ATLAS Hadronic Calorimeters 101

- Hadronic showers
- ATLAS Hadronic Calorimeters
  - Tile Calorimeter
  - Hadronic Endcap Calorimeter
  - Forward Calorimeter
- Noise and Dead Material

First ATLAS Physics Meeting of the Americas
20 August 2007

M. Lefebvre
University of Victoria
Hadrons in ATLAS

- hadronization of partons
- and subsequent decays
- hadronic decays of taus
Nuclear interactions

Inelastic nuclear processes
- determines the interaction of energetic hadrons
  \[ p, n, \pi, K, \ldots \rightarrow Z,A \]

- Excitation and breakup of nucleus
  - nucleus fragments and secondary particles

- cross section depends \(~\text{only on}~ A\)
  - \( \sigma_{\text{inelastic}} \approx \sigma_o A^{0.7} \quad \sigma_o \approx 35 \text{ mb} \quad A \text{ in g/mol} \)

- hadronic absorption length
  \[
  \lambda_a = \frac{A}{N_A \sigma_{\text{inelastic}}}
  \]
# Interaction and hadronic absorption lengths

<table>
<thead>
<tr>
<th>Material</th>
<th>Z</th>
<th>A</th>
<th>$\rho$ [g/cm$^3$]</th>
<th>$X_0$ [g/cm$^2$]</th>
<th>$\lambda_a$ [g/cm$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen (gas)</td>
<td>1</td>
<td>1.01</td>
<td>0.0899 (g/l)</td>
<td>63</td>
<td>50.8</td>
</tr>
<tr>
<td>Helium (gas)</td>
<td>2</td>
<td>4.00</td>
<td>0.1786 (g/l)</td>
<td>94</td>
<td>65.1</td>
</tr>
<tr>
<td>Beryllium</td>
<td>4</td>
<td>9.01</td>
<td>1.848</td>
<td>65.19</td>
<td>75.2</td>
</tr>
<tr>
<td>Carbon</td>
<td>6</td>
<td>12.01</td>
<td>2.265</td>
<td>43</td>
<td>86.3</td>
</tr>
<tr>
<td>Nitrogen (gas)</td>
<td>7</td>
<td>14.01</td>
<td>1.25 (g/l)</td>
<td>38</td>
<td>87.8</td>
</tr>
<tr>
<td>Oxygen (gas)</td>
<td>8</td>
<td>16.00</td>
<td>1.428 (g/l)</td>
<td>34</td>
<td>91.0</td>
</tr>
<tr>
<td>Aluminium</td>
<td>13</td>
<td>26.98</td>
<td>2.7</td>
<td>24</td>
<td>106.4</td>
</tr>
<tr>
<td>Silicon</td>
<td>14</td>
<td>28.09</td>
<td>2.33</td>
<td>22</td>
<td>106.0</td>
</tr>
<tr>
<td>Iron</td>
<td>26</td>
<td>55.85</td>
<td>7.87</td>
<td>13.9</td>
<td>131.9</td>
</tr>
<tr>
<td>Copper</td>
<td>29</td>
<td>63.55</td>
<td>8.96</td>
<td>12.9</td>
<td>134.9</td>
</tr>
<tr>
<td>Tungsten</td>
<td>74</td>
<td>183.85</td>
<td>19.3</td>
<td>6.8</td>
<td>185.0</td>
</tr>
<tr>
<td>Lead</td>
<td>82</td>
<td>207.19</td>
<td>11.35</td>
<td>6.4</td>
<td>194.0</td>
</tr>
<tr>
<td>Uranium</td>
<td>92</td>
<td>238.03</td>
<td>18.95</td>
<td>6.0</td>
<td>199.0</td>
</tr>
</tbody>
</table>
Hadronic Showers

- More complex than EM showers
  - visible EM O(50%)
    - $e^\pm, \gamma, \pi^0 \rightarrow \gamma\gamma$
  - visible non-EM O(25%)
    - ionization of $\pi^\pm, p, \mu^\pm$
  - invisible O(25%)
    - nuclear break-up
    - nuclear excitation
  - escaped O(2%)

- Only part of the visible energy is sampled
Compensation

Each component fraction depends on energy

- visible non-EM fraction decreases with $E$
  \[
  \left( \frac{E}{E_0} \right)^{m-1} \quad 0.80 \leq m \leq 0.85 \\
  E_0 \approx 1 \text{ GeV for } \pi^\pm \\
  E_0 \approx 2.6 \text{ GeV for } p
  \]

- pion (and jets) response non linear with $E$
  - “$\pi$” is the response to a pion
  - “e” is the intrinsic response to visible EM
  - “h” is the intrinsic response to visible non-EM

  
  \[
  "\pi" = "e" \left[ 1 - \left( \frac{E}{E_0} \right)^{m-1} \right] + "h" \left( \frac{E}{E_0} \right)^{m-1} \quad \Rightarrow \quad "\pi/e" = 1 - (1 - h/e) \left( \frac{E}{E_0} \right)^{m-1}
  \]

- in ATLAS, $e/h > 1$ for each sub-detector
  - invisible energy is the main source of $e/h > 1$
  - $e/h = 1$ is a compensating calorimeter
Hadronic Showers

- Large fluctuations of each component fraction
  - non-compensation amplifies fluctuations
- Hadronic calibration attempts to
  - provide some degree of software compensation
  - account for the invisible and escaped energy
Calorimeter types

- **Homogeneous calorimeters**
  - the detector is the absorber
  - good energy resolution
  - limited spatial resolution, especially longitudinal
  - only used for electromagnetic calorimetry

- **Sampling calorimeters (as in ATLAS)**
  - the detector and absorber are separated
  - only sample part of the shower
    - additional sampling fluctuations affect energy resolution
  - limited energy resolution
  - good spatial resolution
Energy Resolution

General parametrization

\[ \frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E} \]

- stochastic or sampling term
- constant term comes from inhomogeneity, bad calibration, non-linearity
- noise term including electronic and pileup noise

- this is an approximation
  - \( a, b \) and \( c \) generally depend on \( \eta \)
- at high energy the constant term dominates!
Typical Detector Components

[Diagram showing the typical components of a detector, including tracking chamber, electromagnetic calorimeter, hadron calorimeter, and muon chamber. Particles such as photons, electrons, muons, pions, and protons are indicated entering and exiting through different layers.]
ATLAS Calorimeters

- Tile barrel
- Tile extended barrel
- LAr hadronic end-cap (HEC)
- LAr EM end-cap (EMEC)
- LAr system within 2m radius
- LAr EM barrel (EMB)
- LAr forward calorimeter (FCal)
Calorimeters

- **EM Barrel**
  - $|\eta| < 1.4$

- **EMEC**
  - $1.375 < |\eta| < 3.2$

- **Tile**
  - $|\eta| < 1.7$

- **HEC**
  - $1.5 < |\eta| < 3.2$

- **FCal**
  - $3.2 < |\eta| < 4.9$

varied granularity
varied techniques
many overlap regions
Physics Requirements

Hadron and Forward Calorimeters

- Benchmark channels $H \rightarrow WW \rightarrow \text{jet jet X and Z/W/t}$ require good jet-jet mass resolution
- Higgs fusion $\rightarrow$ good forward jet tagging
- $E_{t\text{Miss}} \rightarrow$ calibration, jet resolution, linearity

Design goals for jets (combined with EM calorimeter)

- $\sigma(E)/E = 50\%/\sqrt{E} \oplus 3\%$ for $|\eta| < 3$ (E in GeV)
- $\sigma(E)/E = 100\%/\sqrt{E} \oplus 5\%$ for $3 < |\eta| < 5$
Tile Calorimeter

Sampling calorimeter made of plastic scintillator and steel

Light signal proportional to energy deposition in plastic

Notice orientation of scintillator plates

PMT

WLS fiber

Plastic scintillator inside steel absorber structure
Tile Calorimeter Cells
## Tile Cell Count

### offline/Calorimeter/CaloIdentifier/CaloIdentifier/TileID.h

<table>
<thead>
<tr>
<th>element</th>
<th>range</th>
<th>meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>section</td>
<td>1 to 15</td>
<td>section number (1 = Barrel, 2 = Extended Barrel, 3 = Gap Detector, i.e. gap scin E1-E4 and ITC cells D4, C10, 4 = Ancillary detectors)</td>
</tr>
<tr>
<td>side</td>
<td>-1 to 1</td>
<td>-1 = negative eta, 1 = positive eta, 0 = undefined (both sides)</td>
</tr>
<tr>
<td>module</td>
<td>0 to 63</td>
<td>module number by phi</td>
</tr>
<tr>
<td>tower(eta)</td>
<td>0 to 15</td>
<td>0-15 = tower number by pseudorapidity with 0.1 increment in eta</td>
</tr>
<tr>
<td>sample</td>
<td>0 to 15</td>
<td>0 = A, 1 = B = BC = C, 2 = D, 3 = special gap scin cells E1-E4</td>
</tr>
<tr>
<td>pmt</td>
<td>0 to 1</td>
<td>PMT number in the cell (0 = side close to module with smaller number)</td>
</tr>
<tr>
<td>adc</td>
<td>0 to 1</td>
<td>ADC number for the PMT (0 = low gain, 1 = high gain)</td>
</tr>
</tbody>
</table>
One Tile Calorimeter Module

~ 20 Tonnes
**Tile Calorimeter Front End Electronics**

- Process 10000 PMT signals
- Effective 16 bit dynamic range
  - up to 2 TeV in a single cell
  - down to 30 MeV per cell
    - must see muons @ 350 MeV/cell for calibration, monitoring, electron identification
- Readout should not degrade calorimeter energy resolution
  - electronics noise low when merging cells into jets
- Radiation-tolerant > 10 years
- Provide level-1 trigger tower sums
- Electronics located in 256 “drawers”
  - each one 3 m long, 50 kg
Tile Calorimeter Calibration System

Every TileCal channel can be calibrated and monitored with 3 systems:

1. **Cesium**: single cell equalization
2. **Electrons**: setting of EM scale
3. **Charge injection**: check linearity, calibrate gain, dual gain 16 bit ADC
   
   Energy = [30 MeV - 2 TeV]
Calorimeters

- **EM Barrel**
  - $|\eta| < 1.4$
- **EMEC**
  - $1.375 < |\eta| < 3.2$
- **Tile**
  - $|\eta| < 1.7$
- **HEC**
  - $1.5 < |\eta| < 3.2$
- **FCal**
  - $3.2 < |\eta| < 4.9$

varied granularity
varied techniques
many overlap regions
**Liquid Argon Calorimetry**

**LAr ionization chamber**

\[ i_d(t) = -\frac{dQ}{dt} \]  
\[ i_d(t) = i_o \left( 1 - \frac{t}{t_d} \right) \]

considering only the electron drift and assuming \( RC >> t_d \)

**typical values:**

\( T = 87 \text{ K} \), \( \rho = 1.40 \text{ g/cm}^3 \)

\( X_0 = \rho \times 13.9 \text{ cm} \)

\( W = 23.6 \text{ eV} \)

\( U_0 = 2 \text{ kV over 2 mm gaps} \)

\( t_d \approx 450 \text{ ns} \) (compare to LHC 25 ns!)
Liquid Argon Calorimeter Pulse Shape

- triangle current pulse, shaping, sampling

Fig. 1. (a) Drift current and integrated charge vs time for an ion chamber calorimeter. (b) Response of a shaping amplifier to a short current pulse ($\delta$). (c) Response of a shaping amplifier to the current form shown in (a). The dots indicate where the beam crossings (every 15 ns) would appear if $i_p(\delta) = 20$ ns.
Hadronic Endcap Calorimeter

D.M. Gingrich et al. (ATLAS Hadronic End-cap Calorimeter Group), *Construction, assembly and testing of the ATLAS hadronic end-cap calorimeter*, Journal of instrumentation, 2007_JINST_2_P05005.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>HEC1</th>
<th>HEC2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of wheels</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Weight of each wheel</td>
<td>67,300 kg</td>
<td>89,900 kg</td>
</tr>
<tr>
<td>Number of modules per wheel</td>
<td>32</td>
<td>32</td>
</tr>
<tr>
<td>Gap between modules in azimuth</td>
<td>2 mm</td>
<td>2 mm</td>
</tr>
</tbody>
</table>

_Table 1. HEC wheel parameters._

HEC1 wheel being rotated

HEC wheel fully assembled on the assembly table
HEC Calorimeter

HEC2 A wheel on the insertion stand, August 2004
HEC Calorimeter

- Cu/LAr sampling calorimeter
- 2 wheels in each endcap
  - 32 phi modules each
  - 2 readout depths each
- HEC1 wheel
  - 25 mm Cu plates
- HEC2 wheel
  - 50 mm Cu plates
- Readout structure in the 8.5 mm LAr gaps forms an electrostatic transformer (EST)
  - optimize signal/noise
  - reduce HV requirement
  - limits effects of failure modes

operating HV: 1800V
### HEC Module Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Front modules</th>
<th>Rear modules</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of copper plates</td>
<td>25</td>
<td>17</td>
</tr>
<tr>
<td>Thickness of first plate in module</td>
<td>12.5 mm</td>
<td>25.0 mm</td>
</tr>
<tr>
<td>Thickness of standard plates in module</td>
<td>25.0 mm</td>
<td>50.0 mm</td>
</tr>
<tr>
<td>Weight of standard plates</td>
<td>90 kg</td>
<td>180 kg</td>
</tr>
<tr>
<td>Module weight</td>
<td>2,103 kg</td>
<td>2,811 kg</td>
</tr>
<tr>
<td>Distance from copper plate to copper plate</td>
<td>8.500 mm</td>
<td>8.500 mm</td>
</tr>
<tr>
<td>Liquid argon subgaps</td>
<td>1.969 or 1.954 mm</td>
<td>1.969 or 1.954 mm</td>
</tr>
<tr>
<td>Honeycomb thickness</td>
<td>1.816 mm</td>
<td>1.816 mm</td>
</tr>
<tr>
<td>Total thickness of PAD and EST boards in gap</td>
<td>0.625 or 0.685 mm</td>
<td>0.625 or 0.685 mm</td>
</tr>
<tr>
<td>Number of read-out gaps</td>
<td>8+16 = 24</td>
<td>8+8 = 16</td>
</tr>
<tr>
<td>Number of read-out segments</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Number of read-out towers</td>
<td>24+23 = 47</td>
<td>21+20 = 41</td>
</tr>
<tr>
<td>Number of preamplifier boards</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Number of preamplifier chips</td>
<td>42</td>
<td>28</td>
</tr>
<tr>
<td>Number of low-voltage lines</td>
<td>12</td>
<td>8</td>
</tr>
<tr>
<td>Number of calibration distribution boards</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Number of calibration lines</td>
<td>28</td>
<td>16</td>
</tr>
<tr>
<td>Number of high-voltage lines</td>
<td>4+4 = 8</td>
<td>4+4 = 8</td>
</tr>
<tr>
<td>Number of tie rods per module</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Tie rod diameter</td>
<td>12 mm</td>
<td>16 mm</td>
</tr>
<tr>
<td>Tie rod stress</td>
<td>78 MPa</td>
<td>79 MPa</td>
</tr>
<tr>
<td>Tie rod thread root stress</td>
<td>125 MPa</td>
<td>118 MPa</td>
</tr>
<tr>
<td>Outside diameter of spacers for 8.5 mm read-out gaps</td>
<td>17 mm</td>
<td>23 mm</td>
</tr>
<tr>
<td>Maximum stress on the copper by the spacer</td>
<td>138 MPa</td>
<td>138 MPa</td>
</tr>
</tbody>
</table>
HEC module geometry

This drawing is in the plane of the middle $\phi$ of a HEC module and shows the 7 readout families and the $\eta$ boundaries passing through the pad $\rho$ boundaries at the middle $z$ of pad board families.
not to scale!

HEC Padboard Families
HEC Pad Board Families
HEC Readout Layers (or depths)

not to scale!
**HEC Cell Count**

*offline/Calorimeter/CaloIdentifier/CaloIdentifier/LArHEC_ID.h*

<table>
<thead>
<tr>
<th>element</th>
<th>range</th>
<th>meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>pos/neg</td>
<td>-2 or 2</td>
<td>-2 = negative HEC (C side), 2 = positive HEC (A side)</td>
</tr>
<tr>
<td>sampling</td>
<td>[0,3]</td>
<td>[0,1] = first wheel, [2,3] = second wheel</td>
</tr>
<tr>
<td>region</td>
<td>[0,1]</td>
<td>0 : outer part, 1 : inner part</td>
</tr>
<tr>
<td>eta</td>
<td>[0,9]</td>
<td>Outer part region 0, samplings 0 and 1, 1.5&lt; ( \eta ) &lt; 2.5, ( \delta \eta = 0.1 )</td>
</tr>
<tr>
<td></td>
<td>[1,9]</td>
<td>Outer part region 0, samplings 2, 1.6&lt; ( \eta ) &lt; 2.5, ( \delta \eta = 0.1 )</td>
</tr>
<tr>
<td></td>
<td>[2,9]</td>
<td>Outer part region 0, samplings 3, 1.7&lt; ( \eta ) &lt; 2.5, ( \delta \eta = 0.1 )</td>
</tr>
<tr>
<td></td>
<td>[0,3]</td>
<td>Inner part region 1, samplings 0 and 3, 2.5&lt; ( \eta ) &lt; 3.3, ( \delta \eta = 0.2 )</td>
</tr>
<tr>
<td></td>
<td>[0,2]</td>
<td>Inner part region 1, samplings 1 and 2, 2.5&lt; ( \eta ) &lt; 3.1, ( \delta \eta = 0.2 )</td>
</tr>
<tr>
<td>phi</td>
<td>[0,63]</td>
<td>Outer part, ( \delta \phi = 0.1 )</td>
</tr>
<tr>
<td></td>
<td>[0,31]</td>
<td>Inner part, ( \delta \phi = 0.2 )</td>
</tr>
</tbody>
</table>

* 5632 active cells in the full HEC
Calorimeters

- EM Barrel
  - $|\eta| < 1.4$
- EMEC
  - $1.375 < |\eta| < 3.2$
- Tile
  - $|\eta| < 1.7$
- HEC
  - $1.5 < |\eta| < 3.2$
- FCal
  - $3.2 < |\eta| < 4.9$

varied granularity
varied techniques
many overlap regions
Forward Calorimeter Assembly
- 3 modules
  - 0.9 m diameter
  - 0.45 m long
- FCal1: Cu/LAr
- FCal2: W/LAr
- FCal3: W/LAr

FCal

- recessed to reduce neutron albedo in the central cavity
- not much room left for $9.5\lambda$
FCal

- **Novel electrode structure**
  - thin annular gaps form by tubes in an absorber matrix, which are filled with anode rods of slightly smaller radius

- **Electrodes along z**
  - not pointing!

- **All radiation hard materials**

- **Small gap thickness**
  - short drift times
    - reduce ion buildup
  - small HV needed

<table>
<thead>
<tr>
<th>Type</th>
<th>Absorber</th>
<th>Gap (µm)</th>
<th>Number of Electrodes</th>
</tr>
</thead>
<tbody>
<tr>
<td>FCal1</td>
<td>EM</td>
<td>250</td>
<td>12000</td>
</tr>
<tr>
<td>FCal2</td>
<td>HAD</td>
<td>375</td>
<td>10000</td>
</tr>
<tr>
<td>FCal3</td>
<td>HAD</td>
<td>500</td>
<td>8000</td>
</tr>
</tbody>
</table>
FCal 2/3 Structure and Assembled Modules

- Liquid Argon Gap
- Tungsten Rod
FCal Cell Count

```c
* Connected channels :
* ---------------
* pos_neg = +/- 2 (A/C side)<br>
* 
* module = [1,3] : 1 EM , 2-3 Hadronic <br>
* 
* phi = [0,15] <br>
* 
* eta = [0,62] module 1 ; <br>
* eta = [0,31] module 2, except phi=3,4,11,12: eta = [0,30] and phi=0,7,8,15: eta = [0,29] <br>
* eta = [0,15] module 3, except phi=2,10: eta = [0,14] (old FICAL desciption) <br>
* except phi=5,13: eta = [0,14] (new FICAL desciption) <br>
* 
* 3524 connected cells in total <br>
```
Endcap Cryostat

- Only HEC has active electronics in the LAr
  - preamp + sums
- Front End Boards
  - 3 gain readout
    - 10 bit ADC
    - effective 16 bit
  - SCA pipeline
Equipped endcap cryostat C being lowered into position
Calorimeters: Signal Noise (Incoherent)

- **Electronic noise**
  - unavoidable basic fluctuation on top of each calorimeter cell signal, typically close to Gaussian (symmetric)
  - ranges from \( \sim 10 \text{ MeV} \) (central region) to \( \sim 850 \text{ MeV} \) (forward) per cell
  - independent of physics collision environment
  - coherent noise contribution in cells generated in the calorimeter and/or in the readout electronics typically much smaller than incoherent cell electronic noise
    - “fake” pile-up noise avoided
Calorimeters: Signal Noise (Incoherent)
Calorimeters: Signal Noise (Coherent)

- **Pile-up noise**
  - generated by (many) minimum bias events (MB) in physics collisions
  - depends on instantaneous luminosity
  - illuminates basically the whole calorimeter
  - major contribution to out-of-time signal history due to calorimeter shaping functions (total of ~625 MB/triggered event affect the signal @ $10^{34}$ cm$^{-2}$s$^{-1}$)
    - slow charge collection in LAr calorimeters (~500 ns) versus high collision frequency (25 ns bunch crossing to bunch crossing) generates signal history in detector
  - Introduces asymmetric cell signal fluctuations from ~10 MeV (RMS, central region) up to ~40 GeV (RMS, forward) similar to coherent noise
    - “real” showers generated by particles in pile-up event introduce cell signal correlation leading to (large) coherent signal fluctuations
Calorimeters: Signal Noise (Coherent)

Pile-up Noise in Calorimeter Cells

- FCal1
- FCal2
- FCal3
- HEC1
- HEC2
- HEC3
- HEC4
- PS
- EM1
- EM2
- EM3
ATLAS Absorption Length Budget (TDR)

![Graph showing absorption length budget for ATLAS calorimeters, with regions labeled for Tile barrel, Tile extended barrel, Hadronic endcap, Forward calorimeter, EM barrel, EM endcap, and Material in front of Muon System.](Image)
Dead material

- Energy losses not directly measurable
  - Signal distribution in vicinity can help
- Introduces need for signal corrections up to $O(10\%)$
  - Exclusive use of signal features
  - Corrections depend on electromagnetic or hadronic energy deposit

- Major contributions
  - Upstream materials
  - Material between LAr and Tile (central)

Cracks

- Dominant sources for signal losses
  - $|\eta| \approx 1.4 - 1.5$
  - $|\eta| \approx 3.2$
- Clearly affects detection efficiency for particles and jets
  - already in trigger!
  - Hard to recover jet reconstruction inefficiencies
- Generate fake missing $E_T$ contribution
  - Topology dependence of missing $E_T$ reconstruction quality
Summary of (some) Calorimeter Beam Tests