Operational experience with the ATLAS Pixel Detector

Tayfun Ince, on behalf of the ATLAS Collaboration

Universität Bonn, Germany
E-mail: Tayfun.Ince@cern.ch

The ATLAS Pixel Detector is the innermost element 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. The detector performance is excellent: 96.2% of the pixels are operational, noise occupancy and hit efficiency exceed the design specification, and a good alignment allows high quality track resolution.

Keywords: LHC; ATLAS; Pixel

1. Introduction

Many potential new physics as well as the Higgs boson may be discovered at the Large Hadron Collider (LHC$^1$) through decay channels involving b-quarks. The most crucial part of ATLAS$^2$, a sophisticated detector designed to exploit discovery potential of the LHC, for the identification of b-quark induced jets is the Pixel Detector$^3$ which is the innermost component surrounding the collision centre. With about 80 million individually amplified pixels and close proximity to the collision centre, the Pixel Detector, operating in a 2 T magnetic field, helps to reconstruct the trajectories of several hundred charged particles coming from the collision centre every 25 ns (50 ns in 2011 LHC collisions) and offers the only technology to identify b-jets by measuring their decay vertices slightly away from the collision centre with an intrinsic resolution of 10 $\mu$m in $r$-$\phi$ and 110 $\mu$m in $z$.

The Pixel Detector which uses the hybrid pixel technology is made of
1456 modules in three layers of the barrel region and 288 modules in three layers of the forward regions, with the closest layer being just 5 cm away from the collision centre. Fig. 1 illustrates the geometrical layout of the Pixel Detector on the left and a pixel module on the right. Each module has an active area of $16.4 \times 60.8 \text{ mm}^2$ and consists of 47232 pixels bump bonded to 16 front-end (FE-I3) readout chips. The $n^+\text{-in-}n$ silicon is the sensor material used, and the pixels are mostly $50 \times 400 \, \mu\text{m}^2$ in area with a thickness of 250 $\mu\text{m}$. About 12% (long and ganged) of the pixels are covering regions between the FEs and therefore slightly larger in size. Data from the 16 FEs are collected by the module controller chip (MCC) and sent to the off-detector elements of the data acquisition system. The pixel modules are designed to withstand radiation up to NIEL $10^{15} \, 1 \text{ MeV n}_{eq}/\text{cm}^2$ and 50 MRad. In order to limit the effects of radiation, the modules are cooled down to an average temperature of -13 °C with an evaporative $C_3F_8$ cooling system integrated into the module support structure.

2. Detector calibration

Several properties of the Pixel Detector need to be tuned or calibrated or both in order to determine a charged particle hit over electronics noise, the amount of charge deposited and the association of the hit to the right bunch crossing. These tunings and calibrations are re-done many times over the course of the Pixel Detector lifetime to compensate for the changes in
operating conditions and the effects caused by radiation damage.

2.1. Optical links

The Pixel Detector readout system is composed of the on-detector BeO optoboards connecting the pixel modules to the off-detector readout drivers (RODs) over a distance of about 80 meters via optical links. A pixel module receives commands, calibration data and trigger signals through a link (TTC) at 40 MHz. The data from a module is transmitted with a vertical cavity surface emitting laser (VCSEL) array to the ROD through optical fibers. Each module in the innermost layer, called the b-layer, has two data-links each of which transmitting 80 Mb/s effectively providing 160 Mb/s readout speed to cope with higher occupancy (hit rate) expected compared to the outer layers. In layer 1 and the disks (forward regions), there is one data-link per module with a readout speed of 80 Mb/s, while in layer 2 (the outermost barrel layer) one data-link each with a 40 Mb/s speed. The on-detector laser power, and the off-detector laser threshold and the sampling phase are tuned to settings that avoid data readout errors. Optical corruption is measured in units of bit flips as a function of the laser threshold and the sampling phase by sending a known pattern data to the detector and reading it back. Frequency of the optical link calibration is driven by the replacement of the failing (for reasons still under investigation) off-detector VCSEL arrays. The replacement of a few, typically 2-3, VCSEL arrays and re-tuning of the corresponding parameters take about 4 hours and is done sometimes as often as once per week during a period when the LHC does not provide stable collisions.

2.2. Front-end electronics

A pixel cell is made of a charge injection circuitry to aid calibration, a preamplifier for collected charge, a discriminator to reject electronics noise and a digital component to transfer hits to the peripheral circuitry, called end of column (EOC) from where they are sent to the MCC when a trigger arrives. For each hit, its time-over-threshold (ToT), location and time are recorded. The ToT is the time in which the preamplifier signal is above the discriminator threshold. It is measured in units of bunch crossings (BC i.e. 25 ns) and is proportional to the deposited charge.

The target discriminator threshold for 2011 LHC collisions is 3500 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 digital to analog converter (DAC), determining the discriminator threshold and counting the number of generated hits. The optimal DAC setting corresponding to the target threshold for this pixel is then the one at 50% efficiency. If the 7-bit DAC does not produce sufficient range of thresholds for the tuning target, a 5-bit DAC per FE is used first to globally shift the threshold per FE. A dispersion of 40 e among all pixels over the whole detector is achieved with this tuning procedure. Noise for the normal and the long pixels is about 170 e, and for the ganged pixels it is about 300 e. 0.1% of the pixels in the detector are masked from data taking to reduce the noise rate down to $10^{-6}$ hits/pixel/event.

The ToT tuning target is 30 BCs for a charge for 20000 e which is the most probable for a minimum ionizing particle. The optimal setting resulting closest to the target ToT per pixel is determined by injecting a number of test charges at 20000 e and varying a 3-bit DAC similar to the threshold tuning. There are two 8-bit DACs per FE available in addition to tune for the target ToT. The ToT tuning is performed with a 1 BC resolution. Fig. 2 shows the improvement obtained on the position resolution on the left and the particle identification (protons, kaons and pions are clearly visible) via the measurement of the energy loss on the right using the ToT.

Assigning a detected hit to the correct bunch crossing (i.e. collision) is an equally crucial piece of the measurement of a charged particle passing through the Pixel Detector. Accounting for the trigger delays using the cosmic particles, the different cable lengths from the measurements during the installation and the remaining module-by-module variations using the collision particles result in a timing measurement with a module-by-module
dispersion of only 0.17 ns. 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 the time-walk. Due to the time-walk, the effective in-time threshold (lowest charge hit detected within the same BC) is about 4800 e for a target threshold of 3500 e. The time-walk is compensated using the FE-I3 hit doubling mechanism in which a hit with a ToT below a certain value (currently at 7 BC) is written twice: one with the same BC time and one with the previous BC time. Using this recovery mechanism, the in-time threshold is reduced to about 3700 e, just 200 e above the target threshold.

3. Detector performance

The Pixel Detector has been operating with a data taking efficiency of 99.9% in ATLAS since November 2009 when the LHC started delivering stable collisions. The down-time of 0.1% is dominated by, for the matter of the Pixel Detector safety, the warm start procedure that is followed once the LHC establishes stable collisions. During this short time, the beam background rates and the collimator positions are checked to ensure safety requirements before ramping up the bias voltage (currently at 150 V and can be increased as high as 600 V) and switching on the pixel preamplifiers. 96.2% of the Pixel Detector is operational at the time of the conference. 64 modules and 48 FEs are disabled (removed) from data taking mostly due to the problems with communication or the bias voltage supplies. The percentage of the modules and the FEs disabled is increased from 2.1% to 3.8% over three years of operation beginning with the commissioning of the detector in 2008.

The efficiency of a charged particle track having hits for the Pixel Detector layers crossed is about 99% excluding the disabled modules. The remaining 1% is due to the disabled FEs and about 0.14% of the pixels with the missing bump connections or the analog failures.

4. Radiation damage

The radiation damage on the Pixel Detector will result in an increase of the leakage current, an increase (decrease before type inversion) of the bias voltage needed for the full depletion of the sensors and a decrease in the charge collection efficiency. The effects of radiation damage are monitored regularly in order to compensate when necessary to avoid decrease in performance.
Two of the methods used to measure changes in the leakage current are dedicated pixel-by-pixel calibration measurements using the FE-I3 capabilities and the measurements per half stave (i.e. 6 or 7 modules) using the bias voltage power supplies. The increase in the leakage current per module is already measurable for all of the layers while only for the b-layer (innermost layer) per pixel.

Before type inversion, the decrease in the sensor depletion voltage is measured via a cross-talk method. This method uses the fact that cross-talk between un-depleted pixels is much higher compared to fully depleted pixels in isolation from each other. To make the measurement, a high enough charge is injected to the neighboring pixels to generate a cross-talk hit in the measured pixel only when it is not fully depleted, and the injections repeated number of times at each bias voltage to produce an efficiency S-curve for the determination of the bias voltage ensuring the full depletion.

Fig. 3 presents the average increase in the leakage current per module as a function of time on the left and the results of the depletion voltage scans on the right. From July to August when the LHC delivered about $1.5 \text{ fb}^{-1}$ of data, the depletion voltage is decreased as expected before type inversion under irradiation. As for June to July, the depletion voltage increased due to the reverse annealing effects of a cooling shutdown for several days.

5. Conclusions

The ATLAS Pixel Detector is calibrated and performing very well. The detector is monitored regularly and re-tuning (optimization) is done routinely to ensure steady performance.
The effects of radiation damage are measured to be within expectations. At the time of the conference, the LHC has delivered about $4 \text{ fb}^{-1}$ of integrated luminosity, corresponding to a fluence of NIEL $10^{13} \text{ 1 MeV } n_{eq}/\text{cm}^2$. The Pixel Detector can stand for $O(10^2)$ more radiation.

References