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ATLAS Trigger and Data Acquisition upgrades for the High Luminosity LHC

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Abstract

The ATLAS experiment at CERN is constructing an upgraded system for the "High Luminosity LHC", with collisions due to start in 2029. In order to deliver an order of magnitude more data than previous LHC runs, 7 TeV protons will collide with an instantaneous luminosity of up to 7.5 x 10e34 cm-2s-1, resulting in much higher pileup and data rates than the current experiment was designed to handle. While this is essential to realise the physics program, it presents a huge challenge for the detector, trigger, data acquisition and computing. The detector upgrades themselves also present new requirements and opportunities for the trigger and data acquisition system.

The design of the Trigger and Data Acquisition (TDAQ) system upgrade comprises: a hardware-based low-latency real-time Trigger operating at 40 MHz input rate, Data Acquisition which combines custom readout with commodity hardware and networking to deal with 4.6 TB/s input, and an Event Filter running at 1 MHz input rate which combines offline-like algorithms on a large commodity compute service with the potential to be augmented by commercial accelerators. Commodity servers and networks are used as far as possible, with custom ATCA boards, high speed links and powerful FPGAs deployed in the low-latency parts of the system. Offline-style clustering and jet-finding in FPGAs, and accelerated track reconstruction are designed to combat pileup in the Trigger and Event Filter respectively.

This document reports the recent progress on the design, technology and construction of the system.

1 Introduction

The Large Hadron Collider (LHC) will be upgraded to become High-Luminosity LHC (HL LHC) during a long experimental shutdown starting in 2026 and concluding with a return to operations at the start of 2029. During the run period (years of 2029-2041), high-pileup conditions (simultaneous p-p collisions) resulting in up to 200 events per proton-proton collision bunch-crossing are expected to occur and a total dataset of up to 4000 fb^{-1} will be collected.

In preparation for the HL-LHC, ATLAS is introducing new sub-detectors: the Inner Tracker (ITk) [1] [2], the High Granularity Timing Detector (HGTD) [3], and additional Muon chambers [4] will be added. The remaining sub-detectors will go through different electronics upgrades: the Liquid Argon (LAr) Calorimeter [5], the Tile Calorimeter [6], the Muon Spectrometer (MS) [4], and the TDAQ system [7] [8].

The HL-LHC environment will impose different challenges on TDAQ, among them are coping with higher pile-up as well as scanning and processing more complex events. The increase in detector coverage will improve the triggering capabilities, but the additional information available along with high pileup will come on the expense of having to deal with bigger sizes of events than in the current run (4.6 MB *vs.* 3 MB). The new Physics plan will still require identification of low momentum objects, and TDAQ will have to comply while maintaining the trigger rates sufficiently low in order to keep only the most relevant events. Furthermore, TDAQ will have to support both the new and upgraded sub-detectors as well as to accommodate their electronic constraints. All these requirements and more, were taken into account when designing the HL-LHC upgrade of the TDAQ system.

2 The HL-LHC Upgrade of TDAQ

TDAQ will be composed of 3 main systems: the Level-0 (L0) Trigger, Data Acquisition (DAQ), and the Event-Filter (EF). During operations, the data will flow from the sub-detectors and into the L0-Trigger systems at 40 MHz. Within 10 µs (*vs.* 2.5 µs today) the L0 systems will need to identify the different physics objects, calculate event-level physics quantities, form Trigger Objects (TOBs), and finally make the trigger decision which will then be propagated back to the sub-detectors in the form of a L0-Accept signal (L0A).

In response, both the sub-detectors and the L0 systems will transmit their complete event-data information through the DAQ system and into the EF at 1MHz (*vs.* 100 kHz today). The EF will reconstruct and select events matching specific acceptance criteria. Events passing the selection (event size of 4.6 MB *vs.* 3 MB today) will be transferred to permanent storage at the ATLAS Offline Computing Center at 10 kHz (*vs.* 3 kHz today). The overall architecture is shown in Figure 1.

2.1 L0 Trigger system

The L0 Trigger system is composed of 4 main systems: the L0 Calorimeter Trigger (L0Calo), the L0 Muon trigger (L0Muon), the Global Trigger, the Central Trigger Processor (CTP) and associated Muon Interface (MUCTPI). While each of these system have different responsibilities, they are all based on ATCA technology with processing algorithms running over FPGAs, and data routed through optical links at 9-25 Gb/s.

The L0Calo is responsible for identifying different physics objects (e.g. electrons, photons, jets) and calculates physics quantities (e.g. Missing E_T) based on calorimeter data. It is composed of 4 Feature EXtractors (FEX): electron FEX (eFEX), jet FEX (jFEX), global FEX (gFEX), all of which were installed for LHC Run 3, plus new HL-LHC addition, the forward FEX (fFEX) for additional trigger coverage in the forward region. Each of the FEXs will output the information in the form of TOBs, and transmit them to the Global Trigger for further processing.

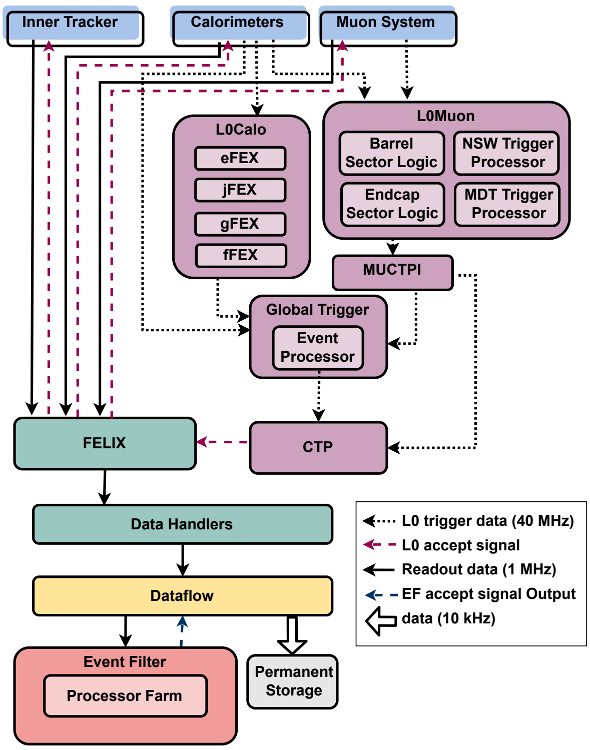

Figure 1: The TDAQ architecture for HL-LHC. Black dotted arrows indicate the L0 data flow from the sub-detectors and into the L0 trigger system. Red dashed arrows illustrate the L0A transmission to the detectors. Black solid arrows indicate the resulting trigger and sub-detector data transmission through the DAQ system [8].

L0Muon is composed of 4 Trigger-Processors (TP), 3 upgraded TPs: The RPC (Resistive Plate Chambers) Sector Logic (SL), the TGC (Thin Gap Chambers) SL, the NSW (New Small Wheel) TP, and a new system - the MDT (Monitored Drift Tubes) TP. The TPs will rely on full granularity data coming from all muon systems and a subset of data from the Tile Calorimeter. The RPC SL will use additional chambers to retrieve hit information and the MDT-TP will contribute data from the muon precision chambers, which is expected to result in higher quality trigger candidates without compromising on the trigger efficiency as demonstrated in Figure 2 (left). The candidate information will be then transmitted to the MUCTPI, (a legacy system with updated firmware) which will combine the information and form the final muon-candidate selection before transmitting it to the Global Trigger.

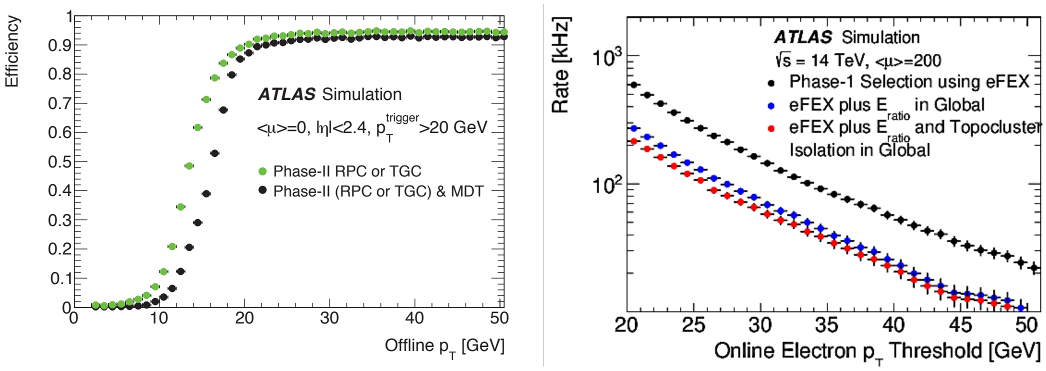

Figure 2: Left: L0Muon trigger ($\eta < 2.4$) efficiency with (black) or without (green) MDT information [7]. Right: Level-0 trigger rates for electrons, with (red, blue) and without (black) the Global Trigger [7].

The Global Trigger is a new system that will be included in the L0-Trigger chain. It will use information coming from the Calorimeters, L0Calo, and MUCTPI, at a total input rate of 50 TB/s. The data will first go through time-multiplexing in the Global MUX before passing through the Global Event Processor (GEP). The GEP will execute "offline-like" processing algorithm that will run on Xilinx Versal Premium FPGAs in order to identify physics objects (electrons, jets, tau-jets, Muons, Missing E_T), perform topological clustering, pileup subtraction and Anti-kT jet finding as well as refining the candidate identification from previous stages and performing topological selections. The additional processing step done by Global will make it possible to maintain low pT thresholds and trigger rates, as demonstrated in Figure 2 (right). The Global Trigger's output data will be transmitted to the CTP through a dedicated CTP interface. An illustration of the system is shown in Figure 3.

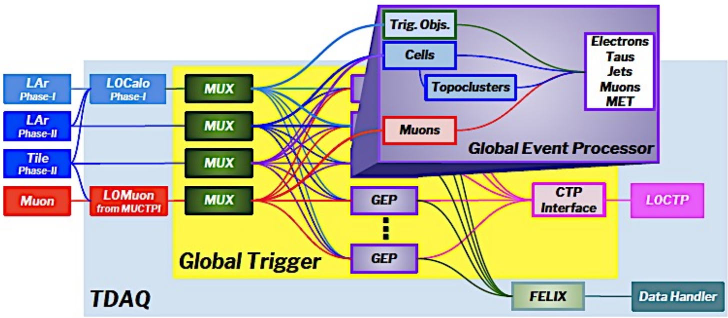

Figure 3: Illustration of the Global Trigger system processing and trigger decision flow [7].

The CTP is the final step in the L0-Trigger processing chain, and will be upgraded from VME to ATCA technology for HL-LHC. Serving as an interface with the LHC to receive the beam timing signals, it will also align and combine the different digital inputs (1024 *vs.* 512 today) coming from the Global Trigger, the MUCTPI and various forward detectors. The CTP will then make a final decision in the form of a L0A signal based on the trigger menu configuration, the prescale factors, and the recorded dead-time. The L0A will be transmitted at fixed latency to the ATLAS sub-detectors along with the 40 MHz beam synchronous clock through the Timing, Trigger and Control (TTC) system, using a new system - the Local Trigger Interface (LTI), and an upgraded Front End Link eXchange (FELIX) as illustrated in Figure 4.

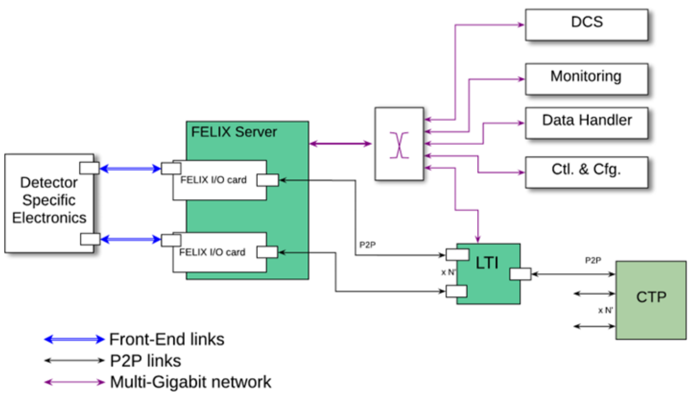

Figure 4: The Level-0 Timing and Control paths [7].

2.2 DAQ system

The DAQ system is composed of: FELIX, Data-Handlers (DH), Dataflow (DF), network and online software.

Once the CTP has made the L0-trigger decision, the L0A signal will be propagated to the different sub-detectors using FELIX, a system composed of PCs hosting FPGA I/O cards, that is responsible of propagating trigger and command signals as well as routing data into the DAQ system. In response to the L0A, both the sub-detectors and the L0 systems will submit their full event data through FELIX and into the DHs at 1 MHz rate, implying a total bandwidth entering the system of 4.6 TB/s. The DH will perform data formatting, subdetector specific process and preliminary aggregation prior transferring them to the DF system, which is in-charge of aggregating data from each DH system into complete events, before transporting them to the Event Filter and out to permanent storage as required, applying suitable compression. Both the DH and the DF systems are composed of commodity servers.

2.3 The Event Filter

Following an architectural review over recent years, the decision was recently made to change the Event Filter design from one which incorporated custom hardware-based tracking to one based on commodity technologies. The specific nature of these technologies, which may incorporate FPGA and GPU accelerators integrated with software running on commodity servers, will be decided in 2025 after a comprehensive analysis.

The EF will run event reconstruction algorithms on the input data provided by the DF at 1 MHz rate. Different reconstruction elements are being studied, among them are track reconstruction, topological cluster and muon reconstruction. The main goal is to improve reconstruction performance while keeping CPU-usage low. An example of the types of studies under way include that shown in Figure 5, which compares the performance of an upgraded tracking software prototype with a legacy tracking implementation.

Once the reconstruction is complete and the EF has made the final event selection decision according to the trigger menu, the selected events will be transferred through the DF systems and into ATLAS permanent storage at a rate of 10 kHz.

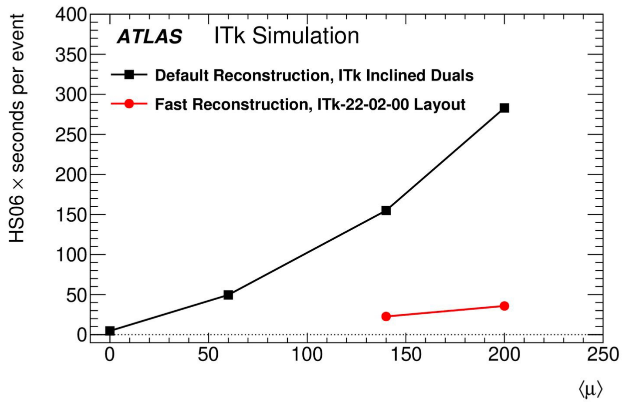

Figure 5: CPU-usage comparison for track reconstruction as a function of average pile-up, using: (black) the tracking software available at the beginning of HL-LHC planning (2017) *vs.* (red) an upgraded software prototype (2022) [8].

3 Conclusions

The ATLAS TDAQ system is being extensively upgraded ahead of the start of the ATLAS HL-LHC program. The experienced gained from the Run 3 upgrades and the Run 3 itself are being used to further improve the HL-LHC TDAQ design and implementation plan. Based on dedicated studies, the introduction of the Global Trigger into the L0 system will refine the event selection, allow the physics menu to include low momentum objects while keeping reduced trigger rates in order satisfy storage and throughput constraints. The new as well as upgraded firmware and software will include more sophisticated algorithms, and will improve triggering capabilities as well as the object reconstruction. Moreover, the increase in detector coverage, available higher-granularity input data, inclusion of information from new detector system at trigger level, and usage of more advanced technology in the EF, will contribute to higher reconstruction performance and reduced event rates.

At this stage all the requirements on TDAQ have already been identified and addressed, and the project development is at an advanced stage. Most of the L0 Trigger systems have already tested preliminary hardware prototypes and are planing updated versions. Both firmware and software are developing rapidly and the overall project is preparing for cross-system integration tests.

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