Future of the ATLAS Liquid Argon Calorimeter

Christopher Anelli
on behalf of the ATLAS experiment

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University of Victoria
Liquid Argon Calorimeter

Sampling Calorimeters

- **EMB**: LAr - Lead, $|\eta| < 1.475$
- **EMEC**: LAr - Lead, $1.375 < |\eta| < 3.2$
- **HEC**: LAr - Copper, $1.5 < |\eta| < 3.2$
- **FCAL**: LAr - Copper, $3.1 < |\eta| < 4.9$ and LAr - Tungsten

- 182,500 channels.
- The layers of each module have different granularities.
- Largest fraction of energy deposited in middle layer. (EM Calo)
- Fine granularity used to reconstruct incident particle’s direction.
• Drift electrons induce triangular pulse, amplitude proportional to deposited energy.

• Pulse passed through Bipolar CR -(RC)^2 filter, with programmable shaping time. (baseline 13 ns)

• 25 nano-second sampling.

• High energy particles shower in the calorimeter, ionizing the LAr.

• HV readout electrodes placed between grounded absorbers.

• Drift gap of 2.1 mm corresponding to electron drift time of 450 ns (for EM Calo)
Improvements to the LAr Calorimeter are currently under way, with Canadian institutes actively involved:

- For Phase-I Upgrade calorimeter signal is split between new “SuperCell” based LAr Trigger Digitizer Boards (LTDB) and legacy Tower Builder Boards (TBB).
- SuperCells are groupings of calorimeter cells offering:
  - Finer Granularity
  - Layer Information
- Will improve trigger efficiencies and reduce trigger rates while maintaining or even lowering trigger thresholds.
- Splitting between the two trigger electronics requires new baseplanes.
- Baseplanes for the HEC were designed at TRIUMF and tested at the University of Victoria.
High Luminosity LHC

Phase-II Upgrade and HL-LHC:

- 7.5 \times 10^{-34} \text{ cm}^{-2}\text{s}^{-1} peak luminosity.
- 25 \text{ ns} bunch spacing (40 MHz)
- Expected integrated luminosity of 4000 fb\(^{-1}\) (over ~12 years)
- Up to 200 average minimum bias events per bunch crossing
- Increased radiation damage to detector
Upgrade Motivation

Technical Motivations:

Preserving physics reach (i.e., Higgs) for higher data taking rates requires updated triggers:

• Current readout electronics are incompatible with new Trigger System. Upgraded triggers require higher trigger rate (1MHz), longer latency, and higher granularity calorimeter information.

• Existing front-end electronics will reach the limit of their radiation tolerance before the end of the HL-LHC.

Performance Example:

Simulation shows upgraded ATLAS detector can maintain sensitivity to golden, H-> γγ channel.

Optimistic scenario: increased statistics reduce global constant term to design value, 0.7%.

Pessimistic scenario: term remains same as 2015, 1% barrel and 1.4% endcap.

\[
\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c
\]
Existing readout electronics will be completely replaced:

Front-End

- Pulse shaping optimized to minimize total noise.
- New calibration board.
- Full granularity, each cell is digitized and sent to the backend.

Off Detector

- New, LAr Signal Processor (LASP) board to process digitized inputs and output energy and timing information.
- Information is sent from the LASP to new, L0 Triggers.
Front-End Design

The Front-end board has separate ASICs for the Preamp/Shaper, Digitization, Serialization, and Optical Transmission:
The Preamplifier and Shaping will be implemented on a single ASIC.

- 65 nm and 130 nm CMOS prototypes have both been explored.

### 130 nm

- Linearity better than 0.5%, up to 7 mA.

### 65 nm

- Linearity better than 0.2%, up to 10 mA.

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**Final design will be on a 130nm chip merging aspects of both prototypes.**
The LAr cell’s electronic noise must be less than MIP signal. Requiring ADC’s least significant bit (LSB) value to be less than electronic noise leads to a dynamic range 16 bits wide.

- Readout electronics utilize 14 bit ADCs.
- To cover 16 bit range a two gain system is utilized.
- Energy of gain switching chosen so photons from $H \rightarrow \gamma\gamma$, have the same gain as electrons from $Z \rightarrow ee$ (used for energy scale calibration.)
Digitization handled by 40 MHz, 14 bit, radiation hard, ADC. ASIC consists of:

- Dynamic Range Enhancement block (+2 bits), DRE.
- Successive Approximation Register block, SAR.

- Have tested ENOB at 20 MSPS.
- Digitization of simulated pulses by the ADC.
- Commercial ADC IP blocks may be available for purchase.
In the back-end, Phase-II Upgrade introduces new LAr Signal Processor (LASP) based on FPGA technology:

- Processes digitized waveforms from each of the calorimeter cells.
- Digital filtering algorithms to calculate energy and timing of LAr pulse.
- Interfaces to L0, hardware triggers and Data Acquisition (DAQ).
- Buffer data while awaiting trigger decision.
Each LASP module contains two LASP units each with its own processing FPGA:

- LASP board design is based on Advanced Telecommunication Computing Architecture (ACTA)
- Each unit includes detector-optical receiver and transceiver arrays.
- FPGA takes inputs from up to 4 FEBs, covering 448-512 calorimeter cells.
- A test board is being developed based on the Intel Stratix 10 FPGA.

Desire reliability: so LASP processors will not need to be replaced over 10+ years of operation.

Stratix 10 Development Kit
• Current digital filtering algorithm uses **optimal filtering coefficients (OFC)**, to extract each cell’s energy and timing information.

• In some cases, other algorithms such as the **Wiener Filter**, may better suppress the pileup noise. Studies are ongoing.

\[
A = \sum_{i=1}^{5} a_i(s_i - \mu) \\
A \tau = \sum_{i=1}^{5} b_i(s_i - \mu) \\
\chi^2 = \sum_{i=1}^{5} [a_i(s_i - \mu)]^2 - E \sigma_i - E \tau \sigma_i \\
\]

*Only 4 samples used since Run-2*
LAr Calorimeter interfaces with the L0 (L1) triggers:

- Data bandwidth and links to the FPGA depends on the number of cells transmitted to the trigger.

- For the L0 global trigger, an energy threshold of 2 times the cell noise, $2\sigma$, is applied.

- For $2\sigma$ threshold $\sim$5.5% of cells are normally transmitted.

- However, high energy particles or noise bursts can cause individual FPGAs to transmit a significantly greater fraction of cells.

- Planned bandwidth sufficient to transmit 30% of cells, $\sim$153.

- Also requires bit pattern (512 bits) reflecting which cells are above threshold.

- Total per LASP module bandwidth to the L0 Global Trigger is expected to be 102.4 Gbps.
Beyond the Phase-I Upgrades and Run 3 the LAr Calorimeter will remain critical to ATLAS physics during the HL-LHC. In preparation for the full-replacement of the LAr Readout Electronics:

- A new Technical Design Report of the LAr Phase-II Upgrades has been prepared.
- Tests of first prototype front-end components.
- Simulation of off-detector readout and expected LAr Calorimeter performance.
- Results are guiding new ASIC design and test board construction.
- Target is for system installation during 2024-2025 of LS3.
Backup Slides
• Review: the amplitude of the LAr readout electronic’s pulse shape scales with energy.

• Amplitude is calculated from 5 samples, each weighted by an optimal filtering coefficient, $a_i$.

$$U = \sum_i a_i S_i$$

• Knowing the shape of the normalized pulse, the optimal filter sets the coefficients to minimize the uncertainty on $U$, $\text{Var}(U)$.

$$\text{Var}[U] = \sum_{ij} a_i a_j R_{ij}$$

• Subject to the constraints:

$$\sum_i a_i g_i = 1 \quad \sum_i a_i g_i' = 0$$

Becomes a minimization problem with 2 Lagrange multipliers.
One finds that optimal filtering coefficients are defined as:

$$a_i = \lambda R^{-1}_i g + \kappa R^{-1}_i g'$$

Where the Lagrange multipliers are also functions of the pulse shape and the inverse autocorrelation function.

$$\lambda = \frac{Q_2}{\Delta} \quad \kappa = \frac{-Q_3}{\Delta}$$

$$Q_1 = g^T R^{-1}_i g \quad Q_2 = g'^T R^{-1}_i g' \quad Q_3 = g'^T R^{-1}_i g \quad \Delta = Q_1 Q_2 - Q_3^2$$

The autocorrelation function, $R_{ij}$, is a weighted combination of the electronic and PU autocorrelation functions, that depends on the variance of the pileup energy distribution.

$$R_{ij} = \frac{R_{ij}^e + \mu \left( \frac{(\sigma_{MB})^2 + (\mu_{MB})^2}{f_{sampl}^2 (\sigma_e)^2} \right) \sum_k g_{k-i} g_{k-j}}{1 + \left( \frac{(\sigma_{MB})^2 + (\mu_{MB})^2}{f_{sampl}^2 (\sigma_e)^2} \right) \sum_k g_k^2}$$
Dynamic range:

A few studies can be performed to cross-check the current conclusions. The extrapolations based on Monte Carlo on the maximum currents expected can be cross-checked using 2016 data (extrapolation of dijet spectra). For the tails of the electron distributions, simulation of single high-$|p_T|$ electrons clusters is ongoing, and can be used for the TDR.

For the HEC, the absence of saturation will be checked at the preamplifier level. As this information is not kept in the standard ATLAS simulation, where only the summed signals are present, a dedicated setup will have to be used.

Gain switching

The main driver for setting the gain switching at specific energies is the extrapolation of the electron energy scale from the calibration on the $Z$ peak to the photon energies of $H\to\gamma\gamma$ decays. As a result, $H\to\gamma\gamma$ Monte Carlo samples can be used to estimate in every layer and calorimeter region the energy for which most of the photons would end up in the high gain. After the rest of the parameters is set (LSB and max of dynamic range), it can be studied which gain and ADC schemes would fit this requirement. Since the calorimeter measures energy rather than transverse energy, the noise has significant pseudorapidity dependence, as shown in Figure 4. The consequence is that, if one LSB value is fixed for the full calorimeter, the dynamic range to be covered by the high gain may be too large. An option to investigate is to set the LSB and gain switching energy in a few large bins in pseudorapidity to relax the requirements on the electronics.

Total Noise in the LAr readout electronics combines electronic noise and as well pileup (in-time and out-of-time) noise.

The noise varies by subdetector, $|\eta|$, and layer.

For the L0 global trigger, there is proposed energy threshold on the calorimeter cells, of twice the cell’s total noise, $2\sigma$. 