Operation and Performance of the ATLAS Silicon Micro-strip Tracker

Y. Pylypchenko for the ATLAS Collaboration

Abstract—The SemiConductor Tracker (SCT) is the key precision tracking device in ATLAS, made from silicon micro-strip detectors processed in the planar p-in-n technology. The completed SCT has been installed inside the ATLAS experimental hall since 2007 and has been operational since then.

In this paper the current status of the SemiConductor Tracker is reviewed, including results from the latest data-taking periods in 2009 and 2010, and from the detector alignment. The main emphasis is given to the performance of the SemiConductor Tracker with the LHC in collision mode and to the performance of individual electronic components.

I. INTRODUCTION

ATLAS [1] is one of the two large general purpose detectors built at the Large Hadron Collider (LHC) [2] to explore physics at TeV scale. It consists of several detector subsystems. Closest to the interaction point is the Inner Detector, the charged particle tracker immersed in a 2 T axial magnetic field provided by a superconducting solenoid magnet. The Inner Detector comprises two silicon detectors, the Pixel Detector and the SemiConductor Tracker, and a Transition Radiation Tracker. The liquid argon electromagnetic calorimeters surround the Inner Detector. The electromagnetic calorimeters are, in turn, surrounded by hadronic calorimeters. The outermost system of the ATLAS detector is the Muon Spectrometer which relies on a set of massive superconducting air-core toroid magnets.

ATLAS started collision data taking in December 2009. Integrated luminosity recorded in 2009 during stable beams and for proton-proton collisions at 900 GeV centre-of-mass energy equals $12 \mu\text{b}^{-1}$. The LHC collision energy was increased to the unprecedented 7 TeV in March 2010 and ATLAS recorded 45 pb^{-1} for 7 TeV proton-proton collisions during 2010. In addition to that $9.17 \mu\text{b}^{-1}$ of data were taken during heavy ion (Pb) collision run at 2.76 TeV centre-of-mass energy per nucleon at the end of 2010.

II. THE ATLAS SEMICONDUCTOR TRACKER

The SemiConductor Tracker (SCT) forms the intermediate tracking layers of the ATLAS Inner Detector (see Fig. II). With 61 m^2 of an active silicon area and 6.3 million readout channels it provides precision measurements in the radial range $30 < r < 56 \text{ cm}$ for charged particle tracks with

$|\eta| < 2.5^1$. It is made up of a barrel and two endcaps

Fig. 1. A schematic view of the ATLAS Inner Detector.

comprising 4088 silicon micro-strip modules. The 2112 barrel modules are arranged to form four concentric layers covering pseudorapidity range $|\eta| < 1.1$ to 1.4 depending on the layer. The 1976 endcap modules, arranged in nine disks in each of the endcaps, extend the η coverage to $|\eta| < 2.5$. All barrel modules are identical [3], whereas the endcap modules come in four types differing primarily in shape [4].

The general layout of the SCT module represents the two pairs of identical, single-sided silicon micro-strip sensors each with 768 active p-strips on n-type silicon bulk. The pitch is $80 \mu\text{m}$ for barrel modules and $57\text{--}94 \mu\text{m}$ for endcap modules, while the sensor thickness is $285 \mu\text{m}$. For most of the modules each pair of sensors is wire-bonded, forming 126 mm long strips. The sensors are glued back-to-back on a thermal pyrolytic graphite baseboard and rotated by a 40 mrad stereo angle to provide a z-measurement capability. This module design allows for intrinsic strip efficiency greater than 99% and a space-point resolution of $17 \mu\text{m}$ in bending $r - \phi$ plane and $580 \mu\text{m}$ z-direction.

To limit the radiation damage effects, such as reverse annealing and leakage current, and to decrease the noise levels, the SCT detector is cooled down by evaporative cooling

¹ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point. The counterclockwise beam direction defines the z-axis, the positive y-axis points towards the center of the LHC ring and the positive x-axis points upwards. Cylindrical coordinates (r, ϕ) are used in the transverse plane with respect to the beam and the pseudorapidity η is defined in terms of the polar angle θ as $\eta = -\ln \tan(\theta/2)$.

The signals from the strips are processed in the front-end ABCD3TA ASICs [6], realized in the radiation hard DMILL technology and working in the binary readout mode in which the signal from the silicon strip is amplified, shaped and discriminated yielding only hit or no-hit information.

Each module is served by its own independent power supply, with a low voltage power supply for the on-detector electronics and optical communication components, and a separate high voltage card providing the bias voltage for the module sensors. The typical depletion voltage is approximately 60 V, while the default reverse bias voltage is 150 V, at which the SCT is operated when there are stable beams. In the absence of stable beams the bias voltage is kept at 50 V for safety reasons.

III. OPERATION OF THE ATLAS SEMICONDUCTOR TRACKER

Disabled Readout Components	Endcap A	Barrel	Endcap C	SCT	Fraction (%)
Disabled Modules	5	10	15	30	0.73
Disabled Chips	5	24	4	33	0.07
Masked Strips	3,364	3,681	3,628	10,673	0.17
Total Disabled Detector Region					0.97

disabled SCT modules and chips as well as masked strips during the data taking in 2010 is shown in Fig. 2. 13 modules

There were problems with the off-detector optical transmitters sending clock and control signals to modules (TX plugins), which were resulting in unexpected failures during the running period. This problem is understood to be due to the ingress of humidity into the VCSEL. Since redundancy can be used for optical connections a TX plugin failure does not necessarily imply a gap in the acceptance. There are also replacement transmitters with different, more robust VCSELs.

In the following various aspects of the SCT operation demonstrating the performance during 2009-2010 are described.

A. Noise level

Number of chips

Inner barrels: $7.2\text{e-}06, -2.2^\circ\text{C}$
 Outer barrel: $1.3\text{e-}05, 4.9^\circ\text{C}$
 Middle endcaps: $1.1\text{e-}05, -7.8^\circ\text{C}$
 Outer endcaps: $1.6\text{e-}05, -7.5^\circ\text{C}$

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SCT Calibration
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Log₁₀(occupancy)

Fig. 3. The distribution of the noise occupancy for each chip split up for the different parts of the SCT. Dashed line shows the TDR specification. The temperatures of the silicon sensors shown on the plots are derived from the measured hybrid temperatures using a correction determined from simulation.

Fig. 4. The distribution of the input noise estimated from noise occupancy test in the different parts of the SCT. The temperatures of the silicon sensors shown on the plots are derived from the measured hybrid temperatures using a correction determined from simulation.

In the second method the occupancy at different thresholds is measured by injecting various known charges. For each value of injected charge the threshold is scanned over the entire range and a complementary error function is fitted to the average occupancy. The variance of this distribution characterizes the noise. Both methods yield compatible results.

B. Hit efficiency

Fig. 5 shows the number of hits per expected hit which represents the intrinsic silicon strip efficiency. It is evaluated for two types of tracks: SCT standalone and combined Inner Detector tracks, both satisfying the requirement of a transverse momentum above 1 GeV. For standalone tracks at least 7 SCT hits are required, excluding the hit under test for efficiency, while for combined tracks at least 6 SCT hits are required. The values obtained for both types of tracks are compatible being of about 99.8% and 99.9% for the strips in SCT endcaps and SCT barrel respectively. This is higher than the design requirement of 99% for the intrinsic silicon strip efficiency.

C. Strip occupancy

A comparison of the number of hit strips per module side for 900 GeV collision data and Monte Carlo simulated events is plotted in Fig. 6. The plot contains all SCT modules both from barrel and endcaps. Both distributions are normalized by number of events. Good agreement over several orders of magnitude can be seen between the data and Monte Carlo distributions. The discrepancy in the first bin is due to a lower level of noise in the simulation than in data. Noise in the simulation is appropriate for readout of one bunch crossing while the data were collected over three bunch crossings leading to a higher noise level.

D. Lorentz angle

The Lorentz angle is the angle by which charge carriers in the silicon sensor drift in the presence of the magnetic field. It depends on magnetic field strength, module temperature and

Fig. 5. The intrinsic silicon strip efficiency is shown for tracks measured in the SCT endcap C (upper plot) and the SCT barrel (lower plot). The data used are from 7 TeV collision run taken in September 2010.

Fig. 6. The number of strips per module side from a 900 GeV run compared with a 900 GeV minimum bias Monte Carlo sample.

bias voltage. The Lorentz angle can be obtained by determining the track incidence angle in the plane perpendicular to the magnetic field which yields the minimum average cluster width (Fig. 7). This angle equals the Lorentz angle and is zero in the absence of the magnetic field. Fig. 8 shows the measured Lorentz angle in each layer of the SCT barrel. The extracted values and their statistical errors are shown for 900 GeV collision data and cosmic ray data collected with the SCT operating under nominal conditions. The model prediction that is also shown on the plot takes into account the fact that the layers are not operated at the same temperature. The measured values can be seen to lie within about 1σ of the model prediction, although systematically above it. Further investigations are ongoing.

Fig. 7. The SCT cluster size (in strips) plotted as a function of the track incidence angle for the four layers in the SCT barrel.

Fig. 8. The values of the Lorentz angles extracted for four SCT barrel layers.

E. Alignment

The tracking and invariant mass reconstruction performance depend on the precision of the positioning of the silicon modules. The alignment procedure is applied to accurately determine their position and correct for systematic effects that could bias the tracking. Fig. 9 shows an impressive agreement between the measured K_S^0 mass using 900 GeV collision data and the world average value [9], indicating that the performance of the alignment was very good already in 2009.

In 2010 the SCT alignment approached the ideal case. Fig. 10 shows the x residual distribution for 7 TeV collision data compared to Monte Carlo simulation with a perfectly aligned detector. The residuals are calculated as the difference between the measured hit coordinate and the expected position obtained from track extrapolation. Tracks used for the calculation were selected to have transverse momentum greater than 2 GeV and at least 6 silicon hits. As can be seen the data are in a very good agreement with the perfectly aligned detector simulation.

V. CONCLUSIONS

The ATLAS SemiConductor Tracker is fully operational and is being successfully used in ATLAS data taking contributing to physics results.

Fig. 9. The invariant mass of pion pairs from $K_S^0 \rightarrow \pi^+\pi^-$ decay reconstructed from 900 GeV collision data using the information from the entire ATLAS Inner Detector.

Fig. 10. Distribution of the local x unbiased residuals of the SCT barrel modules (upper plot) and the SCT endcap modules (lower plot). Full blue circles show the data residuals after the detector alignment, and the open red circles show the residuals using Monte Carlo with a perfectly aligned detector (normalized to the number of entries in the data distribution).

It demonstrated an excellent performance in 2009 and 2010: 99.3% of the SCT modules were operational, the noise occupancy level and hit efficiency exceeded the design specifications and the alignment being very close to ideal allowing for on-line track reconstruction and invariant mass determination. Measurements of the quantities such as occupancy and Lorentz angle demonstrate the understanding of the detector and allow for fine tuning of its Monte Carlo simulation.

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