Analysis of the CMS End Cap VPT

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1 Introduction

The goal of this report is to summarize my work and experience in the past four months of working at CERN with the Boston University Geneva Physics program. While at CERN, I worked for the CMS experiment, one of the largest experiments at CERN. More specifically, I was directly involved in anlyzing data from the end cap detectors in the CMS electron calorimeter detector. The overall goal of the project was to determine whether or not an LED system put in place to improve the accuracy of the detectors was successful. This was done by comparing real data from the CMS end cap and comparing it with experimental data found in the lab.

Analysis was done using both the C++ programming language and the CERN ROOT analysis framework. All data used was data taken from the CMS end cap from the month of October in 2011.

2 CMS

2.1 End Cap

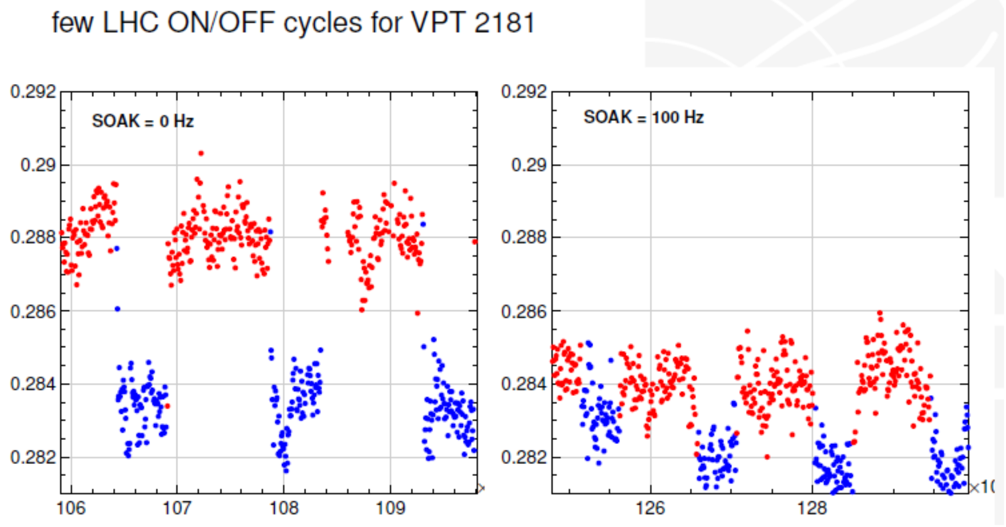
The focus of my work had to do with the end cap detector. Each endcap is made up of 7,324 Lead Tungstate crystals (PbW04), and each crystal is 3 x 3 x 22 cm. These crystals react to particles in the form of scintillation light in photon showers. The two end caps are labeled as EE+ and EE-. All of the data used for this project was taken from the EE+. The Lead Tungstate crystals are fairly radiation resistant, meaning they will not take a debilitating amount of damage from the LHC beam, however there are still some effects. Fortunately, at the right temperatures, the crystals are capable of self recovery, returning themselves to their original state. The process of self recovery occurs when the beam is turned off, though the effects are noticable when the beam is on the tail end of a fill.

In order to capture the scintillation light from the crystals, vacuum phototriodes are attached to the end of the crystals with a special adhesive that does not interfere with the photons. The vacuum phototriodes (VPTs) are different than those in the barrel of the CMS ECAL detector, as the VPTs are able to operate within a much higher amount of radiation.

2.2 The Problem With VPTs

Despite how precise and how radiation resistant the VPTs are, they still possess one significant draw back. Sudden large changes in radiation (such as the beginning and ending of an LHC fill) can greatly affect the reponse of the VPTs. Forunately, it was discovered that these changes in response can be significantly reduced by continuously pulsing the VPTs with a low rate of blue light provided by an LED monitoring system.

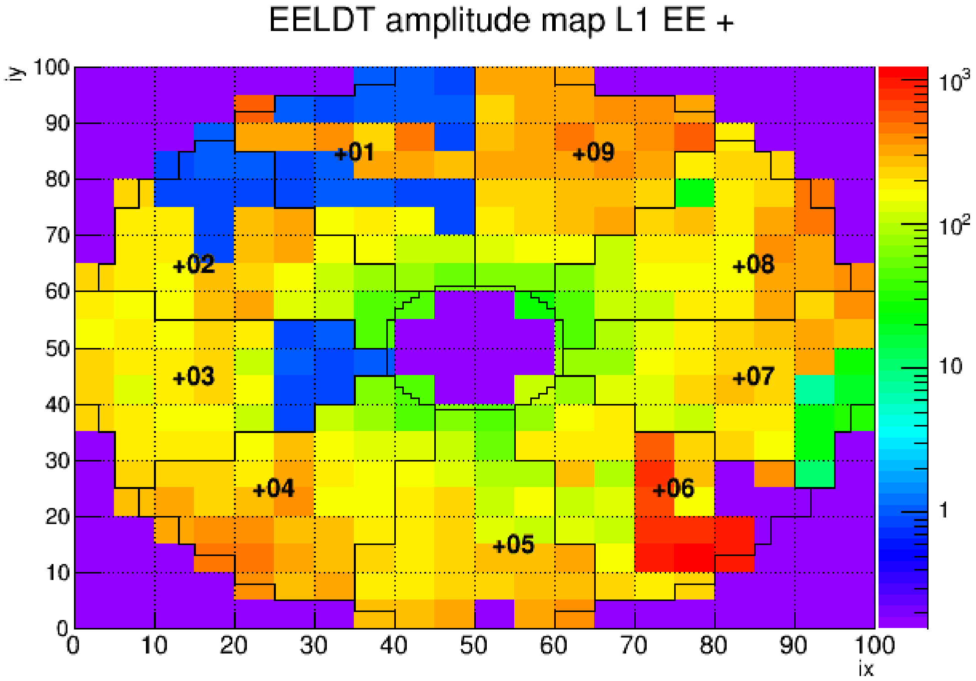
Figure 1: Lab Data of VPTs



The left hand plot in Figure 1 shows the response of VPTs in the lab when the soak light is off, while the right hand plot shows the response when the soak light is pulsing at 100 Hz. The red data points indicate when the beam is on, blue points indicate off. The x and y axes denote time and normalized response of the VPTs, respectively.

My role was to look at data from the month of October, 2011, from the EE+ VPTs. During this time period, some of the LED pulse lights had malfunctioned, resulting in there being areas with the soak light on, and some with the light off. By comparing the data from these two regions, the goal was to determine if the lab data accurately predicted what happened in the LHC. The regions of EE+ with malfunctioning LED lights can be seen in blue in figure 2.

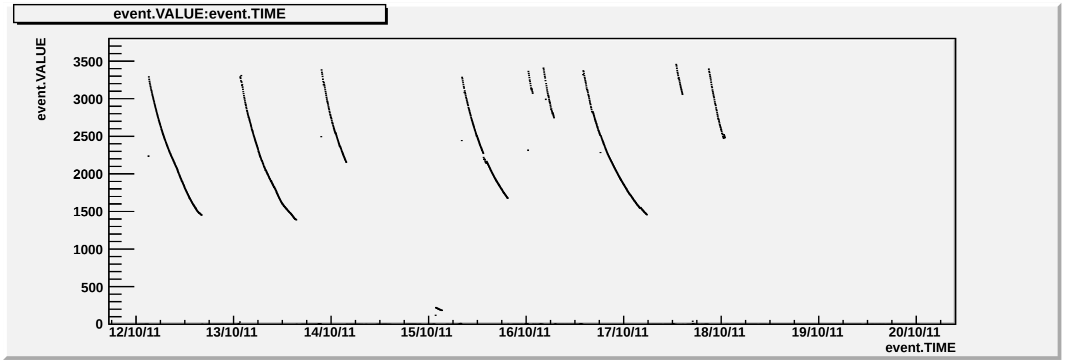
Figure 2: Malfunctioning LEDs



3 Method

Before analysis could begin on malfunctioning and working LED regions, we need to understand the effects of the actual LHC beam on the response of the crystals. In the lab setting, the crystals were exposed to a constant amount of radiation, whereas in actual CMS detector, the beam luminosity undergoes exponential decay. Figure 4 shows the fills of the LHC for the time period in question.

Figure 3: LHC Fills in October, 2011



Y axis is the luminosity of the LHC beam in units of

$$10^{29} * cm^{-2} * s^{-1}$$

3.1 Encoding of VPTs

In the end cap, each crystal channel is given an x and y coordinate, with each coordinate going from 1 to 100, inclusive. For the purpose of recording data, each channel is encoded with single eight digit hexadecimal id number, such as 0x34005481.

In most computer programming languages, including c++, a hexadecimal value is denoted with the 0x prefix. In order to decode the channel ID numbers, it is important to understand the following operators:

$$x << n$$

This operator is known as the left bitshift operator, and is a binary operator. It appends n zeroes to the binary representation of x. In other words, the left bit shift operator can be expressed as the following:

$$x << n = x * 2^n$$

This operator is commonly used for isolating parts of a bitmask or 32-bit word that one wishes to decode.

The second operator is called the bitwise AND operator, and is written as follows:

$$x\&y$$

This operator compares each binary digit of x and y bit by bit. If both the *nth* bit of x and y are equal to 1, then the *nth* bit of x&y is 1, otherwise, it is 0.

To get the x and y coordinate from the ID value, the following formulas are applied:

$$x = ((id) << 7)\&0x7F$$

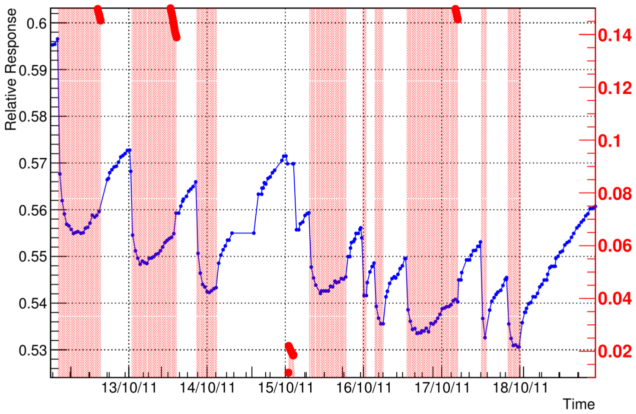
$$y = (id)\&0x7F$$

For example, applying these formulas to 0x34005481 gives an x coordinate of 41 and a y coordinate of 1. Thus, the x and y coordinate can be extracted from it's ID number, and we can relate an individual crystal's response over time to its position in EE+.

3.2 Plotting the Channels

From this point, we are in a position to plot the realitive response of individual channels. Figure 4 shows the response of crystal in position 41, 41 vs time. The blue line indicates the response of the laser, while the red regions indicate when the LHC fill is on.

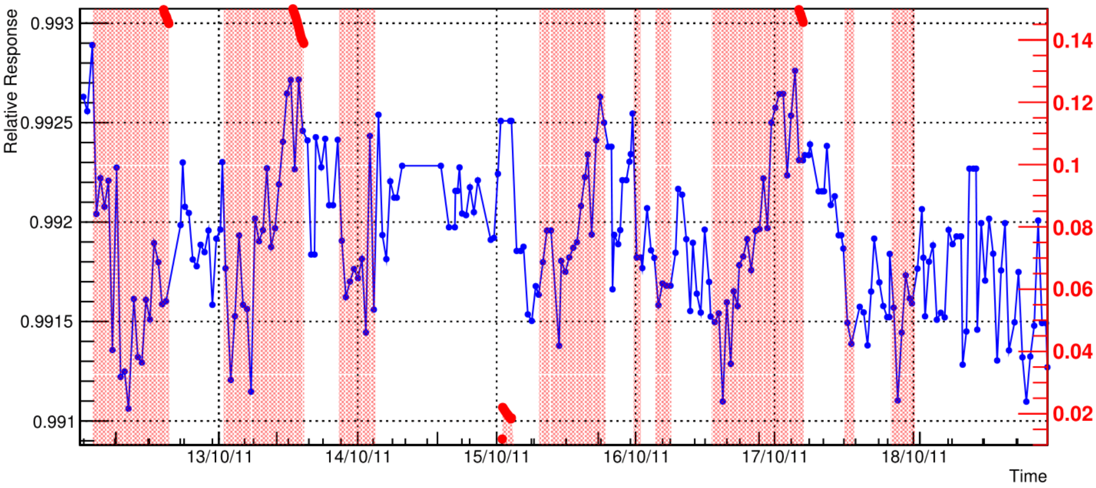
Figure 4: LHC Fills in October, 2011, Channel 41,41



This channel is very close to the center of EE+, as the beam goes through what would be channel 50,50. This plot clearly demonstrates how when the beam is on, this response of this channel undergoes exponential decay, until it eventually reaches an equilibrium when the intensity of the beam has sufficiently decayed. At this point, the recovery of the crystal overtakes the radiation damage, and the response begins increasing. In between fills, the response increases linearly. The value of the responses are all normalized so the value of the response at the very first run in January 2011 is equal to 1.

Figure 5 shows the same plot, but in channel 50,100, the topmost channel in EE+.

Figure 5: LHC Fills in October, 2011. Channel 50,100

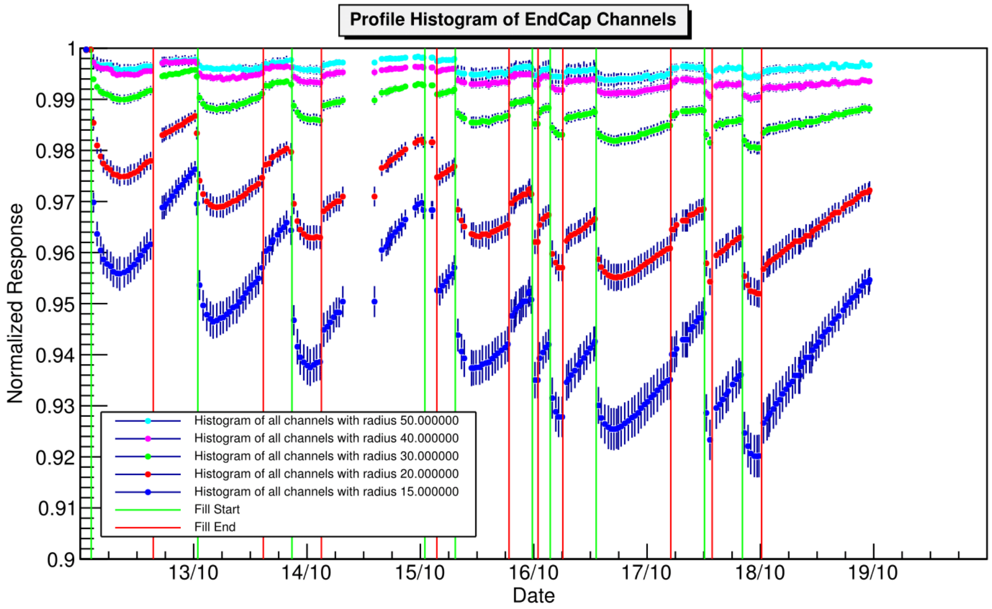


As we can see, the response in this outer most channel, which is much farther away from the beam than that of the previous plot, is far more erratic, and even more difficult to qualify. In order to compensate for this, two techniques were applied.

The first was to normalized the data to the 12th of October 2011 at 2:00, the time of the first data point. The second was to average over the an entire band of a certain radius of EE+, as it can be assumed that the only component of position of channels that affects the response is the radius. Doing this for several different radii gave the following histogram.

Figure 6 clearly demonstrates that the same progression is happening for

Figure 6: LHC Fills in October, 2011, All Channels



every band in EE+. The only difference is that the magnitude of the changes decreases as the radius of the band decreases. With this information, we are now in a position to analyze the behavior of the channels with faulty LEDs compared to channels with functional LEDs.

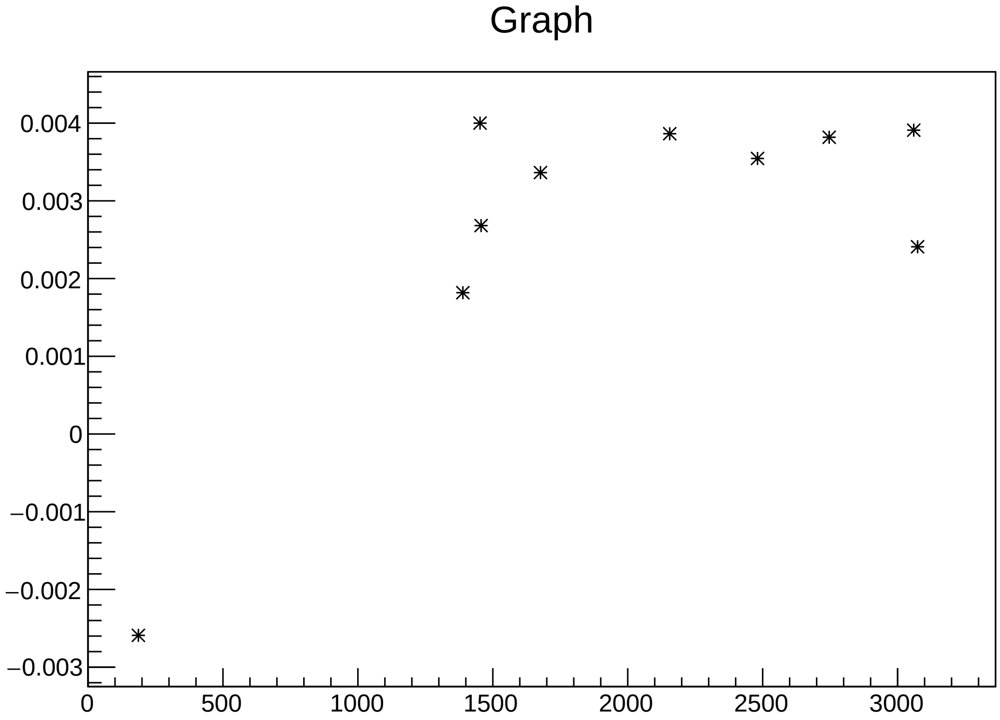
3.3 Broken LEDs

If we again examine Figure 1, we see that the principle difference between the LED pulses being on and off is that the sudden change in response when the LHC beam activates and deactivates is much larger when the LEDs are off. It is clearly seen in Figure 6 that similar jumps occur in EE+ when the LHC fills begin and end. We want to do this quantitatively, so we need an accurate method for calculating the difference between the response. First off, it was decided to use the jumps at the end of the fill, as the LHC beam tends to shut down at different intensities each run (as seen in Figure 3), giving us another variable to work with.

Since the recovery of crystals in the time between fills is assumed to be linear, we used a linear regression to extrapolate the response at the exact moment the fill ended, from which we then subtracted the response value just before the fill ended, to get a magnitude for the change in response. Figure 2 was then used as a lookup table to determine whether or not each channel was in the region with working LEDs. Averaging over all working channels within the band of radius equal to 25, and plotting the difference in response against the beam intensity at the end of the fill gave the following plot.

Figure 7: Change in Response at End of Fills vs Beam Intensity at End of Fills

Only includes channels with LED pulsing

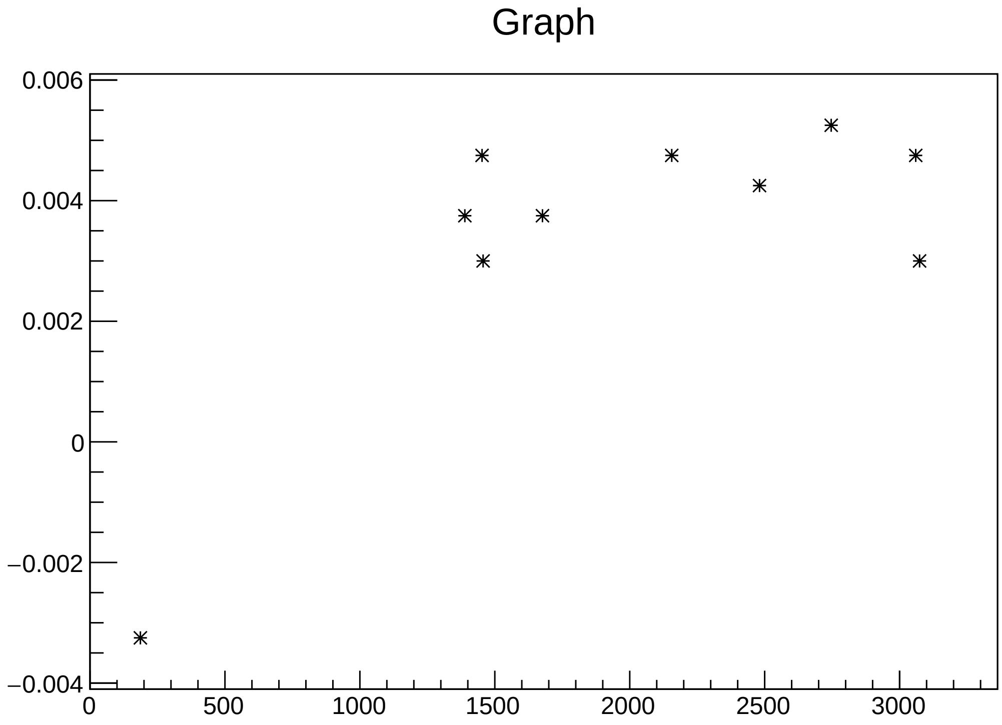


Each data point on this plot represents the end of a fill. The point in the bottom left is an outlier, as this fill had an intensity an order of magnitude lower than any of the others, and was significantly shorter. The units of beam intensity are the same as those in Figure 3.

Apart from the one outlier, the changes in responses seem to be fairly constant with respect to the beam intensity at the end of the fill. Figure 8 shows the same data, but for channels without LED pulsing.

Figure 8: Change in Response at End of Fills vs Beam Intensity at End of Fills

Only includes channels without LED pulsing



As we can see, the change in response in the broken channels is only slightly higher than that in the working channels. In Figure 1, it is shown that the change in response is much greater without the LED than with the LED.

4 Conclusion

Unfortunately, time consraints prevented me from continuing the analysis further. Although the change in response with LED flashing was lower than that without LED flashing, the magnitude of the difference is not nearly as high as seen in the lab. So, while the final result is inconclusive, hopefully those who continue working at CMS will be able to continue working where

I left off.

Had I had more time, I would have liked to examine the change in response at the beginning of the fills as well, and done a similar comparison as done above. I would also have liked to plot the change in response as a function of radius, to see the correlation between distance from the beam and change in response. This would have been done for each of the fills, and of course for functioning and malfunctionng LED flashing.