PROCEEDINGS OF SCIENCE

Commissioning of the ATLAS Experiment

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The ATLAS experiment based at the CERN Laboratory in Switzerland is expected to be one of the key experiments of its generation. Its results will help elucidate such fundamental questions of physics as the origin of mass and the existence of dark matter in the universe. After 15 years of design, construction, and installation, ATLAS is ready to collect first data from the high-energy proton-proton collisions of the Large Hadron Collider (LHC). The commissioning of the ATLAS detector is a critical step in attaining these physics goals. Details are provided here on the status of the ATLAS experiment in September of 2008, just after having observed first beams in the LHC.

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1. ATLAS Commissioning

The ATLAS detector [1] commissioning exercise has consisted of system-specific calibration runs, in which for example the electronic noise of readout channels was measured or calibration pulses were injected into the detector cells to see their response. Also of critical importance have been the cosmic ray runs, in which real signals from cosmic muon events are measured in the detector. Cosmic rays are used to establish the proper functioning of the detectors by observing either energy deposited in the calorimeters or muon tracks in the inner detector and muon spectrometer. The early in-situ cosmics studies in 2005 and 2006 involved just a few calorimeters modules and used the barrel hadronic calorimeter to provide the trigger. These "stand-alone" cosmic runs gave way to combined runs in which more and more detector subsystems participated as they completed their own preliminary system-specific commissioning. These cosmic runs have also been valuable to develop and commission the online and offline data quality monitoring tools. "Milestone weeks" were also established in part to focus the integration of the subsystems with the level-1 and high-level trigger systems of ATLAS, thereby exercising the full readout and trigger chain of the experiment prior to first LHC collisions.

Such calibration and cosmic runs have provided vital input into the readiness of the detector prior to first collisions by identifying dead or inefficient channels; verifying the timing, alignment, and signal reconstruction of the various subdetector; and providing the initial calibration constants of the experiment. This paper presents a brief overview of the ATLAS detector and the status of its commissioning effort just after the first beams were injected in the LHC in September 2008.

2. Trigger

The trigger is at the heart of the experiment, making decisions on which events should be permanently recorded and which should be discarded. The ATLAS trigger consists of three levels. The level-1 trigger uses reduced granularity information from the calorimeter and muon systems to identify potentially interesting events such as high p_T muons, electrons and photons, jets, τ-leptons, and events with large missing transverse energy. The level-2 trigger is seeded by Regions-of-Interest (RoI) provided by the level-1. The full detector granularity in the RoI is used along with tracking information. The event filter uses offline analysis procedures to further select the event, with potential access to the full event. This full trigger chain reduces the event rate from the 40 MHz provided by the LHC to the 200 Hz that can be permanently stored to disk and tape.

3. Inner Detector

The inner detector system which extends to a pseudorapidity of $|\eta| = 2.5$ provides momentum and vertex measurements of charged particles as well as electron identification. The inner detector consists of a three-layer silicon pixel detector with 80.4 million readout channels located close to the interaction point. The silicon microstrip detector (SCT) located at larger radius provides four space points and has 6.3 million readout channels. Furthest away from the interaction point is the Transition Radiation Tracker (TRT) providing track-following up to $|\eta| = 2.0$ with its 351,000 readout channels. The inner detector system is immersed in a 2 T solenoidal field.

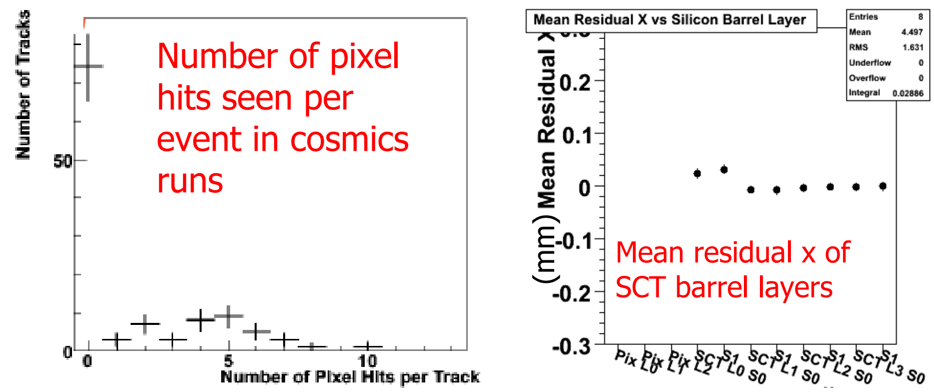

Figure 1: Left: the number of pixel hits observed per event during cosmic runs. Right: the mean residual x coordinate value of the SCT barrel layers.

The dedicated commissioning effort of the inner detector has resulted in a system that is approximately 97.5% operational. Much of the 2.5% of channels lost are due to cooling leaks and heater problems in the end-cap and can be recovered during the 2008-9 winter shutdown resulting in a nearly fully operational system in time for first LHC collisions in 2009. The SCT and TRT have been collecting cosmic data already since spring of 2008 while the first in-situ cosmic runs with the pixel detector date to mid-September 2008. Figure 1 (left) shows the number of pixel hits observed per event during these first cosmic runs, indicating that many cosmic events generated hits in nearly every layer of the pixel detector. Analyses of such cosmic runs have already resulted in preliminary alignment constants for the inner detector system. Figure 1 (right) demonstrates, as an example, the mean residual x coordinate value of the SCT barrel layers. With such results, misalignments in the inner detector system can be identified and corrected for prior to first proton-proton collisions.

4. Calorimeters

The ATLAS calorimeters are of the sampling variety. The lead-liquid argon electromagnetic calorimeter has 175,000 channels and extends to a pseudorapidity of $|\eta| = 3.2$. It consists of three sampling depths in its precision region which matches that of the inner detector system. The hadronic calorimeter consists in the barrel region ($|\eta| < 1.7$) of a steel-scintillating tile detector with three sampling depths (approximately 10,000 channels) and in its end-cap region ($1.5 < |\eta| < 3.2$) of a copper-liquid argon calorimeter detector (approximately 6,000 channels). In the very forward region where the radiation environment is the harshest, the forward calorimeter extends out to $|\eta| = 4.9$ with, for each end-cap, a copper-liquid argon module for electromagnetic measurements and two tungsten-liquid argon modules for hadronic measurements. Such a calorimeter system provides in the overlap region with the inner detector fine granularity with good resolution and linearity for precision measurements of electrons and photons while providing coarser granularity in other regions sufficient for jet reconstruction and missing transverse energy measurements.

The ATLAS calorimeters have been performing in-situ commissioning tests since 2005. In this time, a good overview of the calorimeter performance has been achieved. Approximately 0.01% of

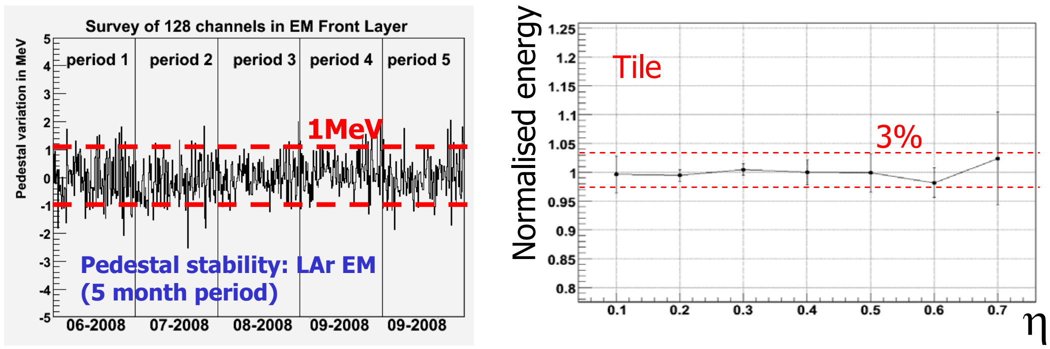

Figure 2: Left: Stability of the pedestal value is demonstrated at the MeV level over a five month period for the barrel electromagnetic calorimeter first layer. Right: tile calorimeter energy deposited by cosmic muons normalised by the distance traveled in the tile calorimeter as a function of pseudorapidity. Energy scale and uniformity are demonstrated at the 2-3% level.

the electromagnetic calorimeter channels are expected to be unuseable for first physics in 2009. A further 0.5% of channels with front-end board readout problems can be repaired during the 2008-09 winter shutdown. The hadronic end-cap calorimeter has approximately 0.1% dead channels. However a low voltage power supply problem which impacts a further one quarter of an end-cap can be resolved at this shutdown. The tile calorimeter has 1.5% dead channels, all of which can be repaired this winter. All forward calorimeter channels are operational. It should be noted that approximately 6% of the calorimeter cells are not at nominal high voltage and will be corrected offline.

The commissioning effort is now more focused towards long-term stability checks such as monitoring pedestal stability over a period of months, predicting the calorimeter signal shape and comparing with cosmic results, and establishing the first calibration constants for collision data. As an example, Fig. 2 (left) shows that the liquid argon barrel has a pedestal mean stability at the few MeV level over a period of five months. An equivalent check reveals a stability of the tile noise at a level of 2% over a period of three months. The hadronic and electromagnetic calorimeters are able to detect energy deposited by cosmic rays. The η dependence of the energy deposit is in agreement with expectations at the 5% level for the liquid argon barrel calorimeter and 2-3% for the tile calorimeter, as shown in Figure 2 (right). Other physics studies have been performed with these cosmic events such as demonstrating the expected correlation between the energy as measured at the level-1 trigger and as measured in the calorimeter readout. Jet studies have been under-taken investigating the impact of cosmic ray air showers as sources of non interaction-point jets.

5. Muon Spectrometer

The muon spectrometer consists of an air-core toroid magnet system providing a bending power of up to 5.5 Tm in the barrel region and 7.5 Tm in the end-caps, precision tracking chambers and trigger chambers. The precision tracking chambers provide the track coordinate in the bending plane and consist of three barrel layers and three end-cap wheels. Monitored Drift Tube (MDT) technology is used everywhere up to a pseudorapidity of $|\eta| = 2.7$ except in the innermost layer for

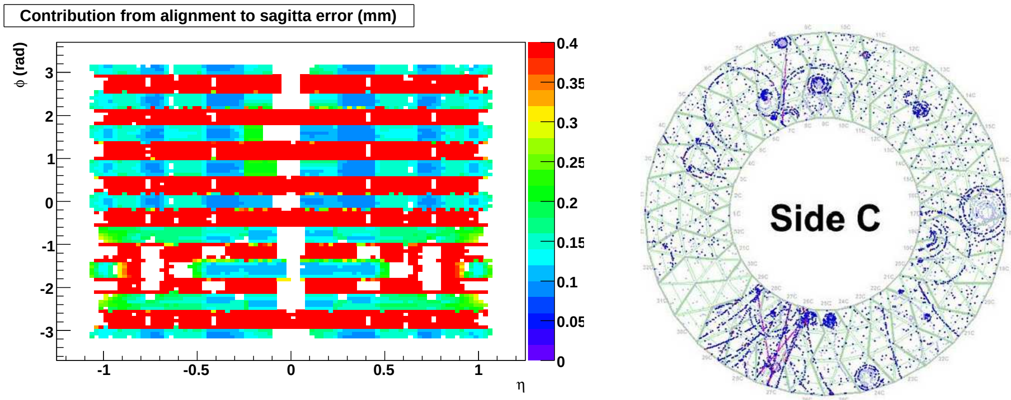

Figure 3: Left: Sagitta errors (in mm) in the even and odd sectors of the muon system when using absolute optical alignment. Sectors in white are not covered by the required three MDT chambers needed to perform such an alignment. Right: Tracks in the transition radiation tracker when the solenoid field is turned on.

$2.0 < |\eta| < 2.7$ where Cathode Strip Chambers (CSC) are used due to the high rate environment. The trigger chambers provide bunch-crossing identification, triggering, and a coordinate measurement orthogonal to the precision tracking chambers. In the barrel region of $|\eta| < 1.05$, three double-layer Resistive Plate Chambers (RPC) are used while four wheels of Thin Gap Chamber (TGC) technology are used in the end-cap region of $1.05 < |\eta| < 2.7$.

The muon system is fully installed, except for the few chambers for which installation was planned only in 2009-2010. It has well been integrated into the data acquisition system. The MDT's are well able to observe cosmic ray events, seeing on average approximately six hits per layer per track and tight spatial correlations have been observed between MDT and RPC hits as well as MDT and TGC hits.

This muon spectrometer system is expected to provide a stand-alone (i.e. no inner detector) p_T resolution of approximately 10% for 1 TeV tracks. This implies that the sagitta of the track needs to be measured with a resolution of 50 μm. Achieving this desired accuracy imposes stringent requirements on the alignment of the muon chambers. This requires that the relative alignment of the three chambers per outward-going tower be known to the 30 μm level. This will be accomplished by a combination of track-based alignment algorithms and an optical system of 12000 optical sensors. The geometer survey puts the positioning accuracy of the 1200 MDT chambers at the 5 mm level. A preliminary study of the barrel alignment of the upper sector of the spectrometer using the optical system in absolute mode provides a precision of approximately 200-300 μm. If this alignment error is propagated to the muon sagitta by use of a Monte Carlo of the optical alignment system, it indicates that a sagitta error of 50 μm in the odd sectors of the muons spectrometer and 400 μm in the even sectors would be obtained, see Figure 3 (left). Alignment with curved tracks are then needed to connect the odd and even sectors. See Ref. [1] for more details. The alignment and timing of the muon system has been an on-going activity since the summer 2008 global cosmic runs.

6. Combined Systems Studies

Over a three-week period in July/August 2008, the barrel and end-cap toroids were ramped to full current (20.5 kA) and full field (4 T) in combination with the solenoid magnet (7.7 kA, 2 T) which provides the magnetic field for the inner detector. Figure 3 (right) shows beautiful bubble chamber-like quality tracks in the transition radiation detector when the solenoid magnet was turned on during cosmics data-taking.

Cosmic events have been used to correlate tracks as seen in the inner detector and in the muon spectrometer. Already in the early cosmic runs of March 2008, θ and ϕ resolutions on the order of 10 mrad were observed between inner detector information (SCT+TRT) and the muon system (MDT). However, the ATLAS magnet system was not turned on for these cosmic events. The August 2008 cosmic runs with magnetic fields do indicate a strong correlation between the momentum as observed in the inner detector and in the muon spectrometer. The global cosmics runs of 2008 are being used for the overall alignment of the inner detector and muon system.

7. Conclusions

The ATLAS detector has been performing in-situ commissioning tests for the past three years. In this time, essentially the entire detector has been fully tested with calibration runs. Most of the subsystems have joined the ATLAS combined cosmic runs which now occur frequently. As a result, a good overview of the status of the subsystems for first LHC collisions in 2009 has been achieved. Most activities in the near future are geared to further commissioning of the detector with cosmic events. Some interventions will be required during the 2008-09 winter shutdown which will recover most of the ailing channels due to, for example, cooling leaks, a failing low voltage power supply, and front-end board readout problems. After this shutdown, the level of remaining inaccessible problems will be at a very low, sub-percent level. Initial calibration and alignment constants have been obtained and will be further refined as the large calibration and cosmics statistics that have been taken in 2008 are analysed in detail.

References

[1] The ATLAS Collaboration, G. Aad et al., The ATLAS Experiment at the CERN Large Hadron Collider, JINST 3 (2008) S08003.