CERN Summer Student Program

Developement of a Plotting Tool
Project Report

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Abstract

Currently, the preparation for the upgrade of the High Luminosity Large Hadron Collider (HL-LHC) is ongoing. To prepare the ATLAS experiment for the intensified amount of collisions, the Inner Detector (ID) will be replaced by an all-silicon semiconductor detector, the Inner Tracker (ITk). The HL-LHC will bring scientific advancement demanding the new Pixel Detector to operate in extreme conditions. To secure the reliable operation of the ITk Pixel Detector, it is essential to test the modules beforehand. A pivotal aspect is electrical tests which secure the operational quality of the modules.
In order to glean significant insights from electrical tests and make such data accessible in an intuitive manner, it's imperative to utilize a robust plotting and analysis tool. This tool, which features flexible input parameters, is a major component of my responsibilities as a CERN Summer Student, a task undertaken in close collaboration with Shigeki.

1 Introduction and Motivation

The majority of the research done at the CERN Nuclear Research Centre aims to acquire scientific fundamentals about the Standard Model (SM), the currently most successful theory to describe particles and their interactions. In order to test predictions made by the Standard Model (SM), the Large Hadron Collider (LHC), the biggest and most powerful particle accelerator ever, accelerates protons or heavy ions up to very high energies. At nearly the speed of light, bunches of particles are brought to collision. The resulting fragments and new particles are detected and tracked in ingenious experimental setups featuring different kinds of detectors, inter alia, the ATLAS experiment. CERN plans to take the first data with the upgraded LHC with higher luminosity, the High-Luminosity Large Hadron Collider (HL-LHC) from 2029. With the HL-LHC, the experiments at CERN face new challenges. ATLAS expects a peak instantaneous luminosity of $7.5 \cdot 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ which is 5 times higher than the current instantaneous luminosity indicating more radiation damage in the detector and higher pileup. To prepare for the upcoming intensified amount of radiation, the current Inner Detector (ID) of the ATLAS experiment is upgraded to an all-silicon Inner Tracker (ITk). As a result of the intensified radiation, it is necessary to increase the radiation hardness. The ITk contains hybrid modules. These modules are sensors, bump bonded with frontend (FE) readout electronics. To ensure reliable and durable functionality under such extreme conditions of operation as near the beamline, the modules are tested beforehand, especially in terms of their electrical properties.
The increase in luminosity will benefit the statistical uncertainty of measurements. On top of that, more frequent observations of rare phenomena are predicted. This includes the Higgs boson precision measurements such as precise Higgs boson couplings and Di Higgs production which also allows for Higgs self-coupling measurements. Moreover, the search for new physics and physics beyond the Standard Model (BSM) such as Supersymmetry will profit from the HL-LHC program.

2 ITk Pixel Detector

The current ID system will be replaced by an all-silicon Inner Tracker (ITk). Besides the outer barrels and the outer endcaps, there is a replaceable inner barrel system. All of them are made up of more than 9000 modules (thin Silicon and FE chips) comparable to the one shown in Figure 1. The majority of these modules are n-in-p planar quad modules, meaning, that there are 4 chips per module. These chips are called RD53C. To allow high precision, each chip is segmented into 384 $\times$ 400 pixels making a total number of 153,600 pixels. They comprise a hybrid design, which means, that the sensor is directly connected to the readout electronics via small metal bump bonds. The whole detector system is cooled with CO_2.

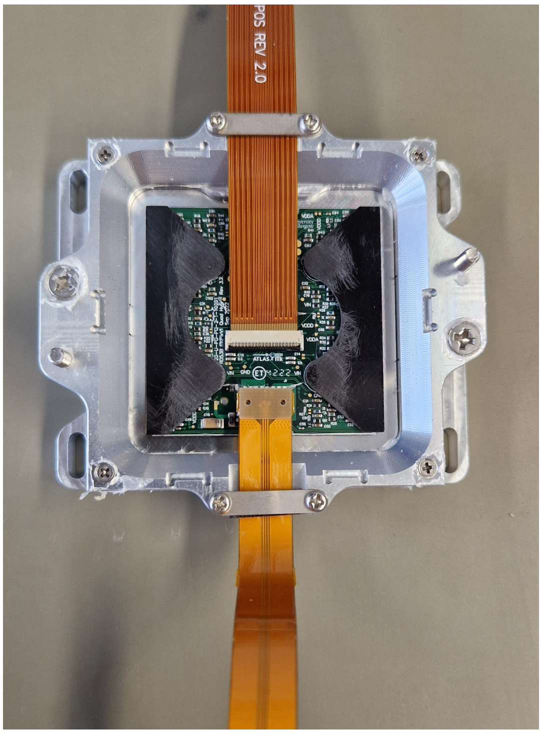

Figure 1: One of the modules on which electrical QC was performed in its carrier

Moreover, the ITk has an advanced serial powering system, which together with the reduced number of readout cables, optimises the total number of cables in the Inner Detector regions.

3 Scans and Tests

The key points to ensure the operational quality of the modules are the electrical tests and scans performed to verify the functionality of the chips. As shown in Figure 2, multiple electrical tests are part of the production chain at both, warm and cold temperatures. The readout is done with the YARR software which is based on FPGAs.

Warm and Cold Tests

Concerning the testing, cold and warm tests are differentiated. This refers to the temperature the module is cooled to during the performance of the test. Warm tests are performed with a module temperature of 20 °C whereas cold tests are performed in an environment of −15 °C. In both cases, the module has to be cooled because otherwise, its power consumption heats the module quickly.

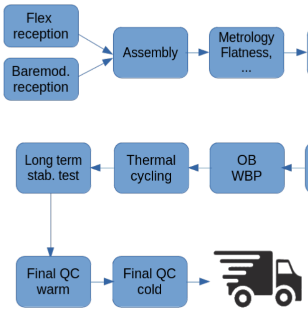

Figure 2: The schematic production flow for the ITkPix quad modules

Digital and Analog Scan

These two tests verify the basic operation of all pixels. The chip can inject charge into the analogue and in the digital part of the module. Usually, for YARR, 100 signals are injected. In case a pixel measures more than 102 or less than 98 signals, the corresponding pixel is labelled “bad“. These pixels are excluded from the measurements, which is called masking. The last possible result is that some pixels show no hits in the analogue scan. These pixels are called “dead“. Dead pixels occur for example when the module is mechanically damaged.

Threshold Scan

All sensors have an adjustable threshold that is set to a fixed value. A threshold is a minimum amount of charge that counts as a hit. The threshold is given in units of elementary charge.
As not every electron, that is randomly ionised, should be counted as a signal, the threshold is set to a certain value high enough that it is only reached by incoming high energetic ionising particles. Below this defined threshold, the discriminator in the chips suppresses the noise that occurs.
The threshold scan probes the value of the threshold for every pixel.

Noise Scan

As briefly mentioned above, not all pixels will have the defined number of hits in an analogue scan. The noisy pixels register hits without a signal. Such pixels are labelled “bad“ in an analogue scan and are masked using a noise scan. After masking, problematic pixels do not occur in the occupancy map in the further tests. As a consequence, noisy pixels do not influence their neighbouring pixels’ results.

Disconnected Bump Scan

A continuous problem resulting from the hybrid design of the detector is disconnected bumps. Usually, the small metal bumps connect the chip and the sensor. The connection is created by melting the metal bumps to permanently connect sensor and chip. When the bumps are disconnected, the electric charge can not be processed. As this limits the functionality of the module, it is important to know if any of the four chips has disconnected bumps. To find out, the disconnected bump scan is performed.
For disconnected bump scan, the capacitive behaviour of a pixel is probed when injecting charge in the neighbouring pixels. A pixel with disconnected bump will not see the influence of the charge injected in the neighbouring pixels. Thus, the detection works indirectly, via the pixels crosstalk.

4 Plotting tool

To extract relevant and meaningful data from the electrical tests and to present it in an intuitive and accesible way, we need a plotting and analysis tool. This plotting tool is the major part of my work done here at CERN, together with Shigeki. In general, we took care, that the plotting tool has a flexible input, meaning multiple possible different input types and formats allowing to plot data from different institutes around the world. We implemented multiple options such as FE dividing lines or adjustable axis ranges. Furthermore, we kept the hard coded items to a minimum.
In a first step, the json data is converted to root data. Secondly, a config must be created. In this config, the stages and modules are specified and the path to the data is given. The config now has the official stages names defined. Next, the IV plotting and the plotting of the YARR scans can be performed. For detailed information on the plotting tool, we wrote a README. On top of that, the GitLab-repository is linked here.

4.1 IV Plotting

With the IV tool, it is possible to compare up to 7 stages or modules. The flexible plotting tool can handle different possible data formats. We implemented a lucid summary page. Besides several cosmetic changes, like title position and axis label size and position, a pivotal aspect of the IV plotting is the temperature correction of the current.

$$I_{leak} = I_{meas} \cdot \left(\frac{T_{norm}}{T_{sensor}}\right)^2 \cdot \exp\left[-\frac{E_{gen}}{2k_B}\left(\frac{1}{T_{norm}} - \frac{1}{T_{sensor}}\right)\right] \tag{1}$$

$$\sigma_{I_{leak}} = \sigma_{I_{meas}} \cdot \left(\frac{T_{norm}}{T_{sensor}}\right)^2 \cdot \exp\left[-\frac{E_{gen}}{2k_B}\left(\frac{1}{T_{norm}} - \frac{1}{T_{sensor}}\right)\right] \tag{2}$$

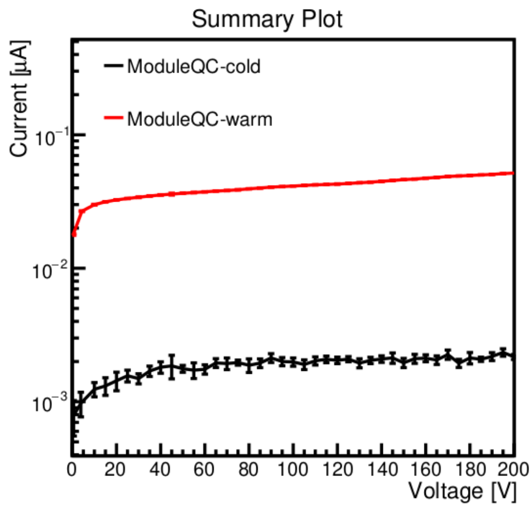

Figure 3: IV-curves before temperature correction

As shown in Figure 3, the uncorrected currents differ mainly because the IV curves were taken at different test temperatures. Equation 1 shows the relation between measured current I_{meas} and real current I_{leak}. The uncertainties σ_{leak}, that are plotted as error bars, follow a similar dependence as presented in Equation 2. Figure 4 shows the linear as well as the logarithmic plot of the corrected currents. The summary plot on the left compares the curves directly. The currents are all normalised to 20 °C.

4.2 YARR Scans

With the YARR plotting tool, it is possible to compare up to 6 modules or stages, one less than for the IV plotting, due to an additional summary plot. The YARR scans first of all show the Occupancy maps or 2 D histograms (Figure 5 leftmost plots). For optimal comparison, they have the same colour bar range. Next, there is the number of pixels per occupancy. And finally, there is the number of failing pixels per FE and stage and their evolution. As an example, Figure 5 shows an analog scan. For the threshold scan, the threshold map and the noise map are shown first as in Figure 6. In this case, the first summary plot shows the threshold and noise distribution respectively. The second summary plot shows the evolution of the mean threshold or noise per FE and stage. Also lately added to the YARR plotting are the Gaussian fits of the noise or threshold distribution per FE or module and their evolution presented in Figure 7. This is still to be added to the pdf-file created in the end.

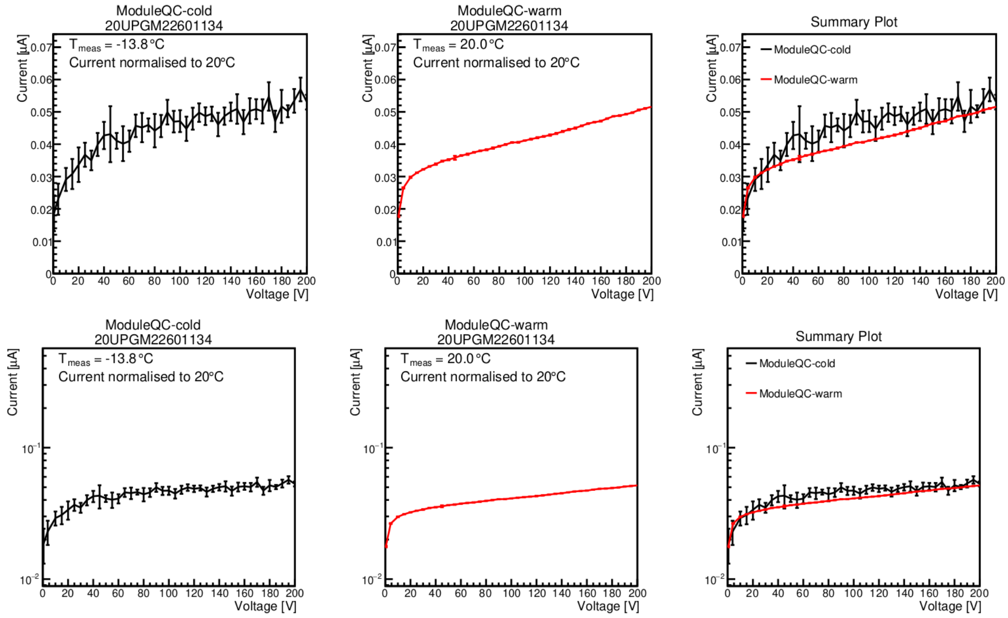

Figure 4: Linear and logarithmic scaled corrected IV curves

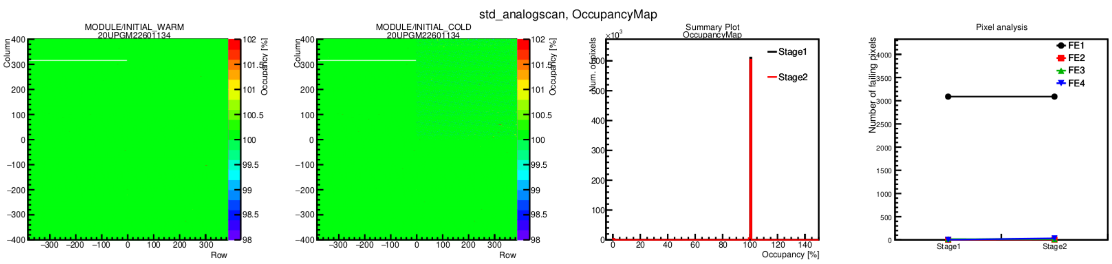

Figure 5: Analog scan plotted with the new plotting tool

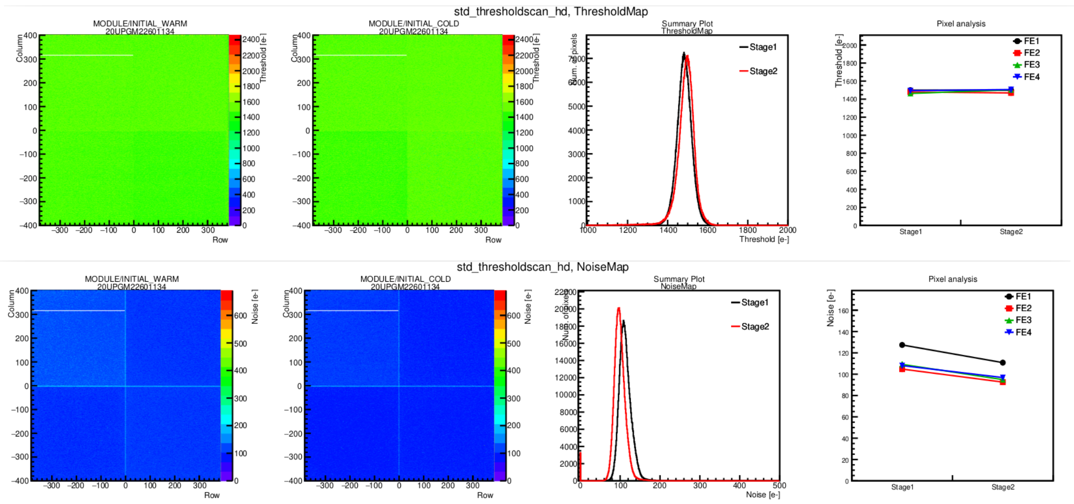

Figure 6: Threshold scan and noise scan plotted with new plotting tool

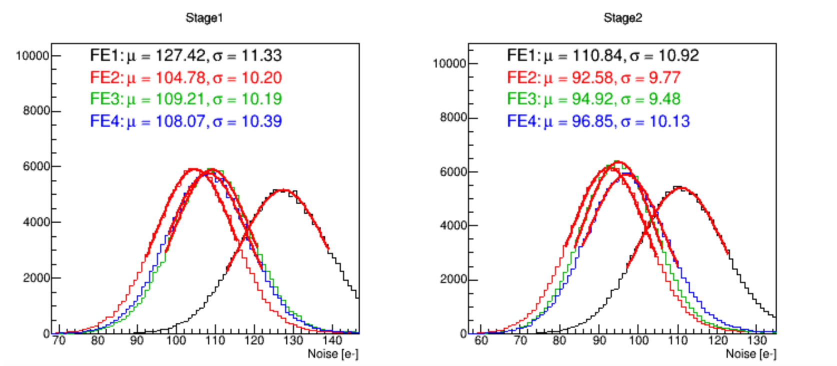

Figure 7: Gaus fit of the noise distribution per FE and stage

5 Summary and Outlook

We have a plotting tool ready to be used for both, IV and YARR scans. There are still some points that Shigeki and I want to add to the plotting tool such as dead pixel analysis or X-ray scan. In case of feedback and inspiration please do not hesitate to reach out to Shigeki or me. We are always happy to receive constructive criticism. I definitely improved my Python and my root skills working on the plotting tool, one of the biggest coding projects I have worked on so far.

Acknowledgement

I would like to thank Dr. Hassnae el Jarrari and Dr. Susanne Kühn for giving me the opportunity to work on such an interesting topic. Thank you for choosing me as a CERN Summer Student. It is really a dream coming true for me. I am grateful for the advice also beyond the scope of the work. Next, I would like to thank Shigeki. Your groundbreaking work is the base of my project. Thank you for introducing me to the code and working with me on the plotting tool. On top of that, I would like to thank Dr. Milou van Rijnbach for the feedback and coordination of the plotting tool. Moreover, I would like to thank Florian for his wise ROOT and Git expertise as well as for his patience. In general, I would like to thank the whole group. I felt really welcome and enjoyed the time here. I am optimistic, that it was not my last time at CERN and I am already looking forward to the next time.