Characterization of the Ecal crystals light yield and amplification chain

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Abstract

This note presents the studies performed to characterize the HPS-Ecal signal amplification chain. This includes the $PbWO_4$ crystal itself, the APD, and the preamplifier. First, a simple model of the full HPS-Ecal amplification chain is developed and employed to derive the required gain for the preamplifiers. Then, the theoretical value is compared to those obtained from dedicated measurements performed on the amplifiers. Finally, the measurements performed on a single HPS-Ecal crystal are shown and discussed. The simple setup employed included all the elements foreseen in the HPS-Ecal setup, and permitted to measure the crystal light-yield, as well as the time-shape of the amplifier output signal that is finally compared to the theoretical model.

1 HPS-Ecal amplification chain model

In this part a very simple model of the amplification chain, sufficient for our needs, is presented. The aim is double. First, theoretically establish the gain needed for the preamplifier, all the other parameters being already set. The second point is to determine the duration of a typical signal entering the preamplifier since its gain depends on it.

1.1 The gain

The gain, G_{TOT}, of the amplification chain is the product of:

- the light yield, LY, of the crystals expressed in photons/MeV
- the quantum efficiency, QE, of the APD
- the surface ratio, S_R, between the active surface of the APD and the surface of the crystal
- the gain of the APD, G_{APD}, expressed in electrons per photon
- the gain of the preamplifier, G_{PA}, expressed in V/pC or pC/pC.

The corresponding formula is therefore:

$$G_{TOT} = LY \times QE \times S_R \times G_{APD} \times e \times G_{PA}, \tag{1}$$

where e is the elementary charge. Some of these parameters are already fixed:

$$QE = 0.7, \qquad S_R = \frac{10\times10}{16\times16}, \qquad G_{APD} = 150$$

The gain of the preamplifier is limited by the maximum input voltage of the fADC, which is 2 V. Simulations have shown that the maximum energy deposited in a single crystal with a 6.6 GeV electron beam is about 4.2 GeV (fig. 1).

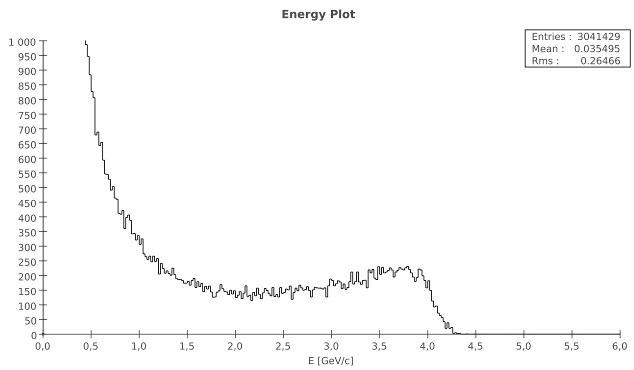

Figure 1: Energy deposited in one crystal when 6 GeV electrons stop in the calorimeter.

Thus, considering a light yield of 120 ph/MeV [1, 2], the gain of the preamplifier must verify:

$$G_{PA} = 0.604 \text{ V/pC}$$

Due to the constraints on the components, the expected gain is around 0.620 V/pC. Under these conditions, the total gain is thus:

$$G_{TOT} = 0.49 \text{ mV/MeV} \tag{2}$$

1.2 Time response

The aim of this part is to determine the duration of the input signal entering into the preamplifier, since its gain depends on it. The shape of the output signal from the preamplifier is also discussed.

Two elements are responsible for the signal before the preamplifier:

- the crystal
- the APD

The time response of the crystal depends on how it was grown. It is the sum of two decreasing exponantial, one with a time constants of 5 ns and the other one of 10 ns.

According to the documentation available on the website of Hamamatsu, the cut off frenquency is linked to the time needed to go from 10 % to 90 %, T_{1to9} of the signal by the following formula:

$$T_{1to9} = \frac{0.35}{f_{cut}} \quad ,$$

where f_{cut} is given in the documentation for an impedance of 50 Ω. The preamplifier has been designed to have a low input impedance of $R_{eq} = 23$ Ω. Therefore, the cut off frenquency is:

$$f_{cut} = \frac{1}{2 \times \pi \times R_{eq} \times C} = 26 \text{ MHz} \quad ,$$

where C is the capacitance of the APD and is equal to 270 pF. Using this time constant, the rise and fall of the output signal of the APD last about 14 ns.

Convoluting the contributions, the output signal of the APD has the shape shown in fig. 2. The rise of the signal can be fitted by a gaussian with $\sigma = 13$ ns. This value is important as it is the one that will then be used to determine the gain of the preamplifier.

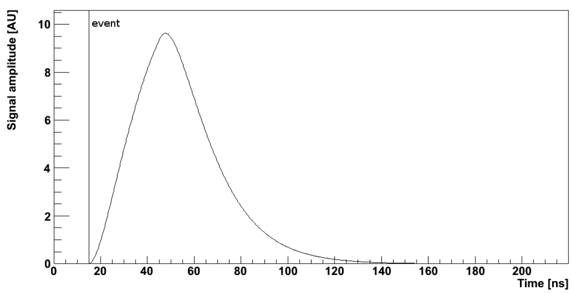

Figure 2: Simulation of the output signal of the APD. The responses of the crystal and the APD are convoluted.

2 Experimental preamplifier characterization

This section aims to show the dedicated measurements performed to characterize the HPS-Ecal amplifiers. Results are then compared to what was obtained from the model previously presented, to validate it and verify the validity of the asumptions on the different parameters.

2.1 Gain of the preamplifier

In this section the tests performed to evaluate the gain of a preamplifier are presented. The setup is composed of a preamplifier that receives a charge sent by a voltage generator through a capacitor. The signal is a falling edge where the signal needs 10 ns to go from 10 % to 90 % of its maximum value. The output is then read by a oscilloscope connected via a 50 Ω resistor.

The 10 ns condition has been confirmed by two different means. Firstly, by the simulation of the input signal of the preamplifier presented in the first part of this document where it was shown that simulation predicted that the input signal has a raise time between 10 and 14 ns. Secondly, by direct measurements with an old version of the preamplifier. Indeed, tests with cosmic rays have shown that for the old preamplifier, the total gain of the amplification chain is around 0.76 mV/MeV. To obtain a comparable gain with this preamplifier, the falling edge of the signal must last 10 ns.

Preamplifiers adapted to the need of HPS experiment have been developped at Orsay and tested. Three values were measured:

- the maximum amplitude of the output signal to obtain the gain in V/pC
- the integral of the signal to obtain the gain in pC/pC
- the standard deviation of the noise when the preamplifier does not receive any signal (see next part)

The results obtained for the two first quantities are summarized fig. 3.

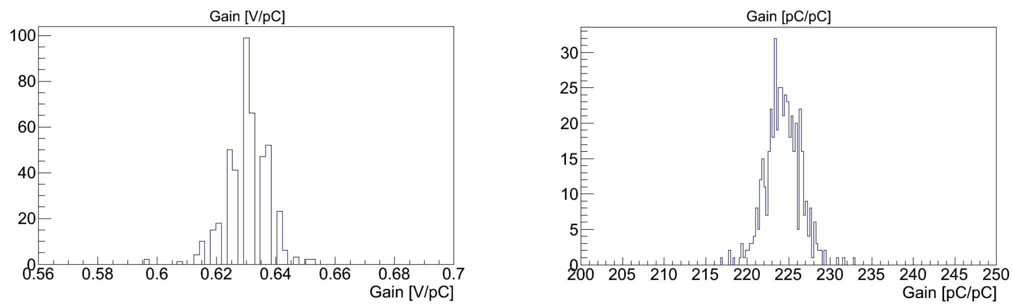

Figure 3: From left to right and top to bottom. Gain distributions measured in V/pC then in pC/pC. Standard deviation of the noise.

A gaussian fit of the gain expressed in V/pC shows that the average value is 0.63 V/pC while the standard deviation is 6.5×10^{-3} V/pC. The corresponding average integrated gain, expressed in pC/pC, is 224.27, with a standard deviation of 2.08 pC/pC.
One can see that the gain is a 2.5 % higher than expected to reach 2 V for the maximum energy deposition. Nevertheless, one should keep in mind that the calculations are considering a perfect case where there is no loss nor attenuation. Also, the signal rise corresponds to the fastest signal envisioned and the gain in V/pC decreases for slower signals.

At low energy the gain variations between preamplifiers are negligeable but it is no longer the case at higher energies. Considering the example where 3 GeV have been deposited in one crystal. The expected standard deviation at this energy is $\sigma_E = 77$ MeV ≈ 77 fADC counts. While a preamplifier with a gain of 0.610 V/pC, respectively 0.650 V/pC, will let a signal corresponding to 2955 fADC counts, respectively 3148 fADC counts. Based on these results it has been decided to group the preamplifiers with the APDs, a preamplifier with a high gain being paired with an APD having a low gain. This coupling improves the gain uniformity of the calorimeter and ensure that between a pair APD-preamplifier the gain difference is never more than 3 % (fig. 4).

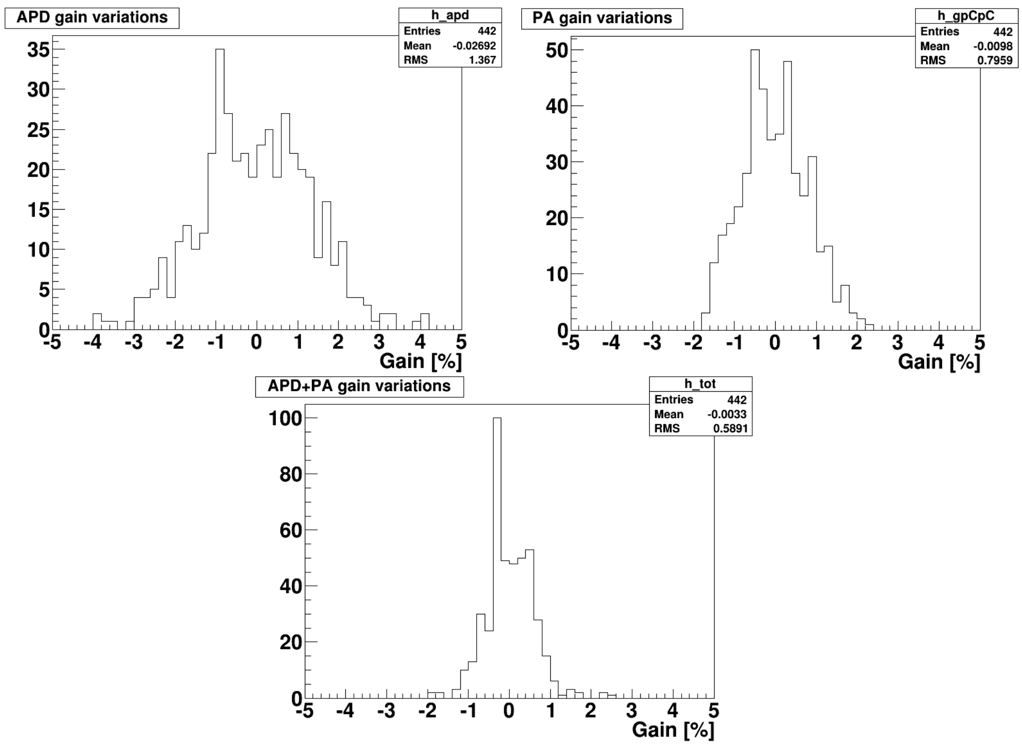

Figure 4: From left to right and top to bottom. Gain variations of the APD, then of the preamplifiers. Gain variations when APD and preamplifiers are coupled.

2.2 Noise of the preamplifier

The noise presented fig. 5 is obtained when there is no APD connected to it. To take into account the presence of the APD, a capacitor of 270 pF must be connected to the preamplifier. Four measurements have been done using such a capacitor. The first preamplifier had a low noise, the second high noise, while the two others were close to the most probable value of the distribution. When the capacitor is added, the preamplifiers are still ordered in the same way as a function of their gain. The difference between the lowest and the largest value is 0.07 mV, while the central values were around 1.14 mV. From these results, the theoretical threshold at the level of the fADC can be calculated.

There are three sources of noise:

- the preamplifier
- the fADC
- the photoelectron Poisson noise

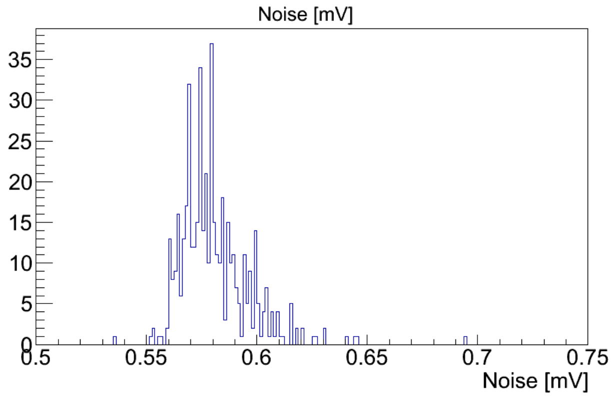

Figure 5: Standard deviation of the noise when the preamplifier does not receive any signal and when no APD is connected.

As explained before, each ADC channel will correspond to 0.5 mV, so it means that lowest and highest noise preamplifiers will induce 3 ADC counts on average which corresponds to about 3.3 MeV.

The noise of the fADC itself is 1.3 counts which corresponds to about 1.3 MeV.

All together the total noise is thus:

$$\sigma_{noise} = \sqrt{1.3^2 + 3.3^2 + E/N_{\gamma_e}} \tag{3}$$

Where $N_{\gamma_e} = 120$ is the number of photoelectrons per MeV.

3 HPS-Ecal single channel characterization

The measurements performed on a single HPS-Ecal $PbWO_4$ crystal are here presented. The goal was to measure the absolute crystal light yield, and to obtain a reasonable parametrization of the amplifier output signal wave-shape. For both tasks, a simple cosmic-ray setup was employed.

3.1 Experimental setup

A dedicated cosmic-muons telescope setup was developed for these measurements. The setup foresaw three plastic scintillators counters, horizontally aligned. Each counter was read at both ends by a fast PMT. The six-fold coincidence signal provided the trigger for the data acquisition system. The crystal, inserted in a copper enclosure for thermal stability, was coupled by means of optical glue[1] to an Hamamatsu S8664-1010 APD, connected to a HPS amplifier. The crystal was positioned in between the plastic scintillators, aligned horizontally and perpendicular to them. The angular spread of the cosmic rays was thus reduced, due to the limited acceptance of the telescope+crystal assembly in this configuration, at the price of a lower signal rate. During measurements, the temperature was kept constant at +18 °C by means of an external chiller, and the temperature was monitored trough different PT-100 sensors.

3.2 Light-yield measurements

For the light-yield measurements, a CAEN v1720 fADC was employed to digitize and store analog signals from the amplifier. This board has the same properties of those employed in the

[1]Dow Corning 3145 RTV clear, the same employed in the HPS-Ecal crystal assembly.

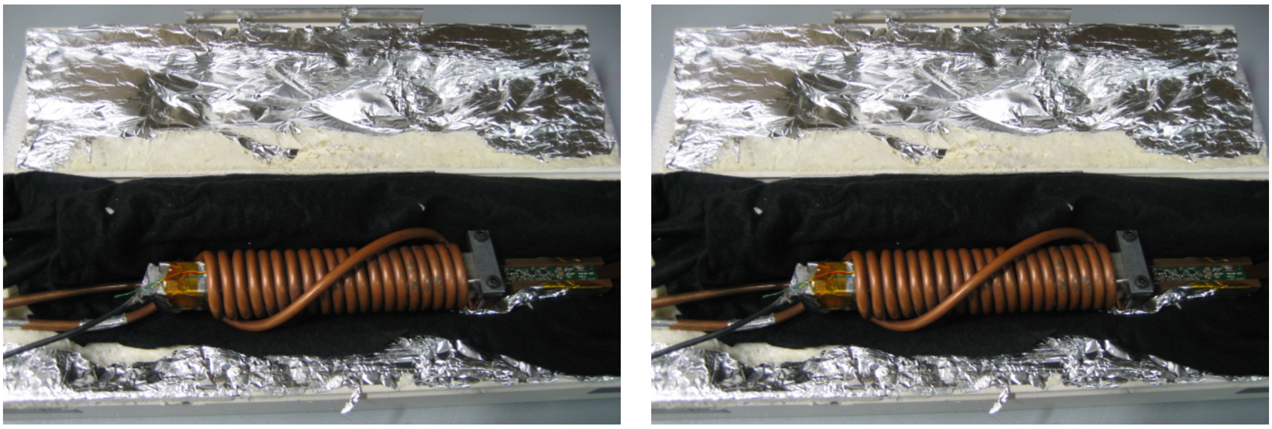

Figure 6: Left: the copper enclosure for light yield measurements. The $PbWO_4$ crystal is inserted in the holder between the pipes, and the APD coupled to the amplifier (visible on the right). The external box provides thermal insulation and light tightness. Right: the cosmic ray telescope. The crystal is inserted in between the three counters, horizontally aligned.

HPS experiment, i.e. the sampling rate (250 MHz), the resolution (12 bits), and the dynamic range (2 V). For each trigger, data in a 800 ns window centered on the signal position was digitized and stored on disk for later analysis. No online analysis or filtering algorithms were applied.

To obtain, for each digitized signal, the corresponding *charge*, different numerical integration methods were employed. The charge was obtained summing the digitized samples within a certain integration window, via the formula:

$$Q(pc) = \sum_{i=1}^{N} V_i(mV) \cdot \frac{T}{R} \quad ,$$

where T is the sampling period (4 ns) and R the fADC input impedance (50 Ω).

The algorithms differed in the following properties:

- The total number of ditigized values N to be included in the sum.
- The position of the integration window with respect to the signal. This can be fixed, or be determined dynamically event-by-event, knowing the peak position. In the latter case, one has also to define the number of samples before the peak position N_{bef} and the number of samples after the peak position N_{aft}.
- The pedestal subtraction. This can be done event-by-event, determining the pedestal value by applying the same integration algorithm to the points before the integration window, out-of-time with respect to the signal, or just by subtracting a fixed value to all the measured charges.

Different tests were performed to determine the best charge integration method, that can clearly identify the cosmics rays energy deposition peak in the overall measured distribution. The best results were obtained using $N = 17$, $N_{bef} = 5$, and $N_{aft} = 12$, perfoming the pedestal subtraction with a fixed, event-independent value.

A typical acquired signal is shown in Figure 7, left panel. The integration window is highlighted by the two vertical blue lines. The right panel shows the overall charge distribution from the measure, without any selection cut applied. Most of the values are centered around the pedestal, and correspond to events with a cosmic ray triggering the DAQ but not passing trough the crystal. The predominance of these events is due to the geometrical alignement employed, discussed above, to minimize the angular spread of muons actually passing trough the crystal. Signals from cosmic muons appear as a distinct shoulder, approximately at 2-3 pC.

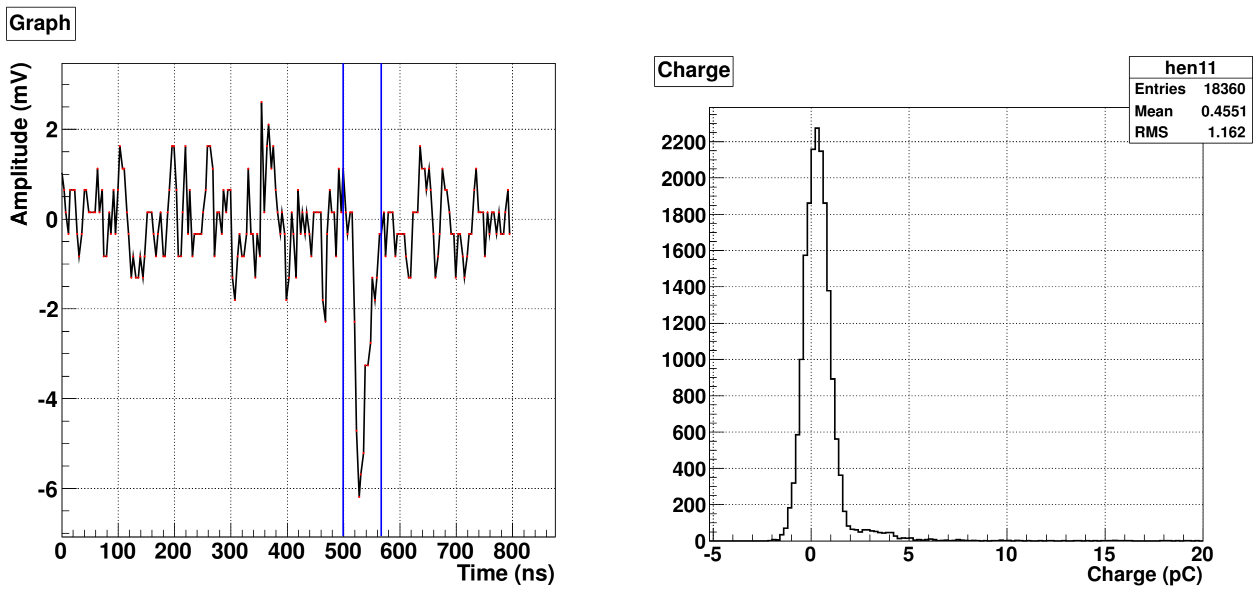

Figure 7: Left: a digitized signal from the single crystal light-yield measure. The black line has been added for better readibility. The integration window is highlighted by the two vertical lines. Right: charge distribution from the single crystal light-yield measure. No analysis cuts are applied at this stage.

To reduce the background, one can exploit the fact that signals coming from cosmics not passing trough the crystal do not manifest any correlation in between the counters and the crystal itself. The peak position, defined event by event by the position of the largest sample, would be, therefore, randomly distributed within the acquisition window. The resulting charge distribution is reported in Figure 8.

To derive the crystal light yield from these data, one has to measure the charge, in pC, corresponding to the most probable energy deposition of the cosmic rays. This, in turns, correspond to an abolute energy of approximately 15 MeV, as obtained by means of MonteCarlo simulations. The most probable value can be obtained by performing a best fit to the charge distribution with the sum of a gaussian function for the pedestal, and a Laundau function convoluted with a gaussian function for the cosmic rays signal.

The obtained result is also shown in Figure 8. The Landau peak and the pedestal position are[2], respectively, 2.912 pC and 0.425 pC. The most probable energy deposition thus correspond to a charge of:

$$Q_{MP} = 2.487\, pC$$

From this, one can derive the crystal light-yield by converting the charge in the number of electrons and dividing this by the gain of the amplifier, the gain of the APD, and the most probable energy deposition:

[2]Due to the specific implementation of the Landau function within the ROOT framework, the parameter "MP" is **not** the most probable value of the distribution, that has to be evaluated numerically.

$$LY_{phe} = \frac{Q_{MP}}{e \cdot G_{APD} \cdot G_{Ampli} \cdot E_{MP}} = 30.8 \text{ phe / MeV}$$

One can also derive the light yield, in optical photons emitted per deposited MeV, by taking into account the APD quantum efficiency ($QE \simeq 0.7$) and the ratio of the APD surface to crystal surface ($S_R = 0.3906$), getting:

$$LY_\gamma = \frac{LY_{phe}}{QE \cdot S_R} \simeq 112.6 \text{ photons / MeV}$$

This number is close to the one used in the amplification chain model (120 photons / MeV). The obtained result suffers a significant systematic error, due to different sources: first, the fact that the nominal parameters of the amplification chain were used to derive, from the measured charge, the corresponding number of primary electrons in the APD, before the avalanche. Second, the fact that the short integration window employed may cut the signal tail at large times, thus resulting in a lower measured charge than the real one. An educated guess for these systematic effects is not lower than 10 - 15 %.

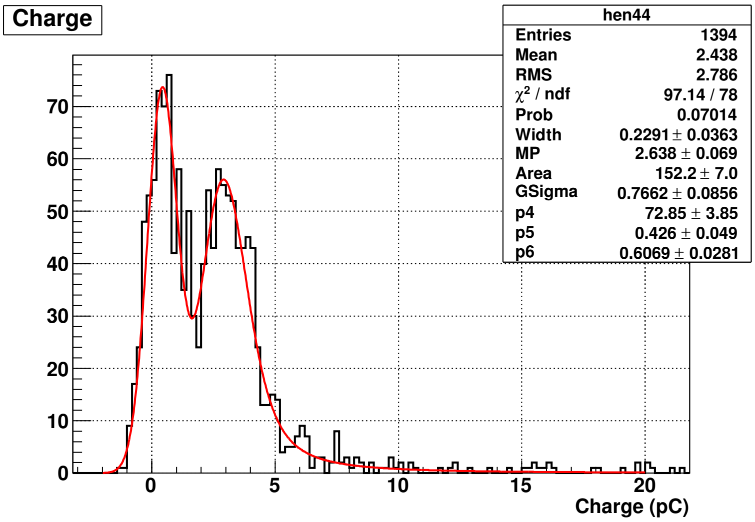

Figure 8: Charge distribution from the HPS-Ecal crystal+APD+amplifier, obtained with cosmic rays.

3.3 Output signal wave-shape measurements

Even if the wave-shape of the amplifier signal can be studied from the previous measurements, the small amplitude, $\simeq$ 10mV prevent to obtain definite conclusions. The experimental setup was therefore modified as follows. The crystal was oriented vertically, to have cosmic muons passing trough the whole axis, depositing a high amount of energy, and thus producing very high pulses. Also, we employed a fast oscilloscope, with a much higher sampling frequency and input bandwidth, to record signals. A typical measured waveform is reported in Figure 9. The two superimposed curves are the results of two independent fits, performed with the following functions:

- Red: the sum of two gaussian functions, with the same amplitude and different widths, continuosly connected at the signal peak position.

- Green: a 3-pole function, i.e.

$$f(t) = A \cdot t^2 \cdot \exp(-t/\tau)$$

For all the measured signals, the 3-pole function provided a better parametrization of the experimental data. The distribution of the parameter τ is reported in Figure 10, left panel. The presence of two peaks in the distribution is not an analysis artifact, but really due to the presence of signals with different shapes, as shown in the right panel. This feature can be due to the specific setup employed to test the HPS single crystal, but will require further investigation.

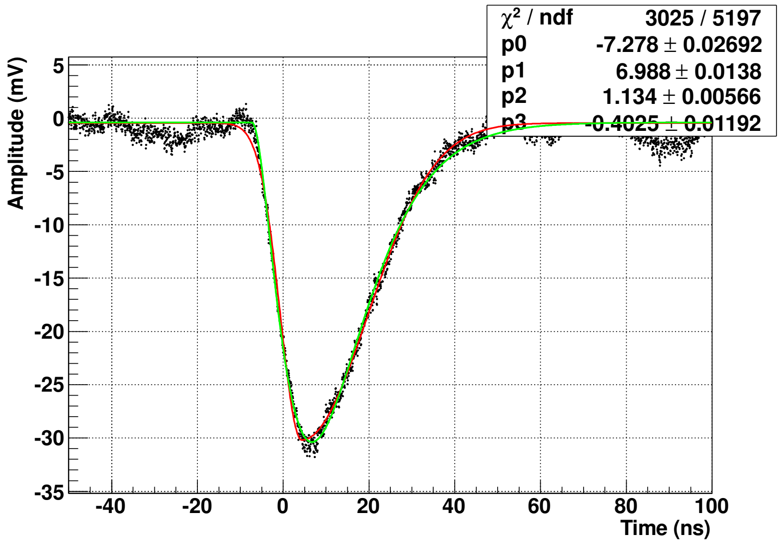

Figure 9: A typical wave-shape from a single HPS-Ecal channel. See text for the meaning of the two curves

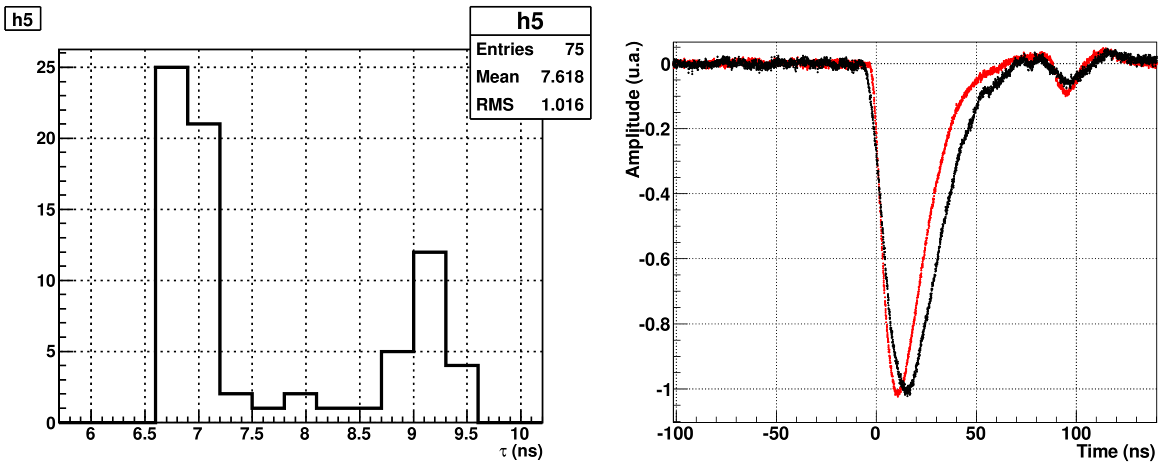

Figure 10: Left: the distribution of the τ parameter. Right: comparison between two signals with τ parameter belonging to the two peaks of the distribution (both signals have been normalized to have the same amplitude).

4 Conclusions

A simple model of the amplification chain has been employed to determine the gain needed for the preamplifier. The characterization of 470 preamplifiers has shown that the gain and noise dispersion is very small. Nervertheless, preamplifiers and APD and coupled which leads to a 3 % gain uniformity of the calorimeter.

The light yield of a $PbWO_4$ crystal was then measured, with a custom cosmic-ray setup. The charge corresponding to the most probable energy deposition was converted to the number of primary photo-electron in the APD by using the nominal amplifier gain, as previously derived. Given the most probable energy deposition of 15 MeV, derived by MonteCarlo simulations, the crystal light yield (coupled to a LA-APD) was evalueated to be:

$$LY = 30.8 \text{ phe/MeV}$$

The output signal shape from the whole amplification chain was also measured, using a fast oscillscope. The best signal parametrization was found with a 3-pole function, i.e.

$$f(t) = A \cdot t^2 \cdot \exp(-t/\tau) \quad ,$$

with $\tau \simeq 7$ ns. Further measurements are required, since few signals with different shapes (nominally, with higher τ) were measured.

Overall, this note has shown the consistency between simulation and measurement of the signal produced by the amplification chain.

References

[1] P. Lecoq, et al., Nucl. Instrum. Methods A, Vol. 365 (1995) 291-298

[2] CMS-ECal technical design report