FERMI NATIONAL
ACCELERATOR LABORATORY

**Summer School at FERMILAB
and other US Laboratories**

CONTROL SYSTEM FOR BURN-IN SYSTEM OF CMS SILICON MODULES

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August-September 2018

Not only is the Universe
stranger than we think,
it is stranger than
we can think.
-Werner Heisenberg, Across the Frontiers

Abstract

The aim of my work was to configure all the hardware and software control system for the Burn-in system that will be used to test the CMS Outer Tracker modules at a specific operating temperature.

In the mid 2020s the *LHC* (Large Hadron Collider) accelerator will be upgraded to deliver over 3000 fb^{-1} of proton-proton collision data at 14 TeV; to fully exploit the discovery potential of the *HL-LHC*, the *CMS* (Compact Muon Solenoid) detector will be upgraded as well: the new silicon tracker will be essential to maintain the capabilities of the *CMS* detector in the harsh environment expected at the *HL-LHC*. The new outer tracker will be capable of providing tracking information to the first-level trigger at 40 MHz for the first time at hadron colliders; furthermore cutting edge technologies will be adopted to ensure the longevity and efficient perfomance of both tracker sensors and tracker electronics over the course of the *HL-LHC* (10 years). The outer tracker will base its functioning on new silicon modules, which will have to work at temperatures lower than -35 °C, to mitigate the effect of high radiation dose they will be exposed. Quality control of each one of the (about) 13000 modules is therefore an integral component of the production phase. To test the proper working of the silicon modules at low temperatures, Fermi National Accelerator Laboratory developed the Burn-in system, an experimental setup where modules can be operated at pre-defined temperatures and humidity levels. This setup must work un-attended and provide fail-safe modes to reduce risks.

My contribution to the project starts here, since I configured, developed and tested the control system of the Burn-in satation. A BeagleBone Black (BBB) is the main unit, connected to temperature sensors and relays, in order to monitor and adjust the temperature and dew point of the thermal chamber where the modules will operate for 24h with temperatures cycling from room to operating temperature. To correctly interface with all the system devices, I debugged and configured an electronic control board called the “Burn-in Box Controller Interface". To perform tests in safety mode, I developed software, written in C++ and integrated in OTS-DAQ (the data acquisition software developed by the Fermilab Scientific Computing Division), for the quality control of the modules, consisting of a handler for all fault-/failure conditions. The system can now be controlled using a user friendly GUI, which provides different interfaces to configure/start/stop the tests and monitor the system status with graphs that show the time response of the main variables during testing.

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Part I

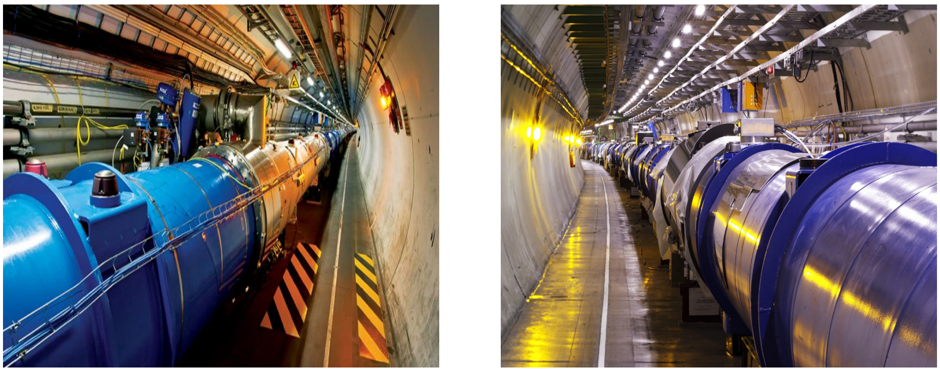
Initial background

Chapter 1

CMS experiment

1.1 LHC: Large Hadron Collider

The *LHC*, that stands for Large Hadron Collider, is the largest particle accelerator in the world, in fact it consists of a 27 kilometres ring, and it is situated in Switzerland, at *CERN* [1]. It is used to make protons collide with a frequency of 40 MHz and a very high energy, in order to generate and to discover new particles. In the figure 1.1 a little segment of the accelerator ring is shown.



(a) (b)

Figure 1.1: Large Hadron Collider, situated at *CERN*.

The proton-proton collider is currently operating at a center of mass-energy of 13 TeV: inside the accelerator, two high-energy particle beams travel at close to the speed of light before they are made to collide, with a frequency of 40 MHz. The beams travel in opposite directions in separate beam pipes, two tubes kept at ultrahigh vacuum. They are guided around the accelerator ring by a strong magnetic field maintained by superconducting electromagnets. Just prior to collision, another type of magnet is used to "squeeze" the particles closer together to increase the chances of collisions; nowaday the number of interactions per bunch-crossing is on avergae equal to 40.

Four multipurpose experiments are installed along the ring: *ALICE*, *ATLAS*, *CMS*, *LHCb*. The dataset intially delivered by the LHC and collected by *ATLAS* and *CMS* experiments allowed for the historical discovery of a Higgs boson in 2012.

Starting from the mid 2020s, the accelerator will be upgraded to the *HL-LHC* (*High Luminosity-LHC*).

1.2 CMS: Compact Muon Solenoid

One of the four experiments located around the *LHC* accelerator ring is *CMS*, that stands for Compact Muon Solenoid. It is a cylindrical particle detector designed for high-energy collisions, formed by different layers used to detect particles and measure their properties, as shown in figure 1.2.

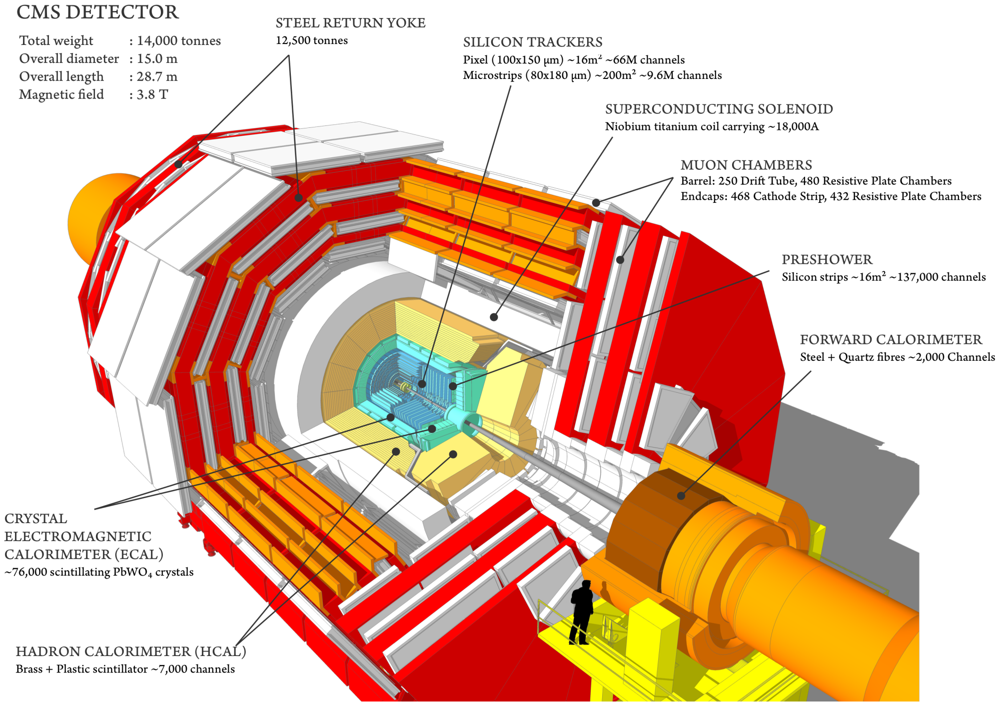


Figure 1.2: Sectional view of the Compact Muon Solenoid detector, situated at *CERN*.

An unusual feature of the *CMS* detector is that instead of being built in-situ like the other giant detectors of the LHC experiments, it was constructed in 15 sections at ground level before being lowered into an underground cavern near Cessy in France and reassembled. The complete detector is 21 metres long, 15 metres wide and 15 metres high [2].

1.2.1 CMS sub-detectors

Each sub-detector consists of layers of material that exploit the different properties of particles to detect and measure the energy and the transverse momentum of each one. Like a cylindrical onion, each sub-detectors use this key data to build up a picture of events at the heart of the collision [3].

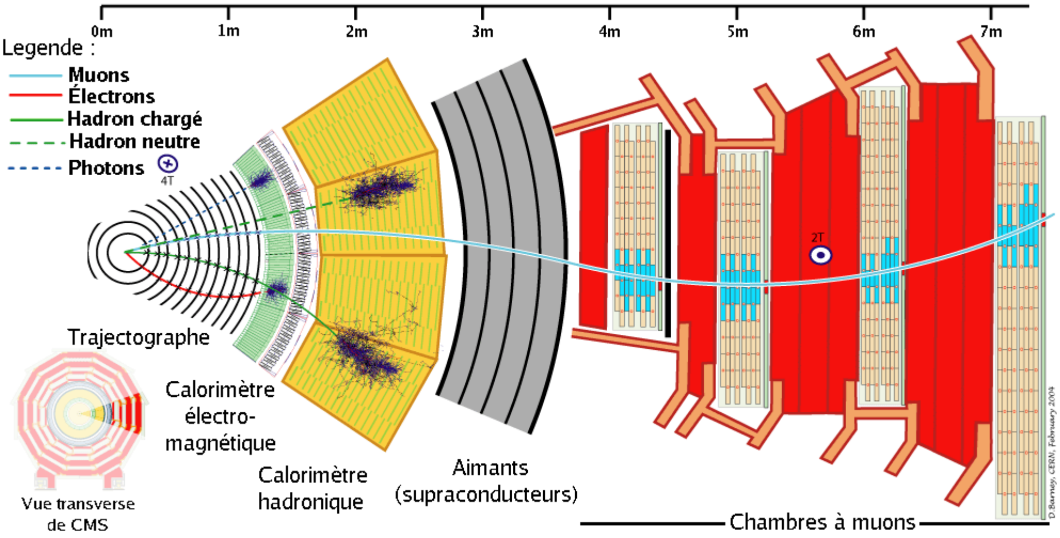


Figure 1.3: Layers of *CMS*.

As shown in figure 1.3, the first layer is a high quality central silicon tracker, composed by an inner and an outer tracker: a particle emerging from the collision and travelling outwards will first encounter it, made of silicon pixels (inner) and silicon strip (outer) detectors. These accurately measure the positions of passing charged particles allowing physicists to reconstruct their tracks. Charged particles follow spiralling paths in the *CMS* magnetic field and the curvature of their paths allow to measure their transverse momenta. Then there's the Electromagnetic Calorimeter, that can detect electrons and photons with a high resolution method, because these particles are stopped by the calorimeters, allowing their energy to be measured. Then there's the Hadron Calorimeter, designed to entirely surround the EM calorimeter and prevent particles from escaping, used to detect charged and neutral hadrons, particles that interact by the strong force, that deposit most of their energy into it [4]. A strong magnet is therefore needed to allow accurate measurements even the very high momentum particles, such as muons: the higher a charged particle's momentum, the less its path is curved in the magnetic field, so when we know its path we can measure its momentum. The Superconducting Solenoid, formed by this magnet, is a coil of superconducting wire that creates a magnetic field when electricity flows through it. Finally the last layer, the Muon Chambers, is composed by a high performance system to detect and measure muons.

To cope with the higher number of interactions per bunch-crossing and the large doses expected from the *HL-LHC*, the *CMS* detector must be upgraded.

1.3 Experiment upgrade

In the mid of 2020's the new accelerator (*HL-LHC*) will be upgraded to deliver over 3000 $fb^{-}1$ of proton-proton collision data at 14 TeV, causing a radiation damage 10 times larger than that expected during the previous run, because of the higher particle's dose deposited on the active elements of the detector. As a consequence, the *CMS* will be completely upgraded and the *Phase-2 CMS* detector will be installed. The *Phase-2 CMS* detector will have a new tracker providing information to the *L1 trigger* at 40MHz and capable of sustaining high radiation dose.

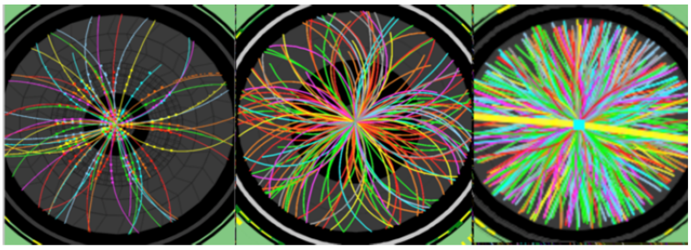


Figure 1.4: Event with ∼5, 10, 200 interactions per bunch crossing (left, middle, right).

Furthermore, the new accelerator will run at a number of interactions per bunch-crossing as high as 200 on average, so the *CMS* tracker granularity will be increased, from the current 66 millions to 2 billions channels.

Chapter 2

Outer tracker modules

The *CMS* outer tracker will be made of about 13000 silicon modules: they can be divided into two configurations, Strip-Strip (*2S*) and Pixel-Strip (*PS*), based on the sensors they're made of, and they will be used together to reconstruct the path of the particles in order to obtain the resultant momentum.

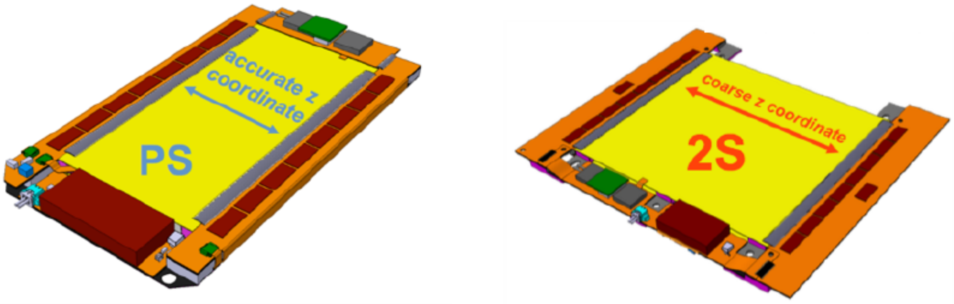


Figure 2.1: Two different types of silicon modules.

These modules must be tested in particular temperature conditions (-35 °C), because, due to radiation damage and thermal runaway, they will run at that temperature in the real experiment.

2.1 Description and behavior

The main idea behind the modules is that they are constituted by two sensors, physically separated by few millimeters, but still they are read out by the same electronic circuits. This allows them to make online measurements at 40 MHz, and send them to *CMS*.

2.1.1 Silicon sensors

Each sensor that composes a module is an inversed biased n-in-p junction: when a charged particle passes through the junction after the collision, it leaves a track by creating an electron-hole pairs, so that the electrons drift to the anode and generate the signal.

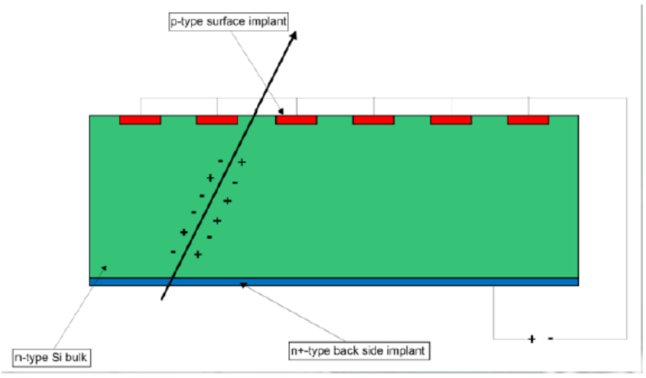


Figure 2.2: Example of silicon sensor.

The leakage current is proportional to the temperature, as expressed in the equation 2.1.1.

$$I_{leakage} = T^{3/2} e^{E_g/kT}$$

In order to avoid the thermal runaway, the sensors must be kept at low temperatures. Low operating temperatures allow to maintain the noise at low levels and to reduce the radiation damage.

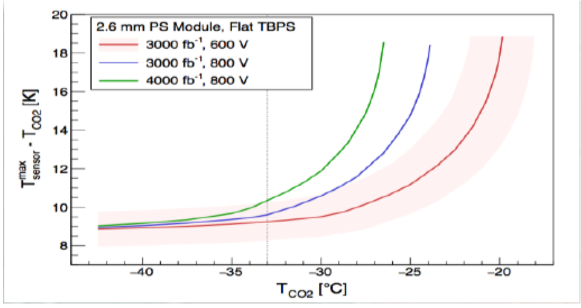


Figure 2.3: The leakage current of a silicon sensor, function of the temperature.

As you can see in the figure 2.3, the current value increase according to the equation 2.1.1. The picture show the relation between $T_{sensor}^{max} - T_{CO_2}$ and T_{CO_2} itself (T_{CO_2} represents the operating temperature since the cooling system is based on evaporative CO_2).

It's simple to conclude that to avoid thermal runaway the operating temperature of the sensors must be lower than -35 °C.

Part II

Main work

Chapter 3

Burn-in System

As already described in the chapter 2, the outer tracker modules have to work for long term at a low operating temperature in order to mitigate the high radiation dose they're exposed; in fact, the experiment will have a duration of about 10 years, so the silicon modules must properly work for the entire time.

The Burn-in System was developed by the Fermi National Accelerator Laboratory to perform quality control of the silicon modules inside a thermal chamber, in order to stress them and check their resistance at a low temperature.

Finally, the Burn-in System will be distributed in every *CMS* module production center in the World.

3.1 Overview

The system is composed of different parts concerning data acquisition, control and actuation, in order to monitor the temperature and the humidity and adjust them. The principal components are listed below and described in detail in the indicated sections:

- 1 **Thermal chamber**: also referred to a *Cold Box*, where the modules will be inserted using custom made support structure (3.2);
- 1 **Electronic control board**: to interface all the main devices (3.3);
- 1 **BeagleBone Black**: the microcontroller the control the entire system (3.3.1);
- 3 **Analog (*RTD*) and 10 digital temperature sensors**: used to monitor the *Cold Box* and the plate temperatures (3.3.2);

- 1 **Dew Point Temperature sensor**: used to measure the dew point temperature in the *Cold Box* (3.3.3);
- **6 Solid-State Relays (*SSR*)**: Chiller, Right/Left Peltiers, Warmup relay, Dry Air Flux relay, activated and de-activated to adjust the temperature in the box (3.3.4).

In figure 3.1 the complete block diagram of the Burn-in System is shown.

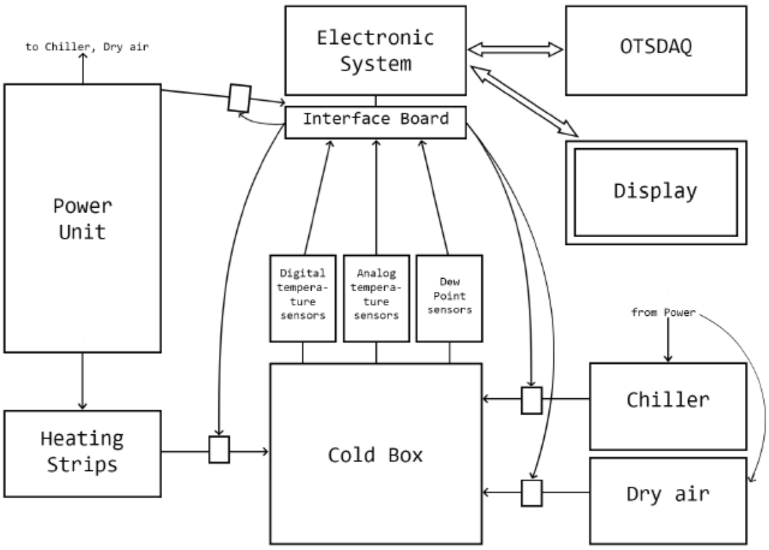


Figure 3.1: Burn-in System Control Schematic.

The tests will last 24 hours, with 4/5 cycles from operating to room temperature. One of the main features of the Burn-in System will be the capability of operating un-attended for the entire duration of the tests.

My work dealt with set up, configuration and debug of the entire Burn-in system, testing devices, replacing components and updating the electronic board in order to make the system more robust, as described in the next sections.

3.2 Thermal chamber

The thermal insulated chamber contains a slot where 10 silicon modules are vertically inserted using carriers.

In figure 3.2 it's possibile to see the front internal view of the thermal chamber developed at Silicon Detector Facility at Fermi National Accelerator Laboratory.

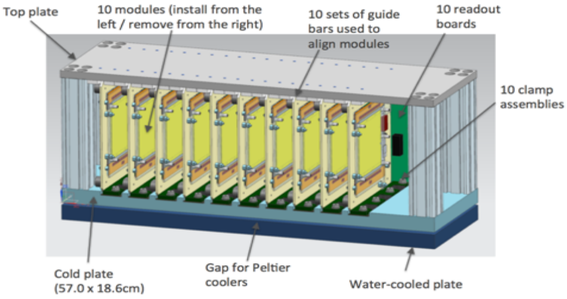


Figure 3.2: Thermal chamber mechanical design.

A clamping mechanism ensures the thermal contact with the modules. The power consumption, after irradiation, is equal to 7W for 2S modules and 9W for PS modules; given that it is dominated by the front-end electronics, this estimate is adopted as the requirement for the cooling system.

In figure 3.3 the actual *Cold Box* prototype is shown, which soon will be updated.

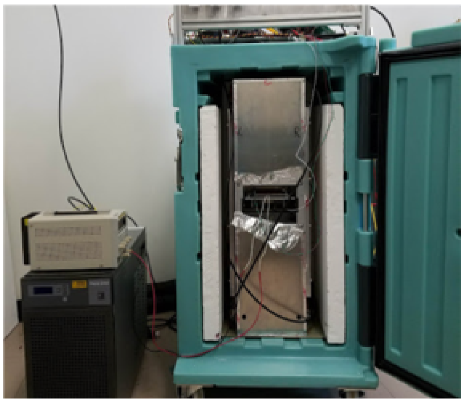


Figure 3.3: Thermal chamber actual prototype used for the tests.

3.3 Electronic control board

The system was built to monitor and adjust the temperature and the humidity inside the *Cold Box*.

The electronic board, shown in figure 3.4, is used to interface all the principal components of the system. It consists of a set of slots to plug-in the BeagleBone, all the sensors and the relays, and a set of configuration circuit used to connect the devices to the microcontroller, consisting of particular amplifiers and filters.

The board, also referred as “Burn-In Box Controller Interface” will be produced for all CMS centers where the Burn-in system will be used.

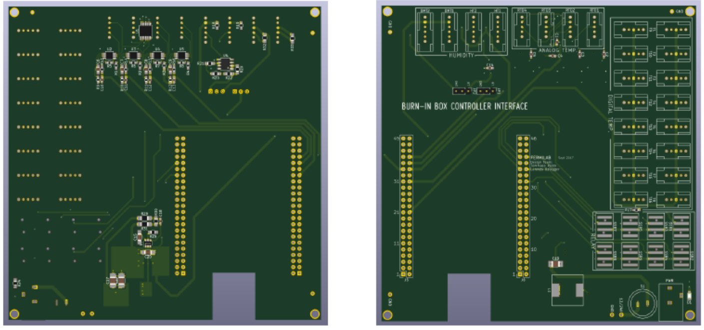


Figure 3.4: Electronic control baord.

My contribution dealt with replacing components, debugging and configuring the entire electronic board to test the correct functionalities of the devices, to achieve a better resolution in the data acquisition, changing the gain of the amplifiers, and to improve the system.

In figure 3.5 the electronic control board with all the sensors and the actuators plugged-in.

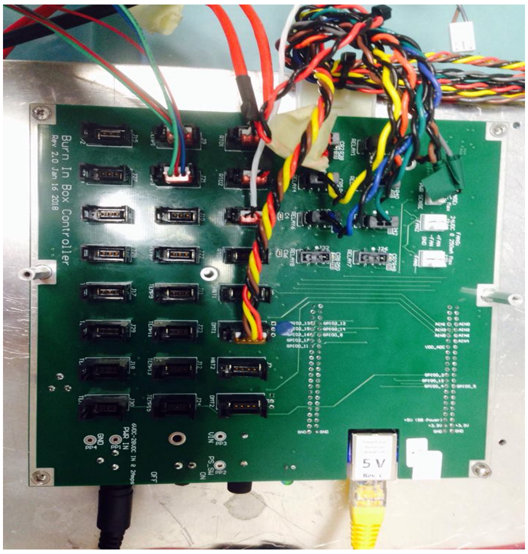


Figure 3.5: Electronic control baord configured and connected to all the devices.

3.3.1 BeagleBone Black

The heart of the control system is the BeagleBone Black (BBB) controller [5], shown in the figure 3.6.

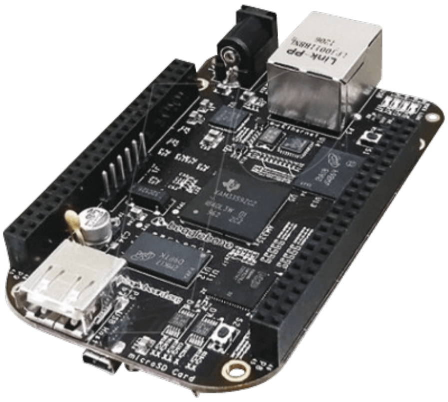


Figure 3.6: BeagleBone Black board.

It is a low-cost electronic board that runs Debian Linux OS; it supports C++ software integrated in OTSDAQ (the generic data acquisition software developed by Fermilab Scientific Computing Division).

Using a Ethernet port, that allows *SSH* access through the local network, the BeagleBone could be controlled and configured. Its I/O pins were used to acquire data from the digital temperature sensors and to control the relays with binary output signals. It is also provided of a 12-bit *ADC* (that accept values in the range [0; 1.8] V) used to acquire temperature values from the analog sensors (*RTD*s and Dew Point sensor).

C++ and BBB code

After having learnt the basic concepts of C++ language [6], I approached the BeagleBone software.

It is composed of a structure of different classes, that implement istances of all the devices involved in the system. In each class there are methods used to acquire data or to actuate the specific device. Then there are all the classes related to the interface between the microcontroller and the board, and all the functions to configure, to run and to control the system.

I had to modify the code in order to acquire concrete real data from the sensors (I changed the formulas used to convert the signal of sensors read-out channels into temperature/humidity value, according to the sensors datasheets [7]) and to have the ability of control the relays and check the system status. During all these steps I developed new methods in order to improve the system functionalities.

3.3.2 Analog and Digital Temperature sensors

The most important variable to monitor is the temperature, so the system provides both analog and digital sensors to measure it. The sensors used are the following ones:

- *OMEGA SA1-RTD*: PT100 *RTDs* analog sensors with high precision temperature measurement (accuracy < 0.35 °C at -33 °C) and response time lower than 1 second [8]. Additional circuitry was needed to connect the *RTDs* to the 12-bit *ADC* of BBB, since they are resistors and the analog pins only accept voltages in the correct range mentioned before (section 3.6). The electronic circuit is shown in figure 3.7, which uses 0.05% tolerance resistors and high precision amplifiers (the first one is used to have 1 mA as output, in order to minimize the error due to self-heating of the sensor, while the second one is used to adjust the voltage inside the correct range). I replaced them both because some of them are damaged and to change the second ones gain too, from 13.65 V/V to 10.25 V/V for a better data acquision resolution.

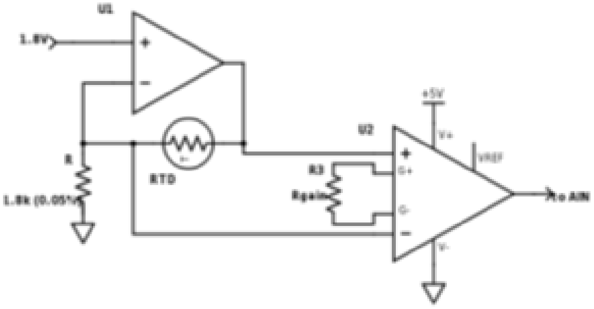


Figure 3.7: *RTD* temperature sensor electronic scheme used to connect it to the BeagleBone Black *ADC* analog input.

- *DS18B20*: digital sensors are powered by the BBB and communicate via a *1-wire* connection [9], so it is possible to connect all the sensors to the same pin (after having configured it for input measurements) and simply to read the temperature values. The operating range of the sensor is [-55,125] °C, with an accuracy of about ± 1 °C. Additional circuitry is composed by a 4.7 kΩ pull-up resistor, placed between the data wire and the power unit, as shown in figure 3.8.

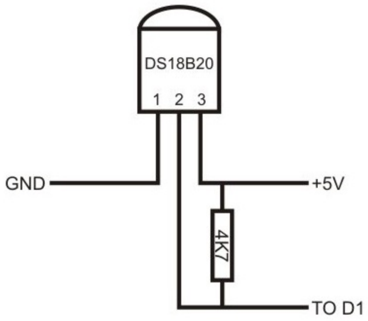


Figure 3.8: Digital sensor DS18B20.

The choice of using also analog temperature sensors was made because of the slow response time of the digital ones, that makes them not suitable to handle safety-failure cases.

3.3.3 Analog Dew Point sensors

Another important variables to monitor are the dew point and the humidity inside the *Cold Box*; the dew point sensor integrated in the system is a VAISALA DMT143, chosen for its %RH accuracy and fast response time [10]. The sensor analog output range is [4, 20] mA, so it could be simply read by the BeagleBone *ADC*.

Figure 3.9: Dew Point analog temperature sensor.

The humidity is calculated using the dew point and the ambient temperature inside the thermal chamber.

3.3.4 Solid State Relays

The Solid State Relays are digital actuators that can be activate/de-activated in order to adjust the temperature and the humidity values inside the *Cold Box*.

SSRs have 2 channels for the input (IN+ and IN-) and 2 channels for the load; they have to be connected to the load since they require power to work correctly, and they can be controlled optimaly using the BBB. The electronic scheme of the relays is shown in figure 3.10.

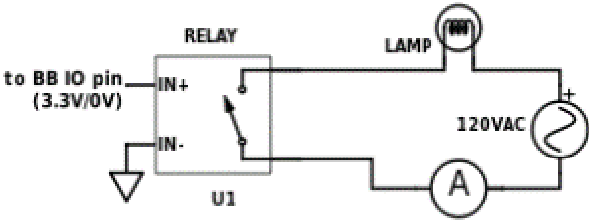


Figure 3.10: Relay electronic schematic.

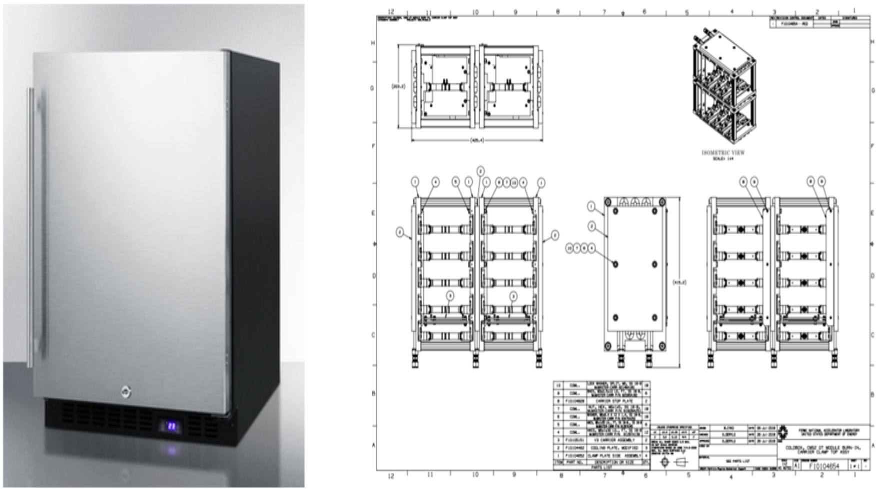
The 2 Peltiers relays (left and right) are used to cool the thermal chamber, so they are essential to low the tempertature to -35 °C and keep it in the range of operating value. The Chiller is properly used to cool the external part of the Peltiers, due to the fact that they overheat. The Warmup relay is necessary for the opposite action, in fact it is used to warm up the temperature inside the box. Finally, the Dry Air Flux relay is very useful to make the dew point temperature decrease, because during the correct operating tests it must always be lower than the ambient temperature in order to avoid the components oxidation.

3.4 Updates of the Burn-in system

Soon the Burn-in system will be upgraded:

- a **new (commercial) enclosure** will be provided, so the fridge will be changed in order to achieve a better insulation (figure 3.11(a));

- a **new support structure for modules** will be installed, consisting of two sections with five cooling plates each (figure 3.11(b)); the structure will have a support for the PS modules too;
- a **new Chiller** will substitute the actual one, with a power increased from 160 W @ -40 °C to 260 W @ -40 °C; this update will let the installation of Peltiers optional;
- the development of feed through by PU once cable (Low/High-Voltage, optical) panel will be finalized.



(a) New commercial fridge

(b) Internal view of the new system enclosure, with 2 sections of 5 slots each.

Figure 3.11: New enclosure for the thermal chamber.

Chapter 4

Quality Control

In the second part of the intership, I approached software development writing code in order to perform different tests and to handle fault/failure situations, to make the system be able to work well in every kind of condition.

4.1 Software development

To perform quality control of the modules inside the thermal chamber I developed different methods and classes to check the correct behaviour of the system while changing the temperature inside the box.

4.1.1 Control algorithm

This section is focused only on the main control algorithm; obviously I'm not gonna describe all classes, methods and functions that I implemented, but it is relevant to explain briefly how the system simply operates during the tests.

The quality control system (pricipal version) is developed in order to do the following instructions:

- read the current values of plate and ambient temperatures;
- switch the Chiller on;
- check if the plate temperature is lower, equal or higher than the set-point temperature;
    - switch the two Peltiers if the plate temperature has to be decreased;
    - switch the Warmup relay if the plate temperature has to be increased;

  - keep the relays off if the plate temperature is in the target range.

- repeat the same instructions.

4.1.2 Temperature cycles test

First, I performed a primary type of test consisting in 3 temperature cycles. The plate temperature of the *Cold Box* was changed in order to reach 3 different targets (10 °C, 15 °C, 20 °C, with a tolerance of 0.2 °C) and to keep it for few minutes respectively.

In figure 4.1, the first plot obtained shows how the temperature on the plate reaches each set-points and it is mantained inside the range defined by the tolerance. The final value (20 °C) is just reached, then the test is stopped.

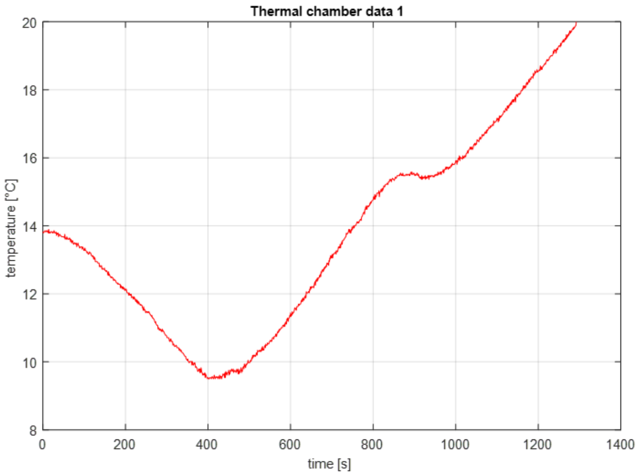


Figure 4.1: Temperature cycles test performed.

As already mentioned in the previous chapter 3, the temperature current value is acquired using the temperature sensors, and the average is computed, while it is adjusted to the target value acting on the different relays. I developed the control algorithm used for the *Feedback Control* of the temperature inside the thermal chamber.

After this step, the software was modified to save datas (during the tests) even from the dew point sensors, so the humidity was calculated, and from the relays too, in order to have a complete scenario of the system status.

4.2 Fault and failure handling

Due to the correct operation of the control loop, the interest moved to the addition of a handler fot fault and failure conditions, to avoid situations that could have damaged the Burn-in system or that could damage, in the future, the modules plugged-in.

Three principal conditions were considered in the update of the control algorithm, to prevent a unsafe behavior of the system variables:

- OUT-OF-RANGE CONDITIONS -> during the tests it is checked that the variables of interest are inside the correct operating ranges:
  - *Dew point temperature* safety range equal to [-80, 20] °C;
  - *Thermal chamber ambient temperature* safety range equal to [-35, 30] °C;
  - *Thermal chamber plate temperature* safety range equal to [-35, 30] °C.
- FAULT CONDITION -> dew point temperature value must always be lower than the ambient temperature by a given safety margin (equal to 5 °C); if this condition is not satysfied the relays are turned off and the dew point is decreased;
- PELTIERS MALFUNCTIONING -> continuous check of the correct operation of the Peltier relays; the system advices if one of them is damaged.

Figure 4.2 shows the result of one of the tests done in order to check the new quality control system; the target was set to 0 °C, with a tolerance of 0.2 °C.

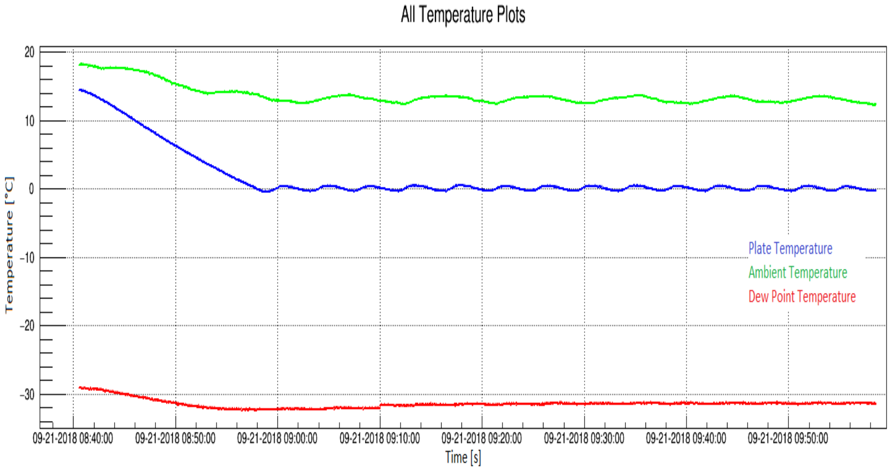


Figure 4.2: A single temperature cycle test performed after fault/failure handler addition.

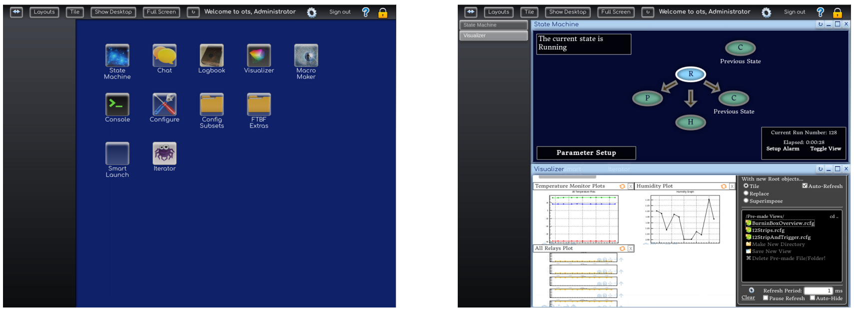
4.3 Integration in OTSDAQ

OTSDAQ (off-the-shelf data acquisition) is a ready-to-use data-acquisition system, developed by the Scientific Computing Division [11]. It provides a library of supported front-end boards and firmware modules, that work with low-cost hardware, used for data readout and other DAQ functions. It provides a user interface, used to configure and connect to the Burn-in System.

First, my code was integrated into the data-acquistion system, then I worked directly on OTSDAQ software to modify and set up the GUI in order to perform experimental tests with the *Cold Box* and finally to add significant graphs in order to have a real-time view on the status of the system. In this final step I became familiar with *ROOT* language, used to plot all the variables of interest.

The user friendly GUI (figure 4.3(a)) is composed by different button necessary to communicate with the system. The most important ones, listed in the same order they have to be used to perform a test, are:

- *Configure*: used to set up all the system parameters, like the BeagleBone IP Address, Communication Stream Port, set-point temperature, tolerance; after the first configuration, it could be pressed just if we want to overwrite some parameters, otherwise the previous configuration is still valid;
- *StateMachine*: used to configure, start, pause and stop the system (at the top of figure 4.3(b) is shown the internal view of the StateMachine);
- *Visualizer*: used to have a look on all the plots of the relevant quantities of the system, like plate, ambient and dew point temperatures, humidity, relays status (at the bottom of figure 4.3(b) some plots are shown).



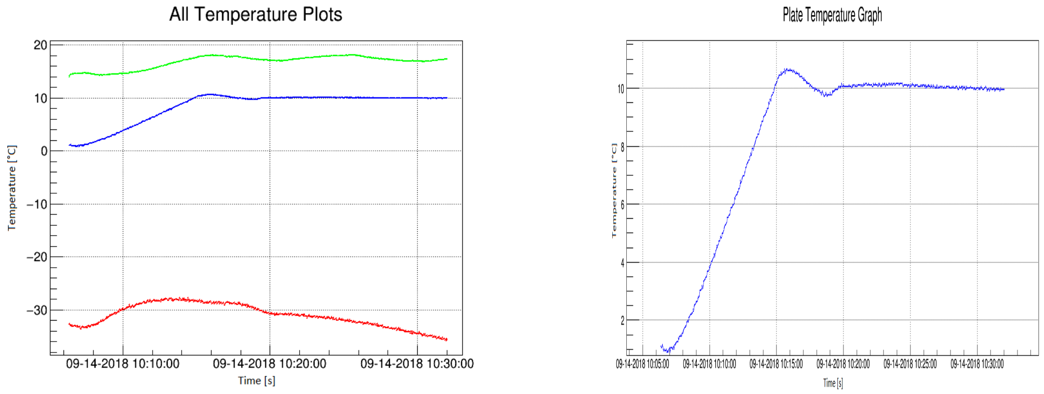
(a) OTSDAQ GUI, starting page.

(b) OTSDAQ GUI, State Machine and Visualizer.

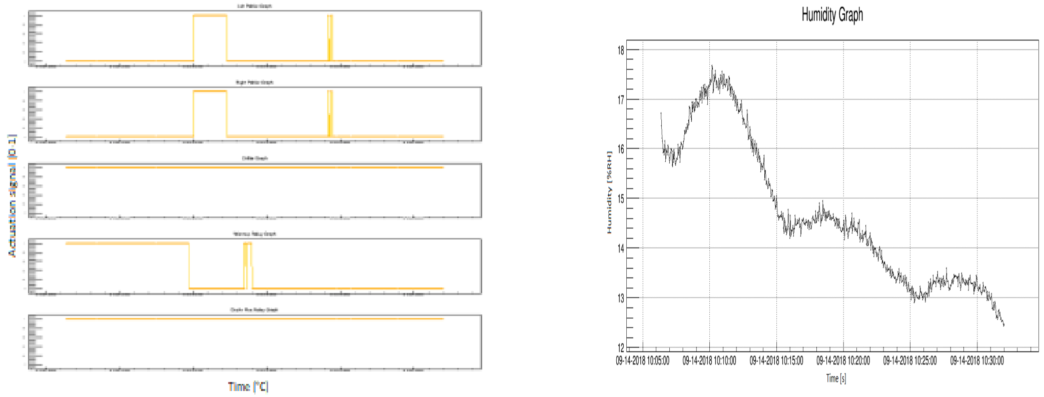
Figure 4.3: OTSDAQ user interface views.

4.4 Final tests

Finally, the system is finalized and complete in all its parts, so in this section there are reported the results inherent one of the final tests. In the first group of 4 figure (4.4) the most significant variables to monitor are plotted.



(a) All temperature plot (b) Plate temperature plot



(c) Relays status (d) Humidity plot

Figure 4.4: Final test results.

In the first graph (4.4(a)) the plate, the ambient and the dew point temperatures acquired are plotted, drawn with blue, green and red line respectively: the test was performed using a set-point temperature equal to 10 °C and a tolerance of 0.2 °C, so on the y-axis the unit is °C, while on the x-axis the unit is expressed in seconds, becuase it is reported the real time while the test was done; the dew point temperature is manteined far from the ambient temperature as expected. In the second one (4.4(b)) the attention is focused on the plate temperature, which reaches the target and mantains the correct fixed value, showing the goodness of the control algorithm, while in the third figure (4.4(c)) it is possible to have a look on the relays status: due to the fact that they can only be switched on/off, the signal sent to the actuators is just a binary value. In the final figure of that group (4.4(d)) it is monitored the humidity, which is calculated using the dew point temperature and the *Cold Box* ambient temperature.

In this final figure (4.5) the attention is again focused on the correlation between the actuation and the response of the system, showing how the relays are optimally controlled to keep the plate temperature inside the correct target range.

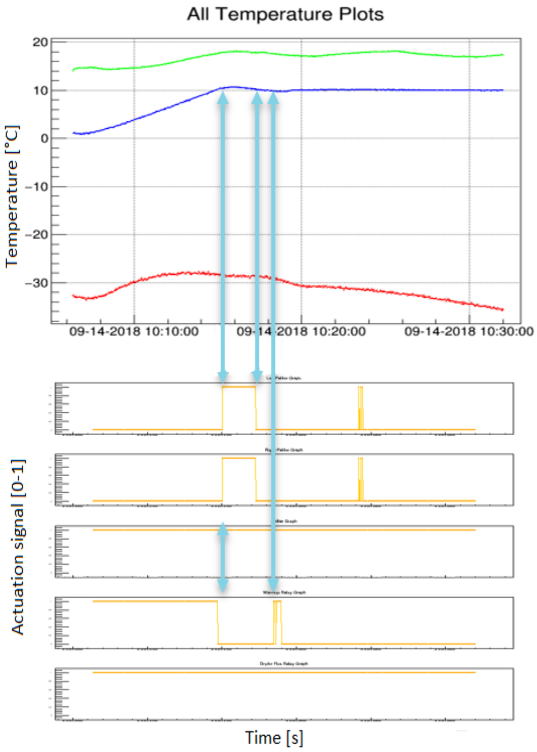


Figure 4.5: Focus on the action of the quality control algorithm.

4.4.1 Stress tests

On the 27th and the 28th of September a workshop for the *HL-HLC CMS Outer Tracker* was held, where I exposed my work on the system and the results obtained during the previous weeks, concluding with a live demonstration of the Burn-in system operating functionalities.

Due to the workshop, the system was moved to the SiDet, situated in the Fermilab area; in the new building, in the “Fish Tank”, I performed some stress tests to check again the correct behavior of the system and to test it in particular critical conditions. The results obtained, shown in figure 4.6, were very rewarding.

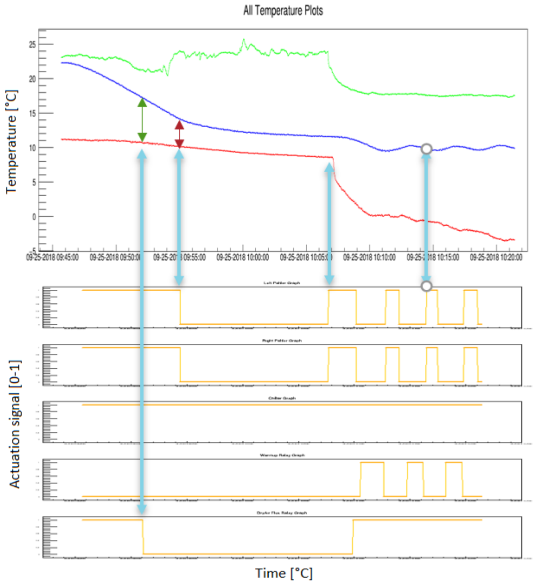


Figure 4.6: Stress test results.

Till the third blue arrow, starting from the left side of the picture, the door of the thermal chamber was kept open, in order to let the dew point temprature value grow. The green arrow shows that the safety margin between the dew point and the plate temperature is respected. The red one, instead, show that the dew point is critically so close to the current plate temperature, so all the relays are turned off. After the third blue arrow the door was closed, so the system could perform correctly the test estabilished before, because of the dew point temperature decreasing.

Chapter 5

Conclusions

My internship at Fermilab concluded with the finalization of the project I was assigned, in fact the Burn-in System is now finalized:

- Control board correctly set up and configured for sensors measurements and relays actuation;
- Software developed with fault/failure conditions handling and avoidance;
- Possibility to test the system with a user friendly interface

Furthermore, having finished a week before my departure, thanks to my supervisors I had the possibility to have a talk in an international meeting with the *CERN CMS International* group, where I presented the results obtained, and a workshop I already mentioned with the Fermilab *HL-LHC CMS Outer Tracker Module* group where I exposed my work on the Burn-in system and the final results with a live demonstration.

Concerning the aspects directly related to my work:

- I learnt the basics concepts of detectors for collider physics (CMS at LHC);
- I debugged and configured the electronic control board of the Burn-in System;
- I learnt C++ language (and a little bit of *ROOT* language) and I improved my skills about Linux;
- I developed and deployed quality control software to let the system work safetly under each type of conditions;

- I integrated control SW into OTSDAQ;
- I tested the system and obtain optimal results even under critical conditions.

Future steps include the updates of the Burn-in *Cold Box*, described in the section 3.4, and testing the system with modules, when the production will end.

A special thank to my supervisors ANADI CANEPA and LORENZO UPLEGGER, for supporting me every day, for trasmitting me the right motivation during the work and for the great opportunities regarding the meeting with *CERN* and the workshop at Fermilab.

Then I would like to thanks all the beautiful people I met at Fermilab, the ones that allowed me to have such a great experience full of cultural exchanges and professional improvements, and in particular the italian guys I lived amazing adventures with, during the internship.

Finally, I would like to thanks my parents for supporting me from home and for giving me the opportunity to attend this wonderful experience.

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