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

Jana Faltova[a,*], **on behalf of the FCC-hh detector working group**

[a] *Charles University,*
Faculty of Mathematics and Physics, V Holesovickach 8, 18000 Prague, Czech Republic

E-mail: jana.faltova@cern.ch

The physics reach and feasibility of the Future Circular Collider (FCC) with centre of mass energies up to 100 TeV and unprecedented luminosity has delivered a Conceptual Design Report early 2019. The new energy regime opens the opportunity for the discovery of physics beyond the standard model. Proton-proton collisions at 100 TeV will produce very high energetic particle showers in the calorimeters from both light jets and boosted bosons/top quarks. The reconstruction of such objects sets the calorimeter performance requirements in terms of shower containment, energy resolution and granularity. Furthermore, high-precision measurements of photons and electrons over a wide energy range are crucial to fully exploit the physics potential of the hadron collider, especially given the large amount of collisions per bunch crossing the detectors will have to face (pile-up of $\langle\mu\rangle = 1000$). The reference technologies for the high-granularity calorimeter system of the FCC-hh detector are presented: liquid argon (LAr) as the active material in the electromagnetic calorimeters, and the hadronic calorimeters for $|\eta| > 1.3$ (endcap and forward region), and a scintillator-steel (tile) calorimeter as hadronic calorimeter in the barrel region. The simulation framework and the reconstruction chain, that includes the calibration and clustering of calorimeter cells and the estimation of pile-up induced, and electronics noise are introduced. The performance studies for single particles and jets in the combined calorimeter system are presented. In conclusion, the achieved performances will be compared to the physics benchmarks of the FCC-hh experiment.

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1. Future Circular Collider project

The Future Circular Collider (FCC) is an ambitious project of the collider complex for a post-LHC era with CERN as a host laboratory. The tunnel length and infrastructure are defined by a requirement for a circular hadron collider FCC-hh with centre of mass energy of 100 TeV using 16 T bending magnets. Whereas, the electron-positron collider FCC-ee is foreseen as a first step of the FCC project to be built in the nearly 100 km long tunnel. Main goals of the FCC-ee physics programme are precise measurements of the electroweak sector. As a next step, the FCC-hh is designed to allow a direct search for massive particles up to 40 TeV. In addition, precise measurements of the standard model parameters will be also performed. The integrated programme of the FCC-ee and FCC-hh colliders will lead to very precise measurements, e.g. Yukawa Higgs boson couplings are expected to be measured with an uncertainty better than 1% and the Higgs boson triple gauge coupling better than 10% [1].

The FCC-hh collider will run at very high luminosity with a peak of $3 \times 10^{35}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, resulting in the integrated luminosity of O(20) ab^{-1} per experiment. Such high luminosity results in requirements on the radiation hardness of the materials used in the FCC-hh detector, especially in the forward region close to the beam pipe. Assuming 25 ns bunch spacing, the average number of pile-up collisions as high as 1000 is expected in the ultimate scenario. The proposed detector has to be able to deal with the conditions of the FCC-hh experiment. The calorimeters designed for the FCC-hh experiment and their performance are discussed in this paper.

2. Geometry of the detector for FCC-hh

Concerning the wide range of physics programme at FCC-hh [1], the detector for the FCC-hh experiment has to be able to detect, measure and identify particles with transverse momenta from 20 GeV up to 20 TeV. Another important aspect for the detector design comes from the fact that the particles produced in 100 TeV collisions will be highly boosted and many objects will appear in the forward region. Therefore, precise measurements of the FCC-hh detector up to $|\eta| = 4$ are neccessary together with measurements of e.g. tagging jets up to $|\eta| < 6$.

The proposed FCC-hh detector is shown in Figure 1. The reference detector concept represents a concrete example that fulfils the performance and physics requirements. Moreover, different options were also studied [2]. Only the reference detector is discussed in this paper.

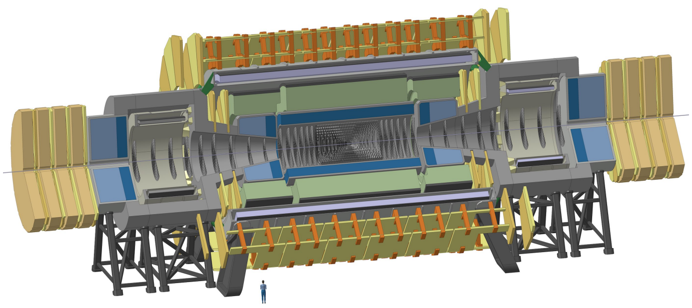

Figure 1: The proposed layout of the FCC-hh reference detector. [2]

First, the central part of the detector ($|z| \leq 10$ m) is designed as follow: A silicon tracker composed by layers of pixels, macro-pixels and strip modules/sensors covers the radius of 2.5 cm-160 cm from the interaction point. The next component is the electromagnetic calorimeter (ECAL) using liquid argon (LAr) technology with lead absorbers up to $|\eta| < 2.5$. Following hadronic calorimeter (HCAL) is composed of scintillating tiles and stainless steel/lead in the central region ($|\eta| < 1.8$) and of LAr technology with copper absorbers in the endcaps ($1.6 < |\eta| < 2.5$). The tracker and the calorimeters are placed inside a solenoid coil with a magnetic field of 4 T. The most outer region is built by gas muon chambers. Second, the forward region of the detector is composed by the tracker ($|z| > 10$ m) placed inside smaller solenoids providing the magnetic field of 4 T. The forward calorimeter system based on LAr technology is placed outside the solenoid at $|z| > 16.5$ m, followed by the muon chambers. The overall length of the FCC-hh detector is approximately 50 m with a radius of 10 m, which is comparable with the dimensions of the LHC experiments.

3. Calorimetry system for FCC-hh

Two different technologies for active medium, the noble liquid and scintillating tiles, are considered for the calorimetry system in the FCC-hh reference detector. The thickness of the electromagnetic calorimeter is around 30 radiation lengths (X_0) and provides together with the hadronic calorimeter an overall thickness of more than 10.5 nuclear interaction lengths (λ). This ensures 98% containment of high energy hadron showers [3].

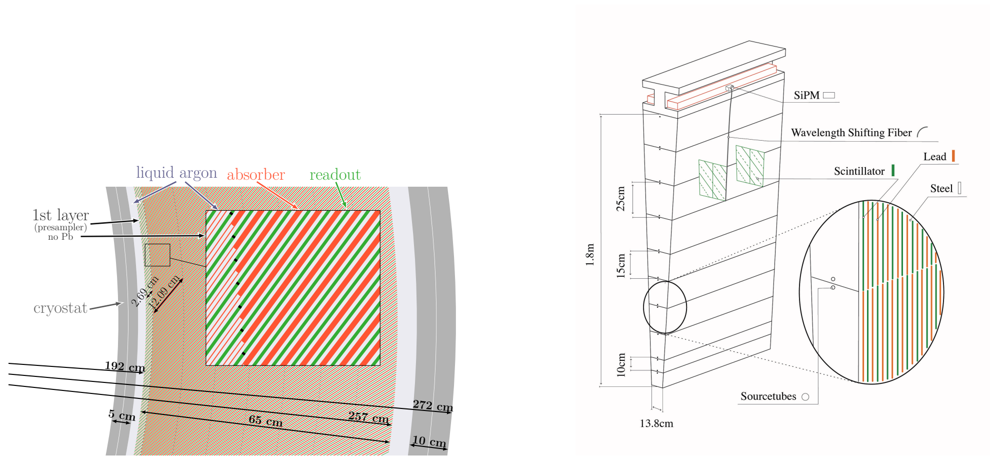

Figure 2: (a) The cross section of the electromagnetic barrel calorimeter. (b) Schematic view of one module of the hadronic barrel calorimeter. The optical components (scintillating tiles, wavelength shifting fibers and the SiPMs) are shown. [5]

The liquid argon (LAr) is chosen for the ECAL and also for the HCAL in the endcaps and forward region following the example of the ATLAS LAr calorimeter [4]. The main reasons for this choise are its intrinsic radiation hardness, as well as stability and uniformity of the response. The ECAL barrel forms a cylinder with a radius from 192 cm to 257 cm. The amount of material in front of the ECAL barrel is around 1.5 X_0 at $\eta = 0$ including the aluminium cryostat wall. The low material budget in front of the calorimeter is crucial especially for measurements of low energetic particles [5]. The layout with straight lead planes (thickness of 2 mm) inclined in the radial direction are considered in the barrel region as shown in the Figure 2 left. The readout of the detector is designed with multilayer Printed Circular Boards (thickness of 1.2 mm). The high granularity can be achieved with such design. Eight longitudinal layers and the cell sizes of $\Delta\eta \times \Delta\phi = 0.01 \times 0.009$ in the 'normal' layers and $\Delta\eta \times \Delta\phi = 0.0025 \times 0.018$ in the 'strip' layer are considered. The 'strip' layer is designed to enable efficient identification of π^0. The expected number of channels is about 2.5 millions.

The scintillating tile calorimeter is considered for the central ($|\eta| < 1.8$) hadronic calorimeter. The design is motivated by a very good performance of the ATLAS Tile Calorimeter [6], but with a finer granularity of $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$ and 10 longitudinal layers of the size from 10 cm to 25 cm. The calorimeter is a sampling calorimeter using stainless steel, lead and scintillating plastic tiles with a ratio between volumes of 3.3 : 1.3 : 1. The orientation of the scintillating tiles is perpendicular to the beam line in this design. The scintillation light will be transferred from the scintillating tiles through the wavelength shifting fibres to pixelised silicon photomultipliers (SiPM). The HCAL barrel consists of 128 modules. A schematic view of one of the modules together with the optical components is shown in Figure 2 right. The proposed granularity of $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$ leads to a total of 300000 readout channels. The segmentation in $\Delta\phi$ is fixed by the geometry, but the segmentation in $\Delta\eta$ can be increased if each tile is read separately.

As the radiation levels increase with pseudorapidity, liquid argon technology is used for both electromagnetic and hadronic calorimeter in the endcaps and forward calorimeter. The calorimeters are formed by lead/steel or copper plates (thickness of 2 mm) perpendicular to the beam axis with the gaps filled with LAr. Results of the first performance studies in the endcap and forward calorimeters can be found in [5].

4. Performance of the calorimetry

The geometry of the detector described in Section 2 is implemeneted in the FCC software framework (FCCSW) [7]. So-called full simulations are used to study the performance of the calorimeter system. Single particles have been simulated with realistic operational conditions, e.g. magnetic field in the inner tracker. The expected electronics noise per cell was estimated and was added to the simulated energy deposits cell by cell. The effect of the in-time pile-up was derived from dedicated minimum bias data. The contribution of the pile-up was added to the cell energy as another noise term. The correlations between neighbouring cells were neglected. The out-of-time pile-up was not considered. The experience from the LHC experiments shows that this contribution can be efficiently corrected for.

Two reconstruction algorithms were developed and used for the performance studies. The sliding window algorithm is used for the measurements of electrons and photons, while topological clustering for single hadrons and jets. Details about the clustering algorithms can be found in [5].

4.1 Electrons and photons

Electrons and photons start showering in the material before the calorimeter, in the tracker or in the cryostat. Not only because of that, two corrections are applied on the simulated energy deposits. First, a layer dependent sampling fraction to correct for the increasing LAr gap with the calorimeter depth is applied. Second, a correction for the losses in the dead material in front of the calorimeter is considered. This correction depends on the energy deposited in the pre-sampler (first layer of the ECAL).

The energy resolution for single electrons in different pile-up scenarios is shown in Figure 3 left. The stochastic term increases from 8.2% (no pile-up) to 10% (average number of pile-up collisions $\langle \mu \rangle = 1000$). The required energy resolution is fulfiled even for the ultimate pile-up scenario. The high number of simultaneous minimum bias collisions degrades the noise term to 1.31 GeV for the highest expected pile-up. The ECAL energy resolution is crucial for the reconstruction of the $H \to \gamma\gamma$ decay. The width of the Higgs boson invariant mass distribution is expected to be 1.3% in the case with no pile-up and 2.3% for $\langle \mu \rangle = 1000$ [5].

The improvement of the performance in the presence of high pile-up is crucial. The development of advanced reconstruction techniques is neccessary for pile-up mitigation. The key aspect is the fine segmentation of the calorimeter which will allow precise combination of the measurements in the tracker and in the calorimeter.

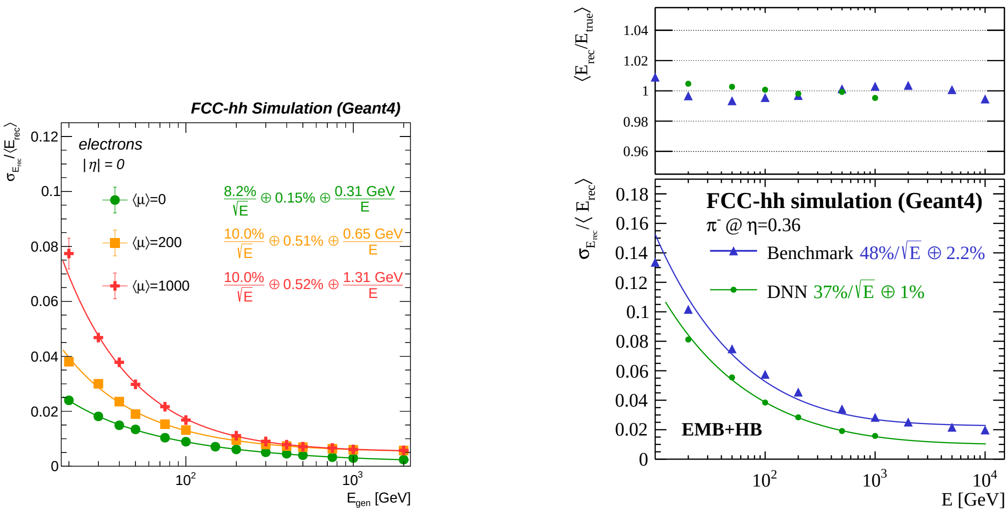

Figure 3: (a) Energy resolution for electrons at $\eta = 0$ in difference pile-up scenarios. (b) Energy resolution for pions using standard energy calibration method ('benchmark') and deep neural network ('DNN'). [5]

4.2 Single hadrons

The proton-proton collisions with the centre of mass energy of 100 TeV will produce jets with transverse momenta up to 40 TeV. The FCC-hh detector has to be able to reconstruct low energetic jets as well as jets of tens TeV. The reconstruction of single hadrons is a first step before the reconstruction of jets. Beams of single charged pions π^- entering the reference detector were used for the energy resolution curves as shown in Figure 3 right. Two different reconstruction techniques are compared. The first one, so-called benchmark method [5], adds energy deposits in ECAL and HCAL cells considering different e/h ratio in these two systems. Moreover, a correction for the energy loss in the dead material betweeen the ECAL and HCAL is applied. Using this simple method, a stochastic term of 48% for single pions is achieved. The second one, advanced reconstruction technique, makes use of the high granularity of the calorimeter system.

This technique employs deep neural network and shows stochastic term of 37% can be achieved using calorimeter information only.

5. Conclusions

The calorimeter system of the FCC-hh reference detector has been proposed and implemented in the FCC software framework. The performance studies using simulations of the single particles proved that such a calorimeter is suitable for the FCC-hh experiment and fulfils the requirements. Further R&D has just started in order to proceed to a technical design of these calorimeters. Studies of the possible usage of the noble liquid electromagnetic calorimeter for the electron-positron collider experiment (e.g. FCC-ee) has proceeded as well.

Acknowledgement

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