Design and performance studies of the calorimeter system for an FCC-hh experiment

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Abstract. The study of physics reach and feasibility of the Future Circular Collider is ongoing. The goal for the proton–proton collider (FCC-hh) is centre–of–mass collision energy of 100 TeV and integrated luminosity of 20 ab$^{-1}$, extending the research carried out at the current High Energy Physics facilities. Detectors for the FCC experiments need to be designed taking into account the difficult conditions, in particular the radiation load of the detector and the enormous number of the simultaneous collisions (in–time pile–up), expected to be reaching the level of $\langle \mu \rangle = 1000$. Additionally, the boost of the produced particles calls for a higher granularity of the detectors and higher energy of the produced particles requires thicker calorimeters to ensure shower containment. The baseline calorimetry system for an FCC experiment is presented. Liquid argon is used as an active material for the electromagnetic calorimetry, as well as for the hadronic calorimeters for $|\eta| > 1.6$. Plastic scintillator is used in the hadronic calorimeter in the central region. Presented single particle measurements meet the design energy resolution goal of $\frac{\sigma_E}{E} \leq \frac{10}{\sqrt{E(\text{GeV})}} \pm 0.7\%$ for photons and electrons and $\frac{\sigma_E}{E} \leq \frac{50}{\sqrt{E(\text{GeV})}} \pm 2.5\%$ for pions. An estimation of the effect of pile-up is presented, with the clear indication that pile–up mitigation is the main challenge of the FCC-hh collisions and is now the main focus of the detector design studies.

1. The Future Circular Collider
The Future Circular Collider (FCC) is a project that focuses on the next generation of accelerators. There are three collider configurations under consideration: hadron–hadron (FCC-hh), electron–positron (FCC-ee) and hadron–electron (FCC-eh). FCC-hh accelerator drives the design of the infrastructure (the tunnel), with FCC-ee as a first step, and FCC-eh to be placed once the proton accelerator is operating. The goal for the centre–of–mass collision energy of the proton–proton collider is 100 TeV, to be achieved in the tunnel of 97.75 km in circumference and with 16 T bending dipole magnets [1]. The outcome of the FCC study is currently being summarised in the Conceptual Design Report.

2. FCC-hh experiment
Extension of both, the energy regime to 100 TeV and the total integrated luminosity to 20 ab$^{-1}$ (over 25 year operation), leads to a natural gain in the discovery potential of the FCC-hh collider (compared to High Luminosity LHC with 14 TeV and 3 ab$^{-1}$ respectively [2]). The potential of the FCC-hh experiment and requirements on the detectors are described in detail in the same proceedings [3].
The baseline detector is presented in Fig. 1. The calorimetry is made of sampling calorimeters and is presented in dark blue (electromagnetic), light blue (hadronic using liquid argon as active material) and green (hadronic with scintillator as active material). The detector covers pseudorapidity range \(|\eta| < 6\), and especially at the forward region the radiation hardness of the detectors is vital. Table 1 summarises the 1 MeV neutron equivalent fluence and the radiation dose for integrated luminosity of 30 ab\(^{-1}\). The dose of 8 kGy for the hadronic barrel is below the safety limit for the scintillator tiles, but in the endcaps and in the forward region the hadronic calorimeter calls for a more radiation hard material, such as liquid argon.

The reference calorimetry for FCC-hh experiments is based on ATLAS calorimeters [4, 5]. It ensures a good intrinsic energy resolution over wide energy range, high stability and uniformity of response, constantly validated in a large scale HEP experiment at the LHC. However, due to the higher collision energy at FCC, in order to maintain the sensitivity to the boosted objects, reject \(\pi^0\)'s, provide excellent pointing capabilities, a larger transverse granularity is required. Furthermore, in order to facilitate reconstruction using e.g. particle flow techniques, and in order to mitigate the pile–up, also the longitudinal segmentation needs to be increased. The thicknesses of the detectors is larger than those of the calorimeters at the LHC experiments to contain high–energy objects, thus reducing the shower leakage and limiting the punch–through
to the muon chambers. The material budget of the FCC-hh detector is presented in Fig. 2. Thickness of the electromagnetic calorimeters (including the tracker) is no smaller than 29.5 $X_0$ and including the hadronic calorimeter it is at least $11 \lambda$.

![Figure 2: Material budget of the detector expressed in units of (a) radiation length and (b) nuclear interaction length. The amount of the material is measured from the centre of the detector to the outer boundary of the calorimetry. The spike at $|\eta| < 2.5$ corresponds to the inner wall of the cryostat of the endcaps.](image)

3. Liquid argon calorimeter

Liquid argon (LAr) is used as an active material in the electromagnetic calorimetry and in the hadronic calorimeters in endcaps and in forward region, following the ATLAS LAr calorimetry [4]. Due to a higher longitudinal segmentation required, the electromagnetic barrel cannot use the accordion structure, and in place of the bent electrodes, straight multi-layer printed circuit boards (PCB) are employed. Figure 3 presents a schematic view of the layout of the electromagnetic barrel. Absorber and readout plates are inclined by $50^\circ$ from the radial direction in order to ensure high sampling of all particles (neutral and charged). The absorbers are 2 mm thick lead plates covered with steel, except for the first layer (the presampler), where lead is not used in order to enlarge the sampling fraction and to reduce the signal dependence on the azimuthal angle. Information from this layer is used to correct for the energy deposited in front of the calorimeter (in particular in the cryostat). The presampler is also thinner than the rest layer by a factor of 4.5. The PCB electrode is 1.2 mm thick and ensures the readout from 8 longitudinal layers and with pseudorapidity granularity of $\Delta \eta = 0.01$ ($0.0025$ in the second layer). The granularity in azimuthal angle is determined by the width of two modules (two readout plates) and is equal to $\Delta \phi = 0.009$. A study is carried out in order to determine if such transverse and longitudinal granularity is sufficient in terms of pointing capabilities and $\pi^0$ rejection. Due to the constant thickness of the absorber, the liquid argon gap is increasing from 1.15 mm at the inner detector radius to 3.09 mm at the outer radius. Such intrinsic change of the sampling fraction must be corrected for with a proper calibration with different values of a sampling fraction for each detector layer.
Figure 3: Schematic view of transverse cross-section of the electromagnetic barrel.

Table 2: Summary of the dimensions of the material used in LAr calorimeters. LAr thickness is given in between the absorber and electrode.

| Unit | absorber material | thickness (mm) | sampling fraction |
|------|------------------|----------------|------------------|
|      | absorber | LAr | PCB |                      |
| B. ECAL | lead | 2 | 1.15–3.09 | 1.2 | 0.13 – 0.3 |
| E. ECAL | lead | 1.5 | 0.5 | 1.2 | 0.07 |
| F. ECAL | copper | 10 | 0.1 | 1.2 | 0.003 |
| E. HCAL | copper | 20 | 2 | 1.2 | 0.03 |
| F. HCAL | copper | 40 | 0.1 | 1.2 | 0.0008 |

The endcaps and the forward calorimeters consist of parallel absorber and PCB discs. Both electromagnetic and hadronic parts are immersed in the same cryostat. Thickness of the absorber and liquid argon gaps, together with the sampling fraction are summarised in Tab. 2.

Energy resolution for electrons and photons in different electromagnetic calorimeters is presented in Fig. 4. In the barrel ($\eta = 0$) energy resolution is equal to $\frac{\sigma_E}{\langle E \rangle} = \frac{8.1\%}{\sqrt{E(\text{GeV})}} \oplus 0.15\%$, well below the requirement of $\frac{\sigma_E}{\langle E \rangle} \leq \frac{10\%}{\sqrt{E(\text{GeV})}} \oplus 0.7\%$. In the endcaps ($|\eta| = 2$) it is very similar ($\frac{\sigma_E}{\langle E \rangle} = \frac{7.6\%}{\sqrt{E(\text{GeV})}} \oplus 0\%$), with a negligible constant term due to the idealistic constant ratio of active and passive material. In the forward detector ($|\eta| = 4.5$), where liquid argon gap is decreased in order to avoid ion build-up in high particle densities, the sampling fraction is very small and therefore energy resolution deteriorates to $\frac{\sigma_E}{\langle E \rangle} = \frac{23\%}{\sqrt{E(\text{GeV})}} \oplus 0\%$.

An estimation of the electronics noise has been performed assuming a readout similar...
Figure 4: Energy resolution for electrons simulated in electromagnetic barrel ($\eta = 0$, blue circles), endcaps ($|\eta| = 2$, red squares) and forward detector ($|\eta| = 4.5$, green diamonds). Electrons are reconstructed with sliding window algorithm with window of size $\Delta \eta \Delta \phi = 0.07 \times 0.17$. No noise is included.

The energy resolution for electrons and photons obtained for three pile–up scenarios $\langle \mu \rangle = 0, 200, \text{and } 1000$ is presented in Fig. 5a. Without the presence of in–time pile–up only electronics noise contribute to the noise term of energy resolution. The effect of pile–up is significant and the noise term increases from $0.3 \text{ GeV}$ to $2.0 \text{ GeV}$ for $\langle \mu \rangle = 200$ and to $4.4 \text{ GeV}$ for $\langle \mu \rangle = 1000$. It has clearly a large impact on the width of the invariant mass of $H \rightarrow \gamma \gamma$ as can be seen in Fig. 5b. Introduction of pile–up mitigation techniques is necessary, first of all by decreasing the size of the reconstruction window, using a dynamical reconstruction instead of a fixed window, and ultimately using the position and time information from the tracking detector.

4. Tile calorimeter

Design of the hadronic calorimeter in the central region is based on the ATLAS Tile calorimeter [5]. It uses scintillating tiles and steel absorber. For the FCC-hh experiments, steel is partially replaced with lead in order to bring the calorimeter closer to compensation. Furthermore, instead of using the photo-multiplier tubes, silicon photo-multipliers can be used, and thanks to their much smaller dimensions, an increase of the longitudinal readout segmentation can be achieved. Figure 6 shows a schema of the Tile calorimeter for the FCC-hh experiment. There are 10 longitudinal layers, 256 tiles in the azimuthal angle (giving $\Delta \phi = 0.025$), each 3 mm thick, with 5 mm thick steel and 4 mm lead absorbers. Readout segmentation in pseudorapidity is $\Delta \eta = 0.025$. Light is transported with wave–length shifting fibres to the silicon photo-multipliers that are placed at the back of the detector. On both sides of the central hadronic barrel there are two so-called extended barrels, in order to ensure the minimum depth of $11 \lambda$ for full pseudorapidity coverage. The dimensions of tiles are the same as for the central barrel, with the exception of the longitudinal segmentation, as two last layers are removed in order to ensure sufficient space for the necessary services.
Energy resolution for single pions matches the design goal of $\frac{\sigma_E}{E} \leq \frac{50\%}{\sqrt{E\text{[GeV]}}} \oplus 2.5\%$. For QCD jets, the simulation has been performed without the magnetic field, as it has a large impact on the low-momentum jet component. A study together with the tracking detector is necessary to correctly assess the jet reconstruction capabilities in the presence of the magnetic field.

Pile–up is estimated from minimum bias simulation, however due to the changing number of cells building the cluster, it is in the first approach estimated for each cell, not taking into account the correlations between adjacent cells. Thus, the effect of pile–up is largely underestimated. A study of the reconstruction with both signal and pile–up events, instead of the estimation of the noise, is on-going.

Pile–up noise affects only the sampling term of the energy resolution, as the larger the number of simultaneous collisions, the smaller the cluster size, as can be seen in the decrease of the response (top plot in Fig. 7). Pile–up mitigation techniques need to be applied in order to improve the measurements in the low-momentum regime. In particular, information from the tracking detector should be taken into account (including the time measurements).

5. Summary and outlook
A baseline design for the FCC-hh calorimetry is presented. Preliminary results for simulation of single particles reveal an excellent energy resolution. Pile–up mitigation in the electromagnetic calorimeter is clearly the biggest challenge, and is a focus of current studies. Both reconstruction procedures in the calorimeters and combination with tracking detectors is necessary in order to mitigate the effect of the in–time pile–up. Tracking detector is moreover essential in the low-momentum jet measurements, in order to maintain momentum resolution achieved in simulation without the magnetic field.

References
[1] FCC-hh design study, https://fcc.web.cern.ch/Pages/fcc-hh.aspx
Figure 6: Schematic view of the module of hadronic barrel.

Figure 7: Transverse momentum resolution (bottom) and ratio of reconstructed to generated momentum (top) for QCD jets in central region ($|\eta| < 1.3$) simulated in electromagnetic and hadronic calorimeters (without presence of the magnetic field) and reconstructed with topological clusters. For this study each tile has been read-out separately. Three pile–up scenarios are presented: $\mu = 0$ (green circles), 100 (orange squares), and 1000 (red triangles).

[2] G. Apollinari et al., *High-Luminosity Large Hadron Collider (HL-LHC): Preliminary Design Report*, CERN Yellow Report (2015)

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[4] ATLAS Collaboration, *ATLAS liquid-argon calorimeter*, Technical Design Report (1996)

[5] ATLAS Collaboration, *ATLAS tile calorimeter*, Technical Design Report (1996)