Noble Liquid Calorimetry for FCC-ee

Martin Aleksa

- Introduction: LAr Calorimetry at LHC
- Calorimetry of the FCC-hh Reference Detector
- Requirements for FCC-ee Calorimetry – Would Noble Liquid Calorimetry Work?
- Conclusions & Outlook

Based on Material from the FCC CDR Summary Volumes (https://fcc-cdr.web.cern.ch/) and studies by the FCC-hh Calorimetry Group (https://indico.cern.ch/category/8922/), which have been published recently in https://arxiv.org/abs/1912.09962

January 16, 2020
3rd FCC Physics and Experiments Workshop, CERN — M. Aleksa (CERN)
Introduction – LAr Calorimetry at LHC
Sampling calorimeter
- with Pb absorbers and active LAr gaps (2mm in barrel, 1.2 – 2.7mm in endcap)

Advantages of liquid argon (LAr) as active material
- linear behavior
- stability of the response over time
  - ideal to understand systematic effects using large statistics of e.g. Z→ee events and develop corrections
- radiation tolerance

Advantages of accordion geometry
- it allows a very high η-φ granularity and longitudinal segmentation (PS, L1, L2, L3)
- it allows for very good hermeticity since HV and signal cables run only at front and back faces of the detector
- it allows for a very high uniformity in φ

Incident electrons create EM showers in Pb
\(X_0=0.56\text{cm}\) and LAr gaps
\(X_0=14.2\text{cm}\)
secondary \(e^+\) and \(e^-\) create \(e^-\) ion pairs in LAr \(W=23.3\text{eV}\)

Ionized electrons and ions drift in electric field (2kV for 2mm gaps in barrel) and induce triangular signal
\(\approx 450\text{ns }e^-\text{ drift time}\)

Design resolution:
\[
\sigma(E) = \frac{10\%}{E} \oplus \frac{0.2}{\sqrt{E}} \oplus 0.2\%
\]
Achieved Resolution and Linearity (e.g. Run1)

- **Resolution measurement:**
  - Assuming correct sampling term $a$ of 10% GeV$^{1/2}$ (validated with $J/\psi$ width)
  - Noise term $b \approx 200 – 300$ MeV per cluster (+ pile-up noise)
  - Template fit of constant term $c$ using $m_{ee}$ invariant mass (Z-peak)

- **Linearity measurement** with $J/\Psi$, Z-peak (and E/p)

\[ \sigma_E / E \text{ for } e^\pm \text{ from Z-decays: } 1.7 – 1.9\% \]

\[ \text{for central barrel} \]

\[ \text{linearity } 10^{-3} \text{ for 20-60 GeV} \]

\[ \Rightarrow \text{ in the central barrel, extracted value in agreement with } \phi \text{ non-uniformity} \]
What Limits Granularity in ATLAS LAr?

- In the ATLAS LAr calorimeter electrodes have 3 layers that are glued together (~275µm thick)
  - 2 HV layers on the outside
  - 1 signal layer in the middle
- All cells have to be connected with fine signal traces (2-3mm) to the edges of the electrodes
  - Front layer read at inner radius
  - Middle and back layer read at outer radius
- limits lateral and longitudinal granularity
- maximum 3 long. layers
FCC-hh Detector – Calorimetry
FCC-hh Calorimetry

- Good intrinsic energy resolution
- Radiation hardness
- High stability
- Linearity and uniformity
- Easy to calibrate

High granularity
- Pile-up rejection
- Particle flow
- 3D/4D/5D imaging

ATLAS LAr+Tile
arXiv:1305.4551

CMS HGCal
arXiv:1708.08234

FCC-hh Calorimetry
Reference Detector

Inspired by ATLAS calorimetry:
- Excellent conventional calorimetry
- In addition high granularity to optimize for Particle Flow techniques, pile-up rejection, boosted objects...
- → ECAL, Hadronic EndCap and Forward Calo (≥30X₀):
  - LAr / Pb (Cu)
- → HCAL Barrel and Extended Barrel (≥10λ):
  Scintillating tiles / Fe(+Pb) with SiPM

Other options considered for ECAL (see CDR)
- Digital Si/W
- Analog Si/W
Compared to ATLAS, FCC-hh Calo needs finer longitudinal and lateral granularity
- Optimized for particle flow
- 8 longitudinal compartments, fine lateral granularity
- Granularity: $\Delta \eta \times \Delta \phi \approx 0.01 \times 0.01$; first layer $\Delta \eta \times \Delta \phi \approx 0.0025 \times 0.02 \rightarrow \sim 2.5M$ channels

Possible only with straight multilayer electrodes (no accordion)
- Active material LAr
- Straight absorbers (Pb + stainless steel sheets), 50° inclined with respect to radial direction
- Readout and HV on straight multilayer electrodes (PCBs, 7 layers, 1.2mm thick)
- Sampling fraction changes with depth $f_{\text{sampl}} \approx 1/7$ to $1/4$ (LAr gap 2 x 1.15mm to 2 x 3.09mm)

Required energy resolution achieved
- Sampling term $\leq 10%/\sqrt{E}$, only $\approx 300$ MeV electronics noise despite multilayer electrodes
- Impact of in-time pile-up at $<\mu> = 1000$ of $\approx 1.3$GeV pile-up noise
- Efficient in-time pile-up suppression will be crucial (using the tracker)

Precision on Higgs self coupling $\lambda$:
$\delta \lambda / \lambda \approx 7\%$

Plots A. Zaborowska, C. Helsens, M. Selvaggi
How to Achieve High Granularity?

Realize read-out electrodes as multi-layer PCBs (1.2mm thick)

- Signal traces (width $w_t$) in dedicated signal layer connected with vias to the signal pads
- Traces shielded by ground-shields (width $w_s$) forming 25Ω – 50Ω transmission lines
- $\rightarrow$ capacitance between shields and signal pads $C_s$ will add to the detector capacitance $C_d$
- $\rightarrow C_{cell} = C_s + C_d \approx 100 – 1000pF$
- The higher the granularity the more shields are necessary $\rightarrow C_{cell}$ increases

$\rightarrow$ Serial noise contribution proportional to capacitance $C_{cell}$

$\rightarrow$ 4 – 40MeV noise per read-out channel assuming ATLAS-like electronics

Hadronic showers:
Energy sums over O(500-10000) cells

Plots A. Zaborowska, J. Faltova
Performance of ECAL

- Position resolution important to perform combination between tracks measured by inner tracker and calorimeter clusters
- Fine \( \phi \) segmentation in the first layer (\( \Delta \eta \times \Delta \phi \approx 0.0025 \times 0.02 \)) and fine \( \eta \)-segmentation of other layers (\( \Delta \eta = 0.01 \)) crucial for \( \pi^0 \) rejection (\( H \rightarrow \gamma \gamma \))
  - Excellent results obtained using MVA with up to 15 variables
  - Deep Neural Network based analysis shows similar results
Barrel HCAL:
- ATLAS type
  - Scintillator tiles – steel
- **Higher granularity** than ATLAS
  - $\Delta \eta \times \Delta \phi = 0.025 \times 0.025$
  - 10 instead of 3 longitudinal layers
  - Steel -> stainless Steel absorber (Calorimeters inside magnetic field)
- SiPM readout → faster, less noise, less space
- Total of 0.3M channels

**Combined pion resolution (w/o tracker!):**
- Simple calibration: $44%/\sqrt{E}$ to $48%/\sqrt{E}$

**Jet resolution:**
- Jet reconstruction impossible without the tracker @ 4T → particle flow.

$e/h$ ratio very close to 1 → achieved using steel absorbers and lead spacers (high Z material)
Combined Performance for Hadrons

- **FCC-hh calorimetry**: High granularity of EM and HCal
- → Ideal for particle flow techniques (but not yet implemented in SW)
- → Which resolution can be achieved with calorimetry only, if using the full shower-imaging information?
- **First results** obtained using a **convolutional neural network**
  - Training with 8M events (without electronics noise for the moment)
  - Excellent results obtained → **Sampling term of 37%/\sqrt{E} (!!!)**

Plots C. Neubüser, J. Kieseler
Requirements for FCC-ee Calorimetry
Calorimetry requirements:

- **Excellent jet energy resolution** (~30%/√Ē)
- **Particle ID**

→ High granularity calorimetry based on particle flow

- Same technologies as for CLIC/ILC under study
  - e.g. Si/W ECAL and Scintillator/Iron HCAL
- **On top of that fibre-sampling dual-readout calorimetry** could be a very interesting option for future leptonic colliders
  - Fine transverse granularity
  - Need longitudinal segmentation to separate e/γ from π⁺⁻⁻⁻! → Idea with fibres of different length
  - Excellent hadronic resolution (simulation ~35%/√Ē)

- **Noble liquid based calorimetry**
  - Calo only: Simulation with DNN calib. for LAr ECAL + TileCal HCAL: ~37%/√Ē
  - Fine granularity → particle flow reco with ID

“CLIC-detector revisited - CLD”

“IDEA”
Requirements for FCC-ee Calorimetry

- **Energy range of particles:**
  - All particles ≤ 182.5 GeV
    - → $22X_0$ and 5-7$\lambda$ sufficient
  - Measure particles down to 300 MeV (e.g. photons)
    - → Little material in front of the calorimeter
    - → Low noise (noise term dominant at small energies, $b \ll 300$ MeV)!

- **EM resolution as good as possible** ($\leq 15%/\sqrt{E}$)
  - e.g. for CLFV $\tau$ decays $\tau \to \mu\gamma$

- **Jet resolution must be excellent** ($\sim 30%/\sqrt{E}$) to separate W and Z decays

- **Position resolution of photons:** $\sigma_x = \sigma_y = (6 \text{ GeV/E} \oplus 2) \text{ mm}$  
  - Particle ID:
    - $e^\pm/\pi^\pm$ separation,
    - $\tau$ decays with collimated final states, separate different decay modes with minimal overlap (e.g. $\pi_0$ close to $\pi^\pm$)

### Dimensions: Example CLD

<table>
<thead>
<tr>
<th>Concept</th>
<th>CLICdet</th>
<th>CLD</th>
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</thead>
<tbody>
<tr>
<td>Vertex inner radius [mm]</td>
<td>31</td>
<td>17</td>
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<tr>
<td>Tracker technology</td>
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<td>Silicon</td>
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<tr>
<td>Tracker half length [m]</td>
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<td>2.2</td>
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<tr>
<td>Tracker outer radius [m]</td>
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<td>Inner tracker support cylinder radius [m]</td>
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<td>ECAL absorber</td>
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<td>W</td>
</tr>
<tr>
<td>ECAL $X_0$</td>
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<td>22</td>
</tr>
<tr>
<td>ECAL barrel $r_{\text{min}}$ [m]</td>
<td>1.5</td>
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<td>ECAL barrel $\Delta r$ [mm]</td>
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<td>202</td>
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<tr>
<td>ECAL endcap $z_{\text{min}}$ [m]</td>
<td>2.31</td>
<td>2.31</td>
</tr>
<tr>
<td>ECAL endcap $\Delta z$ [mm]</td>
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<td>202</td>
</tr>
<tr>
<td>HCAL absorber</td>
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<tr>
<td>HCAL $\lambda_1$</td>
<td>7.5</td>
<td>5.5</td>
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<tr>
<td>HCAL barrel $r_{\text{min}}$ [m]</td>
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<tr>
<td>HCAL barrel $\Delta r$ [mm]</td>
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<td>1166</td>
</tr>
<tr>
<td>HCAL endcap $z_{\text{min}}$ [m]</td>
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<td>2.4</td>
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<tr>
<td>HCAL endcap $\Delta z$ [mm]</td>
<td>1590</td>
<td>1166</td>
</tr>
<tr>
<td>Solenoid field [T]</td>
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<tr>
<td>Solenoid bore radius [mm]</td>
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<td>Solenoid length [m]</td>
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<tr>
<td>Overall height [m]</td>
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</tr>
<tr>
<td>Overall length [m]</td>
<td>11.4</td>
<td>10.6</td>
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Could Noble Liquid Calorimetry Work? (1/2)

**Dimensions:**
- ECAL: $22X_0 \rightarrow \sim 60$ cm radial space for FCC-hh type LAr/Pb calorimeter (including 15cm cryostat thickness)
  - Could be further reduced to $\sim 45$cm by using W instead of Pb
- ECAL+HCAL: 5-7$\lambda$ : $\rightarrow \sim 1.2$ m radial dimension for TileCal (FCC-hh style)
- Calorimetry within $\Delta r = 1.65$m ($W$ ECAL + TileCal) to $\Delta r = 1.8$m ($Pb$ ECAL + TileCal).
- Only slightly bigger than CLD ($\Delta r_{CLD} = 1.4$m)

**EM resolution:**
- **Sampling term** of $\approx 10% / \sqrt{E}$ quite easily achievable
- Resolution at low energies dominated by **noise term**
  - Noise term $\approx 300$MeV achieved with FCC-hh calorimeter
  - Noise term of $\leq 100$ MeV seems possible for low energy deposits (optimized cluster size, see back-up)
  - In addition for large cell capacitances: Could probably gain factor 1.5 when going to slower shaping times $\tau \geq 100$ ns (FCC-hh $\tau = 45$ns)
- To measure down to 300 MeV need to **minimize material in front of the calorimeter** $\rightarrow$ ”thin” Al cryostat or carbon fibre cryostat (R&D program at CERN has been launched, see next slide and talk by H. Ten Kate after this talk)
R&D on Low Mass Composite Cryostats

LOW MASS COMPOSITE: CALORIMETERS AND DETECTOR MAGNETS

✓ Cryostat in HEP detector should profit from similar development in aerospace cryotank: CHATT, CCTD, SpaceX Programs

ATLAS Cryostat for the barrel calorimeter.

SpaceX ITS LOX tank. The tank is made of carbon fibres, it is approximately 12 meters in diameter.

✓ Investigate how to tailor these new processes and materials for HEP cryostat: thermal insulation, feed through, rad loads

See WG4 contribution at EP R&D WS
Could Noble Liquid Calorimetry Work? (2/2)

- **Jet resolution**
  - **Requirement:** (~30%/√E) to separate W and Z decays
  - **Calo only:** hadron resolution (π) achieved in FCC-hh (LAr ECAL + TileCal HCAL):
    - Benchmark reconstruction: ~48%/√E
    - Simulation with DNN calibration ~37%/√E
    - Already close to the required 30%/√E
  - **Particle flow** will further reduce the jet resolution (not simulated yet)
  - **Future jet energy reconstruction** will probably use machine learning to combine tracker information and full 3D imaging information

- **Particle ID:**
  - Fine granularity in $\eta$, $\phi$, depth can be adjusted according to needs (PCB)
  - E.g. FCC-hh first calorimeter layer 5mm x 20mm cells (x 9cm depth)
  - Similar segmentation of read-out electrode would lead to cell sizes of 2.5mrad x 2.5mrad for FCC-ee

- **Position resolution:**
  - For FCC-hh achieved $\sigma_{\eta} \approx 2 \times 10^{-3}/\sqrt{E}$
  - $\Rightarrow \approx 4.4\text{mm}/\sqrt{E} \Rightarrow \approx 1\text{mm for 20GeV (2mm for 5GeV)} \Rightarrow$ sufficient

- **Timing:**
  - ATLAS LAr: Timing resolution of 150ps achieved for EM showers $\geq 30\text{GeV}$, 65ps for EM showers $\geq 100\text{GeV}$
  - Possibility to further improve this resolution – studies needed and planned
Towards an FCC-ee Experiment

• **FCC-hh style calorimeter has been implemented into FCC-ee Experiment in FCC SW** (see talk by C. Helsens this morning)

• **First implementation:**
  – Inner Tracker: DREAM-like drift chamber
  – ECAL: FCC-hh style LAr/Pb calorimeter
  – HCAL: FCC-hh style Tile calorimeter (Fe absorbers)
  – Solenoid coil outside the calorimetry

• **Options which will be studied**
  – Inner tracker: Si tracker
  – ECAL: W absorbers, LKr as active material, granularity optimization
  – HCAL: CLD-like HCAL, LAr HCAL
  – Solenoid coil in front of the ECAL, integrated into LAr cryostat (need thin coil and low-material cryostat)

• **EP R&D work package**
• **H2020/AIDA++ EoI has been submitted**
Next Steps

• Funding from CERN EP R&D has been obtained for this project
  – Three fellows will start to work in the coming months
    • General SW framework & finalization of Lar calorimeter implementation into FCC SW. Implementation of particle flow
    • Performance & Physics simulation to define necessary granularity. Read-out PCB design for required granularity while keeping low noise requirement. Studies on optimization of timing resolution
    • Cryogenic feed-through design for high-density signal feed-throughs

• On top of that there is interest by 5 institutes (F, CZ, US) to collaborate and contribute to
  – PCB design
  – Read-out electronics
  – Physics & Performance simulation
Conclusions and Outlook

• **Noble liquid calorimetry** has been **successfully used for LHC experiments** (ATLAS LAr Calorimeter)
  – Strengths: Stability, pointing resolution, particle ID, radiation hardness
• **Noble liquid calorimetry** is **proposed for the reference detector of FCC-hh**
  – Simulations show that such a calorimeter would fulfil physics requirements for FCC-hh
• **Noble liquid calorimetry** is also an **interesting option for a FCC-ee experiment**!
  – Preliminary considerations: such a calorimeter could be feasible and would fulfil physics requirements for FCC-ee
  – Potentially cheaper than other options!
  – High stability of response will give us handles to keep systematic errors down (and develop corrections)
  – Layout has been adapted to an FCC-ee experiment
    • Noble liquid calorimeter has been implemented into FCC-ee experiment in FCC SW
    • → Start full-sim studies and optimization (see talk by C. Helsens in the morning)!
• **Please join us if you are interested in this promising option!**
Thank You for Your Attention!

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LHC Calorimeters Requirements

→ LHC Calorimeters were designed for benchmark channels: SM precision measurements, Higgs discovery and measurements, discovery of heavy resonances.

Large dynamic range: 10 MeV – 3 TeV (noise level up to highest energy deposits per cell)
→ ≈16bit dynamic range (several gains necessary)

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→ ≈16bit dynamic range (several gains necessary)

Energy resol. $\left( e^\pm, \gamma \right)$: $\sigma_E / E \approx 10\% / \sqrt{E} \oplus 0.7\%$ (for $H \rightarrow \gamma \gamma$ mass with 1% resolution @ 120 GeV)
→ precise mechanics & electronics calibration

Linearity: 0.1%, $10^4$ around the Z-peak (for W-mass measurement!)
→ pre-sampler (correction for dead material), layer weighting, electronics calibration

Fast shaping to optimize signal/noise ratio:
→ 40 MHz sampling rate (LHC bunch crossing)
→ Digital filtering for signal reconstruction

Minimal coherent pickup noise (<5% of incoherent noise)

Minimal dead time at Level 1 (L1) 75 – 100 kHz trigger rate and storing of signals during the latency of the L1 trigger of up to 2.5 μs (100 bunch crossings)
→ realized with switch capacitor array of 144 bunch crossings
ATLAS
- Sampling calorimeter (LAr-Pb), 3 longitudinal layers + presampler, 173000 channels), E range MIP – TeV
- High lateral granularity
  - $\Delta\eta=0.0031$, $\Delta\phi=0.025$
- Presampler + 3 longitudinal layers
- Radiation resistance
- Good energy resolution
- Very stable response in time
  - rms in time $=3 \times 10^{-4}$
  - $\rightarrow$ ideal to understand systematic effects using large statistics of e.g. $Z \rightarrow ee$ events and develop corrections!
- Outside solenoid field (behind the coil) $\rightarrow$ 3 – 6 $X_0$ in front of calorimeter
- Main correction: dead material correction using presampler
- Strength: background rejection (e.g. $\pi^0$), stability, photon vertex measurement (pointing)

CMS
- Homogeneous calorimeter (75000 PbWO$_4$ crystals + PS in forward direction), E range MIP – TeV
- High lateral granularity
  - $\Delta\eta=\Delta\phi=0.0175$
- No longitudinal segmentation
- Radiation resistance
- Excellent energy resolution
- Response impacted by radiation
  - after laser correction rms $\approx 2 \times 10^{-3}$
- Inside strong solenoid field $\rightarrow$ only 0.4 – 1.9 $X_0$ in front of calorimeter
- Main correction: Laser correction to compensate impact of radiation
- Strength: little material in front, energy resolution
Requirements for FCC-hh Detector

• **ID Tracking target**: achieve $\sigma_{p_T} / p_T = 10\text{-}20\% @ 10 \text{ TeV}$
• **Muons target**: $\sigma_{p_T} / p_T = 5\% @ 10 \text{ TeV}$
• Keep **calorimeter constant** term as small as possible (and good sampling term)
  – Constant term of $<1\%$ for the EM calorimeter and $<2\text{-}3\%$ for the HCAL
• **High efficiency** $b$-tagging, $\tau$-tagging, particle ID!
• **High granularity** in tracker and calos
• **Pseudorapidity** ($\eta$) coverage:
  – Precision muon measurement up to $|\eta|<4$
  – Precision calorimetry up to $|\eta|<6$
• → Achieve all that at a pile-up of 1000! → Granularity & Timing!
• On top of that radiation hardness and stability!

Used in Delphes physics simulations
During last years converged on reference design for an FCC-hh experiment

- Radiation simulations
- Demonstrate in the CDR document, that an experiment exploiting the full FCC-hh physics potential is technically feasible
- → Input for Delphes physics simulations
- Room for other ideas, other concepts and different technologies
- See FCC CDR Summary Volumes
  - [https://indico.cern.ch/event/750953/](https://indico.cern.ch/event/750953/)
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    - In addition for large cell capacitances: Could probably gain factor 1.5 when going to slower shaping times $\tau \geq 100$ ns (FCC-hh $\tau = 45$ns)
  - To measure down to 300 MeV need to **minimize material in front of the calorimeter** $\rightarrow$ ”thin” Al cryostat or carbon fibre cryostat (R&D program at CERN has been launched, see next slides)
Challenge: Good photon energy resolution down to 300MeV:
- 30% resolution at 300MeV if noise level can be kept below 100MeV
- → Cluster size optimization (only first layers have significant energy deposits) → less cells per cluster → less electronics noise

→ Only 3.5% of the energy in layers 5 to 8 (for 300 MeV photon)

Courtesy A. Zaborowska