ATLAS Silicon Pixel and Strip Detector: Commissioning with Cosmic Data

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Abstract

The ATLAS detector at the CERN Large Hadron Collider (LHC) started taking data in autumn 2008. In the innermost part of the detector, high-resolution silicon pixel and microstrip sensors provide excellent momentum and vertex measurement. These two silicon detectors, Pixel and SemiConductor Tracker (SCT), were successfully installed inside ATLAS in 2006-2008. After connection of cooling and services and verification of their operation, the detectors are now in the final stage of the commissioning phase. An extensive period of calibrations and cosmic ray data taking was undertaken in 2008, recording more than 400,000 tracks in the Pixel Detector and 2 millions in the SCT. By the end of the year, more than 96% of the Pixel Detector and 97% of the SCT were calibrated and taking data. Cosmic ray events were used to align the detector, check the timing of the front-end electronics and measure the performance.

Key words: Silicon pixels, semiconductor tracker, ATLAS, commissioning

1. Introduction

ATLAS is a general purpose detector operating at the Large Hadron Collider (LHC) at CERN. With a design luminosity of $10^{34}$ cm$^{-2}$s$^{-1}$, the LHC will collide two proton beams every 25 ns at a center of mass energy up to 14 TeV. The LHC challenging environment imposes stringent requirements on the ATLAS detector: high granularity, fast, radiation hard electronics and sensor elements are needed to cope with the high interaction rates and particle fluxes. The ATLAS Inner Detector (ID) is designed to withstand such conditions and provide excellent momentum and vertex resolution for particles with $|\eta| < 2.5$ [1]. The ID is immersed in a 2 T solenoidal field and comprises, as shown in Fig. 1, the Pixel Detector, the SemiConductor Tracker (SCT) and the Transition Radiation Tracker (TRT).

2. ATLAS Silicon Detectors

The silicon precision trackers (Pixel Detector and SCT) are arranged in concentric cylinders around the beam axis in the central barrel region, and in disks perpendicular to it in the end-caps. A track crossing the ID volume leaves three high precision hits in the Pixel Detector and four in the SCT.

A critical feature of the silicon detectors is radiation hardness. The innermost pixel layer (sitting only 5 cm from the interaction point) will have to be replaced after three years of LHC operations at the nominal luminosity. The rest of the Pixel Detector (outer layers and disks) and the SCT, instead, are designed to withstand a 1 MeV neutron equivalent fluence of $1 \cdot 10^{15}$cm$^{-2}$ and $2 \cdot 10^{14}$cm$^{-2}$ respectively, corresponding to ten years of operations. In order to limit reverse annealing and leakage current, the two silicon detectors are cooled to a temperature of $-5$ to $-10$ °C using $C_3F_8$ as a coolant.

Figure 1: The Inner Detector envelope with its three sub-detectors: Pixels, SemiConductor Tracker and Transition Radiation Tracker.
2.1. The Pixel Detector

In the innermost part of the tracking volume, the highest granularity is achieved by silicon pixels: with approximately 80.4 million read-out channels, the Pixel Detector has an intrinsic accuracy of 10 µm (Rφ) and 115 µm (z, R).

A pixel module consists of a 250 µm thick silicon sensor [2], segmented in pixels of typical size 50 × 400µm², bump-bonded to 16 Front End (FE) chips fabricated using 0.25 µm CMOS technology. The sensors use n-in-n technology to achieve the optimal radiation tolerance. A flex-hybrid, that routes signal and power, is wire bonded to the FE chips. On the flex board there is also a Module Control Chip (MCC), a digital chip running with a 40 MHz clock, synchronous with the LHC crossing rate.

For hits above threshold and flagged by a trigger Level-1 (L1) accept, the pixel address, a time stamp and the digitized amplitude (Time over Threshold, ToT) are sent to the MCC which formats the data and sends it to an optoboard.

2.2. The SemiConductor Tracker

The SCT sits outside the Pixels. An SCT module consists of two pairs of identical single-sided micro-strip sensors of typical pitch 80 µm, glued back-to-back at a stereo angle of 40 mrad. All barrel modules [3] are identical, whereas end-cap modules come in three different designs [4]. The AC-coupled sensors [5] use p⁺ implants in an n-doped substrate of thickness 285 µm. The space-point resolution provided by each module is 17 µm in the Rφ direction and 580 µm in z, R.

For each module there are 12 ABCD3T [6] chips, realized in radiation hard technology DMILL, which provide the binary read out of 128 channels each. The signal from the silicon detector is amplified, shaped and compared to a programmable discriminator threshold of 1 fC. The binary information is then fed into a 132-length-pipeline which provides the required L1 latency. Following the arrival of a L1 trigger, the data is compressed and serialized for output.

3. Installation and Commissioning

3.1. Overview of Pixel and SCT Commissioning

The insertion of the ID in the ATLAS cavern commenced with the SCT Barrel in August 2006 and was followed by the SCT end-caps and the Pixel Detector in May-June 2007. After insertion, each sub-detector part was checked for optical and electrical connections and cooling tests were performed. The SCT barrel was signed-off in April 2007 and the end-caps in February 2008. The SCT was run combined with TRT and other sub-detectors already in Spring 2008. The Pixel Detector commissioning was constrained by the ATLAS installation schedule and was delayed by some evaporative cooling problems. Therefore it was included in combined data-taking for the first time on September 14th 2008. On September 10th 2008, when first beam circulated in the LHC, the Pixels and the SCT barrel were turned off for safety reasons, whereas the SCT end-caps were operated at reduced voltage (20 V) and raised threshold (1.2 fC). A fruitful period of calibrations and combined cosmic runs followed from October to December 2008.

3.2. Connectivity and Services

As previously mentioned, the Pixel and SCT detectors need to be operated at low temperature to limit radiation damage. The installation and commissioning of the cooling system was slowed down by major problems with the heater components and the cooling plant in 2007-2008, which in turn delayed the commissioning of the silicon detectors. After a cooling plant failure in May 2008, the cooling system was successfully recovered in August 2008 and ran continuously for the whole cosmic data-taking period. Further repairs have taken place during the first few months of 2009 to guarantee the operational reliability of the cooling system.

Optical links provide digital transmission of the trigger timing and control commands to the Pixel and SCT modules and of data from the modules to the off-detector electronics. Commissioning of the optical links included tests of the down-link and up-link and individual tuning of the operational parameters (optical receiver threshold and delay, VCSEL transmission power). During operation an elevated infant mortality rate of the off-detector transmitter board (TX plug-ins) was observed. Further investigations showed evidence that the VCSELS had been exposed electro-static discharge (ESD). This resulted in a small variable fraction of modules being disabled in 2008. Replacement of TX plug-ins with a new production batch has started and is planned to be completed by August 2009.

Finally, another important step was the commissioning of the electrical connections and power supplies. The Detector Control System allows a continuous monitoring of individual power supplies and of environmental variables and guarantees that the detector can be operated safely via an interlock system.
4. Cosmic Data

During the cosmic ray data-taking period in autumn 2008, more than 7 million tracks were collected in ATLAS, both with solenoid field off and on. Of these, approximately 2 million tracks traversed the SCT and 420 thousands the Pixel Detector.

The fraction of modules operated was approximately 96% for the Pixel Detector and 99% (97%) for the SCT barrel (end-caps). A large fraction of the non-operated modules were due to problems with the cooling plant: three pixel cooling loops in the disks and two SCT loops in the end-caps were unavailable during the cosmic data taking period. All but one loop were recovered for 2009 running: one SCT loop is affected by a non-accessible leak and will therefore result in 13 permanently non-operational modules.

Both detectors achieved the required low noise occupancy after threshold tuning and noise masking, as shown in Fig. 2. The noise occupancy per bunch crossing for each Pixel layer and end-cap is at the level of $10^{-10}$. For the SCT barrel and end-caps, the noise occupancy measured per channel at the operating voltage of 150 V is significantly below the specifications of $5 \cdot 10^{-4}$.

The cosmic ray data has proven extremely useful for performance and Lorentz angle studies, detector alignment and for timing-in the sub-detectors with the rest of ATLAS.

4.1. Performance

The performance of the silicon detectors was studied by measuring the intrinsic hit efficiency of Pixel Detector and SCT both with and without solenoid field. Considering only the operational modules and using aligned geometry, the pixels hit efficiency was found to be about 99.8%. For the SCT, the intrinsic hit efficiency for field-on data is about 99.9% in the barrel and between 99.0% and 99.5% in the end-caps, which were not properly timed-in with respect to the trigger.

4.2. Lorentz Angle Measurement

Accurate knowledge of the Lorentz angle is necessary for the detector alignment and spatial resolution. The Lorentz angle was measured as the track incidence angle which leads to a minimum cluster size. Cosmic rays are suitable for such studies since they cross the silicon sensors over a wide range of incident angles. In Fig. 3 the average cluster size for tracks in the SCT barrel is plotted versus the incident angle. Data from cosmic runs with magnetic field on and off and Monte Carlo simulations are shown. The minimum corresponds to the Lorentz angle and yields the value of $3.93 \pm 0.03$ (stat.) $\pm 0.10$ (syst.) degrees, which is in agreement with the predicted value of $3.69 \pm 0.19$ (syst.). In the absence of magnetic field the Lorentz angle is compatible with 0. The Lorentz angle was measured also with the Pixel Detector, leading to similar results. Further studies of the Lorentz angle are going to be performed with the first LHC collisions using minimum-bias events.

4.3. Alignment

The data collected during the cosmic run provided sufficient statistics to significantly improve the alignment of both Pixel Detector and SCT barrel region. Due to the geometry of cosmic data, alignment of the end-caps is more difficult and will have to wait for first LHC collisions. Figure 4 shows the residual distribution in $x^1$, for nominal geometry and preliminary aligned ge-

\[ x^1 \] is the local precision direction measurement.
geometry. The residual is defined as the measured hit position minus the expected hit position from the track extrapolation. The present alignment already approaches the resolution obtained in a Monte Carlo simulation assuming a fully aligned detector.

5. Conclusions

Great progress was achieved in the commissioning of the Pixel Detector and the SemiConductor Tracker in 2008. Both detectors were calibrated and run under realistic conditions, recording high statistics of cosmic-ray events. Valuable experience was extracted from the data-taking period, allowing to study and improve the detector performance and alignment. Problems observed with the cooling system and the optical links have been addressed and will be solved by August 2009. Operations have recently resumed after the shutdown period and it is expected that more than 98% of the Pixel Detector and 99% of the SCT will be operational.

The ATLAS silicon trackers are in good shape, waiting for the LHC start-up later in 2009.

References