CERN Online Summer Studentship Report

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Upgrade of the Trigger System of the ATLAS Calorimeter

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Summary

This document aims to sum up all that I have learned during my online Summer Studentship at CERN. My project constitutes of trying to find a way to use the gFEX module to detect Noise Bursts in the ATLAS calorimeter. The objective is to use gTowers as inputs for an algorithm, to compare several cycles and detect an anomaly between the largest signals in each cycle. Given the limited time for such enormous enterprise, we focused the work on some initial algorithm design. Future developments are to be pursued beyond the scope of this document.

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1 Introduction

High energy physics is a crucial part of the exploration and study of our universe. It is a portal to understanding essential questions about the basic constituents of matter. For such, a highly complex set of experiments is arranged to try and understand the nature of the fundamental particles providing insights into the laws that govern the cosmos.

These experiments are designed by physicists and engineers to take place at the European Organization for Nuclear Research, (Conseil Européen pour la Recherche Nucléaire - CERN) home to the largest and most powerful particle accelerator in the world, the Large Hadron Collider (LHC). The LHC is responsible for colliding beams of protons against each other at near the speed of light to mimic the conditions instants after the Big Bang.

1.1 The Large Hadron Collider

Sitting at 100 meters below the surface, the LHC is CERN's most recent and main accelerator, built as a 27 kilometer ring with a highly sophisticated structure to direct and also accelerate the particles.

On their journey, the two particles beams travel in separate ultrahigh vacuum pipes guided by superconducting electromagnets before colliding at close to the speed of light in specific locations. Due to the superconducting material of the electromagnets, the accelerator must be cooled down using liquid helium to near absolute zero [2] .

The collisions happen at a constant rate of about 40 MHz or 25 ns, in four specific locations of interest which are the positions of the particle detectors. They are ATLAS, CMS, ALICE and LHCb as show on figure 1. The focus of this report will be on ATLAS, its calorimetry system and Trigger System.

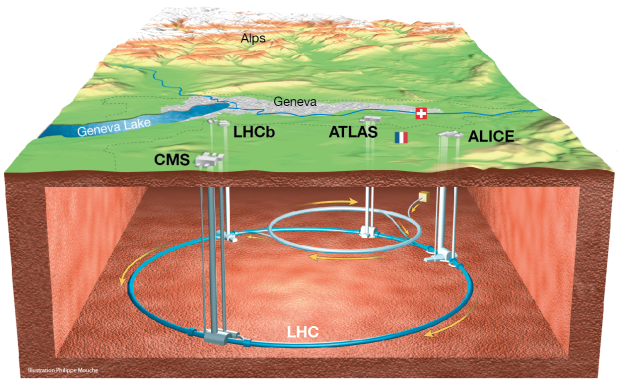

Figure 1: Overview of LHC and its experiments under the French-Swiss border near Geneva

1.2 A Toroidal LHC ApparatuS

ATLAS, as shown in figure 2, is one of the four major experiments at CERN, being responsible for the detection and measurements of the paths, momentum and energy of the new particles which emerge in every direction as a result of the 14 TeV collisions that happen in the detector centre. The protons within each beam are grouped in bunches and squeezed down in size to increase the odds of a collision [4]. ATLAS weighs around 7000 tonnes and it is formed by four major subsystems organized in layers, being the Inner Detector, Calorimeters, the Muon Spectrometer and the Magnet System [3]. The Inner Detector is responsible for measuring the momentum, direction and charge of electrically-charged particles produced in each collision, and the Muon Spectrometer identifies and measures the momenta of Muons.

ATLAS has a right-handed coordinate system with the x-axis pointing towards the centre of the LHC tunnel, and the z-axis along the tunnel. The y-axis points vertically. Along with the x, y, z coordinate system, there is the azimuthal angle ϕ and it is measured from the x-axis, around the beam (The detector design is symmetrical in phi). And finally there is the Pseudo-rapidity, denoted by the letter η, which describes an angle with respect to the axis of the colliding beams, it has the value 0 for particle trajectories that are perpendicular to the beam, and positive or negative values for those at an angle to the beam. [8]. For brevity, in the following, we will only discuss in more detail the energy measurement system, the ATLAS calorimeters.

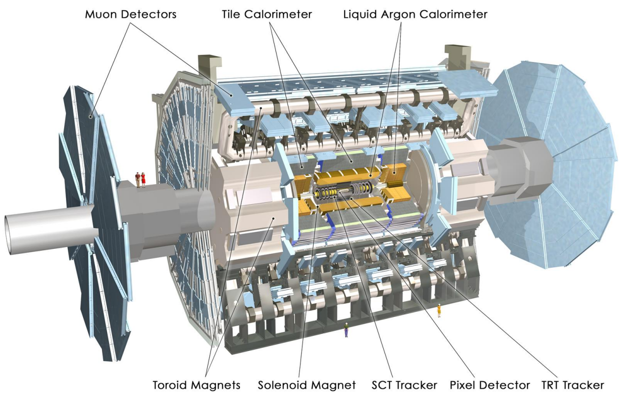

Figure 2: Overview of ATLAS and its subsystems

1.2.1 Calorimeters

The ATLAS calorimeters measure the energy of most particles with the exception of muons and neutrinos. There are two kinds of calorimeters that are used in the experiment: electromagnetic calorimeters that measure the energy of electrons and photons and the Hadronic calorimeters which harnesses the energy of particles such as protons, pions and neutrons.

The Liquid Argon (LAr) Calorimeter and the Tile Hadronic Calorimeter (TileCal) are the two ATLAS calorimeter subsystems. The LAr Calorimeter surrounds the Inner Detector and measures the energy of electrons, photons and hadrons (in the forward region). It is formed by layers of lead (copper in the hadronic forward region) that absorb incoming particles, converting them into a shower particles. These particles ionise the liquid argon in between the layers and generate an electric current that is proportional to the incident particle's energy. This way, the energy is converted by such device into an electric signal.

The Tile Calorimeter encompasses the LAr Calorimeter and measures the energy of hadronic particles in the central region. It is formed by iron and scintillating tiles. The iron induces a cascade of hadronic particles and photons. The photons are collected by the scintillating tiles and are are captured by optical fibers and converted into electrical signal by photo-multipliers that convert light into electrical signal, thus forming the cells of the calorimeters.

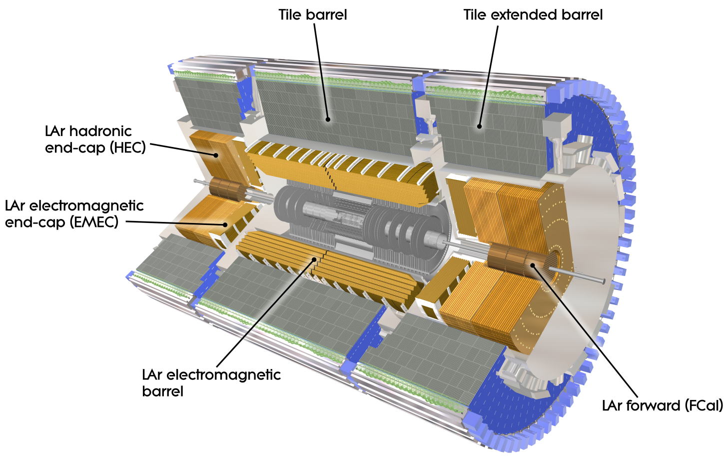

Figure 3: Cut-away view of the ATLAS Calorimeter System

1.3 Trigger System

Inside the LHC, in ATLAS, there are up to 1.7 billion proton-proton collision happening each second, which in total generates more then 60 terabytes of data per second [12]. Nevertheless, not all collisions will have interesting features that may lead to new breakthroughs. Therefore, to reduce the flow of data to manageable amounts, ATLAS uses a two-level online event selection filter. The trigger system, picks out approximately 1000 of the 1.7 billion collisions that occur each second in the detector.

The Level-1 Hardware Trigger, built with custom-made electronics, works on a compact set of information coming from the calorimeters and muon detector. The decision time to decide whether to keep or discard the data of the Level-1 trigger is less than 2.5 micro seconds. To accomplish this, it uses signals from the detector with coarser granularity. Still, it accepts up to 100,000 events per second for the second stage, the High-Level Trigger (HLT).

The HLT is a software based trigger, which refines the data from the hardware-based Level-1 Trigger. It provides a very comprehensive analysis either by looking at the whole event for selected layers of the detector, or by analyzing the data in smaller and isolated regions of the detector. Around 1000 events per second are selected and sent to a final storage system for offline analysis.

2 ATLAS Upgrade

The number of potential collisions per surface unit over a given period of time is called luminosity and it is an essential indicator of an accelerator's performance and rare physics discovery potential [1]. In order to deal with the far beyond nominal instantaneous luminosity that will be delivered by the LHC in the next decade, the ATLAS Experiment is undergoing many upgrades to maintain its performance at the highest possible level for Run 3 and for the High-Luminosity LHC (HL-LHC), Run 4 [6].

One of these upgrades is called the Phase-I upgrade and it will impact, amongst other areas, the LAr calorimeter readout electronics. The calorimeter trigger system (L1 Calo) will be equipped with the new Feature Extraction boards (FEXs), in order to provide more refined processing of the calorimeter data, and to obtain a better discrimination between jets, photons, electrons and taus [6].

2.1 Global Feature Extraction (gFEX)

2.1.1 Overview

As part of the ATLAS Phase-I Upgrade, the Global Feature Extraction system (gFEX) is being added to the L1Calo system allowing to use full-scan algorithms and triggering on unique features derived from its ability to search in the whole calorimeter using a single hardware module [10]. The gFEX module is able to perform a number of algorithms running at 40 MHz, for instance algorithms to select large-radius jets by means of wide-area jet algorithms refined by sub-event information. It will substantially enhance the selectivity of the ATLAS Level-1 trigger and therefore increase sensitivity to key physics channels.

2.1.2 Architecture and Design

The gFEX system receives all the information from gTowers (0.2 x 0.2 in the η x ϕ space projective from the nominal collision point) in the TileCal and LAr calorimeters, processes that information and makes the trigger result available to the rest of the L1 Trigger System. The functionality of the gFEX is implemented using four Field Programmable Gate Arrays (FPGA) [11]. The current production version, 4c, of the gFEX board uses 3 Virtex Ultrascale+ pFPGAs for data processing and 1 Zynq Ultrascale+ hybrid FPGA for control and monitoring [7]. Each gFEX FPGA has 100 input channels that receive multiplexed signals through optical fibres.

2.2 Noise Bursts

Noise bursts are a known phenomena that affect a large fraction of the detector during a small period of time, typically between 1 nano second and 1 micro second. Up until now, this noise, that does not have a physics-like proper shape, is treated by applying a time veto of 1 mili second around two close in time noise burst candidates [5] [9]. Now, with the help of the gFEX board, the aim of this project is to detect these spurious signals that happen inside the detector with more precision to better define the veto time window used.

3 The Project

The aim of this project is to use the gTowers from the LAr calorimeter as inputs so that they go through a created HDL module that processes these inputs and finds when the noise burst starts and ends.

The project starts by understanding the inner working of separated modules treating regions associated in the η/ϕ plane, called jet_engines. To create such new module, the idea of the jet engine operation module was used as a starting point. The jet engine HDL module calculates the sum of calibrated gTowers based on its specific algorithm. The calibrated gTowers, shown in figure 4, are built from input from LAr and the Tile Calorimeters. To simplify the problem, looking at only FPGA_A from figure 4, there is a logical grid of 32 rows and 12 columns, and therefore FPGA_A consists of 64 jet engines that are organized to process in parallel the received inputs. Each jet engine receives 6 calibrated gTower inputs in a sequential temporal fashion, and so each Jet Engine covers 6 cells.

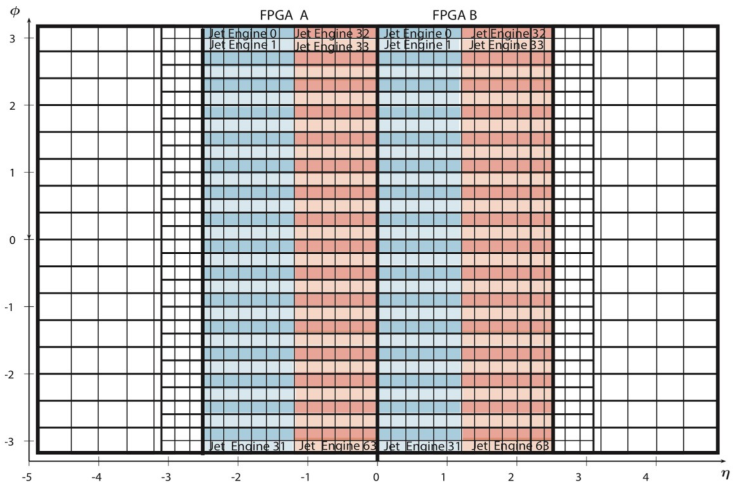

Figure 4: gTowers η(horizontal axis) x ϕ (vertical axis) and the definition of jet engines.

3.1 Algorithm

The objective of the algorithm described below is to find the most energetic gTower out of however many jet engines we have. This algorithm does not accomplish our main goal but it is a step in that direction. Thus, with these specific details and goals in mind, a HDL module was created called jet_engine.vhd as shown in figure 5. This module has 3 inputs, being the clock, je_inp, which is the actual input signal of 16 bits bringing the energy of each of the six gTowers, and the eta_ind, which has 3 bits, being the eta indicator for each gTower input. This module receives 6 calibrated gTower cells during a cycle of 7 clock periods as shown in figure 6. The last clock periods is used for signal processing. As outputs the module has the biggest_gt, which represents the energy of the most energetic gTower in a cycle, and the eta_ind_out which corresponds to the eta related the most energetic gTower in that cycle.

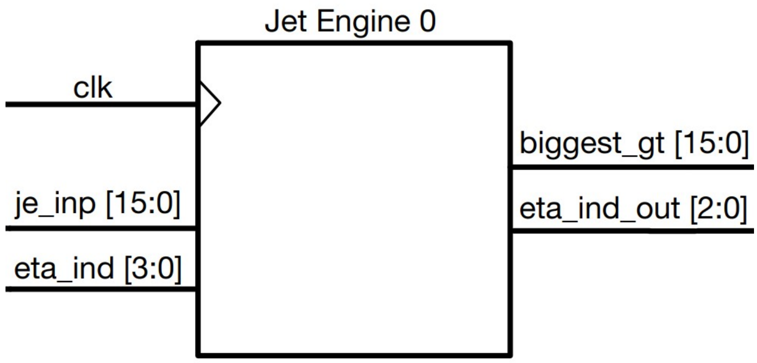

Figure 5: Module jet_engine.vhd

Figure 6: Signal Outputs

In order to meet our goal, another block containing 2 jet engines was created and implemented as shown in figure 7. This two jet engine HDL module, gfex2.vhd, can easily be extrapolated to 32 or 64 jet engines. This bigger module has 1 clock input, 1 eta_ind input, and N jet_eng inputs, N being the number of jet engines used. In this case, N=2, and consequently there are 2 other inputs, each one corresponding to an input for each jet engine. Regarding the outputs there are 3, biggest_gt_out, with 16 bits, that outputs the most energetic gTower in a cycle among all jet engines, eta_ind_out, with 3 bits, that outputs the corresponding eta value for the biggest gTower found, and the Jet engine number which tells from which jet engine the biggest value came from.

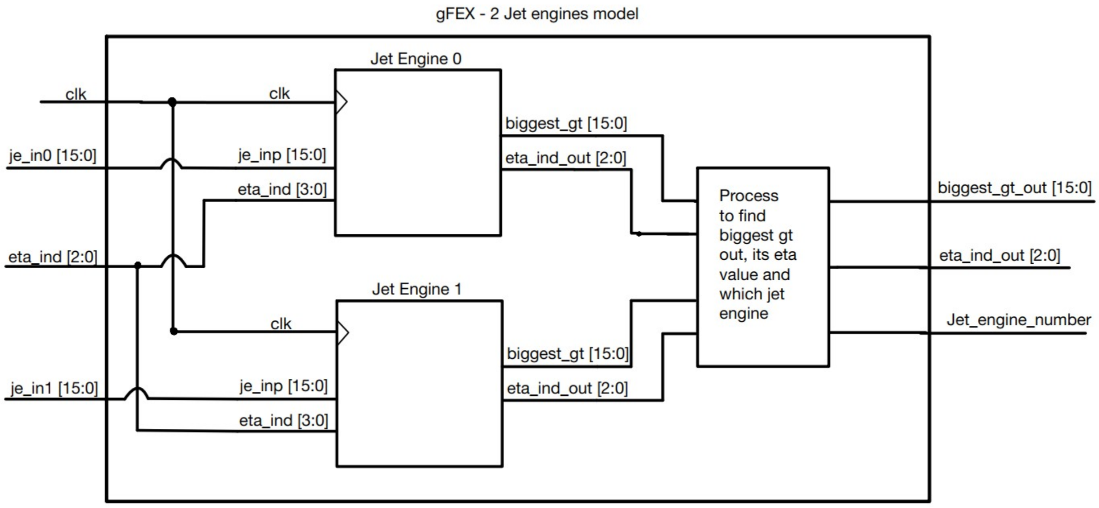

Figure 7: Module containing 2 jet engines

This module, gfex2.vhd, was tested using the simulation software ModelSim with a test bench file alongside a stimulus file. The stimulus file has 2 columns that are common for all jet engines and an additional column for each jet engine as figure 8 shows. The last two columns refer to the input for each jet engine, 0 and 1 respectfully. The first column refers the wait time between each input, and the second column regards the eta indicator for each gTower. The output for this module, incited by the stimulus file can be seen on figure 9. As shown by figures 8 and 9, the third and fourth column refer, respectfully to je_in0 and je_in1.

```
1 ns 000 AAAA 1111
1 ns 001 1111 1111
1 ns 010 FFFF 1111
1 ns 011 1111 1111
1 ns 100 1ABC 1111
1 ns 101 1111 1111
1 ns 110 1111 1111
1 ns 000 AAAA 1111
1 ns 001 1111 BBBB
1 ns 010 CCCC 1111
1 ns 011 1111 DD11
1 ns 100 CCCC 1111
1 ns 101 AAAA 1100
1 ns 110 1111 1010
```

Figure 8: Text file describing the inputs for two Jet Engines

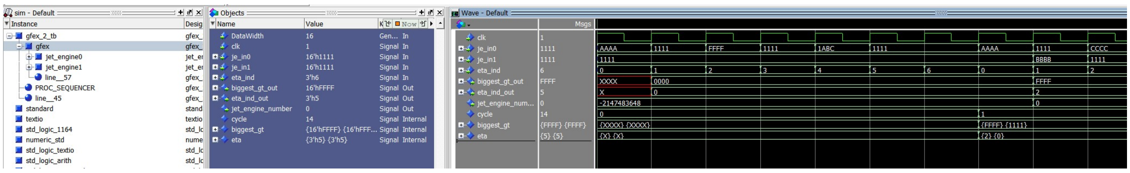

Figure 9: Output for 2 jet engine module

4 Conclusion and Next Steps

Unfortunately, due to the short period of the internship (8 weeks), the full algorithm to detect noise bursts was not built, but great first steps have been made. With the algorithm described above, the biggest gTower among all Jet Engines can easily be identified. Therefore, to actually detect noise bursts, a more complex algorithm will have to be built on top of this existing one to compare the biggest gTower from a certain cycle with the biggest gTower from M previous cycles, so that an anomaly can be detected and be processed correctly.

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