CAEN Electronic Instrumentation
Tools for Discovery

From Analog to Digital DAQ Transition in Physics Application

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Summary

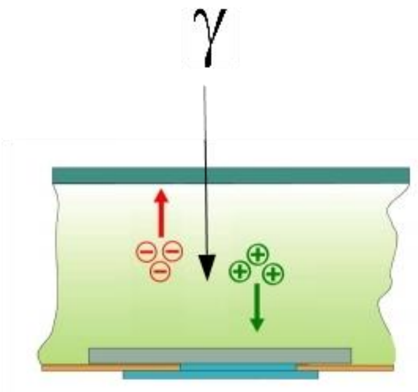
- **Fundamentals**
  - Definitions
  - Detectors
  - Measurements and analysis
- **Detector Readout Electronics**
  - Comparison between analog and digital readout chain
  - Waveform digitizers
  - Data streaming and online data processing
  - Oscilloscope mode and List mode
- **Pulse Processing Algorithms**
  - Digital pulse processing algorithm: DPP-PHA
  - Digital pulse processing algorithm: DPP-QDC and DPP-PSD
  - Advanced zero suppression algorithms: DPP-ZLE & DPP-DAW
- **Digital vs Analog: advantages and drawbacks**
- **Introduction to ASICs for physics applications**

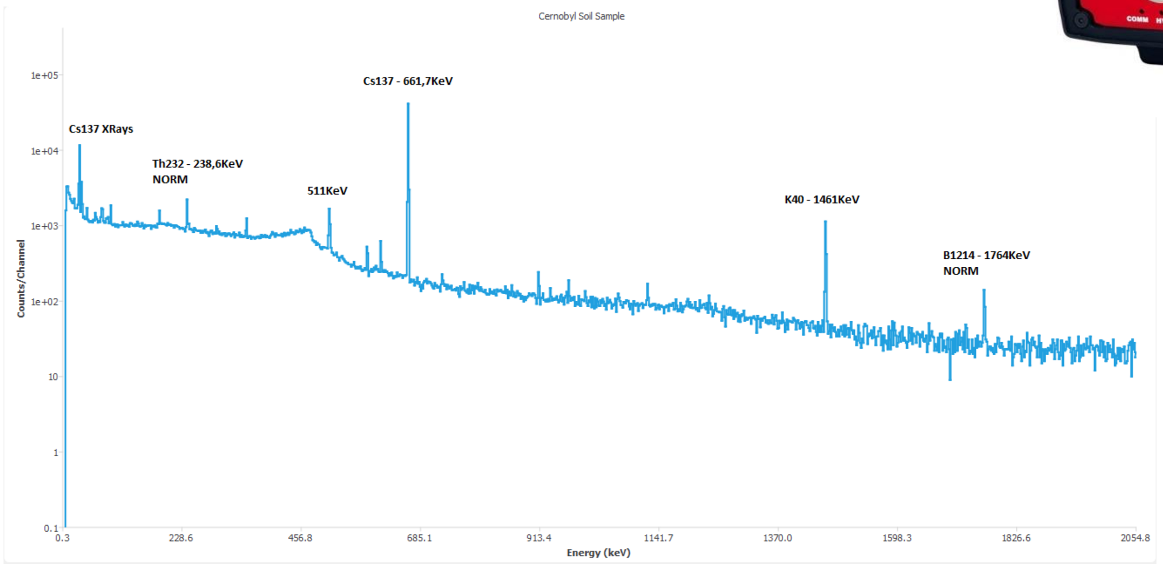
Fundamentals

Definition

Spectroscopy is the study of the interaction between matter and radiation with the aim to get information about the energy distribution of the source

Radiation: charged (α, β, light nuclei) or neutral particles (photons – X and γ in our case – and neutrons)



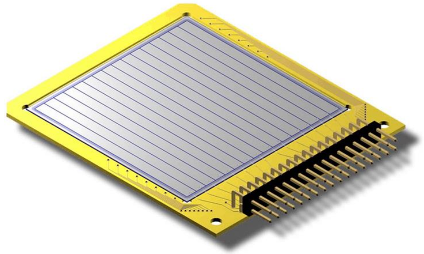


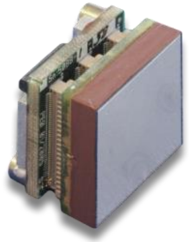
Detectors in a nutshell

High resolution spectroscopy

Semiconductors: **HPGe, Silicon, CZT**

Depending on the detector geometry and thickness, energy range and resolution changes





Mid-resolution spectroscopy

Scintillators: **NaI, CsI, LaBr3, CeBr3, …**

Bigger crystal for higher detection efficiency

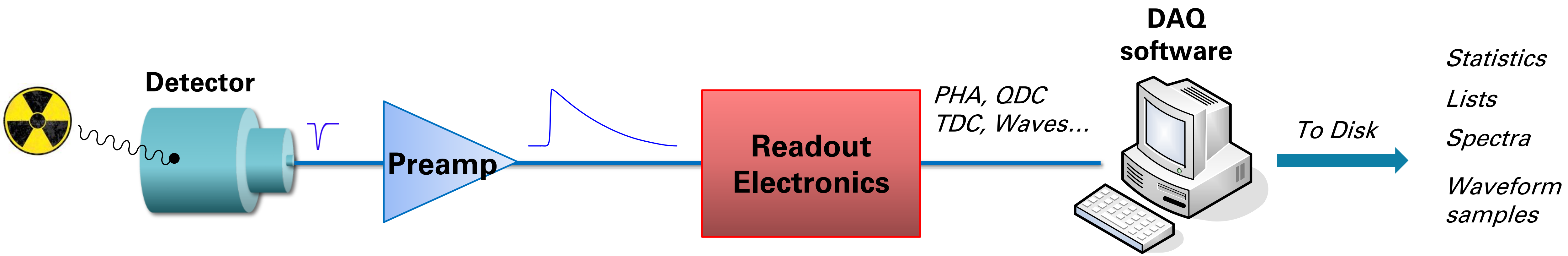
Low-resolution spectroscopy

Scintillators: **BGO, Plastic scintillators, …**

Typically used for active shieldings: AntiCompton or Anticosmic Shield

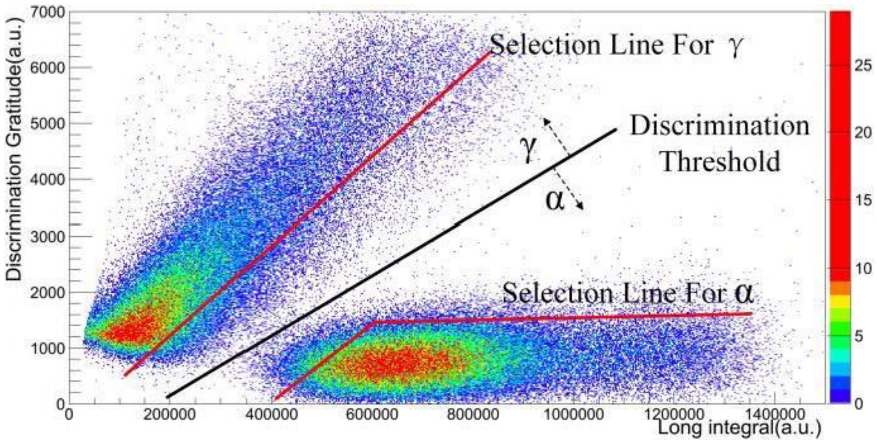
Measurements and analysis - 1

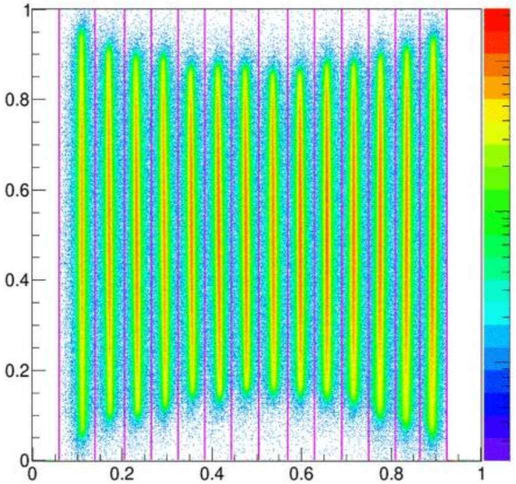
- A **charge pulse** is produced when a particle interacts with the detector. Amplitude and shape of this pulse depends on the detector characteristics as well as the particle type.
- **Preamplifier**: required in most cases to amplify the weak charge pulse generated by the detector. Low noise, high sensitivity, typically installed very close to the detector.
  - **Charge Sensitive Preamps**: optimized for energy resolution, slow output, changes shape
  - **Fast (current) preamplifier**: mostly used for timing applications, fast output
- **Readout electronics**: aims to acquire pulse characteristics such as Pulse Height (PHA), charge (QDC), Timing (TDC), Shape, and, in some cases, full waveforms

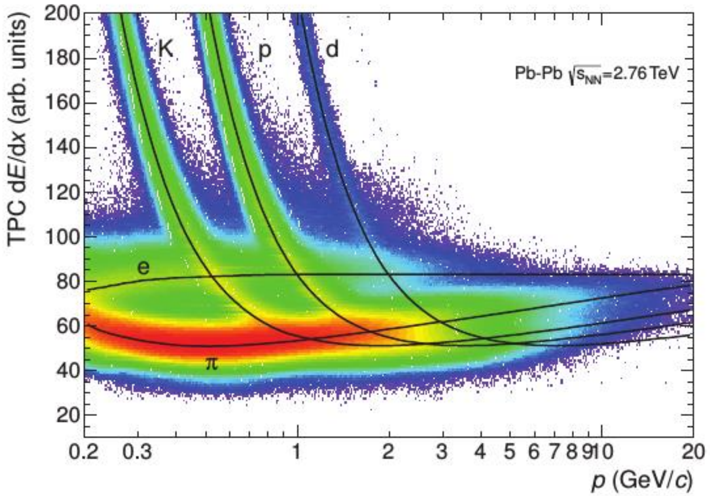


Measurements and analysis - 2

Multiparametric analysis is the study of the interaction between matter and radiation in which different information (energy, time, pulse shape, correlation, position) are used together.







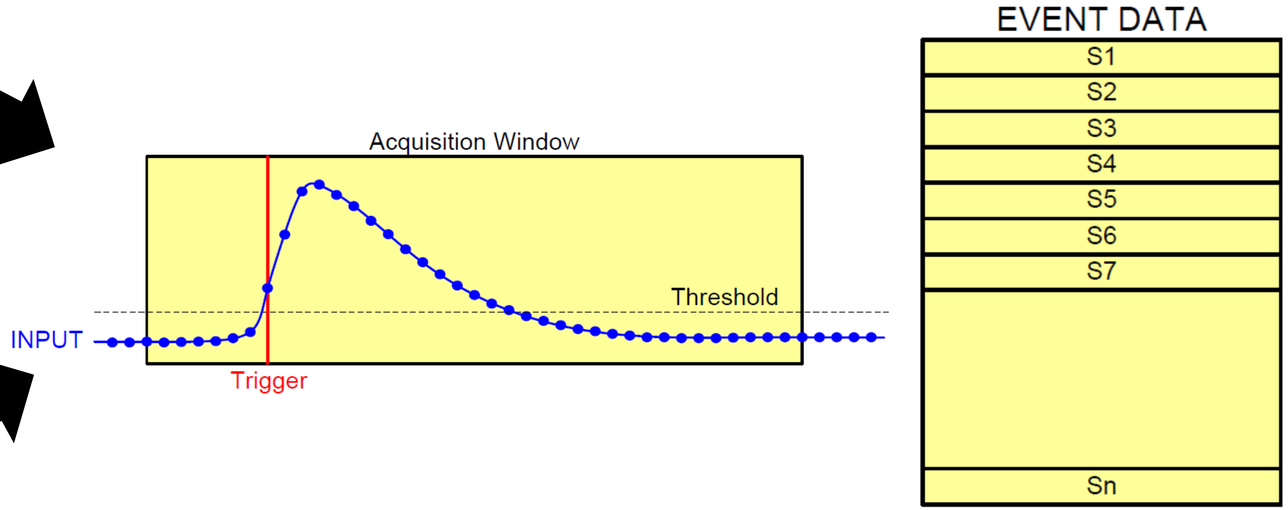
Involved detectors:

- same as traditional spectroscopy
- others (wire chambers, TPCs, GEMs, RPCs,...)

Detector Readout Electronics

Digitizers vs Oscilloscopes

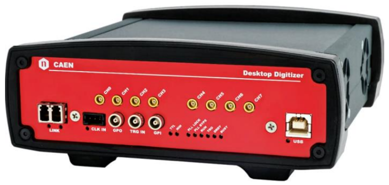
The principle of operation of a waveform digitizer is the same as the digital oscilloscope: when the trigger occurs, a certain number of samples (acquisition window) is saved into one memory buffer

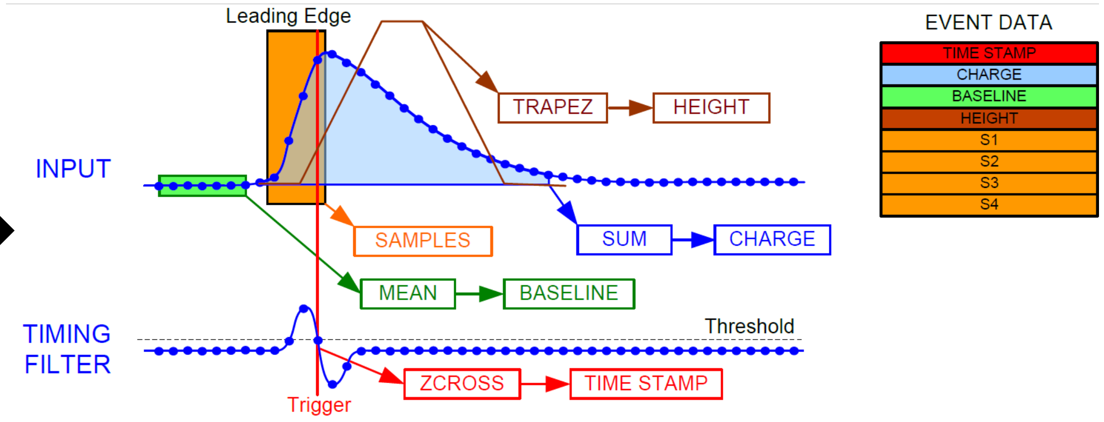


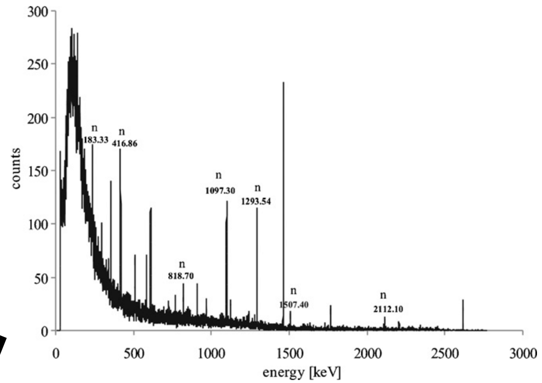
Digitizers vs Oscilloscopes

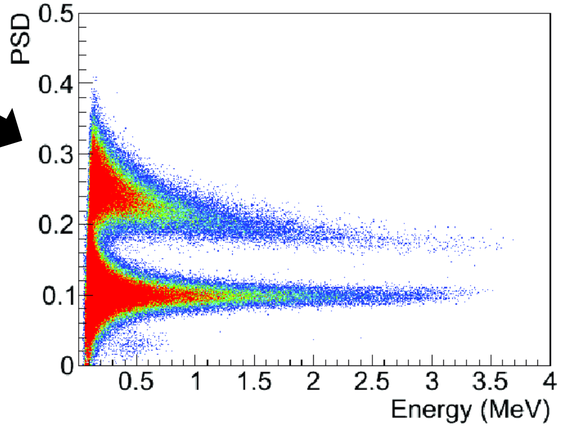
There are important differences:

- no dead-time between triggers (Multi Event Memory)
- multi-board synchronization for system scalability
- high bandwidth data readout links
- on-line data processing (FPGA or DSP)

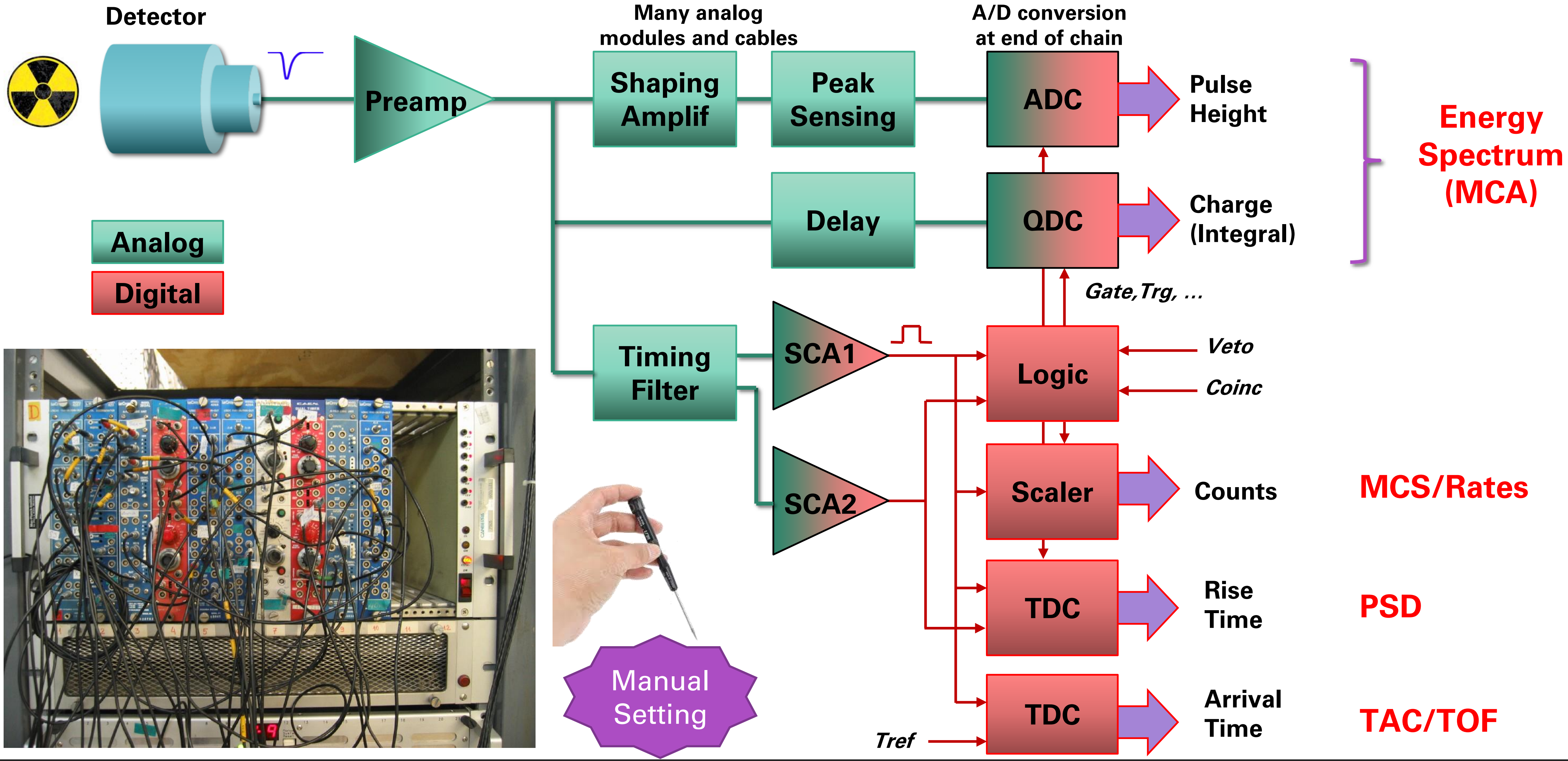




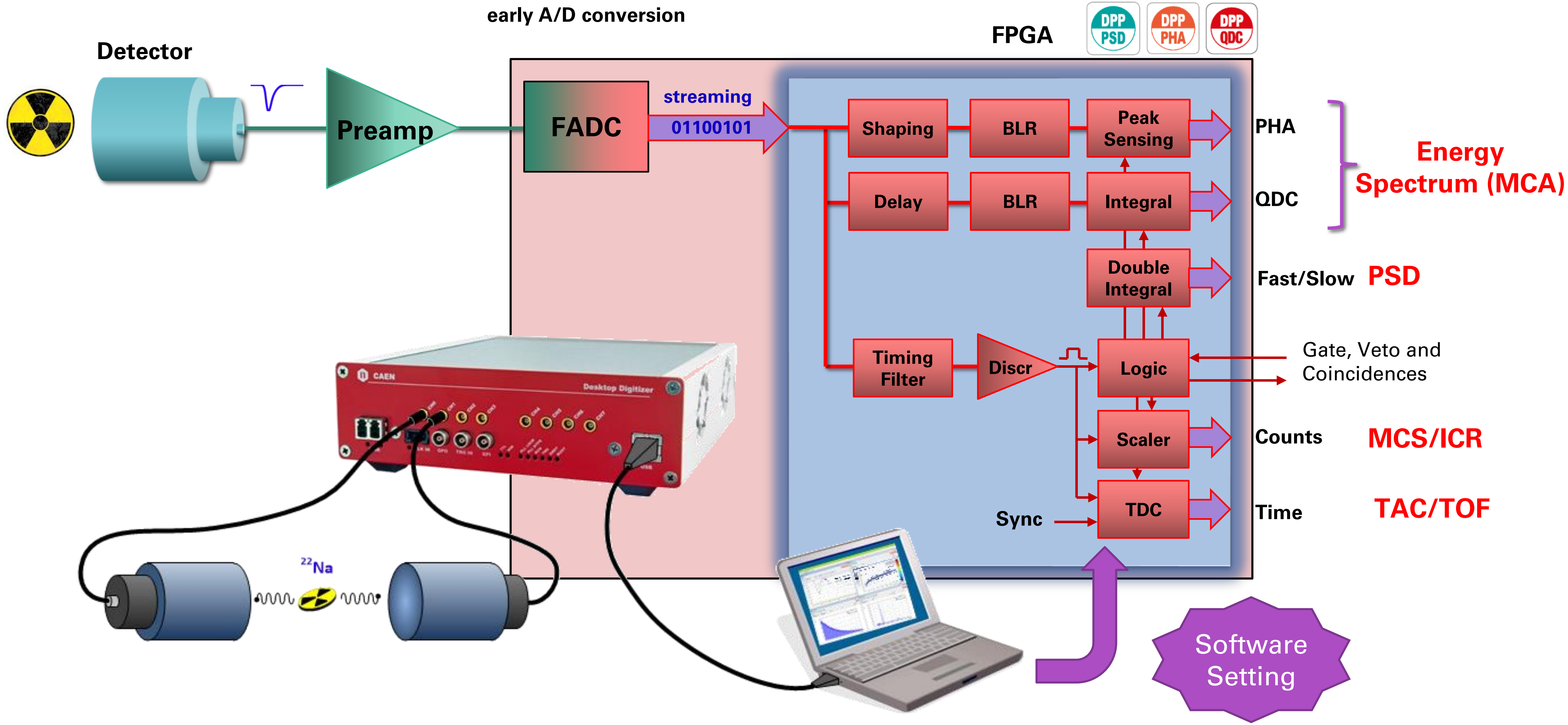




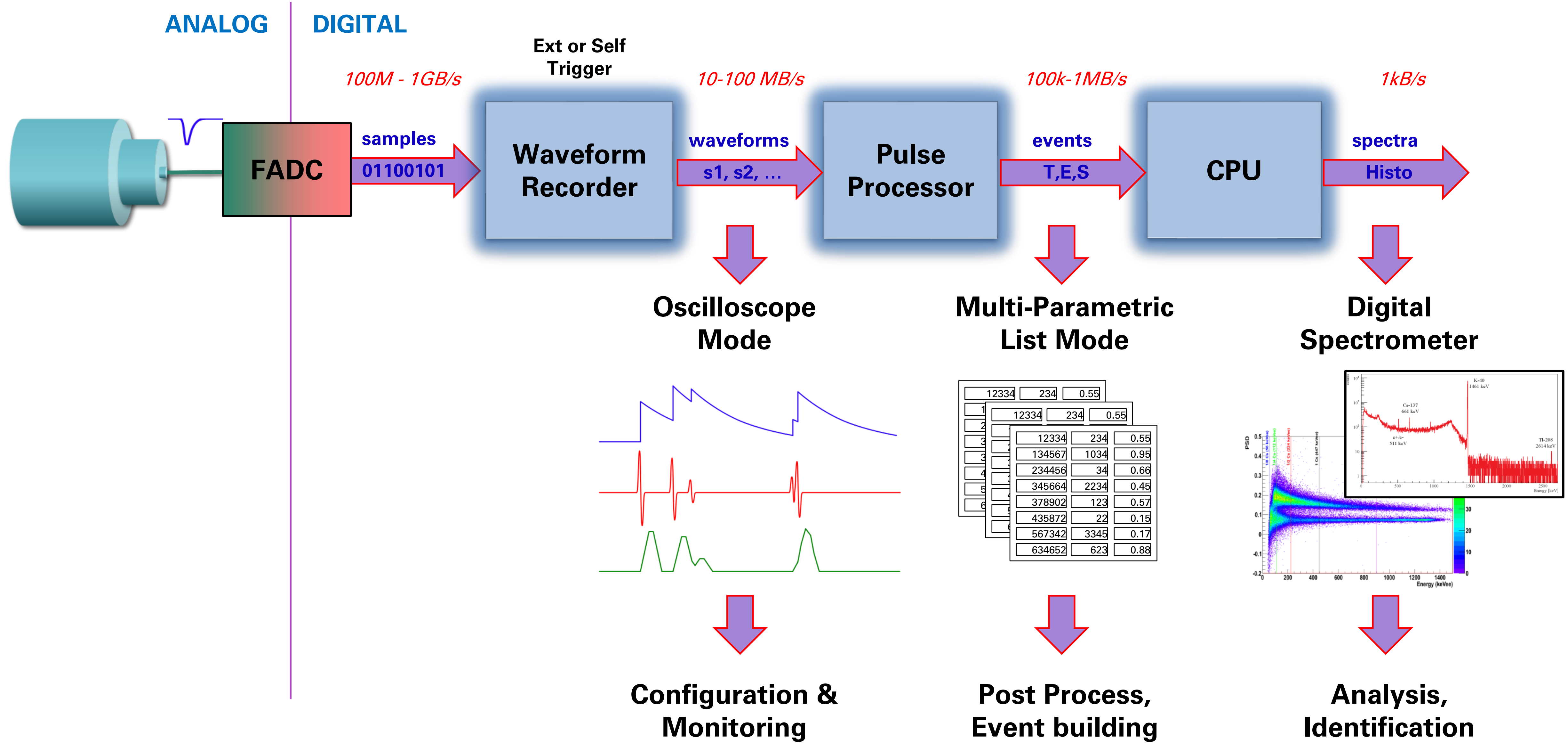
Traditional Spectroscopic/Multiparametric Analog Chain



The Digital Approach: All in one



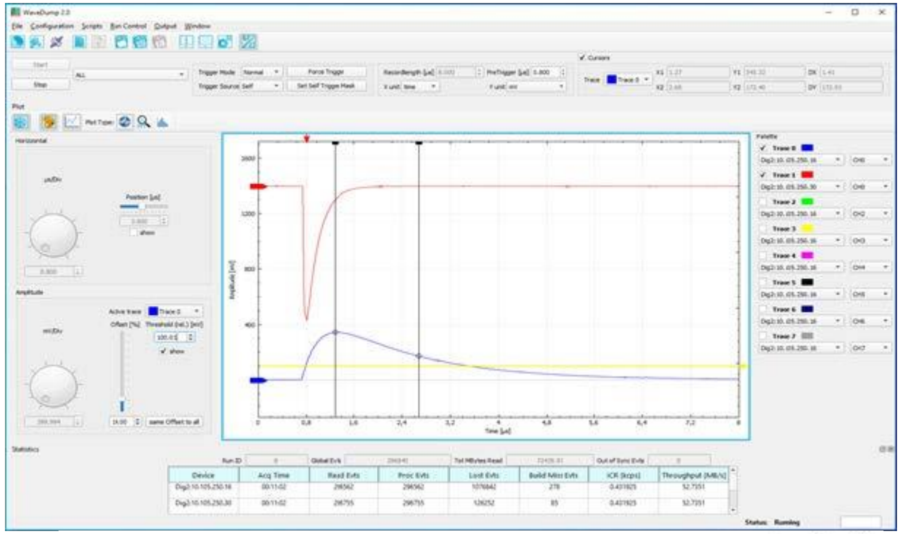
The Digital Approach: Digital Acquisition Chain



Trigger scenarios

1. **Common trigger**: All channels receive the common trigger and save a certain number of samples around this trigger in a local memory buffer.

Oscilloscope Mode: Waveform acquisition

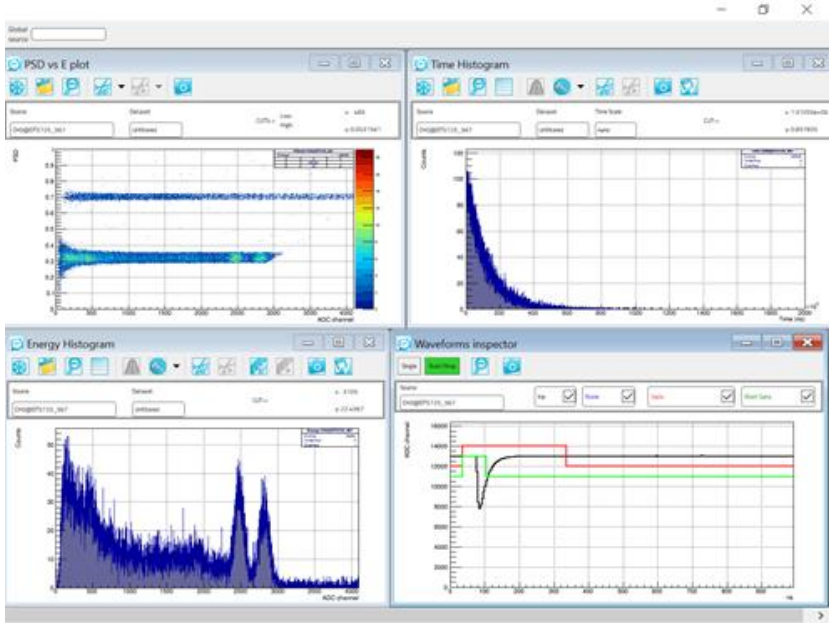


2. **Self trigger/Trigger-less**: Each channel independently acquires data, creating its own self-trigger.

Required information is not the complete waveform but only specific characteristic parameters (pulse height, charge, time stamp..)

Algorithms in the FPGA process the pulse waveform and extract these parameters.

DPP Mode: List acquisition



Trigger scenarios

Intermediate situations between the oscilloscope mode and the DPP mode.

1. DPP algorithms only for pulse identification and trigger generation using appropriate trigger logic (coincidences, multiplicities, etc.) to generate a global trigger that opens the common acquisition window to save waveforms on all channels simultaneously.

2. Acquire in list mode with DPP (independent self-triggers) but with a common validation signal for all channels ---> list data saved only if it belongs to a certain time interval. This approach enables the implementation of coincidence logic, veto logic, etc.

Pulse Processing Algorithms

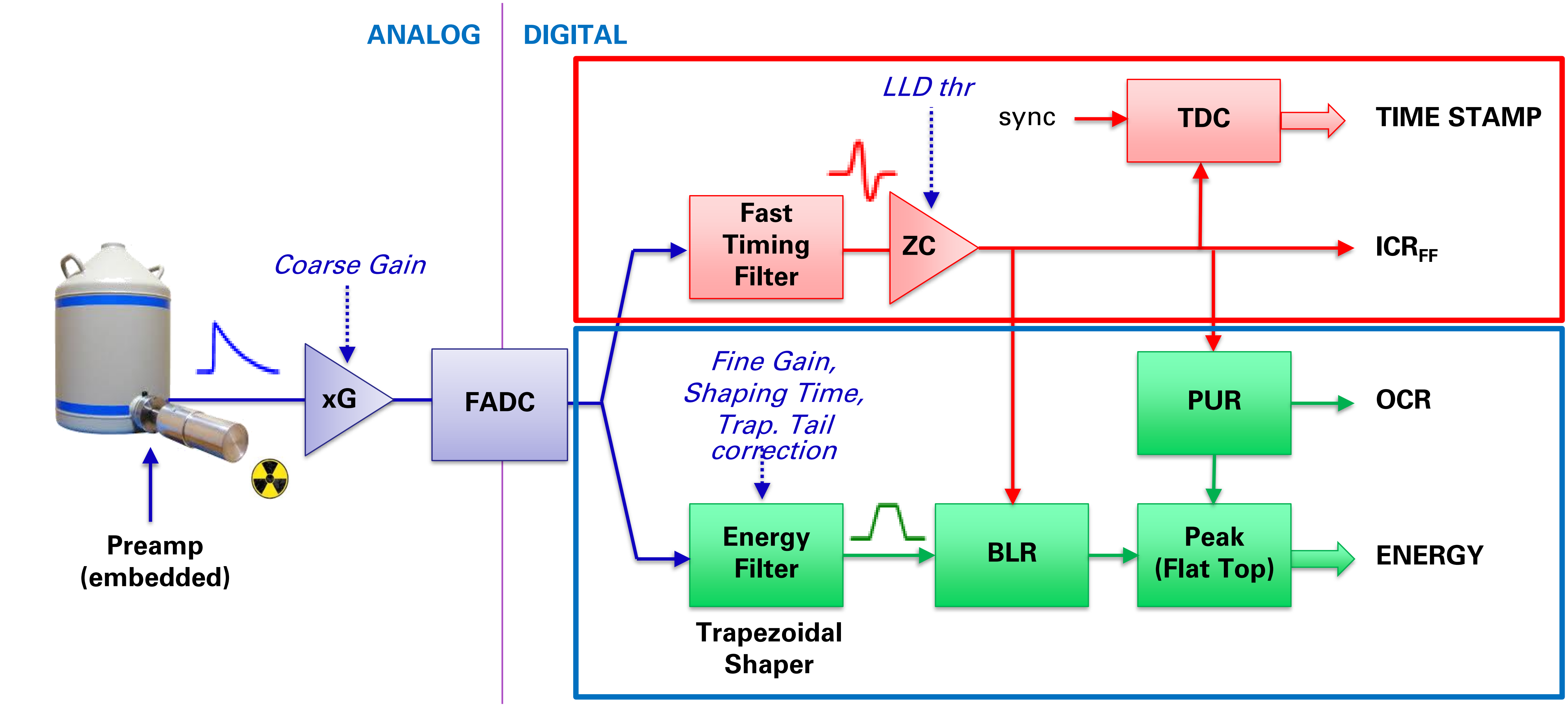
DPP-PHA

The DPP-PHA

Typical signal for DPP-PHA:
Rise Time: ~ 100 ns
Decay Time: ~ us to tens us

x780/x781 - 14 bit 100 MS/s Dual/Quad MCA
V1782- 16 bit 100 MS/s Octal MCA
Hexagon – 16 bit 100 MS/s Single/Dual MCA

The DPP-PHA Algorithms and Block Diagram



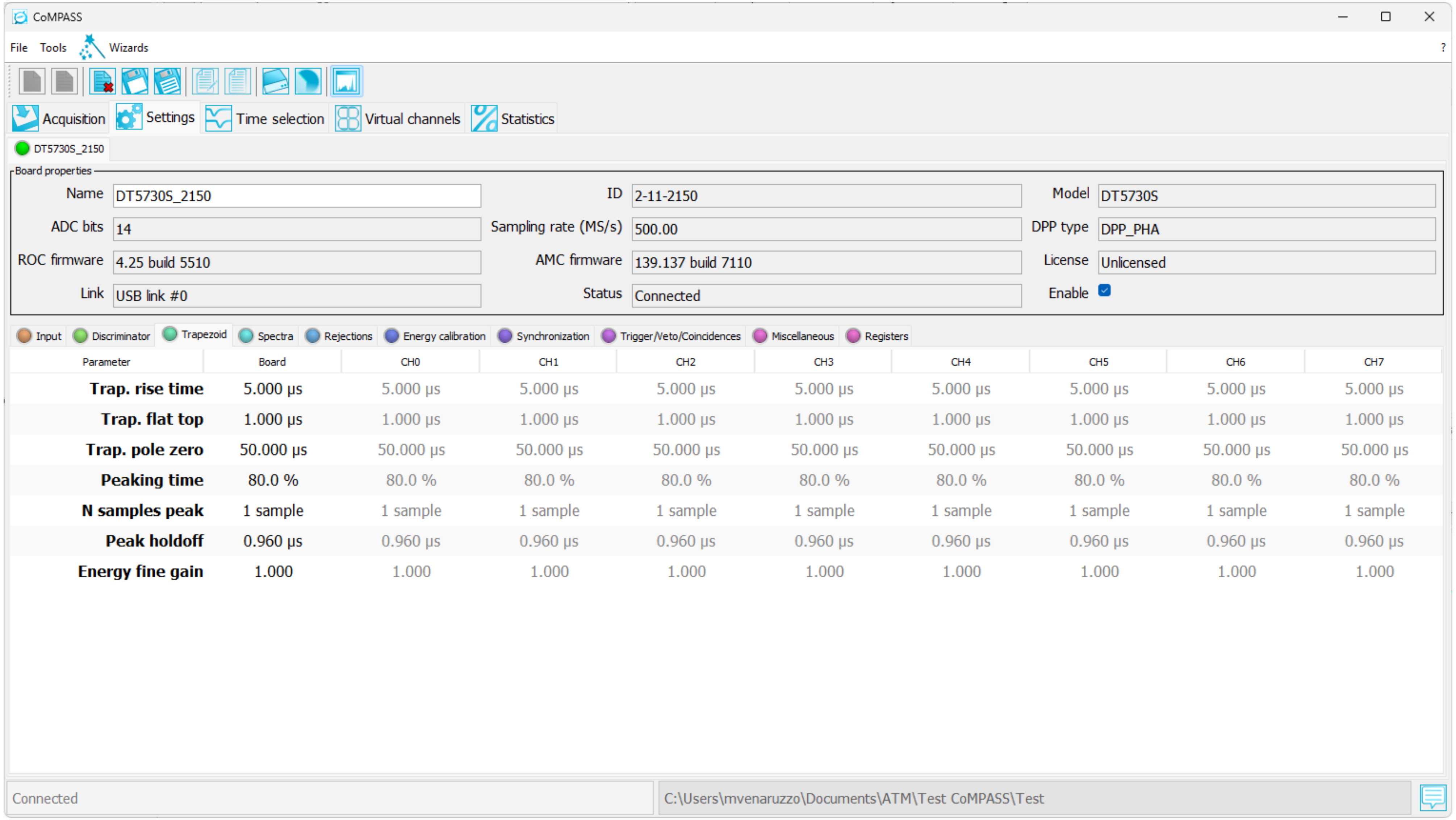
The DPP-PHA Algorithms and Block Diagram

1. Duration of the trapezoid can be programmed:
   - longer duration --> better energy resolution.
   - longer duration --> higher pile-up probability between two trapezoids (more dead time)

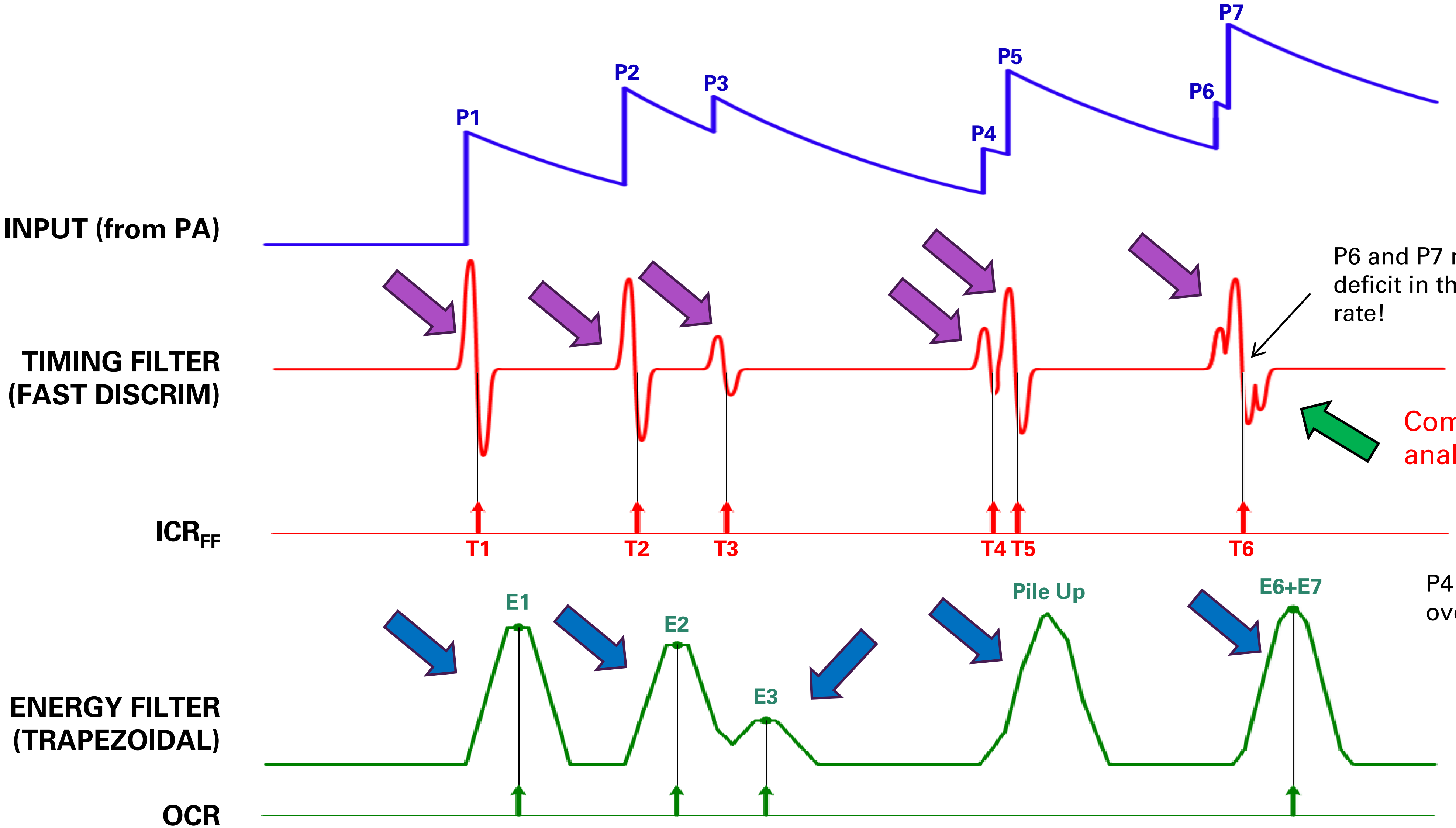
2. Dead time not related to the ADC conversion but to the processing algorithm.

3. Data produced by the DPP-PHA:
   - the time stamp of the pulses
   - amplitude of the pulse,
   - the input and output count rates (ICR and OCR)
   - (if necessary) raw waveforms --> higher data throughput (usually for debug only)

The DPP-PHA Algorithms and Block Diagram



The DPP-PHA Signals



P6 and P7 not resolved: deficit in the input count rate!

Complex waveform analysis!!

P4 and P5 trapezoid overlapped: Pile up!

P6 and P7 generate only 1 trapezoid: sum peaks!

DPP-QDC/PSD

The DPP-PSD

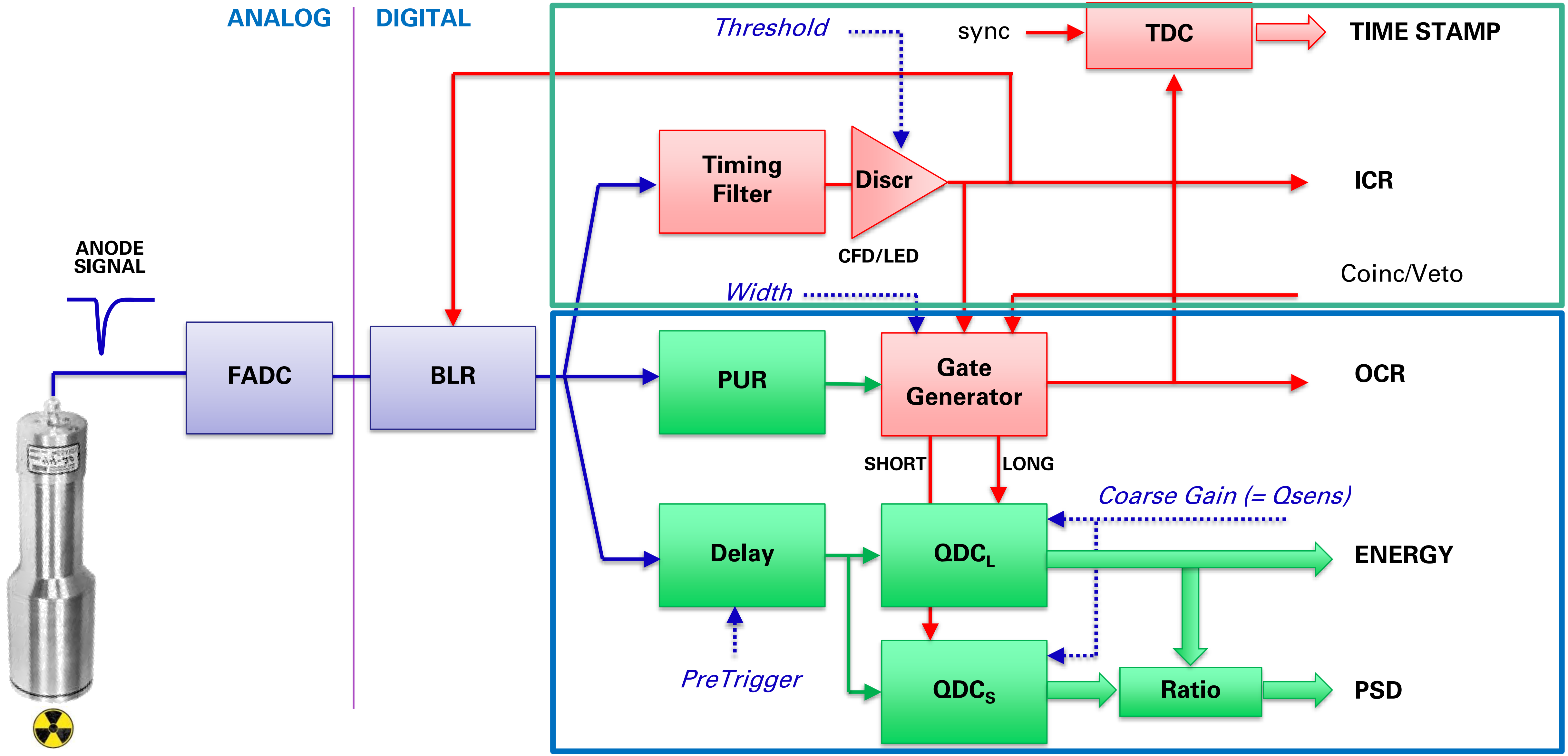




Typical signal for DPP-PSD:
Rise Time: ~ few ns
Decay Time: ~ few ns to few us


x725/x730 - 14 bit 250/500 MS/s Digitizer
x751 – 10 bit 1GS/s Digitizer

The DPP-PSD/QDC Algorithm and Block Diagram



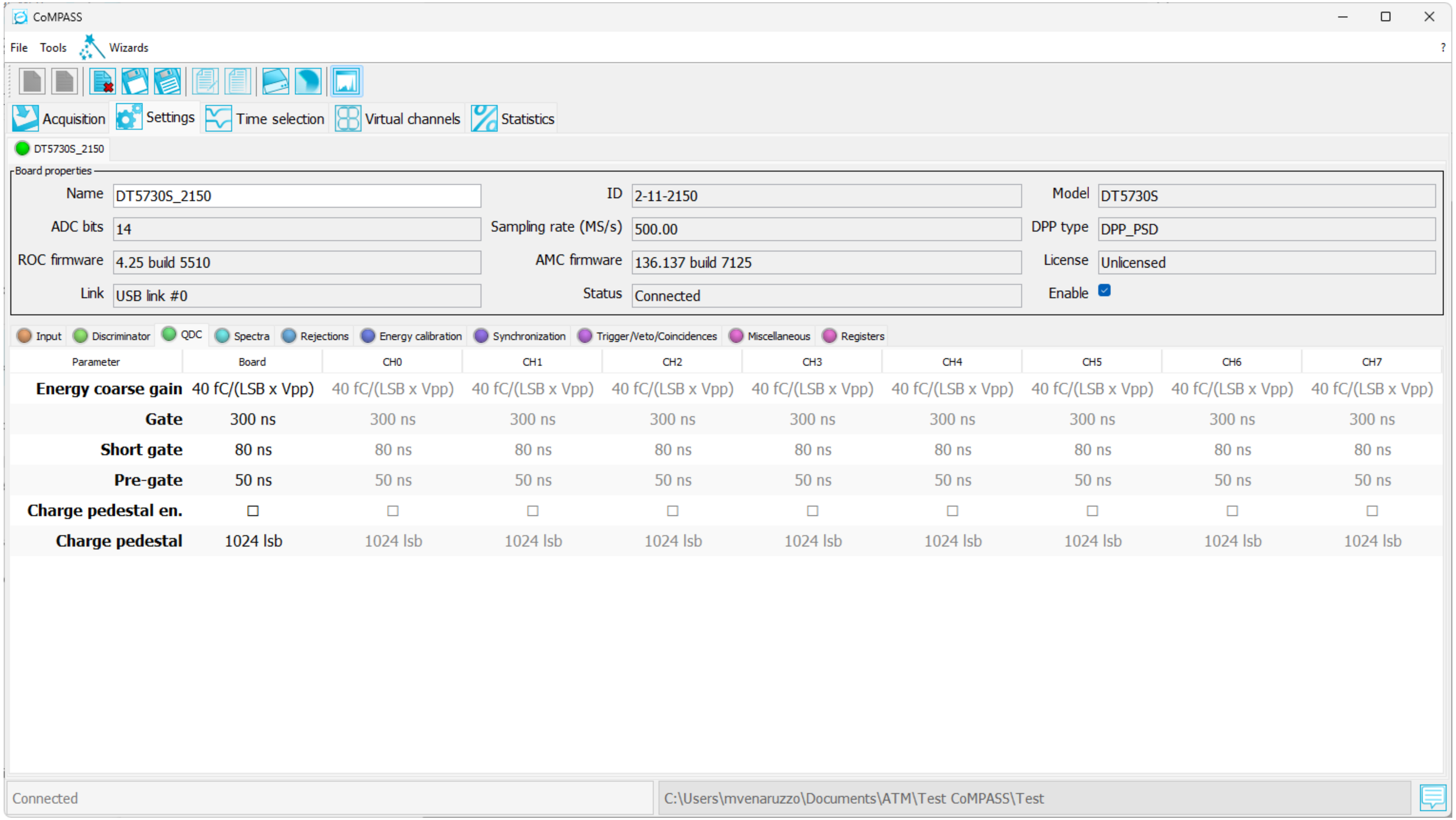
The DPP-PSD/QDC Algorithm and Block Diagram

It is possible to use an external gate, program coincidence or anti-coincidence between external and internal gates.

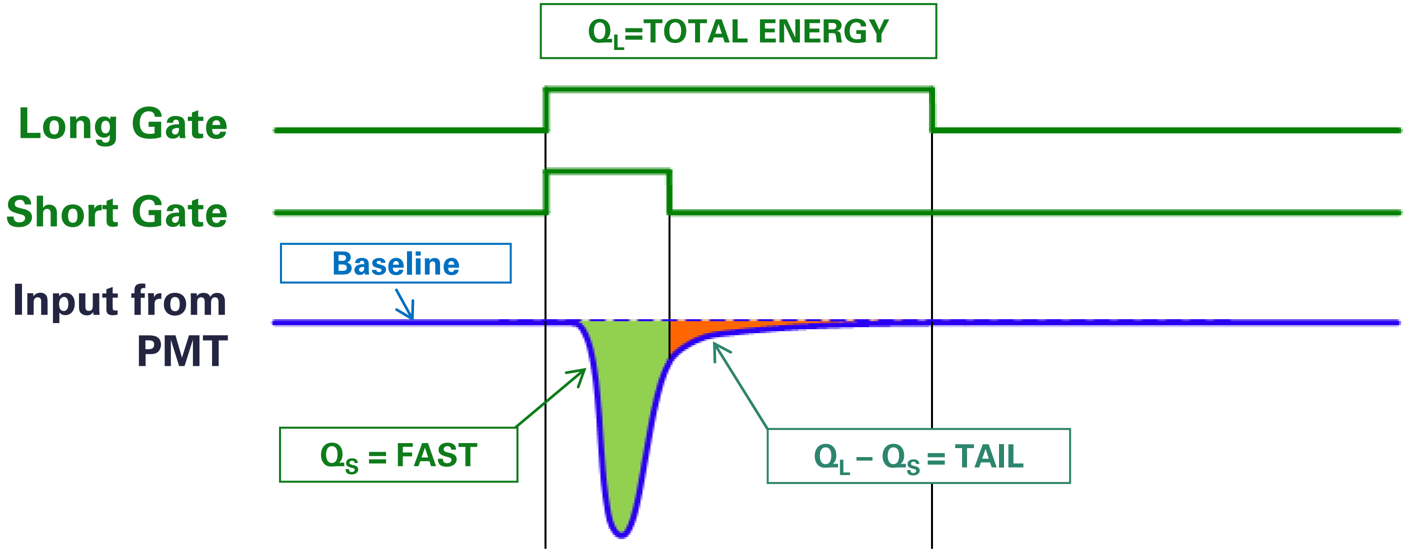
It is possible to introduce a delay on the signal.

All parameters for integration are programmable!

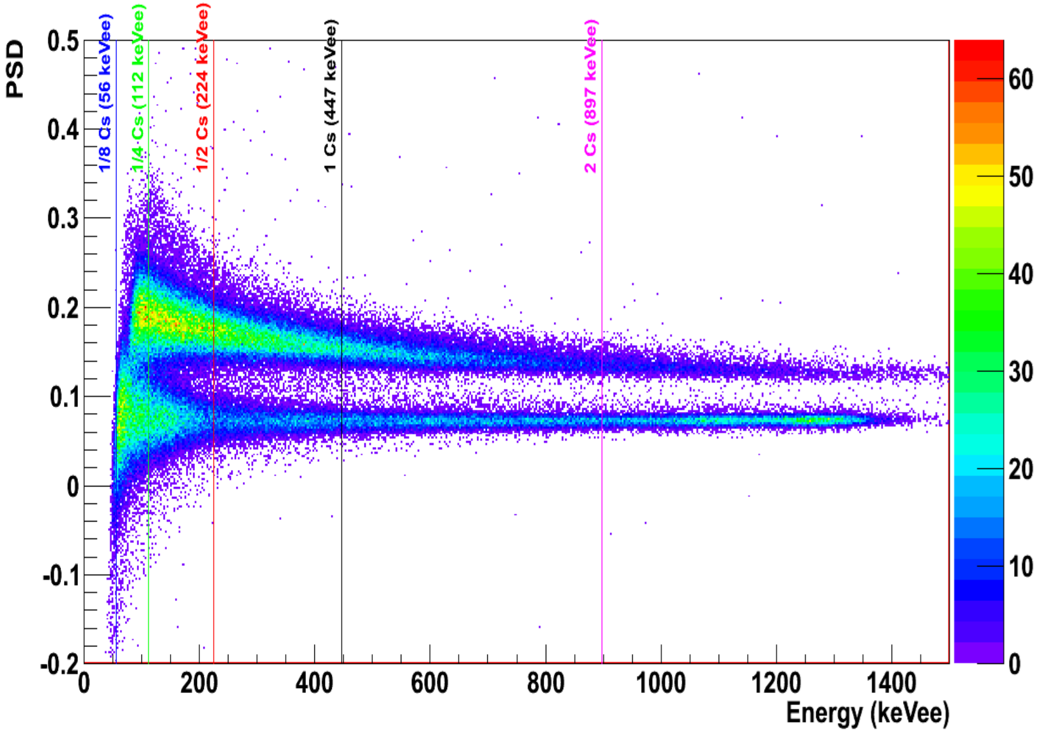
The DPP-PSD/QDC Algorithm and Block Diagram



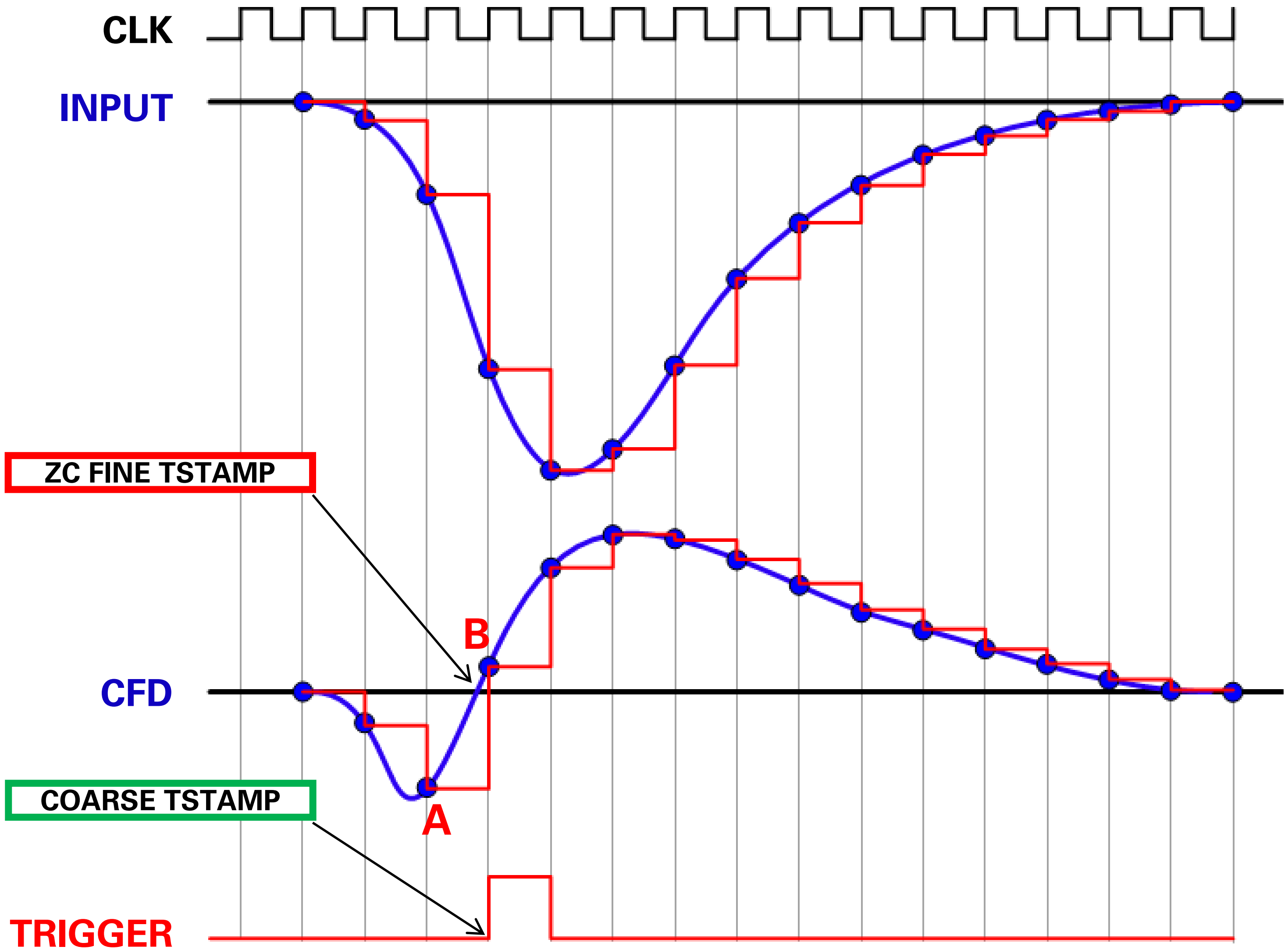
The DPP-PSD/QDC Signals



$$PSD = \frac{TAIL}{TOTAL}$$



Digital CFD + TDC



digital CFD: same principle as analog

$\mathbf{CFD_{N+1} = f * S_N - S_{N-D}}$ f=Fraction, D=delay

COARSE TSTAMP $= T_{CLK}$ * Clock Counter

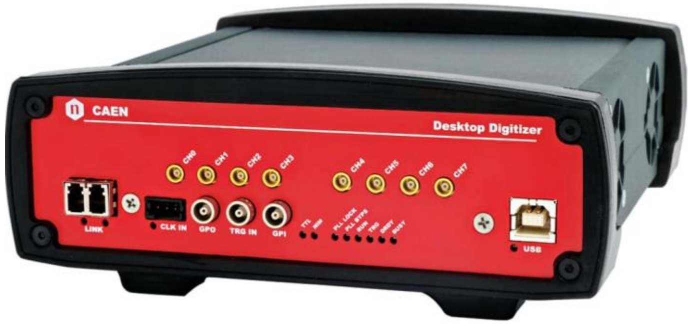
FINE TSTAMP $= - T_{CLK} * B/(B-A)$

Digital CFD + TDC

Linear interpolation: good curve fitting if Leading Edge > 3-5 TSAMPLE

Faster signals produce artifacts and bad timing resolution

ZC calibration algorithm corrects interpolation errors for signals as fast as ½ TSAMPLE



x730S - 14bit 500 MS/s digitizer

Resolution: ~100 ps RMS for 2 ns rising edge @ 500 MS/s

Advanced Zero Suppression

DPP-ZLE and DPP-DAW

The Zero Suppression Algorithms

Many applications: necessary to acquire the "raw waveform" of signals from detectors.

Synthetic parameters (height, charge, time stamp) are not sufficient to retrieve the required information.

Advantages:

- Raw waveform preserves the complete signal information
- Possible in offline analysis to extract the desired parameters

Drawback:

- very high volume of data, typically not sustainable ---> dead-time and data loss

Waveform processing algorithms: focused on identifying regions of interest, allowing for the suppression of unnecessary data.

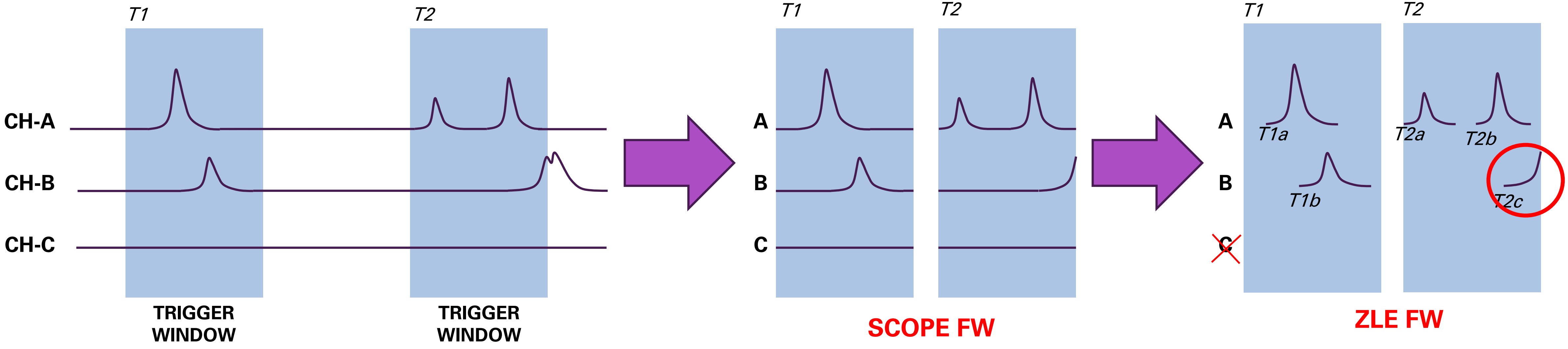
Advanced Zero Suppression - 1: ZLE firmware

Standard scope firmware (raw waveform readout) produces huge amount of data. Data reduction algorithms are often mandatory.

Common triggered acquisition: not all channels are fired and not at the same time => long portions of baseline with no information of interest.

The aim of the ZLE firmware is to **suppress the empty channels** and trim the fired channels to **keep only the significant parts**. Each chunk is time stamped within the window.

Pulses across the trigger window will be cut (loss of regions of interest).



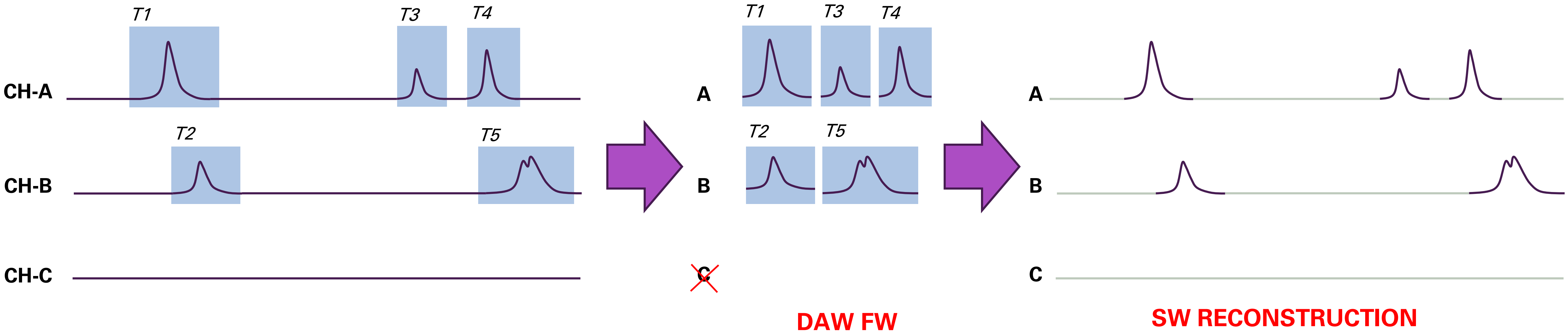
Advanced Zero Suppression - 2: DAW firmware

Triggerless waveform acquisition: no common acquisition window, each channel is self triggered

Input pulses with different width or piling-up => the **acquisition window must be dynamically adapted** to the length of the region of interest

Channels run independently: when fired, a channel saves a waveform of the required size to fit the pulse, together with the relevant time stamp. **No pulse cutting!**

Event building in the software reconstructs the correct position of each chuck by mean of the time stamps



DPP-ZLE and DPP-DAW comparison

DPP-DAW

- unless in case of excessive data throughput, it is dead-time free and no data loss
- less suitable when searching for sparsely correlated events across different channels
- very small pulses that do not exceed the trigger threshold may be lost

DPP-ZLE

- data loss as seen in the case of cut-off events
- thanks to the global trigger, it is possible to set a much lower suppression threshold than the trigger threshold.

Digital vs Analog

PROs and CONs

Digital vs Analog: PROs and CONs

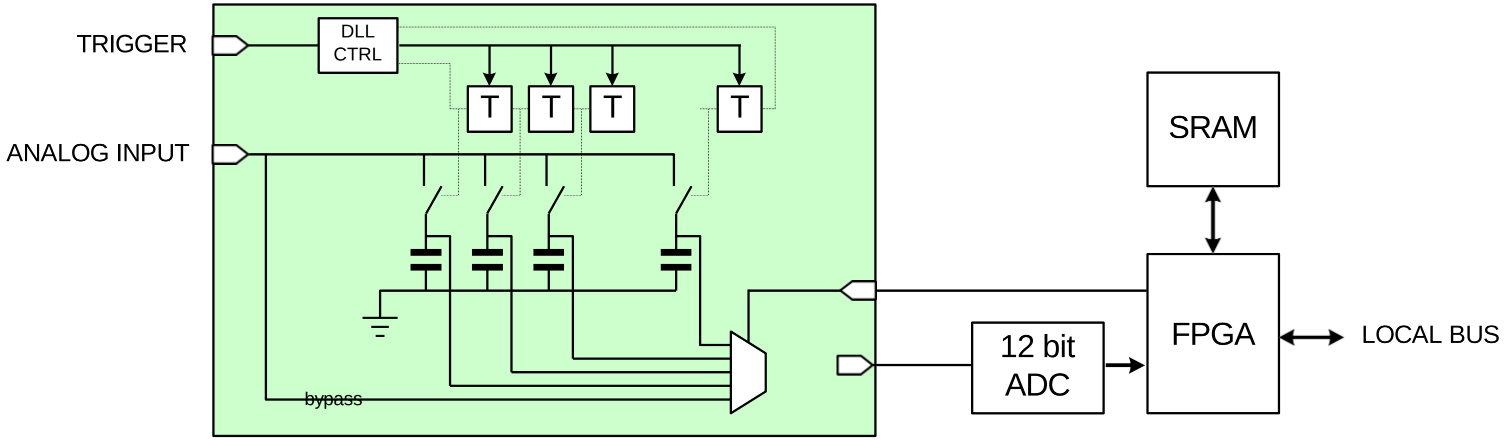
- **Flexibility**: waveform digitizer: a general-purpose readout system that can be tailored to the specific application reprogramming the DPP algorithms. The analog system is “hard-wired”.
- **Multi-parametric**: the digital solution provides multiple output parameters (pulse height or charge, arrival time, pulse shape, etc…). More outputs can be provided by reprogramming the algorithms. In the analog chain, more outputs means more boards.
- **Dead-time**: Flash ADC reads the input signal continuously and has no conversion time. Dead time can be in the processing algorithm but is typically lower than analog. Digital allows for higher trigger rate, unless waveform readout is needed; in this case, memory and link occupancy can drastically reduce the rate.
- **Trigger Logic**: Coincidence, Anti-coincidence, Multiplicity… can be embedded in the DPP algorithm. No need of coincidence units and tangled wiring. Time stamped list outputs allow for post-processing event building.
- **Complexity**: digital systems have many parameters to set => complex interface and steep learning curve compared to analog. Embedded oscilloscope helps in debugging and tuning. Once done, digital is easier to replicate and maintain.
- **Cost**: waveform digitizers are cheaper than analog systems for “slow” signals (e.g. charge sensitive preamps). The digitizer becomes expensive for fast signals (need 1 GS/s or more). Switched capacitor arrays can read very fast signals at low cost, but high dead-time and fixed acquisition window must be accepted.

Switched Capacitor Array Digitizers

Switched Capacitor Array Digitizer

Switched capacitor arrays can read very fast signals at low cost

- **x742: 32+2 channels in a VME board, 5 GS/s, 12 bit, 1024 points**
- **x743: 16 channels in a VME board, 3.2 GS/s, 12 bit, 1024 points**



Two drawbacks:

- but high dead-time
- small fixed acquisition window

Currently available algorithms

	62.5	100/125	250	500	1000	> 1000	Description
Scope	Ready	Ready	Ready	Ready	Ready	Ready	Oscilloscope mode, all channels triggered simultaneously
PHA	Not Available	Ready	Ready	Ready	Not Available	Not Available	Spectroscopy with Charge Preamps and PMTs
PSD	Not Available	Ready	Ready	Ready	Ready	Not Available	Neutron/Gamma/Alpha discriminations with Scintillators
TDC	Not Available	Ready	Ready	Ready	Ready	Not Available	Digital CFD or LED, Resolution < 1 ns (<100 ps with 500/1000 MS/s)
QDC	Ready	Ready	Ready	Ready	Ready	Not Available	Self-gated charge integrator
ZLE/DAW	Not Available	Ready	Ready	Ready	Not Available	Not Available	Waveform fragments (zero suppression, adaptive acquisition window)
Open FPGA	Not Available	Ready	Coming soon	Coming soon	Not Available	Not Available	User defined Algorithms and Output Data Content

• Ready • Coming soon • Not Available

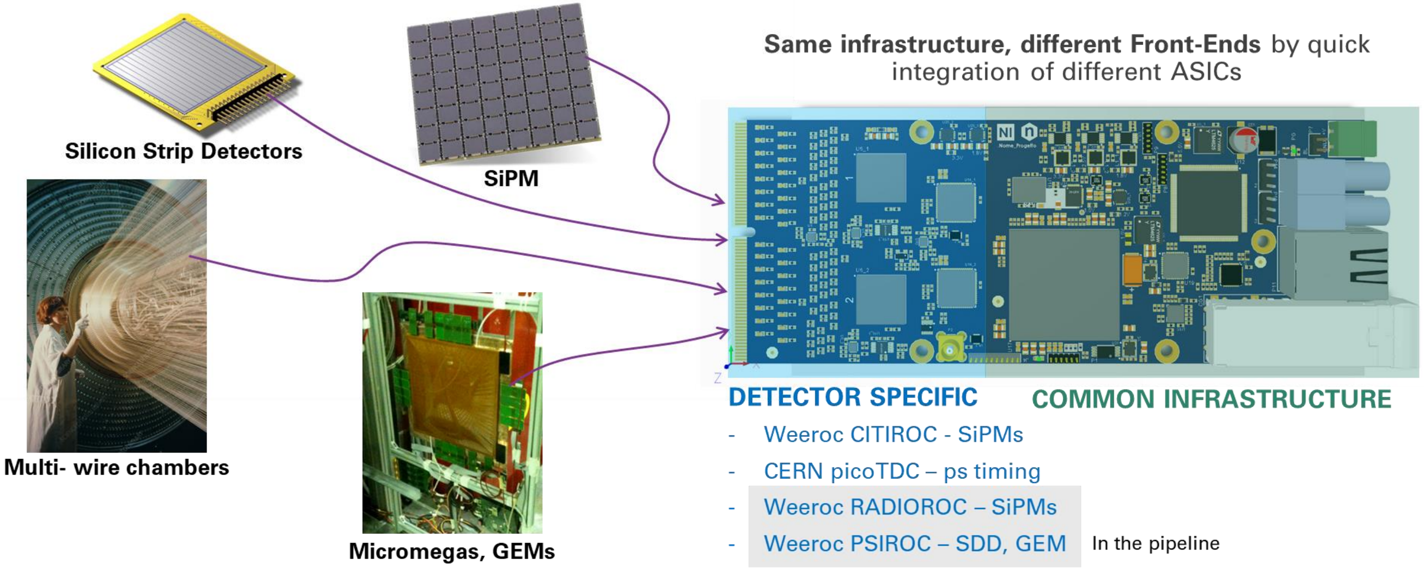
Introduction to ASICs for physics applications Processing Algorithms

ASIC for physics applications - 1

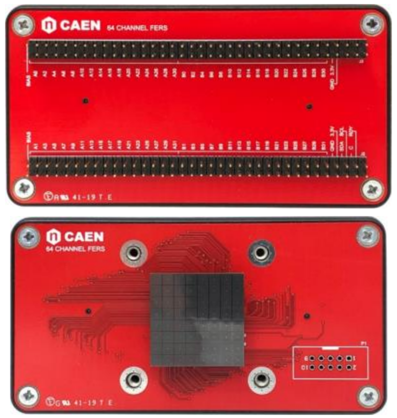
- Many physics applications, especially HEP, require thousands channels or more. **High channel density** goes together with low power, reduced space, short cables, low cost per channel
- Readout electronics based on a dedicated **ASIC** is the typical solution
- Often, the ASIC implements in one chip the full analog chain, with many channels (typ. from 8 to 64). The A/D conversion takes place at the end of the chain, either inside the ASIC or with an external ADC
- In other cases, the ASIC implements a “switched capacitor array” digitizer, that is an ultra fast, high density waveform digitizer with small memory depth (i.e. short acquisition window)
- Typically, the ASICs are highly specialized for a particular detector and application => there are many different ASICs developed by companies or research institutes to cover most applications

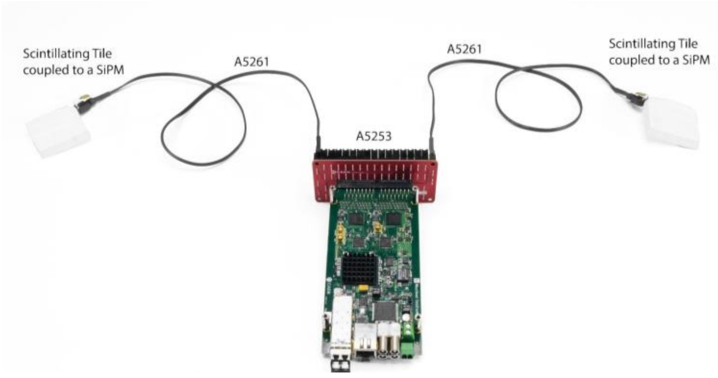
ASIC for physics applications - 2

- The motivation for developing a common infrastructure that makes it fast and easy the integration of different ASIC is very strong in the community



- **FERS**: Front End Readout System. A little card housing one or more ASIC and providing controls and readout interfaces to enable the use of the ASICs with no need of hardware, firmware and software developments





Thank you for your attention

Any question/curiosity?

Backup slides

Multiparametric Acquisition

Application Examples

Multiparametric DAQ Applications

(Some) **Experiments**:

- Gamma-ray spectroscopy of fission fragment nuclei with Clover detectors
- Dark Matter
- Neutrino experiment
- Photonuclear reactions
- Neutron capture

Medicine and radiopharmacy production

- Gamma Camera and nuclear medicine imaging
- Very Low Background Whole Body Counting System
- TDCR

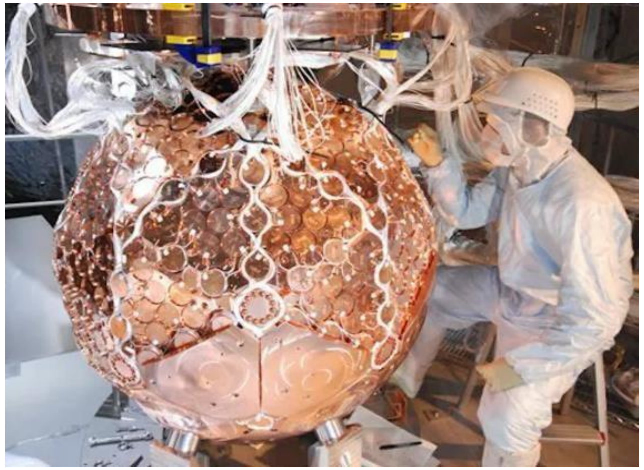
Safeguards

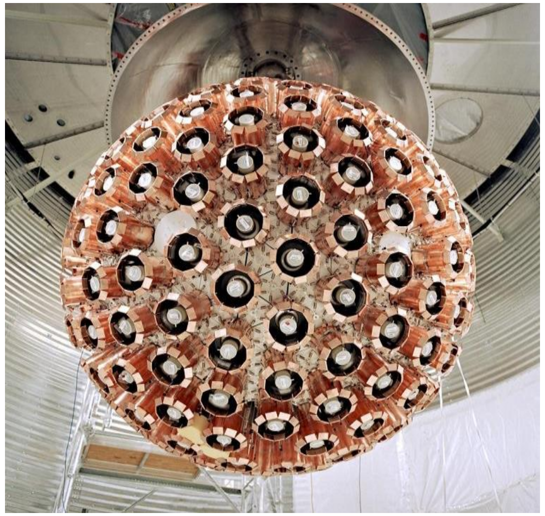
- Nuclear Fuel Verification (Fast Neutron Coincidence Collar System);
- Combined Gamma and Neutron measurements for SNM detection;
- Tagged neutron inspection systems
- Tap water monitoring system

Waste Assay Measurements

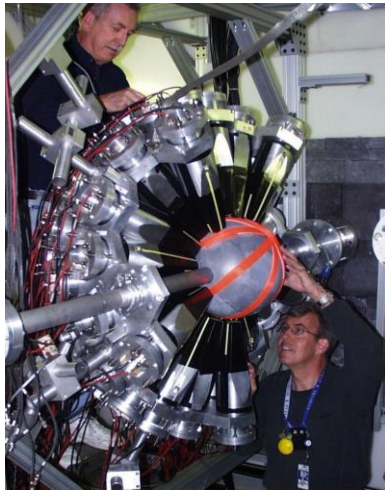
Multiparametric DAQ Applications: Experiments

- **Xmass** @ Kamioka (Japan): Dark Matter → **672** channels = 84 V1751s (1 GS/s, 10 bit) with custom FW (**ZLE**)





- **DEAP-3600** @ Snolab (Canada): Dark Matter. **255** PMTs = 32 V1720s (250 MS/s, 12 bit) + 5 V1740 (62.5 MS/s, 12 bit). Tot: **576** readout channels

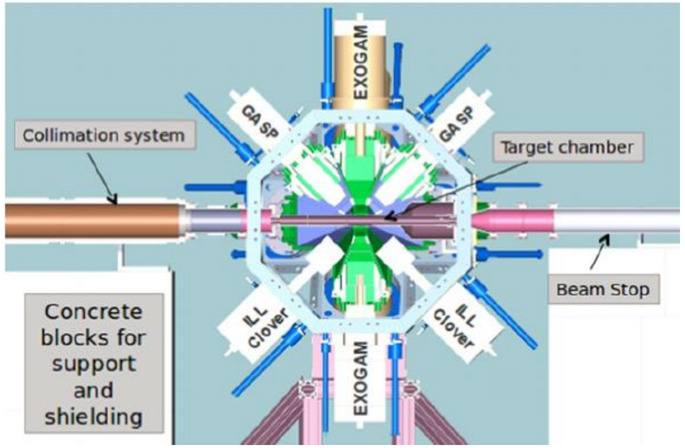


- **Dance** @ Los Alamos (USA): neutron capture. **162** segments (BaF_2 crystals): 12 V1730s (500 MS/s, 14 bit) with **DPP-PSD**

Multiparametric DAQ Applications: Experiments

- **Dhruva** @ BARC (India): gamma-ray spectroscopy of fission fragment nuclei → **Multi-detector** readout: 8 **Clover** detectors with **ACS** + 16 **$LaBr_3$** => 4 V1724s (100 MS/s, 14 bit, **PHA**) + 1 V1720 (250 MS/s, 12 bit) + 1 V1730 (500 MS/s, 14 bit, **QDC-PSD**)

- **Prospect** @ Yale/ORNL (USA): oscillation signature of sterile neutrinos. **360** PMTs = 22 x V1725s (250 MS/s, 14 bit) with **ZLE**



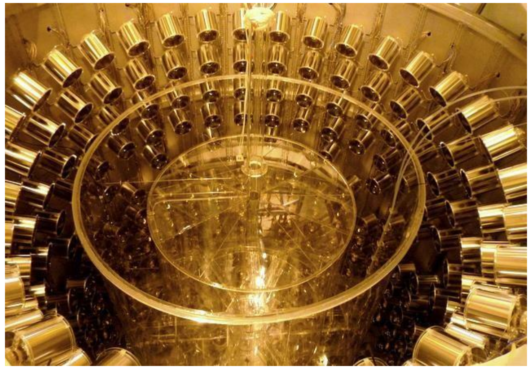
- **Exill** @ ILL (France): lifetimes of low-lying excited states. HPGe => 10 V1724s (100 MS/s, 14 bit + PHA) + $LaBr_3$ => V1751s (1 GS/s, 10 bit)

Multiparametric DAQ Applications: Experiments

- **XENON1T** @ LNGS (Italy): Dark Matter→ **248** PMTs = 32 V1724s (100 MS/s, 14 bit). **Trigger-less** DAQ with custom FW (**DAW**)

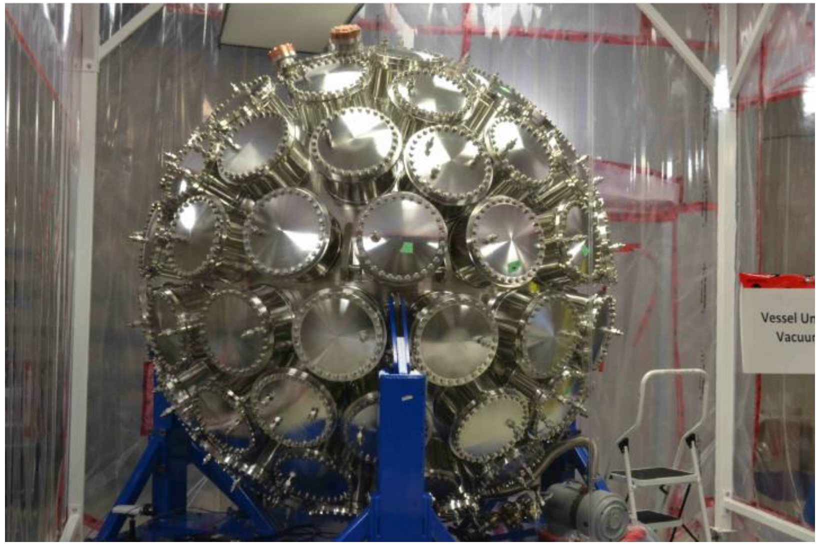
- **Eliade** @ ELI-NP (Romania): photonuclear reactions at Extreme Light Infrastructure → **Clover** detectors: 36 V1725 (250 MS/s, 14 bit + PHA) + **$LaBr_3$**: 2 V1730 (500 MS/s, 14 bit + QDC-PSD)

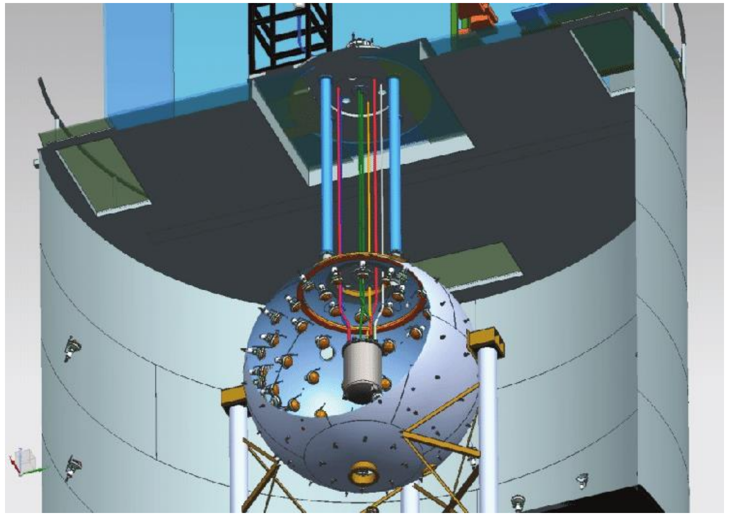
- **Double-Chooz** @ Chooze Power Plant (Ardenne, France): neutrino oscillation → **368** PMTs = 46 V1721s (500 MS/s, 8 bit)



Multiparametric DAQ Applications: Experiments

- **Mini Clean** @ Snolab (Canad): Dark Matter. 150 kg fiducial volume of liquid argon or 85 kg fiducial volume of liquid neon. with 92 sensitive photodetectors == > 8 V1720 (12bit, 250 MS/s) with Waveform Recoding firmware



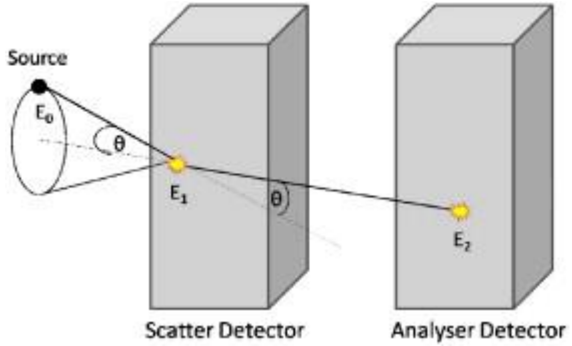


- **Dark Side** @ LNGS (Italy): Dark matter. Currently using V1720s **=> VX2745** (64 ch, 125 MS/s, 14 bit)

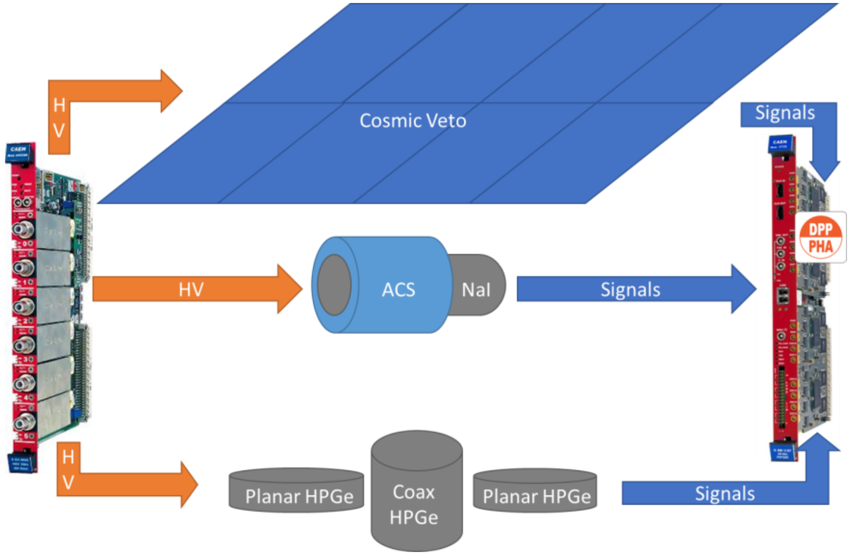
... AND MANY OTHERS!

Multiparametric DAQ Applications: Medicine and radiopharmacy production

- **SPECT**: Single Photon Emission Computed Tomography @ Liverpool University (UK). Localization of a gamma-ray source through the reconstruction of interaction sequences in position and energy sensitive strip detectors: 4 V1724s + PHA



- **WBC**: Whole Body Counter system @ JRC (Italy): measurement in very low background. Gamma Spectroscopy with multi-input 16 k MCA and Anticoincidence with plastic cosmic veto: 2 V1725s + PHA and PSD

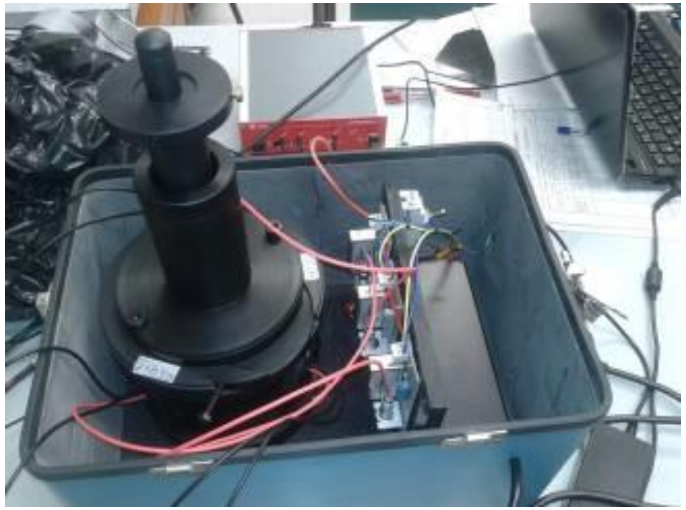


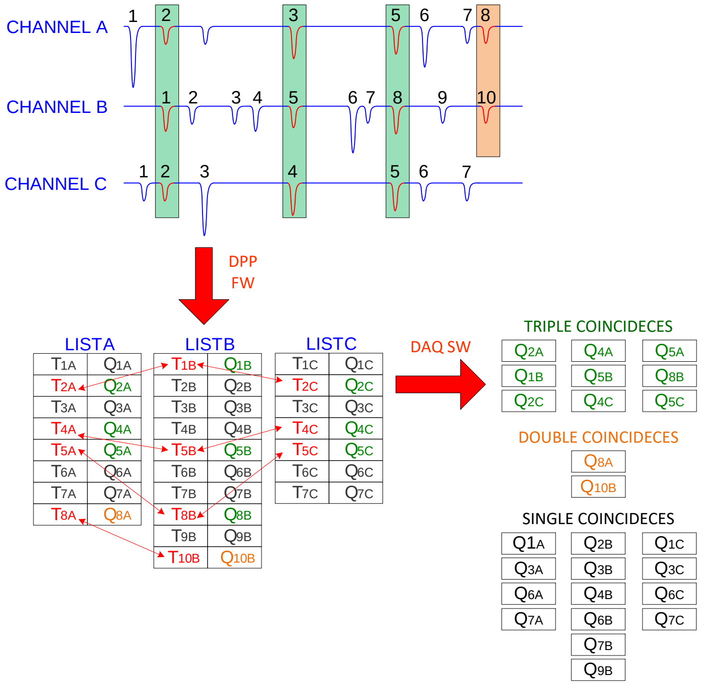
Multiparametric DAQ Applications: Medicine and radiopharmacy production

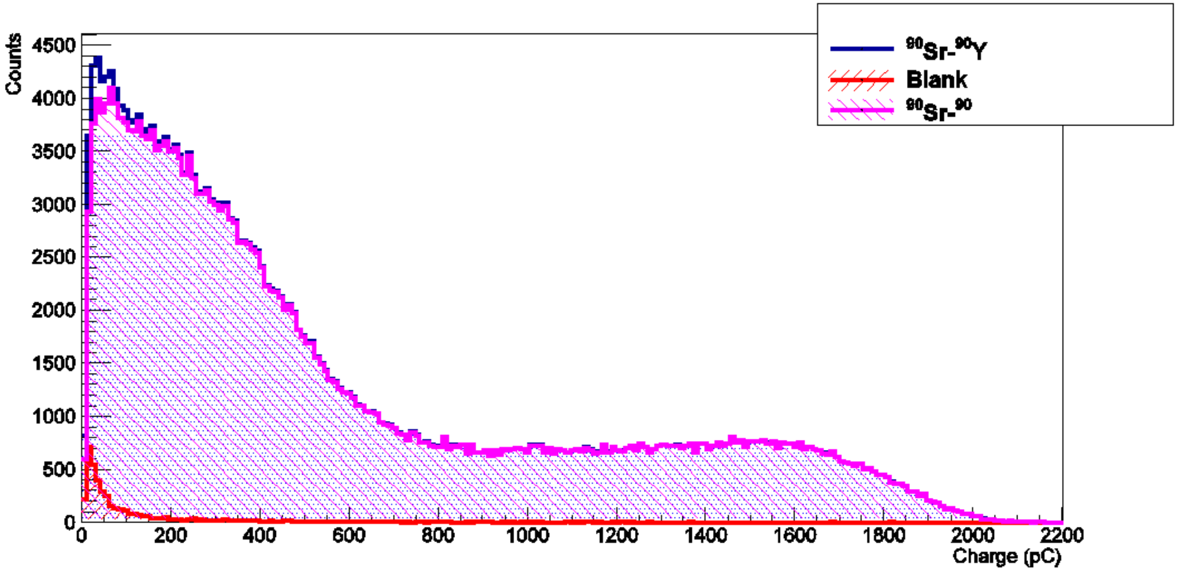
- **TDCR** @ ENEA (Italy): evaluation of a radiosource activity by means of the Triple to Double Coincidence Ratio.

Replacement of the traditional analog chain (based on the MAC3 analog module) to readout and process the signal from 3 scintillattors

==> DT5720/DT5725/DT5730/DT5751 + DPP-PSD firmware and dedicated software running the TDCR analysis on the acquired data

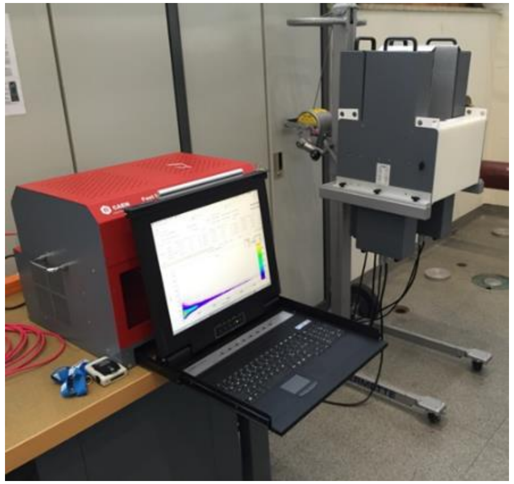




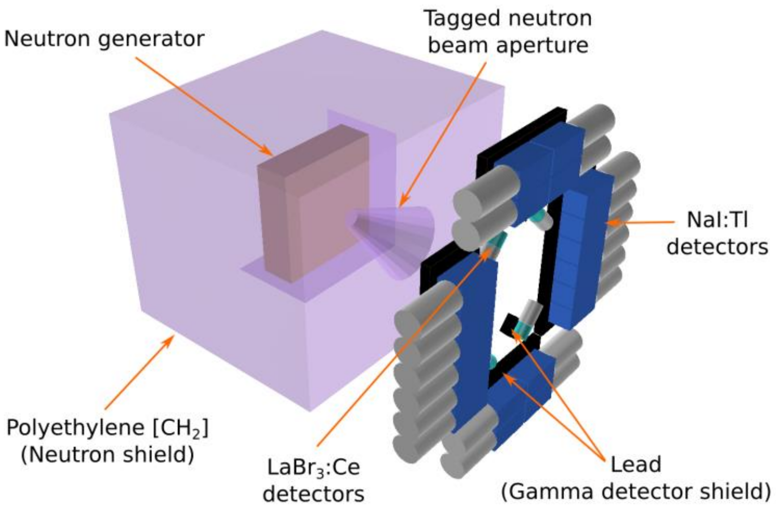


Multiparametric DAQ Applications: Safeguards

- **Fast Neutron Collar** @ IAEA (Austria): non destructive assay of NPP's Fresh Fuel Rods . 4 V1730s (500 MS/s, 14 bit) **with fast waveform readout (300 MB/s) and PSD**

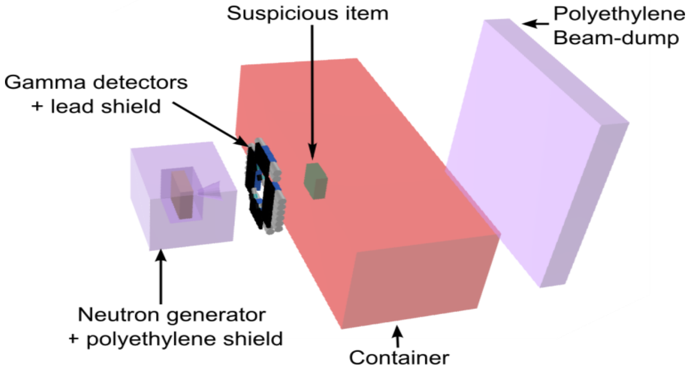


Statistical uncertainty in the measurement of the ^{235}U enrichment < than 1% with 15 minutes acquisition time. System immune to Gd mass variation



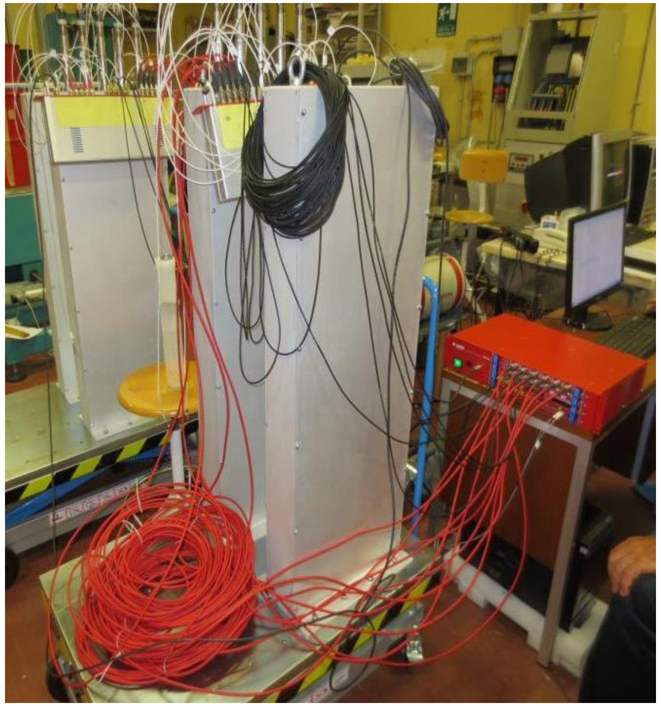
- **Relocatable Tagged Neutron Inspection System (C-BORD)**

@ Rotterdam port (The Netherlands): movable system for detection of illicit material via TOF (alpha-gamma) and Energy correlation.



Multiparametric DAQ Applications: Safeguards

- **EDEN** @ ENEA (Italy): uncover radioactive and nuclear threats including those in the form of Improvised Explosive Devices (IEDs), the so-called "dirty bombs" via the Neutron Active Interrogation (NAI) technique and Differential Die-Away Time Analysis method ==> He3 tubes + **V1495 and custom coincidence and counting FW**



- **Tap Water Monitoring (Water-NET)** @ North Waterworks Plant, Warsaw (Poland). Mitigate radiological threats like:
  - Emergency at nuclear facilities
  - Transportation accident involving the shipment of radioactive material
  - emergency involving the loss, theft, or discovery of radioactive material (as the so-called orphan sources);
  - a terrorist attack utilizing radioactive materials, such as a "dirty bomb"...