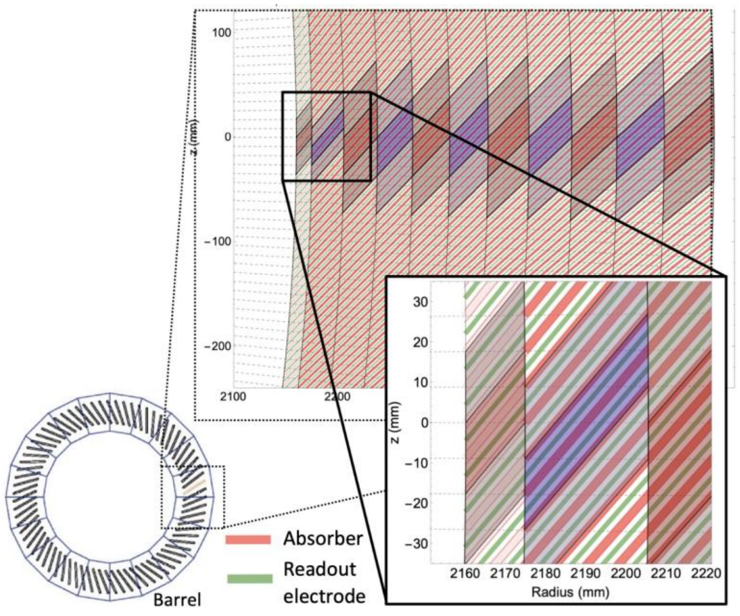
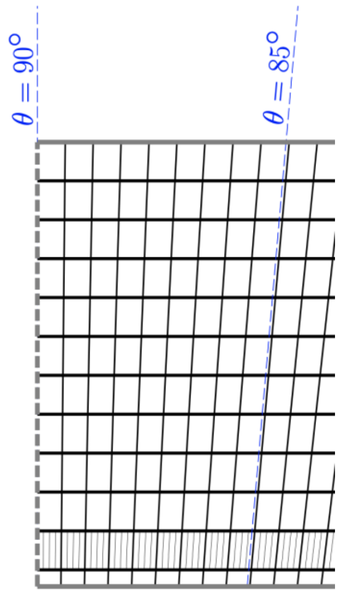
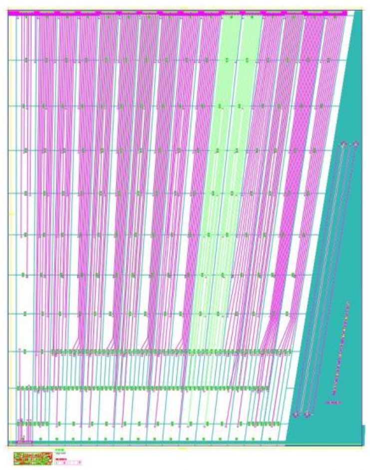
# ECAL barrel

High granularity read-out is allowed by the PCB technology.

- Straight read-out electrode with $50^{\circ}$ inclination angle.
- 40 cm in thickness, or 22 $\chi_0$.
- Segmentation in θ and 11 radial layers.
- The 2nd or the 3rd radial layer with narrow strips segmented in θ for $\pi^0$ detection.
- Signal traces go inside the electrode toward the edge of θ-tower.



ALLEGRO ECAL barrel read-out. The granularity is 10 times higher than ATLAS.



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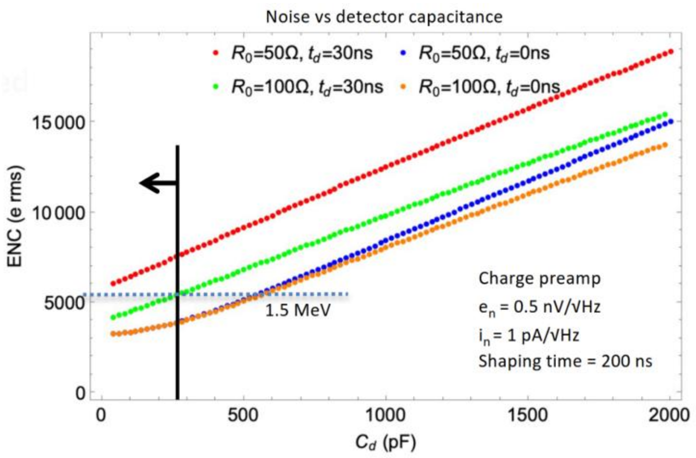
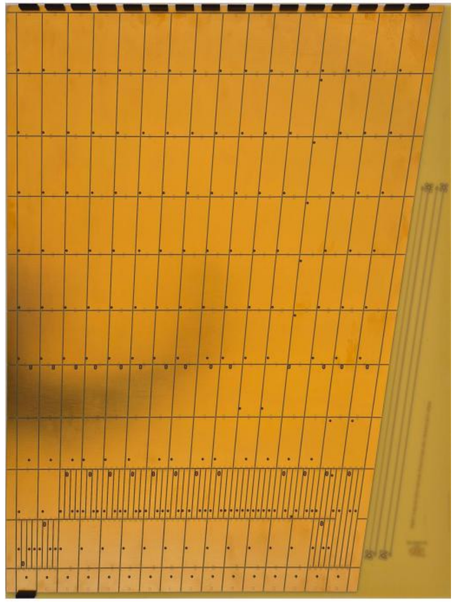
# ECAL barrel read-out electrode

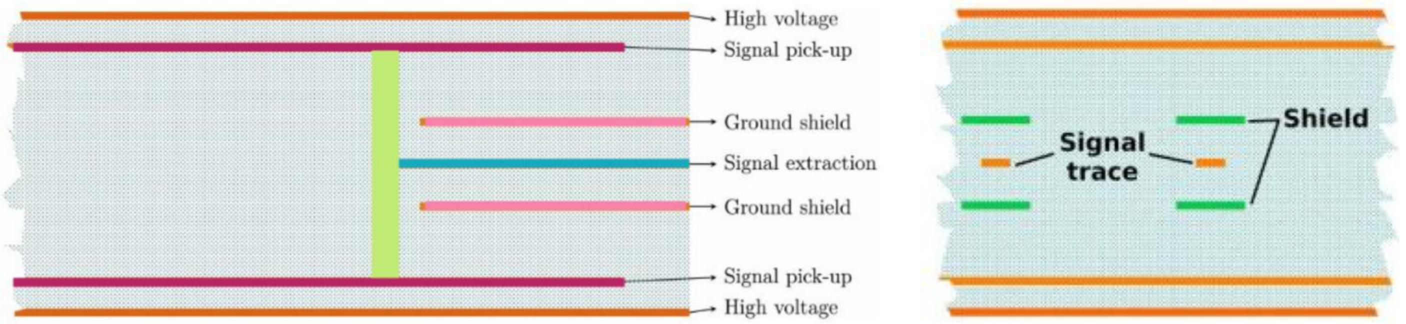
- High granularity of read-out cells leads to smaller signal amplitude.
- Use shielding to suppress the cross-talk generated by various coupling between calorimeter cells and signal traces.
- Choose proper size of shielding to limit the increase in noise due to larger detector capacitance.



The latest prototype ALLEGRO ECAL barrel read-out PCB.

The next step of the R&D is the HV distribution. Results are expected in 2026.




Sectional view of read-out PCB



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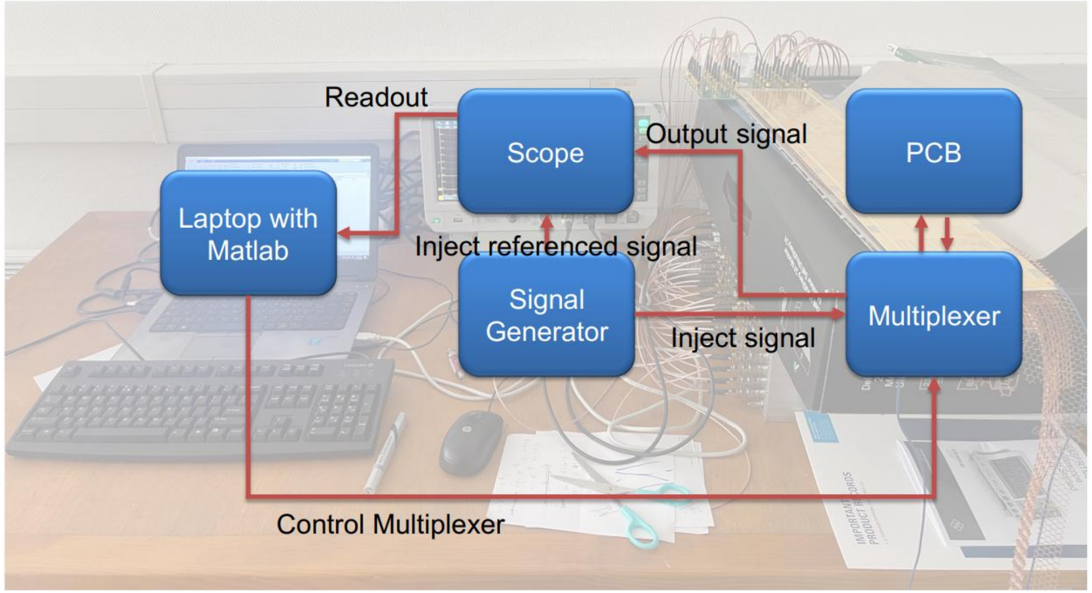
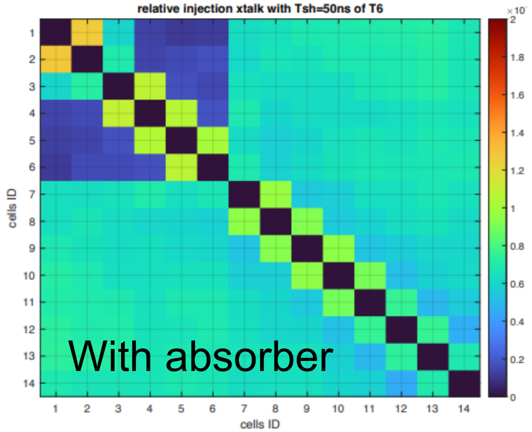
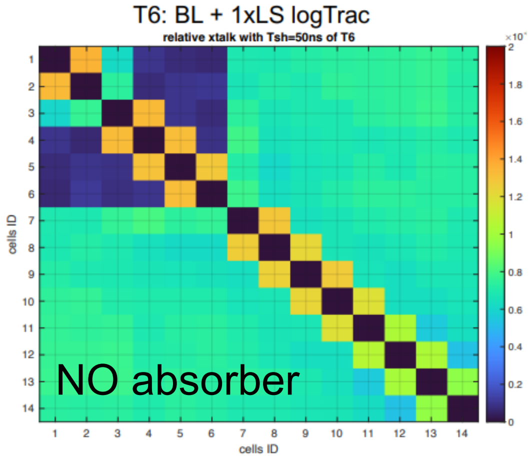
# Measurement of electrode properties




- Automised measurement setup built at IJCLab.

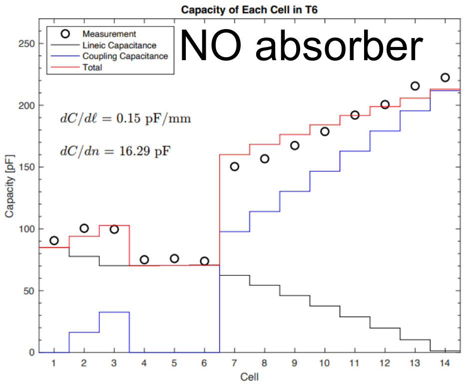


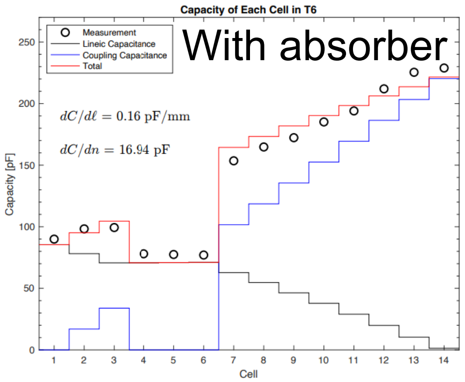




Measurement of relative cross-talk between read-out cells.

With a pulse shaping time of 50 ns, the relative cross-talk is suppressed below 2 per mille.

Adding the absorber decreases the cross-talk by about 10%.




Measurement of capacitance. Adding absorber -> capacitance increases by ~5%.

Another test bench running in parallel at CERN!



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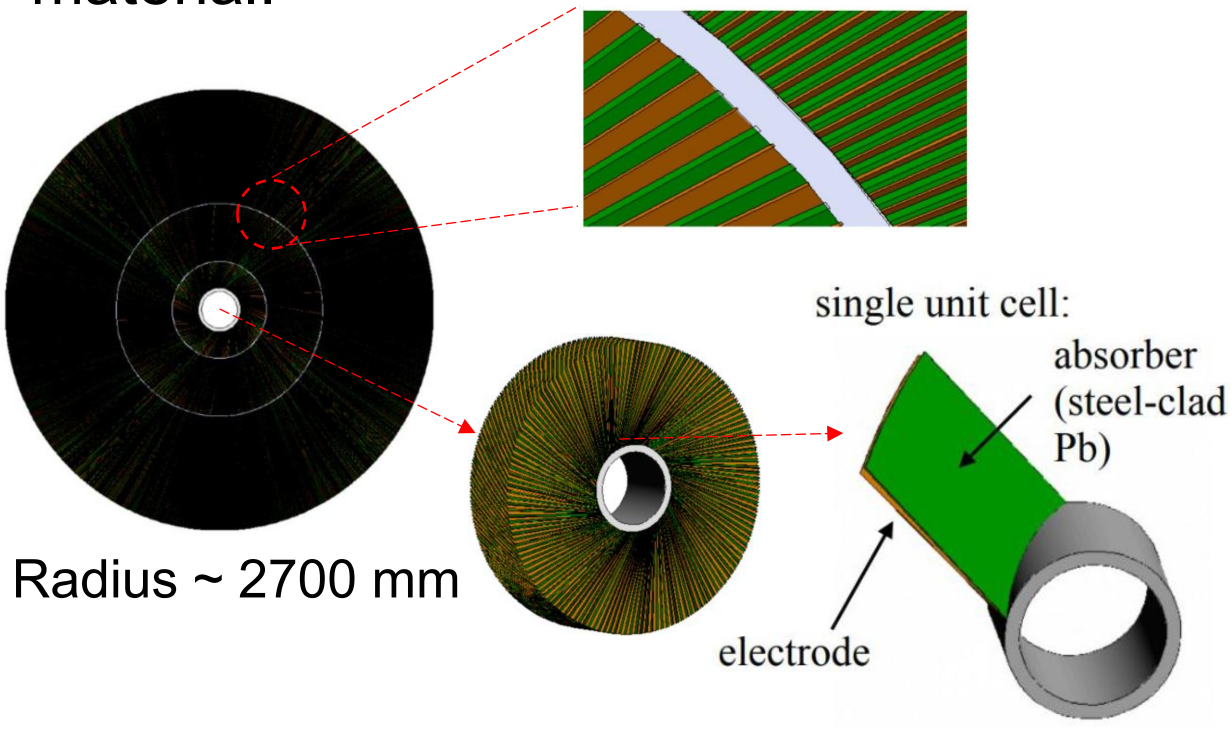
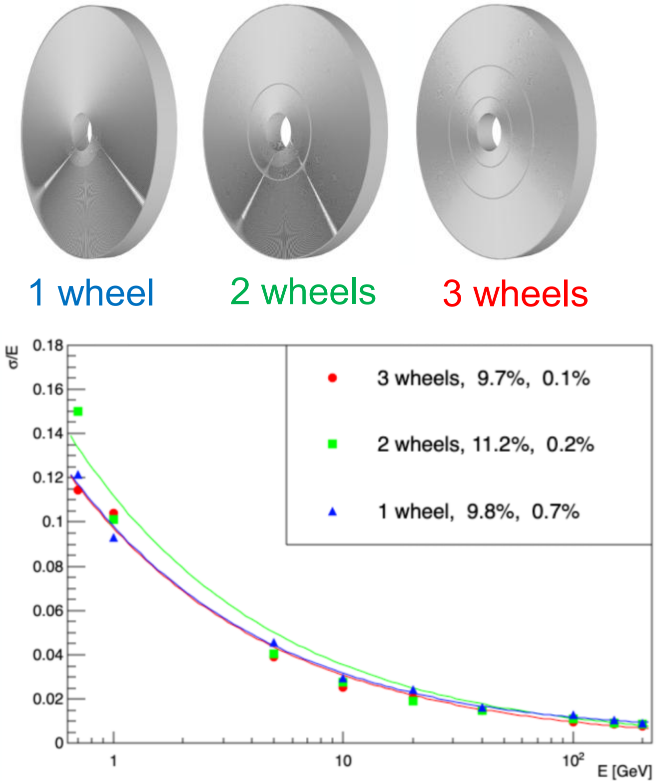
# ECAL end-caps

- Baseline design: 3 nested wheels with turbine-like layout.
- Tapered (varying thickness) or flat absorbers will be chosen based on the material.




Structure of baseline end-cap design.




The final choice may be determined by construction practicalities.



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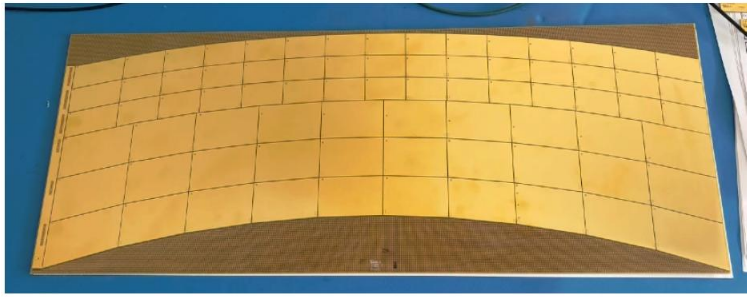
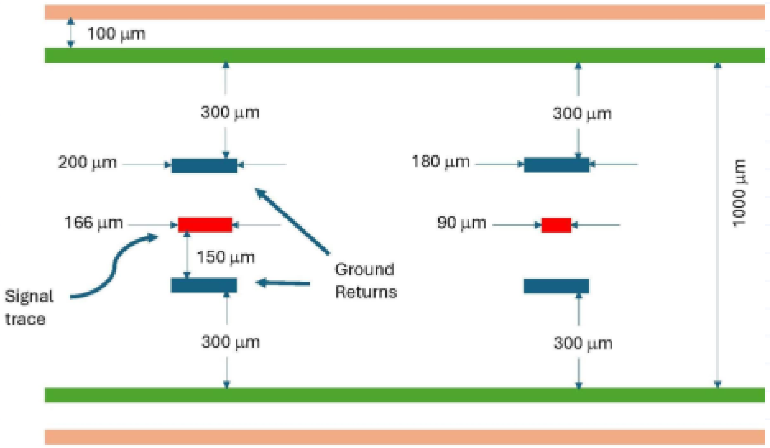
# ECAL end-cap electrode design

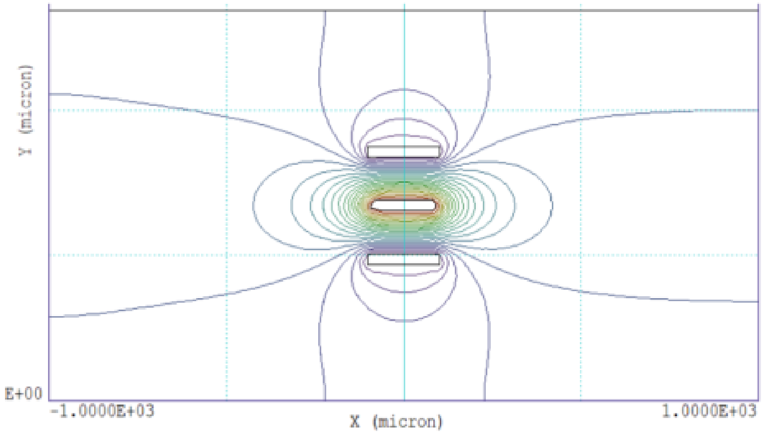
Dedicated PCB design in Arizona:

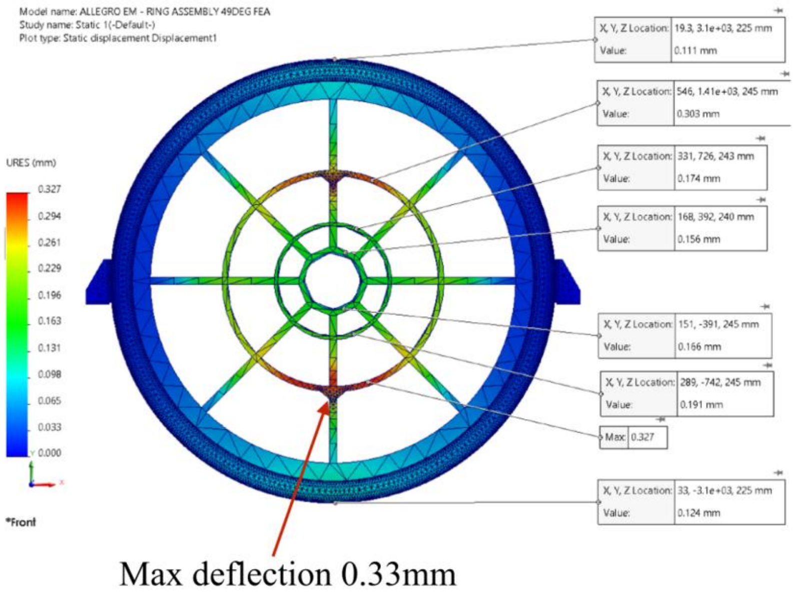
- Flat PCB with shape adapted to the turbine-like end-cap.
- Study of transfer line characteristic impedance: simulation required, backed by measurements.
- First proto-type arrived in the lab.
- Mechanical studies on-going.



The PCB proto-type.



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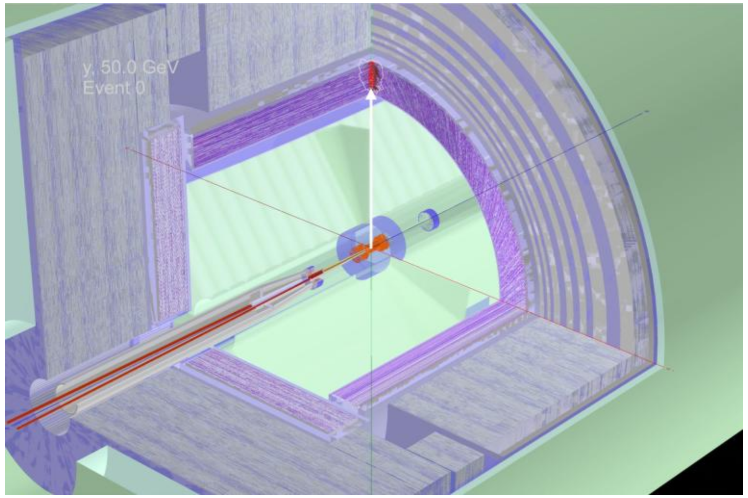
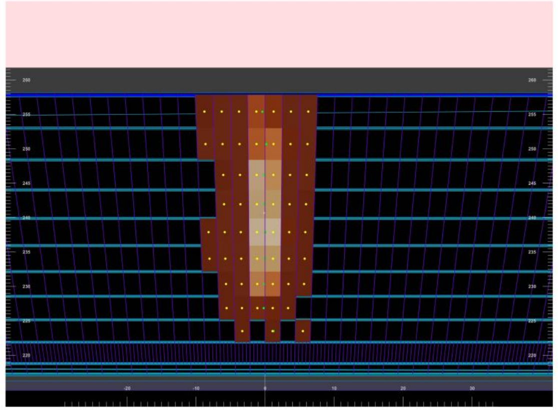
# Overall status of full simulation

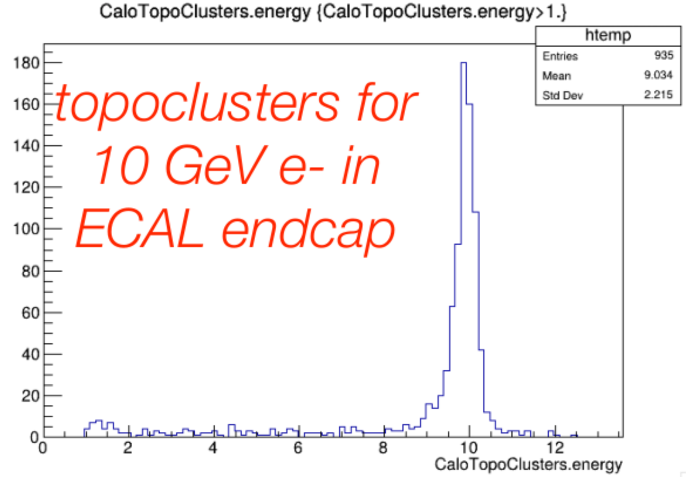
- ECAL detector model is fully implemented in ddsim.
- Simple digitization is taken as a sum of Geant4 energy deposit, corrected by pre-calculated sampling fraction for each layer. -> Realistic digitization on-going.
- Reconstruction is available for both fixed-size sliding window (SW) cluster and topo-cluster (major contributions from APC).




Response of ALLEGRO calorimetry to a 50 GeV photon.



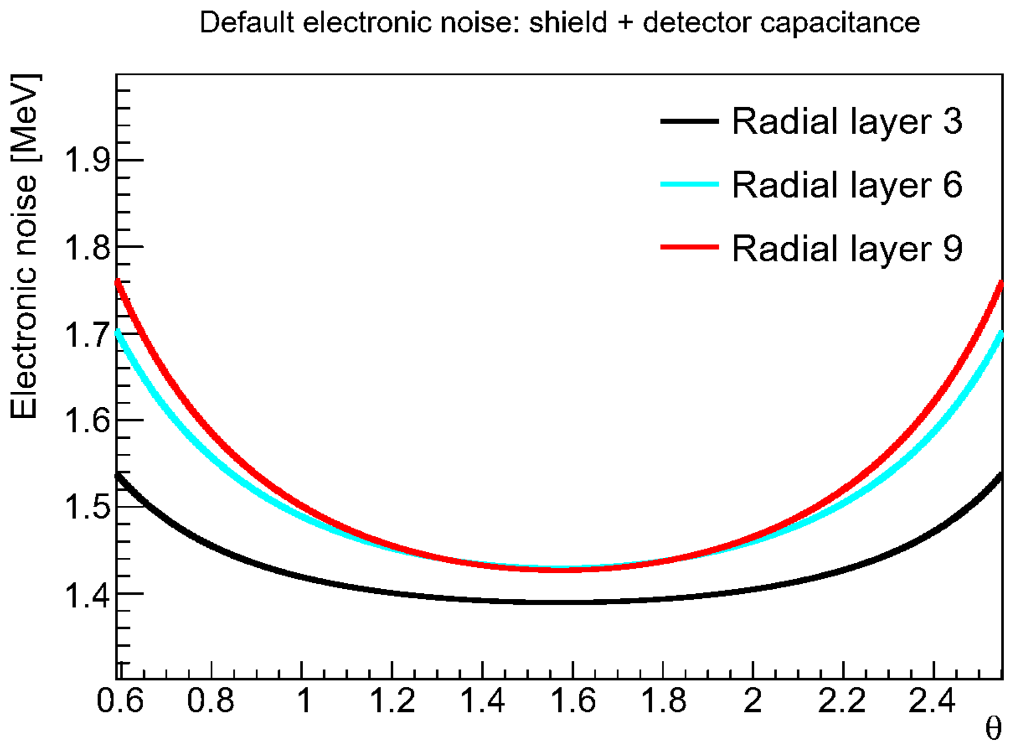
Reconstruction of a photon with ECAL-only SW cluster in the barrel region.



# Implementation of electronic noise

- Calculate the average level of electronic noise as a function of radial layer and θ.
- For each event in the full simulation, after the digitization, randomly draw the value of electronic noise for individual ECAL cells, following a Gaussian distribution.
- With the noise filter enabled, cells with energy below a certain threshold are removed from the cell collection, which reduces the input size to clustering algorithms.

Activities at APC and LAPP.




Pre-calculated conservative estimation of electronic noise, depending on radial layer and polar angle θ (unit in radian).

Noise level calibrated to MeV.



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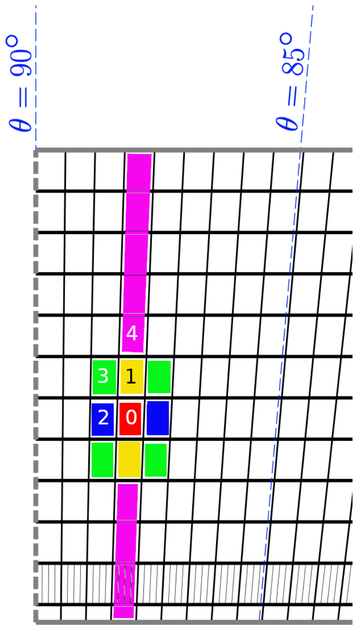
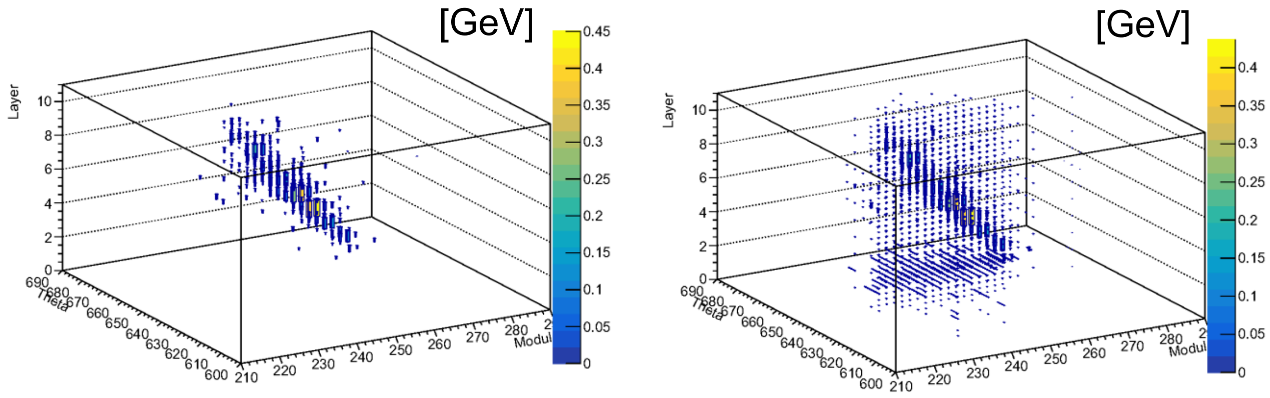
# Implementation of ECAL barrel cross-talk

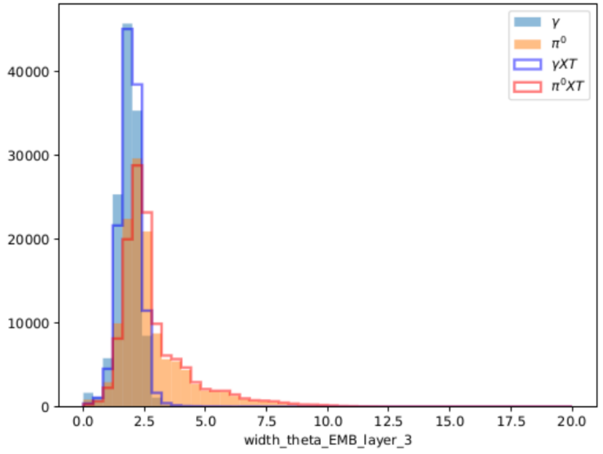
- Assuming four types of cross-talk on the read-out electrode.
- Minor impact on the energy resolution but causes a shift to ECAL shower shape variables, therefore affecting the particle identification performance.




Coefficients of 4 different cross-talk types (0.04%-0.7%) are taken from the measurement with 50 ns shaping (outdated PCB).




ALLEGRO ECAL signals in each cell for a 5 GeV photon shower, before and after adding cross-talk.

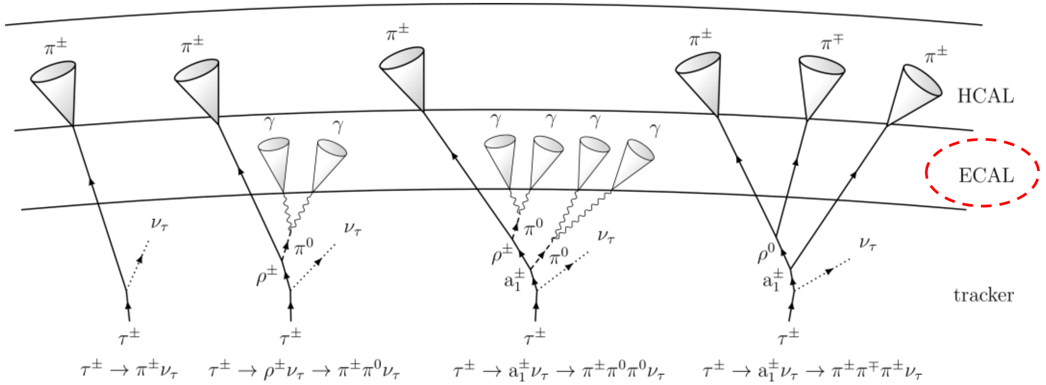


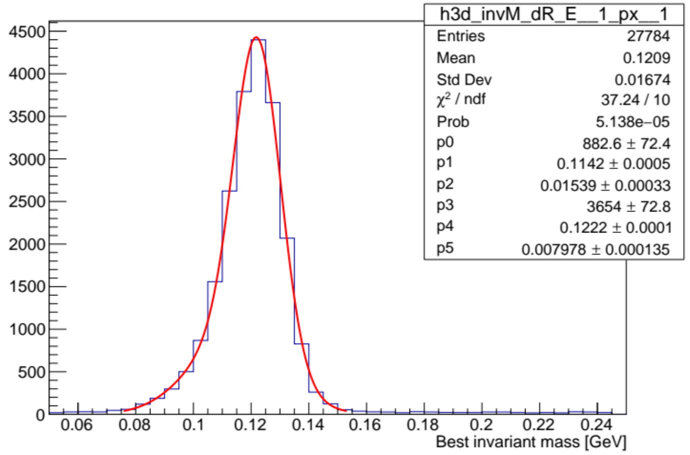

Shower shape variable "θ width" shifted by cross-talk.

Activities at APC and LAPP.

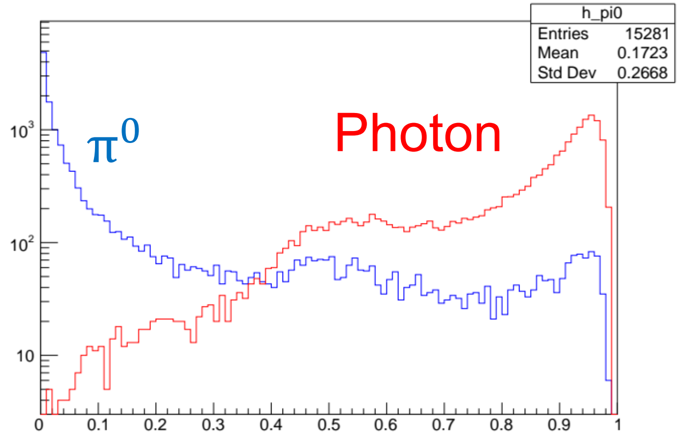
# Photon-$\pi^0$ separation based on ECAL

- Reconstruction of resolved $\pi^0$ by pairing clusters in the $\pi^0$ invariant mass window.
- Unresolved $\pi^0$ are separated from photons via machine learning method.
- Identification of tau decay mode by counting number of reconstructed $\pi^0$ in the ALLEGRO ECAL.




$\pi^0$ invariant mass distribution reconstructed by ALLEGRO ECAL.




BDT score of photon-$\pi^0$ separation trained with cluster energy and shower shapes.

BDT training uses input $\pi^0$ from ee->ZH, H-> ττ process at √s=240 GeV.



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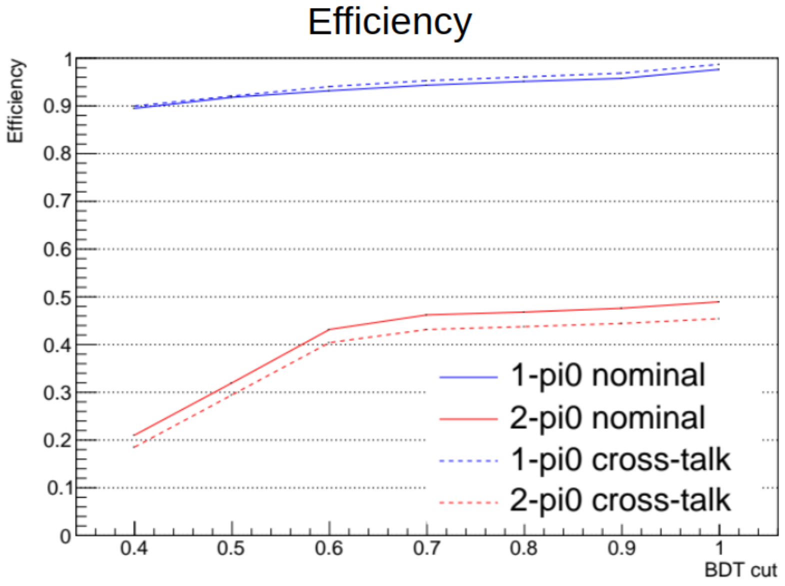
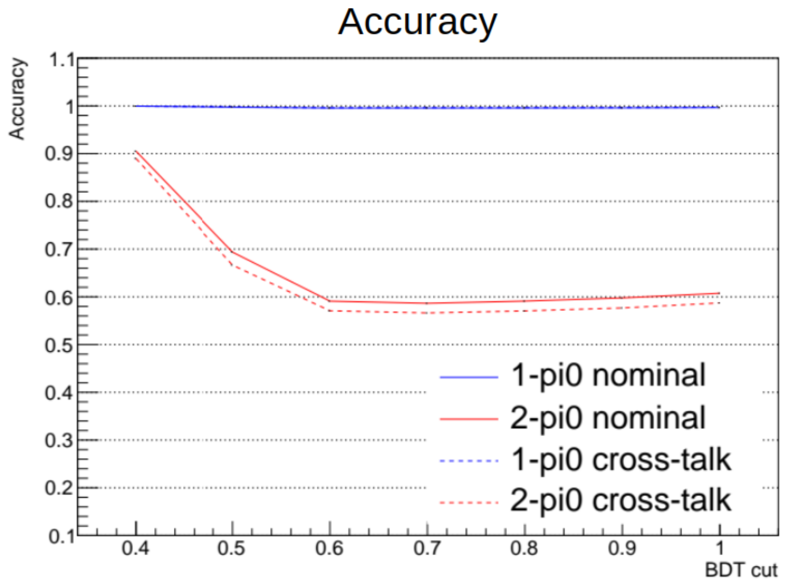
# Photon-$\pi^0$ separation performance

- Partial identification of tau decay mode via $Z \rightarrow \tau\tau$ @ 91.2 GeV, by counting the total number of reconstructed $\pi^0$.
- Performance quantified with efficiency and accuracy.




Studies carried out at LAPP.

See the talk in ALLEGRO ECAL workshop for more details.

Method complementary to particle flow reconstruction.
Further studies will be carried out to optimise the performance.



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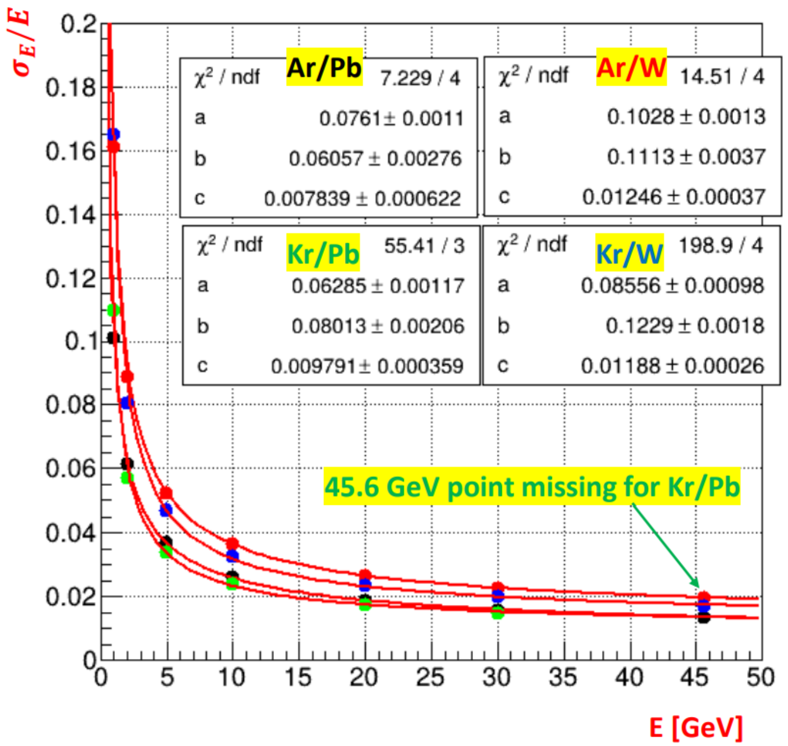
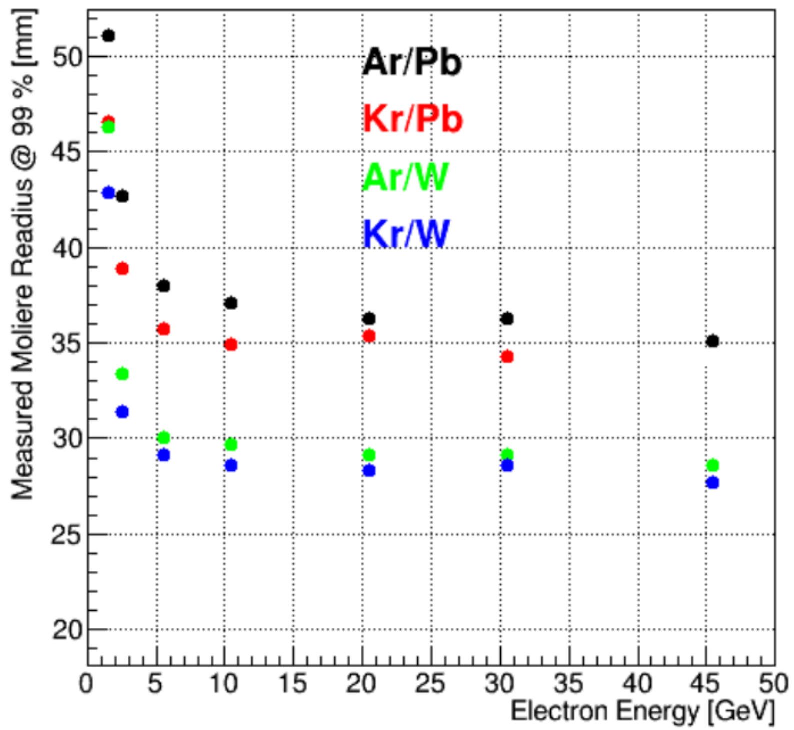
# Optimisation of ECAL materials

- The energy resolution is mostly determined by the active material.
- The Moliere radius mainly depends on the absorber.




Electron energy resolution with SW clusters.
Only Ar/Pb calibrated: sampling rate 7.6%

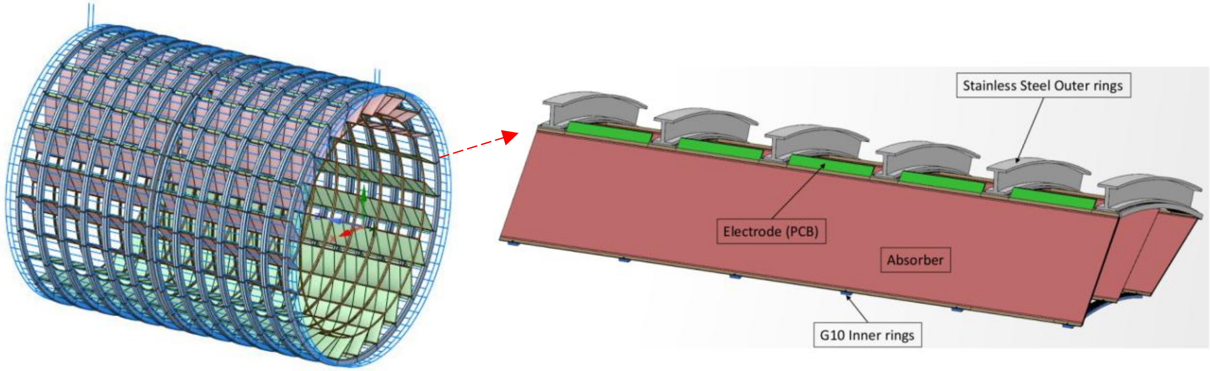


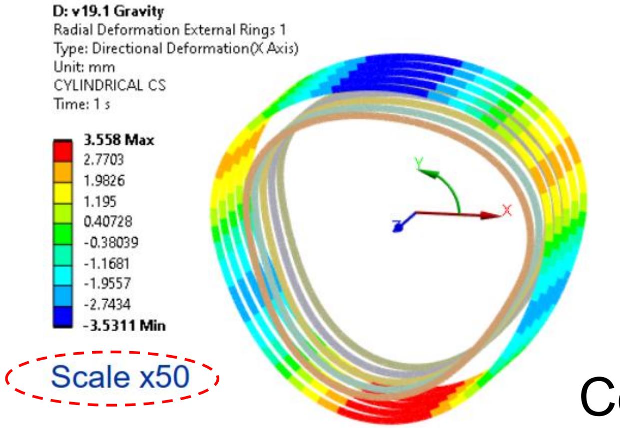

Measurement of Moliere radius.
99% shower energy ~ 3.5 × Moliere radius.

Contributions from CPPM.

# Mechanical structure and absorber prototype

- Assembly test of external rings and bars at CERN is scheduled for January 2026.




The external rings of ALLEGRO ECAL barrel and simulated deformation due to gravity.

Contributions from CPPM.

- Absorber with 0.1 mm stainless steel clad is chosen for its resilience against the different thermal expansions between lead and steel.

One setup of cold test: clamped to the frame. The cold test is performed by a liquid nitrogen bath at 77 K, followed by warming to room temperature.



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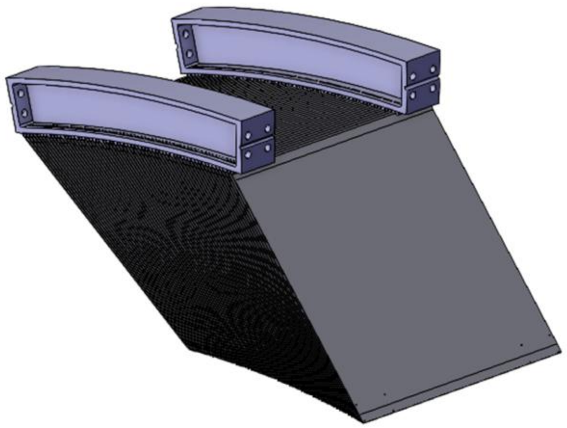
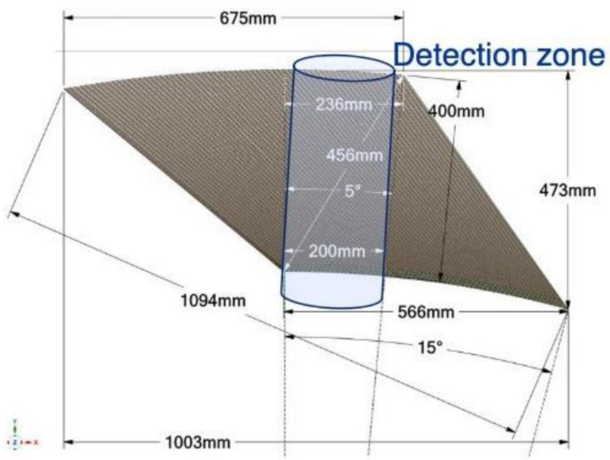
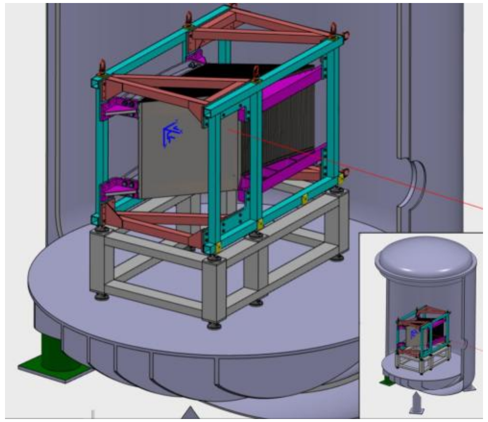
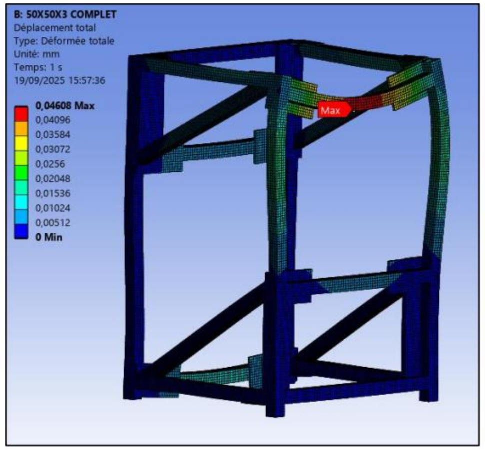
# ECAL barrel test-beam prototype

The test-beam prototype: part of the ECAL consisting of around 64 repeats of absorber and read-out electrodes.








- 64 repeats of absorber and read-out electrodes are capable of containing the development of a typical shower.

Contributions from CPPM.

Progress in prototype mechanics:

- 500 kg prototype and 221 kg assembly frame.
- Mechanical properties simulated by FEM analysis. Low deformation < 46 µm.



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# Summary

Rapid progress in almost all aspects of ALLEGRO ECAL R&D, demonstrating that it is a realistic detector concept for high performance calorimetry designed for FCC-ee.

- Prototypes of both ALLEGRO ECAL barrel and end-cap readout electrodes have been produced. The measurement of electric properties has been carried out. Study of the HV distribution just began.
- Various tools are available in the full simulation for the optimization of the detector design aiming at specific physics goals.
- With the assistance of FEM analysis and lessons learned from cold tests, the mechanical structure for test-beam prototype is quickly converging.


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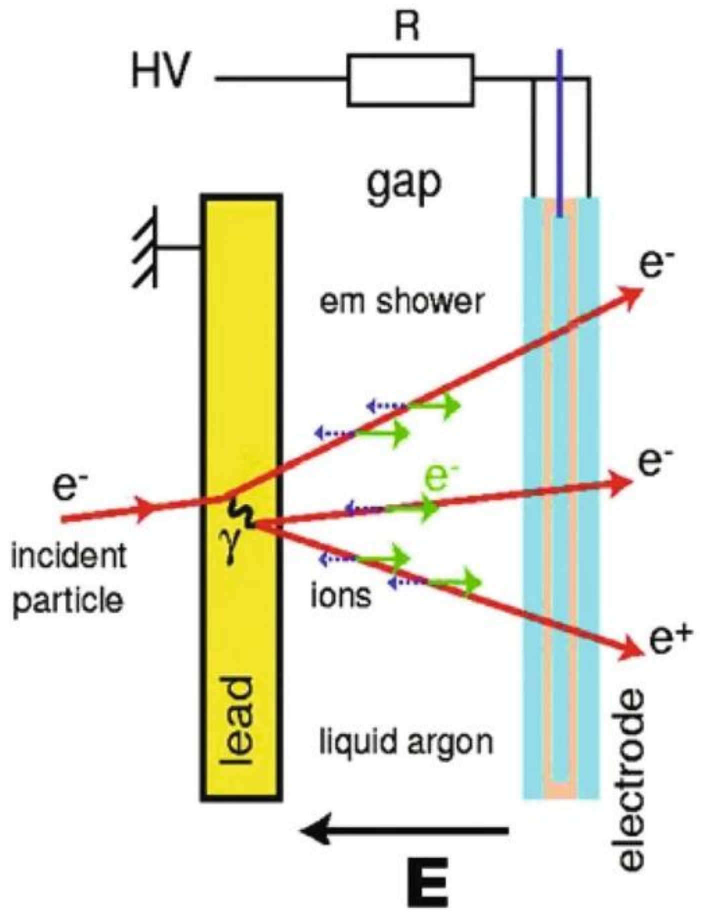
# Backup

# Noble-liquid calorimetry

- Sampling calorimeter technology. Repeated layers of absorber, noble liquid and read-out electrode.
- EM showers start in the absorber. Electrons produced in the showers ionize the liquefied noble gas and induce signals.
- Advantages: Mature technology (D0, ATLAS, …), good energy resolution, linearity, stability and uniformity, timing properties.
- Challenges: signal extraction and complex mechanical structure inside the cryostat.

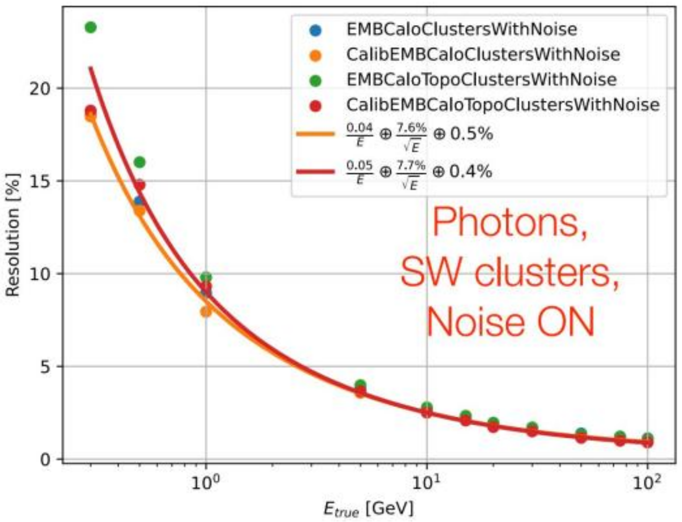



EM shower and signal induction

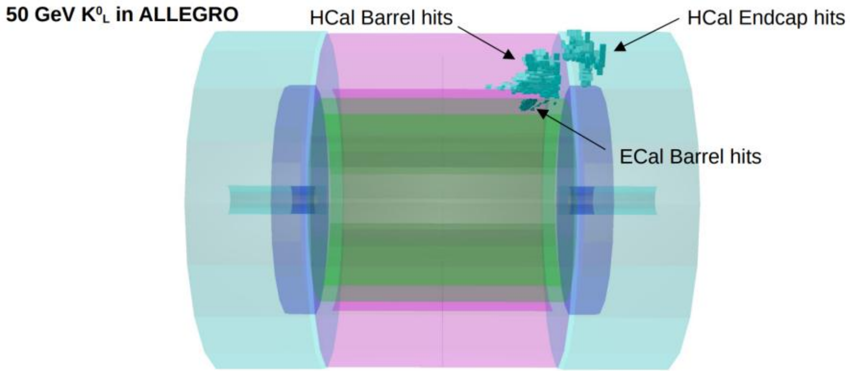
C. W. Fabjan, D. Fournier, *Particle Detectors and Detector Systems*

# Energy calibration and particle-flow

- ECAL energy resolution to single electrons: a 7% sampling term is achieved for the baseline Pb+LAr combination.
- Machine learning techniques are introduced to improve the energy resolution.
- Particle-flow object (PFO) reconstruction with PandoraPFA is under development.




BDT-regression based calibration implemented in Gaudi improves cluster energy resolution.




Adaptation of PandoraPFA-based tools in Key4hep/FCCSW to ALLEGRO.



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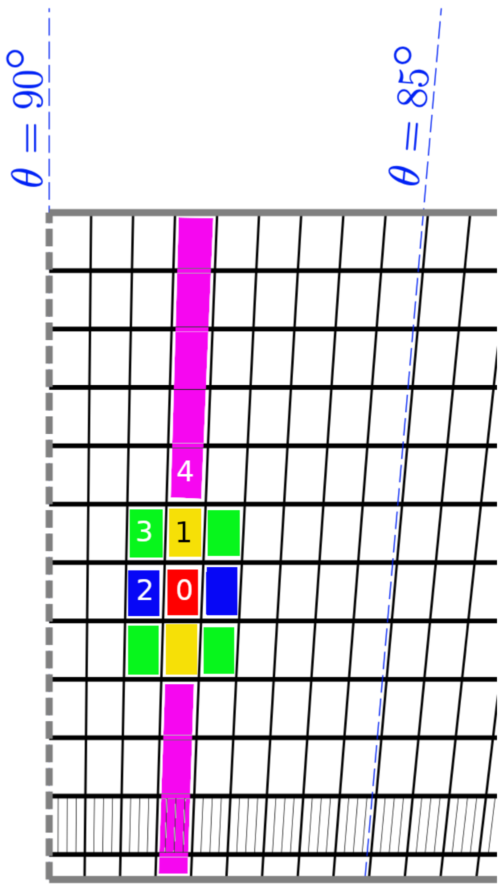
# Cross-talk coefficients.

- Taken from measurements with 50 ns shaping time.




| Type | 1: Radial | 2: Theta | 3: Diagonal | 4: Tower |
|---|---|---|---|---|
| Crosstalk | 0.7% | 0.3% | 0.04% | 0.1% |



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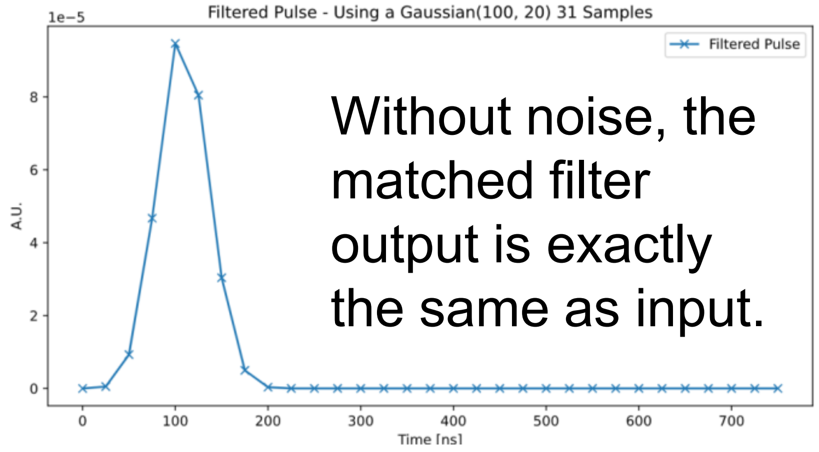
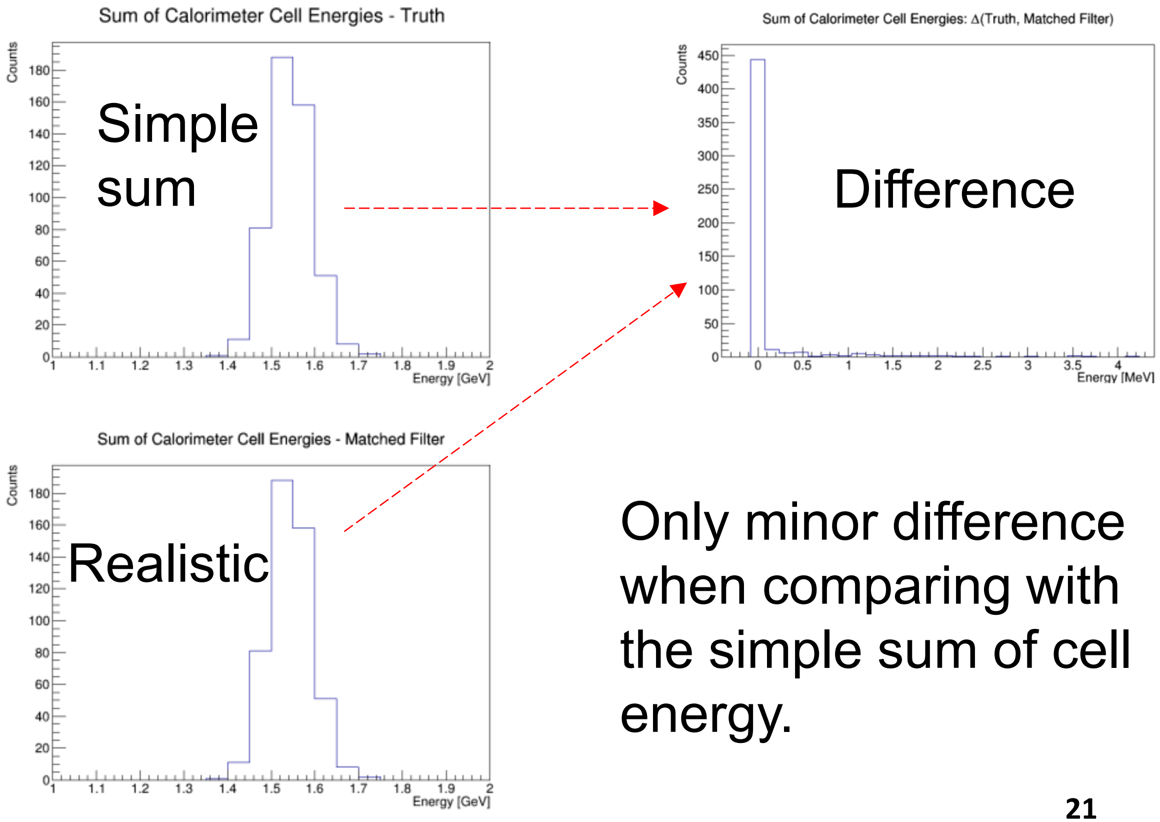
# Realistic digitisation

- Digitisation of cell hit: simple sum of cell energy -> digitized samples.

$$S_i = \sum_{\substack{hits\ in \\ a\ cell}} E_h \cdot \left(g_j - \delta t \cdot g_j'\right)$$

- Matched filter pulse is obtained by applying the matched filter to a Gaussian input pulse.
- With correct normalisation, the energy and peaking time of the hit are extracted.
- True energy can be recovered even with some noise, after the application of the “whitening filter”.




Only minor difference when comparing with the simple sum of cell energy.



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# Realistic digitisation

- Matched filter defined as:

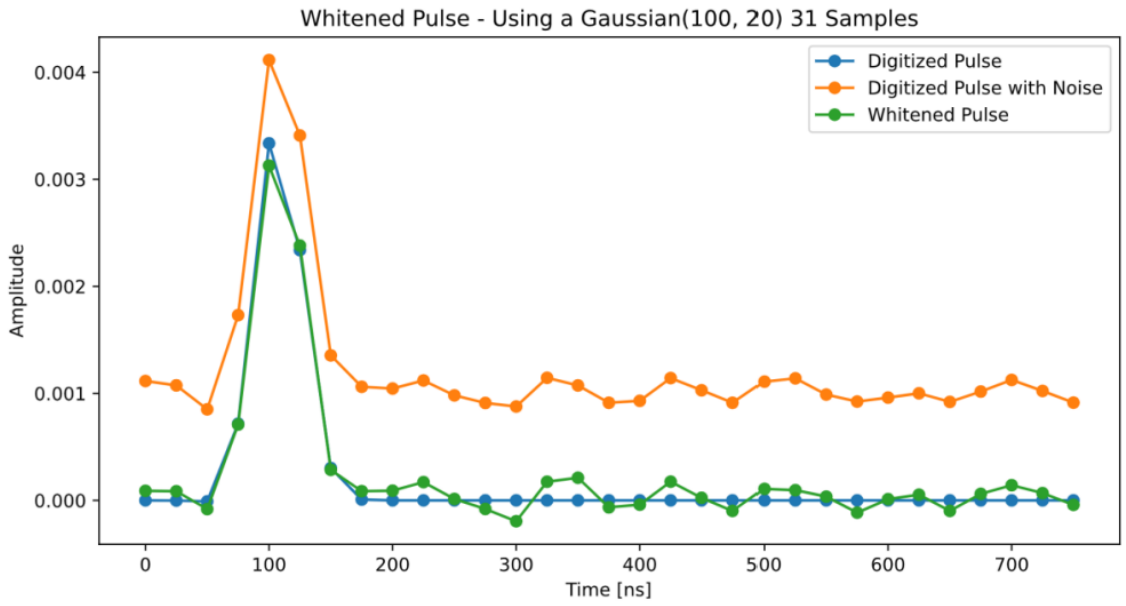
$$\boldsymbol{M} = \frac{\Sigma^{-1} s}{s^T \Sigma^{-1} s}$$

- $s$ is the time-reversed conjugate of the "signal" portion of the pulse → 5 samples around the peak of the pulse

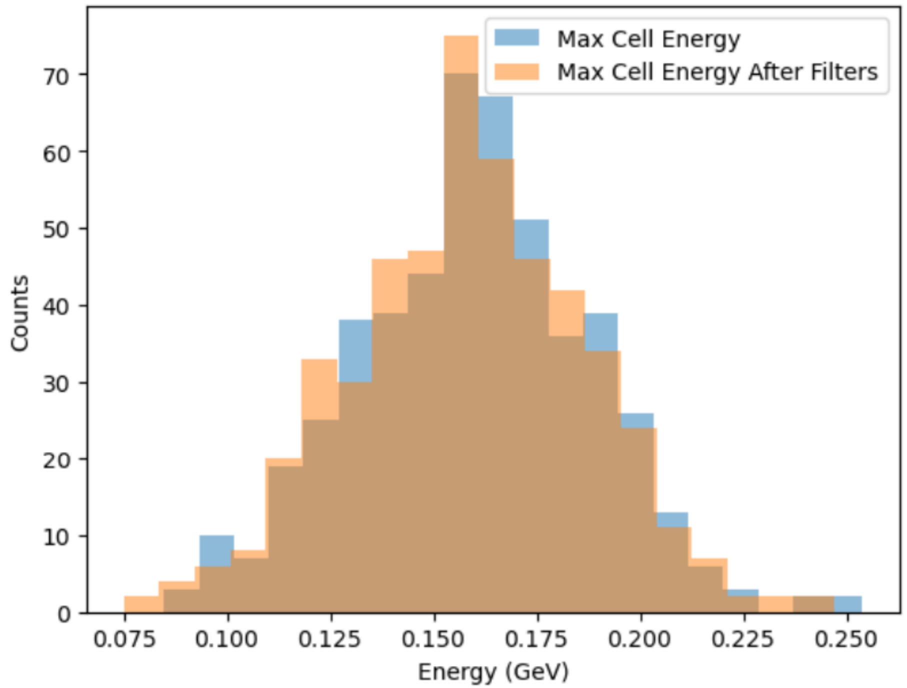
- Whitening filter applied before the matched filter

$$D_{Whitened} = \boldsymbol{\Sigma}^{-1/2} (D - \mu)$$

- $\mu$ is a vector of the mean noise in sample $i$ extracted from the simulation




The effect of the whitening filter.




Recovery of true cell energy after filters.



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# Explore the possibility of cold electronics

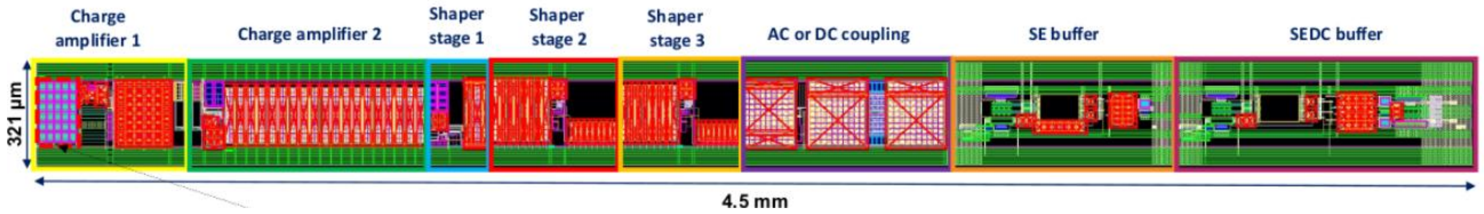
ALLEGRO ECAL barrel contains about 2M channels.

- Warm electronics needs to deal with the routing of signal cables. Avoid long read-out cables -> reduced capacitance.
- Cold electronics should reduce the electronic noise of the read-out significantly.
- Cold electronics requires room for boards+HV, powering and signal cables.

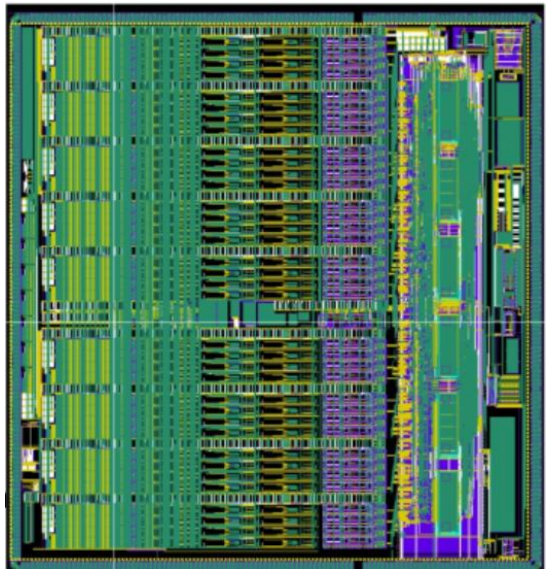
Omega Microelectronics

Brookhaven National Laboratory

Front-end channel layout



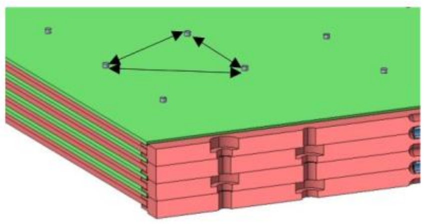

CHARMS250 cryogenic analog front-end ASIC @ BNL

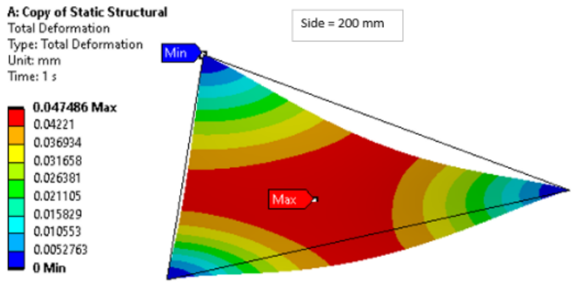


CALOROC1C chip for ALLEGRO ECAL @ Omega Labs

# Spacers

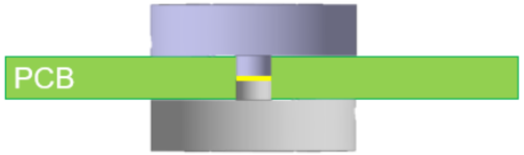
Spacers are placed between read-out electrodes to maintain the gap for the flow of liquefied noble gas.



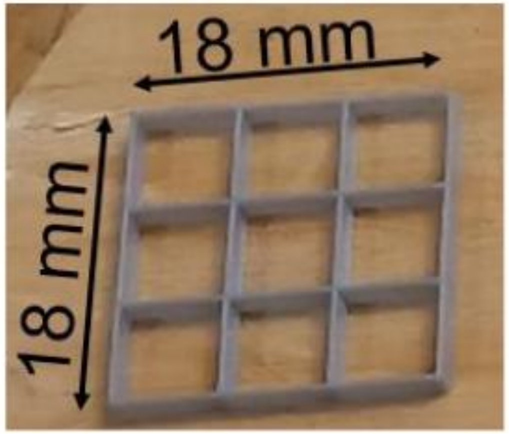



The maximal interval is determined from FEM analysis.

- A distance of 200 mm leads to normal deformation less than 50 μm.




Solution A: pins
Exact position and good tolerance, but concentrated force.




Solution B: 3D print mesh
Distributed force and easy to build, but burring needed, and difficulty in material characterization.

Solution C: honeycomb
Distributed force, easy assembly, but expensive, tolerance unknown.



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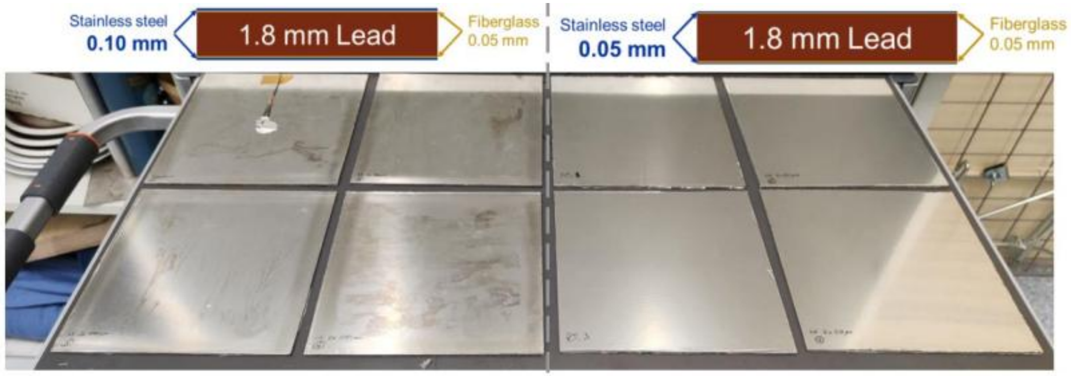
# ECAL absorber cold test

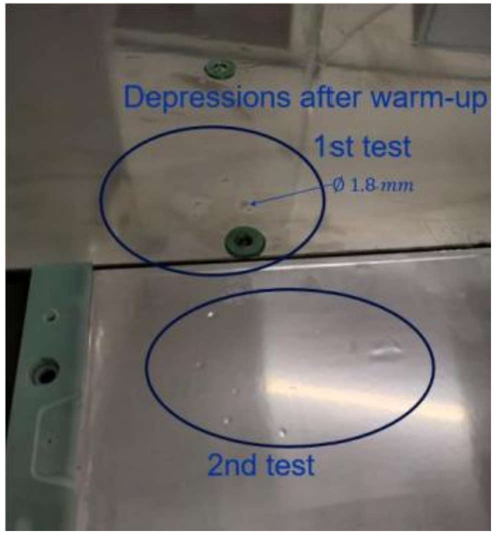
Test of two absorber designs performed with liquid nitrogen bath of 77 K: 0.1 mm steel clad vs 0.05 mm steel clad.

- Deformations appear only on the 0.05 mm steel, because of different thermal expansions of lead and steel.
- Consequently, the absorber with 0.1 mm stainless steel clad is chosen to be the default.




Two absorber designs with different thickness of steel clad.

One setup of cold test: clamped to the frame




Depressions on the absorber with 0.05 mm steel clad after cold tests.



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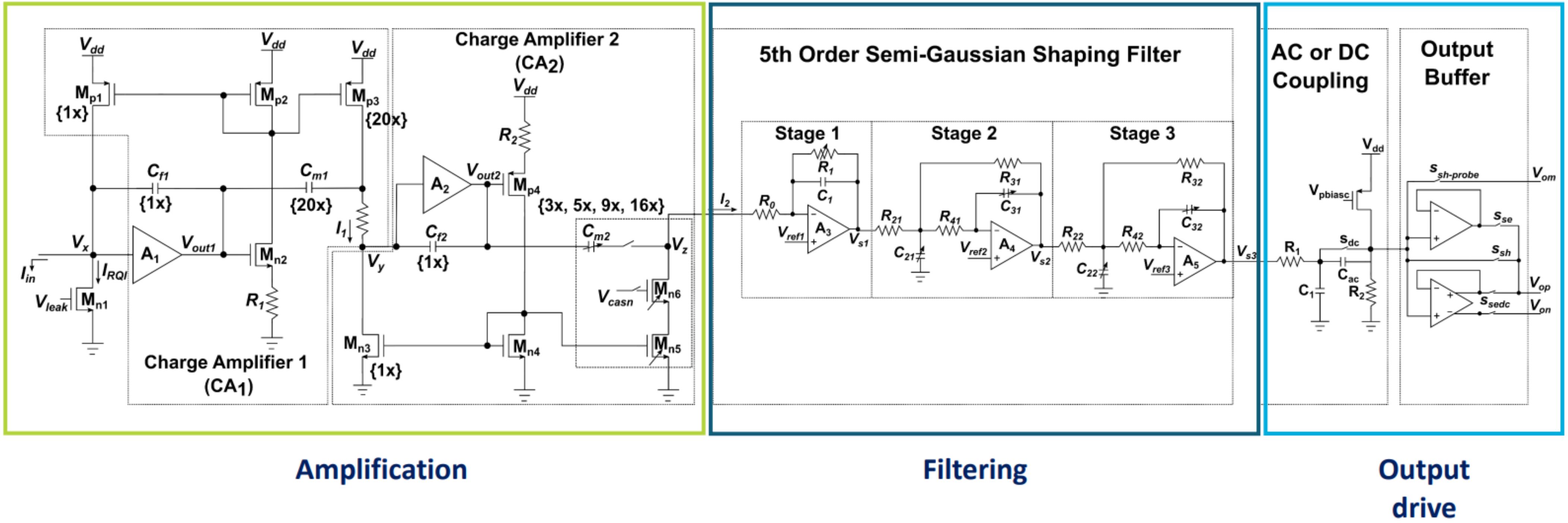
# Explore the possibility of cold electronics

## CHARMS250 core channel circuits



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