Tests and Final Integration of the ATLAS Semiconductor Tracker

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Abstract— The Silicon Tracker (SCT) is part of the Inner Detector at the ATLAS experiment at CERN. Its basic building blocks are 5 different types of silicon strip modules. In total more than 15000 p-on-n single-sided silicon strip sensors of an area of about 61 m² were used to produce 4088 SCT modules. An overall module production yield of 92% could be achieved, where the silicon modules comply with the tight electrical, thermal and mechanical specifications. The macro-assembly of 2112 barrel modules to the four barrel support cylinders was successfully carried out. The nine disks of one endcap are fully populated with 988 modules, and for the second endcap more than 50% of the modules are already mounted. Test results operating complete barrels will be presented as well as a description of the test setup. The different integration steps of the SCT with the surrounding Transition Radiation Tracker (TRT) will be explained. The installation of SCT and TRT into the ATLAS pit will happen during 2006.

Fig. 1. Schematic drawing of the SCT. The barrel part is 1.53 m long and consists of four concentric barrel layers at increasing radii: B3, B4, B5 and B6. The two SCT endcaps are formed by 9 disks each. On the barrels 2112 identical silicon strip modules are mounted, whereas 1976 silicon modules of 4 different sensor geometries are required to cover the forward and backward direction. The diameter of the SCT is 1.2 m and its total length amounts to 5.6 m, covering a pseudo-rapidity η up to $|2.5|$.

I. INTRODUCTION

WITH 46 m $\times$ 22 m ATLAS will be the largest detector at the large hadron collider (LHC) at CERN. Detector construction is in its final phase with the first particle beam expected in 2007. The SCT is part of the ATLAS central tracking system, the Inner Detector, located inside a 2T solenoid, between the innermost pixel layers and the TRT [1]. The SCT consists of 4 cylindrical concentric barrel layers and 9 disks in the forward and backward direction forming endcap A and C. Barrels and disks are populated with 4088 SCT modules, which comprise over 15000 p-on-n silicon strip sensors [2]. Fig. 1 shows the basic layout of the SCT.

The focus has shifted from the production and characterization of single components like support structures, silicon modules or power supplies and data acquisition (DAQ) modules towards more general system aspects. Together with the software preparations, the assembly of barrels, endcaps and the integration into the Inner Detector as well as its commissioning inside the ATLAS cavern represent the current challenges.

II. ASSEMBLY OF THE SCT BARREL

In the barrel part of the Inner Detector, barrel layers 3-6 follow three pixel layers (0-2). The aim of the SCT is to provide four precision space points per track within the high track density close to the interaction point, with as low a material budget as possible and in a harsh radiation environment (expected 1 MeV neutron equivalent fluence of up to 2×10^{14} n/cm² during the detector lifetime of 10 years).

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A. The SCT barrel module

To fulfill the above requirements, silicon strip modules have been designed. A barrel module consists of 2 pairs of single-sided AC-coupled p-on-n strip sensors with polysilicon bias resistors produced by Hamamatsu Photonics, Japan, glued at a stereo angle of 40 mrad back-to-back onto a TPG (thermal pyrolytic graphite) baseboard [3]. Each sensor has an area of 63.56 $\times$ 63.96 mm², a strip pitch of 80 μ m, and the sensor pair is connected in series via wire bonds, resulting in a total strip length of 126 mm.

The 1536 strips per module are read out with 12 128-channel ASICs (6 for the top sensor pair and 6 for the bottom pair) called ABCD3TA [4]. The ASICs were designed in the radiation-hard BiCMOS DMILL process and comprise preamplifier, shaper, discriminator and a digital data buffering circuitry. To guarantee a uniform detector response with this binary readout architecture, the thresholds can be equalized with a 4-bit DAC per channel, and each channel can be electrically characterized using the internal charge injection circuit. The ASIC was optimized for the 40 MHz LHC bunch crossing rate and the maximum first level trigger rate of 100 kHz.

The ASICs are mounted on a 4-layer copper-polyimide flex circuit laminated to a carbon-carbon substrate to transport the produced heat effectively to the cooling area [5], [6]. This hybrid wraps around the silicon sensors, using only 2 copper layers in the bending region. The hybrid distributes high and low voltage to the modules and includes one thermistor per side for temperature monitoring. The ASICs for optical readout are mounted on kapton tapes called 'dog-legs' that are connected to the low-mass tapes serving the module with

power.

Finally, the cooling connection onto a Cu/Ni cooling pipe is provided via a BeO facing on the TPG baseboard.

The production of these barrel modules took place at several clusters (Japanese, Scandinavian, US and UK cluster) and followed very strict quality assurance procedures. Components and final modules had to pass various electrical and mechanical tests as well as long-term tests in order to be accepted. Some of the mechanical tolerances are as small as $5\text{ }\mu\text{m}$ [7]. The SCT barrel module production finished in December 2004. An overall yield of about 91% could be achieved. The module performance has been evaluated during several test beams, for irradiated and non-irradiated modules (see for example [8]).

Fig. 2. Photograph of barrel 6, the largest of the four SCT barrels. 672 silicon strip modules were mounted with robots on this barrel.

B. The SCT barrel macro-assembly

For the four support cylinders carrying the barrel modules and all the services, a carbon fiber - honeycomb sandwich material was chosen thanks to its long radiation length, radiation hardness, low outgassing, mechanical stiffness and high dimensional stability with respect to temperature and moisture. After having added mounting pads and brackets for services and modules and after metrology, the barrels were shipped from Switzerland to the Rutherford Laboratory (RAL), where all the services were mounted (grounding tapes, cooling pipes, detector control sensors, alignment components, low mass tapes and optical fiber harnesses).

The macro-assembly of the modules to the barrel structures took place at Oxford University [10]. In total 2112 silicon modules had to be mounted on four cylinders. For hermetic coverage neighboring modules had to overlap with a clearance of 1 mm. Moreover the mounting precision had to be on the order of $30\text{ }\mu\text{m}$ and the modules to be screwed to the brackets, avoiding at each step to damage sensors or bonding wires. Due to these constraints a robot was developed for this operation [9]. With this robot up to 36 modules could be mounted per day. Fig. 2 shows a photograph of barrel 6.

Once fixed on the barrels, the modules were tested so that they could be replaced in case of a serious problem. For the tests at Oxford evaporative cooling plants based on C_3F_8 or C_4F_{10} were used, as well as final power supplies and readout hardware. Dedicated DAQ software was developed [11], and a detector control system (DCS) guaranteed the safe operation of the modules [12]. As soon as a barrel has been fully assembled with modules and passed all the acceptance criteria, it was put into a storage and transport container and shipped to CERN in a truck with temperature & humidity control and a shocklog monitor.

Upon its arrival at CERN, the barrels are installed in a clean-room, visually inspected, the cooling circuits leak tested and the barrels prepared for the reception tests.

III. ASSEMBLY OF THE SCT ENDCAPS

A. The SCT endcap modules

The 18 disks of endcaps A and C are made of carbon fiber covered with up to 132 SCT endcap modules arranged in 3 rings: the 'outer' and 'inner' rings on one side of the disk with 52 and 40 modules, respectively, and a 'middle' ring of 40 modules on the other side [3], [13]. This arrangement together with the overlap of neighboring modules allows hermetic coverage.

Like for barrel modules, the SCT endcap modules have been produced and quality controlled at various clusters all over the world (central European, CERN-Switzerland and UK-Valencia cluster). Their construction principle is very similar to the barrel one with a few exceptions. Due to the circular geometry of the endcap disks, inner, short middle, long middle and outer modules use wedge-shaped silicon sensors of different dimensions, with a strip pitch varying between 55 to $95\text{ }\mu\text{m}$. Roughly 75% of the sensors were produced by Hamamatsu Photonics and a quarter from CiS, Erfurt, Germany. The modules are read out with the same ASICs as the barrel modules, but the ASICs are mounted on a different hybrid, sitting at the end of the module, consisting of a 6-layer flexible circuit with copper traces sandwiched between polyimide layers and laminated onto a carbon-carbon substrate [13]. Unlike the barrel modules, this hybrid carries two more chips, DORIC and VDC [14], used for the optical readout and to provide clock and command signals (for barrel modules, these chips are mounted on the 'dog-legs'). Therefore, three optical fibers, which are terminated by an opto package containing a PIN diode and two VCSELs [15], are connected to each module. All SCT modules have redundant connections between neighboring modules that allow a module to be configured and read out by its neighbor in case of a broken fiber or similar problem (see Fig. 3). Electrical test results of these modules can be found in reference [16]. 1976 modules (plus contingency) have been produced in total with a yield of 92.9%.

Fig. 3. Detail of disk 6A showing outer and inner endcap modules (the uncovered space between the two rows is filled by middle modules mounted at the back of the disk). On the hybrid the main cooling block is visible as well as the 6 readout ASICs that read out the strips of the top sensors. Power tape connections can be seen as well as the opto package with the three opto fibers and the redundant links between neighboring modules.

B. The SCT endcap assembly

The service assembly to the endcap disks took place at RAL and NIKHEF. The mounting scheme of the SCT endcap modules for cooling purposes is different compared to the barrel modules: each module has two mounting surfaces, one at the main cooling block on the hybrid and the other one on the far-end cooling block at the end of the sensors. These precision mounting pins have a tolerance in $r-\phi$ of $100\text{ }\mu\text{m}$. The connection to the cooling blocks is made via AlN facings to the TPG spine. The cooling loops are arranged in quadrants providing cooling power for up to 13 modules.

Module assembly to the disks takes place at the University of Liverpool for endcap C and at NIKHEF for endcap A. Modules are mounted manually using precision tooling and two cameras. In July 2005 all 9 disks for endcap C have been equipped with modules and tested. For endcap A more than 50% of the modules have been mounted and tested by the end of October 2005.

Once disks are completed, they are positioned with special tooling into the endcap cylinder. Services are then added to the cylinder and connected to the disks. This procedure is currently underway at the two sites. The endcaps will be shipped to CERN in early 2006 for final assembly and reception tests. At CERN two parallel setups are under preparation to perform reception tests for the two endcaps.

IV. TEST RESULTS WITH SCT BARRELS

Going from small systems like single silicon modules to larger systems like a whole barrel or the complete SCT or inner detector, it is always wise to monitor the detector performance. Scaling might for example result in bad thermal performance or an important increase in noise. Therefore it was crucial to make a complete set of measurements for fully mounted barrels. At Oxford University barrels 3, 4 and 6 were tested as a whole and at CERN all modules of barrels 3 and 5 were

Fig. 4. Input noise of the full barrel 5 (576 silicon modules) tested at CERN. The average temperature on cooling pipe outlets and hybrids was $4.5\text{ }^{\circ}\text{C}$ and $16.5\text{ }^{\circ}\text{C}$, respectively. An average ENC noise of $<1600\text{ e}^{-}$ was measured.

read out at once. The barrel modules were cooled using a C_3F_8 evaporative cooling system (and C_4F_{10} for the warm tests at Oxford). Due to the many connections per cooling loop, separate leak tests were carried out prior to the readout tests. In the end stable thermal running conditions could be achieved. The modules were powered using final high and low voltage custom power supplies. They provide high voltage and low voltage for the silicon modules, voltage for the PIN diodes and the VCSELs and monitor the temperature on the hybrids. The detector control system can monitor and control the different parameters of these power supplies, and a hard-wired interlock system automatically switches off power to certain groups of modules in case of an over-temperature. The DCS monitors as well the >200 sensors mounted at different locations on each barrel like humidity sensors or temperature sensors on the outlets of each cooling loop, and it archives the data [12]. Control streams and data processing were provided through final SCT off-detector hardware consisting of read-out drivers (RODs) and back-of-crate cards (BOCs). Each ROD can control and monitor 48 SCT modules.

During the full barrel readout tests, all digital and analog functions of the SCT modules have been evaluated for each channel like threshold, gain, offsets or noise (see Fig. 4). The results of these tests can be summarized as follows:

- Simultaneous stable operation of up to 1 million readout channels was achieved.
- Stable thermal operation of full barrels during all the measurements; the measured rms temperature spread of all modules on a barrel (hybrid temperature) was smaller than $1\text{ }^{\circ}\text{C}$.
- Reliable operation of DAQ, DCS and interlock system.
- All SCT module currents were smaller than $1\text{ }\mu\text{A}$ at 150 V bias during the final cold test operation (see Fig. 5).
- More than 99.7% of all SCT barrel channels were fully operational.

V. ATLAS INNER DETECTOR INTEGRATION

A. 4-Barrel Integration

One crucial step of the Inner Detector Integration that takes place in a surface building at CERN was the assembly of the

Fig. 5. The average B5 detector current for 150 V detector bias voltage and the same running conditions as for the left measurement was as low as 150 nA.

four individual barrels and the thermal enclosure to form the complete SCT barrel. For this purpose a complex mechanical tool set was prepared based on a rail system and sliding beams. In July 2005 the insertion of the largest barrel into the thermal enclosure started (see Fig. 6 left).

Each barrel arrives at CERN supported by a spindle on

Fig. 6. Left: Photograph at the start of the B6 insertion procedure into the thermal enclosure. Thermal enclosure, B6, the rail system and the sliding beam can be seen. Right: Insertion of the last barrel, B3.

pedestals inside an inner container. It has to be transferred to a platform that moves it transversally on a rail system. Once in its final position, the spindle gets attached to the sliding beams, transferring the barrel weight from the platform that gets unmounted to the sliding beams. Fine alignments are possible for most of the parts.

To prepare the integration of B6, the thermal enclosure was mounted inside a so-called cradle and 'rolled over' B6. The clearance between the low mass tapes sticking out from the barrel modules and the flange of the thermal enclosure is 5 mm. When this operation is accomplished, the barrel is locked into place.

The same procedure is followed for the integration of the other barrels, from the largest down to the smallest one. Each time before a new barrel gets inserted, the spindle has to be dismantled and all the services of the previous barrel have to be unfolded and fixed to the temporary service support structure on the cradle (compare Fig. 6).

The last barrel was successfully inserted end of September 2005.

To finish the 4-barrel integration with the thermal enclosure,

Fig. 7. Schematic drawing of the barrel SCT insertion into the TRT. The SCT sits in its cradle with the services arranged in the ISSS and the cradle fixed on a cantilever. The TRT barrel is inside the inner detector trolley and will roll on rails over the SCT.

the bulkhead has to be mounted and sealed at both ends. All low mass tapes, readout and alignment fibers, DCS wires and cooling capillaries have to be mounted and sealed inside their respective grommets, a very delicate operation. The pixel supports have to be installed as well as mechanical handling points. Finally the inner thermal enclosure has to be inserted and the thermal enclosure end-covers mounted.

B. Barrel SCT-TRT Integration and Combined Tests

Once the 4-barrel assembly finished, the integration procedure of barrel SCT with barrel TRT can start. The tooling is again based on a similar concept: a rail system and cantilever tools. To prepare the insertion, the services have again to be re-arranged. An Insertion Service Support Structure (ISSS) will be fixed onto SCT cradle extensions and all the SCT services transferred to the ISSS. Wheels will be mounted on the cradle in order to be able to roll it to the insertion area in the CERN surface building. On the other side the TRT will move onto the inner detector trolley. This trolley is then 'rolled over' the SCT (see Fig. 7). This operation will take place in December 2005.

After the integration of the SCT with the TRT common tests will be performed. This will be the last chance for small changes or improvements before the installation in the pit and is the first time the two detectors will operate together in their final mutual position. There has been a combined test beam in 2004 where slices of each detector took data simultaneously, but this configuration was not adequate to study for example common mode noise.

Therefore in January 2006 it is planned to cable up two opposite phi-sectors of SCT and TRT. The main points of interest for these common tests are:

- Establish the first common SCT-TRT detector operation (e.g. cooling).
- Finalize and optimize the grounding schemes to minimize common mode noise.
- Investigate potential cross-talk between SCT and TRT services.
- Test the common DCS system.

- Exercise the common operation of the SCT and TRT DAQ system and add improvements.

In case no major problems show up, everything has been prepared to perform a common cosmics run. Scintillators will be added above and below the mentioned phi-sectors for triggering purposes. This phase will allow to study

- Stability of the system.
- Establish synchronous readout of SCT and TRT.
- Prepare software analysis tools: use of databases, data handling, online monitoring, offline analysis, archiving.
- Check the detector alignment in case enough statistics can be gathered.

The installation date for barrel SCT-TRT into the ATLAS cavern is May 2006. The pixel detector will be added later together with the beam pipe to complete the ATLAS Inner Detector.

In parallel to the work mentioned above a lot of effort has to be invested in the preparations for the commissioning of the detector in the pit. Thousands of cables have to be tested, connected to patch panels and each channel re-tested after the detector has been wired up. A functional cooling system and detector control system has to be assured as well in the new environment.

C. Endcap SCT-TRT Integration

As already mentioned, two complete SCT endcaps with 9 disks of endcap modules each will arrive at CERN. Visual inspection and leak and pressure tests will be performed. To allow parallel work it was decided to prepare two endcap tests systems for electrical tests. Each system will allow to connect all the DCS sensors and test one full disk at a time in the final hardware configuration.

After the reception tests, the SCT endcap will be transferred to a cantilever stand. The thermal enclosures will be fitted and all seals checked. The SCT will be aligned to the rail system and the TRT endcap mounted inside the inner detector trolley. Once again the principle of the trolley 'rolling over' the SCT in a controlled way will be applied (see Fig. 8).

This integration phase will be followed by a series of common readout tests similar to the barrel combined tests. It is planned to read out one quadrant of consecutive SCT-TRT slices.

VI. CONCLUSIONS

Over the last years more than 4088 barrel and endcap silicon strip modules have been produced. The module production teams achieved an overall yield of about 92%. The macro-assembly of modules to the four barrels was successfully terminated in July 2005, and the integration of the four barrels and the thermal enclosure is in its final stage. Readout tests of complete barrels have been performed at Oxford and CERN and prove that their thermal and electrical performance is conform to the specifications. More than 99.7% of all 3.2 million barrel readout channels are functional. The tests were realized

Fig. 8. Schematic drawing of the endcap SCT integration with the TRT. The SCT endcap is fixed at a cantilever stand. The TRT endcap is inside the inner detector trolley and will roll on rails over the SCT.

with dedicated detector control and data acquisition systems using final SCT power supply and readout modules. After the integration of the barrel SCT with the TRT common tests and a cosmics run are planned beginning of 2006. The assembly of the two endcaps is also well underway, and reception tests and the integration with the endcap TRT is under preparation at CERN. Installation dates for barrel and endcaps are May, July and August 2006, respectively. First ATLAS data taking with LHC collisions is expected in 2007.

REFERENCES

- [1] ATLAS Detector and Physics Performance Technical Design Report, *CERN/LHCC/99-14*, ATLAS TDR 14, 25 May 1999.
- [2] D. Robinson et al., Silicon microstrip detectors for the ATLAS SCT, *NIM A 485 (2002) 84-88*.
- [3] Y. Unno, ATLAS silicon microstrip detector system (SCT), *NIM A 511 (2003) 58-63*.
- [4] F. Campabadal et al., Design and performance of the ABCD3TA ASIC for readout of silicon strip detectors in the ATLAS semiconductor tracker, *NIM A 552 (2005) 292-328*.
- [5] Y. Unno et al., Application of Cu-polyimide flex circuit and Al-on-glass pitch adapter for the ATLAS SCT barrel hybrid, *NIM A 541 (2005) 286-294*.
- [6] T. Kondo et al., Construction and performance of the ATLAS silicon microstrip barrel modules, *NIM A 485 (2002) 27-42*.
- [7] J.N. Jackson, The ATLAS semiconductor tracker (SCT), *NIM A 541 (2005) 89-95*.
- [8] F. Campabadal et al., Beam tests of ATLAS SCT silicon strip detector modules, *NIM A 538 (2005) 384-407*.
- [9] S. Terada et al., Design and development of a work robot to place ATLAS SCT modules onto barrel cylinders, *NIM A 541 (2005) 144-149*.
- [10] G. Viehhauser, Macro-Assembly of the ATLAS Barrel SCT, *IEEE NSS Conference Records*, 16-22 Oct. 2004, pp. 1188-1191.
- [11] A. Barr, Calibrating the ATLAS Semiconductor Tracker Front End Electronics, *IEEE NSS Conference Records*, 16-22 Oct. 2004, pp. 1192-1195.
- [12] A. Sfyrila et al., The Detector Control System for the ATLAS Semiconductor Tracker Assembly Phase, *IEEE Trans. Nucl. Sci.*, vol. 52, no. 4, August 2005.
- [13] L. Feld, Detector modules for the ATLAS SCT endcaps, *NIM A 511 (2003) 183-186*.
- [14] D.J. White et al., Radiation hardness studies of the front-end ASICs for the optical links of the ATLAS SemiConductor Tracker, *NIM A 457 (2001) 369-377*.
- [15] A.R. Weidberg et al., The Production of the ATLAS SCT Optical Links, presented at the 11th Workshop on Electronics for LHC and Future Experiments, Heidelberg, Germany, 12-16 September 2005.
- [16] M. Mangin-Brinet et al., Electrical test results from ATLAS-SCT end-cap modules, *ATL-INDET-2003-004*.