Phase-II Readout Electronics Upgrades of the ATLAS LAr Calorimeter

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Abstract

The high-luminosity LHC will operate at 5-7 times the luminosity of the original design. New readout electronics for the ATLAS LAr calorimeter are necessary due to the increased radiation damage and for compatibility with the new trigger system. The 182,500 LAr calorimeter cells will be readout at 40 MHz with a 16 bit dynamic range. First prototypes of the front-end electronics using 65 and 130 nm CMOS technologies have been tested. Design studies of the off-detectors digital filtering algorithms and bandwidth requirements have been performed. An overview of the LAr Phase-II electronic design is presented.

Keywords: ATLAS, Phase-II Upgrade, Calorimetry, Liquid Argon Calorimeter, Readout Electronics

1. Introduction

Following the planned upgrade to the high luminosity LHC (HL-LHC) in 2026 instantaneous luminosities will increase to $7.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, and over a 12 years period 4000 fb^{-1} of data is expected to be collected by the ATLAS experiment. Increased radiation damage to the detector will cause components of the current front-end electronics to reach their radiation tolerance before the end of the HL-LHC. Higher luminosity will produce more events above the current trigger thresholds, and with the average number of interaction per bunch crossing expected to reach as high as $\langle \mu \rangle = 200$ there will be increased pileup noise. In order to preserve physics performance, the HL-LHC is upgrading to a new trigger system that will require higher trigger rates, longer latency, and more granular calorimeter information. Where the current readout has a latency of $2.5 \mu\text{s}$ for the level-1 trigger and a maximum readout rate of 100 kHz, the HL-LHC trigger system will have level-0 (level-1) triggers requiring 10 (35) μs latency and a maximum readout rate of 4 (0.8) MHz. In addition, for the first time the trigger will utilize the full granularity of the LAr calorimeter. For the

two reasons of increased radiation damage and incompatibility with the new trigger system, a complete replacement of the readout electronics is planned for the Phase-II upgrades.

2. LAr Calorimeter

As shown in Figure 1, the LAr calorimeter consists of four sub-detectors: the electromagnetic barrel and end-cap (EMB, EMEC), the hadronic end-cap (HEC), and the forward calorimeter (FCAL). All four sub-detectors are sampling calorimeters with liquid argon as the active material and absorbing layers of lead for the EMB and EMEC, copper for the HEC, and both copper and tungsten absorbers for the FCAL. The EMB covers a region of $|\eta| < 1.475$, the EMEC $1.375 < |\eta| < 3.2$, the HEC $1.5 < |\eta| < 3.2$ and the FCAL $3.1 < |\eta| < 4.9$.

There are 182,500 channels in the full LAr calorimeter system. As shown on the lower half of Figure 1, the layers of each module have different granularities. The fine granularity in the first layer aids in reconstructing the incident particle's direction and is useful for discriminating prompt photons from π^0 decays. The Electromagnetic calorimeter (ECAL) is further designed so that the bulk of the EM shower is deposited in the second layer, whereas only the tail of the shower is collected in the third layer. The characteristic accordion geometry of the ECAL is azimuthally hermetic, and with its pointing nature, allows the calorimeter to reconstruct the direction of neutral particles such as photons.

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Figure 1: The ATLAS LAr calorimeter system (top). A sketch of an EMB module where the $|\eta|$ and ϕ granularity for each of the layers is shown (bottom) [1].

3. Operation

High energy particles shower in the calorimeter ionizing the liquid argon. HV readout electrodes are placed in the liquid argon between grounded absorbers. The potential difference causes the ions and electrons to drift, inducing a triangular pulse, the amplitude of which is proportional to the deposited energy. For a 2mm gap between the ground and high voltage the electron drift time corresponds to approximately 450 ns. The triangular pulse is then amplified and passed through a bipolar CR-(RC)² shaper. The net integral of the shaped pulse is zero, allowing, on average, the out-of-time pileup contributions to cancel the in-time pileup contribution. The peaking time of the shaped pulse is approximately 50 ns.

4. Readout Electronics

Figure 2 shows a complete schematic of the Phase-II readout electronics. The readout electronics include the on-detector

Figure 2: Schematic of the LAr calorimeter readout electronics. Front-End Board (FEB) and LAr Signal Processor (LASP) will be installed in the Phase-II Upgrade, the LAr Trigger Digitizer Board (LTDB) and LAr Digital Processing System (LDPS) will be installed in the Phase-I Upgrade [2].

Front-End Boards (FEB) and the backend LAr Signal Processors (LASP).

4.1. Front-end

The front-end board (FEB) is responsible for amplification, pulse shaping, digitization, and transmission to the off-detector electronics. Each FEB handles 128 channels. This section describes the R&D and design for two of FEB's key ASICs, the Preamplifier-shaper and the Analog to Digital Converter (ADC).

Preamplification and shaping are implemented on a single ASIC. Two prototypes have been constructed and tested. The first design uses a 130 nm CMOS with a low noise, line terminating preamplifier. The second uses a 65 nm CMOS with a fully differential amplifier and passive feedback. Both prototypes show good linearity: the 130 nm is better than 0.5% up to 7 mA and the 65 nm better than 0.2% up to 10 mA. For the Phase-II upgrade, both designs will be merged into a 130 nm chip [2].

For Phase-II each cell is digitized at the bunch crossing rate. Digitization is handled by 40 MHz, 14 bit, radiation hard ADCs. Each ADC ASIC consists of a 12 bit SAR, and an additional 2 bit DRE block.

The readout must cover a wide range of cell energies from the energy of a minimum ionizing particle (MIP) to the maximum cell energies expected for hypothetical TeV scale particles. In addition, the least significant bit (LSB) of the ADC must be smaller than the electronic noise. As a result, covering the full range of energies requires a dynamic range of 16 bits, which can be achieved using a two gain system. Figure 3 shows the estimated quantization noise as a function of energy for the high and low gains. Gain switching occurs near the maximum energy digitized by the high gain, and is set such that photons from $H \rightarrow \gamma\gamma$ decays utilize the same gain as electrons from $Z \rightarrow ee$ decays used for energy scale calibration. This choice

reduces one of the dominant systematic uncertainties for measuring the Higgs boson mass.

Figure 3: Estimated quantization noise as a function of energy for the high (red) and low (blue) gains. Quantization noises are for the middle layer of the EMEC [2].

4.2. Back-end

The off-detector LASP processes digitized waveforms, selects a gain, implements digital filtering algorithm, interfaces with the trigger and data acquisition system (DAQ), and buffers the data while awaiting a trigger decision.

The LASP board design is based on the ACTA standard. Each LASP FPGA takes inputs from 4 FEBs and covers up to 512 calorimeter cells. The LASP is based on FPGA technology, and a test board is currently being developed using the Intel Stratix 10.

Digital filtering algorithms, implemented via FPGAs, process the sampled waveforms to extract energy and timing information. The Optimal Filter (OF) algorithm is currently used by the LAr calorimeter, but to deal with the increased pileup conditions more sophisticated algorithms capable of out-of-time pileup correction are also under study. Figure 4 compares simulated, cell noise for OF calculated energies to those calculated using a filter with out-of-time pileup subtraction, the Wiener Filter with Forward Correction (WFFC). As shown, for the high pileup scenarios, the WFFC can potentially outperform the OF.

For the interface with the level-0 (level-1) triggers, the LASP FPGA bandwidth depends on the number of cells transmitted. For the level-0 global trigger only channels above an energy threshold of twice the cell's noise (2σ), are transmitted. Implementing this selection criteria necessitates also transmitting a bit pattern of 512 bits to identify the cells that pass. Normally, $\sim 5.5\%$ of cells will be above the 2σ threshold, representing the slightly non-gaussian behavior of the energy distribution. However, as shown in Figure 5, for high energy particles or noise bursts the fraction of cells in an individual FPGA above threshold can be significantly greater. Accounting for this, the planned FPGA bandwidth will be sufficient to transmit 30% of the cells, corresponding to 102.4 Gbps sent to the level-0 global trigger.

Figure 4: Simulation of the total noise in different pileup scenarios for cell energies calculated with the Optimal Filtering algorithm (black) and the Wiener Filter with Forward Correction (red). The Optimal Filtering coefficients are optimized for each of the pileup levels. Noise values are for cells in the Endcap of the Hadronic Calorimeter with $|\eta|=2.8$ [2].

Figure 5: Number of cells in an individual FPGA above the 2σ noise threshold for minimum bias (Minbias) events (black) and for high energy dijet (red) and 4 TeV Z' (blue) events. Values are for an FPGA covering cells in the middle layer of the EMEC, $1.6 < |\eta| < 2.8$ [2].

5. Performance Studies

Simulations of the upgraded detector's performance have been done, in particular, for the important Higgs mass measurement in the $H \rightarrow \gamma\gamma$ channel. Figure 6 illustrates that the upgraded detector will be able to maintain the same level of sensitivity as achieved during Run-2.

Figure 6: Mass resolution from the $H \rightarrow \gamma\gamma$ channel. The Run2 scenario is shown in blue. Different HL-LHC scenarios for $\langle \mu \rangle = 0$ and $\langle \mu \rangle = 200$ are highlighted in red and green. Vertex selection is done with a neural network discriminant using track and photon information [2].

6. Summary

The LAr Calorimeter will remain a critical part of ATLAS physics throughout the HL-LHC. For the Phase-II upgrades, a full replacement of the LAr readout electronics is in progress. These upgrades are necessary due to the increased radiation damage and for compatibility with the new trigger system.

References

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