# The correlation between the light loss in crystals of the CMS electromagnetic calorimeter and the measurements of the radiation hardness

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*Abstract*

*The properties of the crystals of the electromagnetic calorimeter of CMS are measured before their installation and now, during the operation of the large hadron collider. In this note, some correlation between $\mu$- the irradiation hardness of the crystals and the measurements of the light monitoring system are examined. It seems that there is not direct correlation between these properties, a dependence to the position of the crystals can be seen. Furthermore some properties of the light monitoring data is analyzed. The analysis is only done for the endcaps and not for the barrel.*

## The Large Hadron Collider (LHC) and the Compact Muon Solenoid (CMS)

In the 27 km long tunnel of the LHC proton beams are accelerated and hit against each other. The proton - proton collusions, with an energy of several $TeV$, are then detected and measured by six detectors.
CMS is one of the two large experiments at the LHC. The aim of CMS is to explore physics at the $TeV$-Scale, discover the Higgs boson and to look for evidence of physics beyond the standard model (supersymmetry, extra dimensions). Furthermore also heavy ion collusions are measured with CMS.

## The electromagnetic calorimeter

The electromagnetic calorimeter (ECAL) of CMS is build of lead tungstate ($PbWO_4$) crystals. Its aim is to measure and identify electrons and photons. The ECAL must be able to provide excellent energy resolution to identify the decay of a Higgs boson to two photons. Furthermore the electromagnetic calorimeter has to provide good measurements in the harsh radiation environment of the LHC.
The ECAL is separated into three parts, the central barrel and two endcaps. The barrel is made of 61200 crystals while each endcap contains 7324 crystals. Furthermore in front of the endcaps a preshower detector is placed. Avalanche photodiodes / vacuum phototriodes ($APD/VPT$) are used for the barrel / endcaps respectively to measure the scintillated light. For a detailed paper over CMS and ECAL see [1].

## The endcaps

The two endcaps are divided in Dees. Dee one and two form together an endcap, which is called EE+, while Dee three and four form EE-. Each Dee contains 138 standard supercrystals, a group of $5 \times 5$ crystals, and 18 partial supercrystals at the outer and inner circumferences. The crystals have a front face cross section of $28.62 \times 28.62 mm^2$, a rear face cross section of $30.0 \times 30.0 mm^2$ and a length of $220 mm$ [2]. Each crystal can be identified by its position (IX, IY) in the plane perpendicular to the beampipe. If not indicated, the plots shown in this analysis are for EE+. The same analysis is also done for EE-. The results/figures are similar.

## $\mu$ - the irradiation hardness of the crystals

The crystals are grown in China and Russia. This process is not perfect, so that the crystals are not totally identical. Due to this, the property $\mu$ is measured. Therefore the crystals were radiated, so that so called 'colour centers' are formed at irregularities. These colour centers absorb light. Due to this, not the whole amount of light, that is send through the crystals, is measured with the phototriodes. The assumption is, that after this radiation all potential colour centers are developed and that $\mu$ is an indicator for the minimum light which should be measured. The ratio between the sent light $L_0$, the measured light $L$ and $\mu$ with $l$ the length of the crystal in $m$ is:

$$\frac{L}{L_0} = e^{-\mu l}$$

The Chinese crystals are made and measured at the Shanghai Institute of Ceramics (SIC) and some of them also at CERN. The Russian crystals are only measured at CERN. The left part of figure 1 shows the measurements of $\mu$ , while on the right side the correlations between a measurement at CERN and SIC can be seen. If the crystal is measured at CERN, this measurement is chosen for the left figure, otherwise the SIC measurement is taken. As seen in this figure, $\mu$ is not measured for all crystals, most measured crystals are in the inner or outer ring. A condition for the crystals was, that the value of $\mu$ should not be larger than 1.6 to lose not to much light. In this figure it can be seen that also crystals are used which do not fulfill this condition (the orange and red crystals in the left map). The measurements of SIC are most of the time smaller than the one of CERN. Due to this it is possible that $\mu$ is measured in China and that $\mu$ is less than 1.6. Therefore the crystal is accepted, while the CERN measurement is higher than 1.6 and used for the graphic.
A map of the position of the Russian and Chinese crystals can be found in figure 2. On the left side is EE+ while on the right side is EE-. The Chinese crystals, indicated by red, are at the inner and outer rings. Most of the crystals are Russian. The block of Chinese crystals at the left part of EE- belongs to a test beam area. There is one crystal in EE- with an unknown producer.

## Measurements with the laser monitoring system (LM)

The crystal properties change under radiation. The colour centers that are formed absorb the light. When there is no radiation, the colour centers get smaller and disappear, the crystals recover. The transparency of the crystals is always measured with the ECAL laser monitoring (LM) system. The LM measures the transparency every $20 - 30 min$ . Therefore a pulse is sent through the crystals and measured with the phototriodes. Blue light with a $\lambda = 440 nm$ , close to the emission peak of scintillation light from $PbWO_4$, is used. The idea is to correct the measurements of ECAL with the information over the individual crystals

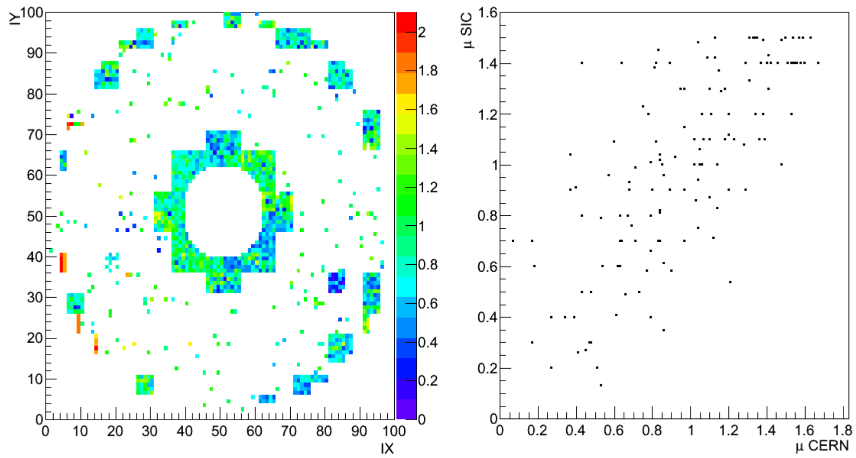


Figure 1: On the left site, the values of $\mu$ for the different crystals are shown. The right side represents the measurements of $\mu$ of CERN and SIC. The measurements correspond to EE+.

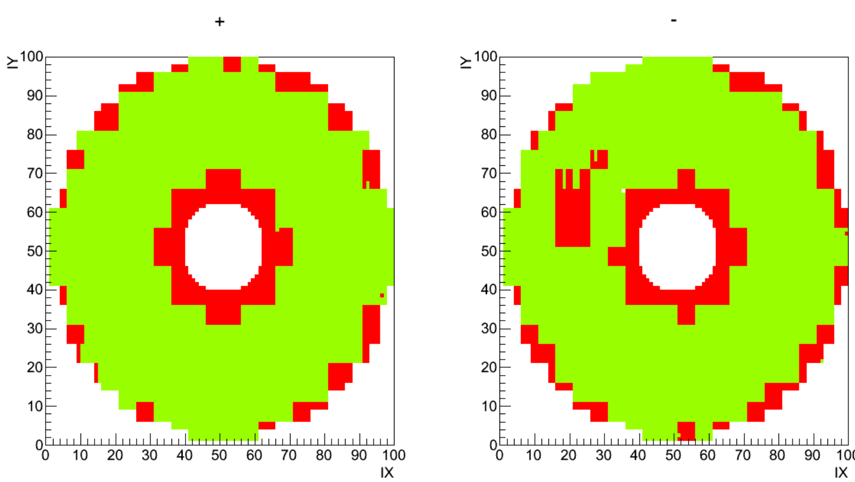


Figure 2: A map of the position of the Russian and Chinese crystals. The Chinese crystals (in the inner and outer ring) are red, the Russian crystals green.

of the LM[2]. Furthermore there are measurements with blue and orange LED light. If not indicated, the data is obtained form the blue laser measurements. The evaluation of the measured light in time, measured with the blue light of the crystal with position $X = 35$ and $Y = 35$ in EE+ can be seen in figure 3. The time is given in UNIX time, the measurements are done between the end of February and the begin of June 2011. The red striped surface indicates, that the LHC was on. It can be seen, that the amplitude of $\frac{VPT}{PN}$ decreases when there is radiation and increases when the LHC is off. The amplitude increases to values around 1.1, when the superconducting magnets are set off. The measurements are normalised to the amplitude at the end of February. For the values of $\frac{VPT}{PN}$ are the measurements of the vacuum phototriodes divided by the measurements of the PN diodes.

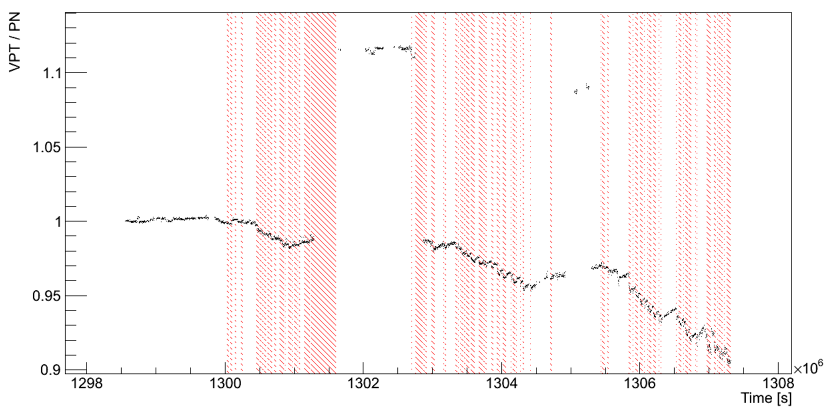


Figure 3: The development of the measured light of the crystal X=35 and Y=35 in EE+. The red shadowed surfaces indicated that the LHC was on, and that there was radiation.

# Light loss during the operation of the LHC

## Measured light depending on the distance of the crystal through the center of the endcap

The crystals change different, depending on their $\mu$ and their position. To show this, the first ($1298.54 \times 10^6 < t < 1298.64 \times 10^6$) and last ($1307.28 \times 10^6 < t < 1307.31 \times 10^6$) measurements of the LM, so $\frac{VPT}{PN}$ are averaged. The average of the first measurements is called $amplitude_{start}$ while the averaged value of the last measurements is called $amplitude_{stop}$. $amplitude_{stop}$ is divided by $amplitude_{start}$ to get a value for the amount of light that is measured, compared to the measurement of the end of February. The amount of light measured, depending on the distance R of the crystals through the center of the endcap, can be seen in figure 4 for all crystals of EE+. The green data points correspond to the Russian crystals, while the red ones correspond to crystals produced in China. Also here, it can be seen, that the Chinese crystals are installed in the inner/outer ring. Figure 5 shows the R dependence for the crystals, which have a $\mu$ measurement. As expected more light is measured at larger distance through the center. There is more radiation close to the center of the endcap, so that there are more colour centers formed and less light is measured.

In figure 4 it can be seen that there are some crystals with a small amount of measured light at $R > 40$. The development of the measured light, measured with the blue laser, in time

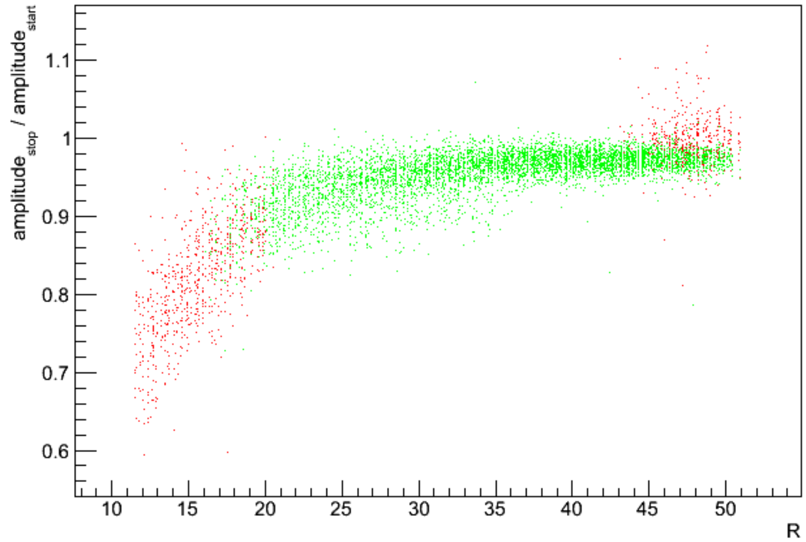


Figure 4: The amount of light measured depending on the distance to the center of the endcap. Due to more radiation at the inner ring, there is a higher light loss close to the center. The green data points correspond to Russian crystals, the red data points to Chinese ones.

for four crystals can be seen in figure 6. These crystals behave very different and against all expectations. Three of the four analysed crystals (not 38/91) are already identified as problematic channels. They were detected by comparing the response of each channel to laser light versus its response to real physics data. This comparison is done in 2009 and 2010 [3]. There are also crystals with $amplitude_{stop}/amplitude_{start} > 1$ with $R > 40$ (no further research is done on these crystals).

## Correlation between the light loss and $\mu$ at special positions

In figure 5 it can be seen that there a two regions with many measurements of $\mu$. The region with a radius of $11 - 19$ is separated into three rings with $R = 12 \pm 1$, $R = 15 \pm 1$ and $R = 18 \pm 1$ while the region of the outer ring is classified in $R = 46 \pm 1$ and $R = 49 \pm 1$.
The dependence between $\mu$ and the measured light for the crystals in these rings can be seen in figure 7. The error of $\mu$ is chosen to be 0.01/0.1 for the CERN/SIC measurements, due to the fact that $\mu$ is measured with two/one digit after the comma respectively. The error of $amplitude_{stop}/amplitude_{start}$ is the standard deviation of the averaging. The measurements are wide spread and it is not possible to correlated $\mu$ and the measured light / light loss in a simple way.

## Precision test of $\mu$ and the LM

Most crystals have a big error in $\mu$ so that it is chosen to have a closer look at these measurements. Furthermore a closer look is done on the measurements of the LM. This is possible due to the measurements with three different light sources.
To have a precision for the measurement of the LM the following amplitude is calculated:

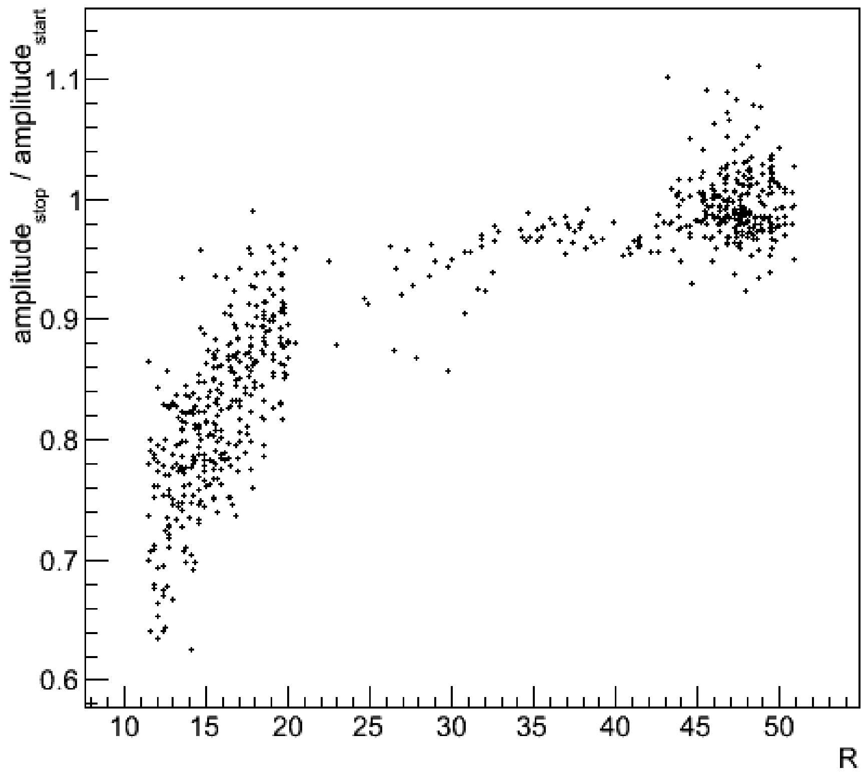


Figure 5: The light loss depending on on the distance to the center of the endcap. For the crystals with a measured $\mu$.

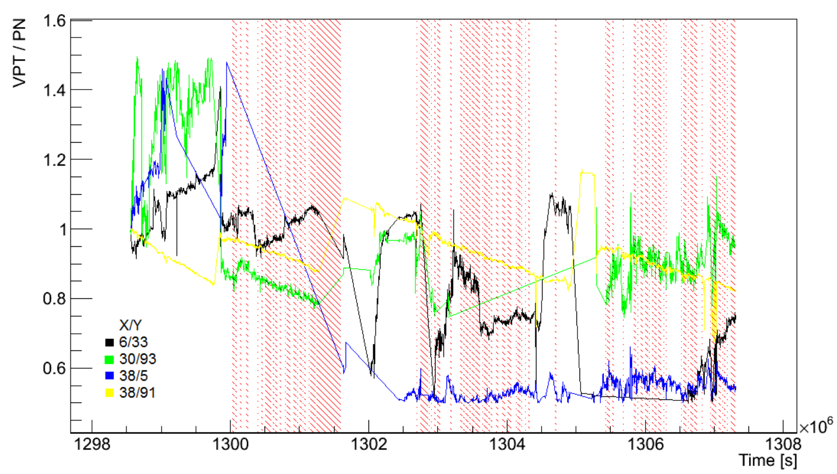


Figure 6: The behavior of four crystals, with a high loss of light, in time.

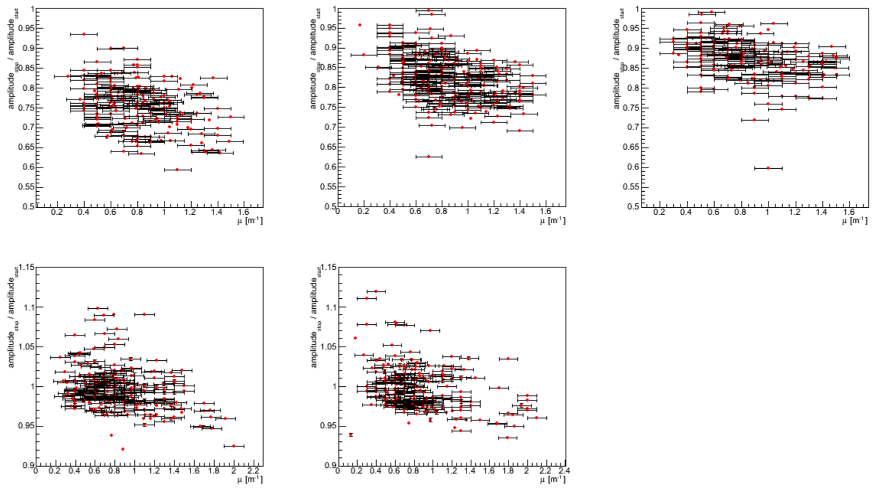

Figure 7: The amount of light measured vs $\mu$ for crystals in several rings. The top figures correspond to $R = 12 \pm 1$, $R = 15 \pm 1$ and $R = 18 \pm 1$ from left to right. And the bottom ones to $R = 46 \pm 1$ and $R = 49 \pm 1$.

$$A_{blue/LED} = 2 * \frac{Amplitude_{blue} - Amplitude_{LED}}{Amplitude_{blue} + Amplitude_{LED}}$$

where $Amplitude_{blue}$ is the measurement of $amplitude_{stop}/amplitude_{start}$ with the blue laser and $Amplitude_{LED}$ is the measurement of $amplitude_{stop}/amplitude_{start}$ with the blue LED light. $A_{blue/LED}$ would be zero, if the measurements were identical. The distribution of $A_{blue/LED}$ can be seen in the right part of figure 8. The values are distributed around zero, and a Gaussian fit is done. For figure 9 the assumption is done, that crystals have good LM measurements if $\|A_{blue/LED}\| < 0.02$. This means, that the difference between the two measurements is less than 0.2. The values around $-0.07$ correspond to 6 supercrystals (219, 220, 227, 228,235, 236). These supercrystals form together a block of $10 \times 15$ crystals.

The precision of $\mu$ is verified with the same method. Therefore

$$\mu_{SIC/CERN} = 2 * \frac{\mu_{SIC} - \mu_{CERN}}{\mu_{SIC} + \mu_{CERN}}$$

is calculated with $\mu_{SIC}/\mu_{CERN}$ the values for $\mu$ measured at SIC/CERN respectively. The distribution of $\mu_{SIC/CERN}$ can be seen in the left figure of 8. In this case it is chosen that the measurements are good, if $\|\mu_{SIC/CERN}\| < 0.5$. It can be seen, that the measurements of the LM are more precies than the measurements of $\mu$. Both quantities have values round one, while $A_{blue/LED}$ is one order of magnitude smaller than $\mu_{SIC/CERN}$.

When combining these two precision test, 44 crystals remain with a good measurement for $\mu$ and the measurements of the LM. For these crystals the average of the blue and LED light measurements and the average of $\mu$ is calculated. These values are plotted against each other for the different rings in figure 9. Also in this figure it is not possible to see a clear correlation between the measured light and $\mu$.
There are crystals in three of the five rings with more or less the same value for $\mu$ but very different values for the measured light. These measurements are indicated with the ellipses. The development of the measured light in time with the blue laser and the LED light for the

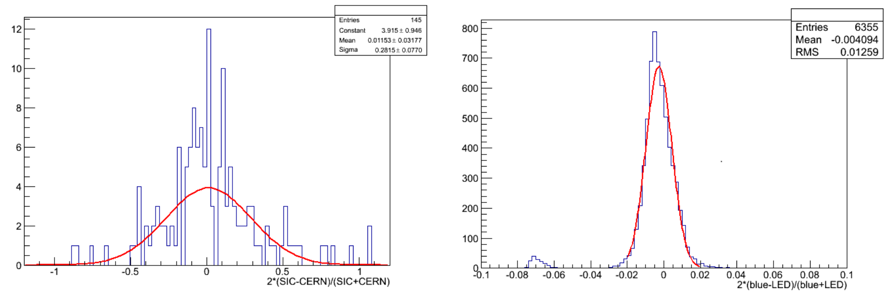


Figure 8: Left: The distribution of $2*(\mu_{SIC} - \mu_{CERN})/(\mu_{SIC} + \mu_{CERN})$ with a Gaussian fit. Right: The distribution of the relative percentage difference (2 times the difference divided by the sum) of the LM for the blue laser and the blue LED

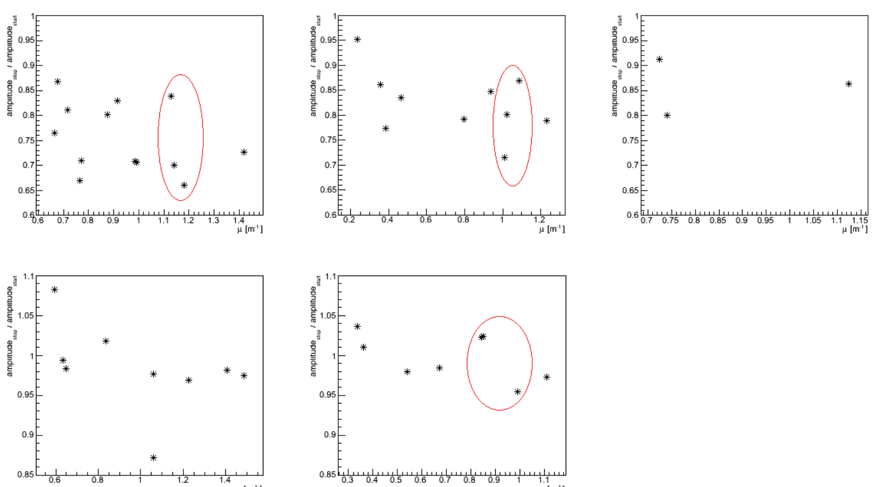

Figure 9: The light loss vs $\mu$ for crystals in several rings. Crystals are only used, if the measurements for $\mu$ and the light loss are good. An average for $\mu$ and the light loss is used. The top figures correspond to $R = 12 \pm 1$, $R = 15 \pm 1$ and $R = 18 \pm 1$ from left to right. And the bottom ones to $R = 46 \pm 1$ and $R = 49 \pm 1$.

crystals of the inner ring can be seen in figure 10. It can be seen, that the crystals behave the same in the beginning of the measurements. Furthermore, the measurements of the blue laser and the LED light are the same for two crystals while one crystal behaves different for the two light sources.

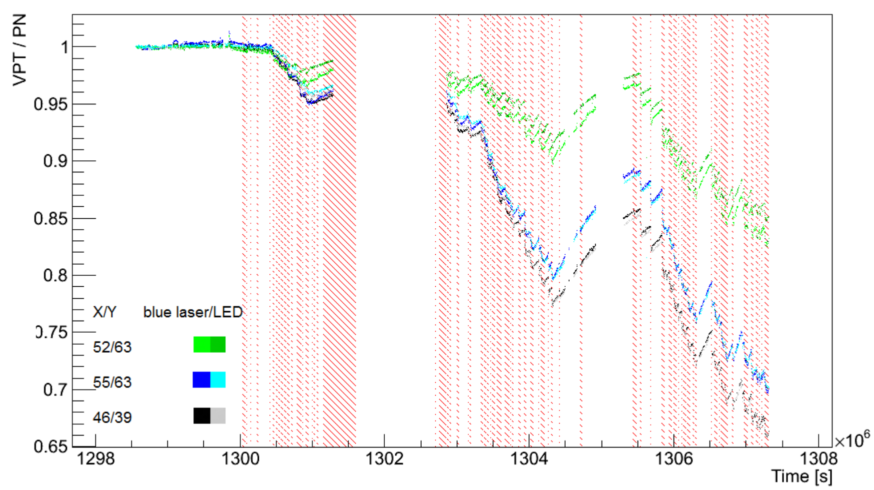


Figure 10: The development of three crystals in time. The measurement is done with the blue laser and the LED light.

It was expected to see a correlation between $\mu$ and the light loss. Due to the assumption, that all colour centers are fully developed before $\mu$ is measured, $\mu$ should be an indicator for the maximum light loss. It is chosen to accept only crystals with a $\mu$ less than 1.6. The light measured should be therefore more than 67.3%. A crystal with a small $\mu$ should lose less light, when the colour centers are fully developed compared with a crystal with a large $\mu$. The assumption was, that this is also true, when the colour centers are not fully developed. It seems that the relation between $\mu$ and the light loss is more complicated and that further factors should be taken into account.

From $\mu$ it is know which amount of light should be at least measured, this amount equals $e^{-0.22\mu}$. For figure 11 $e^{-0.22\mu}$ is subtracted from the amount of light measured by the LM and plotted in a histogram, on the left for the Chinese crystals, on the right for the Russian ones. The crystals can be categorized into two groups. When this quantity is larger than zero, more light is measured than expected by a total darkening. If the $amplitude_{stop}/amplitude_{start} - e^{-0.22\mu}$ is less than zero, less light is measured than expected. This means that there is a light loss outside the crystals. An assumption is, that the phototriodes lose the missing amount of light. The light loss of the phototriodes is measured before the installation and is supposed to be small compared with the light loss in the crystals. Both groups can be seen in the Chinese and Russian production. The Russian production has less crystals where this value is less than zero. A reason for this could be, that the crystals are not installed at the inner ring of the endcap (less radiation). Furthermore are less entries in that histogram, due to the fact that most measurements for $\mu$ are done for the crystals of the inner and outer ring, where the Chinese crystals are installed.

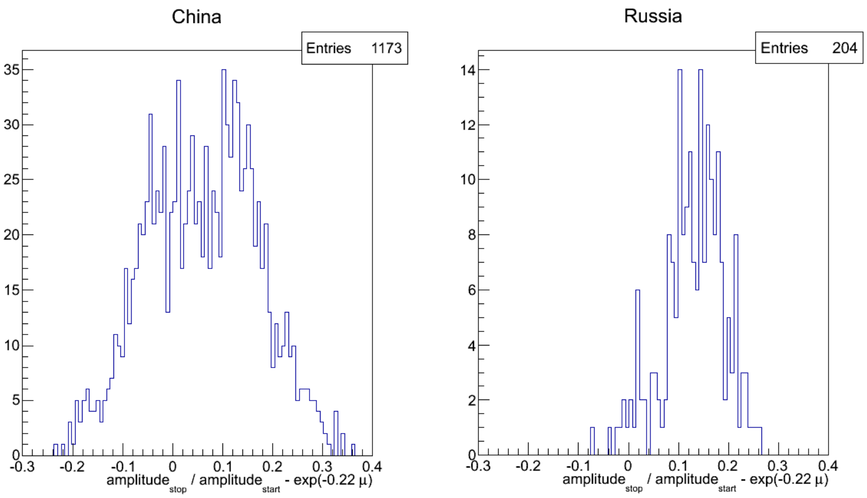


Figure 11: This figure shows the distribution of $amplitude_{stop}/amplitude_{start} - e^{-0.22\mu}$ on the left side for the Chinese crystals, on the right side for the Russian crystals.

# Recovering and darkening

If there is no radiation, the crystals recover. That means, that the colour centers become smaller and disappear if there is enough time. If there is radiation, the crystals are in a darkening phase. All crystals have a different velocity for the darkening and recovering phase. According to figure 12, it seems that the recovering and darkening is linear in time. Therefore a linear fit is done for one recovering and darkening region. The darkening region is the same as the stop region. For the recovering region, the measurements between $1306.35 \times 10^6 < t < 1606.50 \times 10^6$ are chosen. This regions are marked with the vertical black lines.

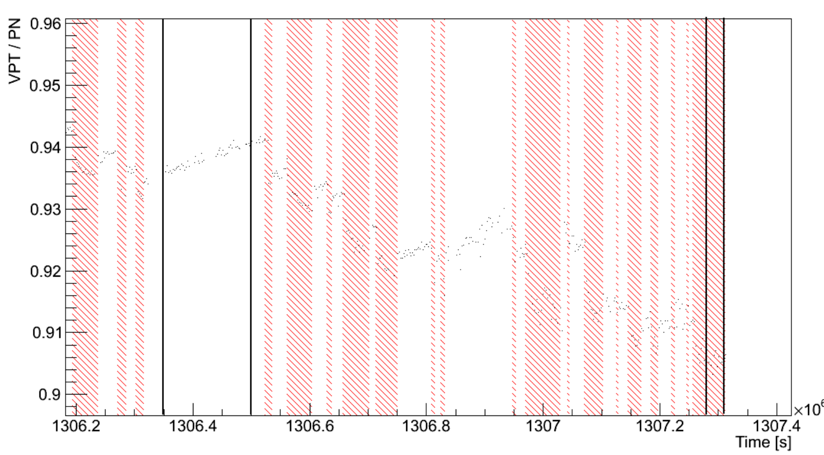


Figure 12: The figure shows the recovering and darkening area used in the analysis. It can be seen, that the time dependences is linear.

To perform the fit, the time is rescaled. Therefore $t_0$ is defined in the middle of each region. Then the slope and intercept of both regions for all crystals of the endcap are calculated. The intercept is the value of $VPT/PN$ at $t_0$, therefore this value should be around one. The histograms of the slope and intercept of the recovering and stop region can be found in figure 13. At the top for the recovery region and at the bottom for the stop region. As expected the intercept is peaked around one. The slope is in the order of $10^{-6}s^{-1}$. This means that the crystals recover the amount per second. It was expected, that the recovery slopes should be positive, due to the fact that the crystals recover. This can not be seen for all crystals. There are also crystals that have a negative slope. An example of these crystals are the crystals shown in figure 6. For the slopes of the stop area were only negative slopes expected. This is not the case, too.

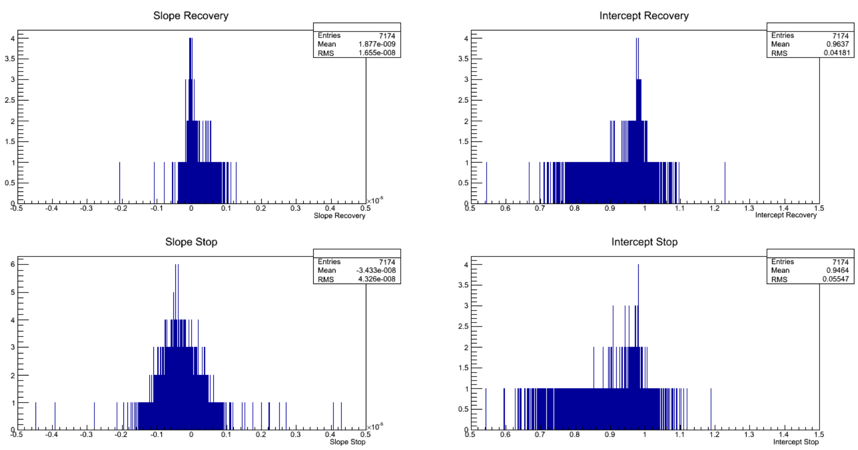


Figure 13: In the top graphics the distribution of the slope and intercept of the recovery region can be seen. The bottom pictures show the distribution of the darkening area. The slope are of the order of $10^{-6}$.

Next it was searched for a correlation between the properties of the recovery and the stop area. Therefore the slopes and intercepts of the stop region are set against the calculations of the recovery region. The result can be seen in figure 14 on the left for the slopes and on the right for the intercepts. The coloured measurements correspond to the special crystals of figure 9 with red for the crystals of the inner ring, green for the crystals of the second ring and blue for the outer ring. For these crystals also the error bars are drawn. It can be seen, that there is no correlation between the two slopes, the points are wide spreed. Furthermore the error on the stop slopes for the green and red crystals is three to four times larger than the values itself. The big error of the slopes of the darkening region could also explain, why the crystals are not darkening during that radiation period. The slope of the darkening area could be positive, while the error is so large, that this assumption has a big uncertainty.

Through the points of the intercept plot it is possible to fit a straight line. Within a few % it is possible to predict the light loss. The fit is done for the following figure. To have a closer look on the distribution some cuts are done. This means that the measurements are only drawn when the error of all (four) parameters were under a certain threshold (error slope recovery $< 0.2 \times 10^{-9}$, error intercept recovery $< 0.0002$, error slope stop $< 0.05 \times 10^{-6}$ and error intercept stop$< 0.0005$). The thresholds are chosen due to the distribution of the errors. The distribution of the slopes and intercepts of the recovery area against the one of the stop area can be seen in figure 15. The cut removes the special measurements of the crystals of the inner ring. The measurements of the outer ring are still there. Also in this figure, these values are drawn with error bars. The error bars of the stop slope are still of the order of the value itself. It seems that it is difficult to make a good fit. It is possible, that $VPT/PN$ is decreasing, but that the slope is positive due to outliers. In figure 12 it can be seen, that measurements are not lying totally on a straight line, but that they are going up and down. The points of the slope (left of fig 15)form still a big blob and it is not possible to fit something. For the intercept, a straight line is fitted. If the crystals had a big light loss before they reached the recovering area, so a small intercept in the recovery area, they have also big light loss in the time after the recovery. The difference between the two intercepts is large. If the crystals had an intercept around one in the recovering area, they have also an intercept around one in the darkening area. These crystals are more radiation resisted or had less radiation.

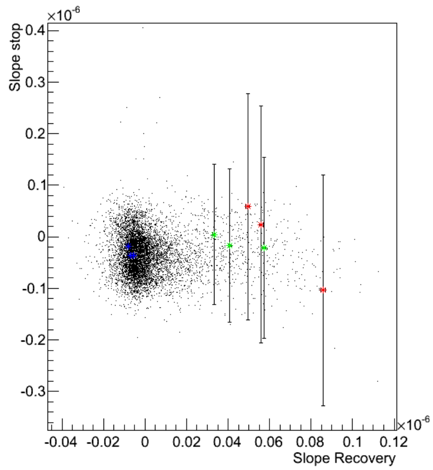


Figure 14: The slope (on the left) and intercept (on the right) of the two regions against each other. The data points of the crystals with more or less the same $\mu$ but very different light loss (figure 9) are drawn with errorbars

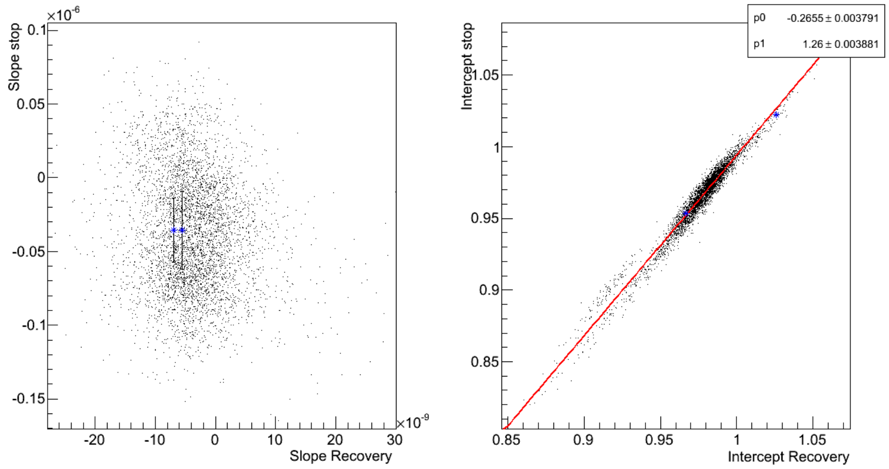


Figure 15: A closer view on the previous figure. A linear fit is done for the data points of the intercept. The fit function is: $intercept_{stop} = p_0 + p_1 * intercept_{recovery}$

# Conclusion

After this analysis it can be said, that there is no direct dependence between the irradiation data $\mu$ and the light measured with the light monitoring system. This can be seen in figure 7 and 9. A dependence between the LM data and the distance of the crystal trough the center can be seen in figure 4. This figure shows, that there is indeed less light measured close to the center of the endcap, as expected due to more radiation there. In addition it can be said, that there is no big difference between the Russian and Chinese crystals. Furthermore shows the analysis, that there is a dependence between the amount of light measured in a recovery region and a darkening region. There is, see the left figure of 15, a linear dependence. It is also possible to classify the crystals into two groups, due to their light responds at the end of June. There are crystals, which have not reached full developed colour centers, and there are crystals which lose more light than expected, figure 11. In addition it is possible to find strange/ not good behaving crystals.

# Outlook

With this analysis, the research in the dependences between the different parameter is not finished. The following research can be done to understand the behavior of the crystal better:

- Further correlations between recovering/darkening and the measured light
- Dependences between the measurements of the LM and the production number (not only the place)
- Search for strange behaving crystals, e.g. the crystals with a high amount of light measured at a large R

## Data sources

To make this analysis and figures three data files are used:

- For the measurements of $\mu$: $\mu$-induced (called Irradiation ECAL or SIC irradiation) by Dee, crystal barcode and ix and iy - E-mail from E. Auffray to D. Cockerill on the 15th of May 2011
- For the production place of the crystals: Crystal final LY values by crystal barcode and ix, iy, iz - E-mail from F. Cavallari to D. Cockerill on the 18th of May 2011
- For the measurements of the light monitoring system no special name or person, who spreads the data, is known. The following is done with measurements itself, to get the data as used for this analysis.
    1. Laser/LED pulses recorded during Calibration Sequence in CMS
    2. Light Monitoring Farm reconstructs events
    3. Marc Dejardin stores summary of results from step 2
    4. Alexander Ledovskoy extracted a small fraction of that information

## Acknowledgment

I would like to thank David Petyt and Dave Cockerill for the supervision during the six weeks, I stayed at CERN. Thank you for answering my questions, giving me new interesting views on my plots and giving me suggestions for further plots. Furthermore I would like to thank Alexander Ledovskoy for a good introduction in the topic and a efficient method to handle the data of the LM system. My thank goes also to Nikhef and the high energy department of the Radboud University Nijmegen, for the possibility to be part of the summer student program.

## References

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[2] The CMS Collaboration, "Performance and operation of the CMS electromagnetic calorimeter", Journal of Instrumentation, March 2010, Volume 5; doi: 10.1088/1748-0221/5/03/T03010

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