

Commissioning of the ATLAS Pixel Detector with Cosmic Ray Data

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The Pixel Detector is the innermost tracking device of the ATLAS experiment at LHC. This note reports about the commissioning progress made between Summer 2008 and Fall 2009 to prepare the detector for a successful data taking at LHC. The overall status and the expectations for long term operations in the coming years are reported after a quick overview of the calibration studies and their impact on the cosmic ray measurements.

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1. Introduction

The ATLAS detector [1] is one of the general purpose experiments installed at the Large Hadron Collider (LHC) at CERN, and the largest high energy apparatus ever built. The detector is subdivided in three main systems:

- an Inner Detector operating inside a solenoidal magnet at 2 T and described with some details later;
- a barrel and end-cap hybrid calorimetry system based on LAr technology and different types of absorber materials for the central electromagnetic calorimeter and end-cap electromagnetic and hadronic calorimeters and on iron-scintillator technology for the central hadronic calorimeter;
- a Muon Spectrometer in a toroidal field of 4 T produced by a large air-core toroidal magnet system, with a variety of gas chamber technologies.

The ATLAS Inner Detector includes three different sub-detectors: an outer straw-tubes based tracker with particle identification capabilities based on transition radiation effects (Transition Radiation Tracker, TRT), a silicon strip detector (SemiConductor Tracker, SCT) and finally the innermost silicon pixel detector (Pixel Detector).

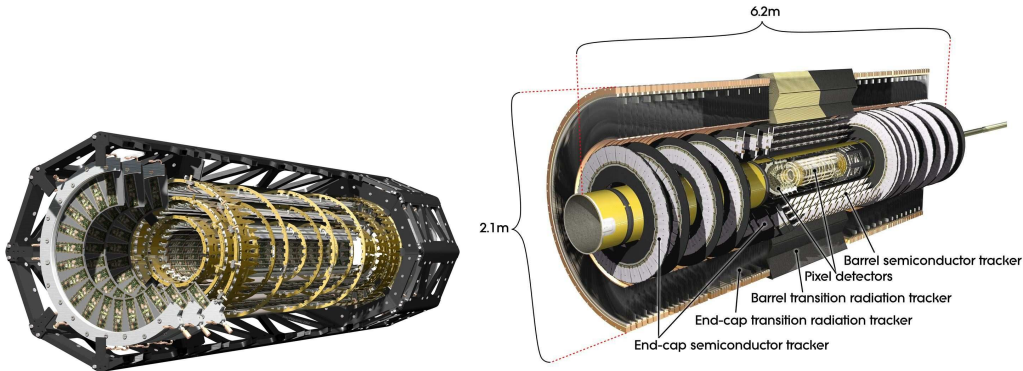


Figure 1: The ATLAS Pixel Detector (left) and the full Inner Detector (right)

The Inner Detector is 6.2 m long and has a diameter of 2.1 m (fig. 1). It has an acceptance in the range $|\eta| < 2.5$ ($|\eta| < 2$ for TRT). The Inner Detector has been designed to achieve a momentum resolution of $\sigma(p_T)/p_T = 0.05\% p_T [\text{GeV}/c] \oplus 1\%$. A further requirement is an impact parameter resolution of $\sigma(d_0) = 10 \mu\text{m} \oplus 140 \mu\text{m}/p_T [\text{GeV}/c]$, in the range $0.25 < |\eta| < 0.5$,

2. The ATLAS Pixel Detector

2.1 Properties and requirements

The Pixel Detector is built out of 1744 identical modules assembled in three barrel layers and three disks on each side of the barrel (fig. 1). Each of the six disks is made of eight sectors with

six modules each (288 modules in total). Each barrel layer is built with modules on local supports (staves) and on each staff there are thirteen modules (1456 modules in total). The total number of channels is approximately 80 millions [2].

The innermost layer is placed at only 50.5 mm from the interaction point, with small clearance from the beam pipe. These extreme conditions imposed a requirement for a radiation tolerance up to 500 kGy for a fluence of 10^{15} 1 MeV $n_{eq}cm^{-2}$ and the adoption of an evaporative C_3F_8 -based cooling integrated in the modules supports to keep the modules' temperature below 0 °C. The detector is operated at a coolant temperature of -20 °C (corresponding to about -17 °C on detector) since Summer 2009 to be ready for first collisions; the cooling system is able to operate down to a coolant temperature of -30 °C.

The detector has been designed, built and tested to achieve a position resolution in $r - \phi$ of less than $15 \mu m$, three track points for $|\eta| < 2.5$, a time resolution of less than 25 ns and a hit detection efficiency higher than 97 %.

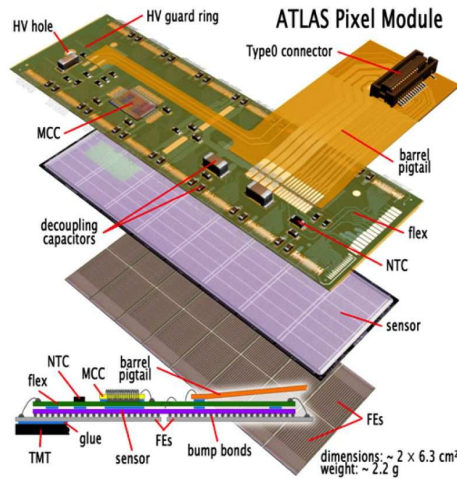


Figure 2: The ATLAS Pixel Module

2.2 The ATLAS Pixel Module

The Pixel modules (fig. 2) are built using $250 \mu m$ thick n-on-n Si sensors with 47232 pixels with a normal pixel size of $50 \mu m \times 400 \mu m$, except for a fraction of long pixels with a size of $50 \mu m \times 600 \mu m$; these latter pixels are located in the inter-chip regions. Each module is operated at a bias voltage of 150-600 V (150 V are used for the present, not yet irradiated, detector) and read out using 16 Front-End chips (FE-13 ASICs [3]) with 2880 readout channels each. The 16 chips read out in total 46080 channels, but all 47232 pixels are readout, as pixels in the inter-chip regions are ganged together.

The FE-13 front-end chip allows for pulse height measurements by means of the Time-over-Threshold determination. Zero-suppression is performed on chip. An event building chip, the Module Controller Chip (MCC) [4], collects the data from the 16 readout chips. The data is then converted into optical signals and sent via optical fibres to the off-detector electronics. The MCC also provides clock and control signals to the individual front-end chips.

3. The Pixel Detector Commissioning

The Pixel Detector installation was completed in Spring 2008 and, after an initial preliminary test period for fixing a few initial problems with the cooling system, the period between August and December 2008 was dedicated to functionality checks, calibrations and finally cosmic ray data taking.

The detector was completely commissioned for the first time with the final cooling system and a first calibration campaign was conducted to establish a baseline configuration, setting the thresholds at about 4000 e and preparing for a first cosmic ray data taking. A total of about 240000 tracks were collected with both solenoidal and toroidal magnetic fields off and a total of about 190000 tracks with both magnetic fields on. In addition, a few data taking periods were dedicated to alignment studies with the solenoid and/or the toroid magnets off. After a consolidation period for the cooling system, the commissioning program was resumed during May to July 2009 with a short calibration period. Then a cosmic ray data taking period was started again and about 90000 tracks were collected with both magnetic fields off and about 180000 tracks with both magnetic fields on.

After a further consolidation period, to integrate more pressure sensors on the cooling circuits, the detector was finally set at an operating temperature of -20 °C, that will be kept until the first signs of damages by radiation will show up. Starting from mid-August 2009, the detector entered again an intense phase of calibration to prepare several different configurations at different thresholds: 3500 e and 3000 e . The configuration at 3500 e was then used during a cosmic ray data taking period started in September 2009 and lasting until the LHC start up in Fall 2009. The accuracy of the position measurement of shallow tracks clearly profited from these data. These intense calibration and data taking periods allowed to establish all main performance parameters for the Pixel Detector. In addition a final classification of the detector failures was done and about 2 % of the detector is not operable. The main source of failures is from optical and electrical services, while only about 0.3 % of the failures are caused by front-end chip failures.

3.1 The calibration procedures and results

The Pixel Detector has a large set of possible calibration parameters. The first important step in calibrating the detector consists in setting up the optical communication between the detector modules and the off-detector readout electronics.

A large set of parameters of the front-end electronics can be calibrated and tuned to achieve a small dispersion of those parameters, across all channels on a front-end chip, on a complete module and finally on the complete detector. An internal calibration circuitry in each front-end chip allows to inject test charges into the pre-amplifier input, simulating in this way a charge deposition in the sensor, with a predefined value of charge and timing.

The front-end chip contains a discriminator stage per pixel to allow for an efficient noise rejection via the setting of a threshold, determined from the fitting of the noise integral function. The threshold can be set via a 7-bit DAC that allows an adjustment for each pixel. The DAC settings are determined via calibration scans. The subsequent tuning procedure allows to obtain a homogeneous threshold setting among different pixels, eliminating response differences, within the achievable threshold dispersion.

The results obtained are quite good, as can be seen in figure 3. It shows the results already achieved in 2008, with a dispersion of $40 e$ for the threshold distribution over 95% of the channels, with a mean value of about $4000 e$. In 2008 few cooling circuits were not operated, while in 2009 all circuits have been switched on. The noise has been measured to be approximately $200 e$ for most pixels, being slightly higher for longer and ganged pixels. The threshold-to-noise ratio is ~ 25 for the majority of the pixels in the detector.

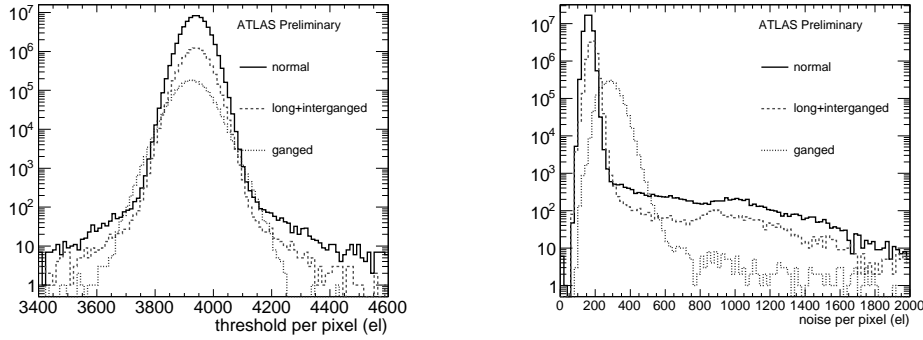


Figure 3: The threshold (left) and noise (right) distributions per pixel for the $4000 e$ threshold setting. Both plots are in log scale to enhance the small contributions of the tails.

The fraction of masked pixels because of high noise is at the level of 0.01 % and the noise occupancy after masking noisy pixels is at the level of 10^{-10} hits per bunch crossing per pixel (fig. 4). The measured noise occupancy and noise distribution per pixel is far better than the one from design expectations: figures of the level of 10^{-5} hits per channel per trigger were used as guidelines for the front-end chip design [3].

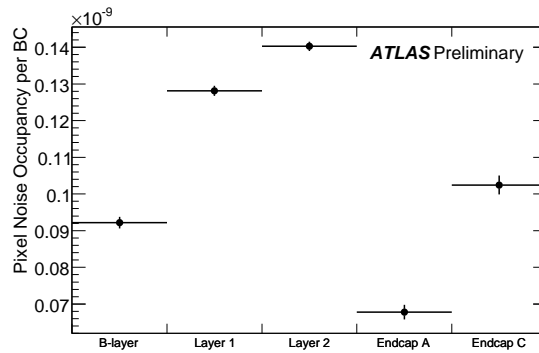


Figure 4: The noise occupancy for the Pixel Detector barrel layers and end-cap disks

When a charge deposited in the sensor is above the discriminator threshold, the front-end electronics stores the Time-over-Threshold (ToT) quantity, i.e. the time during which the pre-amplifier output is above threshold. By design the ToT has a nearly linear dependence on the amplitude of the pre-amplifier output and therefore on the charge released in the sensor. A 3-bit DAC allows to

adjust the pre-amplifier feedback current and therefore the ToT value and its behavior. The ToT response is calibrated and tuned, via charge injections, to have a homogeneous response of approximately 20000 e , corresponding to the most probable value for the charge deposited by one m.i.p. in the silicon sensor. A ToT target value of 30, in bunch crossing (BC) units (1 BC = 25 ns), is obtained. This information is confirmed by measurements with cosmic-ray muons (fig. 5), where tracks are required to have a crossing angle α within 0.44 rad of normal incidence. Corrections for the crossing angle are applied.

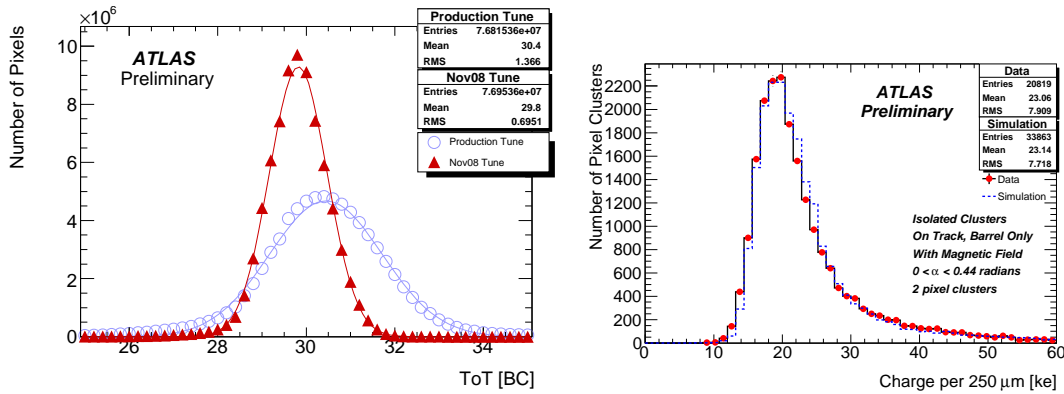


Figure 5: The ToT calibration distribution before and after the tuning for a homogeneous response across all pixels (left) and the response to cosmic ray muons that confirms the ToT calibration of 30 BCs for the expected 20000 e response (right).

3.2 Commissioning with cosmic rays

The commissioning with cosmic rays has been an important verification for the quality of the calibration results. Given the large number of channels and the angular distribution of the cosmic rays, it is difficult to achieve a comprehensive characterization of the full detector, however the results obtained confirmed the expectations fully. The data taking with LHC beam will help in sorting out the last and finest details, but the cosmic ray data taking periods helped in the preparation of the detector to be in the best possible condition.

The Pixel Detector readout chips have the possibility of opening a readout window with a length of up to 16 bunch crossing units. That simplifies enormously the task of internal synchronization between the Pixel Detector modules and later with the rest of the ATLAS sub-detectors, at the expense of an increased dead time, as expected. However, thanks to the accurate calibration constants, it was possible to start the data taking with cosmic rays with an 8 BCs-wide readout window and to be able to arrive at the end of the cosmic ray data taking period at a 5 BCs-wide readout window, with a hit distribution already clearly contained in just 3 BCs.

In order to obtain this result, reported in figure 6, two steps were needed: a good time alignment between different readout crates was achieved correcting the cable lengths based on oscilloscope measurements; a good time alignment between modules was achieved using the precise information about the length of the optical fibres connecting the detector to the off detector electronics. The remaining effects to be taken into account are the trigger jitter value, the random

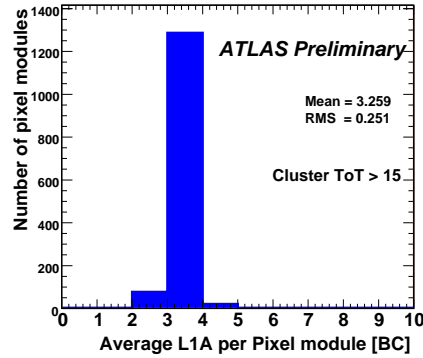


Figure 6: The Pixel Detector timing plot showing the hit time with respect to the beginning of the readout window. The hits are well confined in 3 BCs.

phase of the cosmic rays' arrival time with respect to the 40 MHz clock and the time walk effects for low charge depositions. The plan is to start the data taking with beam using a readout window of 5 BCs, that can rapidly be reduced to 3 BCs and later to 2 BCs and finally to 1 BCs, as the timing-in of the detector is progressively improved as enough data will become available for all 80 million channels.

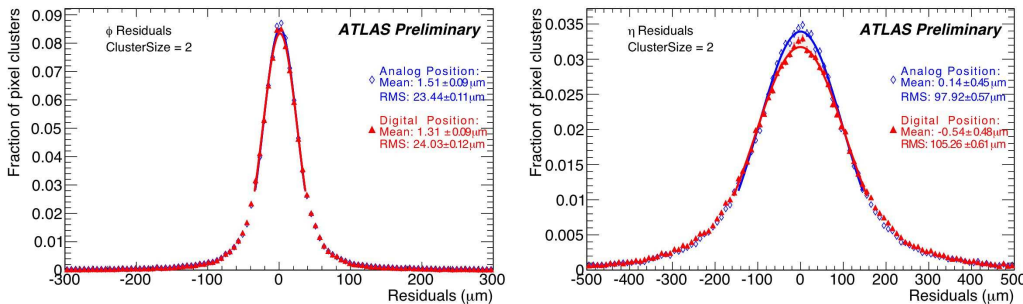


Figure 7: The Pixel Detector resolution in the precision (left) and in the beam direction (right).

The cosmic ray run allowed a step forward in the alignment of the Pixel Detector both internally and combined with the rest of the ATLAS Inner Detector. The results obtained are mostly relevant for barrel modules, as not enough triggers were available for a good alignment of the end-cap modules. That will be possible as soon as the LHC will restart. The final alignment is not yet at the expected level due to the limited amount of data. However, a large improvement has been obtained with respect to the initial measurements obtaining an improvement for the space resolution in the precision direction from the initial $128 \mu\text{m}$ to $24 \mu\text{m}$; equally for the resolution along the beam direction the improved alignment allowed to go from the initial $282 \mu\text{m}$ to $105 \mu\text{m}$. Figure 7 shows the residual distribution for the both the precision coordinate and the beam direction coordinate. The tracking efficiency has been measured to be higher than 99.7 %.

Finally, the measurements using the magnetic field allowed to determine the Lorentz angle for

the Pixel Detector sensors, by looking at the cluster size versus the track angle with and without magnetic field. The measured value of $\theta_L = (213.9 \pm 0.5)$ mrad is close to the expected value of 225 mrad (fig. 8). In addition it was possible to measure the behavior of the Lorentz angle with the temperature, i.e. the temperature dependence of the electron mobility. The measured value of $d\alpha/dT = (-0.78 \pm 0.18)$ mrad/K is in agreement with the theoretical expectation of -0.74 mrad/K [5].

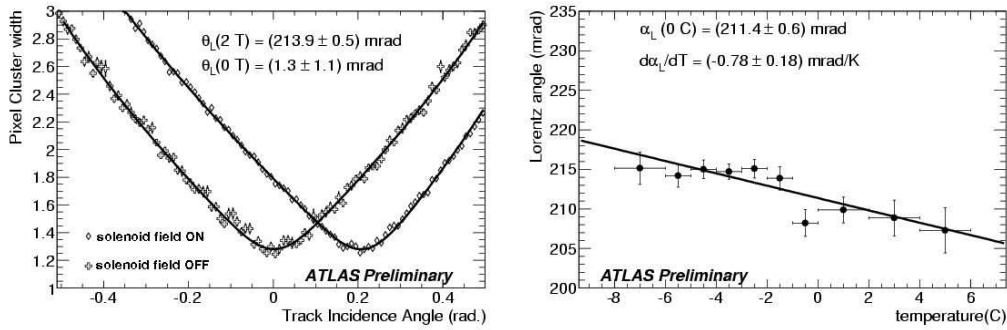


Figure 8: The Lorentz angle plot (left) and the Lorentz angle dependence on the operating temperature (right)

4. Conclusions

The ATLAS Pixel Detector has been commissioned in a relatively short time in a few commissioning periods during 2008 and 2009 and the results obtained met the expectations in terms of noise (200 e for most pixels), threshold dispersion (40 e for a 4000 e threshold setting) and m.i.p. response (20000 e).

The cosmic data taking period has been extremely useful for a good determination of the detector timing, allowing a quick reduction of the readout window size, to obtain a satisfactory spatial resolution (24 μm in the precision direction) and tracking efficiency ($> 99.7\%$), and finally to assess the detector noise occupancy at the level of 10^{-10} hits per bunch crossing per pixel, with just a 10^{-4} fraction of masked pixels.

The results of the intense periods of calibration and cosmic data taking are being documented in a large number of notes and a summary article is in preparation.

The detector is operated at a coolant temperature of -20 °C and all cooling loops are in operation. About 98 % of the available channels are operational and the ATLAS Pixel Detector is ready for data taking at the LHC with a few different threshold configurations to study possible beam effects in addition to normal operations. We are looking forward to a successful long period of running at the LHC.

References

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