PSoC Based Coincidence Detector
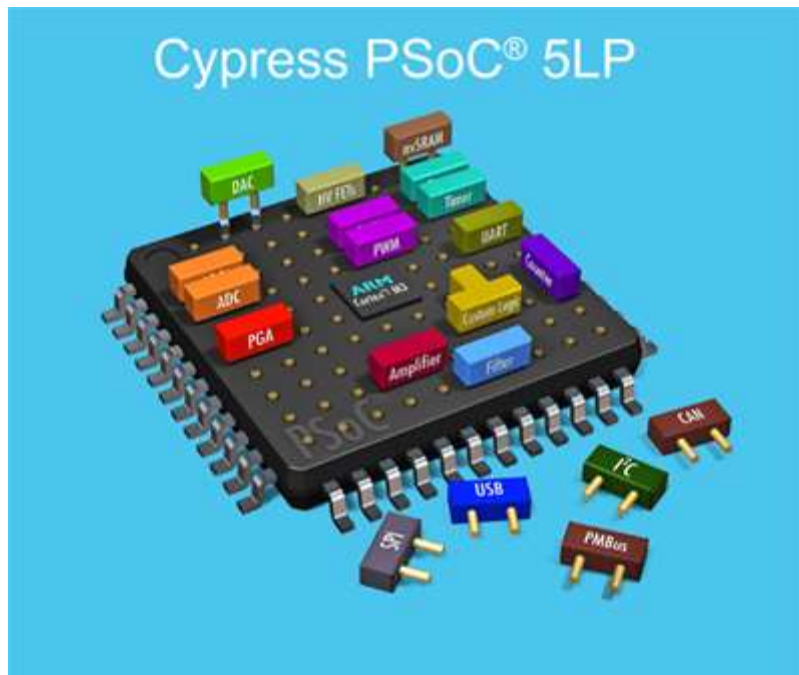
Using PSoC for a Coincidence Pulse Detection Equipment

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PSoC

In this document we describe an application of **PSoC** component having the aim to realize a high-precision coincidence detection circuit to be applied in the detection of nuclear signals.

PSoC (Programmable System-on-Chip) is a family of microcontroller integrated circuits by Cypress Semiconductor. These chips include a CPU core and mixed-signal arrays of configurable integrated analog and digital peripherals. A PSoC integrated circuit is composed of a core, configurable analog and digital blocks, and programmable routing and interconnect. The configurable blocks in a PSoC are the biggest difference from other microcontrollers. PSoC has three separate memory spaces: paged SRAM for data, Flash memory for instructions and fixed data, and I/O Registers for controlling and accessing the configurable logic blocks and functions.

PSoC resembles an ASIC: blocks can be assigned a wide range of functions and interconnected on-chip. Unlike an ASIC, there is no special manufacturing process required to create the custom configuration — only startup code that is created by Cypress' *PSoC Designer* (for PSoC 1) or *PSoC Creator* (for PSoC 3 / 4 / 5) IDE.

PSoC resembles an FPGA in that at power up it must be configured, but this configuration occurs by loading instructions from the built-in Flash memory. PSoC most closely resembles a microcontroller combined with a PLD and programmable analog. Code is executed to interact with the user-specified peripheral functions (called "Components"), using automatically generated APIs and interrupt routines. *PSoC Designer* or *PSoC Creator* generate the startup configuration code. Both integrate APIs that initialize the user selected components upon the users needs in a Visual-Studio-like GUI.

In our application we used the model **PSoC 5LP**. For development we used both the CY8CKIT-059 kit and the more complete board CY8CKIT-050, both are shown in the images below :

CY8CKIT-059

CY8CKIT-050

Coincidence Detector

With PSoC 5LP, a coincidence detector circuit has been realized, it accepts two analog input signals produced by SiPM or PMT sensors. It counts the pulses of both the channels and the coincidence channel. The firmware stored in the microcontroller also calculates the pulse rates (CPS and CPM) and also calculates the deviation σ of the counting result. The data are presented on a two-line display with 16 characters . The image below describes the block diagram of the circuit :
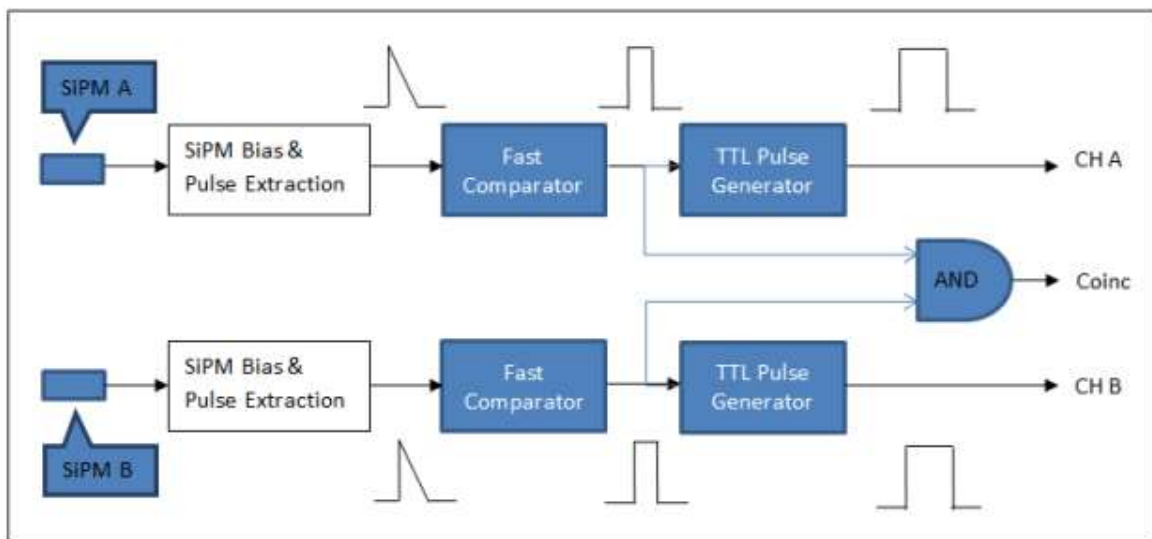
The image below shows the PSoC 5LP board used for development of the system and the power supply and amplification sections for the SiPM sensors.
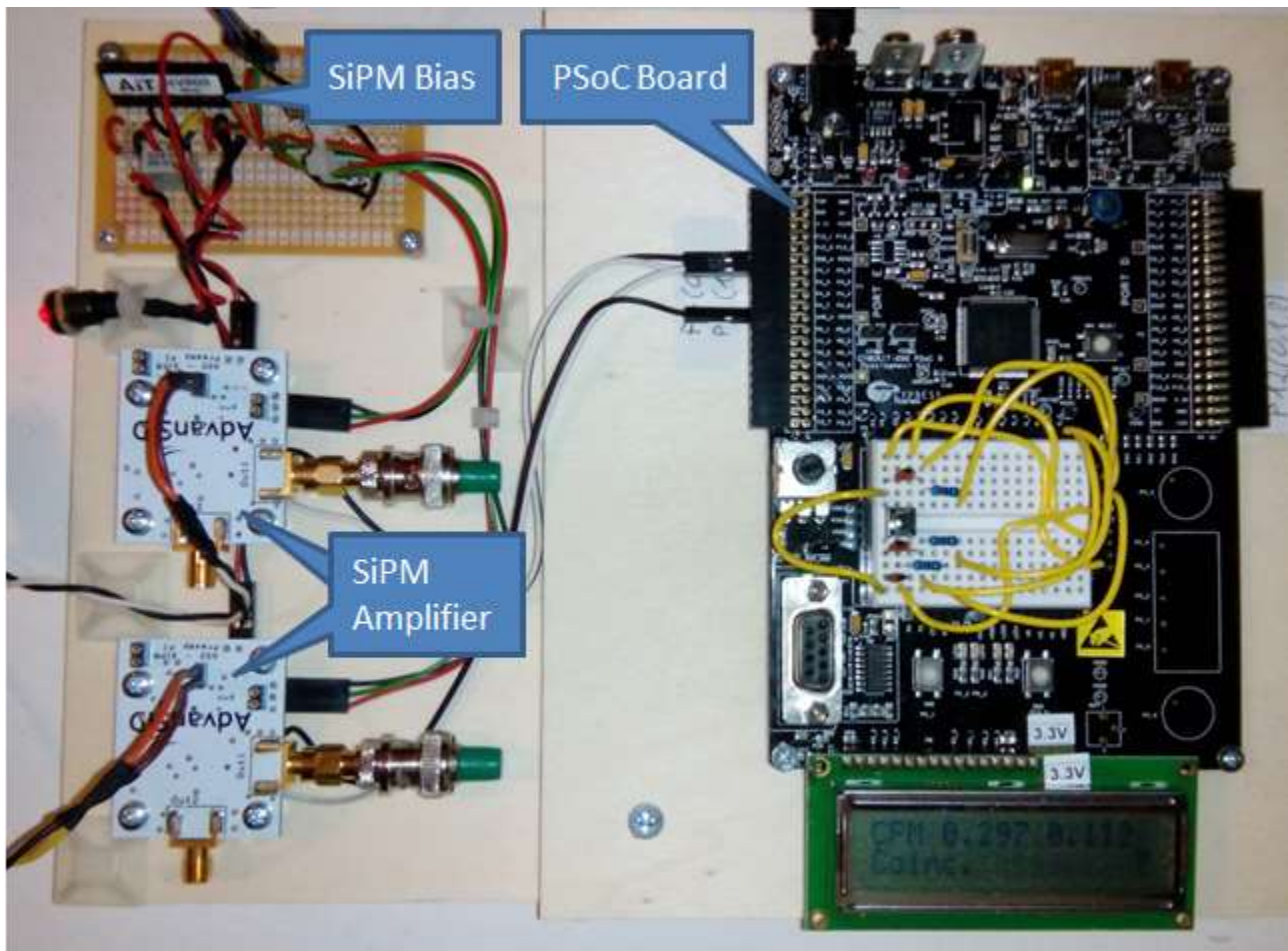

Firmware

The PSoC 5LP has been programmed with the development system PSoC Creator, freely downloadable from the manufacturer's website. Using this tool, with a rich and simple graphical interface, the chip is programmed and are all the used components are defined and configured.

We go through the main points of the project.

Clock Signals

The system is synchronized by means of a series of clock signals, the main of which is the **BUS_CLK** that has a frequency of **58MHz** (this frequency is set in configuration and depends on the characteristics of the circuit that is being achieved), it synchronizes the operation of all the components. The period of this signal is about **20ns** , this is important because it corresponds to the minimum duration of the signals that can be managed correctly by the system. Signals shorter than 20ns may be managed incorrectly or may not be read by the system. In our project we have established for the signals a minimum duration of**40ns**, well above the limit of 20ns.
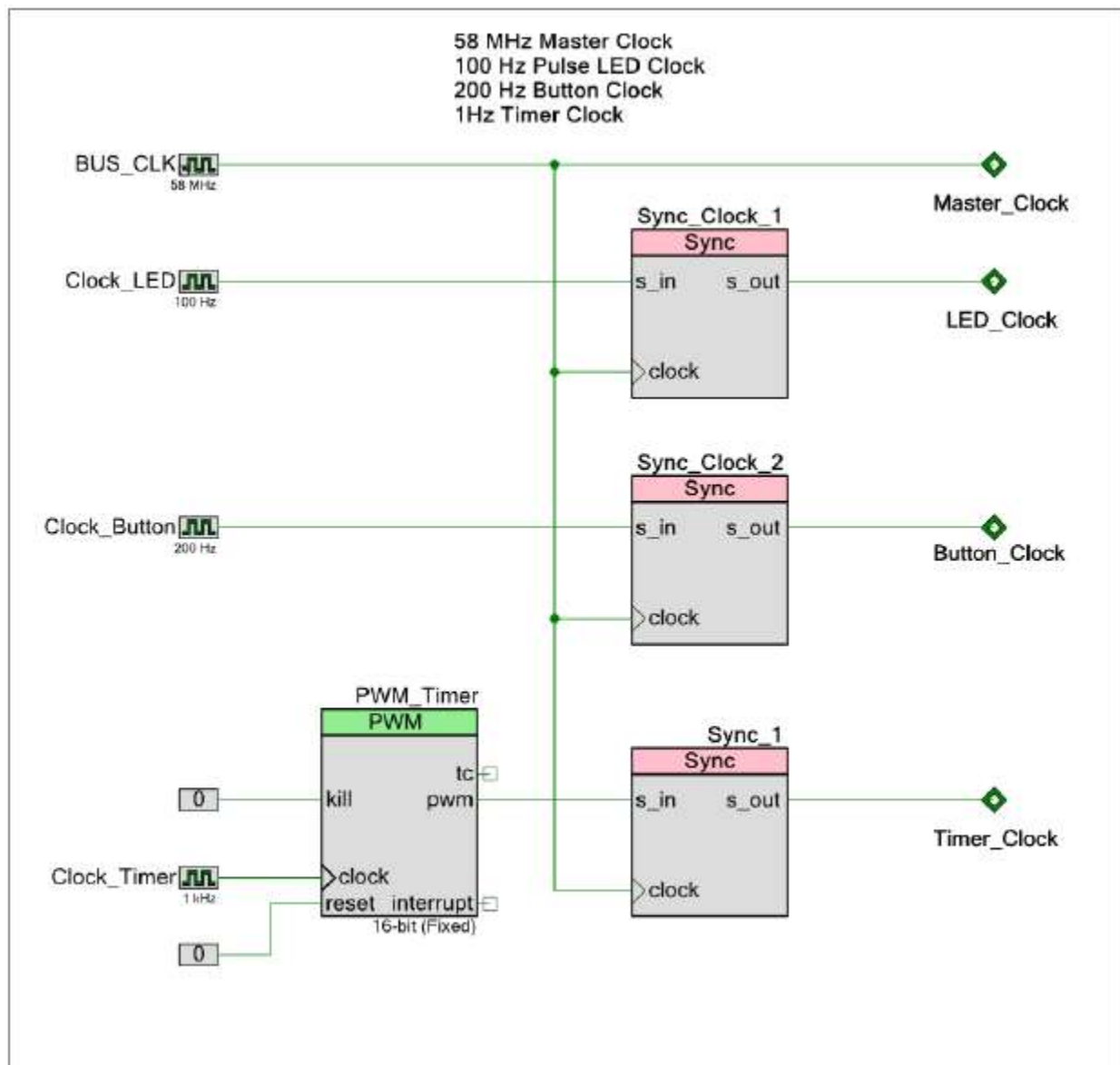
Comparator

The analog input pulses coming from the two sensors (Pin_A and Pin_B) are sent to two comparators which perform the comparison against a **programmable threshold** in order to produce a positive digital pulse when the signal is above threshold. The threshold is generated by two DAC converter that can take the value from the software or by an external trimpot if you want a configurable threshold. In our case we used the "low noise" potentiometer already present on the development board. For our signals the threshold was set to **100mV**. The comparators have been configured as **"fast"** and with **hysteresis** to prevent false pulse. The signal from the comparator output is sent to a D-type Flip Flop, **"edge detector"**, with an external RC network, in order to obtain stable pulses with fixed duration of **40ns**.
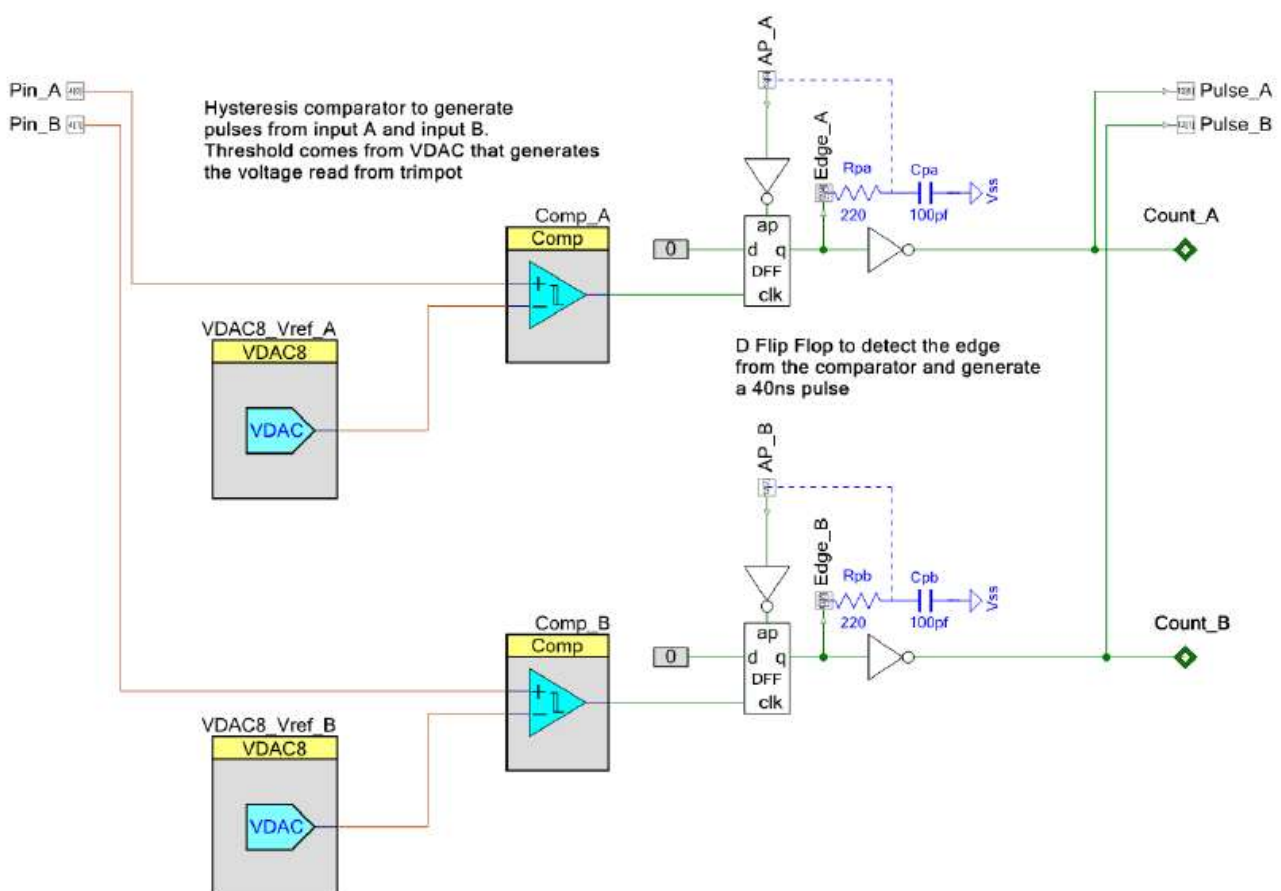
Coincidence Detector

The pulses produced by the comparators are sent to an **AND logic gate** which performs the **"coincidence"** of the signals. Since the coincidence pulse may have a variable duration, downstream it is placed a D-type Flip Flop with external RC network to obtain a clean pulse of 40ns. The latter also produces a further pulse of 0.01s used to turn on a LED in order to give a **visible feedback** of the coincidence event.
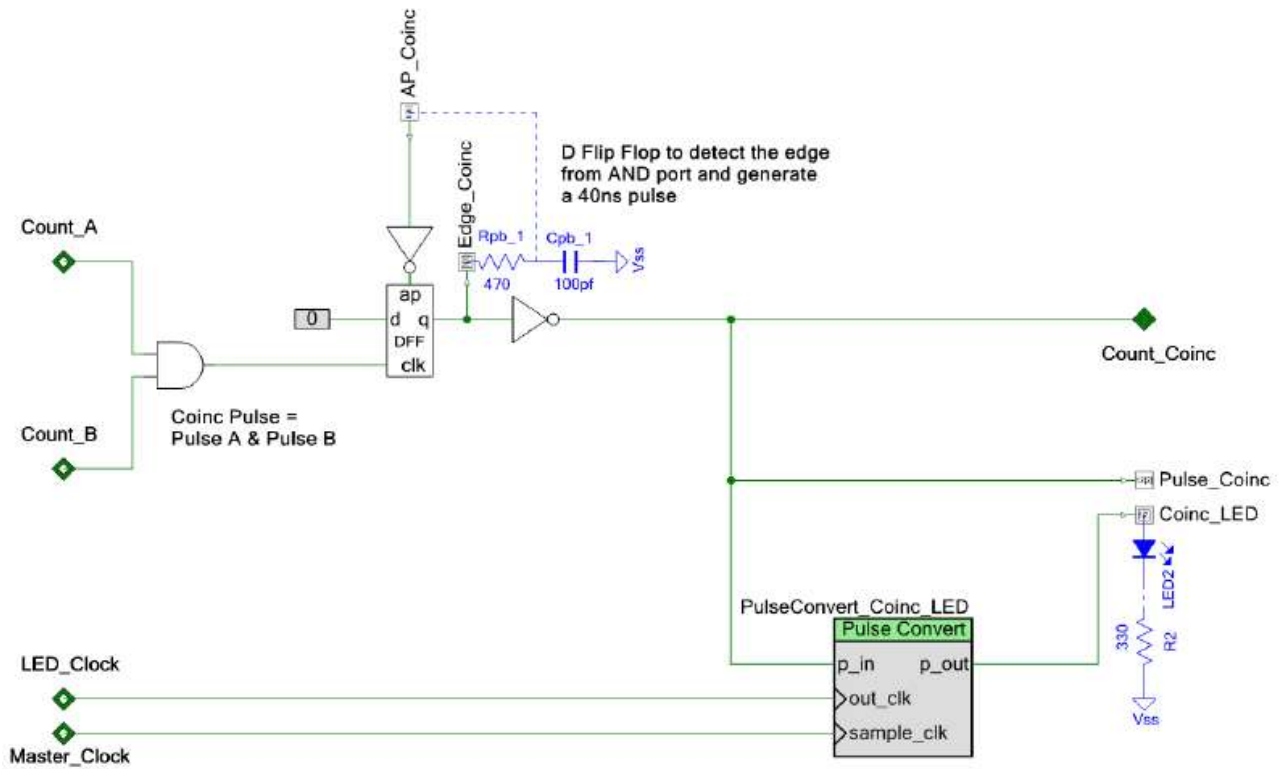
Counters

The pulses of channels A and B and the coincidence pulses are sent to digital counters which perform the pulse counting. There is also a counter that counts the seconds so as to measure the duration of the counting operations.
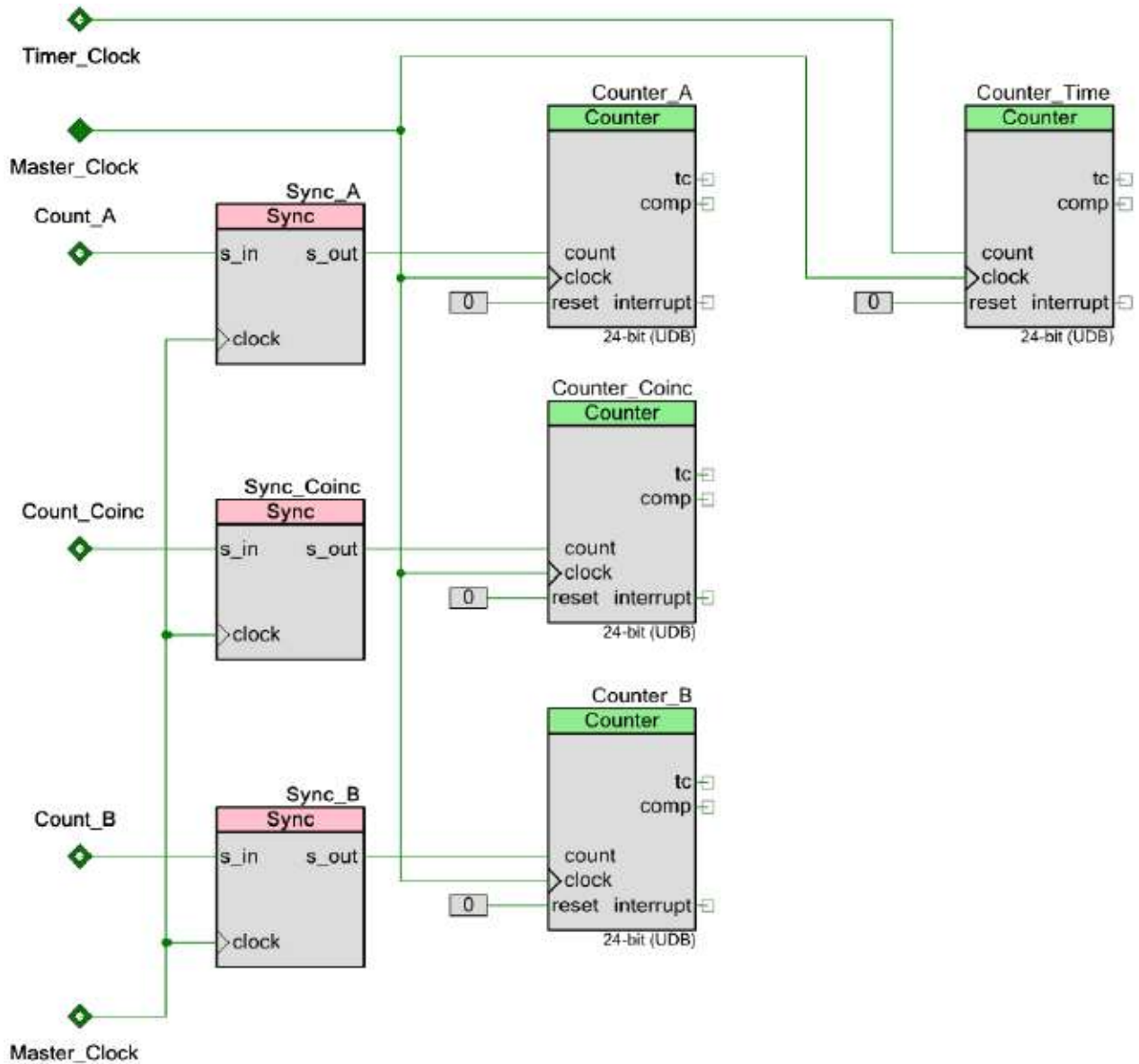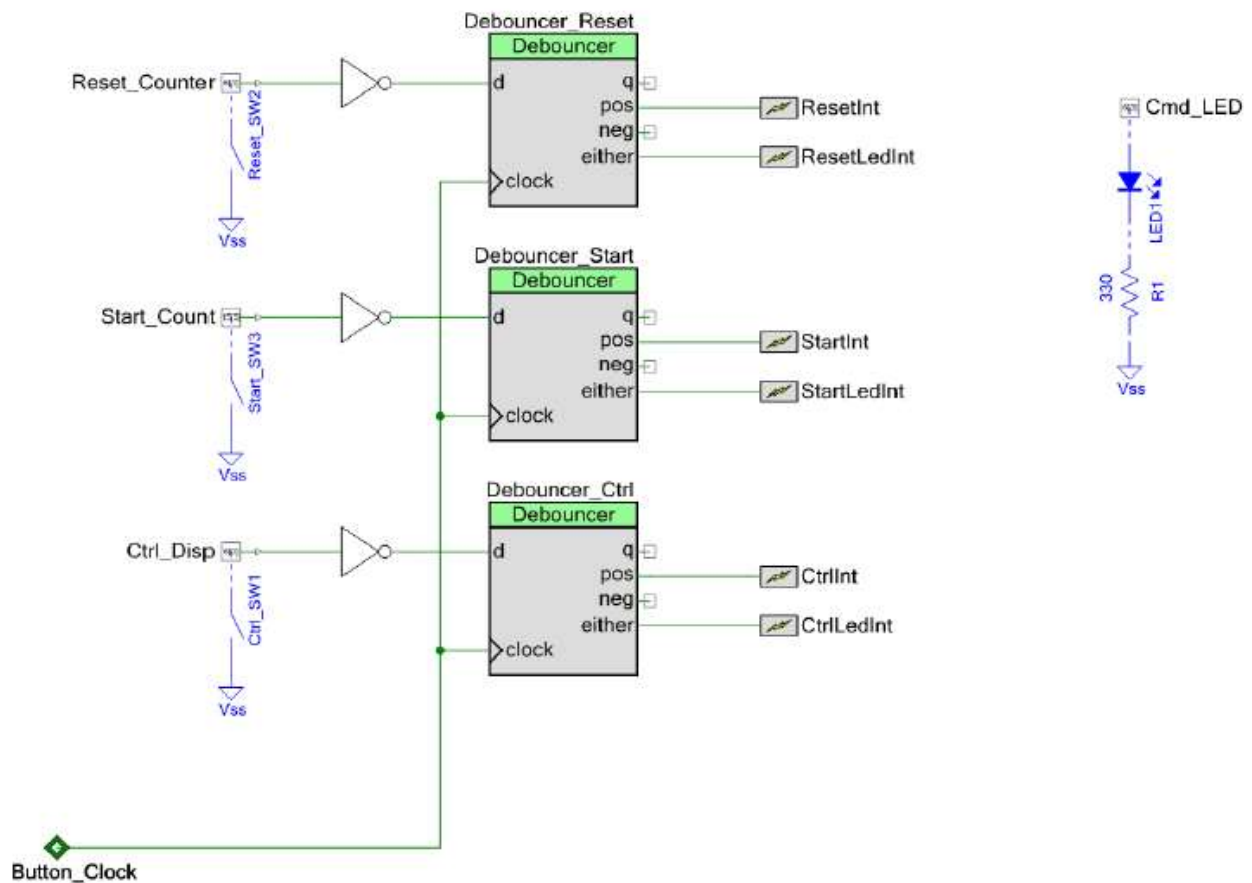
Control Buttons

The system is equipped with three buttons and a LED that lights up when you press any of the three buttons.
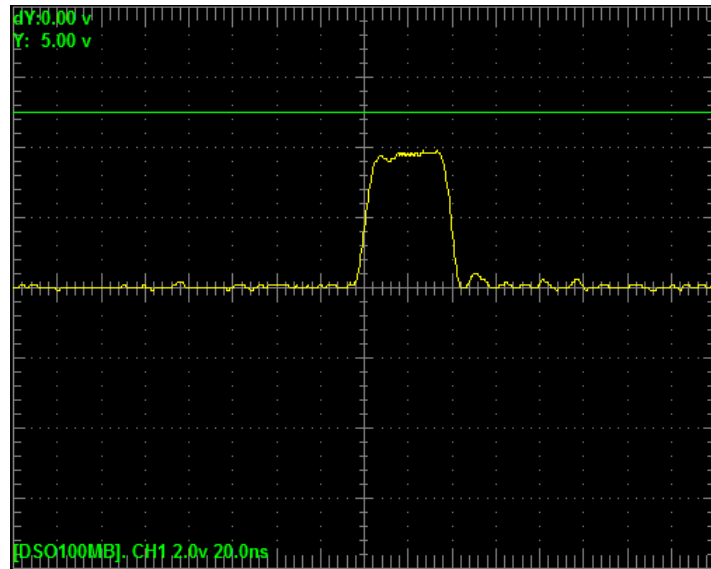
The functions of the three buttons are as follows :

- Counters Reset
- Counters Start / Stop
- Display Switch

Pulse Examples

In the picture below you can see the typical pulse produced by the circuit. The FWHM is of **40ns**, the rising and falling edges of the pulse are approximately 5-10ns, while the amplitude is about 3.5V (the PSoC is operated at 3.3V).

In the image below we compare the signal produced by SiPM with the pulse generated by the circuit. It can be noted that the pulse is delayed with respect to the rising edge of the signal of about **80ns**. This delay is due to the **response time** of the PSoC comparator cannot be reduced.
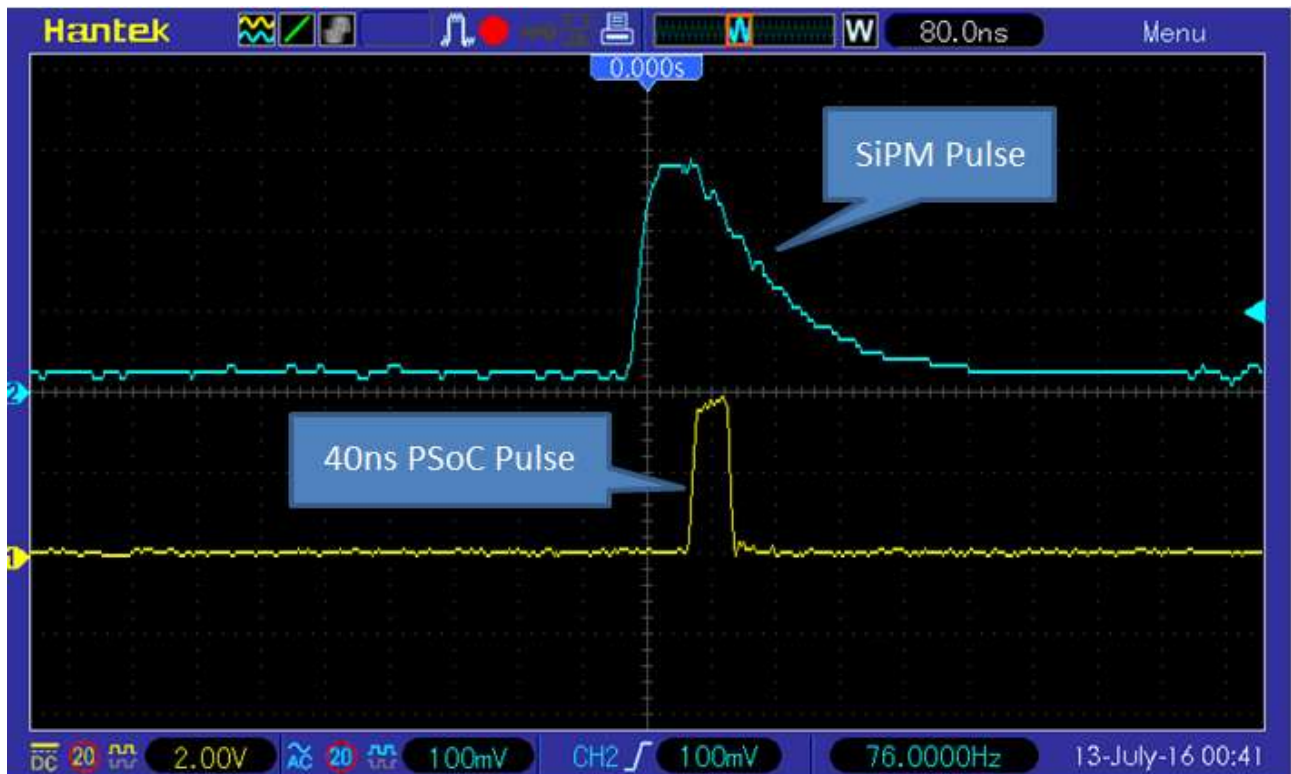
In the image below we perform an estimate of the pulse time **jitter**. Most of the pulses fall in a time range of about 20ns, then by adopting a duration of **40ns** we ensure adequate coverage in the detection of coincidences.
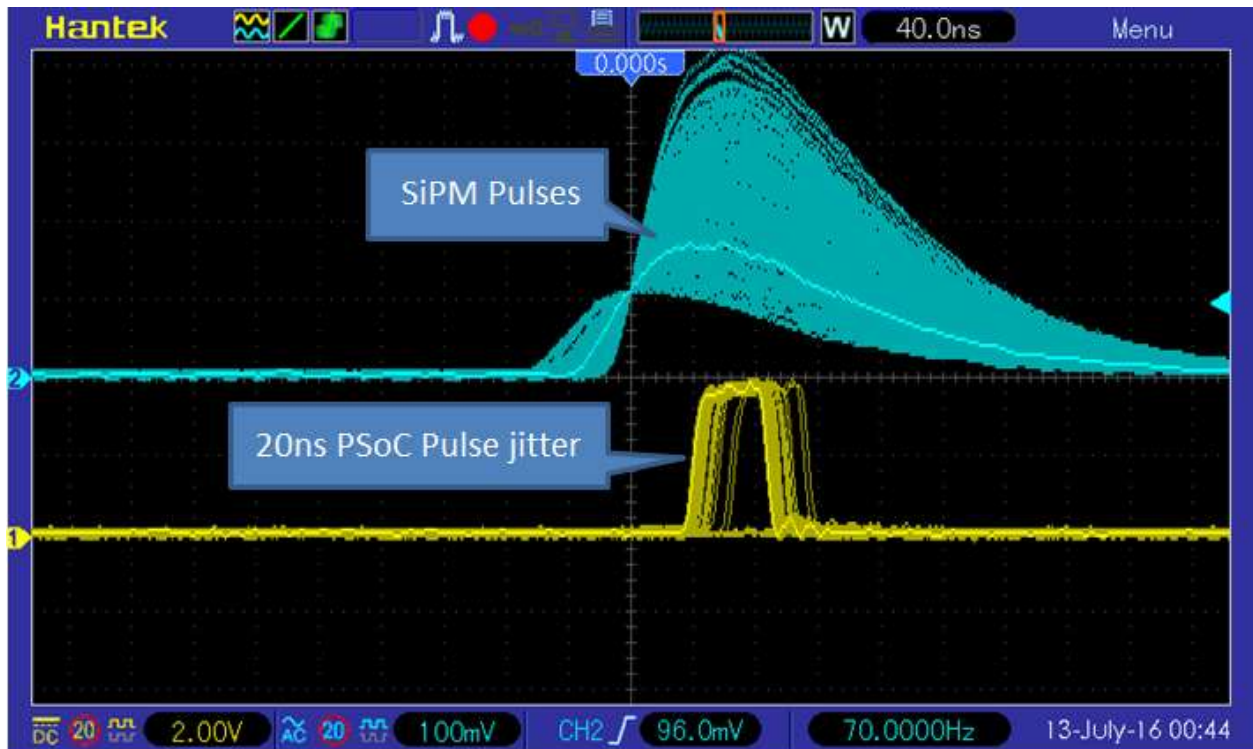
This image shows instead the typical case of two coincident pulses, as we see the temporal overlap is good and this assures us the production of an output coincidence pulse.
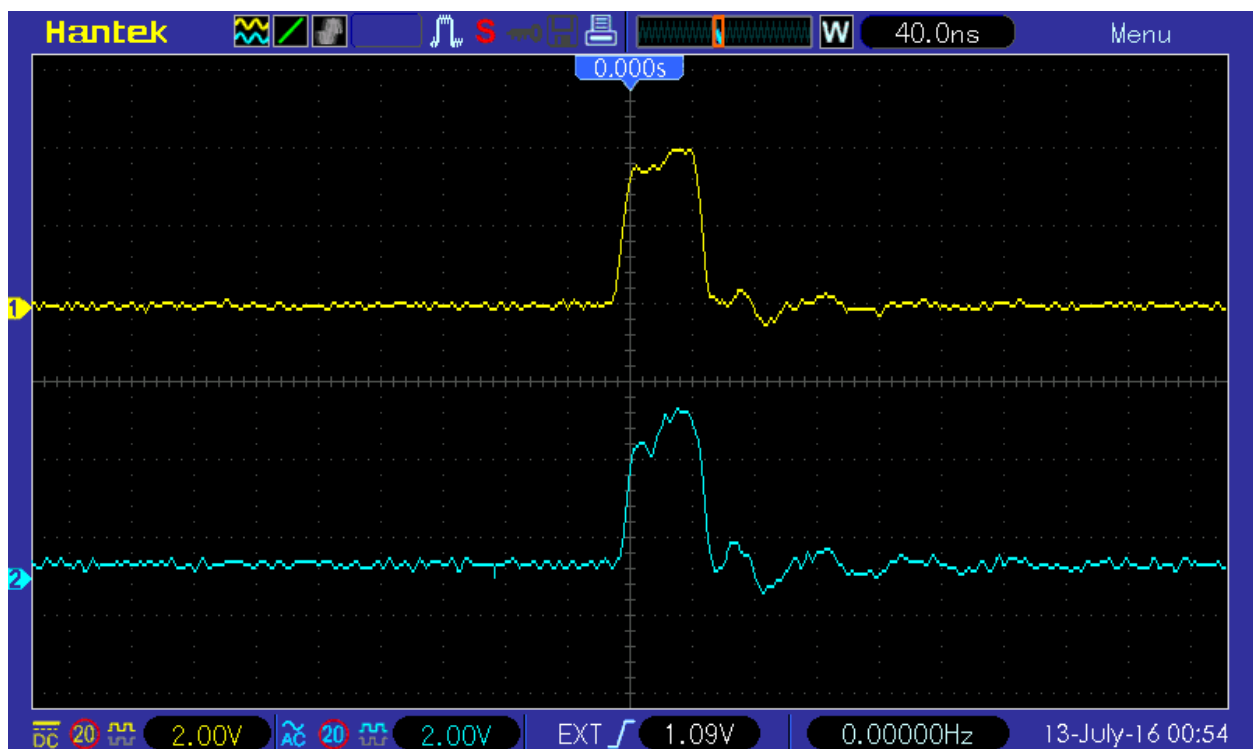
Test with SiPM Sensors and LYSO Scintillators

The coincidence circuit is used primarily with SiPM sensors coupled to a scintillator SiPM. The images show the sensor with its light-tight container.

An evaluation of random coincidences has been made, by arranging the sensors as shown in the picture below, separated by two lead ingots with a thickness of 5cm. This screen is necessary because the intrinsic radioactivity of LYSO, probably because of the X-ray fluorescence, generates a non-negligible rate of coincidences when the two sensors are placed near each other. With the lead screen this contribution is made negligible and remain only random coincidences.
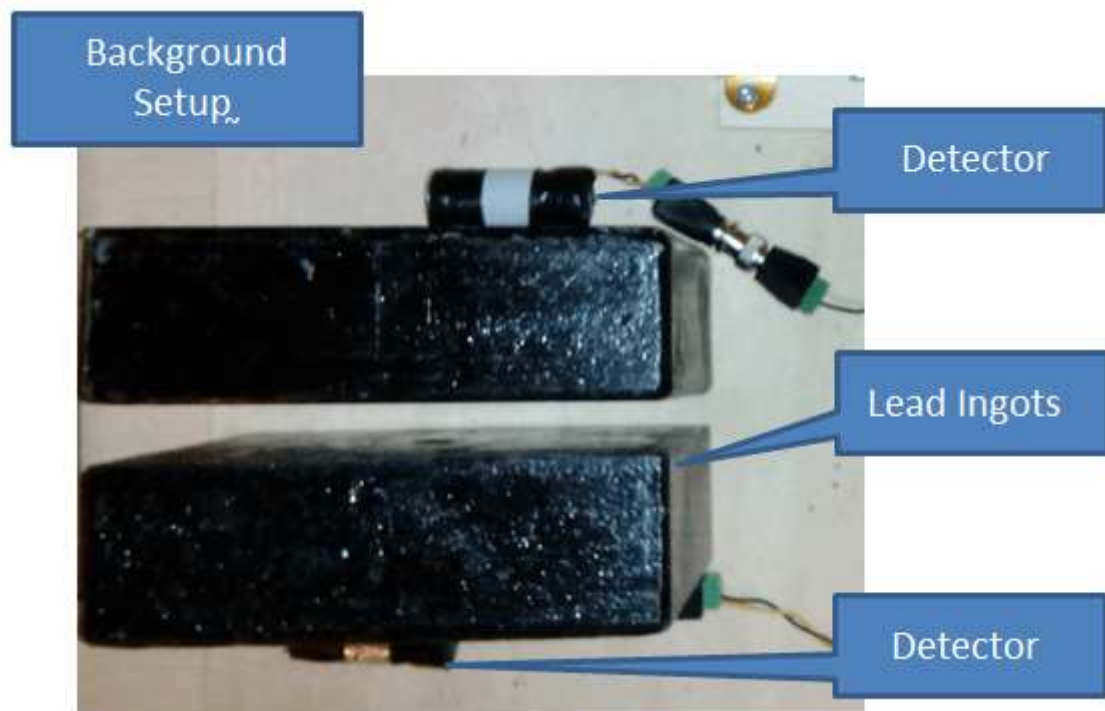
Likelyhood of false coincidence

If we assume that the coincidence circuit has a time resolution equal to τ, then the probability of accidental coincidences is the following :

$P = 2\tau C1C2 = 2 \times 40 \times 10^{-9} \times C1 \times C2$
T = 40 nsec (time resolution of PSoC circuit)
C1 = counting rate detector 1
C2 = counting rate detector 2

By adjusting the discriminator threshold at 100mV (corresponding to about 100 keV) we obtain the following counting rates :

C1 = 87,8 CPS
C2 = 88,0 CPS
$P = 2 \times 40 \times 10^{-9} \times 87,8 \times 88,0 =$ **$0,618 \times 10^{-3}$ s^{-1}** or **0,037 CPM**

The measured coincidences rate has the following values :

Time = 24 h = 86400 s
$\sigma = 0,006$
0,042 ± 0,006 CPM

In good agreement with the theoretical value.

Positron Annihilation

When a positron gets in contact with an electron, an annihilation process is achieved and their mass is converted into energy, in most cases in the form of two photons in the high energy gamma- rays, according to the following process:

$e^+ + e^- \rightarrow 2\ \gamma\ photons\ (511keV)$

A positron may be generated by **β radioactive decay** or by interaction with matter of photons with more than 1,022 MeV energy : this last process is called pair production, as it generates an electron and a positron. In our case we used the Na 22 β isotope that decays by emitting a positron.
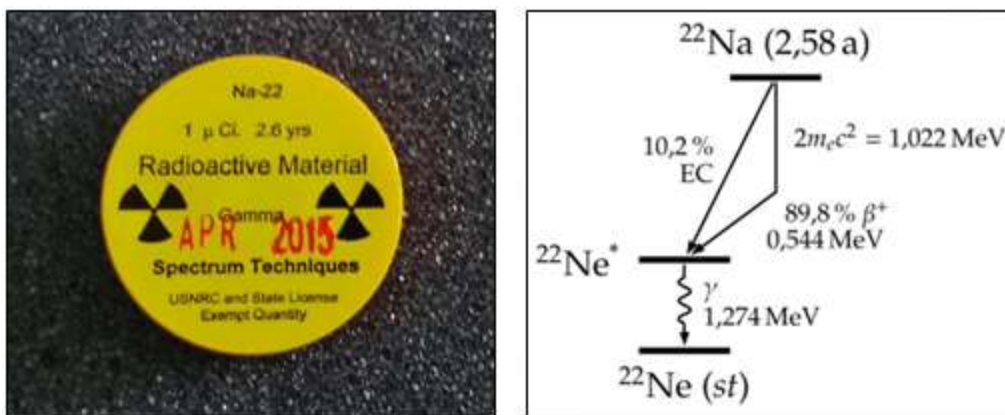
The isotope **[22]Na** decays (in 99.95 % of cases) with half-life of 2.6 years for positron emission or electron capture to the first excited state of the Ne 22 at 1.274 MeV (which subsequently relaxes to gamma photon emission). The positrons emitted by the source annihilate in the material that acts as a support to the source, **producing two gamma photons of 0.511 MeV energy each**.

The two **0.511 MeV** gamma photons are emitted at **180° from each other**. This allows to carry out measurements of angular correlation and coincidence.

The diagram of the experiment is the following :
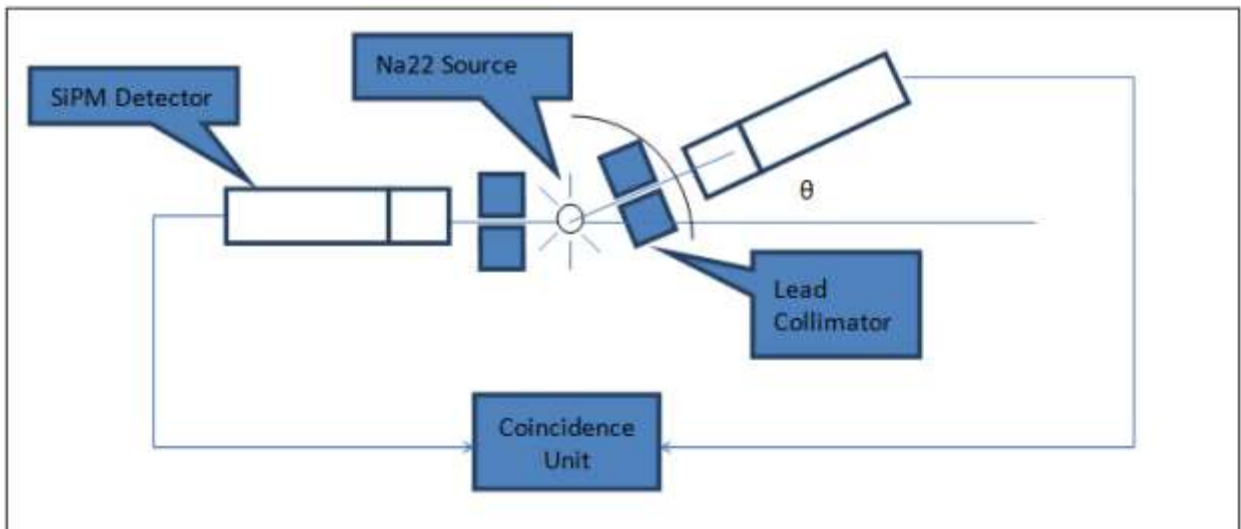
In the image below it is shown the experimental setup:
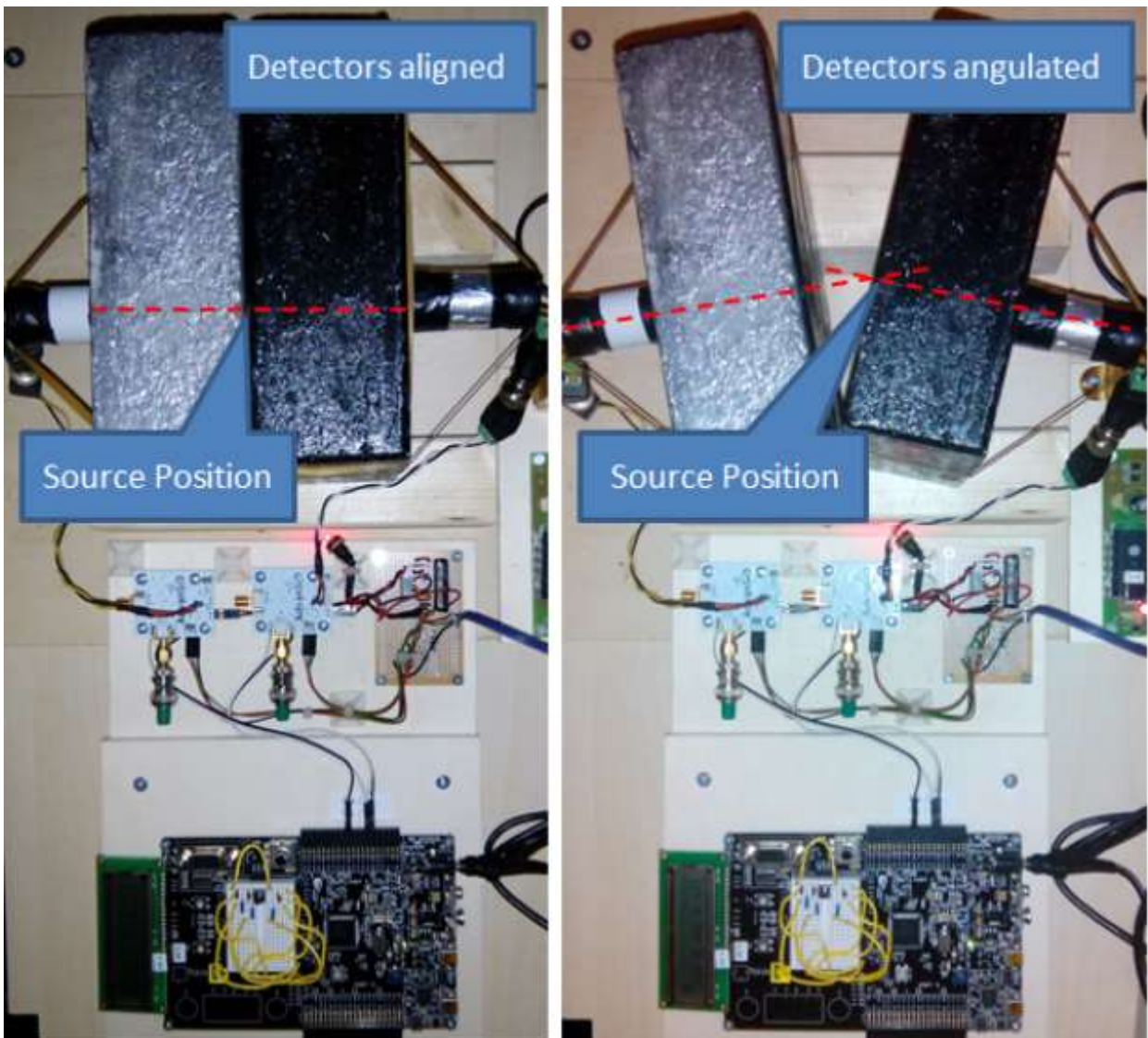
There have been two measurements, the first with the detectors aligned (left image) and the second with the detectors angled between them but both aligned to the source.

Detectors Aligned

Time = **3100 s**
Coincidence Rate **= 59,2 ± 1 CPM**
Detector 1 Rate = **102,0 CPS**
Detector 2 rate = **109.8 CPS**

Detector Angled

Time = **3700 s**
Coincidence Rate **= 0,257 ± 0,064 CPM**
Detector 1 Rate = **93,6 CPS**
Detector 2 Rate = **109.7 CPS**

In the measurement with the detectors angled, the detector 1 is little further from the source than the detector 2, and in fact the value measured by the detector 1 is slightly lower. It is clear that the rate of coincidences count goes to virtually zero as soon as the two detectors are positioned off axis, this is a proof of the fact that the gamma photons emitted from the positron annihilation, because of conservation of momentum, are spatially phase-shifted exactly by 180°.

Entangled Gamma Photons

The experiment described in this post is the repetition of the famous experiment of **Wu – Shaknov** in which it will demonstrate the angular correlation of gamma photons emitted from the annihilation of the positron and subsequently scattered by a **compton** scatterer.
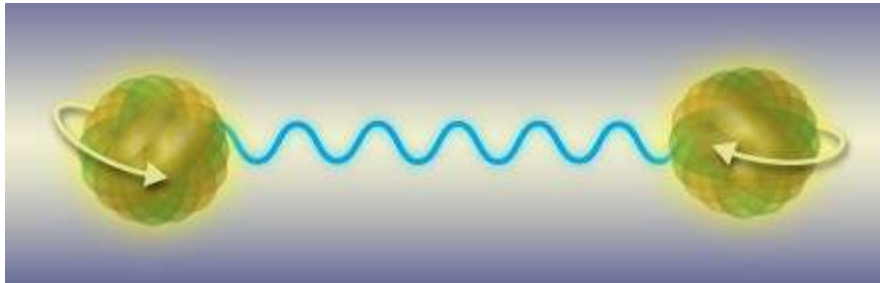

We have already explained that the two gamma photons of 511 keV, for the conservation of momentum, are emitted on the same line but in opposite directions. From theoretical considerations also it is known that they have spin phased out by π/2 . The two photons that result from the annihilation of the positron have all what is need in order to form a single quantum system, from which it follows that the two gamma photons are entangled one to another.

The following diagram represents the experiment setup. The Na22 source of gamma photons is placed in between two lead ingots, with a hole in the center to give rise to two collimated beams of gamma rays. The collimated beams hit two **iron cylinders** that act as **compton scatterer**. The SiPM detectors with LYSO scintillator crystal are placed laterally so as to capture the radiation scattered at around 90° angle. One detector is maintained in a fixed position, while the other is positioned **parallel** to the first and subsequently placed **orthogonal**. The two detectors are operated in **coincidence mode** to detect only the photon pairs generated by the same annihilation.
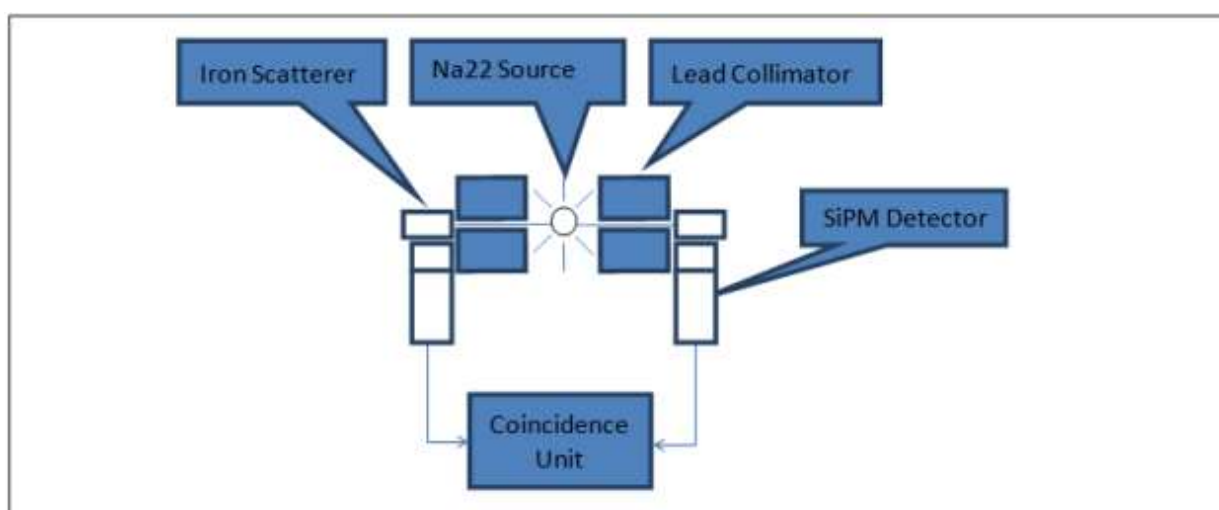
Scheme of gamma photons and scattering :
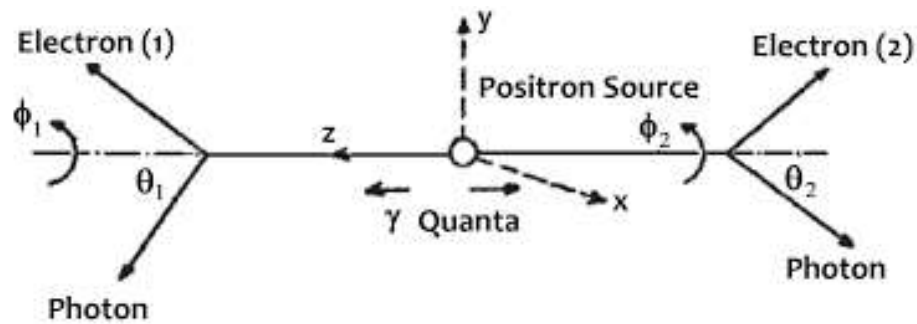
The two gamma photons produced from annihilation have spin phased out by π/2 and their state of entangled photons should ensure that this angular correlation manifests itself with different counting rates in relation to the relative position of the two detectors. **In particular, you should have the greater count rate when the two detectors are positioned orthogonal and minimum when they are parallel, the ratio between the two counting rates should have a value equal to 2.**

The images below shows some details of the experimental setup :
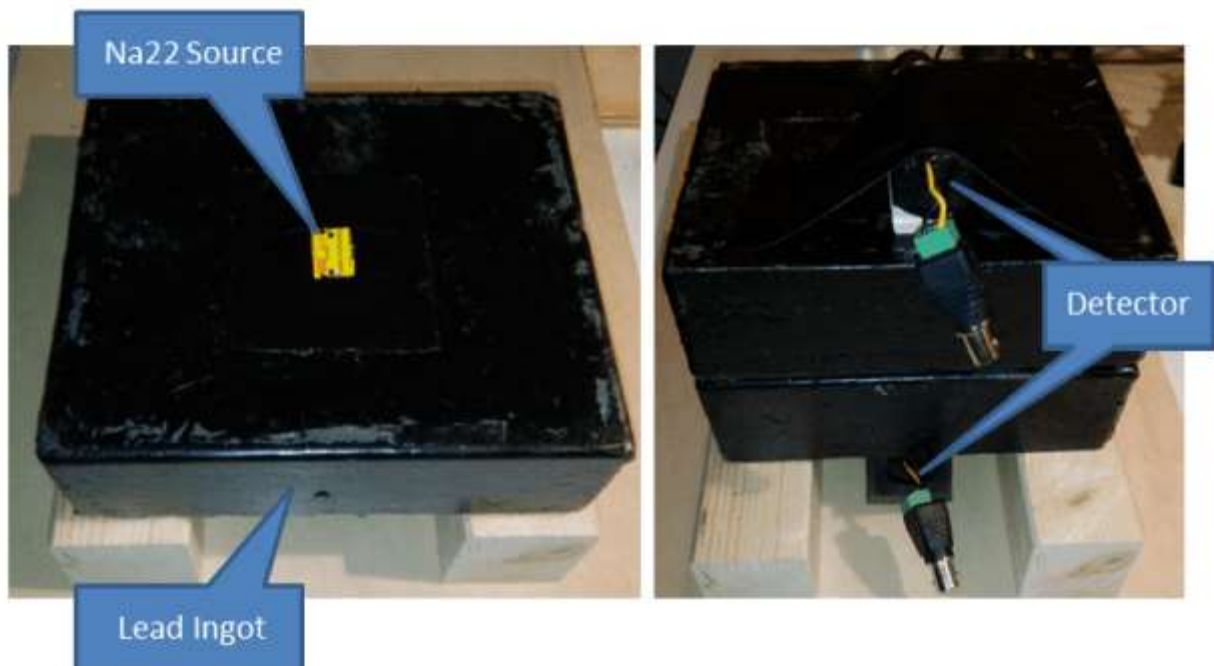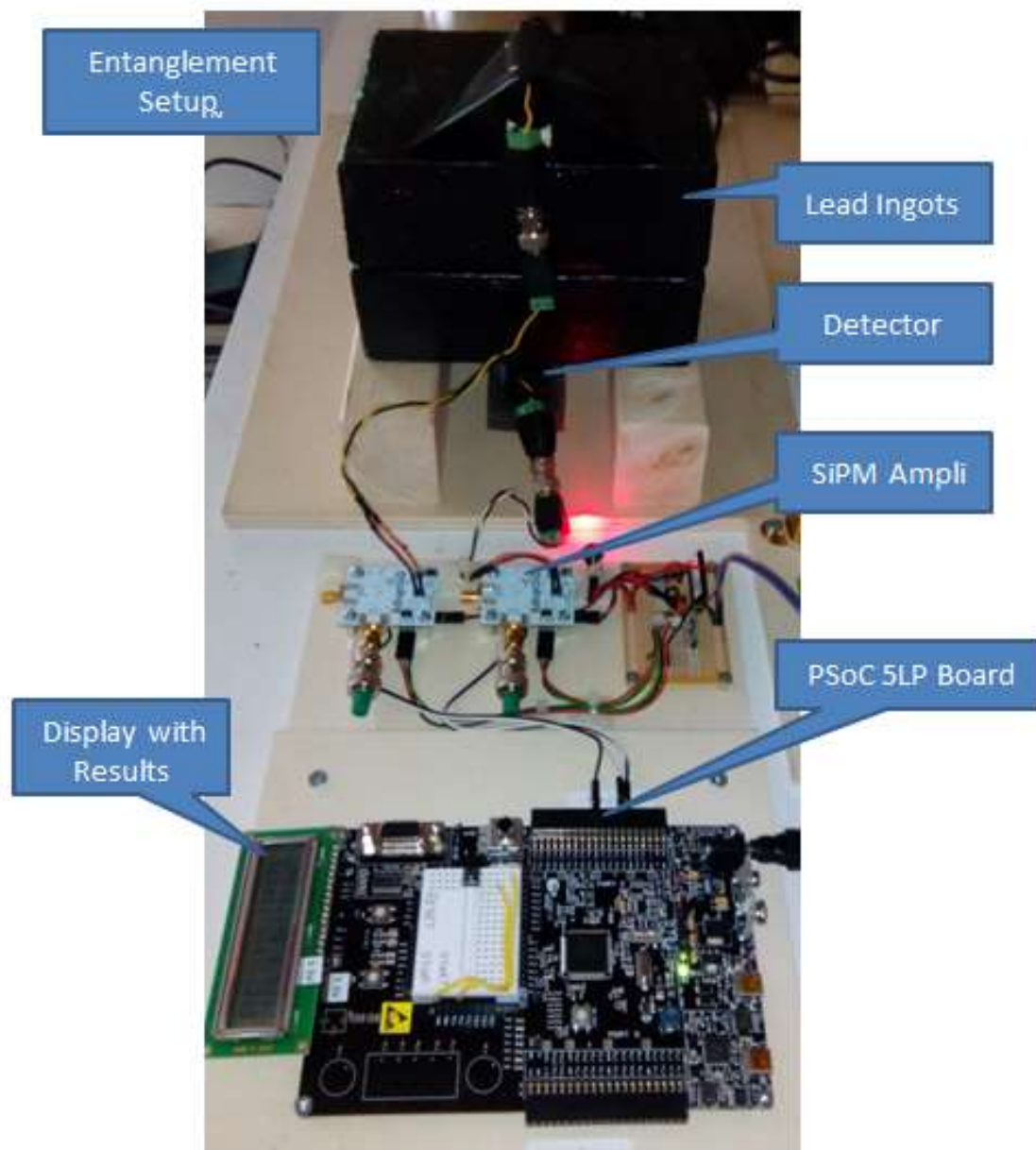
Geometrical Data

Lead ingots : **150x150x50 mm**

Hole : diameter **10 mm**

Scintillator : **LYSO 4x4x20 mm**

Position of the Crystal : **touching compton scatterer**

Distance of the Crystal **: around 10 mm down the scatterer front face**

Distanza of the scatterer face and the source : **50 mm**

Parallel Detectors

Background Measure without Compton scatterer

Time = 104049 s

Coincidence Rate = **0,091 ± 0,007**

N events = 158

Detector 1 Rate = 85,4 CPS

Detector 2 Rate = 90,8 CPS

Measure with Compton scatterer

Time = 87613 s

Coincidence Rate = **0,178 ± 0,011**

N events = 260

Detector 1 Rate = 88,8 CPS

Detector 2 Rate = 91,6 CPS

Coincidence Rate (background subtracted) = 0,087 ± 0,013

Orthogonal Detectors

Background Measure without Compton scatterer

Time = 90874 s

Coincidence Rate = **0,066 ± 0,007**

N events = 100

Detector 1 Rate = 87,3 CPS

Detector 2 Rate = 91,5 CPS

Measure with Compton scatterer

Time = 87126 s

Coincidence Rate = **0,229 ± 0,013**

N events = 333

Detector 1 Rate = 88,6 CPS

Detector 2 Rate = 92,5 CPS

Coincidence Rate (background subtracted) = 0,163 ± 0,015

Parallel and Orthogonal Values Ratio

$Detector_\parallel = 0,087 \pm 0,013 \ CPM$
$Detector_\vdash = 0,163 \pm 0,015 \ CPM$

$Detector_\vdash / Detector_\parallel = 0,163 / 0,087 = \mathbf{1,87}$

These values are compatible with the theoretical predictions (and the experimental verification made, for example, in the experiment of Wu-Shaknov) establishing a greater counting rate in the case where the detectors are orthogonal. This is considered a confirmation that the emitted gamma photons are polarized at planes shifted by 90° phase.

This result is compatible with the hypothesis that the two gamma photons are entangled.

Note on Background Measurement

It is interesting that in the background rate measurement you get a value greater than the theoretical one, calculated on the based of the time resolution of the detector which is **0,037 CPM**. This can be explained by the fact that the detectors were placed on two horizontal planes one above the other : so it is **not negligible the contribution of cosmic rays**. In fact, the measure with detectors parallel (that is vertically aligned) is greater than with detector orthogonal .

Cosmic Rays and Plastic Scintillators

We continue the document about PSoC describing the application of the coincidence detection circuit to the case of cosmic rays. These have been treated in numerous articles and so here we simply expose the results we obtained using the PSoC-based coincidence detector. The system has been connected to two SiPM detectors coupled to plastic scintillators, as described in the figures below :

The plastic scintillators are particularly sensitive to charged particles and therefore they are suitable for the detection of β rays and cosmic radiation, which are composed for the most part by muons. The pulses detected by the individual sensors are for the most part due to the passage of the muon through the plastic scintillator. Positioning the two sensors one above the other, as shown in the figure below, we select the muons which go through both plastic crystals, thus with direction and suitable energy.
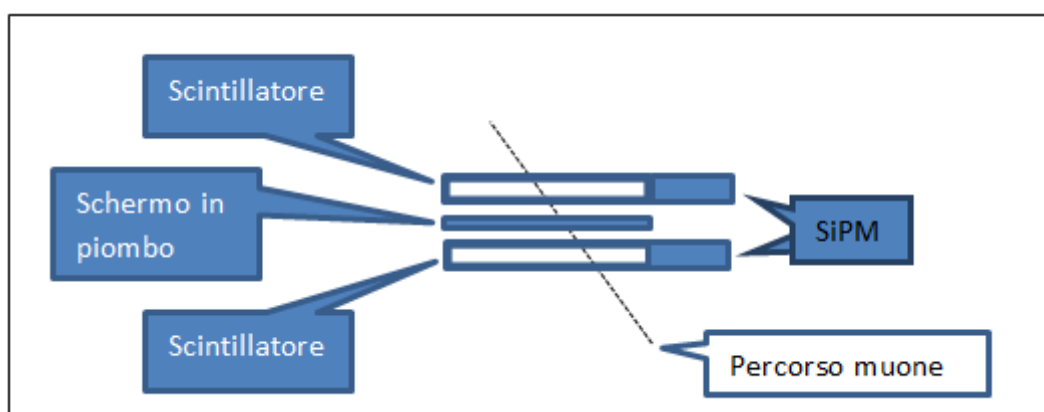
Placing instead the two sensors side by side we obtain the coincidences due to distinct particles that have originated from the same primary cosmic ray, that is, they belong to the same cosmic shower.
The experimental setup is shown in the images following :

Stacked

Side by side

Higher Detector

Lower Detector
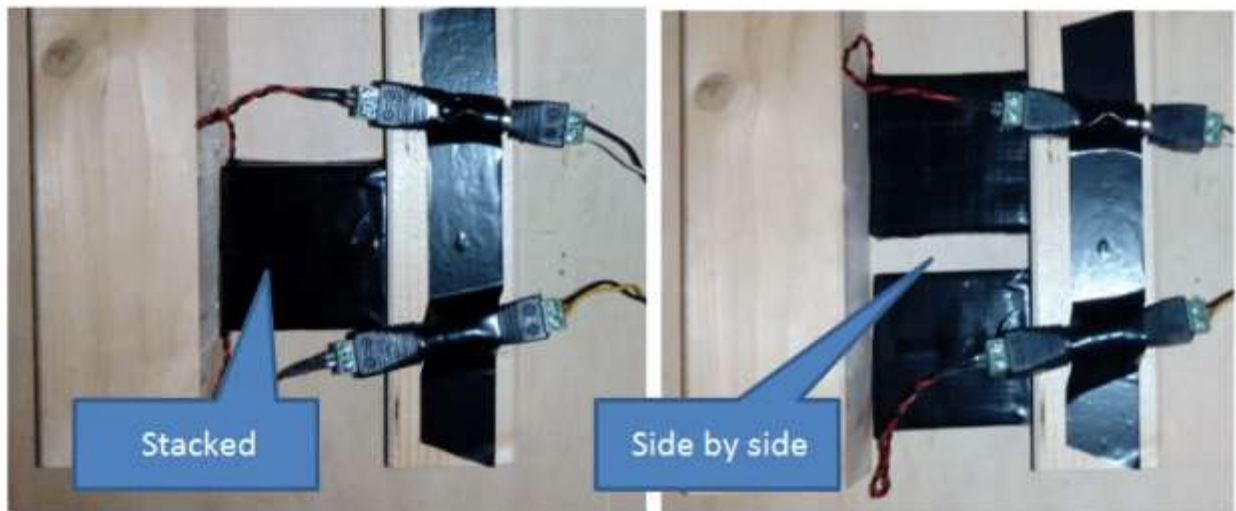
Results

Detectors Side by Side in Contact

Time = **27088 s**
Coincidence Rate **= 0,137 ± 0,01 CPM** – Pulses **62**
Detector 1 Rate = **12,4 ± 0,2 CPM** – Pulses **5609**
Detector 2 Rate = **14,7 ± 0,2 CPM** – Pulses **6631**

Detectors at 50 cm distance

Time = **25622 s**
Coincidence Rate **=** Pulse **1**
Detector 1 Rate = **11,4 ± 0,2 CPM** – Pulses **4849**
Detector 2 Rate = **12,7 ± 0,2 CPM** – Pulses **5431**

Detectors stacked in contact

Time = **17492 s**
Coincidence Rate = **5,68 ± 0,14 CPM** – Pulses **1655**
Detector 1 Rate = **16,5 ± 0,2 CPM** – Pulses **4801**
Detector 2 Rate = **16,2 ± 0,2 CPM** – Pulses **4719**

Detector stacked at 65 cm

Time = **20959 s**
Coincidence Rate = **0,03 ± 0,01 CPM** – Pulses **11**
Detector 1 Rate = **16,4 ± 0,2 CPM** – Pulses **5736**
Detector 2 Rate = **17,6 ± 0,2 CPM** – Pulses **6133**

Muon Flux

Muon Flux slm = **0,6 part/cm2 min sterad**
Detector Surface Area = **32,5 cm2**
Calculated Detector Flux = **19,5 part/min sterad**

The values measured by the individual detectors vary from **12 to 17 CPM**, so rather close to the "theoretical" value of **19 CPM**. It must take into account that the quantum yield of detectors is probably less than one, especially for the muons that pass away from SiPM : for these muons the probability of being detected is lower.

In case of stacked detectors the value of coincidences is a bit lower, being about **CPM 5,68** : in this case it must be taken into account that the useful solid angle is reduced, also due to the lateral position of the SiPM. Increasing the distance between the detectors causes a diminishing count because the solid angle is reduced very much, by placing the detectors at **65 cm** of vertical distance the value is reduced to **0.03 CPM**. With the detectors positioned side by side the coincidence value is **0.14 CPM**, low but not zero, demonstrating the existence of **cosmic showers**. Increasing the distance between the detectors the value is practically reduced to zero, at **50 cm** distance, in different hours of measure, there has been only one pulse in coincidence.