The ATLAS SemiConductor Tracker - overview and status

Lars Eklund on behalf of the SCT Collaboration [a]

[a] *ISV, Uppsala University, SE-751 21 Uppsala, Sweden*

Abstract

The ATLAS SemiConductor Tracker (SCT) in one of the three tracking detectors making up the ATLAS inner detector. The trackers 4088 silicon detector modules covers an area of over 60 m2, distributed over 4 barrel cylinders and 18 end-cap disks. The back-to-back mounted silicon sensors provide space points for track reconstruction. The sensors are read-out via front-end ASIC and binary data from selected events are read out via optical links. A large number of prototypes have been built and measured with test-pulses, in beam tests and in a small scale system tests. The radiation hardness of the components has been verified by a series of irradiations with subsequent thorough measurement programs. The SCT is now close to its final design and series production of detector modules is about to start. The final assembly and Quality Assurance of the SCT detector modules will be done in production at Universities, organizing themselves in Production Clusters.

1 Introduction

The ATLAS experiment[1] is one of four experiments to be built at the Large Hadron Collider (LHC). ATLAS has 4π coverage consisting of Inner Detector (ID), Electromagnetic Calorimeter, Hadronic Calorimeter and the Muon Spectrometer. The ID is a detector system designed for Tracking, Particle Identification and Vertex Reconstruction. The SemiConductor Tracker(SCT)[2] is an essential part of the Inner Detector. This paper will give an overview of the design and performance of the SCT detector module, at this stage just before serial production of detector modules will start. The organization of the production will also be described briefly.

The SCT has four barrel cylinders with radii ranging from 299 to 514 mm and 18 end-cap wheels, with a maximal distance in z of 5.6 m. In total, 4088 detector modules are tiled on the barrels and wheels. This geometry gives a coverage for $|\eta| < 2.5$, providing four space points per track. The total area covered by silicon sensors is 61 m^2 and there are 6.3 million strips read out by custom made front-end electronics. The SCT detector module will operate in a magnetic field of 2T. Each module consumes 5-7 W of electrical power in front-end electronics and silicon sensors, a heat load has to be absorbed by the bi-phase cooling system. In order to limit the reversed annealing of the sensors and to reduce the leakage current, the operation temperature is chosen to be around -7 °C measured at the sensors. The design philosophy of the detector module is that no off-line alignment should be needed internally within the module. Furthermore, the SCT detector modules will operate in a harsh radiation environment. The estimated maximal radiation dose after 10 years of LHC operation is 10 $MRad$ ionizing dose or $2 \times 10^{14} n/cm^2$ 1 MeV NIEL equivalent.

2 The SCT Detector Module

There are five different designs of the SCT detector modules. The 2112 barrel detector modules have the same design, whereas the 1976 end-cap detector modules are made in four slightly different types. The difference between the end-cap module types is only in their geometry, depending on their position on the wheels. They are called inner, middle, short middle and outer modules. Through a number of design choices, the barrel and end-cap modules have evolved in different directions. E.g. the barrel detector module has the electronic read-out bonded at the center of the silicon sensors and are cooled via a sliding cooling block on the side. In contrary, the forward modules have the electronics bonded to the end of the sensors and have a fixed central cooling block.

Each silicon sensor[3] has 768 p^+ in n bulk strips with 80 μm pitch for barrel and 50 to 90 μm pitch for end-cap detector modules. The sensors are single sided, mounted back to back with a 40 mrad angle between the strips to provide a two dimensional read-out. The read-out strips are AC-coupled to the front-end electronics and the detector bias is applies via a bias contact on the back side. The sensor thickness of 285 μm gives an charge deposition of 3.6 fC from a minimum ionizing particle.

Briefly, the mechanical assembly of a barrel detector module can be described as follows. Four silicon sensors, two daisy-chained on each side, are glued on to a baseboard[3]. The baseboard is made of Thermo Pyrolitic Grafite encapsulated with 20 μm epoxy. As well as giving mechanical stability, the baseboard ensures the good thermal performance of the module. The baseboard has BeO facings at the interface to the cooling block. The electronics hybrid[3] consists of a printed circuit flex mounted on two carbon-carbon (C-C) bridges. The bracket shape of the C-C bridge gives an air gap between the electronics hy-

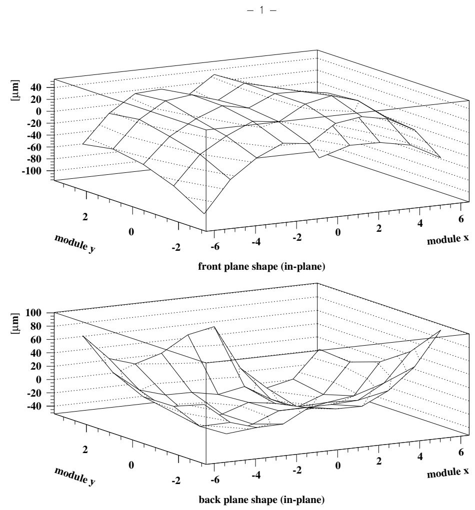

Fig. 1. Out-of-plane profile of a prototype detector module built by the Scandinavian Module Production Cluster

brid and the sensors which thermally decouple the front-end ASICs and the sensors. The hybrid is wrapped around the sensor/baseboard sandwich in such way that the feet of the C-C bridge are standing on the BeO facings of the baseboard, providing a good heat path from the front-end electronics to the cooling block.

12 custom made front-end ASICs[3] are mounted on the electronics hybrid, each one featuring 128 binary read-out channels. The ASICs are produced at ATMEL (Nantes), in the radiation hard DMILL BiCMOS technology. The analogue front-end of the chip is made of bipolar devices and the digital part in CMOS technology. The chip is designed for the LHC bunch-crossing rate 40 MHz and has a 132 cell digital pipeline, to store events 3.2 μs awaiting Level 1 trigger decision. Expected Level 1 frequency is 100 kHz, at which the front-end chip handles up to 1% occupancy. Clock, commands and event data is sent via optical links[4] between the DAQ system and the detector modules. The communication between the chips and from the chips and to the optical links is done via LVDS signals. Any single-point failure in the communication network should not degrade the performance of the module, since every part is designed with redundancy.

3 Performance

The thermal performance of the detector modules has been studied via simulations, thermal prototypes and complete detector detector modules. Thermal simulations, confirmed by measurements, of barrel modules have shown that the silicon sensor is 3-5°C and the chips are 14-18°C above the temperature of the cooling block. The temperature of the cooling block installed in SCT will be around -15°. The mechanical precision of the assembly in the sensor plane is expressed by 13 measured parameters[5]. These define the relative position of each silicon sensor, the angle between the strips on the two sides and the positioning with respect to the mounting holes. The critical point in meeting the specification of these parameters is the relative position between the two sides. With special care, the required precision has been achieved. Since the silicon wafers are processed only on one side, the sensors have an intrinsic bow of about 100 μm. The silicon sensors are glued on to a comparatively soft baseboard in a manner to minimize internal stresses in the assembly. Hence, the intrinsic bow of the detectors can be seen in the out-of-plane profile as shown in Figure 1.

An extensive program has been performed to assure the radiation hardness of the detector module and all its components. All components have to be qualified up to the estimated maximal dose of the SCT. There have been special programs for some of the crucial parts of the detector module. For instance, irradiation of silicon starting from R&D of prototype sensors, to pre-series and now Quality Assurance of delivered production batches. The basis of the detector irradiations have been a permanent installation at the CERN PS accelerator using 24 GeV/c protons, but many cross-checks have been made with irradiations elsewhere.

The final design iterations of the front-end electronics were largely driven by radiation hardness aspects. Irradiations have been made of single chips, hybrids with front-end electrics and with complete detector module assemblies. The program includes complete characterization of the performance before and after, as well as continuous monitoring during the accumulation of dose. These characterizations include e.g parametrization of the analogue front-end performance such as noise, gain and channel-to-channel matching of the comparator thresholds. In particular, the matching requirements led to the addition of an individual correction circuitry for the comparator threshold of each channel. One issue of concern in the digital performance is the LVDS communication between the chips. After observed failures in this circuitry it was given a more robust design. The irradiated prototype detector modules have been studied in a variety of ways. In addition to standard measurements in the lab, there have been specialized studies to determine the exact failures of the ASICs and more general studies of the performance of irradiated prototypes in Beam Tests and small scale Systems Test. Similarly as for the silicon sensors, the irradiation program will continue during production as a part of the Quality Assurance procedures. In parallel with the programs of measuring the effects of the accumulated dose, there have been measurements of the expected Single Event Upset rate. It has been done with both pion and proton beams, showing that the problem can be handled with a reasonable reset and reconfiguration frequency.

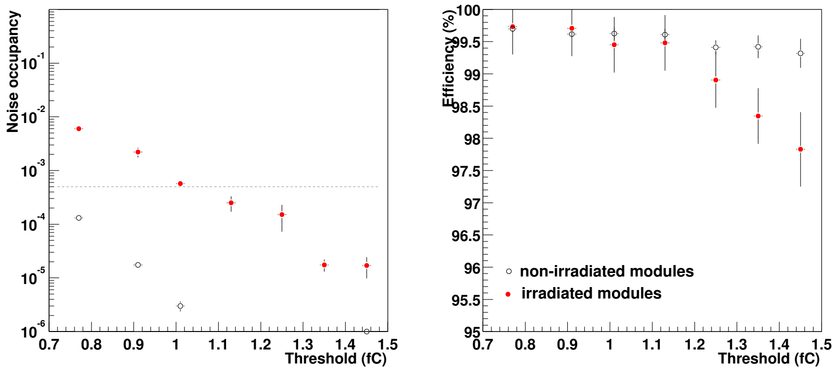

Fig. 2. Noise and Efficiency as a function of comparator threshold. Results from Beam Test August 2001. The requirement of efficiency is set to 99%, since the analysis only includes perfect strips. This allows for 1% bad strips to still meet the overall requirement of 98%.

The Beam Tests of detector modules have evolved from a part of the R&D of prototypes to-wards a parametrization of the performance of the detector modules to be used for simulations of the SCT. Results confirmed that the detector modules meet the specifications[6], both before and after irradiation to specified dose. The noise requirement is 1500 ENC before irradiation and 1900 ENC after. This corresponds to a noise occupancy of $< 5 \times 10^{-4}$ at nominal (1 fC) comparator threshold. A competitive requirement is a total efficiency of 98% at nominal threshold. Figure 2 shows that even if the requirement in noise occupancy is only just met, there is still an operational widow given by the margin to the efficiency specification. To parametrize the performance, measurements have been done at number of incident angles and many other features of the detector module has been studied. The measured resolution orthogonality to the strips is 21-24 μm, in good agreement with what is expected from the 80 μm pitch of the sensors and binary read-out. A small scale system test of about 15 barrel detector modules is performed at CERN. The purpose is to test the detector modules in a replica of the SCT environment. A sector with the detector modules mounted in correct geometrical position, equipped with cooling, cabling, low-mass tapes and optical links is in place. Studies of cross-talk and pickup has shown that with careful grounding and shielding schemes, the same good performance as from single module measurements has been achieved.

4 Production

The final assembly and Quality Assurance of the SCT detector modules will be done in institutes around the world. The institutes are organized in Production Clusters, responsible to deliver a determined number of modules fully within specification. The work is divided differently in each cluster depending on the resources and know-how that is available. A part of the assembly procedure will be done by industry for some clusters. Each component has its own production plan, with quality specifications to meet. The silicon sensors are delivered from Hamamatsu and CiS to the production clusters where a Quality Assurance (QA) program is performed. The baseboards and electronics hybrids have already been subject to their quality assurance procedures before delivery to the Production Clusters. The front-end ASICs are delivered from ATMEL to CERN on wafers. The screening and classification of chips is done on at three sites with identical custom made screening stations. The selected chips will be distributed to the production clusters for mounting on hybrids.

To ensure even quality and high yield across all production sites, a Quality Assurance program is defined[7]. It not only defines which measurements that will be made, but as well documents the exact procedures in the production. Tests include for instance visual inspection, reception tests, metrology of the sensor/baseboard assembly and leakage current measurements of the silicon sensors. The electrical performance of the detector modules is confirmed at several stages. To catch infant mortalities an to spot errors in the assembly, some aging tests are done. There is burn-in of the electronics hybrid with ASICs mounted and thermal cycling and of the complete assembly and long term stability tests. The qualified module is finally fully characterized electrically. All results and actions are recorded in the SCT Data Base, which also handles the tracing of components.

References

[1] ATLAS Technical Proposal, CERN/LHCC/94-43 (1993)

[2] ATLAS Inner Detector TDR Volume 2 CERN/LHCC/97-17 p 385

[3] ATLAS SCT Barrel Module FDR, ATLAS-SCT-BM-FDR-5

[4] ATLAS SCT Opto-Package FDR

[5] Proposed Conventions for Module Survey, S. Snow http://hepwww.ph.man.ac.uk/groups/atlas/module/specs.html

[6] Beamtests of Prototype ATLAS SCT Modules at CERN H8 in June and August 2000, ATL-INDET-2002-005

[7] ATLAS SCT Barrel Module FDR, ATLAS-SCT-BM-FDR-7