Commissioning and Operation of the ATLAS Pixel Detector

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Abstract

In December 2009 the ATLAS experiment at the CERN Large Hadron Collider (LHC) recorded the first proton-proton collisions at a center-of-mass energy of 900 GeV, and in March 2010 at the unprecedented energy of 7 TeV. The ATLAS Pixel Detector is the innermost detector of the ATLAS experiment at the Large Hadron Collider at CERN. It consists of 1744 silicon sensors equipped with approximately 80 million electronic channels, providing typically three measurement points with high resolution for particles emerging from the beam-interaction region, thus allowing to measure particle tracks and secondary vertices with very high precision. Before the start of LHC operations, the completed Pixel Detector was operated for many months under realistic conditions in the ATLAS experimental hall. This allowed to optimize the operating parameters of the system, and to qualify the detector with physics data from cosmic muons. After the commissioning phase the Pixel Detector arrived to the first LHC pp collisions run with very good records: 97.5% of the Pixel Detector is operational. Noise occupancy and hit efficiency exceed the design specifications. The alignment is close enough to the ideal one to allow good track reconstruction and invariant mass determination. A review of the commissioning and of the first operational experience with the Pixel Detector will be presented, including monitoring and detector calibration procedures, and the timing optimization process, as the detector operation progressed from commissioning with cosmic ray data to commissioning with collisions and finally to steady-state data taking. In addition, the current status of the Pixel Detector and its response to LHC high energy proton-proton collisions will be presented.

Keywords: Pixel Detector, ATLAS

1. Introduction

The ATLAS detector is built around the interaction region located at point 1 of the Large Hadron Collider (LHC) ring at CERN and is one of two general purpose experiment designed to study physics in the new energy frontier which the LHC has and will reach. At design parameters, proton-proton collisions will take place every 25 ns in bunches of 1.2x10^{11} protons per bunch at an energy of 7 TeV per beam for an expected instantaneous luminosity of 10^{34} cm^{-2} s^{-1}. The ATLAS detector must be able to cope with the high rate of particle interactions while maintaining a good energy resolution, particle identification, pattern recognition and vertex reconstruction [1]. To accomplish this, the detector is broken up into three subsystems. The Inner Detector (ID) consists of the Pixel Detector, the SemiConductor Tracker and the Transition Radiation Tracker which operate in a 2 T solenoid magnetic field and provide tracking and particle identification. Surrounding the ID are a system of calorimeters which use LAr-based technology and iron-scintillator technology for energy measurements and particle identification. The outer system is a Muon Spectrometer located in a 4 T toroidal magnetic field needed for tracking and momentum measurement for the surviving muons.

This paper will focus on the ATLAS Pixel Detector, specifically the details relating to the operation of the detector during the first year of LHC running. An outline of the Pixel Detector Section (2) and the readout chain will be given, followed by the operational aspects of the detector which includes detector calibrations, (Section 3.1) noise measurement and reduction (Section 3.2), and integration with the ATLAS DAQ. Finally, an overview of the data taking for the 2010 run will be given with detector status and data-taking efficiency (Section 4).
2. The ATLAS Pixel Detector

2.1. Layout and Structure

The ATLAS Pixel Detector [2] is designed to provide at least \( \eta < 2.5 \) three precision measurement points for tracks with pseudorapidity. It consists of a three-layered barrel region and two endcaps each containing three disks (Fig. 1). The barrel layers have radii of 50.5 mm, 88.5 mm and 122.5 mm and are 800 mm long. Each disk contains 48 individual modules and the disks are located \( \pm 495 \) mm, \( \pm 580 \) mm and \( \pm 650 \) mm from the interaction point in the z-direction. The barrel layers have overlapping staves of 13 modules each which are rotated 20° (Fig. 2) to compensate for the Lorentz angle in the 2 T magnetic field of the ID. The disks are divided into 8 sectors of six overlapping modules each for full coverage. The 1744 modules that make up the Pixel Detector are identical and cover a surface area of 1.7 m². The modules are cooled using an evaporative \( \text{C}_2\text{F}_6 \) cooling plant which is segmented into 88 loops. Two barrel staves (a bistave) or two disk sectors (a bisector) make up one cooling loop. The operating temperature for 2010 is about \(-17°C\).

![Figure 2: A cross-section of the barrel layers of the ATLAS Pixel Detector. The radial distances from the interaction points are given in millimeters.](image)

2.2. The ATLAS Pixel Detector module

The ATLAS Pixel Detector modules (Fig. 3) consist of a \( 250 \) \( \mu \)m thick silicon sensor with \( n^+ \) pixels implanted on the n-doped bulk with a \( p^+ \) backplane. The 60.8 mm x 16.4 mm sensor is bump-bonded onto 16 Front-End chips (FE-I3) which are wirebonded to a flexible multi-layer printed circuit board (flex board) that is glued to the opposite side of the sensor. The FE-I3 chips [3] utilize 0.25 \( \mu \)m CMOS technology and have 2880 readout channels. The nominal pixel size is \( 400 \) \( \mu \)m x \( 50 \) \( \mu \)m. To enable full coverage in the regions between front-end chips, larger \( 600 \) \( \mu \)m x \( 50 \) \( \mu \)m pixels are utilized in the long pixel direction while ganged pixels are used for seamless coverage in the short pixel direction. Each pixel contains an analog and a digital circuit which performs pre-amplification of the collected charge along with hit discrimination, measurement of the Time-over-Threshold (ToT) and digitization of the hit information. An 8-bit DAC and a 5-bit DAC for each pixel allows for pixel by pixel tuning of the hit threshold and charge calibration respectively. Zero-suppression is performed on the FE chips so that only pixels with hits are read out. The modules are designed to withstand the expected lifetime dose of 500 kGy.

![Figure 3: The ATLAS Pixel Module](image)

2.3. Readout

Communication to the Pixel Detector is provided by an optical link which connects the off-detector Read-Out Drivers (RODs) to the modules over a distance of 80 m. Each module has one downlink (TTC) which provides clock, trigger signals, detector calibration data and commands to each FE. The MWC is mounted on the flex board which also contains an NTC thermistor for temperature monitoring and provides the bias voltage to the sensor (currently 150 V). Each module has 47232 pixels for a total of \( \approx 80 \) million channels in the ATLAS Pixel Detector.
Figure 4: A schematic of the readout system for the ATLAS Pixel Detector which can each be read out at 80 MHz for an equivalent readout speed of 160 MHz. The layout of the pixel readout system from the signal generation in the sensor to the off-detector RODs can be found in Fig. 4.

3. Detector Operations

3.1. Detector Calibration

In order to optimize operation of the Pixel Detector, regular checks of the working points for both the readout systems and the pixel modules must be made. The first step is to establish stable communication through the data and TTC optical links for each module. These so-called “optical scans” check that the transmitting VCSELs for each link are sending light and also select a stable sampling point for the data-links in the laser-threshold/sampling-time phase space. Following this, the calibration parameters for the front-end electronics are measured and a parameter tuning is performed if necessary. The tuning parameters are a 7-bit DAC which allows for pixel by pixel threshold tuning and a 5-bit DAC which allows for pixel by pixel charge calibration. The target signal threshold for the 2010 run period is 3500 electrons. The threshold calibration parameters are determined by injecting known charges into the analog portion of each pixel circuit and measuring the fraction of hits observed for a given injected charge. The threshold is defined as the charge for which 50% of the events register as hits and is measured using a fit to an error function. The electronic noise is the Gaussian width about the threshold measured from the error function fit. The measured thresholds and noise distributions for 2010 can be found in Fig. 5.

The ToT calibration constants are necessary to translate the ToT value into a measure of charge that is collected in the pixel. The ToT is measured in units of bunch crossing intervals (BC) which have a 25 ns width. The target ToT tuning for the 2009 and 2010 run period is such that 30 ToT should correspond to 20000 electrons (the approximate charge deposited by a minimum ionizing particle). This corresponds to a charge resolution of approximately 660 electrons (1 ToT). For more information on calibration procedures and the Pixel Detector’s calibration parameter distributions, see [5].

3.2. Noise Occupancy

The noise occupancy is defined as the fraction of hits measured per pixel which are uncorrelated with activity in the detector. In order to minimize the amount of noise, special data runs are taken with a random trigger and no beam in the LHC to determine which pixels are “noisy”. Noisy pixels are defined as those pixels which have a noise occupancy of greater than $10^{-5}$ hits per BC. All noisy pixels are masked at the module level and are not read out. This online noise mask is remeasured monthly, when modules are retuned or when the detector has been thermal-cycled. The fraction of masked pixels in the online mask is at the level of 0.01%. While the online mask is included into each module’s individual configuration (hardware), a second level of protection against noisy pixels is employed at the data reconstruction level. This offline mask is measured in a 36-hour calibration loop which follows the completion of every data run. Any noisy pixels not masked online are removed from the first reconstruction of the data. The evolution of the noise occupancy as the offline mask is applied is shown in Fig. 6. Using both the online and offline masks, the noise rate in the Pixel Detector is less than $10^{-9}$ hits per pixel per BC.

3.3. Operation with beams

The primary concerns for operations with beams in the LHC are to ensure the safety of the Pixel Detector, to ensure the highest data taking efficiency and to check the quality of the data during the run. During periods with unstable beams in the LHC, the Pixel Detector must be kept in a safe, STANDBY state which requires that the sensors remain unbiased. This safety
is enforced with a hardware interlock on the high voltage system which is linked to a signal sent by the LHC when beams are stable. An unbiased, undepleted sensor can lead to a large number of noise hits per module which can occupy the data acquisition system (DAQ) such that no triggers can be processed. This is problematic for ATLAS as the DAQ system is started while satisfying the safety requirements. To avoid the Pixel Detector to remain in the ATLAS DAQ system and while satisfying the safety requirements.

At the start of a data-taking run, each module is configured such that the preamplifiers for each pixel are switched off so that the sensor is decoupled from the analog portion of the pixel circuit and then the high voltage is switched off to unbias the module. Under these conditions, there are no hits in the entire detector and the Pixel Detector can still be included in the ATLAS readout. When the LHC declares the beams to be stable, the trigger is paused, the bias voltage is applied and all modules are reconfigured with the preamplifiers switched on. Using this procedure, the safety of the Pixel Detector is respected and the data-taking efficiency is increased with respect to a complete restart of the ATLAS DAQ as the time necessary for the warm start procedure is on the order of several minutes while the time needed to restart the ATLAS DAQ can be significantly longer.

The data-taking efficiency can also be reduced due to high rates of noise, modules and readout links with hardware problems, loss of the clock signal or corruption of the module configuration. Such issues can slow down or block the data acquisition completely. To counter this, the Pixel Detector DAQ has the ability to automatically remove and reinsert modules from the readoutchain during a run. Modules with occasional excess noise or background track hits can be automatically reinserted back into the DAQ.

Monitoring of the data quality is available online by sampling events directly from the data stream from several steps along the trigger chain. The occupancy, ToT and readout error distributions are monitored from both level-1 (all triggers) and level-2 (Event Filter) triggers on the per module level. More complex and detailed information of events such as cluster properties and track reconstruction properties is available through the online monitoring but is sampled only from the level-2 triggers and at a greatly reduced rate due to the processing load. Such monitoring is essential to recognizing, diagnosing and fixing issues as quickly as possible to ensure the highest possible data quality.

4. Data taking and performance

During the 2010 run period, 97.3% (1697 of 1744 modules) of the Pixel Detector was included in the ATLAS DAQ. This corresponds to 47 modules being inactive due to problems in communication or retrieval of data, open high voltage circuits, low voltage shorts, inability to receive the clock signal or failure of an optoboard (single point failure affecting 6 or 7 modules). The highest fraction of failures is located in the barrel layer-2 which has 4.1% of modules inactive (28 of 676) as shown in Tab. 1. It is also possible to remove single or multiple front-end chips from an individual module’s readout which are found to be defective. Forty-four front-end chips are disabled (0.16%) of the 27904 total chips on the detector. In addition to these inactive modules and front-ends, some modules may be temporarily removed from data-taking due to failures of the off-detector vertical-cavity surface-emitting lasers (VCSELs) which provides communication to the modules via the optical link. The failing components are accessible and can be replaced promptly.

In order to minimize the number of hits lost to mistimed modules and hits misplaced due to the timewalk effect, the readout window of the Pixel Detector can be adjusted to record up to 16 consecutive BCs for each level-1 trigger provided by the ATLAS DAQ. At the beginning of 7 TeV LHC operation in March of 2010, the Pixel Detector used a 4 BC readout window. The timing of each module was adjusted such that track-associated hits are recorded by the second of the four consecutive triggers (Fig. 7) with hits mistimed due to the timewalk effect recorded by the third and fourth consecutive triggers at a less than 0.1% level. Through a campaign of time delay scans in the spring of 2010, the time delay per module was measured and optimized to allow for further reduction of the readout window with minimal loss in efficiency. As of October 2010, the Pixel Detector has reached the design readout window of 1 BC. In order to compensate for the timewalk effect, low charge hits are written twice in the module’s readout architecture. If the measured
The Pixel Detector has participated in ATLAS data-taking for all stable LHC operations with beam which began in November 2009. Beginning in March of 2010, stable collisions have been recorded at a record center-of-mass energy of 7 TeV. While initial instantaneous luminosity was low due to a minimal number of filled bunches, the LHC has made steady progress throughout the year and has recently surpassed the goal of providing $10^{33} \text{ cm}^{-2} \text{s}^{-1}$ (Fig. 8). As of October 2010, ATLAS has recorded 20.11 pb$^{-1}$ of data with all subdetectors included (Fig. 9). As described earlier, the Pixel Detector is only taking data during run periods which are declared stable by the LHC. The Pixel Detector efficiency for data-taking has been measured to be 97.7%. This efficiency is measured as the fraction of time in which the Pixel Detector is ready and active in the ATLAS DAQ for all declared stable beam periods. The luminosity-averaged efficiency for all ATLAS subdetectors can be found in Table 2. The dominating contribution to the Pixel Detector inefficiency is due to the time necessary to perform the warm start which activates each Pixel Detector module in the ATLAS DAQ. This inefficiency is expected to be reduced with additional operational experience and increased automation of the warm start procedure.

ToT is below threshold, currently 6 ToT, the hits are written first with the original timestamp and then again with the timestamp of the previous 25 ns time bucket.

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### Table 2: Luminosity weighted relative fraction of detector uptime and good quality data delivery of the various ATLAS subsystems during LHC fills with stable beams at a center-of-mass energy of 7 TeV between March 30th and August 30th of 2010, corresponding to an integrated luminosity of 3.6 pb$^{-1}$ recorded by ATLAS during stable LHC beams.

<table>
<thead>
<tr>
<th>Inner Tracking Detectors</th>
<th>Calorimeters</th>
<th>Muon Detectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel</td>
<td>LAr EM</td>
<td>Tile</td>
</tr>
<tr>
<td>SCT</td>
<td>LAr HAD</td>
<td>98.6</td>
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<tr>
<td>TRT</td>
<td>LAr FWD</td>
<td>98.5</td>
</tr>
<tr>
<td></td>
<td>Tile</td>
<td>98.6</td>
</tr>
</tbody>
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5. Summary

The ATLAS Pixel Detector has been commissioned and included in the ATLAS data-taking for LHC operations at center-of-mass energy of 7 TeV for all of 2010. The average operational threshold of pixels was 3500 electrons with a dispersion of $\approx 40$ electrons. The noise occupancy was measured to be less than $10^{-7}$ hits/pixel/BC using only an online noise mask and can be further reduced to a level below $10^{-9}$ hits/pixel/BC using an additional offline noise mask. The offline mask is extracted during a prompt 36-hour calibration loop and applied for the
full data reconstruction. Data-taking efficiency is improved by way of the warm start procedure which allows for safe operation of the Pixel Detector while still staying inside the ATLAS DAQ.

The Pixel Detector has 97.3% of all modules included in data-taking and is running at an average temperature of \( \approx -17^\circ C \) with all 88 cooling loops operational. The readout window size for 2010 has been reduced stepwise from 4 BC in March of 2010 to the design readout window size of 1 BC as of October 2010. The total recorded ATLAS-ready luminosity is 20.11 \( \text{pb}^{-1} \) and the Pixel Detector’s data-taking efficiency has been measured to be 97.7%.

References

[5] M. Keil these proceedings