FCChh Hadronic Calorimeter and performance

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Coralie Neubüser, Michele Selvaggi, Anna Zaborowska

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12.04.18
1. Discussion of design baseline choices
2. Performance (pions, jets)
Challenges for Hadronic Calorimetry at FCC-hh

1. High radiation levels
2. Containment of multi-TeV hadron showers
3. Large number of pile-up

$\rightarrow \eta$ dependent requirements
$\rightarrow$ meet performance goals

<table>
<thead>
<tr>
<th></th>
<th>1 MeV neq $[\text{cm}^{-2}]$</th>
<th>dose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barrel</td>
<td>$\leq 3 \times 10^{14}$</td>
<td>$\leq 6 \text{ kGy}$</td>
</tr>
<tr>
<td>Endcap</td>
<td>$\leq 2 \times 10^{16}$</td>
<td>$\leq 1 \text{ MGY}$</td>
</tr>
<tr>
<td>Forward</td>
<td>$\leq 5 \times 10^{18}$</td>
<td>$\leq 5 \text{ GGY}$</td>
</tr>
</tbody>
</table>
FCC-hh detector

total length $\sim 47$ m, height $\sim 18$ m

<table>
<thead>
<tr>
<th>HCAL Barrel / Ext. Barrel</th>
<th>HCAL Endcap</th>
<th>HCAL Forward</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>\eta</td>
<td>&lt; 1.5$</td>
</tr>
<tr>
<td>Sci-Pb-Steel (1:1.3:3.3)</td>
<td>LAr-Cu (1:5)</td>
<td>LAr-Cu (1:200)</td>
</tr>
<tr>
<td>$\Delta \eta &lt; 0.025, \Delta \phi = 0.025$</td>
<td>$\Delta \eta = 0.025, \Delta \phi = 0.025$</td>
<td>$\Delta \eta = 0.05, \Delta \phi = 0.05$</td>
</tr>
<tr>
<td>10/8 layers</td>
<td>82 (21 eff.) layers</td>
<td>52 layers</td>
</tr>
<tr>
<td>$\sigma_E/E \sim 50%/\sqrt{E} \oplus 3%$</td>
<td>$\sigma_E/E \sim 50%/\sqrt{E} \oplus 3%$</td>
<td>$\sigma_E/E \sim 100%/\sqrt{E} \oplus 5%$</td>
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</tbody>
</table>

Forward Calo up to $\eta=6$
Radiation levels

Barrel
ATLAS like Sci tile Calorimeter

- readout at outer radius ($\sim 10^{11} \text{ neq cm}^{-2}$)
  $\rightarrow$ replace photomultiplier tubes by SiPMs
  $\rightarrow$ single channel readout, timing

- current ongoing R&D on scintillator material and SiPM technology fulfil requirements (6 kGy)

$\rightarrow$ mechanical structure feasible, assembly study done at JINR (N. Topiline)
$\rightarrow$ first test of Sci tiles in FCC size started at LIPP institute, Lisbon (R. Goncalo)
Optimisations of Barrel Tile HCal

- included Pb absorbers
  → Scintillator/Pb/Steel (1:1.3:3.3)
- decreasing non-compensation by suppression of EM response
  Pb: $X_0 = 0.6$ cm, $\lambda_n = 17.6$ cm
  (Fe: $X_0 = 1.8$ cm, $\lambda_n = 16.8$ cm)
- reduces total depth $[\lambda_n]$ from 8.9 (full Steel) to 8.5

\[
\begin{align*}
\text{Sci:Steel (1:4.7)} & & \text{stochastic term} & & 42.2\% \text{GeV}^{1/2} \\
\text{Sci:Pb:Steel (1:1.3:3.3)} & & \text{constant term} & & 3.3\% \\
& & e/h & & 1.23
\end{align*}
\]
Containment and calorimeter depth

- multi TeV hadron showers penetrate up to $12\lambda_n$
- avoid leakage to preserve small constant term

$$\frac{\sigma_E}{E} = \frac{\alpha}{E} + c$$  \hfill (1)

<table>
<thead>
<tr>
<th>depth [$\lambda_n$]</th>
<th>stoch. term [% GeV$^{-1/2}$]</th>
<th>const. term [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>41</td>
<td>5</td>
</tr>
<tr>
<td>9</td>
<td>43</td>
<td>4</td>
</tr>
<tr>
<td>10</td>
<td>43</td>
<td>3.1</td>
</tr>
<tr>
<td>11</td>
<td>43</td>
<td>2.7</td>
</tr>
<tr>
<td>12</td>
<td>43</td>
<td>2.4</td>
</tr>
</tbody>
</table>
Containment and calorimeter depth

**Barrel** $|\eta| < 1.5$: 1.8 m thick HCal ($\eta = 0$) → 8.5 $\lambda$ HCal only
→ 10.5 $\lambda$ incl. ECal → 12 $\lambda$ (incl. supports) punch throughs seen in muon chambers

**Endcap & Forward** $|\eta| = 1.4 - 6.0$: cover min. 12 $\lambda$
High pile-up environment

- High transverse and longitudinal granularity
  Barrel max. granularity:
  → 10 longitudinal layers (0.5 to 1.25) \( \lambda_n \)
  → \( \Delta \eta \leq 0.006, \Delta \phi = 0.025 \)
  → 1,305,600 channels

- timing
  → Sci + SiPMs already possible \( \sim 30 \text{ ps} \)
    (CMS timing layer)

500 GeV \( \pi^- \), \( \eta = 0.36 \)
Combined calorimeter performance
Single $\pi^-$ reconstruction

Reconstruction methods:

1. cell level:
   \[ E_{\text{rec}} = E_{\text{em}} + E_{\text{had}}^{\pi} \]

2. benchmark:
   \[ E_{\text{rec}} = E_{\text{em}} \cdot a + E_{\text{had}}^{\pi} + b \cdot \sqrt{|E_{\text{em}, \text{lastL}} \cdot a \cdot E_{\text{had}, \text{firstL}}|} + c \cdot (E_{\text{em}} \cdot a)^2 \]

3. topo-cluster: clustered Calo cells
   - benchmark reconstruction recovers the lost energy up to 5%
   - expected decrease in response after topo-clustering \( \leftarrow \) thresholds
   - next step include benchmark on cluster level

### Performance Results

<table>
<thead>
<tr>
<th></th>
<th>HCal only</th>
<th>ECal + HCal benchmark</th>
<th>ECal + HCal topo-cluster</th>
</tr>
</thead>
<tbody>
<tr>
<td>stochastic term</td>
<td>38.8%</td>
<td>45.9%</td>
<td>51.0%</td>
</tr>
<tr>
<td>constant term</td>
<td>2.5%</td>
<td>2.5%</td>
<td>2.5%</td>
</tr>
</tbody>
</table>
Jet reconstruction

Simulations: 100 TeV pp collisions, $p_t$ range of di-jets from 20 GeV to 10 TeV

Reco with FastJet:
anti-$k_t$ jet algorithm based on $d_{i,j} = \min\left(\frac{1}{p_{ti}^2}, \frac{1}{p_{tj}^2}\right) \frac{\Delta R_{ij}^2}{R^2}$
with $\Delta R_{ij}^2 = (\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2$, $\Delta R < 0.4$
matching of reco and gen jets within $\Delta R < 0.3$

1. cell level
2. topo-cluster
   - seed thr. ECAL: 7.5 MeV
   - seed thr. HCAL: 11.5 MeV
   - every neighbour is collected
3. topo-cluster w/ noise
   - seed thr. 4$\sigma$ of cell noise level
   - neighbour thr: 2$\sigma$ of cell noise level
   - in last step all neighbours are collected
Jet energy resolution

- in case of $B=0\,\text{T}$, constant term smaller than 3%
- validated the topo-clustering
Jet angular resolutions

- $\eta$ resolution reaches the average HCal granularity of 0.005
- $\phi$ resolution better than max HCal granularity of 25 mrad
Jet energy resolution
in $\langle \mu \rangle = 100$ – PRELIMINARY

- topo-cluster algorithm successfully reduces the impact of electr. noise to minimum
- first look at impact of pile-up shows need for strategy for PU rejection (e.g. optimise topo-cluster threshold)
Jet energy resolution in $\langle \mu \rangle = 100$ – PRELIMINARY

- no pile-up rejection technique applied, except for topo-cluster threshold
- compared to ATLAS simulations, that include additional pile-up rejection
Jet energy resolution in $B=4T$ – PRELIMINARY

- Large effect of B field, loose large fraction of the jets' energy for $p_T < 500 \text{ GeV}$ (low energetic charged particles do not reach calorimeters)
- Need tracker $\rightarrow$ PFA
Summary & Outlook

▶ full simulation and reconstruction chain in FCCSW established for single hadrons and jets
▶ the hadronic and EM calorimeter of the Barrel region shows promising energy resolutions:

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<thead>
<tr>
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<th>constant term</th>
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<tbody>
<tr>
<td>single particle</td>
<td>51.0%</td>
<td>2.5%</td>
</tr>
<tr>
<td>jets</td>
<td>58.0%</td>
<td>2.6%</td>
</tr>
</tbody>
</table>

→ numerous additions possible (cluster calibration incl. benchmark correction, particle flow, timing)

Next steps towards CDR:
▶ estimations of ultimate pileup scenario
▶ performances of Endcap/Forward
Material budget

FCC-hh simulation
Tile HCAL, outer support
Tile HCAL (EB+50cm in z)
Tile HCAL
LAr HCAL
LAr ECAL
tracker + beampipe

04.04.2018
Coralie Neubüser: FCChh HCal and combined performance
Pileup noise per cell no B field

ECal

HCal

ECal

HCal
Pileup noise per cell in 4T field

**ECal**

- Layer 1
- Layer 2
- Layer 3
- Layer 4
- Layer 5
- Layer 7
- Layer 8

**HCal**

- Layer 1
- Layer 2
- Layer 3
- Layer 4
- Layer 5
- Layer 7
- Layer 8
Energy distributions of clusters, cells in layer 2:

- \( \sum E_{\text{cell}} \)
- \( \sqrt{\sum E_{\text{cell}}^2} \)
- RMS of \( E_{\text{cluster}} \)

Cluster size: \( \Delta \eta \times 7, \Delta \phi \times 17 \), at \( |\eta| < 0.1 \)
$\eta = 0.36$

with depth of cell $d_{\text{particle}}$, along shower axis, within active Calorimeter

$\lambda_{\text{ECAL}} (\eta = 0) = 0.3, \lambda_{\text{HCAL}} (\eta = 0) = 2.2$

$\lambda_{\text{ECAL}} = 29.4 \text{ cm}, \lambda_{\text{HCAL}} = 20.1 \text{ cm}$
Shower images 100 GeV $\pi^-$ at $\eta = 3$. 

Coralie Neubüser: FCChh HCal and combined performance
Benchmark reconstruction

correction for lost energy between E and HCAI (in cryostat)

\[ E_{benchmark} = E_{em} \cdot a + E_{had}^\pi + b \cdot \sqrt{|E_{em, lastL} \cdot a \cdot E_{had, firstL}|} + c \cdot (E_{em} \cdot a)^2 \]  \hspace{1cm} (4)

- optimised with (10 & 100) GeV, (1 & 10) TeV à 400 events
- \( a = 0.978 \), \( b = 0.479 \), \( c = -5.4 \times 10^{-6} \) GeV\(^{-1} \)
Algorithm to cluster Calorimeter cells

Logic algorithm:

1. Finding seed cells above **1st threshold** of noise level in cell
2. seeds are sorted by energy
3. building clusters
4. find neighbours of the seed, include to cluster if above **2nd threshold**
5. the found neighbours become new seeds

repetition of 4 and 5, until no more neighbours found

6. add all neighbours for last seed (**3rd threshold**=0)
Topo-clusters – 500GeV $\pi^-$, w/B field, w/o noise

$z$ axis

cell types:
1 = seed cell
2 = neighbour
Topo-clusters – 500GeV $\pi^-$, w/B field, w/o noise

HCal granularity not 0.01 in $\eta$, decreasing with increasing $\eta$ z axis
c cluster ID