Commissioning of the ATLAS Pixel Detector and operational experience with first data

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The Pixel Detector is the innermost component of the ATLAS tracking system. It was commissioned since 2008 with cosmic ray data and more recently with pp collisions at $\sqrt{s} = 900$ GeV and $\sqrt{s} = 7$ TeV. The read-out electronics was tuned, detection efficiency was measured and noise suppression was implemented. The study of cluster properties allowed to improve spatial resolution and to identify particles by measuring their energy loss.

1. Introduction

ATLAS [1] is a general purpose particle physics experiment at the Large Hadron Collider at CERN. The Pixel Detector [2] is the innermost component of its tracker: it is made of three barrel layers (with radius 50.5 mm, 88.5 mm and 122.5 mm) and two end-caps, each one constituted of three disks. The basic components of the detector are the modules, that are identical for barrel and disks. In the barrel they are arranged in overlapping staves of 13 modules each, while in the disks they form 6-modules sectors. Each module contains 47,232 pixels with a total of more than 80×10^6 pixels over a surface of 1.7 m².

The detector structure is made of low-mass carbon fiber and integrates the cooling system, resulting in a total contribution to X_0 of about 3% per layer. A radiation dose of ~ 500 kGy(Si) is expected during detector life time. The read-out clock is given by the LHC 25 ns bunch crossing (BC). A resolution of 10 μ m in the azimuthal direction and 115 μ m along the beam direction are required, imposing an alignment precision better than 10 μ m.

2. The Pixel Detector module

Each module is composed by a sensor, 16 front-end (FE) chips and a flex hybrid containing control and transmission electronics.

The FE chips are bump-bonded to the pixels using solder or indium bonds with a 50 μ m pitch. Each chip contains 18×160 cells, realized with 250 nm CMOS technology. The FEs provide charge measurement using the time-over-threshold of the output signal (Sec. 4).

The sensor is made of n^+ -in- n silicon with typical pixels size of $50 \times 400 \mu\text{m}^2$ (short side is along the $R\phi$ direction). Some pixels with modified geometries (*long* and *ganged* pixels) are present near to the borders of the FE. The measured sensor thickness is $256 \pm 3 \mu\text{m}$ [2].

A flexible kapton circuit, wire-bonded to the FE and glued on the reverse of the sensor, provides a bias voltage of 150 V. It contains the Module Controller Chip (MCC) that controls the FE and has basic event reconstruction capability.

3. Data taking operations

The Pixel Detector was installed in June 2007. The commissioning with cosmic muon data started in September 2008. More than 600,000 tracks were collected. Since November 2009, the detector is involved in collision data taking: more than 500×10^6 candidates have been recorded, at center-of-mass energies of 900 GeV and, starting from April 2010, 7 TeV. Special procedures exist to switch the detector on and off, in order to ensure that high voltage is provided only when LHC beam is stable.

The intrinsic efficiency was measured by extrapolating cosmic ray tracks through the detec-

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Figure 1. Hit detection time as a function of the injected charge. A MIP corresponds to 20,000 e , with a detection time close to 2 ns.

61 tor and counting the numbers of measurements
 62 on the track and holes where a hit would be ex-
 63 pected but is not found. The measured efficiency
 64 was $(99.974 \pm 0.004(\text{stat.}) \pm 0.003(\text{syst.}))\%$ for the
 65 barrel part, if non-operational modules are ex-
 66 cluded [3]. Irreversible failures involve 46 mod-
 67 ules that correspond to 2.64% of the detector.

68 4. Calibrations of the read-out electronics

69 The read-out FE contains a charge amplifier
 70 with constant-current feedback that ensures high
 71 stability and fast signal shaping through a lin-
 72 ear decay of the shaped signal. The charge col-
 73 lected by each pixel is estimated by the time dur-
 74 ing which the signal is higher than a configurable
 75 threshold. The threshold is set for each module
 76 and can be trimmed at pixel level, by using a 7-
 77 bit DAC. The feedback current itself can be tuned
 78 with a 3-bit DAC for each read-out channel.

79 A threshold of 4000 e was initially used. Af-
 80 ter tuning, the distribution of threshold values
 81 showed high uniformity, with an RMS of 40 e .
 82 The typical electronic noise was 200 e for normal
 83 pixels, giving a very favourable threshold over
 84 noise ratio. For this reason, the threshold has
 85 been lowered to 3500 e for 2010 data-taking.

86 The feedback current is configured in order to
 87 have a 30 BC time-over-threshold (ToT) for a
 88 20,000 e minimum ionizing particle (MIP). The

89 resolution on ToT measurement is described by
 90 the formula $\sigma_{\text{ToT}} = p_1 + p_2 \times \text{ToT}$, where p_1 and
 91 p_2 are parameters fitted from data. For a MIP,
 92 the resolution is about 1 BC (660 e), higher than
 93 the electronic noise.

94 Due to the delay with which it exceeds the
 95 threshold, a hit can be associate to the correct
 96 BC or to the following one. This *time-walk* ef-
 97 fect is studied by injecting known charges into the
 98 read-out electronics and measuring the detection
 99 delay (Fig. 1). The *in-time threshold* is defined as
 100 the minimal signal needed to have correct hit-BC
 101 assignment. This has been measured to be 4870 e
 102 (with 158 e dispersion) for the 3500 e threshold.

103 During cosmic ray data taking, a read-out win-
 104 dows of 5 BC was used. After assessing a better
 105 module synchronization, this was reduced to 4 BC
 106 in 2010, getting a read-out efficiency of 99.95%
 107 for hits associated to tracks. Hits out of the main
 108 BC are mainly located at the edge of the modules,
 109 where some charge can be lost, or in the *ganged*
 110 pixel region, where each read-out channel serves
 111 two different pixels.

112 5. Noise masking

113 The noise rate is dominated by few hundred
 114 pixels. For this reason, noise is reduced either by
 115 excluding pixels from read-out (*online* mask) or
 116 by not using them in data reconstruction (*offline*
 117 mask). The online mask is provided for each read-
 118 out configuration, while the offline mask is com-
 119 puted by using a *calibration loop*. During each
 120 data-taking run, a calibration stream is provided
 121 by triggering empty bunch crossing: pixels are
 122 considered noisy if they have an occupancy larger
 123 than 10^{-5} hits per BC. The reconstruction of the
 124 bulk of data is delayed by 36 hours and is per-
 125 formed masking the noisy pixels just identified:
 126 the noise measured is lower than 10^{-9} hits per
 127 pixel per BC.

128 6. Lorentz angle measurement

129 ATLAS uses a 2 T solenoidal magnetic field to
 130 measure the momentum of particles. The field
 131 causes the charge carriers inside the Pixel Detec-
 132 tor sensor to drift towards the electrodes forming

Figure 2. RMS of residual distribution for cluster local y position with respect to track extrapolation. The distribution is plotted as a function of the track incident angle.

an angle with respect to the normal to the module surface, the *Lorentz angle*. When estimating the particle crossing point, this angle should be subtracted from the incident angle of particles [4].

The distribution of the cluster size as a function of the particle incident angle is fit to measure the Lorentz angle, that corresponds to the minimum of this distribution. A full study of the systematic uncertainties was performed on cosmic ray data, giving a value of $11.77^\circ \pm 0.03^\circ \pm_{0.23}^{0.13}^\circ$, while the theory predicts $12.9^\circ \pm 1.55^\circ$ [3]. On collision data, the measurement is less accurate, due to the smaller range of particle incident angles. The mean temperature of the detector is lower, giving a higher measured value of $12.1^\circ \pm 0.09^\circ$ for a threshold of 3500 e.

7. Charge sharing and spatial resolution

The spatial resolution depends on read-out tuning, on cluster size and on particle incident angle. It is improved by summing to the geometrical center of the cluster a correction term proportional to *charge sharing*. The charge sharing variable is defined as the ratio between the charge collected in the first pixel of the cluster and the total charge collected in the outermost pixels. The weight of the correction is fit from data for different cluster sizes and ranges of incident angle [5].

Fig. 2 shows the RMS of residual distribution with respect to the track extrapolation for the lo-

cal x position of clusters, as a function of the track incident angle. The residual distribution width is determined both by extrapolation uncertainty and by detector resolution. The improvement due to charge sharing correction is clearly visible.

8. Energy loss and particle identification

The specific energy loss (dE/dx) associated to particles is measured from the charge collected in the clusters, after a selection that excludes regions where charge collection is poor. The track dE/dx is defined as the truncated average of the individual cluster energies, by removing the highest charge, in order to reduce the Landau tails.

After plotting the dependence of dE/dx on track momentum and charge, separated bands for pions, kaons and (anti-)protons are identified, in particular in the low momentum region.

9. Conclusions

The Pixel Detector was commissioned with cosmic ray data in 2008 and 2009 and with LHC collision data in 2009 and 2010. The commissioning activity allowed to uniformly tune the read-out electronics response to injected charge and to improve the synchronization of all the modules composing the device. The hit-track association efficiency and the noise rate were measured and an algorithm was developed in order to identify and exclude noisy pixels from track reconstruction. The study of cluster properties allowed to improve the spatial resolution by using information about charge sharing among hit pixels and by precisely measuring the Lorentz angle. Furthermore particle identification was implemented, by exploiting information about particle specific energy loss in the silicon sensors.

REFERENCES

1. ATLAS collab.. *JIST*, 3(08):S08003, 2008.
2. G. Aad et al. *JIST*, 3(07):P07007, 2008.
3. ATLAS collab.. *The ATLAS Inner Detector commissioning and calibration*, arXiv:1004.5293.
4. I. Gorelov et al. *NIMA*, 481:204–221, 2002.
5. S. Montesano. CERN-THESIS-2010-018