

Building and testing a high school calorimeter at CERN

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Abstract

We have designed, built and tested a crystal calorimeter in the context of CERN's first beam line for schools competition. The results of the tests at CERN show that the light output of our calorimeter depends on the energy deposited by particles (electrons and muons) hitting the crystals. Our design can be reproduced by high schools around the world, as we have avoided the use of toxic chemicals.

Introduction

As team Dominicuscollege we were the co-winners of the first Beamline for Schools (BL4S) competition of CERN [1], which was held in 2014. Together with the other winning team, Odysseus' Comrades from Greece [2], we worked at CERN for 10 d to carry out our experiments.

Our proposal was to build a crystal calorimeter (device used for measuring energy) using self-grown KDP crystals. At CERN, our goal was to calibrate and test our calorimeter to see if we would be able to distinguish electrons and muons by their energy deposits.

We want to show that physics is accessible for high school students. Everyone can set up and run an experiment. In short, we want our unique calorimeter to be an inspiration to other students.

In this article, we will show how we made the crystals and the calorimeter, we will explain what we did at CERN and we will analyze the results.

Growing crystals

We have chosen to work with potassium dihydrogen phosphate (KDP) for several reasons,

taking into account that it should be possible to be conducted by high school students:

- (1) KDP is inexpensive
- (2) Young adults are allowed to work with KDP
- (3) KDP grows rather fast
- (4) KDP is well dissolvable in water

We have explored the most favorable conditions under which to grow crystals.

The following tests were performed at the Dominicus College in Nijmegen. First, the right concentration of KDP in the supersaturated solution had to be determined. We noticed that a low concentration resulted in dissolving these crystals, whereas a high concentration resulted in fast growth. However, the resulting crystals had many irregularities and therefore were not transparent. We finally settled for an ideal solution using 110 g of KDP in 500 ml of demineralized water.

We created four test groups, each of which consisted of three beakers containing a supersaturated solution of KDP as well as a seed crystal. The temperature, pressure and humidity in the room were checked on a daily basis, as well as the amount of supersaturated solution in each of the beakers. We daily added some supersaturated

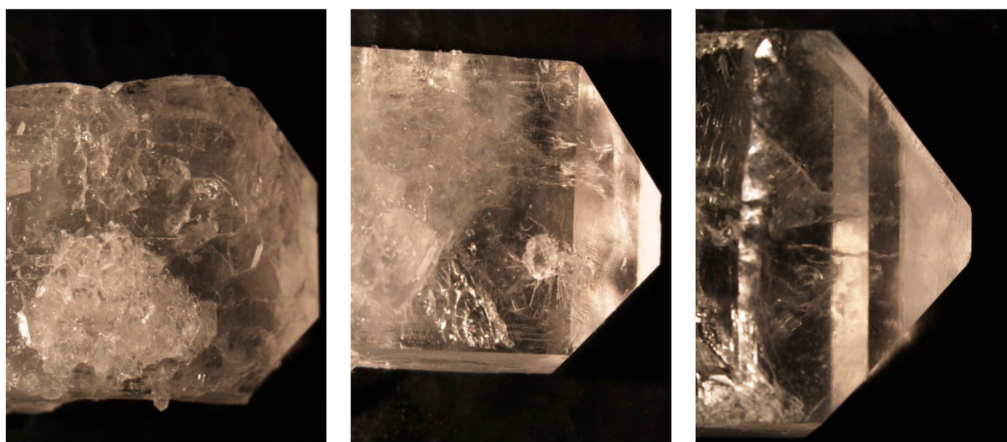


Figure 1. Left: Crystal from the 'Fan' group. Middle: crystal from the 'Control' group. Right: crystal grown in the stock solution of KDP. The irregularities in the 'Fan' group are clearly visible, as well as the clarity of the 'Stock' group. The photos were made with a stereoscope.

solution to the beakers to keep the amount of solution on the same level. The length, width and height of each grown crystal were measured weekly, using a caliper. The different tests performed were:

- (1) Testing if placement under a fan would enhance evaporation thereby influencing the growth of crystals ('Fan' group).
- (2) Testing if a daily refreshment of the supersaturated solution reduces the amount of pollution, thus influences the growth ('Refresh' group).
- (3) Testing if rinsing the crystals on a daily basis, thereby removing irregularities, creates clearer crystals ('Rinse' group).
- (4) A control group in which none of the above actions were performed ('Control' group).

After 18 d, differences between the test groups were clearly visible (figure 1). The crystals from the 'Fan' group had been growing the fastest. However, the resulting crystals were less clear and less regular than those from the other groups. The crystals from the 'Refresh' and 'Rinse' group did not show any significant differences in clarity and size. The crystals of the 'Control' group turned out to be slightly clearer and bigger than the 'Refresh' and 'Rinse' crystals (figure 2).

Our conclusion is that crystals grow best when left alone. This way the crystal grows layer over layer following the crystal lattice, which provides a clear and regular crystal. This conclusion was confirmed when looking at our stock of

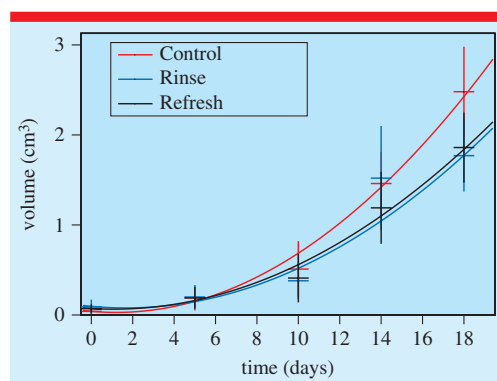


Figure 2. Graphs of the growth rate of the different samples of crystals. The graphs show that the growth rate of the 'Refresh', 'Rinse' and 'Control' groups is more or less the same; in fact, crystals in the 'Control' group have grown slightly faster. We estimated the volume of the crystals using a caliper. Because of the uncontrollably fast and irregular growth of the 'Fan' group, we decided to stop this experiment earlier to save the supersaturated solution for the other three groups. For this reason, the 'Fan' group is not included.

KDP solution. In the days after the tests, some of the most beautiful crystals had been formed in the Erlenmeyer flask that contained the stock of supersaturated solution. The differences in structure between the 'Fan', 'Control' and Erlenmeyer flask crystals are clearly visible.

To create the crystals we used in our calorimeter, we grew 18 small crystals of a few centimetres in each dimension. These were partly grown



Figure 3. Complete setup of the outside (left) and inside (right) of an individual module of our calorimeter.

at school, partly grown at home. At the Radboud University, we were able to use a climate chamber to grow four bigger crystals of approximately $7 \times 5 \times 3 \text{ cm}^3$.

It is important to consider that even though we monitored the environmental conditions, we did not have a climate chamber available at school so we could not control the humidity and temperature. These parameters will have affected the growth and quality of the crystals.

The detection principle of our calorimeter

A crystal calorimeter measures the energy deposited by incoming particles in each crystal. When a high-energy particle enters one of the KDP-crystals, it has a speed greater than the speed

of light in this medium, thereby the Cherenkov-effect occurs [3]. The photons, created in interactions between the particle and the KDP, propagate in a cone-shaped pattern behind the particle, creating a coherent wave front. This effect is called the Cherenkov-effect and is comparable to a shockwave, like a plane breaking the sound barrier. Because the crystal needs to transfer the photons, it is essential to grow the clearest crystal possible.

We can distinguish electrons from muons by looking at their energy deposit pattern in the calorimeters. An electron creates an electromagnetic shower, whereas a muon ionizes minimally. By looking at this difference in energy deposit pattern, we should be able to distinguish electrons from muons.

The calorimeter design

The basis of our design is to have individual crystals read out through a photomultiplier tube (PMT). However, the size of most of the crystals was rather small, so we glued them together using BC600 optical cement. Afterwards, the crystals were wrapped in aluminium foil and fixated with scotch tape.

Our initial idea was to connect the crystals with scintillating fibres to the PMT. These fibres would be attached directly onto the KDP crystal and they would lead the Cherenkov light to the PMT. Because of the size and quality of the crystals, the signal turned out to be too weak to be detectable via fibres. We therefore decided to mount the KDP crystal directly onto the window of the PMT. An optical connection to the PMT was made using optical grease. The PMTs we had available were Philips XP-1911 10 stage tubes, connected to a Kusatsu high voltage supply (HPMC-2.2N-DSY), which is able to deliver up to 2 kV to the PMT.

Figure 3 shows the complete setup of an individual module of our calorimeter. The PMT is housed in a PVC pipe (diameter 5 cm), held in place by a Styrofoam ring. At the back-end connectors for voltage and signal are placed on a PVC-cap. Furthermore a spring ensures that the PMT pushes onto the crystal thus ensuring continuous optical contact. The crystal itself is placed in a wider PVC pipe, with a diameter of 8 cm. The space between the crystal and top cap is filled with bubble wrap. We covered the seams and housing of the crystal with black electrical tape to fixate the housing and to prevent ambient light to influence the measurements. In total we made 9 calorimeter elements: 8 to use and 1 spare.

Calibrating the phototubes and testing the calorimeter modules

Using a cosmic ray telescope, we have used a single piece of scintillator to calibrate each PMT, so each PMT was calibrated sequentially using the same active material.

In order to conduct the experiment, we need to be able to compare the results of each calorimeter module equally. Therefore we will have to calibrate each PMT relatively to one another, in order to ensure that all PMTs give the same output, when receiving the same amount of light. A fast method to accomplish this is to use a cosmic ray

Table 1. Table of calibration parameters for each PMT.

Serial number PMT	Voltage (V)	Efficiency
19734	1303	0.95
20285	1297	0.97
20287	1409	0.96
18857	1330	0.99
20947	1386	0.96
20450	1301	0.98
22279	1415	0.98
20258	1244	0.96
18420	1225	0.96

telescope and measure the efficiency of detecting a cosmic ray muon, using a fixed threshold level (table 1). The efficiency means the number of particles detected each individual Dominicuscollege calorimeter module, divided by the number of particles detected in a scintillator, in 1 min.

It should be noted that at these voltage settings the amount of noise pulses for each PMT was about the same.

Subsequently, each calorimeter element was tested using the same cosmic ray telescope. Pulses from the calorimeter elements were observed in time coincidence with the muon telescope indicating that the calorimeter element was functioning properly before shipping to CERN.

Dominicuscollege calorimeter setup in the CERN T9 test beam

For our experiment at CERN, we built a metal rack in which the calorimeter elements were placed in two rows of four modules each (figure 4). Before moving the calorimeter into the beam line, each calorimeter element was tested again. By focussing the beam on the left row (LG 16–19 (=DCC 0–3)) and on the right row (LG 20–23 (DCC 4–7)) we calibrated the crystals, comparing the energy deposits in the Dominicuscollege calorimeter with the deposits in the CERN lead glass calorimeter, which were placed behind our calorimeter. Together, they should fully absorb the energy of the electron showers.

Experimental setup of the CERN T9 test beam

Figure 5 shows the setup used for our experiment at CERN's T9 test beam [4]. We have used multiple devices to be able to select the type of

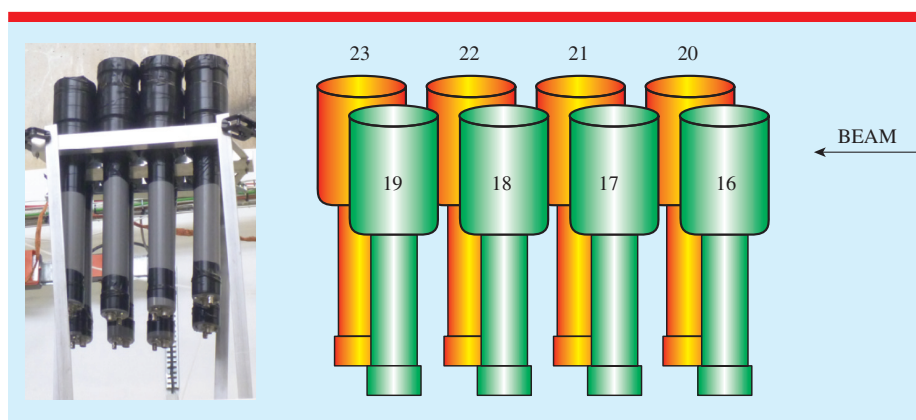


Figure 4. Left: Picture of the Dominicuscollege calorimeter in the CERN test beam. Right: Schematic drawing of our setup, including the numbers of the calorimeter units.

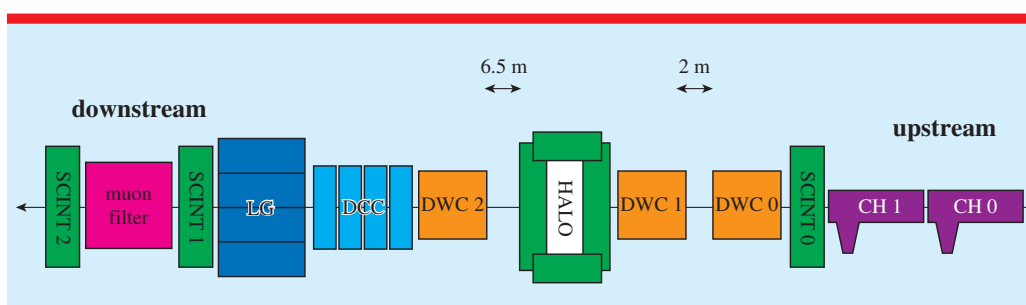


Figure 5. Experimental setup of the CERN T9 test beam. CH = Cherenkov counter, SCINT = scintillator, DWC = delay wire chamber, HALO = halo-counter, DCC = Dominicuscollege calorimeter, LG = lead glass calorimeter. Note that the direction of the beam is from the right to the left.

particle and the path it takes for optimal results in our analysis.

Cherenkov counters (CH 0, CH 1)

The Cherenkov counters are used to identify the type and energy of a particle. The pressure of the gas in these devices can be adjusted in order to select particles by their different energies. When the speed of the particle is greater than the speed of light in the gas, Cherenkov light is produced.

Scintillators (SCINT 0, SCINT 1, SCINT 2)

Scintillators are used to detect the particles when they are coming through. When a charged particle

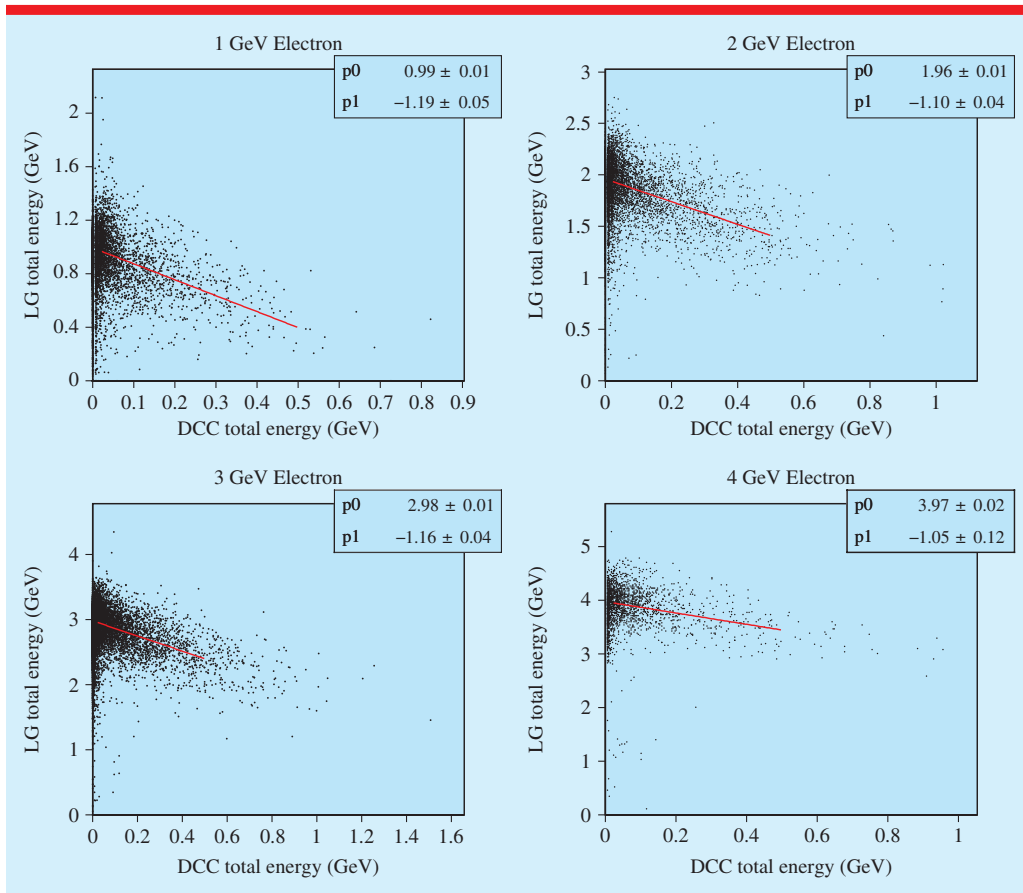
strikes the scintillator, it re-emits the deposited energy in the form of light.

The first scintillator in our experimental setup is scintillator 0, which is used to track time. This scintillator should always be triggered because all particles should go through it.

Scintillator 1 is used to detect whether the particle was able to pass through all delay wire chambers, the halo counter and, most importantly, the Dominicuscollege calorimeter (DCC) and lead glass calorimeter (LG). Using this scintillator, we can rule out certain particles. If, for example, the scintillator is triggered by a particle, this particle is unlikely to be an electron because it would have decayed already by producing an electromagnetic shower in the calorimeters. It is then most likely to be

Table 2. Cuts made to create the graphs for the electron and muon runs, shown in figures 6 and 7.

Device	Electron runs	Muon runs
Cherenkov 0	Yes	Yes
Cherenkov 1	Yes	No
Scintillator 0	Yes	Yes
	Selected to go through between -0.02 and $+0.02$	
	Selected to go through between -0.02 and $+0.02$	
Halo counter	No	No
	Selected to go through between -0.02 and $+0.02$	
Dominicuscollege calorimeter	Ignore	Ignore
Lead glass calorimeter	Yes	Ignore
Scintillator 1	No	Yes
Scintillator 2	No	Yes

**Figure 6.** These graphs show the results of our measurements. They illustrate that when the calorimeters detect an electron, the Dominicuscollege calorimeter measures more energy (DCCTotalEnergy) while the lead glass calorimeter measures less energy (LGTotaleEnergy). Hereby, the total energy of the particle remains the same.

a muon, because muons do not decay in the calorimeters.

Scintillator 2, in conjunction with the muon filter, can tell us whether the particle is a muon

or something else. If the scintillator behind the muon filter detects the particle, it is regarded as a muon and depending on the particle requirements discarded or kept.

Delay wire chambers (DWC 0, DWC 1, DWC 2)

Delay wire chambers are used to determine a 2D position of the particles in the beam. The delay wire chamber contains a grid of wires with 2 mm spacing. Incoming particles will ionize the gas (CO_2 and Ar) inside the delay wire chamber. Due to an electric field around the chamber, the electrons will move towards the nearest wire. Then we can measure the delay between the triggering of the two ends of this wire and calculate the exact position of the particle.

The delay wire chambers are needed to follow the trajectory of a particle. We mainly use this to focus the beam on the two calorimeters. When the particle deviates from its trajectory (measured by a third delay wire chamber), we know something must have happened to it, for example, an electron that possibly had interactions with the surrounding air molecules.

We can also use the trajectory to predict whether the output from scintillator 1 and 2 will be useful when selecting particles. In order for a particle to be useful for our measurements, its trajectory must be somewhat straight, which can be measured by comparing the coordinates of two or three delay wire chambers.

Halo counter (HALO)

The halo counter consists of four scintillators that form a hole in the centre. It is used to detect the beam's halo. The particles in the halo of the beam are not useful in the analysis because they have a high chance of missing some detectors. By selecting the particles that pass through the hole of the halo counter, we get a centred beam in our analysis.

Lead glass calorimeter (LG)

The lead glass calorimeter was our instrument of choice to reliably measure a particle's energy. This calorimeter uses the principle of the Cherenkov effect to detect the particle and measure its energy deposit. We used 16 individual lead glass calorimeter modules and arranged them in a 4×4 pattern perpendicular to the beam axis for added resolution.

Muon filter

The muon filter is a concrete block, which absorbs the energy of all particles, except for muons. This

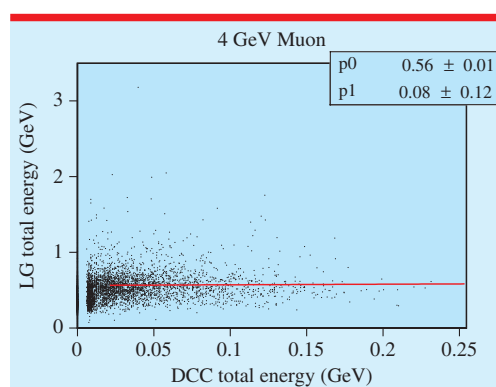


Figure 7. The energy of muons is detected differently. The energy detected by the Dominicuscollege calorimeter (DCCTotalEnergy) is slightly positively correlated to the energy of the muon detected in the lead glass calorimeter (LGTotaleEnergy). This is because the muons barely lose any energy while travelling along the beamline and therefore we are measuring about the same amount of energy in both calorimeters. However, this result is not significant.

Table 3. The slope of the graphs in figures 6 and 7.

Runs (GeV)	Slope
Electron 1	-1.19 ± 0.05
Electron 2	-1.10 ± 0.04
Electron 3	-1.16 ± 0.04
Electron 4	-1.05 ± 0.12
Muon 4	0.08 ± 0.12

results in only having muons in the beam after the beam having passed the muon filter.

Result analysis

We used a trigger mechanism (Nuclear Instrumentation Module, NIM) to filter out all the unwanted signals. After that, all signals were fed into a data acquisition system (DAQ) and then into a computer, which created ROOT files. We could then further analyse the data using these ROOT files and the application 'ROOT' provided by CERN. The data was also fed into several client computers so we could monitor the experiment instantaneously. This involved the ROOT application [5] and LabVIEW [6] (BL4S 3D Event Viewer).

Table 2 shows the cuts in the data that we have used to create the graphs of the electron (figure 6) and muon runs (figure 7). These cuts selected the type of particle needed. 'Ignore'



Figure 8. Director-General Rolf-Dieter Heuer (white shirt, by door) together with the beamline for schools team in front of the T9 test beam at the east area, CERN. (Image: T. Pritchard, CERN. <http://home.cern/about/updates/2014/09/wealth-data-beamline-schools> 16th of September 2014.)

means that we did not use this device to select certain particles for our measurements. ‘Yes’ means that if the device gives a signal, we do include the corresponding particle in our measurements. ‘No’ means that if the device gives a signal, we do not include the corresponding particle in our measurements.

We have chosen to compare the Dominicuscollege calorimeter with the lead glass calorimeters because this allows us to calibrate our calorimeter using the slope.

In the graphs of figures 6 and 7, we have put the energy measured by the lead glass calorimeter on the Y -axis. The results of the lead glass calorimeter are used to calibrate and test our Dominicuscollege crystal calorimeter, which is on the X -axis.

In the electron graphs, we can see an expected negative directional coefficient. This means that when there is an energy deposit in the crystal calorimeter, there will be less energy left to be measured in the lead glass calorimeter. The results show that this, indeed, is the case.

The energy of muons is detected differently. The energy detected is positively correlated to the

energy of the muon detected in the lead glass calorimeter. This is because the muons barely lose any energy while travelling along the beamline and that is why we are measuring about the same amount of energy in both calorimeters. This also means that we can use the energy deposit pattern along a row of calorimeters to decide what kind of particle it is. If the amount of energy is roughly the same in the two calorimeters, we can determine that it is a muon and if it deposits a lot of energy in the Dominicuscollege calorimeter, and less in the lead glass calorimeter, we can say it is an electron.

Conclusion

Using a supersaturated solution of potassium dihydrogen phosphate (KDP) we were able to grow crystals. We have noticed that in order to grow clear crystals the growth rate should not be too large because the crystals need time to order themselves. Our tests show that minimal interference with the growth process yields the best results.

With these crystals we were able to build a functioning calorimeter. By putting the crystals

directly on the photomultiplier tube's windows, it is possible to measure light, produced by electrons and muons in the beam due to the Cherenkov effect.

Our calorimeter performed well at the T9 test beam at CERN. We were able to distinguish the electrons from muons by comparing the energy deposits in the Dominicuscollege calorimeter with the lead glass calorimeter.

Experience

We had an amazing experience at CERN. A whole new world has opened up for us. We learned a lot, saw a lot and heard a lot. What other high school students are able to say that they were allowed to carry out their own experiment at CERN? It was an honor to gain working experience at CERN, we feel very unique and proud of that.

Our journey began with a safety training and computer tests. We received our CERN access cards and dosimeters the following day. Our working days were split up in three shifts, during these hours we kept an eye on the progress of the experiment. Between the shifts, we analyzed the data and explored CERN and Geneva. In addition, we were given tours at various sites including ATLAS, CMS and the CERN Control Centre.

The collaboration with the Greek Odysseus' Comrades team was really educational for us. It was an interesting new way to communicate in English. Another aspect we noticed was that the Greek team had different approaches compared to us. For instance, the Greek team was more theoretical and we were more practical, but we turned this to our advantage and we benefitted from each other's qualities. It was also very pleasant to work with the CERN staff. We really felt that we were in charge of our own experiment and that we were part of the CERN community. The CERN staff taught us with enthusiasm about CERN and the field of particle physics.

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