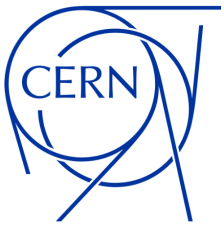

Commissioning of Test Bench for Reception Test of ATLAS ITk Pixel OB Loaded Cells

Summer student project
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Under the guidance of Susanne Kuehn and Hassnae El Jarrari

Abstract

This paper reports the commissioning of a thermal test bench for reception tests of loaded module cells, which will be used to construct the Outer Barrel region of the pixel Inner Tracker (ITk) detector of ATLAS. This all-silicon detector will replace the currently functional tracking system called the Inner Detector during the High Luminosity phase of the LHC. During commissioning, all tested sub-systems of the test bench were found to perform as expected, although certain aspects—such as the air and light tightness of the test box—still offer room for improvement. One of the most thoroughly tested components was the interlock system, which detects critical events where setup requirements are not met and responds by shutting down the necessary test bench systems, thereby ensuring the safety of the loaded cells. To validate the functionality of the novel test bench setup, electrical tests were conducted and the results were compared with those from an established thermal test bench. Based on this initial comparison, the novel setup appears able to reliably reproduce test results, thereby validating its functionality.

Geneva, Switzerland
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Contents

1 Introduction

1.1 HL-LHC and ITk

In preparation for the High Luminosity Large Hadron Collider (HL-LHC), the ATLAS experiment will undergo its Phase II upgrade [1]. As part of this upgrade, the currently functional tracking system, called the Inner Detector, will be replaced by an all-silicon Inner Tracker (ITk) detector. The ITk detector can be divided into two sub-detectors, one consisting of pixel sensors and the other one consisting of strip sensors. Figure 1 shows the full ATLAS ITk layout [2]. Indicated are the different sub-detectors forming the pixel sub-system: the Inner System in yellow, the Outer Barrel (OB) in blue and two Outer End-caps in green. The devices of interest in this report are the pixel loaded cell modules which will be used to construct the Outer Barrel and are described in more detail in the next section.

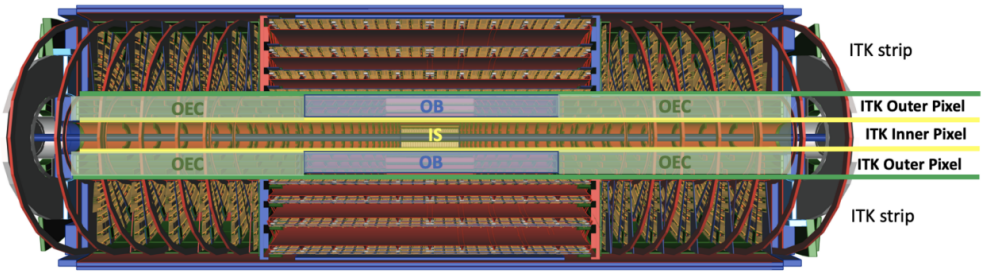


Figure 1: Full ATLAS ITk layout, with the pixel sub-detectors denoted in colour, image form [2].

1.2 ITk Pixel OB Loaded Module Cells

To achieve high precision and tracking efficiency under the high pile-up conditions expected at the HL-LHC, while keeping the material budget as low as possible, the different ITk sub-detectors are constructed of several local support structures [3]. These structures consist of Carbon Fiber Reinforced Polymer (CFRP) skeletons and cooling pipes, providing mechanical support and cooling, respectively. Rather than attaching bare silicon sensors onto these structures, they are combined with other structures which provide support and enable cooling. Figure 2 illustrates the assembly of the quad module loaded cells, the fundamental units that populate the local support structures. The silicon sensors are bump-bonded onto four front-end chips into so-called bare modules. The sensors used in the OB are squared n-in-p planar pixel sensors with a pitch of $50\,\mu\mathrm{m}$ manufactured in a $65\,\mathrm{nm}$ CMOS technology. The thickness depends on their location in the pixel detector. The ones used to constitute the first layer (closest to the interaction point) are $100\,\mu\mathrm{m}$ thick, whereas the ones constituting layer two to four have an active thickness of $150\,\mu\mathrm{m}$. The bare modules are combined with the flex PCBs (Printed Circuit Boards) which provides the interface between the bare module and power and data service cables [4]. The combination of the bare module and the PCB is referred to as the quad module. The quad module is then combined with a bare cell, which holds the module in precise location on the local support and provides mechanical support by means of a graphite tile and enables cooling by providing contact to the cooling pipe by means of a cooling block. The assembly of the quad module and bare cell by means of adhesive is referred to as the quad module loaded cell, which is the subject of this report.

1.3 Quality control testing

Once fully constructed, the ITk pixel OB will consist of 4772 modules. In order to ensure proper functionality of the final ITk detector, the quality of each of these modules should be controlled. To this end, quality control (qc) setups are constructed. The aim of the project described in this report was to finalize the installation and commission one of these setups for the ITk pixel OB loaded module cells.

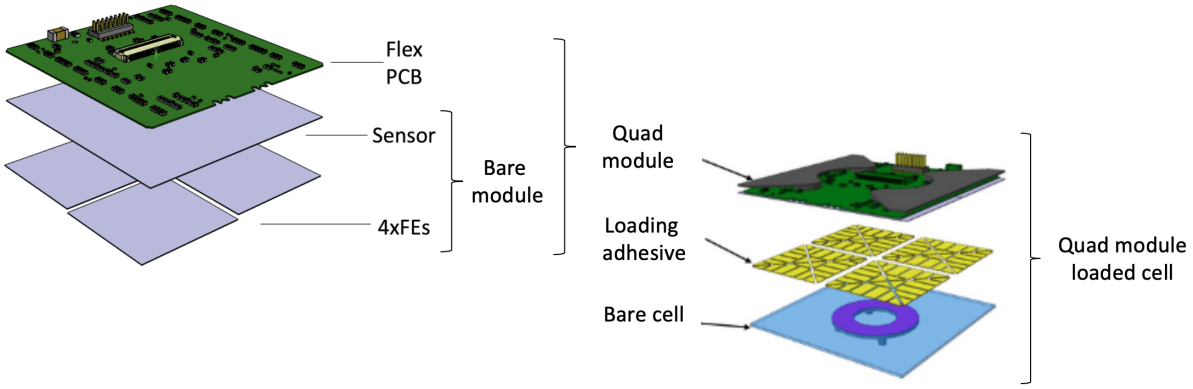


Figure 2: Assembly diagram of the quad module loaded cells, i.e. the objects populating the local support structures in the OB of the ITk pixel detector. Illustration based on [1] and [5].

2 QC setup

2.1 The thermal test bench

The qc setup which is developed for the quality control of the ITk pixel OB loaded module cells is called the thermal test bench, of which a picture can be found in Figure 3. The test bench design allows for the operation and testing of multiple modules at the same time at various steps in the production. More precisely, four modules can be placed in the bench simultaneously; for that reason the test bench is also called the quad setup. This multi-module feature of the qc setup is essential to cope with the large module throughputs during production [6].

The thermal test bench has been designed to carry out electrical and thermal tests to ensure module operation without defects and evaluate the heat dissipation efficiency at the silicon-graphite interface, respectively [7]. In order for the test bench to provide the proper environment for these tests, it has to be equipped with several systems. A picture of the test setup with the main components denoted in white is shown in Figure 3. A more detailed description of the sub-systems of the test bench and their functionalities will be given in section 3.1, which outlines the commissioning of the test setup. A list of all components out of which the setup is constructed can be found in the setup installation manual [8].

2.2 Monitoring

The test bench box is equipped with temperature sensors (PT100 and NTC), door switches, humidity sensors (RH) and light sensors. Data recorded by these sensors are collected by the interlock system, stored in InfluxDB, and visualized on the Grafana dashboard as well as on the interlock GUI. The Grafana dashboard provides an overview of the time evolution of several test bench parameters, as can be seen in Figure 4a, whereas the interlock GUI is a node red GUI used to monitor all parameters and interlock signals. Figure 4b shows the interlock GUI in its untriggered state.

The primary function of the interlock system is to detect critical events in which test setup requirements are not met and to respond by shutting down the necessary test bench systems, thereby ensuring the safety of the loaded cells. This important test bench functionality is extensively examined during the commissioning stage of the setup, described in the following section. During the commissioning tests the interlock GUI is used to check the interlocks reaction, and the Grafana dashboard provides time evolution plots of the different setup parameters.

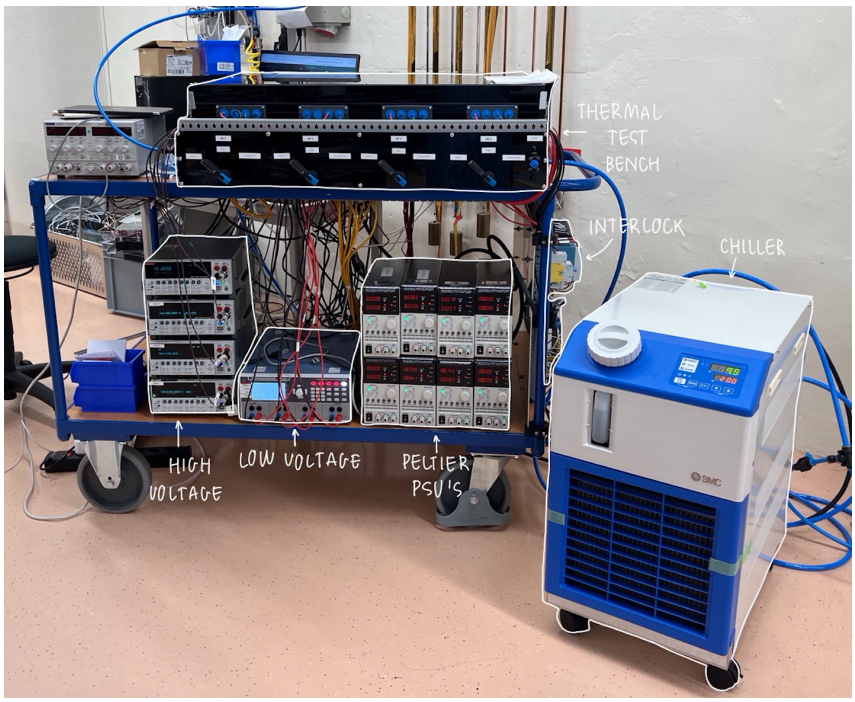


Figure 3: Thermal test bench installed in cleanroom in building 154 at CERN. Main system components to be tested during commissioning are highlighted in white.

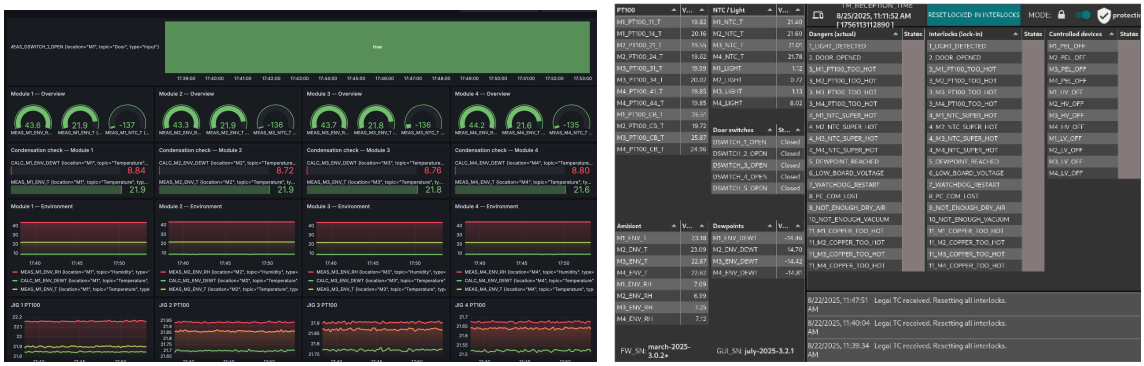
3 Results

3.1 Commissioning of the test bench

Prior to testing loaded cells in the setup, the functionality of the test bench itself should be validated. This is done by performing several tests on the different sub-systems of the test bench during the commissioning stage of the setup. This section outlines the results of the tests described in [**nicola_tests**]. Apart from hardware interlock qualification steps, the document also provides a description of the test stage of the setup. Namely, while carrying out the different commissioning tests, no modules should be present in the test bench. As it is very well possible that some systems of the bench are not yet performing as expected, potentially causing damage to the module. To simulate the module's behaviour in the test bench without risking damage to real modules, a module imitator is used. This imitator consists of a heating resistor (also referred to as "heating element") placed on the jig[1] with thermal paste and a $10\,\mathrm{k}\Omega$ resistor connected to the NTC input. An image of the test bench in test stage, with the module imitators in place, can be seen in Figure 5. The temperature conditions in the test bench box also differ between different tests. Different conditions can be created by adjusting the cooling system settings. For warm conditions, the chiller, providing cooing liquid to the cooling block assemblies in the jigs, is set to $10\,^{\circ}\mathrm{C}$ and the PID control, allowing to change the temperature of the Peltier modules which are also part of the cooling block assemblies in the jigs, is set to $20\,^{\circ}\mathrm{C}$. Whereas for cold conditions, the chiller is set to $10\,^{\circ}\mathrm{C}$ and the PID control to $-5\,^{\circ}\mathrm{C}$. A screenshot of the unengaged interlock GUI under both conditions can be seen in Figure 6.

The first investigated sub-system is the *dry air circuit*. By flushing the box with dry air, the indoor dew point is lowered by humidity reduction, thereby preventing condensation at low module temperatures. For the test bench to be convenient to operate, the dew point should decrease to a sufficiently low level within a reasonable time after the dry air is activated. The exact target value and duration depend on the Peltier settings, i.e., whether they are switched on or off. When the Peltiers are off, the dry air pressure

[1] The test bench box contains four jigs, each designed to securely position one module.



(a) (b)

Figure 4: Software interfaces for system monitoring; Grafana dashboard (a), and interlock GUI (b).

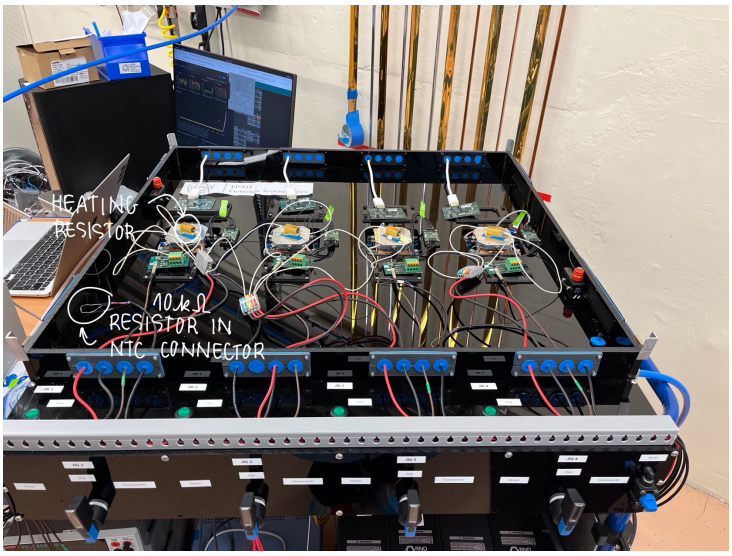
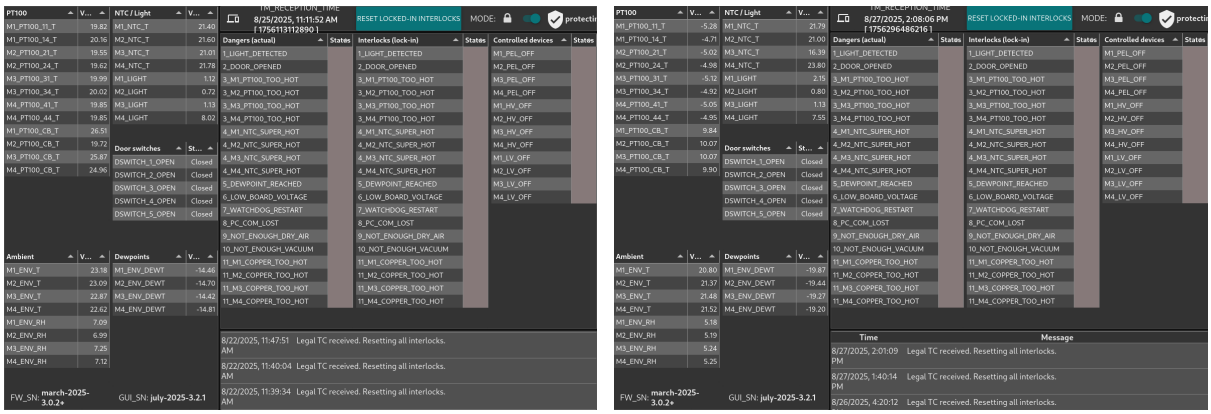


Figure 5: Inside of the test bench box, prepared in test stage, wit the module imitator, consisting ah a heating resistor placed on the jig with thermal paste and a $10\,\mathrm{k}\Omega$ resistor connected to the NTC input, in place.

set to approximately two bar and the chiller to $15.1\,^{\circ}\mathrm{C}$, the dew point fell below $-20\,^{\circ}\mathrm{C}$ for two of the four jigs and below $-19\,^{\circ}\mathrm{C}$ for the other two, within 30 minutes. This meets the expectations. With the Peltiers switched on, the dew point decreased more rapidly: within 10 minutes of applying dry air, three of the four jigs reached below $-20\,^{\circ}\mathrm{C}$, while the remaining jig dropped to $-19.5\,^{\circ}\mathrm{C}$. This result also meets the expectations. Figure 7 shows the evolution of the dew point temperature inside the box as a function of time after the dry air is introduced for both the case in which the Peltiers are switched on and off.

Another important aspect of the dry air supply in combination with the enclosing box is how effectively the test box prevents the dry air to leak out. To check the hermeticity of the box, the setup is prepared in the cold test stage and dry air is applied to the box. Once the amount of dry air in the box reaches a sufficiently high value, the dry air is turned off. It was found that after only two minutes the interlock was engaged as the critical dew point temperature [2] was reached. As this is rather fast, it can be concluded that the box is not very air tight. At the same time, this testing procedure also check the functionality of

[2] In principle it is undesired for the dew point temperature to exceed the minimum temperature in the box, as this means that condensation can take place. For extra precatory reasons though, the interlock already engages when the difference between the dew point and minimal temperature is less than $10\,^{\circ}\mathrm{C}$.



(a) (b)

Figure 6: Unengaged interlock GUI under warm (a) and cold (b) conditions in the test bench.

the interlock to deactivate of the Peltier and HV[3] power supply units (psu's) upon reaching the critical value, which was found to be successful. The increase of dew point temperature as an effect of dry air leaking out of the box over time and a screenshot of the interlock GUI while being engaged upon reaching the critical dew point temperature, can be found in Figure 8.

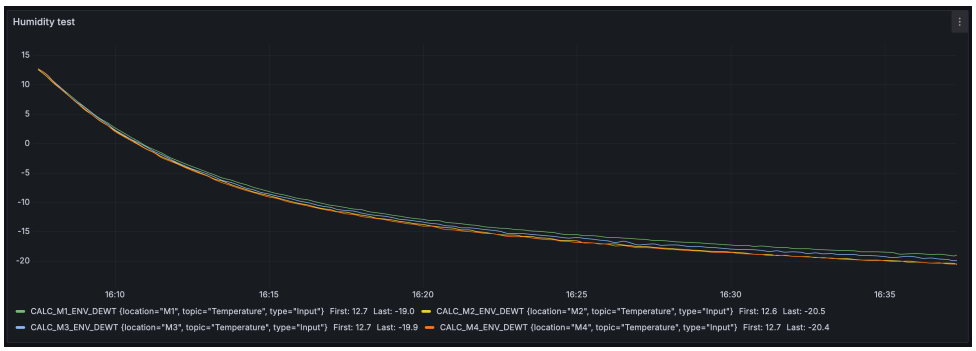
The test bench box is provided with a *box cover* that can be opened to allow convenient placement of the modules. To improve light and air tightness of the box, this cover should be closed at all times during module testing. To monitor this condition, the box is equipped with a door switch, detecting whether the box cover is closed or not. To check the functionality of the door switch and hardware interlock system, the test bench is brought into testing state and the cover is taken off. This event successfully engaged the interlock system which deactivated all psu's.

As already mentioned, the box does not only need to be air, but also *light tight*. This property is especially important when the modules are being operated under HV. Light inside the box is monitored by means of four light sensors, each placed next to one of the four jigs. To test the functionality of the light sensors to detect light sources and of the interlock to engage and deactivate the psu's upon light detection, LEDs are placed inside the box. The LEDs positioned next to each light sensor are then activated sequentially to verify proper sensor response. Each of the four sensors successfully detected the LED light when turned on and the interlock system switched off the psu's upon detection.

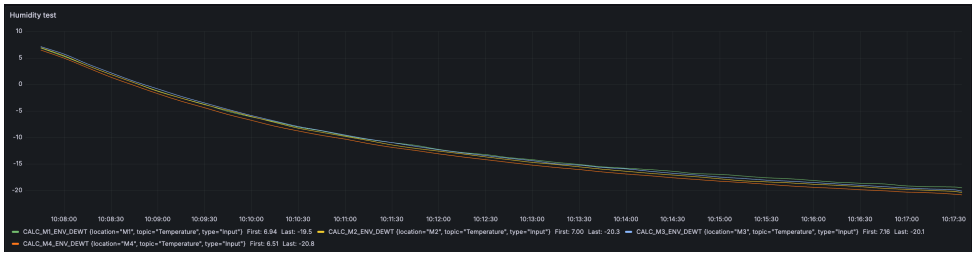
NTC detectors are installed to monitor the sensor temperature. In the test stage, these detectors are connected to $10\,\mathrm{k\Omega}$ resistors. To mimic a critical temperature reading above $40\,^{\circ}\mathrm{C}$, the already installed resistor is shorted through an additional $10\,\mathrm{k\Omega}$ resistor. For each of the four positions, the event successfully activated the interlock system, which in turn deactivated the three PSUs associated with the triggered position.

To regulate the modules temperature, each jig is equipped with a *cooling system* consisting of a cooling block assembly and psu's. The cooling block is constructed of a copper block with internal channels through which the coolant liquid from the chiller can flow. On top two Peltier modules are placed which allow active thermal control and are powered separately by psu's. At the very top of the cooling block, right underneath the heating element or loaded module cell, an aluminium block is positioned for heat dissipation and mechanical support. A scematic representation of the cooling block assembly can be seen in Figure 9. Both a too hot copper block and aluminium block can trigger the interlock and cause

[3]Present in the test setup for sensor biasing, but set to a very low value only to verify deactivation by the interlock system during commissioning.



(a)



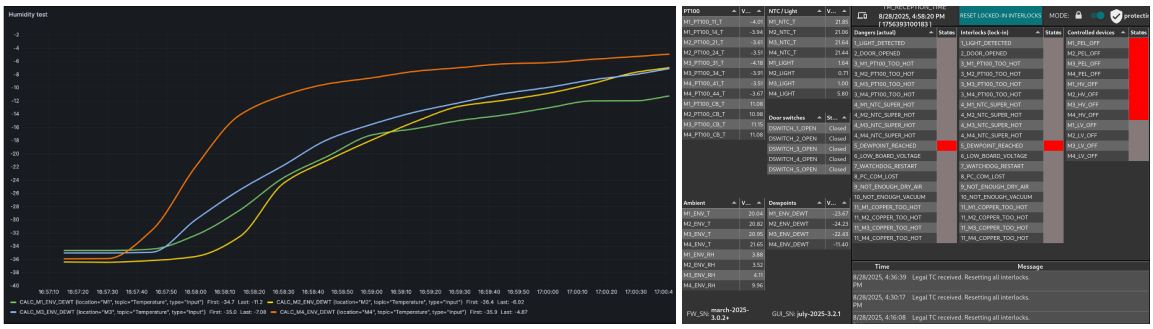
(b)

Figure 7: Dew piont temperature evolution inside the box as a function of time after dry air activation, for both the case in which the Peltiers are switched off (a) and on (b).

the psu's of the corresponding jig position to turn off.
To check the functionality of the chiller to deliver cooling liquid into the *copper blocks* to regulate the temperature and the interlock system to successfully engage when the copper block temperature increases above the critical value, the following testing procedure is followed. First the setup is prepared in the cold state. Then the cooling flow is switched of either by closing a valve in the cooling liquid circuit or turning off the chiller as a whole in case of the second jig off which the valve is currently broken. With no cooling liquid flowing through the copper block and the Peltiers switched on, the copper block temperature starts to increase. By means of the PT100 sensors glued on the copper blocks, their temperature is monitored. For each of the four copper blocks, the chiller was confirmed to provide cooling flow, as their temperatures rose when the flow was blocked. The interlock functionality was also proven as a copper block temperature exceeding $40\,^{\circ}\mathrm{C}$ triggered the interlock which in its turn deactivated the corresponding psu's.
Just like the copper blocks, the *aluminium blocks* are equipped with PT100 sensors monitoring their temperature. To check the functionality of the interlock system to engage upon overheating of the aluminium blocks, the heating elements are connected to the LV[4] circuit, set to about $15\,\mathrm{W}$. Once the setup is stabilized, the Peltiers are switched off, preventing the dissipation of heat from the aluminium blocks underneath the heating element towards the copper block. The temperature of the aluminium block is monitored until the critical temperature of $40\,^{\circ}\mathrm{C}$ is reached. Again, for all four positions the sensors successfully detected the overheating upon which the interlock reacted by deactivating the corresponding psu's.

Finally, a commissioning test was performed to check the FE powering by the *LV psu's*. These power supplies should deliver a stable LV power to the modules. It is especially interesting to check their behaviour upon engagement of the interlock, as turn-off spikes may, but should not, appear. To investigate this, the heating resistor is again connected to the LV circuit. Once the setup is stabilized, the solid state relays are triggered by shorting the NTC resistors and an oscilloscope is used to probe the voltage drop

[4]Present in the setup for FE powering.



(a) (b)

Figure 8: Increase in dew point temperature over time due to dry air leakage from the box (a), and interlock GUI showing activation upon reaching the critical dew point temperature (b).

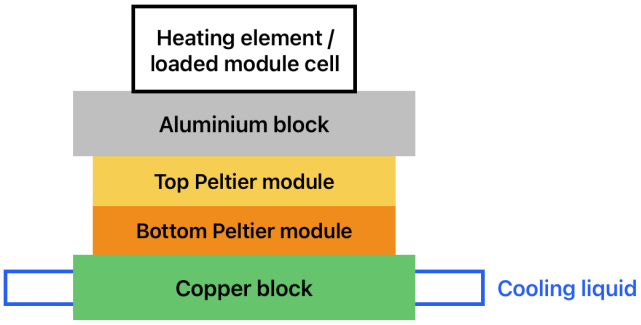


Figure 9: Schematic illustration of the cooling block assembly, indicating the location of the heating element during commissioning and the loaded module cell during final operation of the test bench.

across the heating element after the relays opened. A picture of the waveform on the oscilloscope display for one of the four positions can be seen in Figure 10. For none of the four psu's turn-off spikes were detected.

3.2 Performance comparison

As a final validation of the test bench functionality, electrical tests are carried out on a digital quad (a quad module without a silicon sensor tile) using both setups located in the cleanrooms of buildings 154 (novel setup location) and 161 (location of already established thermal test bench), and the results are compared. Figure 11, made by making use of the plotting tool [9], shows a comparison of the noise in electrons recorded in the setup in building 154 (green) and 161 (blue). The detected noise levels differ only slightly between the two setups and remain within the expected measurement uncertainties, suggesting that the novel setup in building 154 can reliably reproduce the results of the setup in building 161, which validates its functionality.

4 Conclusion and outlook

This paper reports the commissioning of a thermal test bench for reception tests of loaded module cells, which will be used to construct the Outer Barrel region of the pixel Inner Tracker (ITk) detector of ATLAS. This all-silicon detector will replace the currently functional tracking system called the Inner Detector during the High Luminosity phase of the LHC. During commissioning, all tested sub-systems of the test bench were found to perform as expected, although certain aspects—such as the air and light tightness of the test box—still offer room for improvement. One of the most thoroughly tested components was the interlock system, which detects critical events where setup requirements are not met and

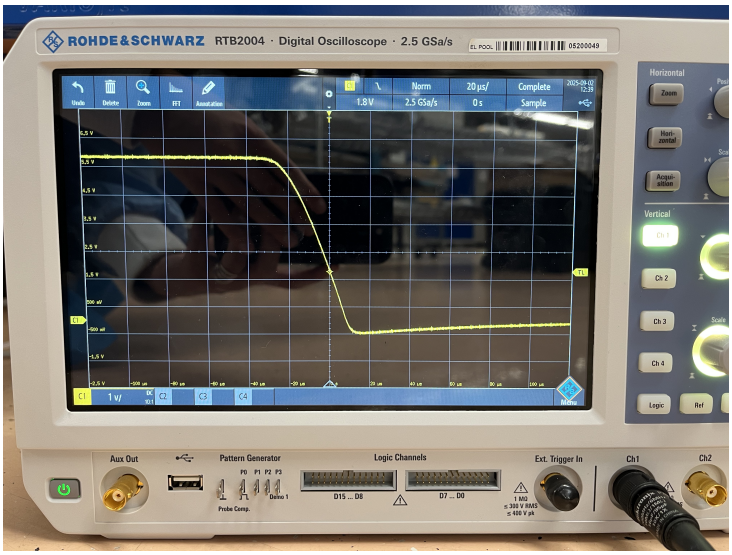


Figure 10: Oscilloscope measurement of the voltage drop across the heating element after relay opening, showing no turn-off spikes.

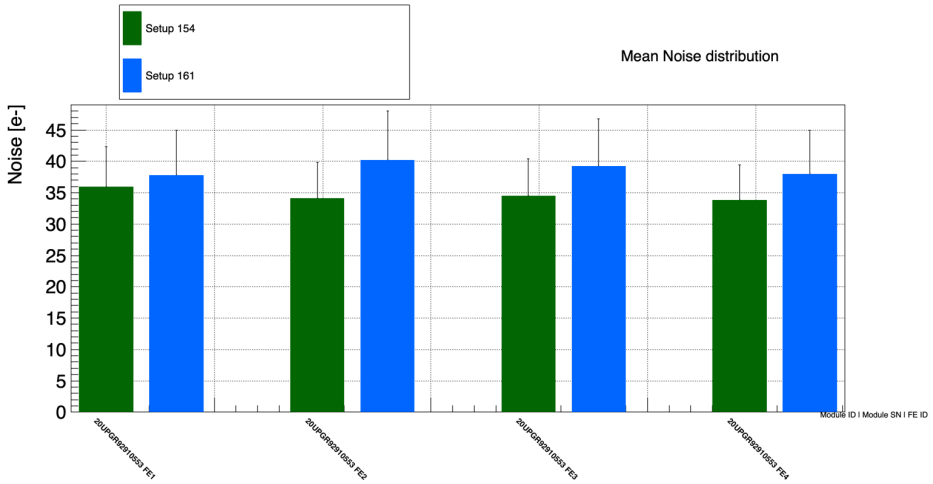


Figure 11: Comparison in recorded noise levels between the setups in buildings 154 (green) and building 161 (blue).

responds by shutting down the necessary test bench systems, thereby ensuring the safety of the loaded cells. To validate the functionality of the novel test bench setup, electrical tests were conducted and the results were compared with those from an established thermal test bench. Based on this initial comparison, the novel setup appears able to reliably reproduce test results, thereby validating its functionality.

Although the thermal test bench is currently fully functional, there are several aspects which should be improved. One of those is the cooling liquid circulation, in which mold formation was detected. The system should first be rinsed with a vinegar solution to eliminate any existing mold, and then filled with a coolant that prevents the formation of new mold. The broken valve of jig two should also be repaired. During testing, a light source on the edge of the test box was detected. The exact location of this source should be determined, e.g. by means of placing a camera inside the box, and eliminated by e.g. black tape.
There are also more tests which could be performed. It is for example not yet determined whether the test box can successfully host four modules in parallel. Also no IV-curves have been constructed with the setup yet.
Finally, some improvements in the software used to perform the qc tests could be performed. As right now the psu's are handled manually and no link with the module data bases is established.

Acknowledgments

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