Noble Liquid Calorimetry for an FCC-ee Experiment

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Introduction

Noble liquid calorimeters have been successfully used in the past (D0, H1, NA48) and are currently operating in NA62 and ATLAS. Their very good energy and timing resolution, stability, linear response, uniformity and radiation hardness make them also very good candidates to **equip detectors at future facilities such as FCC-hh, LHeC and FCC-ee.**

The very demanding FCC-ee physics program and its exquisite statistical precision set strict constraints on the detector designs [1]. A broad R&D program has started to develop a noble liquid calorimeter meeting these detector requirements with, among others, an **increased granularity and a decreased dead material budget before the sensitive volume.**

Detector concept

FCC-ee noble liquid ECAL barrel

- Sampling calorimeter, 40 cm deep sensitive area (22 X_0)
- 1536 Lead or Tungsten absorbers, inclined by 50°
- Noble liquid sensitive 1.2 - 2.4 mm gap: LAr or LKr (or LXe)
- Optimized for Particle Flow (PFlow) → **high granularity** [2]
  - $\Delta\theta = 10$ (2.5) mrad for regular (strip) cells, $\Delta\Phi \geq 8$ mrad, 12 longitudinal compartments (Δr=3.5 cm)

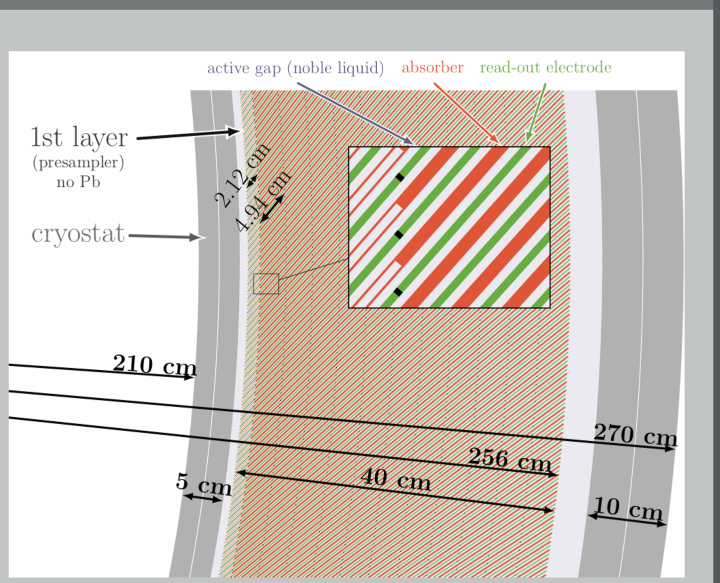


Figure 1: *Layout of the proposed FCC-ee noble liquid ECAL barrel in the r-Φ view.*

Highly granular readout electrodes

Signal extraction

- Purely **analog** until the inner/outer radius of the electrode (cold electronics) or until the cryostat feedthroughs (warm electronics)
- Multi-layer PCB readout electrodes (Fig. 2)
  - Homogeneity, hermeticity, high sampling fraction

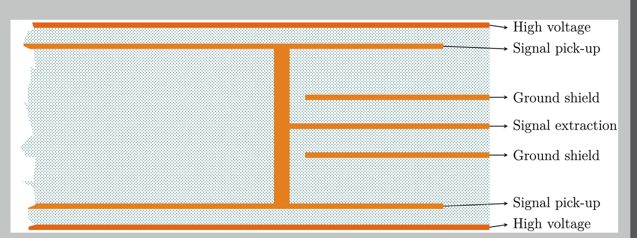


Figure 2: *Cross section of the proposed multi-layer PCB readout electrode.*

Cross-talk

- Capacitive coupling between signal pick-up pads and extraction traces
- Fully derived from FEM studies (Scattering parameters)
  - 12% peak to peak current at the PCB output without ground (GND) shield (Fig. 3)
  - $<$ 2% with two GND shields surrounding signal extraction trace
  - Further **reduced by long signal shaping** (no pile-up noise)
    - **$<$ 1% with one GND shield and shaping time $>$ 150 ns**

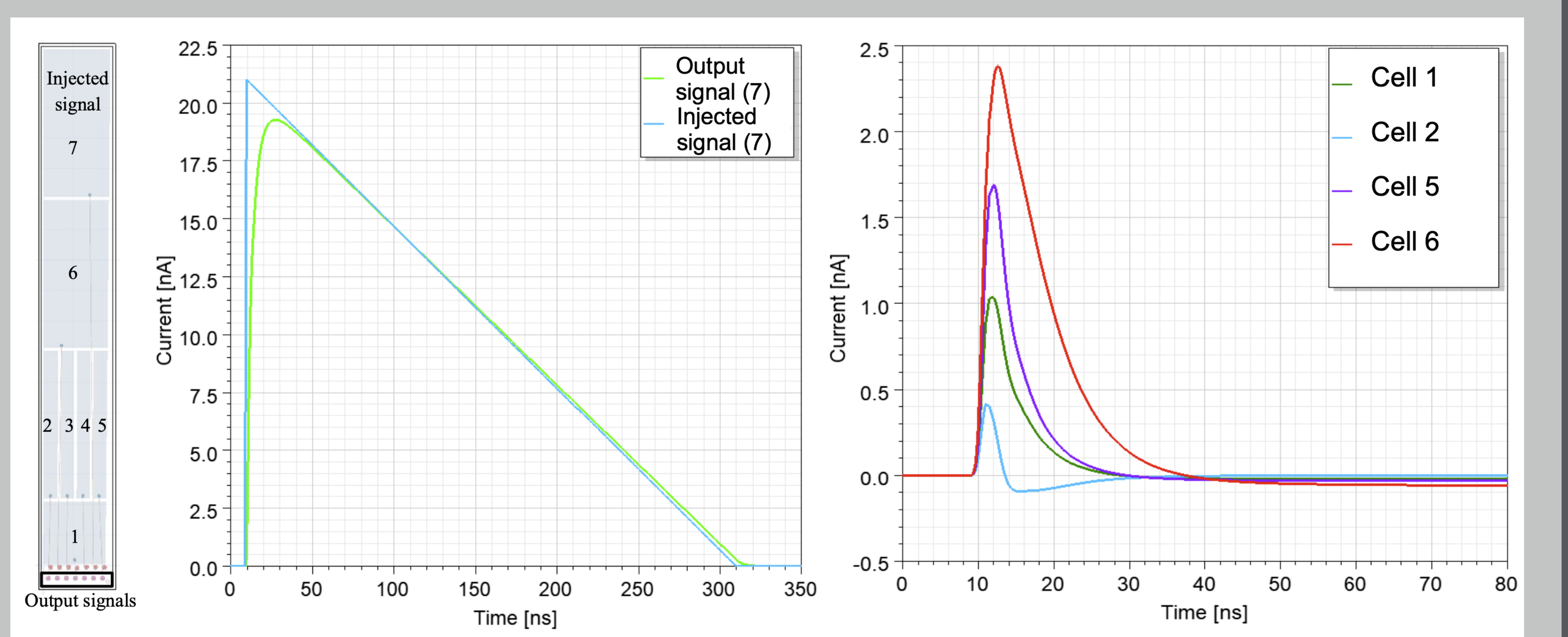


Figure 3: *Layout and cell numbering scheme of the readout electrode chunk implemented in FEM tools (left), signal attenuation (middle) and cross-talk current without shield (right).*

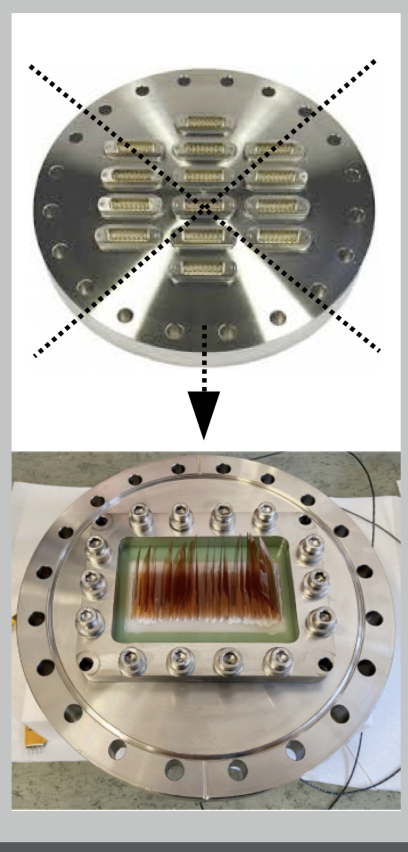
Noise

- Shields increase detector cell capacitance to GND
  - Derived from FEM tools assuming two GND shields/trace (conservative)
  - 20 - 250 pF depending on the cell
- Capacitance to GND + analytical emulation of front-end electronics
  - 0.5 - 2 MeV depending on the cell (charge pre-amp, $e_n = 0.5\ \frac{\text{nV}}{\sqrt{\text{Hz}}}$, $i_n = 1\ \frac{\text{pA}}{\sqrt{\text{Hz}}}$, $\tau_s = 200$ ns)
  - **MIP S/N $>$ 5 per cell**

High density feedthroughs

Increased granularity ↔ increased number of channels to extract from the cryostat (warm electronis sceanrio)

- 2 M channels for the barrel (10 times more than in ATLAS)
- Increased area dedicated to signal extraction (x2)
- Increased number of channel per flange (x5)
  - **Connector-less**
  - 20 000 wires per feedthrough
  - G10 structure with slits, indium seal, Epo-Tek glued Kapton strip cables
  - Observed to be leak tight over several thermal cycles (77 K, 3.5 bar)



Light-weight cryostat

Minimizing material budget before sensitive areas

- Improves track to cluster association (PFlow)
- Increases reconstruction efficiency for low energy particles (Flavour physics)

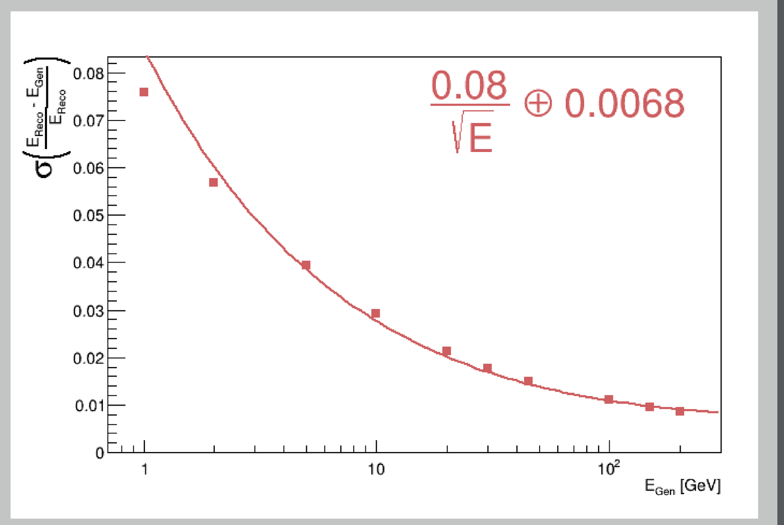
Aluminum → carbon fiber cryostat

- Solid shell and honeycomb sandwich studied
- Can reach **down to 5% of X_0** for the inner cold cylinder
  - **Factor 10 lower than Aluminum solid shell**
- Small scale prototype observed to be leak-tight at warm and cold

Performance studies

Barrel detector geometry and reconstruction implemented in Key4hep [3]

- Conservative benchmark geometry: Aluminum solid shell cryostat, LAr gap, Pb absorbers
- Energy resolution: **8% sampling term**
- τ final state categorization
  - Simplified geometry: cylinders with 2 x 2 x 4 cm^3 cells, no strip layer
  - Based on the number of reconstructed π^0, π^0/γ separation from simple cluster shape variables cut
  - Observed competitive results compared to other studies [4]
  - Will be improved with strip layer and machine learning



Relative photon energy resolution

Reco τ → / Gen τ ↓	$\pi^\pm\nu$	$\pi^\pm\pi^0\nu$	$\pi^\pm2\pi^0\nu$	$\pi^\pm3\pi^0\nu$	$\pi^\pm4\pi^0\nu$
$\pi^\pm\nu$	**0.9560**	0.0425	0.0010	0.0003	0.0002
$\pi^\pm\pi^0\nu$	0.0374	**0.9020**	0.0586	0.0016	0.0002
$\pi^\pm2\pi^0\nu$	0.0090	0.1277	**0.7802**	0.0808	0.0022
$\pi^\pm3\pi^0\nu$	0.0036	0.0372	0.2679	**0.5972**	0.0910

Migration matrix for the assignment of τ hadronic final states

Conclusions & Outlook

Intensive R&D started to adapt noble liquid calorimetry to FCC-ee

- Simulations show that a cross-talk $<$ 1% together with a MIP S/N $>$ 5 is achievable for a typical cell
- A solution for high density connector-less feedthroughs has been identified
- Small scale prototype of a carbon fibre cryostat produced and validated
- First performance results from a full simulation Key4Hep implementation
- Mid-term objective: design and produce a prototype for test beams

References

[1] Azzi P., Perez E. *"Exploring requirements and detector solutions for FCC-ee"*, Eur. Phys. J. Plus **136**, 1195 (2021).

[2] Brient J-C., Videau H. *"The calorimetry at the future e+ e- linear collider"*, arXiv:hep-ex/0202004 (2002).

[3] Ganis G., Helsens C, and Völkl V. *"Key4hep, a framework for future HEP experiments and its use in FCC"*, arXiv:2111.09874 (2021).

[4] Aleksa M., Bedeschi F., Ferrari R., Sefkow F., Tully C.G. *"Calorimetry at FCC-ee"*, Eur. Phys. J. Plus **136**, 1066 (2021).

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