The Abdus Salam International Centre for Theoretical Physics

2456-2

Joint ICTP-IAEA Workshop on Advances in Digital Spectroscopy

6 - 10 May 2013

Analogue - Digital

R. Grzywacz
Univerity of Tennessee
USA

Digital Signal Processing in Nuclear Experiment

Robert Grzywacz

University of Tennessee

Oak Ridge National Laboratory

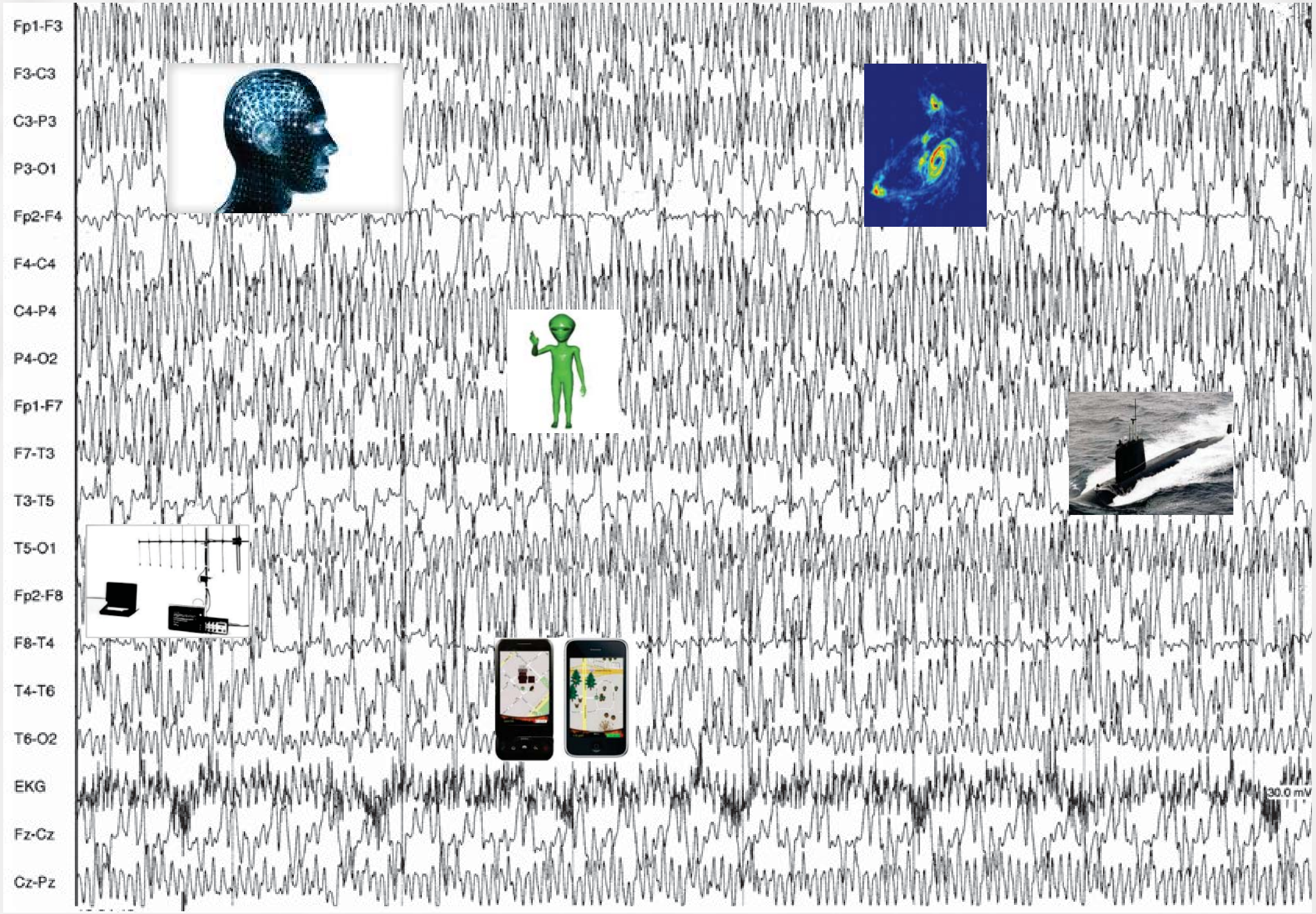
1. Why digital ?
2. Why the pulse shape matters.
3. The essential components of the DSP system.
4. Applications.

Digital signal processing

Signal is processed with numerical algorithms operating on its discrete represention.

The typical DSP problem

DIGITAL SIGNAL PROCESSING



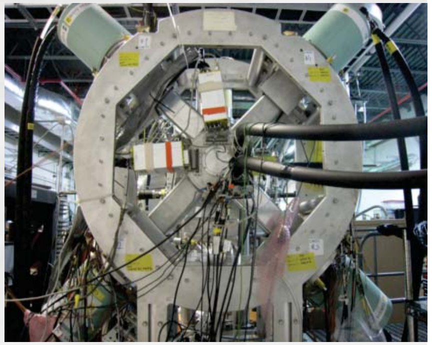
from “Laptop artifact during electroencephalography”

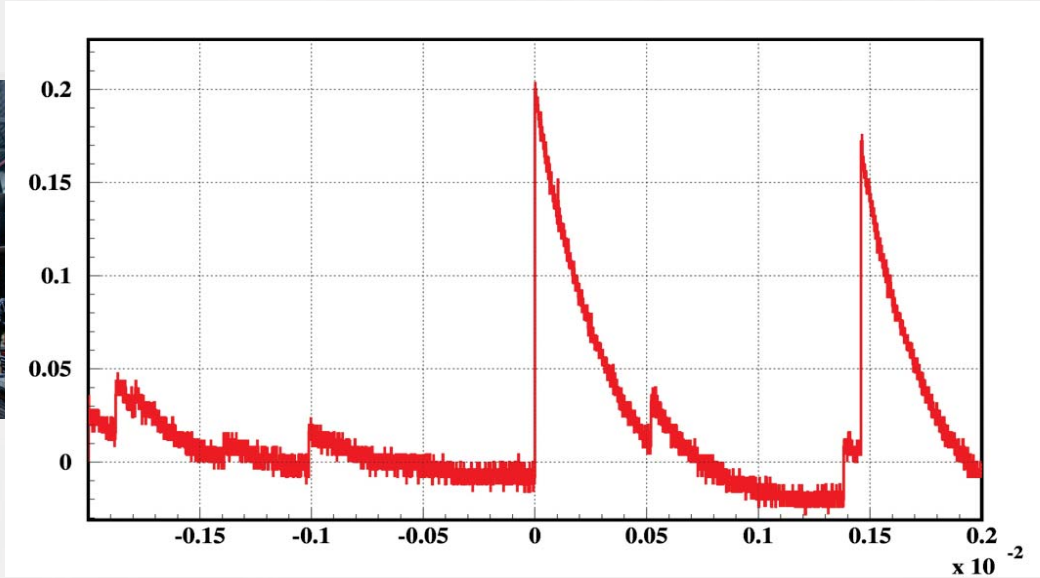
The digital magic

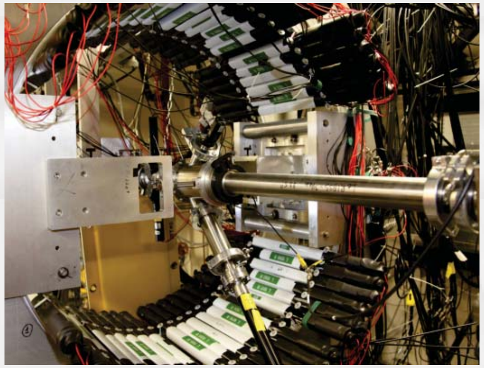
- Signals exist as digital data streams
- Digital information can be stored and retrieved without losses
- Single data stream can be multiplied and each stream processed independently
- Correlations between separate data streams can be made on arbitrary time scale
- Decisions can be made with a preferred, user defined, numerical algorithm

Typical nuclear physics measurement

DIGITAL PULSE PROCESSING







Measure time and amplitudes of individual PULSES

- time scales 100 ps – 100 us
- channel count (1-1000)
- event rate (mHz-MHz)
- pulse shape information (Mhz-GHz)
- high resolution

The "old school" slow-fast coincidence system

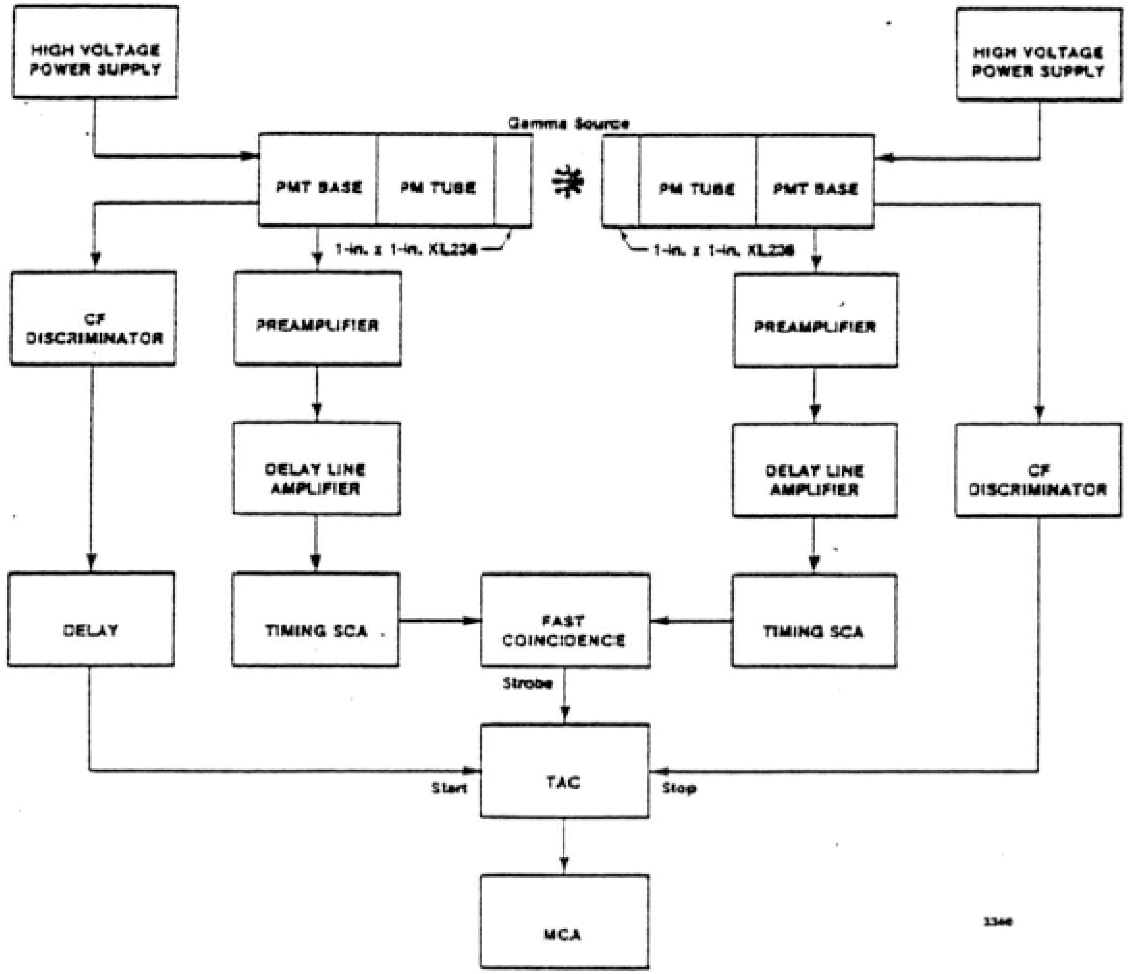
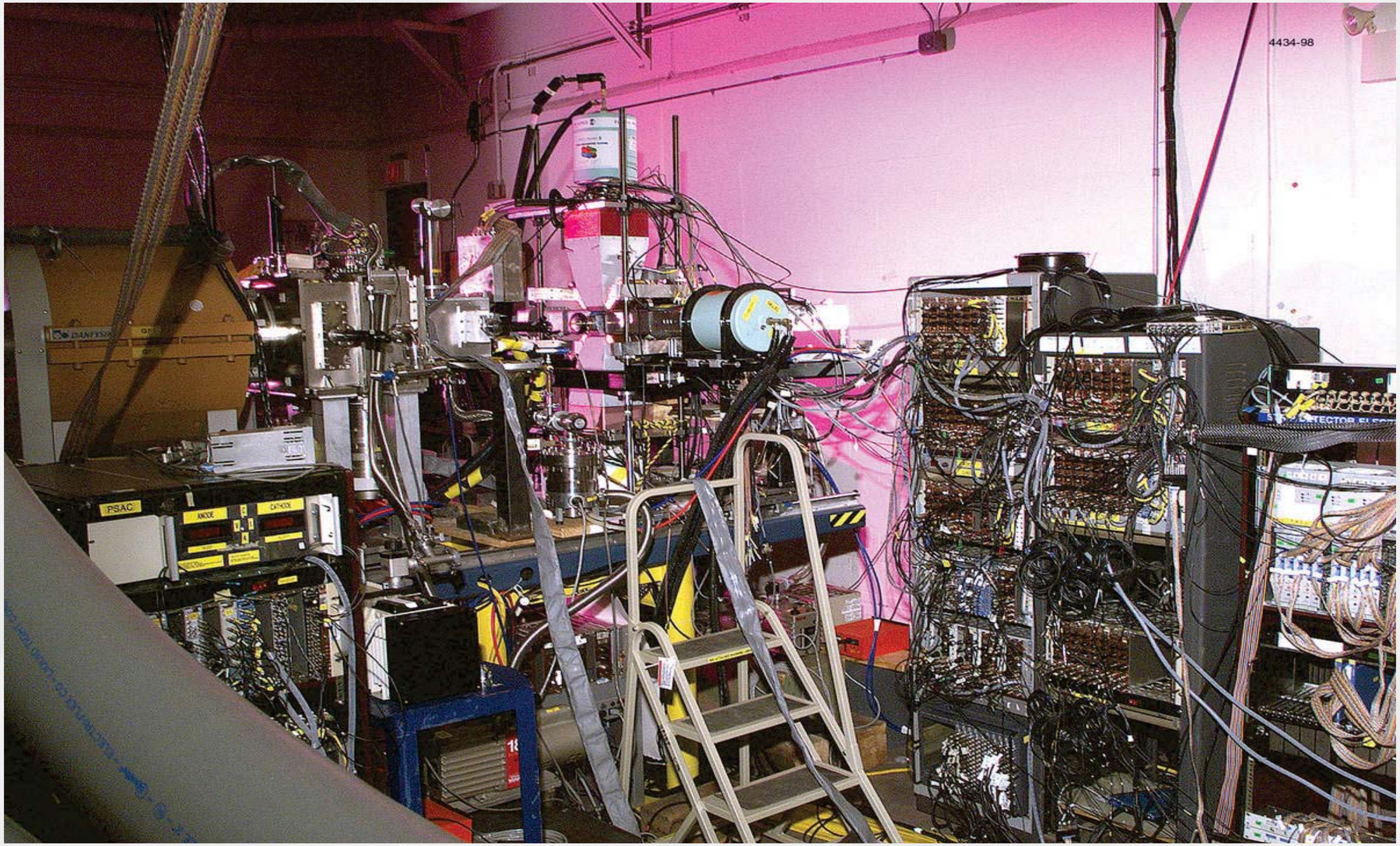


Fig 12. Typical Fast/Slow Timing System for Gamma-Gamma Coincidence Measurements with Scintillators and Photomultiplier Tubes.

It can get complicated ...

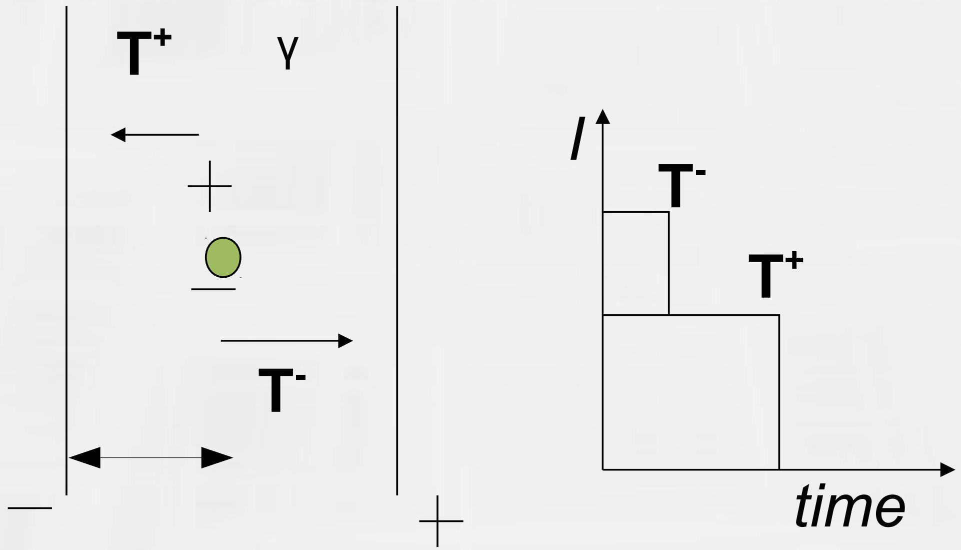


Answers: ASIC+FPGA
or DSP !

From interaction to electric signal

Pulse shape dependence on position in Si(Li) detector (constant electric field)
Drift of the charge inside the detector induces image charges.

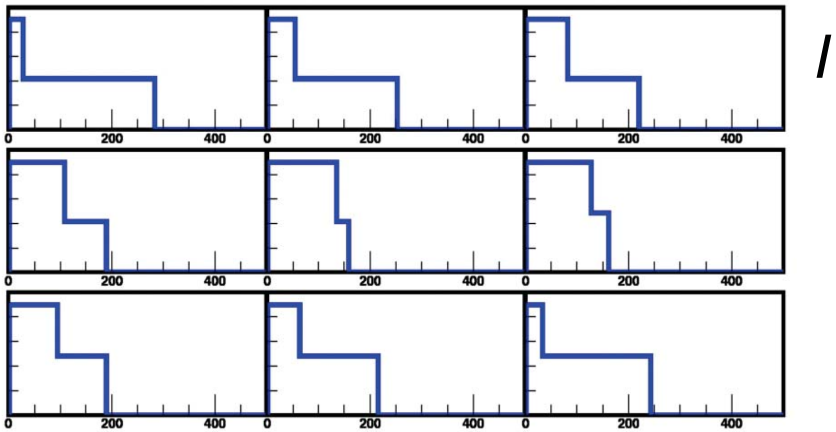
charge drift velocity, location of the interaction, electric field

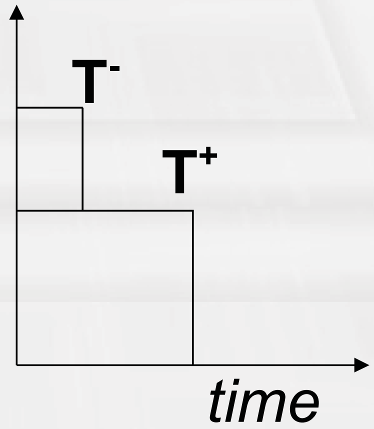


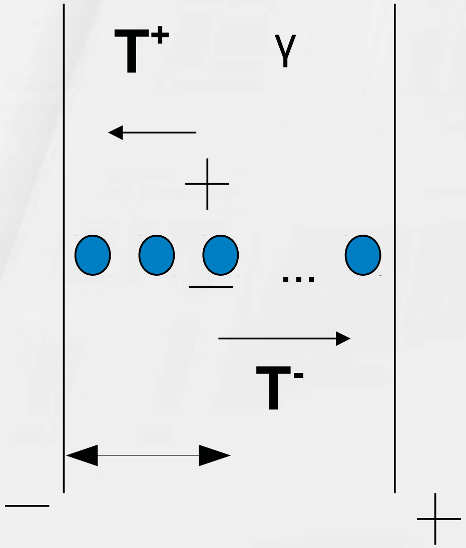
Nucl. Instr. Meth. Volume 22, March 1963, Pages 189-200
Particle identification by pulse shape discrimination in the p-i-n type semiconductor detector
C.A.J. Ammerlaan, R.F. Rumphorst and L.A.Ch. Koerts
Z. He, "Review of the Shockley-Ramo theorem and its application in semiconductor gamma-ray detectors", Nucl. Inst. & Meth. A, vol. 463, pp. 250-267, 2001.

Induced signals for different locations of the interactions

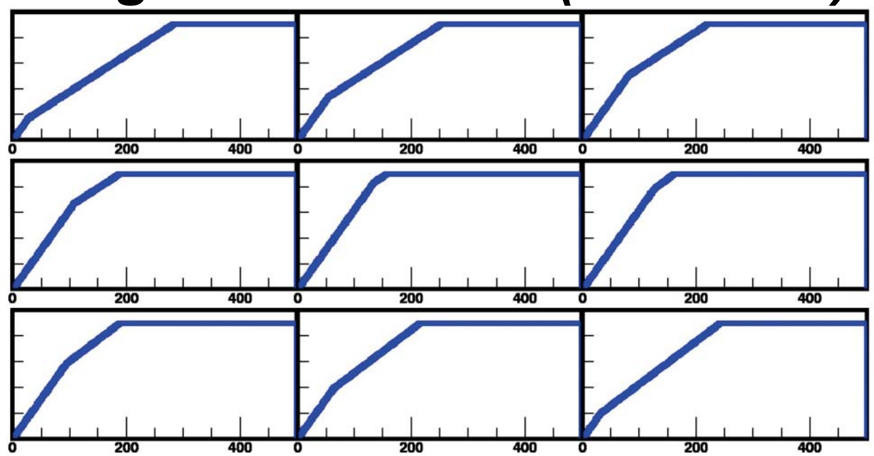
Induced current





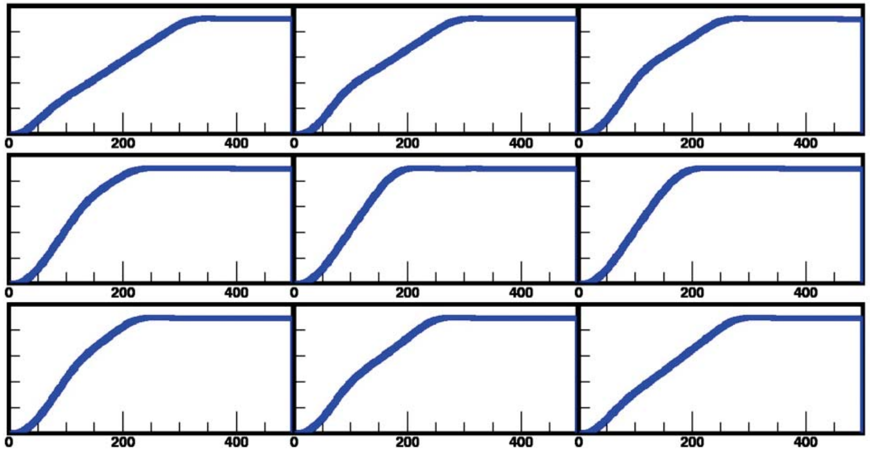


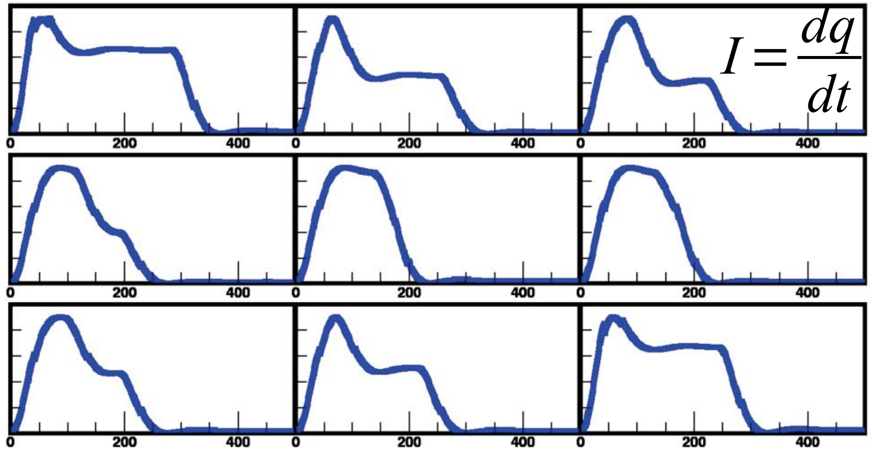
Integrated current (idealised)



Preamplifier response and sampling

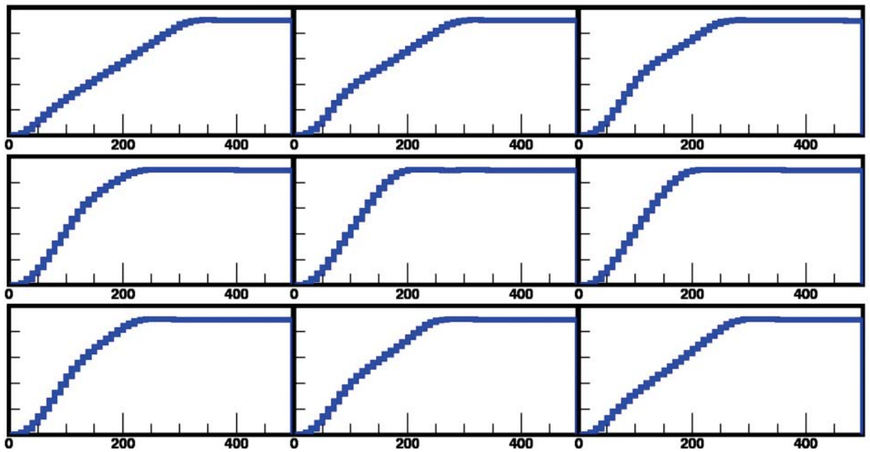
Integrated current (preamplifier)

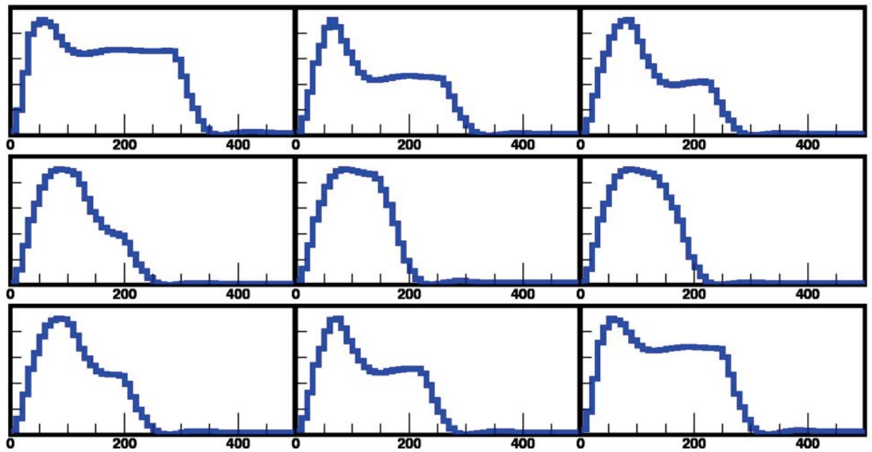




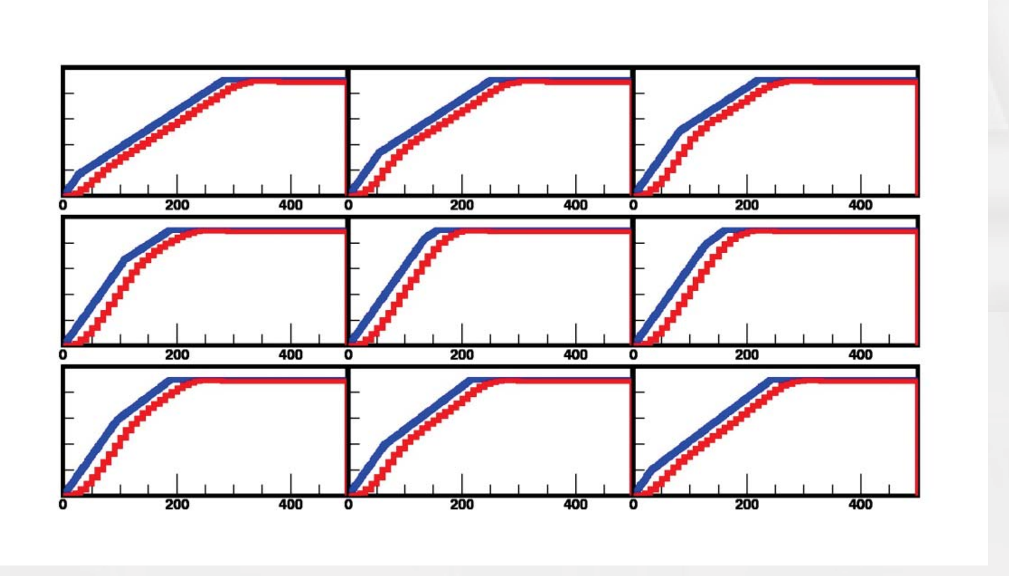
$$I = \frac{dq}{dt}$$

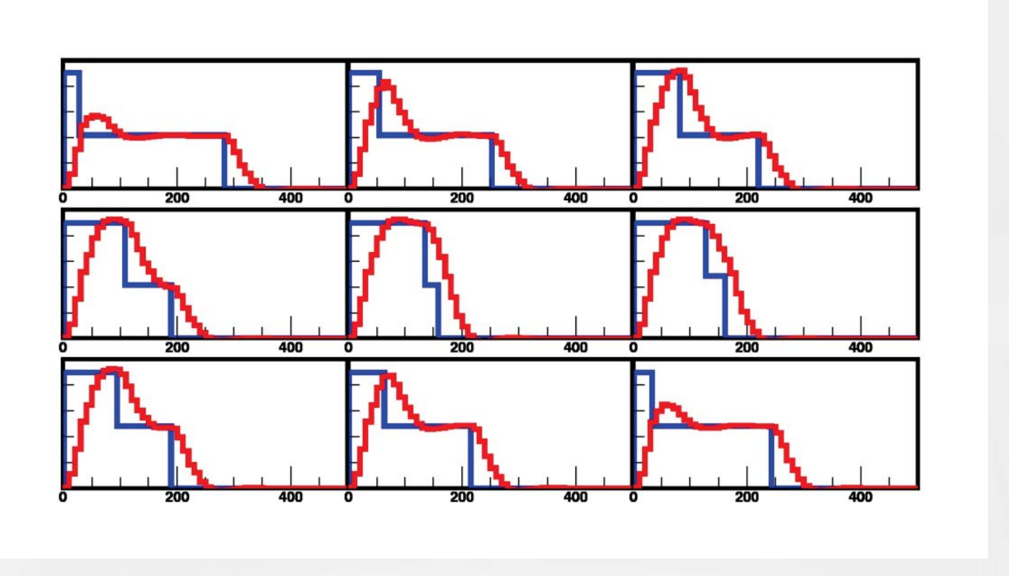
$$I = \frac{\Delta q}{\Delta t}$$





Degradation of signal features





The essential components of the real time DSP system

60 MB/s/channel

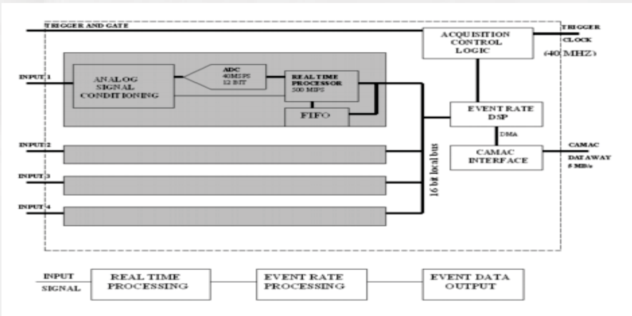
total system load 5.8 GB/s

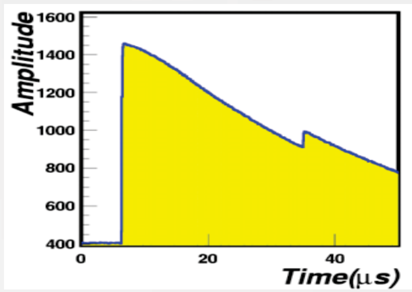
Analog

Digital

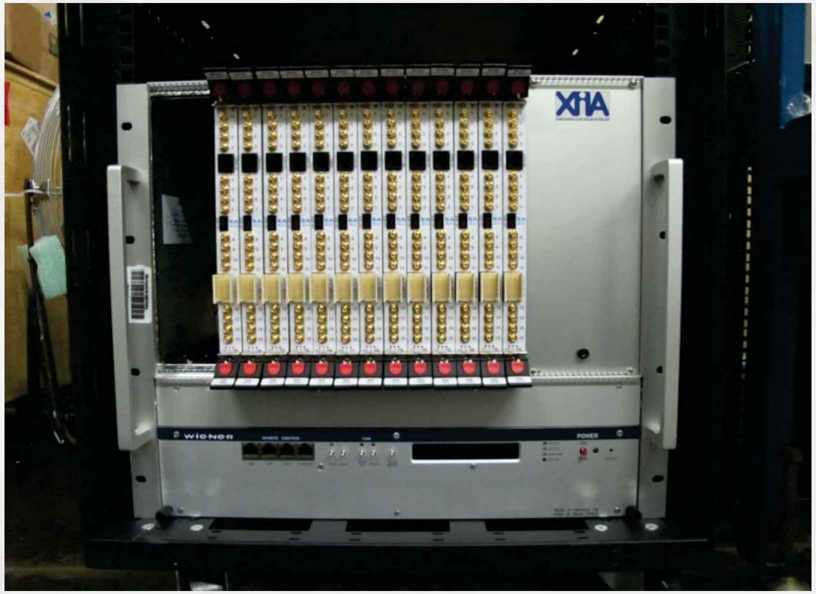
sampling ADC
(40 MHz-100 MHz)

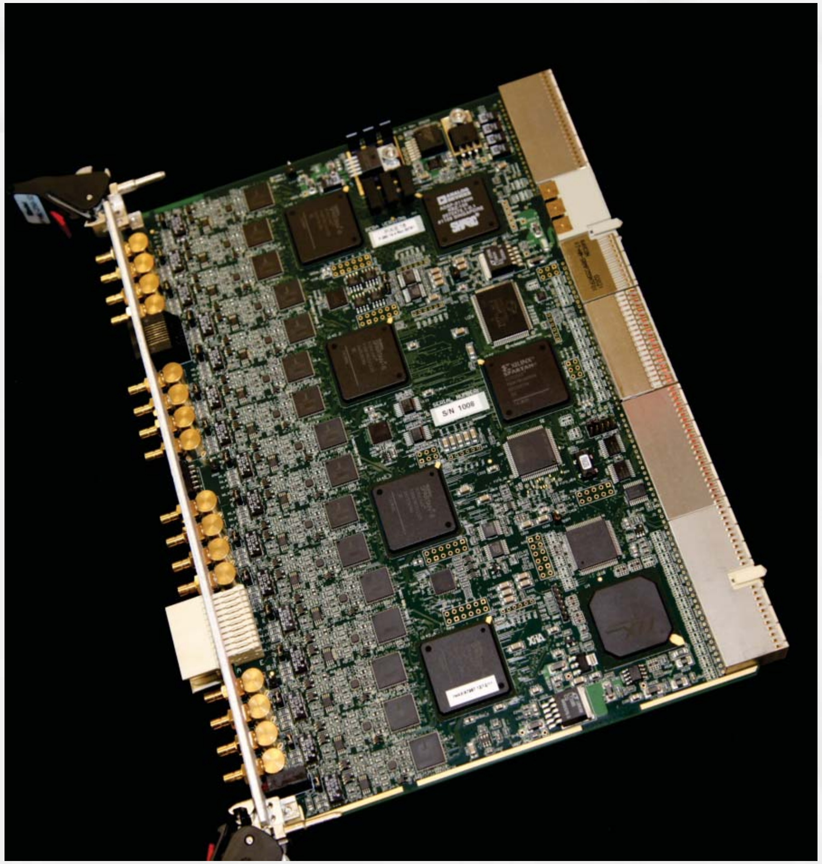
Selective
triggering
0.3Mb/s





An example of digital system





The sampling theorem

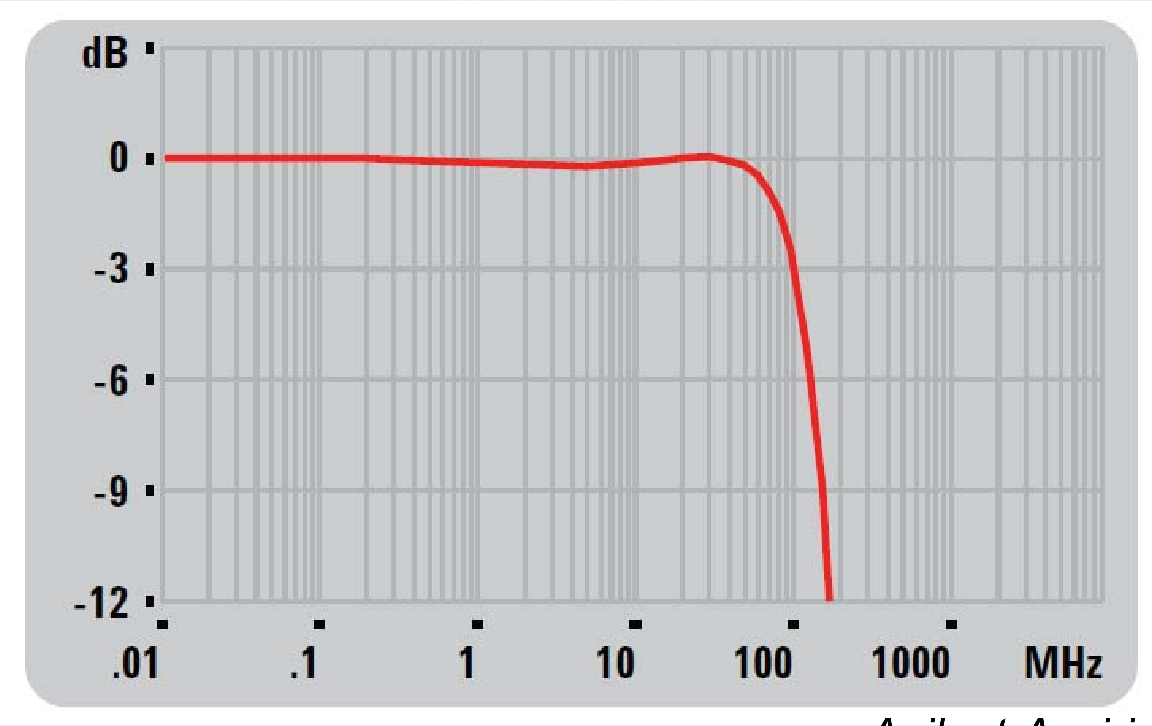
The Nyquist-Shannon sampling theorem:

If the highest frequency component in a signal is f_{max}, then the signal should be sampled at the rate of at least $2*f_{max}$ for the samples to describe the signal completely.

(E.C. Ifeachor, B.W. Jarvis Digital Signal Processing)

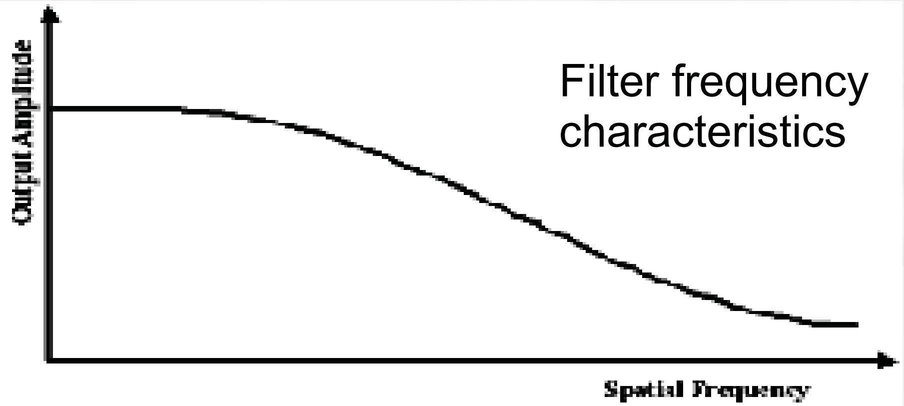
Before digitizing the pulse ...

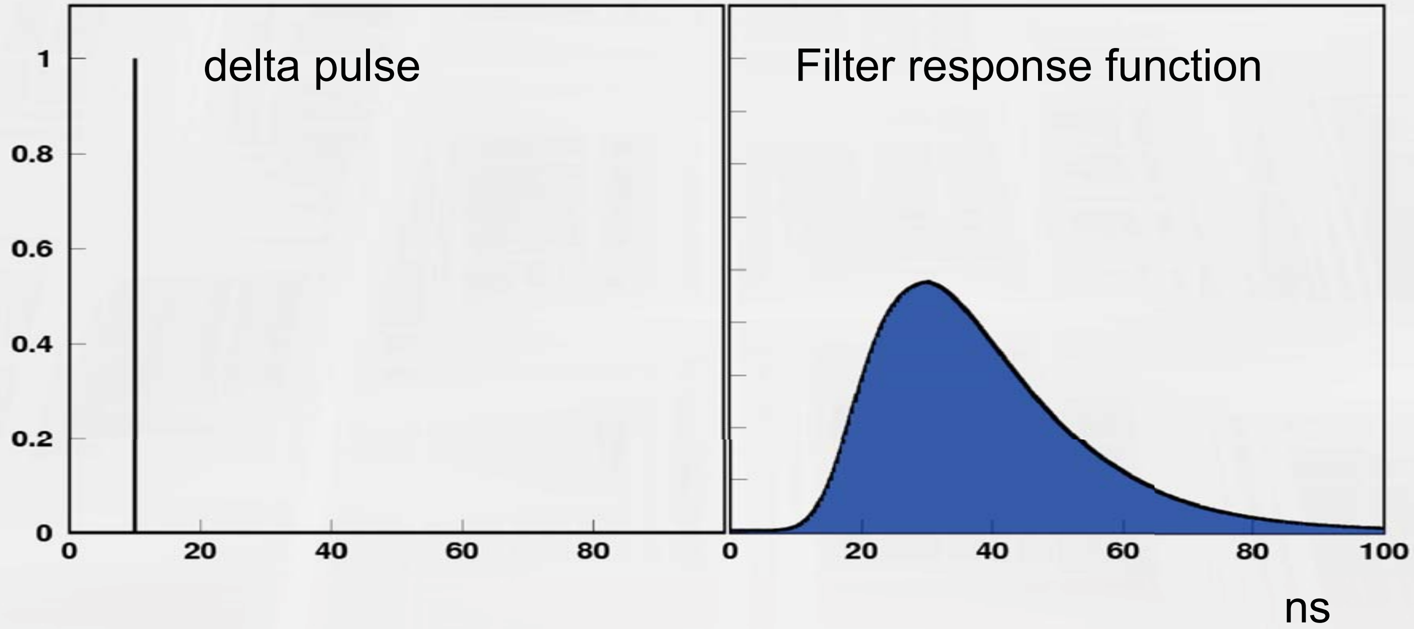
“Analog” Low Pass filter



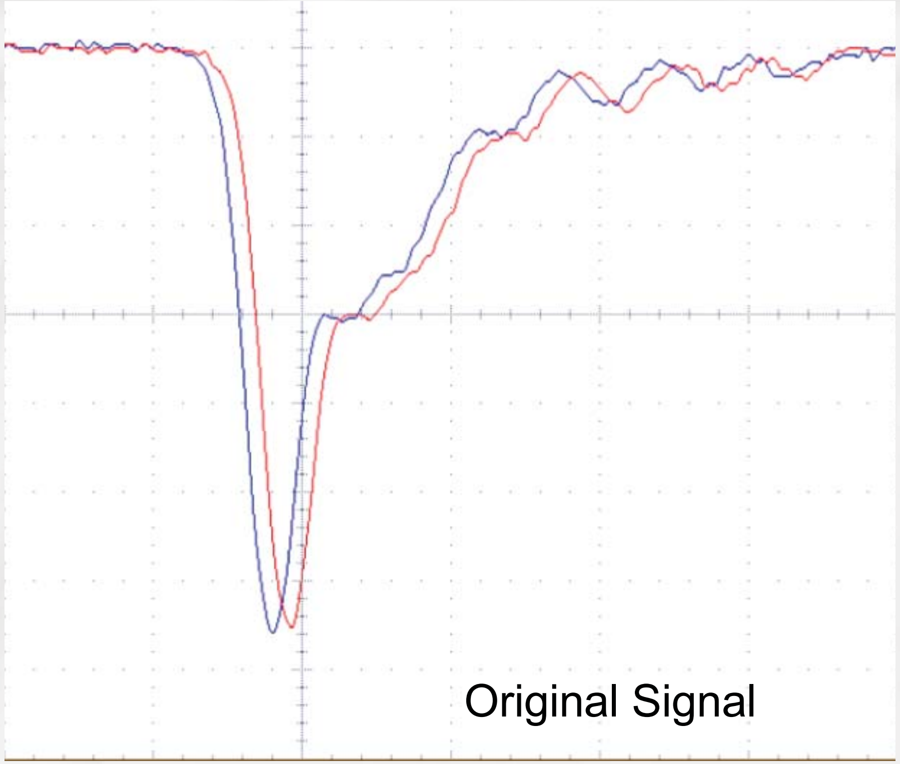
Agilent-Acqiris

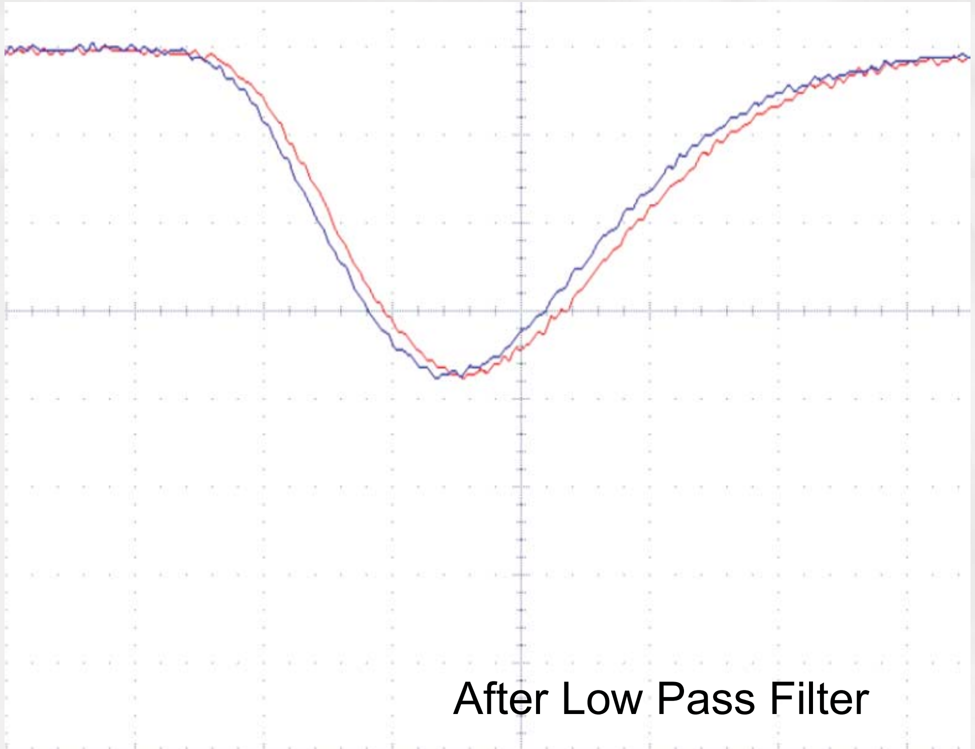
Nyquist filter transformation





Effects of Low Pass Filter [Nyquist]





The basics elements

Map the signal to ADC range !

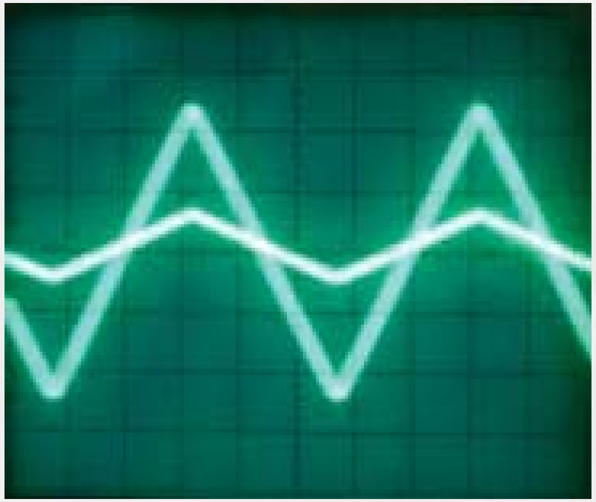
- Adjust offset

  DC+signal

- Adjust gain (attenuation or amplification)

  fixed gain

  variable gain



Sampling ADCs

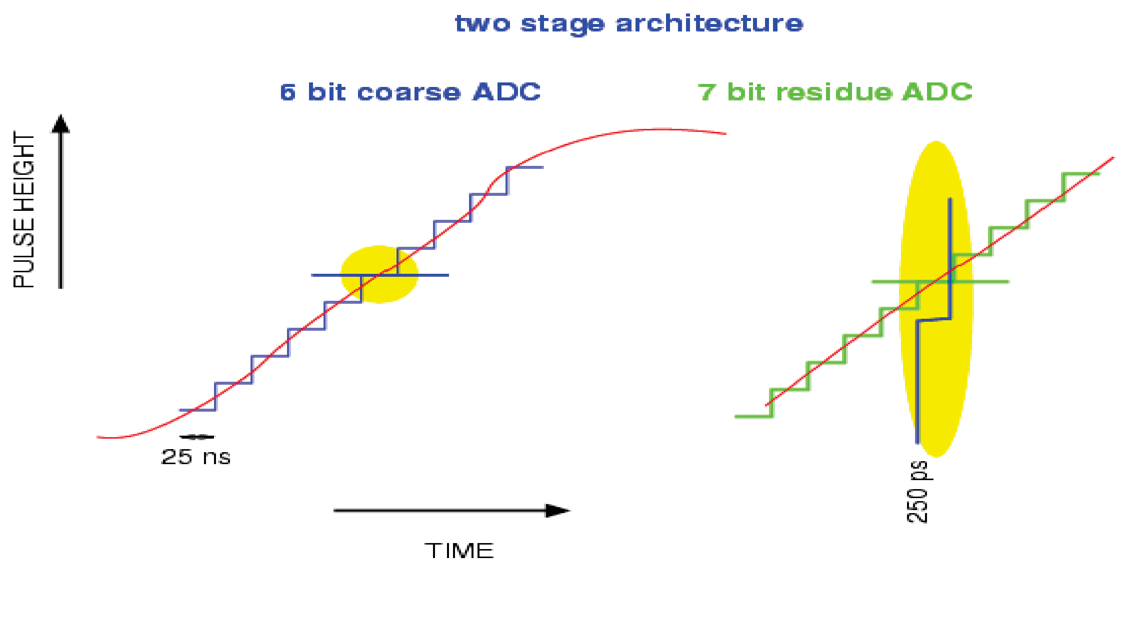
ANALOG SYSTEMS:
peak sensing: Wilkinson ADC

DSP:
flash ADC – bank of 2^{N-1} comparators
switched capacitor arrays
(fast – GHz, but low bit resolution)
pipeline ADC – two step process with subranging ADCs
(high bit resolution, ~100MHz, small power consumption)

- Bit resolution (8-14)
- Dynamic range (~2V)
- Digitization speed (40MSPS-1GSPS)
- Non-linearities

How does sampling ADC work

High bit resolution pipeline ADC



TIMING DIAGRAM

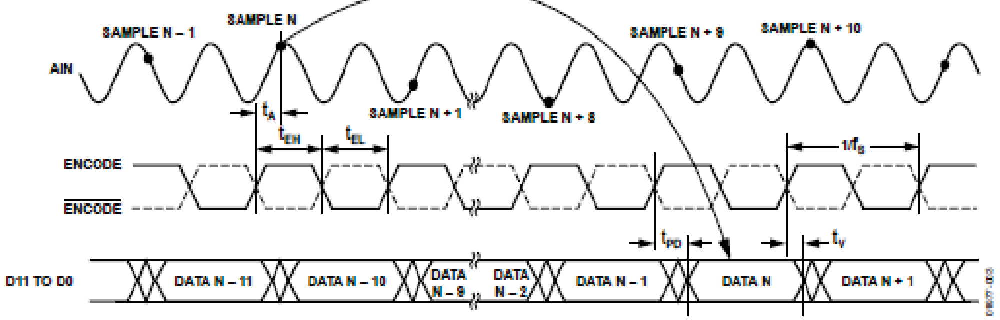


Figure 2. Timing Diagram

FUNCTIONAL BLOCK DIAGRAM

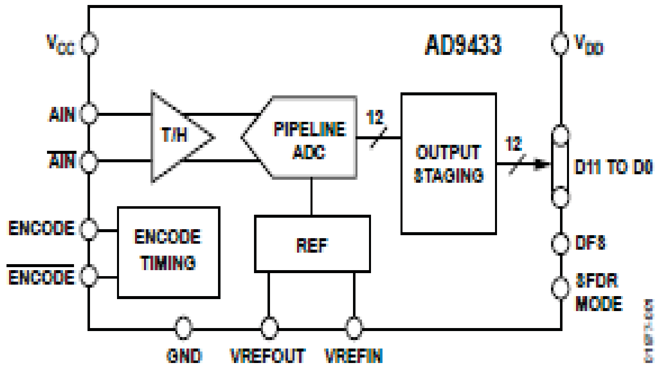


Figure 1.

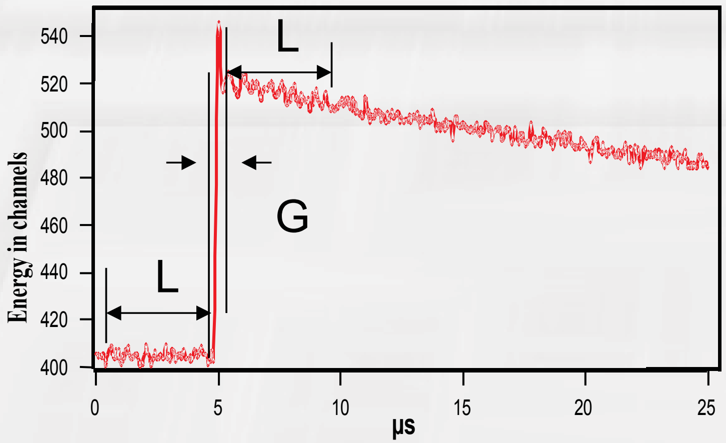
Real Time Signal Processing

1 Gigahertz 10 bit ADC
continous mode:
$10*10^9$=12.5 GB/s
Data has to be triggered and filtered
"REAL TIME"

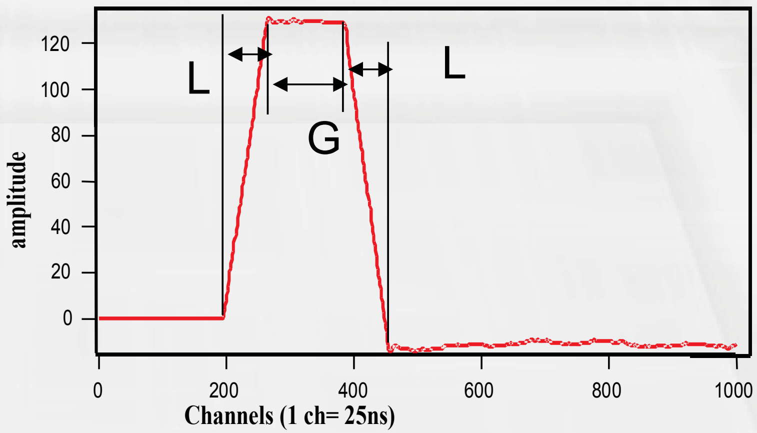
"On-board" vs "post-processing"

Fast Digital Filters

Averaging filter (Trapezoidal filter)



Detector pulse

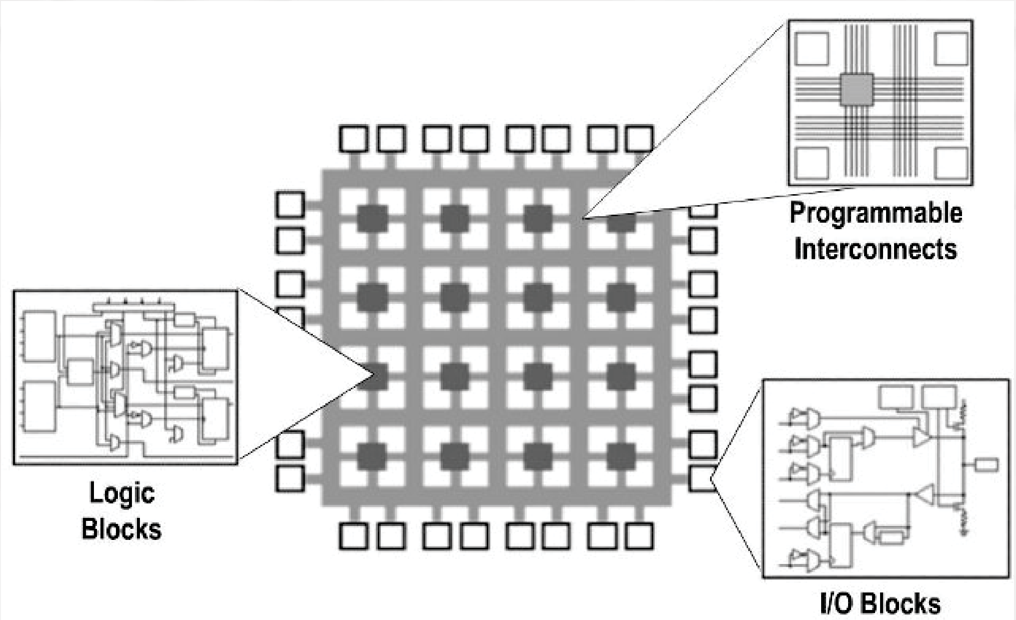


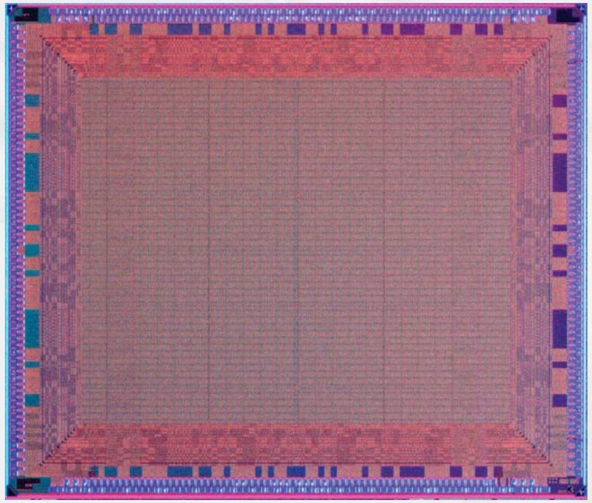
Transformed pulse

Simple to implement in “real-time” system
Energy and “time-over-threshold” operations

Field Programmable Gate Array

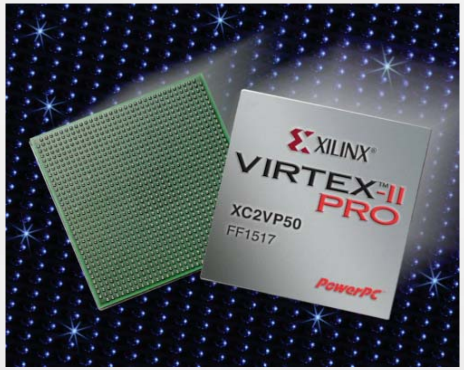
Enables to program algorithm on chip !





Spartan 3A family has devices

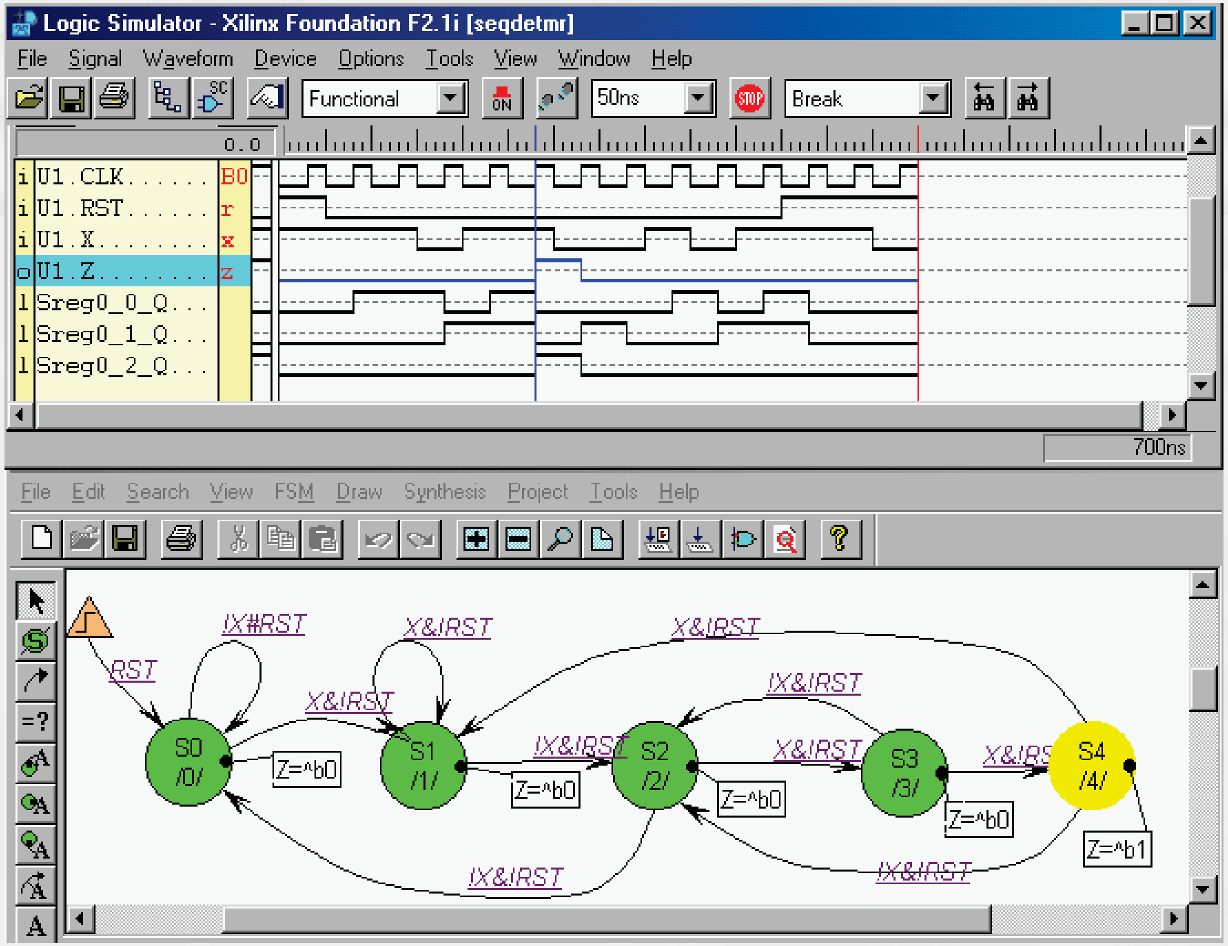
from 176 to 5968 CLBs.



very fast,

parallel (multiple data streams)

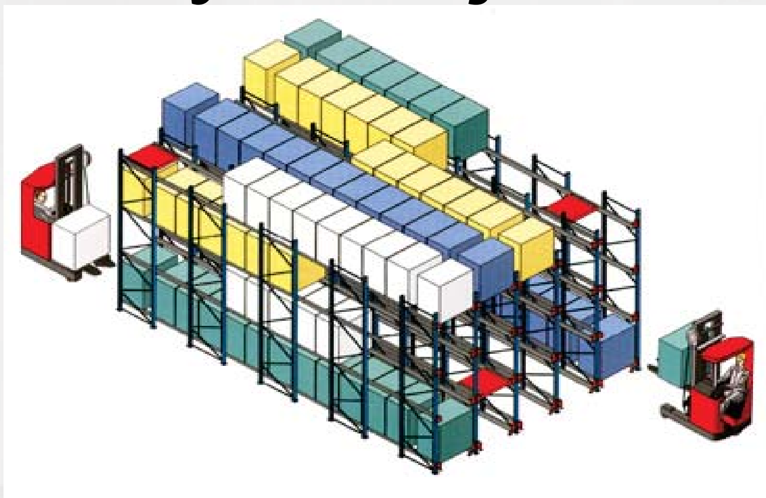
FPGA programming

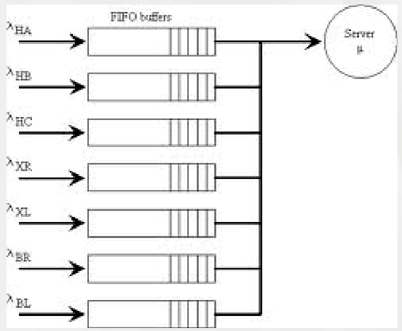


Data buffering:
FIFO as The Time-machine

- Digital information can be stored and retrieved without losses !
- Single data stream can be multiplied and each stream processed independently
- Correlations between separate data streams can be made on arbitrary time scale (also backwards in time)

Causality is a joke !





Data Readout

Digital systems are usually associated with large data streams !

Typical experiment:

500 Hz of 1 us long traces (12 bit) at 100 MSPS

~ 100 kB/second/channel = 360 MB/hour/channel

CAMAC, VME, PXI/PCI, USB

Gb-ETHERNET, INFINIBAND

Redundant Data Storage

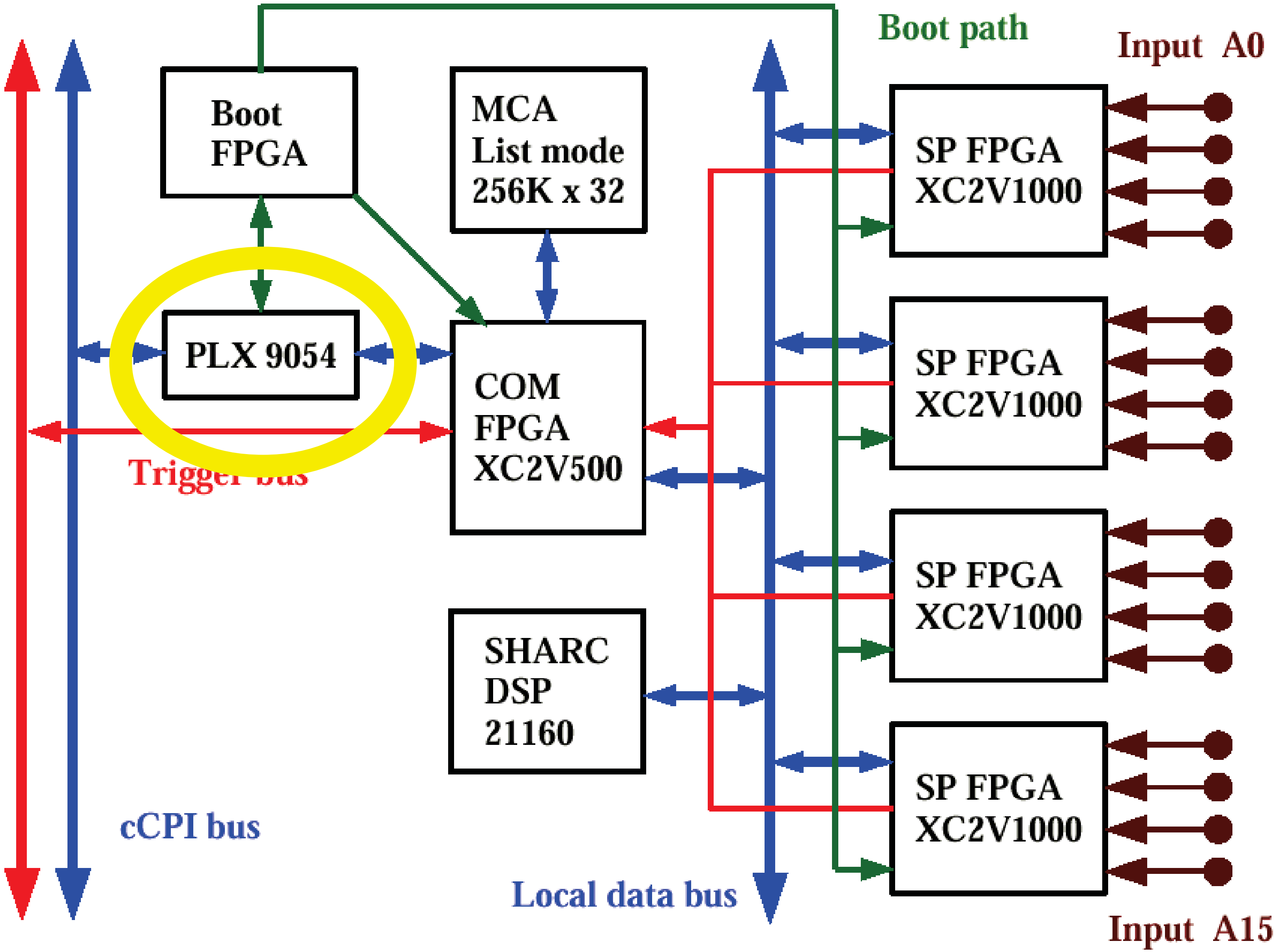
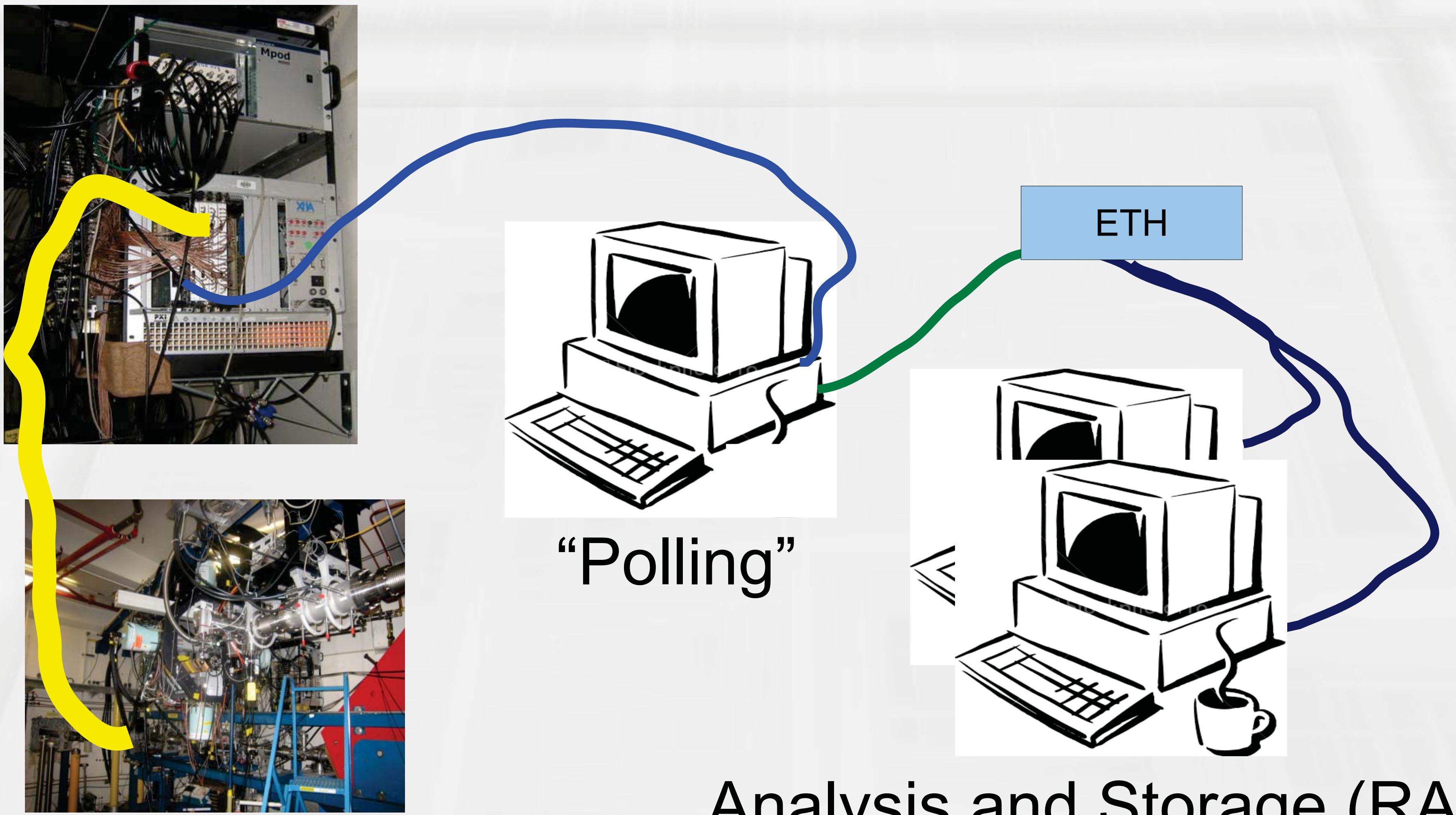


Figure 1: Block schematic of the Pixie-16 spectrometer card. The 16 input sections A0 through A15 contain the digital offset control as well as a 12-bit, 100MSPS ADC for each input channel.

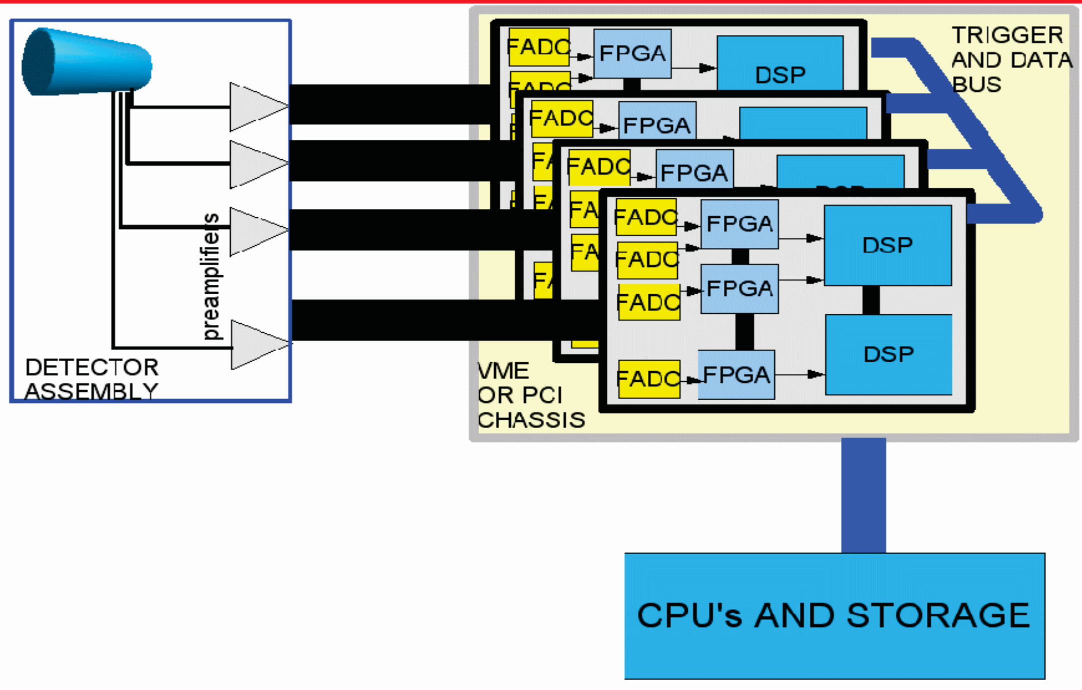
“DGF/PIXIE MODEL”

Detector System -> DSPBoard->PCI BRIGE->PC-> GIGABIT->PC



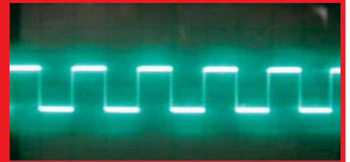
Analysis and Storage (RAID)

Time stamping and event builder



Each channel produces individually time stamped externally tiggered or self triggerd sub-events assembled into data buffers for each module

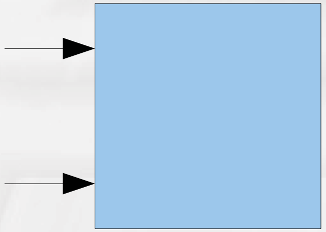
The clock synchronization



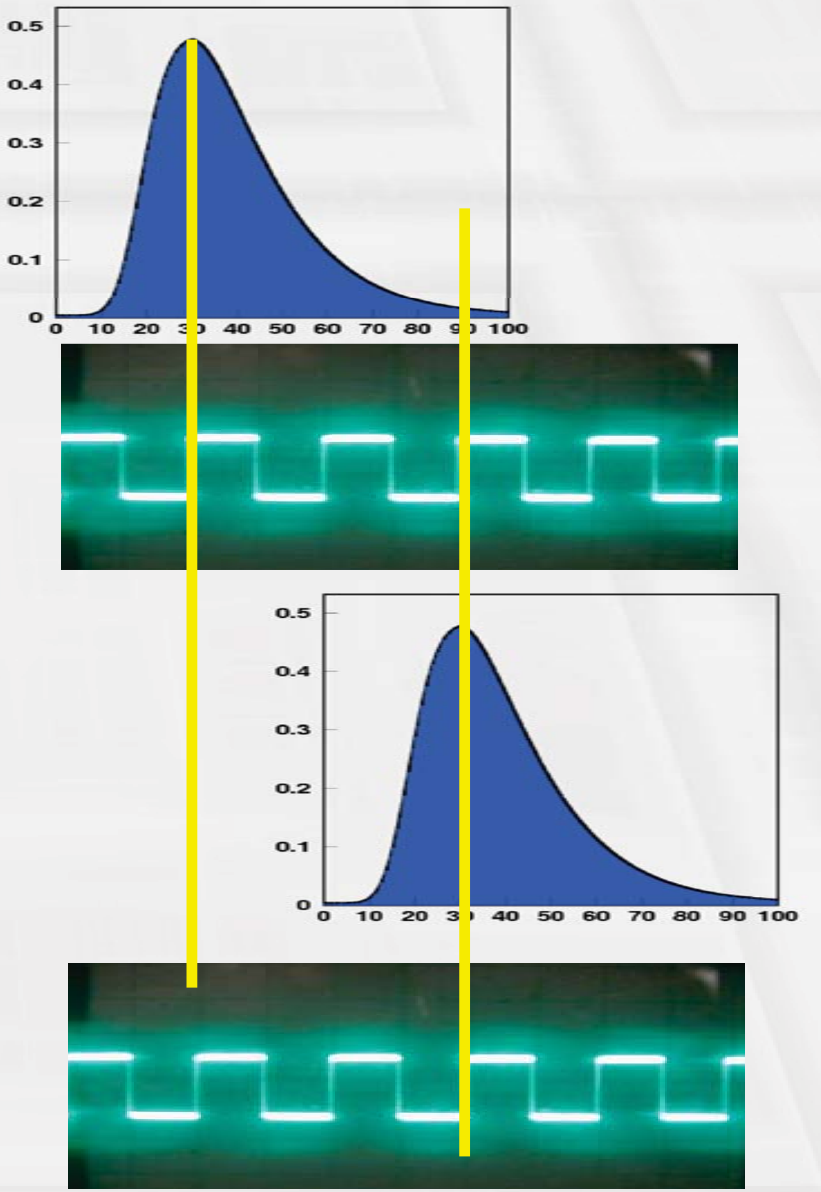
Usual analog timing

Start

Stop



T_{start}-T_{stop}



Sometimes: event time stamping

Digital system is
implicitly syncronized !
Any time correlation
can be measured
with precision only given
by the accuracy of the clock.

34404323422-34404323422=2

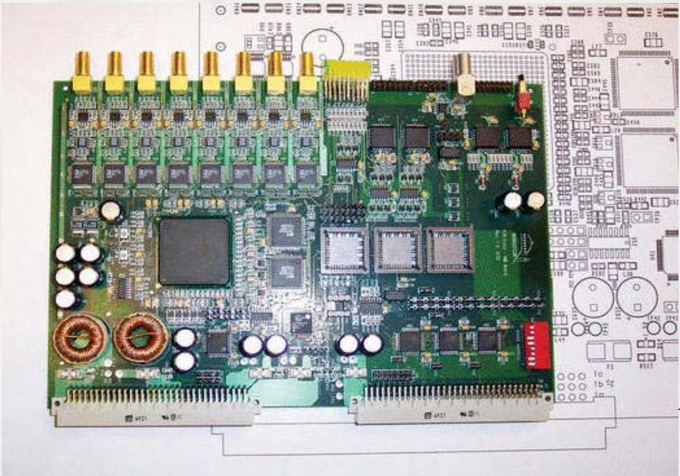
The trigger issue

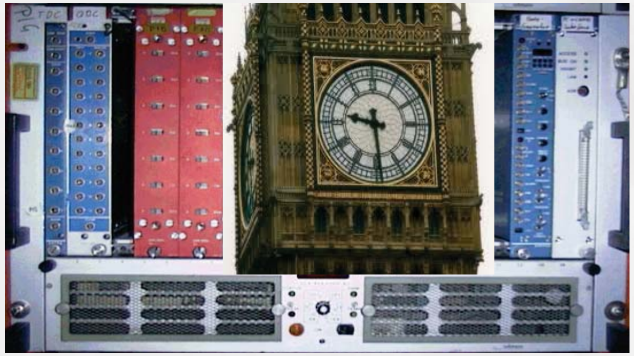
Self-trigger or external trigger

The event synchronization issues ?

How to synchronize analog and digital systems ?

1MHz clock





Event Trigger

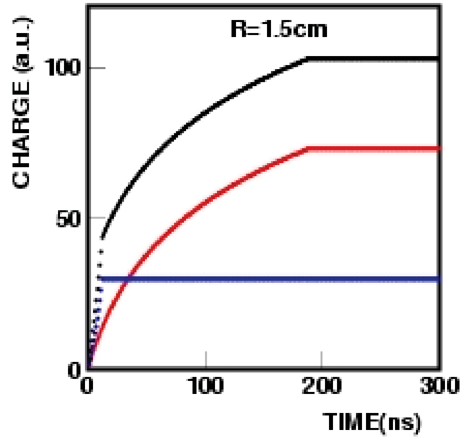
Time stamp each event

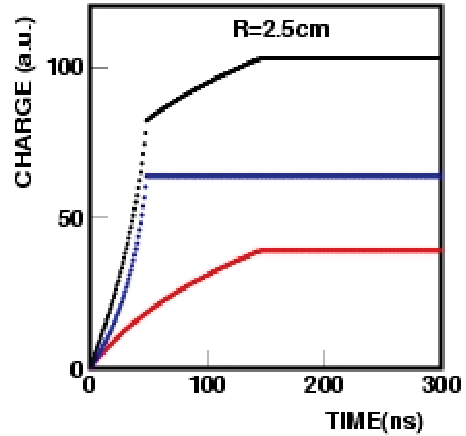
Merge data
streams
Event builder

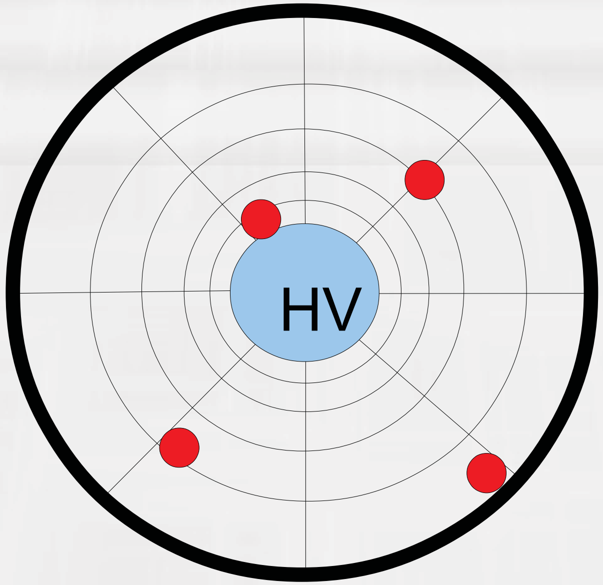
Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms
Volume 261, Issues 1-2, August 2007, Pages 1000-1004

Gamma-Ray tracking

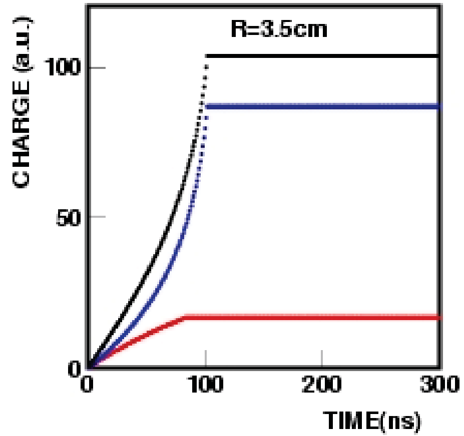
(localization of interactions in the Ge detector)

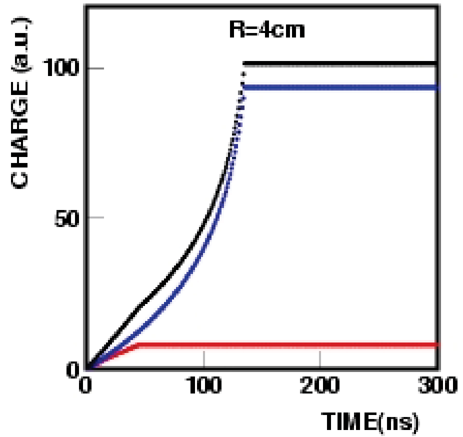




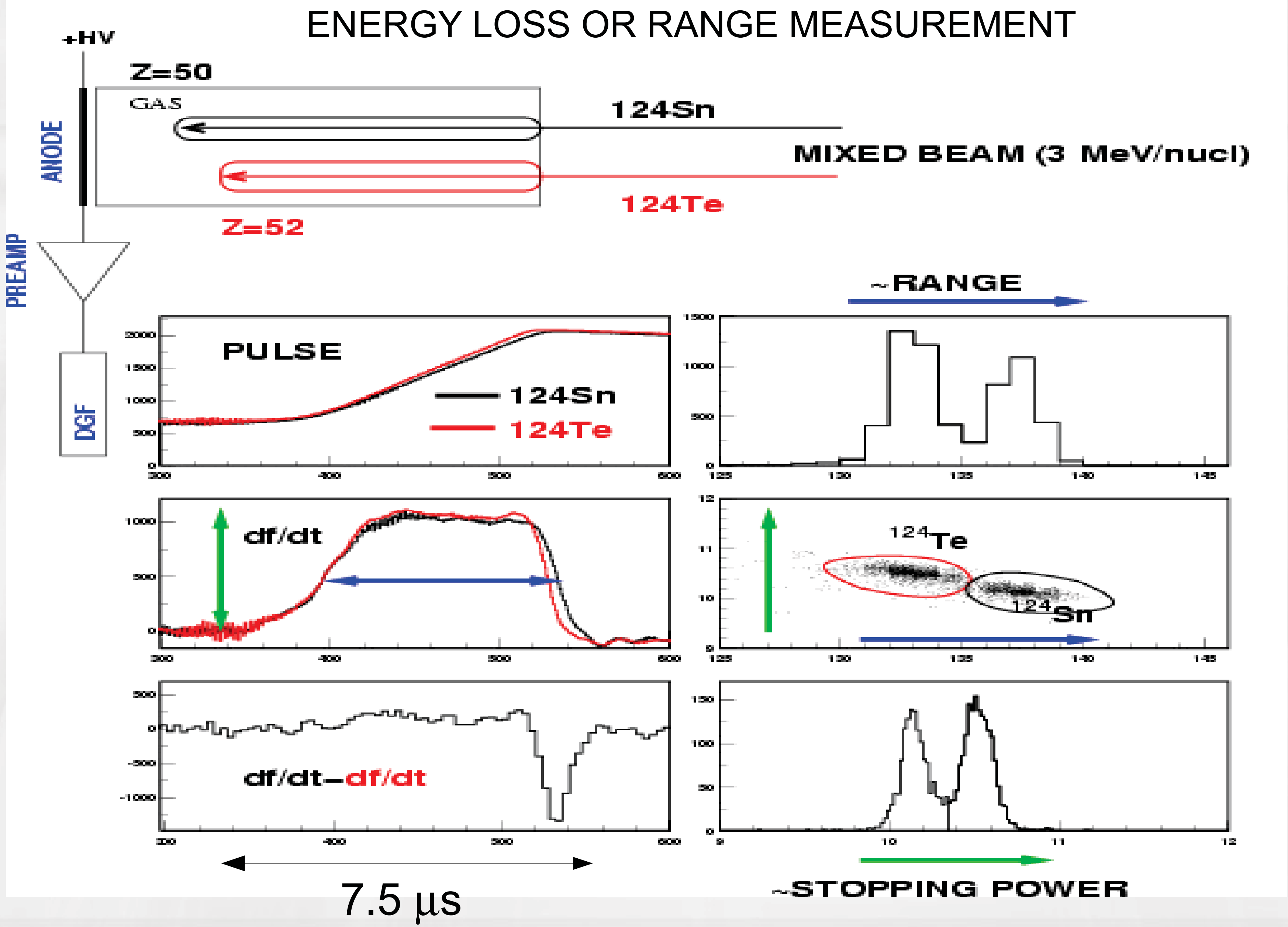


"cylindrical field"





"Bragg" detector: Z identification

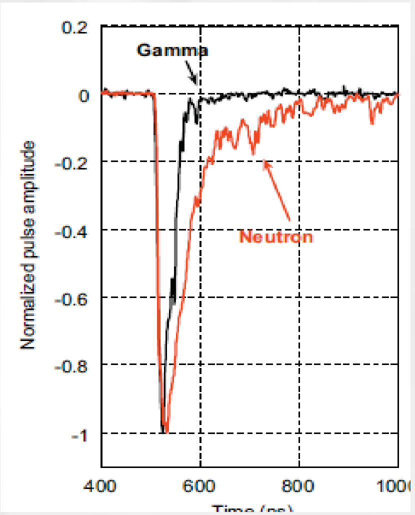


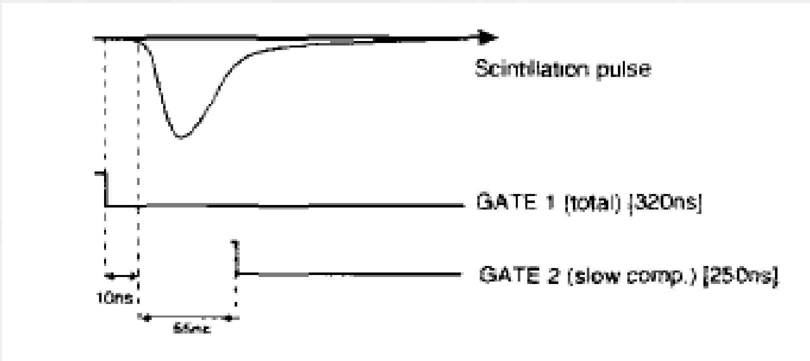
Neutron-gamma discrimination

Neutron induced signals are "slower" due to delayed photon emission after ionization by heavy particle.

Classic n-g discrimination methods:

zero crossing, charge comparison





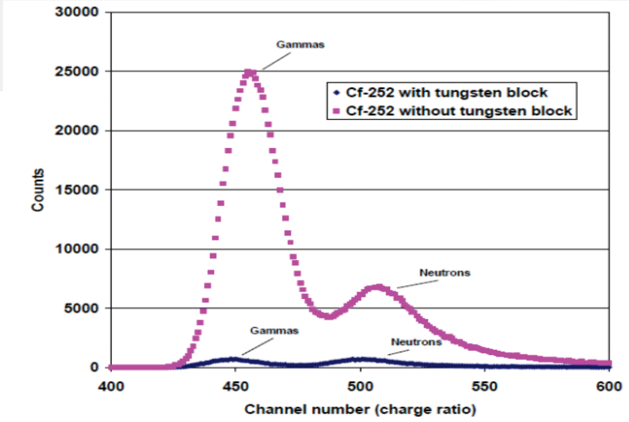


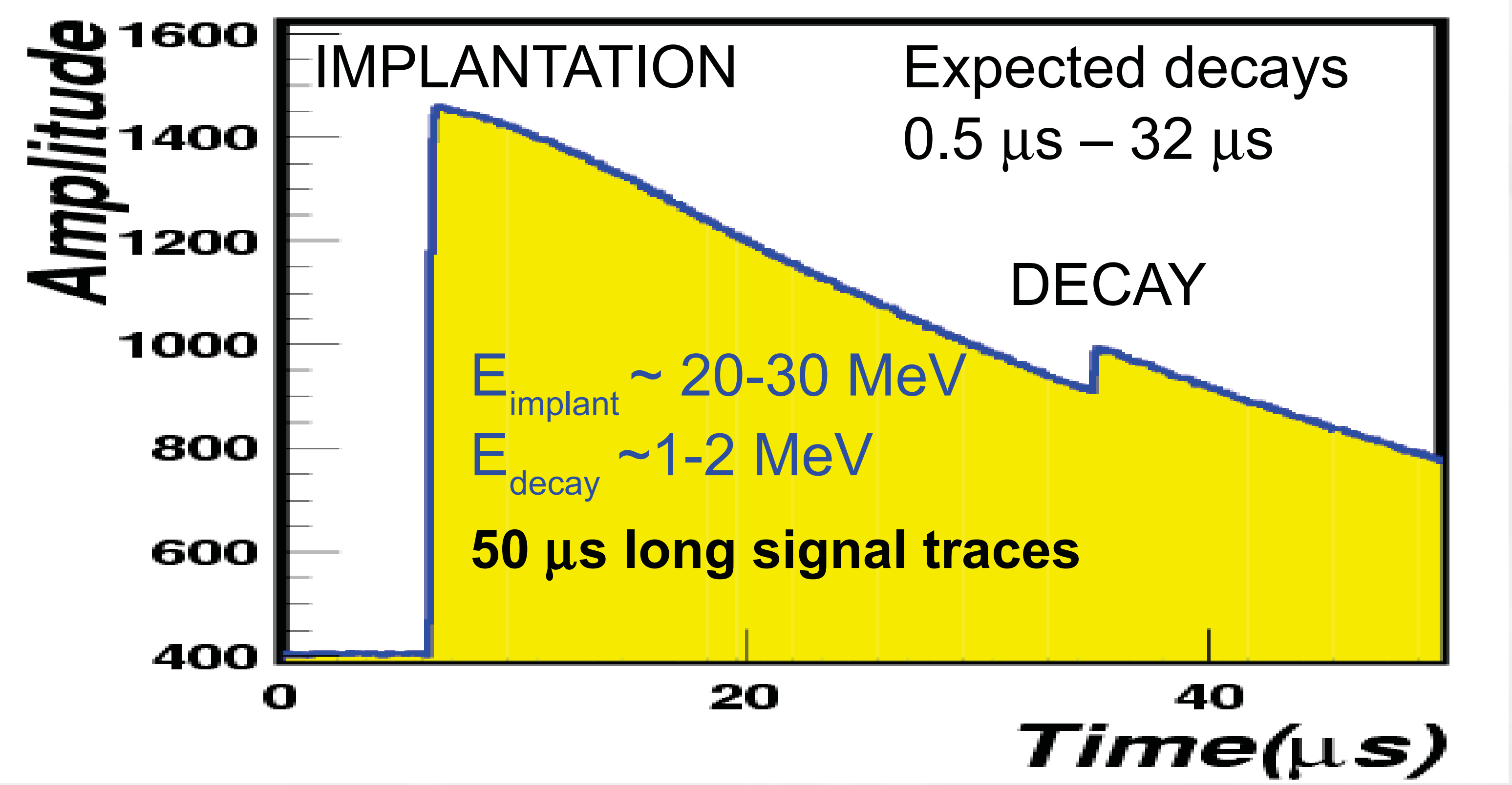
Figure 3. Distribution of PSD module calculated charge ratios for a Cf-252 source, with and without a tungsten gamma shield block.

Pulse shape selective trigger

Proton catcher
Detect very short lived proton emitting nuclei at the final focus of the recoil separator
Very rare event (mHz) in the presence of large implantation (kHz).

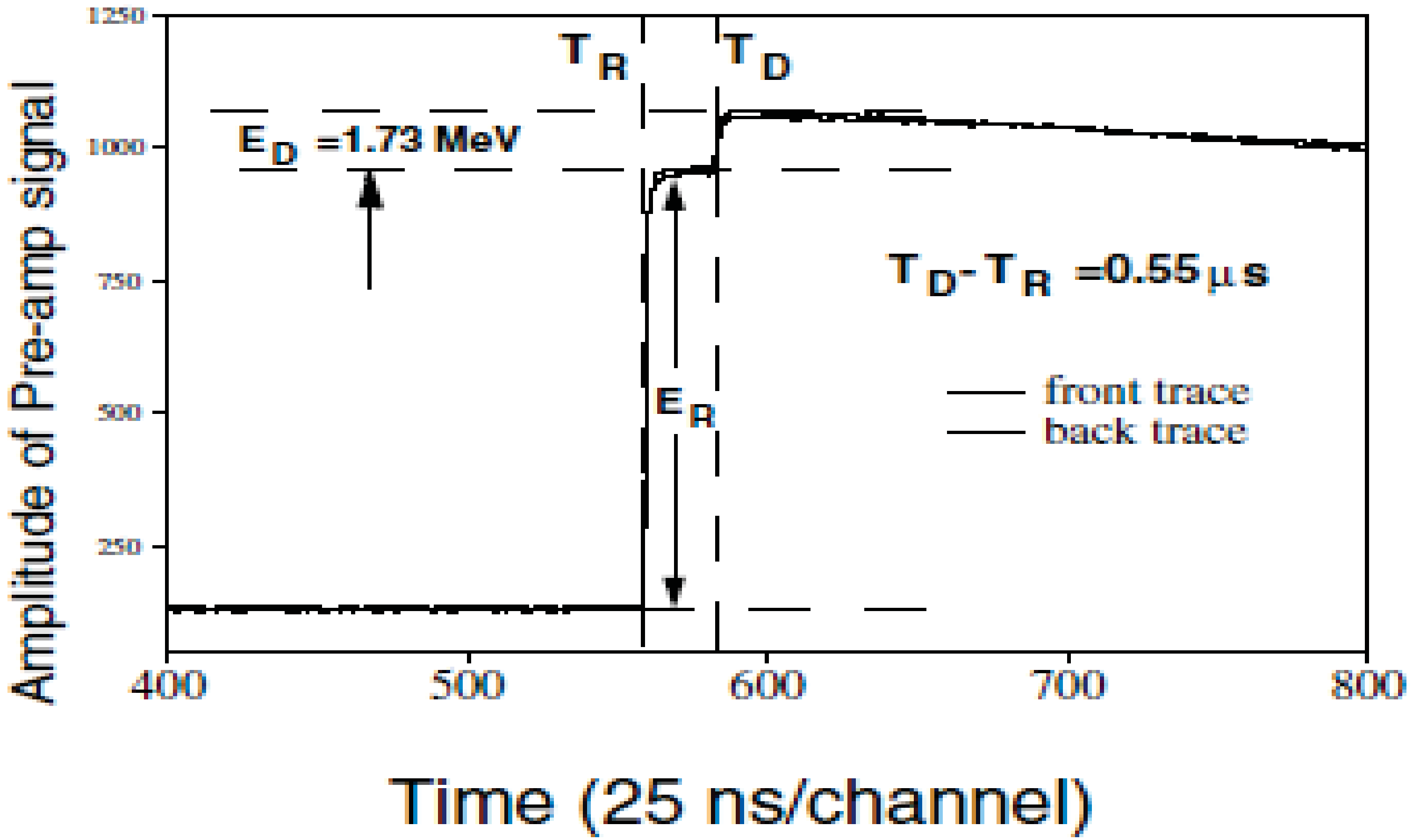
"Proton catcher"

ONLY overlapping pulses are recorded !



H. Hubbard-Nelson, M. Momayezi, W.K. Warburton NIM A422(1999) 41
R.Grzywacz, NIM B204(2003) 649

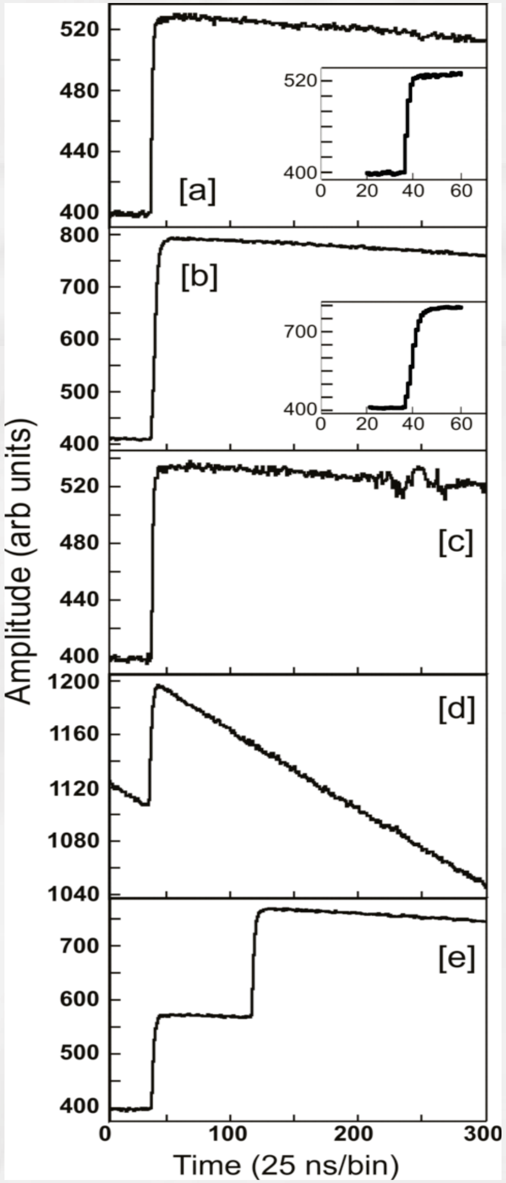
Energy: Single point analysis



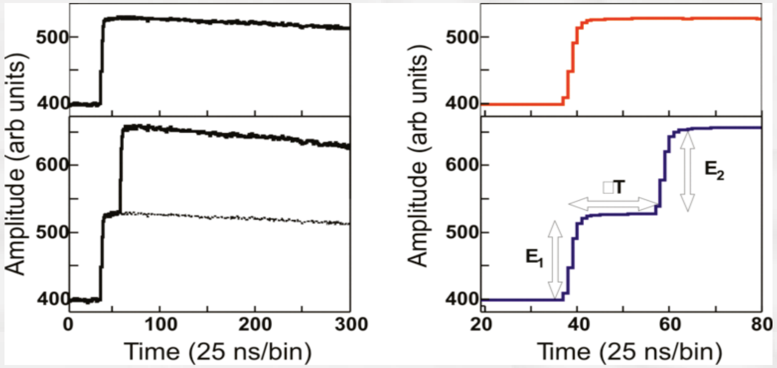
M. Karny et al. Physical Review Letters, 2003; 90 (1)

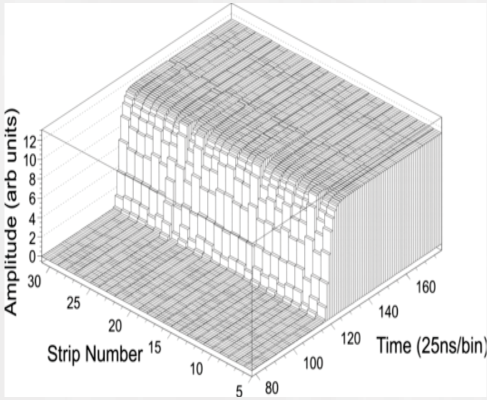
"alpha catcher" (software)

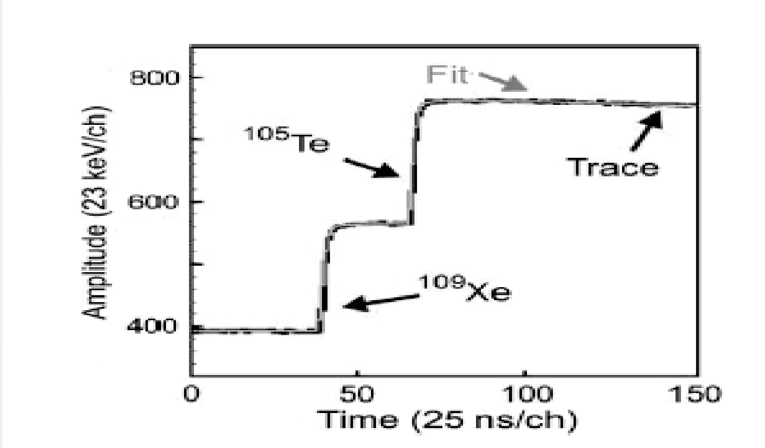
(I. Darby, S.N. Liddick, RG. Nuc. Instr. Meth.)



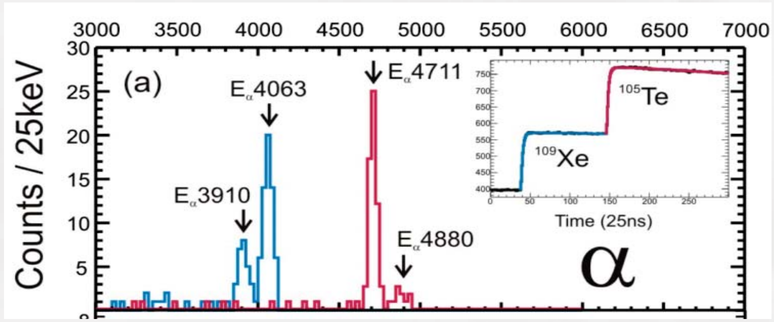
Generate
super-pulse
data base







Search using
single or double
"super-pulse" fit

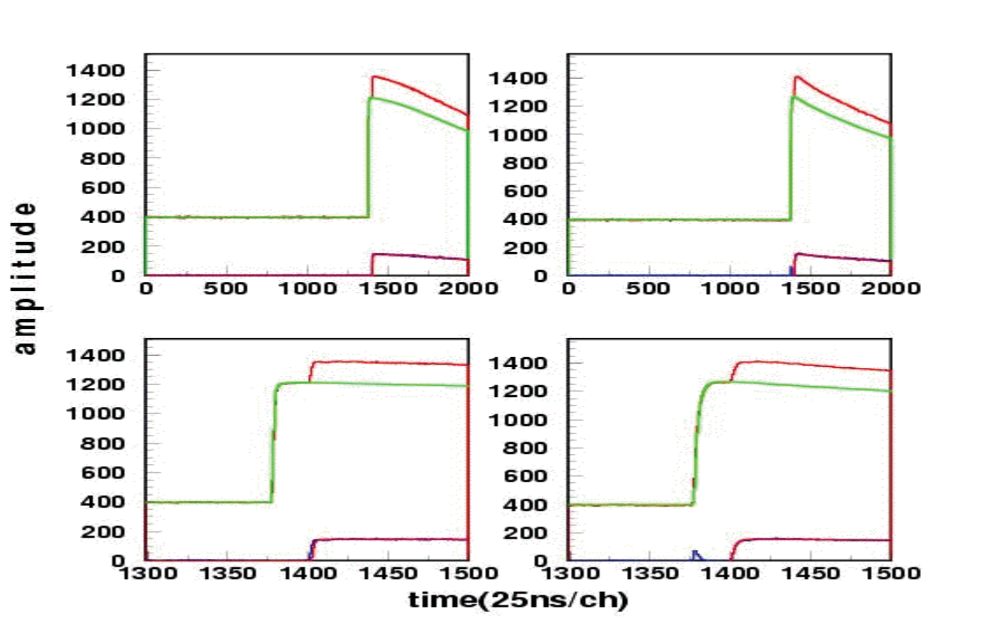


Pulse shape analysis (Energy)

Method of data analysis:
"matching shape"
(Gatti's "optimal filter")

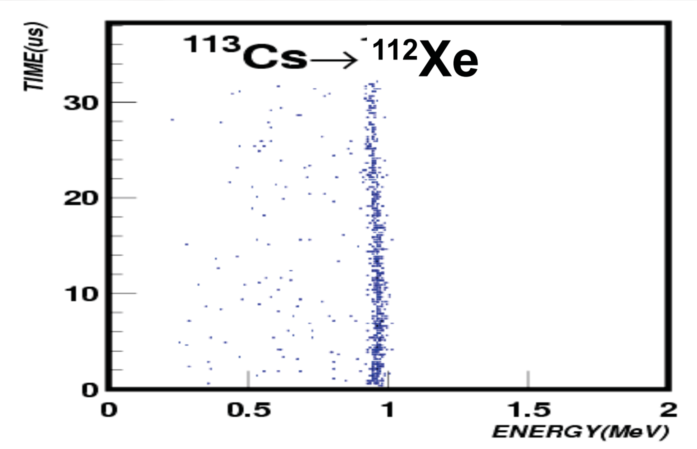
Improved resolution
FWHM ~ 35 keV

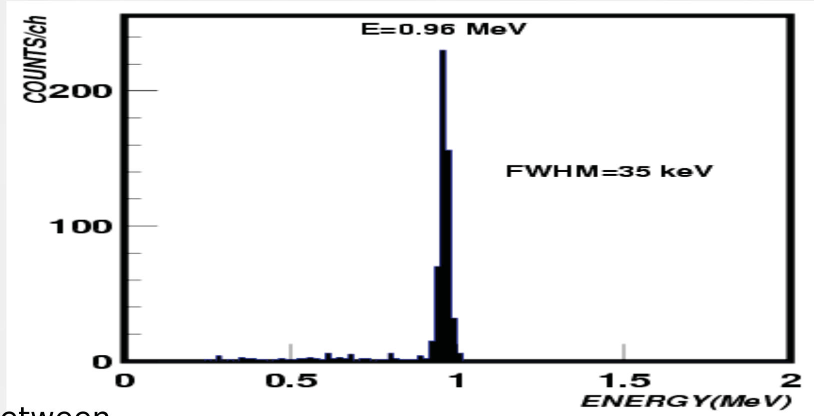
PREVIOUSLY
FWHM ~75keV



R. Grzywacz et al. Eur. Phys. J. A 25, s1.145-s1.147 (2005)

M. Karny et al.Phys. Lett. B 664, 52-56 (2008).





E.Gatti,F.DeMartini,Anewlinearmethodofdiscriminationbetween
elementary particlesinscintillationcounters,NuclearElectronics,vol.2,IAEA
Wilen, 1962,pp.265–276.

Digital signal processing

Powerful method to make compact and flexible system for complex physics experiments

Extremely useful for making compact detection systems.

Optimized for pulse shape analysis

Low-noise performance

Strong dependence on software “Digital gain – digital pain”