Commissioning of the ATLAS Liquid Argon Calorimeters

Mark Cooke
(Columbia University)

on behalf of the ATLAS LAr Calorimeter Group

CIPANP 2009, New Facilities and Instrumentation Session 4, May 29 2009
ATLAS is a general purpose detector designed to probe high energy collisions produced at the LHC at CERN.

Here we will discuss the commissioning of the ATLAS Liquid Argon (LAr) calorimeters.

**General LHC Parameters:**
- 27 km in circumference, ~100 m beneath surface
- Proton-proton collisions at 14 TeV
- Bunches collide at 40 MHz
- Expect ~ 25 interactions per bunch crossing at design luminosity of ~ $10^{34}$ cm$^{-2}$ s$^{-1}$
The Liquid Argon (LAr) Calorimeters of the ATLAS Detector

Electromagnetic (EM):
- Barrel: $|\eta| < 1.475$
- End-caps: $1.375 < |\eta| < 3.2$

$$\eta = 0 \quad \text{Had Tiles}$$
$$\eta = 1.475$$
$$\eta = 3.2$$
$$\eta = 4.9$$

Hadronic End-Cap (HEC):
- 2 wheels per end-cap (front & back)
- $1.5 < |\eta| < 3.2$

Forward Calorimeter (FCAL):
- 3 sections (1st EM, 2nd & 3rd HAD)
- $3.1 < |\eta| < 4.9$

$$\eta = -\ln \tan(\theta/2)$$
Barrel Calorimeter On The Way To Cavern

An End-Cap Calorimeter prepared to be moved into position

Barrel Calorimeter In Final Position Within Toroid Magnets

Completion of An End-Cap Calorimeter
**Properties of the Electromagnetic Calorimeters**

**Cu/kapton readout electrode**

**Honeycomb spacer positions electrode in LAr gap (2 mm)**

**Steel-clad Lead absorber plates (1 to 2 mm thick)**

Accordion geometry allows for complete $\phi$ coverage without cracks.

**Longitudinal segmentation:**
- Presampler [no absorber] (S0) (not shown)
- Front/Strips (S1) : $\sim 4 \times X_0$
- Middle (S2) : $\sim 16 \times X_0$
- Back (S3) : $\sim 2-12 \times X_0$

**Lateral segmentation:**
- S1 : $\Delta\eta \times \Delta\phi = (0.025/8) \times (0.0245 \times 4)$
- S2 : $\Delta\eta \times \Delta\phi = 0.025 \times 0.0245$

Very fine segmentation:
- $\sim 110k$ barrel channels and
- $\sim 64k$ end-cap channels, proportioned 1:8:4:2 among layers
Properties of the Hadronic End-Cap (HEC) and Forward Calorimeters

**HEC**
- Flat copper plate design
- Granularity: 
  \[ \Delta \eta \times \Delta \phi = 0.1 \times 0.1 \] for \( 1.5 < |\eta| < 2.5 \)
  \[ \Delta \eta \times \Delta \phi = 0.2 \times 0.2 \] for \( 2.5 < |\eta| < 3.2 \)
- 2816 channels per end-cap

**FCAL**
- Plates (copper EM, tungsten HAD) have holes drilled longitudinally into which electrode is placed.
- Electrode consists of copper or tungsten rod and tube, separated by radiation hard plastic fiber to produce gap.
- Granularity: \( \Delta \eta \times \Delta \phi \approx 0.2 \times 0.2 \)
- 1762 channels per end-cap
Physics Requirements on the LAr Calorimeters

Energy Resolutions:

**Electromagnetic (EM):**

\[
\frac{\sigma_E}{E} = \frac{10\%}{\sqrt{E}} \oplus 0.7\%
\]

**Hadronic End-Cap (HEC):**

\[
\frac{\sigma_E}{E} = \frac{50\%}{\sqrt{E}} \oplus 3\%
\]

**Forward Calorimeter (FCAL):**

\[
\frac{\sigma_E}{E} = \frac{100\%}{\sqrt{E}} \oplus 10\%
\]

General design requirements:

- Large acceptance in \( \eta \) and full \( \phi \) coverage
- Very good EM energy resolution and fine segmentation (e.g. \( e, \gamma / \pi^0 \) separation).
- Wide dynamic range of readout (need to cover range from pre-amp level noise – 10s of MeV – to order TeV)
- Coherent noise < 5% incoherent noise (e.g. for ME\( _T \))
- Accurate time measurement (exotic non-prompt decays, non-collision background rejection)

Energy resolution mainly determined by:

- **sampling fluctuation term** (dependent on sampling fraction/frequency and shower containment), and
- **constant term** (dependent on mechanical tolerances, time variation of response, and calibration).

Achieving these physics requirements (quickly) necessitates thorough commissioning of the calibration system and physics signal reconstruction (with cosmics and single beam data) before collisions!
Despite the differences in geometry, absorber material, and segmentation, the 3 calorimeters rely on the same basic principles:

• Absorber material initiates shower development which ionizes the LAr medium.
• The HV drifts the ionized electrons, thus creating a current which is read out.

For reference: the response of the EM cal (2 mm drift gaps) to electrons results in a current of 2-3 μA/GeV, and the drift time is about 450 ns for HV = 2 kV.
Signal Processing of the Ionization Current

Front end boards (FEBs) located on the detectors receive the ionization signals and

- amplify and shape them (3 gains, ~ 1:10:100)
- sample and analog store during the L1 trigger latency
- gain select
- digitize upon L1 trigger accept
- transmit samples (typically 5) to read out driver

Shaper is an analog RC-(CR)^2 filter:
- Remove long tail, limit band-width to reduce noise
- RC time constant set to optimize combination of thermal & pile-up noise

40 MHz sampling (LHC Freq)

![Diagram of signal processing and ionization current](image)
Computing Energy and Time From The Sampled Waveform

In normal running, \( N_{\text{samples}} = 5 \).

Optimal Filter Coefficients (OFCs) \( a_i, b_i \) reduce noise and improve precision of \( E \) and \( \Delta t \).

Several *calibration constants* are needed to turn \( A_{\text{max}} \) into \( E_{\text{cell}} \):

\[
A_{\text{max}} = \sum_{i=0}^{N_{\text{samples}}} a_i (s_i - p)
\]

\[
A_{\text{max}} \cdot \Delta t = \sum_{i=0}^{N_{\text{samples}}} b_i (s_i - p)
\]

\[
E_{\text{cell}} = F_{\mu A \to \text{MeV}} \cdot F_{\mu A \to \text{DAC}} \cdot \frac{1}{M_{\text{phys}}} \sum_{i=1}^{M_{\text{ramps}}} R_i \left[ \sum_{j=1}^{N_{\text{samples}}} \frac{a_j (s_j - p)}{M_{\text{cali}}} \right]^i
\]

A calibration system injects a variable amplitude exponential current pulse across the electrode of each channel.

The resulting calibration pulse is used to determine the OFCs and factors (Ramps, Mphys/Mcali) which relate \( A_{\text{max}} \) to \( E_{\text{cell}} \).
Pedestal Stability:
- Sensitive to FEB temperature
- $\Delta\text{Ped} < 1$ MeV
- Stable over long periods (here 4 mo.)

Amplitude Stability:
- Amplitude stability depends on the stability of many factors – calibration pulse, shaper, pedestal.
- If shaper properties drift, OFCs must be recomputed.
- $\Delta\text{Amp} < 0.1\%$ (here comparing different calibration runs for all barrel channels).
Dead Channels For Physics

- Status in May 2009

- η-φ map of dead channels within detector for which a signal cannot be extracted or is not reliable for physics use.

- No repair foreseen for this class of dead channels

- Amount to < 0.02% of total
**Survey of Dead / Problematic Channels (2)**

**Dead Channels In Readout**
- Channels that were not being read out in May 2009.
- Channels are primarily from FEBs for which the optical connection has failed.
- None in HEC/FCAL
- Amount to 0.2% total, to be fixed next time access is available.

**Reduced HV Channels**
- 6% channels operating at below nominal HV
- Channels are good for physics.
- Correction factor applied, slight degradation of signal to noise.
Survey of Detector Noise

• Individual cell noise is primarily determined by the thermal noise of the FEB pre-amp loaded by the detector capacitance.

• Detector capacitance varies with $\eta$ and detector element.

Incoherent noise consistent with design requirements

• In random trigger events, $E_T^{\text{miss}}$ consistent with incoherent noise prediction.

• In events triggered by L1Calo, a tail is observed – examination of pulse shapes indicate true cosmic events
Cosmic events in the LAr Calorimeters have been recorded in situ since 2006
Quality of Physics Pulse Shape Determination (1)

- LAr signals from cosmic muons provide an excellent opportunity to study the physics pulse shape prediction.
- Predicting the physics pulse shape from the calibration pulse requires an accurate modelling of the full effective circuit including the LAr cell.
- Better than 2% agreement between data and the prediction is observed across the full length of the pulse.

- Despite the low rate, cosmic muons have allowed for the study of the pulse shape prediction over a large portion of the detector as installed in the cavern.
- These analyses have recently been extended to single beam data (left) and show good agreement (quantified by $Q^2$) for the EM cal over full $\eta$ coverage.

$$Q^2 = \frac{1}{nDoF} \sum_{i=1}^{n_{\text{samples}}} \frac{(A_i^{\text{data}} - A_i^{\text{pred}})^2}{\sigma_{\text{noise}}^2 + \sigma_{\text{pred}}^2}$$
Quality of Physics Pulse Shape Determination (2)

- The drift time is an important parameter in the physics pulse shape prediction.
- Also sensitive to the purity of the LAr.
- Detailed drift time measurements have been made with ~350k EM barrel cosmic pulses with E > 1 GeV taken in 32 sample read out mode.
- Drift time varies with η as a result of observed ~100 μm shifts of electrode within LAr gap.
- Study has concluded the contribution of the gap variation to the response non-uniformity is not larger than 0.3%.
Energy Response to Cosmic Muons

- Muons are minimum ionizing particles and typically leave small energy depositions in LAr.
- The energy deposition follows a Landau distribution (here fit convoluted with gaussian).
- The most probable value (MPV) scales linearly with distance traversed in detector.

2 cluster methods are studied (3x3 less sensitive to out of cluster E loss for less projective muons).
- Fitted Gaussian noise (σ_G) and Landau width for 3x3 consistent with expectation.
- MPV follows η dependence expected from detector geometry, overall energy scale consistent with MC to within 3%.
The First Beam Induced Events In ATLAS, September 2008
Timing Alignment With Single Beam “Splash” Events

- September 2008 – beam on collimator events recorded by ATLAS
- Large amounts of energy deposited over large portions of LAr (some > 25 TeV total) – many high amplitude signals to perform precision timing studies with common reference time
- Compute TOF from collimator to LAr cells, infer equivalent time from origin.
- Compare w/ prediction: (TOF + known cables delays, etc), align if necessary

Readout variable related to regions of $\eta$ and long. depth

Normal running $N_{\text{samples}} = 5$
Align time such that particles from origin induce signals which peak at 3rd sample.

EMBC: relative time by slot (average over 32 FTs)

Data
Prediction

Layer 2

E (GeV)

A (ADC)

Pulse From Cosmic Run (32 samples)

Used here for illustration

ATLAS
Conclusions

• The physics objectives of the ATLAS experiment place stringent requirements on the LAr calorimeters.

• The LAr calorimeters have been constructed and completely installed with the other sub-detectors in the ATLAS cavern.

• The incoherent and coherent noise of the full calorimeter system is consistent with design requirements. A limited number of dead channels ( < 0.02% permanent, 0.2% to be fixed ).

• The calibration system is being exercised regularly and the constants necessary for signal reconstruction have been shown to be stable to within specifications.

• Signals from cosmic muons have been used to test the physics pulse shape prediction. Such detailed studies also probe very small mechanical deformations.

• The MIP energy deposition of cosmic muons has been studied – the variation with $\eta$ follows the dependence expected from cell depth variation and the overall energy scale is consistent with MC.

• Data accumulated during initial LHC start-up has also been used for pulse shape studies as well as to accurately time in the detector.

The commissioning phase of the ATLAS LAr calorimeters has demonstrated that the detectors, calibration system, and signal reconstruction infrastructure are fully ready for LHC collisions.
Supporting Slides
**Calibration Constants**

pedestals and noise

FEB are read with no input signal to obtain:
- Pedestal
- Noise
- Noise autocorrelation (OFC computation)

ADC → MeV conversion

$$F = \text{ADC2DAC} \times \text{DAC2}\mu\text{A} \times \mu\text{A2MeV}$$

- Scan input current (DAC)
- Fit DAC vs ADC curve with a first (second) order polynomial, outside of saturation region

response to current pulse

All cells are pulsed with a known current signal:
- A delay between calibration pulses and DAQ is introduced
- The full calibration curve is reconstructed ($\Delta t=1\text{ns}$)
Choose coefficients for the expressions:

\[ U = \sum_{k=1}^{N} a_k S_k \quad V = \sum_{k=1}^{N} b_k S_k \]

such to minimize \( \sigma_U \) and \( \sigma_V \) with the constraints:

\[ \langle U \rangle = A \Rightarrow \sum_{k=1}^{N} a_k g_k = 1 , \quad \sum_{k=1}^{N} a_k g_k' = 0 \]
\[ \langle V \rangle = A \tau \Rightarrow \sum_{k=1}^{N} b_k g_k = 0 , \quad \sum_{k=1}^{N} b_k g_k' = -1 \]
A known exponential current pulse is injected at the MB level...

... and reconstructed through the full readout chain. The actual gain of each readout channel is computed.

The shaper output of the ionisation and calibration signal corresponding to the same injected current is different!

- Injected signal shape
- Different Injection point

Calibration Scheme (Basic)
Exponential pulse shape depends on CB elements

\[
\begin{align*}
    f_{\text{step}} &= \left( \frac{r_{\text{cali}}}{r_{\text{cali}} + \frac{R_{\text{cali}}}{2}} \right) \\
    \tau_{\text{cali}} &= \left( \frac{L_{\text{cali}}}{r_{\text{cali}} + \frac{R_{\text{cali}}}{2}} \right)
\end{align*}
\]

- \( R_{\text{term}} \) is such that \( \frac{1}{R_{\text{term}}} + \frac{n}{(R_{\text{inj}}+R_{\text{dump}})} = \frac{1}{R_{\text{cali}}} \)
- The injected calibration current is \( I_{\text{cali}} = \frac{V'_{\text{cali}}}{(R_{\text{inj}}+R_{\text{dump}})} \)

- The ionization pulse is (currently) predicted as:

\[
I_{\text{phys}}(s) = I_{\text{cali}}(s) \times \left( \frac{1 + s\tau_{\text{cali}}}{sT_d(1 + e^{-sT_d})} \right) \times \left( \frac{1}{1 + srC + s^2LC} \right)
\]
High Voltage Correction (Additional Info)

1st bin: <1% correction