Development and Implementation of Optimal Filtering in a Virtex FPGA for the Upgrade of the ATLAS LAr Calorimeter Readout

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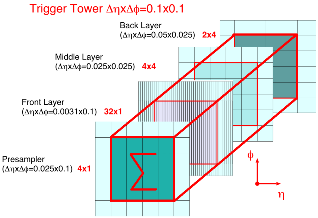
Overview

Motivation

- Upgrade to HL-LHC in two phases ($\approx 2015, \approx 2020$)
  - $L = 10^{34} \times (1 \rightarrow 2-3 \rightarrow 5-7)\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

$\Rightarrow$ new readout electronics for ATLAS Liquid Argon Calorimeters required

- $\Rightarrow$ provide finer granularity to Level-1 trigger system
  - 4 individual calorimeter layers, finer segmentation
- $\Rightarrow$ improve resolution for trigger objects like electrons, photons, jets, missing transverse and total energy
- $\Rightarrow$ reduce trigger rates from background

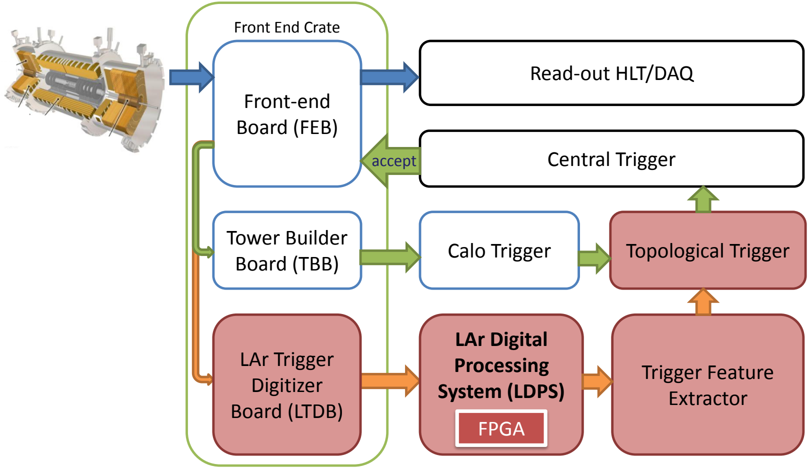


The Challenge

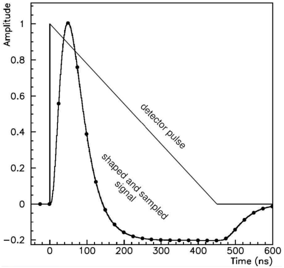
- fully digitized readout (Super Cells)
- $\approx$ 60000 trigger readout channels
- 40 MHz sampling rate

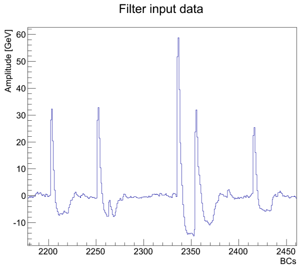
Proposed readout architecture for LAr Barrel and Endcap

Red: new readout modules for Phase-I; other colours: current readout modules



Signal Filter Requirements



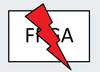


Filter Requirements in Upgrade Scenario

- noise suppression
- correction for out-of-time pile-up
- identification of the correct bunch crossing (BC)
- continuous ADC samples at 40 MHz
- tight latency budget (6 BCs $\approx 150\mathrm{ns}$)

Possible filters

- adaptive filters: adjust transfer function on the fly
  - ⇒ reference signal required, but relatively long transition time
  - ⇒ massive matrix multiplications



→ bad for FPGA resources

- (non adaptive) FIR filters: calculate coefficients in beforehand
  - ⇒ reference signal required, but stable, fix response delay
  - ⇒ multiply-add structures

→ good for FPGA resources

- something in between: IIR filter, Heuristic filter, Wiener filter, ...

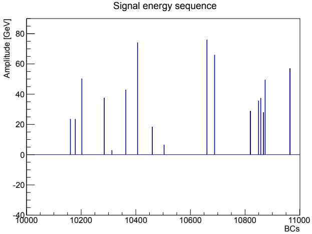
Filter simulation input data generation

- simulated flat signal energy spectrum: 0 - 80 GeV
- pile-up spectrum: 0 - 14 GeV (power-law parametrization [1])

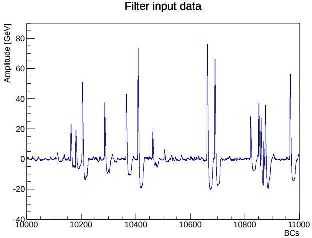
× pulse shapes from detector simulation (LAr Super Cells, Barrel, 2nd Layer)

+ noise RMS: 200 MeV [2]

⇒ sequence of 1M BCs



⇓

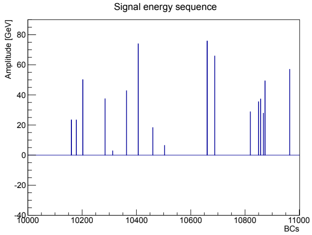


[1] The CMS Collaboration: Measurement of charged hadron spectra in proton-proton collisions at $\sqrt{s} = 14\ \mathrm{TeV}$

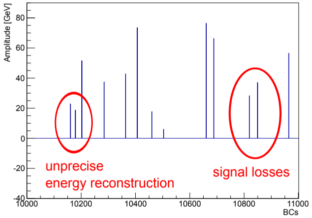
[2] Georges Aad et al: Performance of the electronic readout of the ATLAS liquid argon calorimeters

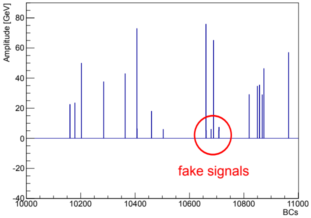
Filter simulation results

simulated input energy spectrum:



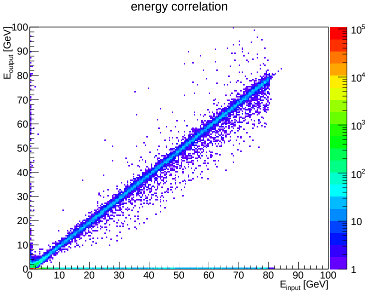
possible filter results:

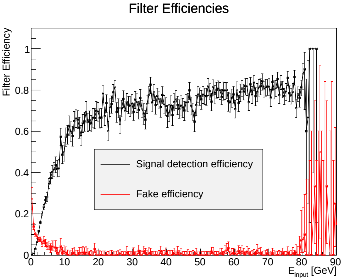




5-staged FIR filter with shape detection

- similar to current implementation in ATLAS LAr Read-Out Driver
- $E = \sum_{i=1}^{5} a_i \cdot (S_i + Ped_i)$
- shape detection: $E \geq 0$ and at least 4 samples compatible with pulse shape g_i: $|S_i - g_i E| < \frac{1}{2^N} |g_i E|$ (easy to implement in FPGA)

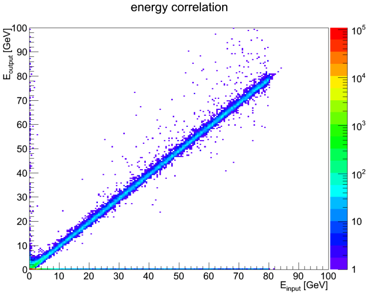


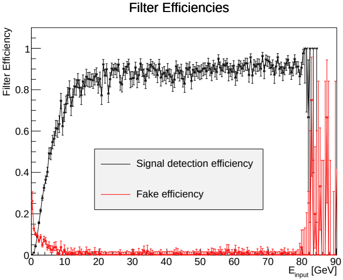


- pile-up enlarges energy spread, poor signal detection efficiency

FIR filter with shape detection and forward correction

- if signal found → correct subsequent samples for known pulse shape: $S_i \rightarrow S_i + \sum_{k,j} g_{k,j} E_k$

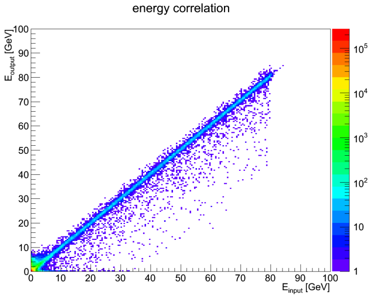


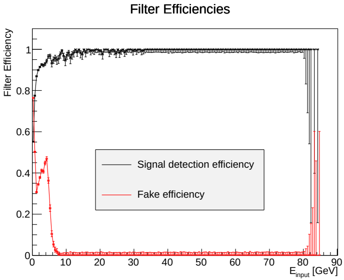


- more precise, improved detection efficiency

3-stage FIR: peak detection (derivative approach)

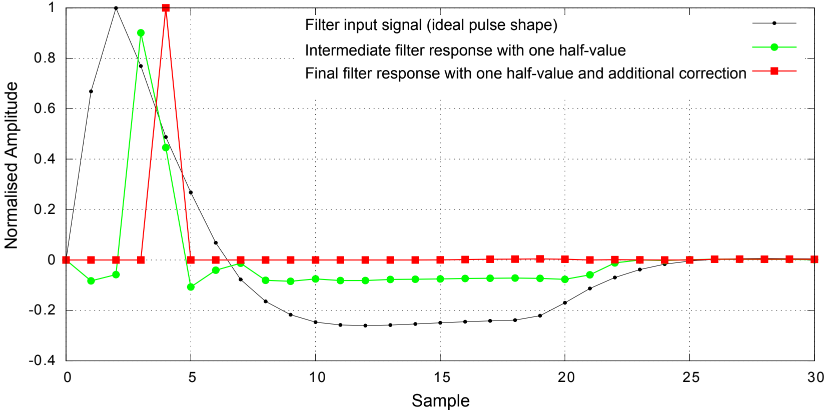
- derivative approach: $E = \frac{w_1}{2} \cdot (S_{i+1} - S_i) - \frac{w_2}{2} \cdot (S_i - S_{i-1})$
- weights depend on pulse shape





- less precise than FIR with shape detection
- fakes only signals at small amplitudes
- almost no signal losses

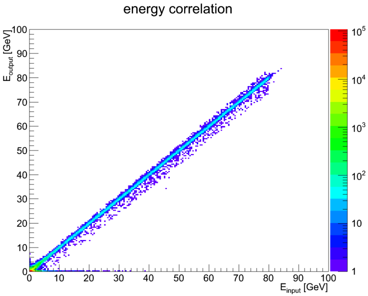
Wiener filter (FIR) with shape correction approach

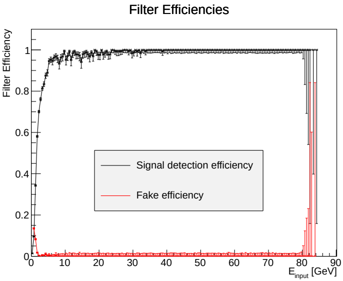


- Final filter response (red) after ≈ 6 BCs (picture shows simulation)

Wiener filter (FIR) with shape correction approach

- combines Wiener filter with internal trigger for shape correction (2 small FIRs and shift registers)





- excellent precision
- no fakes
- almost no losses

Other filters investigated

IIR Filter - discarded

- unstable in filter response (accumulating offset)

Inverse FIR Filter

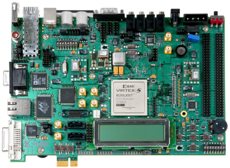
- very sensitive to pulse shape → second tiny peak (2%) after 9 BCs

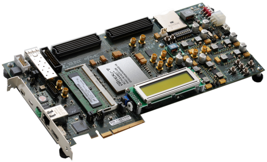
Heuristic Filter

- pile-up suppression by correcting for the history of up to 8 events in 25 BCs

Implementation

- Xilinx Virtex-5, 6 and 7 (ML505, ML605, VC707)





Implementation framework

- Interface with Gigabit Ethernet (UDP/IP)
- Input data buffered in RAM
- Online updatable filter coefficients (SRLC32E)

Resource utilization

Resources for 1 filter unit

filter	DSPs	Slice LUTs	latency (clk/BCs)	max. channels
FIR (shape)	10	$\approx$ 400	42/5.25	8*280
peak FIR	3	ongoing	28/3.5	8*933
Wiener	16	$\approx$ 430	46/5.75	8*175

- All filters use 8-fold multiplexing (40 MHz LHC vs. 320 MHz FPGA)
- Channel estimates for Xilinx VC707 Evaluation board (VX485T-2 with 2800 DSPs and 75900 Slices)
- ATLAS LAr requirement: 1280 channels per FPGA $\rightarrow$ fulfilled

Summary and Outlook

Filter summary

- Wiener filter with shape correction shows best performance
- FPGA resource utilization varies a lot for different filters, but all implementations fulfill ATLAS LAr requirements
- Latency budget met by all filters by design

Future tasks

- Simulation with different physics scenarios
- Simulation of different detector regions
- Pulse saturation effects are under study

The last slide

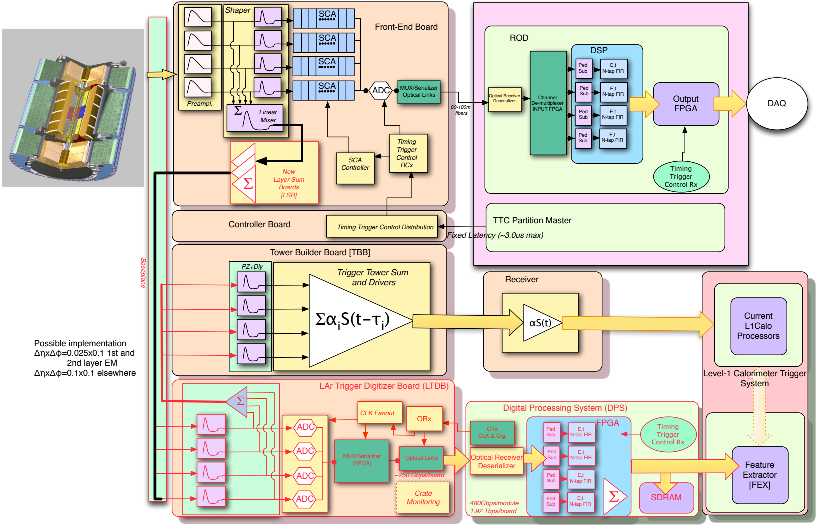
Thanks for your attention!

Your feedback is welcome at any time!

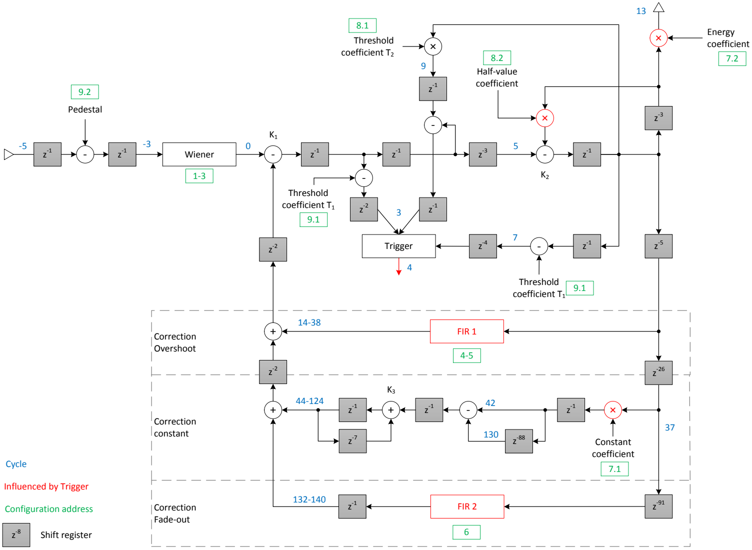
Questions?

Proposed readout architecture for LAr Barrel and Endcap

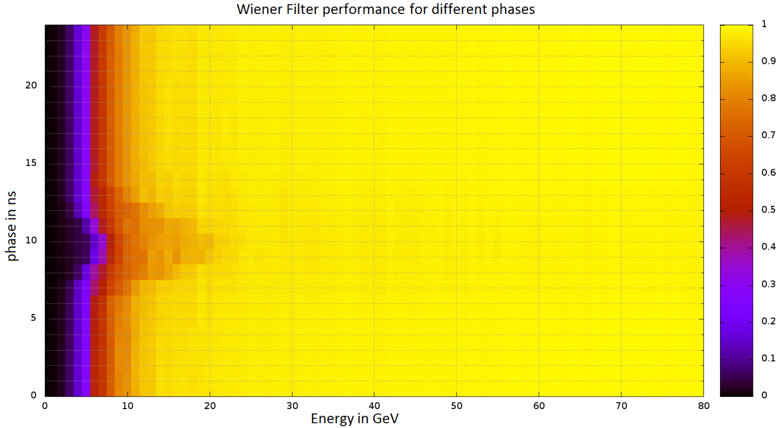
Black: current readout modules; Red: new readout modules for Phase-I



The Wiener filter design in more detail



The Wiener filter phase dependence

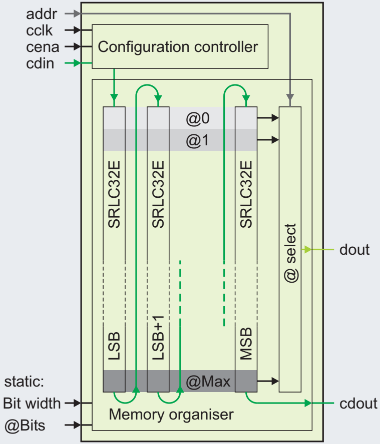


- quality plot: product of precision, inverse fake efficiency and signal detection efficiency

Coefficients module

Updatable coefficients

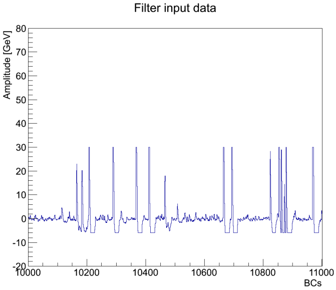
- requirements:
  - instant readout
  - rewritable entries
  - → updatable LUT
- solution:
  - SRLC32E module
- side-effect:
  - 32 addresses minimum
  - bitwise data input
  - changing bit order
  - → offline calculation



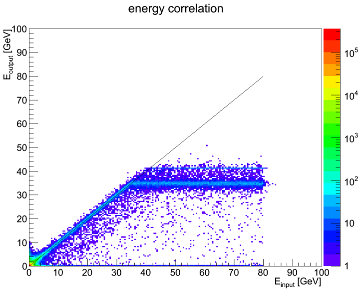
Saturation effects

Some thoughts

- Saturation: pulse changes shape → filters fail or suffer in performance
- Important for trigger: still identify correct BC
- energy reconstruction becomes less important in saturated region
- currently discussed: combination of linear and non-linear amplification region



→ 3-stage FIR



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