MODULE TEMPERATURE TEST AND SIMULATION

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Semester Project Thesis, ETH Zurich

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Abstract

Sensor module cooling has been one of the key concerns during the module development process. Due to the complexity of the module assembly, direct measurement of sensor temperature can be hardly achieved. Under such circumstances, indirect measurement and simulation are the only two methods available to acquire sensor temperature. This document illustrates a temperature simulation process based on CAD techniques and corresponding experimental results. It also includes related indirect measurement results for comparison purpose.

Contents

1 Introduction

This document illustrates a basic temperature simulation experiment conducted at the Instituted of Particle Physics (IPP) of ETH Zurich. It is part of the ongoing upgrade project for the CMS pixel detector. This upgrade project aims to redesign a new pixel module which can meet or exceed the performance standard at a higher luminosity of the accelerator. A cold box was built at ETH Zurich to test the module under different environmental conditions. This semester project focuses on one particularly interest of the module: The temperature of the sensor. To acquire this sensor temperature which cannot be measured directly, a simulation process is introduced.

2 Background

2.1 CMS Experiment and Silicon Tracker

The Compact Muon Solenoid (CMS) experiment is an experiment at the Large Hadron Collider (LHC) which is located at the border of Switzerland and France. LHC is the world's largest and most powerful particle accelerator. It is built deeply underground in a tunnel of 27 kilometres in circumference. At LHC, proton beams travelling toward different directions at a very high speed collide with each other and generate new particles like photons and electrons. These collisions provide scientists with a way to observe and discover new particles and sub-particle structures.

This observation process is where CMS comes into play. CMS is a particle detector that can capture the particles generated from the collisions. Due to the short lifetime nature of many particles, new particles can be generated when particles are scatted away. This poses a challenge for scientists in discovering the original collisions because particles detected may be ones generated during the scattering. Through a multi-layer design (Figure. 1), CMS is able to detect different particles at different layers. Energy deposited in different layers are converted to electronic signals. Then the original reactions can be reconstructed based on the measured energies and momenta.

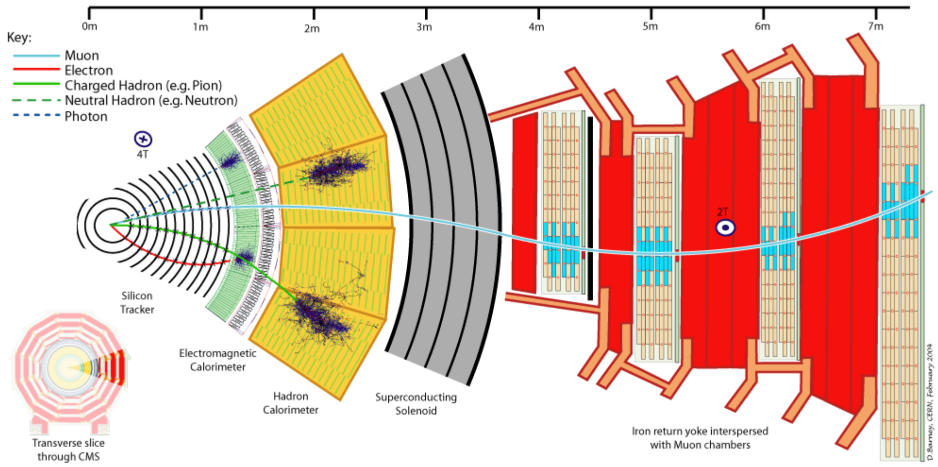

Figure 1: CMS multi-layer design[1]

Silicon tracker is the innermost layer of CMS's multi-layer structure. It is designed to record the path of particles under the effect of a magnetic field. The magnetic field will exert force on charged particles; the more curved the path is, the less momentum the particle has. Therefore, this path will allow to calculate the momentum of the particle.

2.2 Pixel Module Assembly

The pixel modules are located at the core of the silicon tracker, therefore they are exposed to the highest particle intensity during the collision. Each pixel module consists of multiple layers including base strips, read-out chips (ROC), sensor and High Density Interconnect (HDI) layer. These layers are connected with others in different ways. The first layer is the electronics layer. It is connected to the silicon sensor through HDI interface. Beneath the silicon sensor, ROCs are bonded to the sensor through bump bonds which are made of Indium 2.1%, as shown in Figure. 2. This layer consists of 16 read-out chips and each containing 4160 pixels. It is the major power consumption part in the entire assembly. In the bottom, glue is used to connect ROCs and base strips, which are used to fix the module. When a charged particle penetrates the sensor, certain number of electrons on the semiconductor sensor are excited to leave their energy levels. This not only generates electron holes in the silicon, but also induces a current to flow. Under the effect of bias voltage, this induced current ultimately flows to the ROCs where it is amplified for measurements and calculations[2].

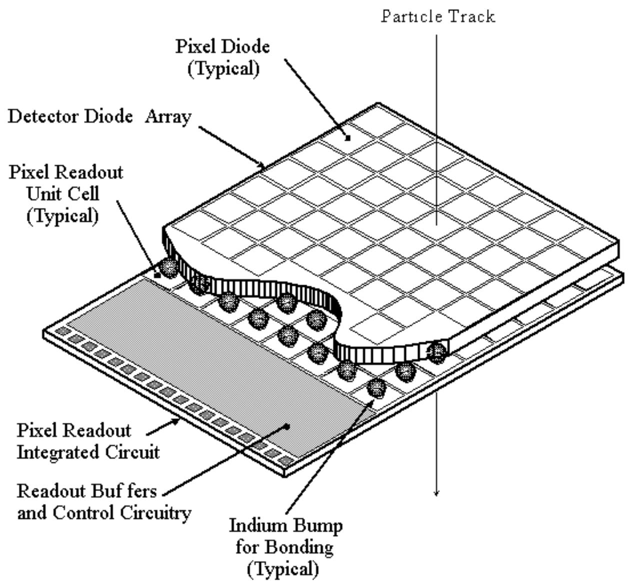

Figure 2: Schematic diagram of ROC and sensor connection [3]

2.3 Cold Box Set Up

Since it is impossible to test the module assembly all the time in the actual LHC environment, a cold box (Figure. 3) was built by ETH CMS Pixel Group to simulate that environment. This cold box achieves its cooling effect by using four peltier elements. These elements are able to transfer heat from one side to the other using Peltier effect. Therefore, it is feasible to use the colder surface to cool the cold box. Meanwhile, these elements are placed on a copper block, in which water flows through and cools the hotter side of these elements. The

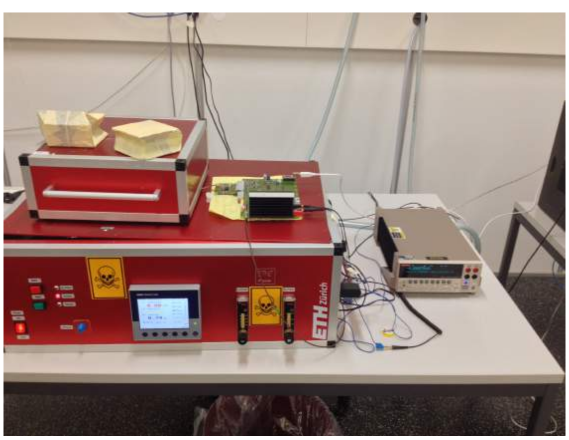

Figure 3: Setup of the cold box

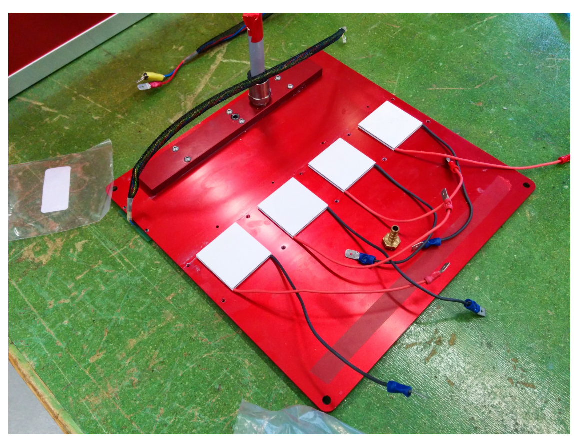

Figure 4: Peltier elements blow base plate

peltier elements are sitting beneath the base plate of the cold box (Figure. 4) and thus are directly cooling the base plate. Above the base plate, certain inner space is left for testing.

The temperature of the box is controlled using a temperature and humidity sensor embedded in the inner space. This sensor is connected with JUMO software, therefore users can easily control the temperature using the screen installed.

Meanwhile, there is also a hole on the base plate connected with dry air to flush the inner space and lower humidity. The entire inner space is equipped with rubber seal and a heavy weight is exerted on the cap during the test to reduce leakage.

3 Experimental Stage

The experimental stage consists of several temperature measurements on the module assembly. They were conducted mainly for two purposes: Simulation input and simulation result references. Because the CAD simulation requires not only an active model, but also input and environmental conditions, it is necessary to measure the temperature of the base plate and air. Meanwhile, with the temperatures of base strip and module holder, it is feasible to compare and tune the simulation.

3.1 Base Plate Temperature Map

Due to the peltier elements embedded beneath it, the base plate acts as the cooling source for the entire cold box inner space. Therefore, its temperature is essentially one part of the input for the CAD simulation.

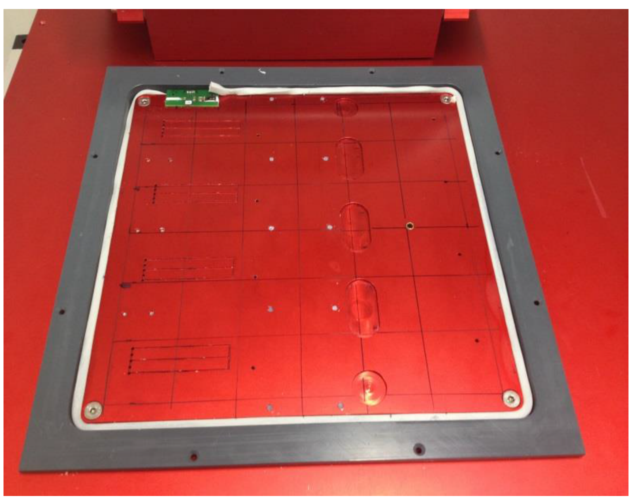

Figure 5: Cold box base plate[5]

The plate, as shown in Figure. 5, is made of aluminum with an oxidation layer on top. To measure the temperature on the plate, a type of sensor called PT1000 was attached to the plate using tapes. Because the sensor resistance is dependent on the temperature, a voltage drop can be measured when the temperature changes. On the plate, 49 data points were chosen in a matrix of 7×7. The distance from the closest edge to both the first and last data point is 1 cm. All the other points are spaced with each other at a distance of 3.83 cm. Due to the limit of the number of sensors, measurements were conducted by each row.

During the measurement, the box was first flushed with dry air to reduce the humidity to be below 9%. Then, the peltier elements below the plate started to cooling the box to the set temperature at T = -25 °C. Temperature measurement started when T reached the set point and became stable. For each sensor, 150 data points were taken and the mean value was taken to minimize the fluctuation.

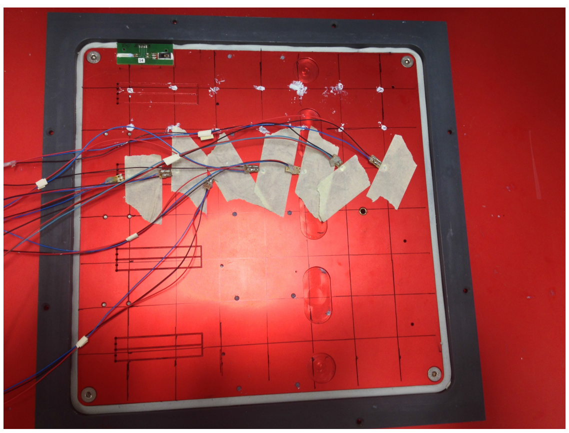

Figure 6: Sensor setup on base plate[5]

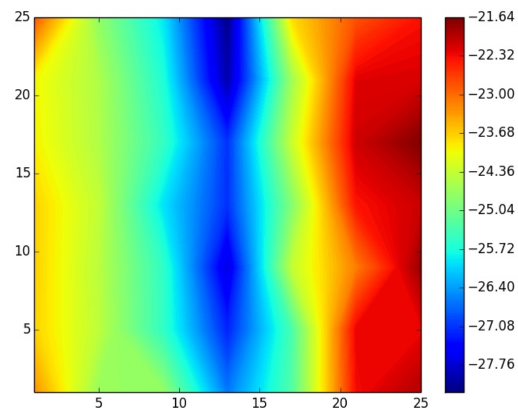

Figure 7: Base plate temperature at -25°C

Figure. 7 shows the interpolated temperature map of the base plate when set point T = -25 °C. This map coincides with the expectation that the coolest part of the plate is at mid where the peltier elements are located. The temperature gradient on the right side of the plate is 6 °C, which is larger than the one on the left side($\Delta T = 5$ °C). On the vertical side, the highest temperature occurs at the lowest end. This is assumed due to the leakage of air because in experiment it was the location of the cap opening.

3.2 Air Temperature

Air temperature in the inner space of the cold box is the environmental condition for the simulation. Because of the air leakage through the sealing and the flushing hole, the air temperature fluctuates greatly. Therefore, only a approximate value is taken into account for simulation. Due to this simplification, the number of data points were reduced to 5×5. This measurement is done using nearly the same techniques except that the sensor was fixed to stick into air, as shown in Figure. 8. Figure. 9 shows a precise temperature gradient map

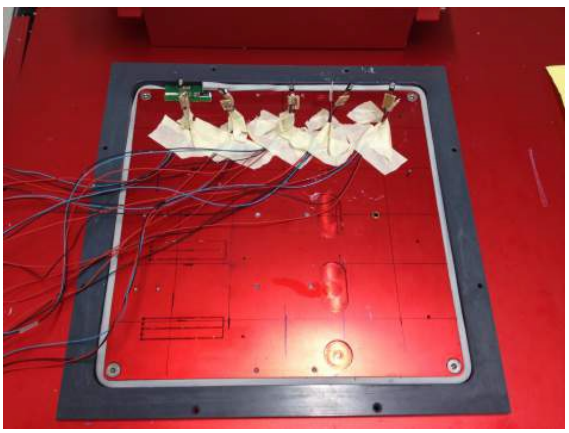

Figure 8: Sensor setup for air temperature measurement[5]

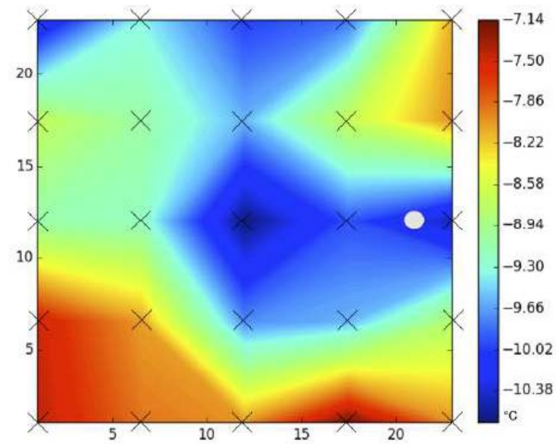

Figure 9: Air temperature gradient at T = -25°C

of air temperature in the box. An average value was taken as T = -9 °C. This value later become the ambient temperature of the simulation.

3.3 Module Holder POF Temperature

In the module test, the module is placed on top of a module holder made of aluminum(Figure. 10). This helps to prevent unexpected damages to the module because it can be moved

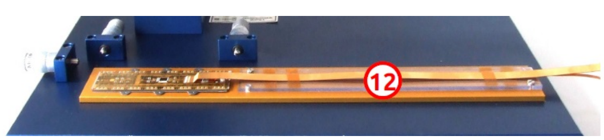

Figure 10: Final module assembly[4]

without being touched. Because ROCs are the major power consuming area in the module, the module holder's temperature varies greatly between ROC power-on (PON) and power-off (POF). The temperature for POF provides a reference for simulation under POF conditions.

This measurement used the same techniques for base plate by attaching sensor to holder surface. 3×7 points were chosen across the holder and only bare holder was used. Because for final assembly the module covers part of the holder, some positions in this measurement are positions directly below the module. Meanwhile, position No. 2 on the base plate (Figure. 11) was chosen as the module holder position.

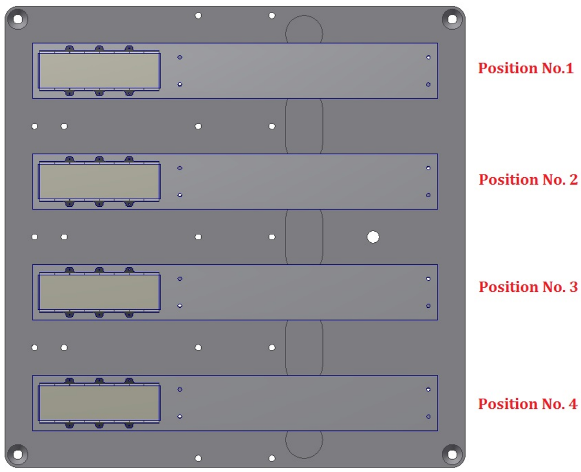

Figure 11: Module holder position map

Figure. 12 shows the gradient across the module holder. It can be easily seen that the gradient is larger on the right side than the left side. This coincides with the base plate temperature distribution.

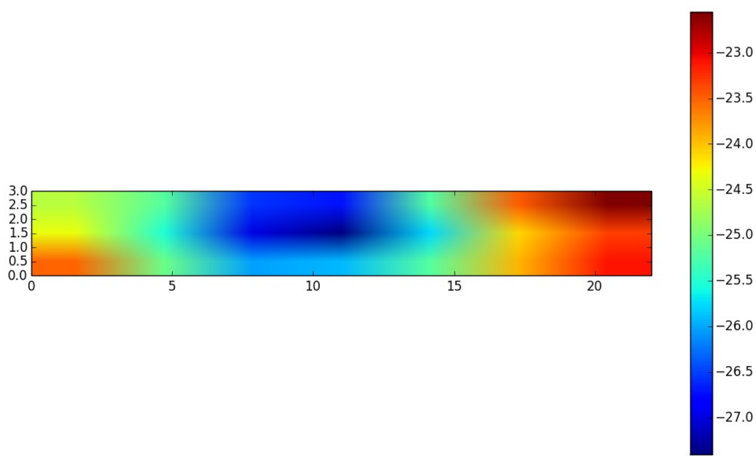

Figure 12: Module holder POF temperature gradient

3.4 Base Strip Temperature

Base strip temperatures were measured for both POF and PON conditions. The temperature difference at two different conditions is the key to tune the simulation. In this experiment, an extra PT 1000 was also placed beneath the module and between the two base strip to measure the temperature of ROC (Figure. 13). Figure. 13 also shows the final temperature comparison between POF and PON conditions. When ROC power is truned on, the temperature rises about 1.7 °C. This value was used significantly later for adjusting simulation.

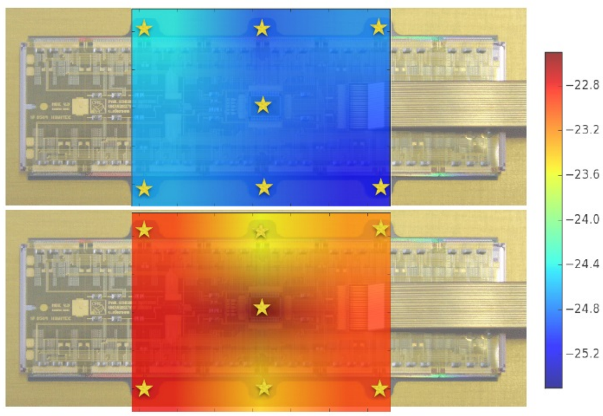

Figure 13: Base strip temperature comparison[5]

4 Simulation&Analysis

The temperature simulation is the core of this document. To start such a simulation, an active model is built as foundation in Autodesk Inventor. Then, this model is imported into ANSYS for temperature test. First, reference points are used to compare simulation and experiment results to make sure there is no large error. Then, the simulation is tuned to be more precise. In the end, a final target temperature is generated from tuned simulation.

4.1 CAD Model

An active model was built for the base plate and module assembly based on their mechanic drawings in Autodesk Inventor. Figure. 14 shows such a model which has all the important parts required for simulation. This model also includes many electronics on the HDI. These small but numerous parts pose a challenge for simulation due to complexity, therefore the model was later on simplified as shown in Figure. 15.

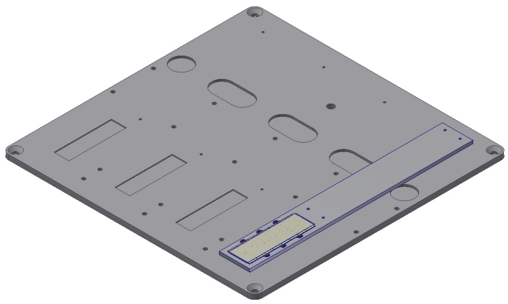

Figure 14: Completed CAD model

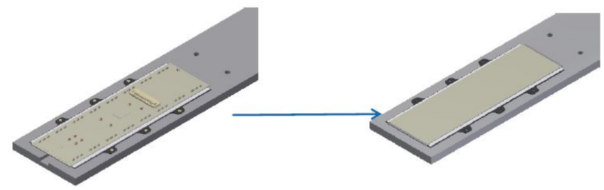

Figure 15: Simplification of electronics

4.2 Module Holder POF Simulation

Module holder acts as a support for module during test. It is made of aluminum and has several holes on it (The 16 smaller holes in Figure. 16). These holes are designed as vacuum holes to fix the base strips. However, during the temperature test, conductive paste and tape was used to glue the base strips instead of vacuum. Temperature of module holder at ROC POF condition is measured for the purpose of comparison. During the test, the module holder was simply placed on the base plate with pins to fix its position (Four larger holes in Figure. 16). There is no paste nor vacuum pressure to attach it to the base plate. Therefore, the contact between them is neither perfect nor known. Since base plate temperature is the only input during ROC POF condition, the contact in the simulation can be evaluated by comparing the temperature of module holder in experiment and simulation.

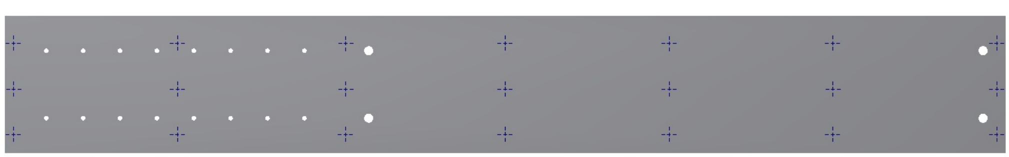

Figure 16: Top view of module holder

Position (x,y)	0.2, 2.4	3.8, 2.4	7.5, 2.4	11, 2.4	14.6, 2.4	18.2, 2.4	21.8, 2.4
	0.2, 1.4	3.8, 1.4	7.5, 1.4	11, 1.4	14.6, 1.4	18.2, 1.4	21.8, 1.4
	0.2, 0.4	3.8, 0.4	7.5, 0.4	11, 0.4	14.6, 0.4	18.2, 0.4	21.8, 0.4

Table 1: Positions of data points on module holder

Data points on module holder were chosen in a 3×7 matrix, as shown in Figure. 16 and Table. 1. In this way, the area not covered by module is also included in the measurement. To apply the temperature gradient of the base plate in the model, several so called ”mesh elements” were built. The number of these mesh elements is the same as the number of data points taken on the base plate (7×7) and the data point position is exactly in the middle of each element. On each element, the temperature is constant, as shown in Figure 17. The set point temperature is -25 °C and air temperature is -9 °C.

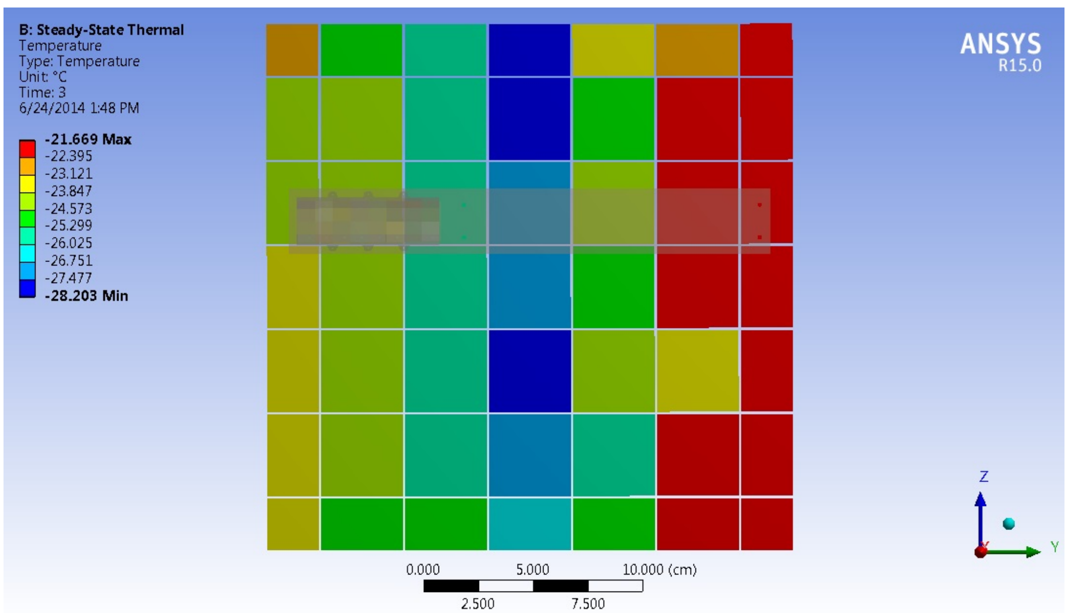

Figure 17: Mesh elements of base plate

Table. 2 shows the temperature comparison between simulation results and experimental results from the experimental stage. ΔT below shows the temperature difference: If the experimental result is colder, ΔT is negative. It can be seen that the largest deviation occurs at the right side of the module holder, which is also the place on base plate the largest temperature gradient occurs. Because of the constant temperature on each mesh element, a precise interpolated base plate temperature was not represented in the simulation, therefore this large deviation is expected.

Experiment (°C)	-24.635	-25.206	-26.549	-26.707	-25.224	-23.467	-22.555
	-24.330	-25.524	-26.984	-27.406	-25.758	-24.098	-23.329
	-23.520	-25.064	-26.040	-25.918	-25.203	-23.926	-23.101
Simulation (°C)	-23.927	-24.524	-25.503	-27.111	-24.327	-22.098	-21.669
	-23.925	-24.523	-25.505	-27.111	-24.329	-22.099	-21.671
	-23.805	-24.454	-25.735	-27.111	-24.592	-22.231	-21.883
ΔT (°C)	-0.708	-0.682	-1.046	0.404	-0.897	-1.369	-0.886
	-0.405	-1.001	-1.479	-0.295	-1.429	-1.999	-1.658
	0.285	-0.610	-0.305	1.193	-0.611	-1.695	-1.218

Table 2: Results of module POF temperature measurement

The average deviation is 0.961 °C. Because this number is relatively small (<1 °C), it is assumed that the contact between base plate and module holder is good enough.

4.3 Base Strip POF&PON Simulation

As mentioned in the experimental stage, the temperature difference of base strip in ROC POF and PON conditions is the key to tune the simulation. Because the ROC consumes most of the power in the module, there will be a obvious ΔT when it is turned on. A PT1000 probe is placed in simulation on the base strip at the same position as in the experiment, as shown in Figure. 18. Then, the temperature difference is recorded easily.

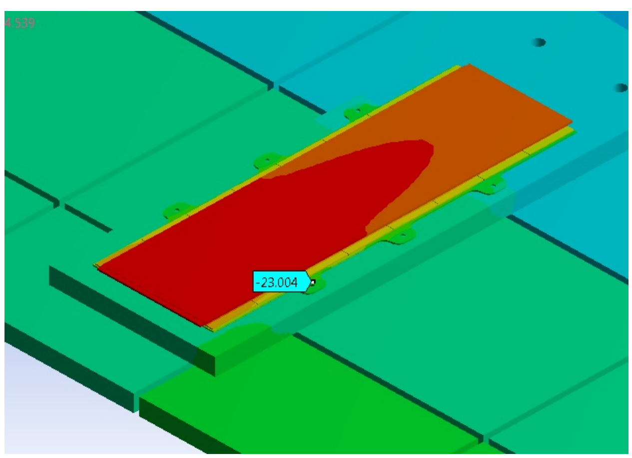

Figure 18: Sensor on base strip

Because when ROC PON, cooling from base plate and heating from ROC reaches a balance on the base strip, all the contacts between base plate and ROC can affect the temperature on the strip. Therefore, by adjusting those contacts so that the temperature difference coincides, it is feasible to improve the simulation results significantly.

Between ROC and base plate, there are three layers of contacts: Base plate to module holder (Plate2Holder); Module holder to base strip (Holder2Strip); Base strip to ROC (Strip2ROC) (Figure. 19).

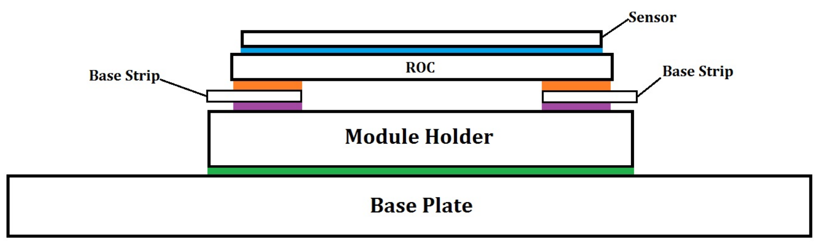

Figure 19: Schematic diagram of entire set up

Since heat transfer between two objects depends on shape and thermal conductivity (k) of the contact, adjusting the thermal conductivity is equivalent to adjusting the shape of contacts. Therefore, layers of a fixed thickness 30 micrions were inserted between objects to adjust the contact. Also, a layer of air was inserted between module holder and ROC so it is possible to observe the temperature gradient in between later on.

Run No	Holder2Strip(Paste) conductivity (W/m*K)	Strip2ROC/Araldite(default=0.11) conductivity (W/m*K)	Plate2Holder(default=237.5) conductivity (W/m*K)	POF Temperature (°C)	PON Temperature (°C)	ΔT (°C)
1	4	0.11	237.5	-24.411	-24.405	0.006
2	1	0.11	237.5	-24.411	-24.404	0.007
3	0.05	0.11	237.5	-24.413	-24.007	0.406
4	0.05	0.05	237.5	-24.414	-24.017	0.397
5	0.03	0.03	237.5	-24.414	-23.59	0.824
6	0.02	0.025	237.5	-24.414	-23.004	1.41
7	0.01	0.025	237.5	-24.418	-21.175	3.243
8	0.02	0.025	150	-24.414	-23.003	1.411
9	0.02	0.02	150	-24.415	-23.032	1.383
10	0.01	0.025	50	-24.417	-21.173	3.244
11	0.025	0.025	50	-24.412	-23.364	1.048
12	0.1	0.05	0.05	-24.474	-23.912	0.562

Figure 20: Results of base strip simulation

Figure. 20 shows the results from the simulation based on different settings of thermal conductivities. Among them, No. 6 and No. 8 are highlighted because they have the closest results to 1.7 °C. Meanwhile, further adjustment of Holder2Strip and Strip2ROC is not recommended because the thermal conductivities are small enough in No.6 (Thermal conductivity of air 0.023).

The adjustment for Plate2Holder is not recommended either because the module holder POF simulation shows this contact is good enough. Therefore, No.6 becomes the top choice for further test. Under such a setup, the temperature difference between base strip and base plate is 1.5 °C.

4.4 Sensor PON Temperature

Sensor PON temperature is the major target of this simulation. Since the simulation model has been tuned to be as close as possible to experiment, the sensor temperature was simply extracted from the simulation as shown in Figure. 21.

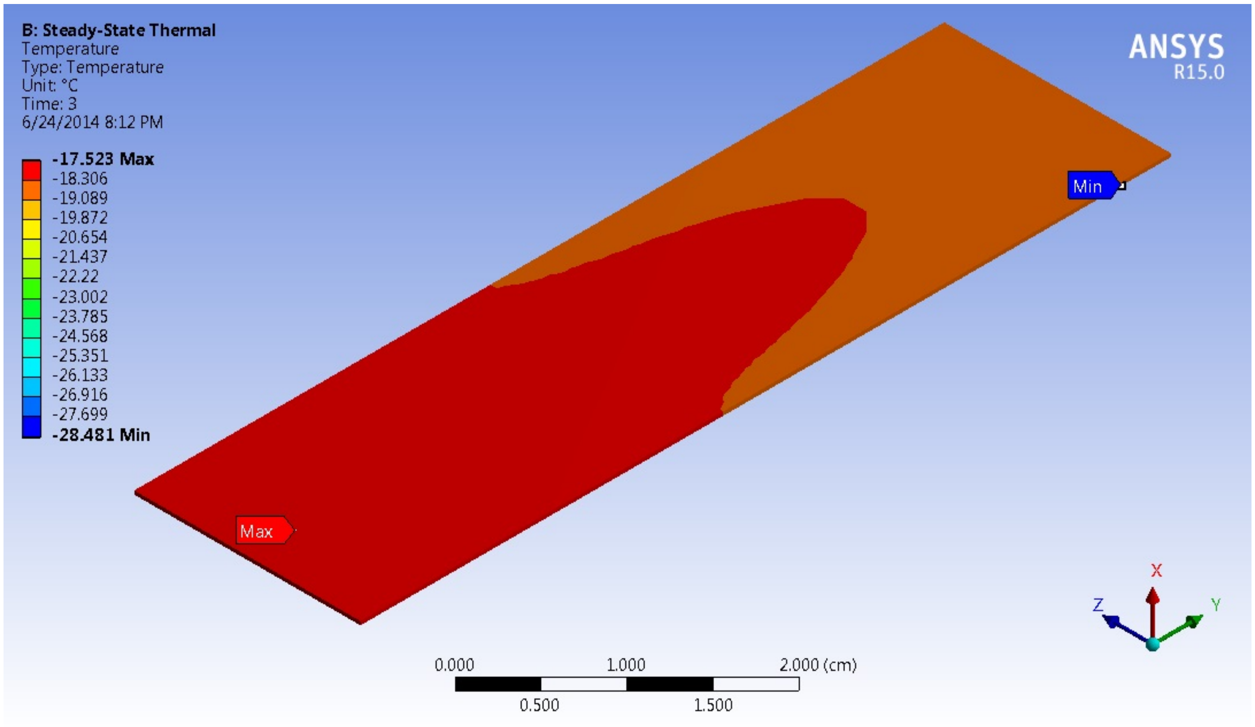

Figure 21: Sensor temperature simulation

From the data acquired, the maximum temperature on the sensor is -17.66 °C, the minimum is -18.83 °C and the mean is -18.25 °C. This implies that the temperature rises from base strip to sensor is 5.5 °C.

Because sensor temperature is also affected by the contact between sensor and ROC, which was not adjusted before, a further investigation was conducted to shown the effect of this contact. The default value of this contact is 1.7 $W/m*K$, which is for Indium 2.1% bond. Adjusting this value from 1.7 to 0.02 $W/m*K$, the temperature floats for approximately 0.5 °C, as shown in Table. 3. Therefore, only small, negligible deviations occurred due to such a contact change.

Thermal Conductivity ($W/m*K$)	Max (°C)	Min(°C)
1.7	-17.66	-18.83
0.5	-17.64	-18.81
0.1	-17.52	-18.51
0.05	-17.39	-18.49
0.02	-17.10	-18.11

Table 3: Positions of data points on module holder

5 Discussion

During the test, another way of acquiring sensor temperature is through indirect measurement and calculations. This provides a result that can be compared with the simulation.

5.1 Comparison

In the experiment, the leakage current of the sensor is measured as well. This allows to calculate the sensor temperature. At set point T = -25 °C, the temperature of sensor is calculated as -28.3 °C (Figure. 22).

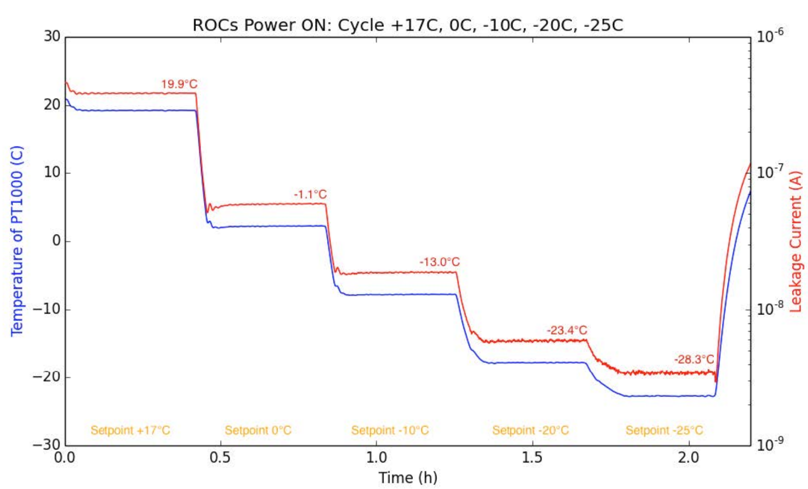

Figure 22: Sensor temperature calculation using leakage current

There is a very large difference between this result and simulation. Because the minimum temperature measured on the base plate is -27.76 °C, the temperature of any part of the module cannot be lower than that value. Therefore, it is believed that the calculated result has a large error.

Meanwhile, a PT1000 sensor was also embedded below the ROC to measure its temperature. It has acquired a value of T = -22.7 °C and the simulation gives a value of -18 °C. However, because the PT1000 beneath the ROC is very hard to control, it might slip off the ROC and was measuring the temperature of air between ROC and module holder, which has a very large gradient from -24 °C to -18 °C. Therefore, the value measured cannot be guaranteed to be accurate.

5.2 Improvements

Due to the limit of time available for this project, several proposed improvements for the simulation model are not able to be implemented. These improvements are believed to be able to address the error problem and improve accuracy of simulation.

Because the simulation was tested on a labtop which has a limited calculation power, it is proposed to use a more powerful computer in the future. In this way, the air around the module and the electronics on the module can be simulated easily.

To achieve a better gradient on the base plate, more mesh elements are required. This will give a much more precise heat transfer from the base plate and reduce the deviations occurred.

As mentioned in the last part of the simulation, the ROC2Sensor contact was adjusted to see the effect on sensor temperature. In an ideal situation, it would be better if the real bonded connection can be built and simulated. This also requires a more powerful computer.

Last but not least, it is proposed to test the simulation in different temperatures. In the current setup, only one single temperature setting was used. This implies that if the set point temperature changes, the model may not be valid anymore. Therefore, two or more temperature settings are required so the model can adapt in all conditions.

6 Conclusion

In this semester project, a model of the module assembly and cold plate were built in Autodesk Inventor and then imported into ANSYS for simulation. The simulation used base plate temperature, air temperature and ROC power as input. The temperatures of module holder, base strips and sensor were extracted from the simulation results.

It is measured that the temperature of sensor is -18.25 °C when the cold box is set at -25 °C. Because the experimentally calculated result is believed to have a large error, we are not able to compare this result with any references. Also, ΔT between base strip and sensor is 7.8 °C.

Due to the limit of time and calculation power, several improvements on the simulation were not able to be implemented. They are proposed in the discussion section as well.

7 Acknowledgments

I would like to thank Andrey Starodumov and Robert Becker for their supervision and guidance through the project. I also want to express gratitude to Simon Strorz for his help during all the experiments.

References

[1] Retrieved from: http://inspirehep.net/record/826852/plots#0

[2] Lucas Taylor, http://cms.web.cern.ch/news/silicon-pixels, 2014/05/06

[3] Retrieved from: http://www.phy.olemiss.edu/HEP/cms/pixel/

[4] Silvan Streuli, BPIX Module Assembly Manual, PSI

[5] Optimization of a cold box setup to perform digital pixel modules qualification at a temperatures down to -30C, Simon Strorz, Retrieved from: http://cmspixel.phys.ethz.ch/proj.html, 2014/06/11