Beamtests of Prototype ATLAS SCT Modules at CERN H8 in 2000

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Abstract

ATLAS Semiconductor Tracker (SCT) prototype modules equipped with ABCD2T chips were tested with 180 GeV pion beams at CERN SPS. Binary readout method is used so many threshold scans at a variety of incidence angles, magnetic field levels and detector bias voltages were taken. Results of analysis showing module efficiencies, noise occupancies, spatial resolution and median charge are presented. Several modules have been built using detectors irradiated to the full ATLAS dose of 3×10^{14} p/cm^2 and one module was irradiated as a complete module. Effects of irradiation on the detector and ASIC performance is shown.

I. INTRODUCTION

Beam tests provide an important opportunity to study how the detector systems fulfil what they have been designed for - detecting particles. Compared to the radioactive source measurements, beam tests much better simulate the realistic environment, with many modules working together, connected via long cables, etc.

In June and August 2000 two types of silicon microstrip modules, barrel and forward have been tested with the pion beams of 180 GeV/c at the CERN H8 SPS beamline [1].

The barrel modules were equipped with square silicon microstrip sensors of a physical size of 64 mm long and 63.6 mm wide with strips in parallel at a pitch of 80 micrometers. A module had a pair of sensors glued on the top and the other glued on the bottom side of a baseboard of the module, being angled at 40 mrad to have a stereo view. The strip length of a module was 12 cm by connecting the pair of sensors. The forward modules (see Figure 1) were functionally very similar, but they had quite different layout and hybrid technology. Their strip length was similar, but they were wedge-shaped with a fan geometry of strips with an average strip pitch of about 80 micrometers.

Strips were connected to the readout electronics, near the middle of the strips in the barrel module and at the end of the strips in the forward modules. A module was equipped with 12 readout chips (prototype ABCD2T [2]), 6 on the top and 6 on the bottom side of the module. Chips were glued on specially-designed hybrids. Several modules have been built using detectors irradiated to the full ATLAS dose of 3×10^{14} p/cm^2 with 24 GeV protons at the CERN proton synchrotron and one module was irradiated as a complete module.

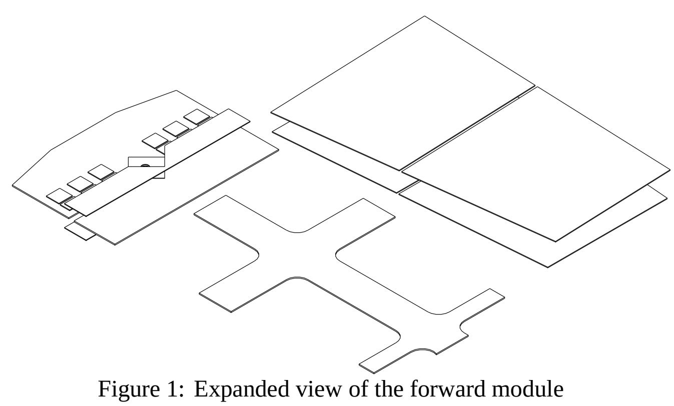

Figure 1: Expanded view of the forward module

The ABCD chip utilises on-chip discrimination of the signal pulses at each silicon detector strip, producing a binary output packet containing hit information sampled at the

40MHz clock frequency and corresponding in time to the beam trigger. The threshold for discrimination is set on a chip-by-chip basis using a previously determined calibration between the threshold (in mV) and the corresponding test input charge amplitude (in fC) which results in 50% occupancy.

To obtain information on pulse heights, threshold scans must be carried out. Our measurement program thus consisted of multiple threshold scans, each at a certain combination of settings of variables of interest which included:

- **Detector bias voltage**, generally covering the range up to expected full charge collection, about +250V for unirradiated detectors and +500V for irradiated detectors;
- **Magnetic field**, i.e. the state on or off of the 1.56T magnetic field;
- **Beam incidence angle**, the modules being rotated about an axis parallel to the detector strips reflecting the ATLAS SCT barrel geometry with respect to the magnetic field direction.

The readout was triggered with an external scintillator system. For each trigger, we record binary information from the modules under test, from anchor planes included for reference and as control samples, and analogue information from the 4 high-spatial-resolution silicon telescopes with analogue readout. In addition, a 0.2ns resolution TDC is used to record the timing of the (randomly arriving) beam trigger relative to the 40MHz system sampling clock so that pulse shape and timing characteristics can be recovered.

More detailed description of the measurement procedure and results can be found at [3] and [4]

II. Beamtest Setup

A sketch of the beamline setup in August 2000 is shown in Figure 2. Ten SCT modules are mounted one after the other in a cooled, light-tight environment chamber on a mechanical system which allows each to be rotated about a vertical. This

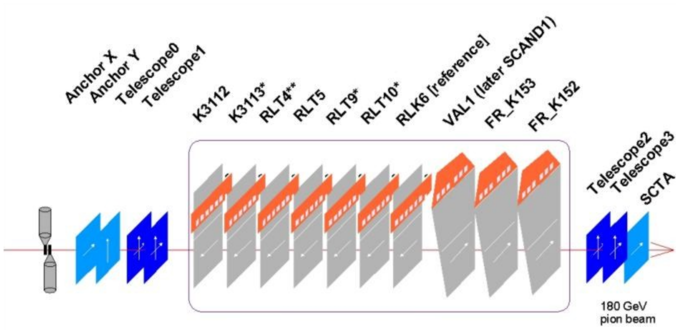

Figure 2: Sketch of the SCT experimental setup at H8 during August 2000. *Barrel modules with irradiated detectors. **Fully irradiated module, RLT4. Module RLK6 was used for reference, with fixed threshold and bias.

chamber can be moved into the 1.56 T Morpurgo superconducting dipole magnet. The field of this magnet is highly uniform over the volume of the SCT modules, and is directed vertically downward, parallel to the detector strips in a configuration which mimics the design arrangement of the SCT barrel modules with respect to particle trajectory, field direction and detector.

Outside the environment chamber there are four telescope modules and two anchor planes, positioned as shown in Figure 2. The telescope have both X and Y sensors of 50 um pitch, coupled to analogue readout.

In addition to the tracking telescopes we had two anchor planes constructed from SCT barrel detectors and hybrids with four ABCD2NT chips. These provide some additional external track information with timing characteristics similar to the modules under test.

The DAQ used for the beamtests was an extension of that generally used for SCT module testing, a system of VME units for control, readout and low-voltage power. The SCT DAQ units include the CLOAC [5], SLOG [6] and MuSTARD [7]. Low-voltage power and slow-control signals came from SCTLV2 [8] low-voltage supplies, while high voltage for detector bias came from linear supplies and from a prototype CANbus-controlled SCT high-voltage power supply. [9]. The DAQ software [10] is an extension of a module testing system [11], a collection of C++ class libraries used in conjunction with the ROOT [12] package running on a PC under Windows NT 4.0.

III. Modules

A. Overview of modules under test

6 barrel and 3 forward modules were tested in the beam. Their positions and names are at Fig. 2. Barrel modules used hybrids of two different technologies: thin film [13] and copper/polyimide [14]. Forward modules were equipped with Kapton-Carbon-Kapton hybrids [15]. They used strip detectors of 3 different thicknesses (285, 300 and 325 μm) from several vendors. Modules K3113, RLT9 and RLT10 have been built using detectors irradiated to the full ATLAS dose of 3×10^{14} p/cm^2 with 24 GeV protons at the CERN proton synchrotron and module RLT4 was irradiated as a complete module.

B. Calibration

We performed a number of in-situ calibration measurements and other studies of all modules prior to, between and after the beamtests to verify or correct the module characterisations using a number of internally-generated test charges across the full charge range of interest, as well as the identification of unusable channels. Last versions of ABCD chip has an additional four-bit threshold trim adjustment for each strip, which must be separately optimised. All unusable channels are recorded and later masked.

IV. MEASUREMENTS

A total of over a 1000 runs of 5000 events each were taken at 5 incidence angles, 2 magnetic field levels and 6 detector bias voltages. At each combination of these settings, a set of threshold scans was performed with 12 charge settings ranging from 0.9 to 4.5 fC chosen to cover in some detail the design operating region near 1.0 fC as well as allowing a study of the fall off at higher thresholds allowing an accurate determination of the median charge collected.

These data are complemented by noise runs (taken in-situ, but with no beam) and local calibration runs.

V. DATA ANALYSIS

In the course of data analysis, tracks are reconstructed from the telescope signals. Events with one reconstructed track are accepted only, to avoid ambiguities.

Binary hits in the module channels are classified to ‘efficient hits’ and ‘noise hits’ according to their proximity to the extrapolated track position and timing. A hit is considered ‘efficient’ if found 100 μm from the track intersection of the module plane. Hits found more than 1 mm from the track are taken as noise hits. Bad channels known from lab and in-situ calibrations and their neighbours are excluded from the analysis. The analysis requires reference (anchor) planes to be efficient for all events. Furthermore, cuts on χ^2, *dX/dZ* and *dY/dZ* are imposed.

In order to monitor the efficiency dependence on the timing of each event, the trigger phase with respect to the 40 MHz system clock is measured using a TDC. Figure 3 shows the efficiency dependence on the charge deposition moment, as measured by the TDC. As the modules were read out in

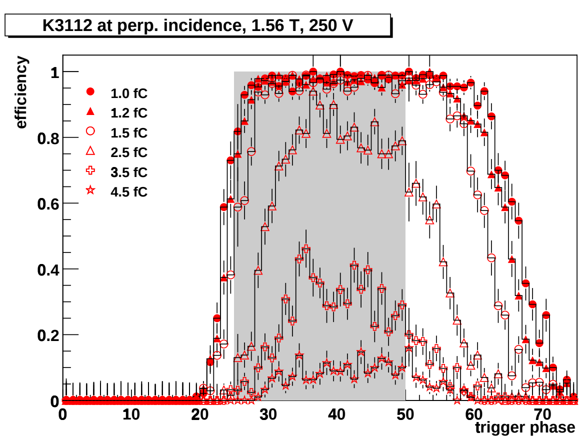

Figure 3: Efficiency dependence on trigger phase for the three recorded clock cycles

ANYHIT compression where three time bin samples around the central time are recorded, the original 25 ns interval (the shaded area in the figure) can be extended on both sides using the full hit pattern information. As expected, the efficiency is seen to be a strongly varying function of the charge deposition moment. As the discriminators in the ABCD were operated with Edge Sensing OFF ("level" mode) the length of the interval in which the modules are efficient depends strongly on the discrimination threshold. Analysis 1 reported here selects a rather broad 12 ns trigger phase window, attempting to minimise the effect on the efficiency while retaining as much statistics as possible.

Three independent data analyses differing mainly in treating the time bin and TDC information were performed, yielding results which are largely identical [16], [17], [18].

Several important benchmark values are then extracted: efficiency, noise occupancy and spatial resolution.

VI. RESULTS

1) S-curves

Figures 4 and 5 show the efficiency and noise results as a function of threshold for unirradiated (K3112) and fully irradiated (RLT4) barrel modules, respectively, for several bias voltages. These data correspond to normal incidence in 1.56T magnetic field.

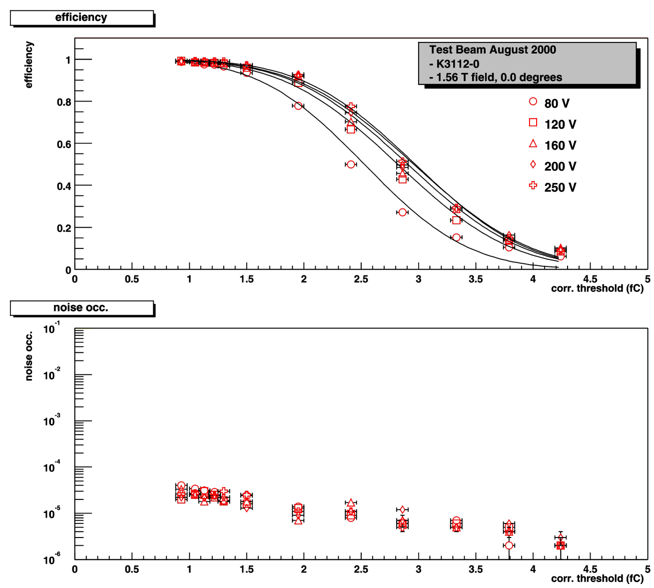

Figure 4: S-curves and noise occupancy in a 1.56 T field, normal incidence for unirradiated barrel module K3112 at all detector bias values studied.

In the non-irradiated modules, the efficiency is seen to be nearly independent of bias voltage down to around 160 Volts. Only at very low voltages (80 V) does the efficiency decay significantly. The modules with irradiated detectors, on the other hand, show a very strong dependence of efficiency on the bias voltage. At 150 Volts virtually no signal is collected. The signal increases slowly with bias voltages all the way up to 500 Volts. The noise occupancies displayed in the same figure were determined using off-track hits.

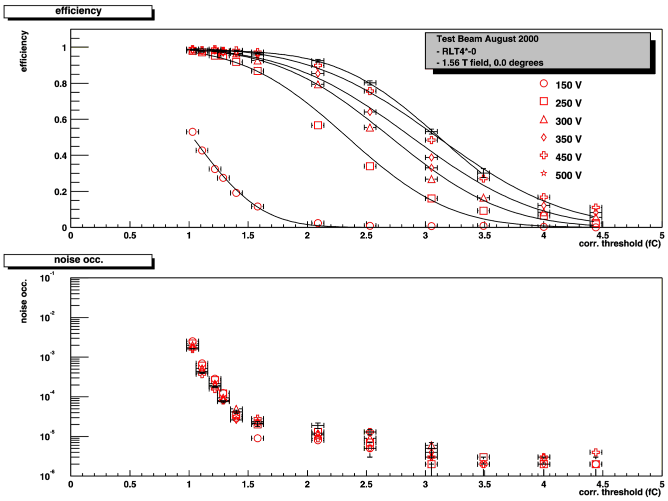

Figure 5: S-curves and noise occupancy in a 1.56 T field, normal incidence for fully irradiated barrel module RLT4 at all detector bias values studied.

2) *Efficiency at 1 fC*

Threshold of 1 fC presents a nominal value for ATLAS running. Therefore, efficiency and noise occupancy at this point is of our interest. Figure 6 shows the dependence of efficiency on bias voltage averaged over all modules and all incidence angles.

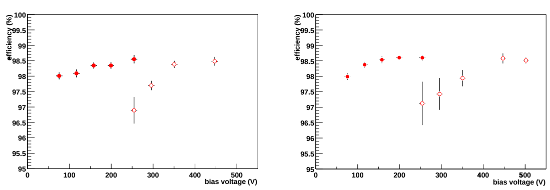

Figure 6: Efficiency at 1 fC without field (left) and in a 1.56 T field (right) for non-irradiated (filled circles) and irradiated detectors (open circles)

Modules with non-irradiated detectors show only a marginal decay of the efficiency at the lowest bias voltages, although the charge loss is already considerable at 120 V. This result is compatible with the 99% benchmark.

The modules with irradiated detectors, as expected, show a very pronounced dependence on bias voltage. On average, 98% efficiency is reached above 300 V.

For other than perpendicular incidence, a net reduction of the collected charge is observed, however, the efficiency at 1 fC at relatively high bias voltage is nearly unaffected for the angle range from 16° to –14°.

3) *Noise occupancy*

Noise occupancies at the 1 fC nominal operating point derived from the off-track hits do not change significantly with any of the scanned variables. The table below gives a global noise number, valid for all incidence angles, bias voltages and magnetic fields, at 1 fC threshold, and also the threshold at the specification noise level of 5×10^{-4}.

From the table follows that unirradiated barrel modules have no measured noise, and irradiated barrel modules are still within or very close to specifications.

High noise of the forward modules has been subject to extensive further investigations. Several effects have been found, which can explain large part of the noise increase. Forward modules were run at substantially higher hybrid and chips temperature. This is known to have a strong influence on the noise, but also on the threshold and calibration DACs, hence the threshold scale of the forward modules was likely wrong. Furthermore, large part of the noise can be attributed to the common noise. This effect has been addressed in later designs.

Table 1: Noise occupancy at 1 fC and lowest threshold setting which satisfies the SCT noise occupancy specification of 5×10^{-4}.

module	***K3112***	***RLT5***	***SCAND1***	***FR153***	***FR152***	***K3113****	***RLT9****	***RLT10****	***RLT4*****
Noise at 1 fC	$<10^{-5}$	5×10^{-5}	$<10^{-5}$	2×10^{-4}	3×10^{-4}	$<10^{-5}$	2×10^{-4}	5×10^{-5}	$<10^{-3}$
Threshold (occ<5×10^{-4})	<0.9	<0.9	<0.8	1.0	1.0	<0.9	<1.0	<0.9	1.2

4) *Median charge*

Median charge collected from the detector is determined from the 50% point of the S-curves. For unirradiated detectors, the charge loss at the lowest voltages can be explained by the ballistic deficit of the shaper. For the irradiated detectors, the situation is complicated – in addition to the ballistic deficit another part of the charge is lost due to charge trapping.

For the highest bias voltages, major fraction of the charge is collected even from the irradiated detectors.

5) *Spatial resolution*

Figure 7 illustrates the spatial resolution in u,v and X and Y as calculated from the intersection of u and v strips.

The resulting X and Y resolution sigmas around 24 µm and 750 µm, respectively, are in a good agreement with the expected values.

Existing data allowed to determine a Lorentz angle, being 2.2°±0.4°, which is in rough agreement with the expected value of 2.8°.

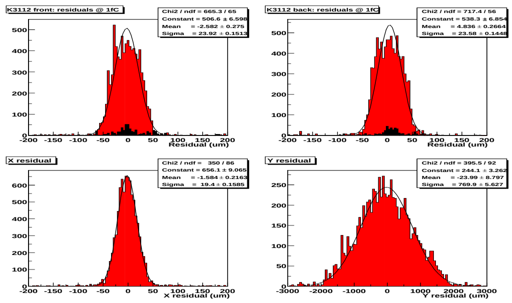

Figure 7: Spatial resolution in u,v and X,Y of K3112, for perpendicular incidence (at 250 Volt detector bias and a 1.56 T magnetic field).

VII. Conclusions

Beamtests of an important sample of SCT modules of both barrel and forward types representing near-final designs with the ABCD2T readout chip were successfully performed covering a wide range of irradiation states, incidence angles, magnetic field states, and detector bias voltages representative of expected operating conditions.

The modules met, or nearly met, most of the relevant specifications of the Inner Detector TDR. An exception was the number of bad channels which was mostly due to the now-understood and addressed ABCD2T trim DAC problem. The unirradiated barrel module prototypes tested in the June and August beams satisfy the noise occupancy specification (5×10^{-4}) down to 0.9 fC threshold. The efficiency at 1 fC is around (99±1)% irrespective of magnetic field and incidence angle. Only at the lowest bias voltages does ballistic deficit of the shaper lead to efficiency loss.

The forward modules were noisier than expected compared to many laboratory measurements. Further investigations attributed this fact to several effects (substantially higher temperature leading to incorrect calibration, common mode noise susceptibility, etc.) This is being addressed in later designs. The efficiency at 1 fC is similar to the barrel modules.

Three modules built with detectors irradiated to 3×10^{14} p/cm^2 and one complete module irradiated to the same fluence were tested. The modules with irradiated detectors had higher noise, but still satisfied the ATLAS noise occupancy specification at 1 fC. The fully irradiated module required a threshold of 1.2 fC to meet the noise specification.

Two out of three modules built with irradiated detectors reach 98% efficiency at a bias voltage of around 350 V. The slightly lower efficiency of the other, K3113, is not fully understood but is probably due to an overestimation of the calibration response, as indicated by the consistently low median charge, and noise and efficiency at 1fC. Batch to batch uncertainties in the ABCD2T calibration capacitors of 10 to 20%, as well as temperature dependence of the gain and calibration charge amplitude all contribute to a systematic uncertainty in the response sufficient to account for this discrepancy. Remarkable is the high efficiency of the fully irradiated module, RLT4. This may be due to the thicker detectors or the altered timing characteristics of the front-end ABCD electronics after irradiation. No charge collection plateau is reached in a bias voltage scan to 500V.

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