Viareggio
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1. Abstract

In recent years a new generation of High-Purity Germanium (HPGe) detectors is having more and more success in low and medium energy nuclear physics applications dedicated to gamma-ray spectroscopy. These detectors, also known as Clover detectors, consist of 4 coaxial N-type high purity germanium crystals, each properly shaped and mounted in a common cryostat to form a structure resembling a four-leaf clover. Typically these detectors are surrounded by a layer of scintillators like BGO or CsI which act as an Anti-Compton Shield, rejecting those events in which the gamma-ray has undergone a Compton scattering inside the germanium crystals and then escaped from the active volume.

In the present note we will describe in detail a Clover readout system solution based on the new fast and high resolution CAEN digitizers. This note will describe the hardware, firmware and Data Acquisition (DAQ) software infrastructure and present several experimental results achieved in a real use case, the Clover experimental setup built at the DHRUVA reactor facility at BARC (India).

2. Introduction

In '90s the production of standard n-type large volume Ge crystals reached something of a ceiling as researchers were unable to develop crystals larger than about 300 cm^3 and diameters of about 70 mm. Beyond the latter value, Ge crystal production, ballistic deficit and neutron damage sensitivity problems were encountered. In addition, such large volume detectors placed approximately 90° to the beam direction undergo a large Doppler broadening of the γ-ray lines. The realization of new and more efficient multi-detector arrays was therefore dependent on the production of new types of Ge detectors. A new concept of Ge detector was developed to overcome these difficulties: the composite Ge detector in which several crystals are assembled in a common cryostat leading to active volumes much larger than accessible with monolithic detectors[1].

3. The Clover Detector

The Clover detector consists of four coaxial *n*-type Ge diodes of 50 mm diameter and 70 mm length mounted in a common cryostat. Each crystal is shaped as shown Figure 1.

Figure 1: Left panel: individual Clover crystal. Right panel: close packing of the four shaped Ge crystals of a Clover detector.

The front face has a quasi-squared section, obtained by beveling two adjacent faces with an angle of 7.1° beginning approximately midway of the crystal length and then cutting the two remaining faces parallel to the crystal axis along its whole length. This enables a close packing of the diodes with a Ge-Ge distance of only 0.2 mm. The total active Ge volume is about 470 cm^3, which corresponds to 89% of the original Ge volume. In order to optimize the signal-to-noise ratio of the composite detector the crystals are held on a minimized crystal holder. This reduces the quantity of material surrounding the crystals. The aluminum housing typically used to hold the crystals is replaced by a grip that holds the diodes by their rear side. Additionally, the crystals are packed very closely together to improve the Add-back factor. The four crystals are mounted in a common cryostat with either a tapered or regular square shaped end cap. Distance between end cap and crystals has been reduced to a bare minimum to improve the solid angle and the efficiency of any veto detector arranged around the Clover cap. The distance between the beveled edges of the crystals and the internal surface of the end-cap is only 3.5 mm. The thickness of the aluminum end-cap is 1.5 mm. A common ground is applied on the outer contacts of the diodes while the high voltage to the inner contacts of the diodes. The energy signal is collected for each crystal from the inner contact via AC-coupling. So called back catcher cryostats are available for given Clover types where a dedicated BGO detector is installed at the rear of the cap. A major advantage of a Clover detector results from of its high absorption efficiency. Results are four times those obtained with a single crystal. Additionally, crystals are mounted without any additional absorbing material, allowing the full energy of a photon Compton scattered and absorbed in a second (or even a third) crystal to be determined. The full energy peak can be obtained by summing (*Add-back*) the energies deposited in the N segments firing. The *Add-back* efficiency is then superior to the sum of the four individual efficiencies[1].

4. The Anti-Compton Shield

The gamma spectroscopy performed with Ge detectors suffers from two main limits; detector efficiency and the difficulty in detecting low intensity peaks in an active-background environment. Obtaining higher efficiencies via larger detectors is one solution. However, this solution can be very expensive. Therefore, it is often necessary to try to reduce the background as a more cost effective way to improve detector performance. In a laboratory setup optimal shielding is not difficult to implement, but massive shielding is not practical for mobile systems intended for outdoor operation. The main contribution to the background in an HPGe gamma spectrometer (excepting background radiation) is due to the Compton scattering. When photons are Compton–scattered in the detector only a portion of their energy is transmitted to the detector. The pulse will not contribute to the main photo-peak but will appear at a lower energy as part of the background. A lower energy gamma peak will be superposed on this background, and its limit of detection will be higher. A practical way to solve the problem is to position an additional detector around the HPGe and operate it in anti-coincidence with the HPGe detector. The crystal in the Compton suppressor absorbs the scattered gamma rays. As a result, the coincident pulses from both detectors (primarily from Compton-scattering) will not be counted and the background will be reduced, thus enhancing the results of the experiment. The Compton suppressor can be designed using NaI(Tl), BGO or CsI crystals. This setup is called an Anti-Compton Shield[3][4]. A typical configuration of a Clover detector surrounded by its Anti-Compton Shield is shown in Figure 2.

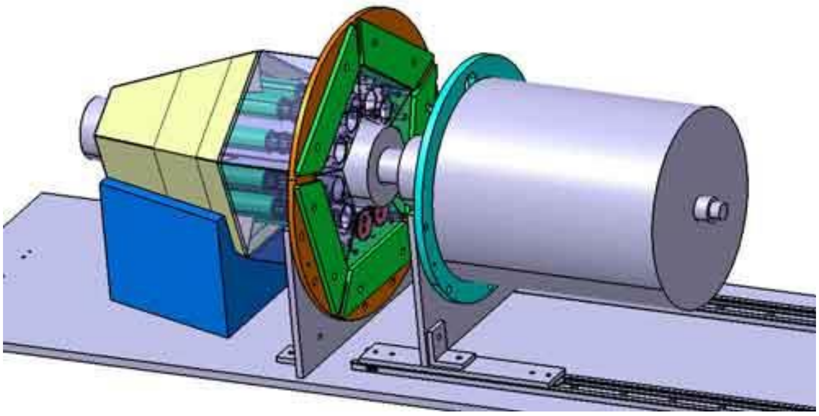


Figure 2: ORGAM 2 experiment at GANIL. Demonstrator Germanium Detector with BGO Anti-Compton Shield. Picture from Orgam Official Webpage.

5. Additional Detectors

An experimental setup based on Clovers is often paired with other kind of detectors, such as $LaBr_3$(Ce) scintillators or Multi Wire Proportional Chamber, whose goal is to provide precise timing or position information in order to have a better picture of the undergoing events.

5.1 $LaBr_3$(Ce) Scintillators

Cerium activated lanthanum bromide detectors (LaBr3 or LaBr3(Ce)), are one of the recent developments in scintillator material for γ-ray detectors. Discovered in 2001, LaBr3(Ce) detectors offer improved energy resolution, fast emission and excellent timing, temperature and linearity characteristics. The typical energy resolution at 662 keV is 3% as compared to NaI detectors at 7%[5]. This features have made LaBr3(Ce) the material of choice for many nuclear physics experiments including γ-ray spectroscopy, medical imaging or industrial applications. The high light yield (165% of that of NaI) and the very short scintillation light decay constant (between 20 and 30 ns) pose LaBr3(Ce) as a well suited candidate material to allow γ-ray spectroscopy at very high count rates[6].

Figure 3: $LaBr_3(Ce)$ Scintillator Assembly. Picture from Saint Gobain Crystals website.

5.2 Multi Wire Proportional Chambers

A multi wire proportional chamber (MWPC) usually consists of a plane of equally spaced anode wires sandwiched between two cathode planes. The cathode planes can be a composed of thin, equally spaced wires, or they can also be made of a continuous plane conductor (Figure 4 left). The gap between the plane of the anode wires and the cathode plane is normally a few millimeters. The chamber is filled with an appropriate mixture of gases depending on the desired mode of operation. Upon application of high voltage between anodes and cathodes the electric field takes the form shown in Figure 4 right.

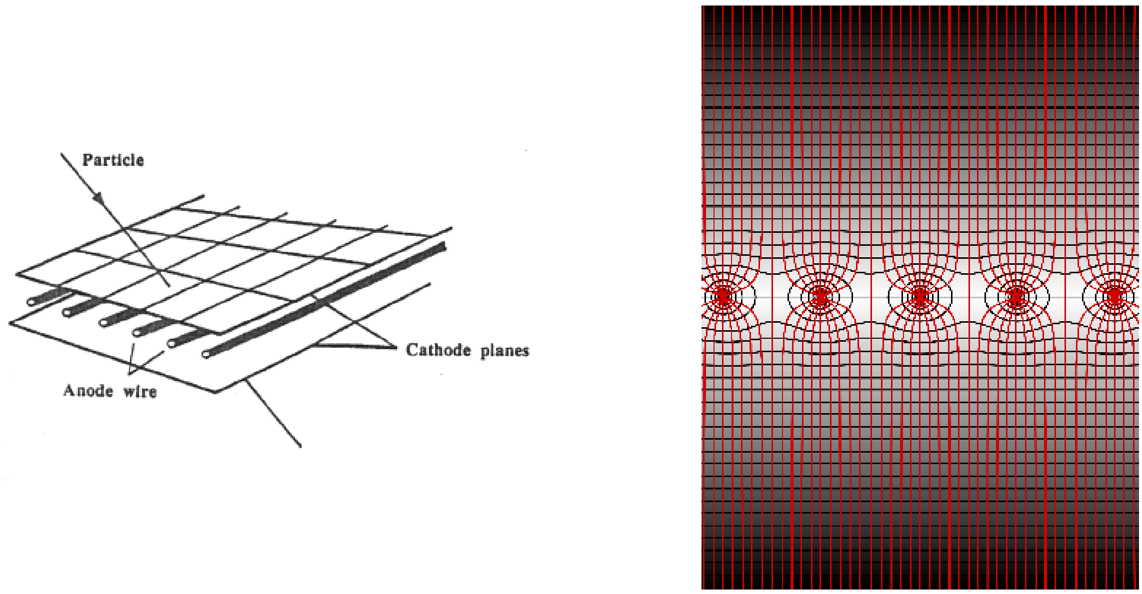


Figure 4: Multiwire Porportional Chamber layout (left) and electric field (right). Pictures from nobelprize.org and en.wikipedia.org.

If an ionizing process occurs in the gas the produced electrons (primaries) will drift toward an anode wire. At a distance away from those wires (distance = ~20 times the wire-diameter) the electric field is basically constant. However, near the wires the electric field becomes inversely proportional to the square of distance (r) to the wire. Therefore, the primary electrons can gain enough kinetic energy so that inelastic collisions with the gas molecules can lead to new ionizations, thus generating secondary electrons. These secondary electrons can undergo further inelastic collisions, eventually resulting in what is called “an electron avalanche” or “charge multiplication”. If the total collected charge is proportional to the number of primary electrons, then the chamber is said to operate in the “proportional mode”. The proportionality constant is called the “multiplication factor”, and is exponentially dependent upon the applied high voltage. This electron avalanche is rapidly (~nsec) collected by the wires, with the positive ions leftover in the trail of multiplying electrons moving toward the cathode. In their motion they induce image charges in all surrounding electrodes. These result in a negative signal on the wire where the avalanche originated. In principle, each wire could act as an individual detector. If it is possible to decode on which of the wires the signal originated then the MWPC is said to be “position sensitive”[7][8].

6. The CAEN Readout System for Clover Detectors with Anti-Compton Shield

CAEN began developing a new family of digitizer products some years ago based on our experience in designing electronics for physics applications. Our goal was to provide a fully digital replacement of most traditional modules such as Multi and Single-Channel Analyzers, QDCs, TDCs, Discriminators, etc... CAEN now offers a complete family of digitizers with differing sampling frequency, resolution, channel count, form factor, memory size and other parameters which may be configured to best fit the application. The digital approach offers superior flexibility, stability and reproducibility, the ability to reprogram and tailor the algorithms to the application, the ability to preserve the information of the signal along the entire acquisition chain, and superior correction of baseline fluctuation, pile-up, ballistic deficit, etc. Simultaneously CAEN has also developed specialized digital pulse processing algorithms which are designed to allow the user to extract specific information such as energy, precise timing, and so forth.

In this note we will consider a system composed of 8 Clover detectors with an Anti-Compton Shield; the latter includes BGO and CsI crystals. High resolution time measurements will be performed through an array of $LaBr_3(Ce)$ scintillators.

6.1 Hardware and Firmware Configuration

The CAEN solution for the readout system of such a setup is based on the following VME digitizers, frontend modules and accessories:

- **N° 3 V1725**: 1-unit wide VME 6U module housing a 16 Channel 14-bit 250 MS/s Flash ADC Waveform Digitizer with 2 Vpp and 0.5 Vpp possible input dynamics on single ended MCX coaxial;
- **N°1 V1730**: 1-unit wide VME 6U module housing a 16 Channel 14-bit 500 MS/s Flash ADC Waveform Digitizer with 2 Vpp and 0.5 Vpp possible input dynamics on single ended MCX coaxial;
- **N°1 V2495**: 1-unit wide VME 6U module suitable for various digital Gate/Trigger/Translator/Buffer/Test applications, which can be directly customized by the user, and whose management is handled by two FPGA. The first one is the FPGA "Bridge", used for the VME interface and for the connection between the VME and the 2nd FPGA (FPGA "User") through a proprietary local bus. The FPGA "Bridge" manages also the programming via VME of the FPGA "User". The FPGA "User" manages the front panel I/O channels and is substantially an empty FPGA available to be programmed by the user according to the desired logic function;
- **N°1 V2718**: a VME to PCI Optical Link Bridge, housed in a 1-unit wide VME 6U module. The unit acts as a VME Master module and can be controlled by a standard PC equipped with PCI or PCIe CAEN Controller cards (like the A3818). The connection between the V2718 and the Controller takes place through an optical fibre cable. Multi-crate sessions can be easily performed, since up to eight daisy chained V2718 (via optical fibre cables) can be controlled by a single A3818, thus building a CONET (Chainable Optical Network);
- **N°1 VME8100**: 8U 21 Slot VME64/64X enhanced crate based on a modularity concept which consist of three detachable parts easily to exchange: the subrack (6U bin with 21 slot monolithic backplane), the pluggable power supply (VME bulk power supply available in different configurations providing up to 2500 W to the backplane), the smart fan unit (2U fan tray with OLED display, local controls and CAN bus, Ethernet, USB, RS232 interfaces) for remote access to the crate;
- **N°1 A3818**: this is not a VME module but a PCI Express x8 card that can plug into both x8 and x16 PC PCI Express slot, which allows the control of up to 4 CONET2 independent networks;
- **N°3 A317**: clock distribution cable that allows to perform CLK OUT - CLK IN connection, and so the synchronization, on CAEN digitizers;
- **N°4 AY2705**: 5 m optical fibre duplex for the connection between A3818 and the digitizer and controller boards;
- **N°8 A659 KIT 8** – 8 MCX to BNC Cable Adapter
- Flat Cables for V1725 – V2495 LVDS connections.

Some of the listed modules are equipped with dedicated firmware for digital pulse processing. In particular:

- The V1725 are equipped with the **Pulse Height Analysis (DPP-PHA)** firmware: DPP-PHA implements a digital trapezoidal filter on the input pulse, replacing the traditional analog chain of shaping amplifier and peak sensing ADC. The digitizer is directly connected to the charge sensitive preamplifier, with no need of additional devices. The Pulse Height Analysis algorithm can perform online baseline restoration, ballistic effect corrections, and manage the pile-up of live time information. The following picture is a simplified scheme demonstrating how the timing and trapezoidal filter implemented in the DPP-PHA firmware work. More details about the DPP-PHA can be found in [9].

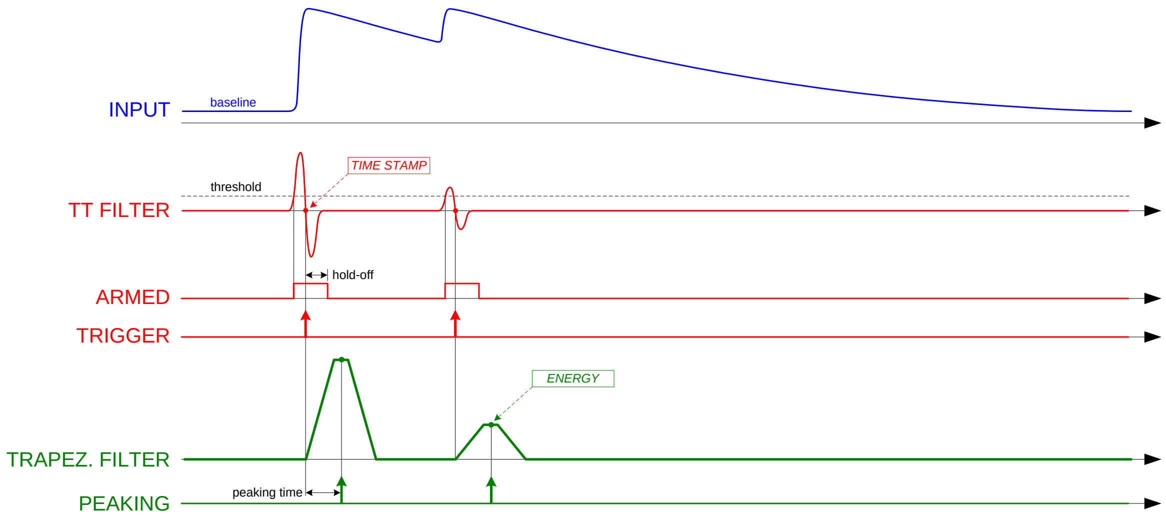


Figure 5: Simplified signals scheme of the Trigger and Timing filter (red) and the Trapezoidal Filter (green). In blue are the input pulses from the preamplifier.

- The V1730 is are equipped with the **Pulse Shape Discrimination (DPP-PSD)** firmware it is based on an advanced on-line Digital Dual Gate Charge Integration algorithm that allows effective data analysis even at high count rates. It performs signal baseline calculation, gate self-generation with programmable parameters, and pedestal subtraction for energy calculation. In the present setup DPP-PSD will be used to identify, with high resolution, the energy and timestamp information from the scintillators. The following picture depicts a simplified scheme of DPP-PSD firmware operation. More details about the DPP-PSD can be found in [10].

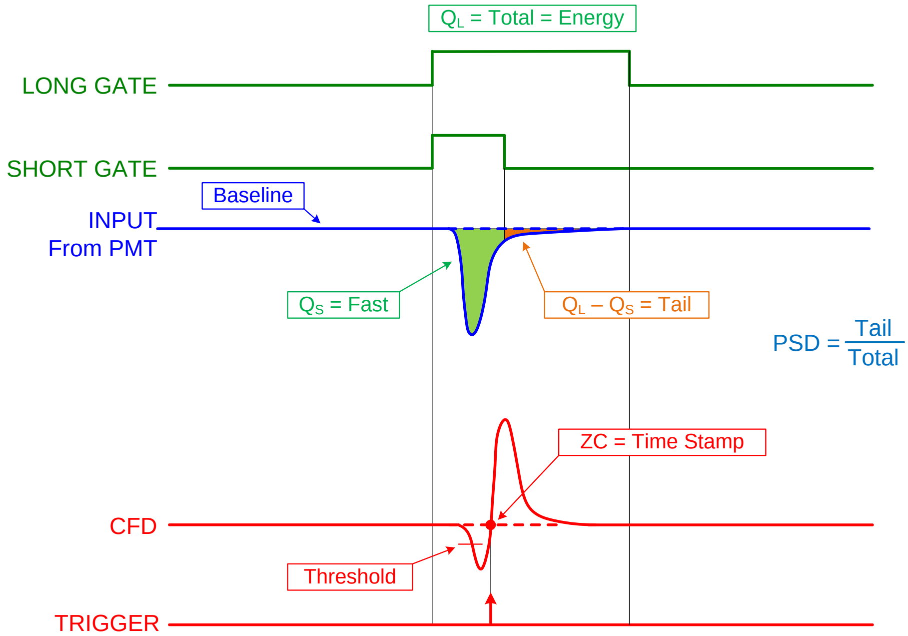


Figure 6: Diagram summarizing the DPP-PSD parameters. The trigger fires as soon as the CFD signal crosses the zero level. Two integration gates (Long Gate and Short Gate) are used to evaluate the pulse energy, the fast component, and the charge in the pulse tail through the integrated charge difference. The PSD will be the ratio between the charge in the pulse tail and the total charge.

The DPP-PSD firmware also implements a fast timing filter (e.g. digital Constant Fraction Discriminator [CFD]), utilizing a linear interpolation of the waveform at the output of the filter. The digital CFD provides superior time resolution, ideal for high precision timing measurements. Figure 7 shows the implementation of the digital CFD in the CAEN DPP-PSD firmware.

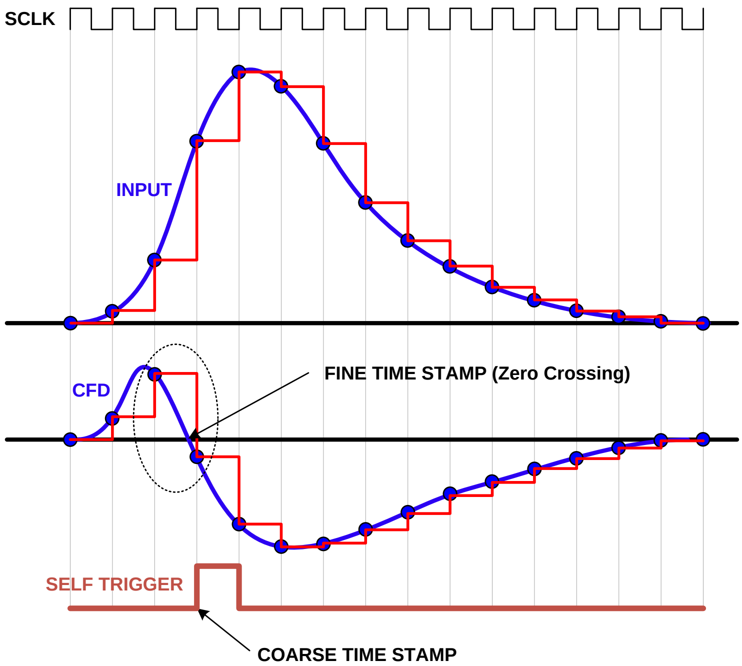


Figure 7: Implementation of the digital Constant Fraction Discriminator in the DPP-PSD firmware.

- The V2495 is equipped with **custom firmware** which provides for the generation of an individual (channel by channel) VETO signal. This VETO signal is required to apply the Anti-Compton Shield for the Clover detectors. With appropriate firmware the V2495 is also able to manage coincidence between different detectors at hardware level according to user defined logical operations.

6.2 System Architecture

The system architecture is shown in

Figure 8 and is composed by the boards and accessories listed above. The CAEN V1725 and V1730 Digitizers are general purpose boards and, thanks to their maximum flexibility, allow the user to read out signals coming from many different types of detectors (HPGe, Clovers, $LaBr_3$(Ce), $CeBr_3$, BGO, CsI, Multi Wire Proportional Chambers, etc.) by simply loading the most suitable DPP firmware onto the FPGA.

In the context of the present application note the V1725 digitizer board will be used for acquiring the signals coming from both the Clover detectors and from the Anti-Compton shield.

In particular, a single V1725 is able to host the signals coming from four Clover detectors (so two V1725 will be used to read all the 8 Clovers signals) while a 3rd V1725 will host all of the Anti-Compton Shield (BGO + CsI) signals.

The signals coming from the Clover detectors and the Anti-Compton Shield are digitized by the V1725. The V1725 implements a digital fast discriminator that generates a signal as soon as a programmable threshold is crossed.

The output of the fast discriminators are sent through the LVDS output to the I/O register of the V2495, which implements a programmable delay and generates the VETO signals (individual channel by channel). The VETO signals are then sent back to the LVDS I/O port of the V1725 digitizers. The V2495 logic unit can be accessed via the VME bus through the V2718 VME Bridge, thus allowing the user to set an appropriate delay which will optimize effectiveness of the Anti-Compton Shield. The V2495 also manages, at a hardware level, the coincidences between different Clovers according to the logic specified by the user.

The signals coming the $LaBr_3$(Ce) detectors are digitized by a V1730 that implements a digital fast discriminator as well. Following the same architecture described above for the V1725, the output of the fast discriminators of the V1730 boards can be sent to the V2495 to perform, at a hardware level, the coincidence logic operations.

The V2495, utilizing custom firmware designed for this experiment, can manage the following data selection criteria:

1. Anti-Compton Shield generated as the logical OR of the signals coming from the BGO and the CsI detectors
2. At least two Clovers
3. At least 1 Clover + 1 $LaBr_3$(Ce)
4. Any 2 $LaBr_3$(Ce)

Additional coincidence criteria can be defined by the users according to their specific needs.

According to the applied selections, the V2495 will then generate a VETO signal (again individual channel by channel) that is sent to the digitizers LVDS inputs for data recording or rejection.

Note: the V2495 custom firmware is an open source VHDL file that CAEN will provide to the user for additional customization at some point in the future.

The data acquisition and control software (described in the following paragraph) allows the user to enable/disable the defined selections (all together, one by one, part of them).

Synchronization among the digitizers is facilitated via daisy chain through the front panel I/O connectors. Additionally, time correlation of events is further maintained by distributing the clock among the digitizers via the A317 clock cables.

The connection between the acquisition PC and the DAQ system (including data transmission and necessary communications with the digitizers and the I/O board V2495) are performed through optical fiber cables, which connect in parallel each board directly to the A3818 PCI Express controller with multiple optical links.

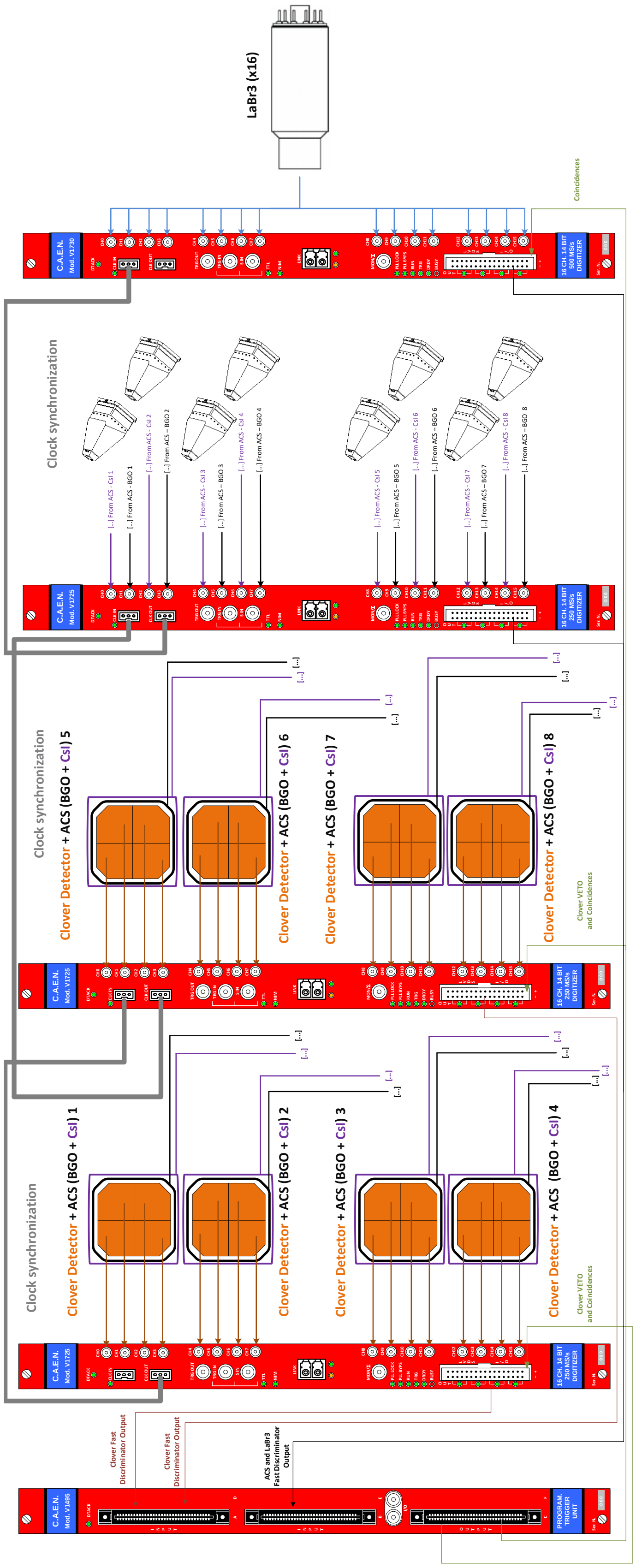


Figure 8: CAEN Readout System for Clover detectors with Anti-Compton Shield and $LaBr_3(Ce)$ scintillators.

6.3 The acquisition and control software

The data acquisition system that CAEN proposes includes a dedicated acquisition and recording system and a DAQ software that will be able to manage the whole setup. The DAQ software conceptual architecture is shown in Figure 9.

The acquisition software is also able to operate with the complete system or with sub-sections of the system. The acquisition software is composed of three main parts: the *Graphic User Interface* (GUI), the *DPP Server*, and the *Plotter*.

The *GUI* allows the user to set and optimize the acquisition parameters, to start/stop the acquisition, to set waveform lengths and spectra binning, to monitor the acquisition statistics, to save the data on the disk, and to perform some post-processing operations such as Clover segment Add-Back and calibration.

The *DPP server* that has the following mains functions:

- Configures the digitizers according to the settings stored in a configuration file that the user modifies via GUI
- Manages the acquisition from the digitizers
- Redirects the data streams to the online processing and visualization algorithms
- Saves the time and energy histograms
- Saves the data in list format: there is one list per channel and includes: TimeStamp, Energy, Flags (these three compose a so called Fragment) and waveforms.
- Saves the data in a raw format that can be used for further offline analysis

The *Plotter* provides the visualization of Waveforms, time, and energy spectra and offers several functionalities such as Energy calibration, zoom/pan, ROIs, and filters definitions etc.

The acquisition software can also perform offline runs in which data are coming from the raw files saved during the standard online run. The software can then apply different filters to produce new spectra.

Beyond the main acquisition software, CAEN also provides an open source C code which offers further customization options.

The C code can perform the following:

- Process the lists produced during an acquisition run (online or offline) and produce a channel-wise, time ordered, fragment list. There is one single list chopped in files of prefixed size or time frames. One fragment = Channel-ID + TimeStamp + Energy + Flags
- Applies the calibration and Add-Back, producing a detector-wise, time ordered, fragment list: same as previous point, but energy is now calibrated and fragments belonging to the same detector (clover) are added back (in a given window). The data format of such a list will include the information about the detector, the energy and the time will be present as in the following example

DET1	T1	E1
DET6	T2	E2
DET4	T3	E3
…		

- Applies further data selection criteria (if any, for instance the coincidences - if not already applied at hardware level) and produces the Event List: fragments that match the coincidence criteria are merged into events and saved to chopped files

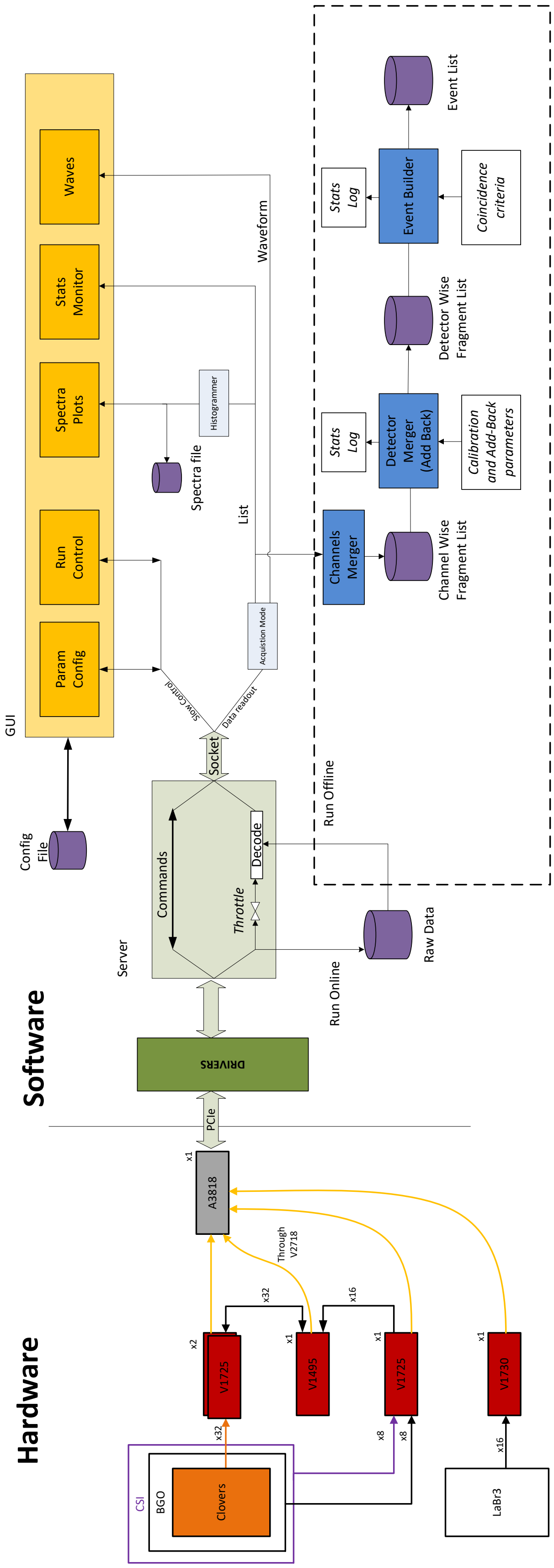


Figure 9: CAEN DAQ Software for Clover detectors with Anti-Compton Shield and $LaBr_3$(Ce) scintillators system.

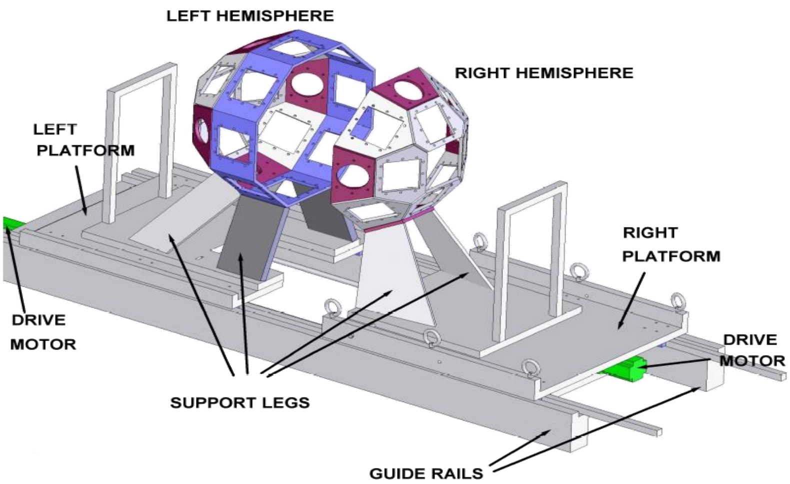
7. Use case: The Clover detector setup at the DHRUVA reactor facility at BARC (India)

In the recent years Clover detectors are becoming more and more popular and the interest, prompting an increased demand for acquisition systems based on digital electronics. CAEN is improving its presence in this market sector by proposing its own digital solutions. These systems are now implemented in several experiments and laboratories all around the world such as DANCE at Los Alamos National Labs (USA), ELI-NP (Romania) and DHRUVA at BARC (India).

In the following the use case of the Clover detector system at the DHRUVA reactor facility at BARC will be described together with characterization measurements and a performance evaluation.

7.1 Experimental Setup

The Clover system at the DHRUVA reactor in the Bhabha Atomic Research Centre (BARC), Mumbai (India) in it's final configuration will be composed of up to 20 Clover detectors with respective Anti-Compton Shield utilizing BGO crystals. The system is completed by 16 $LaBr_3$(Ce) scintillators for precise timing measurements. A conceptual scheme of the DHRUVA proposed final layout is shown in Figure 10.



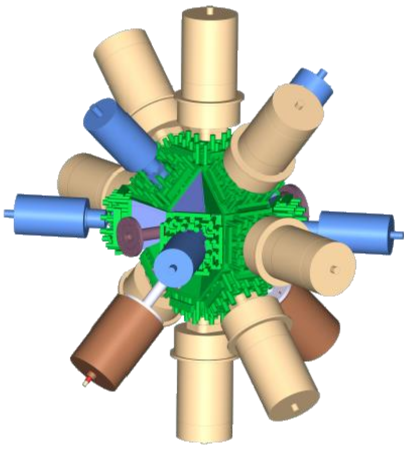


Figure 10: Clover system at the DHRUVA reactor support structure (left) and final detector geometrical configuration (right).

The CAEN Readout System for such a setup is shown in Figure 11 and is composed by:

- N° 4 V1724: 1-unit wide VME 6U module housing a 16 Channel 14-bit 100 MS/s Flash ADC Waveform Digitizer with 2.25 Vpp input dynamics on single ended MCX coaxial;
- N°1 V1720: 1-unit wide VME 6U module housing a 8 Channel 12-bit 250 MS/s Flash ADC Waveform Digitizer with 2.25 Vpp input dynamics on single ended MCX coaxial;
- N°1 V1730
- N°1 V1495: old generation version of the V2495
- N°1 V2718;
- N°1 VME8100
- N°1 A3818
- N°5 A317
- N°4 AY2705
- Flat Cables for V1720 and V1724 – V1495 LVDS connections

The signals coming from the Clover detectors and the Anti-Compton Shield are digitized by the V1724 and the V1720 respectively, which implement a digital fast discriminator that generates a signal as soon as a programmable threshold is crossed.

The output of the fast discriminators are sent through the LVDS output to the I/O register of the V1495, which implements a programmable delay and generates the VETO signals (individual channel by channel). The VETO signals are then sent back to the LVDS I/O port of the V1724 digitizers. The V1495 logic unit can be accessed via the VME bus through the V2718 VME Bridge as is described in the previous chapter. However, in this case the V1495 does not manage the logic operation between different detectors. In this specific setup the acquisition is triggerless and the logic operations are performed offline.

The signals coming the $LaBr_3$(Ce) detectors are digitized by a V1730, which implements a digital fast discriminator. The output of the fast discriminators of the V1730 boards can be sent to the V2495 to perform, at a hardware level, the coincidence logic operations.

Synchronization among the digitizers is facilitated via daisy chain through the front panel I/O connectors. Additionally, time correlation of events is further maintained by distributing the clock among the digitizers via the A317 clock cables.

The connection between the acquisition PC and the DAQ system (including data transmission and necessary communications with the digitizers and the I/O board V1495) are performed through optical fiber cables, which connect in parallel each board directly to the A3818 PCI Express controller with multiple optical links.

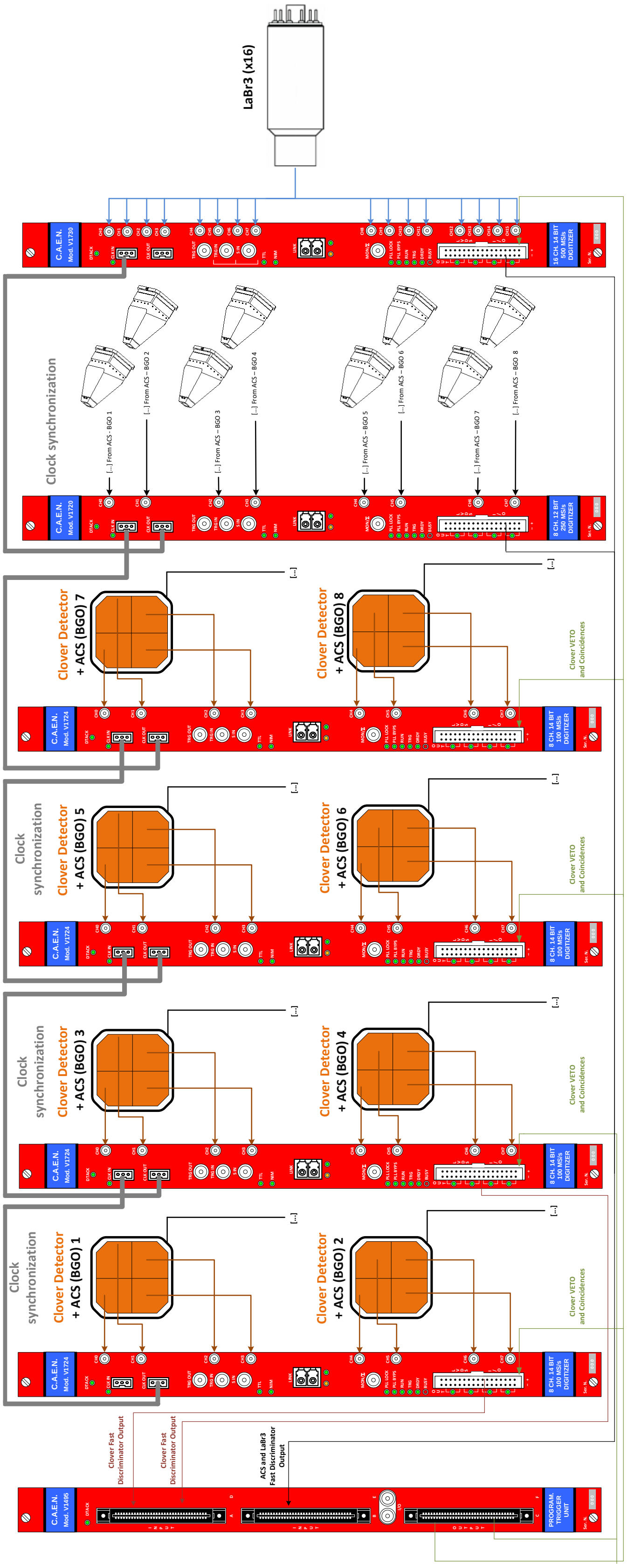


Figure 11: CAEN Readout System for the BARC experimental setup at DHRUVA.

Figure 12: Clover + $LaBr_3$ experimental setup configuration at the BARC test laboratory.

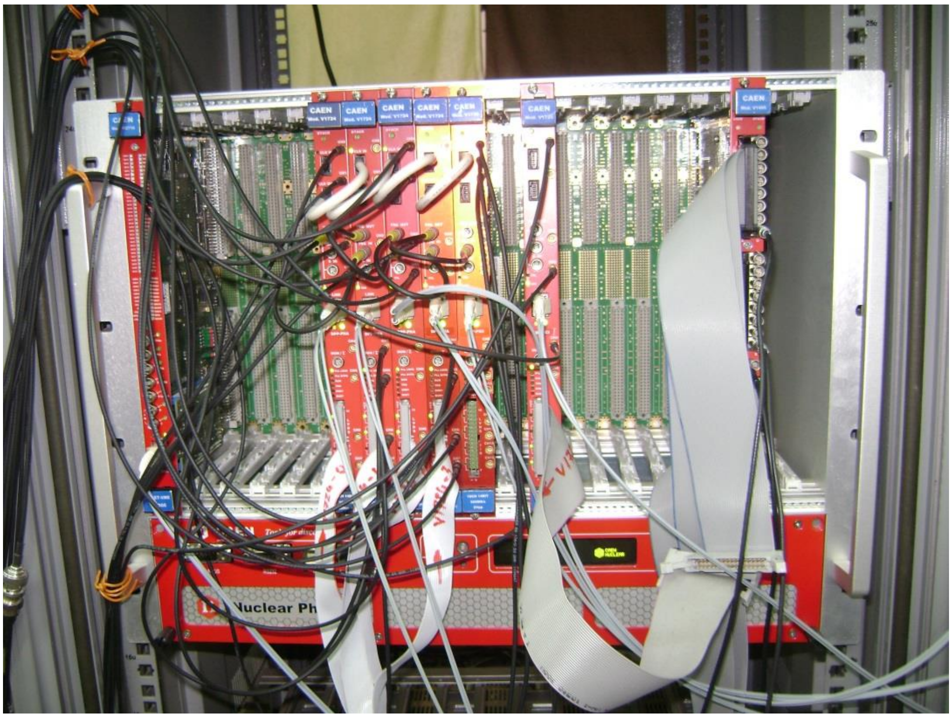


Figure 13: CAEN data acquisition system for the BARC Clover + $LaBr_3$ setup.

7.2 Characterization of the experimental setup

The characterization of an experimental setup composed of Clover detectors and Anti-Compton shield and the evaluation of its performance is performed by a standard set of experimental measurements aiming to determine well-defined quantities. In particular, this evaluation is performed using a ^{60}Co source placed 25 cm away from the Clover detectors and acquiring spectra in direct and total detection modes, then evaluating the spectra both before and after the application of the Anti-Compton shield:

- the *Add-back* factor: a parameters that allows to evaluate the contribution from scattering between the detectors to the total photopeak efficiency of a Clover detector[11]
- the *Peak to Total* (P/T) Ratio: it corresponds to the sum of the ^{60}Co net peak areas divided by the total number of counts in the spectrum for energies from 100 to 1350 keV[12]
- the energy resolution at 1332 keV ^{60}Co peak

Additional characterization measurements which are important for the specific application are:

- $LaBr_3$(Ce) Time-of-flight resolution with ^{60}Co source
- ^{252}Cf spectrum acquisition

All measurements were performed in 30-minute collection intervals. The data, acquired with the CAENDAQ software, were then analyzed with the ***RadWare*** software, a tool provided by the Oak Ridge National Laboratory and widely used in the gamma spectroscopy community.

Much attention has to be payed to the system energy calibration (especially at low energy values) in an effort to optimize *Add-Back* performance. The energy calibration has been performed using an ^{152}Eu source, whose spectrum is shown Figure 14.

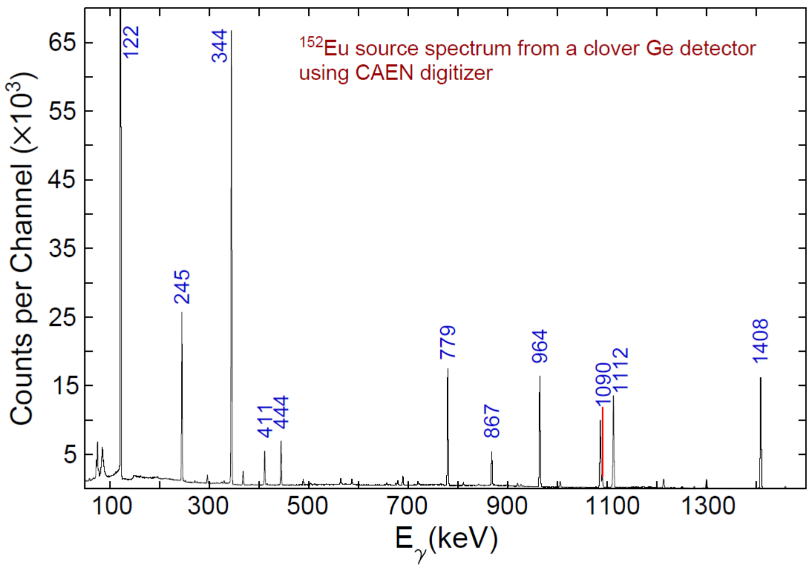


Figure 14: ^{152}Eu calibration spectrum

In this kind of measurements the background is another crucial component. Background can be determined and subsequently removed via dedicated acquisition processes. The resultant spectra have therefore had the background subtracted.

The environmental background spectra recorded by one of the Clover detectors is shown in Figure 15. The ^{60}Co spectrum collected by a single Clover crystal is shown in Figure 16. The ^{60}Co spectrum collected by a $LaBr_3$ is shown in Figure 17. The ^{60}Co source was actually the sum of two different sources whose activities were approximately 73 and 81 kBq.

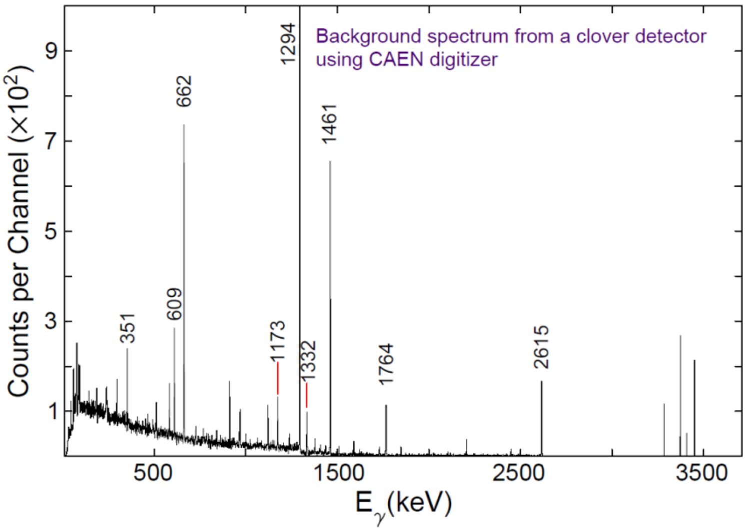


Figure 15: Environmental background recorded by a Clover detector whose signal is digitized by a V1724 (14 bit, 100 MS/s) module.

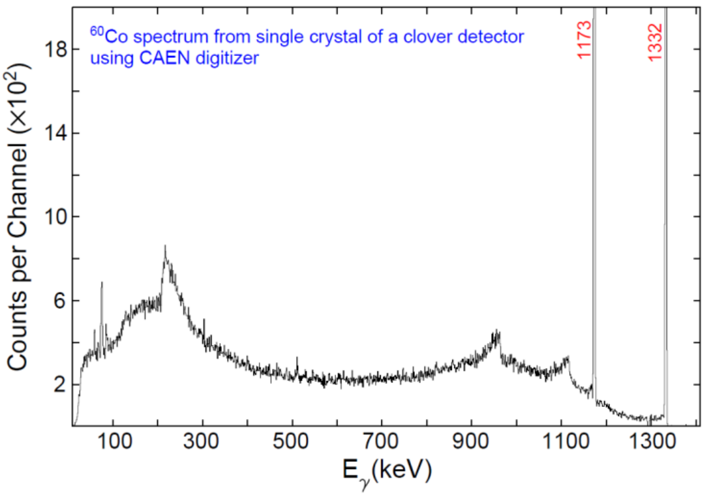


Figure 16: ^{60}Co spectrum recorded by a single Clover crystal.

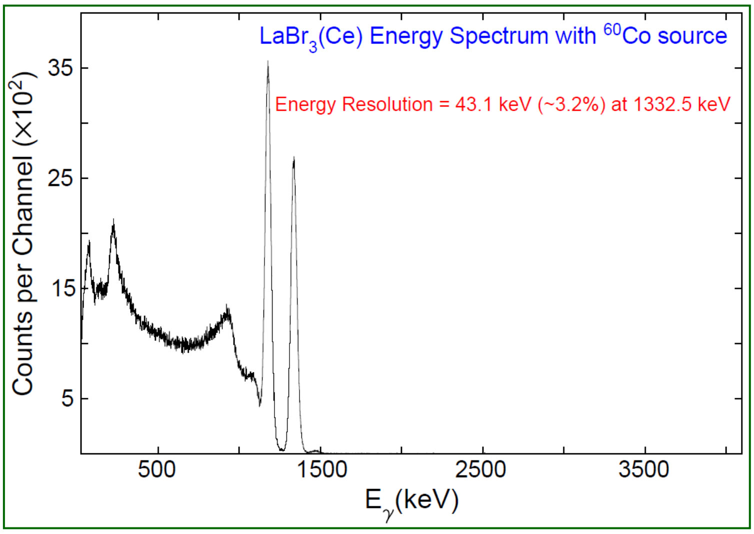


Figure 17: ^{60}Co source spectrum collected by a $LaBr_3$ scintillator whose signal is digitized by a V1730 (14 bit, 500 MS/s) module. Picture from [13].

The input counting rates (ICR) per Germanium crystal, per Clover and per $LaBr_3$ are summarized in Table 1 and in Table 2.

Input Counting Rate	Without Anti-Compton Shield	With Anti-Compton Shield
Single Clover crystal	20-50 Hz	10-35 Hz
Clover	90-100 Hz	40-50 Hz
$LaBr_3$	~ hundreds of Hz up to 1 kHz	

Table 1: Input counting rate during the environmental background data acquisition.

Input Counting Rate	Without Anti-Compton Shield	With Anti-Compton Shield
Single Clover crystal	2-5 kHz	1-2 kHz
Clover	5-10 kHz	2-4 kHz
$LaBr_3$	2-3 kHz	

Table 2: Input counting rates during the ^{60}Co source data acquisition.

Figure 18 shown the *Add-Back* factor as function of the energy and, at the energy of 1332 keV has been evaluated to be **1.50**[13] which is comparable with those reported in literature in previously built acquisition systems for Clover detectors[1][12]. The *Add-Back* windows was fixed at 150 ns.

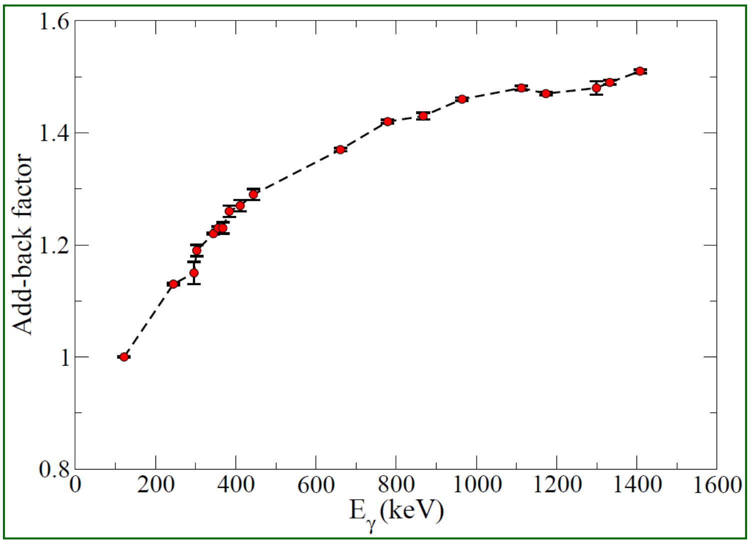


Figure 18: Clover Add-Back factor as function of the energy. Picture from [13].

The Clover energy resolution as function of the energy is shown in Figure 19.

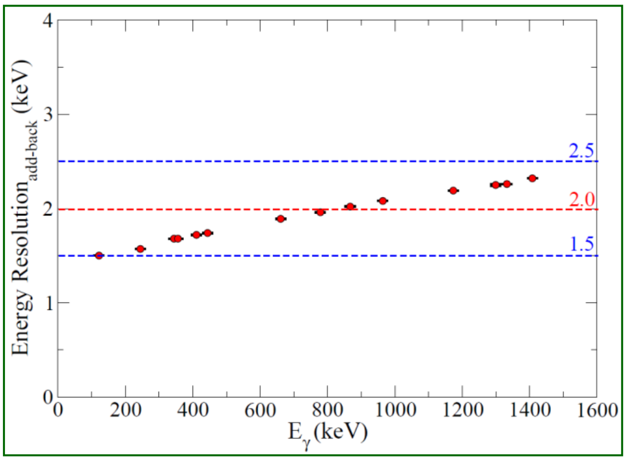


Figure 19: Clover energy resolution as function of the energy. Picture from [13].

On-line time-of-flight (TOF) spectrum for two $LaBr_3$(Ce) was obtained using ^{60}Co radioactive source and it is shown in Figure 20. The timing resolution for $LaBr_3$(Ce) detectors was ~**440 ps**[13].

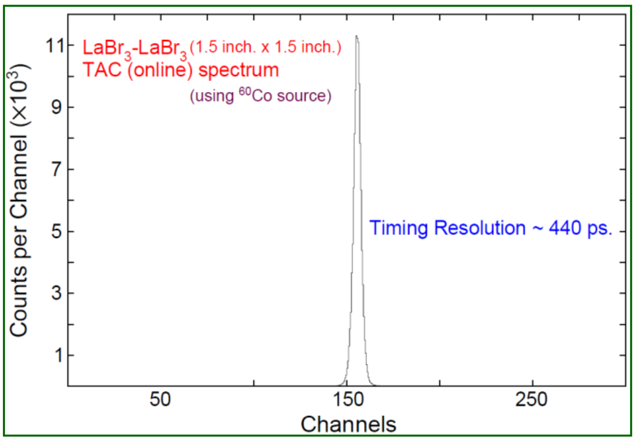


Figure 20: $LaBr_3$(Ce) time-of-flight (TOF) distribution with ^{60}Co radioactive source. Picture from [13].

The Compton unsuppressed and background unsubtracted, Compton unsuppressed and background subtracted and suppressed spectra for ^{60}Co are shown in Figure 21 in black, red and blue respectively.

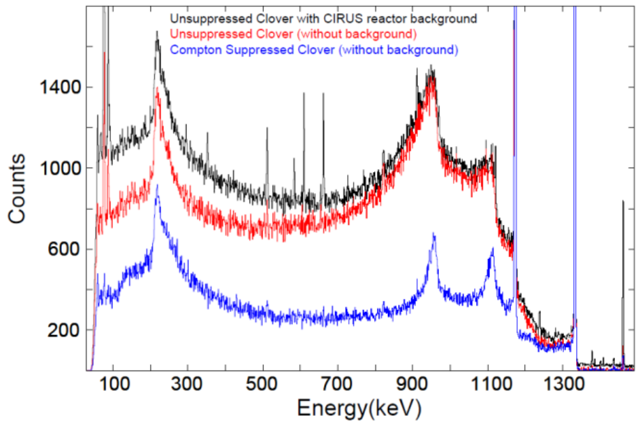


Figure 21: ^{60}Co Spectrum before background subtraction (black), after background subtraction (red), after compton suppression (blue). Picture from [13].

The corresponding *P/T* ratio is measured to be **0.13/0.14** at the detector segment level in the Compton-unsuppressed mode, **0.21/0.24** in the Compton-suppressed one. In *Add-back* mode it was found to be **0.25** and **0.44**[13] before and after the Anti-Compton shield, values comparable with those reported in literature[1][12].

7.3 Californium source acquisition run

The last test performed was a run with a ^{252}Cf spontaneous fission source. The basic purpose of using ^{252}Cf source was to see the real time multi-fold data acquisition using a fission source, and also to see the handling of count rate. The latter couldn't be properly explored due to the source weakness. However we were still able to simulate, to some extent, the real-time planned experimental condition (gamma ray spectroscopy following thermal neutron-induced fission of fissile targets) by acquiring data from a fission source, where hundreds of fragment nuclei are emitted, each having several gamma rays in cascade/coincidence.

The detector ICR during the run are listed in Table 3.

Input Counting Rate	With Anti-Compton Shield
Single Clover crystal	100 Hz
$LaBr_3$	500 Hz
BGO	Some (2 to 6) kHz

Table 3: Input counting rates during the ^{252}Cf source data acquisition.

Figure 22 shows the ^{252}Cf source spectrum acquired by a Clover detector.

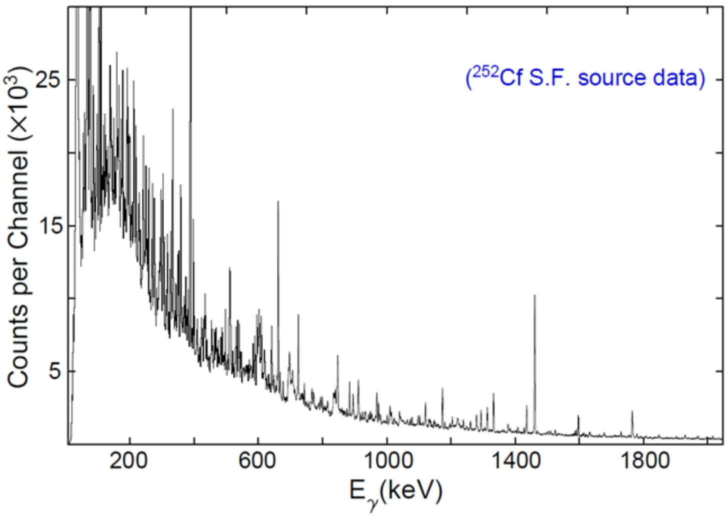


Figure 22: ^{252}Cf fission source spectrum recorded by a Clover detector. Picture from [13].

From the data we developed gamma-gamma coincidence mapping (gamma-gamma matrix). The matrix is useful to identify and check the population of a particular fission fragment nuclei. With this matrix we can also identify the number of gamma rays that are in coincidence (emitted in cascade) for a particular fragment nuclei. This helps in building the so called level schemes (low-, medium- and high-spin structures) of nuclei.

To illustrate, Figure 23 and Figure 24 show the level schemes and the representative gated spectra of ^{144}Ba and ^{148}Ce nuclei. These are well populated nuclei in ^{252}Cf fission data. Even with the limited strength of the used fission source and only 4 detectors available during the run we were able to extract good and clear spectra of these two nuclei.

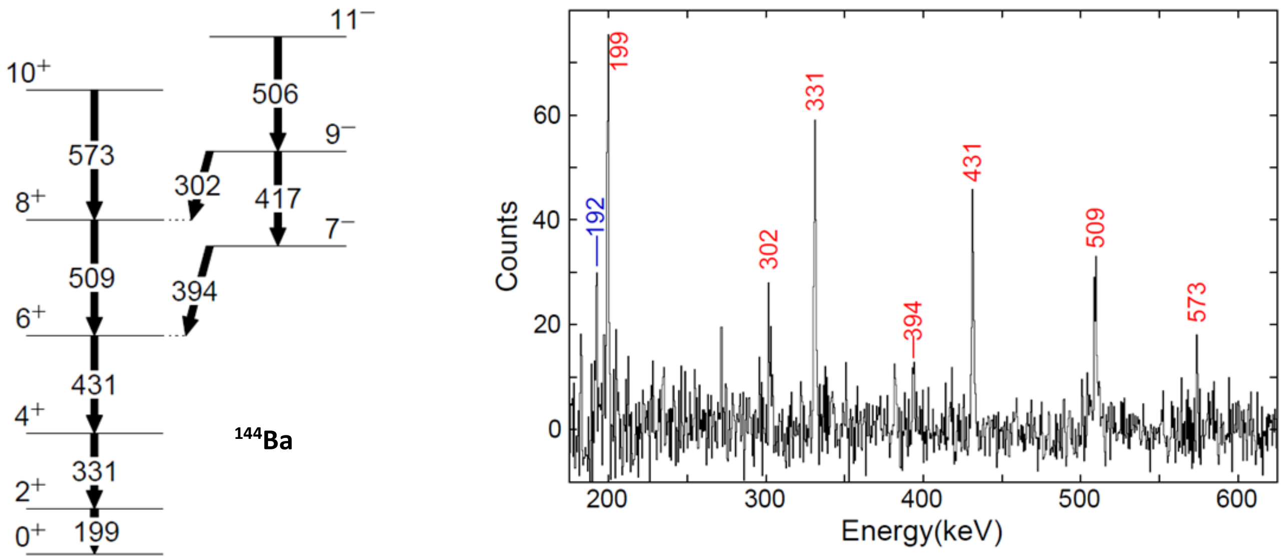


Figure 23: (Left) ^{144}Ba gamma decay scheme. (Right) Gated spectrum of ^{144}Ba from the acquired data with the ^{252}Cf source. Pictures from [13].

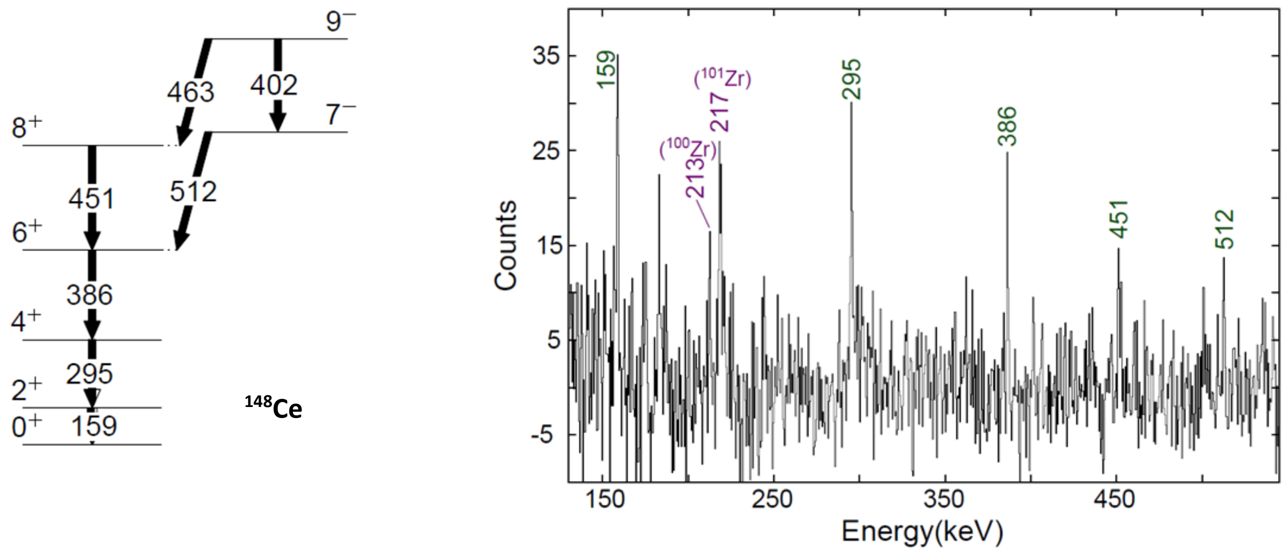


Figure 24: (Left) ^{148}Ce gamma decay scheme. (Right) Gated spectrum of ^{148}Ce from the acquired data with the ^{252}Cf source. Pictures from [13].

8. Conclusions

The Clover detector is a composite detector consisting of four ~21% efficiency crystals mounted in a compact geometry. Typically it is surrounded by an array of BGO and/or CsI crystal acting as an Anti-Compton Shield. The CAEN acquisition system for such an experimental setup is based on new generation front-end electronics boards (Digitizers), which are based on flash-ADC and FPGA running dedicated digital pulse processing firmware which will perform, in a single board, all operations traditionally performed by a full analogue chain. This digital solution has recently been implemented in different experimental setups all around the world, for example the Clover setup at the DHRUVA reactor facility at BARC (India). This system is composed of 8 Clover detectors with BGO Anti-Compton Shield together with $LaBr_3$(Ce) scintillators for precise timing measurements. The related CAEN readout system is composed of the V1724 (14-bit, 100 MS/s), V1730 (14-bit 500 MS/s) and V1720 (12-bit, 250 MS/s) digitizers. The performance of the experimental setup has been evaluated with standard measurements performed with a ^{60}Co source. Evaluation of the system's *Add-back* factor and *Peak to Total* ratio were compared with literature values achieved in similar conditions. Working in the total detection mode, the photopeak detection efficiency of the Clover detector at 1332 keV is increased by a factor **1.50** (*Add-back* factor) relative to the direct mode. The *Peak to Total* Ratio was found to be **0.13/0.14** at the detector segment in the Compton-unsuppressed mode, **0.21/0.24** in the Compton-suppressed one, **0.25** and **0.44** in *Add-back mode* with and without the Anti-Compton Shield, respectively.

9. References

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