ATLAS Silicon Microstrip Tracker Operation and Performance

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Abstract

The Semi-Conductor Tracker (SCT) is a silicon strip detector and one of the key precision tracking devices of the Inner Detector of the ATLAS experiment at CERN LHC. The SCT is constructed of 4088 silicon detector modules for a total of 6.3 million channels. Each module is designed, constructed and tested to operate as a stand-alone unit, mechanically, electrically, optically and thermally. The modules are mounted into two types of structures: one barrel (4 cylinders) and two end-cap systems (9 disks on each). The current results from the successful operation of the SCT Detector at the LHC and its status after three years of operation will be presented. The operation of the detector including an overview of the main issues encountered is reported. The main emphasis is be given to the tracking performance of the SCT and the data quality during the > 2 years of data taking of proton-proton collision data at 7 TeV (and short periods of heavy ion collisions). The SCT has been fully operational throughout all data taking periods, delivering high quality tracking data.

Keywords: ATLAS, SCT, Operations, Performance

1. The Altas Silicon Microstrip Tracker

The Inner Detector \cite{1} of the ATLAS experiment \cite{2}, which is situated at the Large Hadron Collider (LHC) at CERN, comprises the subsystems closest to the interaction point and provide tracking information. It is composed as shown in figure 1 of a gaseous transition radiation tracker (TRT), and two silicon trackers: the pixel detector (PIXEL) and the semiconductor tracker (SCT). An area of 61 m\textsuperscript{2} of silicon with 6.2 million read-out channels composes the SCT; it’s 4088 silicon modules are arranged in 4 Barrel layers and 18 Disks, 9 in each of the two end caps. The Barrel is made of 2112 modules and has a coverage in pseudo rapidity $|\eta| < 1$, while the end caps are made of 1976 modules having a coverage of pseudo rapidity between $1.1 < |\eta| < 2.5$.

The barrel modules consists of two pairs of identical single sided p-on-n silicon micro strips with 80 $\mu$m strip pitch are glued back-to-back to a base board (see figure 2). A stereo angle of 40 mrad between sides provides three dimensional point information with space point resolution of $r_\phi \sim 16 \mu$m and $r_z \sim 580 \mu$m. The endcap modules are similar but comprise wedge-shaped sensors. The operational temperature, nominally at $-7$ °C, is maintained by $C_3F_8$ evaporative cooling.

2. Operational experience

More than 99% of the 6.3 million strips were functional and available for tracking in all data taking periods. Constant work
of shifters and experts during data taking and technical stop periods was crucial in maintaining this high efficiency. The SCT crew consists of a shifter present any time in the ATLAS Control Room (ACR) with a turn over of 8 hours, a pool of experts being on call in weekly blocks.

The SCT Data Acquisition System (DAQ) has proved to be highly reliable with excellent data taking efficiency. There are two potential sources of inefficiency: (i) errors from the front-end ASICs which flag that data fragments from those chips cannot be used for tracking, (ii) and a BUSY signal from the SCT Readout Drivers (RODs) that prevents ATLAS from taking data. The operations issues that impacted on data taking efficiency and data quality are as follows, listed in order from the most to the least significant:

1. In 2012 the SCT operated with pileup of up to \( \sim 30 \) interactions per bunch crossing and occupancy reaching \( \sim 1\% \), which far exceeded the original design expectations. Although these conditions did not directly cause problems to the DAQ, the high occupancy and rate exposed shortcomings in the DAQ processing and decoding of the data which lead to an increasing rate of BUSYS. Although this was the most significant issue impacting on data taking efficiency, it was mitigated by introducing the ability to disable the source of the busy ROD, reconfigure the affected modules, and then to re-integrate the ROD without interruption to ATLAS data taking. It is anticipated this issue will be resolved in later ATLAS runs.

2. A small number of the modules were assembled using sensors from a different vendor (CiS) to the majority (Hama-matsu). A small but significant fraction of those sensors exhibited high leakage currents at high luminosity, correlated with high noise levels. It is suspected that intense radiation may ionise nitrogen gas surrounding silicon and the corresponding accumulated charge on the oxide is responsible for the increase in current. Between data taking periods standby voltage was decreased with respect to the nominal value of 50 V and the high noise and currents were eventually mitigated by reducing the HV down from the nominal 150 V.

3. The optical transmitters (TXs) used to broadcast the commands and triggers to the front-end modules have been problematic in all data taking so far. Individual channel deaths within the 12-channel VCSEL arrays lead to a loss of data from modules, until the TX was replaced or adjusted within the configuration. Early failures were due to the ingress of humidity to the VCSELs, which were addressed by introducing dry air to the racks. Humidity-resistant VCSEL arrays will be installed for future runs.

4. Single Event Upsets (SEUs) can corrupt front-end chip registers, leading to high or low noise from that chip, or desynchronisation of the chips with the rest of ATLAS. In 2011, an automatic reconfiguration of individual modules was implemented, invoked when a desynchronisation was detected. In addition, a global reconfiguration of all modules was invoked every 30 minutes with negligible dead-time to target noise-invoked SEU issues. With these measures, the fraction of the \( \sim 8000 \) data links giving errors was typically at \( \sim 0.2\% \). The increase of ROD BUSYS, as discussed in item 1, and the increase the significant increase of leakage current of a portion of the modules at high luminosity, as discussed in item 2, were dominant in 2012 while items 3. and 4. dominated up to 2011.

3. Monitoring and Performance

3.1. Data Quality

Data Quality (DQ) needs to be optimised during operations. The SCT has its own monitoring tool developed as an analysis software algorithm that it can be run both online and offline. Online: by running the full track reconstruction it ensures tracking and DAQ quality fall within the accepted range. It also allows for rapid investigation of problems during data taking. Offline: the monitoring tools ensure that, after every run, only the portion of data that satisfy strict quality criteria are selected. This quality assessment is done by monitoring track quantities including track parameters, vertex reconstructions, hits maps distributions and track \( \chi^2 \) distributions. Strict quality cuts are applied based on that information and data are precluded from analysis in luminosity blocks corresponding to periods of 2 minutes of data taking on average. Each defect in tracking has a correspondence with a detector defect assigned when a portion of modules unable to deliver reliable data. A detector defect is set if \( 0.1\% \) of the modules are unable to deliver good quality data based on error and noise rates. The efficiency is among the tracking parameters constantly monitored.

\[ \varepsilon = \frac{N_{\text{hits}}}{N_{\text{hits}} + N_{\text{holes}}} \]  

The intrinsic hit efficiency, defined in equation 1 as the ratio of the number of hits on any given track (with transverse momentum higher than 1 GeV) over the sum of holes and hits. A hole on a track is defined as an intersection of the track trajectory with an active detector element where no hit is found recorded [1]. The intrinsic hit efficiency for 2012 is shown in figure 3. For an average hit efficiency lower than 99.5\% in a region, either barrel or end cap, data are not cleared for analysis. As expected a small decrease in the hit efficiency was observed in 2012 with respect to early data taking. The higher track multiplicity, due to the increase of the average number of collisions per bunch crossing increases the probability of tracks sharing hits thus reducing artificially the efficiency. In nominal data taking the SCT hit efficiency was above 99.7\%.

The noise occupancy (NO) which is defined as the probability to record a hit only due to noise is also a closely measured quantity both online and offline by the monitoring tool in empty bunches. Throughout all data taking, the SCT noise occupancy remained significantly lower than the design specification of \( \text{NO} < 5 \times 10^{-4} \). A low data rejection was achieved as shown in Table 1. A slight decrease of the total luminosity weighted data collected and cleared for analysis is observed in 2012 with respect to 2011 due to the increase of issues, discussed in section 2, being related to the rise of the delivered luminosity by the LHC. Throughout all data taking periods the SCT collected and cleared a portion greater than 99\% of the data delivered by the LHC.
3. Line, given the peculiar conditions of its onset. No sign of this behaviour is seen in the Hamamatsu modules.


Portion of Good Data

99

\[ \text{Table 1: Summary of SCT luminosity weighted relative detector uptime and good quality data delivery trough the past three years of operations} \]

<table>
<thead>
<tr>
<th>Data Period</th>
<th>Portion of Good Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>99.9%</td>
</tr>
<tr>
<td>2011</td>
<td>99.6%</td>
</tr>
<tr>
<td>2012</td>
<td>99.4%</td>
</tr>
</tbody>
</table>

3.2. Alignment

Alignment is performed with cosmic and collision data by minimising the \( \chi^2 \) of track hit residuals. For collision data, tracks with \( p_T > 15 \text{ GeV} \) are selected from a jet trigger in order to minimise multiple scattering effects. Particularly for higher momentum tracks, where multiple scattering plays a less prominent role, remaining misalignment effects can be assessed by comparing hit residuals and the momentum scale. Excellent agreement was found in the residual distributions for both barrel and end cap [4]. The resolution in the \( Z \rightarrow \mu \mu \) invariant mass distribution from tracks reconstructed with the full Inner Detector, which is shown in figure 4, is very close to the expectation from Monte Carlo.

4. Radiation Damage

Irradiation of silicon sensors results in damage in the bulk silicon and the dielectric layers, with main effects being the increase in leakage current of the sensor, the change in the effective doping concentration and a change in the interstrip capacitance. A measurement of leakage current during off beam periods was made, and then under the assumption that all high voltage currents are originated from current in the silicon bulk, the measurements were normalised to \( T_{\text{ref}} = 0^\circ \text{C} \) (common factor for all LHC experiments). The measured current was found to be in agreement [6] with the Hamburg/Dortmund model simulated using FLUKA and including self annealing effects based on the different measured sensor temperatures. A conversion of the integrated luminosity for both \( \sqrt{s} = 7 \text{ TeV} \) and \( \sqrt{s} = 8 \text{ TeV} \) to 1 MeV neutron equivalent fluence to each barrel layer was made from simulations on minimum bias

![Figure 3: Intrinsic SCT hit efficiency from combined tracking for each barrel layer from a typical run (206573) in 2012 with \( \sqrt{s} = 8 \text{ TeV} \) [3]. Each track is required to have at least 7 silicon hits.](image1)

![Figure 4: This plot shows the invariant mass distribution of \( Z \rightarrow \mu \mu \) decays [5], where the mass is reconstructed using track parameters from the Inner Detector track of the combined muons only, using about 702 \( \text{pb}^{-1} \) of data collected during spring 2011. Ideal alignment performance based on Monte Carlo is compared to observed performance of data processed with spring 2011 alignment and data processed with updated alignment constants.](image2)

![Figure 5: The measured HV current for four barrel layers is shown [7]. The predicted leakage currents by the Hamburg/Dortmund model [6] are shown while the associated bands show the 1\( \sigma \) statistical and systematic uncertainty. On the top of the plot the measured sensor temperatures are shown](image3)
5. Conclusion

The SCT concluded the first LHC run with excellent overall efficiency. The variety of operational issues were summarised in section 2, which were studied and resolved allowing this high data taking efficiency.

[7] SCT Public Plots https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SCTPublicResults