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Study of new scintillator samples for future detectors

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Abstract. In this research project it was developed a set up for the absolute light yield measurement of new plastic scintillators. A scintillator is a material capable of emitting pulses of light when crossed by ionizing particles and they are mainly used as detectors in particle physics. Generally, scintillator-based detectors consist of three main parts: a scintillating material, a photodetector such as a silicon photomultiplier (SiPM) and a readout system. So, since one of the best metrics to characterize the scintillator is the measurement of the number of photons per MeV, an experimental setup to measure the number of photons per MeV was made to evaluate the performance of new scintillating materials. This paper describes the experimental setup and also the procedures for the SiPM calibration, another important aspect of this setup.

Keywords: SiPM, scintillator, discriminator

1 Introduction

This introduction provides an overview of the working principle of the scintillator tiles and describes how important is the new developments of scintillators to meet the needs of future experiments.

1.1 The working principle of a scintillator

When charged particles traverse a scintillator, a fraction of the energy can be deposited in its material by exciting the medium along the trajectory. Molecules of the substances emit a few percentage of this energy as optical photons, called scintillation. The emitted light can be detected by photo-sensitive detectors such as Photo Multiplier Tubes (PMT) or SiPMs coupled to the scintillator [1]. A good knowledge of scintillators is fundamental for the design of detectors for future high energy experiments, such as those of the Future Circular Collider (FCC) at CERN.

1.2 The Future Circular Collider (FCC)

The Future Collider (FCC) is the project destined to succeed the Large Hadron Collider at CERN. The proton-proton machine is expected to produce collision at center of mass energies of 100 TeV (LHC instead reaches, at most 14 TeV), inserted in 100 km long tunnel (LHC is instead 27 km long). The proposal calorimeter, in the figure 1, consists of steel and lead absorbers, and of plastic scintillator tiles as the active material. The scintillator tiles are coupled one-sided to wavelength-shifting (WLS) fibers that guide the light outside of the calorimeter volume to silicon photomultipliers for the readout.

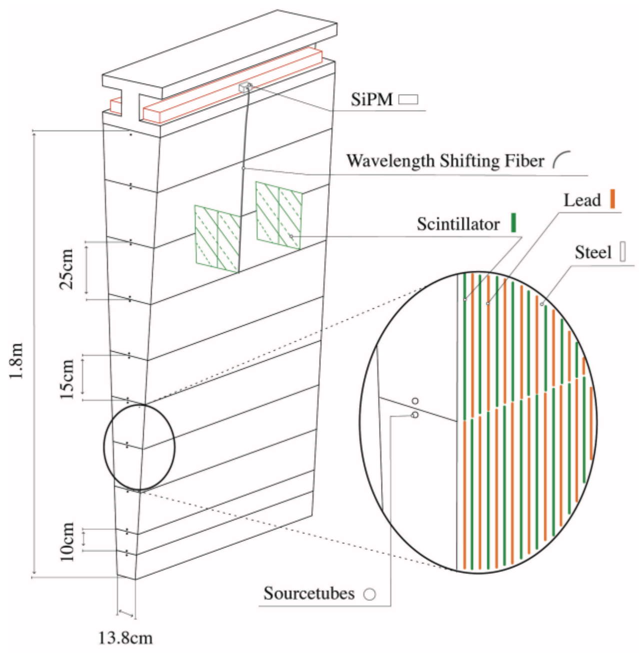

Figure 1. The proposal FCC calorimeter

2 Experimental setup

Since one of the most important things is to increase light yield of scintillators, it was developed a system to measure this quantity in novel scintillating materials. In this section is introduced, after a list of the relevant components of the experimental setup, a general review of the working principle of the above-mentioned setups.

2.1 Relevant components of the experimental setup

Here it's presented a list of the main components of the experimental setup (Figure 2):

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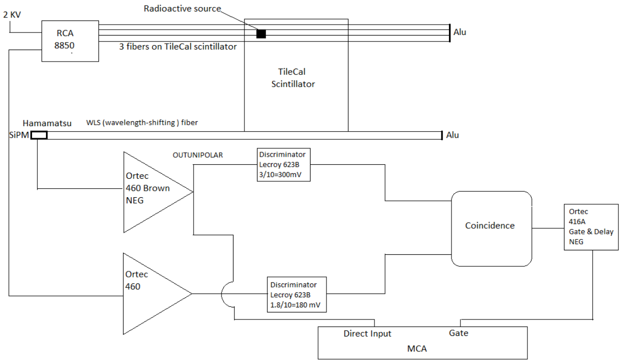

Figure 2. Experimental setup

- Radioactive source: ^{90}Sr ;
- TileCal Scintillator;
- Silicon Photomultiplier: SiPM Hamamatsu;
- 3 scintillating fibers;
- Photomultiplier tubes (PMT): RCA 8850;
- Amplifiers: Ortec 460;
- Discriminators: Lecroy 623B;
- Coincidence;
- Ortec 416A Gate and Delay;
- Multichannel Analyzers: MCA 8000a.

2.2 The experimental setup to measure the number of photons per MeV

The TileCal Scintillator is excited by a radioactive source (^{90}Sr) free to move under the plate of the scintillator and the output of the excitation due to radiation are photons. The scintillation light is collected from the scintillator with a wavelength shifting (WLS) fiber, guiding it until it reaches the light detector, which for this case is a SiPM (Silicon PhotoMultiplier). They have a light-tight wrapping consisting of aluminum foil. In general, wrapping is needed in order to improve the light yield of the scintillator counter. The fraction of the light not confined by total reflection inside the tile can be back-reflected into the tile, thus increasing the number of photons that can be captured by the readout. Above the TileCal Scintillator there are 3 scintillating fibers used for the coincidence and trigger the signals from the TileCal scintillator (the 3 scintillating fibers have also a light-tight wrapping). The light from the 3 fibers is guided until a photomultiplier tube (RCA 8850). After this the two signals go into the amplifiers, where the signals are amplified. In fact the signals from the photomultipliers are low. So an amplification circuit is needed such that the signals produced by the photomultipliers increase in scale. Then the signals are guided until the discriminators, electrical circuits that check whether the signal at a certain instant of time is larger than the noise and smaller than the signal expected from photons. Afterwards the signals arrive into the coincidence that aims to provide a trigger for simultaneous detection of the two signals (one from the collected light on the side of the TileCal Scintillator, the other coming from the 3 fibers). At the end, after the coincidence, there is the MultiChannel Analyzer, from which it's possible to get the spectra of the SiPM, at the different positions of the radioactive source. The MCA works by digitizing the amplitude of the incoming pulse with an analog-to-digital converter (ADC). [1]

2.3 Discriminators and the tuning of the counting rates

The discriminator is an electronic signal processing device that receives the signal from the photomultiplier in input, with a small coaxial connector. It responds when the signal from the photomultiplier exceeds a threshold. If the signal at the output of the photomultiplier is observed with the oscilloscope, it can be observed that the voltage across the coaxial cable has a noise centered around zero and, from time to time, has a rapid decline towards negative functions and a somewhat slower but fairly rapid ascent. To select the events of our interest it's used the trigger menu, when the photomultiplier signal has deviated significantly from what is the typical noise at its output.
An oscilloscope is a type of electronic test instrument that graphically displays varying electrical voltages as a two-dimensional plot of one or more signals as a function of time. It shows a slice of time, over a certain number of divisions, compared to all the time the circuit is connected. So somehow the oscilloscope has to decide which slice of time to show. This part of the circuit is called Trigger. An analog / digital converter converts the voltage signal into a digital number and writes it to a memory. When the trigger condition occurs, nothing is written to the memory and the signal is presented graphically as a function of time. In an acquisition system it is necessary to define what is the condition to stop the acquisition and understand if something interesting has happened. So what in this case is the way to define if something important has happened? When nothing happens, the voltage is a random noise, because every electronic device at finite temperature produces a certain amount of noise. This noise is more or less confined within a band. If the voltage is within this noise band, nothing of interest is happening. When the voltage exceeds these limit voltages (threshold voltages) then something interesting has happened.
To obtain reasonable values of the coincidence count, the discriminator threshold was tuned. Indeed, the threshold should be carefully adjusted so as to ensure that electronic noise is eliminated, but not so high as to also cut out good signals. Below are the tables (1, 2, 3, 4) where they are reported: the counting rate/second of the SiPM/scintillator (Cont 1), the counting rate/second of the RCA/scintillating fibers (Cont 2) and the coincidence count/second (Cont 3) at different values of thresholds. In the tables 1, 2 are shown the thresholds of the discriminator at which the signal from the SiPM (reading the WLS fiber that collects light from the Tilecal scintillator) arrives. After setting the SiPM discriminator threshold at 3 V, the RCA

discriminator threshold, (tables 3, 4), was adjusted. So, this discriminator threshold was set at 3.4 V.

Theoretically, as the SiPM threshold increases, count 1 and 3 (coincidence) should decrease. This matches the results observed in tables 1 and 2. Moreover, count 2 should stay constant. From the results, it does not vary much in table 2, but it does in table 1.
On the other hand, by increasing the RCA discriminator threshold count 2 and 3 should decrease, as it happens in the tables 3 and 4. In this case, count 1 should remain constant, in opposition with what is shown by tables 3 and 4.

It was noted that counting rates were varying when not expected. This is a possible result of electronic instability: in order to have a stabilised noise, some time should have been waited for after the equipment was turned on. One possible explanation, for the fact that counting rates are varying when not expected, is electronics instability: usually the equipments should be turned on and wait some time (~ 30 min) for the electronics noise to stabilise. To prove this hypothesis the measurement should be repeated. So the effect would need more tests to be understood.

Table 1. Coordinates of the source: x=16000 y=5600

Threshold [V]	Count 1 [s^{-1}]	Count 2 [s^{-1}]	Count 3 [s^{-1}]
3.0	33085	40196	4258
3.5	25204	40320	1452
4.0	20977	40898	1064
4.5	17842	41489	809
5.0	15015	42017	614
5.5	13009	42426	525
6.0	10395	42528	356
6.5	5289	43914	170
7.0	3725	44730	122
7.5	2719	44704	86
8.0	1982	45094	63

Table 2. Coordinates of the source: x=2400 y=5600

Threshold [V]	Count 1 [s^{-1}]	Count 2 [s^{-1}]	Count 3 [s^{-1}]
3.0	32063	39641	7829
3.5	31527	39557	5012
4.0	30556	39417	4594
4.5	30025	39321	4310
5.0	29586	39201	4183
5.5	29287	39548	4065
6.0	28926	39591	3824
6.5	27873	39394	3529
7.0	27839	39560	3500
7.5	27498	39726	3451
8.0	27140	39414	3427

Table 3. Coordinates of the source: x=2400 y=5600

Threshold [V]	Count 1 [s^{-1}]	Count 2 [s^{-1}]	Count 3 [s^{-1}]
1.8	32524	39040	7416
2.2	34854	36210	5685
2.6	36564	33129	4187
3.0	38230	30089	3235
3.4	40204	26797	2519
3.8	42055	22943	1877
4.2	44101	18610	1341
4.6	45867	14883	1040
5.0	48105	10788	741
5.4	49984	7244	507
5.8	51055	4744	326
6.2	52375	2726	202

Table 4. Coordinates of the source: x=16400 y=5600

Threshold [V]	Count 1 [s^{-1}]	Count 2 [s^{-1}]	Count 3 [s^{-1}]
1.8	32829	39439	5791
2.2	34473	35986	2936
2.6	36083	33070	2107
3.0	37526	29789	1552
3.4	38357	26233	1129
3.8	40362	18171	780
4.2	41635	14193	586
4.6	42418	10440	391
5.0	44434	7029	273
5.4	45490	4451	182
6.2	47048	2453	59

3 SiPM Calibration

3.1 Silicon Photomultipliers (SiPM)

SiPM (Silicon Photomultipliers) are photon counting devices consisting of a matrix of SPAD (Single Photon Avalanche Photodiode) connected in parallel on a common substrate used in Geiger mode [2]. They are independent of magnetic environments, have spectral photon detection efficiency at up to 50% and provide a single-photon resolution up to few tens of photoelectrons. Each cell has the task of analyzing one or more photons (depending on the size of the pixel) and to do this, avalanche photodiodes are used that use the properties of semiconductors. SiPMs are based on a PN junction, reverse polarized, in order to create a depletion zone. So, when the optical photon hits the depletion region, it creates pairs electron-hole which are accelerated to trigger large charge carrier avalanches as to produce a measurable electrical signal. Basically, the primary charges, produced in the depletion zone by the photoelectric effect, create an avalanche effect that generates a large number of secondary charges. These charges will be the ones that generate the current produced by the photodiode. A typical SiPM pulse-height spectrum is shown in figure 3. The peaks correspond to the number of fired SiPM pixel, i.e. the number-of-photoelectrons $N_{pe} = 0, 1, 2, ..., N$ measured ([2]), as shown later in figure 4.

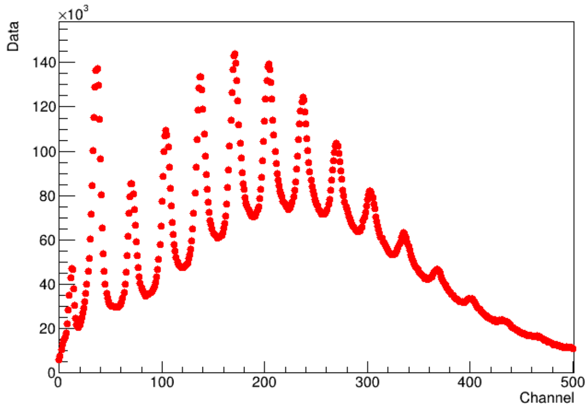

Figure 3. SiPM pulse-height spectrum

3.2 Pulse-height spectra

Pulse-height spectra at different positions of the radioactive source are shown in the figures: 4, 6, 7, 8. The measured SiPM signal values are filled into a single histogram, thus, forming the pulse-height spectra that exhibits the characteristic multi-peak distribution. It was possible, through a programming code, to find the peaks of the spectrum and fit it with a multigaussian (gaussian fit on top of linear background). Through the comparison with the spectrum of the noise ($x = 16400$) it can be noticed which peak is the best candidate for the 0 photons peak and select the pedestal suppression, so the pedestal will be subtracted from the signal (equation 1).

3.2.1 Fits with a multi-peak Gaussian

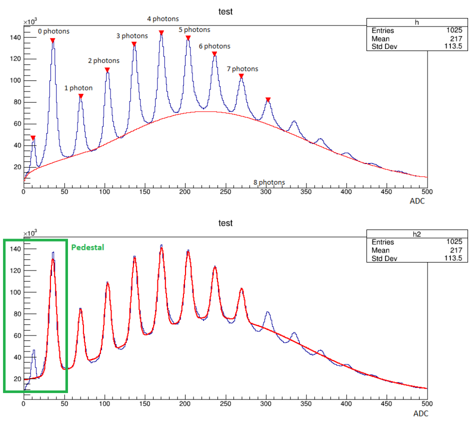

Figure 4. Pulse-height spectrum (15 hours run) at position x=2400 of the radioactive source, max light output of the Tilecal scintillator. Fit with a multi-peak Gaussian (red line).

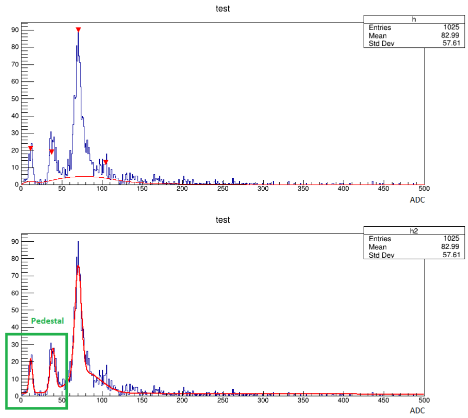

Figure 5. Pulse-height spectrum (15 hours run) at position x=16400 of the radioactive source, min light output of the Tilecal scintillator (noise run). Fit with a multi-peak Gaussian (red line).

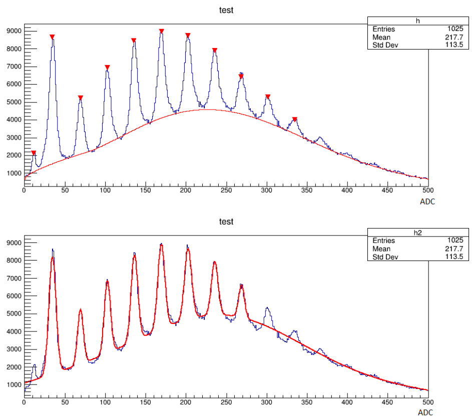

Figure 6. Pulse-height spectrum (1 hour run) at position x=2400 of the radioactive source, max light output of the Tilecal scintillator. Fit with a multi-peak Gaussian (red line).

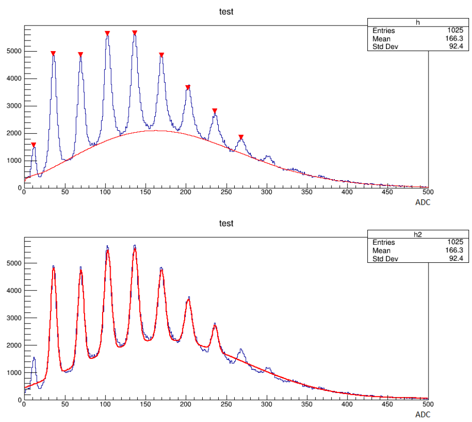

Figure 7. Pulse-height spectrum (1 hour run) at position x=7400 of the radioactive source, near mid scintillator. Fit with a multi-peak Gaussian (red line).

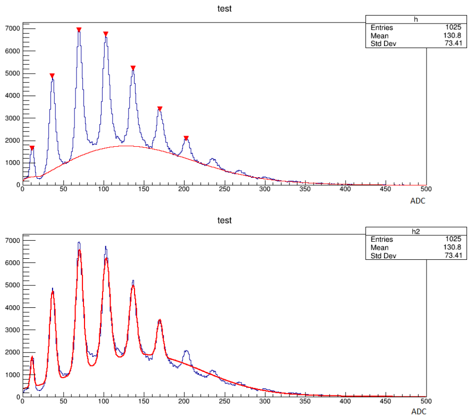

Figure 8. Pulse-height spectrum (1 hour run) at position x=11400 of the radioactive source, min light output of the Tilecal scintillator. Fit with a multi-peak Gaussian (red line).

The 15 hours should be the best run for the calibration of the individual peaks, but it seems to show a slightly shift relative to the other runs, maybe temperature related. So the 1 hour run at the maximum light output is the best choice.

3.3 The model

The SiPM calibration is obtained converting the signal, coming from the SiPM, into the the number of photons. The model used to convert the signal into the number of photons is the following:

$$N_{photons} = \frac{S - Pedestal}{\epsilon_{geom}\epsilon_{coll}\epsilon_{trans}\epsilon_{PD}} \cdot \frac{1}{p_0} \qquad (1)$$

1. From SiPM:
   - S: the signal [ADC]
2. From simulation:
   - ϵ_{geom}: geometrical efficiency, which is the efficiency with which the scintillator intercepts radiation emitted from the source.
   - ϵ_{coll}: collection efficiency, which is the efficiency with which the scintillator collected light at the end of the plate, generally less than the sending end light due to losses in the scintillator,
   - ϵ_{trans}: transmission efficiency, the ratio of the power received over the transmission path to the power transmitted.
3. From the characteristics of the instrument:
   - ϵ_{PD}: photo detection efficiency, defined as the probability of a photon hitting the SiPM to trigger a Geiger discharge.

So, the factor to find to convert the signal into the number of photons will be p_0. Since the dimension of the signal is ADC and the efficiencies are dimensionless, then the dimension of the factor p_0 will be $\frac{\#photons}{ADC}$.

3.4 Estimate of the conversion factor

In the picture of the pulse-height spectrum (Figure 4), the converting factor p_0 is related to the distance of two neighboring peaks. An estimation of the calibration value is done using the information on the individual peak positions resulting from the multi-Gaussian fit and taking the differences between the peaks. So, the first step in the evaluation of the calibration factor is to find the peaks (by the means) and then subtracting them two by two:

$$\Delta_{ptp,i} = \bar{x}_{i+1} - \bar{x}_i \qquad (2)$$

where:
$\Delta_{ptp} = \Delta_{peak-to-peak-distances}$ and $i = N_{photo-electrons}$
The next step is plot the differences and fit them with a constant function, as shown in the figure 9

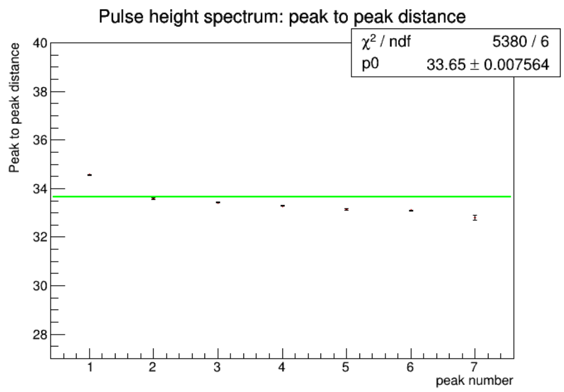

Figure 9. Peak-to-peak distance

4 Results

The obtained result of the converting factor p_0 is

$$p_0 = 33.647 \pm 0.007 \qquad [\frac{ADC}{\#photons}]$$

This factor p_0 can be used to convert the signal into the number of photons using the equation 1, In the residuals plot (the difference between the observed value and the estimated value in percentage) the points don't really oscillate around zero and therefore around the best fit model, as shown in figure 10.
So, it is necessary to repeat and make more measurements and then analyze this feature in more detail. This investigation can be postponed to a future work.

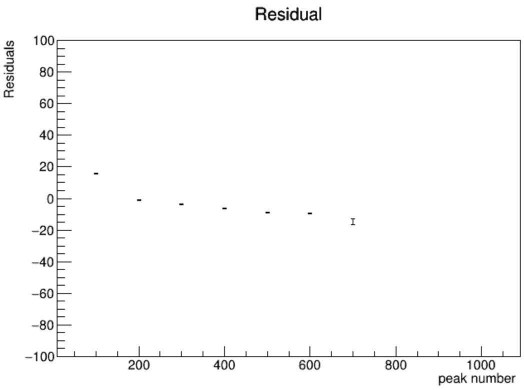

Figure 10. Residuals plot in percentage

5 Conclusions

In this project I contributed to the development of a setup for the absolute light yield measurement of new plastic scintillators, by tuning the setup parameters (such as discriminator thresholds) and performing the calibration of the SiPM. The work consisted firstly in obtaining signal spectra with the Multi Channel Analyzer (MCA), and then in assembling the experimental setup (Figure 2). This lead to the development of a code analyzing the MCA spectrum, by plotting and fitting the spectrum. Finally the Calibration $Signal \rightarrow \#photons$ was obtained.

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References

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