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Design and performance of the calorimeter system for ALLEGRO FCC-ee detector concept

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Abstract. The future circular electron-positron collider (FCC-ee) will be a unique precision instrument designed to offer great direct and indirect sensitivity to new physics. Its primary purpose will be to study the heaviest known particles (Z, W, and H bosons and the top quark) with unprecedented precision, a goal that introduces multiple challenges in the detector design. Key requirements for the detector include excellent energy and angular resolution coupled with strong particle identification capabilities. One of the proposed experiments for FCC-ee is ALLEGRO, a general-purpose detector concept that is currently in its design and optimization phase. This contribution aims to introduce ALLEGRO's calorimeter system, offering a comprehensive overview of the baseline technologies planned for its two calorimeter systems: a highly granular noble-liquid electromagnetic calorimeter and a hadronic calorimeter with scintillating-light readout using wavelength shifting fibers. To assess the calorimeters' performance, test different detector geometries, and fine-tune reconstruction algorithms such as topological clustering, we employ Monte Carlo simulations of single particles. Preliminary results from performance studies with the standalone hadronic calorimeter and combined calorimeters are presented, thus shedding light on the promising capabilities of this newly introduced detector concept for FCC-ee. In addition to these design-focused analyses, we briefly introduce our inquiries into the potential use of machine-learning approaches for particle identification and detector calibration.

1 Introduction

The Future Circular Collider (FCC) is an ambitious project of an accelerator complex in the CERN area for the post-LHC era [1]. An electron–positron collider, FCC-ee [2], is considered a possible first phase. This collider will enable precise measurements of the properties of the four heaviest particles of the Standard Model – the Higgs, Z, and W bosons, and the top quark – as well as those of b and c quarks and τ lepton. The unprecedented data statistics at FCC-ee impose strict requirements on the detector's systematic uncertainties, necessitating an excellent understanding of the detector and the event reconstruction.

Optimal event reconstruction, also known as particle-flow, is achieved when data from the tracking system is complemented by information from the calorimeters. In this context, precision measurements and searches for new particles benefit fully from improved electromagnetic and hadronic object reconstruction provided by new technologies. These include finer transverse and longitudinal segmentation, timing capabilities, multi-signal readout, and modern computing techniques and algorithms.

The requirements arise particularly from the need for high resolution in reconstructed hadronic masses, energies, and momenta (e.g., of H, W, Z bosons) to achieve the precision promised by FCC-ee. Excellent electromagnetic energy resolutions are also crucial for π^0 identification, τ lepton decay reconstruction, and enhancing physics sensitivity to processes accessible via radiative return.

In the following, we present ALLEGRO, one of the detector concepts under study for FCC-ee, focusing on its calorimeters. In the current design, ALLEGRO calorimeter systems include a noble liquid electromagnetic calorimeter and a scintillating tile hadronic calorimeter. Ongoing research and development (R&D) on noble liquid calorimeters aim for a granularity 10 to 15 times higher than the state-of-the-art implementation in the ATLAS Liquid Argon calorimeter [3]. Similarly, the hadronic calorimeter targets a granularity approximately 30 times higher than that of the ATLAS hadronic calorimeter [4].

2 FCC-ee ALLEGRO detector concept

A highly granular noble-liquid sampling electromagnetic calorimeter along with a scintillating tile hadronic calorimeter has been proposed for a possible FCC-hh experiment [5–7]. Recent studies have explored adapting these calorimeter types for use in the FCC-ee experiment [8]. The proposed detector concept, named ALLEGRO, includes a silicon vertex detector, a drift chamber for charged particles tracking, a silicon wrapper layer, electromagnetic calorimeter barrel and endcap, solenoid magnet, hadronic calorimeter barrel and endcap, and a muon tagger, as illustrated in Figure 1. The solenoid coil is located between the electromagnetic and hadronic calorimeter, and can be potentially housed within the same cryostat

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as the electromagnetic calorimeter. R&D on thin carbon-fibre cryostats, thin solenoid coils as well as R&D on high-density signal feedthroughs has been ongoing within the CERN EP R&D program [9] and the ECFA Calorimetry Detector R&D Collaboration (DRD6).

Figure 1. Sketch of ALLEGRO, a detector concept under study for FCC-ee.

2.1 Electromagnetic calorimeter

Noble-liquid calorimetry has proven highly effective in many high-energy experiments, such as ATLAS [3], due to its excellent energy resolution, linearity, stability, uniformity, and radiation hardness. While radiation hardness is less critical for lepton colliders, all other properties are essential for high-precision measurements, for example, at the Z-pole and for the planned Higgs measurement program.

Figure 2 illustrates a possible noble-liquid calorimeter for the central region. This configuration features a cylindrical stack of absorbers, readout electrodes, and active gaps, with an inner radius of the cryostat measuring 214.9 cm. Utilizing liquid argon (LAr) as the active material, the calorimeter consists of 1536 lead/steel absorbers with a total thickness of 2 mm (100 μm steel sheets glued to each side of the lead absorbers), 1.2 mm-thick readout electrodes, and have a total depth of 40 cm. This setup results in an effective thickness of approximately 22 radiation lengths (X_0) and a Molière radius of ≈ 4 cm. Alternatives such as tungsten absorbers or liquid krypton (LKr) could offer even smaller radiation lengths and Molière radii, potentially leading to better particle separation and improved particle-flow reconstruction due to the smaller shower sizes.

The calorimeter components are housed in a cryostat to maintain cryogenic working temperatures. The electrodes and the absorber plates, are arranged radially but inclined azimuthally by 50.2° relative to the radial direction, as shown in Figure 2. Electromagnetic shower signals are captured by electrodes positioned centrally within the noble liquid gap from which one creates readout cells with a segmentation of $\Delta\theta = 10$ mrad and $\Delta\phi = 8$ mrad, with eleven longitudinal compartments. This high longitudinal granularity is achieved by routing signals from both the inner and outer radii of the readout electrodes using traces embedded within a multi-layer Printed Circuit Board (PCB). Several PCB prototypes have been designed and tested to understand the capacitance (noise) and cross-talk of this concept.

Additionally, studies are underway to adapt noble-liquid calorimetry for the endcap region. Here, the inclined plates are reconfigured into 'blades' arranged in a turbine-like structure, as depicted in Figure 3. This arrangement allows for uniformity in ϕ, the possibility to read out all signals from the high-$|z|$ face of the calorimeter, and for the construction to be done using many copies of a few absorber and readout electrode types. One drawback is that the distance between the central planes of adjacent absorbers increases with radius. Two steps are taken to mitigate the resulting non-uniformity in radial response: the design is formed from three nested wheels, where the distance between planes is "reset" to the smallest values at the inner radius of each wheel, and the thickness of the absorber increases with r, such that the sampling fraction is kept approximately constant. While the parameters are still being optimized, in the current simulations the blades are tilted at 41° from the xy plane, the absorbers are 2.9 mm thick at the inner radius of each wheel, with the thickness then increasing linearly with radius. The wheels (from innermost to outermost) contain 144, 272, and 512 absorbers.

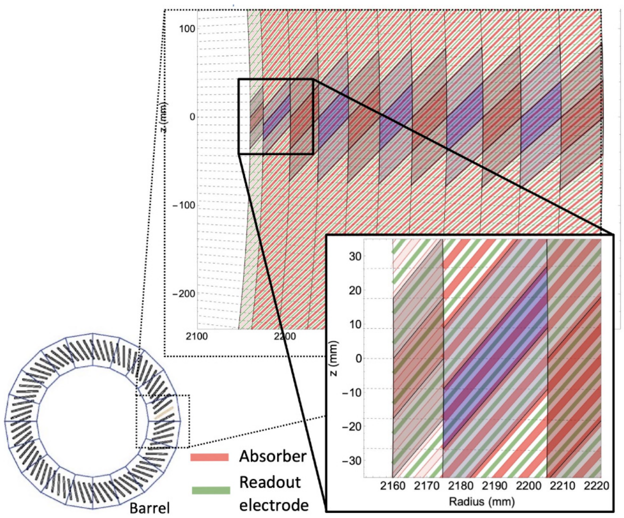

Figure 2. A noble-liquid sampling calorimeter used in the central region of the ALLEGRO detector concept.

2.2 Hadronic calorimeter

A hadronic Tile calorimeter is being studied as a potential hadronic calorimeter for the ALLEGRO detector concept, drawing design inspiration from the ATLAS Tile Calorimeter [4].

Table 1. Dimensions of Scintillating Tile Calorimeter central barrel and endcap calorimeters.

	inner radius [cm]	outer radius [cm]	Z min [cm]	Z max [cm]	# of radial layers
Barrel	280	450	0	280	13
Endcap	360	450	290	340	6
	290		340	390	9
	35		390	545	22

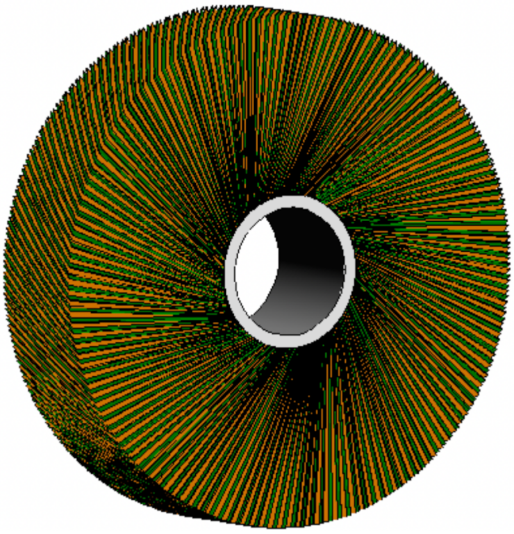

Figure 3. A noble-liquid sampling calorimeter used in the endcap region of the ALLEGRO detector concept, showing the full set of blades around the inner radius.

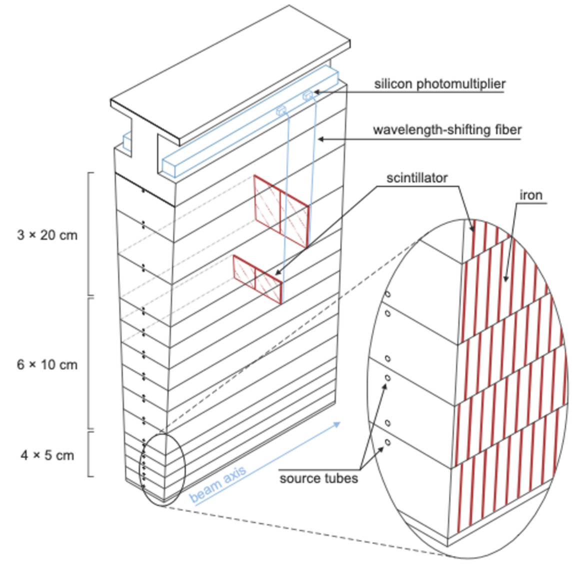

Figure 4. Schematic of one module of the hadronic barrel Tile calorimeter. The optical components (the two scintillating tiles per layer, wavelength-shifting fiber, and the SiPM) are shown.

The Tile calorimeter is a sampling calorimeter composed of stainless steel and scintillating plastic tiles that emit light when charged particles pass through them. The emitted light is captured by wavelength-shifting fibers and transported to silicon photomultipliers (SiPMs) located at the outer radius of the calorimeter, as shown in Figure 4. Contrary to the FCC-hh design [6], in the ALLEGRO detector concept, the hadronic calorimeter will serve as a return yoke for the central solenoidal field. This requires replacing the lead absorbers by stainless steel absorbers, resulting in a less compensated calorimeter and a larger constant term compared to the FCC-hh design.

The calorimeter is structured into two central barrels and two endcap sections. The scintillating tiles are oriented perpendicular to the beam line, and combined with the wavelength-shifting fiber readout, this setup ensures nearly complete azimuthal coverage for the calorimeter. Each section is mechanically divided into 128 modules in the azimuthal (ϕ) direction. Within each module, the scintillators in a given layer are split into two halves, separated by reflective material. Each half is independently read out by a wavelength-shifting fiber, with one fiber on each side connected to separate silicon photomultipliers (SiPMs). This design provides a segmentation of $\Delta\phi = 25$ mrad. The readout cells are defined by grouping 3-4 wavelength-shifting fibers to a single SiPM, resulting in a segmentation of $\Delta\theta = 22$ mrad. The number of longitudinal layers is uniform in the central barrel but varies along the z-coordinate in the endcap sections, as detailed in Table 1. The final detector granularity is subject to further optimization which will be done by using the particle-flow methods.

2.3 Performance

The performance of the electromagnetic and hadronic calorimeters in the central region was evaluated using single-particle simulations of electrons, photons, and charged pions (π^-). The energy resolution of single photons and electrons in the central electromagnetic calorimeter exhibits a stochastic term of 7-8%, which could be further improved by enhancing the sampling fraction or frequency. The energy resolution of single-π^- in the central hadronic calorimeter shows a stochastic term of approximately 40% and a constant term of 3.5%, without applying the magnetic field (B = 0T). The response linearity of the hadronic calorimeter, defined as the ratio of the reconstructed energy to the true energy, is within 1%. Note that electronic noise was not included in the simulation.

To study the energy resolution of single-π^- in the combined simulation of the electromagnetic and hadronic calorimeters in the central region, two calibration methods were employed: the benchmark method and the boosted decision tree (BDT) calibration. The benchmark method, originally developed for ATLAS test beam measurements, corrects for energy loss between the electromagnetic and hadronic calorimeter and calibrates the energy deposits to the hadronic scale. For the FCC-ee studies, an additional correction, based on Ref. [6], was applied to account for energy lost in the material in front of the electromagnetic calorimeter. The BDT calibration utilizes the total cluster energy and the energy deposited in each radial layer within the cluster as inputs. The regression target for the BDT is the true energy divided by the total cluster energy.

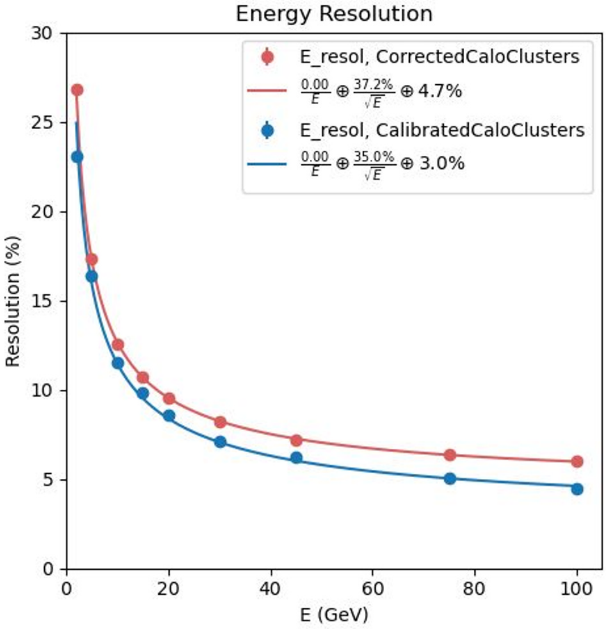

Figure 5. Energy resolution of the combined electromagnetic and hadronic calorimeter using a single-particle simulation of π^-. The benchmark method (red) and BDT calibration (blue) is applied on calorimeter clusters.

The benchmark parameters were derived from the cell energies of both the electromagnetic and hadronic calorimeter, and then used to calibrate the energy of calorimeter clusters. To obtain these parameters a sample set of 5000-10000 π^- events, with energies ranging from 2 GeV to 150 GeV, was used. Due to the energy dependence of hadronic shower shapes, significant variations in the parameters values were observed across the energy range. Consequently, energy-dependent parameters were calculated and applied in this study. Using the benchmark method, a single-π^- resolution achieves a stochastic term of ~37% and the constant term of 4.7% (B = 0T), as shown in Figure 5. The electronic noise was not included in the simulation.

Figure 5 demonstrates that using the BDT calibration, a single-π^- resolution can achieve a stochastic term of 35% and the constant term of 3% (B = 0T). The response linearity is within 2%. The electronic noise was not included in the simulation. It is important to note that this impressive result is based solely on calorimeters measurements. Integrating the planned particle-flow reconstruction with the tracker information will further enhance the hadronic resolution.

3 Conclusions

High granular calorimeters will be crucial for particle reconstruction, identification, and physics measurement in next-generation collider experiments. With its highly granular noble-liquid electromagnetic calorimeter and advanced scintillating tile hadronic calorimeter, ALLEGRO promises to meet the demanding requirements of FCC-ee physics. The preliminary performance studies highlight the potential of this detector concept to achieve high precision in particle measurements and enhance the search for new physics. Ongoing R&D efforts and performance optimizations will continue to refine the design and improve the detector's capabilities.

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