PROCEEDINGS OF SCIENCE

The ALLEGRO Noble Liquid Calorimeter for FCC-ee

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The broad physics programme at the FCC-ee calls for next-generation calorimeters offering high granularity, high energy resolution and allowing for low systematics in measurements. The ALLEGRO electromagnetic calorimeter is a novel noble liquid calorimeter design aiming to achieve these goals by using multi-layer PCBs to achieve high granularity and optimising the design for best energy resolution. Progress in the implementation of the simulation and reconstruction of both barrel and endcap geometries yields promising performance metrics. R&D on all main calorimeter elements is progressing in parallel, with first electrodes and absorber prototypes delivering the expected performance figures. Design studies on the readout electronics and on the mechanical structures are progressing, along with developments for lightweight cryostats made of carbon fiber composites. The plans for a full-scale prototype aiming for beam tests after the Long Shutdown 3 of the LHC are also discussed.

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1. Introduction

The Future Circular Collider (FCC) is a proposed 91 km circular collider at CERN to succeed the LHC in the 2040s, to study the Standard Model and in particular to investigate the electroweak symmetry breaking, and search for new physics beyond the Standard Model (BSM). An electron–positron collider is foreseen as a first stage: the FCC-ee. It is the highest luminosity e+e- collider, and it will therefore provide very high statistics of events at several center-of-mass energies ranging from the Z pole to the $t\bar{t}$ threshold, allowing for a very broad physics programme: from Higgs boson precision physics, to flavour and τ physics, to very precise electroweak and QCD measurements, to BSM searches. Its feasibility study successfully concluded in time for the update of the European Strategy of Particle Physics [1, 2].

The outstanding physics reach of this machine translates into stringent requirements for the detectors. For calorimeters, the desired features are: an excellent jet energy resolution for Higgs and top physics, high electromagnetic energy resolution for flavour and τ physics, the ability to be calibrated very precisely with small systematic uncertainties to match the small statistical uncertainty of precision electroweak and QCD measurements. The requirements also imply that individual particles can be identified, to e.g. count the π^0 multiplicity when reconstructing τ decays. Additionally, the capability to accurately reconstruct the direction of photon clusters can enable the search for some long-lived particles.

ALLEGRO[1] is a detector concept, designed to meet all requirements of a high-performance, general-purpose experiment at FCC-ee. From the collision point outwards, it comprises a silicon vertex detector, a gaseous main tracker, a silicon wrapper, an electromagnetic calorimeter based on liquefied noble gas, a 2 T superconducting solenoid magnet, a hadronic calorimeter, and a muon tagger. Noble liquid calorimetry has been chosen as a cost-effective, mature technology, following decades of successes in particle physics experiments. It can indeed fulfil all requirements for calorimeters at FCC-ee [3]. The sampling term of the electromagnetic energy resolution can be as low as 5% to 8%. High granularity is achievable, with few million channels being suitable for accurate particle flow reconstruction and hence good jet energy resolution. The excellent long-term stability, the linearity and uniformity allowed by the noble liquid ionization measurements make this technology particularly suitable to achieve very low systematics in measurements: the 90 MeV systematic uncertainty achieved by the ATLAS experiment on the Higgs boson mass measurements in the $\gamma\gamma$ channel is a testimony of that statement [4].

The ALLEGRO noble liquid calorimeter is therefore a novel concept aiming to tackle the challenges of going for high granularity and high energy resolution, including minimising the readout noise and the amount of material in front of the calorimeter. The new design ideas are fostered in the DRDCalo collaboration [5], with a goal to develop a full-scale prototype for beam tests by the end of 2029, to demonstrate the feasibility and performance of the concept.

2. Design and Expected Performance

The ALLEGRO noble-liquid sampling calorimeter design features a geometry using alternating planes of absorbers and electrodes with the noble liquid in the gaps between them. In the barrel

[1] A Lepton-Lepton collider Experiment with Granular Read-Out

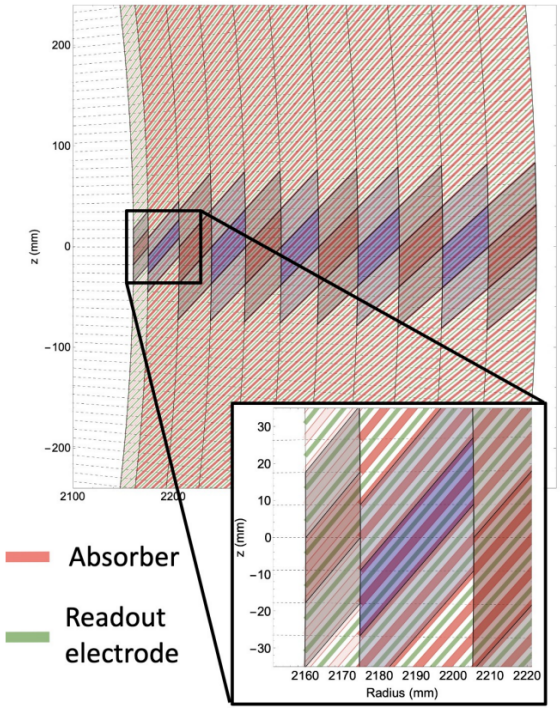

Figure 1: Sketch of the barrel calorimeter design in the (r, ϕ) plane, showing the stacking of inclined absorbers and electrodes. The shaded areas represent some readout cells obtained when reading together two or four electrodes.

the 1536 absorbers are inclined by an angle of 50° with respect to the radial direction, yielding a uniform design without any cracks around ϕ as shown in Figure 1. The gaps range from 1.2 mm at the inner radius to abut 2.4 mm at the outer radius, for a sampling fraction of about 20% and a total depth of 22 X_0. The electrodes are multi-layer PCBs that provide the high voltage and readout the currents induced by the charges drifting in the noble liquid. The internal routing of signal traces minimises the dead areas and allows for significant flexibility of the segmentation in the number of layers and in the z direction. The baseline design therefore features a granularity about 10 times finer than that of ATLAS, with 11 longitudinal layers, and projective cells along θ and ϕ angles.

While most of the design and performance studies performed so far use lead absorbers and liquid argon as active material, the options of using liquid krypton and tungsten absorbers are considered. Decisions will be made based on expected performance gains, technical considerations and cost.

The baseline calorimeter design is implemented in full simulation in the Key4hep software stack, allowing performance studies using preliminary reconstruction techniques. The energy reconstruction of electron and photon showers is calibrated using a boosted decision tree to recover for leakage and other effects, yielding an energy resolution with a sampling term of $7.7\%/\sqrt{\text{GeV}}$ and a constant term of 0.5%, as shown on Figure 2. When using liquid krypton with tungsten absorbers that have smaller X_0 than argon and lead, the thickness of absorbers and gaps can be further optimised, leading to a sampling term as low as 5%. The noise term of the energy resolution can also be improved, by increasing the shaping time to about 200 ns and by installing cold front-end

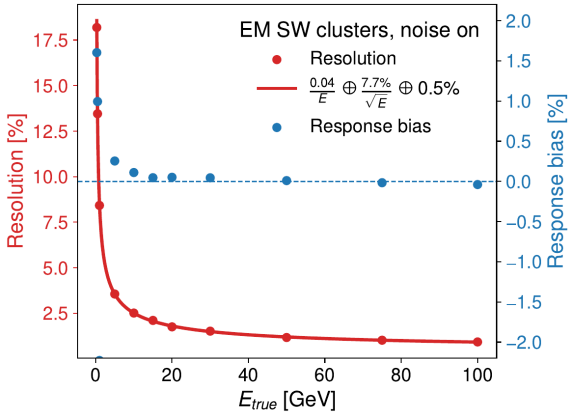

Figure 2: Energy resolution of electron clusters in the calorimeter barrel for the baseline geometry.

electronics directly at the back of the readout electrodes.

Early studies on π^0 reconstruction and identification show promising performance: low energy π^0 creating two separate clusters can be reconstructed with a resolution of 23 MeV, and high-energy, merged clusters can be cleanly separated from single photons based on the shower shapes. These studies pave the way towards the investigation of physics cases such as the classification of hadronic τ decay modes, that will be used to optimise the cell granularity, independently for each layer and along θ. It has already been shown that cells with four times finer granularity in θ placed in the third or fourth layer significantly improve the classification performance. A complete particle-flow implementation is necessary to investigate the performance of jets and hadronic final states in general. A preliminary implementation of the Pandora PFA algorithm has been achieved, while state-of-the-art machine-learning particle flow approaches are also under study.

Adapting the design of the barrel calorimeter to the endcaps sections leads to a turbine design, where the electrodes are tilted both along ϕ and around r. This concept features high sampling frequency, uniformity in ϕ, and can be readout from the high-$|z|$ face. Simulations show competitive performance, with an indicative resolution of $8.2\%/\sqrt{E} \oplus 0.4\%$.

3. Towards an ALLEGRO electromagnetic calorimeter prototype

In parallel to study the ALLEGRO electromagnetic calorimeter in simulation to understand its expected performance and explore design trade-offs, a comprehensive R&D programme is being carried to demonstrate the feasibility of the concept.

Several generations of prototypes of the large-scale PCBs used to deliver the high voltage and readout the signals have been designed and manufactured. They allowed to test various design options on the layout for signal propagation and shielding from cross-talk, to explore the trade-offs between granularity, capacitance (hence noise) and cross-talk. Measurements of the latest prototype demonstrate that sub-permille cross-talk can be achieved for a 200 ns signal shaping time, while keeping the capacitance of the cells between 200 pF and 300 pF. The measurements show good agreement with the FEM simulations of the layouts, giving confidence in future design iterations. The next main steps concern robust high-voltage distribution and the construction of large projective electrodes for the sections at the edge of the barrel.

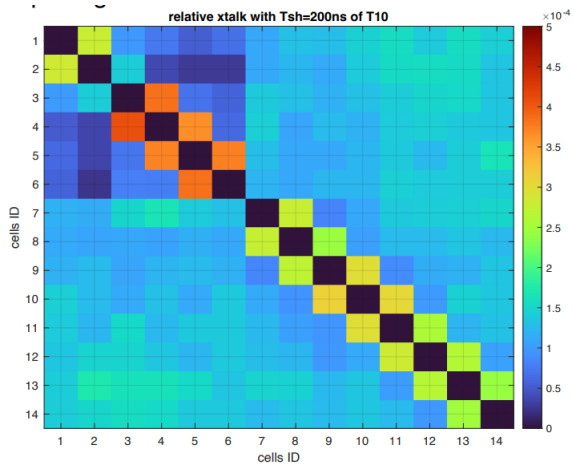

Figure 3: Peak-to-peak cross-talk amplitude for cells in a "tower" of cells corresponding to the 11 layers in depth of the barrel.

Absorber R&D explores manufacturing options for the 1.8 mm-thick lead plates clad with stainless-steel foils, bonded via prepreg. Deformations and defects at cold temperatures can happen because of the differences in the coefficient of thermal expansion of the bonded elements. Cold-tests at 77 K established that 0.1 mm stainless-steel sheets ensure minimal deformation, becoming the baseline choice.

The support structure of the calorimeter should be as compact as possible while providing adequate rigidity to the whole system, and allow precise positioning of the absorbers and electrodes to keep the constant term of the resolution low. The mechanical structure relies on internal and external support rings ensuring precise and uniform LAr gaps, with precisely machined interposer pieces to bolt the absorbers accurately. Optimisation studies have been performed using ANSYS FEM software on the dimensioning of the support beams and on carving holes in them to allow the routing of cables and pipes along the calorimeter.

The ALLEGRO electromagnetic calorimeter barrel will feature about 2 million channels. A readout solution with warm front-end electronics, akin to that of the ATLAS LAr calorimeter, would therefore need routing 2 million cables along the calorimeter and through feedthroughs. A readout design with cold front-end ASICs is therefore investigated, with two designs submitted for fabrication: one based on the cryogenic Dune LArASIC design, the other one being an evolution of the CMS HGCROC chip for the HGCAL. Such a solution will necessitate much fewer cables and avoid any cross-talk issues as signals will be transmitted after digitisation, at the expense of an additional cooling loop in the cryostat to dissipate the heat.

The requirements of high precision measurements (identification efficiency and resolution) even for low energy electrons and photons implies minimising the dead material in front of the calorimeter. Cryostats based on carbon-fiber-resin-polymer (CFRP), already used in aerospace applications, are studied as they can reach as low as 0.03 X_0 per wall using a sandwich of carbon layers with a honeycomb structure. R&D is ongoing from component level to full engineering models, with a preliminary design of a cryostat suitable for the ALLEGRO calorimeter, including plans for a series of demonstrators.

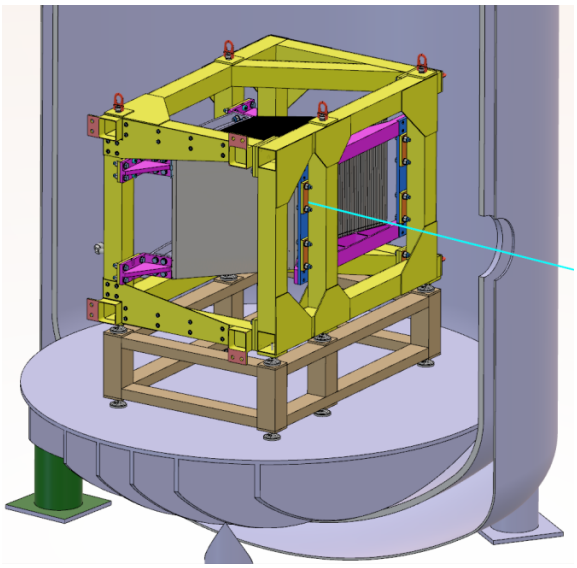

Figure 4: Drawing of the ALLEGRO Ecal barrel prototype held by its support frame, and placed in the H1 cryostat.

The next major milestone of the ALLEGRO electromagnetic calorimeter project in the next five years is the construction and test of a prototype module representative of a calorimeter section, featuring full electromagnetic shower containment, with 64 electrodes and 65 absorber plates. This leads to approximately 5,000 readout channels. The design of the frame that will be used for assembly and transport is already well advanced.

This prototype therefore aims to validate the large-scale mechanical precision and stability, the cold electronics integration and power schemes, realistic noise and cross-talk performance, calibration strategies and overall energy response.

Test-beam campaigns at CERN are planned post-LS3 (2029–2030), coordinated within DRD-Calo, and exploiting existing cryostats and cryogenic infrastructure.

4. Conclusions

Noble-liquid calorimetry is a highly promising solution for the FCC-ee electromagnetic calorimeter. The ALLEGRO concept builds on decades of operational experience while introducing key innovations in granularity, electrode technology, absorber design, mechanics and cryostat transparency. Early simulation results show that the physics-driven performance goals are within reach. A comprehensive and active R&D programme covering all key elements of the detector concept is underway within DRDCalo. Its overall goal is the demonstration of the ALLEGRO design with a full-scale prototype in the next five years.

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