ATL-ITK-PROC-2018-006
02 February 2018

Testbeam Evaluation of Silicon Strip Modules for ATLAS Phase - II Strip Tracker Upgrade

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Abstract

The planned HL-LHC (High Luminosity LHC) is being designed to maximise the physics potential of the LHC with 10 years of operation at instantaneous luminosities of 7.5×10^{34} cm^{-2}s^{-1}. A consequence of this increased luminosity is the expected radiation damage requiring the tracking detectors to withstand hadron fluence to over 1×10^{15} 1 MeV neutron equivalent per cm^2 in the ATLAS Strips system. The silicon strip tracker exploits the concept of modularity. Fast readout electronics, deploying 130nm CMOS front-end electronics are glued on top of a silicon sensor to make a module. The radiation hard n-in-p micro-strip sensors used have been developed by the ATLAS ITk Strip Sensor collaboration and produced by Hamamatsu Photonics. A series of tests were performed at the DESY-II test beam facility to investigate the detailed performance of a strip module with both 2.5cm and 5cm length strips before irradiation. The DURANTA telescope was used to obtain a pointing resolution of 2μm, with an additional pixel layer installed to improve timing resolution to ~25ns. Results will show that prior to irradiation a wide range of thresholds (0.5-2.0 fC) meet the requirements of a noise occupancy less than $1x10^{-3}$ and a hit efficiency greater than 99%.

Keywords: semiconductor; silicon; detector

1. Introduction

1.1. ATLAS upgrade for HL-LHC

The HL-LHC (High Luminosity LHC) will operate at an ultimate peak instantaneous luminosity of 7.5×10^{34} cm^{-2}s^{-1} which corresponds to approximately 200 inelastic proton-proton collisions per beam crossing (pile-up) [1]. It will be operational for more than 10 years and in that time ATLAS aims for a total data set of 4000 fb^{1}. To operate at the higher data rates, withstand the increased radiation levels and the need for high granularity to maintain low occupancy in the high pile-up environment, the current ATLAS Inner Detector (ID) [2] will be replaced by a new Inner Tracker (ITk). The ITk will be all-silicon tracking system that consists of a pixel detector at small radius close to the beam line and a large area strip tracker surrounding it.

1.2. ITK Strips System

The ITk strips system is composed of modules [3]. The strip modules are single-sided with the hybrid circuits carrying the front-end micro-electronics ASICs glued to the sensor surface. Modules are sandwiched on both sides of low mass carbon-fibre support structures with embedded bi-phase CO_2 cooling. Each module consists of multiple rows of strips with a barrel pitch at 74.5μm and ranging from 69μm to 85μm in the forward regions. The local support structures for the barrels are staves with 14 modules on each side while the endcap disks are built from petals with 9 modules of different types per side. For the central barrel region of the strips system, the strips on the inner two cylinders are 24.1 mm long (short-strips) and those on the outer two cylinders are 48.2 mm long (long-strips). The short-strip barrel modules contain two hybrids, each with ten ABCStar read-out ASICs and long-strip modules contain one hybrid with ten ABCStar.

1.3. Motivation for testing

It is important to understand the performance of the strip modules before irradiation, with the most critical parameters being the Equivalent Noise Charge (ENC) in electrons, the gain, the collected charge, the hit efficiency, and the noise occupancy. In addition to standard lab tests, the characterization of a module operated at a particle testbeam is then a vital tool for the evaluation of the module and its associated components.

2. Setup

2.1. Devices under Test

To improve the understanding of modules operating under a series of different conditions, a barrel short- strip sensor was first connected to a barrel hybrid populated with 10 ABC130 (130nm prototype) chips [4]. The sensor used was an ATLAS012 300 um thick n-in-p micro-strip sensor developed by the ATLAS ITk Strip Sensor collaboration and produced by Hamamatsu Photonics [5]. In order to compare results for long and short strips under the same conditions, a long-strip module was approximated by connecting adjacent short-strip columns with wire-bonds to form long (4.8 cm) strips. However, sections of the module were connected to only one column to allow direct comparisons between the two lengths on the same sensor connected to the same front-end ASIC (Fig 1).

In addition, mini-assemblies (called ”DAQload”) consisting of a partially populated hybrid with a single HCC130 and three ABC130s and one ATLAS12 mini-sensors was assembled. This assembly allows rapid testing without using large number of ABC130s or full size sensors (Fig 1).

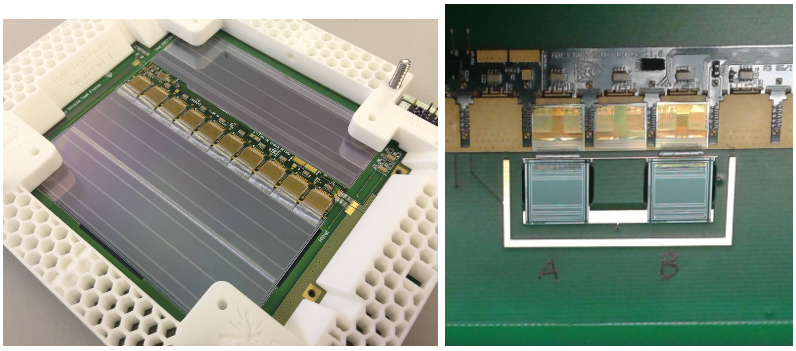

Fig. 1: Left: a fully assembled ABC130 Long- Strip Barrel Module (LS4); Right: a DAQload (DAQload10).

2.2. Testbeam Setup

For the DESY testbeams an electron beam energy of 4.4 GeV was used, with tracking performed using the EUDET-style telescopes, which consist of six MIMOSA26 pixel sensors with a pitch of 18.4 microns. An additional pixel layer with an FEI4 read-out was used to improve the timing of the telescope, allowing individual tracks to be matched to hits on the strip module under test. Tracks were reconstructed using the General Broken Lines algorithm [6], resulting in a pointing resolution of 2 microns [7]. The strip modules were mounted between the third and fourth telescope planes. All devices were read out using the current test hardware (ATLYS FPGA development board) and software (ITSDAQ), integrated with the telescope data acquisition software (EUDAQ) [8].

The size of the beam spot was chosen to be ~1 cm^2, allowing for hits on strips wire-bonded to an individual ABC130 at a time. For each strip device, threshold scans were performed with a minimum of 200,000 events taken for each threshold setting (~2k events/strip). The scans were repeated for each sensor bias voltage being studied, and then for the different positions on the sensors. Additionally, scans were performed without beam to determine the pedestal and noise levels.

3. Results

3.1. Lab Results

The module was fully characterised in the lab for noise and gain. Shown in Figure 2 is the data for both long and short strips. The increase in noise between long and short strips due to the difference in strip capacitance is in agreement with simulation.

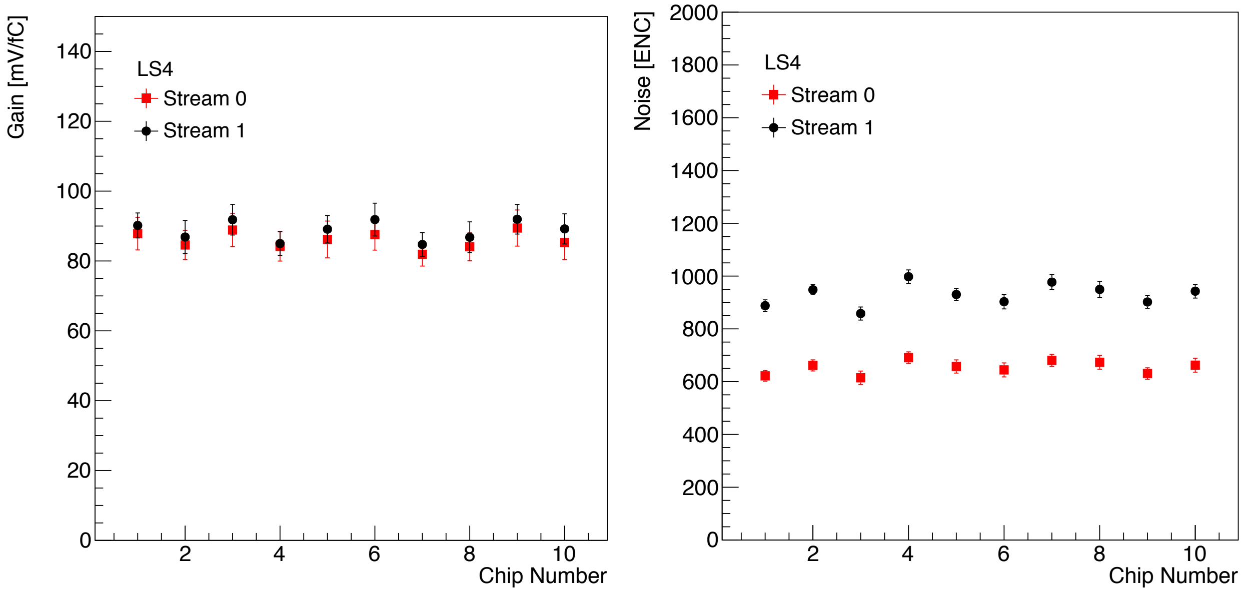

Fig. 2: Left: Gain averaged per ABC130 read-out chip for the long and short strips in module LS4. Right: Input nose in e^- ENC and averaged per read-out chip for long-strip module utilising ABC130 chips, where the long strips are read out in Stream 1 and short strips in Stream 0.

3.2. Module Testbeam Results

In all test beam measurements, threshold scans were performed and the tracks reconstructed with telescope data were used to determine the efficiency at each threshold. The efficiency is defined as the fraction of events in which a cluster is recorded whose centre is within 200 μm from the track position as it passes the device under test. The threshold scans can be used to infer the distribution of the collected charge, as the difference between two points corresponds to the fraction of electrons producing a signal between those two threshold values. The threshold scans are then fit to a skewed error function, allowing for a determination of the most probable value (MPV) for the collected charge.

The efficiency curves were evaluated at the DESY test beam for the long-strip and short-strip regions of a non-irradiated module at two different bias voltages, shown in Figure 3. The differences in the curves arise from different

ABC130 chips attached to the short and long strips. The noise occupancy as a function of the threshold is fit with an error function; the shape describes the distribution well with a minimal non-Gaussian tail in the noise spectrum (3). The signal-to-noise ratio yields values of 30 to 35 for a sensor bias voltage of 400V. [1]

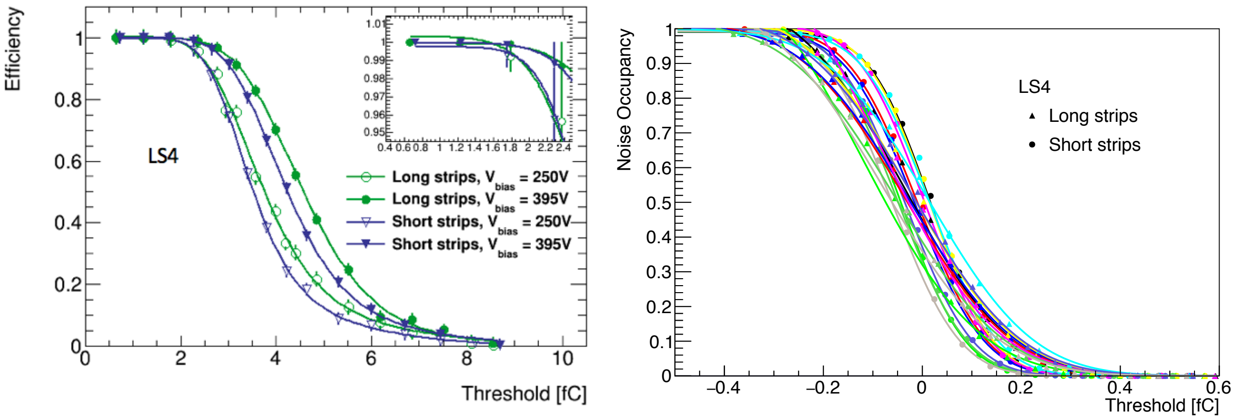

Fig. 3: Left: The efficiency versus the threshold for two bias voltages and two positions on the module LS4. Right: Fit of the noise occupancy vs. threshold distributions with an error function (ERFC).

The excellent pointing resolution from the telescope allows for investigation of the behaviour within and between the strips. Figure 4 shows the hit occupancy as a function of the distance a track passes from the centre of a strip.

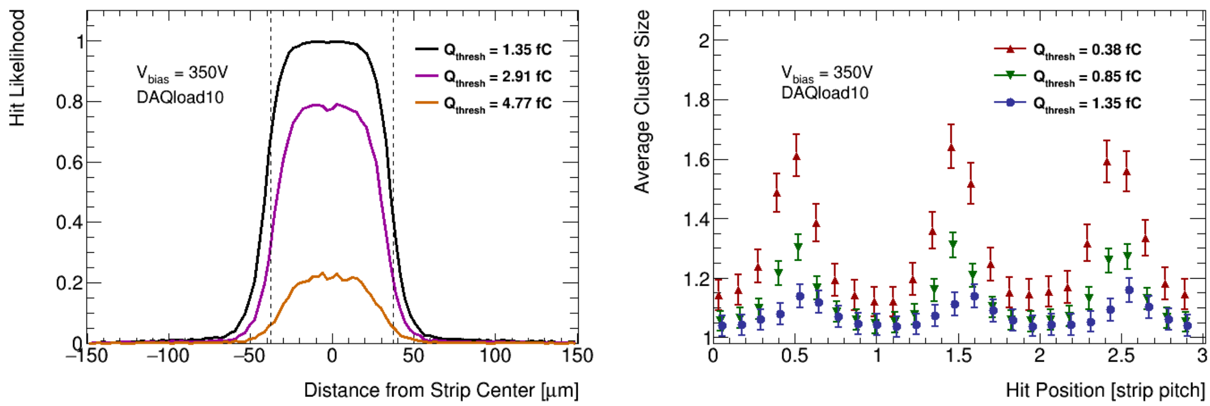

Fig. 4: left: Hit occupancy, as a function of the residual from the track to the centre of the strip. The strip width is indicated with dashed lines. Right: Cluster size versus in-strip position. Average cluster size versus hit position, along three strips. The integer position values correspond to the centre of the strips.

This is defined as the probability that a hit will be recorded in a given strip. The curves show a flat efficiency in the central region of the strips, and a width consistent with the strip pitch of 74.5 micron. There is a drop in the efficiency near the strip edges which is attributable to the effect of charge sharing between strips. This can also be seen by looking at the average cluster size for lower thresholds, as shown in Fig 4. The likelihood of two-strip clusters increases for electrons passing in between two strips, where charge sharing is the highest.

4. Conclusions

An ATLAS ITk Strip barrel module was fully evaluated at a testbeam for electrical performance. The efficiency is greater than 99% for thresholds of up to 2.5 fC at a bias voltage of 400V. The signal-to-noise ratio yields values of 30 to 35. In addition, a flat efficiency in the central region of the strips with a width consistent with the strip pitch is measured. The results are as expected for a non- irradiated module and are well in agreement with the requirements for the ITk. Further testbeams with irradiated parts are necessary to validate the modules and its components for end of life performance at the HL-LHC.

5. Acknowledgements

The research was supported and financed in part by Canada Foundation for Innovation, the National Science and Engineering Research Council (NSERC) of Canada under the Research and Technology Instrumentation (RTI) grant SAPEQ-2016-00015; the National Key Program for S&T Research and Development (Grant No. 2016YFA0400101) of China and CAS-Helmholtz Joint Research Group; the Ministry of Education, Youth and Sports of the Czech Republic coming from the project LM2015058 - Research infrastructure for experiments at CERN; the DST/NRF in South Africa; the Spanish Ministry of Economy and Competitiveness through the Particle Physics National Program, ref. FPA2015-65652-C4-4-R (MINECO/FEDER, UE), and co-financed with FEDER funds; the UK's Science and Technology Facilities Council; USA Department of Energy, Grant DE-SC0010107; and the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement no. 654168. The measurements leading to these results have been performed at the Test Beam Facility at DESY Hamburg (Germany), a member of the Helmholtz Association (HGF).

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