Digital Pulse Processing for Nuclear Research Applications

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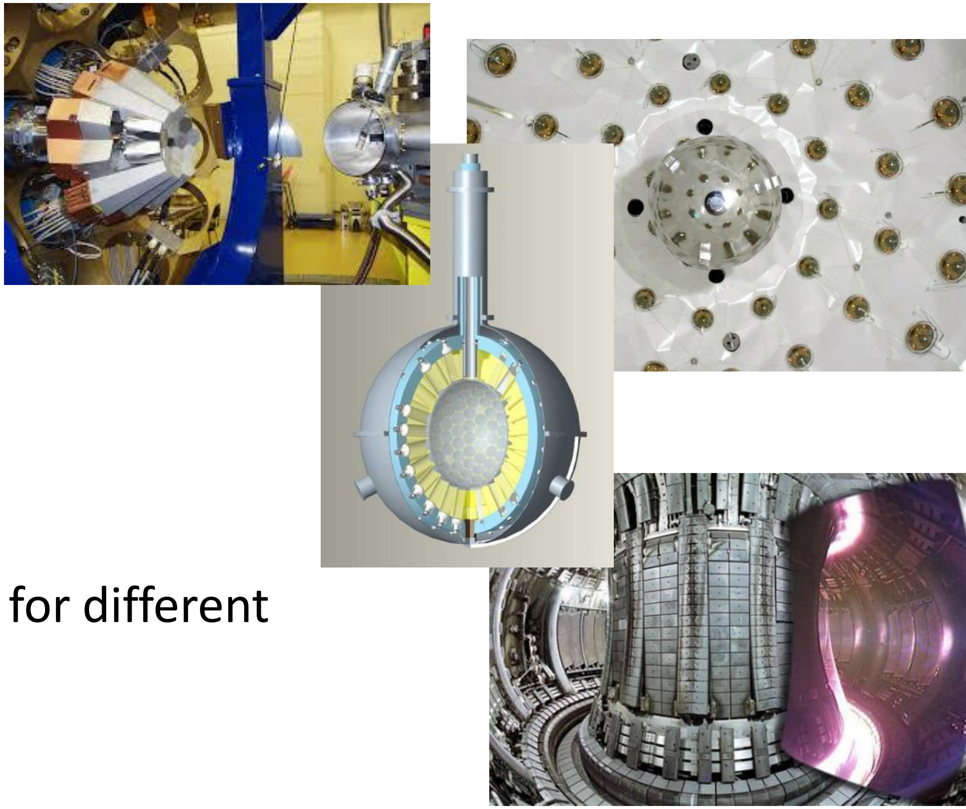
Introduction

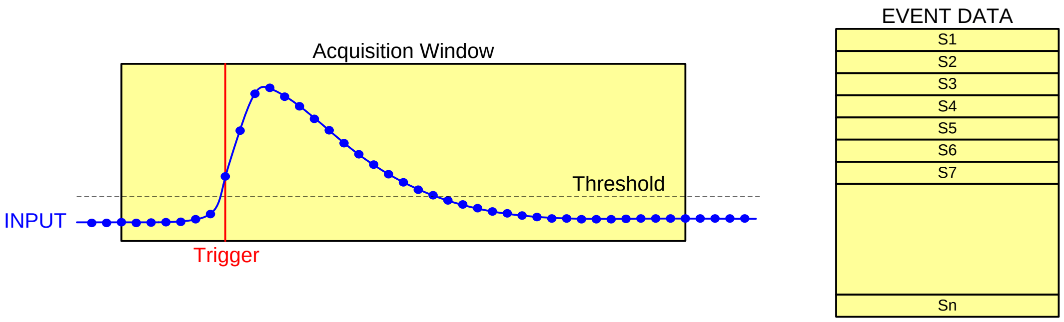
Digital DAQ State-of-the-art in Physics Application

- **Digital Acquisition** is now a standard approach in many Physics fields:
  - High Energy
  - Nuclear
  - Neutrino
  - Dark Matter
  - Fusion
  - ….
- Different Sampling Rate, Bit Depth, FW for different application/detectors

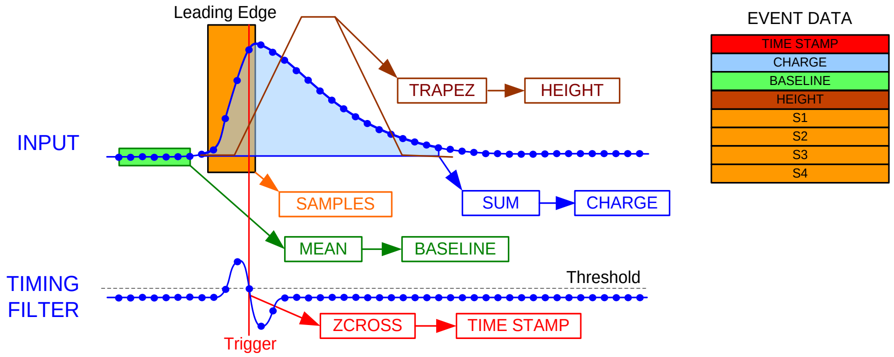


Key Factor of the Digital Approach

- Two basic ways of operation:
  - Waveform Mode: *Readout and storage of full waveforms/pulses*
  - List Mode: *Readout and storage only of relevant information (Energy, Time Stamp) through Digital Pulse Processing*



- Logic And Event Selection (*And, Or, Majority, Coincidence, High Level Trigger*):
  - *On board on-line*
  - *Hardware via Digital External Logic Units*
  - *Off-line via Software*

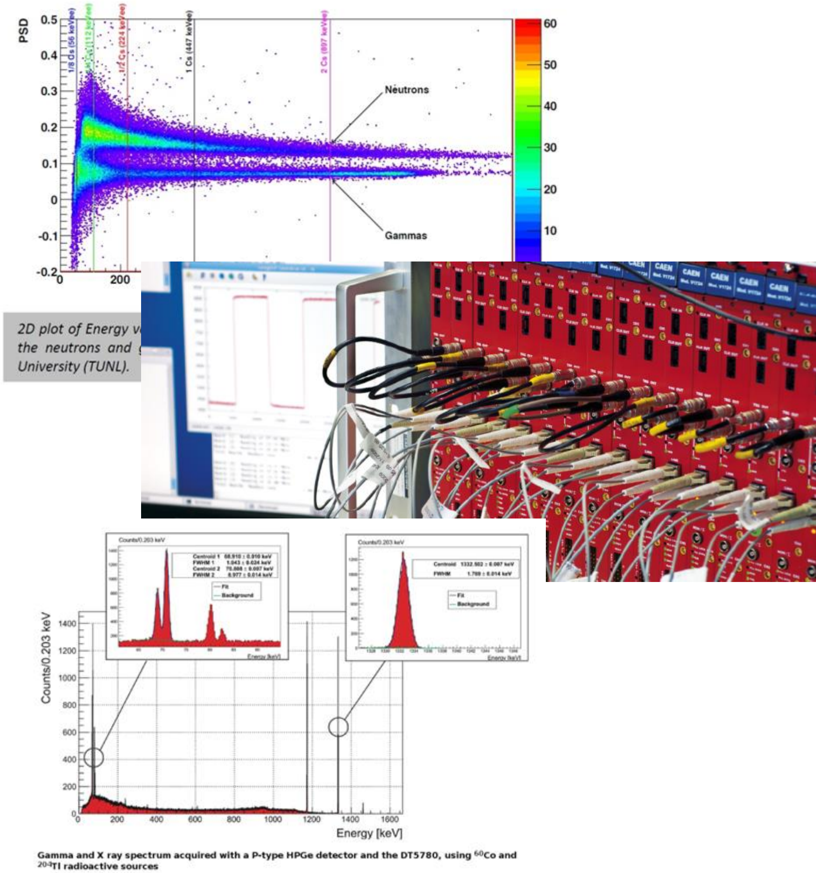


Key Factor of the Digital Approach

- Benefits:
  - ➢ Programmable Digital Pulse Processing
  - ➢ System scalability, Flexibility
  - ➢ Waveforms for off-line SW analysis

    Interfaces for Data Transfer
  - ➢ Simplified Logic/Triggering

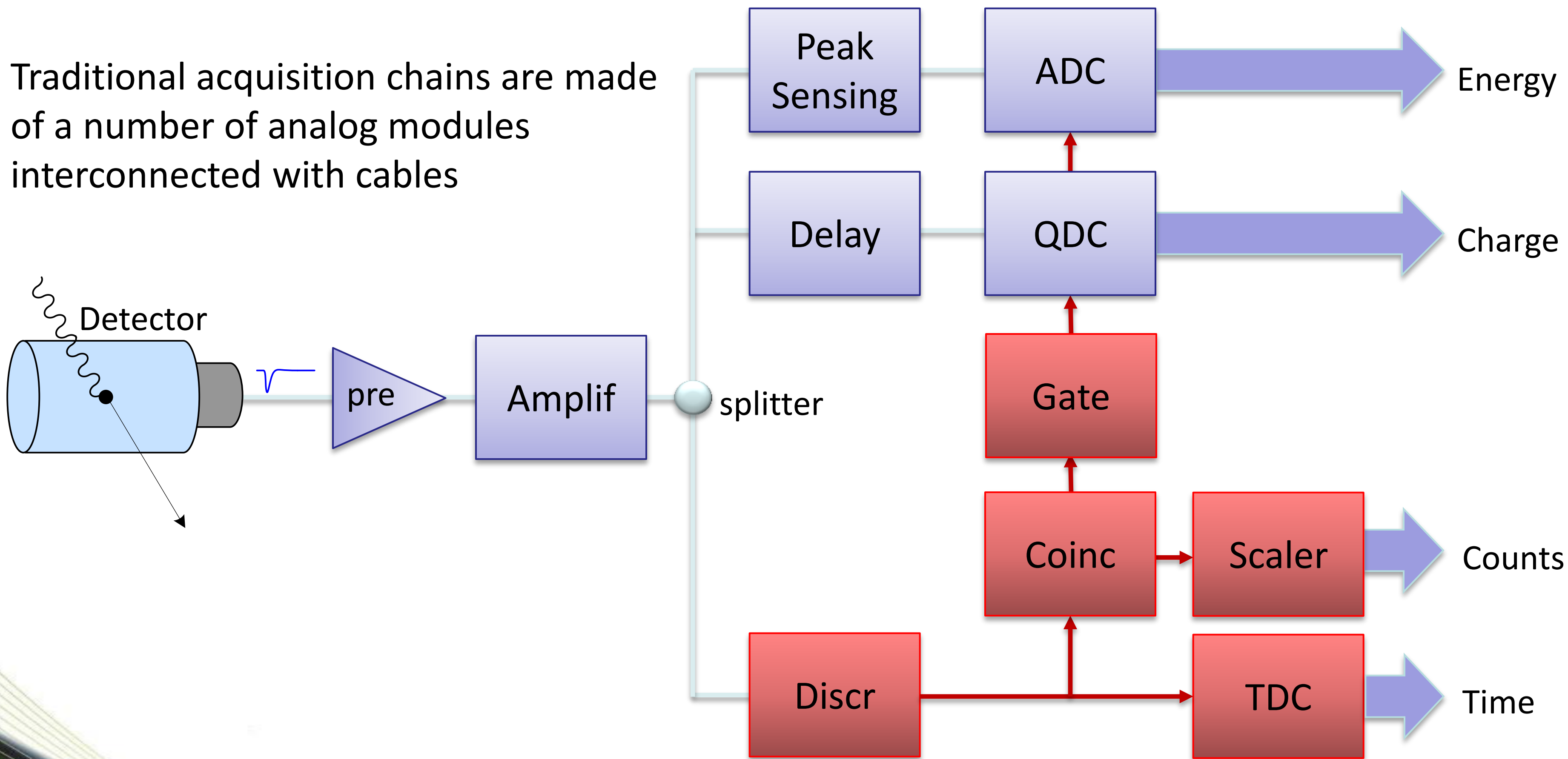
    Front panel I/Os
  - ➢ Simplified Electronic Chain



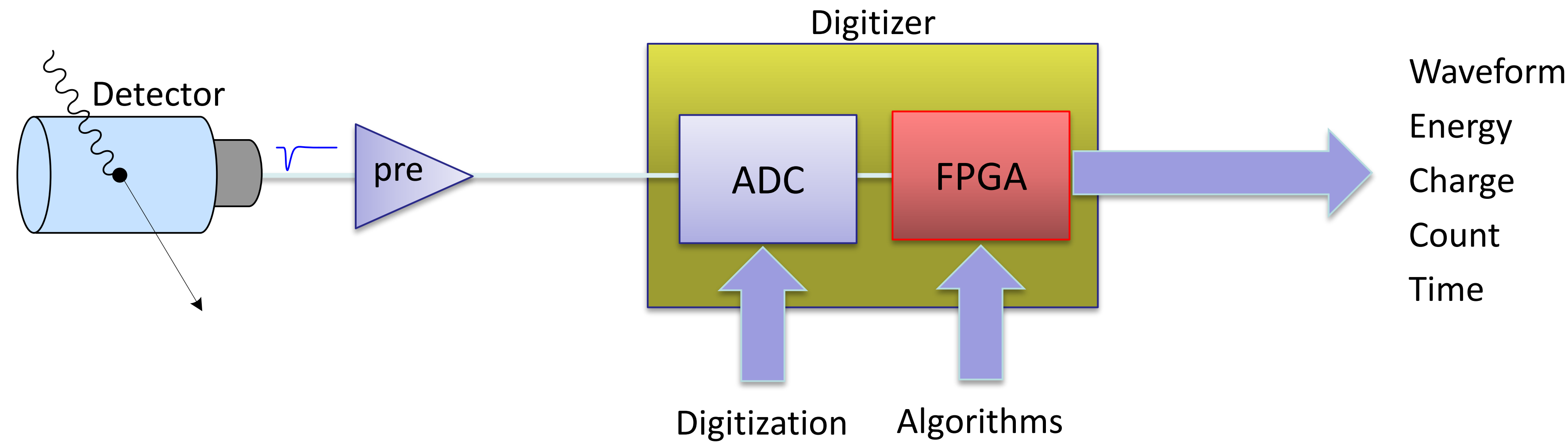
Traditional acquisition chain

A/D conversion at the end of the chain

Traditional acquisition chains are made of a number of analog modules interconnected with cables

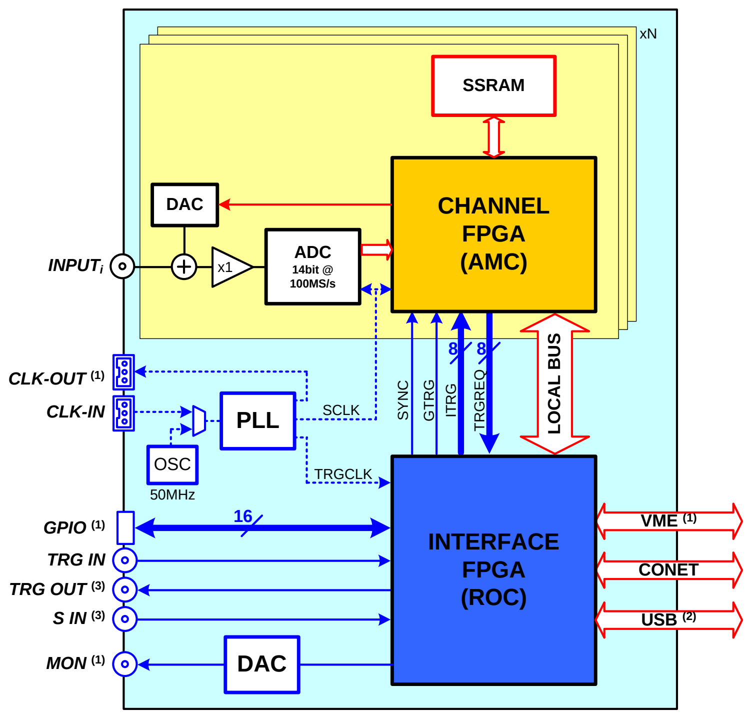


Fully digital acquisition chain

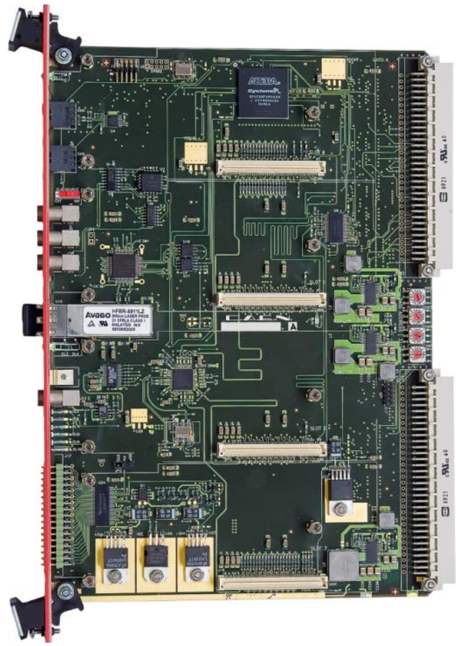


The aim of the Digital Pulse Processing is to make a “all in digital” version of analog modules such as Shaping Amplifiers, Discriminators, QDCs, Peak Sensing ADCs, TDCs, Scalers, Coincidence Units, etc.

Architecture

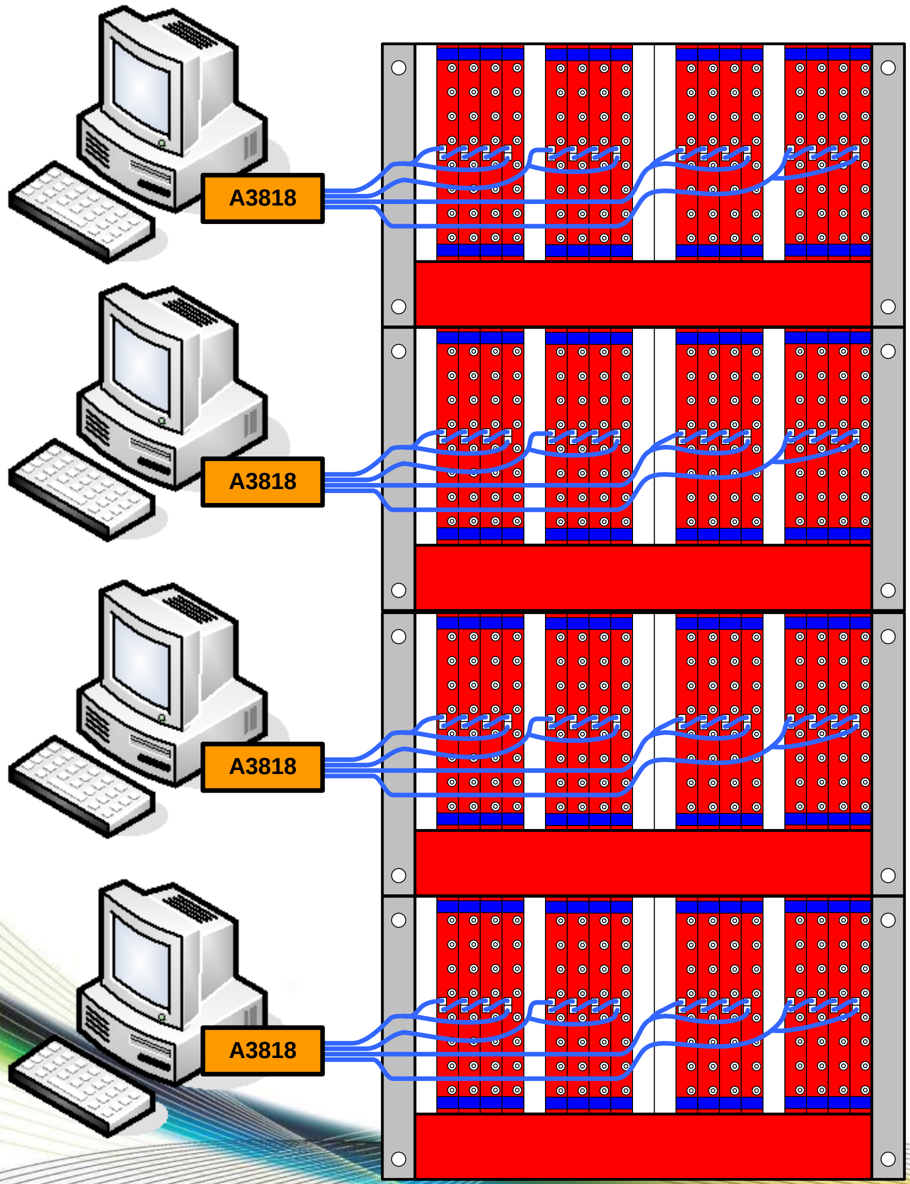


(1) VME boards only
(2) Desktop/NIM boards only
(3) for Desktop/NIM baords, TRG-OUT = GPO, S-IN = GPI



- VME (VME64, VME64X compliant), NIM, Desktop form factors
- Interfaces: Optical Link (CONET), USB 2.0

CONET2 readout example: XMASS

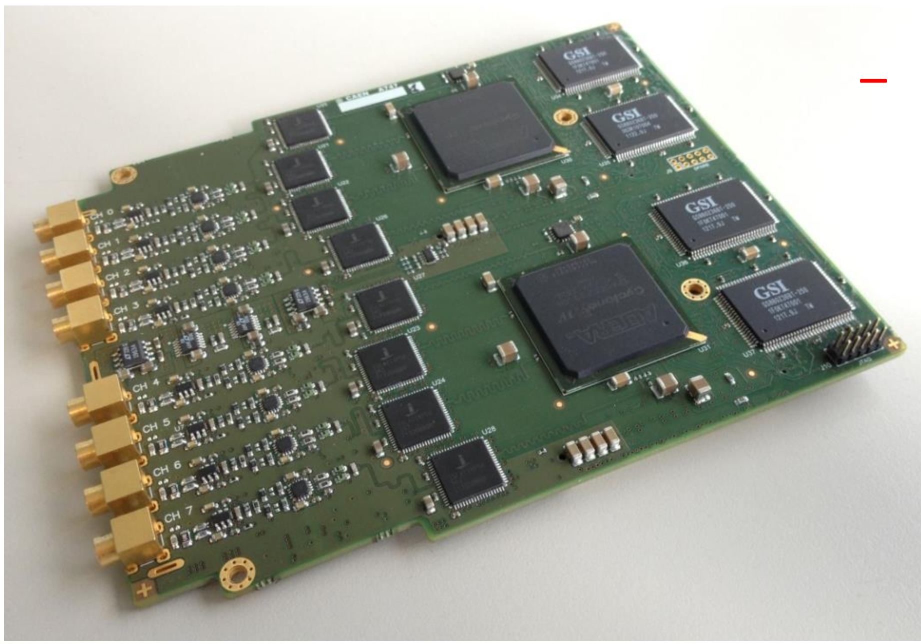


- 64 V1751 modules in 4 VME crates
- 512 channels (10 bit @ 1GHz)
- 4 A3818s 4 link PCIe cards
- 16 parallel CONET2 links
- 4 digitizers daisy chained
- Readout Bandwidth = ~2 MB/s/ch
- Total Bandwidth = ~ 1GB/s

CAEN Tools for Discovery

Fast ADC Technology

- Wide offer
  - Sampling frequency: from 62.5 MHz to 4 GHz
  - Resolution up to 14 bits
  - No conversion dead time

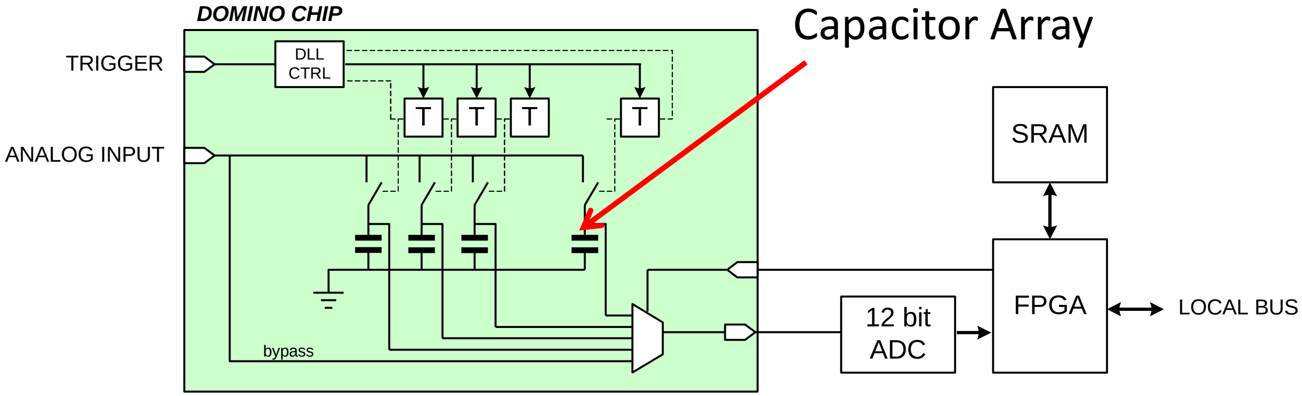


- Coming Soon: waveform digitizer x725
  - Up to 16 channels in one board
  - 250 MS/s, 125 MHz analog bandwidth, with 14 bits dynamic
  - Double input dynamic range: 0.5 and 2 Vpp software set
  - Available in VME, NIM and Desktop form factors
  - Two firmware algorithms available
  - Cost effective digitizer, still high level

Switched Capacitor Technology

- Domino Ring Sample, DRS4

  Chip developed at PSI, Switzerland: http://www.psi.ch/drs/
  - 8 channels per chip, integrated on the **x742** family
  - Up to 5 GSa/s, 500 MHz analogic bandwidth



- Swift Analog Memory (long), SAMLONG

  Design of CEA/IRFU - LAL Orsay, France
  - 2 channels per chip, integrated on the **x743** family
  - Up to 3.2 GSa/s, 500 MHz analogic bandwidth
  - Dedicated software with GUI

Digital DAQ: a step to a complete solution

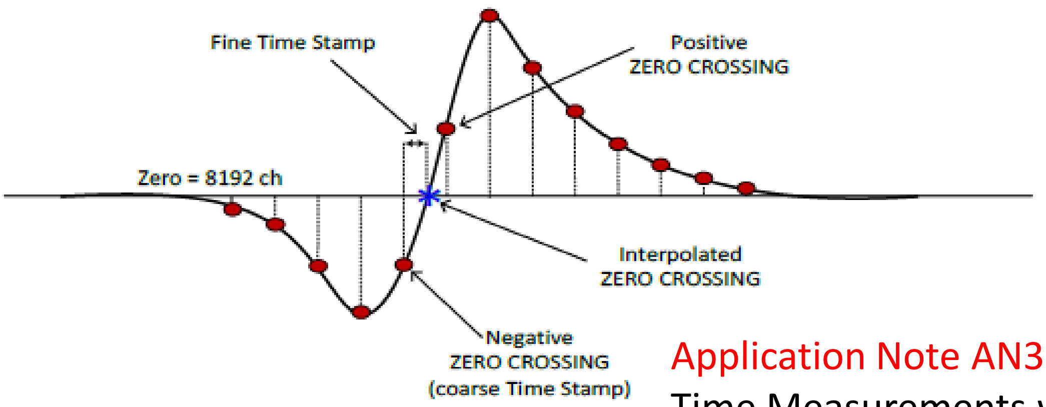
- Energy Measurement:
  - *Same resolution of Analog solutions achieved for most detectors (Pulse Height Analysis, Charge Integration)*
  - *Pulse Shape Discrimination algorithm available*
- Time Measurement?

- Up to now fine *Time Measurements* still relied on traditional chains (CFD+TDC):
  - Digitizers have coarse time stamp, typicaly > 1 ns
  - Off-line interpolation possibility --> waveform acquisition --> high bandwidth requirements

Digital DAQ: a step to a complete solution

CAEN recently developed *On-line Fine Time Measurement*

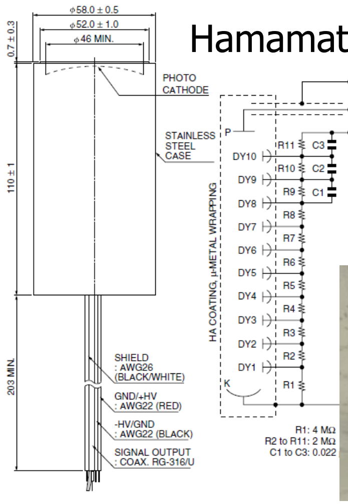
- Implementation of a digital *CFD-like algorithm* on FPGA
- Available on 500 MS/s digitizers, soon available on 250 and 1000 MS/s ones
- *Sub-nanosecond* measurement easily achievable, typically limited by the detector
- List Mode now complete: Energy, PSD, Coarse Timing, Fine Timing



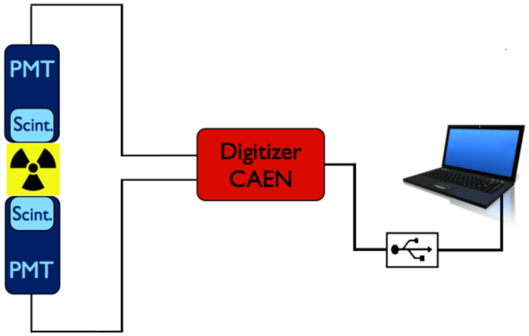
Application Note AN3251 (in preparation)
Time Measurements with CAEN Waveform Digitizers

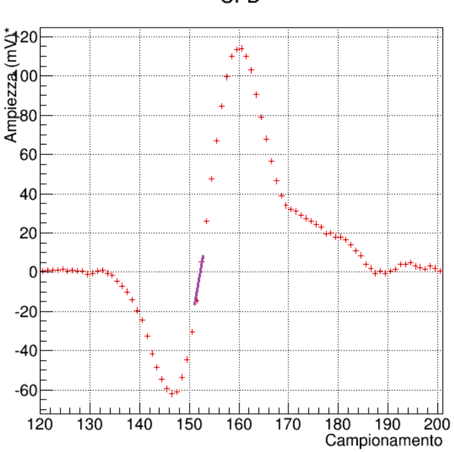
Benchmark test: PMTs

Hamamatsu PMT R4607A-27



EJ-232 scintillator





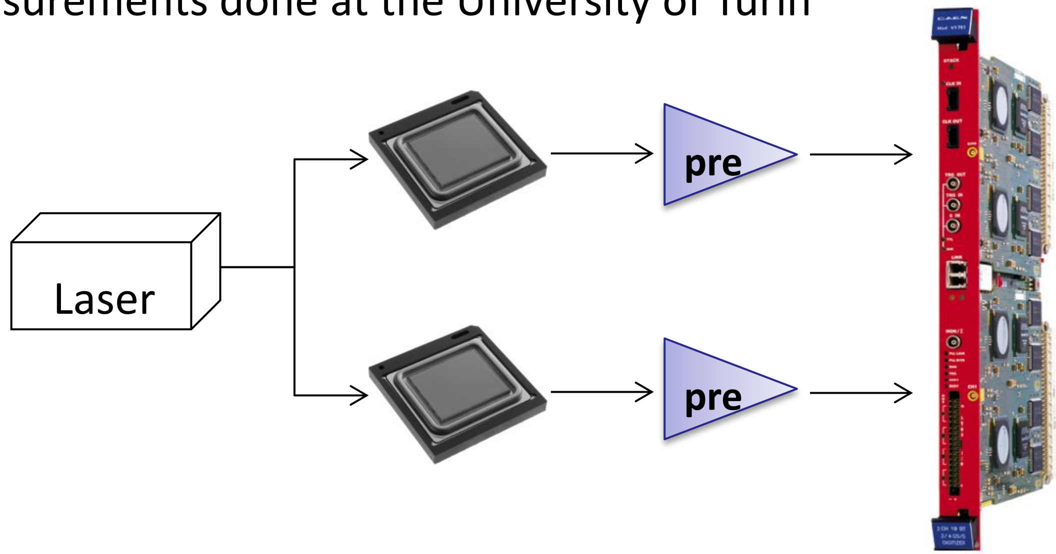
Waveform sampled by V1761
4 GS/s, 1 GHz bandwidth

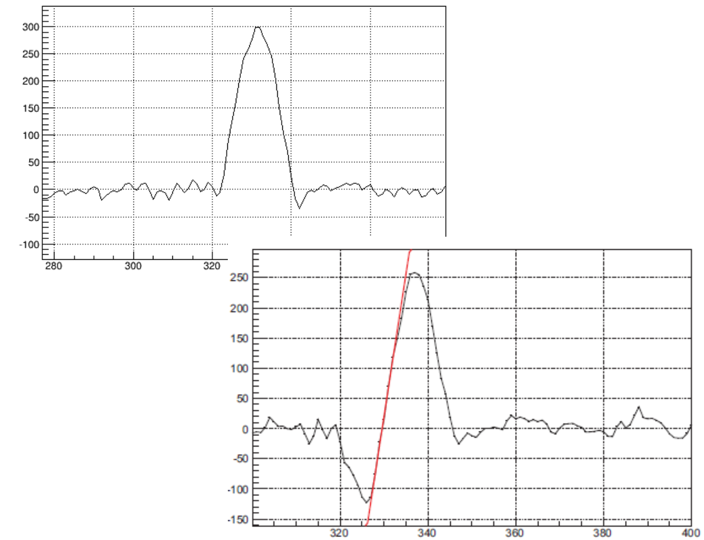
Modello	$\sigma_{LIN1}(ps)$	$\sigma_{LIN2}(ps)$
720	(398 ± 10)	
724	(434 ± 24)	
751	$(357,3 \pm 7,9)$	$(367,3 \pm 7,9)$
751 *DESmode*	$(354,2 \pm 6,3)$	$(350,6 \pm 5,9)$
761	$(353,5 \pm 7,7)$	$(357,1 \pm 5,8)$

- Signal rise time ~4 ns
- Offline CFD algorithm used
  - linear fits around the zero-crossing
- No significant inprovements with sampling spead increase

Benchmark test: Silicon Pixels
(Low-Gain Avalanche Detectors)

Measurements done at the University of Turin





Waveforms sampled with V1751
at 2 GS/s 500 MHz bandwidth

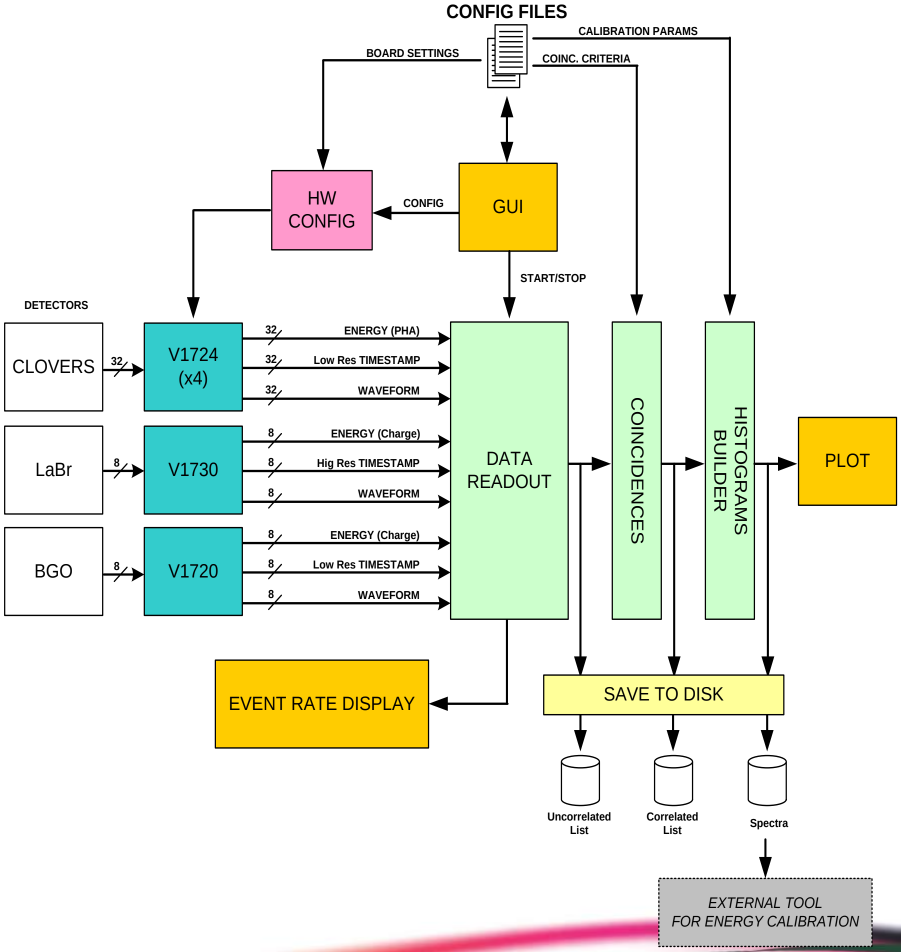
- Signal rise and fall time about 4 ns
- On-line CFD resolution was roughly 200 ps using 500 MS/s digitizer
- Offline analysis
  - Reject noisy events
  - Baseline Calibration (correcting for drifting)

Digitizer	Time Resolution
V1751 @ 2 GS/s	61.7 ± 0.5 ps
V1751 @ 1 GS/s	68.1 ± 0.7 ps
DT5730 @ 500 MS/s	68.8 ± 1.6 ps

Full Digital DAQ: clover detectors and scintillator arrays

BARC (India) required a complete DAQ system to readout n.8 HPGe Clover detectors (32 ch.) provided with BGO Anti-Compton Shields (8 ch.) and pair the resulting events with the $LaBr_3$ scintillators (16 ch.) to increase the timing resolution

- ✓ n.4 V1724 (14 bit, 100 MS/s) running on-line Pulse Height Analysis for Clovers
  → High Energy Resolution
- ✓ n.1 V1720 (12 bit, 250 MS/s) running on-line Charge Integration for ACS
  → Background subtraction and “bad events” rejection
- ✓ n.1 V1730 (14 bit, 500 MS/s) running on-line Charge Integration and Fine Timing for $LaBr_3$
  → Excellent sub-ns Timing Resolution
- ✓ Dedicated SW for event analysis (list mode)
  → Coincidences, Multiplicity, Event Selection, Calibration, Histogram Builder

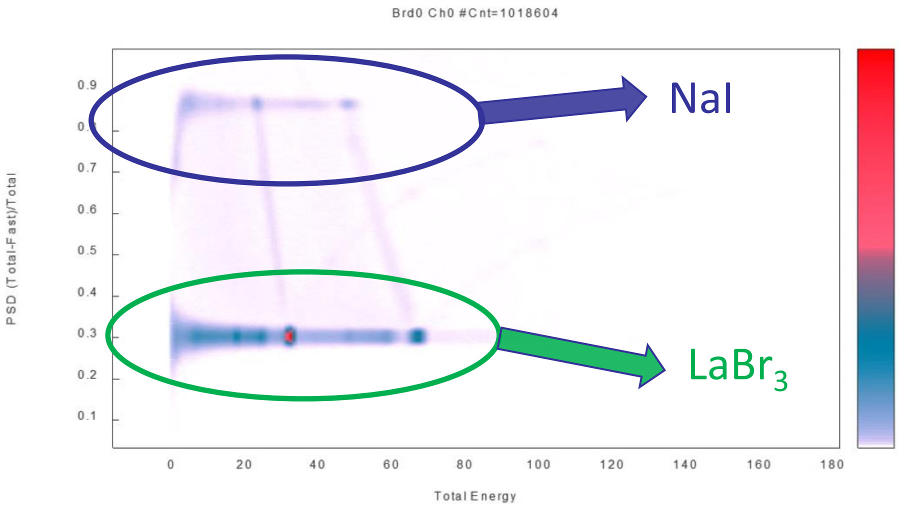


Full Digital DAQ: Phoswich detectors

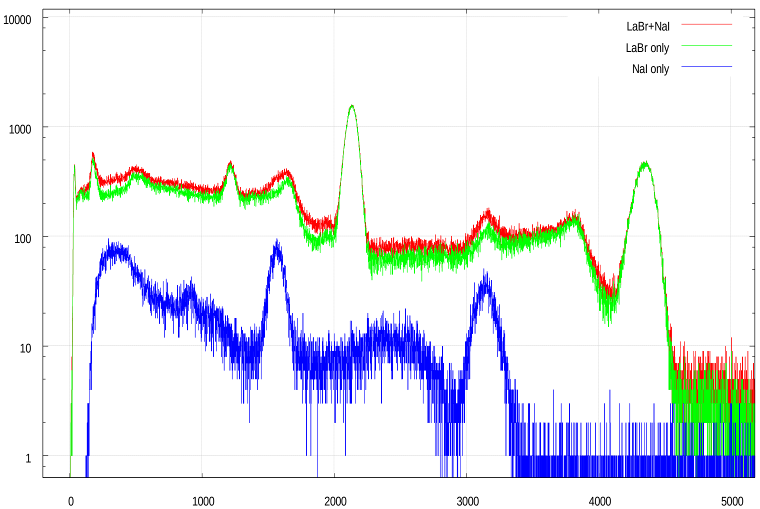
Recently explored the possibility to build a full digital DAQ to readout an array of Phoswich detectors made of $LaBr_3$ and NaI

- ✓ Pulse Shape Discrimination needed to separate the energy released in each scintillator and apply the proper calibration separately
- ✓ Fine Timing needed to exploit the excellent timing capabilities of $LaBr_3$

Test made with DT5730 (14 bit, 500 MS/s) running Pulse Shape Discrimination w/ dual charge integration gate



^{88}Y Source



SiPM Kits

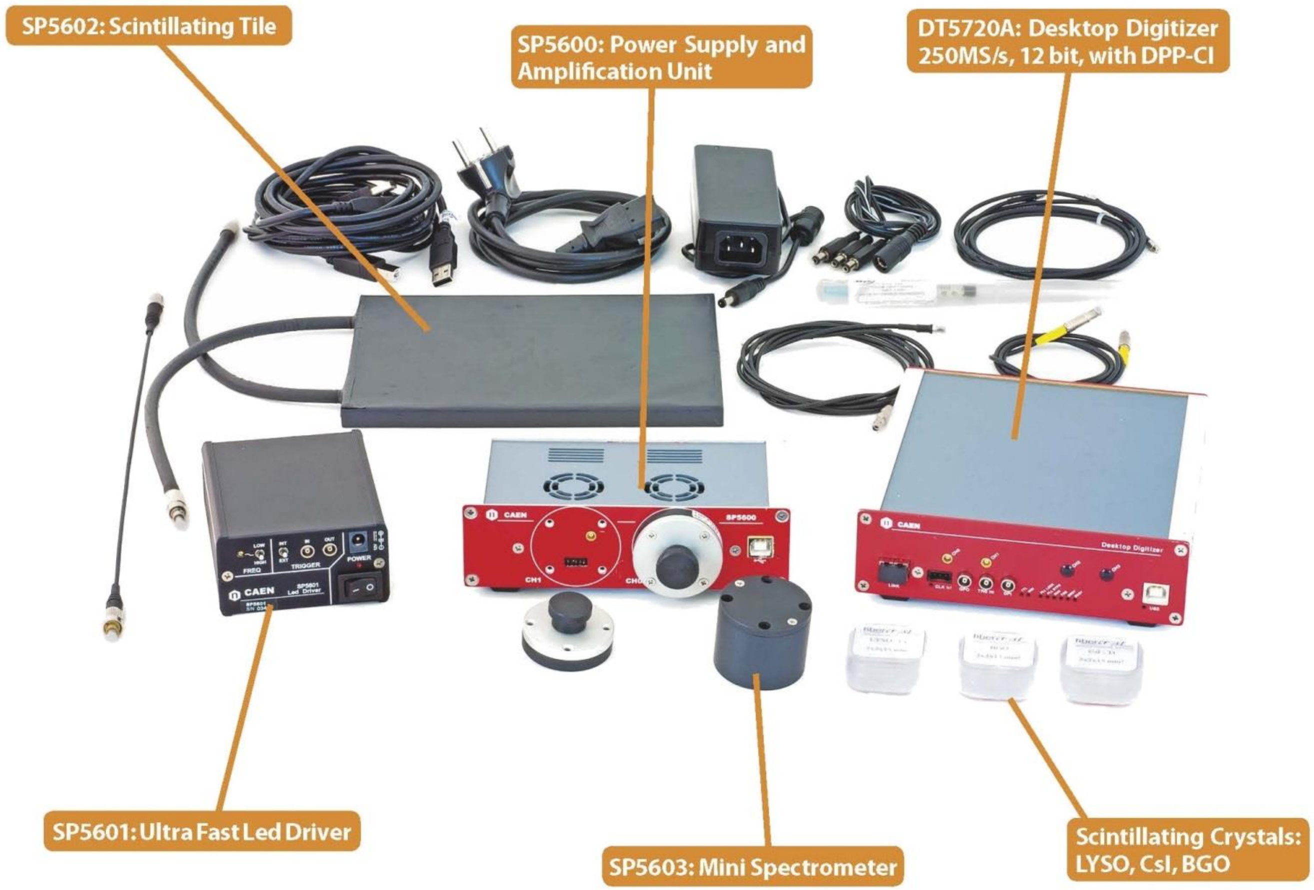
- Silicon Photo-Multipliers (SiPM) are state of the art light detectors and R&D on going

- Despite some drawbacks, fundamental advantages compared to PMTs
  - ✓ high photon sensitivity
  - ✓ reduced noise

- Two kits developed together with the University of Insubria, Como
  - – for users who want to test sensors and characterize them
  - – to perform a series of experiments for undergraduate students

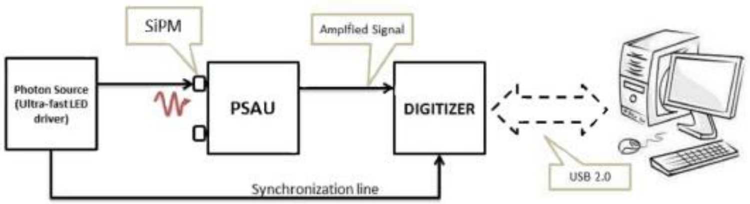
AdvanSiD
ASD-RGB1S-M(G), ASD-NUV1S-M(G)

SiPM Educational Kit Content



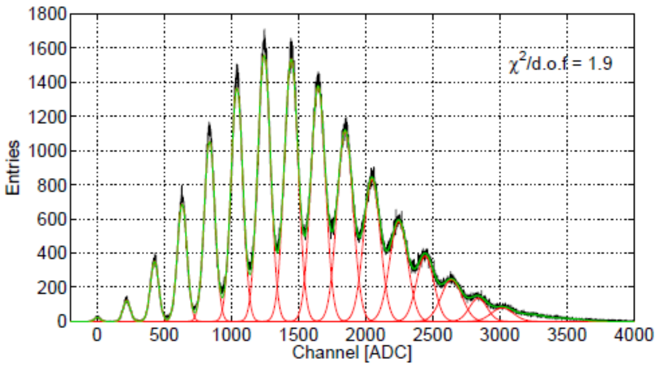
- ✓ A Labview based Control SW and a MATLAB analysis tool
- ✓ Educational Notes

Didactic Experiment



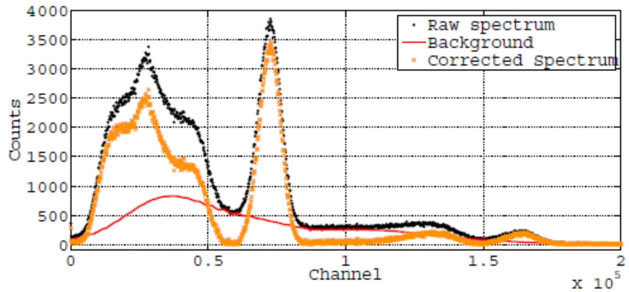
Educational Note ED3127

- LED driver as light source
- Introduction to the SiPM sensor technology
- Photon counting statistic
- Energy resolution



Educational Note ED3163

- Spectrometer with LYSO/BGO/CsI crystals
- ϒ-ray spectroscopy
- Background evaluation, energy calibration, resolution



Educational Note ED3235

- After-pulses in SiPM

Conclusive Remarks on Digitizers

- Suited both for small laboratory tests and highly segmented systems such as particle physics experiments
- May replace several analog devices: discriminator, QDC, ADC, TDC, logic units, **all in one**
- Possibility to implement sophisticated event correlation on-line with board connectivity
- Competitive in time and energy resolution
  - Offline algorithms, using analytic fitting, may give significant improvements

Digital technology always improving

- New communication interfaces
- FPGAs are quickly improving
  - More resources, more processing capabilities
  - Embed microprocessors with high speed communication bus
  - More room for onboard algorithm development

Backup

CAEN Digitizer Offer

Model [1]	Form Factor	N. of ch. [2]	Max. Sampling Frequency (MS/s) [2]	N. of Bits	Input Dynamic Range (Vpp) [2]	Single Ended / Differential Input	Bandwidth (MHz) [2]	Memory (MS/ch) [2]
x720	VME	8	250	12	2	SE / D	125	1.25 / 10
	Desktop/NIM	4 / 2				SE		
x721	VME	8	500	8	1	SE / D	250	2
x724	VME	8	100	14	0.5 / 2.25 / 10	SE / D	40	0.5 / 4
	Desktop/NIM	4 / 2				SE		
x730	VME	16	500	14	0.5 - 2	SE	250	0.64 / 5.12
NEW	Desktop/NIM	8						
x731	VME	8 - 4	500 - 1000	8	1	SE / D	250 / 500	2 / 4
x740	VME	64	62.5	12	2 / 10	SE	30	0.19 / 1.5
	Desktop/NIM	32						
x751	VME	8 - 4	1000 - 2000	10	1	SE / D	500	1.8 - 3.6 / 14.4 - 28.8
	Desktop/NIM	4 - 2				SE		
x761	VME	2	4000	10	1	SE / D	1000	7.2 / 57.6
	Desktop/NIM	1				SE		
SWITCHED CAPACITOR x742	VME	32+2	5000 [4]	12	1	SE	500	0.128 / 1
	Desktop/NIM	16+1						
SWITCHED CAPACITOR x743	VME	16	3200 [4]	12	2.5	SE	500	0.007
NEW	Desktop/NIM	8						

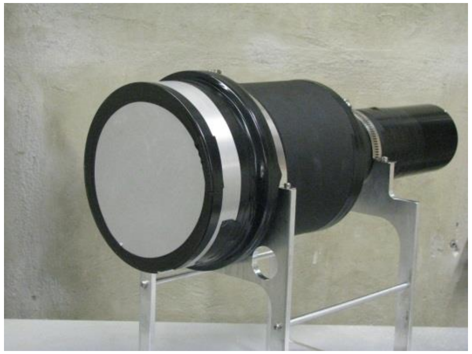
γ-n Discrimination: Test Result

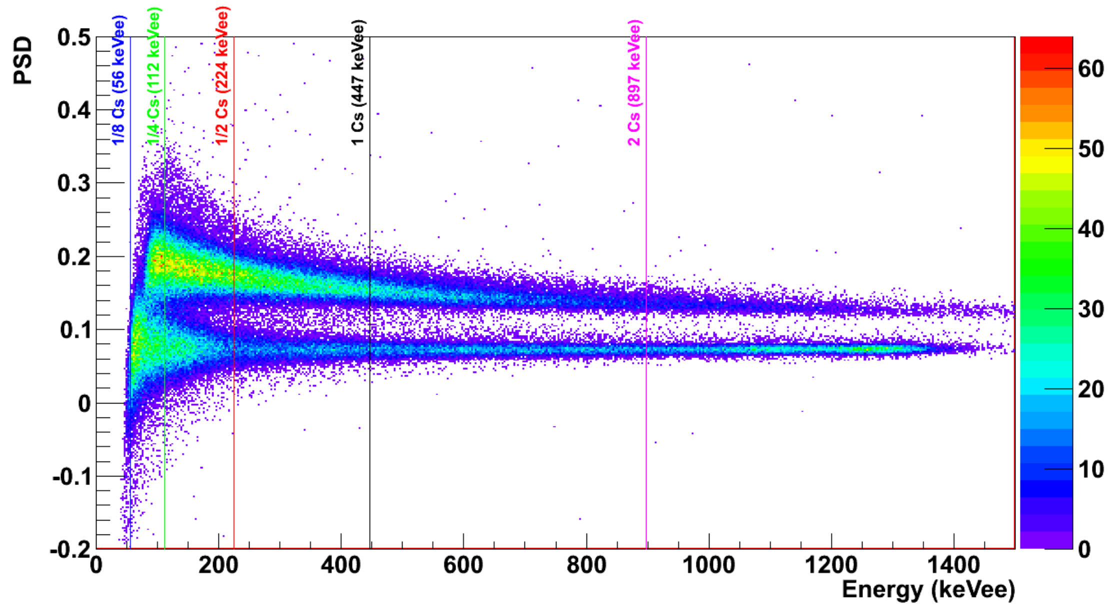
Application Note AN2506

Detector: BC501A liquid scintillator 5x2 inches

x720, 250 MS/s 12 bit digitizer

PMT: Hamamatsu R1250

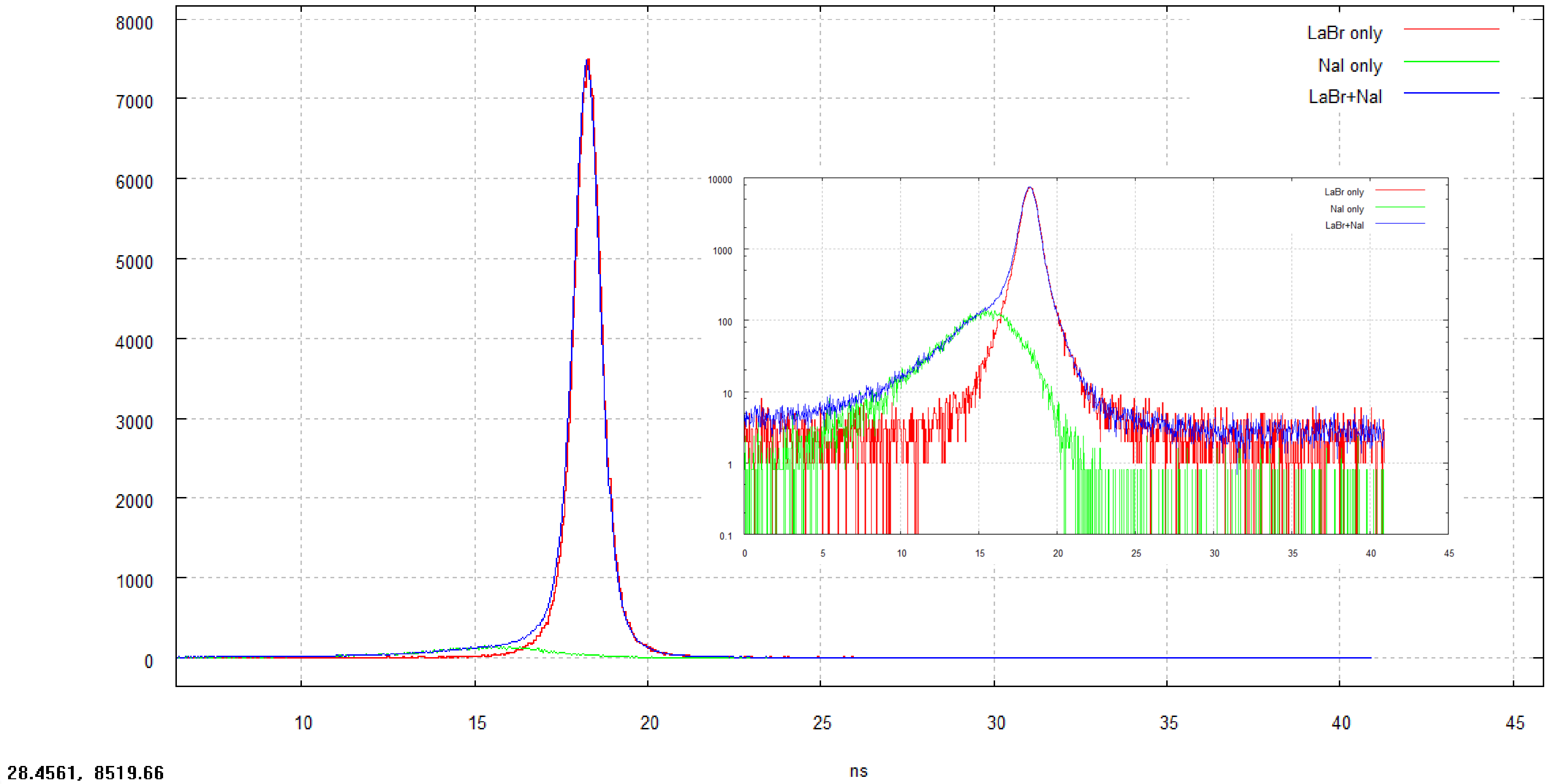




Time of Flight Spectrum

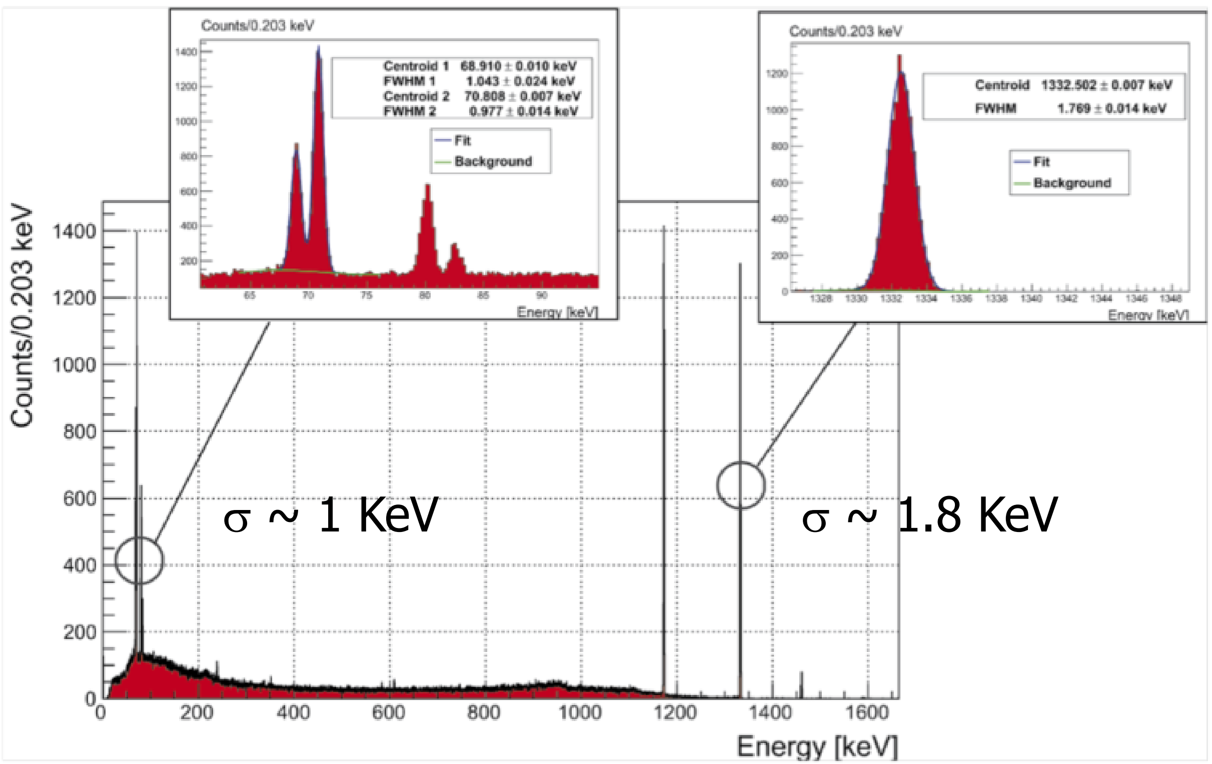
3”x3” $LaBr_3$ to Phoswitch Time Of Flight

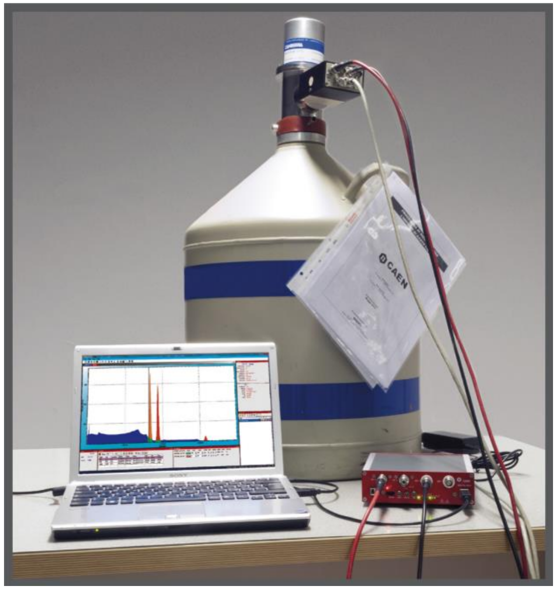
Resolution = down to ~500 ps FWHM depending on the energy range windowing (mainly due to intrinsic resolution of the large detector)



Test Results with HPGe Detector

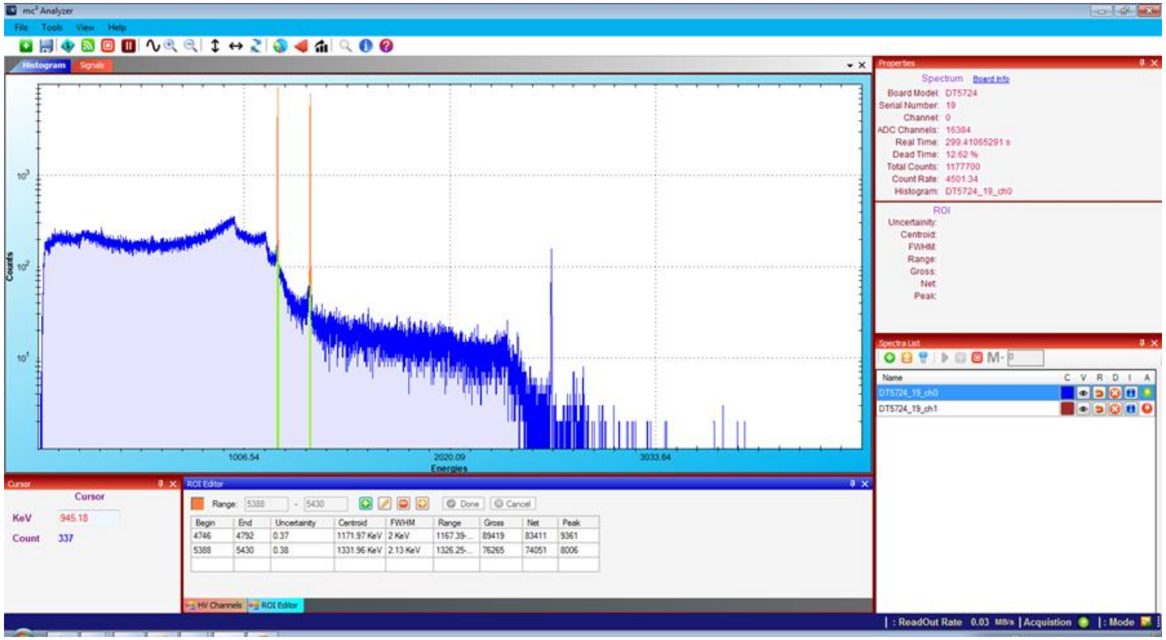
- Tests with CANBERRA Coaxial P-Type detector (20% eff.)
  - Application Note AN3110



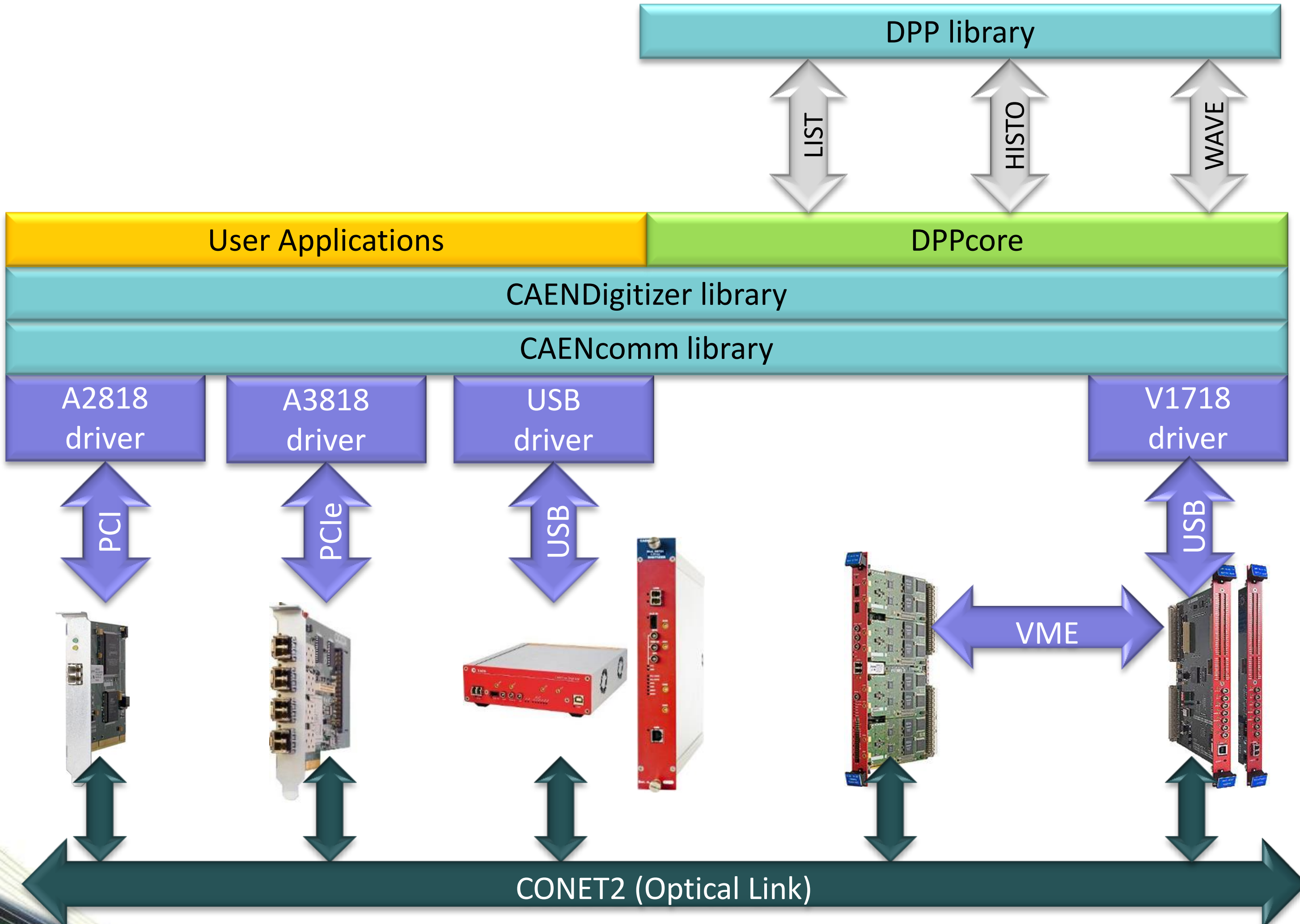


MC² Analyzer

- Spectroscopy software for MCA
- DPP parameters auto-setting, save/restore configuration, manual setting
- Spectra and List files saving and reading (csv, ANSI42)
- Live display of waveforms (input, timing filter, trapezoid) and digital traces (trigger, peaking time, etc.)
- Basic analysis tools:
  - Multiple ROIs definition
  - Energy calibration
  - Peak Search
  - Background subtraction
  - Peak fitting
  - Rebinning



Libraries for Waveform Digitizers



Set/Get Params, Start/Stop
Read Events, etc.

Open/Close, Read, Write

Educational Kit Technical Spec.

SP5600 General Purpose Power Supply and Amplification Unit - Power Supply	Max Voltage 120V, Max Current 100 uA, Temp. Feedback Res. 0.1 °C
SP5600 General Purpose Power Supply and Amplification Unit - Wideband Amplifier	Gain: 1-50 dB, Gain Setting Step: 1 dB, Bandwidth: 100 kHz - 500 MHz, Output Dynamic Range: ± 2V, Discriminator Threshold: ± 2V, min step = 61 uV
DT5720A Desktop Digitizer	Sampling Rate: 250 MS/s , Resolution: 12 bit, Dynamic range: 2 Vpp, DAC Offset: ± FSR/2, Digital Pulse Processing Firmware (DPP-CI) Installed
SP5601 LED Driver	Wavelength: 405 nm (Violet), Pulse Width: 8 ns (Typ.), Triggered via internal pulse generator, or via external source, Tunable intensity and repetition rate, Frequency: From 500 Hz to 5 MHz, FC terminated optical fiber included
SP5602 Scintillating Tile	Scintillating Material: Polystyrene with WLS Fiber embedded, Dimensions: 200x150x10 mm^3 (Active Area: 150x150x10 mm^3), Fiber Termination: FC
SP5603 Mini Spectrometer	Embedded SiPM: Hamamatsu MPPC S10362 -33-50C 100C 3x3 mm^2 Active Area, Crystals (3x3x15 mm^3): LYSO, BGO, CsI, Temperature feedback sensor embedded
SP5650A Sensor Holder	Embedded SiPM: Hamamatsu MPPC S10362 -11-100C 100C 1x1 mm^2 Active Area, Temperature feedback sensor embedded