Operational experience with the ATLAS Pixel Detector at the LHC

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 - Calibration overview
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- Summary and current status of the Pixel Detector

ATLAS

- 44 m long
- 25 m high
- 7 000 tons

Inner detector :

- In a 2T magnetic field
- Sub-detectors :
 - Pixel: n-in-n silicon sensors.
 - SCT: p-in-n silicon sensors.
 - TRT: polyimide drift tubes interleaved with polypropylene fibers.
- Tracking of charged particles with $p_T > 0.5$ GeV (as low as 0.1 GeV) and $|\eta| < 2.5$.

Pixel Detector : overview

- 1744 modules
 - 1456 on the 3 barrel layers (13 per stave) →
 - 288 on the 6 disks (3 on each side)
- Cooling system shared with SCT
 - C_3F_8 circulating in support structure

Pixel Detector

- Innermost layer at 5.05 cm from the beam axis
- IBL (Inserted b-layer) :
 - At ~ 3.3 cm from the beam axis
 - Expected implementation : 2013
 - Starting to take data : 2014

Pixel Detector : modules

- 250 μm thick silicon sensor with an active area of $16.4 \times 60.8 \text{ mm}^2$
- 16 Front-ends per module bump bonded to the sensor
- >80M readout channels (pixels)
- Resolution
 - 10 μm in $R\phi$
 - 110 μm in z
- Modules operating at $\sim -13^\circ\text{C}$ (warmest module at -5°C)
- Modules tilted by 20° in $R\phi$ plane

- Module controller chip (MCC) to send trigger, commands and configuration data, and to perform event building.
 - 2x80 Mb/s data transfer speed in b-layer
 - 80 Mb/s in layer 1 and disks
 - 40 Mb/s in layer 2

Pixel Detector : pixels

- 47232 (328x144) pixels/module, 46080 readout channels bump-bonded to 16 FE chips
- Special pixels with different size/capacitance to cover inter FE chips
 - Sorted with increasing capacitance (noise) : normal, inter-ganged, long, inter long-ganged, ganged, long-ganged,

Sizes :

- Normal/ganged/inter-ganged pixel : $400 \times 50 \mu\text{m}^2$
- Long pixels : $600 \times 50 \mu\text{m}^2$

Calibrations

Calibrations

- Complete calibration process
 - Performed during each technical stop on the whole detector
 - New noise mask is created
 - Takes 3-4 days of ~12 hours shifts
- After dead Tx's replacement
 - Corresponding modules timing is adjusted, optolink and modules are checked
 - ~4 hours
- After power cuts
 - Optolinks and modules are checked
 - ~4 hours
- During calibration time during normal data taking periods
 - Modules throwing errors are retuned
 - ~1 hour

Optolink calibration

Tuned values to avoid readout errors :

- Off-detector sampling threshold vs phase :
- On-detector laser power (Viset)
 - 1 per optoboard (=6 or 7 modules) :

“by eye”

Module 0

Tuning point then
checked with
digital test

Module 6

Module calibration

Adjustable feedback current of
the preamp : defines slope

ToT tuning

Threshold tuning

Threshold calibration

- Tuned at 3500 e
 - 40 e dispersion after tuning
- Pixel noise with this tuning :
 - Normal : ~ 170 e
 - Long : ~ 200 e
 - Ganged : ~ 300 e
- Successful tests performed at the limit threshold of 2400 e
 - $\rightarrow$ we are confident for the next target : tuning at 3000 e

Procedure :

- Inject # of test charges at target threshold, vary 7-bit DAC per pixel and count generated hits. Optimal value is at 50% efficiency.
- If 7-bit DAC per pixel does not produce sufficient range of thresholds for tuning target, use 5-bit DAC per FE first to shift global threshold per FE.

ToT tuning

Time during which signal is above threshold

- In units of Bunch crossing (BC, 25 ns)
- $\text{ToT} \propto \text{deposited charge}$
- **Tuning target : $\text{ToT} = 30 \text{ BC}$ for a m.i.p. (20 ke)**
 - **Resolution : 1BC**

Procedure :

- IFDAC : tune range in which FDAC (feedback current) will be tuned for each pixel

Feedback current dependence
(lower feedback $\rightarrow$ longer ToT)

ToT calibration

- After tuning : calibration : ToT vs deposited charge :
 - Inject varying charges to measure ToT per pixel vs injected charge.
 - Parameterized with $\text{ToT} = p_0(p_1+Q)/(p_2+Q)$ for each front-end and each pixel type
- Used by offline $\rightarrow$ better resolution on position with charge sharing algorithm

Time-walk – ToT doubling

Low charge hits may suffer time-walk, i.e. their signal cross the threshold in the BC following the one they're supposed to be attached to.

In-time threshold : corresponds to the charge crossing the threshold at the very end of the 1st BC → 4800 e

ToT doubling is introduced:

- **in-time threshold : 3700 e**

All charges measured in the 2nd BC with a ToT smaller than the one corresponding to a 3700 e (~7BC) charge will be duplicated into the 1st BC

Noise

- Without noise masking : 1 noise hit/event on the whole Pixel Detector.
- During Pixel Detector standalone runs, noisy pixels (occupancy > 10^{-6}) are identified and masked online
 - $\sim 0.1\%$ for a 3500 e threshold tuning
- Noisy pixel mask then transmitted to offline – additional ones masked offline on run-by-run analysis
- Noise rate after offline masking : $< 10^{-9}$

Hit-to-track association efficiency

- Track selection requirement :
 - 1 hit on b-layer ($\rightarrow$ 100% efficient)
- Disabled modules taken into account
- Disabled FE or dead pixels not (main reason for efficiency decrease in outermost discs)

Ex :

Overall efficiency $\sim 99\%$

Damages

Non-working modules

- On the 14/11/11 :
 - 64 dead modules (6 due to a single optoboard failure)
 - 9 on disks (4 on A side, 5 on C side)
 - 9 on Layer 0 (3 central modules)
 - 7 on Layer 1
 - 39 on Layer 2
 - 48 disabled front-ends
 - → 3.7% of the detector disabled (3.8% if taking into account the disabled FEs)
 - 0.1% of pixels have disconnected bumps (most of them on a couple of disk modules)
 - 0.04% are analog dead –10% of them have merged bumps

The percentage of disabled modules grew from 2.1% to 3.8% in 3.5 years of operations
→ IBL needed to restore the initial performance.

Inactive fraction per layer:

B-layer	3.1 %
Layer 1	1.4 %
Layer 2	5.7 %
Endcap A	2.8 %
Endcap C	3.5 %

Disabled modules by failure type:

Radiation damages

- Effects of radiation on pixels :
 - Increase of leakage current
 - Decrease of voltage for full depletion of sensors until type inversion* (then increase)
 - Decrease in charge collection efficiency (lower threshold needed)
- Leakage current :
 - Leakage current increase already measurable at the module level but only on the b-layer at pixel level

- Increase of 0.17 nA for 2.3 fb^{-1} integrated luminosity for the innermost layer and observation of radial dependence for the endcap modules (pixel level)

*The b-layer is expected to undergo type inversion after 10 fb^{-1} integrated luminosity

Radiation damages

- Depletion voltage :
 - Shows damage increase
 - Indicator of time of type inversion
 - During calibration periods and before type inversion, using cross-talk scans :
 - Injecting charge in a given pixel – reading out neighbors
 - If not fully depleted : high-ohmic short between pixels (cross-talk).
 - If fully depleted : pixels are isolated from each other – no hits.

Module close to depletion voltage ->
white already fully depleted (no crosstalk hits). Structure
appearing shows the sensor production (Cristal polishing)

Summary

Inner Tracking Detectors			Calorimeters			Muon Detectors					Magnets	
Pixel	SCT	TRT	LAr EM	LAr HAD	LAr FWD	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
99.8	99.6	99.2	97.5	99.2	99.5	99.2	99.4	98.8	99.4	99.1	99.8	99.3

Luminosity weighted relative detector uptime and good quality data delivery during 2011 stable beams in pp collisions at $\sqrt{s}=7$ TeV between March 13th and October 30th (in %), after the summer 2011 reprocessing campaign

- Calibrated and very well-performing detector
 - Threshold tuned at 3500 e with a dispersion of 40 e, average noise ~ 170 e
 - ToT tuned to 30 BC with a resolution of 1 BC
 - 96.3% of the detector operational
 - offline noise rate $< 10^{-9}$
 - Data taking efficiency $> 99\%$
 - Hit-to-track association efficiency $\sim 99\%$
- Regularly checked and recalibrated
- Radiation damage : observable but pixels can stand for about 100 times more radiation
- In 2014, thanks to IBL, performance restored and improved

BACK-UP

Threshold

Timing adjustment

trigger delays → done using cosmic ray data
cable length → measured during installation
module-by-module variations

After all adjustment : module-to-module dispersion : 0.007 BC → corresponds to a dispersion of 0.17ns (between modules)

Lorentz angle

- Cluster size vs. track angle with and without magnetic field → Measurement of the Lorentz angle
- Measured value of ~ 211 mrad, close to expected value (225 mrad)
- Theoretically-expected dependence on mobility can be nicely seen when looking at modules of different temperature
 - Measured: (-0.78 ± 0.18) mrad/K, expected: -0.74 mrad/K

dE/dx – particle ID

track dE/dx resolution : 12%

Leakage current

Radial dependence for the endcap modules (pixel level)