

Commissioning of the ATLAS Silicon Tracker

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The ATLAS silicon tracker is installed in the ATLAS cavern and commissioning is well advanced. The assembly and commissioning milestones are reviewed, and the commissioning of the electrical and optical system immediately after installation within the ATLAS cavern is described. The final electrical performance of the barrel section of the tracker after installation and connection to the final services is presented. The silicon tracker performs well within specification.

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1. Introduction

The ATLAS detector [1] is one of two general purpose experiments designed to exploit the 14 TeV proton-proton collisions at the CERN LHC collider. The ATLAS Semiconductor Tracker (SCT) is part of the ATLAS Inner Detector (ID), which is designed to provide pattern recognition, momentum resolution and primary and secondary vertex measurements for charged tracks originating from the pp collisions and which exceed a nominal 0.5 GeV P_T threshold.

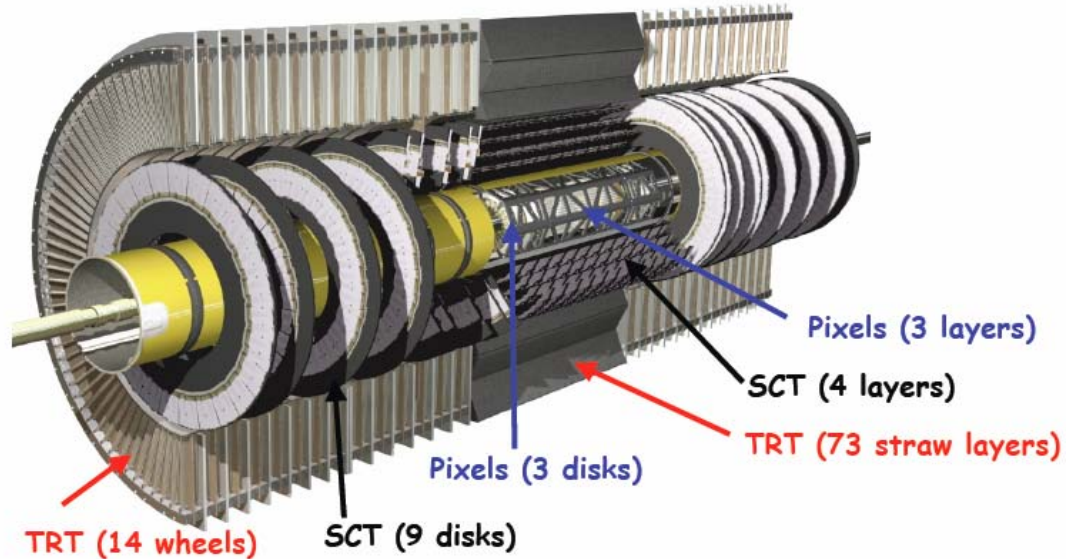


Figure 1: The ATLAS Inner Detector

The ATLAS ID is shown in Fig. 1. It comprises three independent but complementary sub-detectors and is contained within a cylindrical envelope of length 6.8m and radius 1.15m. Closest to the collision region is the Pixel Detector, which provides vertex measurements by the discrete space points provided by pixellated silicon detectors arranged in three concentric cylinders and three end-cap disks on each side. Surrounding the pixels is the SCT, constructed from stereo pairs of silicon micro-strip detectors arranged into four concentric cylinders and nine end-cap disks at each end. The outermost component is the Transition Radiation Tracker (TRT), providing continuous tracking from many layers of gaseous straw tube elements interleaved by transition radiation material.

This paper focuses on the commissioning of the SCT, including its final electrical performance after installation.

2. The SCT

The SCT incorporates 61m² of silicon micro-strip sensors and has ~6.1 million readout channels. It comprises 4088 silicon modules attached to cylindrical or disk-shaped carbon support structures, as illustrated in Fig. 2. The 2112 barrel modules [2] all have an identical

design and are attached to four 1.49m long concentric cylinders of radii 29.9, 37.1, 44.3, and 51.4cm. The 1976 end-cap modules [3] are fabricated in three different wedge shapes to accommodate the more complex geometry of the end-cap disks.

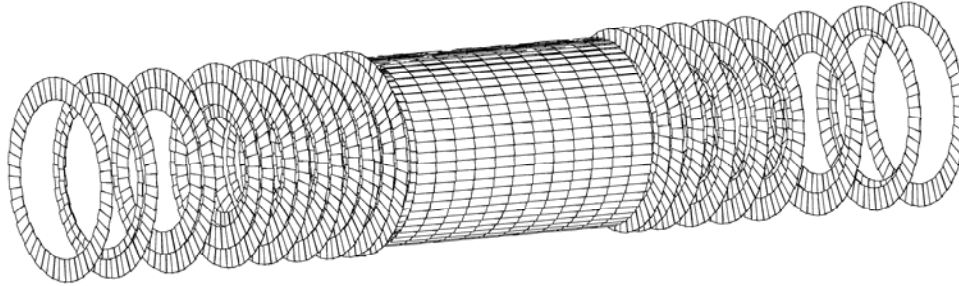


Figure 2: The geometrical layout of the silicon modules on the SCT.

There are nine end-cap disks located on either side of the barrels (designated end-cap A and end-cap C), positioned between 85.4cm to 272cm in Z from the collision point, and with a common outer radius of 56cm. Each disk has one, two or three rings of modules, and all modules within a ring are identical.

The carbon support structures also support the module services, including module cooling circuits, power supply tapes, optical fibres and packages for module communication. The SCT is cooled by an evaporative cooling system using C_3F_8 , which is shared with the pixel sub-detector.

2.1 The Silicon Modules

A photograph of a barrel module is shown in Fig. 3. The barrel and end-cap modules share common design features despite their different shapes.

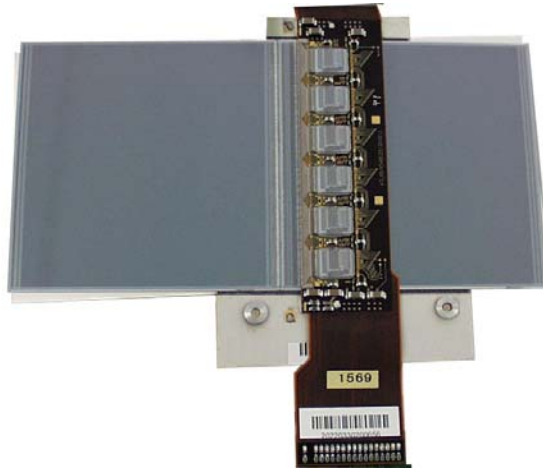


Figure 3: The SCT barrel module

They comprise wire-bonded pairs of single-sided p-on-n AC-coupled micro-strip detectors [4] glued back-to-back on either side of a thermal pyrolytic graphite (TPG) support. The TPG support conducts heat away from the sensors to cooling block contacts and provides the bias contact for the sensors. The sensor pair on each side is rotated relative to the other to form a 40mrad stereo angle. The 80 μm (45.7-74.8 μm) strip pitch of the barrel (end-cap) sensors and the stereo angle provide a tracking precision of approximately 17 μm and 580 μm in the direction orthogonal and parallel to the strips respectively.

There are 768 sensor micro-strips on each side of the module, and the readout is via 6 128-channel ABCD3TA [5] chips on each side. The chips are glued to a hybrid formed from a Cu/Polyimide flex-circuit and incorporating a carbon-carbon substrate for rigidity and thermal conductivity. For the barrel modules, the hybrid forms a bridge above the surface of the sensors, and the chips are wire-bonded down to the sensor strips close to the centre of the module. For the end-cap modules, the bridge structure is not used and instead the hybrid is located at one end of the module.

2.2 Readout Architecture & Timing

The ABCD3TA is an Application Specific Integrated Circuit (ASIC) chip fabricated in radiation hard DMILL technology. It uses a binary readout architecture, whereby the front end signal from each module channel is amplified, shaped and then applied to a comparator which provides output-high for the time duration where the shaped signal exceeds a programmable threshold. The output of the comparator is latched into a 132-deep pipeline array by the 25ns (40MHz) LHC clock to await the ATLAS level-1 trigger decision. A 20ns front end shaping time ensures that the comparator output is high for one or two consecutive clock cycles if the signal is generated by a minimum ionizing particle. On receipt of a positive level-1 trigger decision, up to three consecutive bins in the pipeline are read out. The level-1 trigger latency is finely tuned to ensure the three read bins match 01X (no hit in first bin, a hit in the middle bin, and optionally a hit in the third bin).

The read out on each side of the module is independent, referred to as 'link 0' and 'link 1'. Of the six chips on each side, one is designated as a master. Zero-suppressed data is passed in turn from the furthest slave chip to the master chip using token passing, and from there to the off-detector electronics via optical links[6]. In the event of a chip malfunction, the neighbouring chips can be electronically configured so that the token bypasses that chip. This results in the loss of 128 channels, instead of all 768 channels from that link.

2.3 Module Communication & Powering

Fig. 4 shows a schematic illustrating the module powering and communication scheme. Module powering is provided by the power supplies of the Detector Control System (DCS) [7], comprising 88 power supply crates housed in 22 racks. Each crate provides the full power

supply services for up to 48 modules, via twelve 4-channel low-voltage (LV) cards and six 8-channel high-voltage (HV) cards. The LV cards provide all the programmable voltage supplies necessary for both ABCD chip operation and on-detector optical communication components. The HV cards provide a programmable voltage supply of up to 470V for the module sensors.

Optical links provide the communication between the module and the off-detector electronics. An opto-package connects to each module. It contains a *p-i-n* diode to receive the Timing, Trigger and Control (TTC) optical signals, and two Vertical Cavity Surface Emitting Lasers (VCSELs) for each readout link to transmit the module chip data.

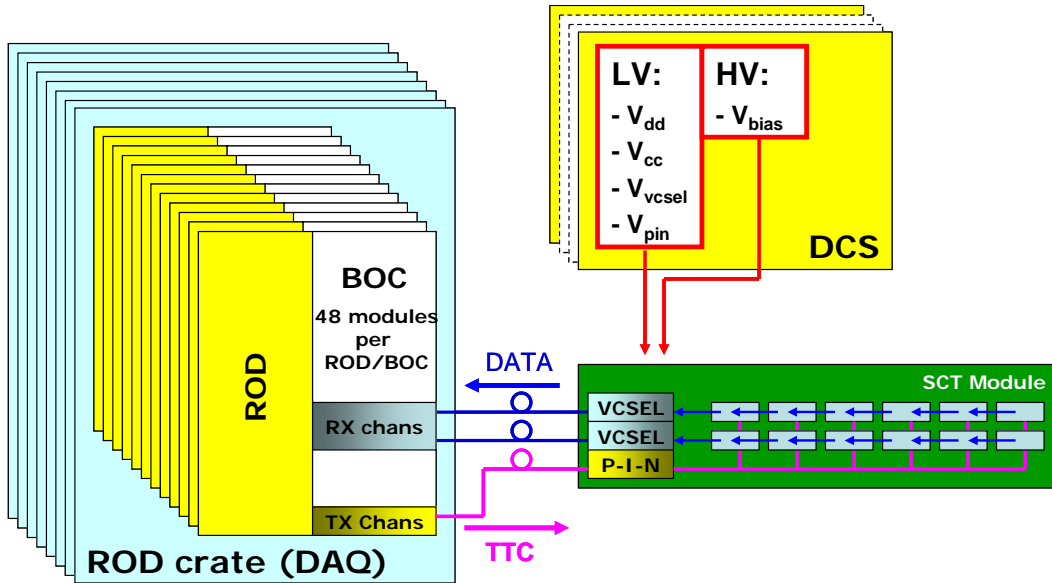


Figure 4: Schematic showing the module powering and communication scheme.

The Back of Crate card (BOC) is part of the SCT Data Acquisition System [8] (DAQ) and acts as the optical interface between the modules and the off-detector electronics. It interfaces the Readout Driver Module (ROD) to up to 48 modules. The ROD is responsible for module configuration, trigger propagation and event data formatting, as well as module calibration and monitoring. There are a total of 90 ROD/BOC pairs housed in 8 9-U VME crates.

Redundancy options are available in the case of broken optical fibres or damaged optical components. In the case of a damaged data fibre or non-functioning VCSEL, the hybrid can be electronically configured so that the master chip can be by-passed and the data routed through the functioning link as illustrated in Fig. 5(a). However this results in the loss of the 128 channels from the bypassed master chip. If the non-working link was discovered at an early stage of the SCT assembly, when the module hybrid was still physically accessible, then a manual modification of the hybrid could be made so that the master chip data is routed behind the slave chip of the same link, as illustrated in Fig. 5(b). In this case, no channels are lost.

Finally, in the case of a broken TTC fibre or a damaged *p-i-n* diode, a bypass mechanism on the optical package can be electrically activated such that the TTC signal is

obtained from the adjacent module. This mode of redundancy potentially saves the loss of all 1536 channels from an entire module.

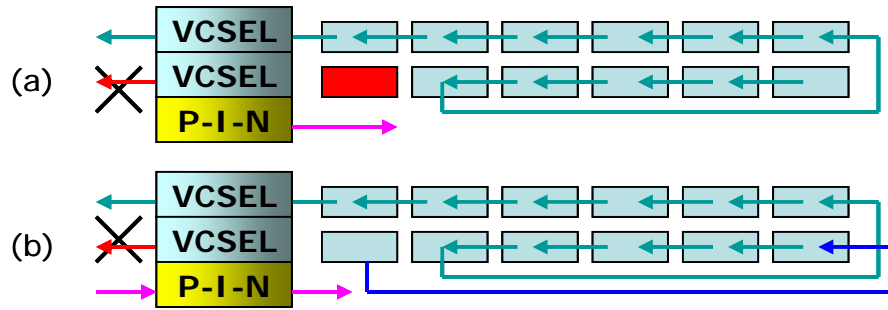


Figure 5: Redundancy options in the case of a broken data fibre or non-functioning VCSEL.

3 Assembly and Commissioning

The assembly and commissioning schedule for the SCT barrels is summarized by the flow chart in Fig. 6. The chart does not include the 5-year (2001 to 2005) programme of procurement and assembly of the sensors, chips and hybrids to modules, which was managed by a large number of SCT institutes and is covered in detail elsewhere [3][4].

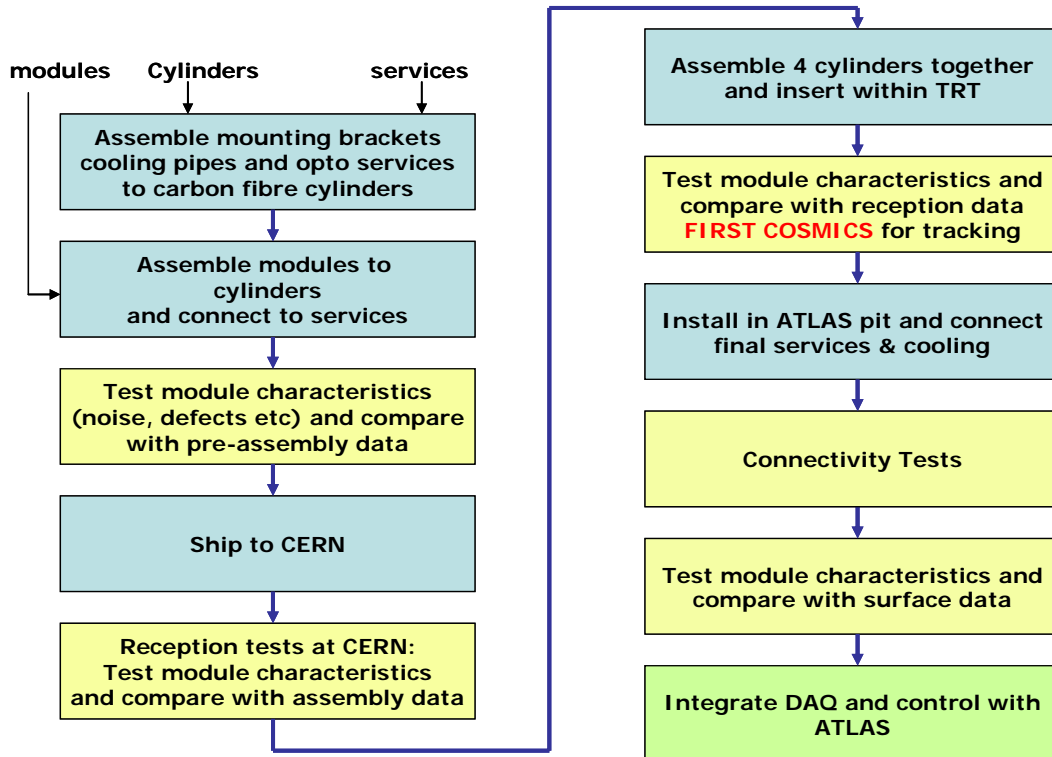


Figure 6: Steps of assembly and commissioning of the SCT barrels

3.1 Barrel and End-Cap Assembly

Modules were assembled to barrels by robot [9] at Oxford, and manually to end-caps C and A at Liverpool and NIKHEF, respectively. Each assembly site was equipped with an evaporative cooling plant, power supplies and a DAQ system to enable modules to be powered and characterized. Due to the tight overlap of modules, they were tested in small numbers immediately after assembly to ensure that modules could be removed and/or repaired if necessary before being obscured by subsequent module mounts.

Barrel assembly started in August 2004 and was completed by August 2005. After a characterization of the full barrel, each assembled barrel was shipped individually to CERN. In contrast, the end-cap disks were assembled together at the module assembly site, and the full 9-disk end-cap was then shipped to CERN.

3.2 CERN Reception Tests

Two of the four barrels and each of the end-caps were extensively tested at the surface reception building at CERN to confirm that there had been no deterioration in module electrical performance as a result of the transport to CERN. This phase of testing also provided a valuable opportunity to test the final DAQ and power supply hardware, and to evaluate the uniformity and stability of the cooling system, which matched closely the final system to be used in the ATLAS cavern.

The four barrels were subsequently assembled together, before insertion within the TRT barrels. The combined SCT and TRT assembly provided the first opportunity to search for evidence of cross-talk between the sub-detectors, and to time in for tracking with cosmic rays. The CERN test system had limited infrastructure (enough hardware to power and test one full barrel), so a segment of the four SCT barrels equivalent to approximately one quarter of all four barrels was cabled and powered together with a 1/8 segment of the TRT. Three planes of scintillators were used (one above the TRT and two below, sandwiching the concrete flooring) positioned in line with the instrumented areas as show in Figure 7(a), to generate a trigger for cosmic rays.

A simple but fast and effective strategy for timing in the SCT with cosmic rays was adopted [10]. The number of coincidental hits on each side of a module was counted as the trigger latency was gradually scanned in steps of 25ns, until a peak was observed in the three consecutive bins sampled in the ASIC pipeline. Once the peak was established, the trigger latency was further scanned in finer steps of 2ns until the relative occupancies of the three bins were optimized as close as possible (given the 25ns jitter of the trigger within the clock cycle) to 01X.

About 450K cosmic ray triggers were taken with the SCT/TRT combined barrels, and a similar number were taken with the SCT/TRT combined end-cap C. The hit efficiencies [11] for the SCT barrels exceeded 99%, as illustrated by Fig. 8.

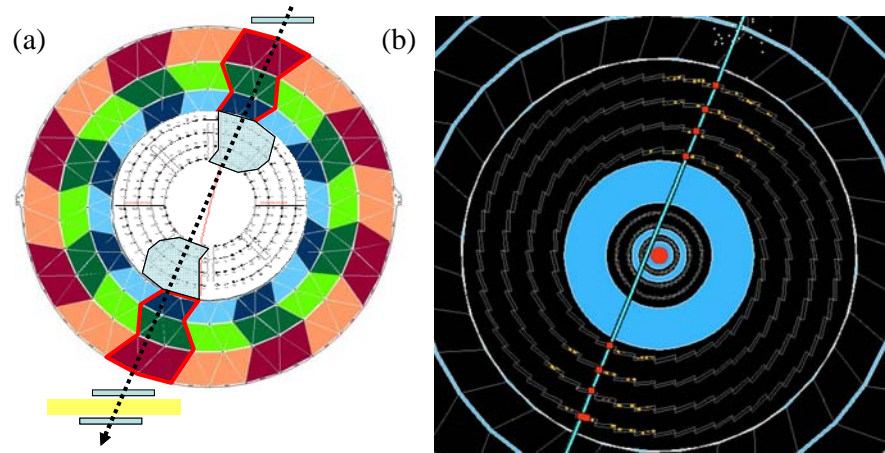


Figure 7: Cosmic ray setup with the combined SCT/TRT Barrels. The instrumented regions of the SCT and TRT are outlined in the schematic in (a). Hits in the four SCT barrels triggered by scintillator coincidence and the reconstructed track are shown in (b).

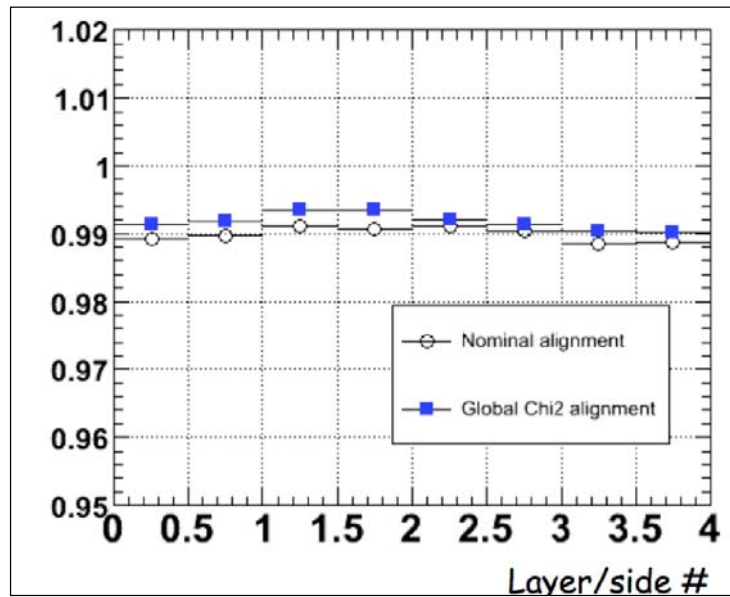


Figure 8: SCT Barrels hit efficiencies from reconstructed tracks

In addition to the cosmic ray data, noise data were also taken to search for evidence of cross-talk between individual SCT barrels/disks and between the SCT and TRT. No evidence of

cross-talk was found, and no deterioration in electrical performance was observed after insertion within the TRT, compared to data taken from single barrels and single disks.

3.3 Commissioning Phases in the ATLAS Cavern

There were three sequential phases to commissioning the SCT following installation in the ATLAS cavern:

1. Verification of the electrical connections by a cable test kit. Each LV card in the power supply crates was replaced by a simple feed-through card to enable a direct measurement of continuities/resistances and thereby verify the connection to the unpowered module. This test highlighted physical connection problems (eg open circuits due to unseated connectors, short circuits due to pinched wires etc) between the power supply crate and the module, but not mapping errors. Of the 2112 barrel modules, several problems were discovered and all were corrected, apart for one module which had an inaccessible broken HV return line.
2. Powering of the modules to verify electrical functionality and check mapping for both electrical and optical connections. In this phase, modules were powered in small groups at a time. Clock and command signals could be sent optically to individual modules to verify that the data returned to the BOC on the correct data fibres. *P-i-n* currents on the receiving module's opto-package, and an optical threshold scan on the receiving BOC, provided reliable indicators of fibre misalignment or dirt at the fibre patch panels. In the cases where no light was received by the module, or no light received by the BOC, the redundancy options listed in Section 2.3 were applied to recover the defective module or link.
3. Full electrical characterisation of the modules, to check for any deterioration in module performance, eg noise increase due to inappropriate grounding.

At the time of submission of this paper, all 3 commissioning phases had been completed for the SCT barrels, but unforeseen problems with the SCT cooling system had prevented any electrical tests of the SCT end-caps.

3.4 Electrical Results

All electrical data presented in this Section refer to the barrels only. Phase 2 of the commissioning yielded 25 non-working data links for the barrels (including one 'slow turn-on' [6] VCSEL), of which 15 had been known prior to installation in ATLAS. Most of these new defective links were due to broken fibres as a result of the installation. The redundancy scheme illustrated in Fig. 5 was applied for these links. In 13 out of the 25 cases, the redundancy mechanism resulted in the loss of data from the master chip of the defective link (as discussed in Section 2.3), resulting in a loss of 13 out of a total of 25344 chips. There were a total of 6

defective TTC connections, but all 6 modules were recovered by using the redundant TTC data from the neighbouring module.

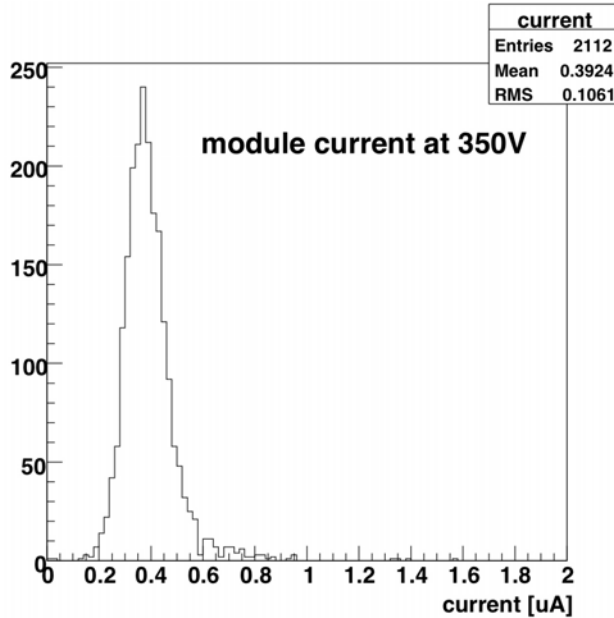


Figure 9: Module currents at 350V bias at 25°C

The module currents at 350V are shown in Figure 9, showing an average of 390nA at 25°C. Of the 2112 modules, one module cannot be operated due to the broken HV line, and one has abnormally high current ($\sim 4\mu\text{A}$ at 300V). The typical module temperature variation, with the cooling plant operational with $\sim 10^\circ\text{C}$ on the cooling pipes, is shown in Figure 10(a). Under these conditions the module temperatures are observed to be $27.1 \pm 1.0^\circ\text{C}$, and the temperature difference between the two sides of the module $0.3 \pm 0.7^\circ\text{C}$ as shown in Figure 10(b).

Electrical tests on a sub-sample of 2092 barrel modules revealed a total of 9946 non-working channels (0.3% of the total from 2092 modules), including the 1536 channels of the module with the broken HV line, and the 1664 channels lost as a result of bypassing 13 master chips by the redundancy scheme.

Average chip ENC noise for the four barrels is shown in Figure 11, showing a uniform noise distribution of $\sim 1700 e^-$ across all four barrels for a module temperature of $\sim 29^\circ\text{C}$. Figure 12 shows the change in ENC noise in comparison with the temperature-corrected data taken from the single barrels before assembly. There is a modest shift of $\sim 60e^-$ which can be attributed to a combination of factors, including module biasing time and system-specific offsets.

Noise occupancy for the barrels (the mean occupancy of individual channels at a nominal 1fC threshold due to noise alone) was measured at $\sim 7 \times 10^{-5}$, approximately an order of magnitude lower than the SCT specification of $\sim 5 \times 10^{-4}$.

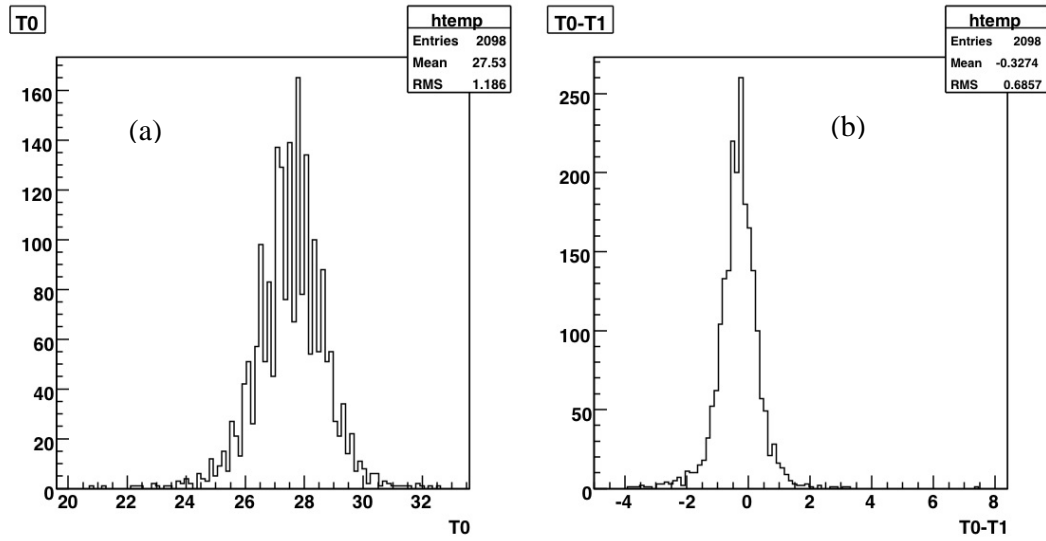


Figure 10: (a) Module temperatures and (b) the difference in temperature between the two sides of the module with cooling plant operational and 12°C on the cooling pipes.

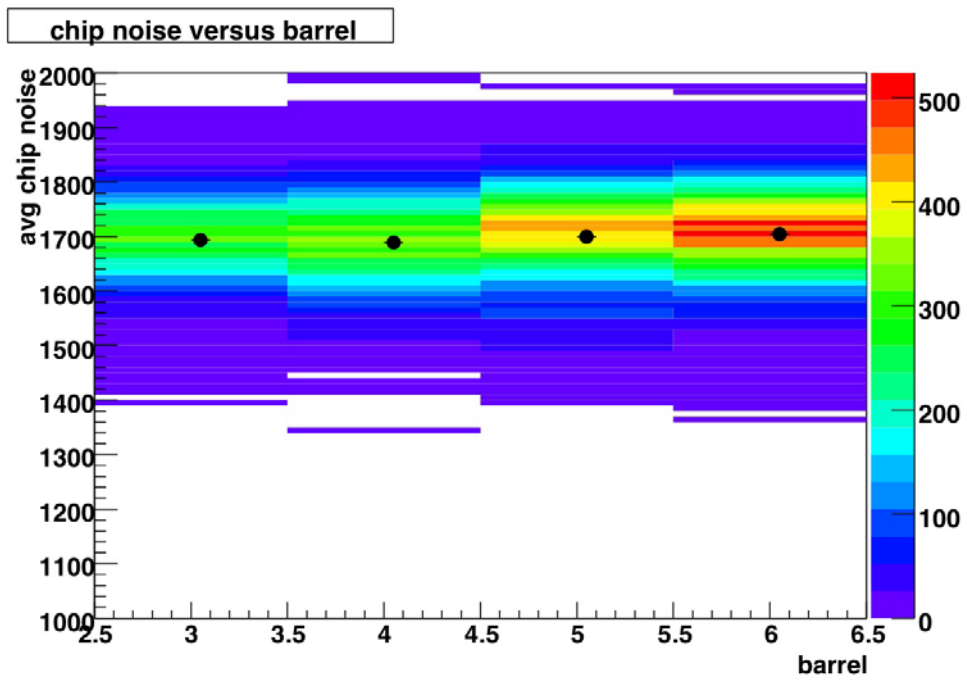


Figure 11: Mean ENC noise per chip for all four barrels.

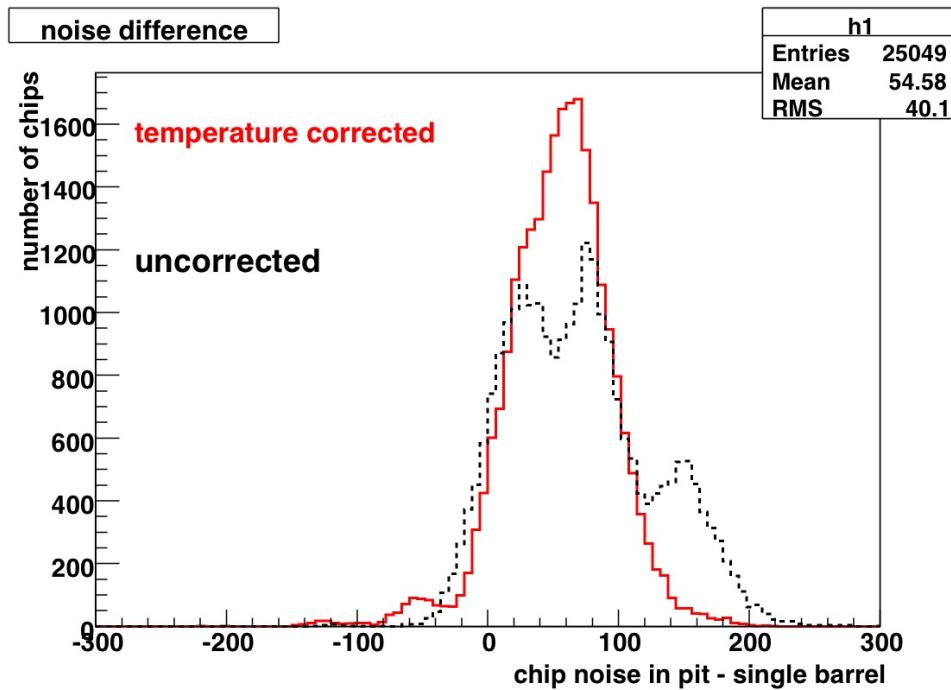


Figure 12: Noise difference between final electrical data and temperature-corrected single barrel data (solid line), and uncorrected data (dashed line).

4 Conclusions

The SCT is fully installed in the ATLAS cavern, and all electrical and optical connections have been tested and verified. A small number of optical links were lost during the installation program, but any channel losses were minimised by application of the redundancy schemes inherent in the SCT design. The SCT barrels have been electrically tested, and the number of defective channels is 0.3% of the total, well within the 1% specification. The chip average ENC noise is a uniform $\sim 1700e^-$ at $\sim 29^\circ\text{C}$ across all four barrels, and there is no evidence of cross-talk between SCT components or between the SCT and TRT. First attempts at tracking with cosmic rays yielded a hit efficiency of $>99\%$ from reconstructed tracks.

The SCT commissioning is expected to complete by the end of 2007, and further commissioning and integration into ATLAS is well advanced in preparation for the first collisions anticipated in 2008.

References

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