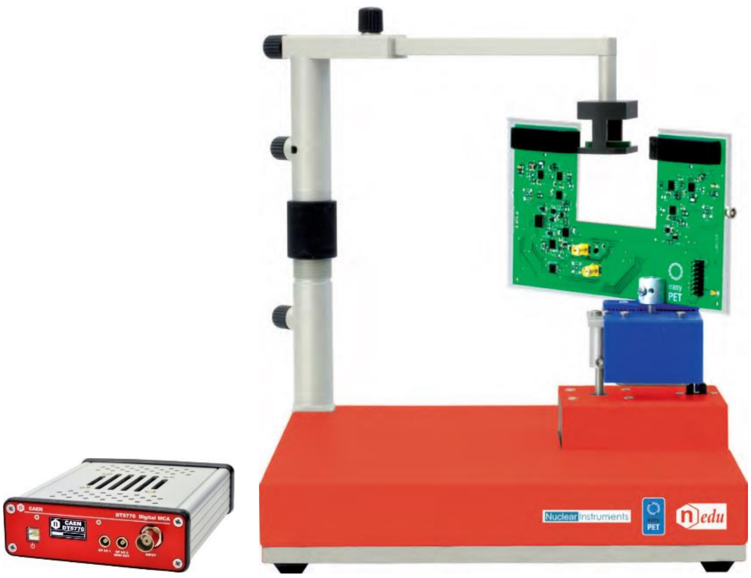
CAEN Educational



Guide GD6258

SP5701

EasyPET Kit

Rev. 1 - 10 October 2017

Purpose of this Guide

This QuickStart Guide contains basic information and examples that will let you use EasyPET in few steps.

Change Document Record

Date	Revision	Changes
July 2017	00	Initial release.
October 2017	01	Modified "Software Interface" paragraph in Chapter 5

Symbols, abbreviated terms and notation

AMC FPGA	Acquisition & Memory Controller FPGA
DPP	Digital Pulse Processing
FPGA	Field Programmable Gate Array
OS	Operating System
U-PCB	U-shaped Printed Circuit Board
ROC FPGA	ReadOut Controller FGPA
SiPM	Silicon Photo-Multiplier

Reference Documents

[RD1] V. Arosio, "Development of a Silicon Photomultiplier based innovative and low cost Positron Emission Tomography scanner", PhD thesis, 2017

[RD2] J. Bushberg, J. Seibert, E. Leidholdt, J. Boone, The essential physics of medical imaging, 2ª ed. Philadelphia: Lippincott Williams & Wilkins, 2002

[RD3] R. Yao, R. Lecomte, E. S. Crawford, Small-animal PET: what is it and why do we need it, 2012

[RD4] V.Arosio at al., The EasyPET: a novel concept for an educational cost-effective positron emission2D scanner, 2016

[RD5] UM4150 – DT5770 User Manual

[RD6] GD2783 - First Installation Guide to Desktop Digitizers & MCA

[RD7] V. Radeka, Trapezoidal filtering of signals from large germanium detectors at high rates, Nuclear Instruments and Methods, Volume 99, Issue 3, 15 March 1972.

[RD8] NEMA Standards Publications, NEMA NU 4-2008 Performance Measurements of Small Animal Positron Emission Tomographs (PETs), 2008.

Some documents can be downloaded at: http://www.caen.it/csite/LibrarySearch.jsp

CAEN S.p.A.
Via Vetraia, 11 55049 Viareggio (LU) - ITALY
Tel. +39.0584.388.398 Fax +39.0584.388.959
info@caen.it
www.caen.it

MADE IN ITALY: We remark that all our boards have been designed and assembled in Italy. In a challenging environment where a competitive edge is often obtained at the cost of lower wages and declining working conditions, we proudly acknowledge that all those who participated in the production and distribution process of our devices were reasonably paid and worked in a safe environment (this is true for the boards marked "MADE IN ITALY", while we cannot guarantee for third-party manufactures).

Index

List of Figures

List of Tables

1 System Overview

CAEN brings the experience acquired in more than 35 years of collaboration with the High Energy & Nuclear Physics community into the University educational laboratories. Thanks to the most advanced instrumentation developed by CAEN for the major experiments Worldwide, together with the University teaching experience at the University of Insubria, a series of experiments covering several applications has been carried out.

CAEN realized different modular Educational Kits. The set-ups are all based on Silicon Photomultipliers (SiPM) state of-the-art sensor of light with single photon sensitivity and unprecedented photon number capability.

Positron Emission Tomography (PET) scanner is the state-of-the-art medical imaging system, capable of providing detailed functional information of physiological processes inside the human body. PET represents a beautiful example of integration of skills and competences from medicine, nuclear chemistry, physics and information technology. SiPM are usually successfully employed for the PET scanners because they allow the measurement of the Time Of Flight of the two coincidence photons to improve the signal to noise ratio of the reconstructed images. They also permit to perfectly combine the functional information with the anatomical one by inserting the PET scanner inside the Magnetic Resonance Imaging device.

The **EasyPET Kit, SP5701**, is a user friendly and portable PET system, designed to explore the physical and technological principles of the conventional human PET scanners. The EasyPET concept, protected under a patent filed by Aveiro University, is based on a single pair of detector kept collinear during the whole data acquisition and a moving mechanism with two degrees of freedom to reproduce the functionalities of an entire PET ring. The main advantages are in terms of the reduction of the complexity and cost of the PET system. It opens the possibility of teaching by doing the basics behind PET imaging, which is certainly an asset to high level educational laboratories.

The EasyPET allows to perform several experiments, covering Nuclear Physic field. What is being proposed has to do with γ rays and with the nuclear imaging, visualizing the reconstructed 2D image in real time during acquisition and performing several didactic experiments related to PET imaging, as well as offline image analysis. The experiments address the essence of the phenomenon as well as exemplary illustrations of their use in medical imaging and industry, complemented by basic and advanced statistical exercises. The goal to inspire students and guide them towards the analysis and comprehension of different physics phenomena.

The SP5701 EasyPET Kit comprises:

- Nr.1 The DT5770, a compact portable 16k Digital MCA for Gamma Spectroscopy, integrating analog front-end with programmable gain and possible AC coupling.
- Nr.1 U-shaped Printed Circuit Board (U-PCB) with two detector cells, each composed of a LYSO scintillator crystal optically coupled to a SiPM and enclosed in a black light-tight. The board is equipped with electronics used for SiPMs supply voltage, signal readout and coincidence detection.
- Nr.1 Solid square base that supports the whole system. Inside this mechanical support there is one stepper motor (bottom), responsible for rotation, and the control unit board, responsible for controlling EasyPET scanning parameters, driving the stepper motors and communicating with the computer.
- Nr.1 Stepper motor (top) responsible for scanning.
- Nr.1 Mechanical support for the source, composed by two arms, vertical and horizontal ones. The arms allow the source holder movement in three directions: z axis (height) and x-y circular movements.
- Nr.2 Radioactive Source Holders, for vertical and horizontal position.
- External AC/DC stabilized 12V power supplies (Switchbox FRA045-S12-A 45W, 12V DC Output, 3.75A) and Power cord.
- Nr:1 External AC/DC 5V power supply and Power cord.
- Nr.2 MCX-LEMO cables.

- Nr.1 MCX-BNC cable.
- Nr. 2 MiniUSB cable.
- Nr.1 Ethernet cables.
- A Graphical Users' Interface.

The purpose of this guide is to provide a hands-on primer on the use of the essential functionalities of the EasyPET Kit. The description of this guide is compliant with the following products.

Item description	Product Code	Image	SP5701 EasyPET Kit	SP5700 EasyPET
SP5700 – EasyPET	WSP5700XAAAA		yes	yes
DT5770 – Digital MCA	WDT5770AXAAA		yes	no

Tab. 1.1: Building blocks of the system

2 Carefulness with Radioactive Sources

The Physics experiments proposed in this manual need γ radioactive source.

There are two radioactive source types for educational purpose: sealed and unsealed sources. In the following experiments, sealed sources have been used. This source type is typically easier to use because the radioactive material is deposited in a plastic disk and sealed inside with a durable epoxy. Problems related to possible spills or decontamination are negligible.

Sealed gamma or beta sources of low activity, such as 0,1 µCi or a little bit more, can be handled directly without significant risk, although it is good practice to utilize tongs. Otherwise, sealed gamma sources with high activity, such as 10 µCi or more, should only be handled with tongs.

Nevertheless, when working with radioactive sources, mitigation of radiation exposures is very important. The basic principles of ALARA can give instructions. ALARA (As Low As Reasonably Achievable) is a radiation safety principle for minimizing radiation doses and releases of radioactive materials by employing all reasonable methods. ALARA is not only a sound safety principle for all radiation safety programs, but is a regulatory requirement.

The three main principles are related to:

- Time**:** minimizing the time of exposure is the simplest way to directly reduce radiation exposure;
- Distance: doubling the distance between the radiation source and human body means to reduce radiation exposure by a factor of 4;
- Shielding: using absorber materials, such as lead for X-rays and gamma rays and Plexiglas for beta particles, to reduce the radiation reaching the body from a radioactive source is an effective way to reduce radiation exposures.

The radioactive sources for educational purpose have a low level of activity and them storing is a relatively simple matter. Solid sealed sources can be safely stored in their own plastic containers of shipment and then they can be put together in a locked cabinet, possibly with an additional shielding of lead sheets or bricks.

Important Note: Gamma Radioactive Source is not included in the SP5700 EasyPET. The recommended source for this application is Na^{22}, a β^+ radioactive source (1/2 inch disc, 10 µCi).

3 Positron Emission Tomography Fundamentals

Nuclear medicine is the radiology branch in which a chemical compound containing a radioactive isotope is administered to a patient. It distributes itself according to the physiologic status of the patient and it is revealed by a radiation detector in order to reconstruct its spatial distribution inside the body. Nuclear medicine produces emission images, as opposed to transmission images of traditional radiology. Nuclear medicine imaging is a form of functional imaging, providing complementary information with respect to the conventional radiology. In fact, rather than yielding anatomic and morphologic images, nuclear medicine allows to obtain information regarding the biologic, chemical, metabolic and molecular processes taking place in a living body [RD1].

Functional imaging constitutes a powerful and non-invasive medical tool for prevention, diagnostic and therapy. It allows the characterization of the biochemical functionalities of organs and tissues, necessary to comprehend the physiologic mechanisms underneath the rising of a disease, avoiding the use of biopsy or surgery. In this way, it permits the early identification of a disease, when there are no structural and morphological modification yet. Functional imaging is also able to establish the stage and the diffusion of a disease, evaluate the most appropriate therapy, according to the specific patient physiology and to the molecular properties of the disease, monitor the treatment efficacy and determine eventual detrimental effect for the patient [RD1].

The traditional nuclear imaging refers to planar images; each point on the image is representative of the radioisotope activity along a line projected through the patient (Fig. 3.1). Tomography technique consists in acquisition of a series of planar images at different projection angles in order to provide an image of an individual slab of tissue, in absence of over- or underlying structures. Positron Emission Tomography (PET) is the most advanced nuclear imaging modality and has a great impact mainly in Oncology. Thanks to its better spatial resolution and sensitivity it has a unique role in diagnostics of subtle pathologies and is a key research tool during studies on experimental animals [RD1].

Particularly when combined with the morphological imaging provided by Computed Tomography (CT) or Magnetic Resonance Imaging (MRI), PET reaches a diagnostic superiority over conventional imaging modalities. On the other hand, the access to a PET scanner at affordable cost is difficult due to the complexity of its technology and construction.

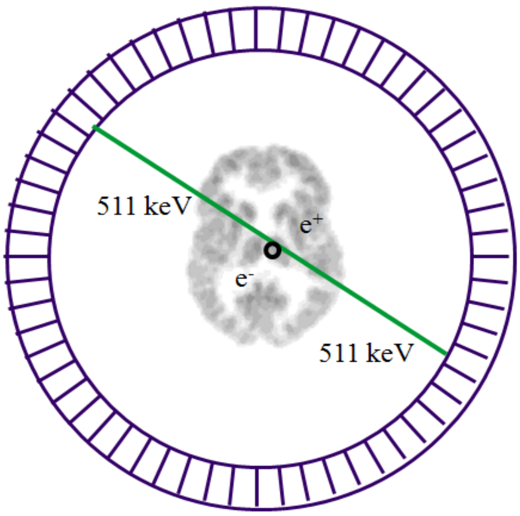


Fig. 3.1: Positron Emission Tomography (PET) general scheme

The underlying principle to PET systems is the detection of high energy radiation emitted from a chemical marker (molecule labelled with a radioisotope) administered to a patient and the generation of images depicting its spatial distribution. The marker is properly chosen in order to associate to molecules involved in biochemical or metabolic processes under investigation (see Tab. 3.1). This allows studying the function of the organ or evaluating the presence of disease, revealed by the excessive concentration of the marker in specific locations of the body.

Nuclide	Half-life (min)	Application	Activity (MBq)
^{18}F	110	Oncology	400
^{11}C	20.4	Neurology	400
^{13}N	9.97	Cardiology	550
^{15}O	2	Cardiology, Neurology	2000
^{82}Rb	1.27	Cardiology	

Tab. 3.1: Main properties of the most used chemical markers in PET

The radioisotope emits positrons which, after annihilating with atomic electrons, result in the isotropic emission of two photons back to back with an energy of 511 keV (Fig. 3.1). The two photons are detected by a ring of detectors, which allows a pair of them to detect two back to back photons in any direction. PET detectors are basically composed of scintillator crystals coupled to photodetectors. The initial systems were composed of BGO (bismuth germanate) crystals coupled to photomultiplier tubes (PMTs), while the most modern PET scanners use brighter and faster LYSO crystals coupled to more sensitive and compact silicon photomultipliers (SiPMs). The detection of the two photons within a coincidence time window allows defining a line that connects two detector units, the coincidence line or line of response (LOR) [RD2].The spatial distribution of the marker is then obtained from the intersection of all the lines of response and the final image is typically reconstructed using iterative algorithms and filtering techniques.

The importance of animal model-based research lead to the production of small dimension PET systems to perform preclinical imaging studies on small animals. These devices give a fundamental contribution to biological and medical research and to the pharmaceutical industry. In fact, small animal PET allows the development of new radiopharmaceuticals and provides the opportunity to investigate disease progression, therapeutic response and eventually consequences of the therapy [RD3]. Since the physical dimensions of the organs of small animals are of the order of mm, small dimension PET systems require a much better spatial resolution (ideally under 1 mm FWHM) than human PET systems (of the order of 4-6 mm FWHM). This is possible since the smaller diameter of the ring allows employing smaller cross section crystals without compromising complexity/cost of the system. In addition, smaller diameter also means a higher detection efficiency.

One of the limitations of small dimension PET systems is the parallax error that results from the oblique penetration of gamma photons in the crystals of the ring, causing an uncertainty in the interaction position determination (Fig. 3.2). This uncertainty increases from the center of the field-of-view (where there is no parallax error since all the photons generated in the center interact perpendicularly with the ring crystals) to the periphery, and therefore results in a non-uniform position resolution. To overcome this problem, several methods to determine the depth of interaction (DOI) in the crystals have been proposed (Fig. 3.2).

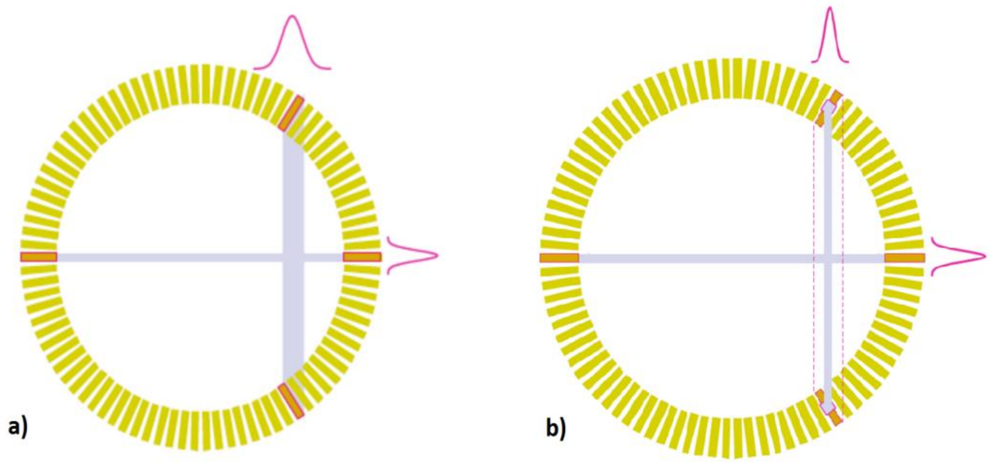


Fig. 3.2: a) The parallax error in the periphery of the field of view. b) The depth of interaction information improves the spatial resolution

4 The EasyPET Concept

The EasyPET described here is an innovative concept protected under a patent filed by Aveiro University (WO201/147130), which can be exploited to achieve a simple and affordable preclinical PET system. EasyPET is a simple, user friendly and portable didactic PET system developed for high-level education, which allows exploring the physical and technological principles of the conventional human PET scanners, using the same basic detectors of state-of-the-art systems. The simplicity of EasyPET derives from the innovative characteristics of the system and its acquisition method.

EasyPET comprehends only two detector modules that move together and execute two types of independent movements, around two rotation axes, so as to cover a field of view similar to that of a complete ring of detectors. The rotation movements are executed by two stepper motors.

The schematic layout of the EasyPET components and acquisition method are shown in Fig. 4.1 and Fig. 4.2, respectively. Following the scheme in Fig. 4.1, the bottom motor (1) has a fixed axis, whose position defines the center of the field of view. The bottom motor supports and performs a complete rotation of a second motor, in predefined steps of amplitude α. The axis of the top motor (2) is thus always positioned within a circumference of radius equal to the distance between the two axes. The top motor, in its turn, supports and moves a U-shaped printed circuit board (U-PCB) (3), where a pair of aligned and collinear detector modules (4) are mounted, performing a symmetric scan of range θ around the center, for each position of the bottom motor. In this way, EasyPET can reconstruct an image of a β^+ radioactive source (5) placed anywhere within a cylindrical field of view between the pair of detectors. The diameter of the field of view is defined by the amplitude of θ, the range of the top motor scan. More details about EasyPET components are reported in Chapter 8.

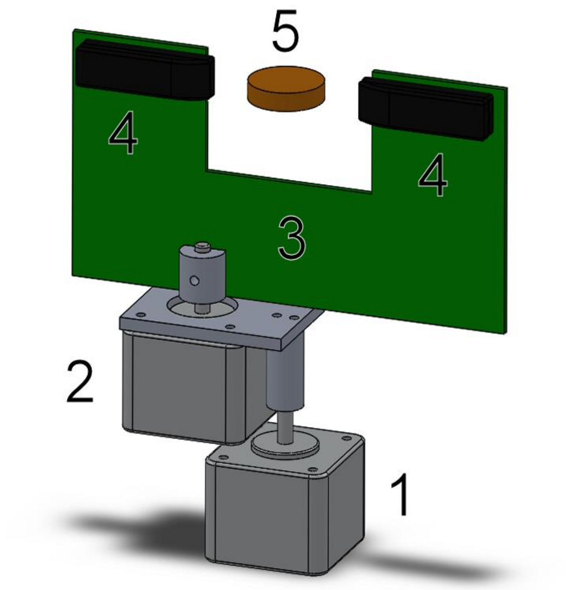


Fig. 4.1: The EasyPET component layout: 1 - bottom motor, 2 - top motor, 3 - U-shaped PCB, 4 - pair of detector modules, 5 - radioactive source

The EasyPET operation principle is simple: the two small detector cells, each composed of a small scintillator crystal coupled to a silicon photomultiplier (SiPM), develop a signal when they detect a photon resulting by the positron annihilation emitted by the source located in the centre of the FOV. The fast electronic readout system allows detecting coincident events resulting from the same decay process: if the signals from each detector are higher than a reference signal and occur within a specific time validation window, they are considered a coincidence event. For each scanning position, the number of coincidences is counted and an image of the accumulated lines of response is reconstructed in real-time.

This novel concept represents a breakthrough in terms of decrease of the system complexity and cost, by reducing the number of detectors required for the acquisition of a PET image. Moreover, the present invention is bound to be robust against image aberration effects due to non-collinear photon emission, scatter radiation and parallax error, since the crystal pair is always kept aligned and collinear during the imaging. The original implementation of the acquisition method based on two degrees of freedom ensures a uniform spatial resolution without the need to measure the DOI. In fact, existing systems with a partial ring of detectors rotating only around their central axis suffer for a degradation of the spatial resolution in peripheral regions of the FOV due to the parallax error [RD1].

The Chapter 7 is dedicated to a series of didactic measurements and experiments, to explore the technological principles behind PET, allowed by using the EasyPET.

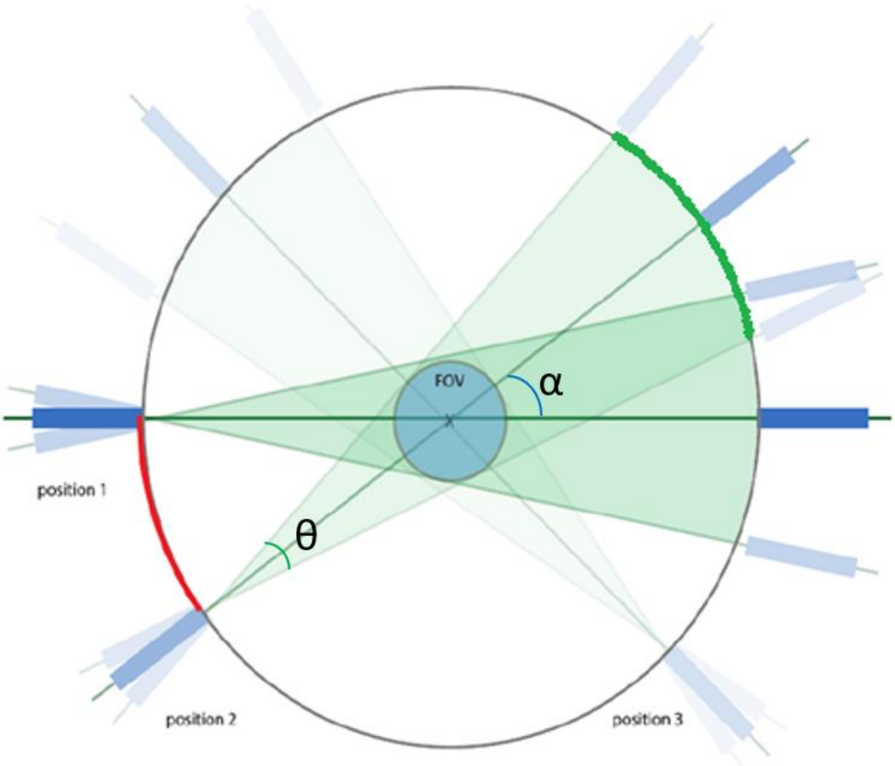


Fig. 4.2: Top-view schematics of the EasyPET image acquisition method with two axes of rotation. α represents the angle step of the bottom motor rotation, while θ represents the scanning angle of the top stepper motor. The two axes are used to move one pair of s scintillation detectors (blue rectangles) so to acquire lines of response covering a cylindrical field of view between the detectors

5 Getting Started

This Chapter will guide the user via a step by step instructions for setting up the system and through the installation of Graphical User Interface (GUI).

Assembling instructions

What's in the red suitcase?

Main components:

- **U-shaped Printed Circuit Board (U-PCB)**.
  Two detector cells, each composed of a LYSO scintillator crystal optically coupled to a SiPM and enclosed in a black light-tight, are mounted on the board. The board is equipped with electronics used for SiPMs supply voltage, signal readout and coincidence detection. There are seven MCX connectors on the board, four on left side and three on the right side, as you can see in the following picture (Fig. 5.1). Starting from the board top, for both sides, the first ones (A) are test inputs, the second ones (B) represent the analog outputs for spectroscopy study and the third ones (C) are the comparators outputs. The last connector (D), on the left side, is the logic coincidence output of the signals coming from comparators.

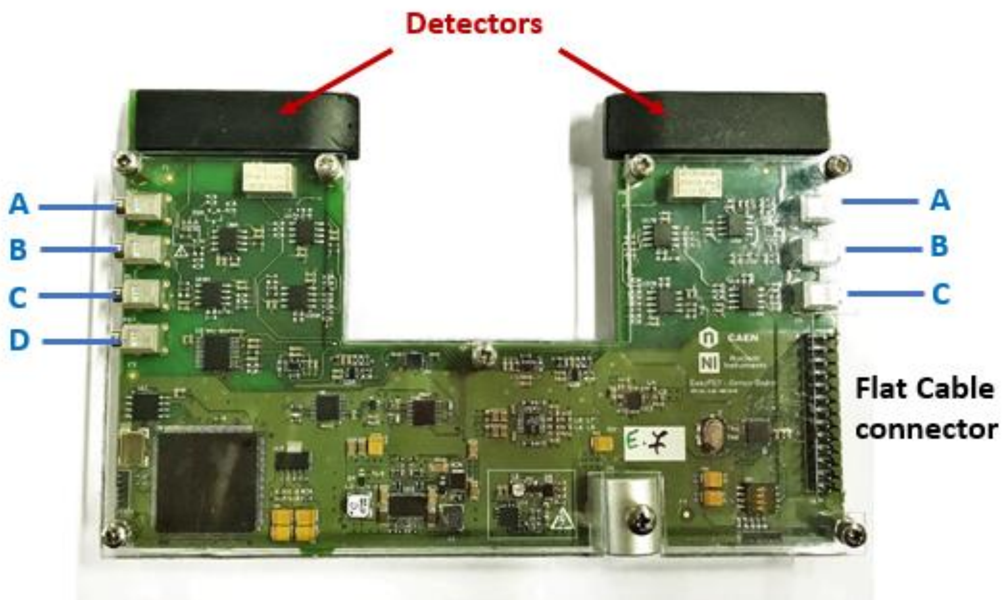


Fig. 5.1: U-PCB with two detector cells (black plastic holders). The board is equipped with electronics used for SiPMs supply voltage, signal readout and coincidence detection

- **Top stepper motor.**
  The mechanical part covering the top motor has been created with a 3D printer, as shown in Fig. 5.2. Its functionality is related to the application of some position sensor for the motors that are required for their relative correct alignment and as a reference in the acquisition starting and ending. The top motor position sensor (1) is a mechanical end-stop placed on one side of the top motor and it is used to align the two motors. The sensor is activated when the board pushes it with its movement. In this way, the orthogonality between the position of the PCB with respect to the bottom motor when it is in the starting/ending position can be determined perfectly. The plastic marker pin (2) allows to activate the optical sensor placed on the mechanical base.

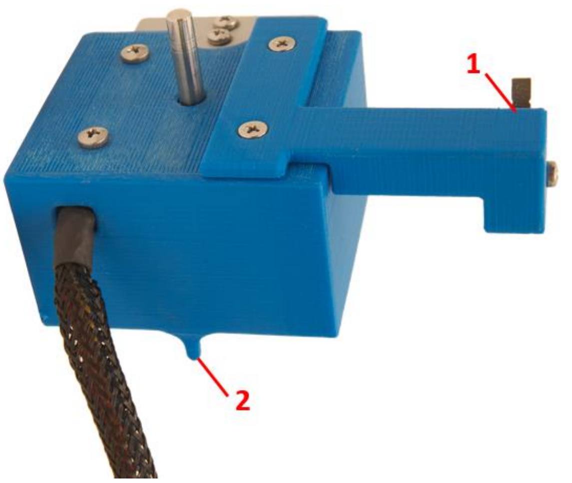


Fig. 5.2: Top Stepper motor is responsible for scanning

- **Mechanical base.**
  Solid square base supports the whole system and is composed by a box to protect the control unit board against accidental cables removal. This board is responsible for controlling EasyPET scanning parameters, driving the stepper motors, and communicating with the computer. Inside the box, there are also the bottom stepper motor and an optical position sensor (1), composed of an infrared light emitter and receptor, being activated when the space between the two is interrupted. In EasyPET, this interruption is done by the pin on the support of the top motor, marking the "zero" position of the bottom motor. This sensor is used to mark the starting and the ending position of the bottom motor. The box is equipped with the power button (2), Mini-USB (4) port and DC input (3) directly connected to the control unit board. It is also provided with two slotted holes to allow to connect the Control Unit to the top motor and to the U-PCB, via flat cable.

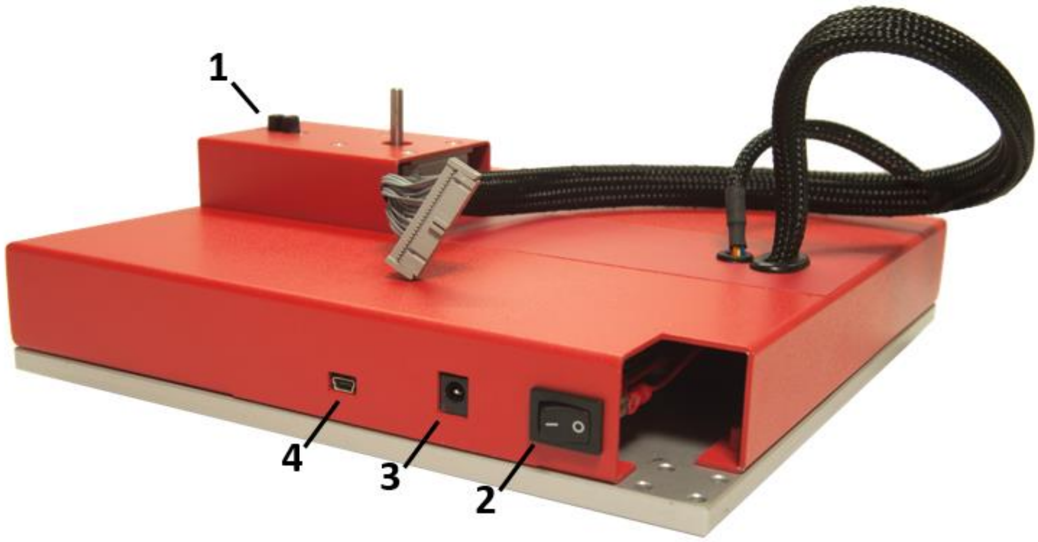


Fig. 5.3: Mechanical base of EasyPET

- **Support of the radioactive source.**
  Two arms, vertical and horizontal, compose the support of the radioactive source whose holder should be placed between the two detectors during the measurements. The two arms permit to decouple the different types of movement in order to be sure to change the position in all the directions independently. As shown in Fig. 5.4, on the vertical arm the threaded ring (5) with micro-metric step (1mm for each complete rotation) is used to set the vertical position of the source and it is hold in the chosen position by using the correspondent knob (1). The other knob (2) on the vertical arm allows to arrange horizontal arm position with respect to the vertical one by describing an arc of circumference.

The horizontal arm is also equipped with two knobs, the micro-metric knob (4) allows to change the radius of the x-y circular movement, while the other one (3) is used to freeze it.

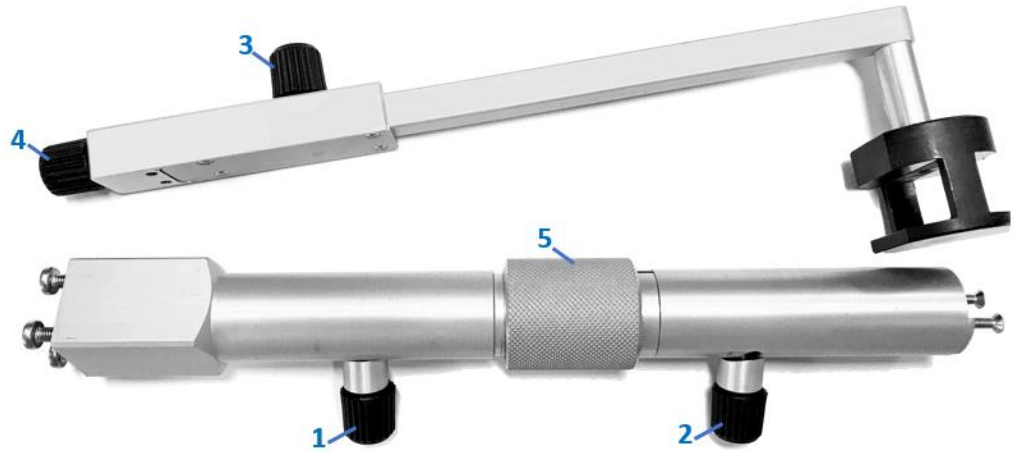


Fig. 5.4: Mechanical support for the source. In the picture, the source holder is already mounted

- **Two radioactive source plastic holders.**
  Depending on the measurement type, two holders are available to place the radioactive source in horizontal position (image reconstruction experiment) or in vertical position (spatial resolution experiment).

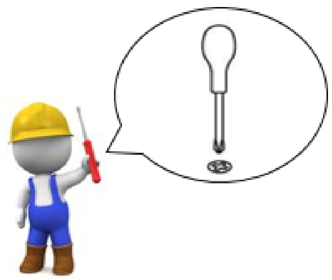
Fig. 5.5: Plastic holders allow horizontal and vertical source position

Important Note: The suitcase contents and depend on what user choose:

- SP5700 – EasyPET: it is composed of the elements described in current Chapter.
- SP5701- EasyPET kit: In addition to the EasyPET components, the user can find in the bag also the DT5770 - Digital Multichannel Analyzer.

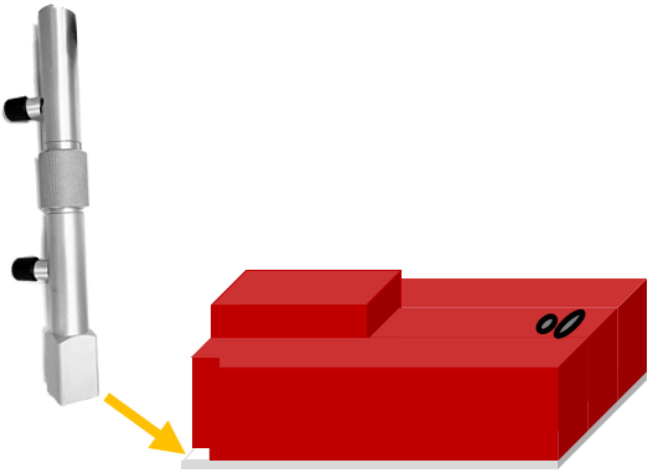
What do you need?

Required tools: Cross screwdriver

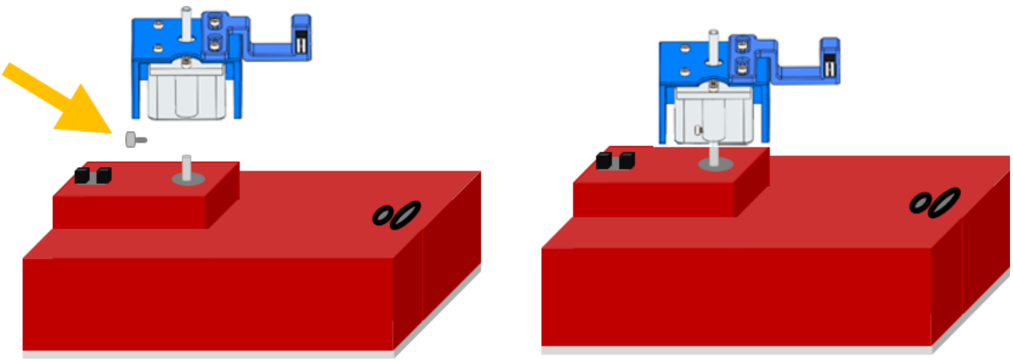


Setting up the EasyPET system

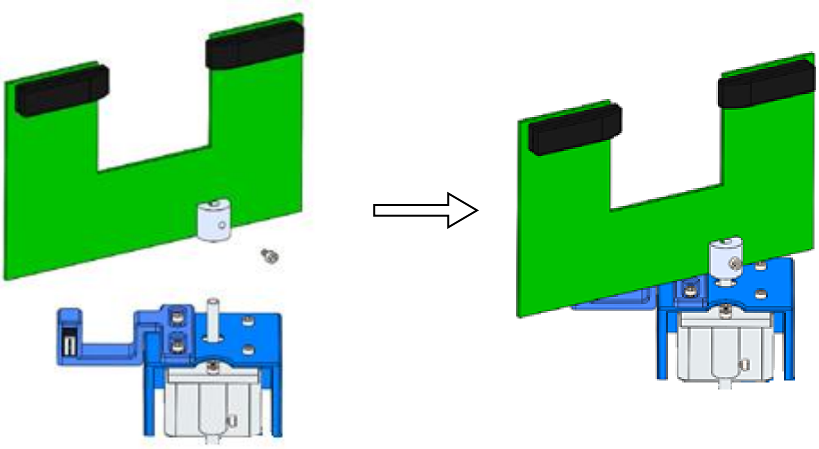
- **Fix the source support to the square base.**
  Using the holes in the corner of the base, attach the vertical arm of the source support to the base with four screws. After that, mount the horizontal arm on the vertical one through two cross screws. Assemble the source holder, or leave what is already mounted, on the other arm end.



- **Fix the top motor to the bottom motor axis placed on the mechanical base.**
  Attach cylindrical support to the axis of bottom motor and carefully tighten the screw (be careful not to tighten too much and damage the screw). Make sure the top motor can rotate freely with the marker passing through the optical position sensor without any obstacles.



- **Fix the U-PCB to the axis of the top motor.**
  Insert the mechanical support of the board on the axis of the top motor and carefully tighten the screw. Take care that the U-PCB can rotate freely without any contact, except the one with the mechanical sensor, as shown in the following picture.



- **Connect the flat (black) cable.**
  Use the flat cable to connect the control unit placed inside the mechanical base to the U-PCB. The cable connector has to be oriented in order to match the red wire together with the white dot printed on the U-board beside the connector.

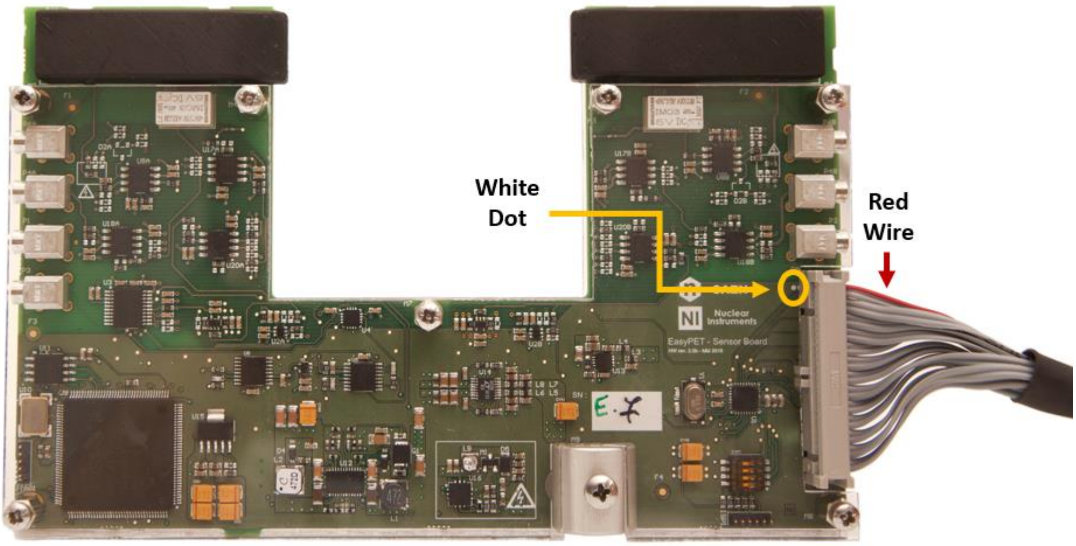


Fig. 5.6: Connection between U-PCB and flat cable

- **Fix the source position**

  Regulate the control and fixing knobs and the threaded ring of the support in order to place the radioactive source between the two detectors housed on U-PCB.

Software Interface

Introduction

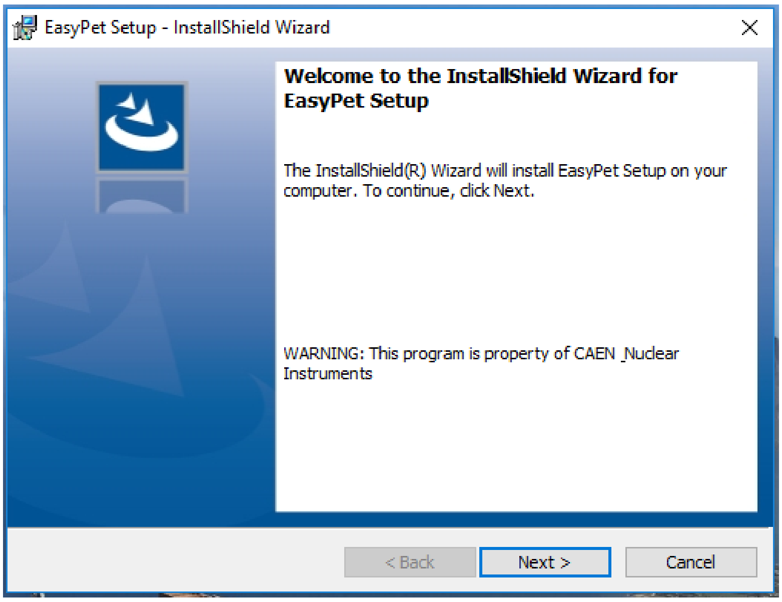
EasyPET is controlled through a Graphic User Interface (GUI), developed in Visual Basic, which allows setting the acquisition parameters, performing the acquisition, visualizing the reconstructed image in real time during acquisition and recording the data for the offline analysis, performing calibration and spatial resolution measurements. The management of the CAEN DT5770 is already implemented in the control software introducing the possibility to visualize and digitize the analog signal of the spectroscopy branch. The software offers the possibility to perform different didactic experiments related to PET imaging, as well as offline image analysis, moreover, allows students to learn the basic features of the SiPM and the techniques to characterize them.

This section is intended to give to the user a complete description of all the functionalities of the software interface.

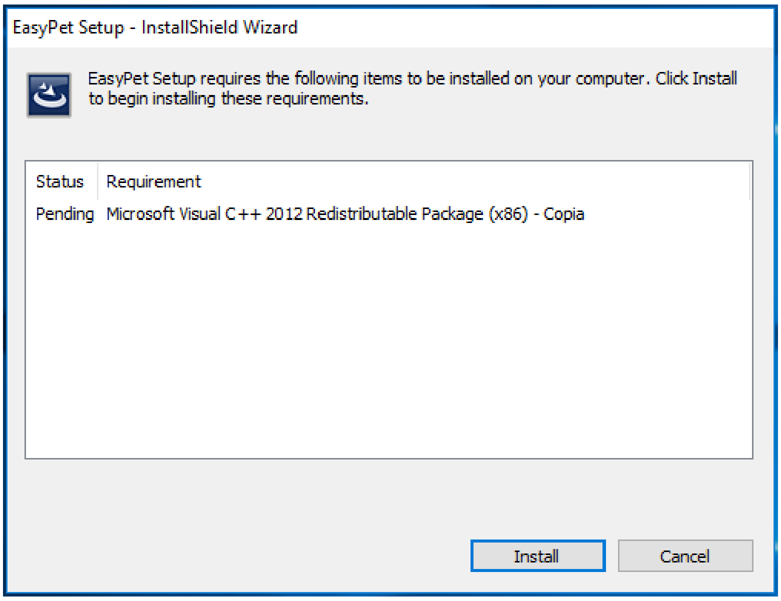
Installation

The CAEN EasyPET Software is compliant with Windows 7, 8 and 10 OS, both 32 and 64 bit.

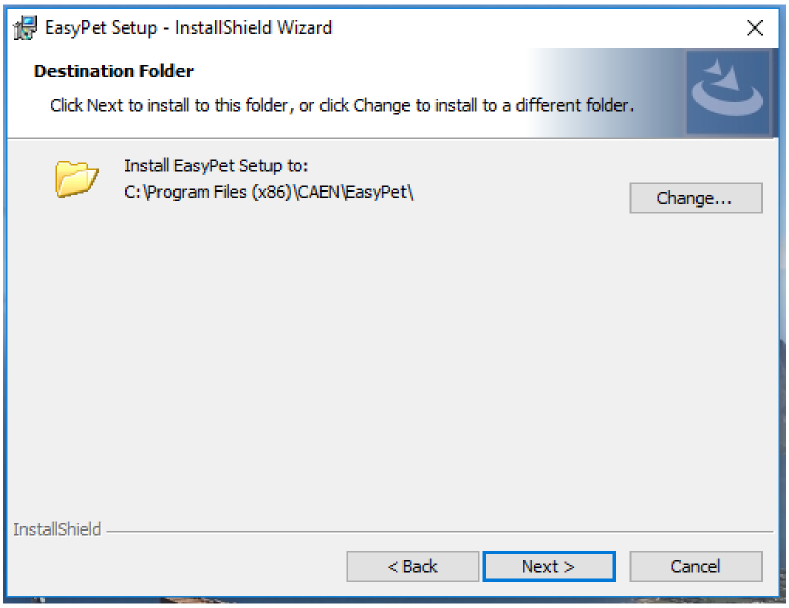
- Download the standalone **CAEN EasyPET Software 1.2.3.6** installation package on CAEN website in the 'Download' area of the EasyPET page (**login is required before the download**).
- **Unpack** the **installation package** and **launch**, as administrator, the **setup file**.



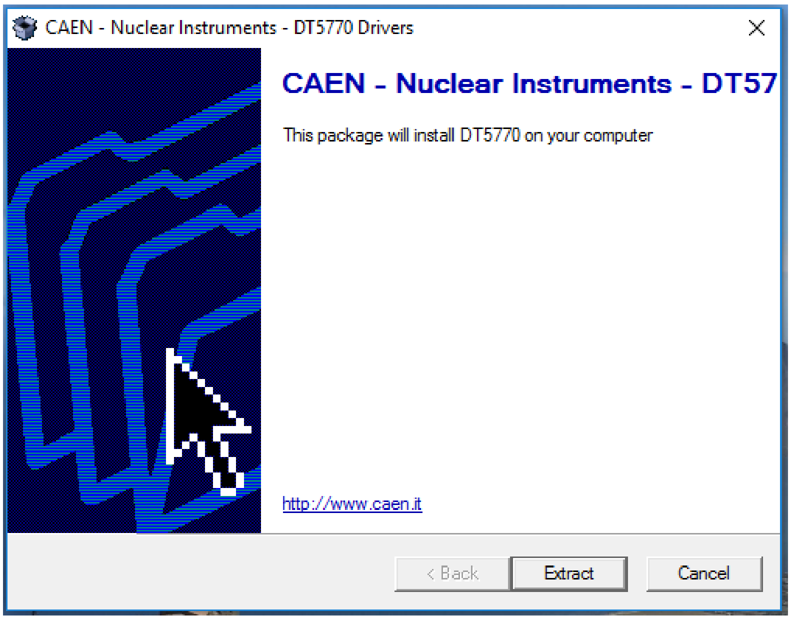
- **If Microsoft .NET is not already installed**, the setup will ask to install it. The operation may take some minutes.
- **If Microsoft Visual C++ 2012 redistributable Package (x86) is not already installed**, the setup will ask to install it as shown in the following picture.



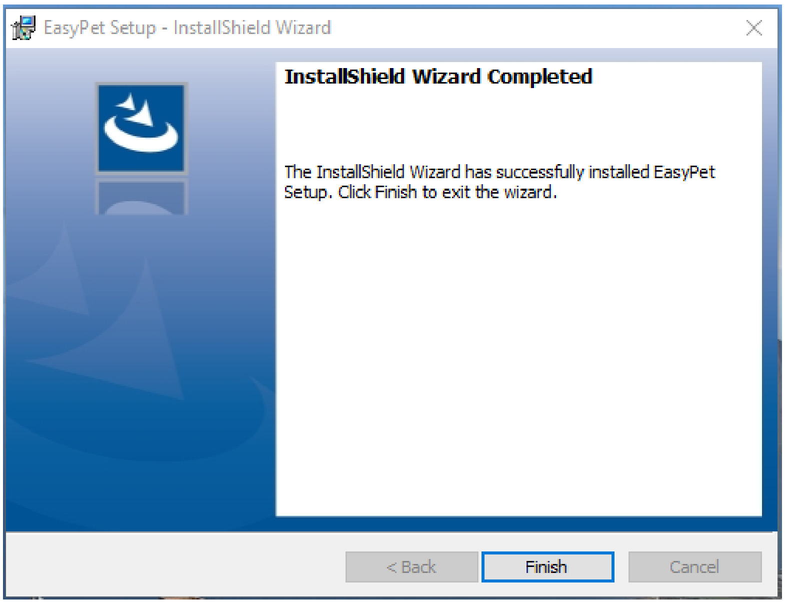
- **Complete** the **Installation wizard** and **Select the destination folder.**



- At the end of the installation wizard, the setup will ask to extract and install the DT5770 driver.



- **Complete** the **driver installation**.
- The setup will create a Desktop icon.
- Launch the program when the setup is completed.



Important Note: The CAEN EasyPET Software is referred both to SP5700 – EasyPET and to SP5701 – EasyPET kit.

Program Execution

The user can run the program in three ways:

- The **Desktop icon** of the program
- The **Quick Launch** icon if the program

- The **.exe file** in the installation path on the user PC.

When the program is opened, a temporary introduction window (Fig. 5.7) shows the collaboration partners, both academic and industrial.

Fig. 5.7: Control software introduction window

Graphical User Interface (GUI)

When the introduction window disappears, the GUI, composed of two tabs (EasyPET Control and Spectroscopy), is opened as shown in Fig. 5.8.

Select the Serial Port in the EasyPET tab and press “Connect” button. If you have also the DT5770, open the spectroscopy tab, select the device from the list and press “Connect” button to start the communication.

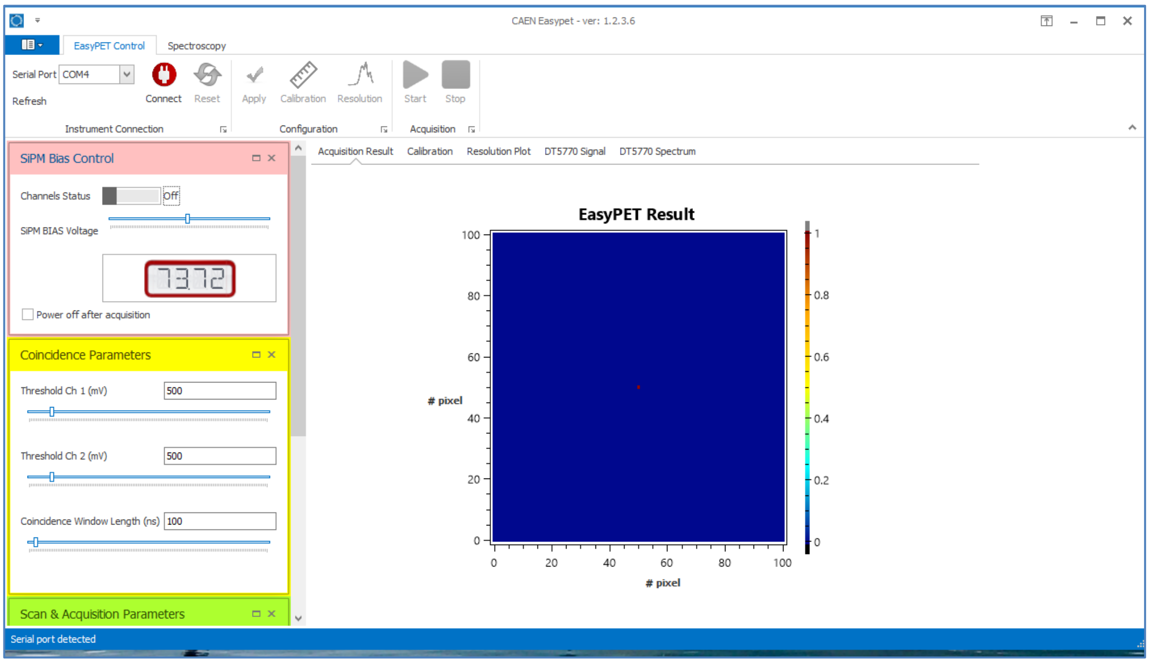


Fig. 5.8: EasyPET Graphical User Interface

The different parts of the user interface and their functions are briefly described in the following subsections related to EasyPET and to the MCA.

The user can assess further functionalities, available for both devices, by pressing the "File Menu" button  on the top left of the GUI.

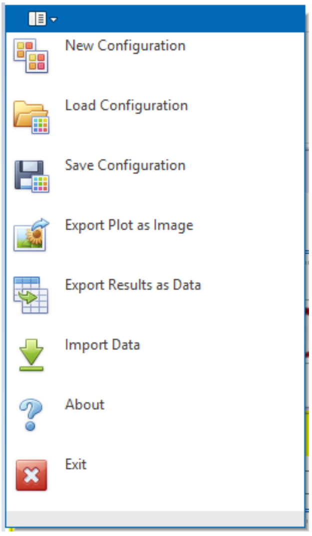
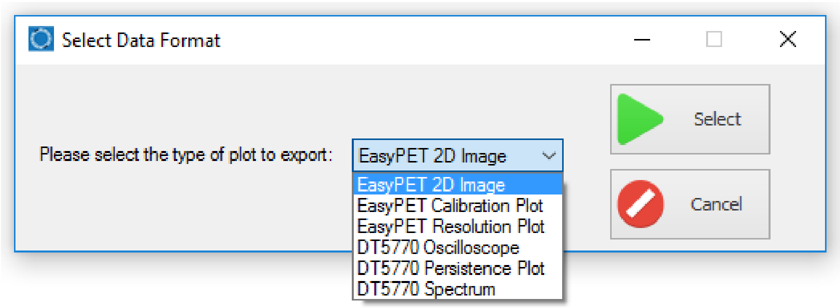
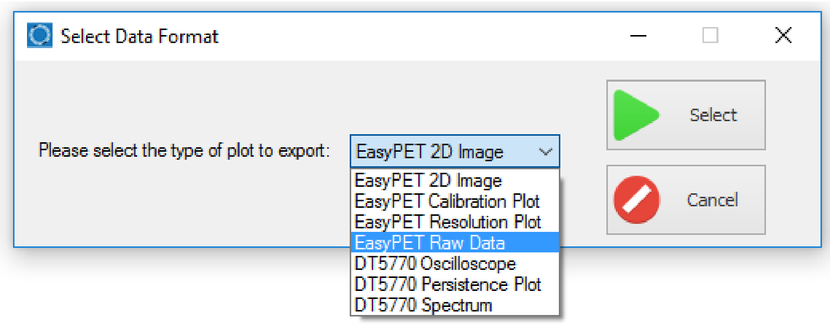


Fig. 5.9: File Menu

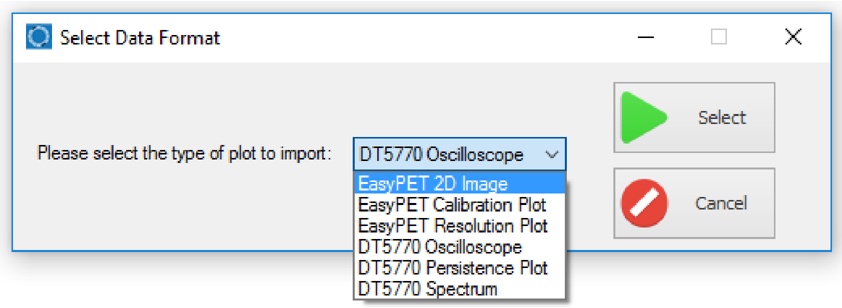
- "**New Configuration**": it clears each parameter and sets the default ones, as they appear when the GUI is started.
- "**Load Configuration**": selection of this function opens a browser window to select the setting file to be loaded. (acceptable file format is **.nec**).
- "**Save Configuration**": it opens a browser window to select the folder destination and the file name. (file extension is **.nec**)
- "**Export Plot as Image**": it opens the "Select Data Format" window. The user can choose, via drop down menu, the type of measurement/result to be exported in **.png** format. This option works with both SP5700 and DT5700.



- "**Export Plot as Data**": it opens the "Select Data Format" window. The user can choose, via drop down menu, the type of measurement/result to be exported in **Comma Separated Values** (**.csv**) format. The user has the possibility to save Raw Data coming from SP5700 and Plots specifying the destination folder and the file name.



- “**Import Data**”: it allows to import results of measurements previously saved. The user can upload Image, Calibration and Resolution Plots acquired by EasyPET. Acceptable file format is **.cvs**.



- “**About**”: it opens the Introduction Window (Fig. 5.7) by adding website as reference.
- “**Exit**”: it closes the GUI.

The EasyPET Control Tab

The EasyPET Control Tab, shown in Fig. 5.10; allows to manage the EasyPET by setting the acquisition parameters and performing the acquisition.

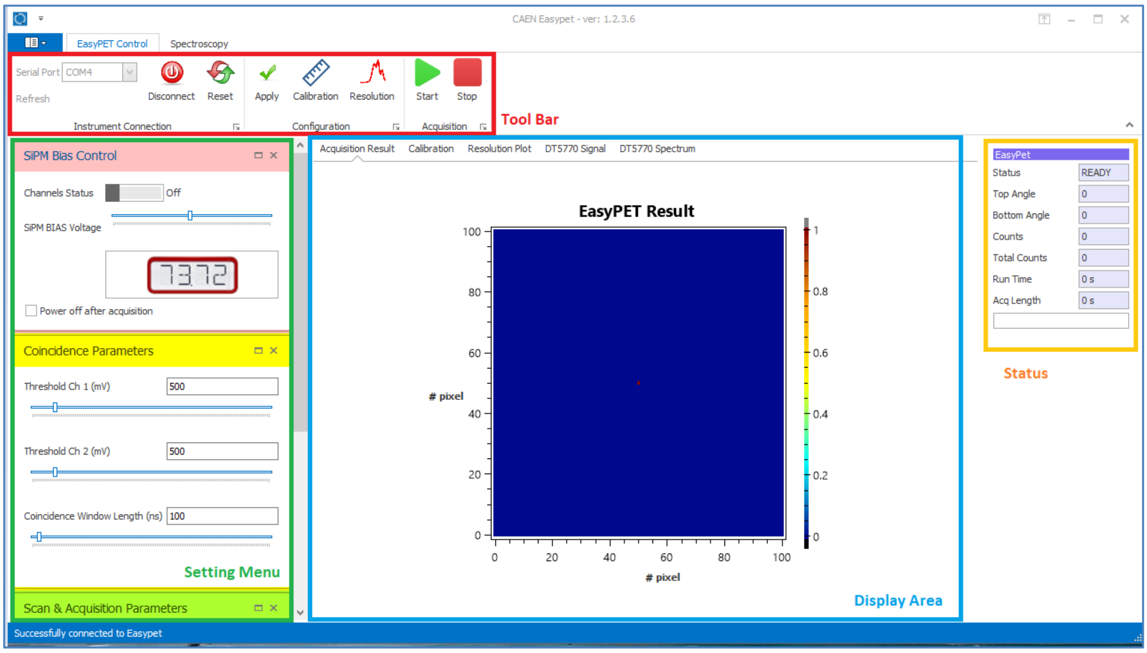


Fig. 5.10: EasyPET Control Tab

Tool Bar

The Tool Bar of the Tab is composed of three sections, as shown in Fig. 5.11.

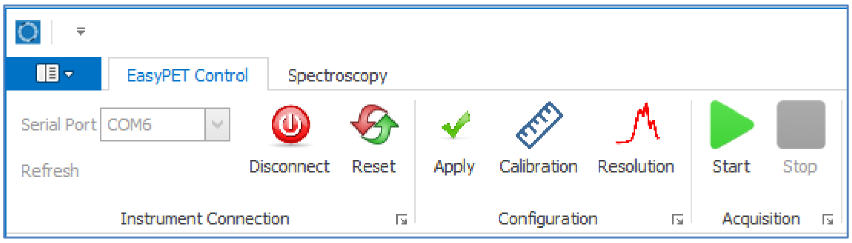


Fig. 5.11: Tool Bar of EasyPET Control Tab

- "**Instrument Connection**" section allows to select the PC communication port for Arduino UNO between the active ports auto-detected by the control software. The "**Refresh**" function, available when there is no connection, allows to update the communication in order to recognize the device. "**Connect**" and "**Disconnect**" buttons permit to open and close the communication with the Arduino module, respectively. The closing of the communication ensures the turning off the SiPM bias voltage in the case the sensor is still biased. The disconnection occurs also when the control software window is closed. "**Reset**" button nullifies the commands previously sent to Arduino and related to the management of the stepper motors.
- In the "**Configuration**" section, three different function are available. "**Apply**" function allows to communicate the selected acquisition and imaging parameters to the control unit. "**Calibration**" starts calibration mode, moving the U-shaped board to a fixed position crossing the center of the field of view and continuously counting the coincidences during successive calibration periods defined in parameters section. This mode allows defining the source height with the highest coincidence count before imaging, by placing the source in the center and adjusting its height via treated ring of the source support. "**Resolution**" opens the "Resolution Measurement" window (Fig. 5.12). This function allows executing a scan of the top motor in predefined steps of 0.9° and covering the region where the source is placed. The Resolution Plot, visualized in the GUI Display Area, shows in real time the

number of coincidence counts for each scanning position. The SiPM bias voltage needs to be ON to perform this measurement.

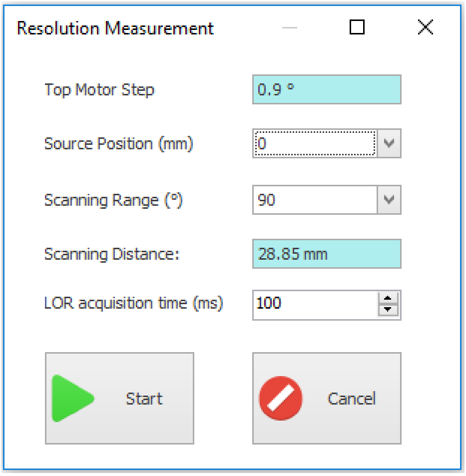


Fig. 5.12: Resolution Measuremets Window

Referring to Fig. 5.12, except the “**Top Motor Step**” already predefined at 0.9°, the user can change:

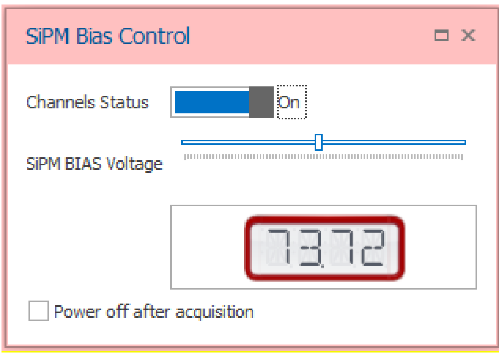
- “**Source Position**”: distance of the source from the center along the line connecting the detectors in the calibration position. Suggested value is 0 mm, means the source is in the center. Negative values are referred to positions between the center and the detector closest to the top motor axis, the absolute value of the distance is the bigger the more source position is close to the detector.
- “**Scanning Range**”: range of the scan performed by the top motor. The range is defined from 0.9° to 90°.
- “**LOR acquisition time**”: acquisition time at each position (LOR) of the scan.

“**Scanning Distance**” shows the maximum distance during the scanning between the source and the detectors, calculated from the source position and the scanning range.

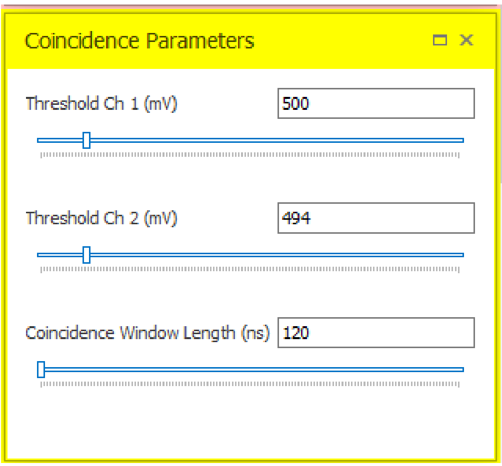
- The “**Acquisition**” section is characterized by “**Start**” and “**Stop**” buttons. The first one is responsible to start a new EasyPET scan for visualizing the reconstructed image in real time during acquisition. “**Stop**” button ends current operation (scan, calibration or resolution measurement) at any time. Once pressed, makes the system stop after a short time and return to the initial position.

Setting Menu

The Setting Menu is divided into three sections: “**SiPM Bias Control**”, “**Coincidence Parameters**” and “**Scan & Acquisition Parameters**”.

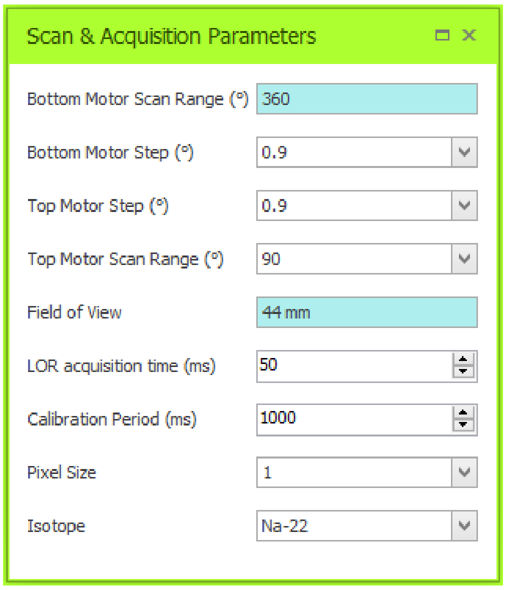


Supply voltage for both the SiPM of the two detector cells of EasyPET.
“**Channel Status**” allows to turn ON or OFF the supply voltage, common for both SiPM (The SiPMs were selected with the closest similarity possible, so as to present the same operating characteristics at the same voltage). A slider permits to adjust the value of the bias voltage within a range of around 7 V in steps of about 30 mV. A check box allows turning it OFF the Bias Voltage after finishing the acquisition.



“**Threshold Ch1**" and “**Threshold Ch2**”: the reference voltage for the two discriminators above which signals are considered as valid events (from 150 mV to 3,3 V).

"**Coincidence Window Length**": width of the time window within which two events of the two detectors are considered as a coincidence and counted. A slider allows adjusting the value from 120 ns to 1.5 µs.



In this section, acquisition and scan parameters can be set to reconstruct the real-time image.
The “**Bottom Motor Scan Range**" is not changeable and fixed at 360°.
“**Bottom Motor Step**": the angle for the bottom motor step (from 0.9° to 180°).
"**Top Motor Step**": the angle for the top motor step (from 0.9° to 90°, depending on scanning range).
"**Top Motor Scan Range**": the θ scanning range of the top motor performed for each position of the bottom motor. The diameter of the “**Field of View**” obtainable with each range is shown in the line below (from 0.9° to 90°, corresponding to a FOV from 1.5 mm to 44 mm).
"**LOR acquisition time**": acquisition time for each step of the two motor positions. The minimum possible value depends on the setting of real time image pixel size, being higher for smaller pixel sizes.
“**Calibration Period**”: time of coincidence counting in calibration mode (up to 10s).
“**Pixel Size**”: pixel pitch of the online image. Smaller pixel sizes require longer LOR acq. times, thus longer times to finish acquisition.
In addition, it is possible to select (“**Isotope**”) the radioactive source in use for the imaging in order to correct the number of counts during the acquisition for the radioactive half-life decay time.

<u>**Display Area**</u>

The display area of the GUI gives a complete Real-time graphical overview of the operating status of the EasyPET (and of the Multichannel Analyzer, if used). It contains three tabs related to EasyPET: **Acquisition Result**, **Calibration** and **Resolution Plot**.

- “**Acquisition Result**” tab: the "Start" button allows to start the 2D image reconstruction by back-projecting the acquired number of coincidence events at each position. The source reconstruction is displayed in real time during the acquisition in this tab of the GUI. On the left menu, all the image acquisition parameters can be set and are applied immediately, adding more versatility to the image data acquisition. The image acquisition stops when the bottom motor has completed the number of complete turns selected above and the pin of the top motor passes through the optical sensor position on the bottom motor. Otherwise, the "Stop" button stops the current operation at any time and make the system to return to the initial position.

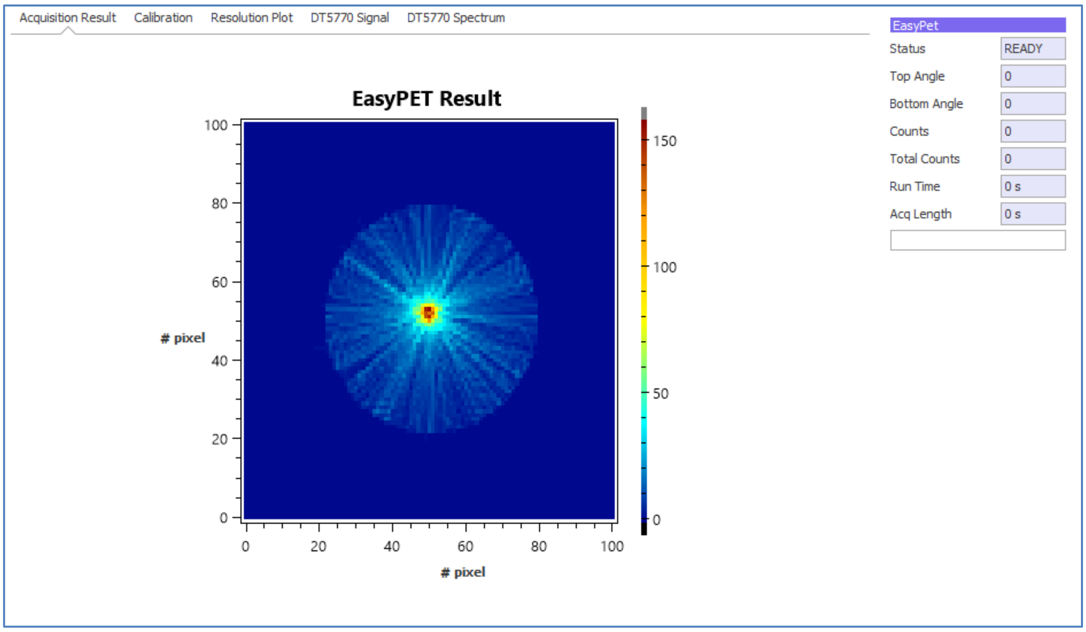


Fig. 5.13: Acquisition Tab of the Display Area

The box Status on the GUI right side allows to visualize the status of the EasyPET acquisition, showing the current position of the system, the coincidence counts and also the total number of counts. Information about Acquisition time is also available as the "**Run time**" of the system, means the total amount of time the EasyPET is running, measured in seconds and the "**Acq. Length**" that is the current acquisition time.

- "**Calibration**" tab: it shows the result of the Calibration function used to determine the best position of the source and as a cross check on the choice of the discriminator threshold. In fact, by comparing the coincidence rates in absence and in presence of the ^{22}Na source the user can be able to understand the importance of the energy discrimination in selecting the events.

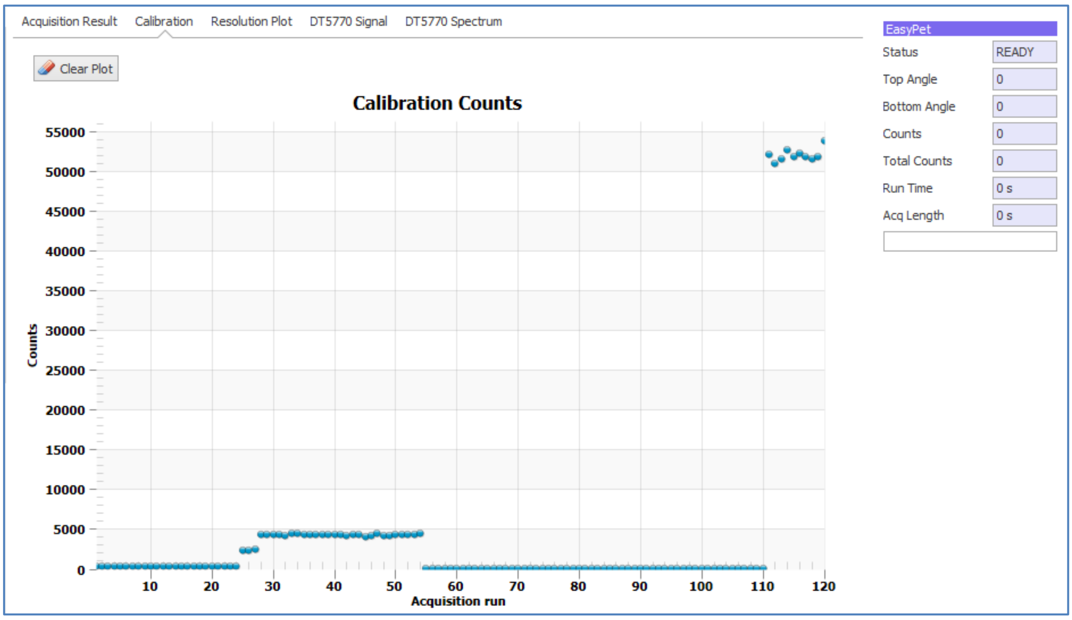


Fig. 5.14: Calibration Tab of the Display Area

- "**Resolution Plot**" tab: once setting the parameters in the "Resolution Measurement" window and start the measurements, the result is shown in real time for each scan position in this tab. It is possible to change online the parameters related to this data acquisition.

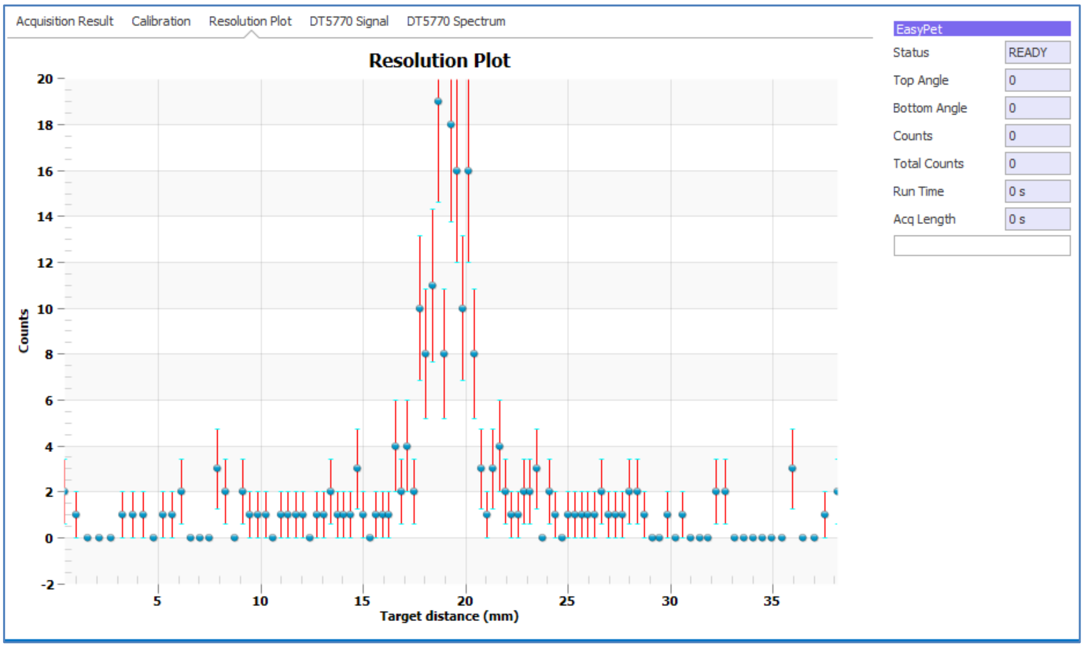


Fig. 5.15: Resolution Plot Tab of Display Area

The Spectroscopy Tab

The Spectroscopy Tab is activated by select the MCA autodetected serial number from the DT5770 list. Press "Connect" button to start the communication. The user, thanks to MCA use, has the possibility to analyse the signal coming from both detectors and perform gamma spectroscopy study.

The DT5770 GUI is composed of several frames: **Tool Bar**, **Setting Menu**, **Display Are**a and **DT5770 Status** (as in the EasyPET GUI).

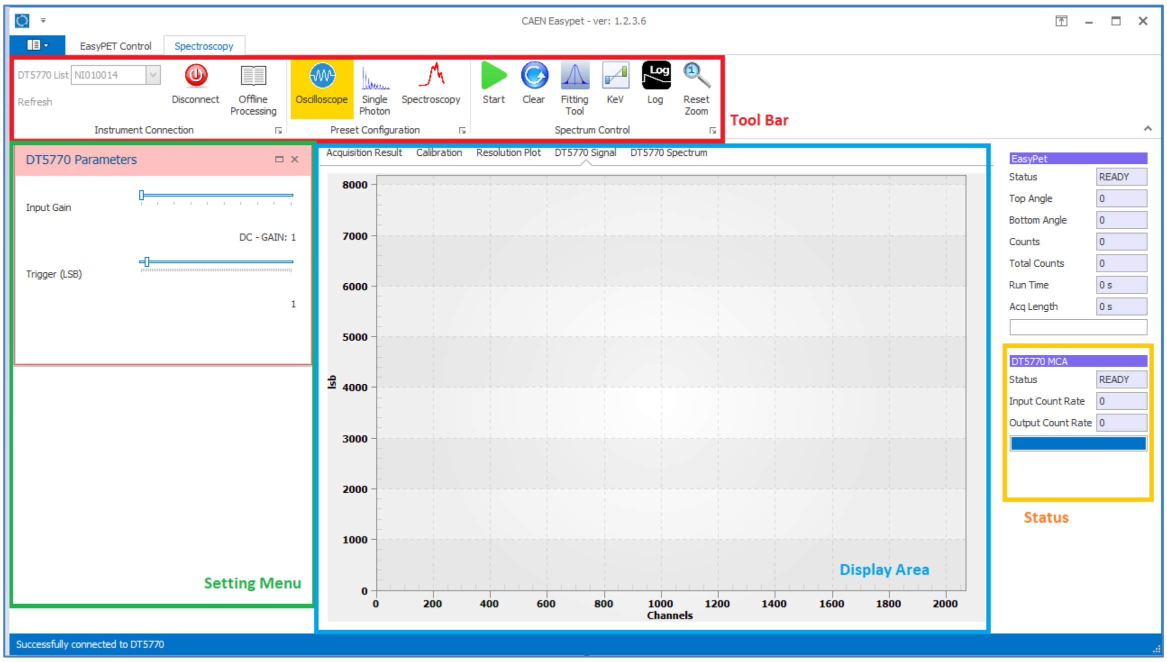


Fig. 5.16: Spectroscopy Tab

Tool Bar

The Tool Bar of the section dedicated to DT5770 is also composed of three sections, as shown in Fig. 5.17.

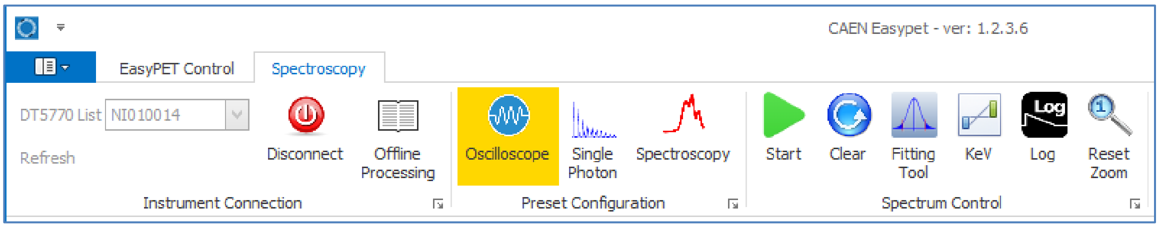


Fig. 5.17: Tool Bar of Spectroscopy Tab

- "**Instrument Connection**" section allows to communication with DT5770 auto-detected by the control software. The "**Refresh**" function, available when there is no connection, allows to update the communication in order to recognize the device. "**Connect**" and "**Disconnect**" buttons permit to open and close the communication.
- "**Preset Configuration**" section allows to observe, in Display Area, the signal and the spectrum both of single photon and of gamma radioactive source by use default setting of DT5770 acquisition parameters, mainly dependent to the signal decay time and amplitude.
- **Oscilloscope** operation mode introduces the possibility to visualize the analog signal of the spectroscopy branch. The user can observe the signals from the SiPM DCR (more details on the next Chapter) together with the ones induced by the LYSO self-emission in no illumination condition and, of course, the signals produced by the photons emitted by the source.
- The other two operation modes, **Single Photon** (Fig. 5.18) and **Spectroscopy**, introduce the possibility to integrate the signals through the trapezoidal filter [RD7], and also in this case different pre-settings of the acquisition parameters allow to visualize, respectively, the Multi-Photon Spectrum generated by the DCR or the source spectra.

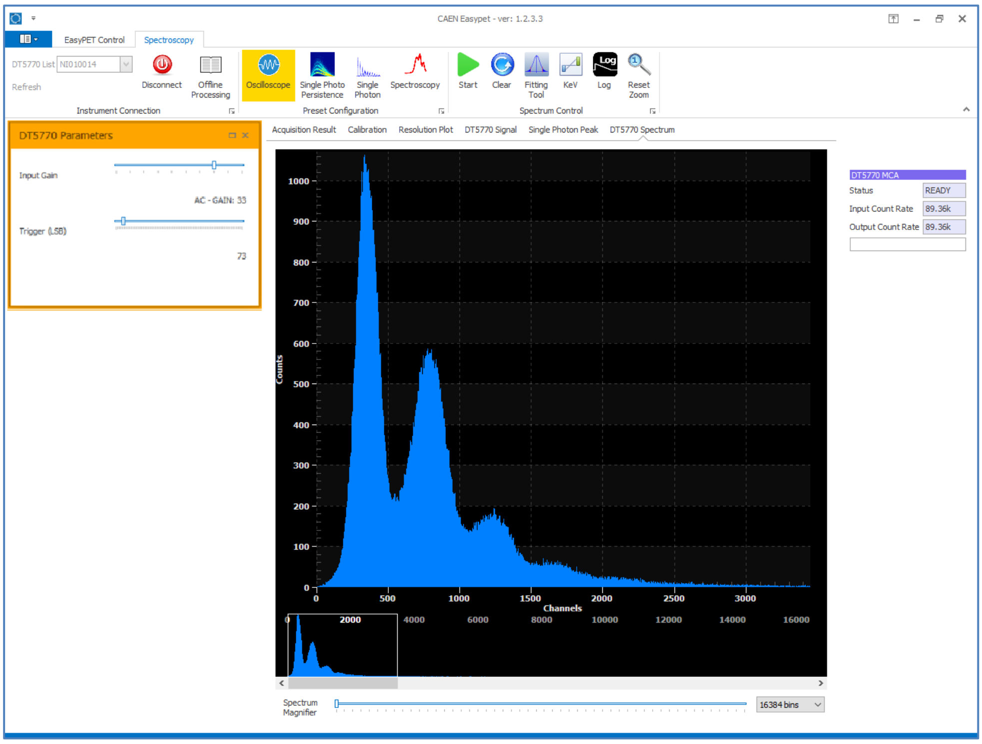
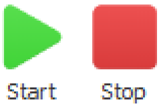


Fig. 5.18: Single Photon Spectrum

These functionalities allow users to learn the basic features of the SiPM and the techniques to characterize them with the dark conditions.

- "**Spectrum Control**" section is composed of a series of buttons that allow manage the acquisition and fit the results with a Gaussian function.



Press the "Start" button to enable the MCA acquisition and press "Stop" to end process. It works both for signal both spectrum acquisition.

The "Clear" button is used to reset the MCA signal acquisition. When it is pressed, the acquisition is stopped, the spectra are cleared and a new acquisition is started again.

The "Fitting Tool" button is enabled only when the MCA is running. When it is pressed a new table appears. It allows to define one or more regions in the spectrum acquired by the MCA to be fitted with a Gaussian function and corrected for a linear underlying background.

When at least two peaks are fitted, the "Calibrate" button in the same Window will be enabled to assess the energy calibration procedure for the MCA, explained in the "Fitting Tool" description.

Once calibrate MCA, this button will be enabled to change x-axis scale from channel to energy.

The "Log" button permits to change the y-axis scale between the linear and logarithmic one.

"Reset Zoom" button allows to reset the zoom previously applied.

"Offline Processing" button allows the access to Fitting tool functionalities when the MCA is not running. When pressed, it prevents the connection to MCA.

<u>DT5770 Setting Menu</u>

The Setting Menu is strictly connected to MCA function in use. Oscilloscope and Single Photon modes have the same parameters to be set. Nevertheless, the default setting of each window depends on measurement type according to default setting of DT5770 filter parameters.

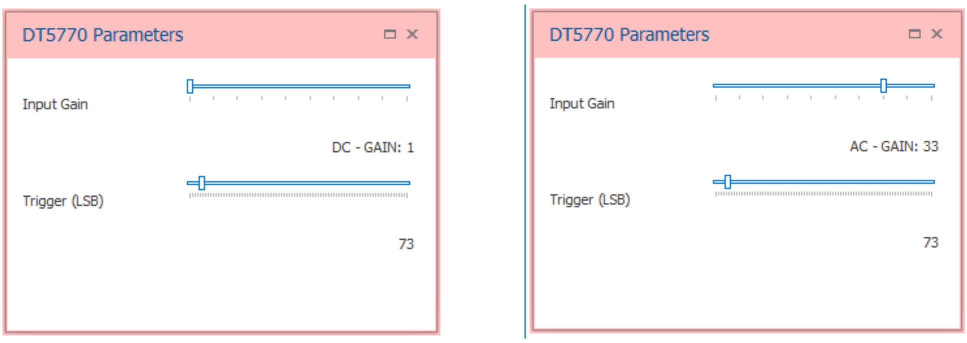


Fig. 5.19: Default setting of DT5770 Parameters window for "Oscilloscope" and "Single Photon" acquisition modality, rispectively

Referring to Fig. 5.19, the user can manage the "**Input Gain"**, passing from DC coupling to AC one, and the "**Trigger (LSB)**", which is the value in LSB of the signal amplitude that a signal has to exceed to be accepted.

The DT5770 Parameters window for Gamma Spectroscopy modality, shown in Fig. 5.20, allows to select the proper "Input Range" between 1.25, 2.5, 5.0 and 10.0 V. It should correspond to the input dynamic range of the MCA and it is a compromise between the digitizer dynamics saturation and the use of too few channels of the spectrum. Clicking on the Trigger Source Menu, it is possible to select an internal or external source of trigger and set its threshold value via the "Trigger (LSB)" cursor.

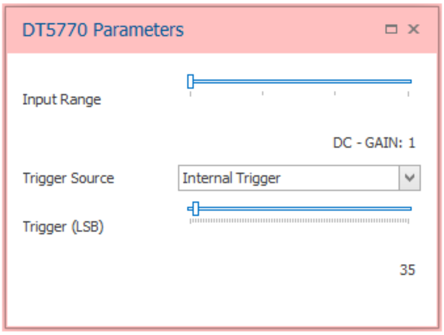


Fig. 5.20: Default setting of DT5770 Parameters window for Gamma Spectroscopy Mode

<u>Display Area</u>

The display area of the GUI contains three tabs related to Multichannel Analyzer: **DT5770 Signal** and **DT5770 Spectrum**

- "**DT5770 Signal**" tab: the "Start" button, after "Oscilloscope" mode selection, allows to acquire the signal waveform of the spectroscopy branch. The user can zoom the signal by clicking the left mouse button, holding down it and dragging the cursor until reach the selection of the desired area.

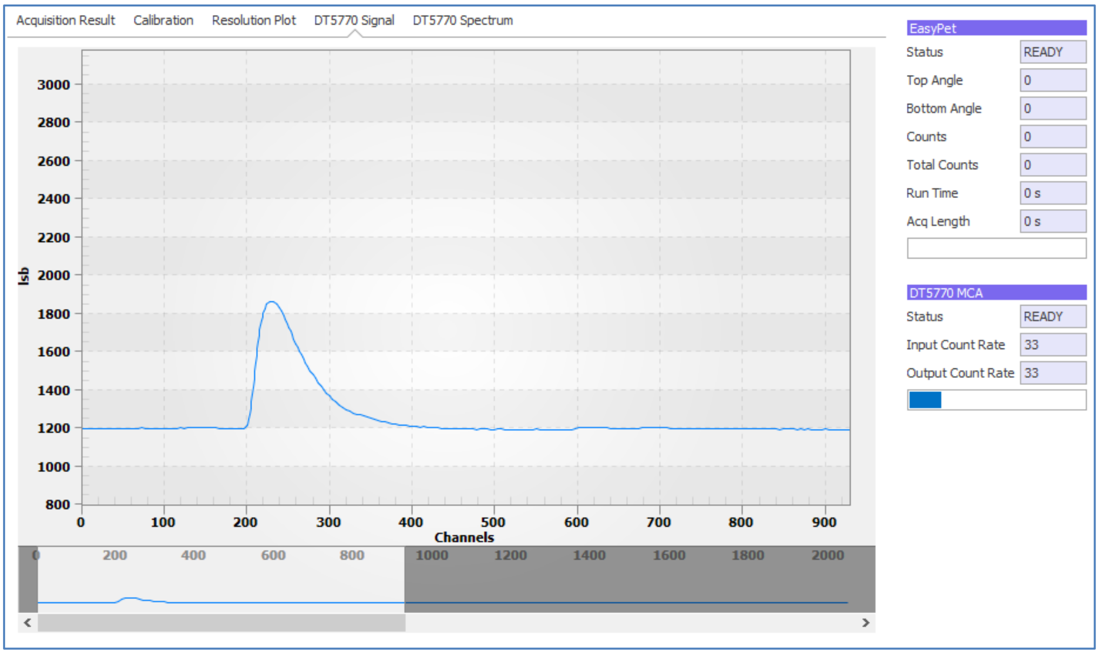


Fig. 5.21: DT5770 Signal tab

- **"DT5770 Spectrum"** tab: allows to visualize both the Multi-Photon Spectrum generated by the SiPM DCR both the source spectra. The spectrum is displayed in real time during the acquisition. On the menu on the left the parameters can be set and are applied immediately, adding more versatility to the data acquisition. On the lower part of the spectrum, the user can act on the spectrum, by using the magnifier and changing the bins number. The zoom modality works as in DT5770 tab.

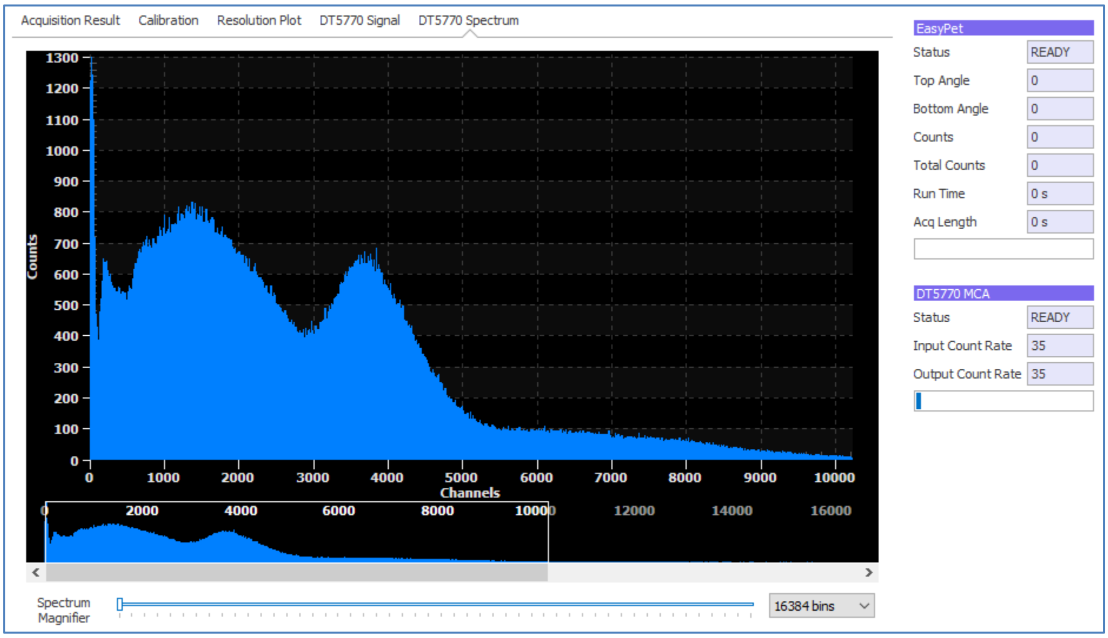


Fig. 5.22: DT5770 Spectrum tab

DT5770 Status

The statistics for the MCA is shown in the "Status" Area. They are always visible, except the "Running Time and Total Counts, activated during spectrum acquisition.

- **Status** box displays if the device is running or not.
- **Input Count Rate** is the events frequency at the input of the MCA;
- **Output Counts Rate** is the frequency of events acquired and processed by the MCA;
- **Running time** is the total amount of time the MCA is running, measured in seconds.

Fitting Tool

The Fitting Tool function is helpful during a spectrum acquisition. Once its button is selected, the fitting tool windows appears.

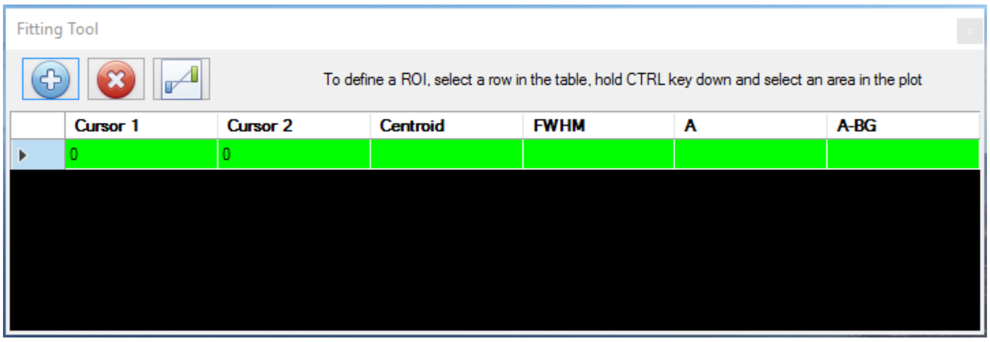


Fig. 5.23: Fitting Tool Window

Referring to Fig. 5.23, it is possible to add rows and remove selected rows by pressing the "**Add**"  and "**Remove**"  buttons. To select a row click on the arrow in the first table column.

When a row has been added, the user has to click in the box correspondent to the label "**Cursor 1**" to insert the channel number that represents the left edge of the fitting region. By pressing enter the number will be effectively introduced in the table and a vertical yellow line will appear in the Display Area graph at the inserted value. At the line is associated a label indicating the number of the row, "**1**" in this case. Repeating the same procedure for the "**Cursor 2**", the fitting region is defined and a Gaussian function will be used to fit the peak, together with a linear function to account for the underlying background. The area underneath the Gaussian function is plotted in green, while the area below the linear function is represented in red. The row of the table will also be populated with the results of the fit:

- "**Centroid - Ch**" represents the mean value of the Gaussian fit function expressed in number of channels;
- "**FWHM – Ch (%)**" indicates the FWHM (2.35 times the Gaussian standard deviation) of the fit functions expressed in number of channels, while in parenthesis is reported in percentage the ratio between the FWHM and the Centroid, i.e. the percentage Energy Resolution;
- "**A**" represents the area of the region defined by the cursors, respectively obtained by summing all the entries of the MCA acquired spectrum ("**A**");
- "**A-BG**" represents the area of the region defined by the cursors corrected with the area of the background contribution calculated from the linear fit, obtained by summing all the entries of the MCA acquired spectrum ("**A-BG**").

When at least two peaks are fitted, the user can use the "Calibrate" button  in the same window to assess the energy calibration procedure for the MCA. As in the previous case, the user can add rows and insert, for each of them, centroid value previously estimated in the "Channels" column and the corresponding energy value in the "KeV" column. Once two rows are filled in, the button "Calibrate" will be enable and the linear energy calibration will be assessed via the corresponding button.

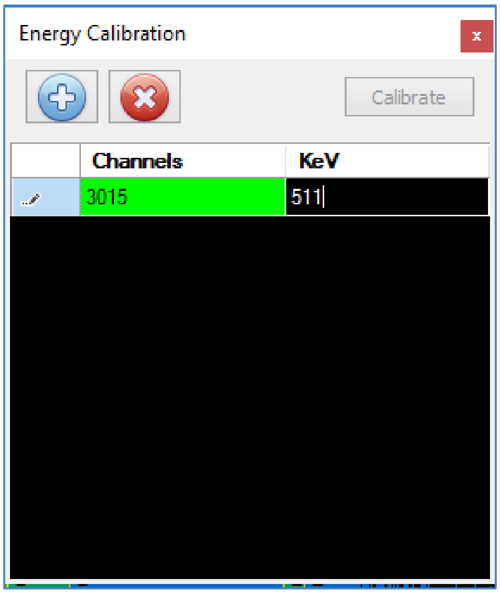


Fig. 5.24: Energy Calibration Window

6 Basic Measurements

This manual section is dedicated to the simple and practical use to perform the first basic measurements by using EasyPET Kit.

Hardware Setup

The first getting start demo proposed in this Chapter makes use of the SP5700 connected via Mini USB to a computer equipped with Microsoft Windows 10 Professional 64-bit OS. External AC/DC power supplies power the device. Please, use only the power supplies shipped with this instrument and certified for the country of use.

The setup could be as reported in Fig. 6.1. The only needed connection is with Computer in order to perform the suggested experiment. The user can also use an oscilloscope to observe the analog signals coming from each detection unit, comparators and coincidence outputs, by using MCX-LEMO cables included in the suitcase.

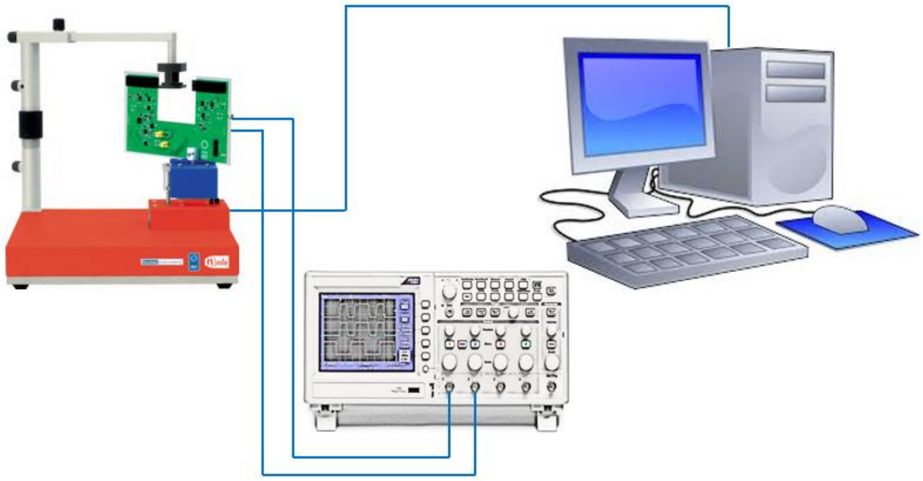


Fig. 6.1: The hardware setup including the EasyPET SP5700 and oscilloscope

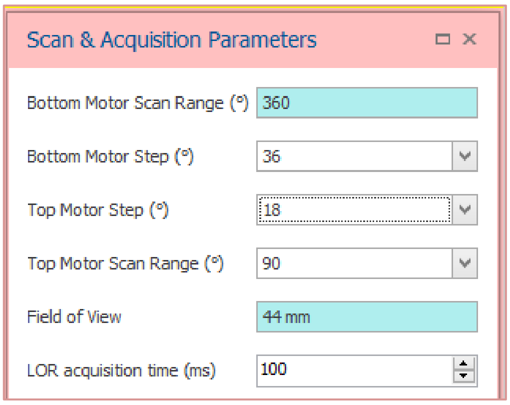
Important Note: Please notice that Radioactive Source is not included in the SP5701 EasyPET Kit. The radioactive source used in this section is Na^{22}, 1/2 inch disc and 10 µCi.
A radioactive source with lower activity can be used, but in that case time of measurements becomes bigger.

EasyPET Commissioning

The first action for the user is to test the assembly and verify that the system works properly:

- ✓ Build the device as explained in Chapter 5.
- ✓ Plug the 12V power supply from a wall plug to the mechanical base and switch ON the power button.
- ✓ Plug the MiniUSB cable from the device to the computer.
- ✓ Run EasyPET software and select the communication port. If only EasyPET is connected, the port will be selected automatically. Otherwise, make sure the right port is selected. Click the button “Connect”.
- ✓ Before to apply any software command, verify that the screws used to attach the components to motor axes are tightened and that the U-shaped board rotation is not obstructed in any direction.

- ✓ Place the top motor so that the marker pin of its blue holder is located on the side closer to the optical sensor (located on the mechanical base). Do not care if the marker pin position is on the right or on the left of the optical sensor, because the software executes scan movements (90° range) to bring the U-shaped board in the correct position.
- ✓ Click “Calibration” to verify the movement correctness in terms of sent commands and execution. When the Calibration starts, the top motor moves around optical sensor until the marker pin is detected by the sensor itself. Once the pin marker detection takes place, the top motor stops and the U-shaped board moves to a position of 90 degrees from the top position sensor. If something does not work, press “Stop” to end process, “Refresh” to nullify commands and return to the initial position. If necessary, re-arrange the plugged cable, check that the cables are not rolled and adjust the position of the U-PCB compared to top position sensor by loosening the screws of its support, sliding it and tightening them back at the adjusted position. Repeat the process until the board is correctly aligned.
- ✓ Flag the ‘ON’ checkbox to bias the SiPM and press “Apply”. Bias voltage value is set by default to the recommended voltage at 25°C (specific for each EasyPET).
- ✓ Click on “Calibration” and check that some coincidence counts, due to the thermal noise, happen. Press “Stop” to end process
- ✓ Check the scan execution. Select the following acquisition parameters for a quick test scan:



- ✓ Click on “Start”. The figure stat to appear in “Acquisition Result” tab and motors begin to move. Check that the movement steps that the motors perform are consistent with the parameters set in the ‘Scan & Acquisition Parameters’ section. When a coincidence is detected a line is drawn in the figure, with a colour corresponding to the number of events. After a complete rotation, the system returns to the initial position and the acquisition raw data and the figure itself can be saved by clicking respectively on ‘Export Results as Data” and ‘Export Plot as Image’ in the File Menu.

Important Note: Please notice that when the sensors are switched off the coincidence counts in the Calibration tab are zero.

What can user do with EasyPET?

Some details about the EasyPET detector system (also described in Chapter 8), composed of a Silicon photo-multipliers (SiPM) coupled to scintillating crystals, before starting measurements session:

- **Silicon Photo-Multipliers (SiPM)** - SiPM are leading edge detectors of light with single photon sensitivity and unprecedented photon number resolving power. SiPM essentially consist of a high-density (up to ~10^4 /mm^2) matrix of P-N junctions connected in parallel on a common Si substrate. Each diode is an Avalanche Photo Diode (APD) operated in a limited Geiger-Müller regime connected in series with a quenching resistance, in order to achieve gain at level of ≈ 10^6. and to guarantee an extremely high homogeneity in the cell-to-cell response. Subject to the high electric field in the depletion zone, initial charge carriers generated by an absorbed photon or by thermal effects trigger an exponential charge multiplication by impact ionization. When the current spike across the quenching resistor induces a drop in the voltage across the junction, the avalanche is stopped. Fig. 6.2 shows the equivalent circuit of a SiPM

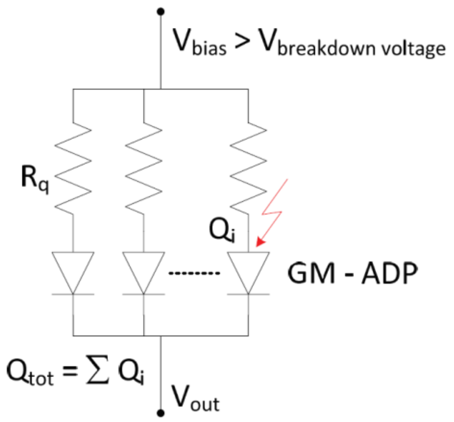


Fig. 6.2: Equivalent circuit of a SiPM: each pixel provides information on whether or not it is fired

SiPM can be seen as a collection of binary cells, providing altogether an information about the intensity of the incoming light by counting the number of fired cells. Thanks to their compactness, robustness, insensitivity to magnetic field, low operating voltages and low power consumption, SiPM have an extremely high potential in fundamental and applied science and industry. SiPM benefit from the rapid evolution of the Silicon technology and the investment of different companies in terms of cost production, design flexibility, detector performances and high-quality mass production, becoming the natural choice for an always wider field of applications. Moreover, due to the characteristic time of the avalanche development they are characterized by an intrinsic time resolution at the 100 ps level, making them the baseline technology for the development of Time Of Flight PET scanners.

The detectors used in this application are Hamamatsu 1x1 mm^2 SiPM, model MPPC S10362-11-050P. This sensor, with its 400 cells, provides a wide dynamic range.

- **Scintillato**r - Even if a SiPM is able to detect very low light intensity, it can be used for detecting a large amount of light in radiation detection with scintillators. Gamma rays (γ), with energy up to 3 MeV, interact with scintillating crystals through three processes: Compton Scattering, Photoelectric Effect and Pair Production (possible for energies greater than 1.022 MeV). The Compton Effect is the collision between a photon and a free electron. The energy of the incoming photon is shared between the scattered photon and the recoiling electron. In the Photoelectric Effect, the incident gamma ray transfers all its energy to a bound electron, which acquire a kinetic energy equal to the incoming gamma energy less the energy necessary to free the electron from its bound state. All these processes convert gamma ray energy into electrons or positrons which collide with the scintillators atoms, raising the atomic electrons into excited states. The de-excitation of these states causes the emission of photons in the visible or near UV region. The amount of light produced in the scintillator is proportional to the energy of the initial gamma ray. In this device, the crystals used are $L_{1.8}Y_{.2}SiO_5$(Ce) (Cerium-doped Lutetium Yttrium Orthosilicate). LYSO is a Cerium doped Lutetium based scintillation crystal that offers high density and a short decay time. It has an improved light output and energy resolution compared to BGO ($Bi_4Ge_3O_{12}$), which has a similar density. Applications that require higher throughput, better timing and better energy resolution will benefit from using LY S O material.

Scintillating crystal features are reported in Tab. 8.1.

Understanding the basics of SiPM sensors

One of the SiPM feature is the so called Dark Count Rate (DCR). The free carriers that induce the avalanche inside the depletion region can also be generated by thermal effects. The results are spurious events occurring randomly and independently from the illumination field. The DCR depends mainly on the sensor technology and on the operating temperature, with a rate from 100 kHz up to several MHz per mm^2 at 25 °C. The DCR decreases with the lowering of the temperature (about a factor 2 of DCR reduction every 8°C). In addition, the operating voltage has an impact on the DCR since it is connected to the electric field and as a consequence to the active volume of the sensor and to the triggering probability of the charge carrier.

It is interesting to analyse the DCR behaviour with respect to the bias voltage of the EasyPET sensors. To DCR studies, run the EasyPET Control software and apply bias voltage to the detectors. The DCR can be obtained by measuring the rate of the sensors outputs exceeding a threshold. The electronics on the board includes a comparator for each channel which provides a digital output when the sensor signal is higher than a threshold. Fig. 6.3 shows one sensor analog output (spectroscopic branch) in blue and the correspondent comparator digital signal in azure. The red line represents the value of the threshold which triggers the comparator output.

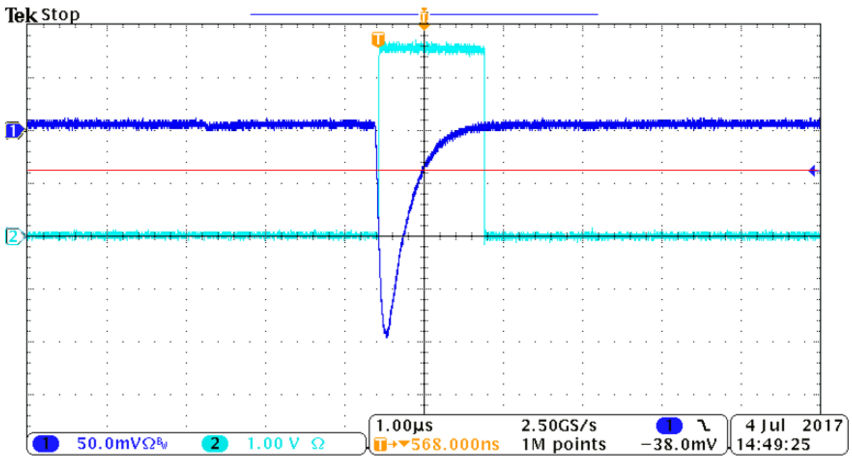


Fig. 6.3: The blue line is the analog sensor output, the azure line represents the comparator output and the red line is the trigger threshold at 300mV. The signal is obtained at 25°C room temperature and with the sensor biased at 73.5 V

The DCR measurement can be performed by setting the threshold in the user interface, connecting the comparator output of the channel under test at the oscilloscope (setup is reported in Fig. 6.1) and counting its frequency. The result of the DCR scan as a function of the threshold value for 73.0 V, 73.5 V and 74.0 V bias voltages is reported in Fig. 6.4.

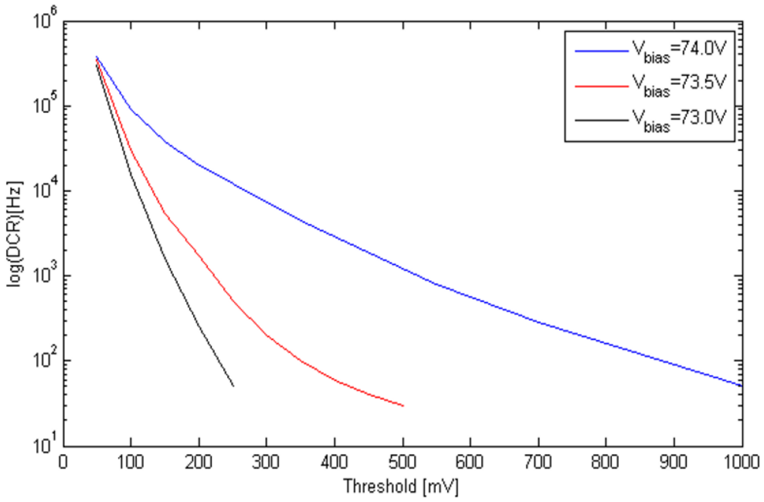


Fig. 6.4: The logarithm of the DCR as a function of the threshold for 73.0 V, 73.5 V and 74.0 V bias voltages at 25°C

It's clear that at low threshold the DCR is considerable and independent from the bias voltage. The increasing of the threshold value causes the DCR to decrease of an amount related to the bias voltage. As a consequence, at low bias the curve slope is quite steep and the DCR is negligible at the threshold of 200 mV, while at higher bias the smooth dependence imposes a threshold of about 1 V to keep the DCR at a negligible level.

Coincidence detection

PET systems are based on the simultaneous detection of two photons back to back with an energy of 511 keV, emitted by positrons annihilation. To perform the imaging measurements with the EasyPET, the two detection units, SiPM based, work in coincidence. It is possible to select as a coincidence signals the events characterized by the occurring of the comparator output of each detector within a time window.

The coincidence detection allows to reduce significantly the system noise due to the DCR. In Fig. 6.5 is illustrated the behaviour of the system noise rate measured in coincidence mode as a function of the threshold for three different bias voltages. It's clear that at each threshold the rate of random coincidence is about two orders of magnitude lower than the single sensor noise rate. In addition, this effect is independent from the choice of the SiPM bias voltage.

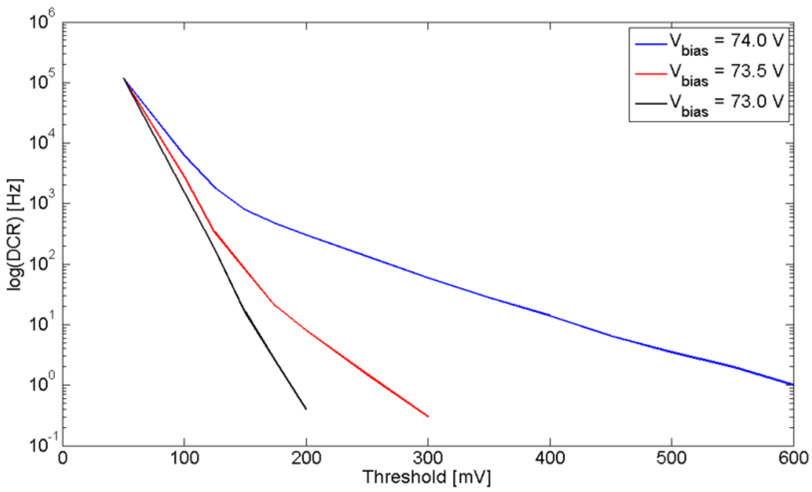


Fig. 6.5: The logarithm of the random coincidence as a function of the threshold for 73.0 V, 73.5 V and 74.0 V SiPMs bias voltages at 25°C room temperature. The time window width adopted is 120 ns

The user can perform the measurement by using the oscilloscope, as in the previous case, by counting the frequency of the coincidence output. Another option to take the data is to use the software Calibration function, explained better in the next subsection. The coincidence counts are estimated on time of Calibration Period (up to 10s).

The implementation of the coincidence detection introduced in the optimization of the acquisition conditions the parameter of the time window width in addition to the bias voltage and the threshold. In order to find the best parameter values is necessary to analyse the response of the system in coincidence mode to the radioactive source with respect to the random events.

Using a ^{22}Na radioactive source the coincidence rate produced by the interaction of the gamma with the two detection systems can be measured. The comparison of this result with the previous random noise measurement allows to study the signal to noise ratio. In Fig. 6.6 is shown how the coincidence signal rate (with the random noise subtracted) in unit of noise standard deviations depends on the comparator threshold for different bias voltages. In the case reported the time window width is set to 120 ns, but the curves behaviours are the same with greater values. A high signal to noise ratio is required in order to obtain a highly contrasted image, with the signal clearly distinguishable from the noise. The plot suggests that is possible to fulfil this requirement at each different bias voltage; the signal to noise ratio will be the same by choosing an appropriate threshold value.

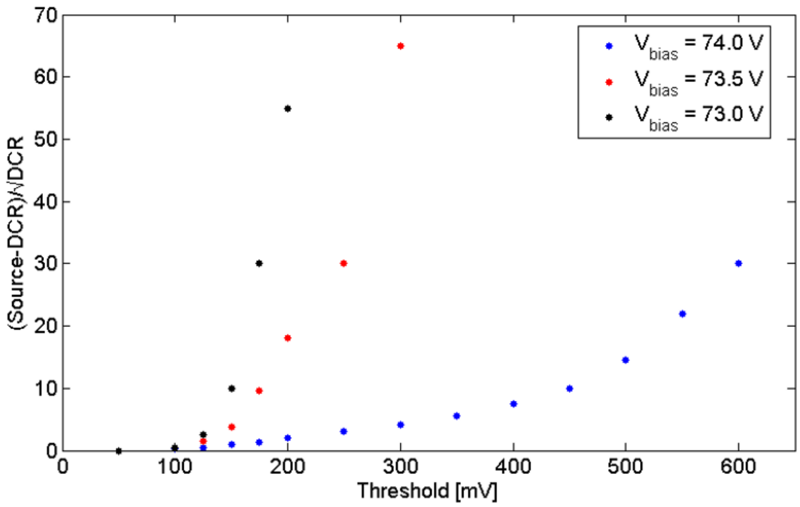


Fig. 6.6: The ratio between the coincidence signal with DCR subtracted and the square root of the DCR as a function of the threshold. Data are acquired with 120 ns time window width for 73.0 V, 73.5 V and 74.0 V SiPMs bias voltages at 25°C room temperature

Calibration

User can apply the Calibration function to determine the best position of the source and as a cross check on the choice of the discriminator threshold. In fact, by comparing the coincidence rates in absence and in presence of the β^+ radioactive source the student can be able to understand the importance of the energy discrimination in selecting the events.

The radioactive source has to be put in the holder, placed in the region between the detectors. The function is activated by clicking "Calibration" button and several coincidence counts different from zero appears on the plot. It is possible to adjust the position of the source by playing with the knobs suitable to place the source holder along a virtual line that connect the detection units and with the threaded ring (Fig. 5.4) used to set the vertical position the source holder. When the radioactive source is aligned with the detectors the coincidence counts is maximum. By removing the source from this position, the counts drop around to zero immediately. A typical example of this procedure is shown in Fig. 6.7

The user can modify the Coincidence Parameters and Calibration Period, set as default at 1s, in the "Scan &Acquisition Parameters" section. Once fixed the coincidence parameters, the number of counts depends on the radioactive source activity and on the calibration period. By using Na^{22} source of 10 µCi about 40 coincidences or more can be counted.

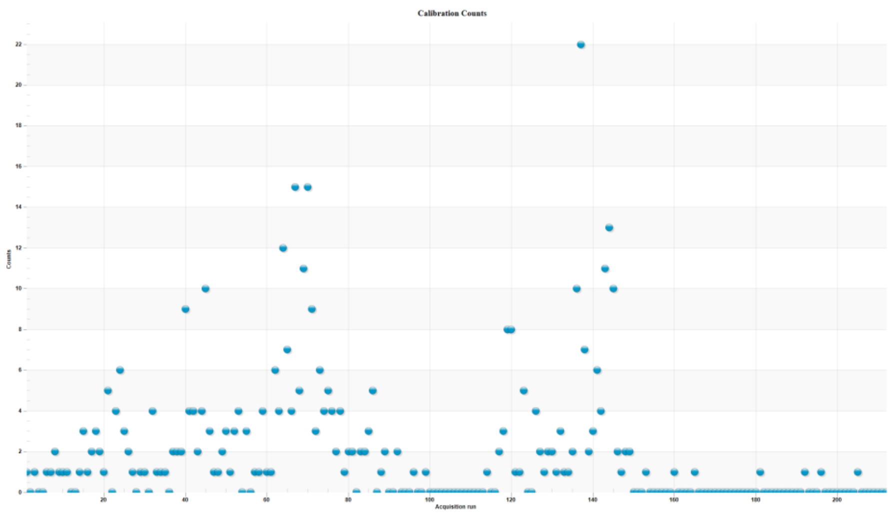


Fig. 6.7: Example of calibration plot corresponding to coincidence counts acquired moving the source in the space between the detection units and removing from there

Important Note: Whenever parameters are changed in Setting Menu, the button "Apply" needs to be pressed to become effective. Otherwise, the system will assume the last parameters sent, even if new ones have been selected.

2D Image Reconstruction

Once these preliminary measurements have been performed it is possible to start with the dedicated imaging studies and, as shown in Fig. 6.8, the realtime image reconstruction by back-projecting the acquired number of coincidence events at each position can be assessed.

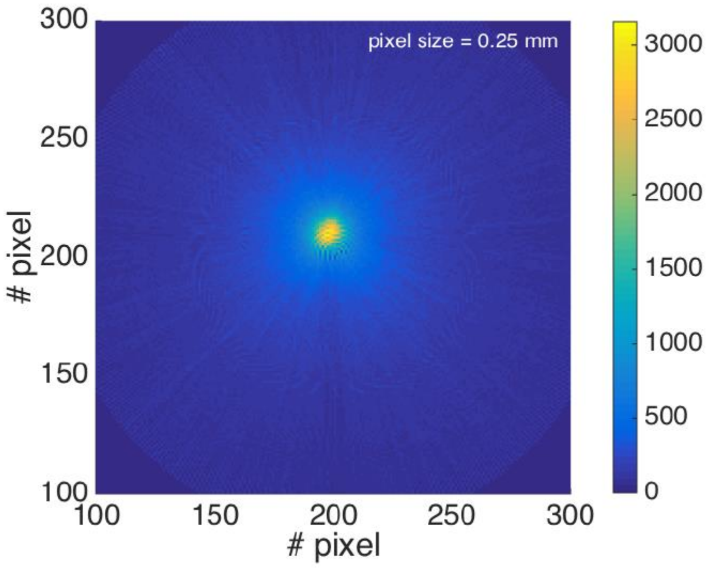


Fig. 6.8: Reconstructed distribution of a ^{22}Na source with an activity of 9.8µCi imaged with a single LOR time acquisition of 0.5 s, bottom step 0.9°, top range 45° and top step 0.9°, for a total acquisition time of 167 minutes

After finding the source position through calibration function, the 2D image reconstruction can be performed. The user can use default values for the scan or can apply different parameters, moreover LOR, pixel size and Isotope type can be set. Bias voltage, thresholds and coincidence window length values play a key role in this measurement. In particular, threshold value has to be chosen carefully, if the threshold is too low, the noise prevents a good measurement due to inability to distinguish the source contribute from the noise. Nevertheless, a higher threshold value decreases the noise but also cut a part of the signal. As a consequence, the system has a lower detection efficiency if the threshold value is increased. This parameter choice is dictated by a trade-off between the signal to noise ratio and efficiency maximization. The threshold value around 200 mV could represent a good compromise.

Once set the chosen parameters, press "Start" button and acquire the 2D image. Change threshold values and repeat the acquisition to observe the differences in the 2D Image acquired.

Image Contrast [RD1]

The reconstructed image quality can be characterized in terms of contrast, which arises from the relative variations of count densities between adjacent areas in the image of an object. Contrast gives a measure of the detectability of an abnormality relative to normal tissue and is expressed as:

$$C = {(I_{max} - I_{min})}/{I_{min}}$$

with I_{max} and I_{min} representing the count densities recorded in the abnormal and normal tissues, respectively. For a given image, a minimum number of counts are needed for a reasonable image contrast. Even with adequate spatial resolution of the scanner, lack of sufficient counts may give rise to poor contrast due to increased noise, so much so that lesions may be missed. The number of count densities depends on the administered dosage of the radiopharmaceutical, uptake by the tissue, length of scanning and the detection efficiency of the scanner.

The EasyPET image contrast has been measured by acquiring an image of a 9.8 µCi of ^{22}Na for about 167 minutes, for a total number of about $6.6*10^6$ counts (Fig. 6.8). Then the above equation has been applied, determining I_{max} and I_{min} from the counts in the source and background regions and considering the image pixel size. Then the contrast has to be divided by the source activity (346.1 kBq) and the total acquisition time, in order to be independent from these contributes. As a result, a value of 60 C/(kBq*s) has been obtained, indicating a good disease detecting capability.

Spatial Resolution

The determination of the minimum distance between two small point sources that can be distinguished by a PET scanner, namely the spatial resolution, is one of the most features of the scanner because it measures its ability to faithfully reproduce the image of an object, clearly depicting the variations in the object radioactivity distribution. Several effects contribute to determine the spatial resolution of the PET image, some intrinsically related to the β^+ annihilation and some depending on the detection system. The dominant factor degrading the spatial resolution is usually the intrinsic resolution of the scintillation detectors.

A β^+ point source translating between two detectors on opposing side (distance d) of the PET emits isotropically back-to-back pairs of annihilation photons. The coincidence rate measured by the detector pair is zero when the source is below the bottom edge of the detectors, increases roughly linearly to a maximum when the source is halfway between the top and bottom edges, then decreases roughly linearly to zero when the source is at the top edge of the detectors. Fundamental limitation to the spatial resolution is due to the irreducible contributions related to the intrinsic property of positron, the positron range and the acollinearity; moreover, another effect is due to the sampling error, which is connected to the distribution of the LORs in all the FOV.

To estimate the spatial resolution of the EasyPET, the user should remove the sensor holder from the EasyPET horizontal arm and assemble the other supplied radioactive source holder. By using this tool, the source can be put in vertical position in the space between the two detectors. An easy solution is to place the source at the same distance from both detector units, so that the source position is set at 0 mm in the "Resolution Measurement" window. If the source is not placed in this position, negative and positive distances, labelled in this way by software, are related to orientation of the axis that connect the two detectors as shown in Fig. 6.9.

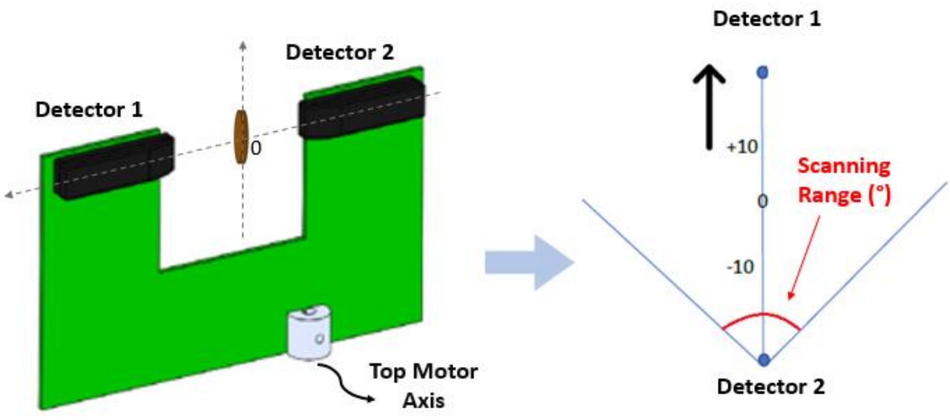


Fig. 6.9: Axis orientation in case of resolution measurements

To verify that the vertical position of the radioactive source is aligned to both detectors, the user can use the calibration function. Once found the correct position, the resolution measurement can start by setting, in addition to the source position, the scanning range and the LOR time acquisition as suggested in Fig. 6.10.

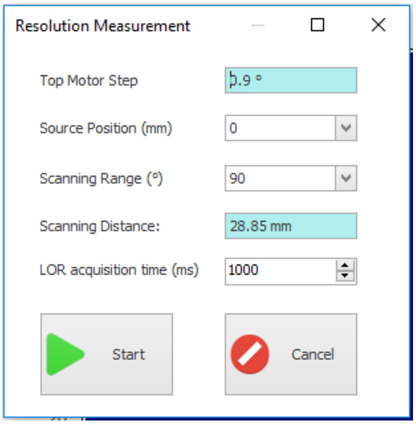


Fig. 6.10: Suggested parameters for resolution measurement

Measurement result is visualized in real time during acquisition in the resolution plot and the final result can be saved as data or picture (Fig. 6.11). The spatial resolution of the system is defined from the Full Width at Half Maximum (FWHM=2.35*σ, where σ is the gaussian standard deviation) of the function, which is determined by fitting the data points with a Gaussian distribution. The result is (1.1 ± 0.1) mm, which is comparable to the spatial resolution of the state-of-the-art small animal PET. For more details about this measurement, look at Appendix A.

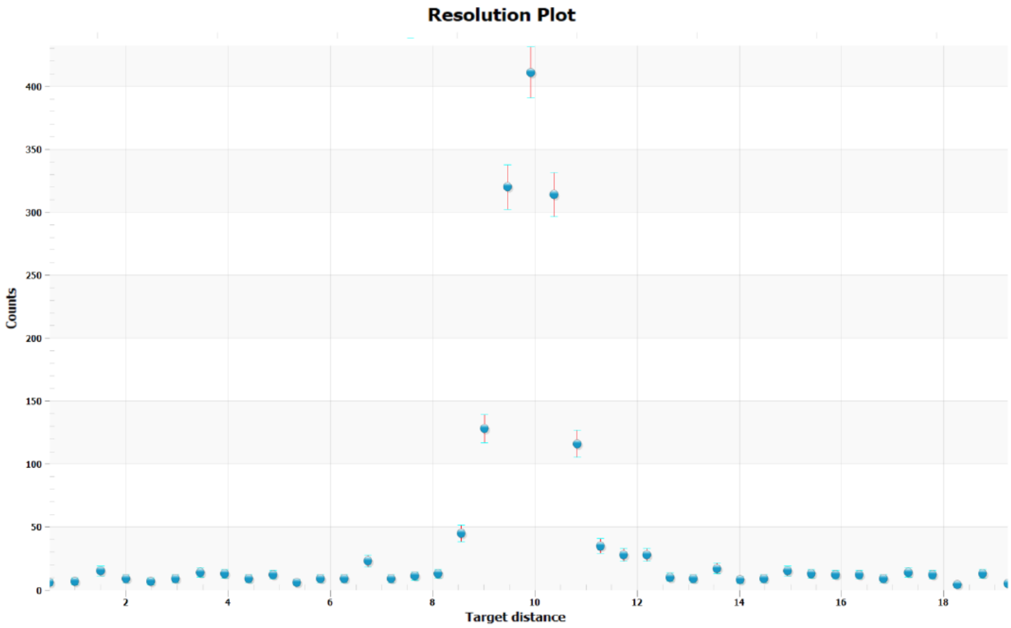


Fig. 6.11: Resolution measurement plot

Can you see γ spectrum?

Hardware Setup

SP5701 - EasyPET kit allows, in addition to the previous described functionalities, to digitize the detector signal and analyse the spectrum. In the following demo, SP5700 and DT5770 are connected via Mini USB to a computer equipped with Microsoft Windows 10 Professional 64-bit OS and an external AC/DC power supplies power both instruments.

Please, use only the power supplies shipped with these instruments and certified for the country of use.

The analog output of SP5700 is sent to the DT5770 Digital MCA through the MCX-BNC cable and the comparator or coincidence output can be used to trigger the MCA, as shown in Fig. 6.12. The EasyPET Software allows to control both devices and acquire data.

Fig. 6.12: The hardware setup including the EasyPET SP5700 and the Digital MCA DT5770

To be able to see a spectrum, the following steps have to be done:

- ✓ Plug the 12V power supply from a wall plug to the SP5700 mechanical base and switch ON the power button.
- ✓ Plug the MiniUSB cable from the EasyPET to the computer.
- ✓ Plug the 5V power supply from a wall plug to the DT5770 and switch ON the power button.
- ✓ Plug the MiniUSB cable from the DT5770 to the computer.
- ✓ Run EasyPET software and select the communication port. If only EasyPET is connected, the port will be selected automatically. Otherwise, make sure the right port is selected. Click the button “Connect”.
- ✓ Power ON the SiPM bias voltage, reduce the default thresholds values and press “Apply”.
- ✓ Open the Spectroscopy tab, and connect the DT5770. If the device is not already recognized, press “Refresh”.

The detector analog signal can be observed in the “DT5770 Signal” window by using Oscilloscope configuration, once “Start” was pressed. Looking the signal behaviour, gain and trigger can be set in the dedicated area.

To acquire the Multi-Photon Spectrum

Before to acquire the Multi-Photon spectrum, stop the active processes, in this case the Oscilloscope mode and run “Single Photon” Configuration via “Start”. Immediately, the spectrum starts growing in the display area due to pre-set parameters. The user can change the parameters value and zoom the histogram in order to optimize the data acquisition.

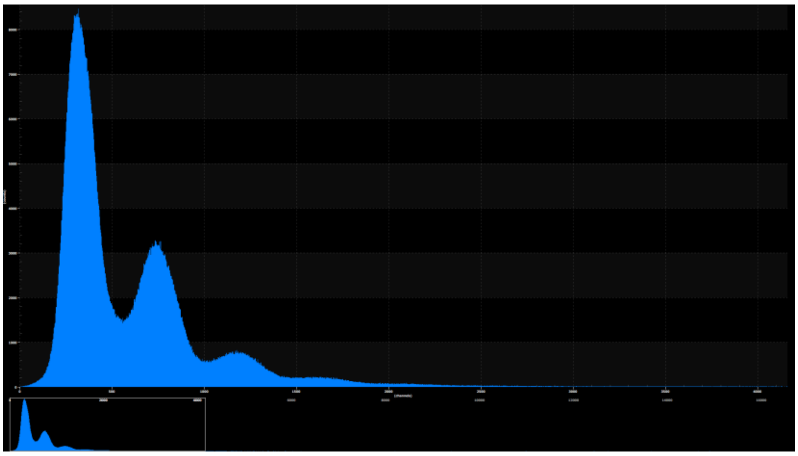


Fig. 6.13: Multi-Photon spectrum

As shown in Fig. 6.13, even without radioactive source contribution, more than one SiPM cell is fired due to DRC and the LYSO self-activity contributions sum. The multi-photon peak spectrum provides several information about the system in use; it is worth recalling here the fundamentals:

- The SiPM multiplication factor can be measured by the peak-to-peak distance. The linearity and the dynamic range of the sensor can be studied as well.
- The photon number resolving power can be obtained at glance and its dependence on the SiPM biasing conditions studied
- A genuine multi-photon peak spectrum fit can provide further insight, namely:
  - A measurement of the width of the Gaussian peaks against the number n of cells, where a trend of the form

    $$\sqrt{\sigma_0^2+\sigma_1^2 \times n^2}$$

    Is expected, being σ_0 related to the zero-photon peak width, so to the system noise, and σ_1 provides an indication of the cell-to-cell variation of the characteristics.
  - An independent measurement of the DCR and the cross-talk, as long as these terms are included in the fitting function
  - An information on the statistics of the emitted photons, usually retained to be Poissonian.
- Moreover, the SiPM biasing can be optimized, trading-off the avalanche triggering efficiency and the spectrum quality, possibly affected by the spurious dark counts.

It has been proved that on the single channel a threshold bigger than 450 mV is required to reduce to a negligible level the contribution of the DCR, which is equivalent to cut the three photons signals. By using the Trigger (LSB) to cut the first four peaks, the typical energy distribution of the LYSO self-activity can be observed.

To acquire the γ Spectrum

The intensity of the light measured by the detecting system (SIPM + scintillating crystal) is proportional to the γ source activity. However, this information is affected and biased by stochastic effects characteristic of the sensor and occurring within the time window: spurious avalanches due to thermally generated carriers (DCR).

Before to acquire a γ source spectrum, take care to measure this entry-level parameter of the SiPM. It is a standard procedure to quantify the DCR as the counting frequency with a threshold corresponding to 0.5 x single photo-electron (p.e.) peak (DCR0.5).

In order to avoid the system be blind to the radioactive source, due to DCR and LYSO auto-activity, a proper cut-off threshold has to be selected. Then the ^{22}Na source has been placed in the centre of the FOV and the spectroscopy signal of one channel has been integrated by triggering with the discriminator output at 450 mV of threshold (Fig. 6.14). By fitting the peak correspondent to 511 keV it can be inferred that the energy resolution is (25 ± 1) %, the peak-to-total ratio result to be (30.6 ± 0.1) % and the number of photons collected are 200 ± 3. In addition, it is possible to affirm that the spectroscopy signals are not saturated till 1275 keV, as its peak is visible in the energy spectrum.

By using several gamma sources placed very close to one detector, linearity study of the detected energy, the calibration of ADC channels in terms of energy (with the implemented Fitting Tool) and the measurement of the peaks resolution as a function of the energy are allowed. In addition, from the Multi-Photon spectrum it is possible to calculate the peak-to-peak distance and determine the number of photons collected at different energies during the acquisition of the radioactive sources spectra. This enables a measurement of the light collection and of the light detection efficiency.

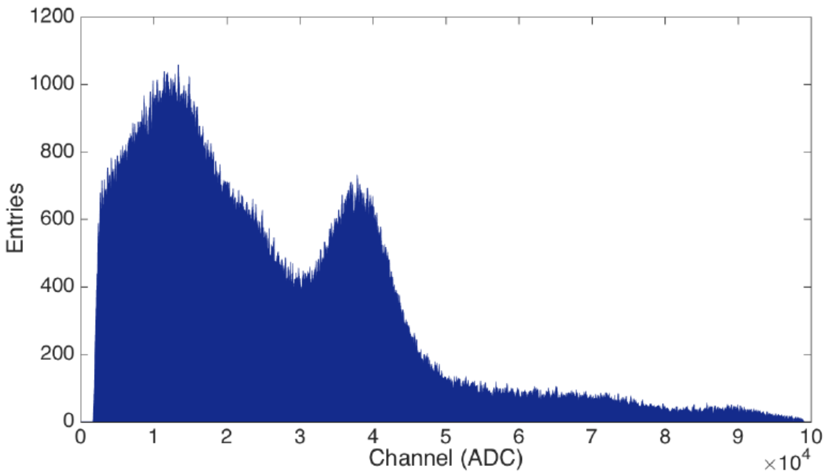


Fig. 6.14: The ^{22}Na spectra for the single channel

It is very interesting also to consider the energy distribution of the coincidence events. Fig. 6.15 illustrates the energy spectrum obtained acquiring the sensor analog output in presence of the Na22 source and using the coincidence signal output as the event trigger. The setup parameters are the same of the previous spectrum, with the additional condition of 120 ns time window width. It is easy to notice a reduction of the contribute of the system noise (peak in zero) with respect to the Compton continuum and the Photopeak. The Compton continuum is considered as a signal as well: the simple geometry of the system with only two opposite and aligned detectors and the implementation of the coincidence detection ensures that the Compton scattering occurring in one or even in both scintillating crystals comes from the same annihilation event.

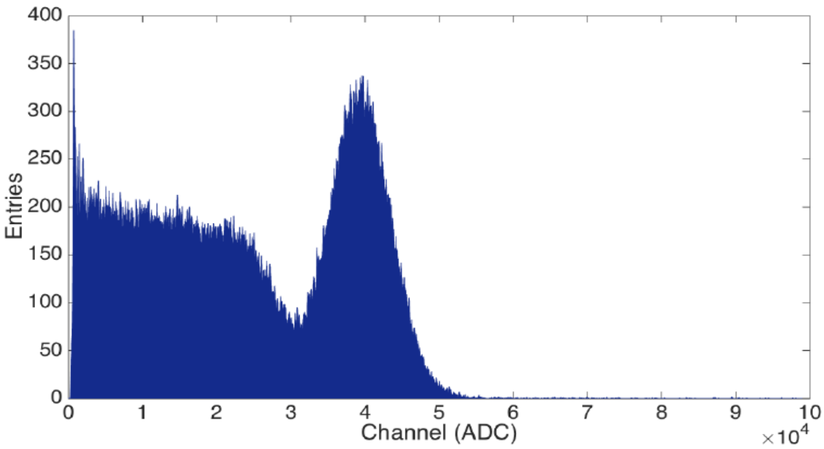


Fig. 6.15: The ^{22}Na spectra for coincidence

By considering the coincidence spectrum of the Sodium source, it is possible to determine the proper threshold which eliminates the noise contribute and allows to take into account only the true coincidences. As already explained before, the Calibration function can be used to determine the best position of the source and as a cross check on the choice of the discriminator threshold. In fact, by comparing the coincidence rates in absence and in presence of the Sodium source the student can be able to understand the importance of the energy discrimination in selecting the events. Once these preliminary measurements have been performed it is possible to start with the dedicated imaging studies and the realtime image reconstruction by back-projecting the acquired number of coincidence events at each position can be assessed.

Important Note: The DT5770 Signal shows only the signal acquired by DT5770, however during Spectrum acquisition it is possible to open the DT5770 signal tab and observe the trapezoidal filter applied to the signal in order to calculate the pulse height and the spectrum itself. This way offers to the user the possibility to check the correctness of digital shaping filters.

7 Educational Experiments

The SP5701-EasyPET Kit opens the possibility of teaching by doing the basics behind PET imaging, which is certainly an asset to high level educational laboratories.
Positron Emission Tomography (PET) scanner is the state-of-the-art medical imaging system, capable of providing detailed functional information of physiological processes inside the human body. PET represents a beautiful example of integration of skills and competences from medicine, nuclear chemistry, physics and information technology.
This section represents an overview of the experiments proposed by CAEN using the Educational kit of your choice. Each experiment has its own identification code (reference ID). For each ID, a step by step guide that includes a detailed description to perform the data analysis of the physical process is available on the CAEN Educational web page.
What is being proposed has to do with radioactive β and γ decays. When an unstable nucleus decays in a cascade leading to a stable nuclide, it emits α or β or γ quanta or a combination of them. The spectroscopy of the emitted γ or β rays is instrumental for understanding the mechanism of the interaction with matter, the fundamentals about detection and the underlying nuclear physics. Moreover, it is relevant in basic and applied fields of science and technology, from nuclear to medical physics, from archaeometry to homeland security. The experiments address the essence of the phenomenon as well as exemplary illustrations of their use in medical imaging, complemented by basic and advanced statistical exercises.
Some experiments proposed in this section are performed by using SP5700 - EasyPET standalone, other experiments need the DT5770 Multi Channel Analyzer together with CAEN portable didactic PET system, SP5701 - EasyPET kit.
Alternatively, if you already have one of the Caen educational kits, you can use the DT5720 in replacement of DT5770, but remember that the EasyPET Control Software does not work with this digitizer.

The experiments proposed by CAEN in Nuclear Imaging field are listed in Tab. 7.1.

Section	Subsection	Reference ID	Experiment	Equipment
Nuclear Physics and radioactivity	**Nuclear Imaging PET**	6131	Basic Measurements: γ Spectroscopy and System Linearity	SP5701 - EasyPET kit
		6132	Positron Annihilation Detection	SP5701 - EasyPET kit
		6133	Two-dimensional Reconstruction of a Radioactive Source	SP5700 - EasyPET
		6134	Spatial Resolution	SP5700 - EasyPET

Tab. 7.1: Physics Experiments performed via SP5600 and SP5701

Basic Measurements: γ Spectroscopy and System Linearity (ID.6131)

Purpose of the experiment:

Gamma spectroscopy studies by using a gamma radioactive source and by analysing the signals produced by the interaction of the gamma with one of the scintillating crystals of the system.

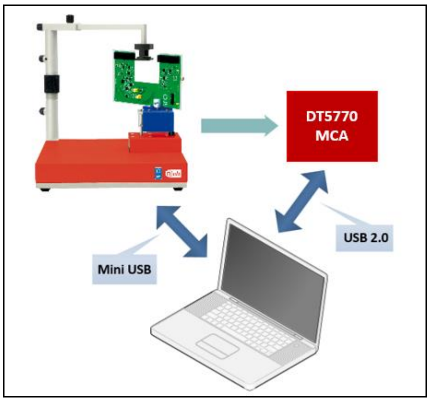
Fundamentals:

The EasyPET detector system is composed of two Silicon Photomultipliers (SiPM) coupled to scintillating crystals. The EasyPET operation principle is simple: the two small detector cells, each composed of a small scintillator crystal coupled to a silicon photomultiplier (SiPM), develop a signal when they detect a photon emitted by the source. In order to perform the gamma spectroscopy measurements using one of the two detector systems, it is important underline that the detector is characterized by a noise component, caused by spurious events occurring randomly and independently from the illumination field. This noise, called Dark Count Rate (DCR), depends mainly on the sensor technology and on the operating temperature, with a rate from 100kHz up to several MHz per mm^2 at 25 °C. The DCR decreases with the lowering of the temperature (about a factor 2 of DCR reduction every 8°C). In addition, the operating voltage has an impact on the DCR since it's connected to the electric field and as a consequence to the active volume of the sensor and to the triggering probability of the charge carrier. This noise component affects the resolution of a generic gamma spectrum composed of system noise peak Compton distribution and Photo-peak.

Requirements:

^{22}Na Radioactive source (recommended: 1/2-inch disc, 10 µCi)

Carrying out the experiment:

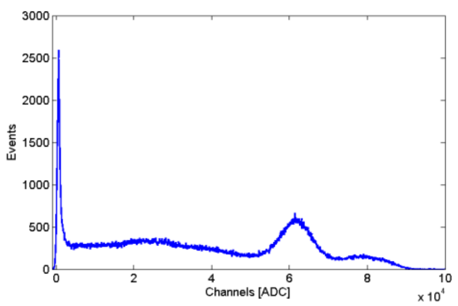


SP5701-Experimental setup block diagram

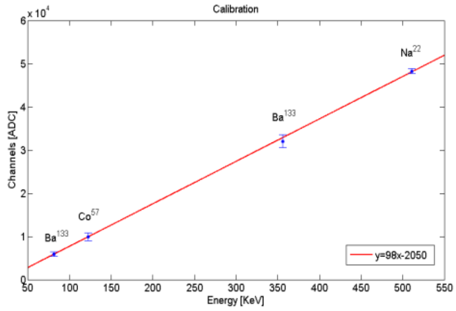
Mount the arm of the source holder on the column fixed to the system base, fix the U-shaped board to the top stepper motor and connect the flat cable to the U-shaped board and to the control unit. Connect to PC and power ON the system. Choose one detection system and connect its analog output to channel input of the DT5720A and use the digital output as digitizer "trigger IN" and choose the threshold in mV of the signal output. Place the radioactive source as close as possible to the detector chosen and acquire the energy spectrum thanks to a digitizer that perform charge integration by processing the signals exceeding a fixed threshold. Repeat the measurements with several gamma radioactive source in order to study the linearity system.

Results:

The γ spectrum shows the Compton continuum, related to the continuum of energies released by the Compton scattered electrons, and the Photo-Peak, the full-energy peak corresponding to the photoelectric absorption of the incident gamma. The peak around zero represents the system noise. The conversion between the channels number and the energy can be performed by a calibration. The system linearity is checked by using several radioactive sources. If the response of the system is linear, the output signals are directly proportional to the incident gamma energies.



Energy spectrum of ^{22}Na source.



Energy Calibration.

Positron Annihilation Detection (ID.6132)

Purpose of the experiment:

Positron annihilation detection by using a couple of detectors composed of a LYSO scintillating crystal coupled to a Silicon Photomultiplier (SiPM).

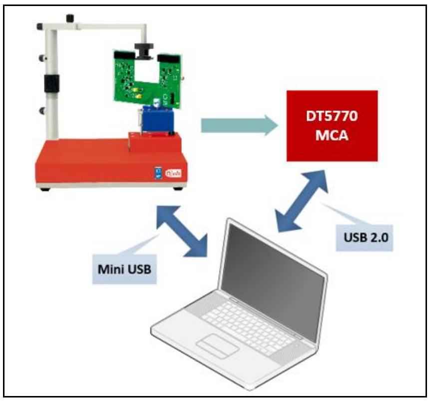
Fundamentals:

The underlying principle to PET systems is the detection of high energy radiation emitted from a chemical marker, a molecule labelled with a radioisotope, administered to a patient. The marker is properly chosen in order to associate to molecules involved in biochemical or metabolic processes under investigation. This allows studying the function of a particular organ or evaluating the presence of disease, revealed by the excessive concentration of the marker in specific locations of the body. The radioisotope emits positrons which, after annihilating with atomic electrons, result in the isotropic emission of two photons back to back with an energy of 511 keV. The two photons are detected by a ring of detectors, which allows a pair of them to detect two back to back photons in any direction. EasyPET comprehends only two detector modules that move together and execute two types of independent movements, around two rotation axes, so as to cover a field of view similar to that of a complete ring of detectors. A fast electronic readout system allows detecting coincident events resulting from the same decay process.

Requirements:

^{22}Na Radioactive source (recommended: 1/2-inch disc, 10 µCi)

Carrying out the experiment:

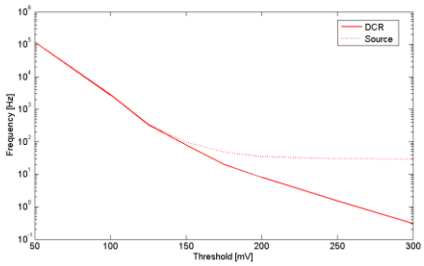


SP5701-Experimental setup block diagram

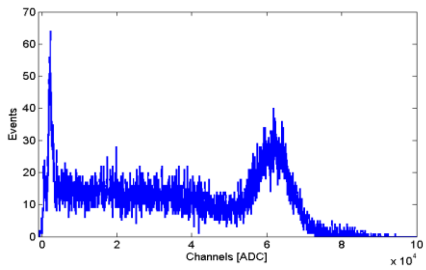
Mount the arm of the source holder on the column fixed on the system base, fix the U–shaped board to the top stepper motor and connect the flat cable to the U-shaped board and to control unit. Connect to PC and power ON the system. Connect the analog output of one detector to channel input of the DT5720A and use as digitizer “trigger IN” the coincidence output characterized by the occurring of the comparator output of each detector within a time window. Place the source holder between the two detectors and measure the DCR frequency as a function of the threshold. Place the 22Na radioactive source in the holder and repeat the measurement. Chose a threshold and acquire the coincidence spectrum thanks to a digitizer that perform charge integration by processing the signals exceeding a fixed threshold.

Results:

The coincidence detection allows to reduce significantly the system noise due to the SiPM DCR. In the optimization of the acquisition conditions, the coincidence detection introduces the parameter of the time window width in addition to the bias voltage and the threshold. In order to find the best parameter values is necessary to analyse the response of the system in coincidence mode to the radioactive source with respect to the random events, at fixed operating voltage. The simple geometry of the system with only two opposite and aligned detectors and the implementation of the coincidence detection ensures that, in the energy distribution, the Compton scattering occurring in one or even in both scintillating crystals comes from the same annihilation event.



Coincidence frequency, with and without 22Na source, as a function of the threshold.



Coincidence spectrum of ^{22}Na radioactive source.

Two-dimensional Reconstruction of a Radioactive Source (ID.6133)

Purpose of the experiment:

Understanding the technique of the nuclear imaging and the setup optimization of the parameters by performing two-dimensional image reconstruction of ^{22}Na radioactive source.

Fundamentals:

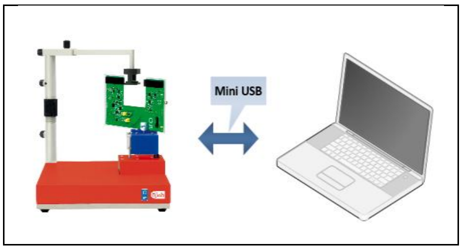
The EasyPET operation principle is simple: two detector modules move together and execute two types of independent movements, around two rotation axes, so as to cover a field of view similar to that of a complete ring of detectors.

The rotation movements are executed by two stepper motors. The bottom motor has a fixed axis, whose position defines the center of the field of view. The bottom motor supports and performs a complete rotation of a second motor, in predefined steps of amplitude α. The axis of the top motor is thus always positioned within a circumference of radius equal to the distance between the two axes. The top motor, in its turn, supports and moves a U-shaped printed circuit board, where a pair of aligned and collinear detector modules is mounted, performing a symmetric scan of range θ around the center, for each position of the bottom motor. In this way, EasyPET can reconstruct an image of a radioactive source placed anywhere within a cylindrical field of view between the pair of detectors. The diameter of the field of view is defined by the amplitude of θ, the range of the top motor scan.

Requirements:

^{22}Na Radioactive source (recommended: 1/2-inch disc, 10 µCi)

Carrying out the experiment:

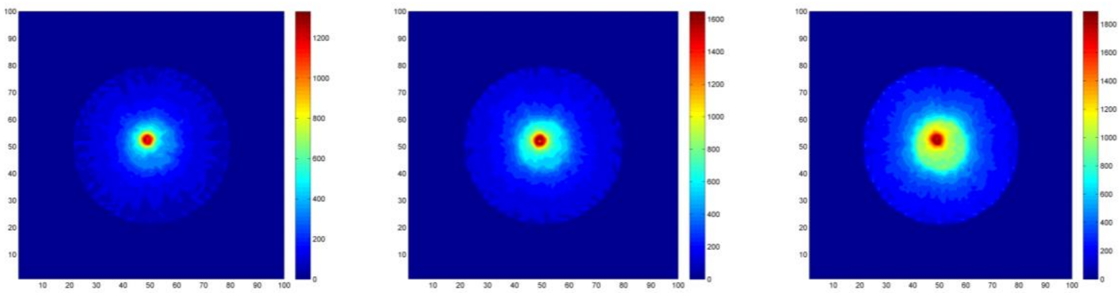


SP5700-Experimental setup block diagram

Mount the arm of the source holder on the column fixed on the system base, fix the U–shaped board to the top stepper motor and connect the flat cable to the U-shaped board and to control unit. Connect to PC and power ON the system. The parameters involved in the setup optimization for the two-dimensional reconstruction of the source image are three: the detectors operating voltage, the coincidence time window, and the threshold. Place the source holder between the two detector modules and tune the parameters to estimate the DCR contribution. Place the 22Na radioactive source in the holder and repeat the measurement tuning the parameters in order to obtain a good image reconstruction of the radioactive source.

Results:

Tuning the parameters, the students can directly observe and understand their effects on the imaging measurements. At fixed threshold, the image contrast changes due to the time window width. The use of the lowest possible coincidence time window of the system is mandatory to achieve a good image contrast. Fixing the bias voltage and the time window, it is interesting to observe how the threshold affects the image contrast. This parameter choice is dictated by a trade-off between the signal to noise ratio and efficiency maximization. The threshold value and the coincidence time window should be set by choosing the best compromise.



22Na source distribution image as a function of coincidence time window, at fixed threshold and bias voltage.

Spatial Resolution(ID.6134)

Purpose of the experiment:

Evaluation of the spatial resolution of a PET system composed of two detector modules.

Fundamentals:

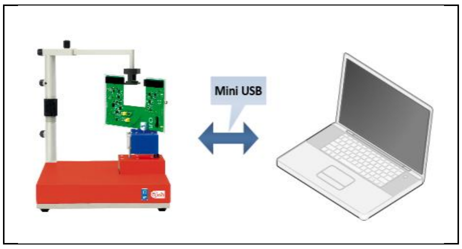
The main goal of the PET studies is to obtain a good quality and detailed image of an object by the PET scanner. The parameters involved and critical to good quality image formation are several: spatial resolution, sensitivity, noise, scattered radiations, and contrast.

The spatial resolution is fundamental characteristics of a tomographic system and its determination is mandatory for a PET system. The spatial resolution of a PET scanner is a measure of the ability of the device to faithfully reproduce the image of an object. It is empirically defined as the minimum distance between two points in an image that can be detected by a scanner.

In the EasyPET the dominant factor determining the spatial resolution is represented by the width of the scintillating crystals. Another effect that degrades the spatial resolution of the system is the so-called sampling error. It is associated to the distribution of the lines of response in the field of view and is a direct consequence of the rotation and scanning granularity.

Requirements:

^{22}Na Radioactive source (recommended: 1/2-inch disc, 10 µCi)



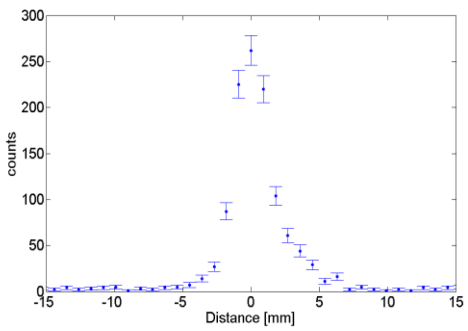
SP5700-Experimental setup block diagram

Carrying out the experiment:

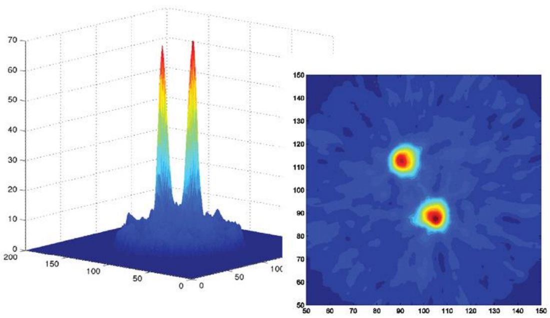
Mount the arm of the source holder on the column fixed on the system base, fix the U–shaped board to the top stepper motor and connect the flat cable to the U-shaped board and to control unit. Connect to PC and power ON the system. Set and optimize the parameters as bias voltage, threshold and coincidence time windows. In order to perform the spatial resolution measurement, the radioactive source is placed between the two detectors, on the line of response passing through the center. Its position is kept fixed while the system acquires the number of coincidence counts for successive scanning positions of the detector pair. The acquisition time is chosen in relation to the source activity to have enough statistics. The system response function is obtained plotting the number of coincidence counts for each position as a function of the distance between the source and the line of response (the distance is calculated as the product of the source-scanning axis distance and the scanning angle tangent). The resulting curve can be interpreted as the radioactive source distribution convoluted with the system spatial resolution.

Results:

The estimated spatial resolution is ~ (1.45 ±0.4) mm, which is comparable to the spatial resolution of the small animal PET systems.



Counting frequency of the beta rays as a function of the number of crossed paper sheets.



^{22}Na sources, 5 µCi, 2.7 mm Ø and 9 mm apart.

8 Devices Description

SP5700 - EasyPET

- **Single pair of collinear detectors executing two types of movements, a rotation and a scan, to provide the image reconstruction of off-centre source positions**
- **Reduced system complexity**
- **Intrinsic immunity to acollinear photon emission**
- **Intrinsic immunity to scatter radiation**
- **Intrinsic robustness against parallax error**
- **High spatial resolution (1.0-0.1 mm FWHM), uniform over the FOV**
- **MiniUSB 2.0 interface**

The EasyPET, protected concept under a patent filed by Aveiro University, aims to achieve a simple and affordable preclinical PET scanner. The innovative concept is based on a single pair of detector kept collinear during the whole data acquisition and a moving mechanism with two degrees of freedom to reproduce the functionalities of an entire PET ring. The main advantages are in terms of the reduction of the complexity and cost of the PET system. In addition, the concept is bound to be robust against acollinear photoemission, scatter radiation and parallax error. The sensitivity is expected to represent a fragility due to the reduced geometrical acceptance. This drawback can be partially recovered by the possibility to accept Compton scattering events without introducing image degradation effects, thanks to the sensor alignment [RD1].

Electronic Boards Description

Two electronic boards, U-shaped PCB and controller unit, constitute the system.

The Arduino UNO micro-controller is placed on U-PCB and allows to manage the micro-stepper motors. It is responsible for the settings of the SiPM bias voltage, the discriminator thresholds, the coincidence gate length and the coincidence counting for each system position. The parameters related to the motor movements are send to the control board, which allows to steer the stepper motor by providing ramp voltage signals to activate alternatively one or two coils. In this way, all the movements are very flowing, the oscillations and vibration of the U-shaped PCB are minimized providing an higher precision on the detecting unit position during the coincidence counting and a better coincidence detection efficiency.

The electronic circuit, sketched in Fig. 8.1, is integrated in the U-shaped board. It is composed by a power supply common for the two SiPM channels and each output passes through a first amplification stage. Then the signals are divided into two branches: the one dedicated to the spectroscopy is only constituted by a second amplifier, while the other used to implement the counting measurement has two additional amplification stages, in which one is also inverting, a leading edge discriminator and finally a coincidence logic which is common for the two channels of this branch. If the amplified signals from each detector exceed a fixed threshold and occur within a specific time validation window, they are considered as a coincidence event. For each scanning position, the number of coincidences occurring during the system stoppage time (both motors are at rest) is counted.

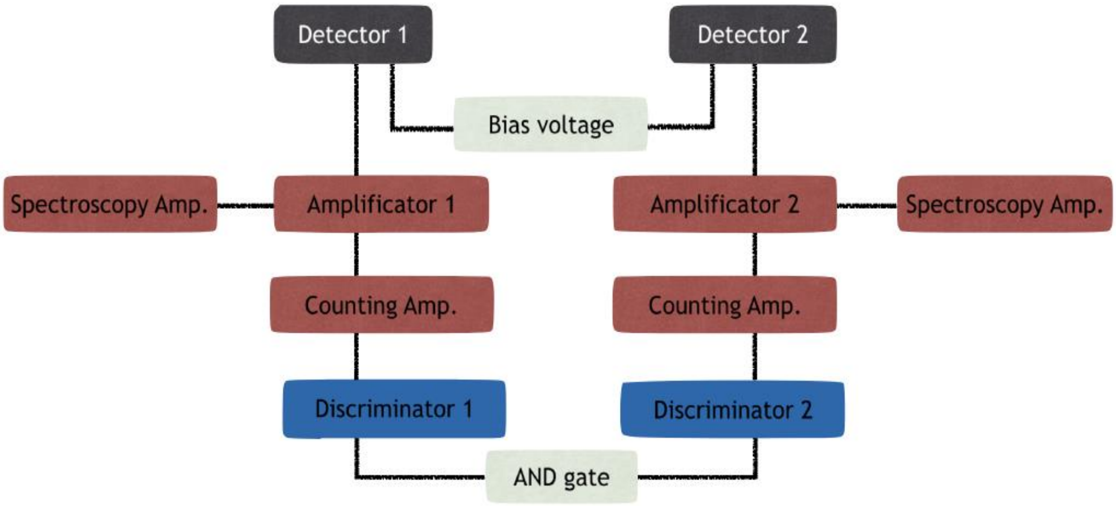


Fig. 8.1: The EasyPET electronic circuit scheme

The implementation of two amplification branches is advantageous considering the educational purposes because the students are guided from the SiPM characterization and the spectroscopy analysis towards the imaging principle with a unique device. The spectroscopy branch results to be very important in determining the proper energy threshold, measuring the energy resolution of the system, the threshold and channel calibration in energy units, assessing the system linearity, and in converting the light collected in number of photons.

The PCB is attached to two bipolar stepper motors (Fig. 8.2), that perform respectively the scan and the rotation. Each motor has a step angle of 1.8° with an accuracy of 5%, a mass of 0.22 Kg and a rotor inertia of 28 g/cm^2. The bottom motor rotates of 360°, while the top motor can scan a range of 180°. As a result, the FOV covered by the device is of 44 mm.

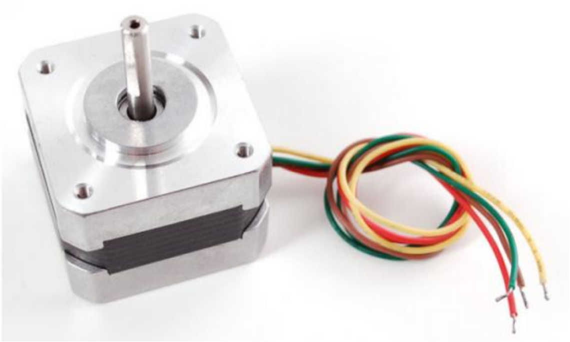


Fig. 8.2: Stepper motor produced by Astrosyn (type Y129**)**

The controller unit is placed inside the mechanical base of EasyPET. The power supply and the USB cables are connected to this board, then the information loaded by the user through the GUI control software are delivered to Arduino on the U-shaped PCB to be interpreted.

The most important figure of merit of the detecting unit performance consists in the coincidence detection efficiency, as it is the basic measurement of the EasyPET. It can be defined as the fraction of detected positron annihilation events with respect to the total number of back-to-back emitted photons. It depends both on the geometrical acceptance of the crystals and on the capability of the whole detecting unit to reveal the photons that fulfill the geometry requirements. This latter quantity is a function of the scintillating material, of the light collection efficiency, of the sensor features and of the electronic noise.

The results of the measured coincidence detection efficiency are summarized in the following picture. More in detail, the Coincidence Detection Efficiency is estimated (0.6 ± 0.2)% at 350 KeV threshold value, while is (2.9 ± 0.6)% at 150 KeV threshold value.

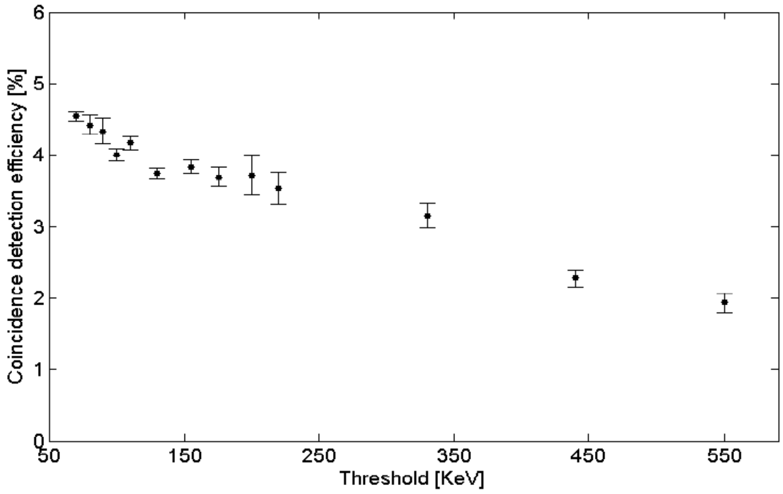


Fig. 8.3: EasyPET Coincidence detection efficiency as a function of Threshold

It can be inferred that the EasyPET concept allows to lower the energy threshold, accepting more events and enhancing the coincidence detection efficiency.

Moreover, the EasyPET sensitivity depends on the geometrical acceptance as well as on the detection efficiency of the coincidence γ emitted from the source. A geometrical acceptance of 2.2% is estimated considering the SP5700 geometry and a pointlike source placed in the system center and emitting back to back photons in coincidence [RD4].

Detecting Unit

The detecting unit is composed by a LYSO scintillating crystals with dimensions of 2×2×30 mm^3 wrapped with an aluminum foil to optimize the light collection by reflecting the light back into the crystal. The only face not covered by the aluminum is the one that is coupled with an optical grease to the SiPM. The light detector employed is a 1×1 mm^2 MPPC produced by HAMAMATSU. The LYSO crystal and the SiPM features are reported in Tab. 8.1 and Tab. 8.2.

Scintillating Crystal	
Density (g/cm^3)	7.18
Decay Time (ns)	40
Light Yield (ph./MeV)	32000
Peak emission (nm)	420
Radiation length (cm)	1.15
Reflective index	1.82

Tab. 8.1: Datasheet features provided by crystal producer

SiPM	
Area (mm^2)	1x1
Pixel size (μm)	50
Peak wavelength (nm)	440
PDE (%)	40
DCR (kHz)	100
Gain (10^5)	7.5

Tab. 8.2: Datasheet features provided by HAMAMATSU

As shown in Fig. 8.4, a small board is used to house the Surface Mount Device (SMD) SiPM. It is also equipped with pins that can be soldered on the PCB exploiting specific designed and drilled holes to guarantee precision and reproducibility of the sensor positioning. As a result, the two front faces of the crystals are at a distance of 5.77 cm. The whole detecting unit is covered with black tape to avoid the room light to impinging on the SiPM.

Fig. 8.4: LYSO crystals 2×2×30 mm^3 by Kinheng Crystal and 1×1 mm^2 MPPC (S10362-11-050P) produced by HAMAMATSU Photonics. On the right side, The EasyPET light-tight case with the housing for the scintillating crystal and the SiPM sensor

Power Requirements

The SP5700-EasyPET is powered by the external AC/DC stabilized power supply provided with the digitizer and included in the delivered suitcase.

Note.: Using a different power supply source, like battery or linear type, it is recommended the source to provide +12 V and, at least, 3.5 A; the power jack is a 2.1 mm type, a suitable cable is the RS 656-3816 type (or similar)

Fig. 8.5: AC/DC power supply provided with the module

DT5770 – Digital Multichannel Analyzer

- **Compact portable 16k Digital MCA**
- **Suited for high resolution Gamma Spectroscopy**
- **Support continuous and pulsed reset preamplifiers**
- **Software selectable coarse and fine gain**
- **DB9 connector for preamplifier power supply**
- **Features Pulse Height Analysis and Charge Integration firmware for energy calculation**
- **Different acquisition modes available: PHA and signal inspector for an easy setup and signal monitoring**
- **USB and Ethernet communication interfaces**

The DT5770 is a compact portable Digital MCA for Gamma spectroscopy. It is suited for high energy resolution semiconductor detectors, like HPGe and Silicon Drift Detector, connected to a Charge Sensitive Preamplifier (CPS). The unit can also properly operate directly connected to a PMT with inorganic scintillators (e.g. NaI or CsI scintillators), provided exponential pulse shape and decay time above 200 ns. It integrates analog front-end with programmable gain and possible AC coupling.

The DT5770 features:

- **1x 150 MS/s 14-bit ADC** on single ended input with BNC connector, featuring 4-step configurable input range (1.25 / 2.5 / 5 / 10 Vpp) and adjustable DC offset via a 10-bit DAC on each input in the full range.
- **1x ±12 V (100 mA) and ±24 V (50 mA) PREAMP bias output** through DB9 connector for preamplifier power supply.

The Digital MCA is equipped with two different firmwares for energy calculation:

- **DPP-PHA Firmware**, that is a Digital Pulse Processing algorithm making the board a spectroscopy acquisition system providing energy spectra (i.e. pulse height histograms) as well as portions of the waveform for debugging, monitoring and pulse shape analysis.
- **DPP-CI Firmware**, that is a digital solution replacing QDC + Discriminator + Gate Generator.

DT5770 houses USB 2.0 and Ethernet interfaces as communication links for configuration, firmware upgrade and data collection.

In the SP5701-EasyPET Kit, the DT5770 is meant to be used with the SP5700 to perform spectroscopic analysis of the signals coming from the U-PCB detection units, both made by a LYSO scintillating crystal coupled to Silicon Photomultiplier.

The following list summarizes what can be done by the Digital MCA in combination with the EasyPET Software:

- receive the signals coming from the SP5700 and adapt to the dynamic range (by the programmable DC offset and Gain);
- detect input pulses and generate a local trigger on them;
- calculate the pulse height by means of digital shaping filters (trapezoidal filters);
- detect pile-up conditions and manage the count loss (dead-time);
- get the spectra internally generated (on-board) through USB or Ethernet link.

- accumulate, plot and save the histograms (energy spectra over up to 16k channels), compensate for the dead-time;
- generate output files (histograms) in Comma Separated Values (.csv) format.
- run the signal inspector that plots the waveforms of the input signals as well as of the internal filters in order to adjust the parameters of the acquisition.

Panels Description

The unit is a Desktop module housed in an alloy box. As shown in Fig. 8.6, the Front Panel is provided with power button (1), OLED display (2) showing acquisition information, one BNC Input connector (5) receiving the analog signals from the detectors and two LEMO connectors: the first one (3) is a general purpose digital input or output, programmed as Trigger IN for the PET application, the second one (4) is another general purpose digital input or output and analog output.

Fig. 8.6: DT5770 Front Panel

The Rear Panel is equipped with connectors to power the device and communicate with computer. Following the indicated numbers in Fig. 8.7, it is possible to observe an Ethernet input (1) to control the DT5770 for configuration, data collection and firmware upgrade, one connector for preamplifier power supply (2), a MiniUSB connector for USB connection to the DT5770 and the power supply DC input connector (4).

Fig. 8.7: DT5770 Rear Panel view

Note on Operating

In PET application, the DT5770 operates on the analog signals provided on its input by applying a PHA algorithm implemented in the equipped DPP-PHA Firmware for the Digital Pulse Height Analysis.

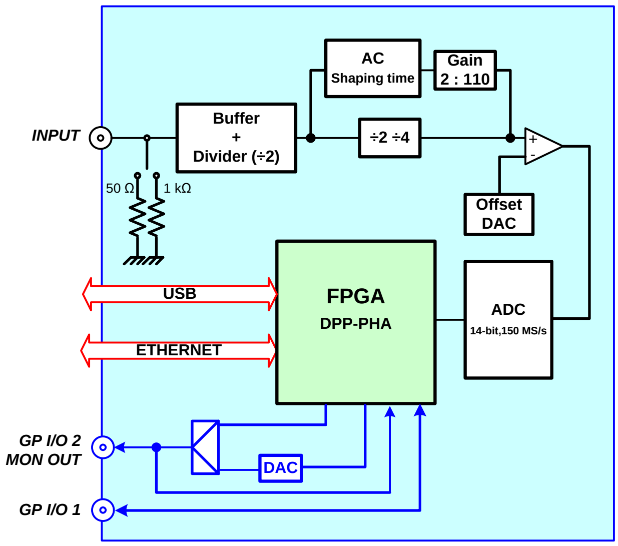


Fig. 8.8: Simplified functional diagram of the DT5770

DT5770 is an acquisition system that receives the analog signal and performs the A/D conversion (@150 MS/s, 14 bit) at the input of the module, just after an analog input stage whose purpose is to adapt the signal voltage swing to the dynamic range of the ADC. After the A/D conversion, the stream of samples is managed by an FPGA programmed to perform on-line Digital Pulse Processing in order to implement the MCA based on the Pulse Height Analysis (DPP-PHA); the algorithms implemented in the DPP-PHA firmware are based on the trapezoidal filter (Moving Window Deconvolution) for the calculation of the pulse height. The energy spectra are build up in the on-board FPGA and made available for the readout.

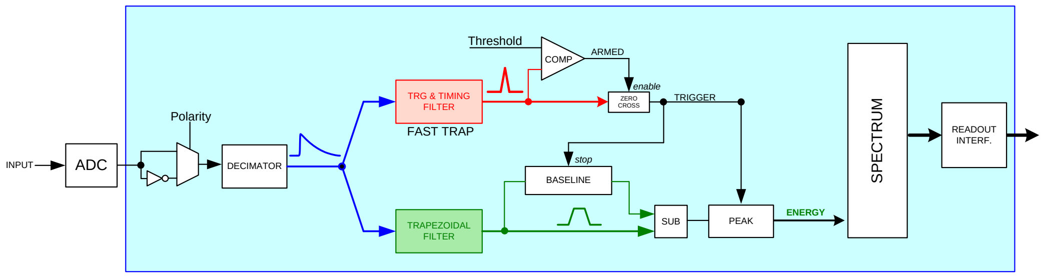


Fig. 8.9: Block diagram of the processing chain programmed into the FPGA

For details about the Technical specifications of the DT5770 and MCA architecture, please refer to the DT5770 User manual [RD5].

Power Requirements

The module can be powered by the external AC/DC stabilized power supply provided with the digitizer and included in the delivered kit (5 VDC, 3.5 A).

Note.: Using a different power supply source, like battery or linear type, it is recommended the source to provide +5 VDC and at least 1.5 A +10%; the power jack is a 2.1 mm type, a suitable cable is the RS 656-3816 type (or similar).

Fig. 8.10: AC/DC power supply unit for DT5770

9 Technical Support

CAEN experts can provide technical support at the e-mail addresses below:

support.nuclear@caen.it
(for questions about the hardware)

support.computing@caen.it
(for questions about software and libraries)

educational@caen.it
(for questions about Educational Solutions)

Appendix A

About EasyPET Algorithms[1]

The Image Reconstruction Algorithm

The data are acquired in list mode and event by event the angular position of both motors and the number of coincidence counts are saved. The online image reconstruction is performed using the simplest algorithm, the back-projection, which is the inverse of the projection process generating the acquired data. The basic idea consists in the discretization of the FOV in order to create a correspondence between the line of response and the pixels of the image.

A matrix of 10×10 cm, enough to contain the maximum possible FOV, is created, representing the image of the FOV itself. The matrix is constituted by elements of a dimension that can be chosen in the range 0.5-2 mm, reproducing the desired granularity of the final image. Then, event by event, the angular position of the motors is converted in Cartesian coordinates to determine the position of the crystals front face in the matrix. The LOR is the straight line connecting the two crystal front face positions. In order to establish which elements of the matrix described the LOR a weighting algorithm is applied. The procedure is schematized in Fig. A.1. As a first step, the projection of the LOR on the x axis of the matrix is divided in many elements as the matrix size (X). Then the elements of the projection of the LOR on the y axis (Y) are obtained by applying the transformation given by the straight line:

$$Y = mX + q$$

where m and q are determined by the two crystal front face positions. As a result, the element step is different on the two axes and their ratio depends on the LOR angle with respect to the x axis. The correspondence between the elements of X-Y and of x-y is determined with a proportion and a rounding up to the higher entire element value. The net effect is the assignation of multiple elements of X-Y to the same element in x-y. As a final step, the elements the matrix elements with coordinates (v_x; v_y) are filled with the number of coincidence counts recorded for that specific motors position. In practice, only the elements of the matrix crossed by a certain portion of the LOR are taken into account for the reconstruction of the image. The fact that the number of coincidences is assigned to each selected element means that each point of the line has the same probability to be the emission source, the assumption of non TOF-PET devices [RD1].

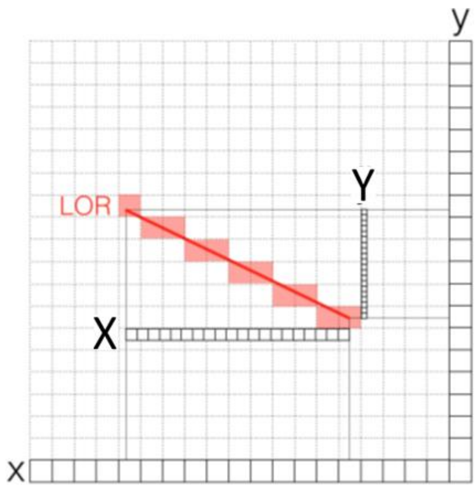


Fig. A.1: The image reconstruction algorithm [RD1]

[1] Appendix related to EasyPET is entirely taken from the PhD Thesis [RD1].

Spatial Resolution

The spatial resolution can be defined as the smallest distinguishable detail level of an image. The NEMA procedure states that the spatial resolution is measured from the FWHM of a point-like source response function, obtained by the projections of the reconstructed image in the x, y and z directions [RD8]. The procedure to determine the spatial resolution is based on the coincidence events counting and can be accomplished even with an extended radioactive source. In fact, the source in use is a 3 µCi ^{22}Na radioactive solution deposited into a 6 mm diameter well in a plastic disk 3 mm thick. The well is filled with an epoxy sealing the radioactive material inside the source. When the source is positioned vertically its activity distribution results to have a sharp edge on one side and a smoothed edge on the other one, as shown in the scheme of Fig. A.2. The properties of the response function of a sharp edge is exploited in order to measure the system spatial resolution without the need to describe exactly the source activity distribution.

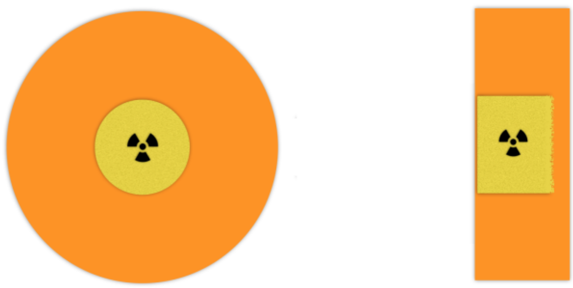


Fig. A.2: The top and side view of the ^{22}Na source scheme (not to scale): the radioactive liquid (yellow) is encapsulated into a plastic enclosure (orange) with a sharp edge on the left and a smoothed edge on the right

The measurement can be perform using the dedicated operation mode programmed in the EasyPET Control Software, and its layout is sketched in Fig. A.3. The ^{22}Na source is placed vertically in the centre of the FOV. The EasyPET performs a scan around the source, symmetrically with respect to the system centre ("Source Position" is set to 0 mm in the software) and for each scanning position the number of coincident events is counted and recorded. The granularity of the scan movement is fixed at 0.9°, the lowest achievable with the EasyPET. Instead, the range of the scan, θ, can be selected by the user, together with the time of data acquisition at each position, which optimal value depends on the source activity. The EasyPET response function is obtained by counting the coincidence events for 30 s in each scanning position, at different source-detectors distances. In Fig. A.4 are reported the number of coincidence counts as a function of the distance D, defined as the distance between the source and the line connecting the front faces of the crystals and calculated at each scanning position i as:

$$D_i = r * tg\ \theta_i$$

where r is half the distance between the two detectors and θ_i is the angular position of the top motor at each step.

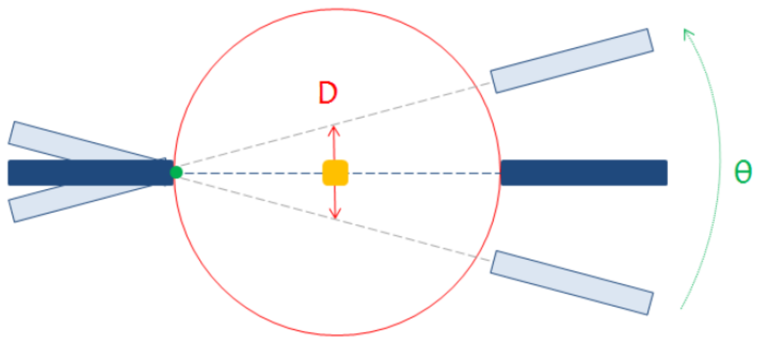


Fig. A.3: The EasyPET setup for position resolution measurement

It can be easily noticed an asymmetry in the distribution: the left side of the peak has a Gaussian behaviour and represents the EasyPET response function to the sharp edge of the source activity distribution, while the righthand one has a wider spread, corresponding to the smoothed edge of the sealed radioactive liquid.

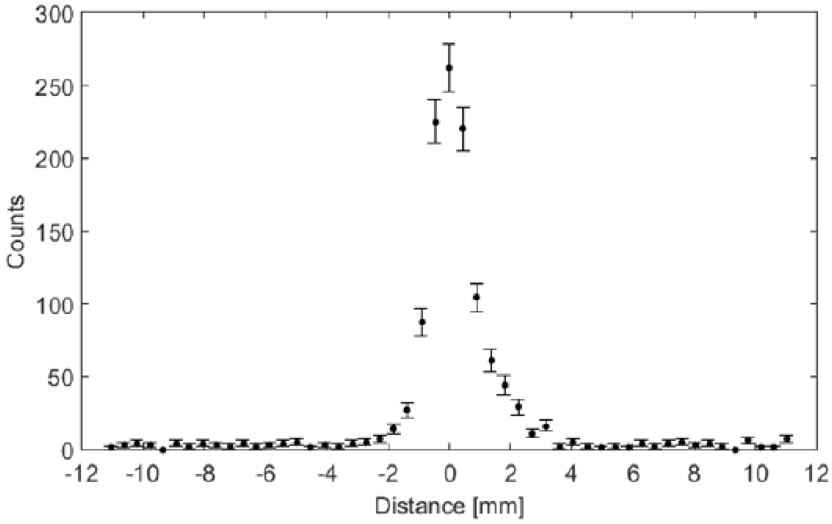


Fig. A.4: The EasyPET coincidence counts measured using a 3 µCi ^{22}Na source as a function of the distance D

The EasyPET spatial resolution can be determined by considering that a sharp edge activity distribution, described with a Step function, is convoluted with a Gaussian function representing the spread induce by the detecting system to produce the edge imaging. Consequently, the derivative of the measured edge response function results to be the Gaussian describing the detecting system, whose FWHM represents its spatial resolution. The plot in Fig. A.5 reports the gradient applied to the data points of Fig. A.4. The first peak corresponds to the derivative of the edge response function and can be fitted with a Gaussian function, shown in red. The values obtained for the fit parameters are reported in Tab. A.1. A spatial resolution of (1.0 ± 0.1) mm FWHM is obtained from the Gaussian fit parameters.

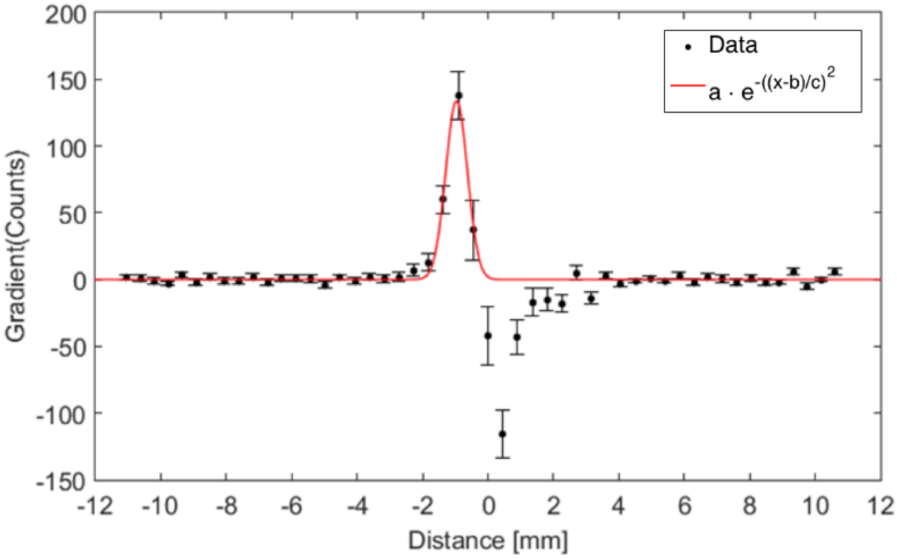


Fig. A.5: The EasyPET The EasyPET gradient of the counts measured using a 5 µCi ^{22}Na source as a function of the distance D

Fit Parameter	Result value
a	134 ± 19
b	-0.97 ± 0.07
c	0.58 ± 0.08

Tab. A.1: Fit parameters and result values of the Gaussian function to the gradient of the number of coincidence counts as a function of the distance D

The EasyPET spatial resolution is expected to be uniform over all the FOV. In fact, irrespective of the source position, the detection of a coincidence will occur only when the source lies on the line connecting the two detectors, avoiding the parallax error. The measurement of the spatial resolution proposed here is independent from the source position, indicating that the result holds in all the FOV. A test has been performed by imaging the same ^{22}Na source with an activity of 3 µCi and a diameter of 6 mm for the same amount of time but placed in two different regions of the FOV. An elliptic fit to the data points corresponding to five times the background contribution is applied to evaluate the reconstructed source dimension. The length of the axes of the two ellipses are compatible: 6.6 mm and 7 mm for the source in the centre and 6.8 mm and 7.2 mm for the source in the off-centre position. The result indicates that the spatial resolution is uniform in all the FOV. Fig. A.6 shows the reconstructed images of the source placed in the centre and in a peripheral region of the FOV, respectively.

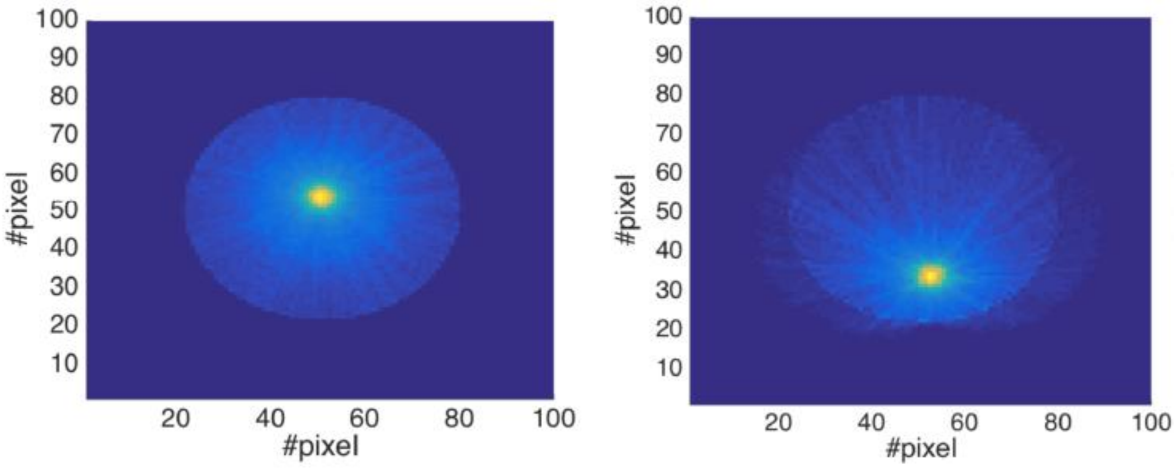


Fig. A.6: Images of the source placed in the centre of the FOV (left) and in a peripheral region (right)

An exemplary illustration of the EasyPET capability in terms of spatial resolution is depicted in Fig. A.7, representing the back-projected image of a PMMA phantom consisting of two wells filled with ^{18}FDG, with a diameter of 5 mm and 2 mm and separated by a thickness of 1 mm. In the reconstructed image, the two source distributions are clearly distinguishable, confirming the measured spatial resolution of 1.0 mm.

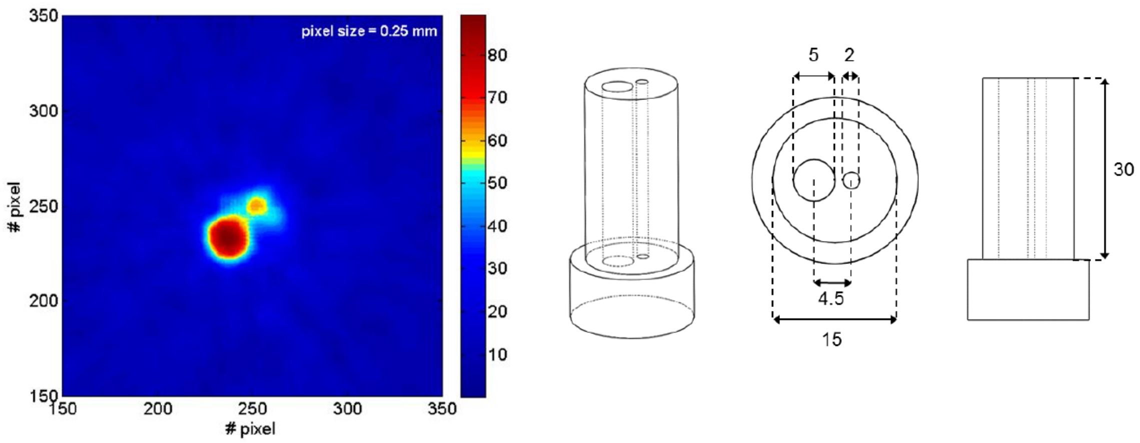


Fig. A.7: Image of two wells in a PMMA phantom filled with ^{18}FDG obtained acquiring a total number of 6150 events in 24 minutes (left) and the schematic layout of the phantom with all the dimensions in mm (right)

CAEN SpA is acknowledged as the only company in the world providing a complete range of High/Low Voltage Power Supply systems and Front-End/Data Acquisition modules which meet IEEE Standards for Nuclear and Particle Physics. Extensive Research and Development capabilities have allowed CAEN SpA to play an important, long term role in this field. Our activities have always been at the forefront of technology, thanks to years of intensive collaborations with the most important Research Centres of the world. Our products appeal to a wide range of customers including engineers, scientists and technical professionals who all trust them to help achieve their goals faster and more effectively.

CAEN S.p.A.
Via Vetraia, 11
55049 Viareggio
Italy
Tel. +39.0584.388.398
Fax +39.0584.388.959
info@caen.it
www.caen.it

CAEN GmbH
Eckehardweg 10
42653 Solingen
Germany
Tel. +49.212.2544077
Mobile +49(0)15116548484
Fax +49.212.2544079
info@caen-de.com
www.caen-de.com

CAEN Technologies, Inc.
1140 Bay Street - Suite 2 C
Staten Island, NY 10305
USA
Tel. +1.718.981.0401
Fax +1.718.556.9185
info@caentechnologies.com
www.caentechnologies.com

CAEN *Tools for Discovery*

Electronic Instrumentation

GD6258 - SP5701 EasyPET Kit rev. 1 - 10 October 2017

00100-0-SIPM0-G000