Testbeam Studies with Silicon Strip Module Prototypes for the ATLAS-Detector towards the HL-LHC

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Abstract

In this report I give a brief overview about my studies as a summer student at CERN from July to September 2016. I worked on testbeam studies with prototype modules for the High-Luminosity LHC (Phase-II) upgrade of the silicon strip tracker of the ATLAS detector.

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1 Introduction

During its first operation period (so-called run 1), the LHC has delivered an integrated luminosity of around $25\,\mathrm{fb}^{-1}$ at a center-of-mass energy $\sqrt{s} = 7$ and 8 TeV to the two general purpose experiments ATLAS [1,2] and CMS [3] that could be used for physics analysis, leading also to the Higgs Boson discovery in 2012 [4,5] and as a consequence of that to the Nobel Price for François Englert and Peter Higgs in 2013 [6]. The LHC continues now its operation in what is called run 2 and later in run 3 at increased $\sqrt{s}$. Starting from around 2025 on it will receive a major upgrade to what is then called the High-Luminosity-LHC (HL-LHC) where one aims to increase the instantaneous luminosity up to $7.5 \cdot 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. To cope with the high luminosity, also the ATLAS detector will recieve an upgrade to an all-silicon tracker in the inner detector region, replacing the currently installed TRT[1] and SCT[2] with radiation hard silicon pixel and strip trackers.

This report summarizes my work as a summer student at CERN from July to September 2016 in the ATLAS Silicon Strip Testbeam Group. Therefore it aims at rather giving the reader an overview than a detailled insight in all the studies that have been done. I assume the reader has basic knowledge of silicon detectors.

2 The Module Prototypes

A lot of different module prototypes have been tested during these studies, for the central region, so-called barrel, and for the forward region, so-called endcap. Because of size limitations, this report will mainly focus on a full sized prototype for the barrel region. The silicon sensor is made out of n-doped strips in a p-doped silicon bulk to prevent type inversion, has a thickness of $\sim 320\,\mu$m and covers an area of $97 \cdot 97\,\mathrm{mm}^2$. The strips are $\sim 20\,\mu$m thick and have a pitch of $74.5\,\mu$m. The binary readout chip with two streams having 128 channels has been manufactured in 130 nm CMOS technology and sits on top of the sensor together with the control electronics. The module has 4 strip segments with a length of 24 mm each, where two of the segments have been bonded together to have a long strip region and one of the short strip segments is not bonded to the readout. There are two identical modules, one of them (called LS3) has been irradiated at the CERN PS with $\sim 24\,\mathrm{GeV}$ protons at -20 °C up to a dose of $7.8 \cdot 10^{14}\,\frac{\mathrm{neq}}{\mathrm{cm}^2}$ with a total ionizing dose of 36.1 Mrad (which one expects at an integrated luminosity of $3000\,\mathrm{fb}^{-1}$ at the end of the HL-LHC phase for the barrel layers), whereas the other module (LS4) stayed unirradiated as a reference. A picture of the LS3 module can be seen in Figure 1, where the beam positions are indicated by the blue circles. The position on the short strips is in the following called position 1, whereas the position on the long strips is called position 2.

[1] **T**ransition **R**adiaton **T**racker
[2] **S**emi**C**onductor **T**racker

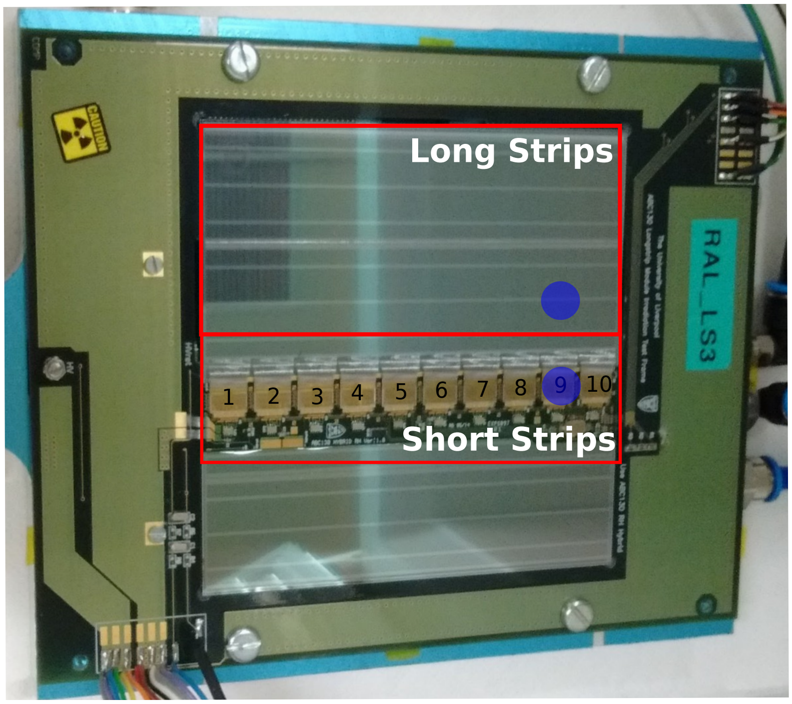


Figure 1: *Picture of the irradiated full size barrel module (called LS3). The long- and the short-strip region is marked, as well as the ASIC[3]numbering used. The rough beam positions are indicated by the blue circles.*

3 About the Testbeam at CERN

To get an insight into the performance and functionality of the developed modules, especially when using an external trigger and minimal ionizing particles (MIP), a series of testbeam studies has been started. The testbeam studies at CERN have been done at the H6-Beamline, where the beam from the SPS is shot on fixed targets to provide at the end a secondary beam of $\sim 120\,\mathrm{GeV}$ pions using installed beam optics. More information about the beamline can be found under Reference [7]. The DUT[4] has been put into a cooling box and adjusted inside the telescope used for the studies. A sketch of the setup can be seen in Figure 2, as well as a real picture of the setup is shown in Figure 3. In addition to the six telescope planes, a pixel sensor (FE-I4) with a shaping time of 25 ns has been added to the setup, since the telescope only has an integration time of $115.2\,\mu$s and one wants to test the module under LHC conditions (25 ns between the bunch crossings). One of my first tasks as a Summer Student was do design a holding to be able to place the DUT inside the cooling box. The modules have been tested in operation with various temperatures, depletion voltages, as well as thresholds for the binary readout. In addition to the beam tests, several electronical tests have been done with the module in the testbeam area, as

[3]**A**pplication-**S**pecific **I**ntegrated **C**ircuit
[4]**D**evice **U**nder **T**est

well as in the lab. In my Summer Student project I analyzed this data.

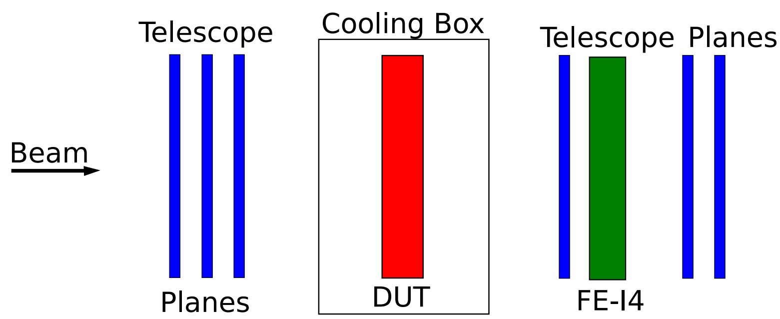


Figure 2: *Schematic setup inside the beam line. The distances are not to scale.*

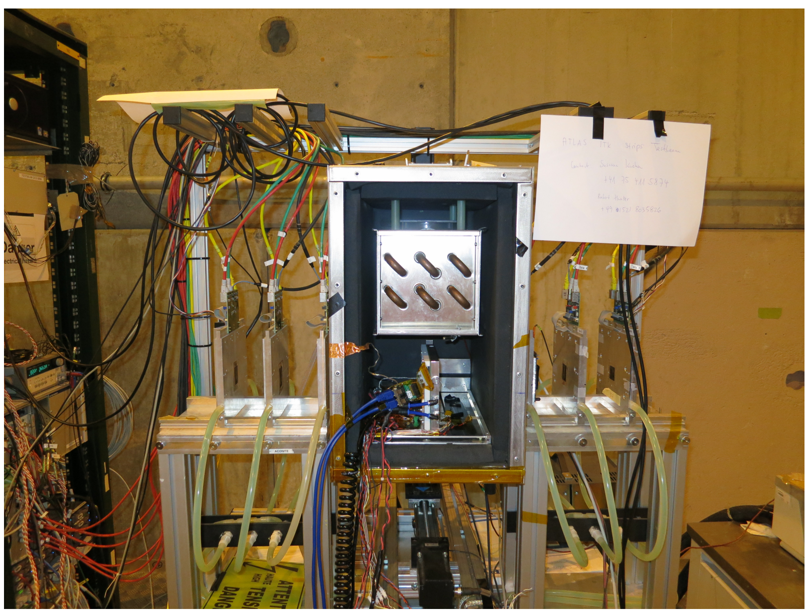


Figure 3: *Picture of the testbeam setup at CERN as drafted in Figure 2.*

4 Reconstruction

For the reconstruction of the data, the software provided by the used EUTelescope was used in combination with the GBL[5] algorithm for track fitting. Since this was not part of my work, I only mention it here briefly, however, more information about the reconstruction can be found in Reference [8]. The reconstruction provides information about the local hits on each plane (telescope, DUT and FE-I4), as well as the fitted track positions.

[5]**G**eneral **B**roken **L**ines

5 Analysis

A dedicated track-based analysis of the testbeam aims at using the telescope as a Reference to test the DUT by being able to compare the measured hits on the DUT with the reconstructed tracks from the telescope in different parametrizations. I used a framework provided by Richard Peschke from DESY[6] to build up a code to analyze the reconstructed data (for more information see Reference [9]). In order to understand in detail the results shown later, I want to define in this section a few necessary parameters.

Efficiency First of all, the analysis software looks at the fitted track positions on the FE-I4 and looks for corresponding local hits in a certain range ($\pm$ 1 pixel). It then extrapolates these hits into the local coordinate system of the DUT and looks there for matches in a range of 10 strips. The efficiency ϵ is then defined as

$$\epsilon = \frac{\text{\# matches on the DUT}}{\text{\# matches on the FE-I4}} \quad .$$

Noise Occupancy The noise occupancy is defined to be the probability of having a hit on a strip caused by noise. Therefore one used special runs without beam and calculated the noise occupancy η as

$$\eta = \frac{\text{\# hits on the DUT}}{\text{\# events} \cdot \text{\# strips}} \quad ,$$

where an event stands for one integration time of 25 ns.

Fit Function To fit the efficiency curves, the skewed complementary error function, taken from Reference [10] as

$$\epsilon = \epsilon_{\text{max}} \cdot f\left(x \left[1 + \underbrace{0.6 \cdot \frac{e^{-\xi x} - e^{\xi x}}{e^{-\xi x} + e^{\xi x}}}_{\text{Empirical Landau Con.}} \right] \right) \quad ,$$

has been used. The variable f is the complementary error function, x is defined as $(q_{\text{thr}} - \mu)/(\sqrt{2}\sigma)$, where μ and σ are Gaussian parameters and q_{thr} is the binary threshold set, $\epsilon_{\text{max}} \in [0.0; 0.5]$ and the additional tanh-term takes empirically care of the theoretically needed Landau convolution (energy loss due to ionization).

6 Results

In a first step, the noise of the modules at a charge deposition of 1.5 fC has been calculated using a responce curve (RC) measurement (which determines the input noise using a

[6]**D**eutsches **E**lektronen**sy**nchrotron (www.desy.de)

calibration charge) as an electrical test. In Figure 4, the results are shown for ASICS 7 to 9 of the LS4 and LS3 module (since there was an issue with the bonding for some ASICS). As one can see the noise is in both cases higher for the long strips, as expected. One can also clearly see an increase from the values of the non-irradiated module to the ones of the irradiated. Next, the efficiency and noise occupancy are calculated as described in Section 5 in dependency of the threshold voltage set. The results for the short and long strips at a bias voltage of 500 V can be seen for the irradiated LS3 module in Figure 5, where the efficiency has been calculated on the track based method previously described. One expects the most probable values (MPV) to get smaller with irradiation but they can be improved with annealing. Later, the threshold voltages can also be converted to theshold charges, using the RC measurements done previously and in the same process the mean noise with absence of a signal (called pedestal) can be subtracted. The analysis of the data was very sucessfull and lead to a great insight into the performance of the module with many interesting studies to follow. The results I produced during my time at CERN, I presented and discussed in various telephone meetings of the group and are also considered to be included in the Technical Design Report of the strip tracker which is under preparation in the ATLAS Collaboration.

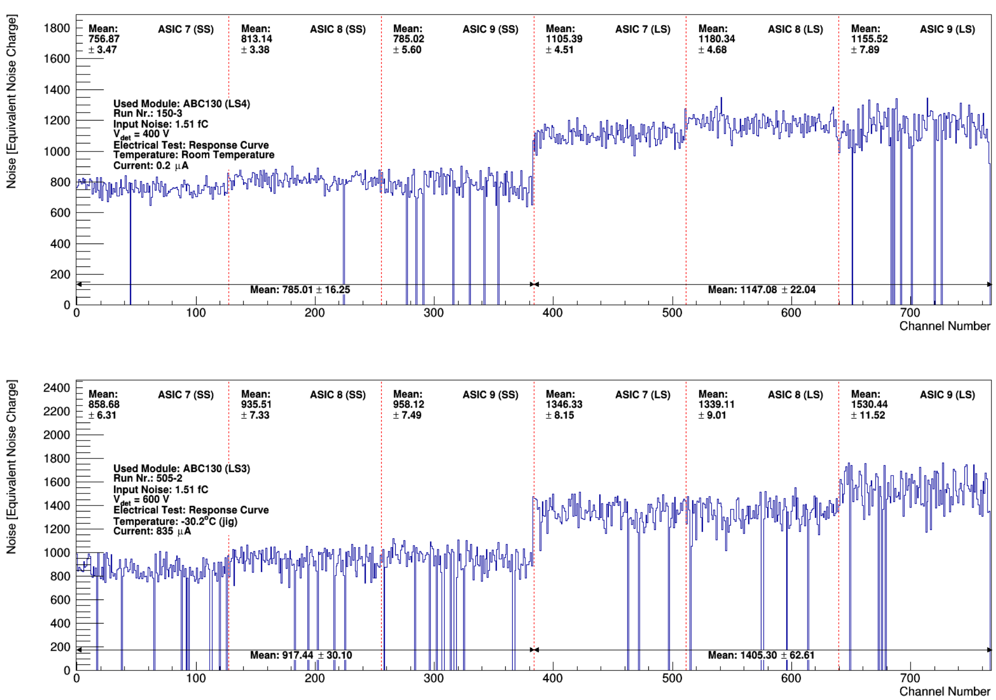
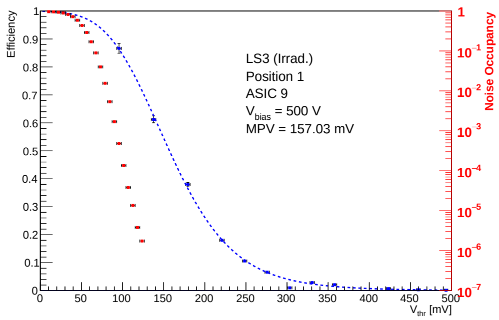


Figure 4: *Noise values and their statistical uncertainty from RC measurements for the unirradiated LS4 module (upper Figure) and the irradiated LS3 module (lower Figure).*



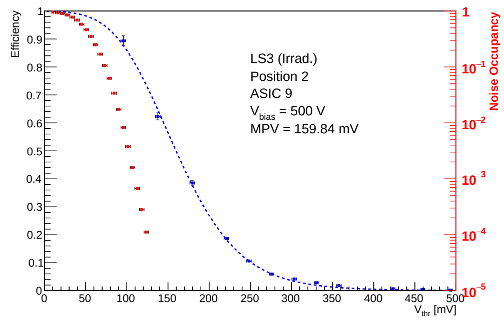


Figure 5: *Track based efficiency and noise occupancy (pedestals not yet subtracted) for the irradiated LS3 module at a bias voltage of* 500 V *for the short strip region (left) and the long strip region (right).*

7 Acknowledgements and my Experience at CERN

At the end of this report and also of my summer at CERN I want to thank all the people that made it possible for me to have an unforgetable experience here. First and foremost I want to thank Dr. Susanne Kühn for giving me an all around insight into running a testbeam as well as her remarkable supervision and helpful advices. Likewise I want to thank the whole testbeam team that helped me solving all the small and large problems I had during my work. Last but not least a big "Thank you" goes to all the people I met here during my time and who made me enjoy my after-work-hours as well.

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