COMMISSIONING OF THE ATLAS DETECTOR
WITH COSMIC-RAY AND SINGLE-BEAMS

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The ATLAS detector has been commissioned with cosmic rays and the first single beam at the Large Hadron Collider, allowing for the detailed performance studies of each detector subsystem. In this paper, the results of the inner-tracker position alignment with large number of cosmic-ray events are presented. In addition, the single-beam events were used for the timing studies of the level-1 trigger system. The procedure for triggering on the single-beam events and the achieved timing accuracy are reported.

1 The ATLAS detector commissioning

The ATLAS detector is being commissioned with cosmic rays since 2005, starting with a small fraction of the full ATLAS system and gradually adding more and more detector components, finally all subsystems were ready for the data taking in summer 2008. The commissioning with cosmic rays allows for the thorough tests of the detector installed in the underground cavern, together with its service systems. Basic studies are focused on the noise level in the detector and amplifier modules, location of hot and dead channels and identification of malfunctioning electronics boards. The test results allow for a regular update of operation parameters, threshold settings and lists of masked channels, as well as for the replacement or repair of the electronics. In this way, the optimal detector operation mode is achieved. Additionally, the trajectories of cosmic-ray particles can be used to align the relative positions of tracking detector modules, as will be shown in section 3.

The cosmic-ray events are triggered by the muon trigger chambers, calorimeter triggers and scintillation counters (MBTS), designed to trigger on minimum-bias events. The central trigger processor (CTP) on the first trigger level (level-1) combines the information from these trigger sources and makes the final Level-1 Accept decision (L1A) which is transferred to the front-end electronics of all subsystems. Following the L1A signal, the data buffered in the pipe-line memory are read out, processed by the event builder and recorded to the mass storage space. In order to consistently read out data belonging to the same bunch crossing, it is important that all sub-detectors are timed-in perfectly.

In addition to the cosmic rays, the circulation of the single-beam at the Large Hadron Collider (LHC) in September 2008 allowed for additional detector performance tests. During several days, the proton bunches containing $2 \times 10^9$ protons of $450$ GeV energy were being injected into the LHC ring and circulated without acceleration. During the first day, the whole ATLAS detector system has been illuminated by the particles from the beam-halo. Two trigger systems have been used to record the single-beam signals: the previously mentioned MBTS and the beam pick-up detectors (BPTX) positioned in the beam pipe 175 m upstream of the interaction.
point. The recorded data allow for the timing adjustments of the trigger systems, as will be shown in the next section.

2 Level-1 trigger timing alignment with single beam

Single-beam events can be used for the trigger timing alignment with respect to the bunch crossings. One set of data has been obtained using MBTS and the level-1 calorimeter trigger system whose relative timing is well understood from previous tests with cosmic rays.

Subsequently these triggers are disabled and data is collected using BPTX without any additional requirement. As long as the life time of the beam is smaller than a few hundred turns, the ATLAS data acquisition system records all data with a trigger rate of 11 kHz, corresponding to 89 $\mu$s for one LHC turn. These buffered data are then read out before the next bunch is injected into the LHC ring.

As the life time of the beam is increasing, the trigger rate needs to be reduced. Therefore, a coincidence between BPTX and MBTS is required. The recorded data are used for the timing alignment of remaining standard level-1 triggers. At the same time, the prescaled BPTX trigger is used to cross-check the main (BPTX+MBTS) trigger. The BPTX discriminated pulse and the signal from the MBTS are traced by oscilloscope and shown in Figure 1.

![Figure 1: The timing spectrum of the discriminated pulse from the beam pick-up detectors (BPTX) and the analog signal of three scintillation counters (MBTS), as traced by oscilloscope. Both BPTX and MBTS show a spike every 89 $\mu$s, corresponding to one turn of the single beam in the LHC ring. After seven turns, the beam intensity falls below the threshold of the BPTX discriminator, while MBTS is still sensitive to the beam activity.

Although other standard level-1 trigger sources (muon trigger, calorimeter trigger etc.) are not used for the event triggering, all available trigger information is recorded by the CTP readout system. The time window for the readout is set to 32 bunch crossings (i.e. 800 ns) and the arrival time of each trigger is monitored. In this way, the timing alignment with respect to BPTX can be efficiently performed, narrowing the relative time distribution from original several bunch crossing units down to only one bunch crossing unit (25 ns) for most of the trigger items, as demonstrated in Figure 2 (left).

The results of additional timing studies for the muon end-cap trigger system are shown in Figure 2 (right). The thin-gap-chamber (TGC) technology is used to trigger on muons in the pseudorapidity range 1.05 $< |\eta| < 2.4$ of the ATLAS muon spectrometer. The system is designed for operation at high rates, with only a small time jitter of 20 ns. The TGC system consists of seven disc-shaped layers with a 25 m diameter on both sides of the interaction point. The signal is read out in a two-dimensional $\eta - \phi$ plane. Based on the hit pattern in multiple layers and the bending power of the toroidal magnet in front of the TGC wheels, the momentum of the trigger candidate is calculated by means of a look-up table. If the measured momentum exceeds the trigger threshold, the signal is sent to the CTP.
Figure 2: (Left) Trigger timing distribution of level-1 triggers issued by the calorimeter (Tau5, J5, EM3), muon trigger chambers (TGC) and scintillator counters (MBTS). On the top-left, the original large spread is shown, as observed on the first day of data taking. On bottom-left, the equivalent distribution is shown after two days of operation. (Right) Trigger timing distribution of the level-1 muon end-cap trigger.

Since the particles from the beam-halo are mostly emitted parallel to the beam line, special trigger logic (TGC\(_{\text{HALO}}\)) with large acceptance has been developed for the single-beam data. The trigger logic requires the coincidence in pseudorapidity \(\eta\) for only two TGC layers, thus providing the sensitivity to the particles emitted in the horizontal direction. In addition, the coincidence between 3 out of 4 layers is required in \(\phi\) direction to ensure clean muon samples. At the same time, the other two (standard) TGC trigger items are used, TGC\(_{\text{MU0}}\) and TGC\(_{\text{MU6}}\). They require the coincidence between all layers and that a track originates from the interaction point. The width of the trigger road is narrower for TGC\(_{\text{MU6}}\) than for TGC\(_{\text{MU0}}\).

The timing distributions of the mentioned TGC triggers are shown in Figure 2 (right) with respect to the bunch crossing (BC) units of 25 ns. Two sharp peaks can be observed at BC=1 and at BC=5, corresponding to the trigger signal from two detector sides: upstream of the interaction point (C-side) and downstream (A-side). The time difference between two peaks appears due to the finite time-of-flight of particles from one side of the detector to the other. The traversed distance of 28 m corresponds to the time-of-flight of about 100 ns, i.e. 4 bunch crossing units. The spread of the distributions around the two peaks is about one bin, demonstrating that a good timing alignment at the level of 25 ns is achieved for all 320 000 channels. It is also interesting to remark the different number of entries in different BC bins. On the upstream detector side, the beam-halo particles are emitted parallel to the beam line. Traversing further to the downstream side, some of the particle trajectories are bent in a 20 m long toroidal magnetic field, such that the track direction could point to the interaction point. Thus, the TGC\(_{\text{HALO}}\) trigger item observes the particle on both sides of the detector, while the other two standard trigger items are sensitive only on the downstream side (A-side) where particles appear to originate from the interaction point. As a result of the presented studies, the global timing of the TGC system is shifted by 5 bunch crossing units to provide the same timing of standard TGC triggers with BPTX for the collision events.

3 Inner Detector commissioning with cosmic ray events

The inner tracker system of the ATLAS detector consists of the pixel detectors (Pixel) in the innermost layers, surrounded by the silicon microstrip detectors (SCT) and subsequently by the transition radiation tracker (TRT). One of the important commissioning goals is the position alignment of more than 6000 inner-tracker detector modules, in order to achieve the designed
tracking accuracy.

In September and October 2008, about 2.7 million cosmic-ray tracks are recorded under nominal settings of the solenoidal and toroidal magnetic fields. The main trigger source for cosmic-ray particles is the level-1 muon trigger with a nominal rate of about 300 Hz. However, only a small fraction of these tracks is traversing the inner detector. In order to study the alignment of the Pixel and SCT system, additional trigger requirement is introduced, selecting only events with more than one track in the inner-tracker region. The selection is a software-based algorithm with an online event selection in the frame of the level-2 trigger. In this way, more than 30% of events triggered by the level-1 muon trigger can be used for the SCT alignment and about 7% of them for the Pixel subsystem.

The residual distribution for the barrel region of the Pixel and SCT subsystems is shown in Figure 3. The residual is defined as the difference between the measured hit position in a given module and the expected hit point obtained from the track extrapolation. The x-direction corresponds to the main bending direction of the track. The pixel size is 50 µm, the SCT strip width is 80 µm. Only the particles with transverse momentum larger than 2 GeV/c and passing near the interaction point (|d_0| < 50 mm, |z_0| < 400 mm) are selected for the iterative alignment procedure. If the nominal detector geometry is assumed for the track reconstruction, the residual distribution is quite poor with a width σ of more than 120 µm for both subsystems (black curve). After applying the alignment corrections, a significant improvement can be observed. The residual distributions become much narrower, with a σ-value of 24 µm for the Pixel and 30 µm for the SCT subsystem (blue curve). The obtained alignment accuracy is close to the expected performance predicted by the Monte-Carlo study with perfect detector alignment (red curve).

![Figure 3: The residual distribution observed with cosmic-ray tracks for the pixel detector (left) and the SCT detector (right). The black curve is obtained assuming the nominal detector geometry, while the blue curve is the result obtained after applying the alignment corrections. The Monte-Carlo prediction for a perfectly aligned detector is shown as a red curve.](image)

4 Conclusions

The ATLAS detector has been commissioned with cosmic-ray events and with the single beam data. A large number of cosmic-ray tracks allows for an accurate alignment of the inner tracker. The first single-beam data at the LHC have been used for the calibration of the level-1 trigger timing, providing a timing accuracy at the level of 25 ns.

References