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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 $7.7\times 10^{33}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ 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.

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 $\sqrt{s}=7$ TeV and in 2012 with $\sqrt{s}=8$ 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 $2\times 6\ \mathrm{cm}^2$ large and has one sensitive planar pixel n-in-n silicon tile. These sensor tiles are 250 μm thick and have $50\times 400\ \mu\mathrm{m}^2$ large pixels[1] in $r\varphi\times z$. 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 ($\approx 10^{15} n_{eq}\ \mathrm{cm}^{-2}$), 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.

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[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.

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0168-9002/

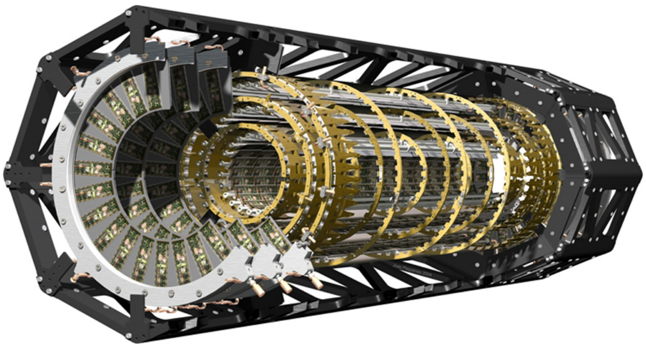

Fig. 1. Computer generated picture of the partially opened Pixel Detector in its carbon support structure.

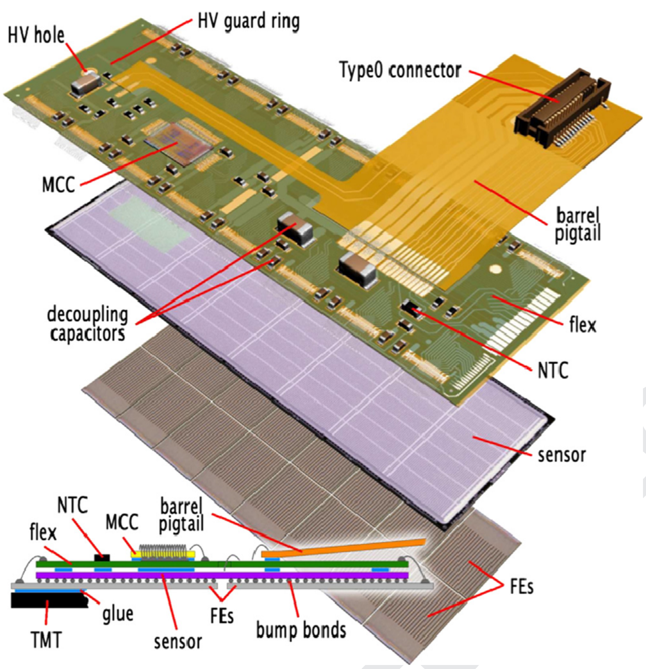

Fig. 2. Exploded Pixel Detector module, showing the 16 Front-Ends, sensor tile and flex PCB with connector.

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).

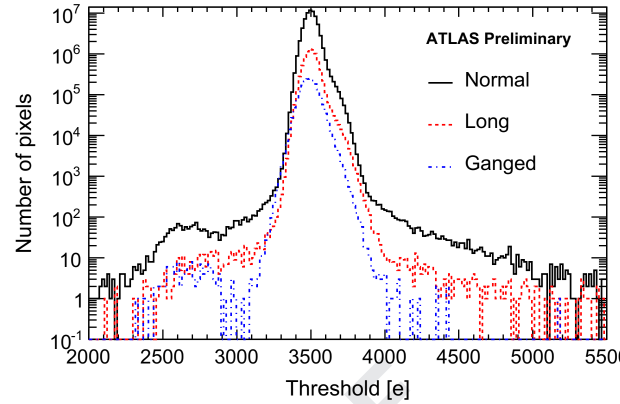

Fig. 3. The calibrated per pixel threshold. Overlayed are the different pixel sizes [3].

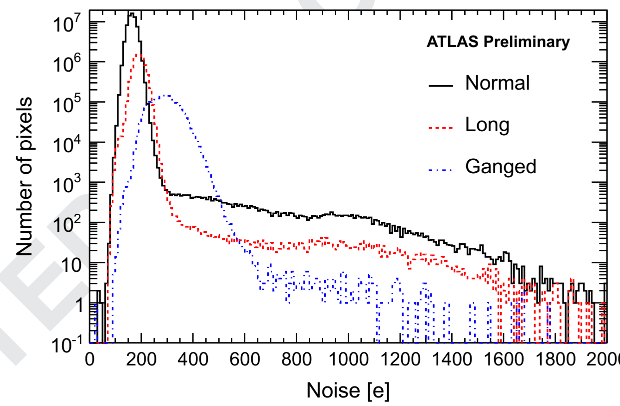

Fig. 4. Measured noise per pixel. Overlayed are the different pixel sizes [3].

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 ($0.5^\circ < \varphi_i < 15^\circ$ and $0.5 < |\eta_i| < 2.0$) 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

[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.

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