Design and tests of a silicon detector module for ATLAS Semiconductor Tracker Endcaps


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The ATLAS Semiconductor Tracker (SCT) will be a central part of the tracking system of the ATLAS experiment. The SCT consists of 4 concentric barrels of silicon detectors as well as two silicon endcap detectors formed by 9 disks each. The layout of the forward silicon detector module presented in this paper is based on the approved layout of the silicon detectors of the SCT, their geometry and arrangement in disks, but uses otherwise components identical to the barrel modules of the SCT. The module layout has been optimized for excellent thermal management and electrical performance, while keeping the assembly simple and adequate for a large scale module production. This paper summarizes the design and layout of the module and present results of a limited prototype production, which has been extensively tested in the laboratory and testbeam.

Keywords: silicon strip detector, LHC, ATLAS experiment, radiation hardness, thermal management

1. Introduction

The ATLAS [1] Semiconductor Tracker (SCT) is part of the ATLAS Inner Detector system [2], which provides charged particle tracking in the center of the ATLAS experiment. The Inner Detector system (ID) consists of a hybrid-pixel detector in its center, followed by the SCT silicon strip detector and a gas straw-tube transition radiation detector surrounding the SCT. A typical track will generate 3 hit points in the pixel detector, traverse eight silicon strip detectors (to give 4 space points) and 36 straw tubes. The goal of the detector is to provide

- a hermetic coverage in a pseudo-rapidity range of |η| < 2.5
- an impact parameter resolution for high $p_T$ tracks of better than 11 $\mu$m in $r-\phi$ and 100 $\mu$m in $z$;
- a momentum resolution for isolated leptons of $\Delta p_T/p_T \approx 0.4 p_T$ (TeV) (the ID is located in a 2 T axial magnetic field);
- a low component mass to ensure a good tracker and electromagnetic calorimeter performance.

In addition to these performance requirements, the SCT has to cope with the environment in a high luminosity LHC experiment. The readout electronics must be fast (≤ 25ns shaping time), have low intrinsic noise and provide efficient signal processing. These electronics tasks have to be performed with minimal input power, typically 7 W total per SCT detector module (4.5 mW/channel) in a radiation hard layout.
One of the main technical challenges at LHC is the high radiation environment, with an expected fluence equivalent to $2 \times 10^{14}$ $1$ MeV neutrons/cm$^2$ in the case of the inner SCT layer for 10 years of operation. It is therefore crucial to demonstrate the radiation hardness of electronics and detectors as well as the overall module. To limit anti-annealing, which results from radiation damage to the bulk of the silicon sensors, the SCT will operate at an ambient temperature of $-7$ °C. To guarantee a stable and sufficiently cold operation of the detector for its entire lifetime, the modules have to have excellent thermal properties.

The large system size, 4088 detector SCT modules with a total of 61 m$^2$ silicon and 6.3 million readout channels, its very restrictive access and the expected lifetime of 10 years poses additional challenges for component and system reliability. An overview of the SCT system and integration considerations can be found in reference [3].

2. Module layout and performance requirements

The SCT consists of 4 concentric barrels at radii of 299 mm, 371 mm, 443 mm and 514 mm with a length of 1.53 m, and two endcap sections of 9 disks each. A schematic layout of the active detector part is shown in figure 1, where each “box” represents one detector module. The SCT is based on 5 different module types: one barrel module and four different forward module types, whose detector shapes vary with their different mounting radii. The SCT requires 2112 barrel modules and 1976 forward modules. On the forward disks, the modules are arranged in concentric rings around the beam axis at three different radii. To achieve a hermetic coverage across the disk, the forward module and silicon detector geometry varies for the three radii. Modules in the three rings are denoted as forward “inner”, “middle” and “outer” module.

Each middle and outer module is based on 4 single sided silicon strip detectors, where two on each side are daisy-chained to give 12 cm long strips. The detector pairs are then glued back-to-back at a stereo-angle of 40 mrad to provide two-dimensional position information in the detector plane. The inner module with 6cm long strips has only two sensors glued back to back. Each module has 768 active strips per side.

The layout of the forward silicon detector module presented in this paper is based on the standard layout of the silicon detectors for the forward SCT, their geometry and positioning on disks, but otherwise uses components similar to the barrel modules. We refer to this particular module design as “KB” module layout, which implements the electronics and hybrid of the barrel module [4] in the forward geometry. The electronics hybrid of the barrel module has been fully developed and showed adequate electrical and thermal performance. It carries the full front-end readout electronics of the module. The development of a fully functional hybrid, which performs to our stringent thermal and electrical requirements, is often complicated by the complexity and sensitivity of the readout electronics and is therefore a major technical challenge, which can result in numerous time consuming prototyping cycles. For those reasons it was deemed advantageous to study a module layout that is based on the forward module and silicon detector geome-
try but uses the electronic hybrid of the barrel modules. A functional design of this kind provided the SCT with a viable back-up layout in case unexpected problems would have been encountered during the prototyping of a dedicated forward hybrid.

2.1. Readout electronics

The detector strips are connected at one end through pitch adapters to the input of the ABCD3T readout chip, in a so-called "end-tap" geometry (six 128-channel chips per side), which are mounted on kapton hybrids with four copper conductor layers. The kapton hybrid is laminated to carbon-carbon support substrates, which provide mechanical support and remove the heat dissipated by the chips (approximately 7W per module).

The ABCD3T readout chip is produced in the radiation hard DMILL process. The input is based on a bipolar analog stage with preamplifier and shaper for each channel whose operation currents can be controlled through DACs. For calibration and module tests, each channel is equipped with a calibration capacitor which allows charge injection into the preamplifier. The shaper is followed by a comparator with adjustable threshold (one per chip) for sparsification. The DC offset of each channel can be adjusted with a 4-bit DAC in 4 selectable ranges to compensate for channel-to-channel variations. The binary output of the comparator is strobed into a 132-cell deep FIFO. Between the comparator and pipeline each channel can be masked off in case it is noisy. The back-end of the readout chip incorporates a de-randomizing buffer and data compression stage. The readout stage also has redundancy links built-in that allow to bypass a faulty chip without breaking the readout daisy-chain. Details on the chip architecture and performance can be found in reference [6] [7]. Each module is read out with its dedicated optical readout and control are implemented on a separate kapton tape. Each module is powered by its own independent power supply.

2.2. Silicon detectors

The SCT detectors are AC-coupled, single sided strip detectors based on p+ strip implants in a n-type silicon bulk [8]. The strip pitch on forward silicon detectors varies between 70 and 90 µm as they feature a constant φ-pitch of 161.5 µrad (outer module) and 207 µrad (inner and middle module). The strips are biased through polysilicon or implant resistors from a common bias line which surrounds all strips on a wafer. The detector edge and guard ring design varies depending on the manufacturer. Due to radiation induced changes of the bulk effective doping concentration, we require the detectors (and all related components on hybrid and supply system) to operate reliably up to 500 V. After irradiation we expect an operating voltage of approximately 350 V, with measured pre-irradiation full depletion voltages typically in the range of 60-80 V.

2.3. KB module layout

The KB module consists of 3 component groups: first the central "spine", which provides cooling for detectors and hybrid as well as serving as structural support; second the detectors which are glued to the spine, and third the electronics hybrid which is also glued to the spine. Figure 2 shows an exploded view of the module and its components together with a photograph of a module. The module is mounted and cooled at the rear end behind the hybrid. The cooling contact is 7mm wide and extends over the full module width. The total module length is 156mm.

The spine consists of a long central piece of thermal pyrolitic graphite (TPG) (part 1a), below the detector and hybrid, and two small pieces of TPG (part 1b), in the area where the hybrid is attached to the spine. The TPG pieces provide the main cooling to detectors (part 1a) and hybrid (part 1b).

Heat generated in the irradiated detectors due to their high leakage current has to be efficiently dissipated in order to avoid thermal run-away. The central TPG (1a) carries the heat from the detectors to the cooling contact with an in-plane heat conductivity of approximately 1700 W/mK.
Figure 2. Schematic layout and photograph of a KB outer module. Labels are used for part reference in the text.

It is wedge shaped to have less thermal resistance close to the cooling point, as the heat load carried by it increases gradually from the module top end to the end closer to the cooling contact. As it is electrically conducting, we also use it to distribute the backplane voltage to the four detector backplanes. Electrical connection between the TPG and detector backplane is made via conductive glue. All TPG pieces are encapsulated in a $5\mu$m thick layer of polyimide. Openings in the encapsulation of the center TPG are made at the position of electrical connection to the detector backplane.

The small TPG pieces (1b) remove the heat from the hybrid and conduct it to the cooling contact. The central TPG is separated from the smaller TPG pieces by two "L"-shaped parts of PEEK (part 1c). They thermally separate the central TPG from the hybrid TPG pieces and also serve as structural reinforcement between spine and detectors. We need to achieve maximum thermal separation between detector and hybrid in order to avoid that the electronics heats the detectors. The "L"-piece also carries a conductor line which brings the backplane bias voltage from the hybrid to the detector backplane of the closer detector pair and central TPG. At the place where the detectors are daisy-chained and at the far detector end, the detector edges are supported by pieces of AlN ceramics (parts 1d). This is required for bonding and a second module mounting point. All central pieces (parts 1a-d) have a nominal thickness of 450 $\mu$m.

The central spine pieces are sandwiched at the cooling and mounting point by two "U"-shaped pieces of AlN (parts 2a). Their function is (a) to interlink the other spine pieces (1a, 1b, 1c), (b) to provide mechanical stiffness to the spine, (c) to serve as the main cooling contact and mounting surface of the module, (d) electrically insulate the spine from the hybrid, the cooling and mounting points, and (e) to provide a flat surface to glue the hybrid to the spine on its narrow forward extensions. They are also the main handling point of the module during assembly and test. The AlN pieces are nominally $250\mu$m thick. At the top and bottom end of the module aluminum washers are glue at the mounting points.
The hybrid consists of the Kapton flex circuit (part 3b), which is laminated to two carbon-carbon bridges (part 3a), one for the front and one for the rear side of the module. The carbon-carbon bridge reaches over the central spine by leaving a 0.8mm air gap between the bridge and the center TPG piece. This air gap minimizes the unwanted heat transfer from hybrid to the center TPG and detectors. The bridge feet are glued to the forward extensions of the AlN facings (2a). The heat dissipated by the chip is conducted from the bridge through the AlN facing into the small TPG pieces. Connection to the hybrid for power supply and data transfer is made through a sideways flexible extension of the kapton circuit and a soldered fine-pitch connector. The hybrid carries the 12 FE readout chip and, mounted in front of them, two pitch adapters (part 3c). The pitch adapters match the coarser pitch of the detector strips to the fine pitch of the chip input pads. The kapton circuit has an analog ground mesh incorporated below the pitch adapter to electrically shield the traces on the adapter.

3. Results of prototype assembly and module metrology

To study the feasibility and functionality of this module layout we assembled a prototype series of eight "outer" KB modules. "Outer" module types were chosen as their layout is the most demanding for thermal and electrical performance. This prototype assembly provides us with insights of the assembly for this module layout, allowed us to define the assembly procedures and prototype all necessary assembly tools. Five of the eight assembled modules have been constructed according to SCT mechanical specification and were surveyed to verify the mechanical precision of the assembly. All constructed modules are electrically functional and were consequently used for tests presented in this paper.

The assembly of the module was an important design consideration for the module layout. We aimed to decouple the functions of all module components in order to simplify the technical specification for each part and allow for a parallel construction of the module component groups. In particular we tried to decouple the construction of the hybrid from the assembly of the rest of the module. This has the advantage that quality assurance tests can be carried out on the fully assembled hybrid and fully assembly detector-spine part separately before those rather expensive sub-assemblies are joined to a module. The production of this large number of modules also requires a simple but precise and repeatable assembly procedure with a minimum of components.

The module is constructed in four phases: the assembly of the spine components, the gluing of the detectors, the gluing of the hybrid to detector-spine subassembly and the electrical connection of detectors to the hybrid.

1. The components in the module center (the TPG parts, all PEEK and AlN pieces, parts 1a-e) are aligned relative to each other and locked in place on a vacuum jig. Conductive and non-conductive glue is deposited in a predefined pattern on one side of the parts. Aluminum precision fittings are glued to the module as mounting and reference points.

2. The two detectors of one side and the AlN ceramic facing (part 2a) are aligned on a separate vacuum jig. The jig carrying the spine parts is then precision fitted to the jig carrying detectors and facing. After the glue is cured the detector gluing step is repeated for the other module side. This completes the assembly of spine and detectors, the detector strips are bonded together and the detectors are tested electrically.

3. The hybrid is preassembled separately with flex-circuit, supports, FE chips and pitch adapters and tested electrically as a separate unit. In the first step of the hybrid assembly to the spine, one section of the hybrid is aligned relative to one detector pair on the spine and glued to the forward extension of the AlN facing. After the glue is cured the module is turned, the hybrid is wrapped around to the other side of the module and glued.

4. In the last step the detector strips are wire-bonded to the pitch adapter, the detector
p^+ bias line is bonded to the hybrid and the detector backplane connection is made.

During the prototype assembly of eight KB modules, we experienced no unforeseen difficulties. We attribute this also to the fact that the hybrid carries only electrical and thermal function but has no mechanical or alignment function, which facilitates its mounting. Safe and convenient handling of the module is facilitated by the large rear module cooling contact and the facings, which can be used as a smooth and stiff handling area.

After the module assembly, the five precision modules were subjected to a standardized quality control procedure [5]. It consists of verifying the detector leakage current at different points of the assembly and a XYZ metrology survey to verify the mechanical precision. The leakage current measurement indicates if one of the assembly steps deteriorated any of the detectors. None of the five precision modules revealed detector current problems such as breakdown or micro-discharges. Figure 3 shows the total module leakage current at room temperature for one module (sum of four detectors) before assembly, after gluing of sensors to the spine and after bonding.

During the mechanical survey the module is mounted in a frame allowing a measurement of the X-Y and Z position of the detectors of both sides with respect to the same reference points.

The parameters given in table 1 characterize the alignment between detector pairs on the front and back of the module. Parameter "MidXF" and "MidYF" denote a translational shift of the front-to-back detector pairs along and orthogonal to the strip orientation respectively. "SepF" and "SepB" characterize the alignment of the two detectors on the same side and "Stereo" denotes deviation from the nominal stereo angle between strips on front and back of the module.

The XY survey for module 1 to 4 shows very good results which are within the module specifications for all modules. The deviation of "MidYF" from the nominal for module 5, still within the tolerances, is due to an accidental vacuum loss on one of the alignment jigs. The Z survey measures the planarity of the detector surface on the front and back of the module. The r.m.s planarity of each detector surface is given as parameter "rmsZ" in table 1. We find a r.m.s. planarity of the strip-side detector surface of 25 μm on average with clear improvement over time as the assembly of the five modules progressed.

4. Results of thermal performance test

Cooling of the module aims at removing the heat generated by the electronics detectors through a single cooling contact and guaranteeing a stable operating condition for irradiated detectors. The detectors need to be operated cold to minimize anti-annealing and prevent so-called "thermal run-away". The power dissipated in the detectors increases their temperature, so the leakage current increases and with it the power dissipation. If the cooling system is not able to remove the power dissipated by the detectors and the power transferred to them externally (e.g. by the electronics and environment), the module will reach an unstable condition, commonly called thermal run-away. Since the thermal run-away represents a catastrophic failure of the module obliging the user to switch it off, the specification on it include several safety factors. The specifications [9] can be summarized as:

- the detectors must operate cooler than -7°C when the hybrid dissipates 7 W, the detectors generate 185 μW/mm² and
are subjected to an external heat load of 0.8 W/module from the environment,

- no thermal run-away shall occur below a detector power density of $240 \mu W/mm^2$, with a hybrid power of 7 W and an environmental heat load of 0.8 W/module.

The cooling system chosen for the SCT is a two-phase evaporative refrigerator cycle based on $CF_8$. The present design of the cooling system envisages a coolant temperature of $-23^\circ C$.

4.1. Setup used for thermal measurements

The setup used for the thermal measurements aims at emulating the experimental environment and module operating conditions. The relevant parameters to be controlled during the tests are the coolant temperature and the effect of convection and radiation on the detector surface. During the thermal measurement the module is electrically operated, meaning that bias voltage is applied on the detector, the readout electronics is powered and data are read back from the FE-chips. The power dissipated in the detectors is calculated from the applied detector bias voltage and the monitored leakage current. The resulting power is corrected for the voltage drop in the biasing resistors. All thermal tests were carried out on an irradiated "outer" KB module (KB-100) which was irradiated to a total fluence of $3 \times 10^{14} 24\text{GeV protons/cm}^2$ at the CERN PS T7 beam line.

The module is mounted on an aluminum cooling block with an effective cooling surface of $5 \times 79 \text{mm}^2$. The cooling block has an average thickness of 2 mm. The cooling block is split in three sections by means of two 1 mm thick thermal insulators: two sections cool the hybrid TPG pieces and one cools the detector TPG piece. This further enhances the thermal separation of hybrid and detector. The cooling block is attached to a 4 mm diameter copper-nickel cooling pipe with 70 $\mu$mm wall thickness. For a thermally optimized cooling block, PEEK is envisaged as the material for the thermal split in the cooling block, and soldering is planned for the attachment of block to pipe. For practical reason during the prototype test, vetronite was used as split material and the block was glued to the pipe. This test implementation limits the heat transfer between the module and coolant. Our test results can therefore be considered conservative with respect to the expected performance.

The temperature of the coolant is fixed with a liquid (ethanol-water mixture) based chiller. The heat transfer coefficient (HTC) of the monophase liquid coolant is lower than the evaporative one in the final system, so the measurements are also conservative in this respect. The module is operated in flushing nitrogen atmosphere and placed in a dedicated test box installed in a climate chamber. The climate chamber allows us to control the "environmental" temperature through the temperature of the box walls and atmosphere. Tuning the temperature of the climate chamber

<table>
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<th>Mod. 3</th>
<th>Mod. 4</th>
<th>Mod. 5</th>
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<td>1</td>
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<td>-1</td>
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<td>± 5</td>
</tr>
<tr>
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<td>-2</td>
<td>-2</td>
<td>-3</td>
<td>± 10</td>
</tr>
<tr>
<td>SepB $[\mu \text{m}]$</td>
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<td>-3</td>
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<td>-1</td>
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<td>0.016</td>
<td>0.008</td>
<td>-</td>
</tr>
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</table>

Table 1
Results of mechanical survey on 5 precision modules (see text for parameter description)
to the temperature of the detectors allows a drastic reduction of the convection and radiation heat load from the environment to the detectors surface.

The module mounting surface, detector, cooling block and environment temperatures were measured with 18 sensors glued at several points and read out with a dedicated LabView interface. Whenever sensors are mounted on or close to the detectors, the detector integrity was verified through repeated leakage current measurements. The sensors are glued to the AlN wings directly adjacent to the detectors and on the AlN cooling facing. The linearity of the temperature sensor measurement was verified in the temperature range from -25°C to +25°C. The calibration of the sensors has been verified with measurements taken at a fixed coolant temperature and no power on the module [10]. Calibration constants were subsequently applied to correct for ambient influence on the temperature measurements for sensors mounted on the cooling block, AlN facings on the module cooling contact and cooling inlet and outlet pipe.

4.2. Results of the thermal stability test

We investigated the module's thermal performance in two test series: In the first test series we studied the module behaviour under conditions leading to thermal run-away in order to identify limitations of the module’s thermal management. In the second test series we operated the module under conditions close to final operation within the limitations of our prototype modules and test setup. Based on these test results we carried out a Finite-Element Analysis (FEA) to predict the precise module performance in the Atlas SCT environment.

To study the thermal run-away behaviour of the module, we adjust the coolant temperature to -10.5°C as measured at the cooling pipe outer surface. The module is electrically read out during the tests at nominal voltage settings to the hybrid and bias voltage is applied to the back plane. Temperature readings of all sensors are taken at different settings of the bias voltage, which result in different values of power dissipation in the sensors. In the voltage range of 0 to 300V, the de-

Figure 4. Location and value of temperature measurements on the KB modules at a coolant temperature of -10.5°C. The gray scale profile displays the simulated temperature distribution for this coolant temperature.
tector power varied from 0 to 1.85W. For each voltage setting, the environmental temperature was adjusted to match the detector temperature in order to minimize influences of convection and radiation.

Figure 4 shows the measured temperature values at different locations indicated as markers for the test at highest detector power. The gray-scale image of the module shows the results of the FEA for this test condition. As expected the highest temperature is observed on the hybrid close to the FE-readout chips. The detector temperature is uniform at approximately 17°C above the coolant temperature, with the warmest point being the detector corners furthest away from the cooling point.

To determine the power density which would lead to thermal run-away of the module, we plot the minimum and maximum measured detector temperatures versus the detector power density normalized to a detector temperature of 0°C. This normalization allows a comparison of different operation conditions. Figure 5a shows this correlation in our measurement range, which ranges from 0 to 58 μW/mm² detector power density at 0°C. The plot shows the constant increase of temperature with increasing power density as expected in stable running. Only at the highest power density a steeper increase of detector temperature, although still operating stably, is observed.

Figure 5b compares the maximum measured detector temperature with the maximum detector temperature obtained in the FEA. The measurement and finite-element analysis indicate a thermal run-away at 75 μW/mm² power density for a test setup coolant temperature of -10.5°C. The thermal run-away starts to develop in the detector corners furthest away from the cooling block.

In the second test we operated the module with a coolant temperature of -18°C and a constant environmental temperature of -2°C. These temperature settings can be maintained stably in the test system and are 5°C higher than the temperatures planned as final operation conditions, which are -23°C for coolant and -7°C environment temperature. The module was operated in the same way as during the first tests, with the bias voltages being varied from 0 to 500V, our maximum operation bias voltage.

The detector power ranges for these settings from 0W to 3.58W, and the power density normalized to 0°C detector temperature ranges from 0 to 172 μW/mm² respectively. The module operated stably for the entire power range including the highest power density and showed no sign of thermal run-away under this conditions. The maximum detector temperature was measured to be -4.5°C at 9μW/mm² and +3.5°C at 172μW/mm². This test was carried out under more demanding conditions than the one envisaged for the final system: higher coolant and environmental temperature, a non optimal choice of thermal separation material in the cooling block, a glue joint rather than a solder joint between the cooling pipe and block and a mono-phase coolant rather than evaporative cooling.

For further understanding of our test results a Finite-Element analysis (FEA) was carried out. The FEA uses mechanical dimensions of all module components together with their respective heat conductivities in order to obtain the temperature distribution across the module [10]. As the only free parameter in the FEA, the coolant temperature is adjusted to match results from the FEA to the measurement results of the first test series. The FEA is then repeated with system and environmental parameters foreseen for the final system in order to obtain a precise prediction under those conditions.

The following parameters have been assumed for the final system: PEEK instead of vetronite cooling block separation, a solder joint between pipe and cooling block, a thermal grease layer between the module cooling surface and cooling block of 100μm and an evaporative cooling system with a heat transfer coefficient (HTC) between 2000 and 4000W/m²K.

Figure 6a shows the expected module temperature distribution for a coolant temperature of -20°C, a HTC of 3000W/m²K, a detector power density normalized to 0°C of 185μW/mm² and an external heat load to the detectors of 0.8W, which are the worst case operation conditions for fully irradiated modules in the SCT endcaps. Un-
Figure 6. FEA predictions for final Atlas operation. Plot (a) shows the temperature distribution across the module. Plot (b) shows the Maximum detector temperature versus power density for three different combinations of coolant temperature and assumed heat transfer coefficient (HTC).
under this conditions we expect a temperature difference between coolant and detector of maximum 11°C, a maximum hybrid temperature of 27°C above the coolant temperature and a maximum hybrid to detector temperature difference of 9°C. Figure 6b shows the maximum detector temperature versus the normalized detector power density for this operation condition with a run-away power density of 300µW/mm². Given the uncertainty in HTC the figure also gives the expected behaviour at HTC=2000µW/mm² and a coolant temperature of -22°C as well as for a HTC=4000µW/mm² and a coolant temperature of -18°C. Under all three conditions, including the nominal, the module design fulfills the specifications (shown as dashed lines) and has sufficient margin against thermal run-away.

5. Results of electrical performance tests

During the electrical tests we evaluate the performance characteristics of the module with respect to its electrical stability, its noise performance as well as gain and threshold uniformity. The electrical performance requirements can be summarized as follows:

- the equivalent noise charge (ENC) of the FE electronics connected to 12cm strip should be less than 1500e⁻ for unirradiated modules, and less than 1900e⁻ for fully irradiated modules at SCT operating temperatures.
- the "noise occupancy", i.e. the fraction of hits resulting from noise, shall be less than 5×10⁻⁴ per strip. This is required to keep the number of noise hits significantly below the number of particle hits and avoid negative effects on the data readout, data volume and track reconstruction.
- the double pulse resolution shall be 50ns or better in order not to deteriorate the efficiency and ensure less than 1% of data loss at the highest accelerator design luminosity.
- each hit needs to be associated with the correct bunch crossing, requiring the edge-sensing discriminator to have a maximum
time walk of 16ns between lowest and highest input signal [6]. The fraction of discriminator outputs, which are shifted to a wrong bunch crossing, should be less than 1%.

5.1. Electrical test setup

The electrical module tests are performed with a dedicated VME-based readout and supply system which has been developed for Atlas SCT module tests. It is based on a VME module which receives, decodes and histograms the data from the module, two VME modules that generate clocks and configure the FE chips, and two VME power supply modules which provide low voltage for the FE and opto-chips, and bias voltage for the detector. All VME modules operate out of a single VME crate which is controlled by a National Instruments crate controller. The control of the VME modules, readout of the detector and online analysis of the data is provided by a custom C++ software package which has been developed within the ROOT framework [11].

During the electrical tests the modules are mounted in a light-tight metal box which supports the module on the AlN facings along the cooling contact. The test box includes a cooling channel below the module cooling contact and is cooled by a liquid cooling system of adjustable coolant temperature. The operating temperature of the hybrid is monitored by two thermistors, which are mounted on the hybrid. Unless otherwise stated unirradiated modules are operated with a FE current setting of $220 \mu A$/channel preamplifier current, a shaper current of $30 \mu A$/channel and a detector bias of 150V. Irradiated modules are operated at $120 \mu A$ preamplifier current, $24 \mu A$ shaper current and a detector bias of up to 500V.

At the start of the test sequence the module is subjected to a so-called trimming procedure, in which the DC offsets of channels are adjusted by a 4-bit DAC to a uniform value across the chip. For sparsification a single threshold is applied per chip. For the measurement of gain and ENC, each channel is equipped with an internal calibration circuit. A known test charge is injected in each preamplifier using an adjustable voltage step that charges a test capacitance on each channel. The gain and noise of the each channel is determined through so-called "threshold scans", where the threshold is continuously increased while a constant charge is injected in each channel. The resulting channel efficiency curve is fitted by a complementary error function. The sequence is repeated for different input charges. The threshold voltages corresponding to 50% efficiency ($v_{t50}$) for different input charges measure the gain curve of each channel and the fitted width of the curves provide a measure of the channel noise. In the calculation of gain and noise the measured value of the test capacitor is taken into account as a calibration factor. Further details of the measurement setup and analysis procedures are provided in reference [12].

5.2. Module performance before irradiation

All KB modules were characterized for their electrical performance before irradiation. During those tests the modules where cooled with a liquid coolant of 17°C. We recorded the hybrid temperatures measured on two thermistors mounted close to the chips on each hybrid side to be from 11°C to 18°C above the coolant temperature. During these tests we measured the following module parameters: gain, equivalent noise charge (ENC), noise occupancy, r.m.s. spread of the threshold around the nominal value of 1 fC expressed as equivalent input charge, hybrid temperature and percentage of defective channels.

Table 2 shows the measured module parameters for all KB modules before irradiation. As can be seen from the table the modules show a uniform gain and noise characteristics. The measured noise occupancy is in the range of $2 \times 10^{-6}$ to $1.1 \times 10^{-5}$ and well below the specified maximum noise occupancy. The number of defect channels is below 1% for all modules except for module KB-103 due to a bonding problem in a local detector area. The measured ENC varies between 1450e- and 1620e- at the respective measured hybrid temperatures. We observe an improvement of noise with decreasing hybrid temperature at the rate of $5.5e-/-°C$ [12]. Based on this rate we expect an improvement of about 150e- in ENC for final hybrid operating temperatures. Figure 7a
shows the noise occupancy scan on module KB-100 which illustrates the decrease of noise hits with increasing threshold and indicates the gaussian noise behaviour of the module. The marker in plot (a) marks the threshold voltage which corresponds to a 1fC threshold. Figure 7b shows the uncorrected average ENC for each chip of several modules. The plot illustrates the good noise uniformity for several modules. It also shows the uniformity across the module with no significant influence of the chip’s position on the hybrid.

5.3. Module performance after irradiation

SCT silicon modules are required to be fully operational after being irradiated with $3 \times 10^{14}$ protons/cm$^2$ which corresponds, safety factors included, to the maximum fluence received over 10 years of LHC operation. We therefore carried out an irradiation test on one module (KB-100) to investigate the module performance after irradiation. The module was irradiated to this fluence at the CERN PS accelerator over a period of 10 days with 24GeV protons. During the irradiation the detectors were biased at 100V and the electronics was fully powered. After the irradiation period the module was annealed at 25°C for 7 days.

Radiation damage causes a performance degradation for both readout electronics and silicon detectors. Radiation damage to the FE chips results in an increase of noise and an increased spread of channel DC offset. Silicon detectors are affected by bulk damage and additional charge accumulation layers at the SiO$_2$-silicon interface. While the latter leads to an increase of interstrip capacitance and hence detector capacitance, bulk damage causes an increase of leakage current and, following the type-inversion of the silicon bulk, an increase in full depletion voltage.

After irradiation, the module was tested in the identical way as before irradiation with the exception that the module was operated at a coolant temperature of -15°C and an environmental temperature of -7°C in a climate chamber. The detector current was measured in the detector voltage range of 0 to +500V, where it reached a maximum current of 2.6mA with fully powered readout electronics. The module operated at a hybrid temperature of +1°C. Channel DC offsets were

Figure 7. (a) Example of noise occupancy scan for module KB-100. The marker indicates the threshold voltage corresponding to a 1fC threshold. (b) The average measured ENC for all 12 chips of several KB modules
Table 2
Module electrical performance parameters measured on KB modules before irradiation. Results are given for each module in the following order: gain, r.m.s. spread of threshold at a mean threshold of 1fC, average hybrid temperature, equivalent noise-charge at the measured hybrid temperature corrected for calibration capacitor value, noise occupancy at a threshold of 1fC, percentage of defect channels per module. Results marked with an asterix (*) do not include the calibration factor.

<table>
<thead>
<tr>
<th>Module</th>
<th>Gain [mV/fC]</th>
<th>Thr. spread @ 1fC [e-]</th>
<th>T [°C]</th>
<th>Noise (ENC) Corr. [e-]</th>
<th>Noise occ. @1fC x 10^{-4}</th>
<th>Defect Chann. [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>b048</td>
<td>48.7</td>
<td>136</td>
<td>28</td>
<td>1590</td>
<td>0.09</td>
<td>0.4</td>
</tr>
<tr>
<td>kb-100</td>
<td>47.8</td>
<td>138</td>
<td>34</td>
<td>1622</td>
<td>0.11</td>
<td>0.2</td>
</tr>
<tr>
<td>kb-102</td>
<td>49.0</td>
<td>203</td>
<td>35</td>
<td>1467</td>
<td>0.02</td>
<td>0.07</td>
</tr>
<tr>
<td>kb-103</td>
<td>48.5</td>
<td>156</td>
<td>33</td>
<td>1600</td>
<td>0.06</td>
<td>1.9</td>
</tr>
<tr>
<td>kb-104</td>
<td>50.1</td>
<td>170</td>
<td>28</td>
<td>1534</td>
<td>0.06</td>
<td>0.07</td>
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<tr>
<td>kb-105</td>
<td>50.9</td>
<td>139</td>
<td>-</td>
<td>1357*</td>
<td>0.06*</td>
<td>0</td>
</tr>
<tr>
<td>kb-106</td>
<td>50.0</td>
<td>156</td>
<td>30</td>
<td>1584</td>
<td>0.04</td>
<td>0.13</td>
</tr>
<tr>
<td>kb-108</td>
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<td>138</td>
<td>30</td>
<td>1482</td>
<td>0.04</td>
<td>0.85</td>
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</tbody>
</table>

6. Results of beam tests with KB modules

In order to evaluate the capabilities of the module design as a tracking detector we tested four unirradiated modules in a testbeam at the CERN SPS H8 beamline with a 180GeV/c pion beam. Two KB module at a time were aligned in the center of a tracking telescope with four X-Y reference silicon detectors, which provided track reconstruction and an independent track extrapolation to the test detectors. The reference detectors are 50μm pitch silicon strip detectors which are read out through charge sensitive VA2 preamplifiers [13] with a peaking time of 1μs. The track extrapolation accuracy to the test detector is approximately 3μm.

All silicon detector modules were operated in a light tight and humidity controlled testbox which also provided liquid cooling at coolant temperatures between -20°C and -15°C to the modules. All modules are placed perpendicular to the beam axis. SCT modules are supplied and readout with an identical system as is used during the module characterization with suitable adjustments to the DAQ software for testbeam operation. The modules are operated with a detector voltage of 150V unless stated otherwise. The setup used for the tests is described in further details in reference [14].

Measurements are taken at different thresholds ranging from 0.7fC to 6.0fC. For each threshold setting 20000 events are recorded and analysed offline. Using the track extrapolation from the
Figure 8. Efficiency scan as a function of threshold applied to modules (a) and comparison of efficiency and measured noise occupancy as a function of threshold for one module near the expected operational threshold of 1fC (b).

Figure 9. Residual distribution orthogonal to the module axis ("X") and along the module axis ("Y") in the detector plane.
reference system, this series of measurements allow to measure the efficiency of the module as a function of signal threshold. A hit on the test detector is assumed valid if its position is in a $\pm 120\mu m$ window around the predicted hit position. The efficiency of four modules as a function of threshold is shown in figure 8a. The efficiency curves show the integral signal distribution above threshold, following the expected behaviour for a Landau-distributed signal distribution. This curve also allows a measurement of the median measured ionization charge in the detector as the 50% point of the efficiency curve. For all modules the median charge was measured between 3.3fC and 3.4fC at a bias voltage of 150V. Increasing the detector bias voltage we observe an increase of median charge at higher bias voltages to typically 3.6fC at 300V.

The signal-to-noise ratio, defined as median charge at 150V detector bias divided by ENC noise measured in the testbeam, ranges from 13.6:1 to 14.8:1 for the different modules. The measured noise occupancy in the testbeam was found to be higher than in previous module characterizations due to the occasional occurrence of common mode noise in the testbeam setup. During the testbeam we measure a noise occupancy at 1fC threshold ranging from $0.7\cdot 10^{-4}$ to $1.2\cdot 10^{-4}$.

Figure 8b shows the efficiency (left vertical axis) and noise occupancy (right vertical axis) of one module as a function of threshold around the expected 1fC operational threshold. The noise occupancy is determined through measurements outside of particle spills. Specifications for minimal efficiency (99%) and maximum noise occupancy ($5\cdot 10^{-4}$) are drawn as dashed lines. From this plot is it clear that those specifications are fulfilled in a threshold range of 0.8 to 1.5fC, although we expect to apply a threshold of 1fC in order to increase the detectors sensitivity to hits where charge is shared between strips e.g. due to track inclination.

Using the reference system we can measure the spatial resolution of the test modules through track extrapolation. At the strip pitch of SCT detector modules and due to the lack of analog hit interpolation, we expect a nearly "digital" resolution given by the strip pitch/$\sqrt{12}$. We measure a r.m.s. spatial resolution of $23\mu m$ orthogonal to the strip direction on each side of the module. The stereo angle between the two detector sides allows a measurement of the two-dimensional hit position in the module plane with better precision orthogonal to the module axis ("X") and worse resolution along the module axis ("Y"). We measure a respective spatial resolution of $\sigma_X=19\mu m$ and $\sigma_Y=750\mu m$ orthogonal and along the module axis. The residual distributions for module KB-102 are shown in figure 9 together with a gaussian fit to the distributions shown as solid lines.

7. Conclusion

We designed, prototyped and tested a silicon detector module layout for the endcap of the Atlas SCT detector. This particular layout aims on integrating identical readout electronics and hybrid for barrel and endcap modules in the geometry of the forward SCT detector. The electronics hybrid is one of the most complex component of the entire module and requires substantial development resources. The described module design, with a common electronics hybrid for the barrel and endcap successfully provided a backup solution in case the development of a dedicated hybrid were not completed in time.

The module was designed following the stringent SCT requirements for electrical performance and with emphasis on excellent thermal management. The design was validated in a prototype assembly of eight modules. This prototype run allowed us to develop and demonstrate the assembly procedure, which we found to be simple yet precise and reliable. The thermal performance was verified on an irradiated module, which showed good temperature uniformity across the sensors. The thermal run-away power density was found to be 300 $\mu W/mm^2$ at $0^\circ$ detector temperature and SCT operations condition, which included the SCT requirements including all safety factors. In electrical tests the modules showed a stable signal response during calibration. The noise and gain was found to be uniform across the module at a level similar to the barrel modules before and after irradiation and conform to specifications. Several modules were addition-
ally tested in a beam test. Testbeam results yield a signal-to-noise ratio ranging from 13:1 to 15:1, an efficiency in excess of 99% and a resolution of 18μm orthogonal to the module axis.

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