Optimization studies for the upgraded readout electronics of the ATLAS Liquid Argon Calorimeter

Alessandro Ambler

McGill University
Supervisor : Brigitte Vachon

15-18th of February 2018

Outline

1 Introduction

2 HEC Electronics

3 Pileup Noise

4 Digital Filtering

5 Results

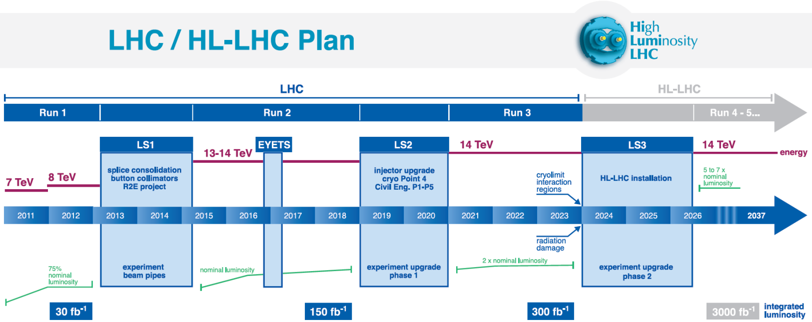
6 Summary

7 References

8 Backup

The Large Hadron Collider

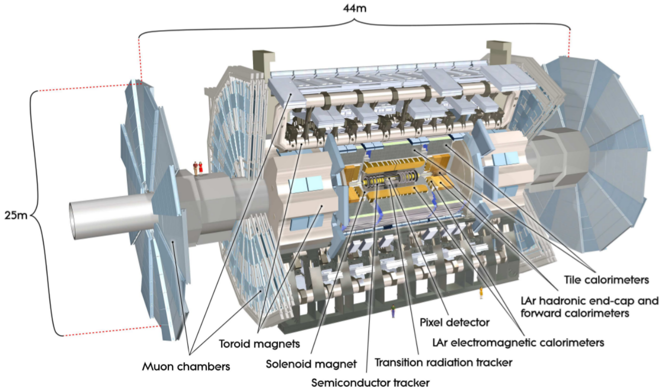
- The Large Hadron Collider (LHC) at the Center for European Nuclear Research (CERN) is designed to accelerate and collide protons at a center-of-mass energy of 14 TeV.
  - 13 TeV was achieved during Run 2.
- The LHC will be upgraded in 2024-26 with the aim of increasing its luminosity by a factor of 5-7.



[1]

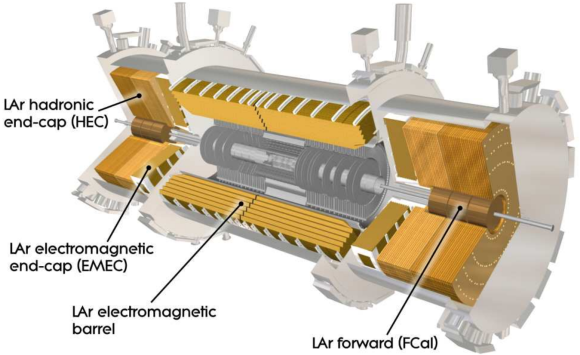
The ATLAS Detector

- ATLAS a general purpose detector located at one of the LHC interaction points.
- ATLAS is composed of multiple sub-detectors.
  - Here we focus on the Liquid Argon (LAr) Calorimeter.
- The LAr Calorimeter is designed to measure the energy deposited by secondary particles resulting from the proton-proton collisions.



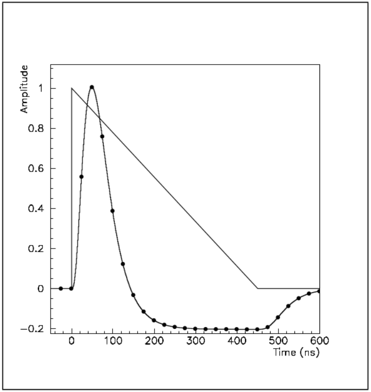
[2]

- Radiation at the HL-LHC will attain levels that the calorimeter electronics were not designed to sustain.
- The current readout electronics are incompatible with the requirements of the planned upgrade of the trigger system.
  - A complete overhaul of the electronics is therefore required.
- My research is on the optimization of the new readout electronics parameters of the Hadronic Endcap (HEC).



[3]

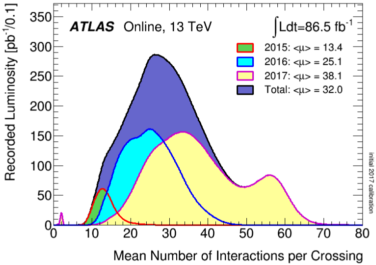
- Ionization of LAr in the gaps produces a triangular signal due to the drift of the electrons.
- Signals from multiple LAr cells then summed to form **readout channels**.
  - 5162 channels divided in ϕ, η (pseudorapidity) and 4 layers (HEC1, HEC2, HEC3 and HEC4).
- Signal then preamplified and shaped by CR-RC^2 shaper.
- Resulting pulse shape is then sampled by an ADC every 25 ns.



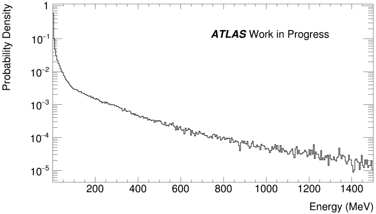
[4]

Pileup Noise

- At every bunch crossing (BC), many minimum bias events which produce secondary particles.
  - Energy deposited by these particles in a channel piles up on top of the desired signal.
  - At HL-LHC: up to $\mu = 200$.
- Main challenge: mitigating the increased pileup noise at the HL-LHC through analog and digital filtering.



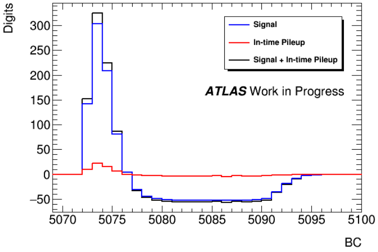
[5]

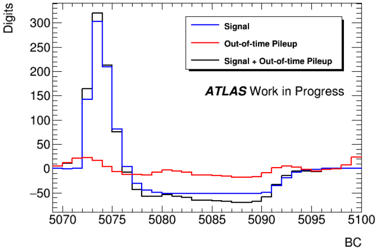


Probability distribution function for a single minimum bias event in a HEC channel in layer 1, $\eta = 2.35$.

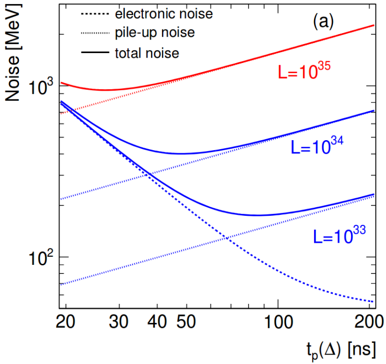
In-time and out-of time Pileup

- Pileup will add up on the signal.
  - In-time pileup: appears as though more energy deposited than there really was.
- Interval between bunch crossings is 25ns, but pulse shape only returns to baseline after 450ns.
  - Out-of-time pileup: signal distorted in non-trivial way.
  - Note: bipolar pulse shape integrates to zero.





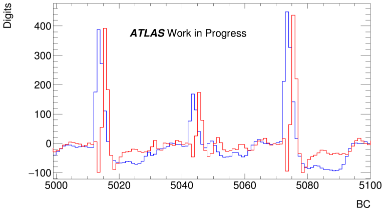
- Shorten shaping time → reduce pileup noise.
- However → increase thermal noise.
  - "Fourier Uncertainty Theorem".
- HEC channels cover wide range of pileup vs thermal noise conditions.
  - Impractical to fine-tune the filter or the shaping time on a channel-by-channel basis.
- Fine-tuning of the pulse shape can be done with digital filtering.



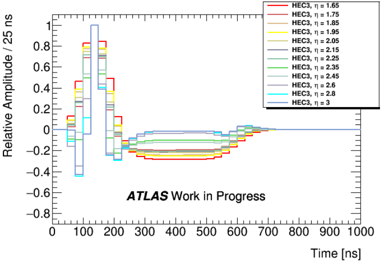
[6]

Optimal Filter

- Optimal Filter (OF): FIR filter that optimizes the width of the sampled pulse shape to minimize thermal vs pileup noise.
  - Coefficients depend on the pulse shape, pileup and thermal noise and their autocorrelation functions.
  - Coefficients are calculated for each channel and ideally each pileup condition.
- As we increase in η in a layer of the HEC for $\mu = 200$, the output pulse of the OF becomes narrower.
  - Pileup noise increases with η.

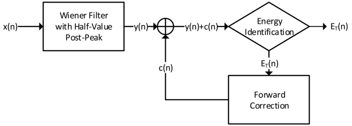


ADC & OF output for HEC layer 1, $\eta = 2.35$ & $< \mu >= 200$

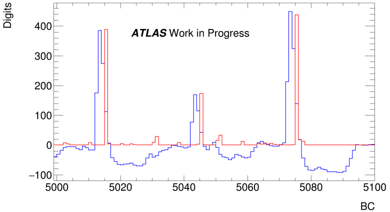


Output of the OF in HEC layer 3 at $\mu = 200$

- Wiener Filter with Forward Correction (WFFC): FIR filter with an IIR extension.
- Deconvolutes the energy deposit at every BC from the pulse shape.
- Extension corrects for negative undershoot.
    - Only outputs a values if its energy identification algorithm detects a signal.



[7]

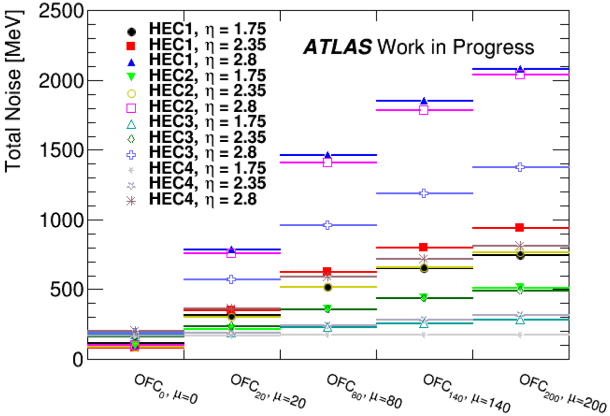


ADC & WFFC output for HEC layer 1, $\eta = 2.35$ & $<\mu>= 200$

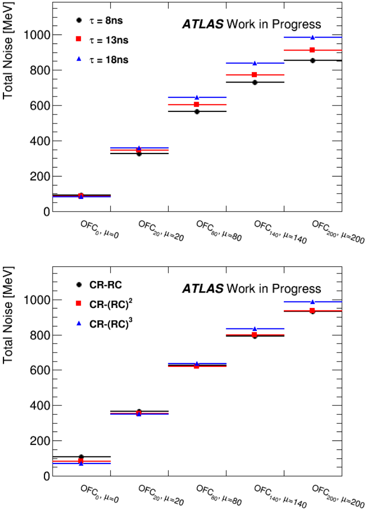
Simulation

- Energy resolution of HEC channels is simulated using the Atlas Readout Electronic Upgrade Simulation (AREUS).
- Analytical description of the pulse shapes and thermal noise power spectral density:
  - Allows for precise simulation of the whole HEC calorimeter.
  - Allows flexibility in tuning the different parameters and components of the electronics chain.
- Minimum bias distributions allow the flexibility to generate data at any $< \mu >$.
- Energy deposits converted to ionization signal, shaped and sampled, taking into account the quantization error of the ADC, and digitally filtered.

- Front layers and at high η: pileup noise increases greatly as μ increases.
- Rear layers and low η: thermal noise remains comparable to pileup noise even at $\mu = 200$.



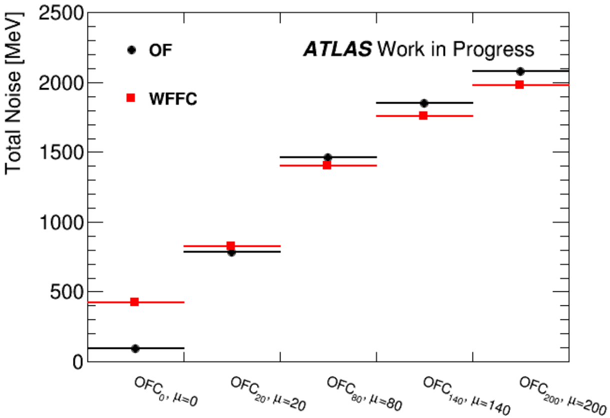
- Pulse shapes with shorter shaping times perform better at high pileup.
- Decreasing shaping time to 8ns improves the energy resolution by 5.5% while adding an RC filter has minimal benefits.



HEC layer 1, $\eta = 2.35$

WFFC

- WFFC can outperform the OF by 5%.
- Caveat: the WFFC is in IIR filter.
  - Needs safeguards to ensure it can be reset if its expected behavior is compromised.
  - Requires additional hardware resources.



HEC layer 1, $\eta = 2.8$

Summary

- A tool was developed that can accurately simulate and test the performance of the readout electronics of the HEC at HL-LHC.
- The energy resolution of the HEC can be tuned by changing different parameters of the analog and digital filtering chain:
  - The analog shaper.
  - The shaping time of the pulse shape.
  - The digital filter.
- Many other parameters have been tested, such as:
  - The sampling rate of the ADC.
  - The filter depth of the digital filters.
  - Etc.
- All results presented in the ATLAS Phase-II TDR.
- Next steps:
  - Develop/test new DSP algorithms to try further reduce the impact of out-of-time pileup.
  - Work on hardware prototyping.

Questions?

References I

[1] https://hilumilhcds.web.cern.ch/about/hl-lhc-project.

[2] The ATLAS Collaboration.
The atlas experiment at the cern large hadron collider.
Journal of Instrumentation, 3(08):S08003, 2008.

[3] D M Gingrich.
Construction, assembly and testing of the atlas hadronic end-cap calorimeter.
Journal of Instrumentation, 2(05):P05005, 2007.

[4] The ATLAS Collaboration.
ATLAS liquid-argon calorimeter: Technical Design Report.
Technical Design Report ATLAS. CERN, Geneva, 1996.

[5] https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResultsRun2.

[6] G Broijmans, H Chen, M Citterio, M Fincke-Keeler, J Kierstead, F Lanni, F G Oakham, H Oberlack, G Perrot, M Raymond, J P Rutherfoord, P Schacht, A Straessner, and J Ye.
ATLAS Liquid Argon Calorimeter Upgrade Plans.
Technical Report ATL-LARG-INT-2010-009, CERN, Geneva, Aug 2010.

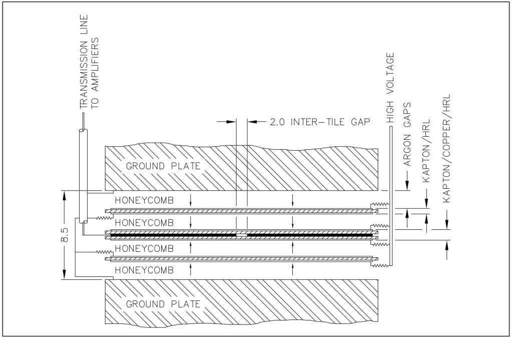
ATLAS Calorimeter Electronics Upgrade
Alessandro Ambler
Introduction
HEC Electronics
Pileup Noise
Digital Filtering
Results
Summary
References
Backup

[7] Johannes Philipp Grohs and Arno Straessner.
Simulation of the upgraded Phase-1 Trigger Readout Electronics of the Liquid-Argon Calorimeter of the ATLAS Detector at the LHC, Jun 2015.
Presented 29 Feb 2016.

[8] L. Kurchaninov.
Modeling of the HEC Electronics Chain.
HEC Notes. CERN, Geneva, 2001.

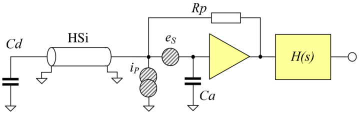
The Hadronic Encap Calorimeter

- The HEC is a LAr and Copper sampling calorimeter.
  - Copper plates act as absorbing material creating particle showers.
  - Charged particles in the shower traversing the gaps ionize the LAr.
- The LAr gaps are instrumented with electrodes.
  - The copper absorber plates are grounded.
  - High voltage electrodes create an electric field within the gap.
  - The electrons drift towards the central electrode creating a voltage drop.
  - Signal is read out through the transmission line.

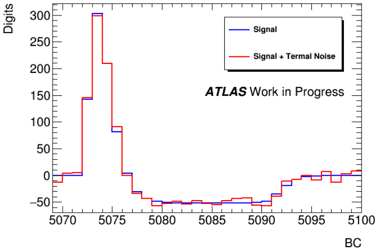


[4]

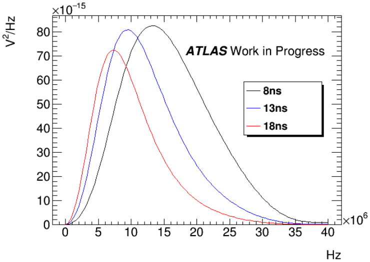
- Thermal noise introduced at the level of the preamplifiers.
- Can be modeled as two independent sources of white noise.
  - Parallel current noise (i_p).
  - Serial voltage noise (e_s).
- Reflections in the signal cables (*HSi*) and flicker noise in the preamplifier chips are also taken into account.
- This white noise is shaped through the rest of the electronics chain.

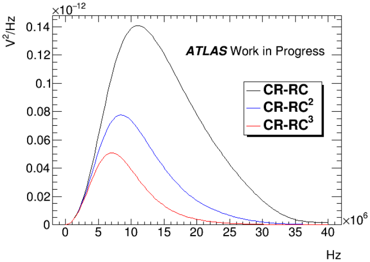


[8]



- Shaping time of pulse has large impact on the power spectral density of the noise.
- Shaping time affected by:
  - Varying the time constants in the CR-RC^2 filter.
  - Adding/removing RC filters.
- "Fourier Uncertainty Theorem": a wider pulse means a narrower frequency spectrum.
  - A pulse shape with a broader peak cuts out more high frequency thermal noise.
  - Increasing the time constants of the CR-RC^2 filters or adding RC filters narrows the power spectral density of the noise.





ATLAS Calorimeter Electronics Upgrade
Alessandro Ambler
Introduction
HEC Electronics
Pileup Noise
Digital Filtering
Results
Summary
References
Backup

- Digital filter: takes a sequence of samples ($x(n)$)(from an ADC for example) and manipulate them in some way to output a sequence ($y(n)$) that enhances or reduces certain aspects of the signal.
- Two main types of digital filters:

- Finite Impulse Response (FIR).
  - Applies a set of N coefficients a_k to an input sequence.

$$y(n) = \sum_{k=0}^{N-1} a_k x(n-k)$$

- Infinite Impulse Response (IIR).
  - Also applies a set of M coefficients b_l to previous outputs of the filter.
  - This filter has memory.
  - Any output will affect all future outputs.

$$y(n) = \sum_{k=0}^{N-1} a_k x(n-k) + \sum_{l=1}^{M} b_l y(n-l)$$