Calibration of Multi-Pixel Photon Counters for a PET camera

Daniel Sanchez Parcerisa

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This report refers to the work of the author in the study of MPPCs for positron emision tomography, under the supervision of Erika Garutti and Martin Göttlich. The main task carried out has been the calibration of the experimental setup and the characterization of the new 2x2 MPPC arrays.

1 Introduction

Positron Emision Tomography is a medical imaging technique in which a positron emitter is injected into a living organism, and image is reconstructed by detecting the two 511-keV photons produced by the positron-electron annihilation inside the organism.

Undergoing research aims to develop PET detection techniques with improved spatial resolution and a better efficiency, which would result in more accurate diagnoses and a lower radiactivity dose for patients. The prototypes currently under study are composed of LOS (Luthetium Ortosilicate, Lu_2SiO_5) scintillating crystals, collecting positrons from a ^{22}Na source, and coupled to Hamamatsu MPPCs [3].

Previous results by the group [1] show an acceptable time and energy resolution for single MPPCs, but Montecarlo studies reveal that at least 2x2 MPPC arrays are needed to achieve the required spatial resolution (less than 1mm). The 2x2 MPPC arrays were received in early August, and this document summarises the tests that they have been carried out up to now.

2 MPPC array

MPPCs, or Micro Pixel Photon Counters, are photon-counting devices consisting of multiple photodiode pixels operating in Geiger mode. Each pixel emits a pulse signal when it detects a photon, and the signal output from the MPPC is the total sum of the signals coming from all pixels (Figure 1). The 2x2 arrays consist of four MPPCs, each one with 3600 pixels, mounted together with a common cathode. Relevant parameters in an MPPC are the gain (amplitude of the pulse emitted when a photon is captured), the nominal bias voltage, the time resolution, and the dark noise rate. These parameters have already been tested [3, 6, 7] and, due to a lack of time, we did not perform these tests again, but relied on the supplier's information to continue the study.

3 Characterization of fully assembled camera

In order to detect the 511 keV gamma rays emitted by the e^+e^- annihilation. the MPPC has to be coupled with fast scintillating crystals, and LOS crystals are used for this purpose [1]. The four crystals are wrapped in reflective foil and packed with the MPPC, mounting the camera as shown in Figure 2. In the working prototype, two cameras will be assembled one opposite to the other (see Figure XX), and they will be used together to determine the exact point of interaction using both angular information (about which concrete MPPC fires in the array) and time-of-flight information.

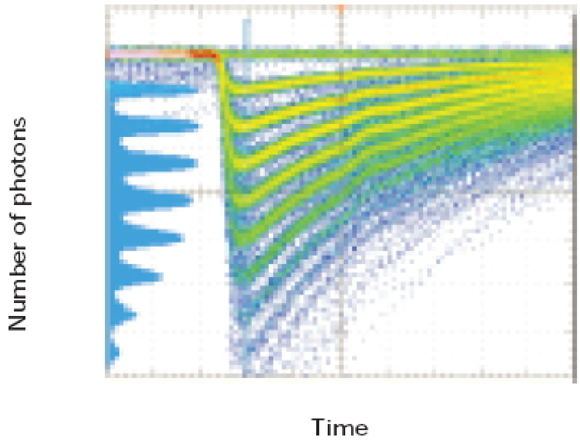


Figure 1: Characteristic response of MPPC depending on the number of firing pixels (source: [3])

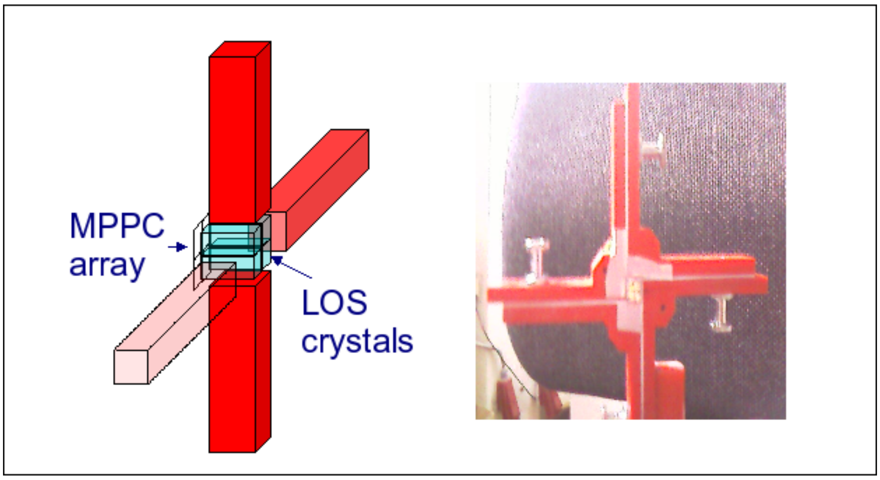


Figure 2: Diagram of the experimental setup

To achieve a good spatial resolution, the cameras have to fulfill some requirements:

- **Good energy resolution**. About 90% of the gamma photons emitted in the source undergo Compton scattering before they reach the detector. When reconstructing the image in a full 4π detector, the Compton scattered events can not be used to determine the line of response [1], so it is important to achieve a good energy resolution to identify and drop the scattered photons with a good efficiency (see Figure 3).
- **Homogeneity of channels**. Obviously, all the channels of the camera (crystal + MPPC pixel) must present the same characteristics and behaviour, within a reasonable uncertainty level.
- **Time resolution**. The spatial resolution is partly achieved by measuring the time-of-flight difference of the two photons emitted in an annihilation event. Hence, the time resolution of the system must be sufficient to measure differences of walk of 1mm, i.e., time differences of the order of 10ps. This topic is not covered in this report, since it has yet to be studied in the future.

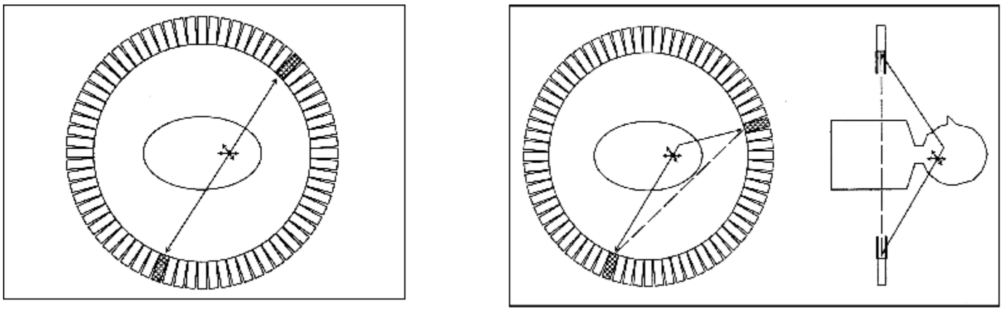


Figure 3: Compton scattered events can not be used in image reconstruction

3.1 Experimental setup and assembling procedure

To test the characteristics of the camera, we assemble the crystals and the MPPC in a mecanical holder, which is then placed in a black box. Crystals must be exchanged under red light to avoid overexcitation, which can influence the measurements (they have their sensitive peak for blue light). Two different configurations are currently being tested. In the first one (*shielded crystals*), each of the crystals is individually wrapped in reflective material, to avoid light crosstalk or leakages. In the second one (*bare crystals*), the four crystals are wrapped together in the same reflecive material, so they can exchange some amount of light. This configuration, though more sensitive to systematic uncertainties, would allow, in principle, to achieve a better resolution by calculating the center of gravity of each event among the four channels. Deciding between those two configurations is one of the open questions that the group is facing in the future. All the measurements shown in this report were taken with shielded crystals, unless where otherwise stated.

During the tests we collected two kinds of measurements: rate and energy. To measure the rate of counts, we connected each individual channel to a discriminator, whose threshold was set in 20mV after some preliminary calibration, and then the discriminator to a scaler. Data was taken in intervals of 10s, up to a point where statistical error in rate was below 3%.

To measure the energy, we connect all output channels to a QDC, and split one of the signals to use as a trigger. Since the QDC requires an interval of 15ns between the arrival of the gate and the start of integration, some delays had to be introduced in the signals 4.

For both measurements, it is vital to check that the width of the output pulse from the discriminator is big enough so that one given pulse does not produce two trigger signals.

3.2 Preliminary studies for light crosstalk and spatial resolution

One of the sources of uncertainties in our setup is light crosstalk, that can happen either between pixels in the MPPC (mediated by infrared photons) or between channels among the scintillating crystals. It is the latter which can have a deeper influence in the resolution.

As a first test for our camera, we performed rate measurements with three different configurations. In the first one, we measured the count rate without any source, taking advantage of the intrinsec radiactivity of the LOS crystals for calibration. In the second one, we placed a ^{22}Na source shielded by a 1cm wide steel block alligned with crystal #1 of the camera. For the third one, we drilled a 2mm hole in the steel block, aligning the hole with crystal #1, and leaving the source in the same position.

Assuming a $\frac{\mu}{\rho}$ coefficient of 0.008414 cm^2/g and a density of 7.85 g/cm^3 for steel, the expected attenuation caused by a block of 1cm width is $\frac{I}{I_0} = 0.517$. Since the hole does not cover the entire solid angle subtended by the crystal, but only a 40% of it, there is an expected 20% increase in the rate of channel #1 from the third to the second configuration, once substracted the contribution by the crystals' intrinsec radiactivity.

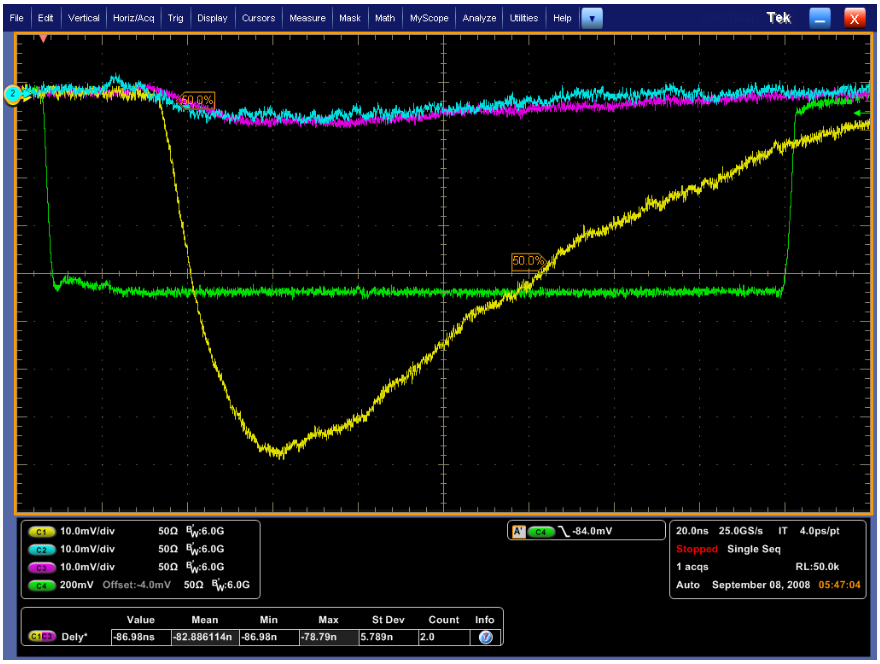


Figure 4: Scope capture showing the delays needed for the signals

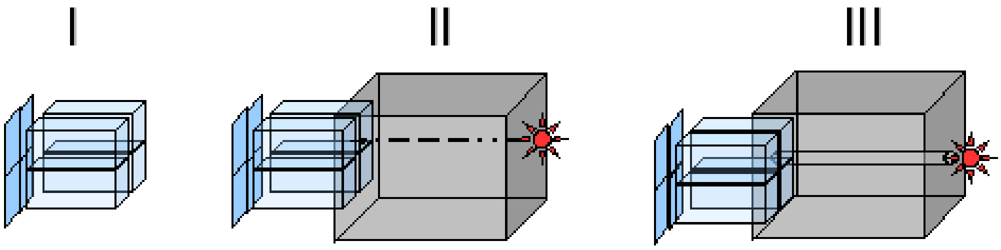


Figure 5: Diagram of the three test configurations

Results in Figure 6 let us draw some conclusions. At first glance, we can observe the expected 20% increase in rate for channel 1, which is promising. Moreover, we observe an increase in the rates of all channels, which could have several causes:

- **Light crosstalk** from channel 1.
- **Uncertainties in the alignment of the source**. Since the intensity of the radiation emitted goes down with r^2, a small transversal shift on the position of the source could cause a noticiable change in all the rates.
- **Differences in temperature**. The breakdown voltage increases about 50 mV for each degree [7], and the both the gain and the dark count rate increase with the bias voltage.

However, observing the unexpected differences among the channels between the rates from intrinsec radiactivity, we conclude that it is neccesary to perform a deeper study of the systematics affecting our measurements.

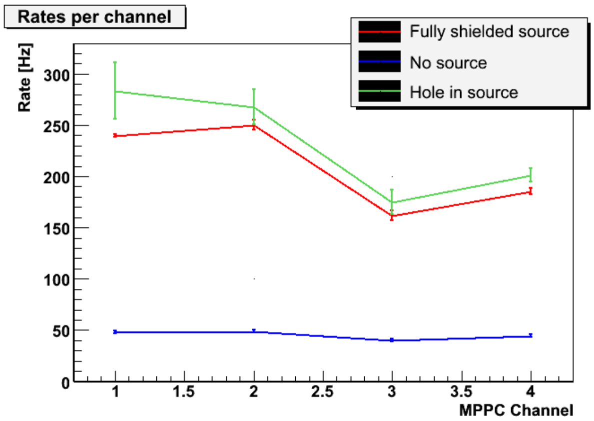


Figure 6: Rates per channel at the three test configurations

3.3 Study of systematic uncertainties

The observed differences (up to 40%) in the decay rate from crystals suggest an inhomogeneity of the channels. In order to find the source of this inhomogeneity, several tests were carried out.

The first factor to consider was a possible missalignment of the crystals and the MPPC. To check for this, the camera was mounted and unmounted several times, with the crystals remaining in the same positions (with respect to the MPPC) or being exchanged. The crystals had already proved to be homogeneous, so no effect was expected after the exchange of crystals. In Figure 7 we observe that the systematics in assembling the camera can influence the rates in less than 10%, except in cases of clear misalignment. We can also see a trend (represented by the mean values) that is not caused by the allignment procedure.

Once checked the allignment and the crystals, we concluded that the difference in the base rate had to come from the MPPC itself. The MPPC was fed with different bias voltages, and the discriminator configured with different threshold voltages ranging from 5 mV to 30 mV. Figure 8 shows that the trend changed with the bias voltage. A closer look at the MPPC specifications showed that some MPPCs have different breakdown voltages in each channel, causing the observed inhomogeneity in their response.

MPPC	Pixel1	Pixel2	Pixel3	Pixel4
1	68.57	68.42	68.68	68.56
2	68.82	68.83	68.82	68.81

Figure 9 shows how the second MPPC, with much more regular breakdown voltages, has a more homogeneous behaviour: the dependence on the systematics of the allignment was reduced to 5%. For fhe following measurements only MPPC2 will be used.

It remains as an open question what to do about this effect: maybe it can be minimised by cleverly tuning the threshold, maybe it can be modeled and corrected for in offline analysis. Apparently, the effect is anyway not relevant when looking at the energies, since the energy of the photoelectric peak is known (511 keV) and can thus be used for calibration. Of course, the ideal case would be to supply a different bias voltage to each of the channel, but this is not feasible with the current electronics.

For all fhe following measurements, only MPPC2 will be used, with a bias voltage of 68.82V and a threshold of 20 mV in the discriminator.

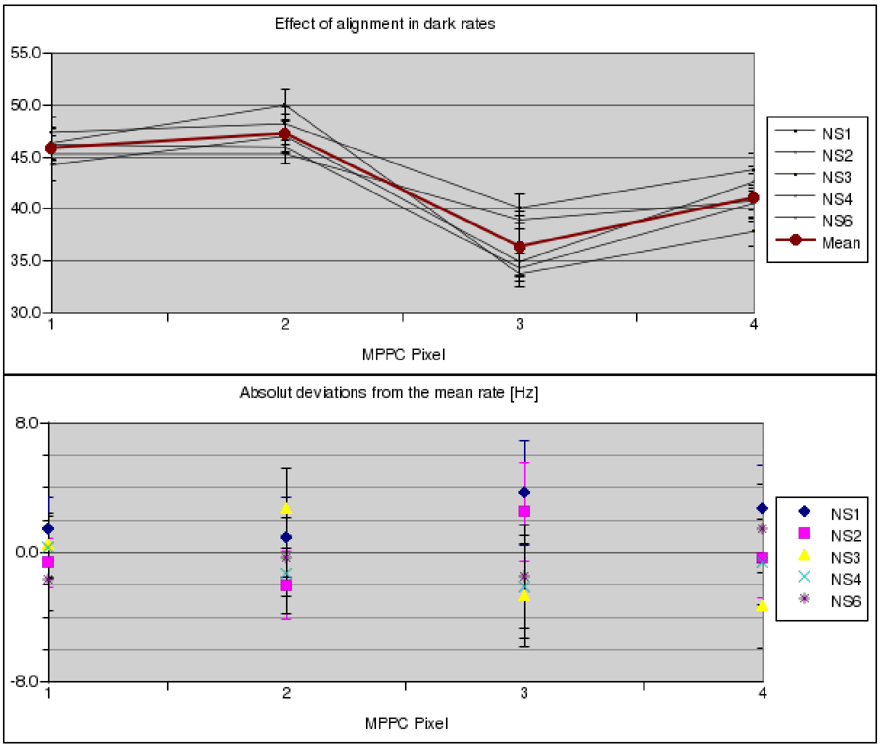


Figure 7: Rates per channel after reassembling the matrix and exchanging the crystals

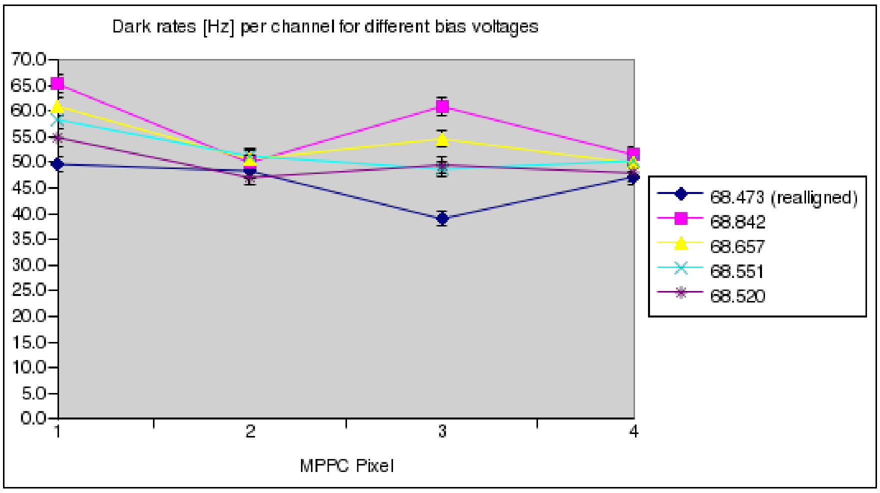


Figure 8: Bias voltage scan (with discriminator threshold fixed at 20mV) for MPPC 1

3.4 Energy resolution and efficiency. Light crosstalk in the energy spectrum.

As it has been already mentioned, the energy resolution is one of the key parameters that has to be improved in order to achieve a higher efficiency in image reconstruction.

In this section we present two series of measurements: in the first one, we calculate the full width half maximum (FWHM) for the photoelectric peak, when triggering in all the four channels, for three different configurations: shielded crystals, bare crystals, and shielded crystals coupled with the MPPC with optical

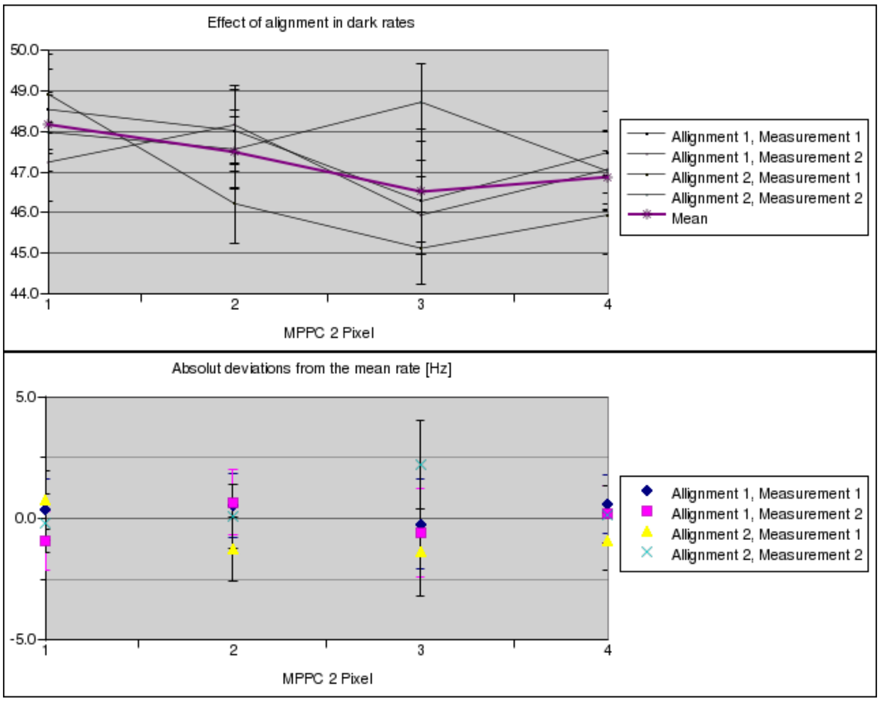


Figure 9: Rates per channel after reassembling the matrix and exchanging the crystals with MPPC 2. Graph shows that the systematic discrepancies have been lowered down to less than 5%.

grease. For all of them, the ^{22}Na source was placed directly on the crystal surface (no shielding) to have a higher rate of events. The second series of measurements give a first insight into observing the effect of light crosstalk in the energy spectrum.

The measured energy resolution (10) let us draw some conclusions. First, a higher efficiency (i.e. more photons collected) achieved by better optical coupling (grease) or a better shielding have a noticeable influence on the energy resolution. The bare crystals are not optimal to be used, unless some offline analysis is performed (centre of gravity reconstruction, which is currently being investigated by M. Göttlich. And secondly, there is still a big gap between the resolution obtained with a single MPPC (12%, as stated in [2]) and the resolution obtained in our 2x2 MPPC arrays, which might be caused by poorer efficiency, or by light crosstalk between the crystals.

Estimating the light crosstalk is precisely the purpose of the final measurement. To do this, we compare two different measurements. First, we take data in the QDC, triggering in channel 1 of the MPPC, and paying attention to the counts in channels 2 to 4, and we compare this data with the counts taken with a random triger from a pulse generator (Figure 11, note the logaritmic scale). All the counts above pedestal that we get in channel two must come from light crosstalk from channel 1. The percentage of light crosstalk is calculated dividing the number of counts above pedestal by the total number of counts.

This preliminary results (Figure 12) show a higher crosstalk rate when using the bare crystals, as expected, and estimate the light crosstalk for shielded crystals in about 4%, with no significant difference between using optical grease or not.

4 Conclusions

The main outcome of the calibration procedure was a better understanding of the experiment overall , both for myself and for the group. We found the problem of the inhomogeneity of the MPPC channels, that will have to be addressed in the future.

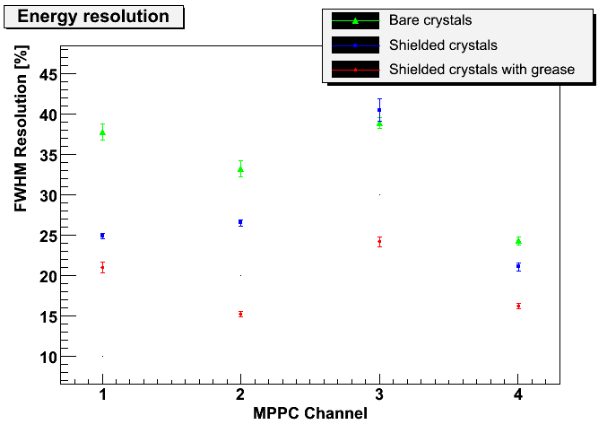
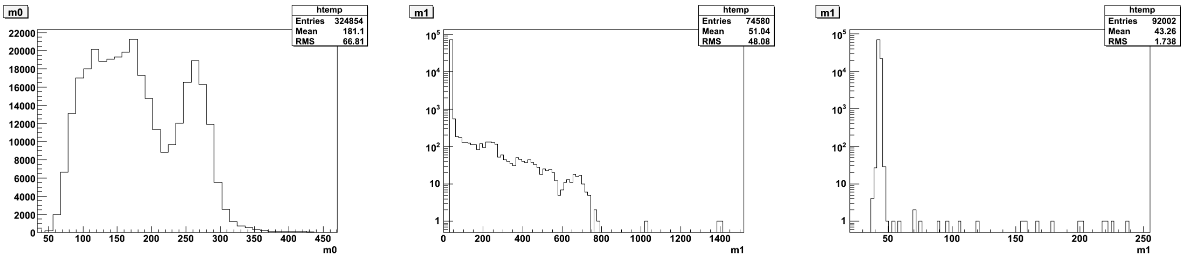


Figure 10: Energy resolution for the three different configurations



Energies channel 1 (triggered) Energies channel 2 Pedestal for channel 2

Figure 11: Energy spectrum for different channels

Moreover, we have a first estimation of the energy resolution of the fully assembled camera [which is around 20%] but we still do not fully understand why it is so much worse than the one-channel MPPC, and what is causingt these fluctuations between channels. Finally, the light crosstalk is estimated in about 4% for shielded crystals, which may explain the decreased energy resolution.

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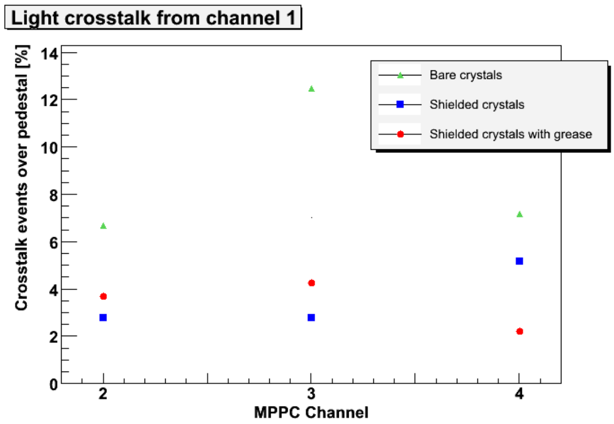

Figure 12: Light crosstalk probability

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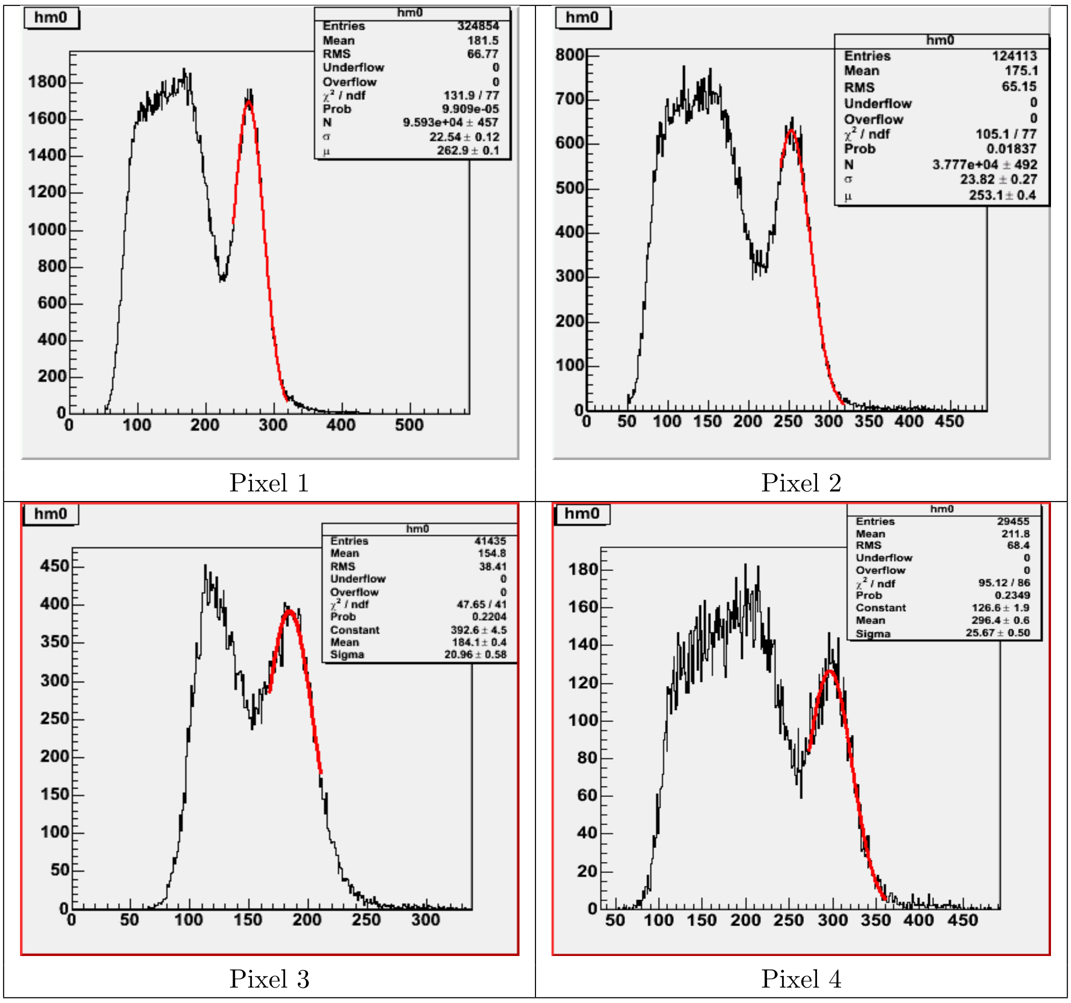

Figure 13: Energy spectrum for shielded crystals

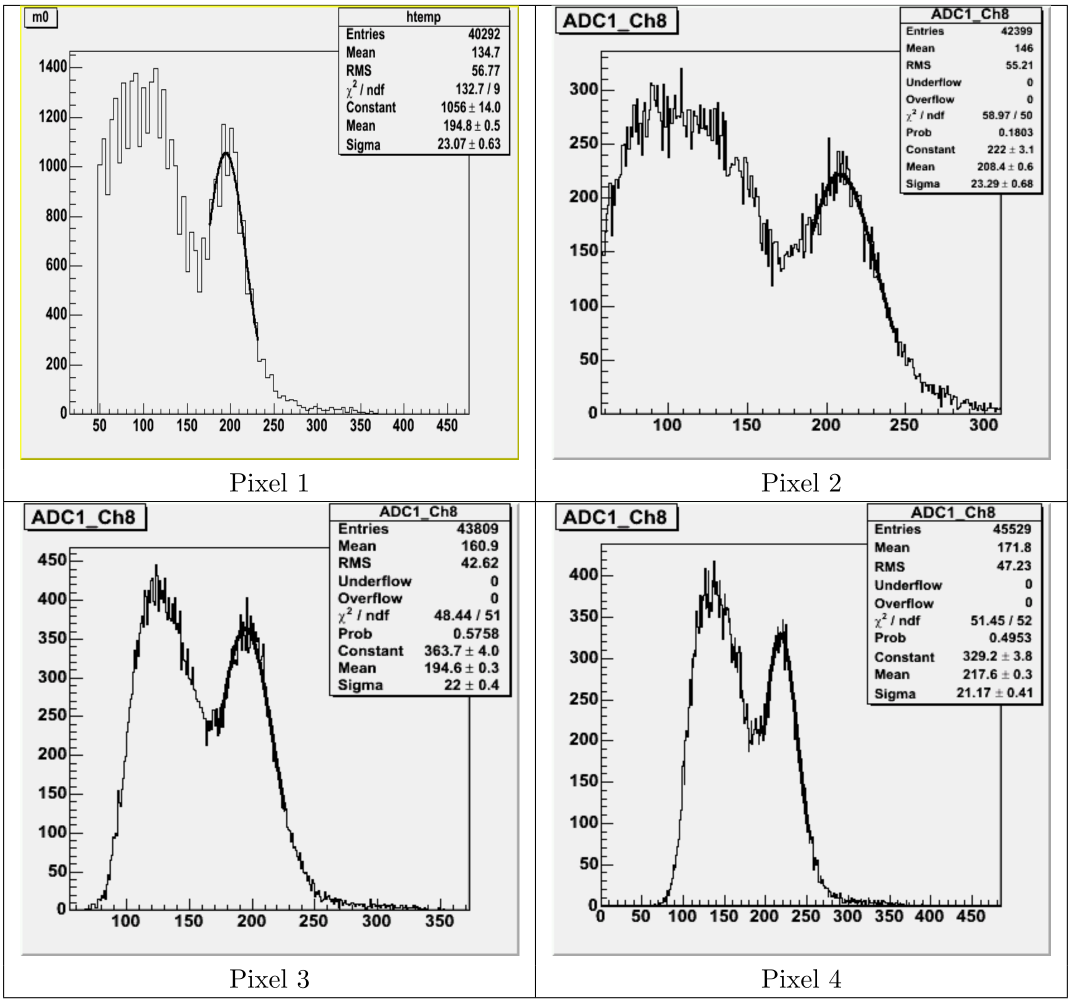

Figure 14: Energy spectrum for bare crystals

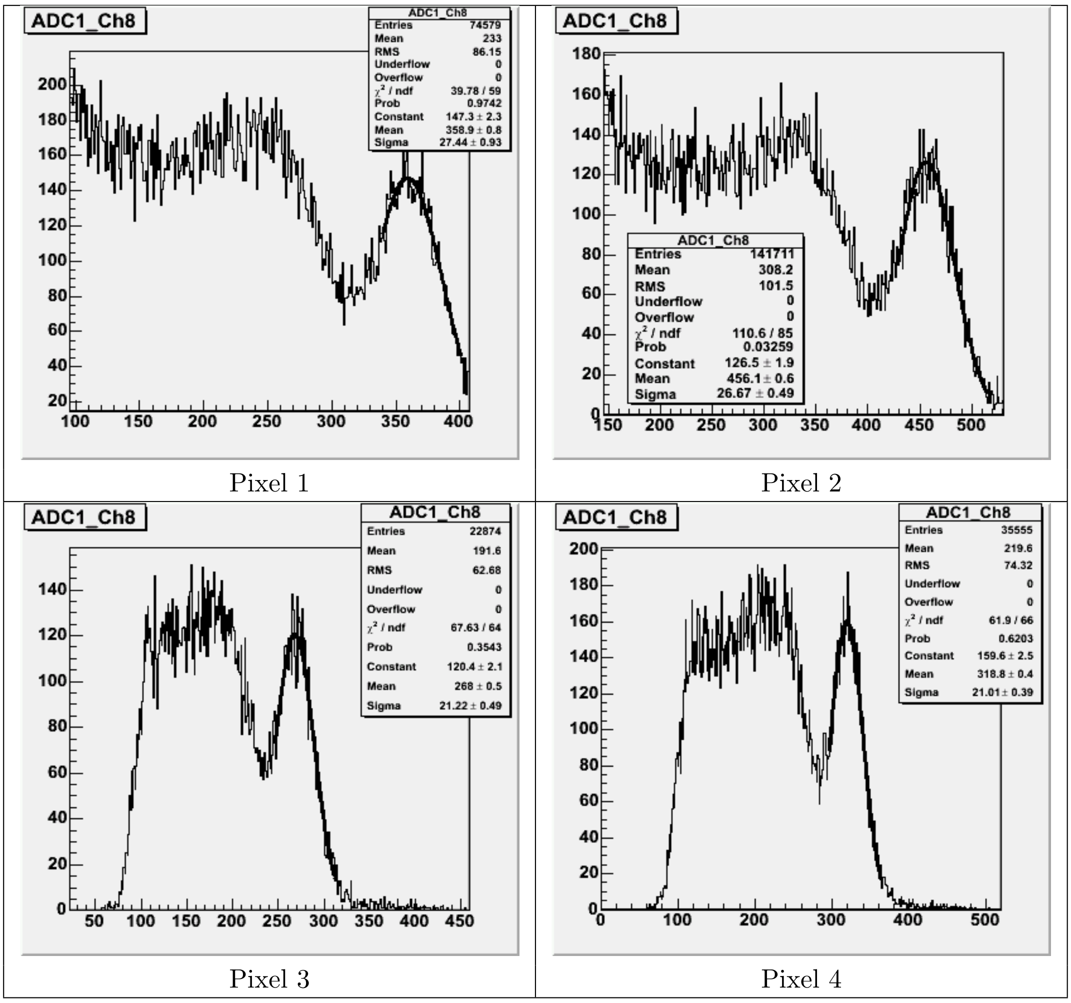

Figure 15: Energy spectrum for shielded crystals with grease