Commissioning and operation of the ATLAS Pixel Detector at the CERN LHC collider

F. Djama

CNRS/CPPM, Aix-Marseille Université, CNRS/IN2P3
163 Route de Luminy, Case 902, 13288 Marseille, France
E-mail: djama@cppm.in2p3.fr

ABSTRACT: The physics program at the CERN LHC collider started in autumn 2009. Since then, LHC regularly delivers collisions of its two proton beams. This talk was devoted to the commissioning and early operation of the ATLAS Pixel Detector. The Pixel Detector is working nicely and all of the required performance like efficiency, resolution and low noise were met. The fraction of working modules is as high as 97.4%. The Pixel Detector fully participates in the reconstruction of charged particles trajectories, and is a key element in finding primary and secondary vertices and in tagging short-lived particles.

KEYWORDS: Large detector systems for particle and astroparticle physics; Particle tracking detectors (Solid-state detectors)

1On behalf of the ATLAS collaboration
1 Introduction

This paper is devoted to the commissioning and early operation of the ATLAS\textsuperscript{1} [1] Pixel Detector at the CERN LHC\textsuperscript{2} collider [2].

1.1 The LHC collider

The LHC is a proton-proton collider located in the vicinity of the CERN laboratory, near Geneva (Switzerland). It has been built in the 27 km long tunnel which previously housed the LEP collider. The LHC beams will reach a design energy of 7 TeV each, and a nominal instantaneous luminosity of $10^{34}$ cm\textsuperscript{-2} s\textsuperscript{-1} will be delivered, thanks to a bunch train scheme of 2808 bunches, with a few $10^{11}$ protons per bunch, and to special low-\(\beta\) insertions, centered on the collision points. The beams are guided along the LHC beam pipe by 1232 superconducting dipole magnets, designed to deliver a magnetic field of 8 T, able to keep 7 TeV proton beams on their trajectories.

\textsuperscript{1}A Toroidal LHC ApparatuS.
\textsuperscript{2}Large Hadron Collider.
The LHC started to deliver usable collisions for physics in autumn 2009 at the injection energy of 450 GeV per beam. It went to 3.5 TeV per beam in 2010, and we expect to reach the nominal energy in 2013.

1.2 The ATLAS experiment

The ATLAS experiment has been built by a world wide collaboration of about 3000 physicists coming from 169 laboratories. Being a collider experiment, it has a central tracking system embedded in a central solenoid magnet, a calorimeter system surrounding the central tracker, and a muon system, as the outer most layer. Large air-core toroids generate the magnetic field for the muon system. This scheme in the central barrel is reproduced in the two end-caps, which complete the detector acceptance in the so called forward region, close to the beams.

The ATLAS tracker has three components: a silicon Pixel Detector, which surrounds the beam pipe, followed by a microstrip silicon detector (SCT\footnote{SemiConductor Tracker.}) and, at higher radii (or larger distances in the end-caps), a gaseous straw tracker with electron identification capabilities, using transition radiation (TRT\footnote{Transition Radiation Tracker.}).

1.3 Physics goals

The physics program at LHC is large and ambitious. ATLAS wishes to exploit the LHC energy to investigate the TeV scale and to look for the Higgs boson, supersymmetric particles and to test the predictions of more exotic models like leptoquarks or mini black holes. The result of these investigations will hopefully lead to an improvement in our understanding of elementary particles and fundamental laws of nature.

ATLAS aims also to benefit from the large LHC luminosity to make precision measurements in less precisely known domains, such as the strong interaction, CP violation and top quark. Deviations from standard predictions may also give hints toward the ultimate model of particles and their interactions.

2 The ATLAS Pixel Detector

2.1 Requirements

Prior to the detector building, the ATLAS collaboration conducted a large simulation effort to define the requirements for its tracking system \cite{3}. The Pixel Detector had to contribute to precision tracking, and be a key element in vertex finding and impact parameter determination. It had also to contain as little material as possible in order to have a small impact on the energy resolution of the calorimeters, to extend its coverage to the end-cap region and to prove radiation hardness up to a total fluence equivalent to \(10^{15}\) 1 MeV neutrons per cm\(^2\).

The main quantitative goals were to reach a single hit resolution of 10 and 100 \(\mu m\) in transverse and longitudinal dimensions respectively, a transverse impact parameter resolution better than 15 \(\mu m\), and a longitudinal primary vertex resolution better than 1 mm.
2.2 Technological choices

The Pixel Detector sensors are made of a 250 $\mu$m thick high resistivity n-type silicon bulk, with $p^+$ and $n^+$ type implantation on opposite sides. The negative bias voltage is applied to the $p^+$ side, while the pixels are obtained on the $n^+$ side by segmenting it into individual diodes, with a typical pitch of $50\mu m \times 400\mu m$. An oxygenated silicon bulk was used, in order to increase the sensor tolerance against radiation \[4\].

The choice of $n^+$ pixels in n-type bulk enables the sensor to be biased even after type inversion. The depletion zone will grow from the back side (the $p^+$ side) and can reach the readout side before type inversion. After type inversion, the depletion zone will grow from the readout side, keeping the readout pixels inside the depleted zone.

The front-end chips were manufactured in the radiation hard 0.25 $\mu$m CMOS technology \[5\], and were bump-bonded to the sensors using two techniques: PbSn solder and evaporative indium.

2.3 The Pixel Detector modules

The module \[6\] is the basic element of the Pixel Detector. It is an assembly of a 1.64 cm $\times$ 6.08 cm sensor, 16 front-end chips, and a flexible integrated circuit (flex) which houses the MCC\[6\] chip (figure 1). Front-end chips are bump-bonded to the sensor and wire-bonded to the flex. The sensor has 144 columns along its longest dimension (400 $\mu$m pitch) and 328 rows along the other dimension (50 $\mu$m pitch).

The 16 front-end chips are arranged in 2 rows $\times$ 8 columns and each of them has 2880 readout channels\[5\]. Front-end chips sample, amplify and discriminate the signal from the sensor, compute the time-over-threshold (ToT), and make hits available to the MCC. On a trigger signal, the MCC reads the available hits for the corresponding LHC bunch crossing, builds the local event and sends

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\[5\]To enable full coverage in the regions between front-end chips, larger $50\mu m \times 600\mu m$ pitch is utilized in the long pixel direction, while ganged pixels are used for coverage in the short pixel direction.

\[6\]Module Control Chip.
Figure 2. A cut-away view of the ATLAS Pixel Detector. The whole system is about 150 cm long and has a diameter of about 30 cm.

it to the central ATLAS data acquisition system. The 40 MHz sampling clock necessary for the hit time assignment is distributed to the individual front-end chips by the MCC.

The ATLAS Pixel Detector has 1744 modules in total.

2.4 The Pixel Detector layout

The Pixel Detector consists of three concentric barrel layers, and three disk layers on each end-cap (figure 2).

The barrel layers are located at mean radii of 5, 9 and 12 cm. Barrel modules are mounted on 80 cm long carbon fiber support structure to form staves. Staves are mounted on the inner side of a cylindrical shell made out of carbon fibers, to form a layer. The three layers have 22, 38 and 52 staves, respectively.

The three disks are located at distances of $|z| = 50, 58$ and 65 cm from the interaction point. Each disk has eight carbon fiber support sectors, and six modules are mounted on each sector, three on each side. The back side modules are rotated by 7.5° to achieve full azimuthal coverage with the rectangular shape of the modules.

2.5 The readout system

The MCC sends events to the data acquisition system outside the detector by means of aluminium wires to optoboards located on service panels, mounted parallel to the beam axis, at about the same radius as the outer layer. On the optoboards, the signal is converted to an optical signal by VCSEL arrays, and is sent to the ATLAS counting room via 80 m long optical fibers.

The final readout speed will be 40 Mb/s for the barrel outer layer, 80 Mb/s for the barrel middle layer and disks, and 160 Mb/s for the barrel inner layer. During the first operational period, all modules were delivering data at 40 Mb/s.
2.6 The Pixel Detector services

High voltage for the sensors bias and low voltage for optoboards, MCC and front-end chips are brought from the ATLAS counting room to the detector using the same service panels which house the optoboards. Inside the detector volume, the voltages are provided to the modules by aluminium wires. The low voltages are regulated at dedicated stations in the ATLAS cavern. The modules’ and optoboards’ temperatures are monitored by the Detector Control System. The whole system is described in [7].

The Pixel Detector cooling system must remove about 17 kW of heat, coming from sensors, front-end electronics and cables. In addition, it has to keep the modules at about -20°C during LHC shutdowns to prevent reverse annealing. We take advantage of the vaporization latent heat of the C$_3$F$_8$ fluorocarbon. The cooling liquid circulates in thin aluminium tubes all along the barrel staves, around the disk sectors and on the service panels [8]. This system maintained the module temperature at about -10°C during the 2009 collision data taking and at about -15°C in 2010.

3 Performance of the Pixel Detector

3.1 Global operation

The ATLAS Pixel Detector has been commissioned in the ATLAS cavern with cosmic rays in 2008 and 2009, and with first LHC collisions in autumn 2009. 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.

The Pixel Detector data acquisition code has been tested and its various functionalities optimized. The cooling service demonstrated its ability in keeping the modules and services temperature at the desired level. The fraction of operating modules amounts to 97.4% and was found to be stable along the data taking period. Non-operating modules are due to various service disconnections (high and low voltage) or are non-configurable modules.

3.2 Detector calibration, noise masking and timing adjustment

The front-end chips compute the hits’ time-over-threshold (ToT). The relationship between the ToT and the released charge is monitored a few times a year, during special calibration runs, by injecting known charges to the output of each pixel cell. Tuning of the thresholds is also part of the calibration procedure. Typical threshold values were about 4000 electrons (3500 electrons in 2010). The ToT distribution is tuned to have the Landau peak (20 000 electrons) at a ToT value of 30 bunch crossings (25 ns units). The mean thermal noise for non-ganged pixels amounts to 160 electrons.

The ATLAS Pixel Detector delivers hits which are assigned to the LHC bunch crossing (BC) in which the rising edge of the signal crossed the threshold. Depending on the synchronization and beam conditions, information from up to 16 BCs may be readout for one trigger signal. Commissioning with cosmic rays started with an 8 BC window, centered around the trigger BC. Thanks to fine time tuning, this window has been reduced during the 2010 data taking, and has recently reached the ultimate 1 BC. There are no more early hits due to unsynchronized modules, and a duplication mechanism allows the recovery of late hits (those at trigger BC + 1), which are due to the timewalk effect for low charge hits.
Figure 3. The maximum time shift applied to the global clock phase delivered to each module, for which all the hits of the module are still assigned to the correct bunch crossing.

Figure 3 illustrates one step of the timing synchronization tuning: It shows for each module the shift applied to the clock phase where the module still delivers hits in the correct BC. The low dispersion shows the good time alignment between the modules.

Online and offline masking procedures eliminate noisy pixels from being considered by reconstruction algorithms. About one thousand pixels, with ± 50% fluctuations were masked, resulting in a very low noise occupancy of the order of $10^{-10}$ noise hit per event and per bunch crossing.

3.3 Vertex reconstruction

Figure 4 shows the beam spot position and dimensions in the transverse (x,y) plane for an LHC fill, reconstructed by fitting the primary vertices of collisions. The measured dispersions in both directions (108 and 96 $\mu$m respectively) agree with the 100 $\mu$m predicted from the beam instrumentation. The reconstructed beam spot is used by the tracking pattern recognition as an additional space point. Reconstructed individual primary vertices help also in improving the resolution on physical quantities which use the angles between particles, like invariant masses. This is especially the case in the search for the Higgs boson in its two-photon decay channel, where the photons are reconstructed by the calorimeters with a limited angular measurement.

Figure 5 displays an event recorded by ATLAS, with four reconstructed primary vertices, and shows the ability of the Pixel Detector to identify and separate several collisions which occurred in the same bunch crossing. A mean value of 20 such collisions in each event is foreseen when LHC will reach its design energy and luminosity.

The quantitative vertex reconstruction performance and its key role in b-jet tagging are beyond the scope of this talk and are discussed in [9].

3.4 Efficiency

Figure 6 shows the intrinsic hit efficiencies for all the Pixel Detector layers. Most of the layers have an efficiency higher than 98.7%, and the slightly lower efficiency for disk layers is due to
Figure 5. A pile-up event, with four reconstructed primary vertices.

Figure 6. Intrinsic hit efficiency for separate Pixel Detector layers.

Figure 7. Occupancy in one of the Disk 3A modules where missing front-end chip contributes to the observed inefficiency in previous figure.

known problems in few specific modules, as illustrated by figure 7. Known dead modules (46 modules out of 1744) are not included in efficiency determination.
3.5 Cluster properties

The ATLAS inner tracker is immersed in a uniform magnetic field of 2 T, parallel to the beam axis. Ionised charge in the silicon sensors drift towards the readout pixels following an angle (the Lorentz angle) with respect to the direction of the electric field. The minimal cluster size is therefore reached by particles which cross the sensor with a transverse incidence angle equal to the Lorentz angle. This is shown in figure 8. The module temperature monitoring allowed us to see the temperature dependency of the Lorentz angle, as shown in figure 9.

The cluster charge has been studied with cosmic rays. Figure 10 shows the charge distribution for two-pixel clusters for incidence angles centered on the Lorentz angle. A 1% residual shift on the simulated charge is still to be understood.

By combining several energy loss measurements performed in different pixel layers crossed by charged particles and with the momentum measured by the whole ATLAS tracker, a dE/dx measurement was obtained. The pion, kaon, proton and deuteron bands can be clearly distinguished (figure 11).

3.6 Spatial resolution

An alignment is performed and the spatial resolution is investigated by looking at unbiased residuals, which are the differences between the measured position of the cluster and the predicted position from the trajectory using all available space points from the whole tracker except for the considered measurement.

In the barrel region, unbiased residual widths of 19 and 105 µm have been obtained for transverse and longitudinal dimensions respectively (figures 12 and 13), which are in agreement with...
Figure 10. Cluster charge measured in cosmic rays for centrally incident particles.

Figure 11. Specific energy loss (dE/dx) as a function of charge-signed momentum.

Figure 12. Unbiased residual distribution in the barrel transverse coordinate (the more precise one) for 2010 collision data (after alignment) and Monte Carlo (perfect alignment).

Figure 13. Unbiased residual distribution in the barrel longitudinal coordinate (parallel to the beam) for 2010 collision data (after alignment) and Monte Carlo (perfect alignment).

the desired single hit resolution. These results are better than those presented in the talk. This is due to a refined alignment which took into account the module bowing.
4 Conclusions

The ATLAS Pixel Detector has been commissioned with cosmic rays and successfully entered full operation mode with the first LHC collisions. It shows excellent time synchronization and noise performance, participates fully in ATLAS tracking and plays its expected key role in vertex reconstruction. The intrinsic efficiency and the single hit resolution are at the expected level. The scale of the energy loss is understood at 1% level and the specific energy deposition ($\frac{dE}{dx}$) is used to identify low momentum charged particles.

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References

[1] ATLAS collaboration, G. Aad et al., The ATLAS Experiment at the CERN Large Hadron Collider, 2008 JINST 3 S08003.
[2] L. Evans and P. Bryant (eds.), LHC Machine, 2008 JINST 3 S08001.
[3] ATLAS collaboration, Inner Detector: Technical Design Report 1, CERN-LHCC-97-016; Inner Detector: Technical Design Report 2, CERN-LHCC-97-017.
[4] RD48 collaboration, G. Lindström et al., Developments for Radiation Hard Silicon Detectors by Defect Engineering — results by the CERN RD48 (ROSE) Collaboration, Nucl. Instrum. Meth. A 465 (2001) 60.
[5] L. Blanquart et al., FE-I2: A Front-End Readout Chip Designed in a Commercial 0.25 $\mu$m Process for the ATLAS Pixel Detector at LHC, IEEE Trans. Nucl. Sci. 51 (2004) 1358; I. Peric et al., The FEI3 Readout Chip for the ATLAS Pixel Detector, Nucl. Instrum. Meth. A 565 (2006) 178.
[6] G. Aad et al, ATLAS Pixel Detector Electronics and Sensors, 2008 JINST 3 P07007.
[7] T. Henss et al., The Hardware of the ATLAS Pixel Detector Control System, 2007 JINST 2 P05006.
[8] D. Attree et al., The Evaporative Cooling System for the ATLAS Inner Detector, 2008 JINST 3 P07003.
[9] ATLAS collaboration, Performance of the ATLAS Secondary Vertex b-tagging Algorithm in 900 GeV Collision Data, ATLAS-CONF-2010-004.