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Construction of the ATLAS SCT Endcap modules

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Abstract

The ATLAS Semi-Conductor Tracker (SCT) uses silicon strip detectors to measure trajectories of charged particles coming from 14 TeV proton–proton collisions at the Large Hadron Collider at CERN. The SCT provides at least four space points, in the radial range of 27–50 cm from the beam, for tracks within the angular acceptance $|\eta|<2.5$. The SCT is built up of 4088 modules, each consisting of two or four silicon detectors, a hybrid carrying several readout ASICS, and other components to support, cool and align the detectors. We report on construction of over 2000 end-cap modules of the SCT by a group of 14 institutes from seven countries. A key aspect of the project was to fully standardise the final module tests and to insist that test data from all institutes was stored in a single central database, while leaving institutes flexibility to vary their module assembly methods to suit local circumstances. First the module specifications and tests used for quality control are summarised, then we describe the main test results. Finally, we report our experience in terms of component quality, assembly and testing rates, yield of good modules and causes of lost modules. At the outset we assumed losses during assembly of 15% and procured components accordingly; in fact, losses were around 7%.

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1. Introduction

The ATLAS Semi-Conductor Tracker (SCT) uses silicon strip detectors to measure trajectories of charged particles coming from 14 TeV proton–proton collisions at the Large Hadron Collider at CERN. The SCT is part of the ATLAS Inner Detector [1], which aims to measure all charged particles having significant transverse momentum within the pseudo-rapidity range $|\eta| < 2.5$. The other parts of the Inner Detector are three layers of silicon pixel detectors at low radius inside the SCT and a layer of densely packed gaseous drift "straw" chambers that provide on average 35 hits on a track outside the SCT.

The SCT provides at least four precise space points, in the radial range of 27–50 cm from the beam, for tracks within the angular acceptance. It is built up of 4088 modules, each consisting of two or four silicon detectors, a hybrid carrying several readout chips, and components to support, cool and align the detectors. The central part is made of four concentric barrels, supporting 2112 identical modules and the end-caps are built up from nine discs on each end, with each disc carrying up to 132 modules of three different types. Thus the module is the main component of the SCT. It can act as a stand-alone particle detector, only sharing some services with other modules on the same disc. This article describes the design of end-cap modules [2] and the production of over 2000 of them.

2. Endcap modules description

The main challenge of the SCT is that it must continue to operate after the radiation dose of 3×10^{14} protons/cm^2, which is expected to be accumulated over 10 years of running in ATLAS. The leakage current and bias voltage of the silicon only remain tolerable after this dose if its temperature is kept below –7 C. It is also necessary to have good rejection against signals from neighbouring bunch crossings that differ from the trigger event by only ± 25 ns. At the same time, with only four layers, the SCT must have

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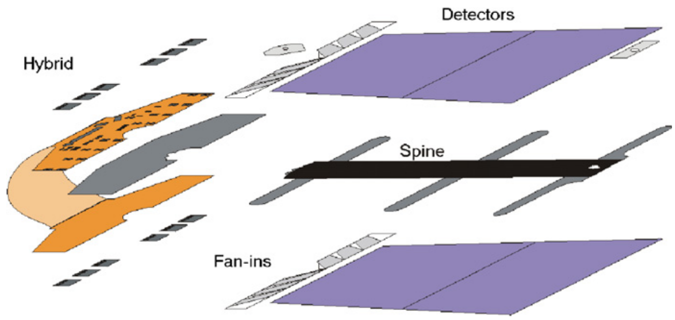

Fig. 1. Exploded view of an SCT endcap module.

efficiency of ~99% per layer to find tracks effectively. We have designed a module that meets these requirements [5], the main components of which are shown in Fig. 1 and described below.

The *silicon sensors* [3] are 280 μm thick and approximately $6\times6\,\text{cm}^2$. Each sensor is divided into 768 p in n strips, with a pitch of 80 μm, giving a resolution of 22 μm. The shape is slightly trapezoid to efficiently tile the disc. In most modules a pair of sensors are chained together to make an effective 12 cm long strip. The strip length is limited to two detectors by consideration of capacitive load on the readout chip and hit occupancy in jets.

The 0.5 mm thick *spine* provides mechanical support and cooling of the detectors. Cooling is mainly due to the pyrolytic graphite (TPG) body, which has exceptionally high thermal conductivity ($1700\,\text{W}\,\text{m}^{-1}\,\text{K}^{-1}$) and carries heat to the cooling blocks at its two ends. Mechanical strength is mainly due to the six aluminium nitride wings which contact each detector along two of its ends.

The *fan-ins*, of 0.3 mm glass supporting etched aluminium tracks, adapt the pitch of the silicon strips to that of the readout chips. They also provide a strong mechanical connection, but thermal isolation, between the detector and the hybrid parts of the module.

The *hybrid* is made up of a six layer copper–kapton flexible circuit, folded round a substrate made of carbon fibres in a carbon matrix. The flexible circuit was chosen for its low cost and radiation length, while the carbon–carbon substrate offers high strength and high thermal conductivity in one direction. The hybrid is populated with 12 ABCD readout chips [4] and two chips for data communication. Communication is normally optical, with electro-optical conversion done in a package that is integrated with the end of the optical fibre.

3. Module production collaboration and methods

A collaboration of 14 institutes with a wide geographical spread developed and prototyped this module over a period of 9 years. By the time this process was complete less than 2 years remained to produce all the modules needed for ATLAS. All available effort was needed to complete the production in time, but dividing the work among so many sites could lead to inefficiency or variable quality. The solution adopted was to split into three clusters of institutes. All clusters received module components from the common suppliers and were responsible for delivering finished and tested modules to the two end-cap assembly sites. Management of work and the flow of components was somewhat devolved to the cluster level. The quality issue was dealt with by defining and agreeing detailed quality assurance (QA) tests that every module must pass. Each institute had to show that it was qualified by making at least four good modules from their first five sets of components. In parallel a common public database for storing and accessing the test results was developed. With these structures in place it was possible to leave each institute a lot of flexibility to choose for themselves how to achieve good results with the resources at their disposal. Automation was only used where it could most easily be implemented: for detector alignment, glue dispensing, wire bonding and electrical testing. Other production steps were done by hand. The total time spent on each module was around 20 man-hours. Despite the large amount of shipping between institutes only a few modules were damaged in transit.

4. Electrical QA specifications

The ABCD is a binary readout chip; in each 25 ns clock cycle a channel produces either a 1 if the input goes above threshold or a 0 otherwise. The chip also includes a built-in charge injector that allows calibration. The method is to first scan the threshold at constant charge injection, taking many triggers and plotting the mean occupancy at each threshold value. The result is an S-shaped curve where the mid-point gives the average response and the width is the noise. Repeating this with different charges leads to a plot of response versus charge. A linear fit to the response curve gives the gain and offset that characterize the channel.

The ABCD also has built-in trim DACs that allow the offset to be adjusted channel by channel. These are switched off during the calibration described above. They are then loaded with values calculated from the response curve fits to give all channels on one chip a common response at the normal operating threshold of 1 fC.

Along the way, dead channels are detected through their low gain, high noise or very outlying offset value. A channel having very low noise, typical of no capacitive load is also flagged as bad because it is probably disconnected from the sensor.

The first specification is that the module must have no more than 1% (15 out of 1536) dead channels as defined above. Second, with the dead channels masked, the threshold is set to 1 fc and the average channel occupancy must be no more than 5×10^{-4}. There are further specifications about the digital functionality of chips and time walk which seldom reveal problems once the chip has made it as far as this. The sensor electrical specification is that it must not draw more than 20 μA leakage current at 350 V. Finally, the module must undergo a 24 h run at low