

Operational experience with the ATLAS Pixel Detector at the LHC

Dominic Hirschbühl on behalf of the ATLAS Collaboration

Univ. Wuppertal

E-mail: dominic.hirschbuehl@cern.ch

The Pixel Detector is the innermost detector of the ATLAS experiment at the Large Hadron Collider at CERN, providing high-resolution measurements of charged particle tracks in the high radiation environment close to the collision region. This capability is vital for the identification and measurement of proper decay times of long-lived particles such as b -hadrons, and thus vital for the ATLAS physics program. The detector provides hermetic coverage with three cylindrical layers and three layers of forward and backward pixel detectors. It consists of approximately 80 million pixels that are individually read out via chips bump-bonded to 1744 n-in-n silicon substrates. In this paper results from the successful operation of the Pixel Detector at the LHC will be presented, including monitoring, calibration procedures, timing optimization and detector performance.

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1. Introduction

The ATLAS detector is built around the interaction region located at one of the interaction points of the Large Hadron Collider (LHC) at CERN and is one of two general purpose experiments designed to study physics in the new energy frontier of the LHC. At design parameters, proton-proton collisions will take place every 25 ns in bunches of $1.2 \cdot 10^{11}$ protons per bunch at an energy of 7 TeV per beam for an expected instantaneous luminosity of $10^{34} \text{cm}^{-2} \text{s}^{-1}$. The physics program started in 2010 at a beam energy of 3.5 TeV and since then the LHC is gradually increasing luminosity to meet the design parameters. The ATLAS detector must be able to cope with the high rate of particle interactions while maintaining a good energy resolution, particle identification, track pattern recognition and vertex reconstruction [1]. To accomplish this, the ATLAS tracking detector is broken up into several subsystems. The Inner Detector (ID) consists of the Pixel Detector, the SemiConductor Tracker (SCT) and the Transition Radiation Tracker (TRT) which operate in a 2 T solenoid magnetic field and provide tracking and particle identification. Surrounding the ID are a system of calorimeters and the outer system is a Muon Spectrometer located in a 4 T toroidal magnetic field.

This paper will focus on the ATLAS Pixel Detector and, in particular, the details related to the operation of the detector during the first two years of LHC running are addressed. An outline of the Pixel Detector and the readout chain will be given, followed by the operational aspects of the detector. Finally, an overview of the data taking for the 2011 run is presented including the detector status and data-taking efficiency.

2. The ATLAS Pixel Detector

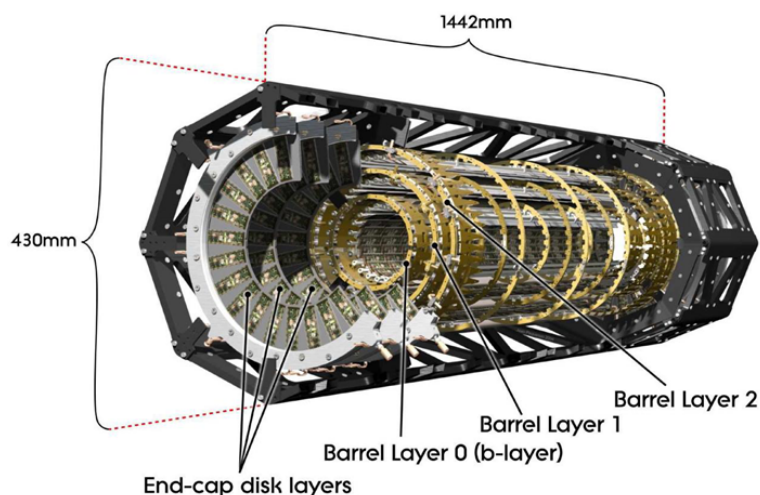


Figure 1: The ATLAS Pixel Detector.

2.1 Layout and structure

The ATLAS Pixel Detector [2] is designed to provide at least three precision measurement points for tracks with pseudorapidity $|\eta| < 2.5$. It is made of three concentric barrel layers and two endcaps each containing three disks, see Fig. 1. The barrel layers have radii of 50.5 mm, 88.5 mm and 122.5 mm, respectively, and are 800 mm long. Each disk contains 48 individual modules and the disks are located at ± 495 mm, ± 580 mm and ± 650 mm from the interaction point in the z -direction. The barrel layers have overlapping staves of 13 modules each which are rotated of 20° to compensate for the Lorentz angle in the 2 T magnetic field. 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, mounted on carbon fibre local supports and cover a surface area of 1.7 m^2 . To absorb the heat produced by the modules, an evaporative C_3F_8 cooling incorporated into the local support structure is used. This allows an operating temperature about -15°C to limit the effect of radiation damage.

2.2 The ATLAS Pixel module

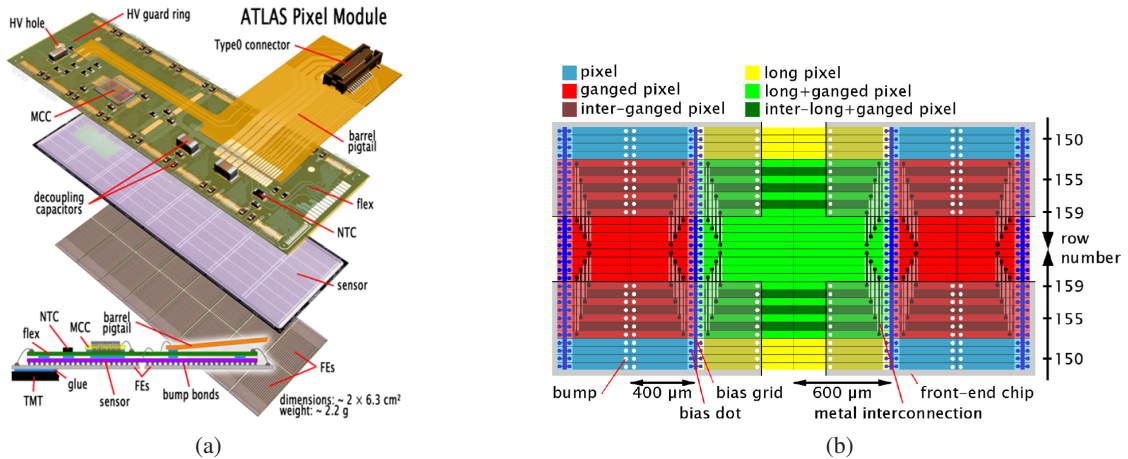


Figure 2: a) Assembly view of an ATLAS pixel module. b) End-region of a pixel sensor at the edge of four front-end chips.

The ATLAS Pixel Detector modules, see Fig. 2a, are made of a $250 \mu\text{m}$ thick silicon sensor with n^+ pixels implanted on the n -doped bulk with a p^+ backplane, 16 Front-End chips (FE-I3) and a module controller chip (MCC)[2]. The FE-I3 chips [3] were manufactured in the radiation hard $0.25 \mu\text{m}$ CMOS technology and have 2880 readout channels, that match a sensor pixel size of $400 \mu\text{m} \times 50 \mu\text{m}$. To enable full coverage even in the regions between front-end chips approximately 10% of the sensor pixels have a size of $600 \mu\text{m} \times 50 \mu\text{m}$ (long pixels). Another 2.5% of the electronics channels have two sensor pixels connected for seamless coverage in the short pixel direction (ganged pixels), see Fig. 2b. Each individual channel contains an analog and a digital circuit. The former performs pre-amplification of the collected charge, discrimination, and a measurement of the Time-over-Threshold (ToT). The latter consists of the digital readout logic to transfer hits to the peripheral circuitry of the chip, the end-of-column (EOC) logic. An 7-bit DAC for each pixel is

3. Detector Operations

3.1 Operational Aspects

The complete ATLAS Pixel Detector has been operated for the first time in the experiment in August 2008, shortly before the arrival of first beam in the LHC. The in-situ calibration, the noise hit masking and a crude version of the reconstruction algorithms were successfully tested and improved all along this period. Since then detector operation has continued without any major problems. Currently 96.7% of the modules are included in the ATLAS DAQ.

The non-active part contains 55 disabled modules (3.2%) 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 one optoboard. Additionally 47 single front-end chips (0.16%) are disabled. It has been found that in particular the front-end failures are linked to thermal cycles of the detector, caused by planned or unplanned stops of the cooling plant or power cuts. A procedure for the switch on has been established, which limits temperature excursions, with first modest results. 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 VCSELs which provides communication to the modules via the optical link. The failing components are accessible and can be replaced promptly.

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. Since the switching off of the high voltage would normally lead to a large number of noise hits per module which can block the data acquisition system (DAQ), the preamplifiers are also switched off, i.e. the sensor is decoupled from the analog portion of the pixel circuit. Under these conditions, there are no hits in the entire detector and the Pixel Detector can still be included in the ATLAS readout. A warm start procedure has been developed to enable the Pixel Detector to remain in the ATLAS DAQ system while satisfying the safety requirements. When the LHC declares stable beams, the trigger is paused and the bias voltage together with the preamplifiers are switched on. Using this procedure, the safety of the Pixel Detector is ensured 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 of the order of several minutes while the time needed to restart the ATLAS DAQ can be significantly longer. At the end of a stable beam period the detector is brought back into a safe state automatically, reacting on either LHC handshake messages or a post mortem signal of an unplanned beam dump.

3.2 Detector Calibration

In order to optimize operation of the Pixel Detector, regular checks and calibrations of the working points for both the readout systems and the pixel modules have to be done. The first step is to establish stable communication through the optical links for each module. These so-called “optical scans” check that the transmitting VCSELs for each link are sending light and also identify a stable working point for the data-links in the laser-threshold/sampling-time phase

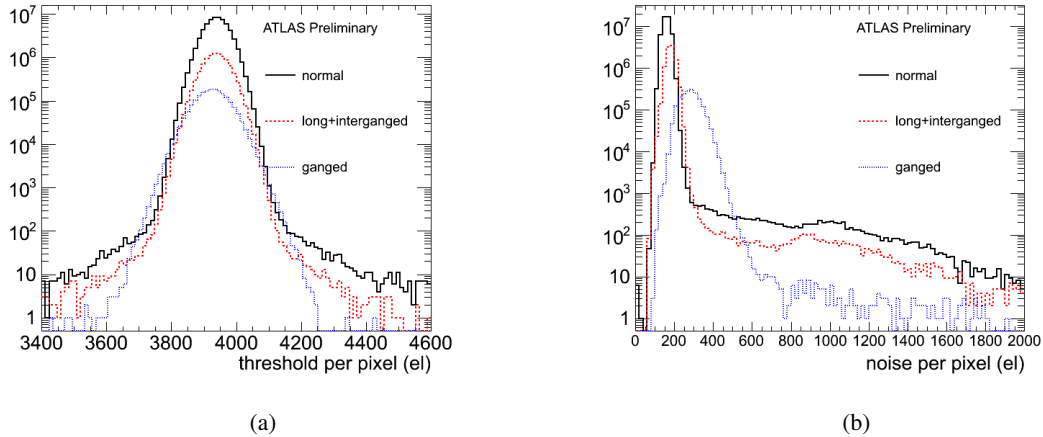


Figure 4: a) Measured threshold values for all scanned pixels in the detector. Prior to the scan the threshold settings have been tuned to $3500e$. b) Noise values obtained from the same threshold scan.

space. Following this, the calibration parameters for the front-end electronics are measured and a parameter tuning is performed if necessary.

The target discriminator threshold for 2011 LHC collisions is 3500 electron charge equivalent (e). Each pixel is tuned to this threshold by injecting a number of test charges at target threshold into the pixel using the charge injection circuitry, varying a 7-bit DAC, determining the discriminator threshold and counting the number of generated hits. The values of threshold and noise are then extracted from an error function fit to the obtained response curve. The setting, for which the response fraction is as close as possible to 50%, is the ideal setting for the given target threshold. Fig. 4a shows the measured threshold values of all scanned pixels in the detector. We see that most pixels are well-centred around the target threshold value and the typical RMS of the threshold distribution after tuning is $\sim 40e$. The noise values obtained from the same threshold scan are shown in Fig. 4b. Typical noise values vary between $\sim 180e$ for the normal pixels and $\sim 300e$ for the class of the ganged pixels. Pixels exceeding a noise occupancy of 10^{-7} hits per bunch crossing (BC) in dedicated noise data taking runs are masked for ATLAS data taking already in the module configuration. At a threshold setting of $3500e$ these pixels typically amount to 0.1% of all pixels.

The ToT information stored together with each hit can be used as a measure for the deposited charge. To be useful for a charge measurement the ToT has to be calibrated. This is done in a way that 30 ToT correspond to $20000e$. This is the number of electron charge equivalents corresponding to the approximate charge deposited by a minimum ionizing particle. The resulting charge resolution is about $660e$ (1 ToT). For an efficient reconstruction, the hits of particle tracks not only need to be detected, but also to be assigned to the correct bunch crossing, i.e. collision. Accounting for the trigger delays, different cable lengths and remaining module-by-module variations a dispersion of only 0.17 ns is achieved. Despite such a good precision, the hits from low charge depositions may end-up in the next bunch crossing, due to the slow rise of the preamplifier pulse above the discriminator threshold. This is called time-walk and leads to an uncertainty in the detection time for different signals belonging to the same collision. The critical quantity to quantify this effect

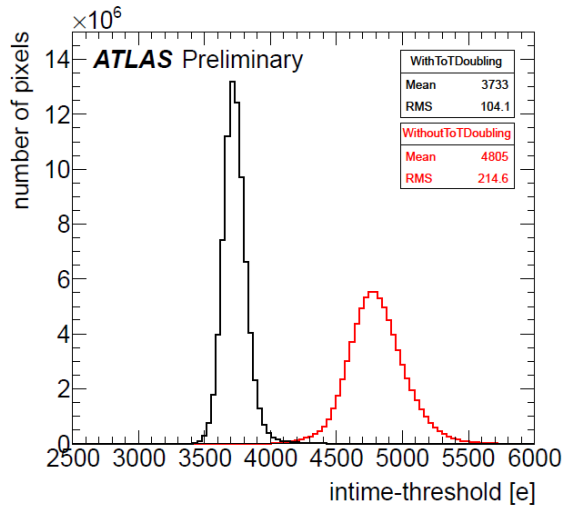


Figure 5: Measured in-time threshold for the full Pixel Detector with and without hit-doubling. All pixel were tuned to an threshold off 3500 e.

is the so-called in-time threshold, i.e. the smallest charge that is detected within the same bunch crossing as a large reference charge. A measurement of the in-time threshold values for all pixels in the detector is shown in Fig. 5. Without corrections, the average in-time threshold is $4800e$, approximately $1300e$ above the discriminator threshold of $3500e$. Charges between $3500e$ and $4800e$ are detected but not assigned to the correct bunch crossing. This behaviour can be improved by a hit-doubling mechanism implemented in the FE-I3 chip. In case the ToT is below a programmable threshold, currently 6 ToT, the hit is written twice: once with the same BC time and one with the previous BC time. This mechanism allows to reduce the in-time threshold to a value $200 - 300e$ above the discriminator threshold, as shown by the second histogram in Fig. 5, at the cost of a slight, $\sim 10\%$, increase in the occupancy.

4. Performance

In order to minimize the number of hits lost to mistimed modules and hits misplaced due to the time-walk 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 LHC operation at a center-of-mass energy of 7 TeV in March of 2010, the Pixel Detector used a 4 BC readout window. 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. Since October 2010, the Pixel Detector is operated with the design readout window of 1 BC.

The Pixel Detector has participated in ATLAS data-taking for all stable LHC operations with beam which began in November of 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 small number of filled bunches in 2009 and 2010, the LHC has made steady progress and has recently surpassed an instantaneous luminosity of $10^{33}\text{cm}^{-2}\text{s}^{-1}$. Typical occupancies at

this luminosity are $1.5 \cdot 10^{-4}$ hits/pixel/BC for the innermost layer, $0.7 \cdot 10^{-4}$ hits/pixel/BC for Layer-1, $0.45 \cdot 10^{-4}$ hits/pixel/BC for the Layer-2, and $0.55 \cdot 10^{-4}$ hits/pixel/BC for the end-caps.

As described earlier the Pixel Detector is only taking data during stable beam runs. The Pixel Detector efficiency for data-taking has been measured to be 99.8%. 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 Tab. 1. The dominating contribution to the Pixel Detector inefficiency is the delay for the warm start, i.e. switching on the HV and preamplifiers after the declaration of stable beams.

Inner Tracking Detectors			Calorimeters	Muon Detectors	Magnets	
Pixel	SCT	TRT			Solenoid	Toroid
99.8%	99.5%	100%	89.3% - 99.5%	99.5%-100%	98.5%	97.9%

Table 1: Luminosity weighted relative detector uptime and good quality delivery during 2011 stable beams in pp collisions at $\sqrt{s} = 7$ TeV between March 13th and June 6th (in %). The inefficiencies in the calorimeters will be partially be recovered in the future. The magnets were not operational for a 3-day period at the start of the data taking.

5. Summary

Since its commissioning in 2008, the ATLAS Pixel Detector has been successfully operated in the ATLAS experiment. Currently $\sim 97\%$ of the detector can be operated in physics data taking, whereas the data-taking efficiency is improved by the warm start procedure and safety is ensured by an automatic action bringing the detector back into a save state after a stable beam period. The detector behaviour is well understood in most aspects and satisfies the requirements both concerning the electronics and module behaviour and the overall tracking performance. The average pixel threshold is 3500 electrons with a dispersion of ≈ 40 electrons. The in-time threshold value without correction is at approximately $4800e$, using the time-walk correction of the FE chips leads to an intime threshold approximately $250e$ above the discriminator threshold. The efficiency of the enabled modules measured in data taking with particle tracks is at 99%, the spatial single-point resolution is according to the expectation. Regular calibration measurements to survey the status of the ATLAS Pixel Detector are performed.

References

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- [3] I. Peric et al., Nucl. Instrum. Meth. A **565** (2006) 178.