



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

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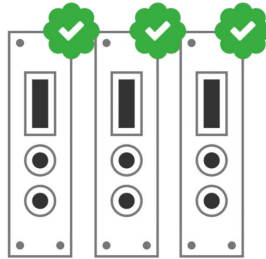
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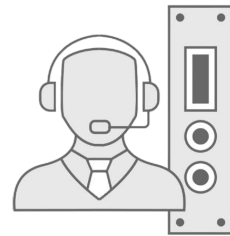
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Purpose of this Guide

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

Change Document Record

Date	Revision	Changes
July 21 st , 2017	00	Initial release.
October 10 th , 2017	01	Modified "Software Interface" paragraph in Chap.5
June 19 th , 2018	02	Modified "Getting Started" and "Calibration" paragraph in Chap.6

Symbols, abbreviated terms and notation


DPP	Digital Pulse Processing
OS	Operating System
SiPM	Silicon Photo-Multiplier
U-PCB	U-shaped Printed Circuit Board

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, 2^a 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] 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>

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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, SP5700**, 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 Physics 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 is to inspire students and guide them towards the analysis and comprehension of different physics phenomena.

The SP5700 EasyPET comprises:

- 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.2 MCX-LEMO cables.
- Nr.1 MCX-BNC cable.
- MiniUSB cable.
- 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. The description of this guide is compliant with the following products.



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

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 their 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.

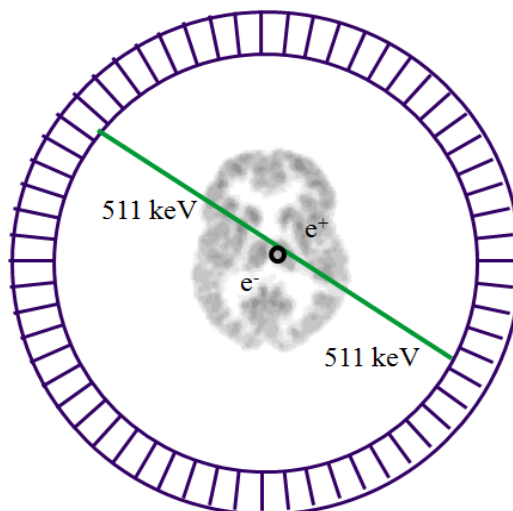


Fig. 3.1: Positron Emission Tomography (PET) general scheme

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).

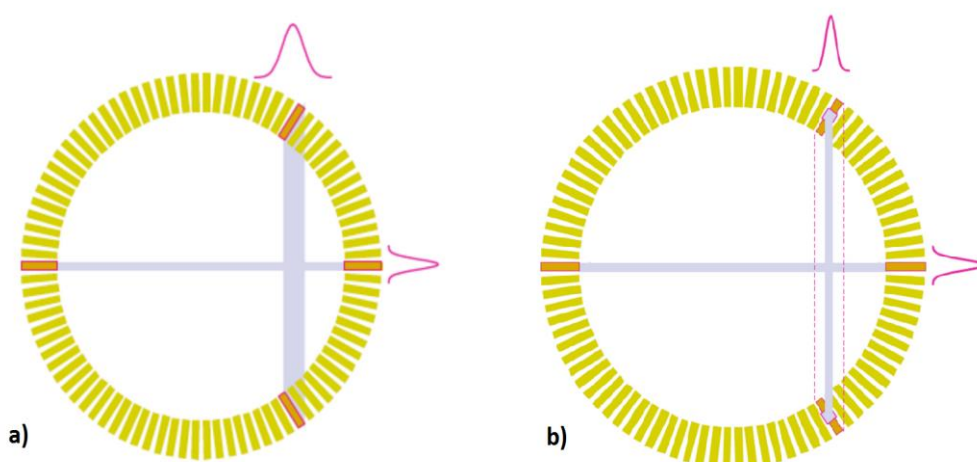


Fig. 3.2: a) The parallax error in the periphery of the field of view. b) The depth of interaction information improves the spatial resolution

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.

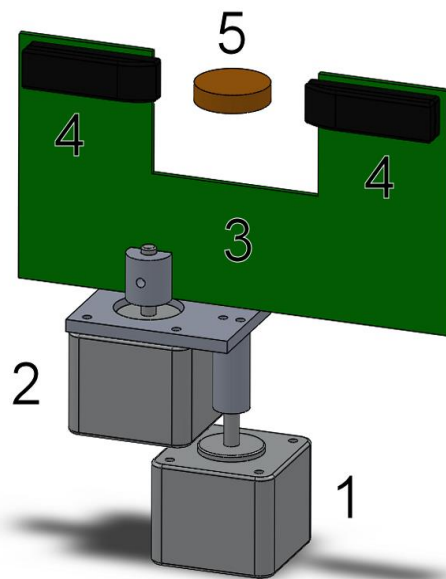


Fig. 4.1: The EasyPET component layout: 1 - bottom motor, 2 - top motor, 3 - U-shaped PCB, 4 - pair of detector modules, 5 -- radioactive source

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.

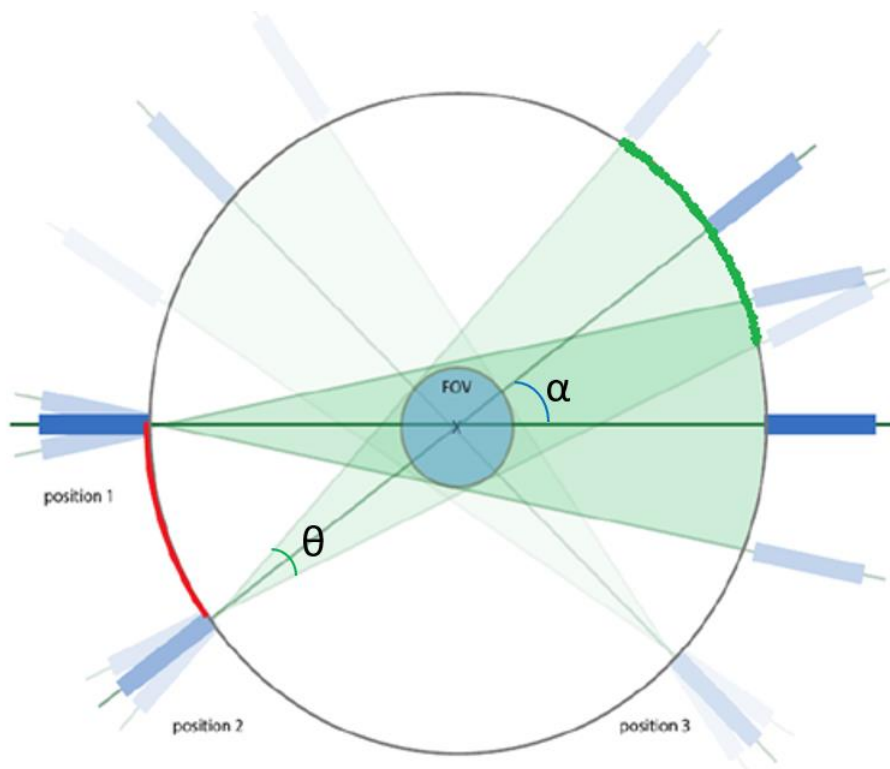


Fig. 4.2: Top-view schematics of the EasyPET image acquisition method with two axes of rotation. α represents the angle step of the bottom motor rotation, while θ represents the scanning angle of the top stepper motor. The two axes are used to move one pair of scintillation detectors (blue rectangles)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

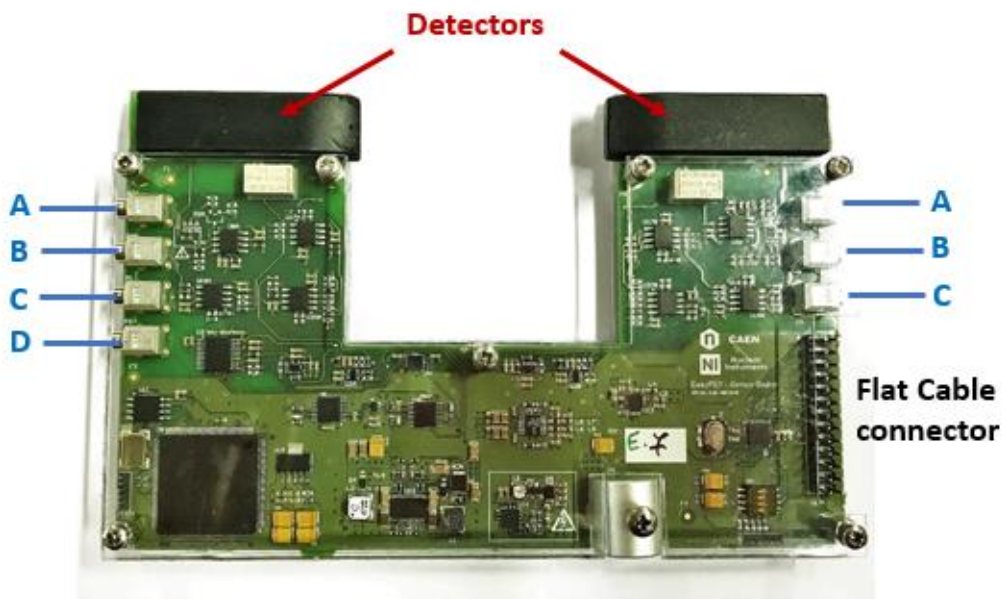


Fig. 5.1: U-PCB with two detector cells (black plastic holders). The board is equipped with electronics used for SiPMs supply voltage, signal readout and coincidence detection

- **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 employment of two position sensors required to the correct alignment of the stepper motors 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.

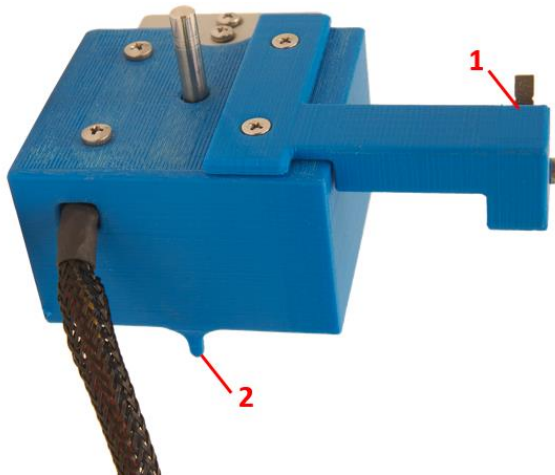


Fig. 5.2: Top Stepper motor is responsible for scanning

- **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.

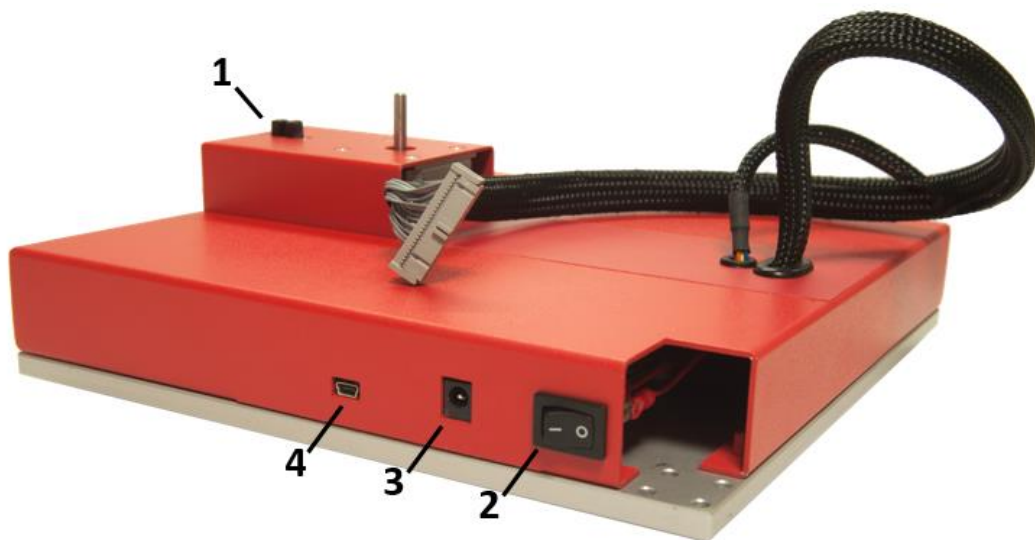


Fig. 5.3: Mechanical base of EasyPET

- **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 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. The other two knobs (2) and (3) can be used as clutch in order to obtain controlled movements in vertical and radial direction. Indeed, the knob (2) on the vertical arm allows to arrange horizontal arm position with

respect to the vertical one by describing an arc of circumference. A strong clamp of the knobs (2) and (3) has to be avoided because it can produce a shift in the chosen position for the radioactive source. 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.

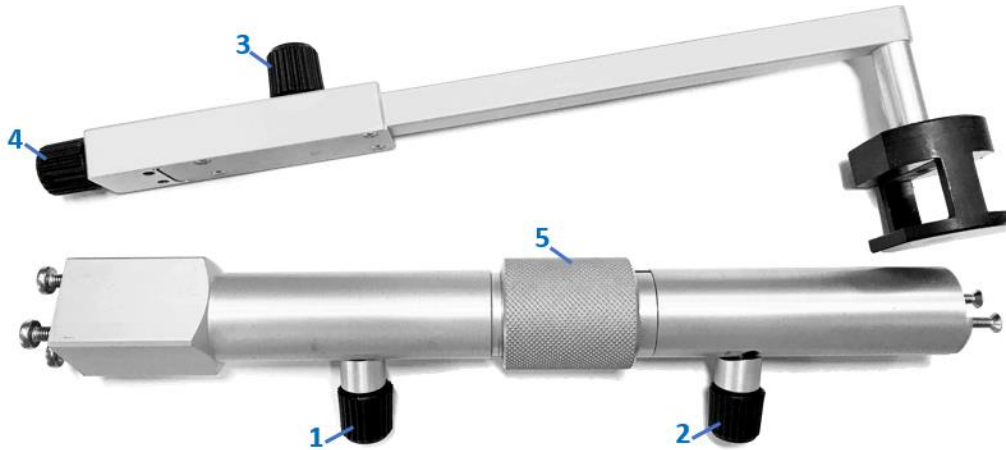


Fig. 5.4: Mechanical support for the source. In the picture, the source holder is already mounted

- **Two radioactive source plastic holders.**

Depending on the measurement type, two holders are available to put 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

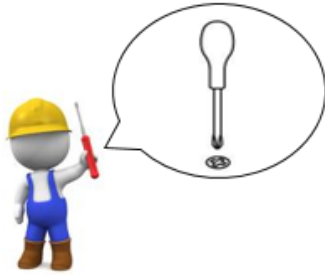
Important Note: The suitcase contents depend on what user choose:



- 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.

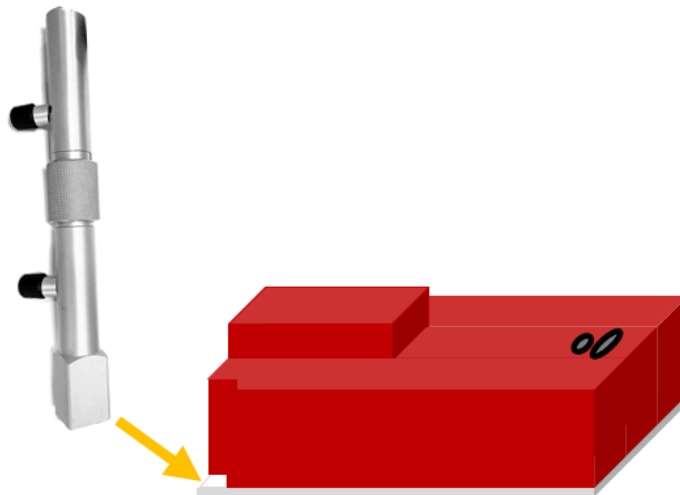
What do you need?

Required tools: Cross screwdriver

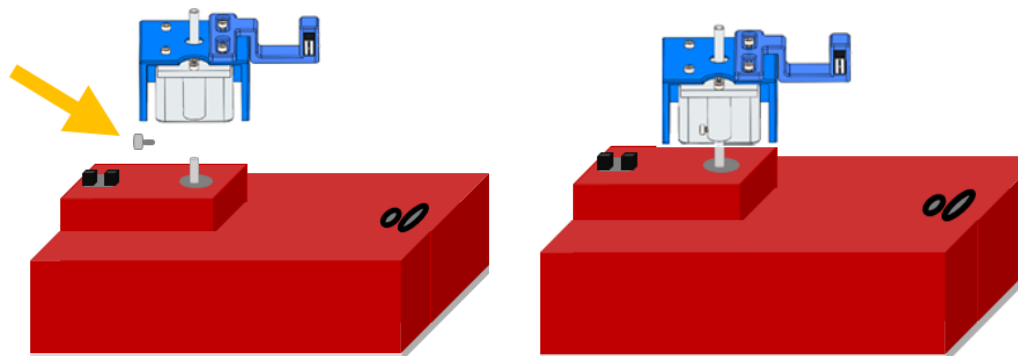


Building the EasyPET system

- 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.

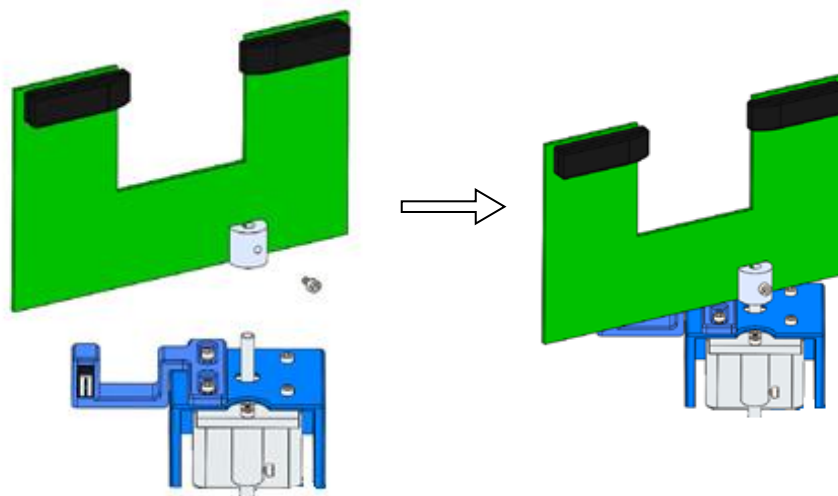


- Fix the top motor to the bottom motor axis placed on the mechanical base.**
 Attach cylindrical support to the axis of bottom motor and carefully tighten the screw (be careful not to tighten too much and damage the screw). Make sure the top motor can rotate freely with the marker passing through the 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.

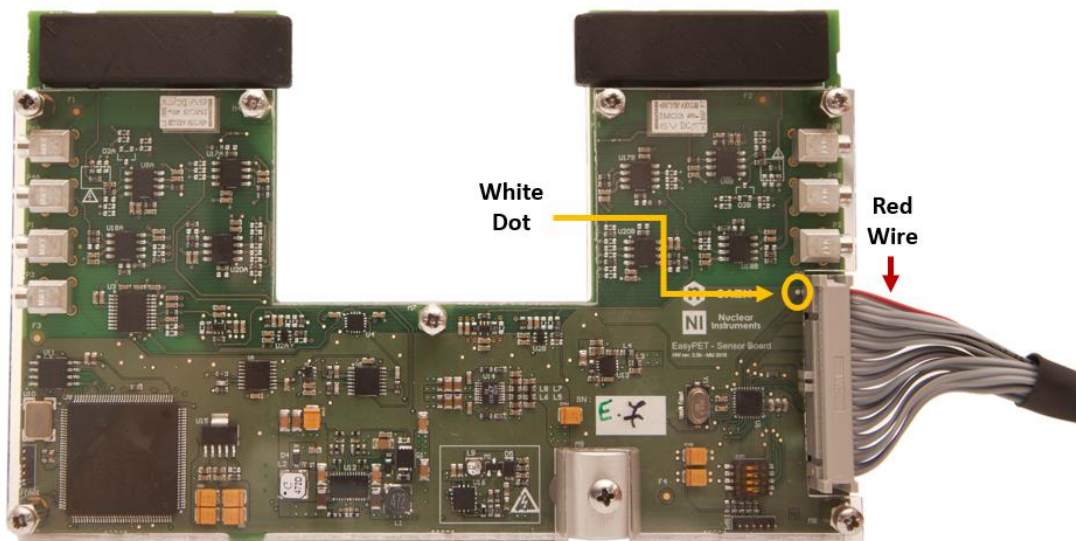


Fig. 5.6: Connection between U-PCB and flat cable

- **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

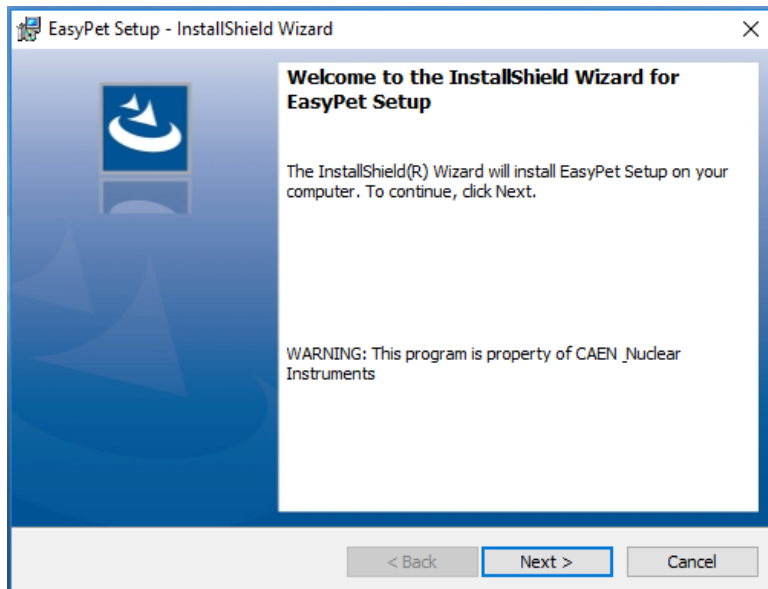
EasyPET is managed through a Graphic User Interface (GUI), developed in Visual Basic, which allows setting the acquisition parameters, performing the acquisition, visualizing the reconstructed image in real time during acquisition and recording the data for the offline analysis, performing calibration 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 related only to EasyPET employment.

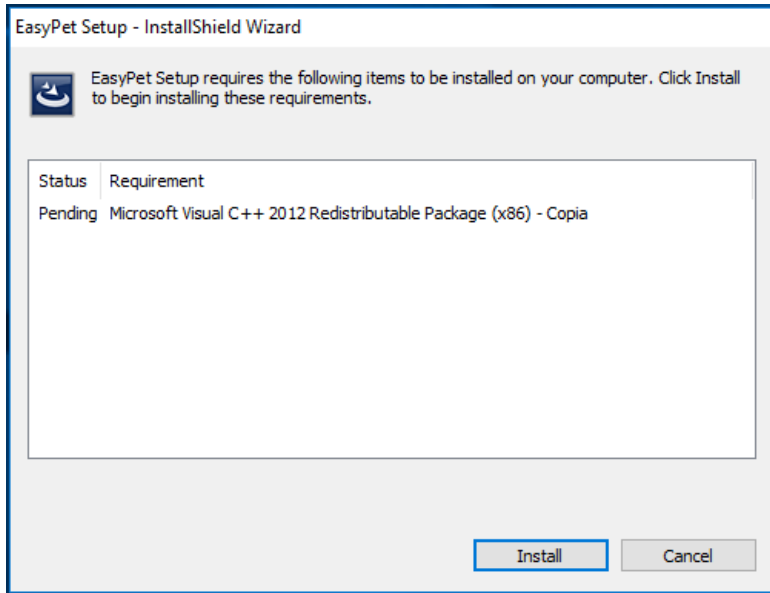
Installation

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

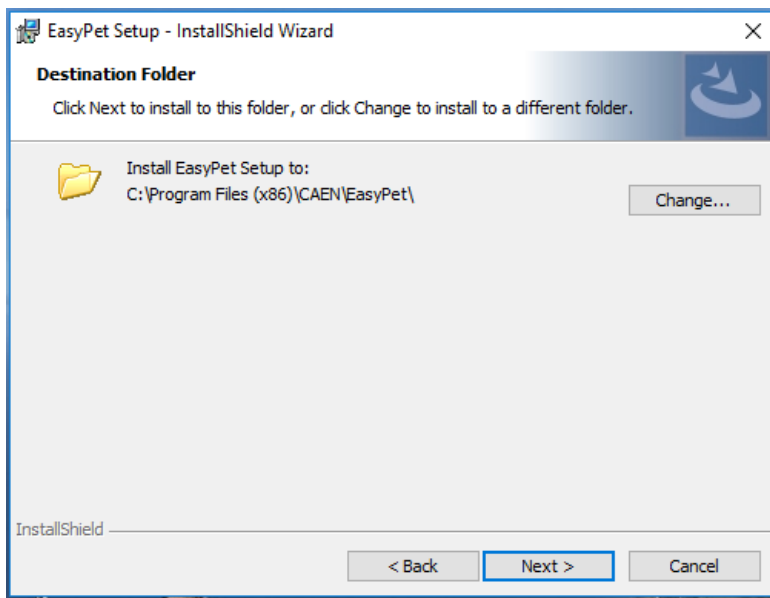
- Download the standalone **CAEN EasyPET Software 1.2.3.6** installation package on CAEN website in the 'Download' area of the EasyPET page (**login is required before the download**).
- **Unpack the installation package and launch**, as administrator, the **setup file**.



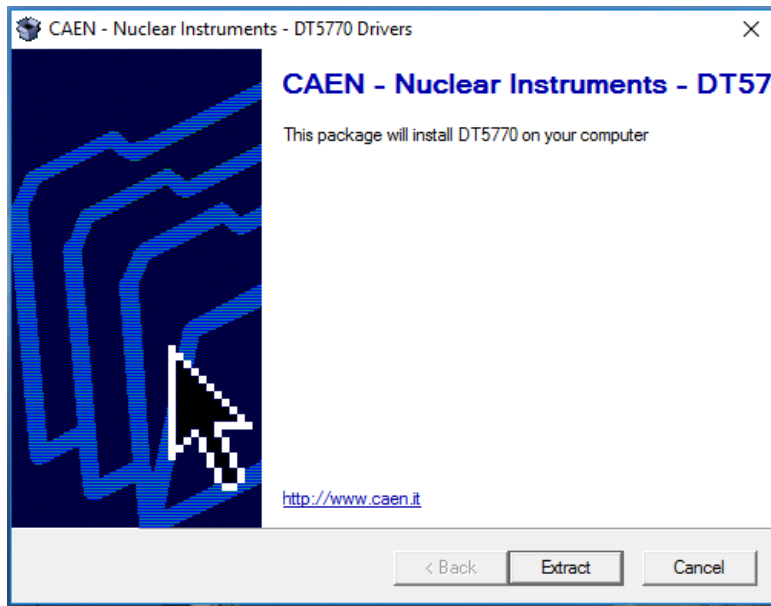
- **If Microsoft .NET is not already installed**, the setup will ask to install it. The operation may take some minutes.
- **If Microsoft Visual C++ 2012 redistributable Package (x86) is not already installed**, the setup will ask to install it as shown in the following picture.



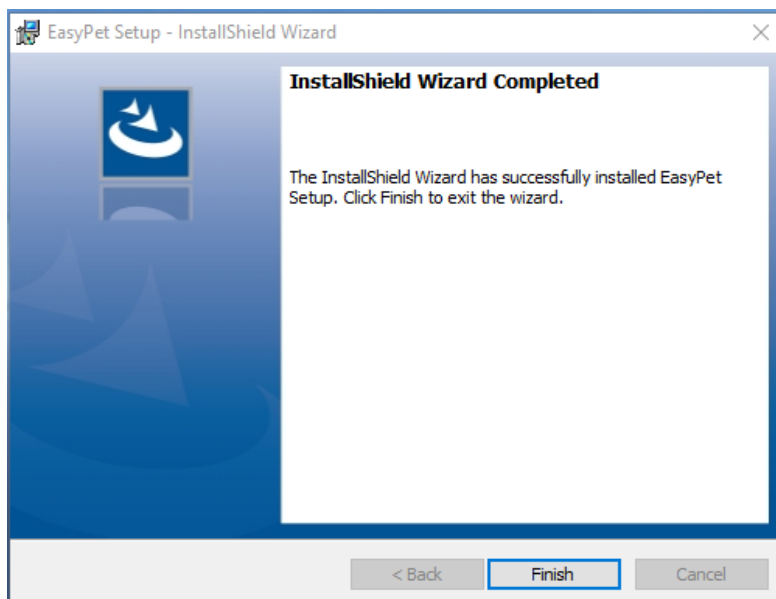
- **Complete the Installation wizard and Select the destination folder.**



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



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



Important Note: The CAEN EasyPET Software run both with SP5700 – EasyPET and with 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.

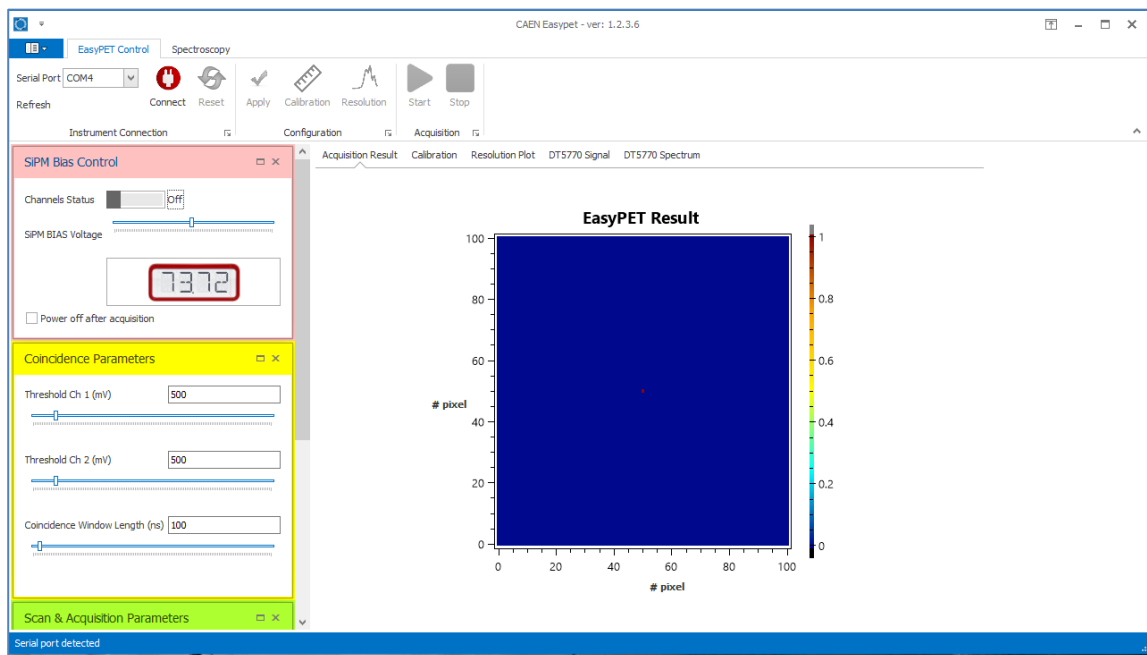



Fig. 5.8: EasyPET Graphical User Interface

The Spectroscopy tab is linked to DT5770 use, so the following subsection only describes the EasyPET Control Tab, related to EasyPET management.

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

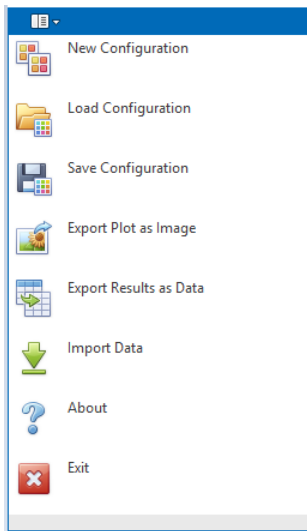
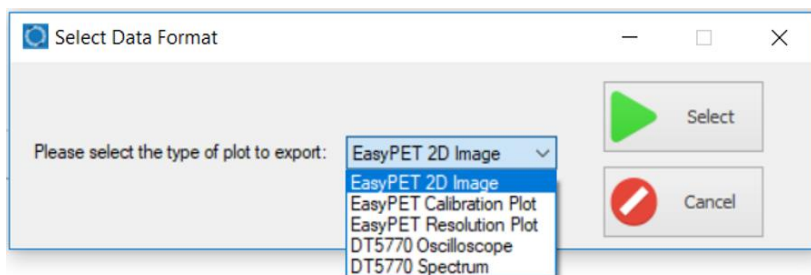
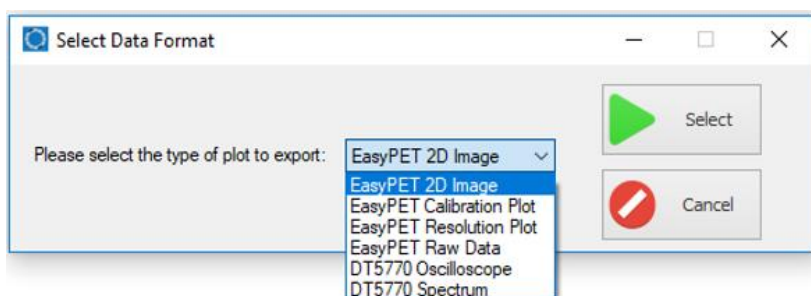


Fig. 5.9: File Menu

- **“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.

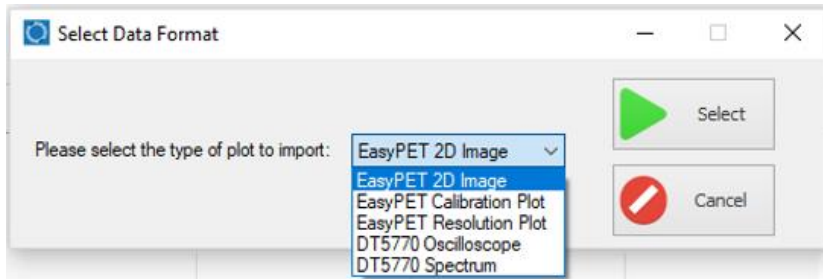


- **“Export Plot as Data”**: it opens the “Select Data Format” window. The user can choose, via drop down menu, the type of measurement/result to be exported in **Comma Separated Values (.csv)** format. The user has the possibility to save Raw Data coming from SP5700 and Plots specifying the destination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



As concern Raw Data, the exported file is composed of 5 columns with the following information: “Run Time (ms)”, “LOR (ms)”, “Bottom Motor Step (°)”, “Top Motor Step (°)” and “Event Count”.

- **“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.

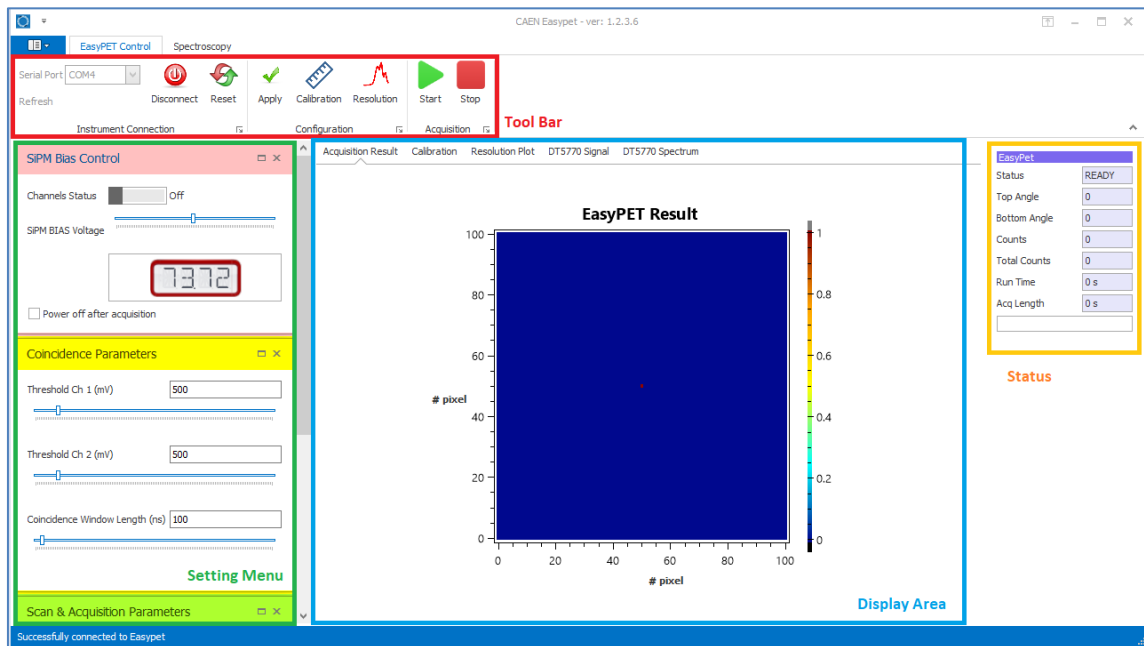


Fig. 5.10: EasyPET Control Tab

Tool Bar

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

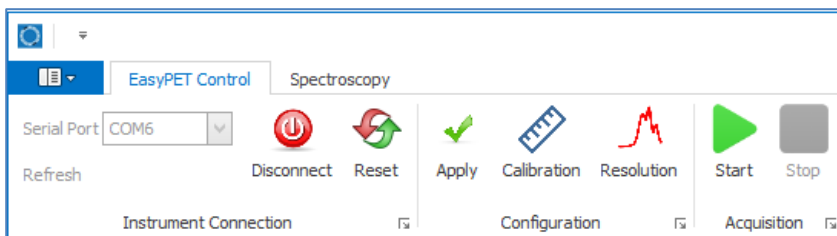


Fig. 5.11: Tool Bar of EasyPET Control Tab

- **"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.

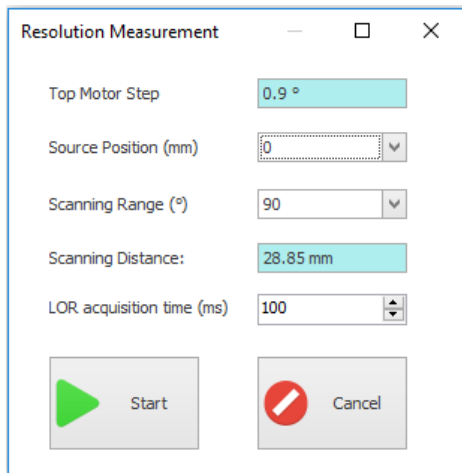


Fig. 5.12: Resolution Measurements Window

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

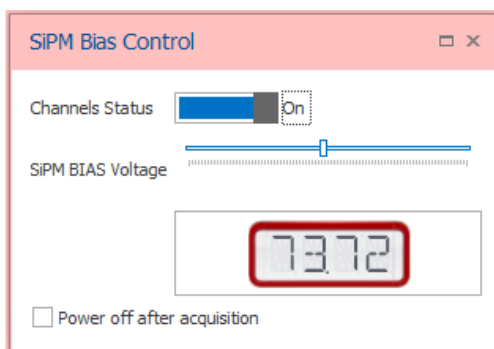
- “**Source Position**”: distance of the source from the center along the line connecting the detectors in the calibration position. Suggested value is 0 mm, means the source is in the center. Negative values are referred to positions between the center and the detector closest to the top motor axis, 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.

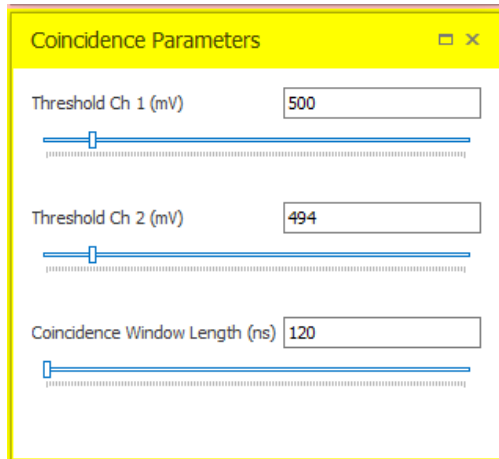
Setting Menu

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



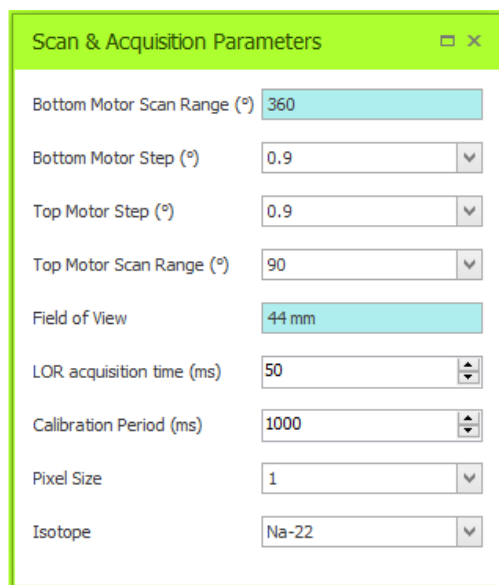
Supply voltage for both the SiPM of the two detector cells of EasyPET.

“**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 μ s.



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.

Display Area

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.

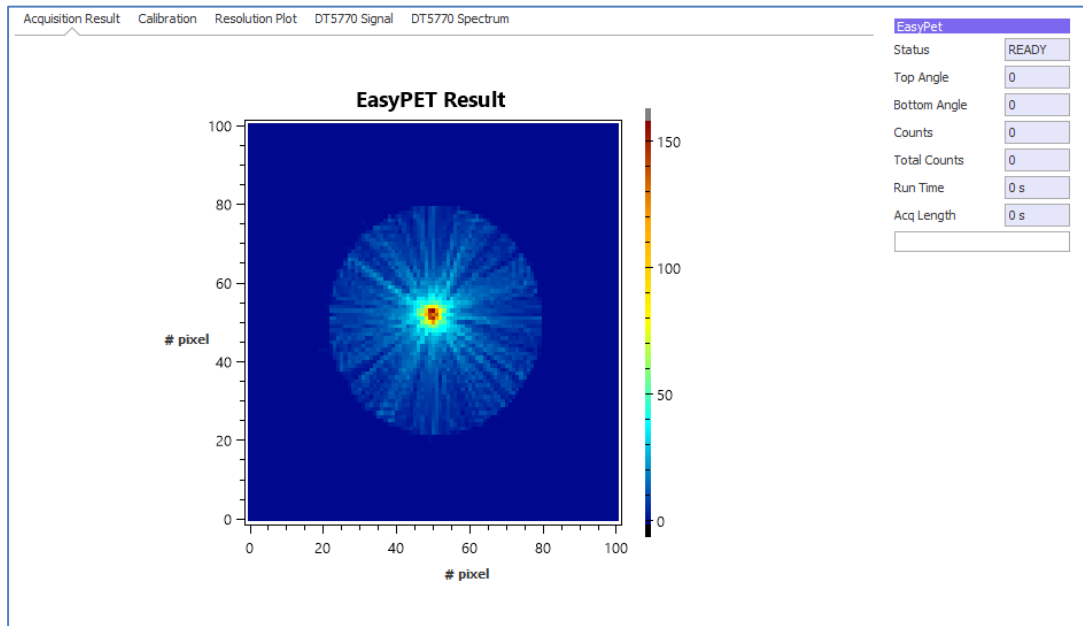


Fig. 5.13: Acquisition Tab of the Display Area

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.

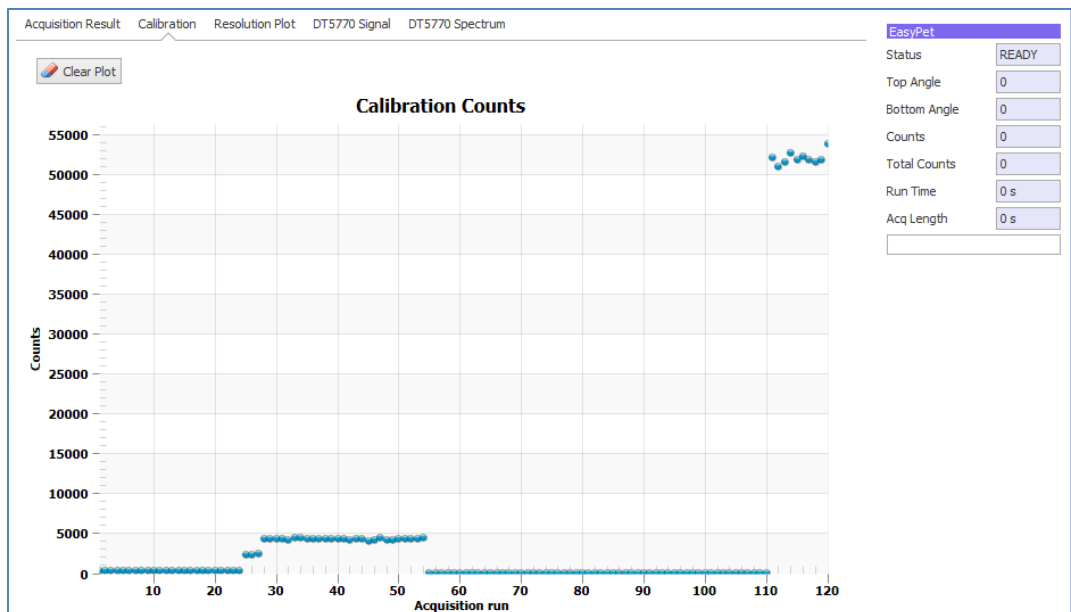


Fig. 5.14: Calibration Tab of the Display Area

- “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.

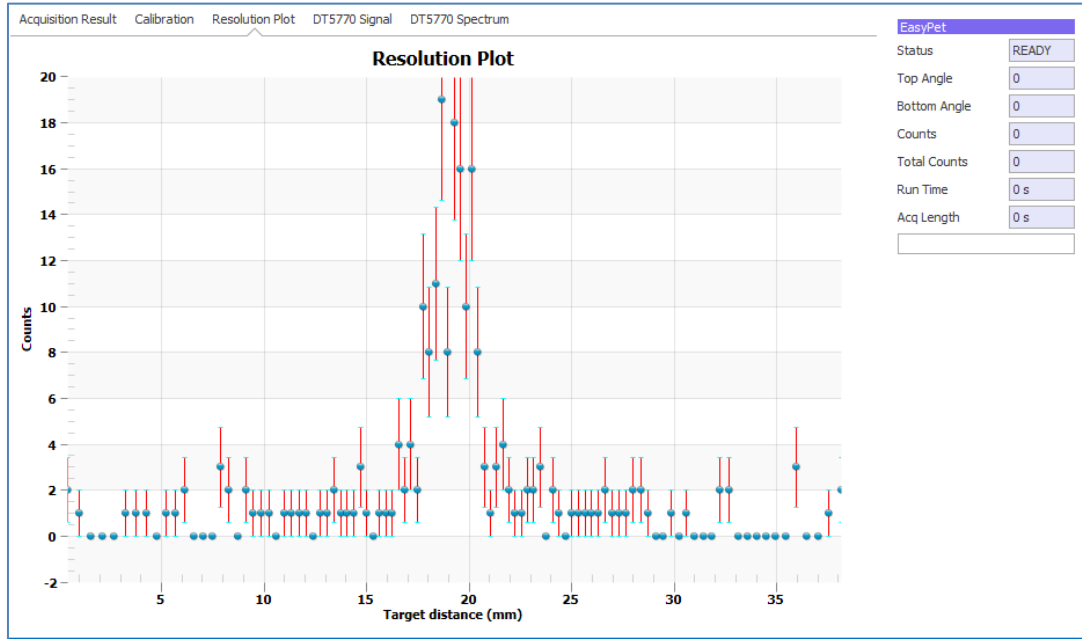


Fig. 5.15: Resolution Plot Tab of Display Area

6 Basic Measurements

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

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 supply powers the device. Please, use only the power supply 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 recommended 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.

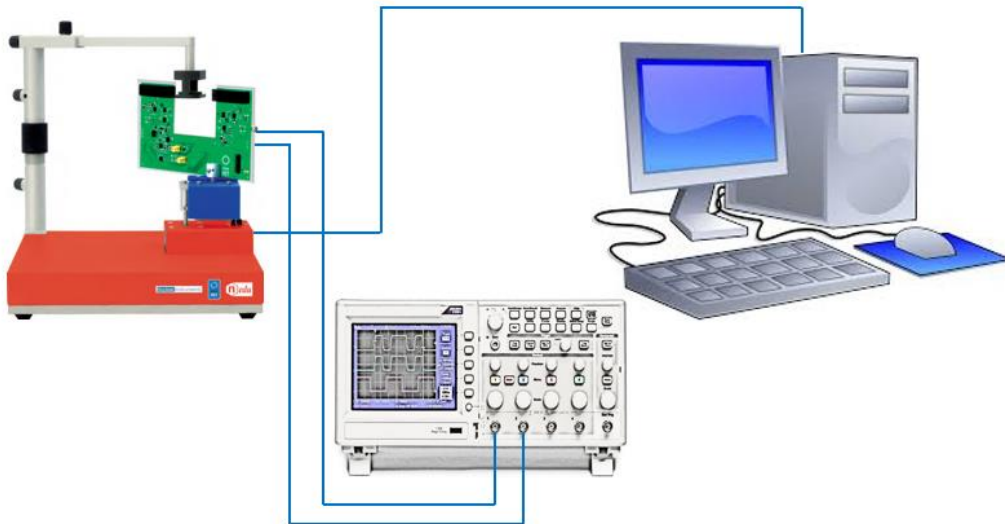


Fig. 6.1: The hardware setup including the EasyPET SP5700 and oscilloscope (not included)



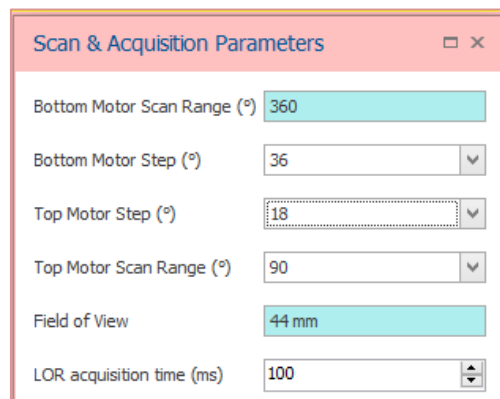
Important Note: Please notice that Radioactive Source is not included in the SP5700 EasyPET. The radioactive source used in this section is Na^{22} , 1/2 inch disc and 10 μCi . A radioactive source with lower activity can be used, but in that case time of measurements becomes longer.

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:



Scan & Acquisition Parameters	
Bottom Motor Scan Range (°)	360
Bottom Motor Step (°)	36
Top Motor Step (°)	18
Top Motor Scan Range (°)	90
Field of View	44 mm
LOR acquisition time (ms)	100

- ✓ 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 $\sim 10^4 / \text{mm}^2$) 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 $\approx 10^6$. 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

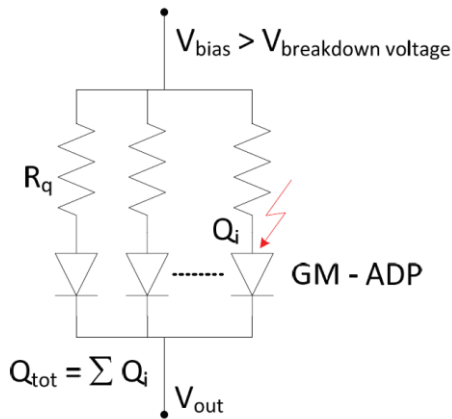


Fig. 6.2: Equivalent circuit of a SiPM: each pixel provides information on whether or not it is fired

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 $1 \times 1 \text{ mm}^2$ SiPM, model MPPC S10362-11-050P. This sensor, with its 400 cells, provides a wide dynamic range.

- Scintillator** - 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 $\text{L}_{1.8}\text{Y}_{0.2}\text{SiO}_5(\text{Ce})$ (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 ($\text{Bi}_4\text{Ge}_3\text{O}_{12}$), which has a similar density. Applications that require higher throughput, better timing and better energy resolution will benefit from using LYSO material. LYSO 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 mm² 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.

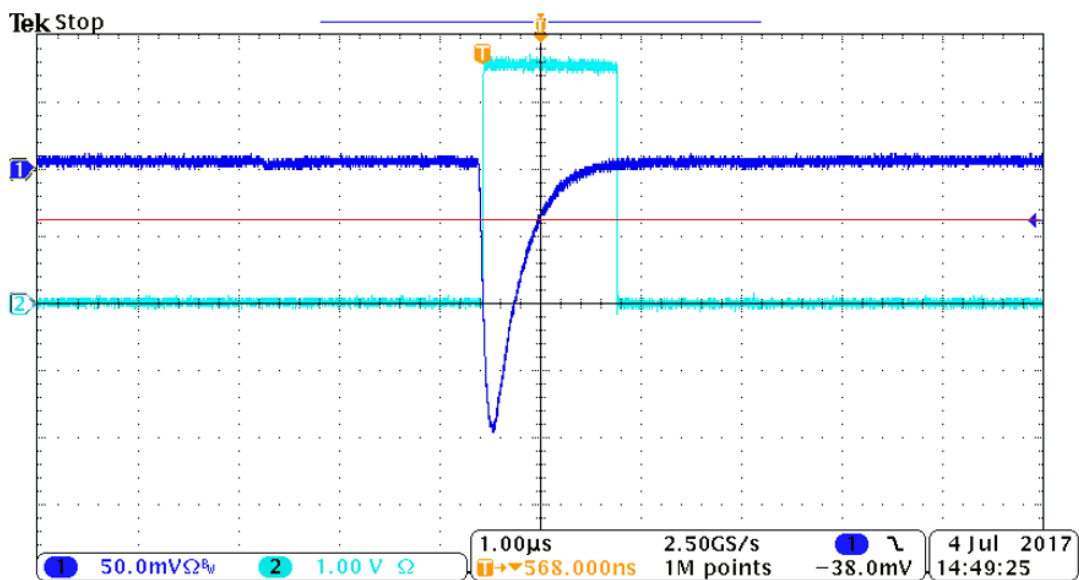


Fig. 6.3: The blue line is the analog sensor output, the azure line represents the comparator output and the red line is the trigger threshold at 300mV. The signal is obtained at 25°C room temperature and with the sensor biased at 73.5 V

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.

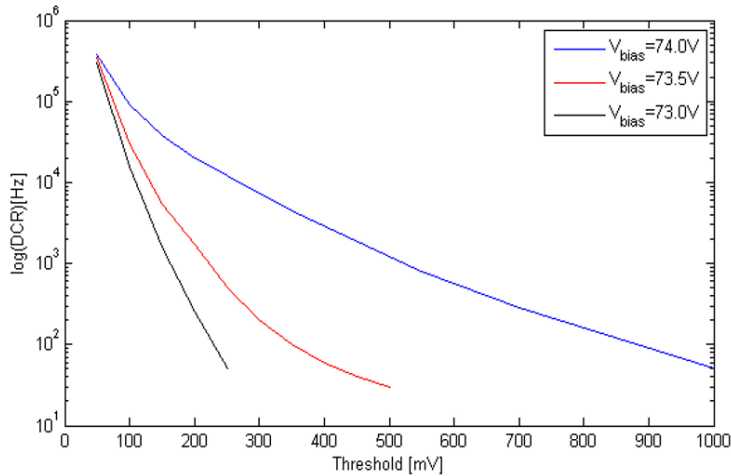


Fig. 6.4: The logarithm of the DCR as a function of the threshold for 73.0 V, 73.5 V and 74.0 V bias voltages at 25°C

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.

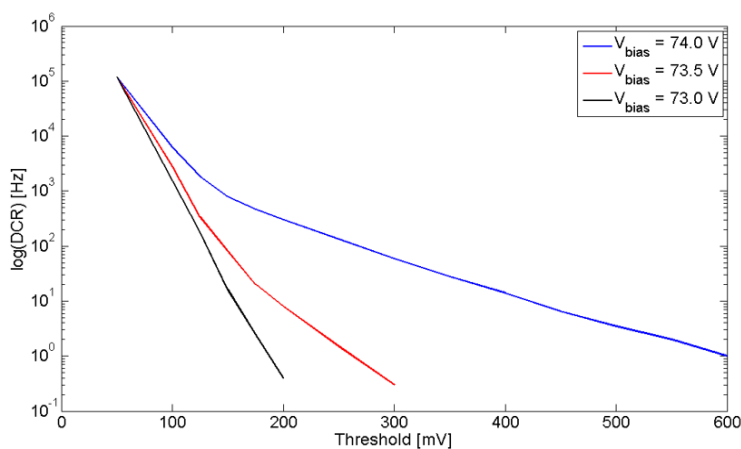


Fig. 6.5: The logarithm of the random coincidence as a function of the threshold for 73.0 V, 73.5 V and 74.0 V SiPMs bias voltages at 25°C room temperature. The time window width adopted is 120 ns

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 is linked to the parameter of the time window width in addition to the bias voltage and to 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 Na22 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.

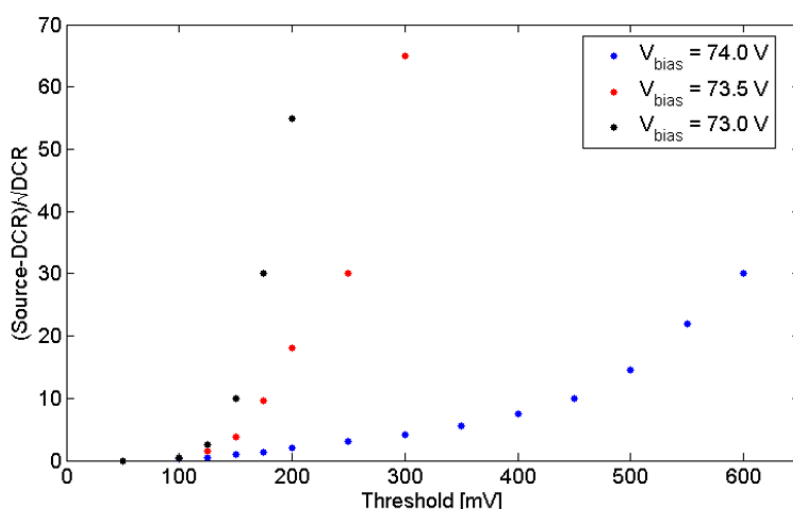


Fig. 6.6: The ratio between the coincidence signal with DCR subtracted and the square root of the DCR as a function of the threshold. Data are acquired with 120 ns time window width for 73.0 V, 73.5 V and 74.0 V SiPMs bias voltages at 25°C room temperature

Calibration

The 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 (5), showed in Fig. 6.7, used to set the vertical position of the source holder. Once the source is approximately near the best position, the knobs (1, 2, and 3) have to be used as clutch in order to obtain a controlled movement in all the directions. The clamp of the clutch knobs has to be avoid because it can be produce a shift in the source position.

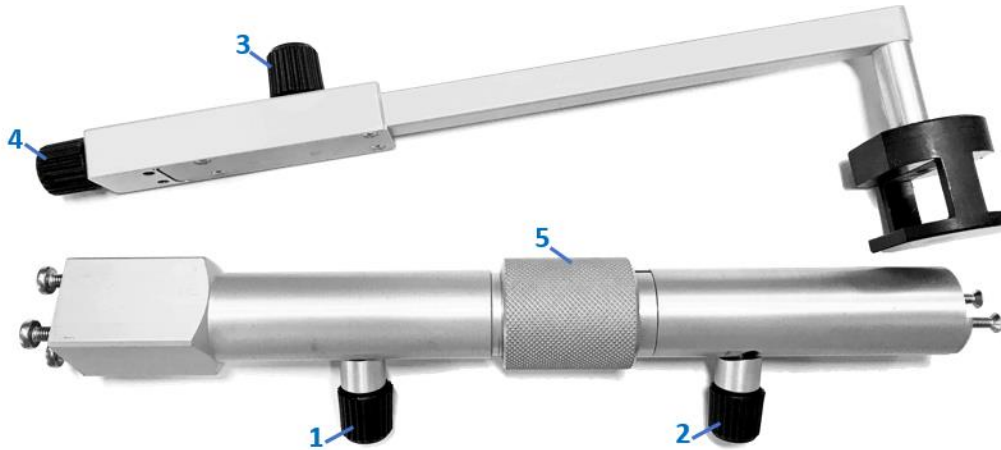


Fig. 6.7: Mechanical support for the source. In the picture, the source holder is already mounted

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. 6.8.

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 Na²² source of 10 μCi about 40 coincidences or more can be counted.

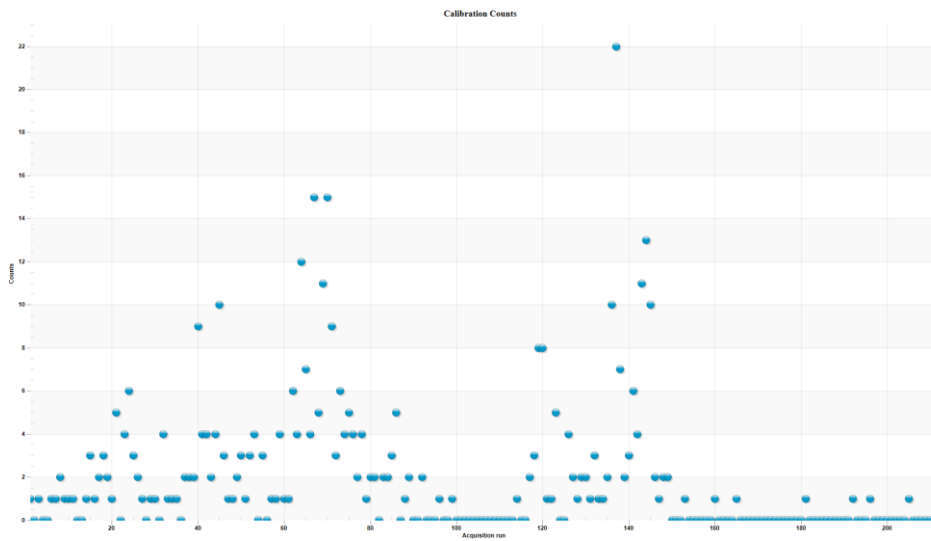


Fig. 6.8: Example of calibration plot corresponding to coincidence counts acquired moving the source in the space between the detection units and removing from there



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. 6.9, the realtime image reconstruction by back-projecting the acquired number of coincidence events at each position can be assessed.

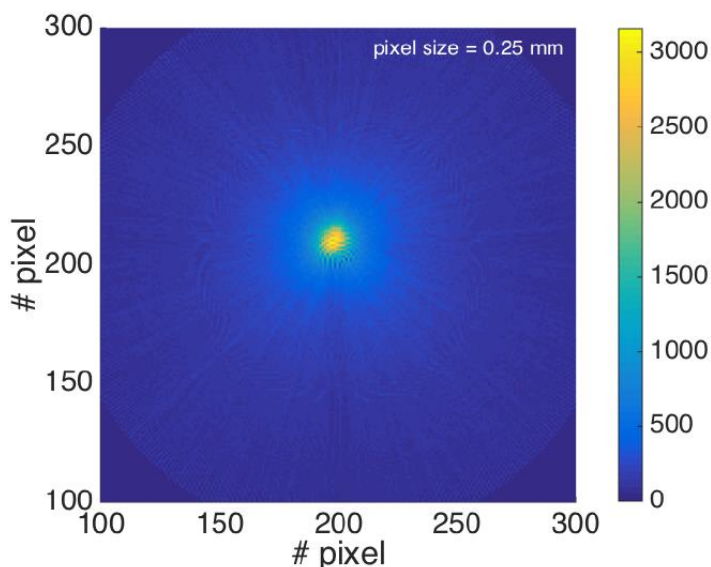


Fig. 6.9: Reconstructed distribution of a ^{22}Na source with an activity of $9.8\mu\text{Ci}$ imaged with a single LOR time acquisition of 0.5 s, bottom step 0.9° , top range 45° and top step 0.9° , for a total acquisition time of 167 minutes

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 $9.8 \mu\text{Ci}$ of ^{22}Na for about 167 minutes, for a total number of about $6.6 \cdot 10^6$ counts (Fig. 6.9). 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. 6.10.

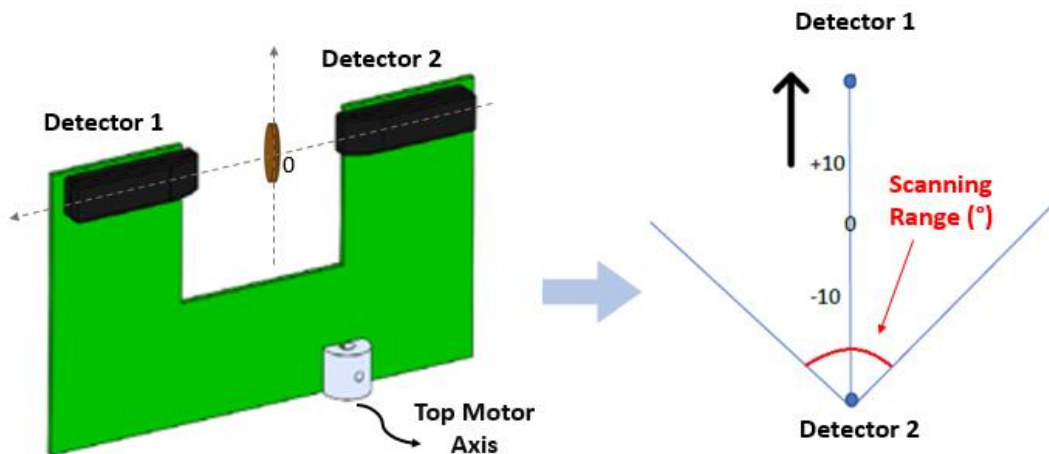


Fig. 6.10: Axis orientation in case of resolution measurements

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. 6.11.

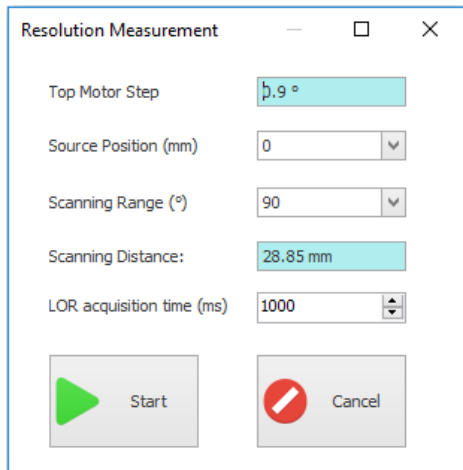


Fig. 6.11: Suggested parameters for resolution measurement

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. 6.12). The spatial resolution of the system is defined from the Full Width at Half Maximum ($FWHM=2.35 \cdot \sigma$, where σ is the gaussian standard deviation) of the function, which is determined by fitting the data points with a gaussian. 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.

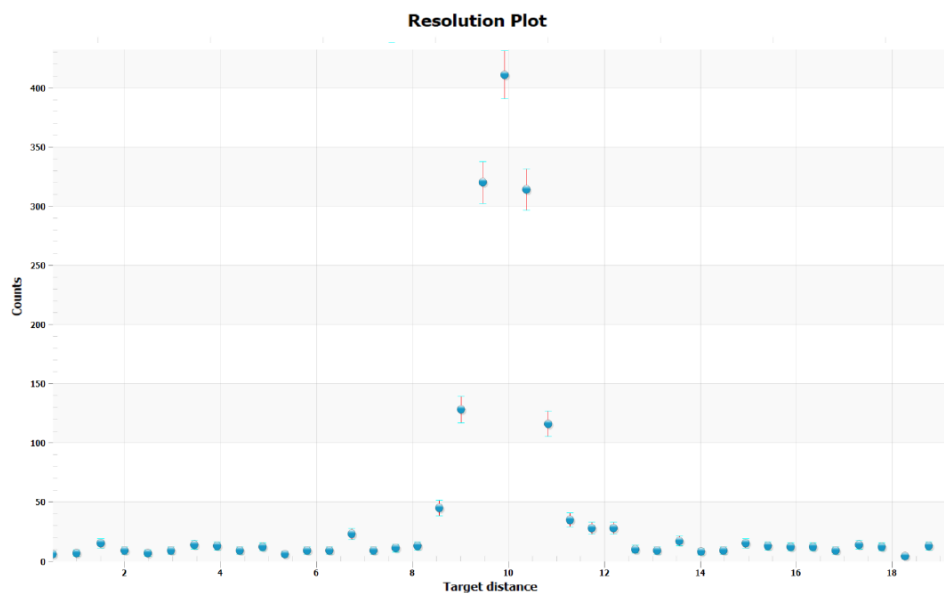


Fig. 6.12: Resolution measurement plot

7 Educational Experiments

The SP5700-EasyPET 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 Chapter represents an overview of the experiments proposed by CAEN using the device 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.

The experiments proposed in this section are uniquely performed by using SP5700 - EasyPET standalone.

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

Section	Subsection	Reference ID	Experiment
Nuclear Physics and radioactivity	Nuclear Imaging PET	6132	Positron Annihilation Detection
		6133	Two-dimensional Reconstruction of a Radioactive Source
		6134	Spatial Resolution

Tab. 7.1: Physics Experiments performed via EasyPET

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:

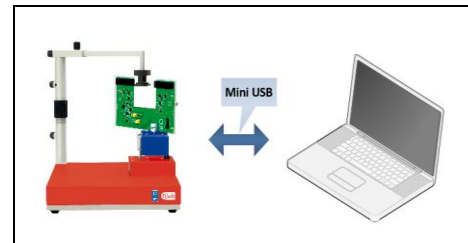
The underlying principle to PET systems is the detection of high energy radiation emitted from a chemical marker, a molecule labelled with a radioisotope, administered to a patient. The marker is properly chosen in order to associate to molecules involved in biochemical or metabolic processes under investigation. 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:

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

Carrying out the experiment:

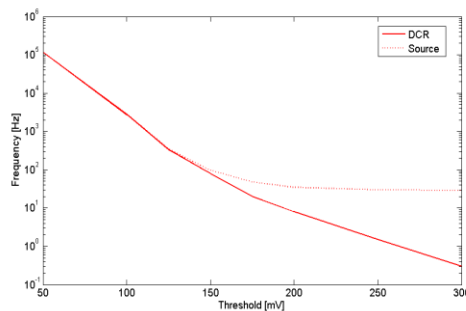
Mount the arm of the source holder on the column fixed on the system base, fix the U-shaped board to the top stepper motor and connect the flat cable to the U-shaped board and to control unit. Connect to PC and power ON the system. Connect the analog output of one detector to channel input of the DT5720A 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.



SP5700-Experimental setup block diagram

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

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.

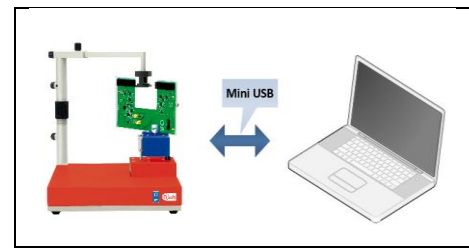
The rotation movements are executed by two stepper motors. The bottom motor has a fixed axis, whose position defines the center of the field of view. The bottom motor supports and performs a complete rotation of a second motor, in predefined steps of amplitude α . The axis of the top motor is thus always 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:

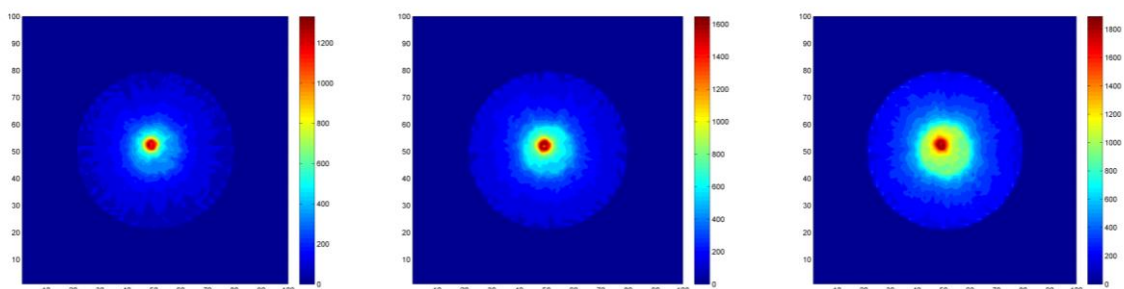
Mount the arm of the source holder on the column fixed on the system base, fix the U-shaped board to the top stepper motor and connect the flat cable to the U-shaped board and to control unit. Connect to PC and power ON the system. The parameters involved in the setup optimization for the two-dimensional 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 ^{22}Na radioactive source in the holder and repeat the measurement tuning the parameters in order to obtain a good image reconstruction of the radioactive source.



SP5700-Experimental setup block diagram

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.



^{22}Na 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 measurement 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.

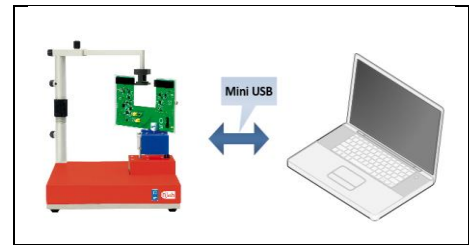
In the EasyPET the dominant factor determining the spatial resolution is represented by the width of the scintillating crystals. Another effect that degrades the spatial resolution of the system is the so-called sampling error. It is associated to the distribution of the lines of response in the field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

Requirements:

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

Carrying out the experiment:

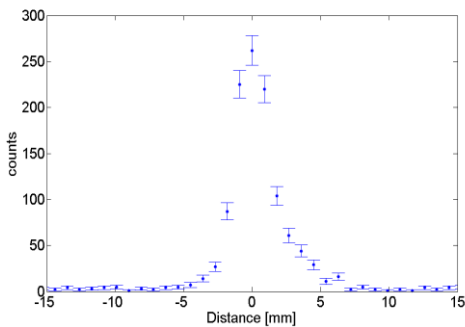
Mount the arm of the source holder on the column fixed on the system base, fix the U-shaped board to the top stepper motor and connect the flat cable to the U-shaped board and to control unit. Connect to PC and power ON the system. Set and optimize the parameters as bias voltage, threshold and coincidence 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.



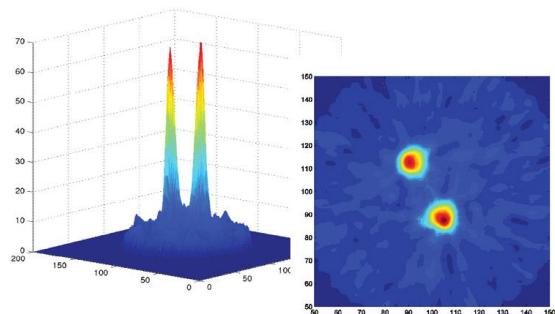
SP5700-Experimental setup block diagram

Results:

The estimated spatial resolution is $\sim (1.0 \pm 0.1)$ 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



²²Na 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.

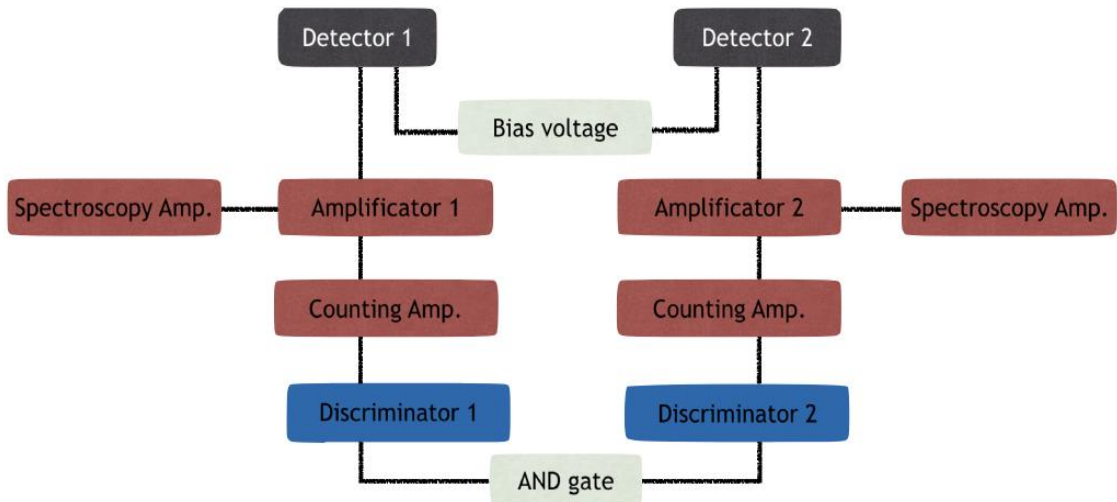


Fig. 8.1: The EasyPET electronic circuit scheme

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.

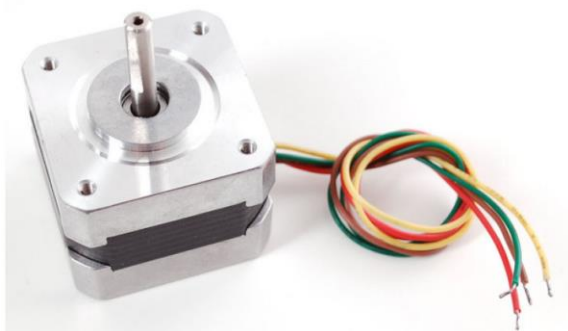


Fig. 8.2: Stepper motor produced by Astrosyn (type Y129)

The controller unit is placed inside the mechanical base of EasyPET and it manages the micro-stepper motors. 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 fulfil 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.

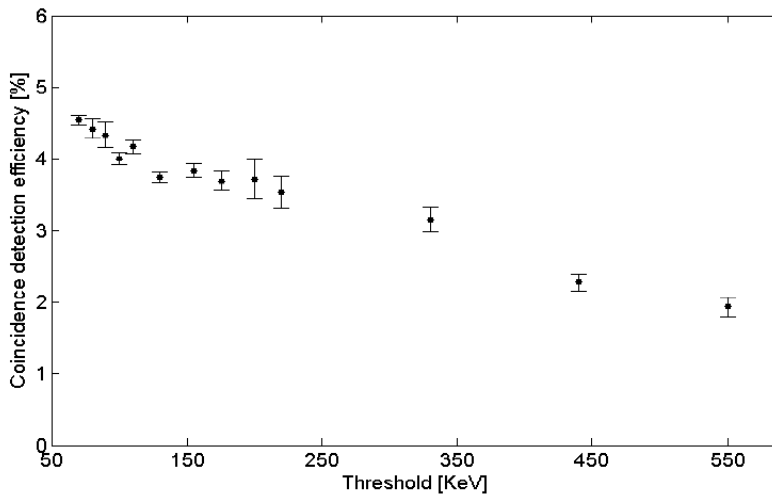


Fig. 8.3: EasyPET Coincidence detection efficiency as a function of Threshold

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 $2 \times 2 \times 30$ mm³ 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 mm² 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 (μ m)	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 $2 \times 2 \times 30 \text{ mm}^3$ by Kinheng Crystal and $1 \times 1 \text{ mm}^2$ 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 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



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 Algorithms¹

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].

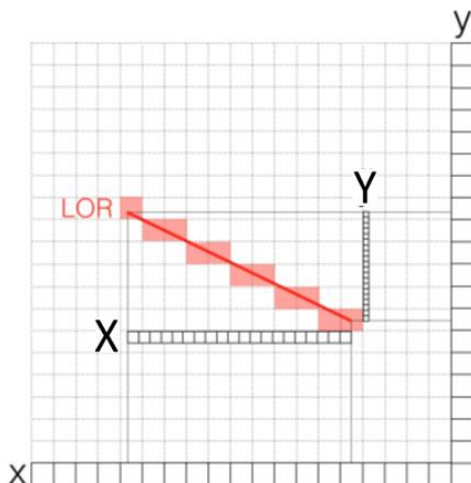


Fig. A.1: The image reconstruction algorithm [RD1]

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 [RD5]. 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 performed 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:

$$D_i = r * \text{tg } \theta_i$$

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

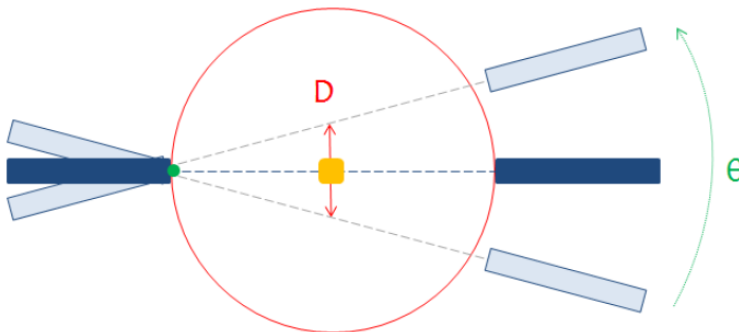


Fig. A.3: The EasyPET setup for position resolution measurement

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.

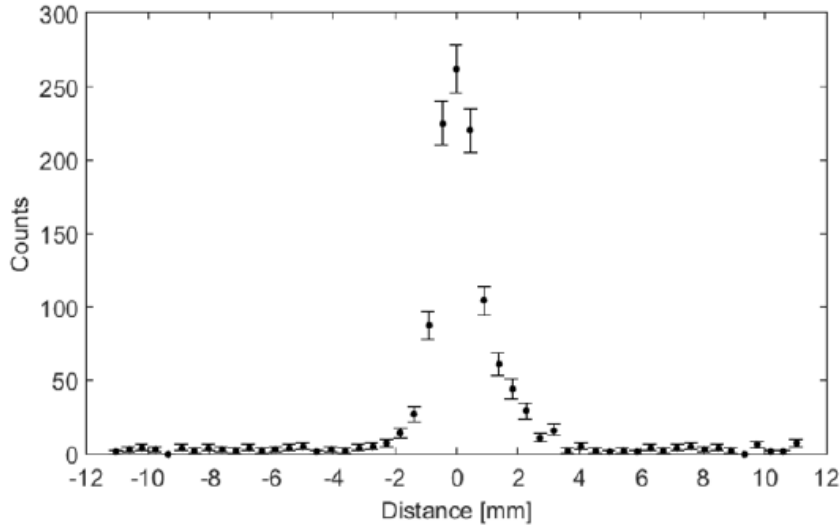


Fig. A.4: The EasyPET coincidence counts measured using a 3 μCi ^{22}Na source as a function of the distance D

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.

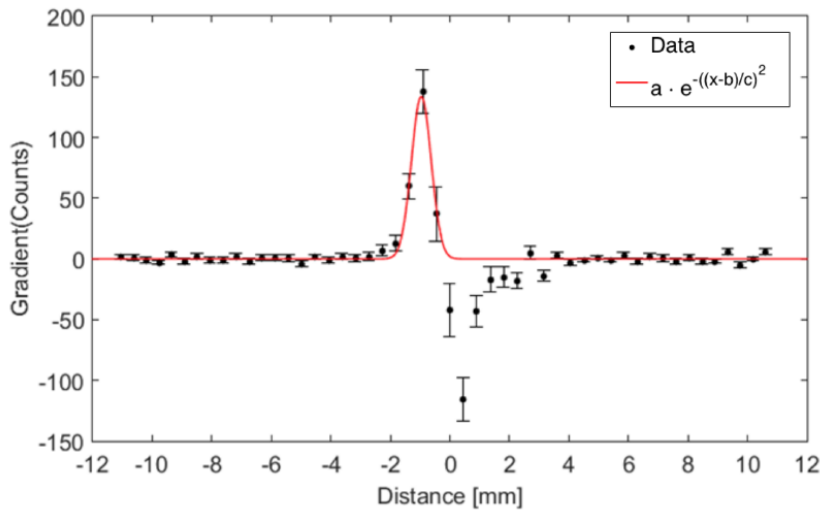


Fig. A.5: The EasyPET The EasyPET gradient of the counts measured using a 5 μCi ^{22}Na source as a function of the distance D

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 $3\ \mu\text{Ci}$ 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.

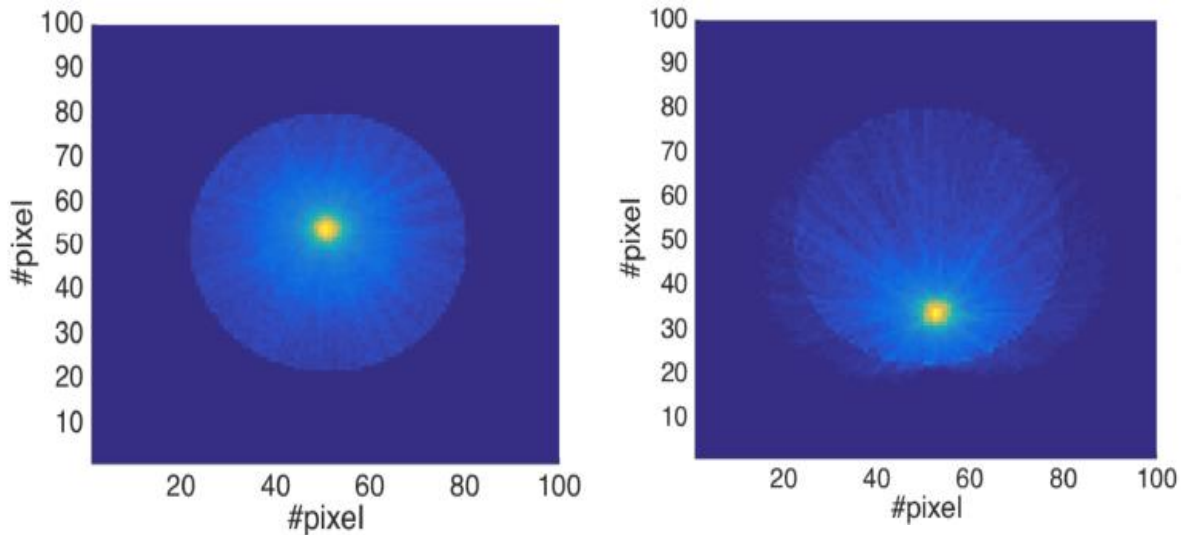


Fig. A.6: Images of the source placed in the centre of the FOV (left) and in a peripheral region (right)

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}F 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.

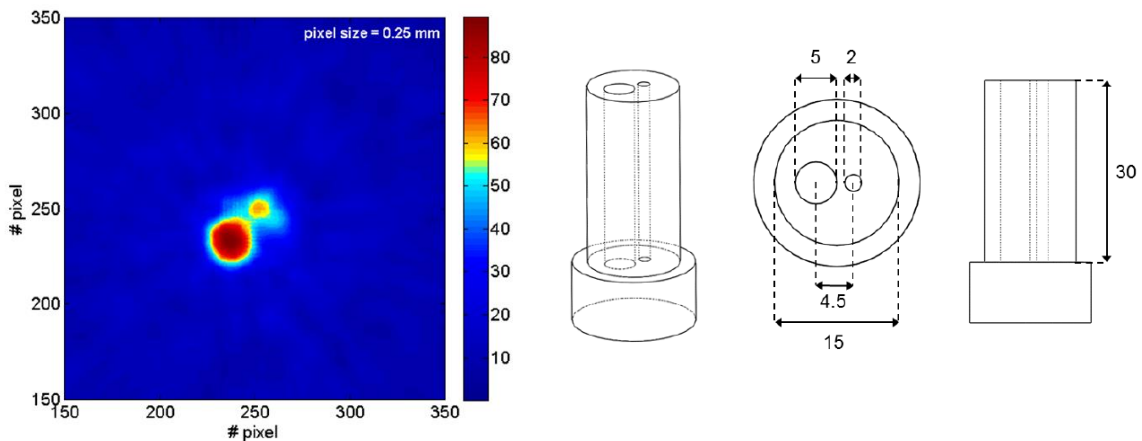
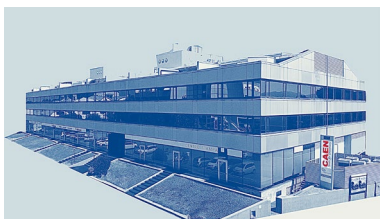


Fig. A.7: Image of two wells in a PMMA phantom filled with ^{18}F FDG obtained acquiring a total number of 6150 events in 24 minutes (left) and the schematic layout of the phantom with all the dimensions in mm (right)



CAEN S.p.A.

Via Vetraia 11
55049 - Viareggio
Italy
Phone +39 0584 388 398
Fax +39 0584 388 959
info@caen.it
www.caen.it



CAEN GmbH

Brunnenweg 9
64331 Weiterstadt
Germany
Tel. +49 (0)212 254 4077
Mobile +49 (0)151 16 548 484
info@caen-de.com
www.caen-de.com

CAEN Technologies, Inc.

1 Edgewater Street - Suite 101
Staten Island, NY 10305
USA
Phone: +1 (718) 981-0401
Fax: +1 (718) 556-9185
info@caentechnologies.com
www.caentechnologies.com

CAENspa INDIA Private Limited

B205, BLDG42, B Wing,
Azad Nagar Sangam CHS,
Mhada Layout, Azad Nagar, Andheri (W)
Mumbai, Mumbai City,
Maharashtra, India, 400053
info@caen-india.in
www.caen-india.in



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