Status and performance of the ATLAS Pixel Detector after 3 years of operation

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ABSTRACT

The ATLAS Pixel Detector is the innermost detector of the ATLAS experiment at the Large Hadron Collider at CERN. The detector provides hermetic coverage with three cylindrical layers and three disks of Pixel Detectors on each side. It consists of approximately 80 million pixels that are individually read out via chips bump-bonded to 1744 n-in-n silicon substrates. In what follows, results from the successful operation of the Pixel Detector at the LHC and its status after 3 years of operation will be presented, including monitoring, calibration procedures and detector performance. The record breaking instantaneous luminosities of \( 7.7 \times 10^{33} \text{ cm}^{-2} \text{s}^{-1} \) recently reached at the Large Hadron Collider generate a rapidly increasing particle fluence in the ATLAS Pixel Detector. As the radiation dose accumulates, the first effects of radiation damage are now observable in the silicon sensors. A regular monitoring program has been conducted and reveals an increase in the silicon leakage current, which is found to be correlated with the rising radiation dose recorded by independent sensors within the inner detector volume. The fourth Pixel Detector layer at the radius of 3.3 cm will be added during the long shutdown 2013–2014 together with the replacement of the Pixel services.

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1. Introduction

The ATLAS Pixel Detector \([1]\) is the innermost tracking detector of the ATLAS experiment \([2]\) at the Large Hadron Collider (LHC) at CERN. The LHC was operated between 2010 and 2012 with increasing collision energy and luminosity. In 2010 and 2011 the LHC ran with a collision energy \( \sqrt{s} = 7 \text{ TeV} \) and in 2012 with \( \sqrt{s} = 8 \text{ TeV} \), in this time the ATLAS Detector recorded 5.3 fb\(^{-1}\) and 21.7 fb\(^{-1}\) respectively. In 2013 the LHC commenced Long Shutdown 1 (LS1) during which, in April 2013, the Pixel Detector was brought to the surface for refurbishment.

2. ATLAS Pixel Detector

The ATLAS Pixel Detector (shown in Fig. 1) has 3 barrel layers and 3 disks on each side. It is 1.4 m long and has a diameter of 0.43 m. The first (B-Layer), second (Layer 1) and third (Layer 2) layers are located on a radius of 50.5 mm, 88.5 mm and 122.5 mm respectively. It provides particle tracking in pseudo-rapidity range of \( 0 < |\eta| < 2.5 \).

The Pixel Detector is made of 1744 Pixel Detector modules (shown in Fig. 2) with a total of 80 million readout channels. Each Pixel Detector layer is \( 2 \times 6 \text{ cm}^2 \) large and has one sensitive planar pixel n-in-n silicon tile. These sensor tiles are 250 \( \mu \text{m} \) thick and have \( 50 \times 400 \mu \text{m}^2 \) large pixels\(^1\) in \( r_\phi \times z \). 16 Front-End chips (FE-I3), each connected to 2880 pixels, are used to read out the full sensor tile. Mounted on the flex PCB are passive components and the module Control Chip (MCC) which combine the 16 Front-Ends in one timing, trigger, control and readout link. The sensor and electronics are radiation tolerant up to an ionizing dose of 50 MRad (\( \approx 10^{15} \text{n}_{eq} \text{ cm}^{-2} \)), corresponding to about 300 fb\(^{-1}\) of delivered data from the LHC.

3. Calibration

The charge deposited in a pixel is measured in units of Time-over-Threshold (ToT) with a granularity of 25 ns (1 bunch crossing). The FE-I3 allows a per pixel calibration of threshold and ToT.

\(^1\) In total there are three different sizes of pixels, large and ganged pixels are found on the edges and in the Front-End interconnection region.
The pixel threshold is tuned to 3500 e (shown in Fig. 3), this is achieved with a dispersion of around 40 e. The noise of each pixel (shown in Fig. 4) is strongly correlated to the size of the pixel in the sensor to which it is connected. The measured noise of the normal pixels is around 180 e, resulting in a comfortable threshold to noise ratio of 20. For larger pixels the noise is slightly increased, but the threshold to noise ratio is never below 10. With this excellent ratio the operational noise occupancy is in the order of $10^{-9}$ per pixel per bunch crossing,\(^2\) while the physics hit occupancy is in the order of $10^{-4}$ per pixel per bunch crossing. Only 0.1% of the pixels need to be masked out to achieve this performance. The in-time threshold is decreased from 4800 e to 3700 e by a mechanism called hit-doubling, in which small hits arriving late are copied to the previous bunch crossing.

The ToT is calibrated to a conversion from 20 ke to 30 bunch crossings ToT. Fig. 5 shows the measured ToT for varying injected charge. The response is mostly linear, with very few outliers. This very fine, analog charge measurement also allows us to determine the $dE/dx$ of traversing particles and distinguish between different kinds of particles via their charge to mass ratio (shown in Fig. 6).

Clearly visible are the different bands from the particles, here pions, kaons, protons and deuterons.

4. Performance

After integration of the Pixel Detector into the ATLAS Detector, 1.5% of the modules were not operational, at the end of 2012 this number increased to 5%. The appearance of new faulty modules is highly correlated to interventions or interlocks, in which the cooling or powering was rapidly switched off. The other 95% of the Pixel Detector delivered in the 2012 run 99.9% good quality data\(^3\) [5].

4.1. Tracking

The efficiency of tracks having associated hits in the different Pixel Detector layers (shown in Fig. 7) is around 99%. The slightly lower outer disk efficiency is due to the higher percentage of dead pixels in these modules, which have been placed there on purpose. The track resolution is greatly improved by the analog readout of the charge compared to a binary readout. The improvement in tracking is shown in Figs. 8 and 9, where the RMS of the local $x$ and $y$ residual is presented with and without the charge sharing algorithm. Especially in regions ($0.5 < |\phi| < 15^\circ$ and $0.5 < |\eta| < 2.0$) where the clusters have more than 1 hit, the charge sharing algorithm improves the resolution of the tracking, because the center of charge gives a more precise measure than the center of

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\(^2\) After offline masking.

\(^3\) Data delivered during stable beams for 21.3 fb\(^{-1}\) pp-collisions and considered as good for physics by the data quality.
the cluster. After the autumn 2010 alignment of the Pixel Detector a resolution in local $x$ and $y$ of $9 \, \mu m$ and $84 \, \mu m$ is achieved.

The overall tracking performance can be described by a transverse impact parameter $d_0$ resolution as shown in Fig. 10, where the ATLAS Inner Detector achieves a $\sigma(d_0)$ of the order of $10 \, \mu m$ over the complete pseudo-rapidity range. This high precision vertexing is crucial for successful, and highly efficient, b-tagging. The high purity b-tagging algorithms have achieved an efficiency of 50%, while only having a fake rate of $0.05\%$ [7].
4.2. Synchronization errors

One of the issues the Pixel Detector is facing in operation is the desynchronization of modules with respect to the ReadOut Driver, rendering the data of these modules not usable for reconstruction. The desynchronization is strongly correlated to the occupancy and happens more often in the beginning of a run. Hence desynchronization is most probably caused by single event upsets in the digital logic of the modules or high bandwidth data bursts. To synchronize the module a reconfiguration of it is needed; to issue the reconfiguration ROD-level monitoring was implemented. The improvement is shown in Fig. 11 and a reconfiguration is happening in the order of ms after the desynchronization. While the ROD is reconfiguring the desynchronized module, data taking is continued normally on all other modules.

5. Radiation damage

Being the closest detector to the interaction point, the Pixel Detector has suffered most from the harsh radiation environment. The radiation damage in the sensors can be evaluated by two quantities, the depletion voltage and the leakage current. The leakage current is measured by the high voltage power supplies and the trend over the years 2011 and 2012 is shown in Fig. 12. The measured leakage current fits well to the prediction, also visible are annealing effects during periods where the cooling was stopped. Being the closest to the interaction point the B-Layer suffered most from the radiation, such that by the beginning of 2012 type inversion already happened. The type inversion of Layer 1 happened at the end of 2012 and Layer 2 will type invert shortly after the LS1.

Before type inversion it was possible to measure the depletion voltage using a cross-talk scan. The cross-talk between the pixels was measured with the sensor being supplied with different high voltages. The number of cross-talking pixels will shrink to a minimum when the depletion voltage is supplied, resulting in an s-curve like plot, in which the point where 90% of the pixels are not cross-talking is thought to be the depletion voltage. Another method to measure the depletion voltage uses tracks passing through the sensor at different depths. This makes it possible to see the size of the depleted zone, but requires to take data while the Pixel Detector is supplied with different high voltages.

6. Repairs and upgrade during the Long Shutdown 1

In April 2013, at the beginning of the LS1, the Pixel Detector was extracted from the ATLAS experiment and brought into a laboratory on the surface (see Fig. 13). Two things will be addressed: The service panels (SQPs) will be exchanged with new ones (nSQPs) and an Inner Support Tube will be inserted into the Pixel Detector in preparation for the Insertable B-Layer (IBL).

6.1. New service panels

The SQPs are getting exchanged with the already assembled nSQPs in the time from April 2013 to October 2013. The new service panels have one major difference to the current service panels, the optical converters for data transmission are no longer located inside the Inner Detector volume, but rather an electrical connection is made to the Inner Detector Endplate. At this place the optical components are also reachable for maintenance in small shutdowns.

The new service panels will also address a big fraction of the 5% inoperable modules, because the failure cause for most of these modules is thought to be in the services.4 Replacing the broken services should make these modules operable again, if the failure is not located on the module. After disassembly of the service panels, all inoperable modules have been tested and in 75% of the cases the services were the problem, 17% show other problems.

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4 Module failure being caused by an open line in the form of a damage wire or solder joint.
which can be repaired and 8% cannot be repaired. This means a maximum of 92% of the 5% inoperable modules can be recovered by installing the new service panels. The installation of the new service panels is well underway and the number of recovered modules looks very promising, to reach this goal.

6.2. Insertable B-Layer

A new Pixel Detector layer will be installed into the Pixel Detector in LS1 at the radius of 33 mm. The IBL will deploy state of the art sensor and readout electronics and planar as well as 3D sensor technology. The IBL will not only help in improving the vertex resolution and b-tagging efficiency, but also compensate for inefficiencies in the Pixel B-Layer which can arise over time due to radiation damage.

7. Conclusion

The ATLAS Pixel Detector achieved an outstanding performance in the first 3 years of operation. The precise calibration of threshold and ToT allow an improvement in the vertexing precision compared to hit-or-no-hit information. Issues during operation, like the desynchronization of modules, have been understood and countermeasures were implemented into the system to increase the efficiency to a maximum. Radiation damage in the sensors is carefully monitored and agrees well with the prediction and the targeted lifetime of the detector. In the LS1 new service panels will be installed and a high percentage of inoperable modules can be recovered, furthermore preparations for the installation of the 4th layer upgrade of the Pixel Detector are underway. The goal is to restart operation of the Pixel Detector after the LS1 in 2015 with an operable fraction of 99.6%.

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