End-cap Modules for the ATLAS SCT

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Abstract

The performance of prototype end-cap modules of the ATLAS SemiConductor Tracker (SCT) are discussed. The results are obtained in stand-alone as well as test beam measurements performed on modules both before and after irradiation with protons with a total dose corresponding to the expectation for ten years of operation at the LHC. Finally, the present status of construction is summarised.

Key words: ATLAS; detector; end-cap; module; SCT; silicon; strip.

1 Introduction

The ATLAS [1] experiment at the Large Hadron Collider LHC will contain a large silicon strip detector as part of the inner tracking detector. This SemiConductor Tracker (SCT) [2] consists of a barrel and two forward end-caps, see Fig. 1a. The barrel and end-cap parts are equipped with about 2000 modules each. The modules are made from single-sided p-on-n silicon strip sensors [3] glued back-to-back, with a 40 mrad stereo angle, on a graphite support structure, and read-out in binary mode by custom made ASICs. For the end-cap modules the 12 ASICs per module, together with components for the optical transmission of commands and data, are mounted on a double-sided hybrid produced from a 6 layer copper/Kapton flex. Three different end-cap module types (inner, middle and outer), see Fig. 1b for an example, made from five different wedge shaped sensor designs are needed. The sensors are 285 μm thick and contain 768 read-out strips with a pitch varying in the range from 55 to

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The general layout of the inner detector a), and a middle module for the end-cap b).

The inner modules only contain two sensors, whereas the middle and outer modules each have four sensors of slightly different shape, such that all module types have different sensor capacitance. Within the tight constraints imposed by the need for radiation hardness, high rate capability, low mass, low cost and overlap between neighbouring modules the design [4] has been optimised for a thermal split between the read-out ASICs and the sensors.

2 Performance of prototype end-cap modules

A number of prototype end-cap modules has been built to verify the design concerning the thermal, mechanical and electrical performance. Some recent results from these modules are reported here. Earlier results can be found in [4], and the performance in multi module tests, together with the module behaviour under deliberate injection of external noise, is discussed in [5].

To achieve a precise tracking the position and orientation of the individual sensors has to be known with high accuracy. To facilitate the detector calibration with tracks, and to be able to reliably contribute to the fast trigger, the module design aims for ‘equal’ modules such that initially only modules and not individual sensors have to be aligned [2]. This imposes strict requirements on the module construction, the strongest being an only ±5 μm tolerance on the reproducibility of the positioning of the sensors perpendicular to the strips. Using precision stages for the sensor alignment and optimising the various steps in the module construction these requirements can be met with high yield. This is demonstrated for some geometrical parameters in Fig. 2. The distributions of deviations from the nominal values shown are well within the tolerances, which are indicated by the dashed lines.

A key issue for the binary read-out scheme is the stability of the modules with respect to noise and gain. The chip-to-chip and module-to-module variation of noise and gain is small, Fig. 3. Since the inner modules only have two sensors
their average noise of about 1000 e\textsuperscript{−}ENC is lower than the noise for middle and outer modules, which is similar and on average amounts to 1350 e\textsuperscript{−}ENC
and 1450\,\text{e}^{-\text{ENC}}. The temperature dependence is about 6 \,\text{e}^{-\text{ENC}} per degree Celsius, the gain is about 50 \,\text{mV/fC}. Since the average signal is about 3.3 \,\text{fC}, the signal to noise ratio, e.g. for middle modules, is about 15 for non-irradiated modules.

The best performance is reached at as high as possible efficiency with as low as possible noise occupancy. For non-irradiated modules, these two quantities are shown in Fig. 4a as functions of the discriminator threshold. The design values of an efficiency larger than 99\% at a noise occupancy of less than $5 \cdot 10^{-4}$ can be reached for a large range of operating thresholds. However, the module performance is deteriorated after receiving the full dose of ten years of operation at the LHC. The radiation damage at the LHC is conservatively simulated by irradiating the modules with 24 GeV protons with a fluence of $3.3 \cdot 10^{14} \,\text{p/cm}^2$. After this treatment the module performance has been significantly degraded [6]. The leakage current rises from a few nA to about 1.5 mA at 400 V for outer modules, and now significantly contributes to the heat budget of the modules. The noise is increased, e.g. for outer modules to about 2100-2400 \,\text{e}^{-\text{ENC}}, and the temperature dependence raises to about 20 \,\text{e}^{-\text{ENC}} per degree Celsius. The collected charge decreases, and the gain drops to about 30 \,\text{mV/fC}. The radiation damage results in a lower efficiency at larger noise occupancy and the design values can only be reached in a very small window of operating threshold around 1.2 \,\text{fC}, Fig. 4b.

![Fig. 4. The efficiency and noise occupancy versus discriminator threshold for a) a non-irradiated and b) a fully irradiated prototype end-cap module.](image)

To verify that, even with the degraded performance expected towards the end of LHC running, high tracking efficiencies at low fake rates can still be obtained, several fully irradiated modules, interspersed with non-irradiated ones, are put into a test beam setup, Fig. 5.

The fully irradiated barrel and end-cap modules, marked with a star in Fig. 5, are placed at about the distances they will have in ATLAS. The position of the 180 GeV pion beam is precisely determined using an external silicon telescope.
with analog read-out. The tracking performance is studied by varying the noise occupancy via the threshold \([7]\). The observed residuals of the space points per module are according to expectations from the geometry, about 17 (800) \(\mu m\) perpendicular (parallel) to the strips. The tracking efficiency is found to be similar for barrel and end-cap modules, and to be consistent with the product of the individual sensor efficiencies. For a track reconstructed from three modules, and at 1.2 fC threshold, an efficiency of more than 97\% at about \(10^{-3}\) fake rate is achieved. For four modules the efficiency is still larger than 97\%, however at a lower fake rate compatible with zero. In conclusion, this demonstrates that the fully irradiated modules still allow for tracking with high efficiency and low fake rate.

3 SCT production status

The SCT Collaboration consists of 284 members from 41 institutions in Asia, Australia, Europe and the US. Consequently, both for the barrel and the end-cap part, the production of modules is distributed among several production centers around the world, requiring a complex logistics. The control of material and test results is provided by a central database \([8]\). Mounting of modules to barrels and end-cap disks is done in Japan, the UK and the Netherlands. The final integration into the ATLAS inner detector will be performed at CERN. For the barrel part module production is well underway and about 1/3 completed, whereas the end-cap module production has just started. The installation of services on barrels and disks has commenced, but no module mounting has been done as of now. The envisaged completion dates are end of 2004 for the barrel and mid 2005 for the end-caps.
4 Conclusions

The ATLAS inner detector will be equipped with a silicon strip detector, the SCT. A number of prototype end-cap modules demonstrates that the mechanical requirements can be met with sufficient yield. The electrical performance of non-irradiated modules is according to the design. In contrast, the irradiated modules only allow for a marginal operating flexibility after receiving the full LHC dose. The series production is underway for barrel modules and has just started for end-cap modules. In December 2004 (May 2005) the barrel (end-cap) part is expected to be ready for integration into the ATLAS inner detector.

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