ATLAS Strip Detector: Operational Experience and Run 1-> Run 2 Transition

Koichi Nagai[*][†]

Department of Physics, University of Oxford, Oxford OX1 3RH, UK
E-mail: `Koichi.Nagai@physics.ox.ac.uk`

The Large hadron collider was operated very successfully during the Run 1 and provided a lot of opportunities of physics studies. It currently has a consolidation work toward the operation at $\sqrt{s} = 14$ TeV in Run 2. The ATLAS experiment has achieved excellent performance in Run 1 operation, delivering remarkable physics results. The SemiConductor Tracker contributed to the precise measurement of momentum of charged particles. This paper describes the operation experience of the SemiConductor Tracker in Run 1 and the preparation toward the Run 2 operation during the long shutdown 1.
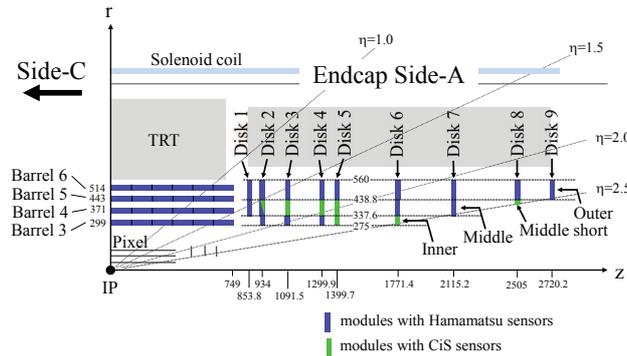
---

[*]Speaker.

[†]On behalf of the ATLAS SCT collaboration

1. Introduction

The Large Hadron Collider (LHC) was operated very successfully during the Run 1 and provided a lot of opportunities of physics studies. It currently has a consolidation work in the long shutdown 1 (LS1) toward to the operation at $\sqrt{s} = 14$ TeV in Run 2. The ATLAS experiment has achieved excellent performance in Run 1 operation, delivering remarkable physics results. The ATLAS detector [1] mainly consists of three parts: Inner Detector (ID), Calorimeter and Muon Spectrometer from inside to outside. The ID is surrounded by 2 Tesla solenoid magnet and provides precise measurement of momentum of charged particles in $|\eta| < 2.5$. The SemiConductor Tracker (SCT) is one of the three ID sub-detectors and contributes to the measurement providing four space points per track. This paper describes the operation experience in Run 1 and the preparation toward to the Run 2 operation during the LS1. The detailed information of operation and performance of the SCT in Run 1 which are not in this paper can be found in [2].

2. The SemiConductor Tracker

Figure 1 shows a cross section view of SCT in the r-z plane in the ATLAS ID. The SCT consists of four cylindrical layers surrounding the interaction point (Barrel) and 9 disks at each end of the Barrel (Endcap).

Figure 1: A quarter cross section view in $r - z$ plane of SCT.

The Barrel is constructed with 2112 rectangular-shape modules [3] distributed on four cylinders. The Barrel uses one unique type of module that is constructed with four rectangular planar p-in-n silicon strip sensors which have a thickness of 285 μm and 768 effective strips with pitch of 80 μm. Two sensor pairs were glued back to back on a thermally conductive mechanical support [4] with 40 mrad stereo angle. Two sensors on each side were daisy-chained producing 768 strips of 12 cm in length. The Endcap consists of 1976 trapezoidal shape modules placed on 18 Endcap disks, using 4 types of modules which were placed in three rings named as outer, middle and inner on disks. The Endcap modules [5] were in principle constructed in the same manner as the Barrel. The strip pitch is varied from 56.9 to 90.4 μm (average of 80 μm). SCT modules are operated with a nominal bias voltage (HV) of 150 V (nominal) but this can be increased up to 500 V.

2

The front-end (FE) readout system provides the binary readout mode, carried out by 12 ABCD FE chips [6] on each module. The ABCD chip is designed to be radiation hard and has 128 channels. Signals from strips are amplified, shaped with shaping time of 20 ns, discriminated and formed in binary data of three time bins per hit. The threshold on the discriminator is defined by an 8 bit DAC for all 128 channels and so-called "Trim-DAC" (4-bit) on each channel which compensate variation among channels.

The schematic view of the SCT off-detector electronics is shown in figure 2. Pairs of Read Out Driver (ROD) and Back Of Crate (BOC) cards distribute trigger signals and commands to module FE through one optical link and receive data from module FE through two optical links, using one optical transmitter (TX) and two optical receivers (RX) on the BOC. The BOC has an interface to the s-link to send the data formatted in the ROD to ATLAS Central DAQ. The system is designed to accommodate up to 2% occupancy at a Level 1 (L1) trigger rate of 100 kHz.
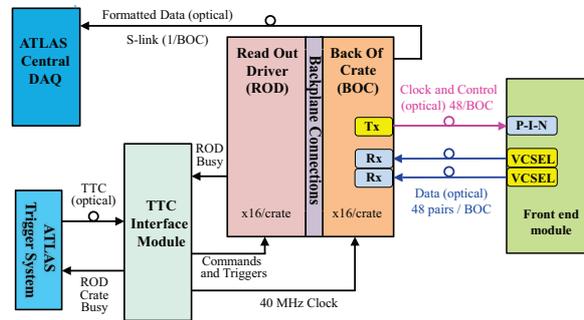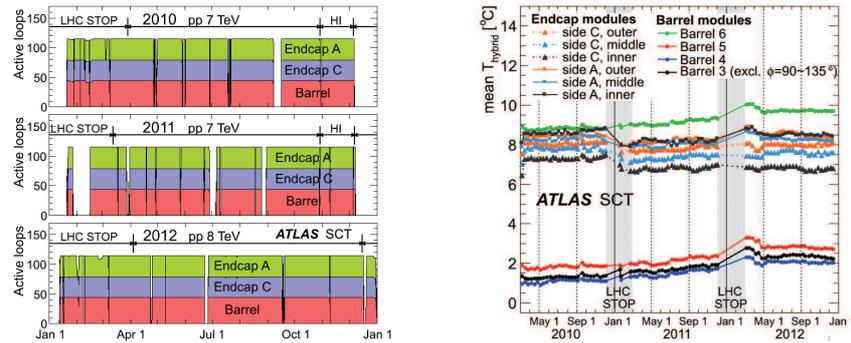

Figure 2: A schematic view of SCT off-detector electronics

3. The operation and experience in Run 1

The SCT was successfully operated through Run 1 where 99% of 6.3 Million strips were operational. The main causes of non-operational strips were disabled modules (0.73%), FE chips (0.11%) and strips (0.18%). Half of the disabled modules are due to cooling problems and the other due to HV/Low voltage (LV) issues. The detail can be found in [2]. The excellent performance of SCT was supported by calibrations and feedback from online and offline monitoring as well as several improvements in the SCT systems in Run 1. The luminosity weighted data taking efficiencies in p-p collisions are 99.9, 99.6 and 99.1% in 2010, 2011 and 2012, respectively. The cause of 0.9% drop in 2012 was dominated by ROD busy problems which cause no data in a part of SCT.

The SCT operation environment was provided by support infrastructures and monitored by DCS systems. The evaporative cooling system established effective cooling through Run 1. Figure 3 shows the number of active cooling loop in SCT out of 116 for each year and temperatures averaged over each layer in Barrel and module type in Endcap in Run 1. As shown in the figure in 2010 the system had several problems, however in 2011 and 2012 the system was significantly more stable followed by accumulated experience. The stoppages in 2012 and 2013 were mainly caused by either periodical maintenance or external problems like power cuts or fire alarms.

Figure 3: The cooling system operation: the number of active loops in SCT for Run 1 period (left) and temperature averaged for each layer in Barrel and module type in Endcap (right).

3.1 Operation of data acquisition system

The Data Acquisition system (DAQ) of the SCT was operated successfully during Run 1 and some issues which appeared in data taking were solved enabling good quality data to be kept. Several recovery actions are automated to gain data taking efficiency, which are established by increase of operation experience. Three major improvements are described below. Modules which have non-zero errors were individually identified and recovered by DAQ system. In the last year in Run 1 the spontaneous corruption of the configuration of modules due to single event upset (SEU) increased. The automated procedure of periodic reconfiguration of global SCT was developed to protect SCT system against SEU. The resulting loss of data was less than 0.03%. The problem was investigated and will be eliminated before Run 2. When ROD busy problem happened during the data taking, it could be loss of data in the rest of run at the beginning of Run 1. Stop-less reconfiguration and reintegration of RODs were introduced in case of busy. The ROD busy caused inefficiency of less than 0.6% in data taking with stop-less recovery. In parallel to the development of recovery procedure the cause of ROD busy was investigated. It was found that some incidents of ROD busy were due to firmware issues in ROD. A new firmware was developed, and consolidation and investigation will start with a recently developed FPGA FE simulator.

Failures of off-detector optical transmitter plugin (TX) on BOC happened during Run 1 operation. The problem was identified as being due to poor ESD precautions at the factory. All TXs were replaced with those produced with improved ESD procedures. However the second batches also showed high death rate caused by ingress of humidity. The TXs were replaced with humidity resistant VCSELs and have been kept in a dry environment by circulating dry air in electronics racks since then. Currently installed TXs were robust during the operation in 2012, however two significant issues developed. One is 10% drop in optical power in one year and the other small but significant death rate. The cause of the drop was investigated but still not yet understood. The death is probably caused by CTE mismatch between glue and VCSELs. SCT group developed more robust TXs using commercially packaged array assemblies called "lightABLE optical engines". Those were tested in a laboratory. Devices passed 1000 hours operation in the environment with 70°C and 85%RH and Bit Error Rate tests. The optical power satisfied the ATLAS specifica-
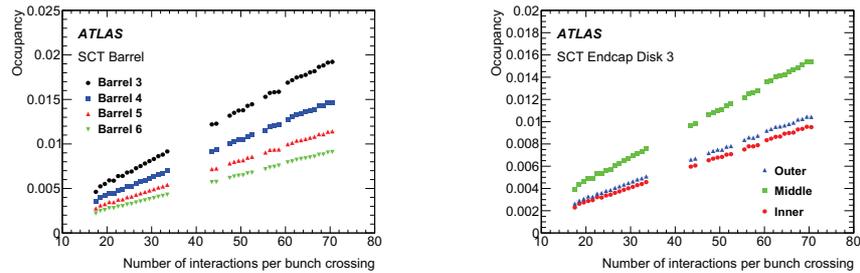
tion. However there were minor tweaks, which are mechanics to fit in the current BOC cards and firmware to adjust the optical power and cooling of the controller. After solving these issues, small number of new TXs were operated successfully in ATLAS at the end of Run 1. The full production was launched and one of eight crates is now fully installed with new TXs which are currently being tested in the DAQ system.

3.2 Calibrations and monitoring of SCT

Three types of calibrations, analog, optical and digital tests were regularly performed between LHC fills. Analog tests were performed to optimise the chip configuration and to measure noise and gain, optical tests to optimise parameter of optical transmission between modules and ROD, and digital tests to examine the functionality of the FE chips. In addition to the above, timing calibrations were performed with low luminosity runs, typically at the beginning of run period to adjust SCT timing to ATLAS.
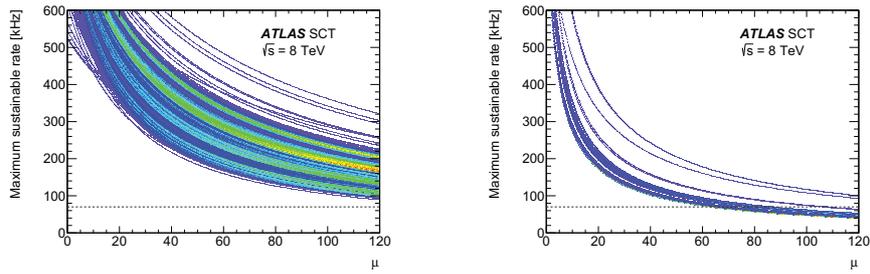
Online monitoring provided immediate feedback of the condition of SCT by monitoring the raw hit data during the data taking and allowed diagnosis of issues during a run. Offline monitoring was performed in prompt calibration after data taking, to check the details of excluded modules, modules with readout errors, hit efficiency, noise occupancy, time bin hit patterns and tracking performance. Assessment of SCT data quality was carried out according to the results from the offline monitoring which may set a SCT defect flag to define data quality for physics analyses.

The detector occupancy was one of the monitored parameters. The SCT was initially designed to have a low detector occupancy of less than 1% with LHC luminosity of $\sim 10^{34}$ $cm^{-2}s^{-1}$ at 40 MHz beam collisions and averaged pile-up of ~ 23. Although the number of pile-up exceeded the design value in 2012 with 50 ns bunch-spacing, no significant loss of tracking due to SCT detector occupancy were observed. A study of the detector occupancy was performed with special high pile-up runs up to 70 and showed that the SCT has an occupancy less than 2% at pile-up = 70 as shown in figure 4. The occupancy study was expanded to estimate sustainable L1 trigger
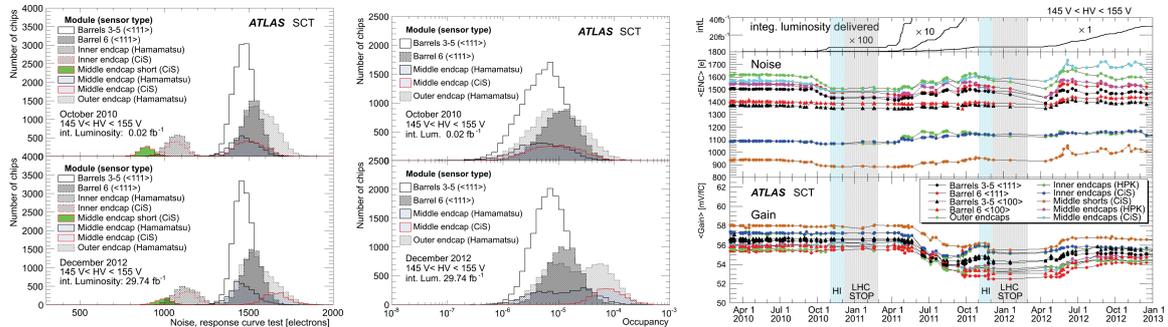

Figure 4: The detector occupancy in SCT Barrels (left) and in SCT Endcap Disk 3 (right), studied with special high pile-up runs.

rates in Run 1. Based on measured data sizes, the sustainable L1 trigger rate for each data link for Modules to RODs and RODs to ATLAS Central DAQ was investigated at $\sqrt{s} = 8$ TeV, assuming the maximum sustainable rate is 90% of bandwidth. The results in figure 5 show that SCT sustains data taking up to the number of inelastic proton-proton interactions per bunch crossing (μ) of 62 with typical trigger rate in 2012 ~ 70 kHz.

Figure 5: The estimated sustainable L1 trigger rates in Run 1. The rates for links between modules and ROD are shown on left and those between ROD and central DAQ on right. Each curves are corresponding to a link.

Equivalent noise charge (ENC) and noise occupancy in SCT are measured in the calibration runs together with gains of FE electronics. In addition the noise occupancy is monitored by several methods during the physics runs. The ENC is determined from a threshold scan in the calibration, and from hits counted in empty events in a physics run. Those values have been monitored In Run 1. Figure 6 shows measurements of the ENC and the noise occupancy in 2010 and 2102, where modules are grouped by module type and position. The ENC and noise occupancy increased in 2012 comparing with one in 2010 however the measured ENC is still far below the requirement of the threshold of 1 fC and the noise occupancy is less than the requirement of 5×10^{-4}. ENC and

Figure 6: Equivalent noise charge (left) and noise occupancy (middle) in 2010 and 2012, and histories of noise and gain in Run 1 together with integrated luminosity (right)

gains of FE amplifiers were monitored through Run 1 as shown in figure 6. Gains are rather stable except the gradual and universal change of a few % in mid 2011 and early 2012. Noise decreased about 7% in late 2010.
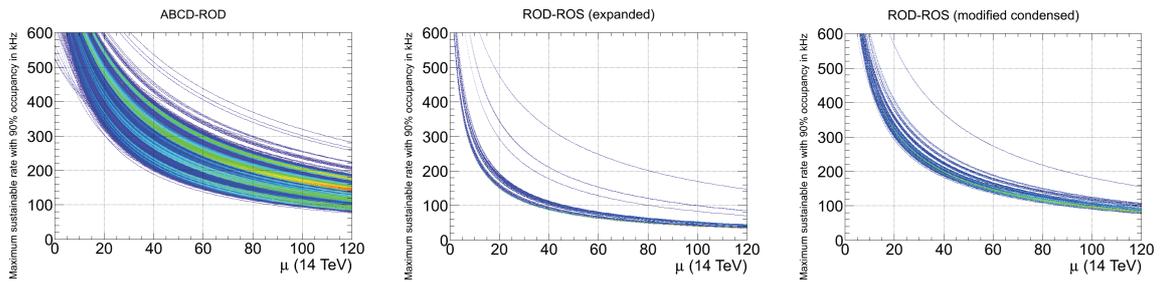
Hit efficiency is defined by the number of hits divided by number of possible hits on tracks. It's taking into account known problems; disabled sensors and chips, but there is no correction for isolated strips disabled due to noise or dead. Measured efficiencies for entire SCT, Barrel and Endcap were $99.74 \pm 0.04\%$, $99.86 \pm 0.03\%$ and $99.59 \pm 0.05\%$ respectively, where errors were systematic only since statistical errors were negligible.

6

4. Preparation toward to Run 2

The SCT has been kept in dry environment but at room temperature after Run 1. Since ID environment was not ready for cooling operation, the periodical calibration was not possible. The recommissioning of the SCT system started in April 2014. All cooling loops have systematically been checked for leak tightness of loops, mapping of sensors and function of cooling system step by step. The SCT cooled down to nominal operation temperature at the end of August 2014 after 18 months shutdown. SCT readout electronics were turned on and careful inspections of the detector are on going in parallel to LS1 maintenance work.
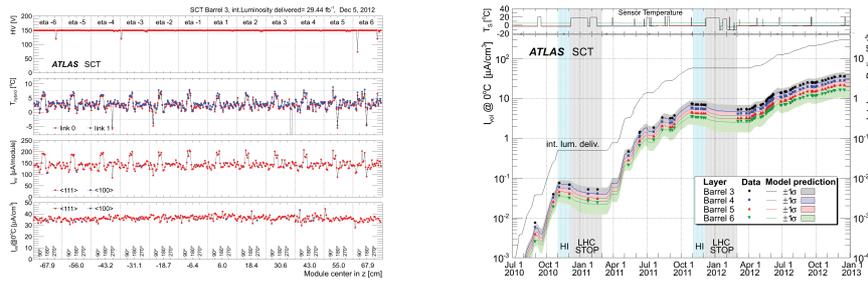
4.1 Sustainable level 1 trigger rates in Run 2

The operation of LHC in Run 2 will provide higher luminosity and 50 pile-ups at L1 trigger rate of 100 kHz at $\sqrt{s} = 14$ TeV. Figure 7 shows results of studies on sustainable L1 trigger rates in Run 2 condition. The results for the rate from modules to RODs satisfy data taking up to $\mu \sim 87$ at L1 trigger rate of 100 kHz. However from ROD to ATLAS DAQ can sustain only up to $\mu \sim 33$. To satisfy the Run 2 requirement, SCT DAQ has been expanded to 128 from 90 pairs of BOC and ROD; the number of S-links (the optical link from the BOC to the ATLAS DAQ) was increased to 128, and data compression on RODs was improved. After the expansion the link is able to cope with data up to $\mu \sim 87$ at an L1 trigger rate of 100 kHz.

Figure 7: Sustainable L1 trigger rate in Run 2 : Modules to ROD (left) and ROD to ATLAS DAQ before/after the expansion of SCT DAQ (middle/right, respectively)

4.2 Leakage current

The large flux of particles through silicon sensors causes radiation damage and will change the basic properties of the material. The effects on SCT modules are monitored through the leakage current on each module. The increase of leakage currents was observed at both 50 V standby and 150 V nominal HV during Run 1. Figure 8 (left) shows high voltage, temperature, observed leakage current and leakage current normalised to 0°C. Current trip limits on bias voltage has been increased from 5nA at the beginning of Run 1 in 2010 to 200 μA at the end of Run 1 in 2012. The observed change of leakage current is in good agreement with the predictions by Hamburg/Dortmund model using FLUKA for conversion of collision luminosity to 1 MeV neutron-equivalent fluence and taking into account the self-annealing effect, as shown in figure 8. Monitoring the leakage current will be used to determine the effect from radiation together with the predictions.

Figure 8: HV, temperature, observed leakage current and the current corrected to 0°C for modules in the innermost Barrel measured in December 2012 are shown on right and the comparison with the predictions by Hamburg/Dortmund model on left.

5. Summary

The SCT was successfully operated in Run 1. A total of 99% of strips were working and showed excellent tracking performance. The performance was supported by accumulated operation experience and improvement of SCT systems. The consolidation and upgrade of SCT systems are carried out during the LS1 to provide high quality data for physics analysis in Run 2. The most challenging requirement for SCT in Run 2 is to cope with the expected high L1 trigger rate up to 100 kHz at high pile-up. The expanded DAQ system promises the good performance in the expected conditions. The radiation effect was observed on SCT sensors, which is consistent with expectations and will be monitored in Run 2. The SCT is expected to show excellent performance in Run 2.

References

[1] ATLAS Collaboration. The ATLAS Experiment at the CERN Large Hadron Collider. *JINST*, 3:S08003, 2008.

[2] ATLAS Collaboration. Operation and performance of the ATLAS semiconductor tracker. *JINST*, 9:P08009, 2014.

[3] A. Abdesselam et al. The barrel modules of the ATLAS semiconductor tracker. *Nucl.Instrum.Meth.*, A568:642–671, 2006.

[4] R.J. Apsimon et al. Application of advanced thermal management technologies to the ATLAS SCT barrel module baseboards. *Nucl.Instrum.Meth.*, A565:561–571, 2006.

[5] A. Abdesselam et al. The ATLAS semiconductor tracker end-cap module. *Nucl.Instrum.Meth.*, A575:353–389, 2007.

[6] W. Dabrowski et al. Design and performance of the ABCD chip for the binary readout of silicon strip detectors in the ATLAS semiconductor tracker. *IEEE Trans.Nucl.Sci.*, 47:1843–1850, 2000.