EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

<u>SUMMER STUDENT REPORT</u>

Development of a Highly Automated Testing Setup for Silicon Sensors

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Abstract

Silicon diode sensors will be used in the High-Granularity Calorimeter (HGCAL) of the upgraded CMS detector. Due to the harsh radiation environment in the HGCAL, however, the changes of the electrical properties of these diodes during irradiation and after annealing have to be studied precisely. To conduct these investigations in a reproducible environment, the objective of this project was to develop a highly automated testing setup for IV, CV and TCT measurements. Within the scope of a CERN summer student project the author of this report was able to improve the temperature control in the experiment by implementing a new PID algorithm and combining the control of the external chiller and the Peltier elements. Furthermore, he developed a software module that automatically performs IV and CV measurements and created a completely new GUI for temperature control, monitoring and measurement operation. In addition, he also installed a new switch box that automatically swaps measurement setups. Thanks to these developments, the setup is now ready to use and has already been tested successfully.

8 September 2023

Contents

1 Introduction

Silicon diode sensors play a crucial role in modern solid state detectors for high energy particle calorimeters. They enable the construction of calorimeters with high spatial resolution, high resilience against radiation and compact dimensions of the detector at the same time. Therefore, silicon sensors shall be used in the so-called High-Granularity Calorimeter (HGCAL) of the Compact Muon Solenoid (CMS) detector for run 4 of the Large Hadron Collider (LHC) at CERN.

Some of these new silicon sensors are already produced as prototypes and their properties have to be studied at CERN. Particularly, the change of their electrical properties after irradiation and during annealing have to be investigated precisely. To conduct these studies in a reproducible environment a highly automated testing setup for the diode sensors shall be developed. This testing setup shall facilitate the execution of IV, CV and TCT measurements (cf. section 4) while keeping the silicon samples at a stable temperature of -20 °C.

When I joined this project in July 2023 as part of the summer student programme of CERN, the basic components which are needed in order to conduct the three mentioned measurement types were already provided in the setup. However, the temperature control was still in an unreliable state and the software for measurement control and data acquisition was still composed of a number of incompatible software tools. My task, therefore, was to rewrite the temperature control software, so the cool down procedure can be performed faster and in a more stable manner. Furthermore, I should develop a comprehensive and highly automated experiment control software, which includes a user-friendly graphical user interface (GUI) and can also be operated remotely.

My work at this project was part of the CERN summer student programme. This programme is organised by CERN every summer and provides a number of students, who are enrolled in a bachelor's or master's programme in physics, engineering or computer science, with the opportunity to join a research group at CERN during the summer months. This year I had the honor to be selected as one of the 300 summer students (out of 8,000 applications) from all over the world for a project supervised by Dr. Matteo Defranchis and Dr. Jan Kieseler. In retrospect I can say that I highly enjoyed joining the work at this outstanding research institute and meeting so many fascinating scientists. But at the same time I was also excited to meet numerous other inspiring summer students who enriched my cultural understanding in many ways.

So in the following chapters I will give a detailed report about my summer student project. Firstly, I will recapitulate the basics of the HGCAL as an upgrade for the CMS detector (section 2). Next I will give an overview of the annealing process of silicon diodes (section 3). Afterwards, I will introduce the experimental setup in the state at my arrival (section 4). With this being said, I will then present my contributions to the project, which are divided into improvements of the temperature control (section 5) and the development of the measurement control software (section 6).

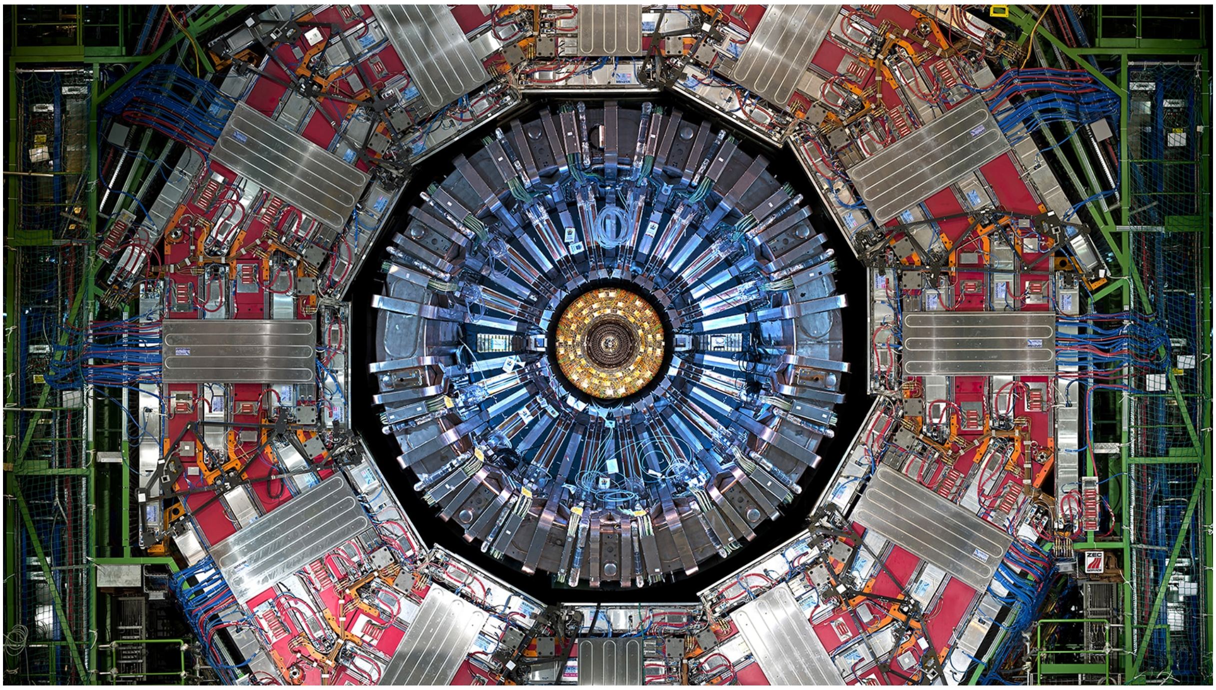

Figure 1: Photograph of the CMS detector at CERN in its opened state.

2 HGCAL Upgrade for the CMS Detector

The Compact Muon Solenoid (CMS) detector is besides ATLAS one of the two big general-purpose particle detectors at the Large Hadron Collider (LHC) at CERN. It is capable of characterizing the decay particles of proton-proton collisions at 13.6 TeV, which are provided by the LHC with a frequency of 40 MHz. During the collision the kinetic energy of the two protons is transformed into mass, which is transferred to all the decay particles. The CMS detector can measure the momenta and energies of (nearly) all stable decay particles. As a general-purpose particle detector it is designed to observe a large spectrum of new physics phenomena that the LHC might reveal. [1]

For the next run, however, the LHC will be upgraded to the so-called High-Luminosity LHC (HL-LHC) providing 10 times more collisions per second resulting in a 10 times higher integrated luminosity. Due to this fact the CMS detector will need to deal with a far higher amount of hard radiation and particle reconstruction.

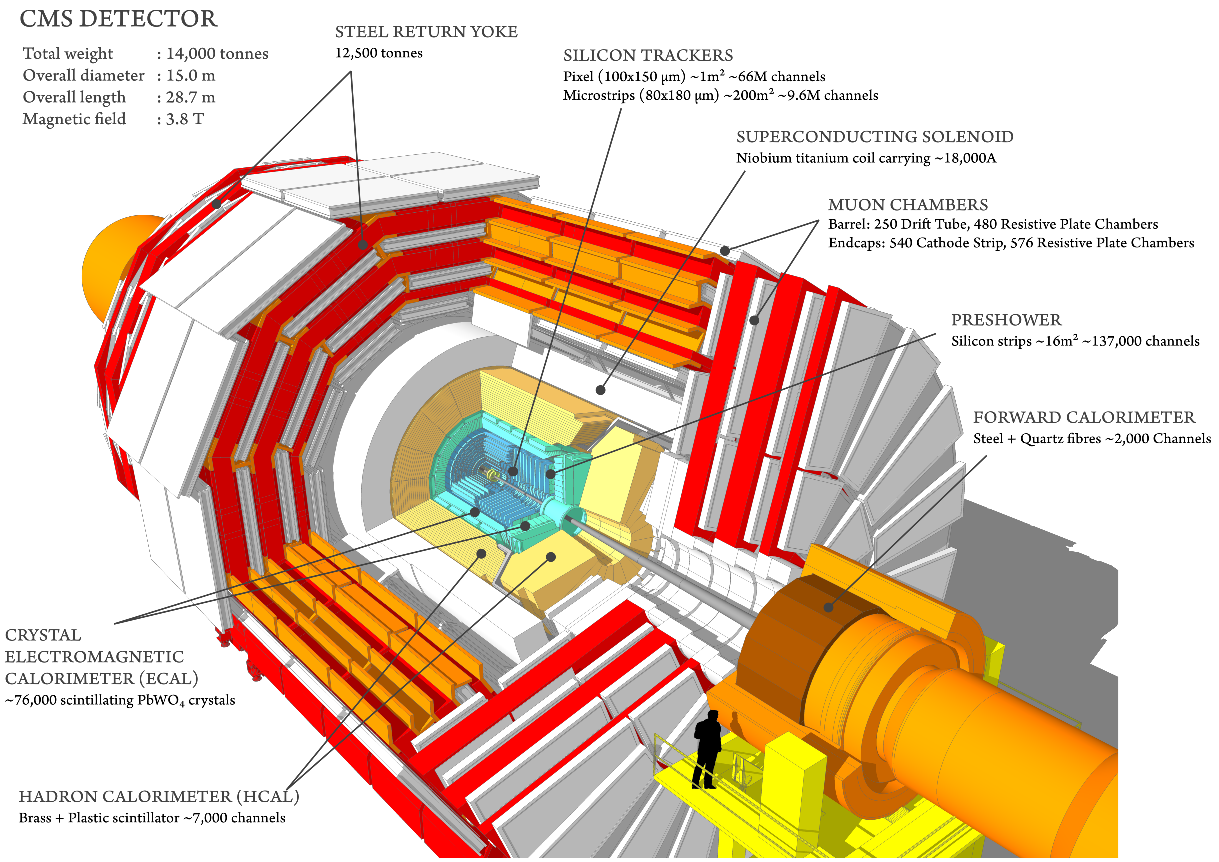

Figure 2: Representation of the CMS detector during run 3. The electro-magnetic calorimeter is illustrated in turquoise and the hadronic calorimeter is shown in yellow. The endcap parts of these calorimeters will be replaced by the HGCAL for the HL-LHC. [2]

One part of the detector which is particularly exposed to this radiation is the endcap calorimeter. Therefore, this part of the calorimeter shall be replaced by the so-called **High-Granularity Calorimeter (HGCAL)**. This new calorimeter will provide higher resilience against hard radiation, increased spatial resolution and timing capabilities in the order of 50 ps to suppress pile-up. In addition, it will cover up to higher pseudorapidity, which for instance will allow for the study of vector boson scattering at HL-LHC being one of the major physics goals of run 4. The HGCAL will be used for all of the electro-magnetic endcap calorimeters and the part of the hadronic endcap calorimeter which is exposed the most to hard radiation.

As sensor technology for the HGCAL silicon diode sensors produced by the company Hamamatsu Photonics K.K. are chosen. With modern manufacturing techniques these semi-conductor sensors can be produced in very high granularity and compact dimensions. At the same time silicon has a relatively high resilience against radiation damage compared to other calorimeter technologies. However, also for silicon diodes there is a noteworthy influence of radiation damage on its electrical properties. Thus, the changed behaviour of these properties has to be studied extensively.

3 Annealing of Irradiated Silicon Diode Sensors

3.1 Basics of Silicon Diode Sensors

In principle, silicon diodes consist of a silicon crystal that is doped with atoms of two different elements. One part of the crystal is doped with atoms which have a higher number of valence electrons, called n-doped area, and the other part is doped with atoms that have a lower number of valence electrons, called p-doped area. Due to the difference in concentration of the valence electrons, some of the electrons drift to the part of lower concentration which, in turn, creates a small electrical field in the junction area. The region, where this electrical field is present, is called depletion region.

When an external electrical field is applied to the diode in reverse bias mode, this depletion region can be extended. In this configuration a small leakage current can be measured at the diode, but this current is independent of the applied electrical field (as long as it is below the break-down voltage). However, if a high-energy particle traverses this region of the diode, it ionises additional electrons and, therefore, a current can be measured. In figure 3 a sketch of this process of a high-energy particle traversing a silicon diode is presented.

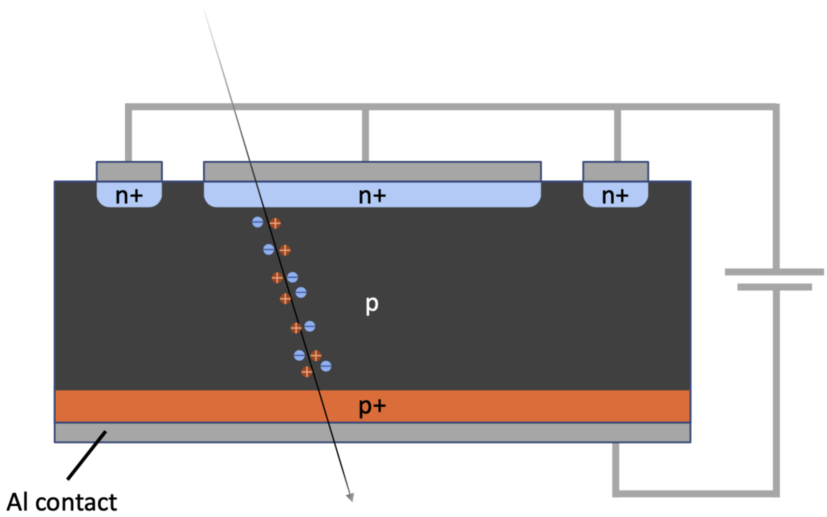

Figure 3: Sketch of a silicon diode sensor with an external voltage that is applied in reverse bias mode. The arrow represents a high-energy particle which traverses the depletion region of the diode and ionises additional electrons. These electrons create a current in the external electrical field, which can be measured. [3]

3.2 Radiation Damage at Silicon Diodes

The main diode bulk characteristics are its depletion voltage, leakage current and charge collection efficiency. Each of these properties, however, is significantly affected by radiation damage of the diode material, which is a serious issue as the leakage current and the charge collection efficiency directly affect the performance of the sensor in terms of energy resolution. The radiation damage occurs when traversing particles collide or interact with the bulk lattice. That can lead to spatial displacements of bulk atoms or other phenomena caused by hadronic interactions. Due to the high luminosity of the HL-LHC this kind of disturbance of the electrical properties will appear to a noteworthy extent.

3.3 Annealing after Irradiation

One possibility to reverse the effects of irradiation of the silicon diodes is annealing. This basically means that the silicon crystal is exposed to high temperatures for a long time which encourages the self-restoration of the crystal lattice.

During irradiation of the diodes their depletion voltage rises and their leakage current increases. After annealing both of these properties decrease again and change back towards their initial values. However, after an even longer period of time a phenomenon known as reverse annealing occurs. This means that the depletion voltage and leakage current increase again. Therefore, it is necessary to determine the optimal annealing time and temperature in order to obtain the best possible restoration of the diode's properties. In figure 4 the depletion voltage over time during an annealing process is shown. [4]

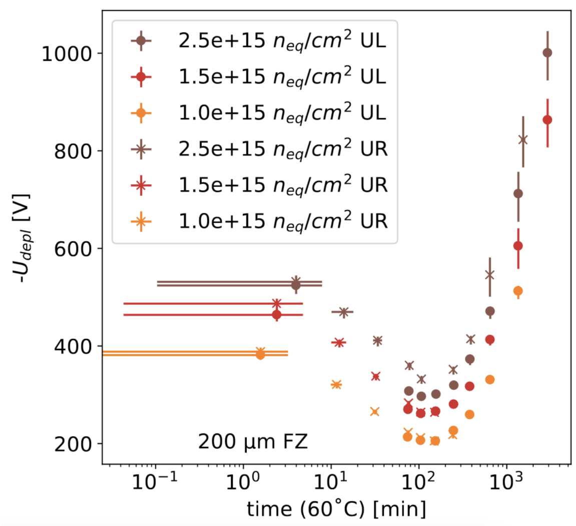

Figure 4: Diagram of the depletion voltage over time during annealing of a silicon diode at 60 °C. [3]

4 Experimental Setup

The objective of this experimental setup is to conduct IV, CV and TCT measurements at a precisely controlled temperature level in a highly automated way. These three experiment types measure the following properties.

IV: The leakage current of the diode in relation to the applied voltage in reverse bias mode is measured.

CV: The capacitance of the diode is measured for different voltages using an LCR meter. This information can be used to determine the depletion voltage and charge collection efficiency of the diode.

TCT: By illuminating the depletion region of the diode material with laser light, atoms are ionized and free charge carriers are created. These charge carriers drift within the external electrical field in reverse bias mode. The resulting transient current is measured and integrated over the time of the laser pulse. This value can be used, again, to calculate the depletion voltage and charge collection efficiency.

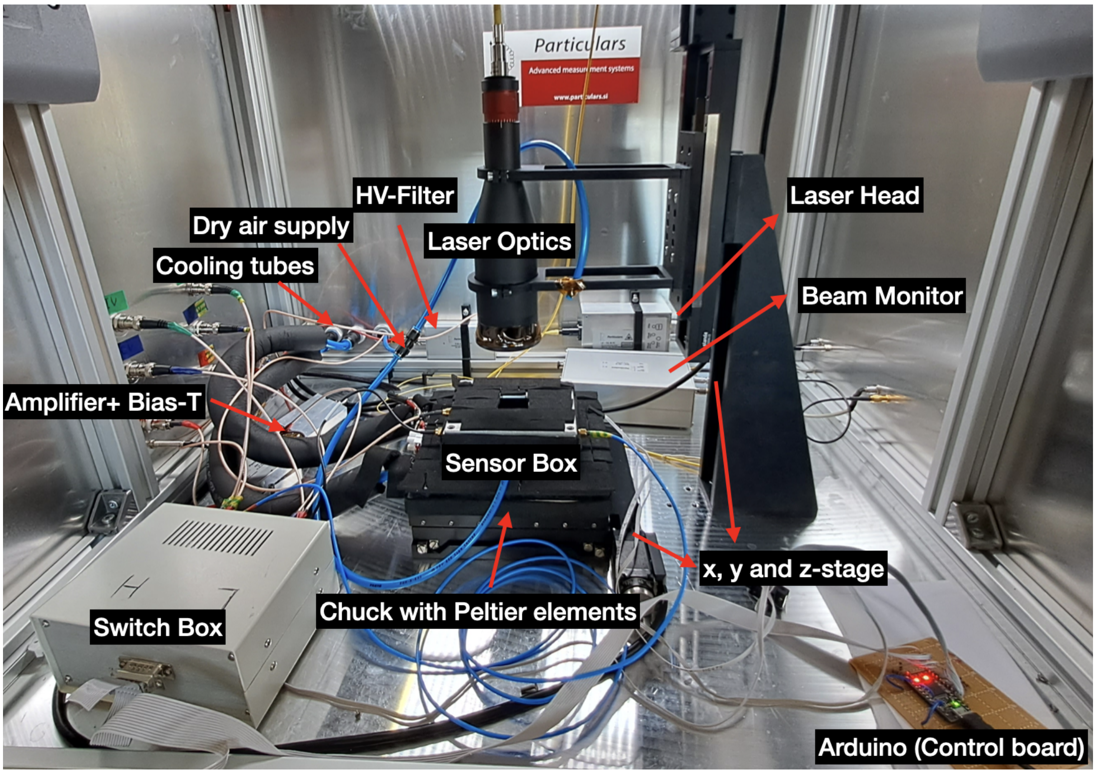

Figure 5: Picture of the experimental setup with labels describing the most important components.

For the experiments the sample silicon diode is mounted on a printed circuit board (PCB) inside the sensor box. This box is closed leaving only a small window open at its top for the laser beam. Cables are connected to the PCB to apply high voltage and to perform the measurements of the electrical properties.

An important part of the setup is its cooling system. It consists of an external chiller (Huber CC-505 with Pilot ONE control unit) which pumps cooled ethanol (typically -30 °C) through the chuck beneath the sensor box. For increased cooling power and more precise temperature control four Peltier elements are installed between the cooled chuck and the sensor box. To avoid water condensation at temperatures below 0 °C on the diode, the sensor box is constantly flushed with dry air.

Another important part of the setup is the laser and a three-axes motorised positioning system, which was purchased from the company Particulars. The actual data acquisition for the measurements is performed by several multi-meters, ammeters and an LCR-meter, which are connected to the sample via an automatic switch box, which was added to the setup by the author of this report. [5]

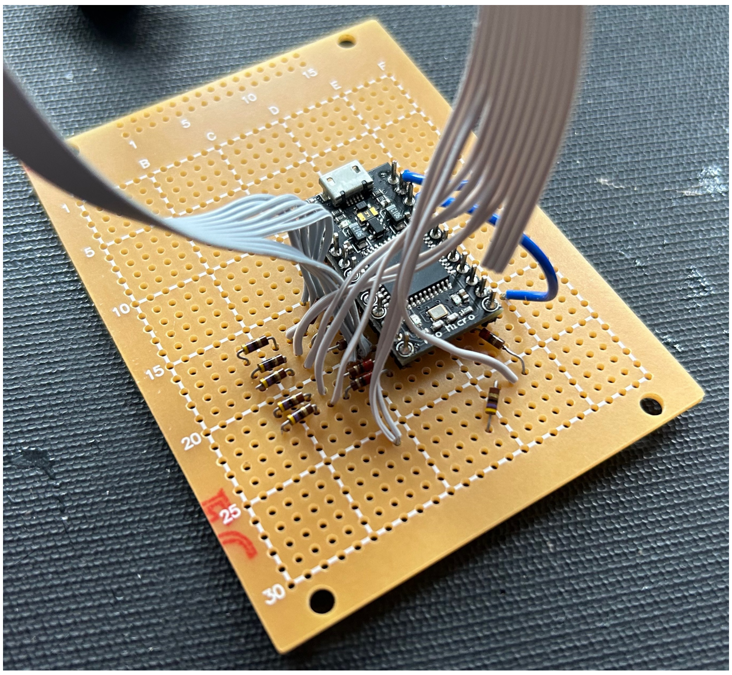

Figure 6: Picture of the Arduino micro-controller, which I soldered onto the breadboard. It is connected to the temperature and humidity sensors as well as to the switch box.

5 Improvements to Temperature Control

The first part of my contribution to automating the experimental setup were improvements in the temperature control, which I will present in this section.

5.1 Installation of New Temperature and Humidity Sensors

To enable a precise temperature control and comprehensive sample environment monitoring, a total of five temperature and two humidity sensors are used in our experimental setup. One temperature sensor is glued onto the copper chuck inside the sensor box measuring the temperature of the PCB. For a temperature monitoring which is even closer to the diode sample, a Pt1000 resistance sensor is glued onto the PCB itself. A third sensor is located inside the sensor box, which measures the air temperature as well as the humidity within the sensor box. A similar sensor is also installed outside the sensor box, but still inside the housing of the experiment, measuring the air temperature and humidity at this position. Finally, the temperature of the cooling liquid of the chiller is monitored.

Three of these temperature sensors and the two humidity sensors are connected to an Arduino micro-controller (cf. figure 6). To connect them I soldered wires to the sensors and mounted them to a breadboard, on which I then placed the micro-controller. With this done, I wrote a firmware for the Arduino to send the sensor data to the main control software on the computer in real time via an USB interface.

5.2 Remote Control of Chiller Machine

For the chiller a Huber CC-505 is used in this setup. To control it, a direct USB connection to the computer is set up. I developed a completely new Python module which only uses standard Python libraries to facilitate the connection to the chiller. With this software module the chiller can be turned on and off automatically and the temperature set-point can be modified directly by the main control software on the computer. Additionally, the internal temperature of the chiller cooling liquid is read out in real time and displayed on the computer. A safety function was also implemented to ensure the chiller is not turned off before reaching the minimum required run-time of the compressor pump.

5.3 PID Control of Peltier Elements

The Peltier elements are controlled using a PID algorithm, which I implemented directly into a module of our main control software in Python. The PID algorithm basically takes the currently measured temperature, compares it with the selected target temperature and then returns the cooling power needed to reach the target temperature. To be concrete the algorithm uses a formula which consists of three terms. These are the proportional term (P-term), which evaluates the difference between current temperature and target temperature, the integrating term (I-term), which takes into account the history of the temperature, and the derivative term (D-term), which considers the speed of temperature change.

The return value describes the currently needed cooling power. For the Peltier elements this cooling power is proportional to the applied current. Therefore, this value is sent by the Python software to a TSX3510P power supply, which is connected to the Peltier elements.

The final relation, however, is still not linear due to two reasons. Firstly, the current applied to the Peltier elements is limited by the power supply (5 A at the moment) and, secondly, the required cooling power is dependent on the current temperature level. As the PID algorithm assumes a linear relation between feedback value and calculated value, a modification has to be implemented to solve this problem. My solution was to also limit the value of the I-term in the PID formula and scale all the PID parameters to the current temperature level.

With my software version the cooling system is now capable of maintaining a constant temperature of -20 °C within a tolerance range of ± 0.3 °C.

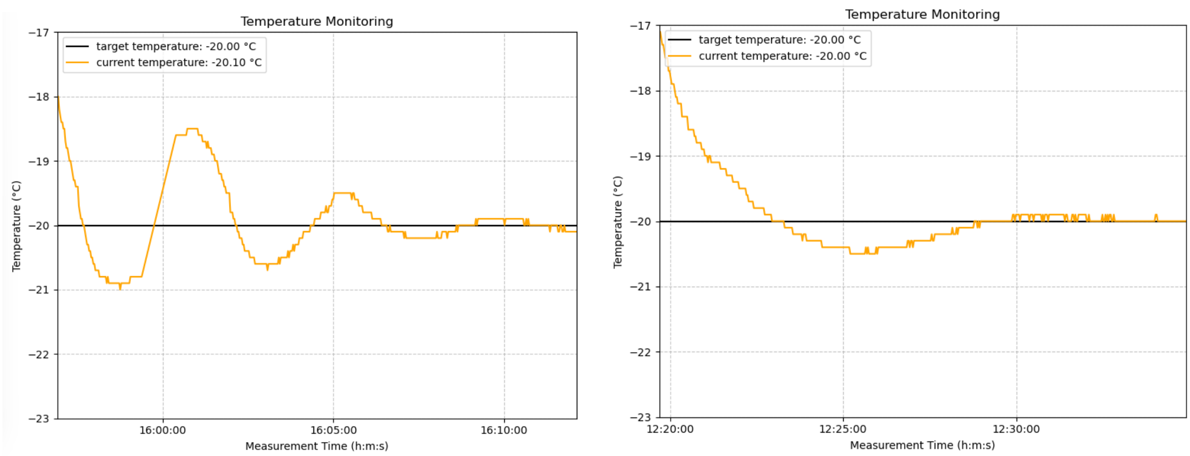

Figure 7: Diagrams of the temperature over time. In the left chart it was controlled by an old version of the PID algorithm resulting in strong oscillations. In the right chart my new version of the PID algorithm was used.

6 Development of a Graphical Control Software

The second major part of my contribution to building this highly automated experimental setup were the development of a remotely controllable software for operating and monitoring the temperature control and automating the operation of IV and CV measurements.

All this functionality is combined into a novel graphical user interface (GUI) which I created from scratch in Qt6 using PySide6 as the official Python 3 library for Qt. The current version of this GUI is shown in figure 8. It consists of three columns. The left column contains the control widgets for the sample temperature (cf. section 6.1), the centre column shows the live display of temperature and humidity values (cf. section 6.2) and the right column consists of the interface for operating the IV and CV measurements (cf. section 6.3).

6.1 Remote Control of Temperature Parameters

The chiller as well as the Peltier elements can be operated directly from the new GUI. To protect the Peltier elements from overheating, the software only turnes them on if the PCB temperature and the internal chiller temperature are below a certain threshold. The current status is indicated with colour and text. This functionality enables a completely automatic and fast cool-down procedure.

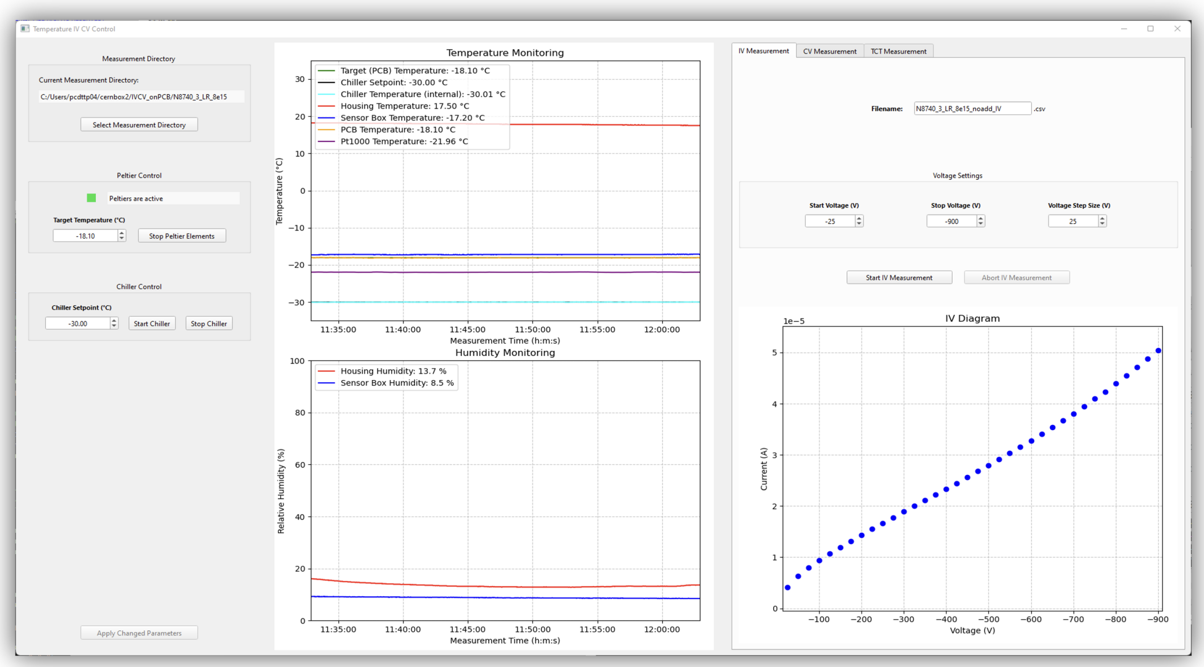

Figure 8: Screenshot of the current version of the GUI I created using PySide6 (Qt6).

6.2 Live Temperature Monitoring

For monitoring the temperature and humidity at several locations within the experimental setup, I developed a new module for our main Python control software which enables the live display of all temperature values in one diagram and all humidity values in another diagram. The representation of these diagrams is presented in figure 9. All sensor values are read out every 2 seconds. They are updated in the graph as well as shown as numeric values in the legend of the chart. At the same time all values are also saved in a CSV file to the hard drive of the computer and sent to the CERNBox cloud service.

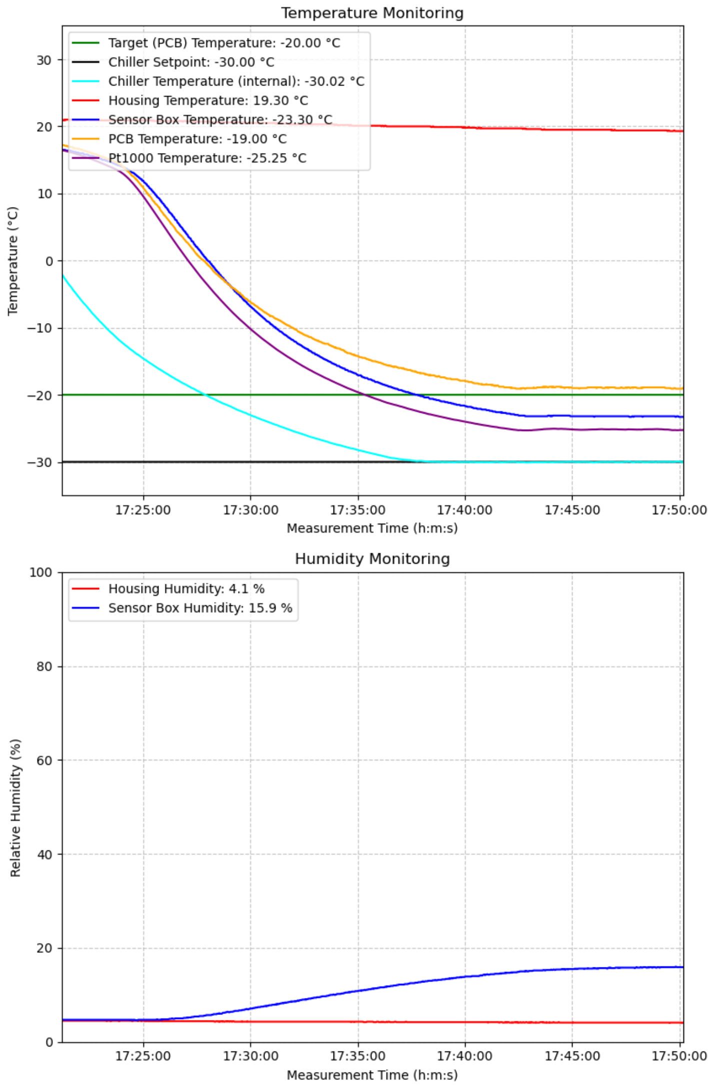

Figure 9: Diagrams of the temperature over time. In the left chart it was controlled by an old version of the PID algorithm resulting in strong oscillations. In the right chart my new version of the PID algorithm was used.

6.3 Automatic Operation of IV and CV measurements

The operation of IV and CV measurements is implemented in the right column of the GUI. By switching between the tabs one measurement type can be selected. After all relevant parameters are adjusted by the user, a voltage scan within the selected range is performed completely automatically. The measured values are displayed in a diagram in real time and saved to the hard drive and the CERNBox cloud service in CSV format.

To connect the sample diode to the correct measurement devices, an electronically operated switch box was installed. I soldered the control pins of the switch box to the Arduino micro-controller I mentioned earlier and enhanced the Arduino firmware, so it takes serial commands from the main Python software on the computer and sends the according signals to the switch box using TTL logic. When a measurement is started from the GUI, the required configuration of the switch box is set automatically.

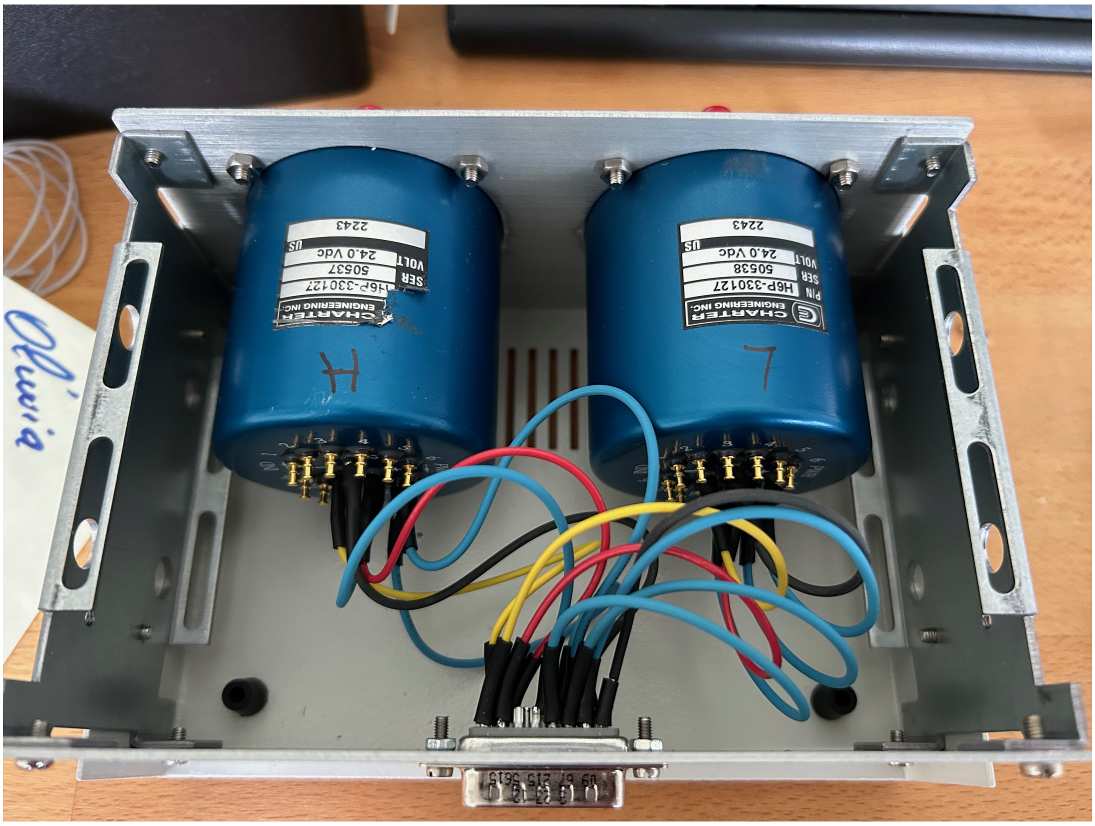

Figure 10: Photograph of the two electrical switches, which are located inside the switch box.

7 Conclusion

For my project in the CERN Summer Student Programme I got the opportunity to improve and automate a testing setup for silicon diode sensors that shall be used in the HGCAL of the upgraded CMS detector. The objective of this experimental setup is to investigate the electrical properties of these diodes during irradiation and after the annealing process.

I improved the temperature control by implementing a new PID algorithm for operating the Peltier elements and combining it with the control of the external chiller. The cool-down procedure works now in a reliable and completely automatic way.

For better environmental monitoring I installed new temperature and humidity sensors, connected them to an Arduino micro-controller and wrote a firmware for it. I developed a new module for the main Python software that provides live readout and display of all temperature values in one single diagram.

Furthermore, I developed a Python module that performs IV and CV measurements automatically, which was possible after I installed a switch box that swaps the respective measurement setups electronically. In addition, I created a graphical user interface (GUI) that allows for easier and more reproducible experiment operation.

The setup is now ready for measurements and has already been used for IV and CV experiments, i.e. this setup facilitates experiments which will be crucial for the final detector design of HGCAL. All the source code I developed for this project is written in Python 3 and is available on CERN GitLab (`https://gitlab.cern.ch/CLICdp/HGCAL/particulars_setup`).

8 Outlook

Although the setup is already fully functional, a number of further improvements are possible. One significant improvement would be the integration of automated TCT measurements into the main Python software. At the moment three additional software packages are used to conduct TCT measurements, which can be seen as an inconvenient situation. Therefore, it would be necessary to control the motorised positioning stages, the laser operation and the oscilloscope readout via Python modules. Form our current point of view all of these points seem to be feasible and are already scheduled to be worked on in the next months.

Another possible improvement in the scope of silicon diode testing would be the implementation of an automatic approach for determining the depletion voltage to enable live analysis for IV and CV measurements. Also the installation of an automatically controlled flux valve for the dry air supply would be of great avail.

References

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