Gamma-ray Spectroscopy through the Digital Gateway

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School on Nuclear Data Acquisition Systems @ IUAC, New Delhi, 21-22 February, 2022

Data @ Gamma Spectroscopy

Data CAN principally be constituted with energy deposited in detection, timing of detection, identity of detector corresponding to detection

Energy, Timing, Detector ID -> PARAMETERS

Analog Domain

Energy of detection -> spectroscopy amplifier.

Timing of detection -> TAC, TDC

Data can be acquired free/unrestricted or in the presence of an event trigger (fulfillment of a USER DEFINED CONDITION)

List Mode Data

EVENT-BY-EVENT information recorded in data files

Remember
Event is the fulfillment of a user defined condition

For each event ->
which detectors have fired,
what are the respective energies (channel numbers),
time (reference) of detection

Data files are STRUCTURED/ORGANIZED into EVENTS.
They are read event wise, for subsequent reduction and data analysis

Appropriate for multi-detector setups, multi-parameter acquisition and generally used in actual experiments

List Mode File in zls Format

block header DAPS | block size | zero | event pattern | 2-byte word/ ADC (13-bit)

4144 5350 05a4 0000 0a00 3f04 0734 0635 0fff
045c 0fff 0fff 045b 0fff 0a00 3f04 018b 0542 06ec
0fff 0fff 0490 0fff 0454 0fff 4001 3f08 072c 05b9

…….till then end-of-block followed by DAPS….

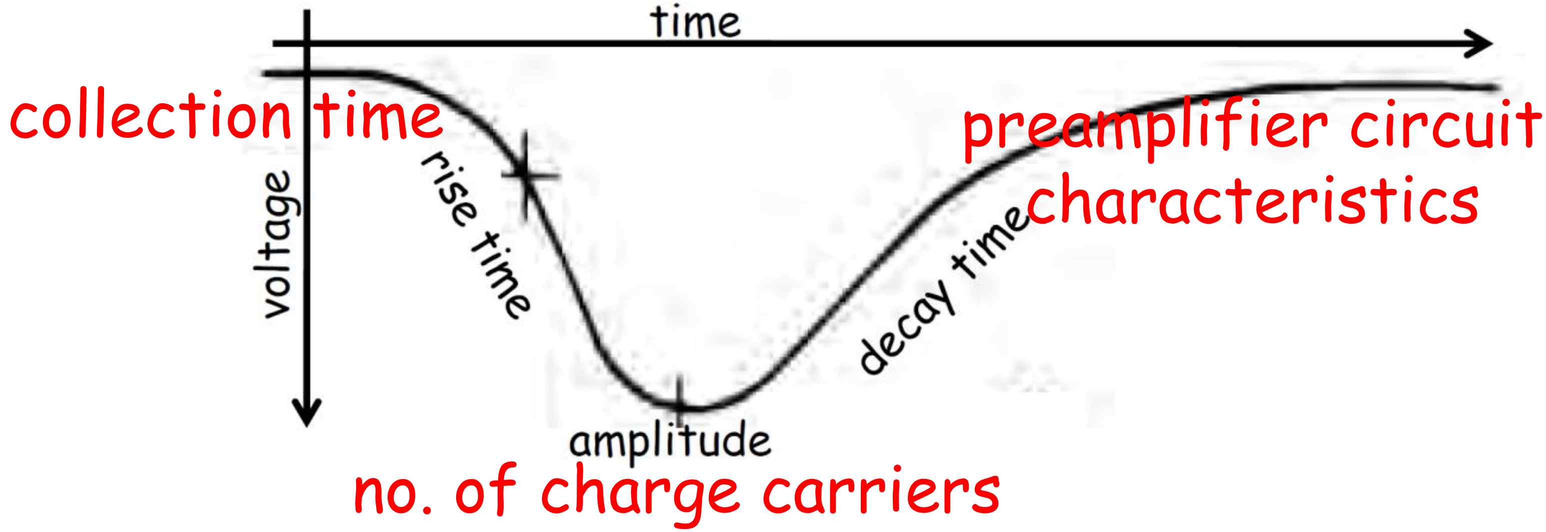
No. of 2-byte words in the event pattern = NPat+15/16 rounded off to preceding lower integer.

Npat = 30 gives two 2-byte event pattern words.

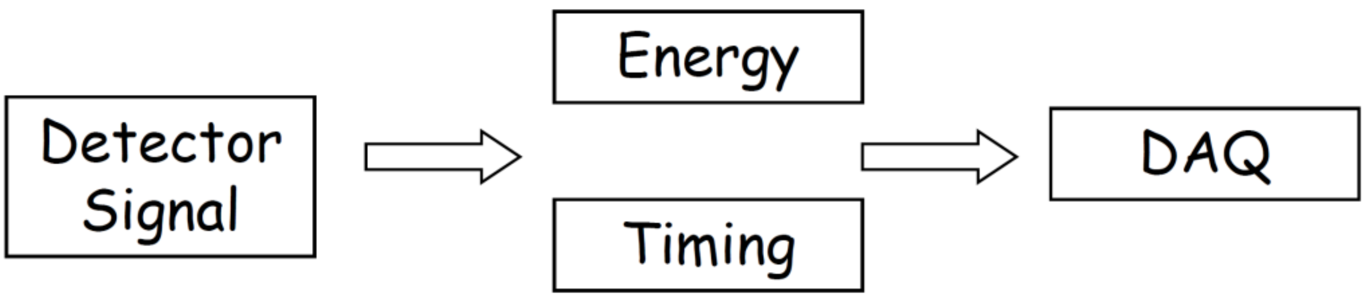
0a00 3f04 : 0000 1010 0000 0000 // 0011 1111 0000 0100
Parameters = 10, 12, 19, 25, 26, 27, 28, 29, 30 : 9

Para.#19 (TDC): 0fff = 0000 1111 1111 1111
= **4095**

Pulse from HPGe Detector

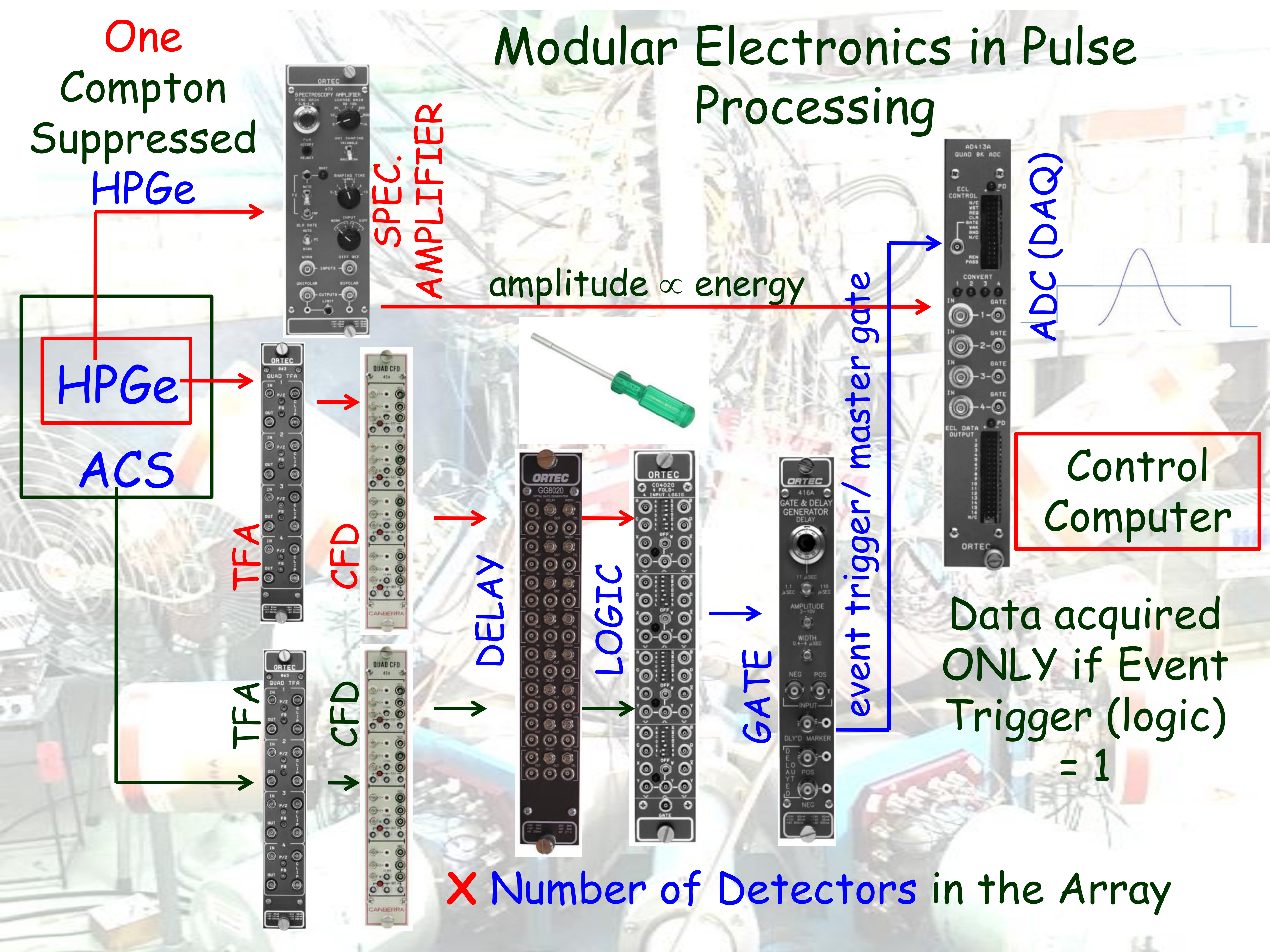


Preamplifier pulse from the detector -> to be processed for energy & timing info



amplitude -> energy deposited in the detection

rise time -> time marker for detection



Modular Electronics in Pulse Processing
One Compton Suppressed HPGe
HPGe
ACS
SPEC. AMPLIFIER
amplitude ∝ energy
ADC (DAQ)
TFA
CFD
TFA
CFD
DELAY
LOGIC
GATE
event trigger/ master gate
Control Computer
Data acquired ONLY if Event Trigger (logic) = 1
X Number of Detectors in the Array
ORTEC
SPECTROSCOPY AMPLIFIER
QUAD TFA
QUAD CFD
CANBERRA
GG8020
CO4020
416A
GATE & DELAY GENERATOR
AD413A
QUAD 8K ADC

Digital Revolution in Gamma-ray Spectroscopy

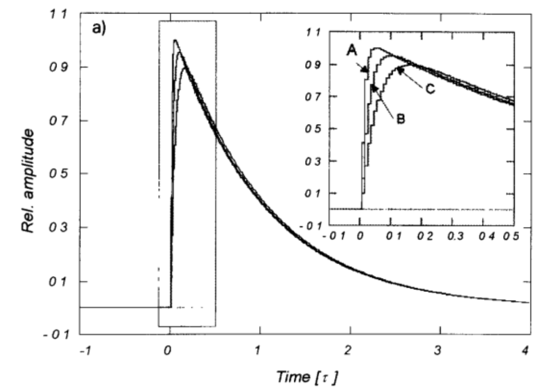
Detector Signal ⇨ Digitization ⇨ Firmware: Recursive Algorithms (Filter) & Validation ⇨ (Time Stamped) Data

Nuclear Instruments and Methods in Physics Research A 345 (1994) 337–345
North-Holland

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

Digital synthesis of pulse shapes in real time for high resolution radiation spectroscopy

Valentin T. Jordanov *, Glenn F. Knoll
Department of Nuclear Engineering, The University of Michigan, 2355 Bonisteel Blvd, Ann Arbor, MI 48109, USA



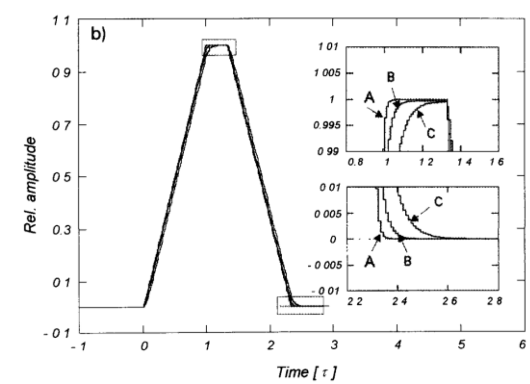
Fast, compact, efficient acquisition systems for contemporary experimental facilities

ELSEVIER
Nuclear Instruments and Methods in Physics Research A 353 (1994) 261–264

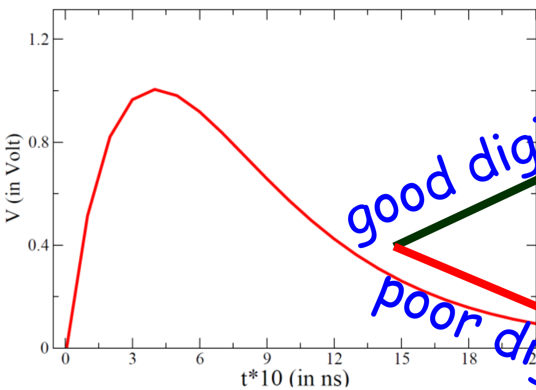
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

Digital techniques for real-time pulse shaping in radiation measurements

Valentin T. Jordanov [a,*], Glenn F. Knoll [b], Alan C. Huber [a], John A. Pantazis [a]
[a] *Amptek Inc., 6 De Angelo Dr., Bedford, MA 01730, USA*
[b] *The University of Michigan, Department of Nuclear Engineering, Ann Arbor, MI 48109, USA*

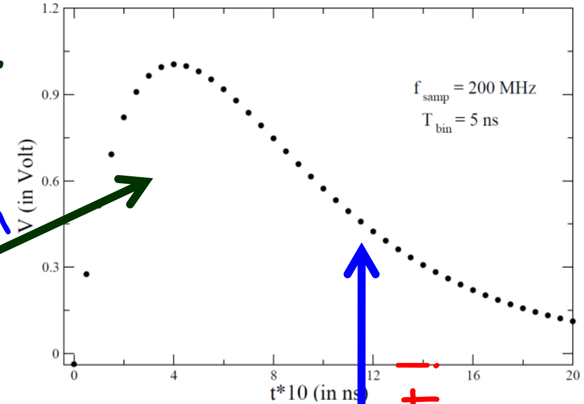


A Naive Look ....

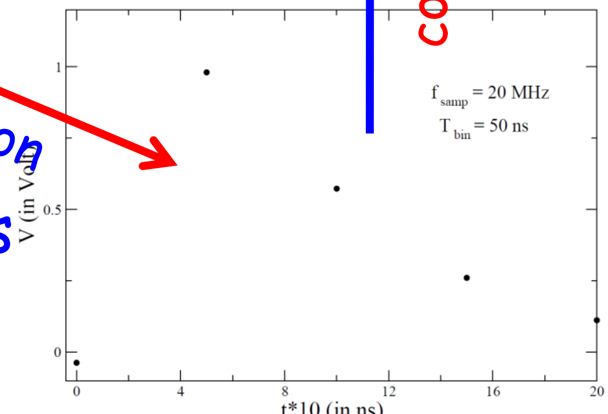


good digitization

poor digitization



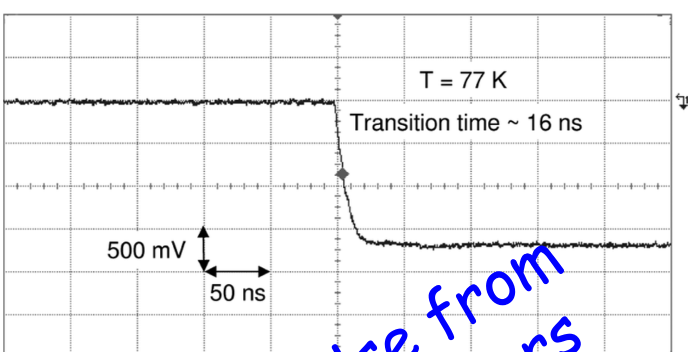
cost !



faster sampling using faster digitizer; faithful representation of the pulse

slow sampling; poor representation of the pulse

digitization: discreteness ("numberification" !!)

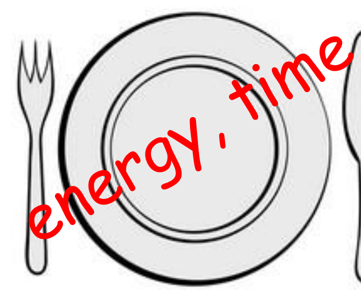


pulse from detectors

50, 125, 76, 800, 1000, 23......

numbers

recursive algorithms



energy, time

Digitizers IN Gamma-ray Spectroscopy

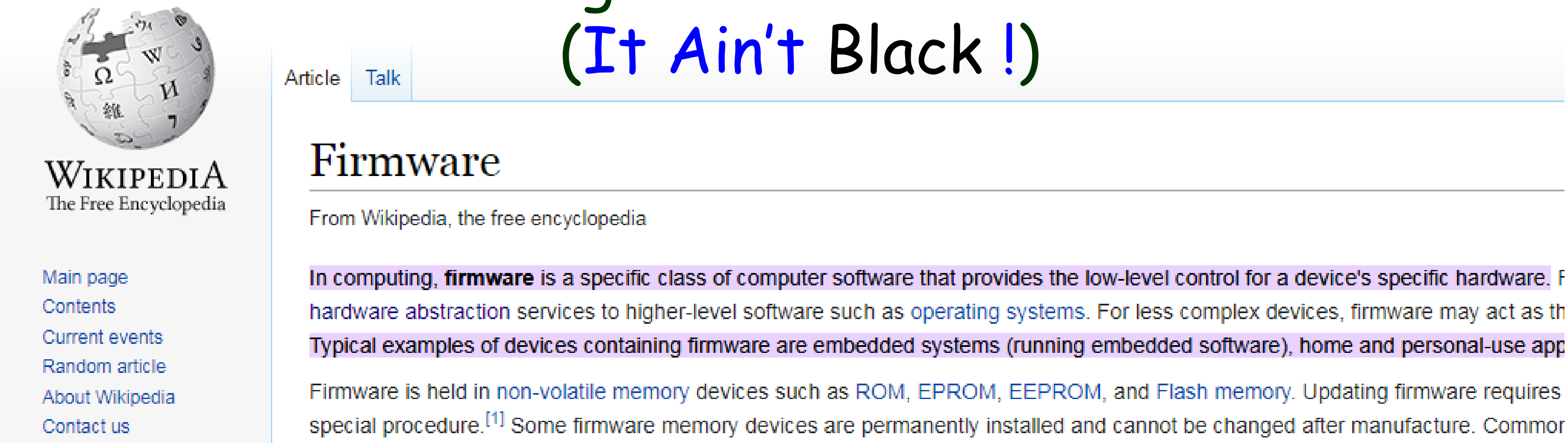
pulse processing
AND
data acquisition

typical setup:
detector pulse
-> digitizer

```
HEADER0:1025
HEADER1:1792
HEADER2:513
HEADER3:32772
15750267  348
30189650  16792
50540414  387
61218162  4496
65012138  1802
84986304  226
93885890  1812
94862904  1201
97517825  14777
111642640  210
111686411  6964
114351260  1007
127908486  1989
129126382  1686
137062876  2676
```

energy, time for
EACH DETECTION
(event ?)

Digitizer Firmware
(It Ain't Black !)

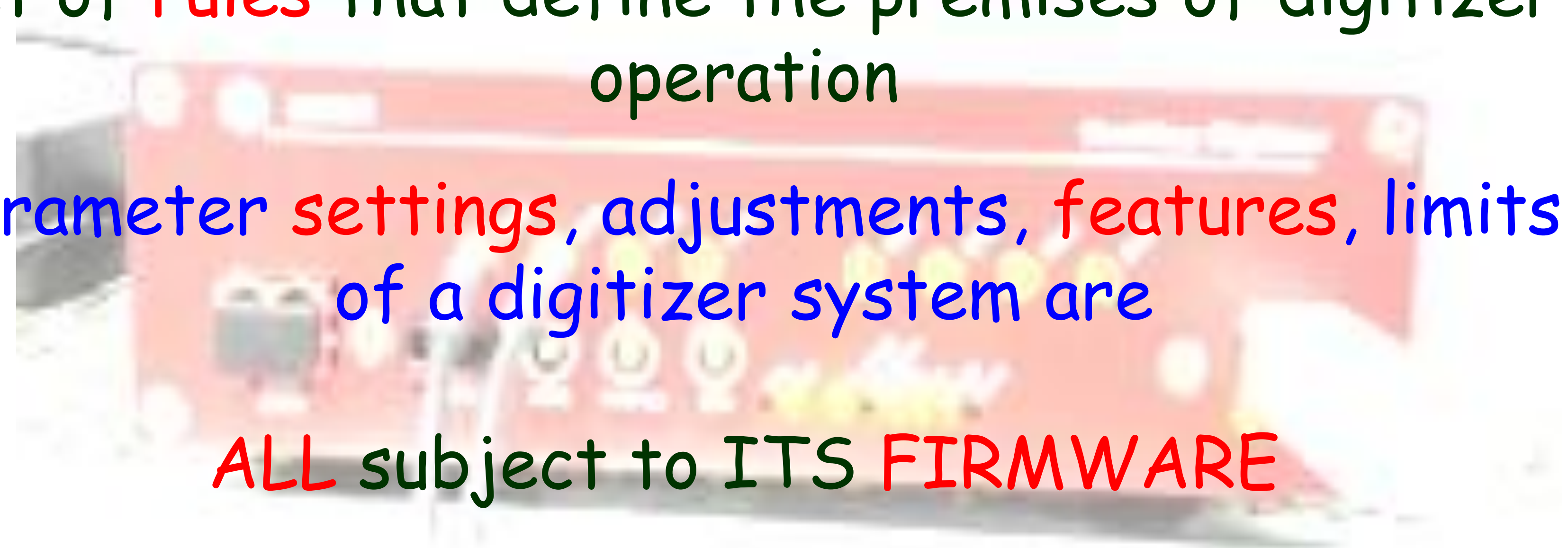

Article Talk

Firmware

From Wikipedia, the free encyclopedia

In computing, **firmware** is a specific class of computer software that provides the low-level control for a device's specific hardware. F
hardware abstraction services to higher-level software such as operating systems. For less complex devices, firmware may act as th
Typical examples of devices containing firmware are embedded systems (running embedded software), home and personal-use app

Firmware is held in non-volatile memory devices such as ROM, EPROM, EEPROM, and Flash memory. Updating firmware requires
special procedure.[1] Some firmware memory devices are permanently installed and cannot be changed after manufacture. Commor



set of rules that define the premises of digitizer operation

parameter settings, adjustments, features, limits of a digitizer system are

ALL subject to ITS FIRMWARE

HPGe detectors with superior energy resolution for spectroscopy. Large arrays of detectors to optimize the efficiency.

Setup of one or different kind of detectors, depending on the physics being addressed

Advances in detector technology, pulse processing techniques. Advent of modern detectors.

Gamma-ray Spectroscopy

Efficient background reduction. Eg. Compton suppression using ACS.

Coincident measurements for unambiguous identification and assignments. (Typical in γ-ray detector array)

Compact electronics, data acquisitions capable of handling more event rates.

Firmware Possibility # 1
The "Triggerless" Mode

Acquire (record) all parameters (signals from the detectors in the setup) UNRESTRICTED.

Validation / Checks offline during data reduction / sorting and analysis.

Superior flexibility to the user in choosing the events of interest under varied conditions, implemented in software.

Appropriate for setups with different types of detectors – for gamma, charge particle, neutrons.

Huge data size (terabytes !). Large processing time.

For pure gamma-ray detection setup ?

Firmware Possibility # 2

Compton Unsuppressed Multiplicity Trigger

Event trigger based on multiplicity of Compton unsuppressed gamma-ray detectors (HPGe Clovers).

ACS veto checked while recording the data. Only the Compton suppressed part of the firing detectors is recorded.

Simplified firmware.

Large data files from Compton unsuppressed trigger. BUT only the Compton suppressed part is recorded. MOST of this is unusable in coincidence analysis.

Large processing time.

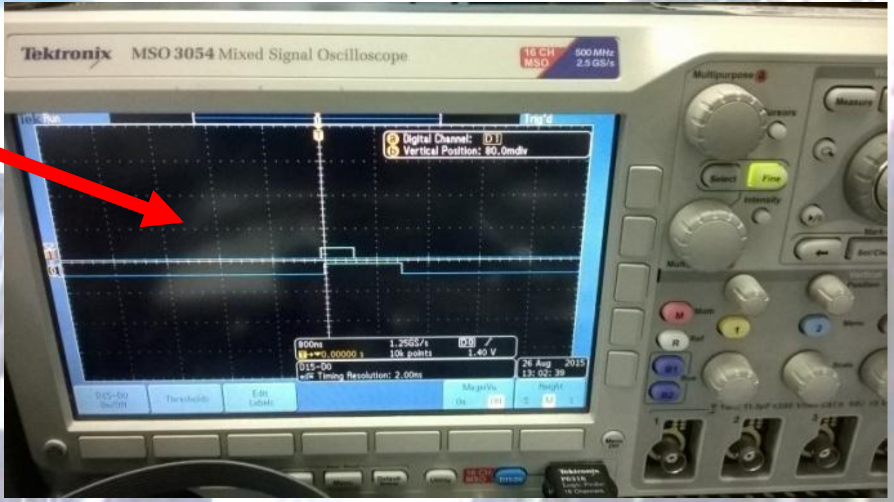
Firmware Possibility # 3
Compton Suppressed Multiplicity Trigger

Event trigger based on multiplicity of Compton suppressed Clover detectors.

(Extending the analog pulse processing methodology to digital domain.)

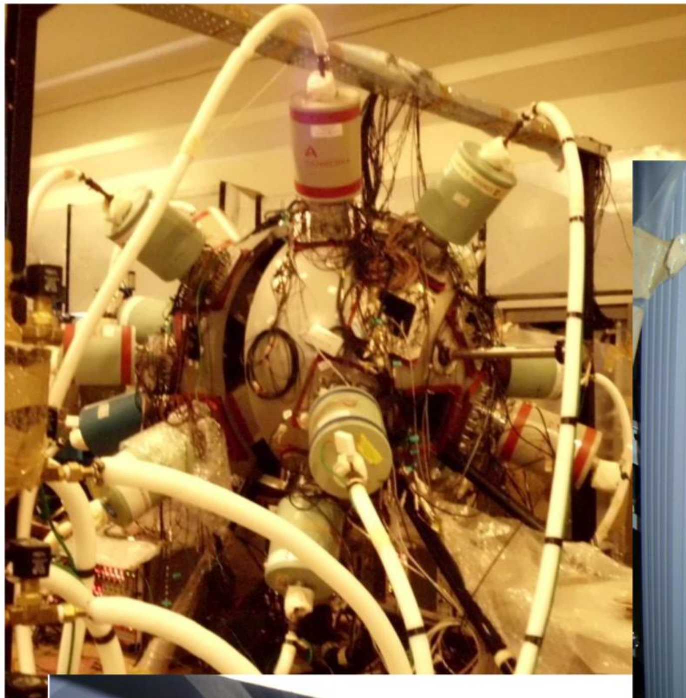
Data files principally consisting of GOOD EVENTS, USABLE EVENTS for gamma spectroscopy analysis

The ritual of "seeing" the signals and setting the delays, the overlaps in the analog domain religiously transported to the digital generation EVOLUTION !



The Stepping Stone

INGA at TIFR, Mumbai (2009-2013)



Around twenty Compton suppressed Clover detectors.

Digitizer (Pixie-16 XIA) based pulse processing electronics + data acquisition system.

Time stamp in-built in the event record.

The beginning of the DIGITIZER ERA in Indian Gamma-ray Spectroscopy Efforts
[Palit et al. NIMA680, 90(2012)]

Digital DAQ of UGC-DAE CSR, Kolkata Centre

Pixie-16 (XIA LLC) modules with 12-bit 250 MHz ADC for digitization

16-channels to support 3 **Compton suppressed** Clover detectors.
(Clovers: channels#0-11 & ACS:channels#12-14)

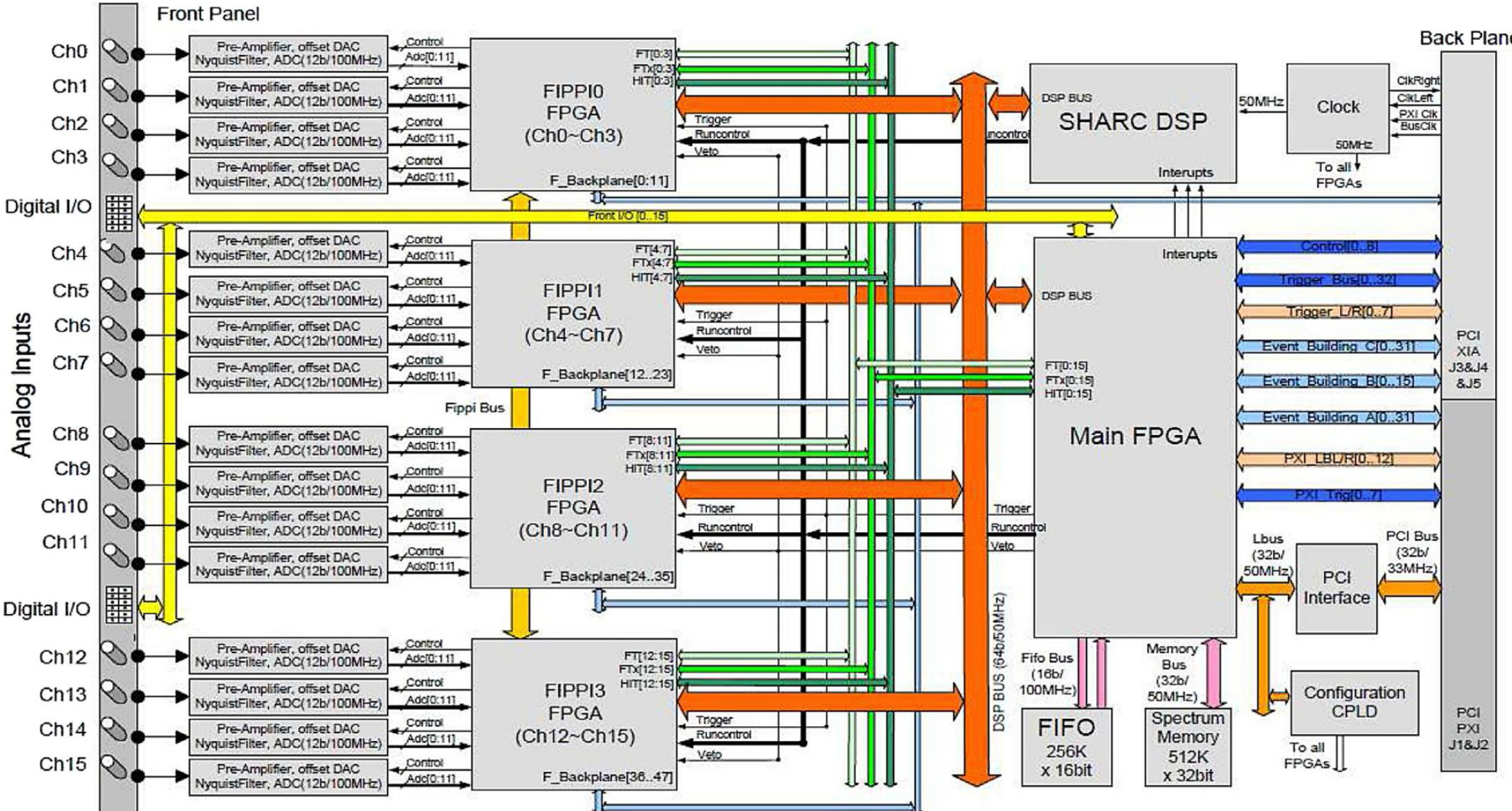
Firmware conceptualized by UGC-DAE CSR, Kolkata Centre & Implemented by XIA LLC (Dr. H. Tan et al.)

Das et al. NIMA (2018)

Discerningly triggerless !

Pulse processing & DAQ for INGA@VECC, 2017-21.

PIXIE-16 Architecture

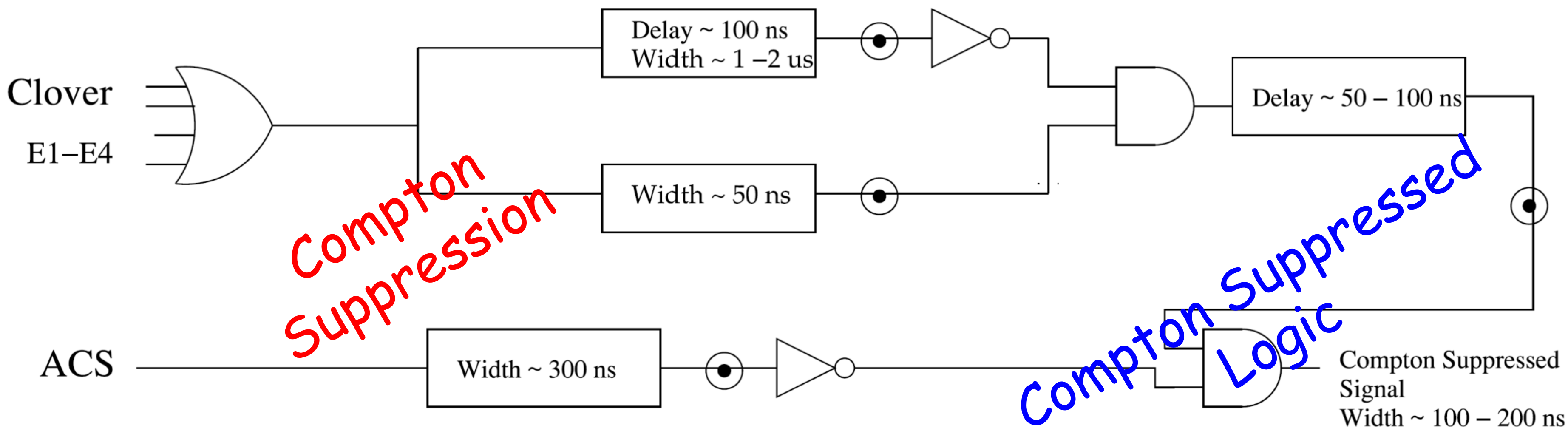


housed in 14-slot PXI crates & controlled through PXI-PCI controller

bridged to the host computer through fiber optic cable

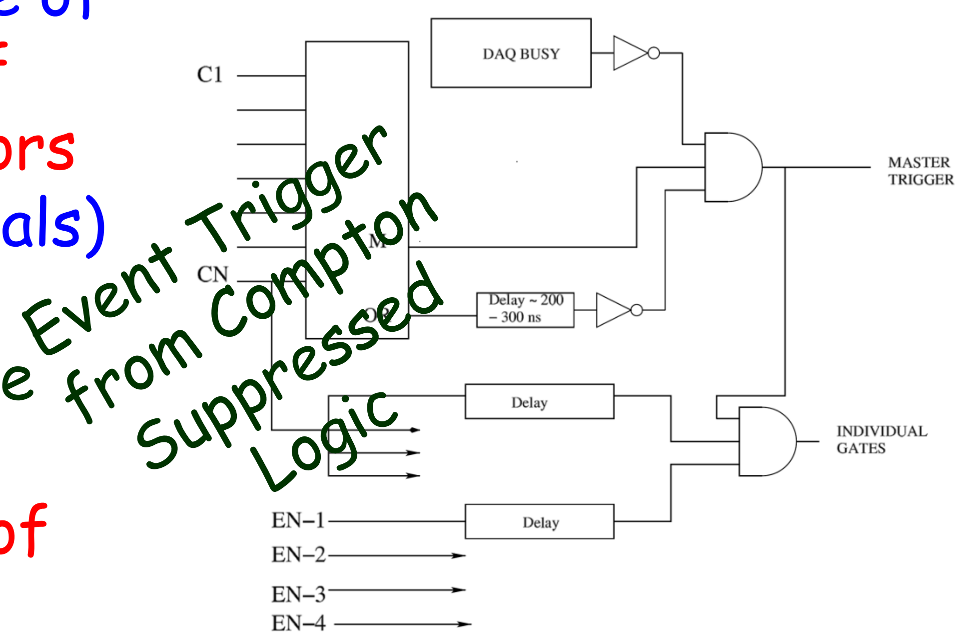
http://www.xia.com

Time Processing for Trigger Generation



Data acquired in the presence of user chosen multiplicity of Compton suppressed detectors (represented by CS logic signals)

Implemented in analog pulse processing electronics (practiced in all campaigns of INGA till 2008).



Extraction of Energy & Time in Digital Systems

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Digital synthesis of pulse shapes in real time for high resolution radiation spectroscopy

Valentin T. Jordanov *, Glenn F. Knoll
Department of Nuclear Engineering, The University of Michigan, 2355 Bonisteel Blvd., Ann Arbor, MI 48109, USA

This paper describes a technique for synthesis of optimal pulse shapes (symmetric triangle and symmetric trapezoid) for high resolution, high throughput spectroscopy, using fast recursive digital algorithms.

The algorithms are suitable for real time implementation, require only simple hardware, and offer flexibility in the adjustment of the output pulse shapes.

N-H
ELSEVIER

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In our previous work [1] we described recursive algorithms for real time pulse processing in high resolution spectroscopy. In that paper we also proposed a hardware configuration for a trapezoidal/triangular pulse shaper. Although we presented some initial results obtained using a quasi-real time system, our further work has now resulted in the assembly and testing of a prototype that operates in true real time.

recursive algorithm: calls itself with smaller/simpler input values -> obtains results for the current input by operating on smaller/simpler inputs
(www.cs.odu.edu)

Trapezoidal Filter in Digital DAQ
(Example: PIXIE-16@XIA LLC, http://www.xia.com)

trapezoidal filter implemented through

$$LV_{x,k} = -\sum_{i=k-2L-G+1}^{k-L-G} V_i + \sum_{i=k-L+1}^{k} V_i$$

L is the filter length & G is the filter gap -> user defined settings on the digitizer

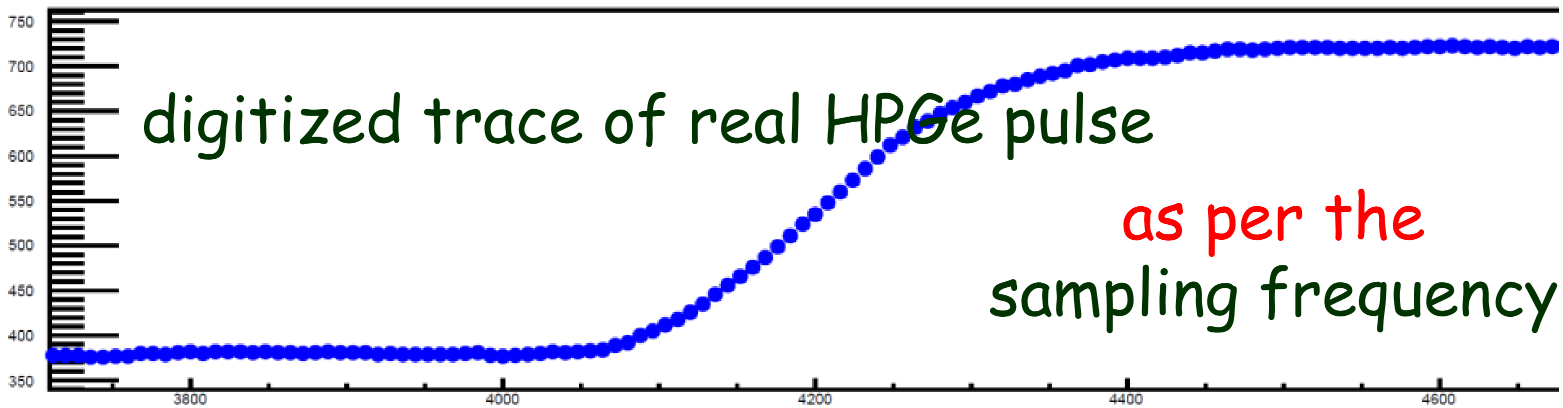
base width of the pulse = 2 L + G

two versions of the filter applied on the digitized pulse

fast filter	slow filter
to detect arrival of pulse (time stamp)	to extract pulse amplitude (energy)

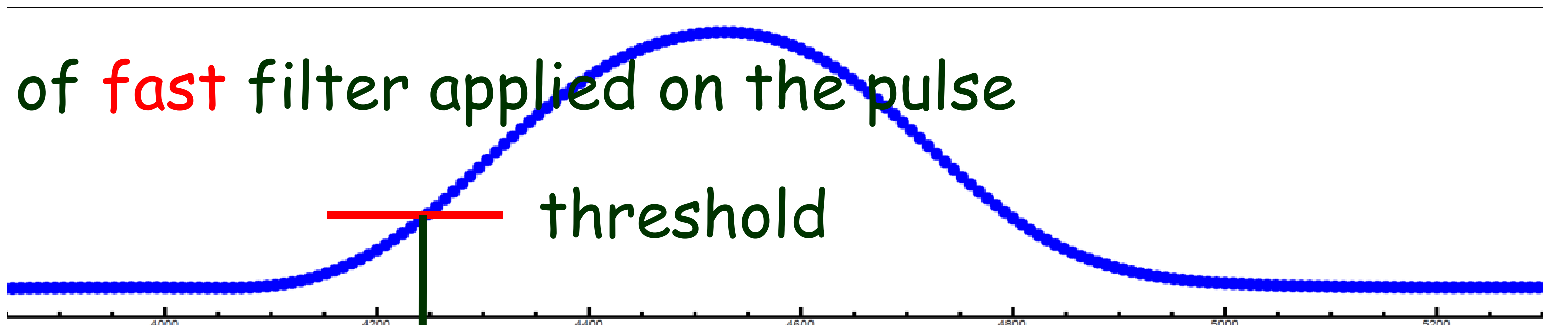
they differ in the choice of length & gap parameters

Trapezoidal Filter Output



digitized trace of real HPGe pulse

as per the sampling frequency

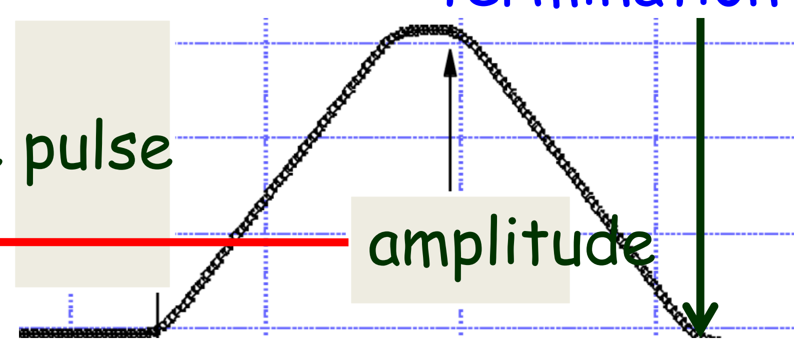


output of fast filter applied on the pulse

threshold

time of arrival of pulse: TIME STAMP

(on the absolute clock)



sharp termination

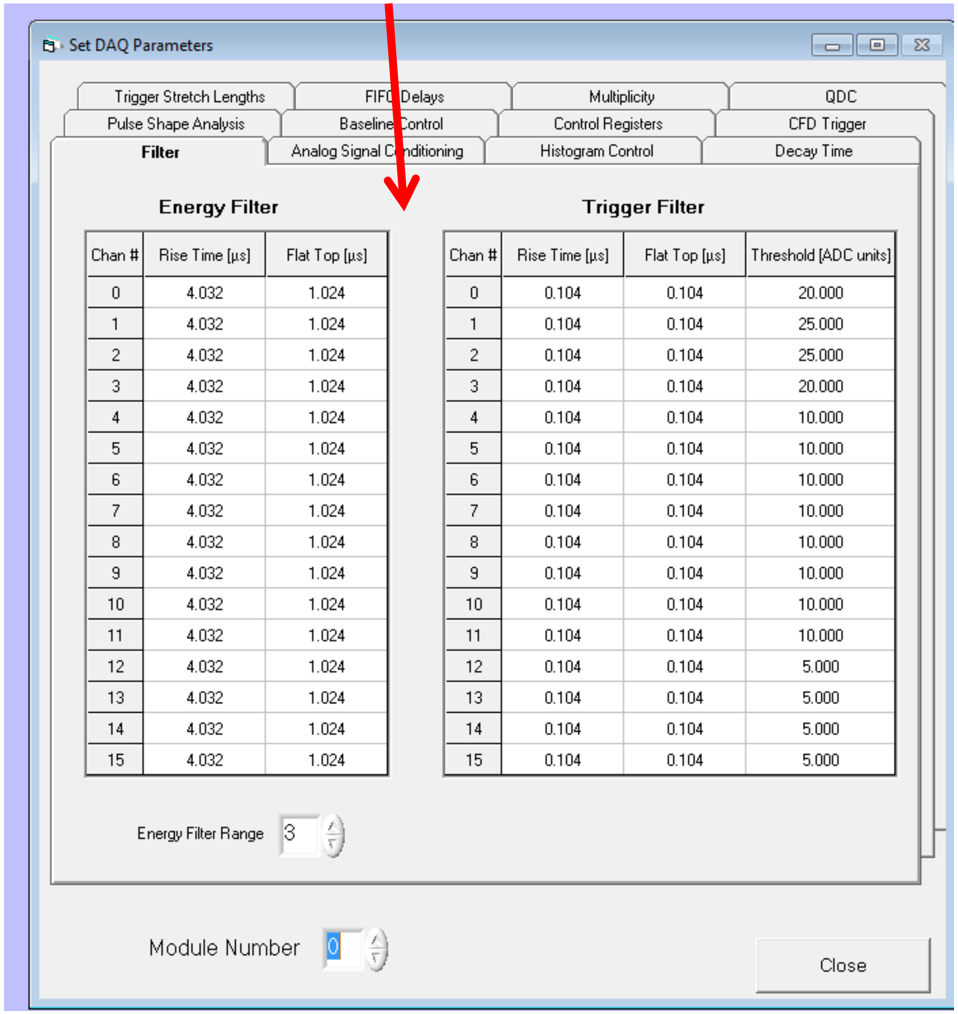
output of slow filter applied on the pulse

measure of energy ← amplitude

Settings thru PIXIE GUI

delays, widths, multiplicity

slow & fast filter

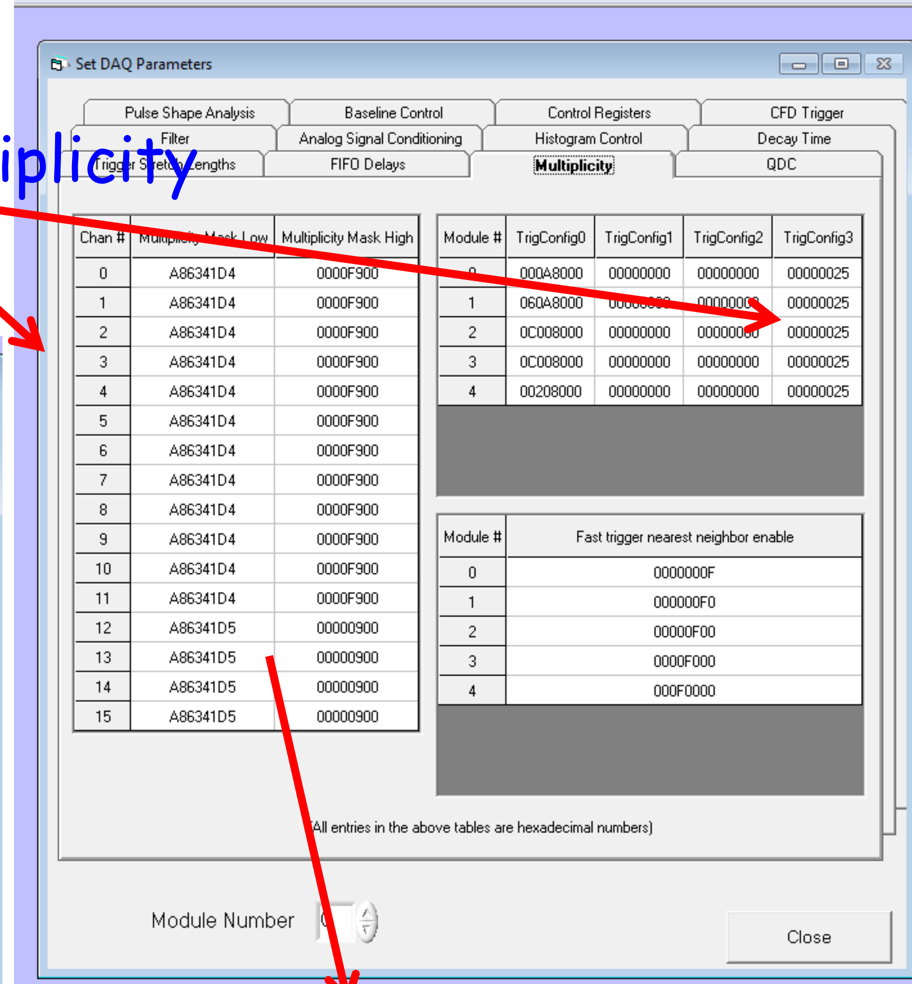


Energy Filter

Chan #	Rise Time [µs]	Flat Top [µs]
0	4.032	1.024
1	4.032	1.024
2	4.032	1.024
3	4.032	1.024
4	4.032	1.024
5	4.032	1.024
6	4.032	1.024
7	4.032	1.024
8	4.032	1.024
9	4.032	1.024
10	4.032	1.024
11	4.032	1.024
12	4.032	1.024
13	4.032	1.024
14	4.032	1.024
15	4.032	1.024

Trigger Filter

Chan #	Rise Time [µs]	Flat Top [µs]	Threshold [ADC units]
0	0.104	0.104	20.000
1	0.104	0.104	25.000
2	0.104	0.104	25.000
3	0.104	0.104	20.000
4	0.104	0.104	10.000
5	0.104	0.104	10.000
6	0.104	0.104	10.000
7	0.104	0.104	10.000
8	0.104	0.104	10.000
9	0.104	0.104	10.000
10	0.104	0.104	10.000
11	0.104	0.104	10.000
12	0.104	0.104	5.000
13	0.104	0.104	5.000
14	0.104	0.104	5.000
15	0.104	0.104	5.000



Chan #	Multiplicity Mask Low	Multiplicity Mask High
0	A86341D4	0000F900
1	A86341D4	0000F900
2	A86341D4	0000F900
3	A86341D4	0000F900
4	A86341D4	0000F900
5	A86341D4	0000F900
6	A86341D4	0000F900
7	A86341D4	0000F900
8	A86341D4	0000F900
9	A86341D4	0000F900
10	A86341D4	0000F900
11	A86341D4	0000F900
12	A86341D5	00000900
13	A86341D5	00000900
14	A86341D5	00000900
15	A86341D5	00000900

Module #	TrigConfig0	TrigConfig1	TrigConfig2	TrigConfig3
0	000A8000	00000000	00000000	00000025
1	060A8000	00000000	00000000	00000025
2	0C008000	00000000	00000000	00000025
3	0C008000	00000000	00000000	00000025
4	00208000	00000000	00000000	00000025

Module #	Fast trigger nearest neighbor enable
0	0000000F
1	000000F0
2	00000F00
3	0000F000
4	000F0000

32-bit words encoding width & delays of HPGe and ACS signals

goodbye !

Data Format

Four 32-bit words per parameter (crystal) recorded

Parameter ID

Index	Data						Description
0	[31]	[30:17]	[16:12]	[11:8]	[7:4]	[3:0]	**Bits [3:0]** – channel number; **bits [7:4]** – PXI slot number; **bits [11:8]** – PXI crate number; **bits [16:12]** – header length; **bits [30:17]** – event length; **bit [31]** – event finish code (0 – good event; 1 – piled-up event)
	Finish Code	Event Length	Header Length	CrateID	SlotID	Chan#	
1	[31:0]						Event time (lower 32-bit of the 48-bit timestamp) recorded by the signal processing FPGA (latched by either the local fast trigger or CFD trigger)
	EVTTIME_LO[31:0]						
2	[31]	[30]	[29:16]	[15:0]			**Bits [15:0]** – event time (upper 16-bit of the 48-bit timestamp); **bits [29:16]** – CFD fractional time × 16384 (0 if CFD trigger is not enabled); **bit [30]** – CFD forced trigger bit; **bit [31]** – CFD trigger source bit
	CFD trigger source bit	CFD forced trigger bit	CFD Fractional Time	EVTTIME_HI[15:0]			
3	[31]	[30:16]	[15:0]				**Bits [15:0]** – event energy; **bits [30:16]** – trace length (0 if no trace is recorded); **bit [31]** – trace out of range flag
	Trace Out-of-Range Flag	Trace Length	Event Energy				

Time Stamp

Energy

Data Format

Event Header (has all info of regular use in gamma-ray spectroscopy)

Index	Data	Description
0	[31] Finish Code; [30:17] Event Length; [16:12] Header Length; [11:8] CrateID; [7:4] SlotID; [3:0] Chan#	**Bits [3:0]** – channel number; **bits [7:4]** – PXI slot number; **bits [11:8]** – PXI crate number; **bits [16:12]** – header length; **bits [30:17]** – event length; **bit [31]** – event finish code (0 – good event; 1 – piled-up event)
1	[31:0] EVTTIME_LO[31:0]	Event time (lower 32-bit of the 48-bit timestamp) recorded by the signal processing FPGA (latched by either the local fast trigger or CFD trigger)
2	[31] CFD trigger source bit; [30] CFD forced trigger bit; [29:16] CFD Fractional Time; [15:0] EVTTIME_HI[15:0]	**Bits [15:0]** – event time (upper 16-bit of the 48-bit timestamp); **bits [29:16]** – CFD fractional time × 16384 (0 if CFD trigger is not enabled); **bit [30]** – CFD forced trigger bit; **bit [31]** – CFD trigger source bit
3	[31] Trace Out-of Range Flag; [30:16] Trace Length; [15:0] Event Energy	**Bits [15:0]** – event energy; **bits [30:16]** – trace length (0 if no trace is recorded); **bit [31]** – trace out of range flag

Parameter ID

Time Stamp

Trace Points

Energy

Trace Data

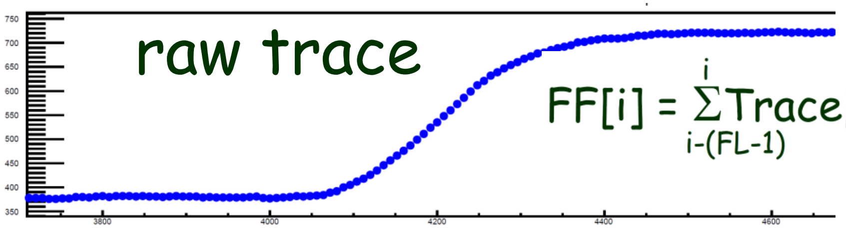
Index	Data		Description
n	Last word of event header [31:0]		Last word of event header. The event header could be 4, 6, 8, 10, 12, 14, 16 or 18 words long
n+1	ADC Data #1 [15:0]	ADC Data #0 [15:0]	Packing of ADC Data #0 and #1
n+2	ADC Data #3 [15:0]	ADC Data #2 [15:0]	Packing of ADC Data #2 and #3

PIXIE-16 User Manual, XIA LLC

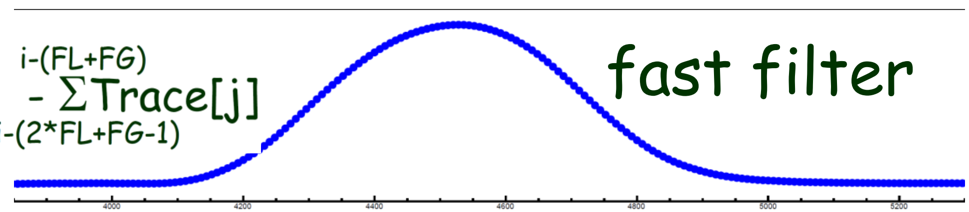
Time Stamping in the Digitizer Data

total time stamp

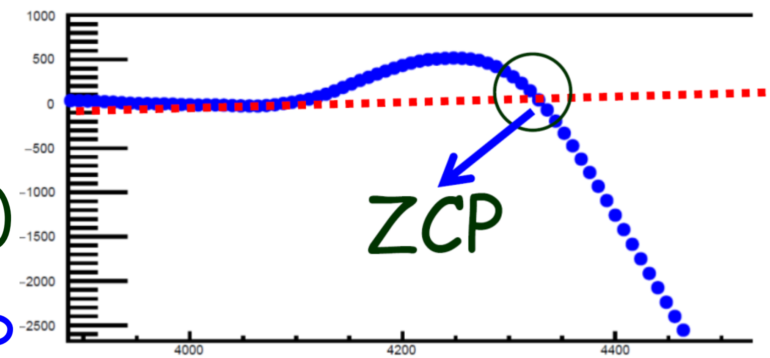
{EVTTIME_LOW[31:0] + EVTTIME_HI[15:0]*2^{32})*2 - CFD_trigger_source_bit + (CFD_Fractional_Time/16384)}* 4 ns



$$FF[i] = \sum_{i-(FL-1)}^{i} Trace[j] - \sum_{i-(2*FL+FG-1)}^{i-(FL+FG)} Trace[j]$$



$$CFD[i+D] = FF[i+D]*(1-w/8) - FF[i]$$



f = CFDOut1/(CFDOut1 + CFDOut2)

before ZCP   after ZCP

w, D: digitizer setting parameters

time stamp for each detection, CALCULATED by the sorting program & used to identify TIME CORRELATIONS between the detections ....

Outline of Data Reduction Algorithms
(Typical for Gamma Spectroscopy)

Data file read event-by-event by the data sorting program with essential knowledge of the data format.

Generate raw spectra of different parameters. Carry out calibration therefrom.

Identification of parameters fired, determination of multiplicity & timing correlation

Possible to further select events based on multiplicity, timing correlation & particular parameter

Gain scaling (matching) of energy (and timing) parameters.

Add (back) energy parameters belonging to same (composite) detector (Clover), event-by-event.

Build the 2D (matrix) / 3D (cube) array with correlated parameters, event-by-event

Data Reduction with IUCPIX
(developed by the NP Group @ UGC-DAE CSR, KC)

SIMPLIFY: refined data format with lesser disk space requirement (25-40 % economy).

MONOSORT: time sorting for individual module.

TIME MERGE: time sorting for data collected from all modules.

TIME CHECK: to confirm the time sequencing of the time merged data file.

PIXSORT: gain matching, addback and sorting into γ-γ matrix (symmetric, angle dependent, polarization, time gated). Energy and timing spectra generation. Input files for constructing the γ-γ-γ cube.

The 1 TB (!) Experiment with Digital INGA @ VECC

quest for tetrahedral symmetry, T. Bhattacharjee et al.

PHYSICAL REVIEW C **97**, 021302(R) (2018)

Rapid Communications

Spectroscopic criteria for identification of nuclear tetrahedral and octahedral symmetries: Illustration on a rare earth nucleus

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search in ^{152}Sm .... experimental signature: E3 transitions (from TD -> GSB)

E3 transitions expected to appear predominantly in singles with no coincident gamma

gamma-gamma trigger would exclude them from acquisition

entire data acquired in **SINGLES** mode

(setup of 12 CS HPGe clovers)

DATA VOLUME ~ **1 TB**

(Analysis is currently in progress)

Outlook

towards application of trace data in LEARNING tracking algorithms

setup: 16-segmented HPGe clover (G. Mukherjee et al. @ VECC)

Digital DAQ (UGC-DAE CSR, KC): acquire data with trace (of individual segments) acquisition enabled

Plan: correlate detection of a (full) energy in a crystal with the segment(s) of detection -> distinguish between the PULSE SHAPES in different segment(s)

Gratitude, for Your Kind Audience

Gratitude

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INGA Collaboration & Local Working Groups for

Digital INGA @ VECC

(Dr. C. Bhattacharya, Dr. G. Mukherjee, Dr. S. Bhattacharyya et al.)

The staff members at the

VECC Cyclotron, the Health Physics Unit and the Target Laboratory