R&D on noble liquid calorimetry for ALLEGRO FCC-ee detector concept

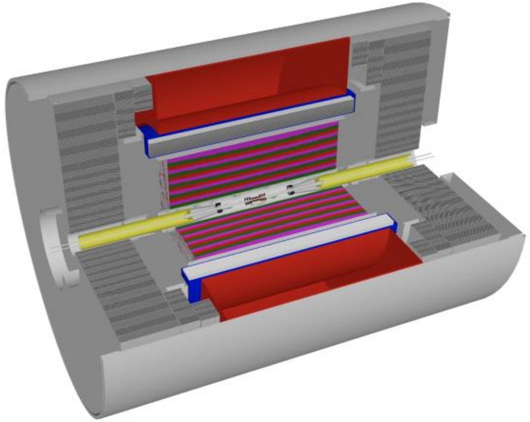
Zhibo Wu

20/07/2024

ALLEGRO detector concept

- A general purpose detector for FCC-ee (√s=90-360 GeV): A Lepton coLider Experiment with Granular calorimetry Read-Out.
- Key feature: High granularity noble liquid EM calorimeter (ECAL).
- 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, HCAL and muon tagger.
- Designed for full FCC-ee physics program and focused on particle flow and particle identification.

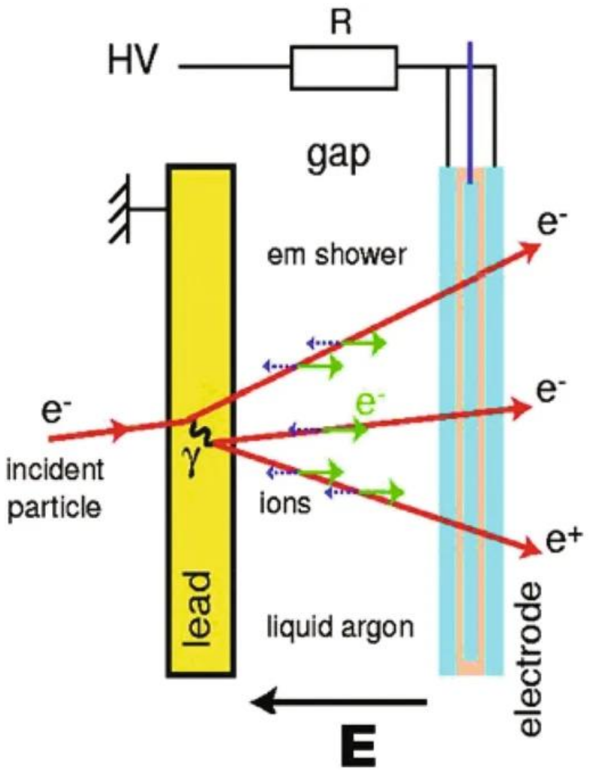
Layout of ALLEGRO



3D-view of ALLEGRO

Noble liquid calorimetry

- Sampling calorimeter technology. Repeated layers of absorber, noble liquid and read-out electrode.
- EM showers start in the absorber. Electron produced in the showers ionise 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.

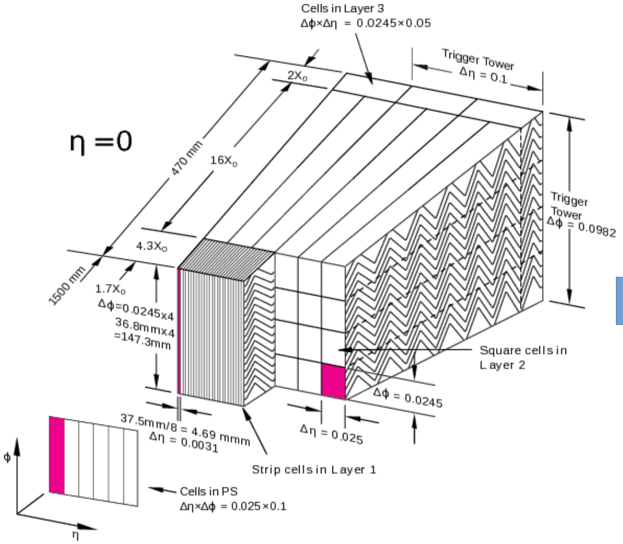


EM shower and signal induction (taken from ISBN 978-3-030-35318-6).

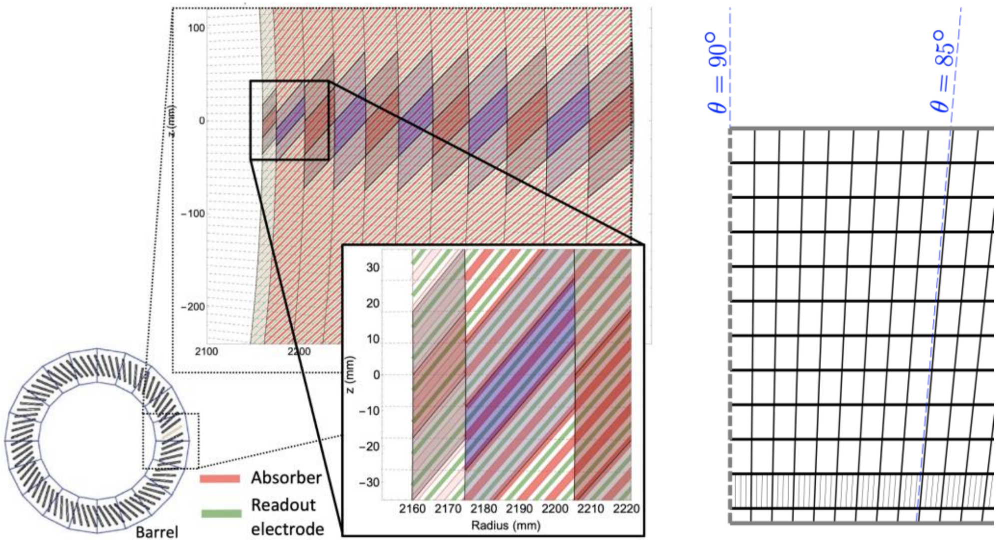
ECAL barrel

The design of the barrel region ECAL is based on the ATLAS LAr ECAL, but adapted to lepton collider experiment.

- 10 times higher granularity.
- New electrode geometry: straight read-out electrode with 50-degree inclination angle.



The accordion-like ECAL of ATLAS



ALLEGRO ECAL with high granularity

Overall goals of R&D

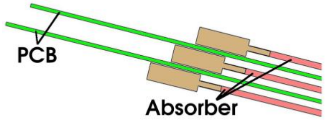
Development of individual elements:

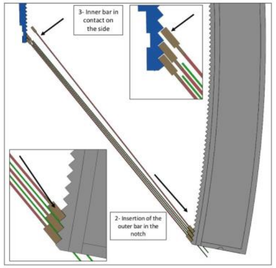
- Mechanics and structure.
- Absorber: material choice, thickness…
- Electrode design: shielding, cross-talk, signal extraction…
- Read-out electronics.

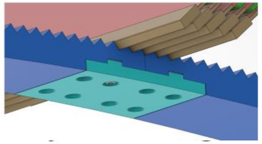
→ Converge to a concept of test-beam module in 3-4 years.

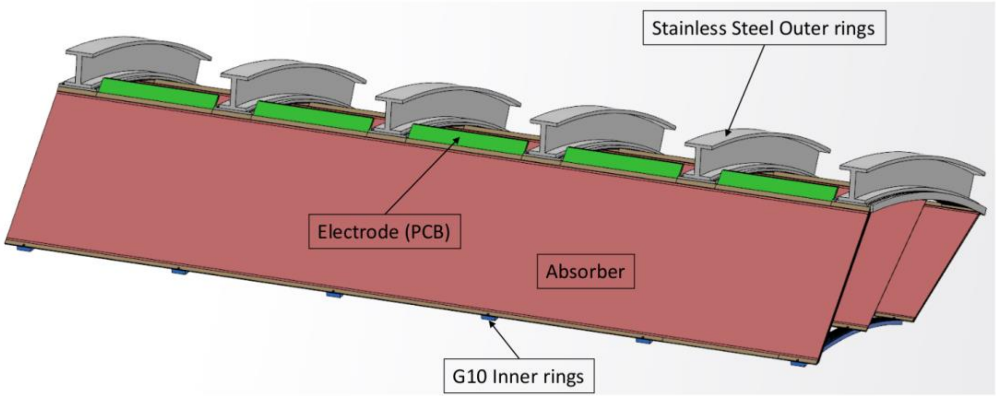
Mechanical and structural design

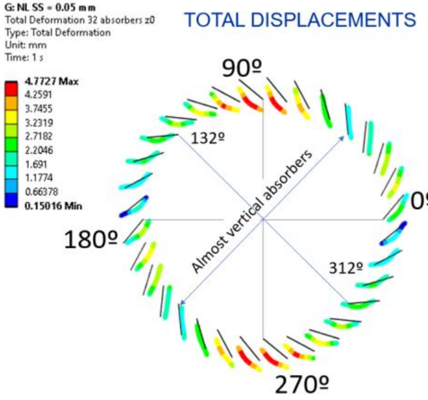
- The mechanical design is studied with finite element analysis.
- The assembly of the ECAL barrel, precise positioning of components, and the interference between PCB read-out and support structure are under study.





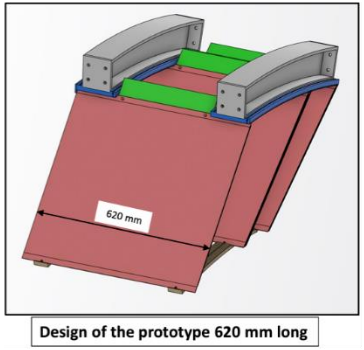


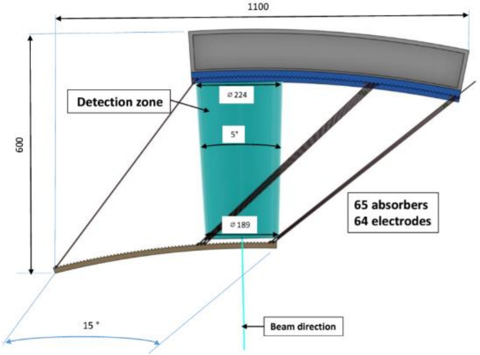




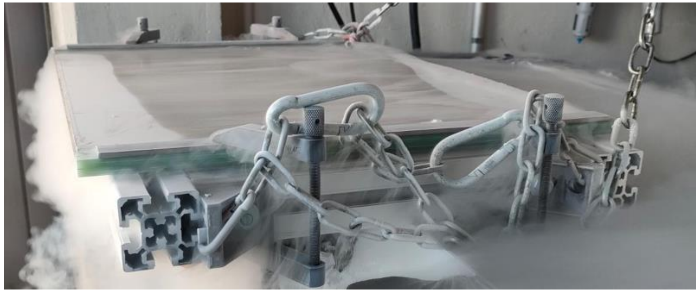
ECAL absorber and test-beam prototypes

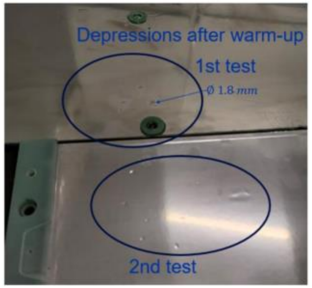
- The first prototype of two absorbers and one electrode built in 2023. Absorber thickness: 1.8 mm of lead and 50 µm steel layers.
- Small depressions observed after a liquid nitrogen bath: Origin under investigation. Thicker steel layers of 100 µm being considered.
- Design of the test-beam prototype to be fixed by autumn 2025. Timeline for beam tests: 2027 - 2028.





Design of the test-beam prototype: A typical shower can be contained by 64 repeats of absorber and readout electrodes.

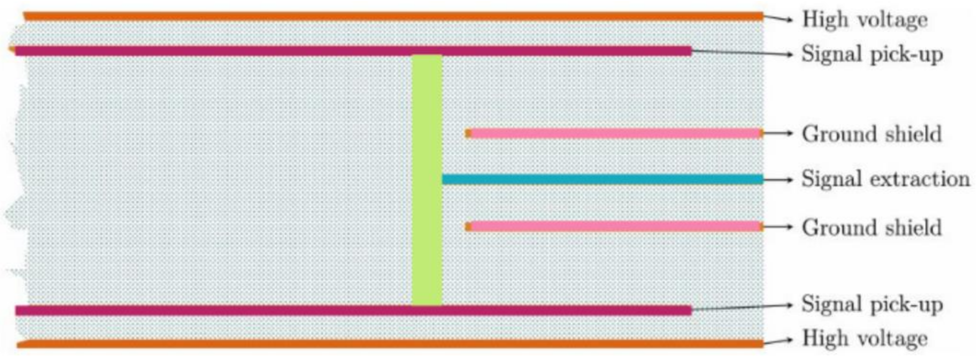


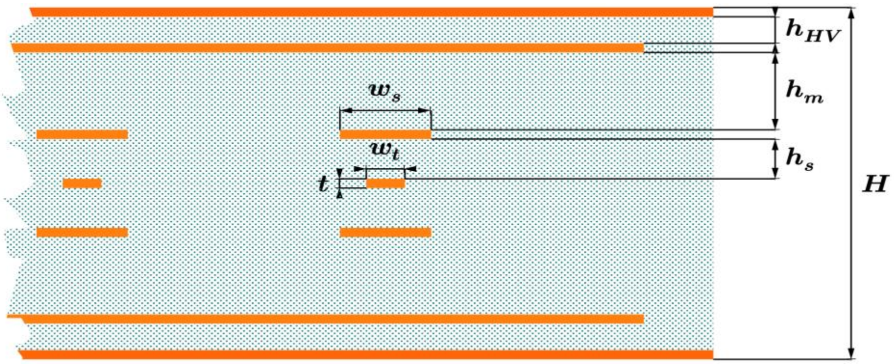


Cold test for the absorber prototype.

Read-out electrode structure

- Printed circuit board technology allows high granularity.
- Various couplings between calorimeter cells and signal traces inside the read-out electrode generate cross-talk → Need for shielding.

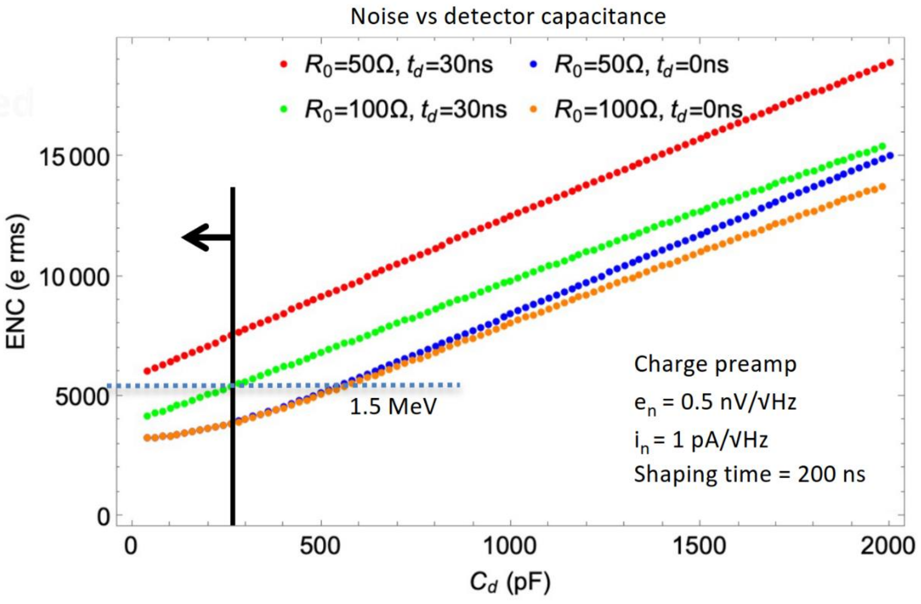




Side view of the 7-layer PCB for the read-out electrode.
The PCB v0 baseline has 2 times wider shields for each signal trace.

Read-out electrode structure

- Printed circuit board technology allows high granularity.
- Various couplings between calorimeter cells and signal traces inside the read-out electrode generate cross-talk → Need for shielding.



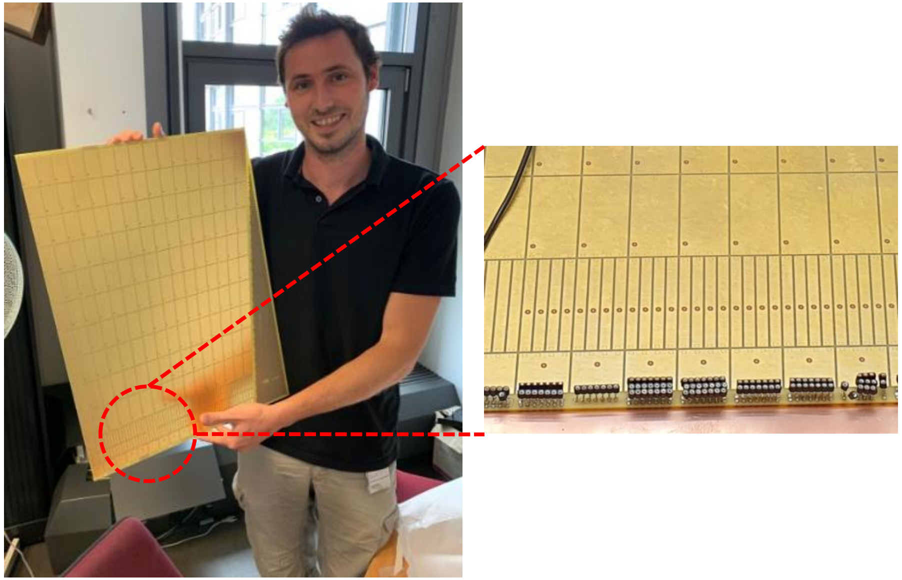
- A wider shielding reduces cross-talk but increases the detector capacitance, therefore resulting in a higher noise level.
- In the meantime, higher granularity also leads to smaller signal amplitude.

→The design of the read-out electrode is a balance among granularity, cross-talk and noise.

$$N \sim C_d \sqrt{\frac{4kT}{g_m \tau_p}}$$

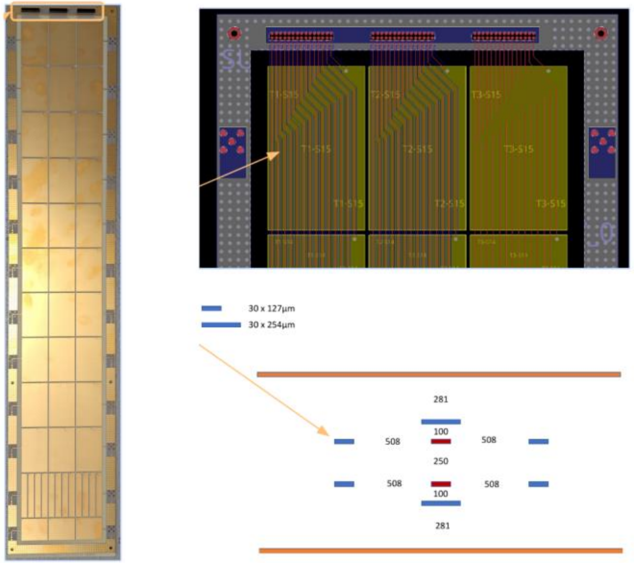
Cold read-out electronics can help achieve a low-noise read-out!

Electrode prototypes



CERN prototype PCB 58 cm × 44 cm

- An inclination angle of 50 degrees → thickness = 40 cm (22 radiation length).
- Segmented into 16 θ-towers and 12 radial layers.
- 4 times higher granularity on the second layer for photon-π0 identification.

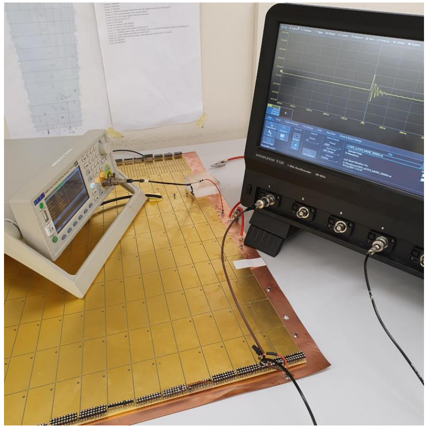


New IJCLab prototype arrived in January

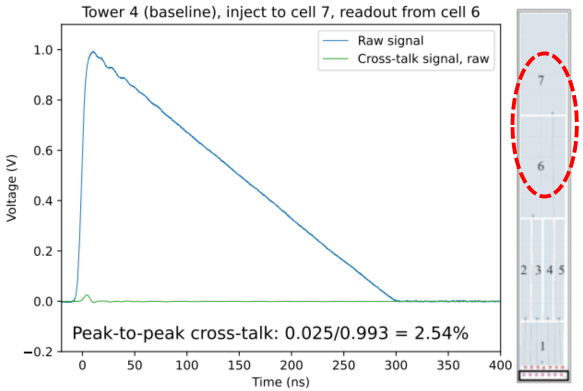
- Double signal traces (which seems to increase cell capacitance significantly).
- New lateral shielding between signal traces in two of the three θ-towers, while the third one is used as reference.
- Connectors for easy signal injection and read-out. Development of automated measurements.

Measurement of electrode cross-talk

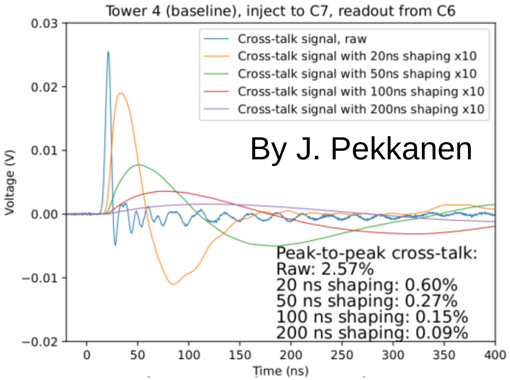
- Electrical properties of the electrode is measurement in the lab.
- With a shaper under consideration, the cross-talk is reduced with long shaping time.



Lab setup:
(a) 300 ns wide 1 V peak is injected to the electrode at 5 ms intervals.
(b) Signals are read from the oscilloscope.



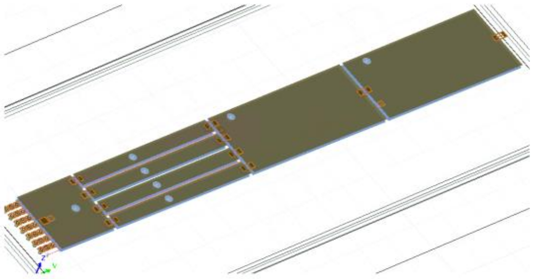
The shark-fin signal appears on the electrode receiving the injection, as well as the cross-talk on a radial neighbour.

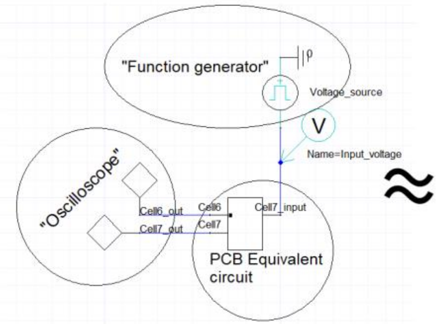


Cross-talk can be efficiently reduced by introducing a pulse shaping (e.g. ATLAS-like RC-CR2 shaper) and choosing a long shaping time (e.g. 200 ns).

Simulation of read-out electrode

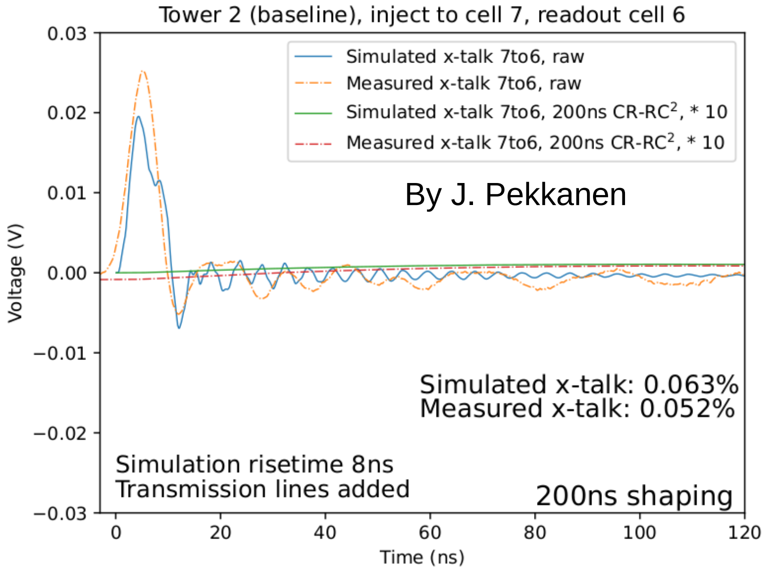
- Electrical properties are also studied by Ansys Electronics Desktop.
- Good agreement of cross-talk shapes between measurement and simulation.





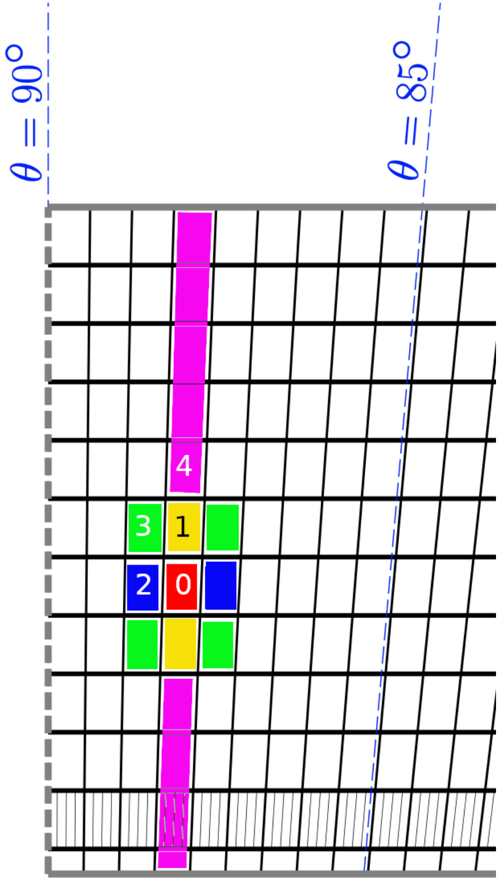
≈

PCB model analysed and converted to equivalent circuit.



Sufficiently good reproduction of the measurement by simulation enables studies of different shielding scenarios.

Cross-talk emulation in the FullSim



- The emulation of electrode cross-talk has been implemented in the full simulation for ALLEGRO (handled by digitisation).
- 4 types of cross-talk neighbours are considered in the emulation.
- Cross-talk coefficients are taken from the measurement with 50 ns shaping.
- Minor impact on energy resolution. Studies of impact on particle identification is on-going, by evaluating the distortion of shower shape variables.

Summary

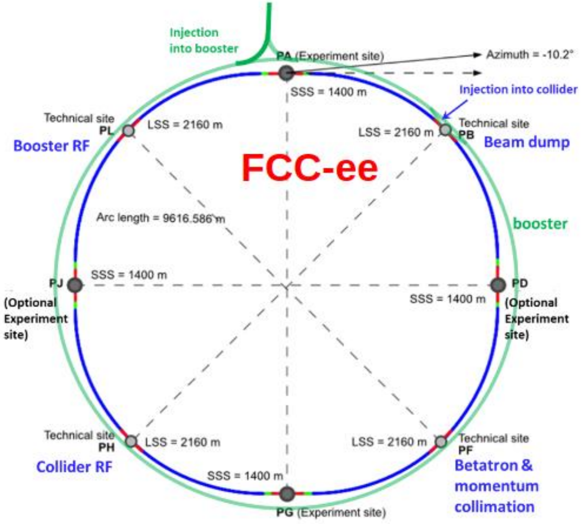
- ALLEGRO is a general-purpose FCC-ee detector concept that has been evolving rapidly. The iconic feature of ALLEGRO is its highly granular ECAL using noble liquid calorimetry technology and multi-layer PCB as read-out electrode.
- Design of the mechanical structure is being optimised.
- The first ECAL absorber prototype has been built and tested in liquid nitrogen bath, paving the way for the test-beam prototype coming in a few years.
- Prototype ECAL PCB’s were produced and tested for electrical properties. Dedicated measurement of electrode cross-talk has been performed, of which the result is reproduced by the simulation.
- The emulation of cross-talk has been implemented in the full simulation to study the impact on physics performance.
- We are part of the DRD6 collaboration.

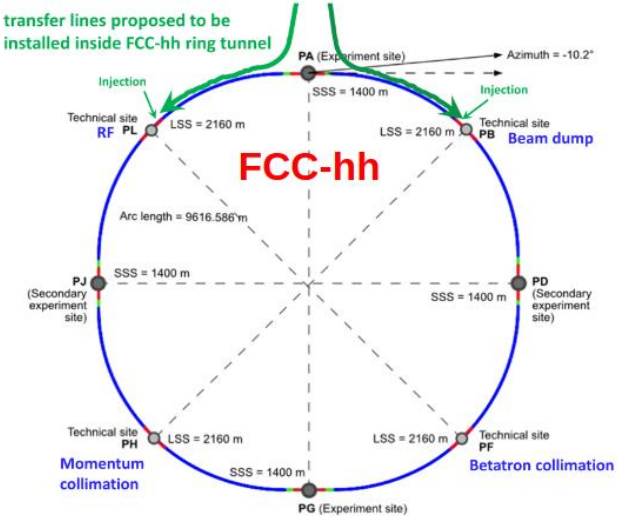
→See Erich’s talk on expected performance of ALLEGRO calorimetry.

Backup

The Future Circular Collider (FCC)

- The next generation collider with a circumference of ~90 km.
- Sgate 1: FCC-ee as Higgs factory, EW & top factory at highest luminosities.
- Stage 2: FCC-hh (~100 TeV): Energy frontier.

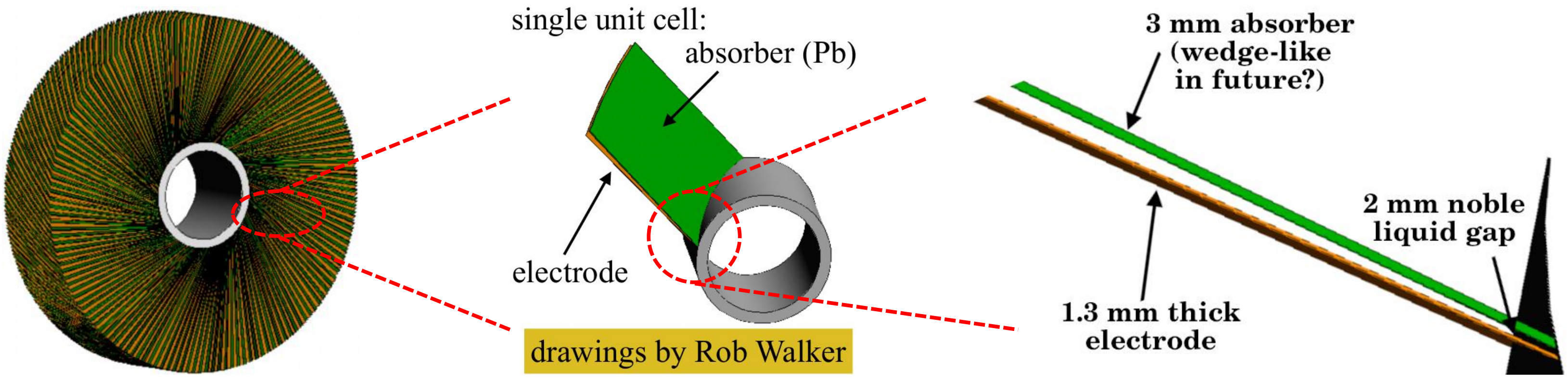




ECAL endcap

The EM calorimeter in the endcap region is also a noble liquid technology sampling calorimeter.

- Requirements: high granularity (thin absorber), no dead material on the inside face, uniformity in azimuthal angle.
- One option: turbine-like geometry with ~240 repeats of absorber and read-out electrode.



The optimisation of mechanical structure in the design is under study.

Hadronic calorimeter (HCAL)

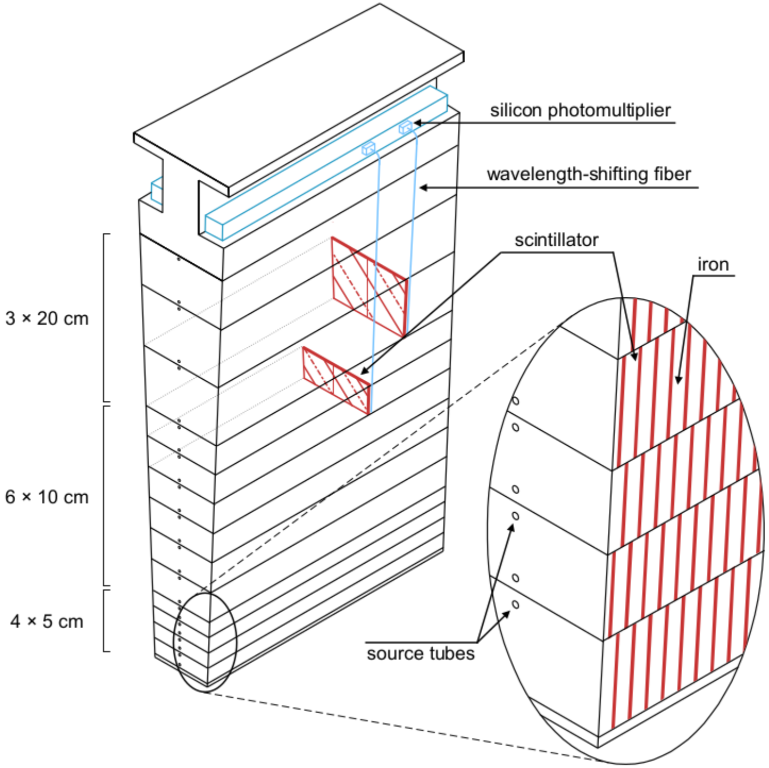
- The design of HCAL comprises alternating layers of steel and scintillators. Also acts as the return yoke of the solenoid.
- Well studied and tested reference for the design: the ATLAS Tile Calorimeter.
- Technical parameters:

(a) 5 mm absorbers and 3 mm scintillators.

(b) 13 radially thickening layers.

(c) 128 azimuthal modules and 2 tiles per module ($\Delta\phi = 0.025$).

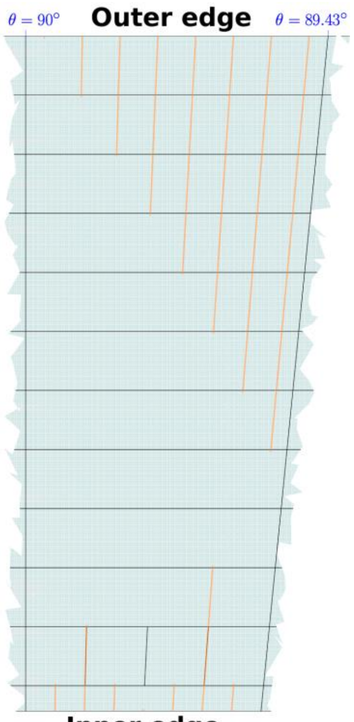
(d) $\Delta\eta = 0.025$ by grouping 3-4 tiles.

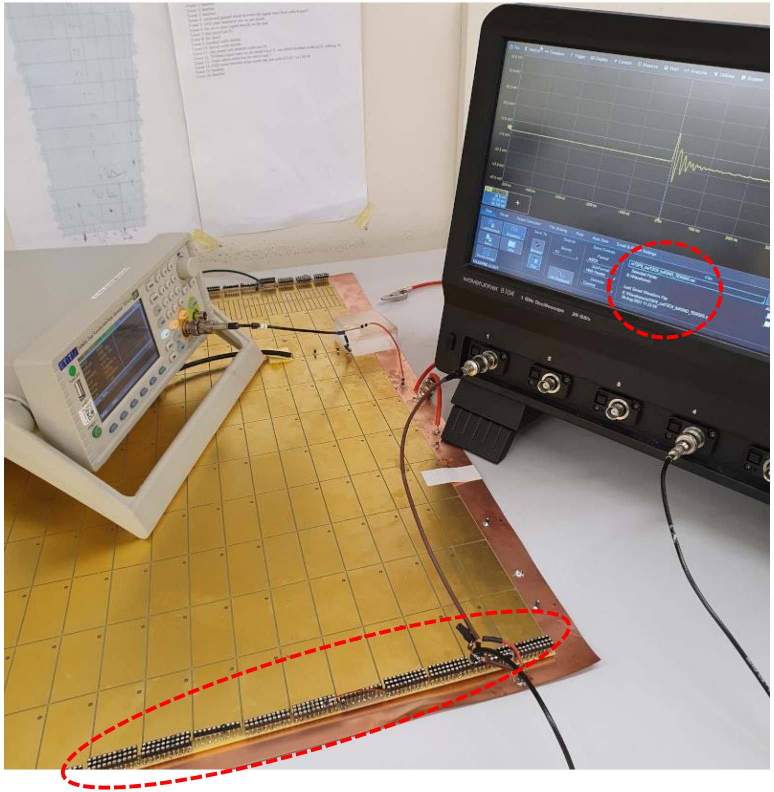


The HCAL barrel baseline geometry.

The read-out scheme

- Signals are extracted from both the inner and outer radial edges, depending on the layer.

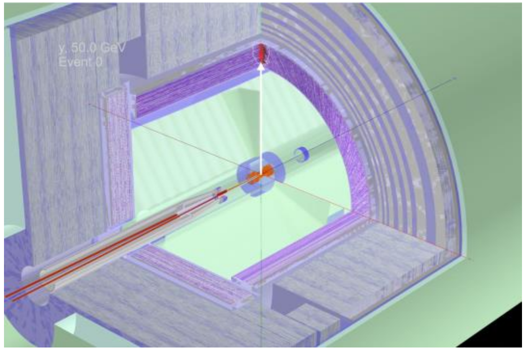




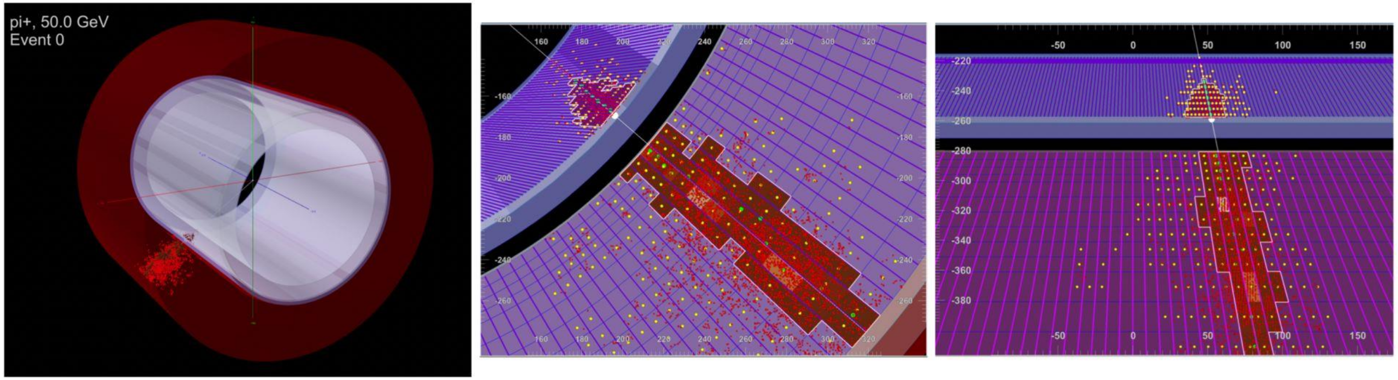
In IJCLab prototype and next CERN prototype, read-out is designed only from the outer edge in order to minimise the amount of dead material in the front.

Full simulation and cluster reconstruction

- Detector full simulation of ALLEGRO has been built to help optimise the choice of granularity and materials.
- Detector geometry definition and visualisation of the simulated event.
- ECAL+HCAL topo-cluster reconstruction has been implemented. Moving forward to the realisation of Particle Flow algorithms.



The response of the ALLEGRO caloimetry to a 50 GeV photon.

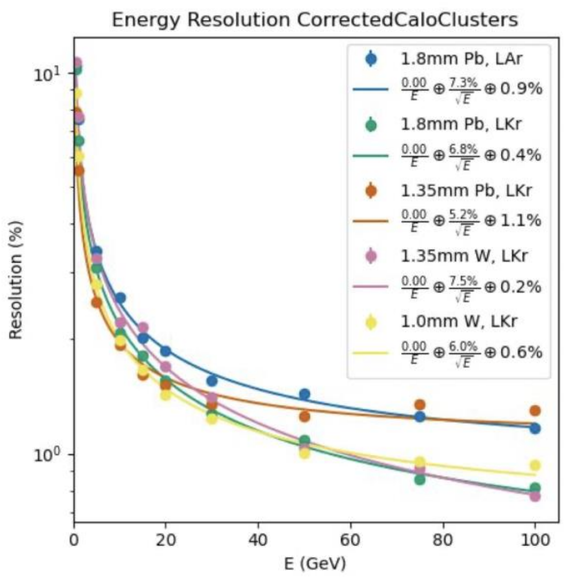


Topo-cluster reconstruction of showers generated by a 50 GeV pion in ALLEGRO calorimetry.

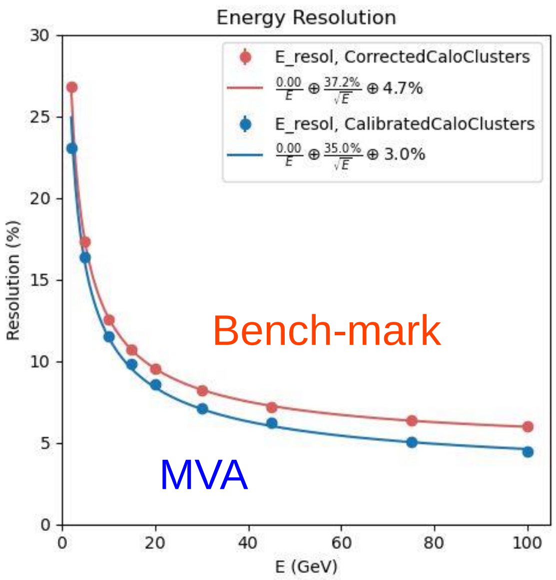
More details covered in Erich's talk and in Filomena's poster.

Expected performance

- ECAL energy resolution to single electrons has been studied for various absorber and active materials. A 7% sampling rate is achieved for the baseline Pb+LAr combination.
- Machine learning techniques are under development to provide better energy resolution for combined ECAL+HCAL cluster reconstruction.

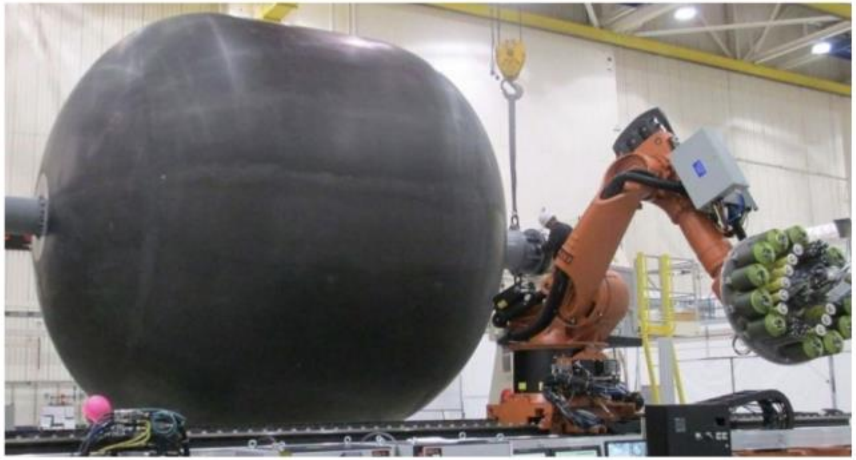


Energy resolution to single electrons for ECAL barrel.



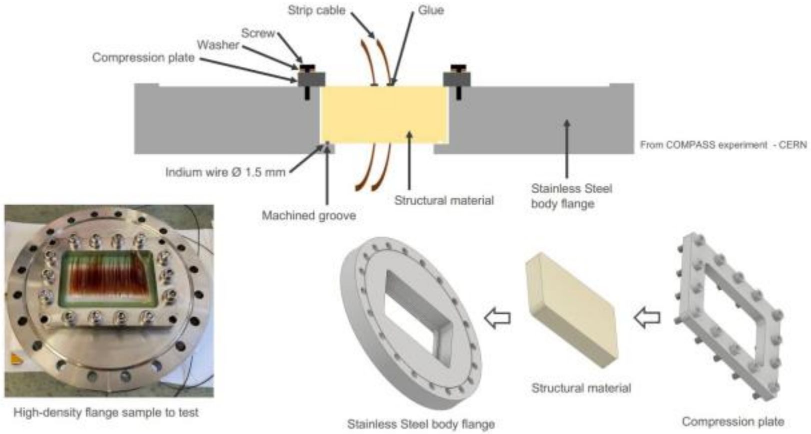
Energy resolution to single negatively-charged pions with ECAL+HCAL cluster reconstruction after different calibrations

Cryostat and feedthrough



NASA lineless cryotank.

Minimise the dead material in front. Ultimate goal of the “transparent” cryostats: a few % of radiation length.



High-density feedthroughs:

- 5 times higher density and 2 times more area compared with ATLAS.
- Successful R&D on connector-less feedthroughs at CERN.