Performance of the ATLAS First-Level Trigger with First LHC Data

Johan Lundberg for the ATLAS collaboration

Abstract—ATLAS is one of the two general-purpose detectors at the Large Hadron Collider (LHC). Its trigger system must reduce the anticipated proton collision rate of up to 40 MHz to a recordable event rate of 100-200 Hz. This is realized through a multi-level trigger system. The first-level trigger is implemented with custom-built electronics and makes an initial selection which reduces the rate to less than 100 kHz. The subsequent trigger selection is done in software run on PC farms. The first-level trigger decision is made by the central-trigger processor using information from coarse grained calorimeter information, dedicated muon-trigger detectors, and a variety of additional trigger inputs from detectors in the forward regions.

We present the performance of the first-level trigger during the commissioning of the ATLAS detector during early LHC running. We cover the trigger strategies used during the different machine commissioning phases from first circulating beams and splash events to collisions. It is described how the very first proton events were successfully triggered using signals from scintillator trigger detectors in the forward region. For circulating and colliding beams electrostatic button pick-up detectors were used to clock the arriving proton bunches. These signals were immediately used to aid the timing in of the beams and the ATLAS detector. We describe the performance and timing in of the the first-level Calorimeter and muon trigger systems. The operation of the trigger relies on its real-time monitoring capabilities. We describe how trigger rates, timing information, and dead-time fractions were monitored to ensure the very good performance of the system.

I. INTRODUCTION

THE ATLAS trigger uses a three-level architecture. The first level trigger [1], is entirely implemented in custom-built electronics and is designed to reduce the rate from the anticipated 40 MHz to less than 100 kHz. An overview is shown in figure 1. The first-level trigger decision is made by the central-trigger processor using information from coarse grained calorimeter information, dedicated muon-trigger detectors, and a variety of additional trigger inputs from detectors in the forward regions. The subsequent higher-level trigger selection is done in software run on PC farms.

For the initial running ATLAS has been equipped with a minimum bias trigger scintillator (MBTS) consisting of 2x16 scintillator paddles located inside of the liquid argon electromagnetic calorimeter. The MBTS is the most sensitive trigger detector and has a large coverage: 2.1 < η < 3.8. It is not radiation hard so its performance is expected to degrade after roughly 1/fb of collisions. At the writing of this paper, the total number of triggered events at 7 TeV has passed 5·10^9, corresponding to more than 8/nb. The LHC running scheme foresees a steeply increasing instantaneous luminosity. The vast majority of triggers were generated by the MBTS.

Numbers as of 18/5 2010.

Johan Lundberg is with CERN, Johan.Lundberg@CERN.CH

Fig. 1. Outline of the ATLAS first level trigger.

II. THE FIRST LEVEL CENTRAL TRIGGER

The first level central trigger forms the first level trigger decision, following the logic defined by the trigger menu. We here give an overview of the main parts of the system and the performance with first beams. The system is built of eleven custom built modules fitted in a single 9U VME 64x chassis, and is running at 40 MHz. An outline is shown in figure 2.

All trigger inputs are delivered as LVDS signals to the three Central Trigger Processor (CTP) input boards CTPIN which are each accepting 4x31 inputs. The CTPIN latches the signals, and applies optional signal shaping and pipelining for per-bunch synchronization. Each of the inputs are monitored with scalars. Of the 372 input signals 160 signals are selected per-bunch synchronization. Each of the inputs are monitored with scalars. Of the 372 input signals 160 signals are selected per-bunch synchronization.
The BPTX monitoring system measures the phase between which monitors the frequency and phase of the LHC bunches. Detectors are also used by a stand-alone monitoring system of the two beams to the central trigger system. The BPTX detectors, BPTX [3], which provide a trigger input for each of the beams were tracked by electrostatic button pick-up beams was done using the CTPMON counters. The clocking with LHC beams.

Both with cosmics data taking and naturally during all runs A. Commissioning of the First Level Central Trigger

Not only those available at the PIT bus.

A higher frequency. In addition, all inputs can be monitored, but unlike the CTPMON they are not bunch-aware. The rates of the 256 items are also monitored with scalars before and after prescale and after veto for the firing plane shower of charged particles over most of the ATLAS detector. This allowed quick timing in of many trigger inputs with respect to the beams directly using the CTPMON scalars, in particular the 2x16 MBTS inputs.

After stable running with both beams the LHC operators let protons collide for the first time on 23rd November 2009. During this first portion of this collision run the BPTX measured a 900 ps offset between the two beams, corresponding to a 13.5 cm longitudinal shift of the proton collision point, away from the center of ATLAS. This shift was corrected during the run. One of the very first evidence of beam-beam collisions was found by observing this shift also in the longitudinal distribution of ATLAS inner detector tracks, as shown in figure 3.

The CTPIN is equipped with enough scalars to monitor all inputs, but unlike the CTPMON they are not bunch-aware. The data-rate of CTPIN are thus much lower than that of CTPMON and can be published and permanently stored with a higher frequency. In addition, all inputs can be monitored, not only those available at the PIT bus.

A. Commissioning of the First Level Central Trigger

The central trigger is in operation for all of ATLAS runs, both with cosmics data taking and naturally during all runs with LHC beams.

The first timing in of the triggers with respect to the beams was done using the CTPMON counters. The clocking of the beams were tracked by electrostatic button pick-up detectors, BPTX [3], which provide a trigger input for each of the two beams to the central trigger system. The BPTX detectors are also used by a stand-alone monitoring system which monitors the frequency and phase of the LHC bunches. The BPTX monitoring system measures the phase between collisions and clock with a precision better than 100 ps in order to guarantee a stable phase relationship for optimal signal sampling in the sub-detector front-end electronics. In addition to monitoring this phase, the properties of the individual bunches are measured and the fill structure (bunch pattern) of the beams is determined continuously during running.

The first level central trigger system distributes the 40 MHz clock to the first level trigger system and the sub-detector frontends. For the very first LHC single beam fills and proton collisions in 2009, the system was operated using an internal clock, not synchronized with the proton bunches. After studies of the LHC clocks, ATLAS commissioned a system for switching between internal clocks and beam-synchronized LHC clocks. The frequency mismatch between the internal and external clock is bridged by phase-locked loops, and the system is protected by a short period of veto while the clock switch takes place. Using the BPTX the bunch phase and frequency are constantly monitored. The frequency increases slightly with the acceleration up to 7 TeV but the relative phase (and thus the longitudinal collision point) remains constant to better than 100 ps.

For the first timing in of the ATLAS detectors and triggers LHC provided so called splashes where a proton beam was steered into a collimator, thereby producing an approximately plane shower of charged particles over most of the ATLAS detector. This allowed quick timing in of many trigger inputs with respect to the beams directly using the CTPMON scalars, in particular the 2x16 MBTS inputs.

After stable running with both beams the LHC operators let protons collide for the first time on 23rd November 2009. During this first portion of this collision run the BPTX measured a 900 ps offset between the two beams, corresponding to a 13.5 cm longitudinal shift of the proton collision point, away from the center of ATLAS. This shift was corrected during the run. One of the very first evidence of beam-beam collisions was found by observing this shift also in the longitudinal distribution of ATLAS inner detector tracks, as shown in figure 3.

The first level central trigger system distributes the 40 MHz clock to the first level trigger system and the sub-detector frontends. For the very first LHC single beam fills and proton collisions in 2009, the system was operated using an internal clock, not synchronized with the proton bunches. After studies of the LHC clocks, ATLAS commissioned a system for switching between internal clocks and beam-synchronized LHC clocks. The frequency mismatch between the internal and external clock is bridged by phase-locked loops, and the system is protected by a short period of veto while the clock switch takes place. Using the BPTX the bunch phase and frequency are constantly monitored. The frequency increases slightly with the acceleration up to 7 TeV but the relative phase (and thus the longitudinal collision point) remains constant to better than 100 ps.

For the first timing in of the ATLAS detectors and triggers LHC provided so called splashes where a proton beam was steered into a collimator, thereby producing an approximately plane shower of charged particles over most of the ATLAS detector. This allowed quick timing in of many trigger inputs with respect to the beams directly using the CTPMON scalars, in particular the 2x16 MBTS inputs.

After stable running with both beams the LHC operators let protons collide for the first time on 23rd November 2009. During this first portion of this collision run the BPTX measured a 900 ps offset between the two beams, corresponding to a 13.5 cm longitudinal shift of the proton collision point, away from the center of ATLAS. This shift was corrected during the run. One of the very first evidence of beam-beam collisions was found by observing this shift also in the longitudinal distribution of ATLAS inner detector tracks, as shown in figure 3.

The first level central trigger system distributes the 40 MHz clock to the first level trigger system and the sub-detector frontends. For the very first LHC single beam fills and proton collisions in 2009, the system was operated using an internal clock, not synchronized with the proton bunches. After studies of the LHC clocks, ATLAS commissioned a system for switching between internal clocks and beam-synchronized LHC clocks. The frequency mismatch between the internal and external clock is bridged by phase-locked loops, and the system is protected by a short period of veto while the clock switch takes place. Using the BPTX the bunch phase and frequency are constantly monitored. The frequency increases slightly with the acceleration up to 7 TeV but the relative phase (and thus the longitudinal collision point) remains constant to better than 100 ps.

For the first timing in of the ATLAS detectors and triggers LHC provided so called splashes where a proton beam was steered into a collimator, thereby producing an approximately plane shower of charged particles over most of the ATLAS detector. This allowed quick timing in of many trigger inputs with respect to the beams directly using the CTPMON scalars, in particular the 2x16 MBTS inputs.

After stable running with both beams the LHC operators let protons collide for the first time on 23rd November 2009. During this first portion of this collision run the BPTX measured a 900 ps offset between the two beams, corresponding to a 13.5 cm longitudinal shift of the proton collision point, away from the center of ATLAS. This shift was corrected during the run. One of the very first evidence of beam-beam collisions was found by observing this shift also in the longitudinal distribution of ATLAS inner detector tracks, as shown in figure 3.
firing in coincidence with one or two passing beams. This setup allowed timing in of the MBTS signals using the bunch monitoring capabilities of the CTPMON board. To reduce the number of PIT bits required for the MBTS the CTPIN boards are equipped to calculate three bit saturating multiplicity for each side. After successful timing in of the MBTS using single beam and collision data, 26 PIT bits were then freed to make room for physics triggers.

An illustrative example of the purity of MBTS collision triggers is shown in figure 4, from a 900 GeV collision run (December 12, 2009). By requiring triggers on both sides in 10 ns coincidence and also coincidence with the passing beams, the background from single beams can be seen to be far less than one per cent. The timing difference between collision and single beam halos arises since the latter reach the first side on its way towards the interaction point, in contrast to collision particles originating in the center which reach the two sides simultaneously. The Beam-Halo background is extracted by looking at non-colliding bunches separately, in the same LHC run. The background normalization is fixed to the ratio of the beam current carried by the paired bunches to the one of the unpaired bunches, assuming the beam backgrounds for all bunches are comparable.

![Figure 4. Example of timing and beam backgrounds for the MBTS trigger.](image)

The bunch mechanism of the first level central trigger processors is an important component of the trigger setup as it defines which trigger items are allowed to fire at which bunch numbers. There are eight distinct bunch groups with their own particular purpose, each defined by a list of LHC bunch numbers. An illustrative example is given in figure 5. The collision bunch group contains the bunch numbers for which the two beams meet in ATLAS, and is thus used by physics data trigger items. The three single beam bunch groups are used to select bunches corresponding to beams passing, but not colliding, in ATLAS. Trigger items using these bunch groups are used for beam background estimates such as that done in figure 4. Another bunch group selects a few bunches after collisions, again for monitoring backgrounds. Two bunch groups have a more technical purpose; the calibration requests group defines the times at which sub-detectors may request calibration signals. The bunch count reset veto leaves a short time slice for distribution of the LHC orbit signal. As the LHC fill scheme can vary from fill to fill, ATLAS has developed and commissioned a procedure for monitoring and redefining the bunch groups using the ATLAS beam pickups, BPTX. An online application measures the fill scheme seen by the BPTX and calculates the corresponding bunch groups. The ATLAS trigger shifter compares the suggested bunch groups to the current configuration of the central trigger processor and may generate a new configuration at the press of a button. Changes to the central trigger configuration are protected by a short veto and stored to conditions databases.

![Figure 5. Illustrative example of the use of all eight bunch groups.](image)

### III. THE FIRST LEVEL CALORIMETER TRIGGER SYSTEMS

The first level calorimeter trigger receives 7200 analogue signals from the Liquid Argon and Tile Calorimeters and sums these signals into so called trigger towers which typically cover $0.1 \times 0.1$ in $\Delta \eta$, $\Delta \phi$. The system consists of nearly 300 custom VME modules of ten different types, housed in 17 crates, underground in a service cavern close to ATLAS. The analogue signals first arrive at the 124 pre-processor crates which perform digitization and bunch crossing identification. The digitized signals are then distributed to 56 cluster processor and 32 Jet/Energy processor modules which both count the multiplicities of identified trigger objects above programmable thresholds. The cluster processors identify electron/photon, single hadron and tau signatures. The Jet/Energy modules identify jets and form triggers based on missing and total transverse energy estimates.

The first level calorimeter trigger was commissioned with cosmic data and was in operation from the first proton events in 2009. A time offset with nanosecond precision is applied independently to each channel to guarantee correct signal sampling. These offsets were calibrated using beam splash events provided by the LHC in November 2009. The obtained timing results and the procedure to obtain them are presented in a public note [4]. Figure 6 shows an example of these results: an $\eta \times \phi$ timing map of the electromagnetic calorimeter trigger towers using all splash events from November 2009.

The mean signal peak time (in ns) with respect to the nominal timing offset is shown. The results are found by fitting the digitized pulses of all tower signals with a Gaussian/Landau
fit function and correcting for the peculiar time of flight of splash events.

The color scale shows the concluded modifications of the timing calibration. The offsets derived with a calorimeter test signal prior to first beam were thus already within ±25 ns. Using the time-of-flight corrected timing measurements from splash events the timing offsets were corrected to an expected timing accuracy of ±5 ns.

The first level calorimeter performed well during 2009 and 2010 data taking. In February 2010, additional splash events were used to further improve the timing. A validation with collision data is ongoing.

The good performance of the first level calorimeter trigger during 7 TeV running can be inferred from the the behaviour of the trigger turn-on curves. An example is shown in figure 7. The figure was produced using p–p collision data from 2010 and shows the efficiency for the electromagnetic calorimeter trigger 'EMS' as function of the transverse energy calculated offline, using uncalibrated clusters.

The calorimeter trigger logic is entirely commissioned. About 99.8% of trigger towers are fully operational, minus approximately 1% due to calorimeter problems. Current activities include further improvements of the timing and energy calibration, and optimization of noise suppression. Finally, it is interesting to note the rate of the first level calorimeter triggers during 7 TeV collisions. This is shown in table I. The numbers show electromagnetic calorimeter trigger rates normalized to an instantaneous luminosity of \( L = 10^{32} \text{cm}^{-2}\text{s}^{-1} \). Note: the luminosity is measured with a large (~20%) systematical uncertainty. Only statistical uncertainties are indicated.

### Example First Level Calorimeter Trigger Rates

<table>
<thead>
<tr>
<th>Item</th>
<th>Rate [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>EM2</td>
<td>1.282±0.005</td>
</tr>
<tr>
<td>EM3</td>
<td>0.515±0.003</td>
</tr>
<tr>
<td>EM4</td>
<td>0.252±0.002</td>
</tr>
<tr>
<td>EM5</td>
<td>0.142±0.002</td>
</tr>
<tr>
<td>EM10</td>
<td>0.021±0.001</td>
</tr>
<tr>
<td>EM14</td>
<td>0.008±0.001</td>
</tr>
</tbody>
</table>

The first level muon trigger is – like the first level calorimeter and the central trigger – a real time system. In contrast to the calorimeter triggers it uses dedicated trigger detectors. The system uses information from two types of detectors: Resistive Plate Chambers (RPC) in the barrel region (\( |\eta| < 1.05 \)) and Thin Gap Chambers (TGC) in the end-caps (\( 1.05 < |\eta| < 2.4 \)).

The first level muon trigger selects events with high transverse momentum and associates them to the corresponding bunch crossing. To achieve this the muon trigger detectors have been specifically designed for a prompt response, with the penalty of a worse (but affordable) time resolution compared to the muon physics detectors (Muon Drift Tubes). The latency is 2 µs, well within specifications. The system looks for geometrical coincidences within different RPC or TGC detector layers inside programmed geometrical windows which define the muon transverse momentum (L1 trigger roads), then selects muons above six programmable thresholds and provides a rough estimate of their positions, with coordinates \( \eta \) and \( \phi \). At the event of a L1 accept this information is forwarded to higher level trigger algorithms. The muon momentum is accessed from the bending of the trajectories (as defined by the trigger roads) in the toroidal magnetic field designed for this purpose alone.

The RPC and TGC triggers were commissioned with cosmic ray events, splashes as well as the ongoing proton-proton collision runs at 7 TeV. Figures 8 and 9 show hit maps of the RPC and TGC systems, using single beam splashes and cosmic muon data from 2009. The higher rate of muon triggers in the end-caps has allowed accurate timing in of the TGC system. The timing is within 3 ns. The current coverage for the RPC is 99.7%, and for the TGC 99.2%. With higher luminosity, more detailed timing and phase measurements will be possible.
Fig. 8. The response of the RPC pivot plane (second of three planes) for a splash event with beam approaching from the right side of the plot. The black areas are due to toroid legs and structures, and service systems at $\eta = 0$. The few white holes are due to detector regions not operated during the splash events.

Fig. 9. Hit position histogram for the TGC made using cosmic ray signals. The hits are calculated from coincidence of wire hits (specifying the $\eta$ coordinate) and strip hits (specifying the $\phi$ coordinate).

V. CONCLUSION

The ATLAS trigger is a real-time system implemented with custom-built electronics running at 40 MHz. It is designed to reduce the rate from 40 MHz to less than 100 kHz.

The first-level trigger decision is made by the central-trigger processor using information from coarse grained calorimeter information, dedicated muon-trigger detectors, and a variety of additional trigger inputs from detectors in the forward regions. The system is fully commissioned. Calibration and tuning of configurations was first performed with cosmic muons, single proton beams and then collisions. ATLAS beam pickups are used to measure the frequency and phase of the beams with respect to the LHC clock.

The total number of triggered events at 7 TeV has passed $5 \cdot 10^8$, corresponding to more than 8/nb. Most of these events were triggered exclusively using the minimum bias trigger scintillator system.

REFERENCES


