ATLAS FTK a – very complex – custom super computer

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Abstract. In the LHC environment for high interaction pile-up, advanced techniques of analysing the data in real time are required in order to maximize the rate of physics processes of interest with respect to background processes. The Fast TracKer (FTK) is a track finding implementation at the hardware level that is designed to deliver full-scan tracks with p_T above 1 GeV to the ATLAS trigger system for events passing the Level-1 accept (at a maximum rate of 100 kHz). In order to achieve this performance, a highly parallel system was designed and currently it is being commissioned within in ATLAS. Starting in 2016 it will provide tracks for the trigger system in a region covering the central part of the ATLAS detector, and will be extended to the full detector coverage. The system relies on matching hits coming from the silicon tracking detectors against one billion patterns stored in custom ASIC chips (Associative memory chip - AM06). In a first stage, coarse resolution hits are matched against the patterns and the accepted hits undergo track fitting implemented in FPGAs. Tracks with p_T > 1GeV are delivered to the High Level Trigger within about 100 µs. Resolution of the tracks coming from FTK is close to the offline tracking and it will allow for reliable detection of primary and secondary vertexes at trigger level and improved trigger performance for b-jets and tau leptons. This contribution will give an overview of the FTK system and present the status of commissioning of the system. Additionally, the expected FTK performance will be briefly described.

1. Introduction

Online event selection for interesting physics in the ATLAS experiment [1] is a very challenging task. The LHC [2] will run with proton-proton collision energy of 13-14 TeV, a bunch-crossing period of 25 ns and luminosities exceeding 10^{34} cm^{-2} s^{-1}. The expected interaction pile-up will reach 80 proton-proton interactions per bunch crossings at Run3 (2020-2022), which will make it more difficult to have efficient online selection of rare events of interesting physics. FTK [3] is an ATLAS trigger upgrade project. It is developed to reconstruct tracks with transverse momentum above 1 GeV for all events accepted by the Level-1 (L1) ATLAS trigger system at a rate of up to 100 kHz. The system performs tracking by a highly parallelized hardware system using custom and commercial electronics. The fast, full event tracking performed by the FTK makes it possible to trigger on some rate processes which require event-wide tracking information like b-jets, and allows in general development of pile-up robust triggers.

2. The ATLAS Detector

ATLAS is one of the general-purpose the particles generated at center of mass energy of 13-14 TeV. In ATLAS, particles are identified and have their momentum and energy measured by the inner tracking detector, electromagnetic and hadronic calorimeters, and the muon system. The inner tracker is inside a 2-T solenoidal magnetic field coaxial withe beam axis. The FTK system is using the ATLAS silicon Inner Detector [4], which consists of Pixel modules and Strip modules, organized as a barrel with co-axial cylindrical layers and two end-caps with discs.

To select interesting physics events, ATLAS has a two-level trigger system. The L1 trigger system is hardware-based and has a maximum output rate of 100 kHz using only coarse information from calorimeters and muon system. In the next stage of event processing, High Level Trigger (HLT), which is implemented as software running in a farm of several thousand CPUs, uses information from all detector systems to select events which are saved to disc at a rate of ~1 kHz.

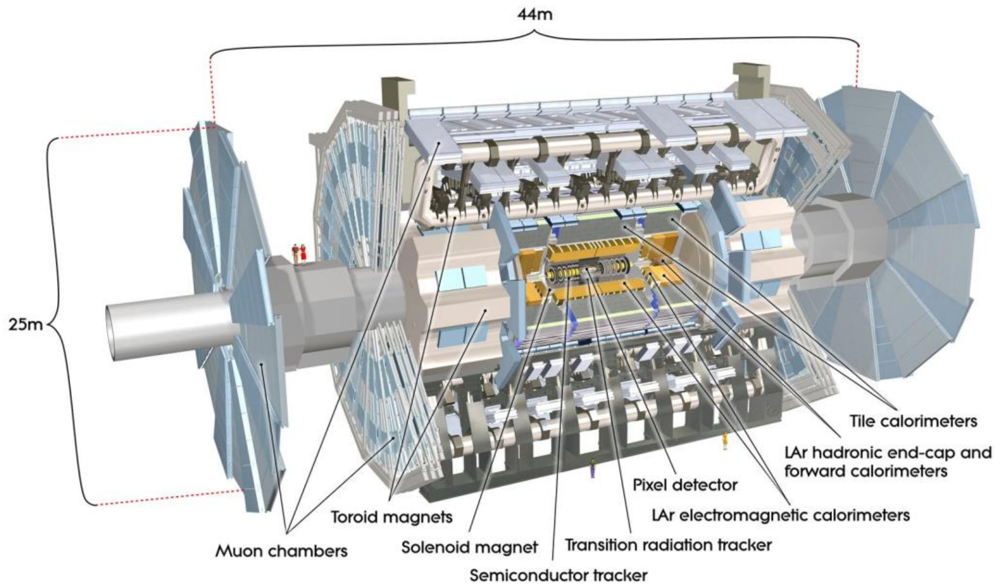


Figure 1. ATLAS Detectors

3. Pattern Recognition and Track Fitting

FTK is a hardware system that reconstructs tracks in real time using information from the inner tracking silicon pixel and strip detectors. For every event which passes the L1 trigger, FTK will provide accurate and complete track information (η, ϕ, p_T, d_0 and z_0) to HLT. This dual requirement of processing speed and accuracy is achieved by FTK system using two-stage processing described below.

3.1. Pattern Recognition

The FTK system finds coarse resolution tracks, called roads, by pattern recognition. A pattern is a list of hits, one for each silicon tracker layer used in the pattern recognition. First, possible patterns are generated by Monte Carlo simulation (MC) using about 50 billion muons, and are stored in a pattern bank. In order to limit the number of necessary pattern the actual readout channels are grouped to form coarser granularity hits. In real physics data, all such hits in the silicon trackers are sent to the pattern bank and are checked against all patterns stored in the bank, similar to a Bingo game. Matching of the patterns is performed concurrently for all patterns once hits are made available in the full-custom ASIC Associative Memory (AM) chips [5].

3.2. Track Fitting

For each pattern with all its elements matched, or all except one, the track parameters (η, ϕ, p_T, d_0 and z_0) are calculated using the full resolution hits using the 8 layer. All hit combinations, made of one hit per layer within the pattern, are fit to determine a goodness of fit. The tracking on the matched pattern is simplified by transforming the helix track parameters and quality estimator calculations in to a set of scalar products of the form

$$p_i = \sum_j C_{i,j} x_j + q_i$$

where X_j are the hit coordinates in the each detector layer, $C_{i,j}$ and q_i are pre-calculated terms, and p_i is either a helix parameter or a term of the χ^2 quality estimator. This approximation can be implemented in modern FPGAs, exploiting their speed and parallelism, to achieve approximately 1 fit/ns.

4. FTK System

Figure 2 shows a schematic of the FTK system. Hit data from the silicon pixel and strip detectors are transmitted from the detector on optical fibers and received by the FTK input mezzanine (IM) where they are clustered. The clustered hits are delivered to each DF board and distributed to the FTK parallelized Data Organizer (DO). The hits are converted to to coarser resolution hits, called Super-Strips (SS) which are appropriate for pattern recognition. The AM board performs the pattern recognition using hits from 8 out of the 12 layers, and sends back matched patterns to the DO. The Track Fitter (TF) uses full resolution hits from the DO to reject fake tracks in each matched pattern. Then, the Second Stage board (SSB) estimates the final track parameters using the full 12 layer information. All reconstructed track information is then merged and sent to the HLT from the FTK-HLT Interface Crate (FLIC). To deal with large amount of input data as well as the large number of track candidates due to the hit combinations at high luminosity, FTK is a highly parallelized system. The information from the ATLAS detector is segmented into 64 regions, and each region is covered by 2 Processor Units (PU) containing 4 units with 16 AM chips each working in parallel. Finally, the pattern recognition is performed with a parallelism of order 5000.

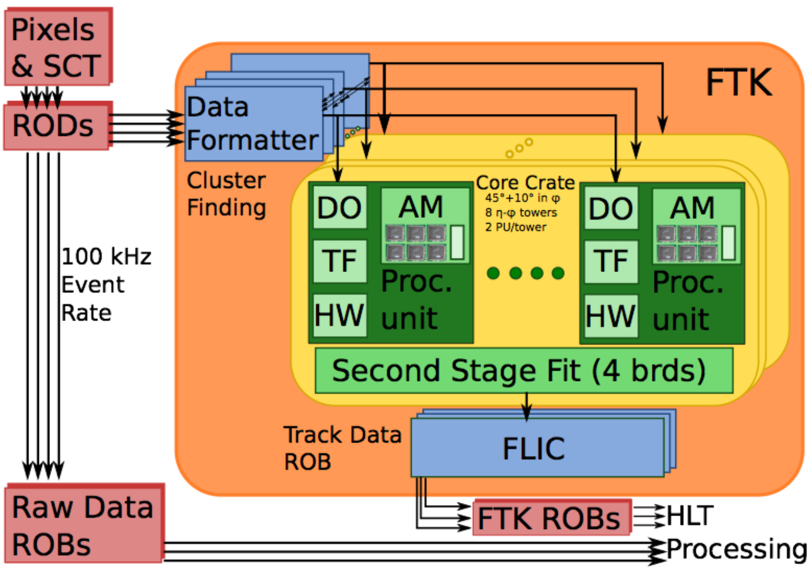


Figure 2. Schematic of FTK System

5. FTK Tracking Performance

5.1. FTK Timing Emulation

The timing of FTK system has been emulated using $Z \rightarrow \mu\ \mu$ with pile-up as the luminosity 3×10^{34} $cm^{-2}s^{-1}$. By accounting for the time to process each word of data for each FTK components (DF, DO, AM, TF, SSB) operating at the full L1 trigger rate of 100 kHz, it is determined that FTK will take on average 50 μ sec per event to perform global tracking by highly parallelized system, as shown in Figure 3. This is fast enough for the HLT requirement order of a few milliseconds.

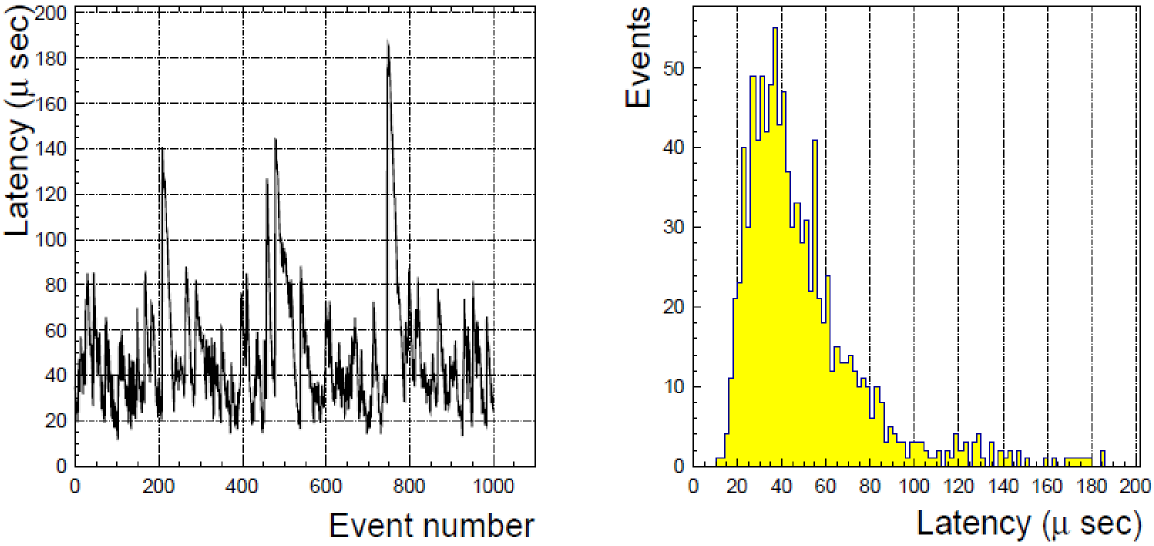


Figure 3. Distribution of FTK latency emulation for $Z \rightarrow \mu\ \mu$ events with 69 pile-up. Event number vs Latency (left), and Latency histogram of 1000 events (right) [3].

5.2. FTK track performance

In order to study the FTK tracking efficiency and resolution single muon and pion MC samples were simulated with a random distribution in the particle helix parameters. Figure 4 shows track finding efficiency with respect to offline tracks and curvature resolution of FTK and offline tracks. There is some inefficiency compared to offline in especially low p_T region, because of differences in the clustering algorithm, the lack of low p_T patterns, and other simplifications. Nevertheless, the efficiency of track finding by FTK is above 90% in all regions. The FTK resolutions for all parameters are also close to with offline, as a shown in Figure 4.

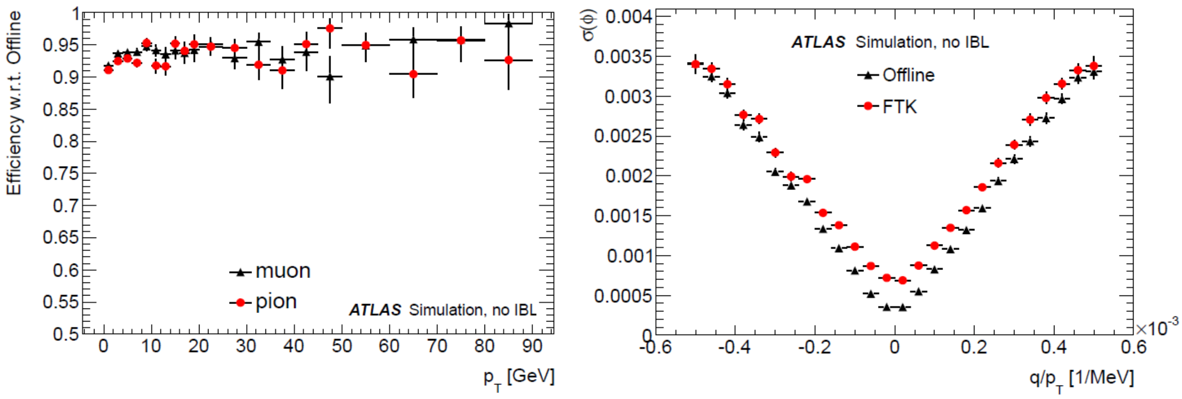
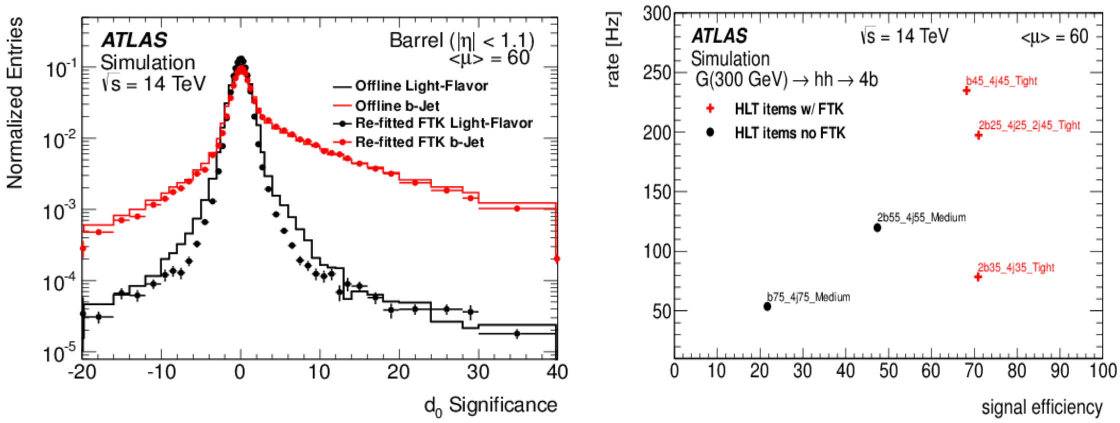


Figure 4. Pion and muon FTK track finding efficiencies with respect to Offline track (left). The ϕ resolution as a function of curvature for FTK and offline tracks (right) [3].

5.3. Example application

New physics that couples to heavy fermions may be rich in final-state *b* quarks, but not necessarily other easily identifiable objects which can be used in the trigger. Given the large QCD production rate of light quarks and gluons, it is important that the ATLAS trigger selects efficiently jets from *b*-quarks while provides large rejection against other jets. The *b* quark jets make characteristic tracks due to the long life time of *b*-quark. The tracks in a *b*-jet are characterised by larger transverse impact parameter, d_0, as compared to tracks in jets from light quarks. Figure 5 shows d_0 significance distribution and trigger efficiency of exotic 4*b* signature (G(m=300 GeV)→hh→4b). The d_0 significance is the significance of the minimum distance of tracks from the collision point in the plane transverse to the beam axis. The *b*-jets exhibit an excess in the positive *d_0* side and this fact can be used for a *b*-jet trigger in the HLT. FTK d_0 significance is compatible with offline as you can see in Figure 5. With FTK active, the CPU power is not spent on the tracking, and thus the HLT can apply a *b*-jet requirement using *d_0* from FTK tracks on the all event that pass L1 trigger before a p_T threshold cut. As a result, due to the lower p_T of the selection a higher trigger efficiency for the exotic 4*b* signature (G(m=300 GeV)→hh→4b) can be achieved with a manageable trigger rate.



Figre 5. Offline and FTK d_0 significance distribution of light flavour and *b*-jet (left). Signal efficiency and rates for b-jet triggers with and without the FTK (right) [6].

6. Summary and Plan

FTK provides full track information to the HLT for tracks with p_T above 1 GeV. The design of the FTK system was described and its expected performance was presented. All FTK boards are produced or ready for production. Currently, commissioning of the system is ongoing with both final and prototype boards. Installation has started in the beginning of 2016, and data taking will start in the middle of year for the barrel region. After that, processor boards will increase to cover the full region by the end of the year. Finally, the number of processing units will increase (128 PU) to the full specification to handle the high pile-up environment.

References

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