Digital signal processing and the studies of short-lived charged-particle emitters

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and
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- Digital magic
- Examples of measurements
- Super-heavies firmware

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Digital magic

Signal is processed with numerical algorithms operating on its discrete representation

- 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 numerical algorithm

Digital Data Acquisition System@ORNL

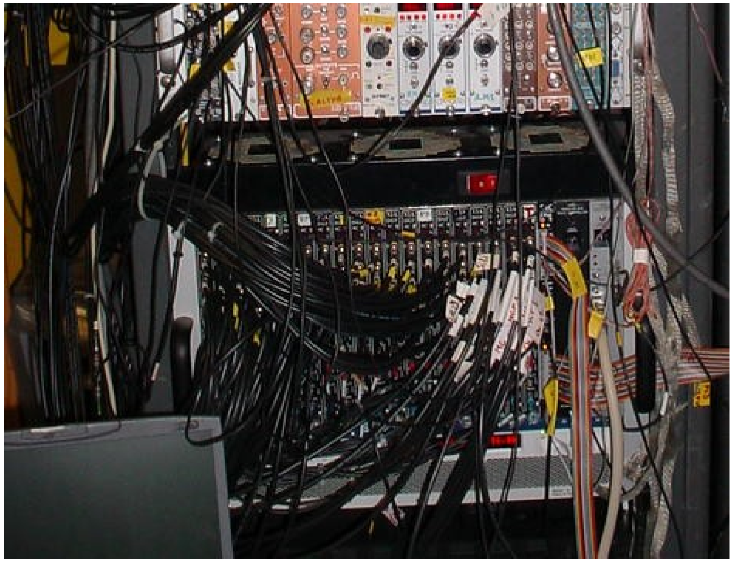
Started with CAMAC based DGF4C modules
40 MHz
H. Hubbard-Nelson,M. Momayezi, W.K. Warburton
NIM A422(1999) 41
R.Grzywacz, NIM B204(2003) 649

Now: (PXI/PCI) Pixie16 (100MHz)
Pixie500 (500MHz)

Pixie 16:
Fully functional data acquisition system used in experiments and producing published data.
Almost a decade of accumulated experience with Digital Data Acquisition Systems.
Very good relationship with XIA LLC (manufacturer).

Digital Data Acquisition System@ORNL

Summary Reviews:
R. Grzywacz et al. , Proc. of ENAM01 Conference 2001, 453. Berlin, Germany: Springer-Verlag, 2003.
R. Grzywacz et al., NIM. B 204, 649 (2003)
R. Grzywacz et al.,NIM B 261, 1103 (2007)
Selected articles: (DGF4C)
W. Królas et al., Phys. Rev. C 65, 031303 (2002)
M. Pfützner et al., NIM A 493 (2002) 155 (GSI)
M. Karny et al. Phys. Rev. Lett. 90, 012502 (2003)
R. Grzywacz et al. Eur. Phys. J. A 25, s1.145-s1.147 (2005)
S.N. Liddick et al., Phys. Rev. Let., 97, 082501 (2006)
C. Mazzocchi et al., Phys. Rev. Let. 98, 212501 (2007)
M. Karny et al., Phys. Let. B 664, 52 (2008)
J.A. Winger et al., Phys. Rev. Lett. 102, 142502 (2009)
I.G. Darby et al., Phys. Rev. Lett. 105, 162502 (2010)
Pixie 16
S. Padgett et al. Phys. Rev. C submitted
S. Ilyushkin et al. Phys. Rev. C submitted
M. Rajabali et al. Phys. Rev C submitted (NSCL)



Many of those experiments were possible only with digital system !

The essential components of the real time DSP system

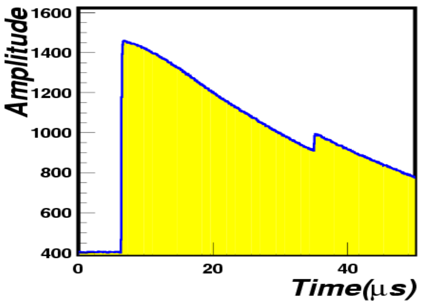
150 MB/s/channel

total system load ~30 GB/s

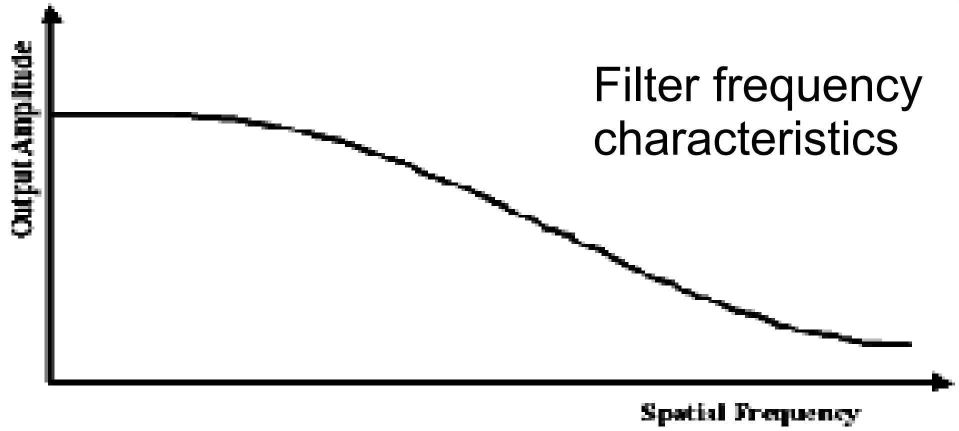
Analog Digital

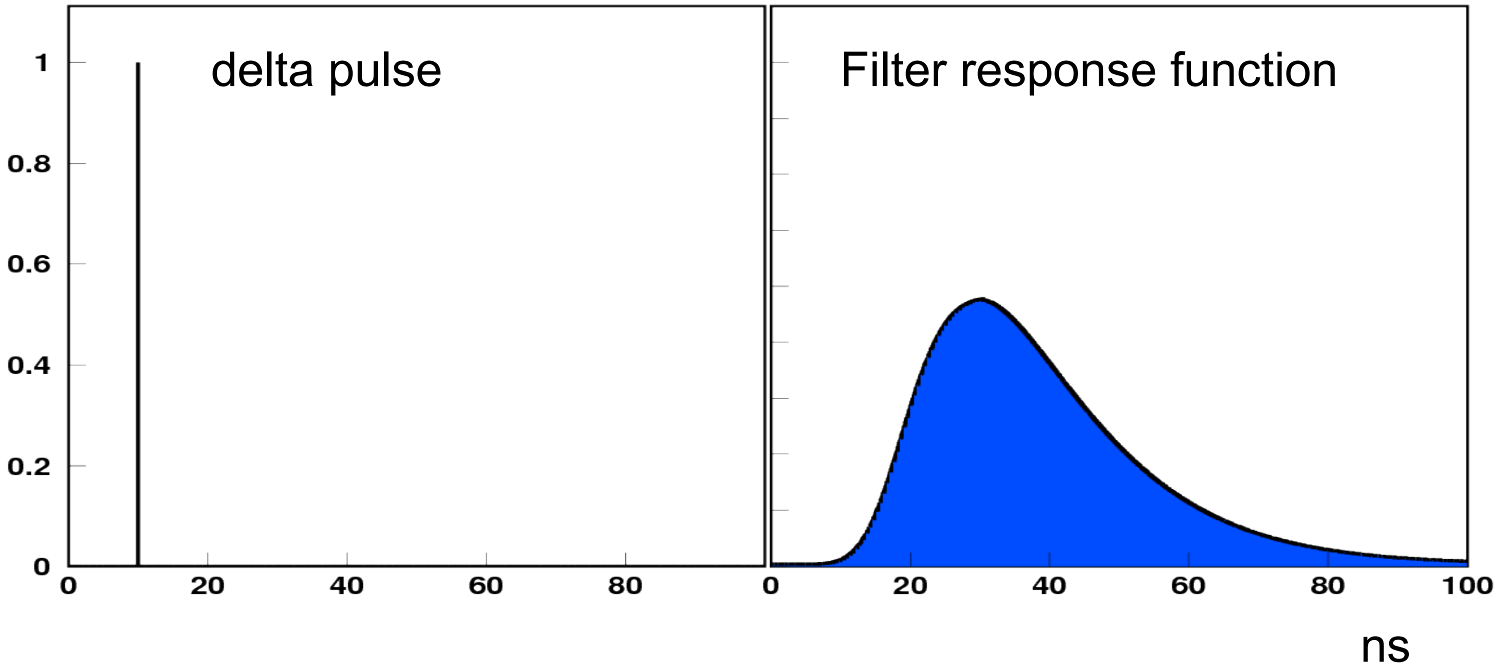
sampling
ADC
(100 MHz)

Selective
triggering
~0.3Mb/s



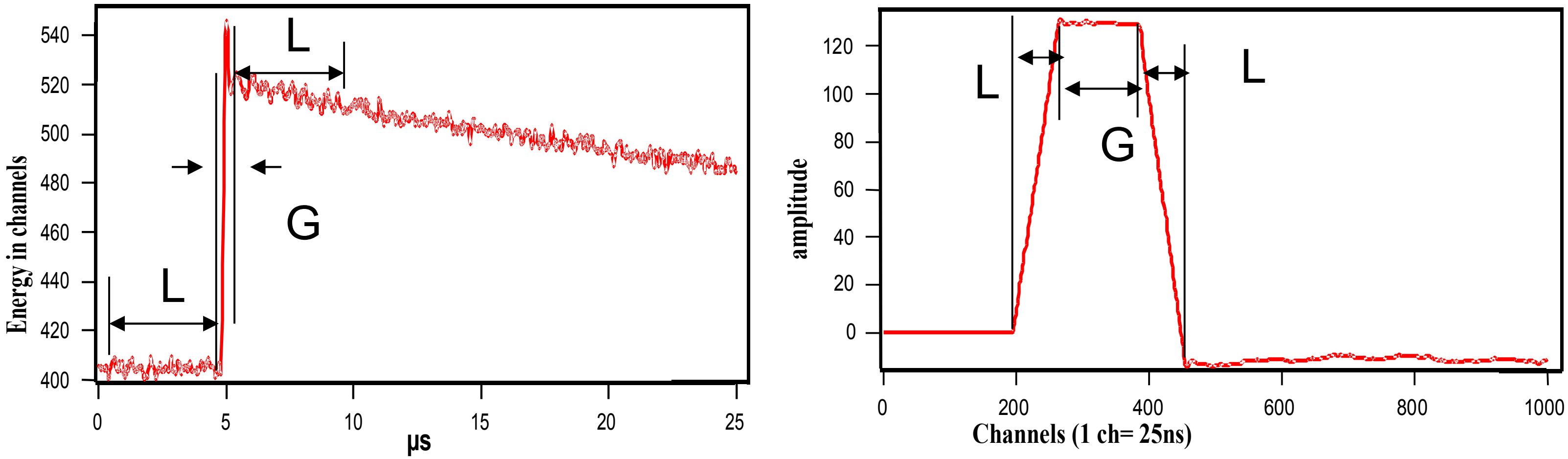
Nyquist filter transformation





Fast Digital Filters

Averaging filter (Trapezoidal filter)

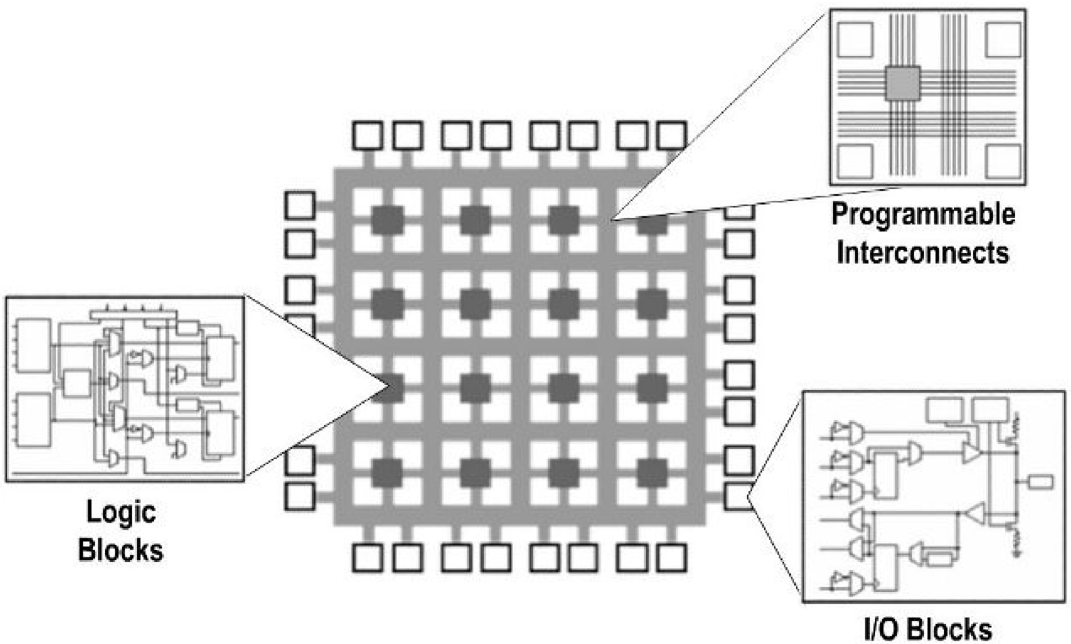


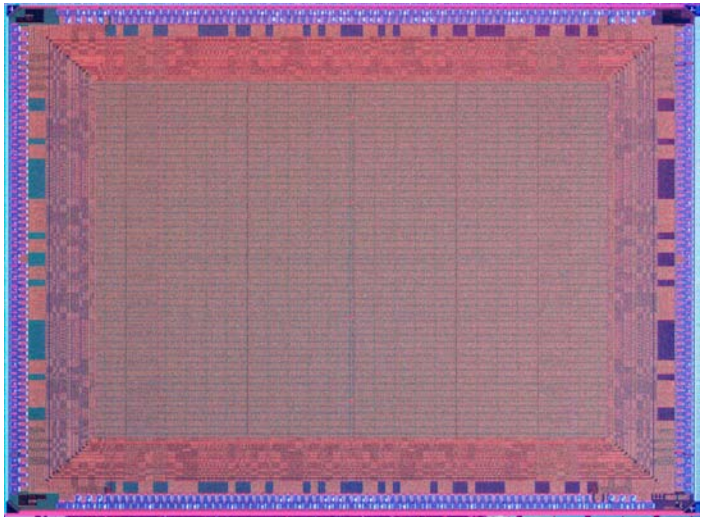
Detector pulse *Transformed pulse*

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

Field Programmable Gate Array

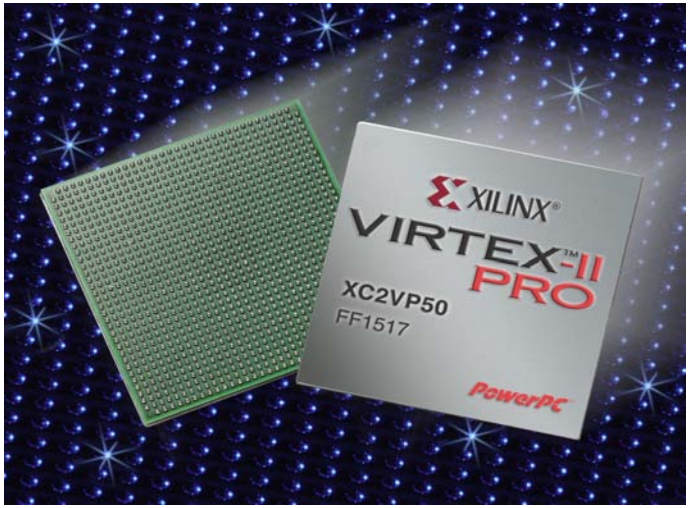
Enables to program algorithm on chip !





Spartan 3A family has devices

from 176 to 5968 CLBs.



very fast,

parallel (multiple data streams)

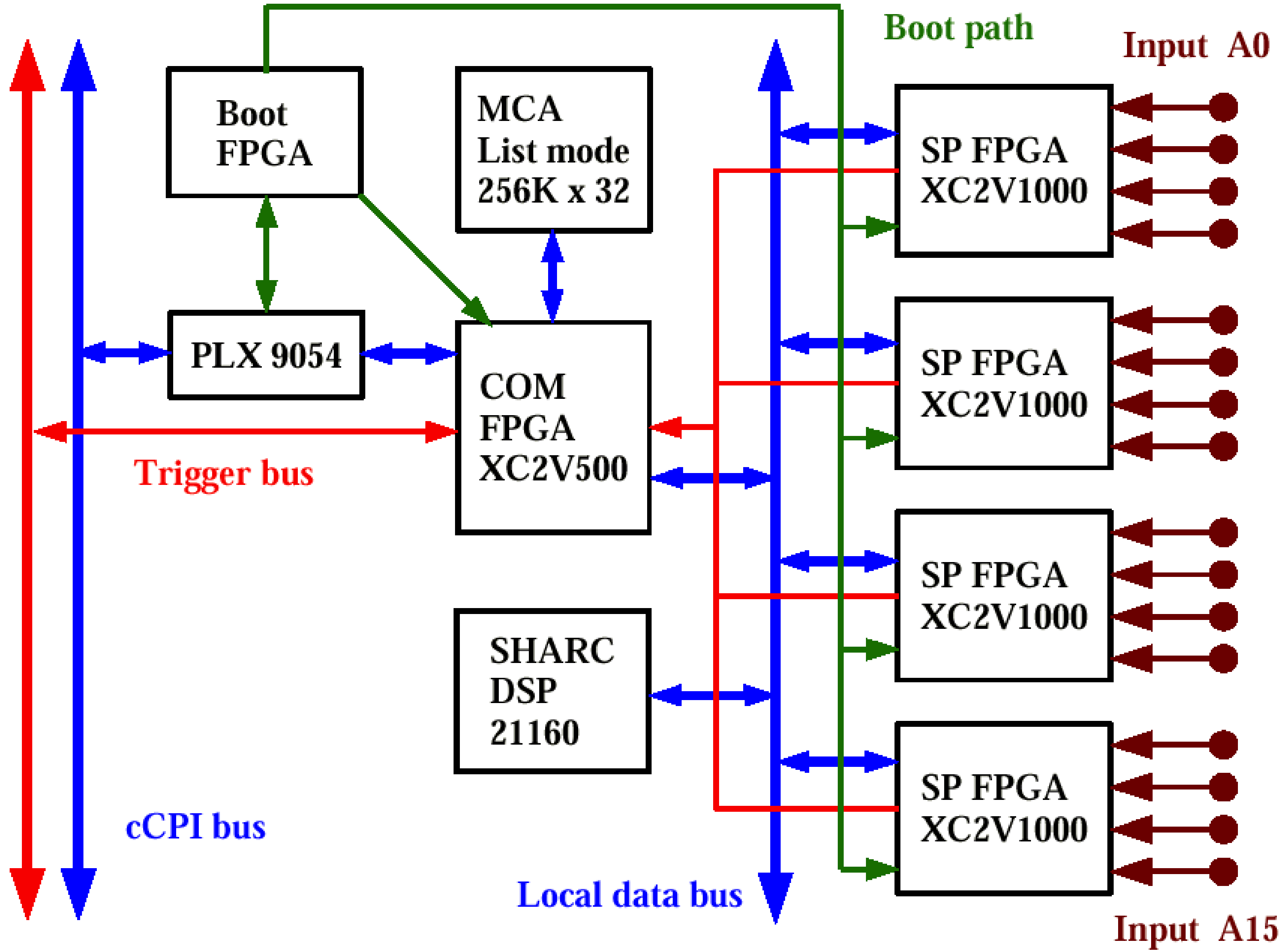
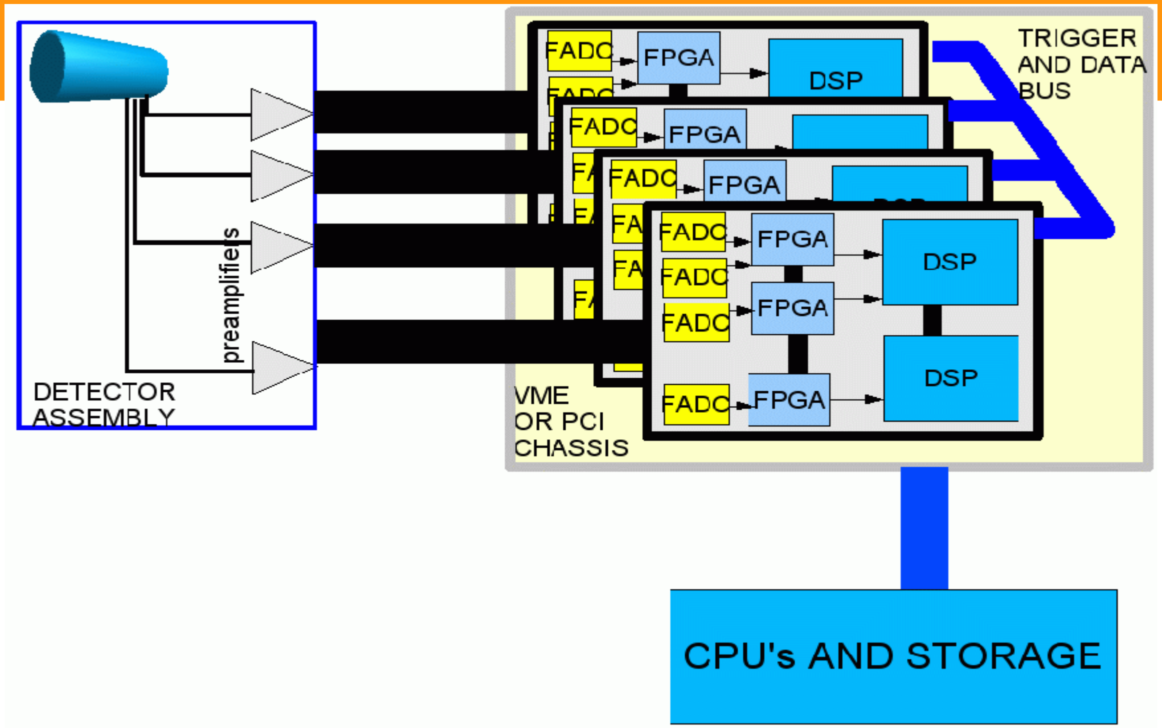
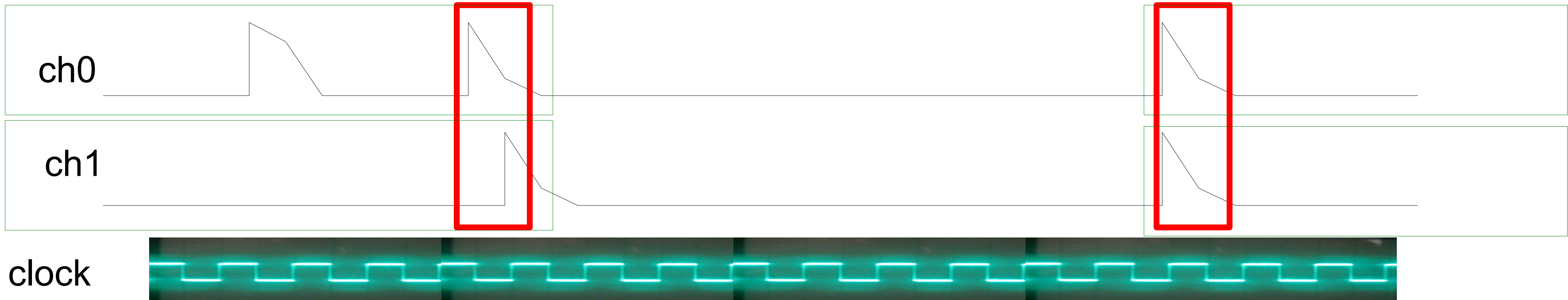


Figure 1: Block schematic of the Pixie-16 spectrometer card. The 16 input sections A0 through A15 contain the digital offset control as well as a 12-bit, 100MSPS ADC for each input channel.

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



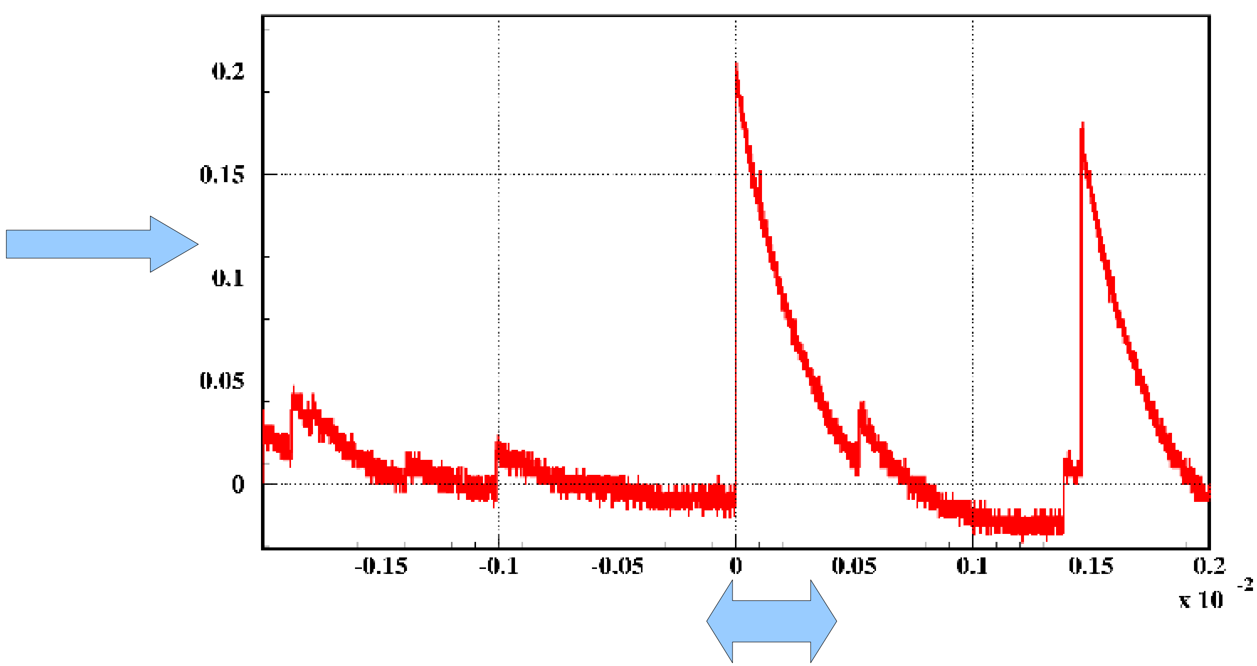
The trigger issue

Self-trigger or external trigger (validation)

Trigger decisions based on:
- amplitude of the pulse
- time correlation ("proton catcher")

Store
Time/Amplitude
Waveform

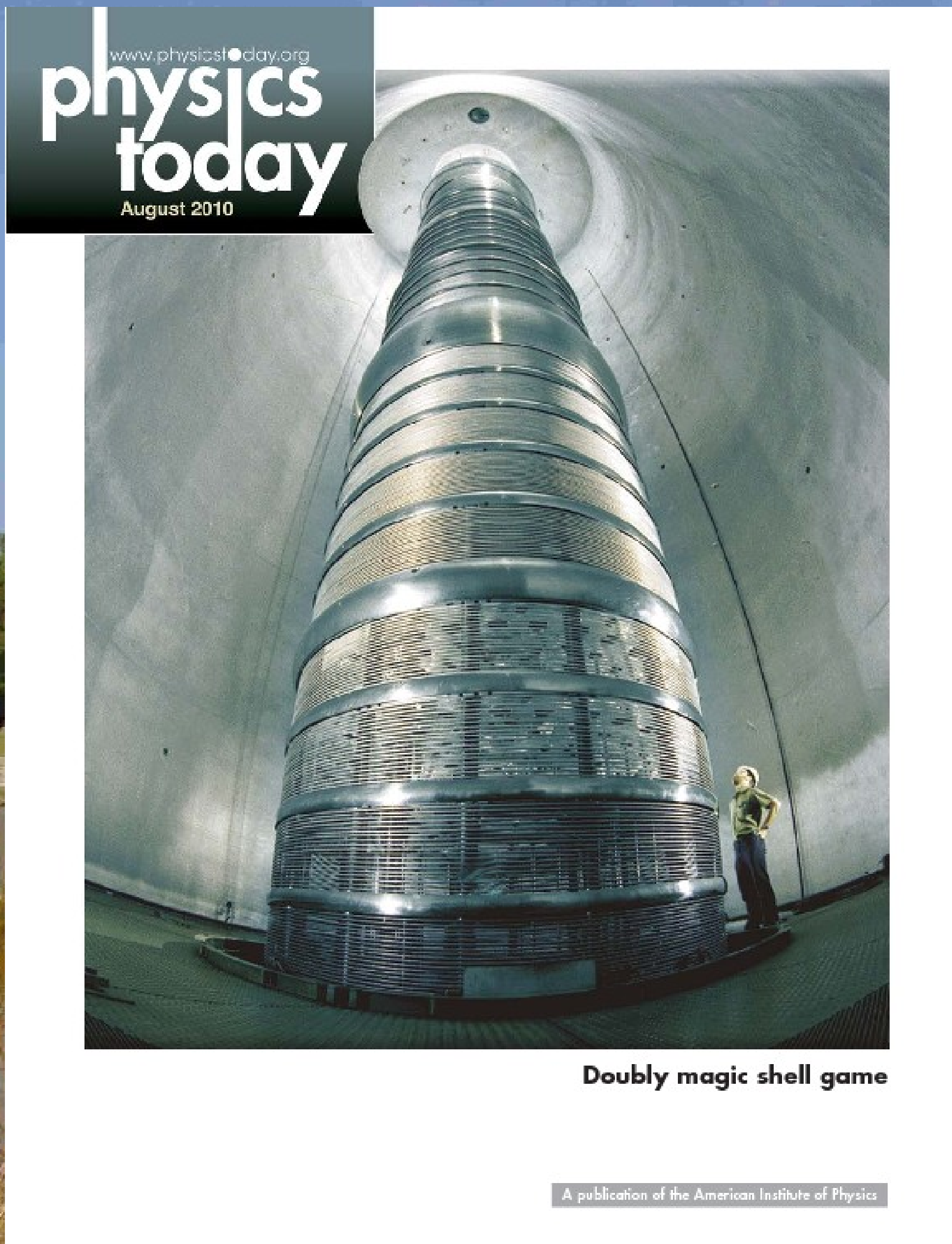
Store
Time/Amplitude
Ignore Waveform

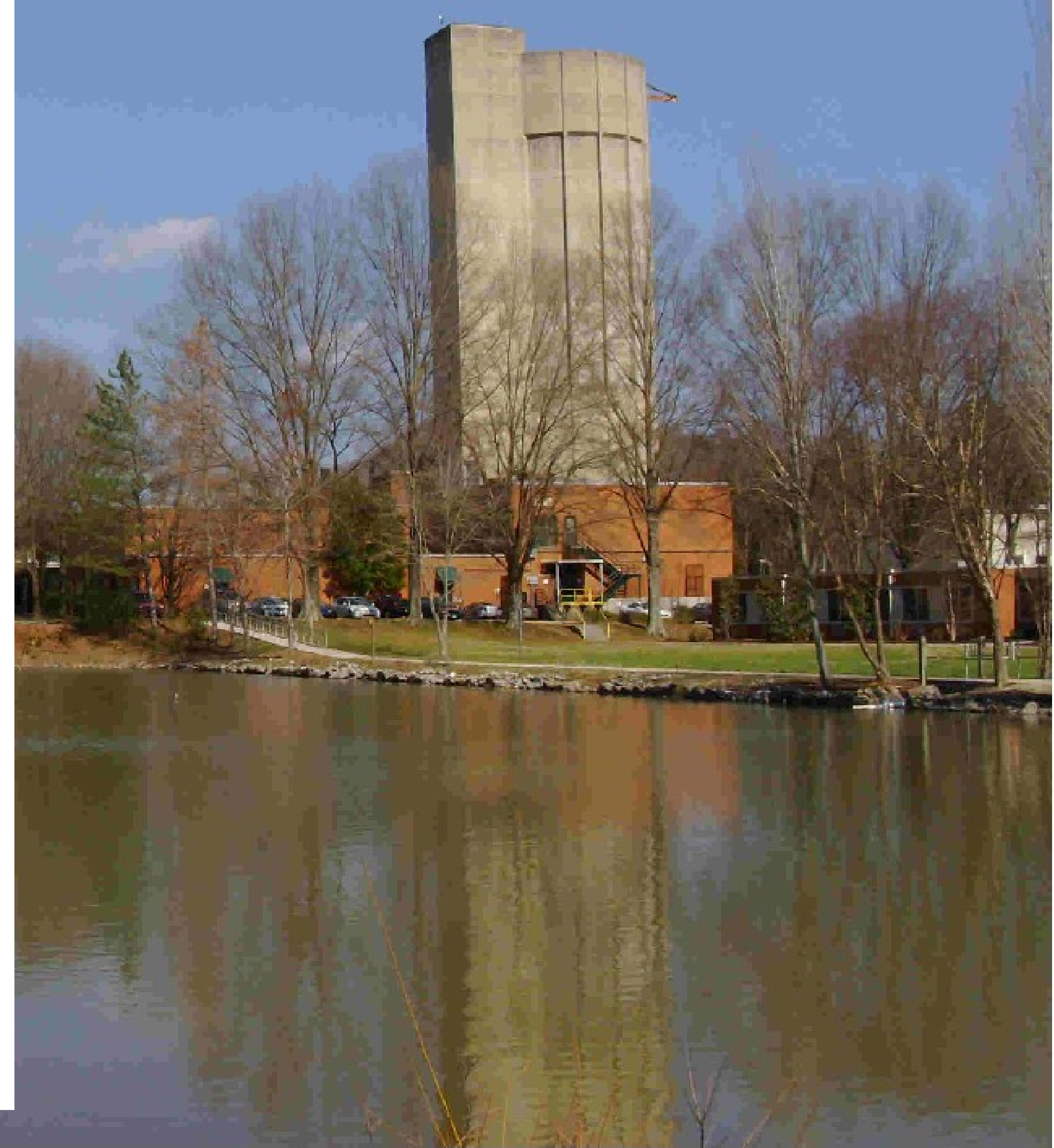


The data volume

Waveform storage may increase
the volume of the data by factor 1000 !
It is technically feasible ...
(fast data bus,cheap data storage, fast computing)
...but requires involved software development !
Can you afford it ?

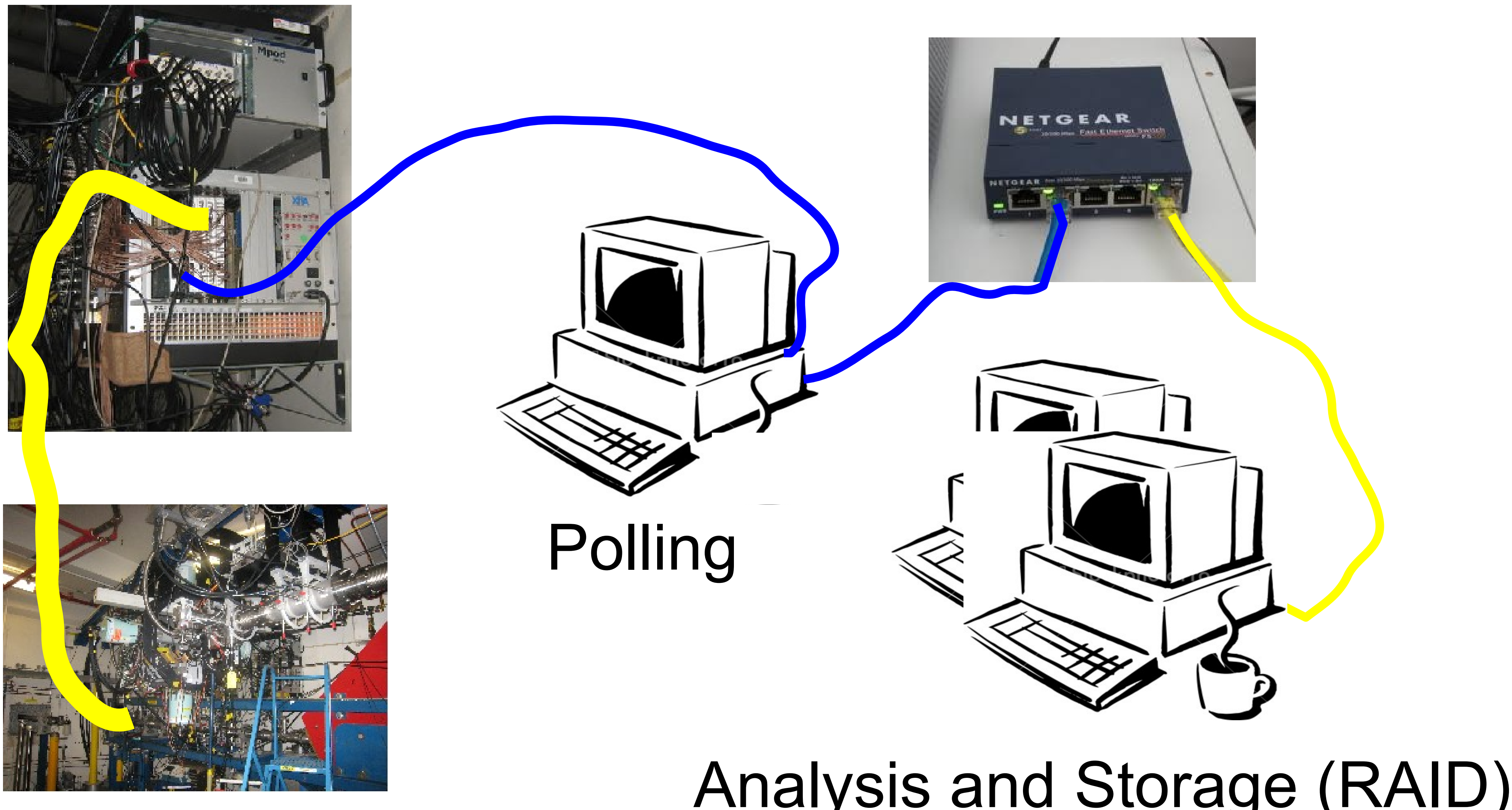
EXPERIMENTS



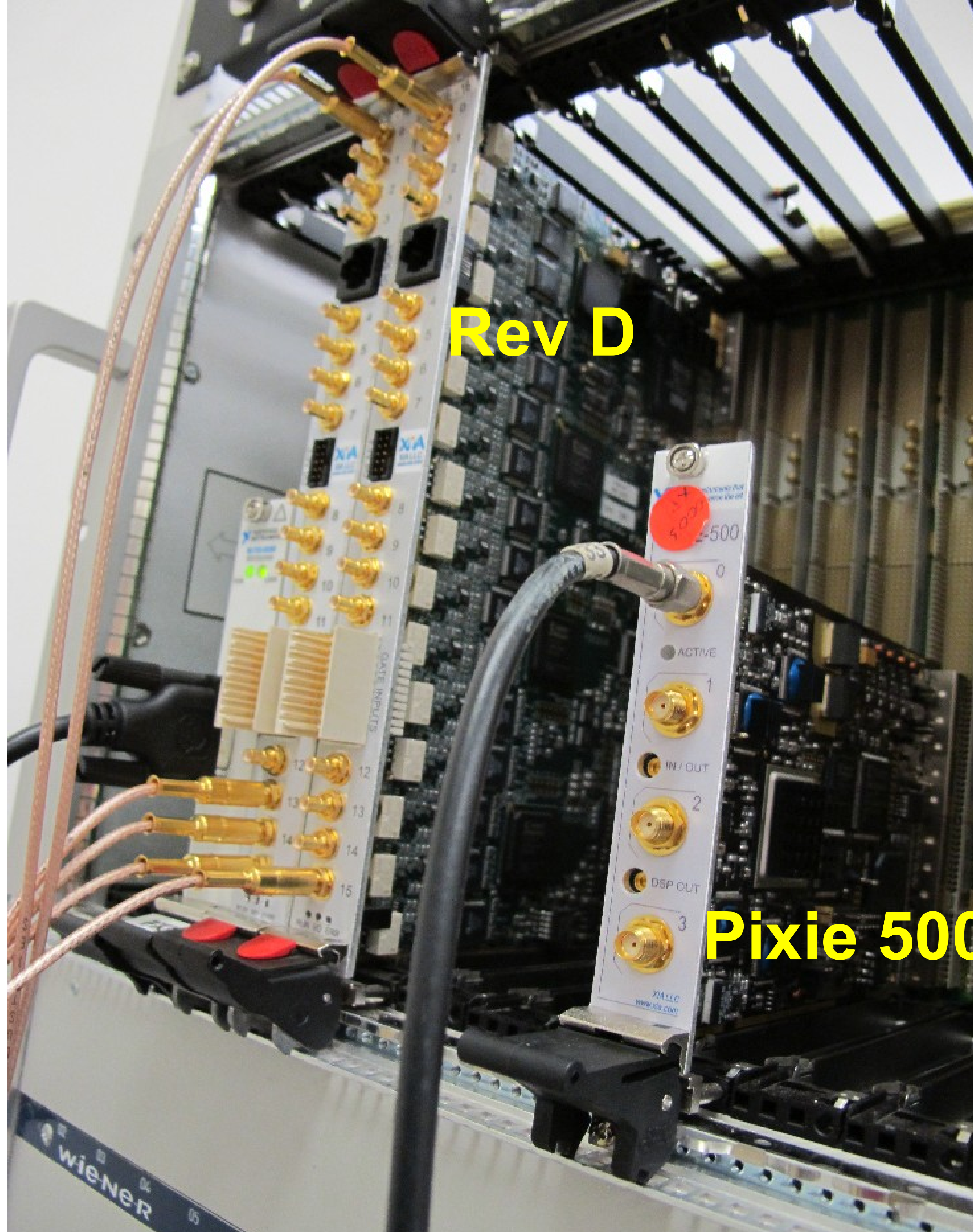


"DGF/PIXIE MODEL"

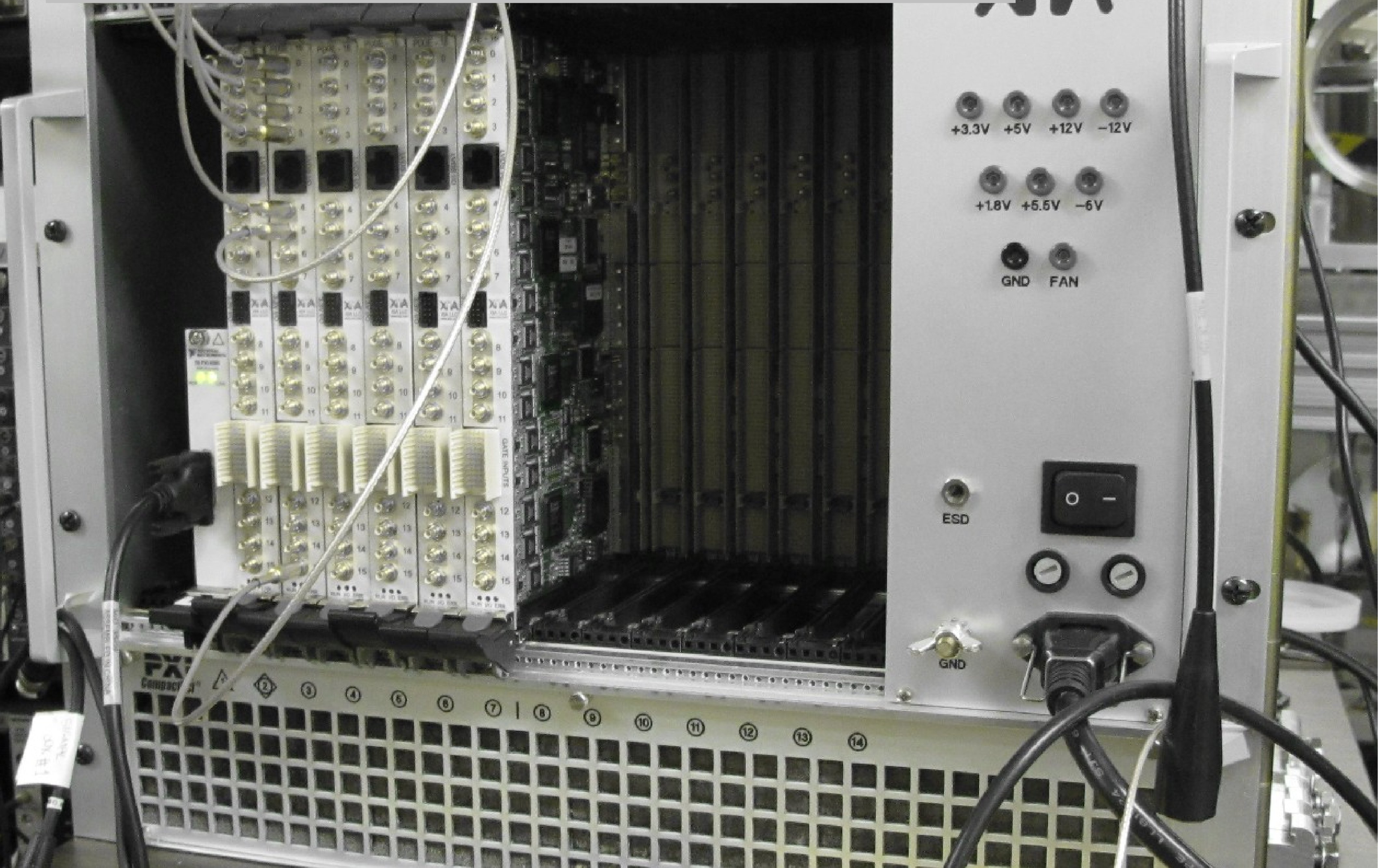
Detector System -> DSPBoard->PCI BRIGE->PC-> GIGABIT->PC



Pixies@ORNL



13 Slot x16ch= 208 channels in one chassis (rev D PIXIE16)



NSCL DDAS (5 chassis)
More than 500 channels
(K. Starosta *et al.*
***now S.N. Liddick*)**

Experimental program with short lived proton emitters (initiated by K. Rykaczewski)!

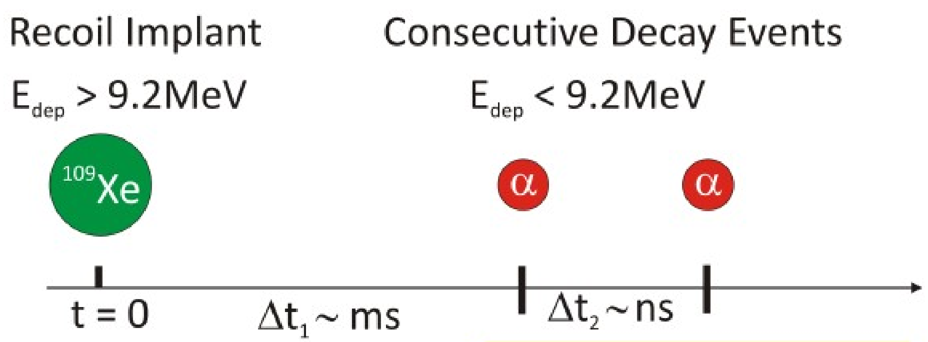
Discovery experiments with short lived radioactivities

- Proton emission in rare earth region
- Alpha decay near ^{100}Sn
- Microsecond Implantation – decay correletion
- Alpha decay chains with sub-microsecond correlations

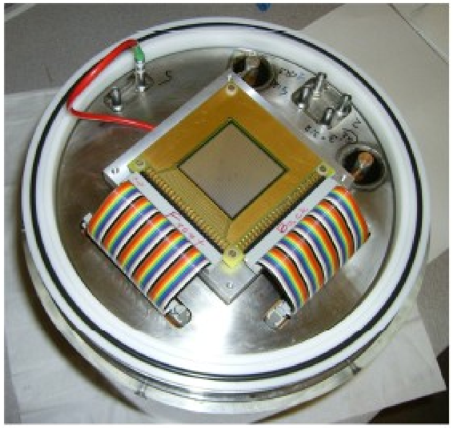
Digital system used in all decay experiments !

HRIBF experimental setup

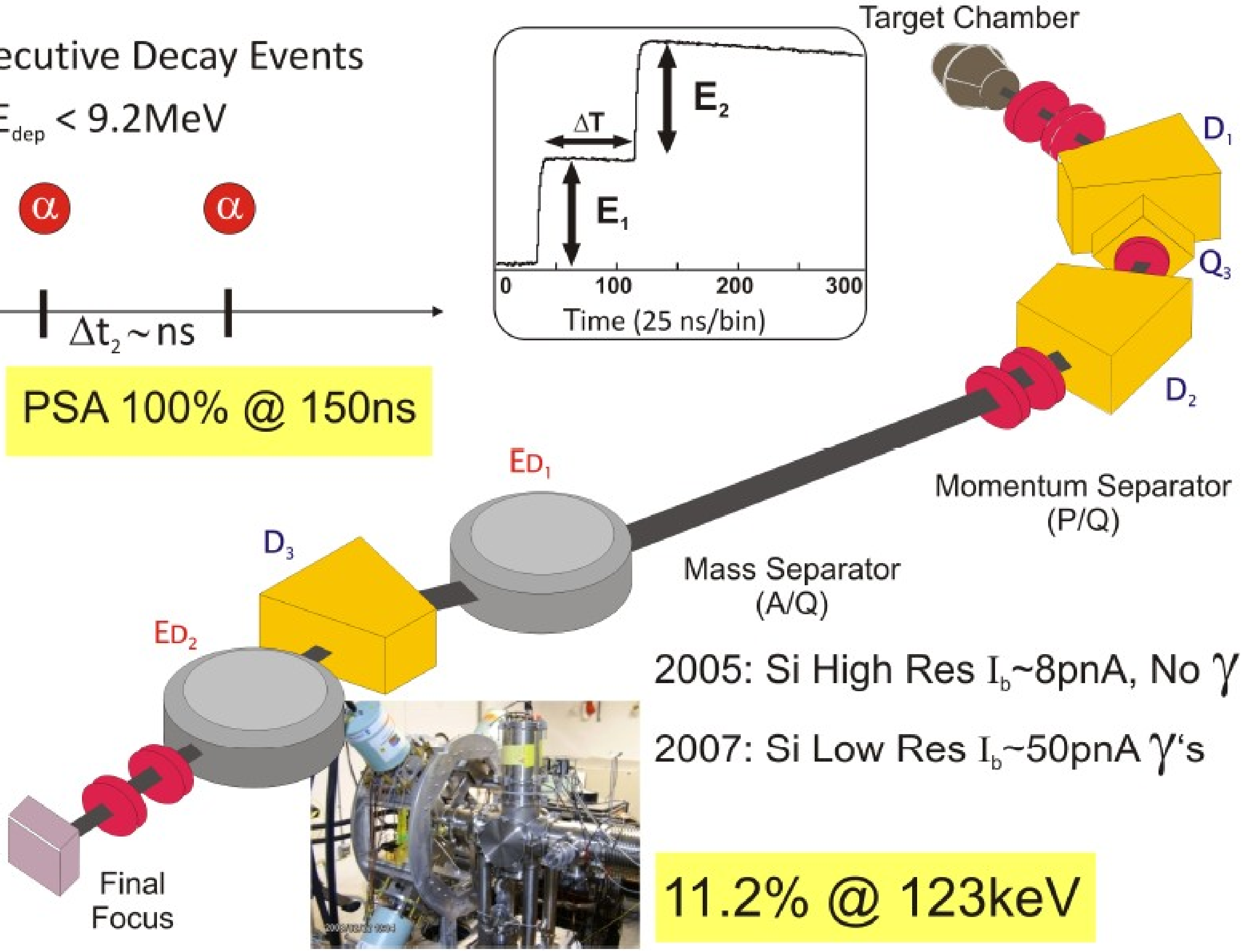
$$^{54}Fe + ^{58}Ni \rightarrow ^{112}Xe^*(3n)^{109}Xe$$



PSA 100% @ 150ns



40 strip 65μm

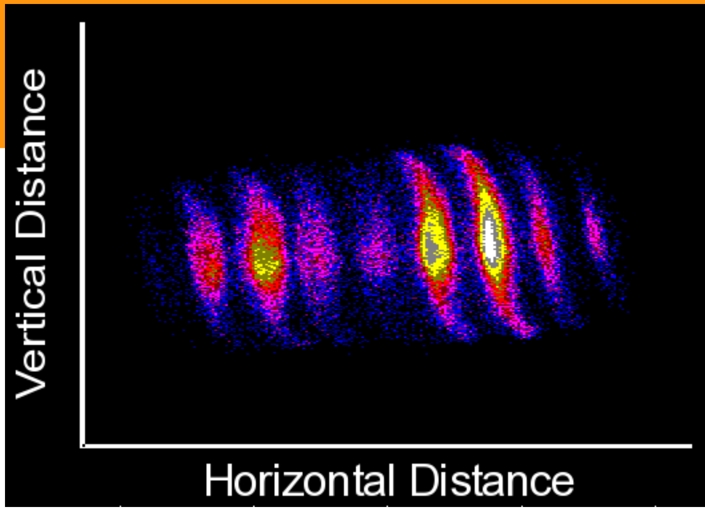


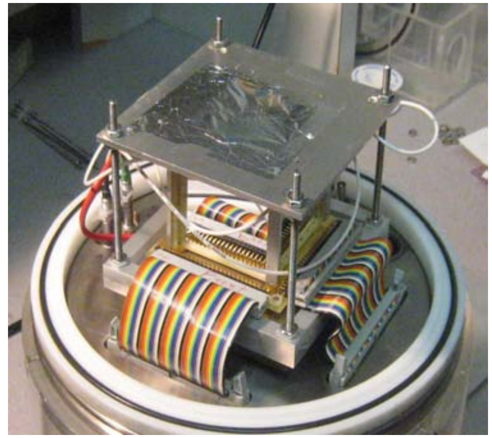
2005: Si High Res I_b~8pnA, No γ

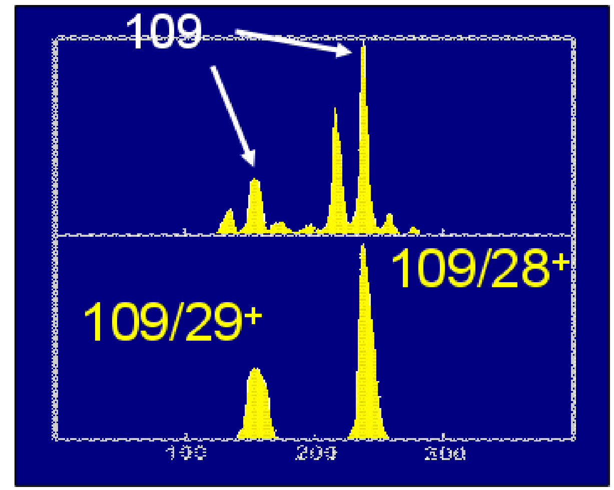
2007: Si Low Res I_b~50pnA γ's

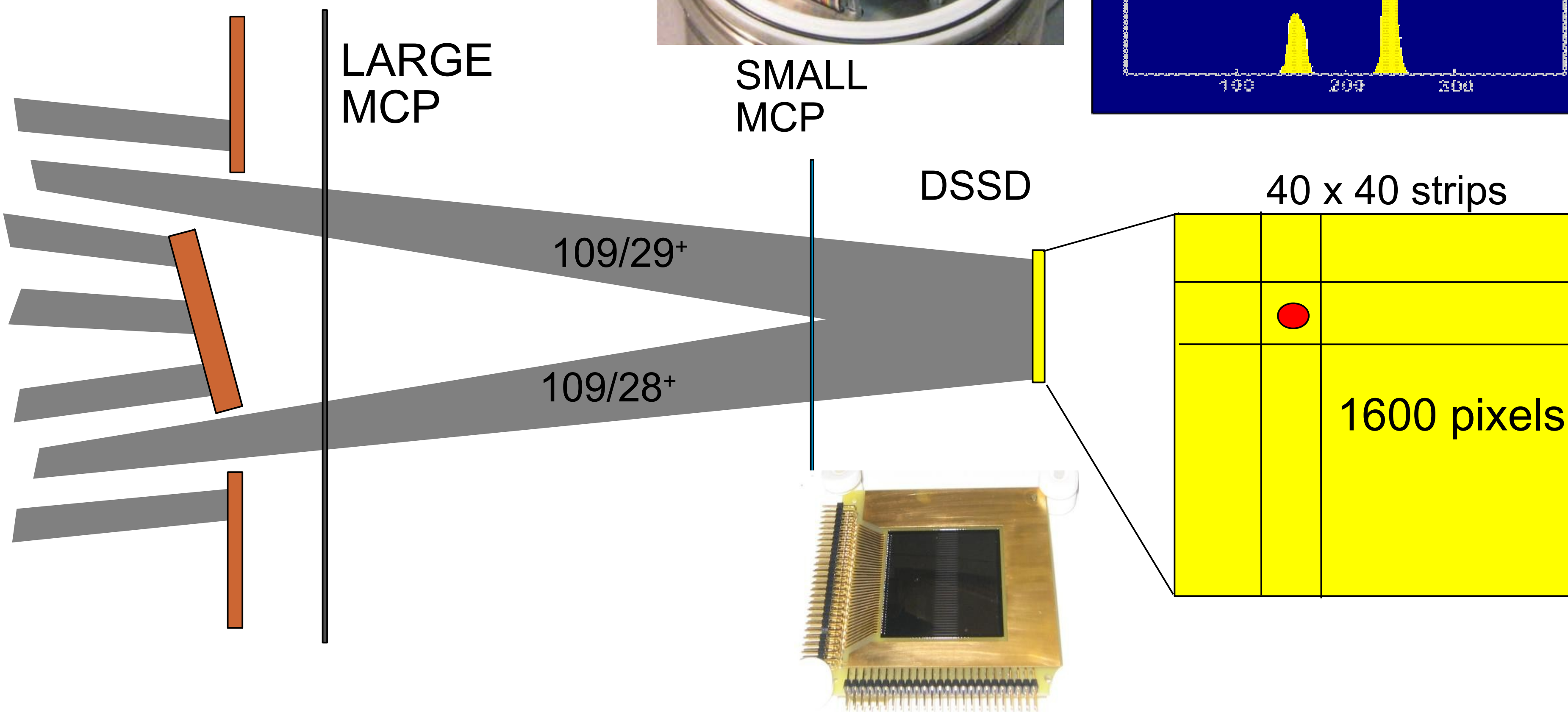
11.2% @ 123keV

RMS Focal Plane detection set-up



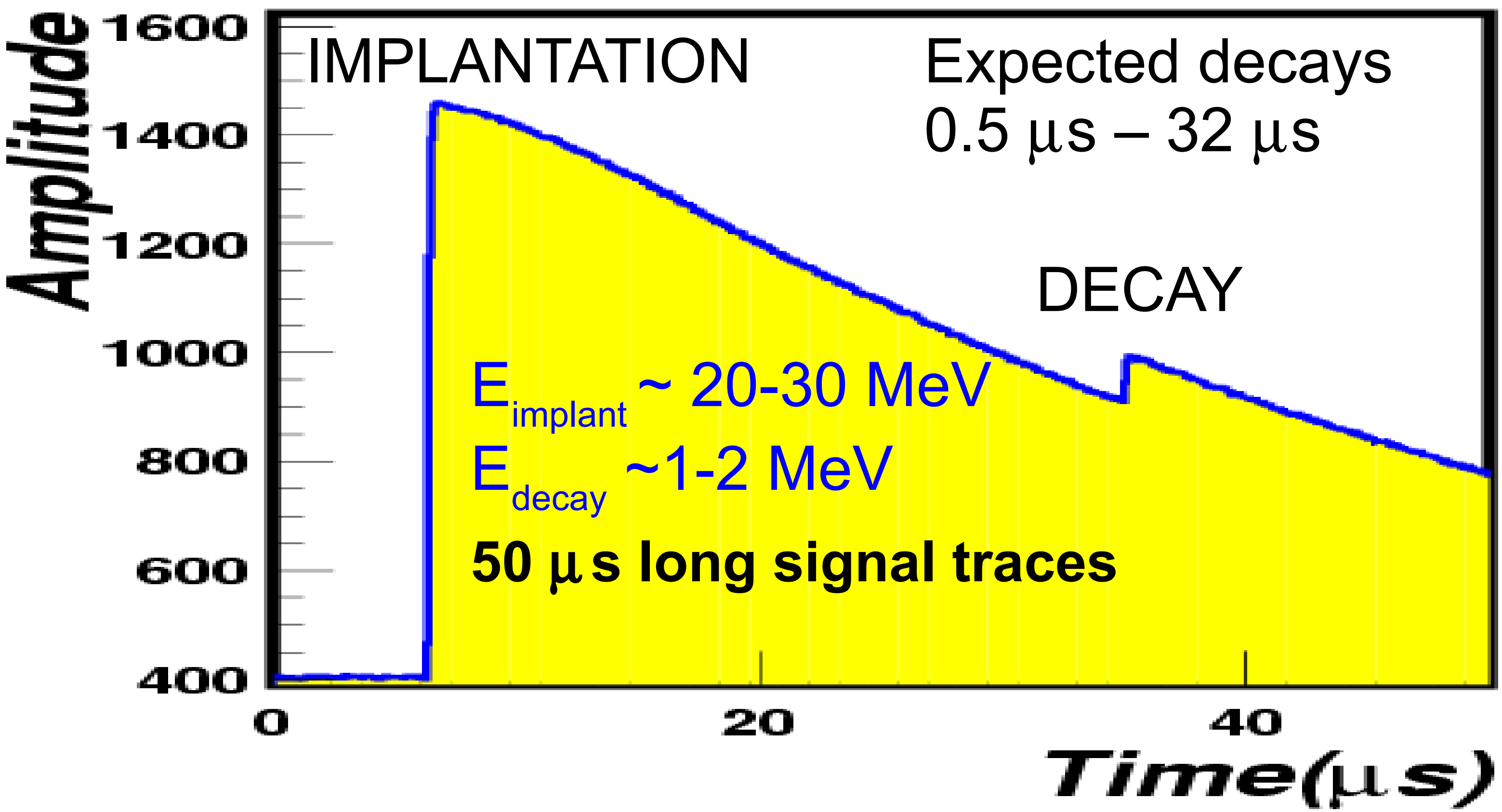






“Proton catcher”

ONLY overlapping pulses are recorded !



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

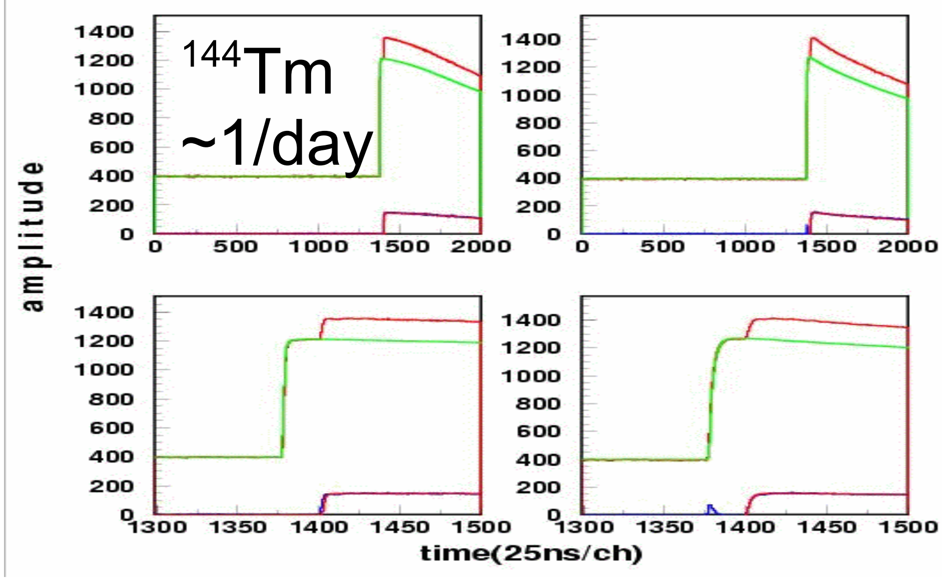
Pulse shape analysis (Energy)

Method of data analysis:
“matching shape”

Improved resolution FWHM ~ 35 keV

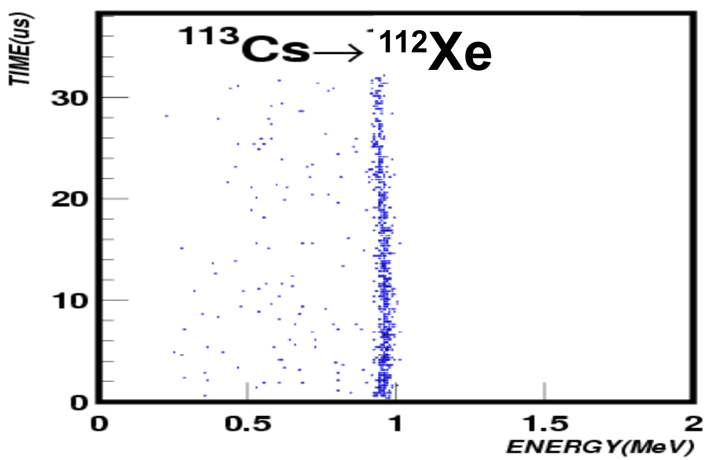
PREVIOUS FWHM ~75keV

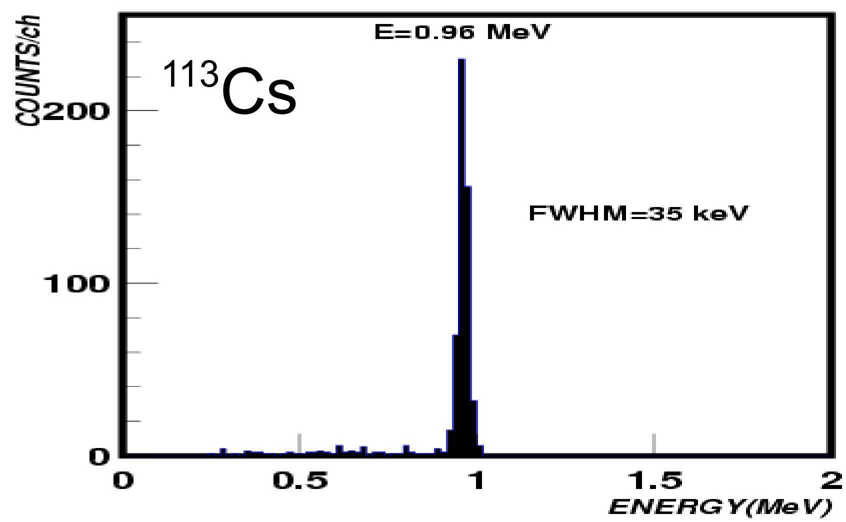
STANDARD FWHM~ 25 keV



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

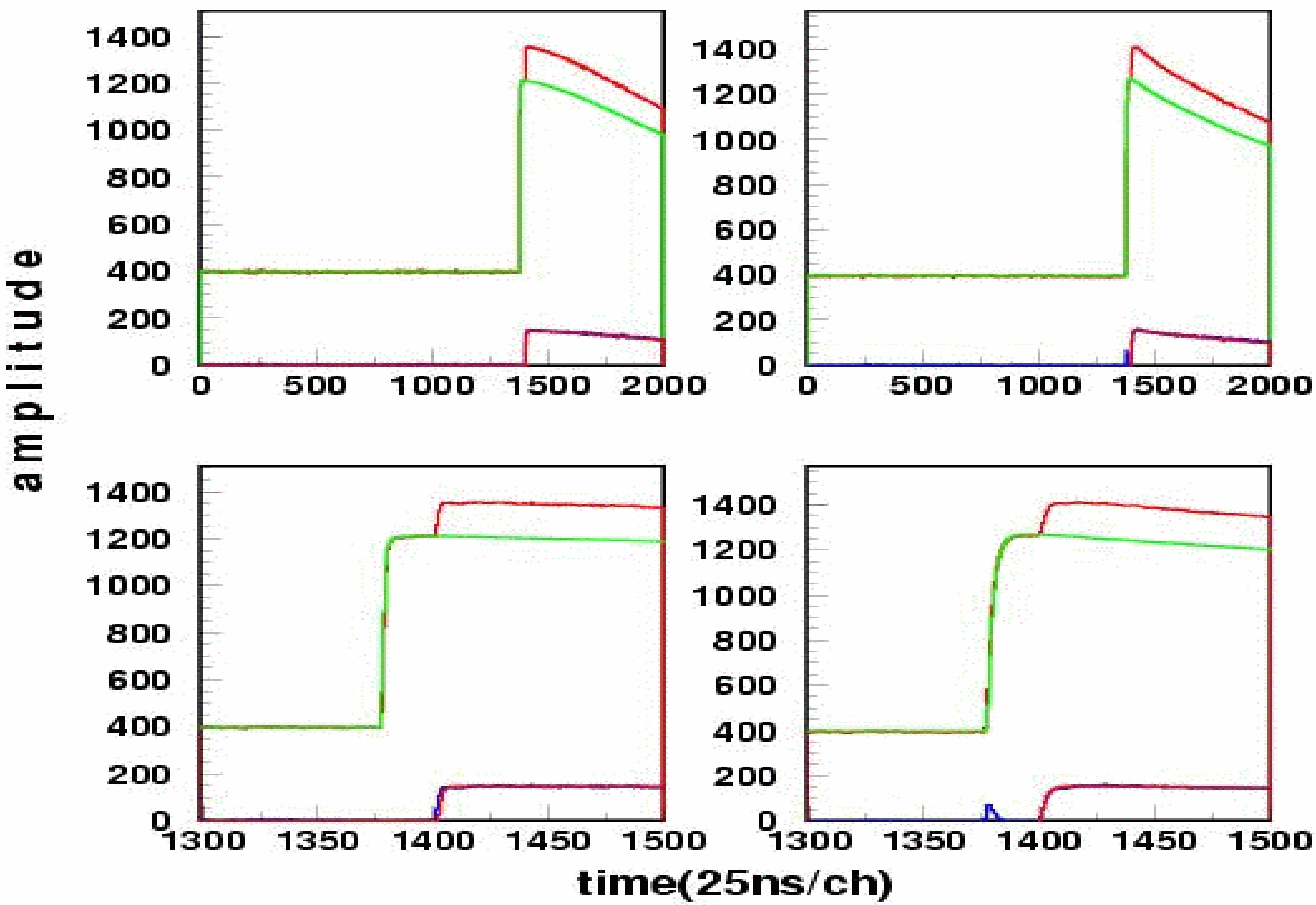
M. Karny et al.Phys. Lett. B 664, 52-56 (2008).





E.Gatti,F.DeMartini,A new linearmethod of discrimination between elementary particlesinscintillationcounters,NuclearElectronics,vol.2,IAEA Wilen, 1962,pp.265–276.

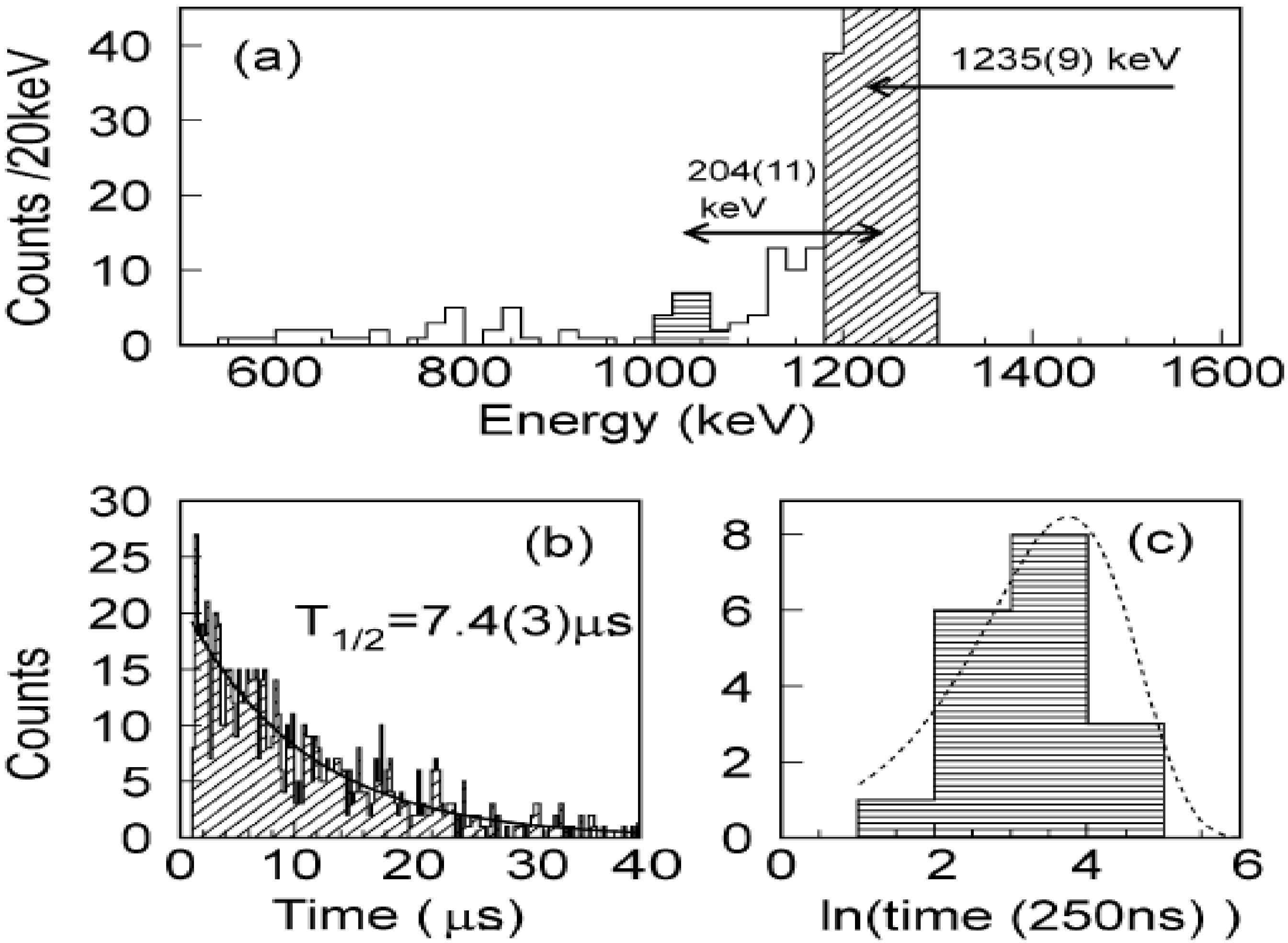
The dynamic range problem
ADC ~2V 4096 ch 0.5mV/ch



Notice different pulse shapes

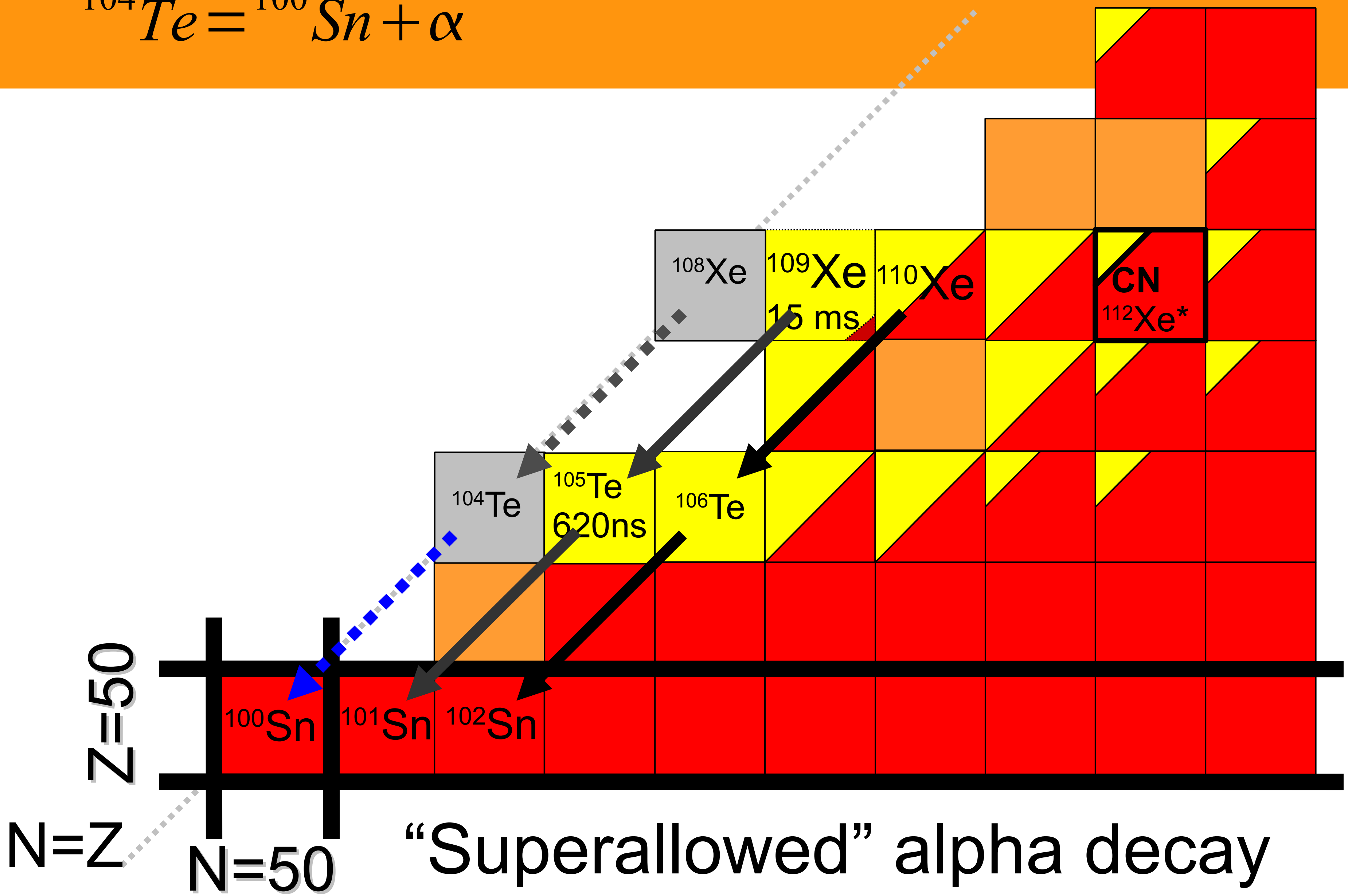
In alpha decay experiments: Recoils ~100 MeV, alphas ~ 4-5 MeV

Fine structure decay of ^{141m}Ho



Nuclear molecules?

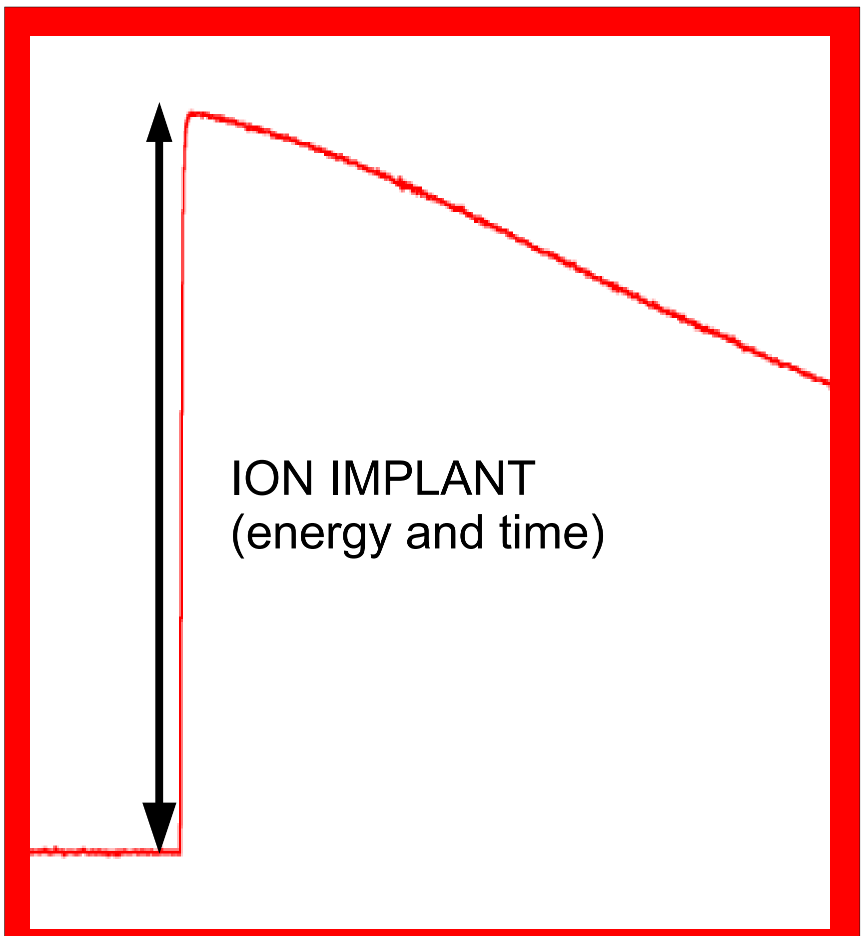
$$^{104}Te = {}^{100}Sn + \alpha$$



"Superallowed" alpha decay

Macfarlane and Siivola, PRL 14,114,1965

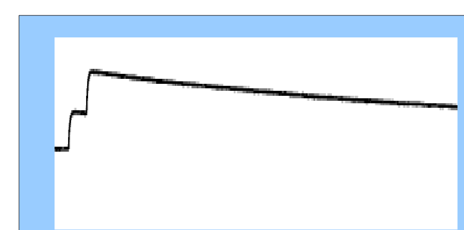
Experimental challenge:
measure closely spaced pulses in same detector with good energy resolution but only for “decay” type pulsees



double pulse - very clean decay signature

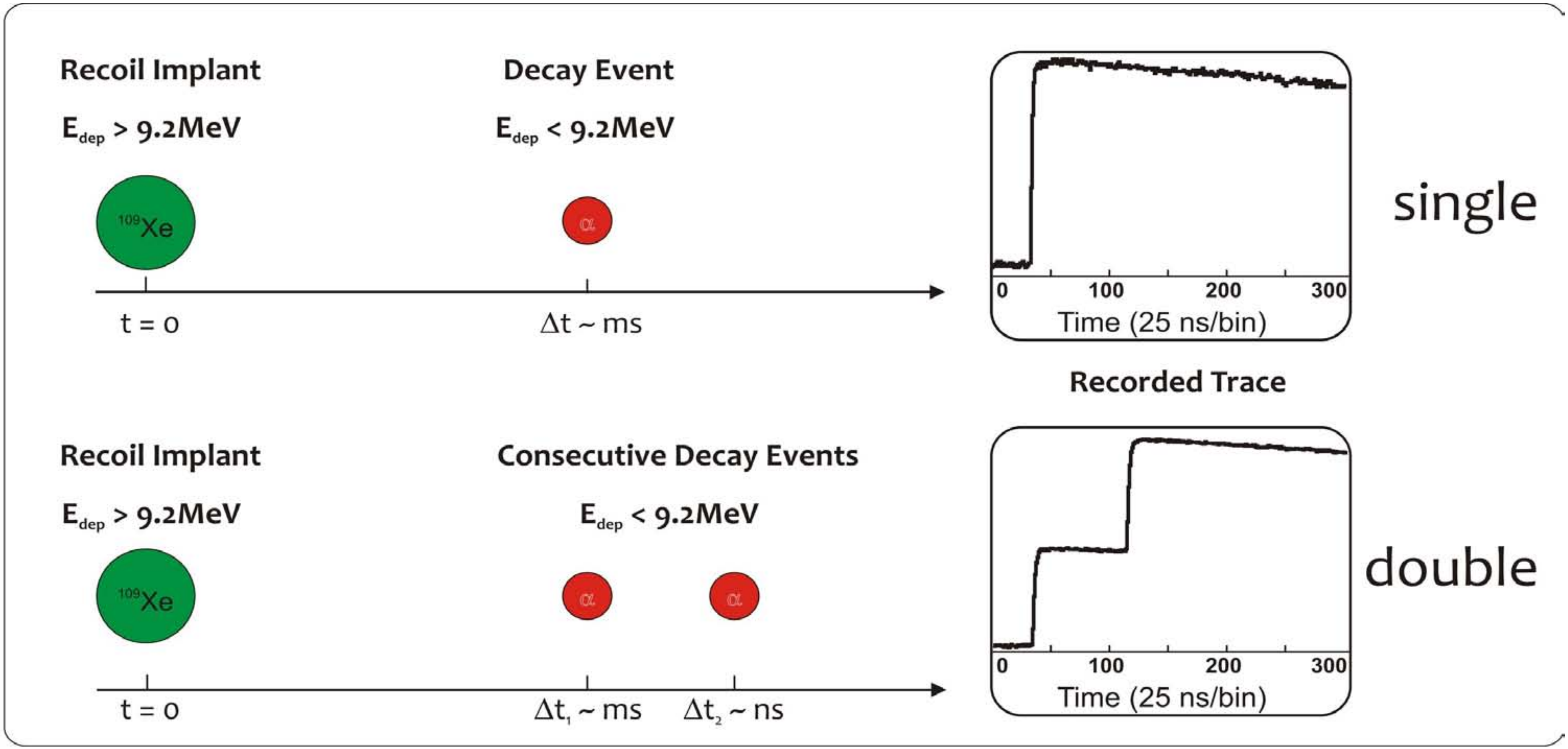
DECAY
(25 μs pulse shape)

~1-100 ms



"alpha catcher"

Ultrasensitive automated method for pileup search and energy analysis using superpulse fitting.

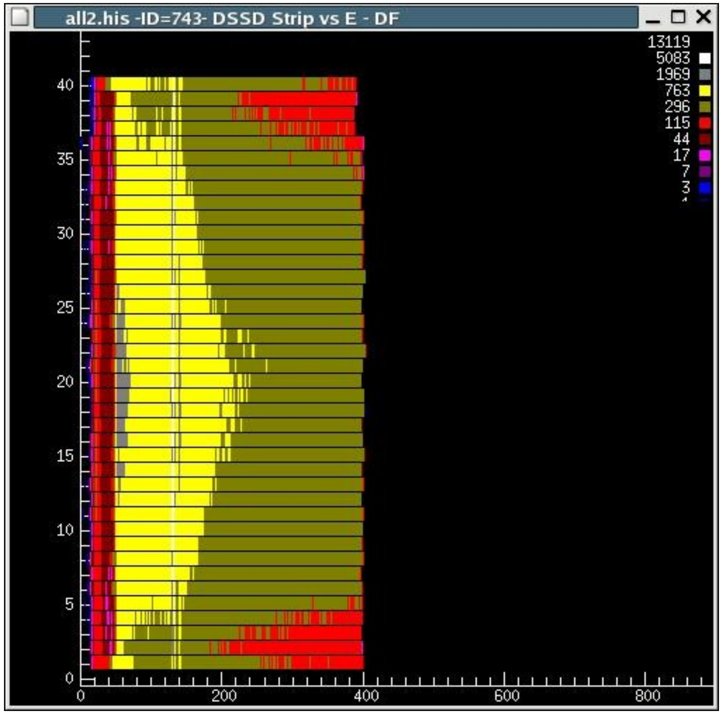


ALL low energy traces are recorded !

S.N. Liddick et al., Phys. Rev. Lett. 97 (2006), p. 082501.
I.G. Darby et al. Phys. Rev. Lett. 105(2010)
R. Grzywacz et al. NIM B Volume 261 (2007) p.1103

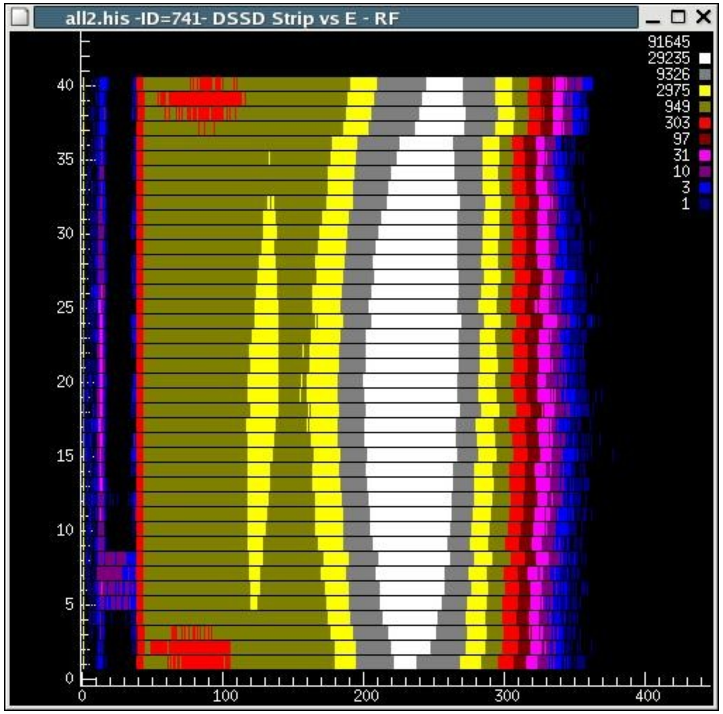
The trigger

DECAYS (pulse shapes)



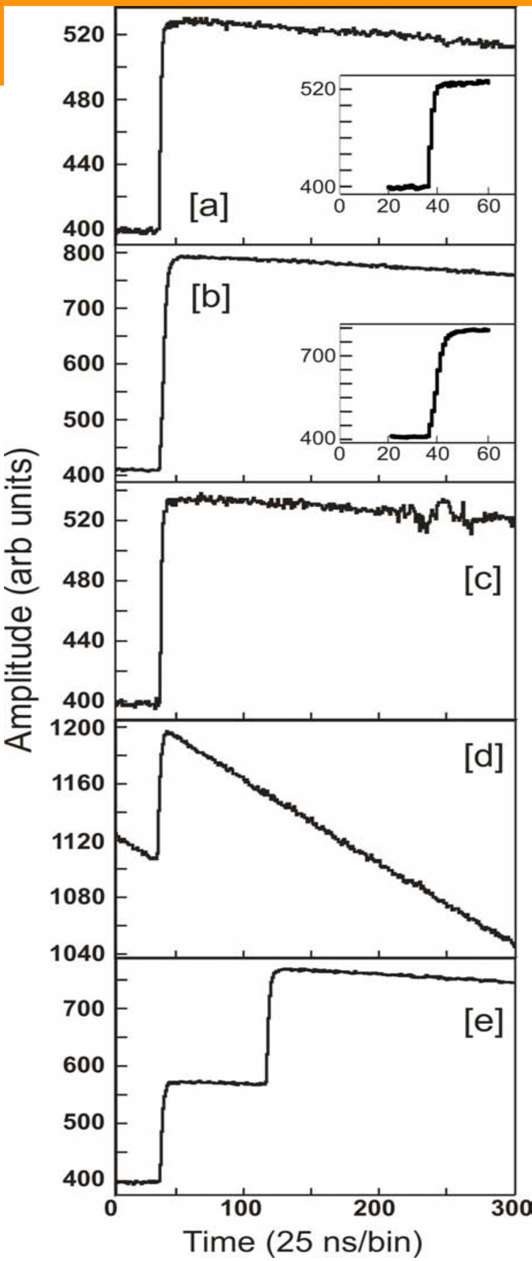
~10 MeV

RECOILS (Energy and time)



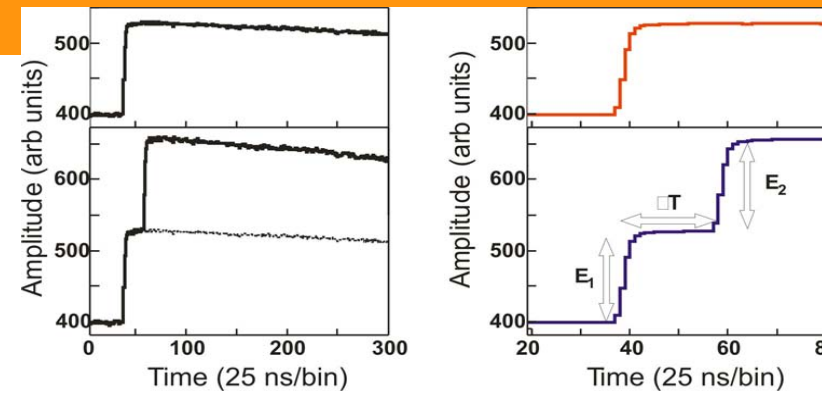
~80 MeV

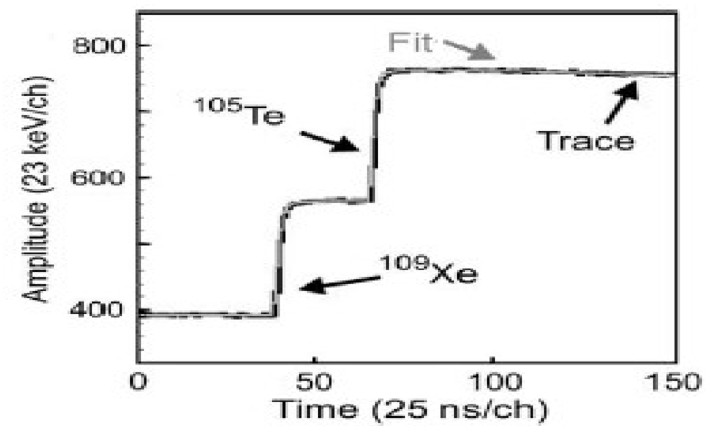
“alpha catcher” (software)

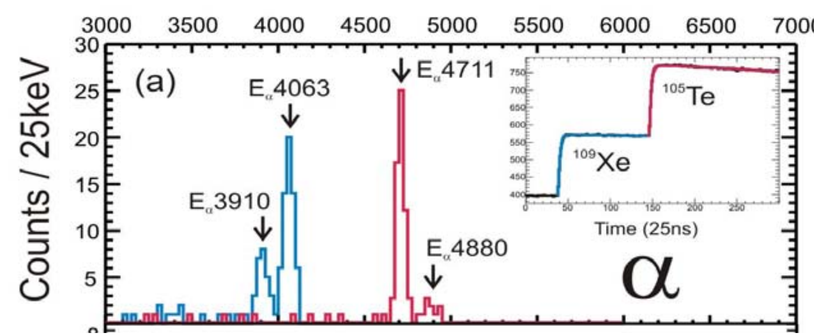


Generate superpulse data base

Search using single and double “superpulse” fit

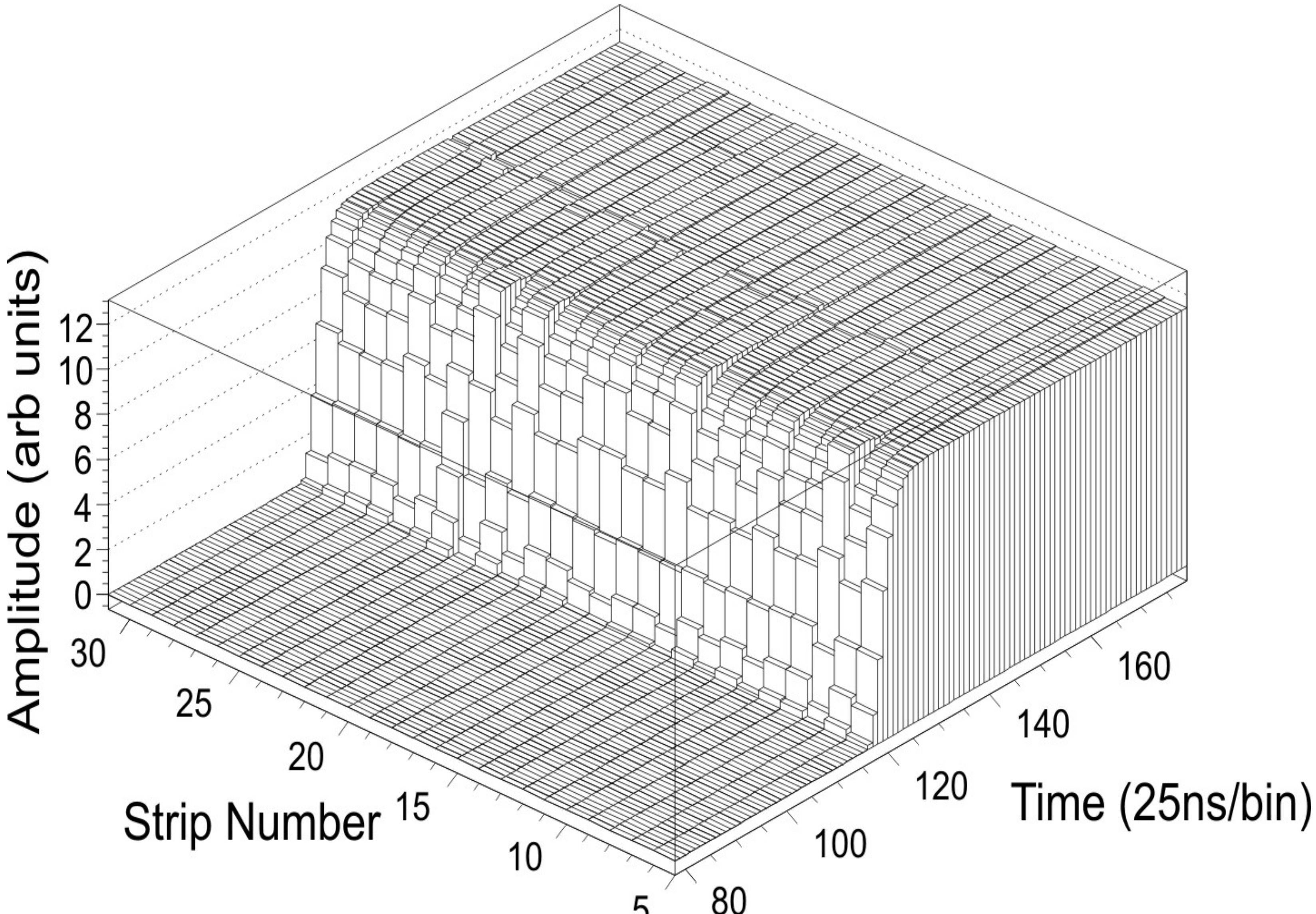




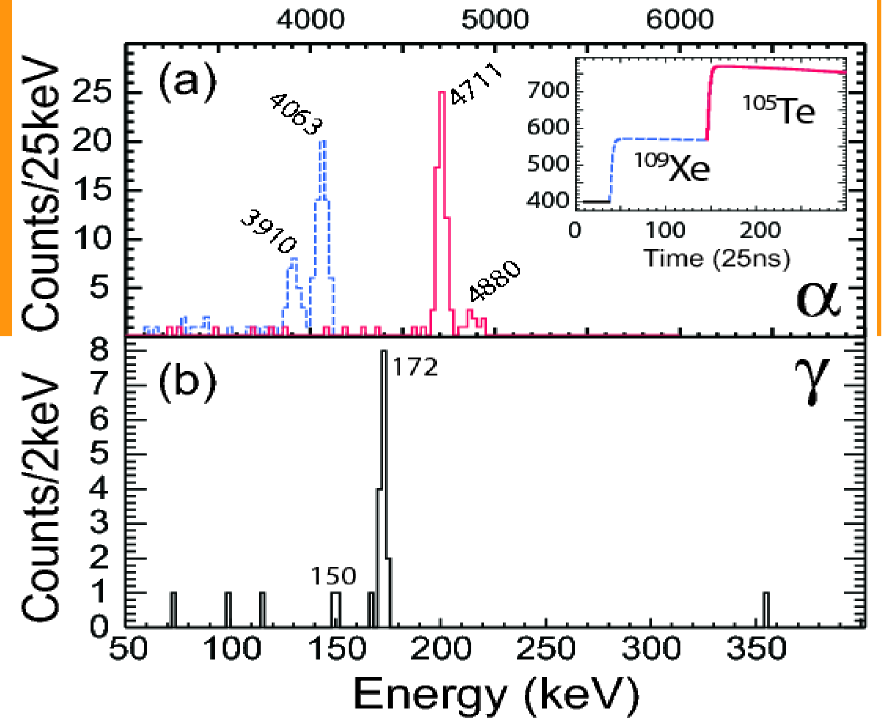


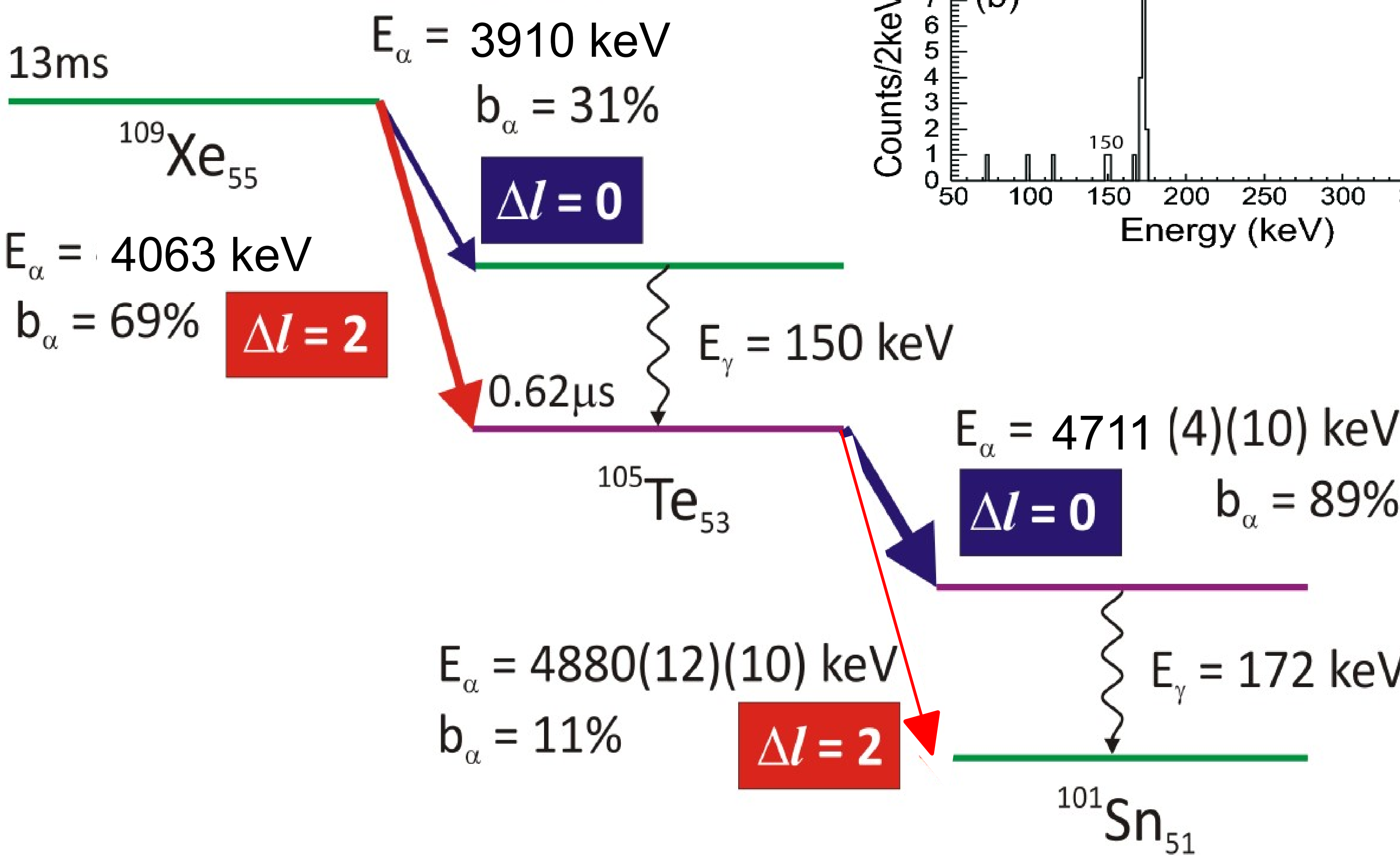
I.G. Darby and S.N. Liddick

Superpulse generation
- on-line data
- accounts for radiation damage

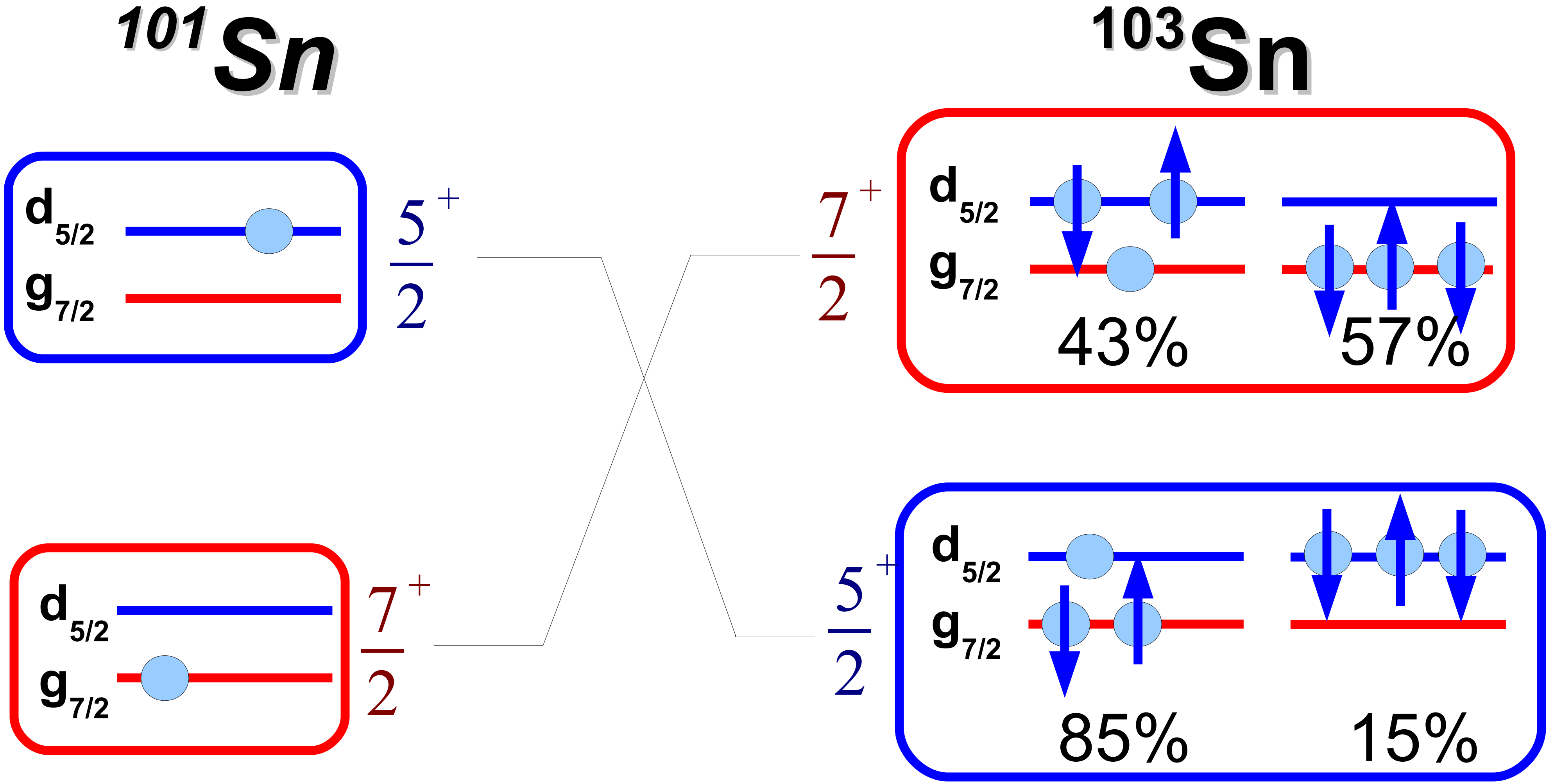


Experimental results
Main decay path: $^{105}Te \rightarrow ^{101}Sn$*





Dominant configurations in $^{101,103}Sn$



Strong pairing ($J=0^+$) TBME for the $(g_{7/2})^2$!!

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Isotope near 'doubly magic' tin-100 flouts conventional wisdom

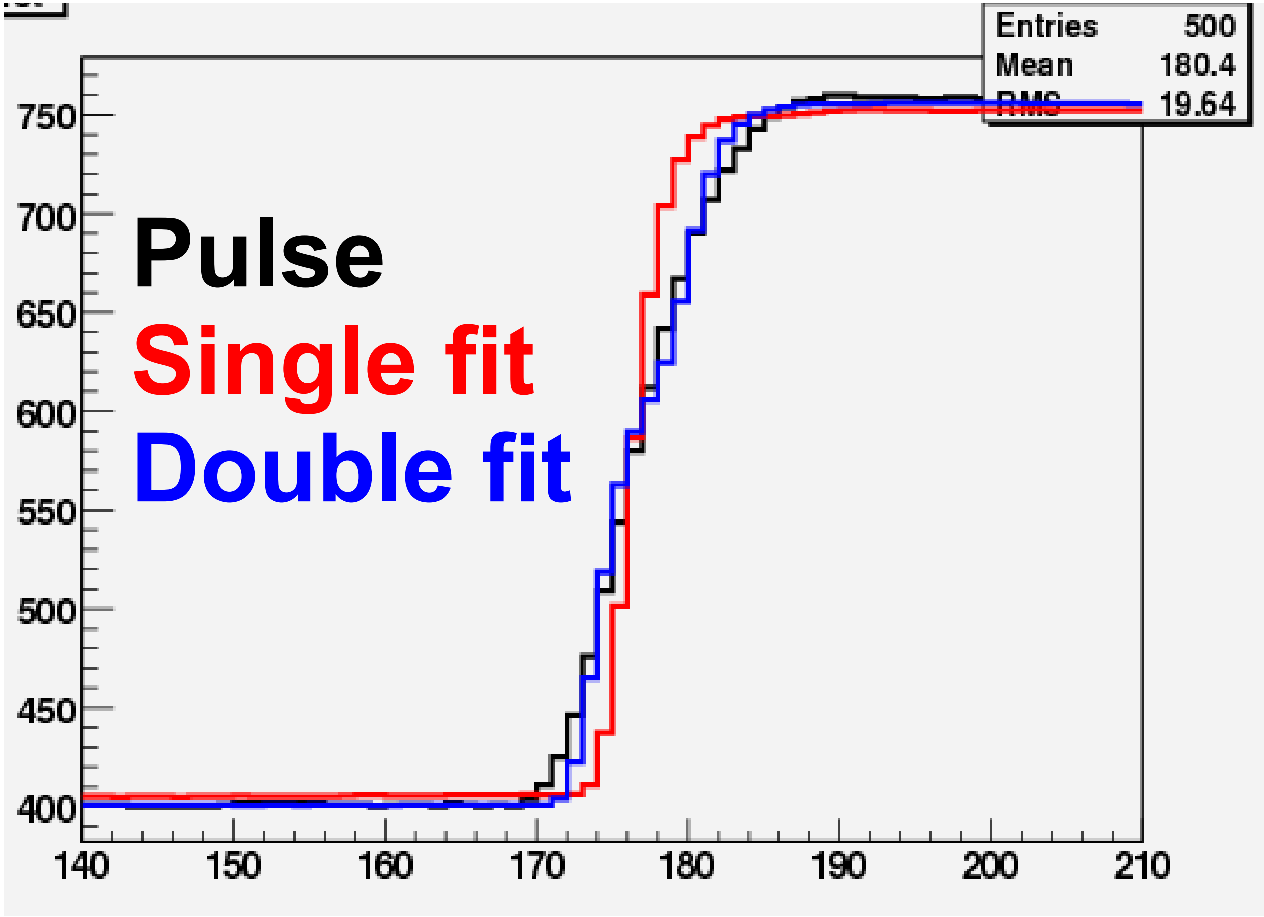
OAK RIDGE, Tenn., Oct. 21, 2010 — Tin may seem like the most unassuming of elements, but experiments performed at the Department of Energy's Oak Ridge National Laboratory are yielding surprising properties in extremely short-lived isotopes near tin-100's "doubly magic"

PRL 105, 162502 (2010) PHYSICAL REVIEW LETTERS week ending 15 OCTOBER 2010

Orbital Dependent Nucleonic Pairing in the Lightest Known Isotopes of Tin

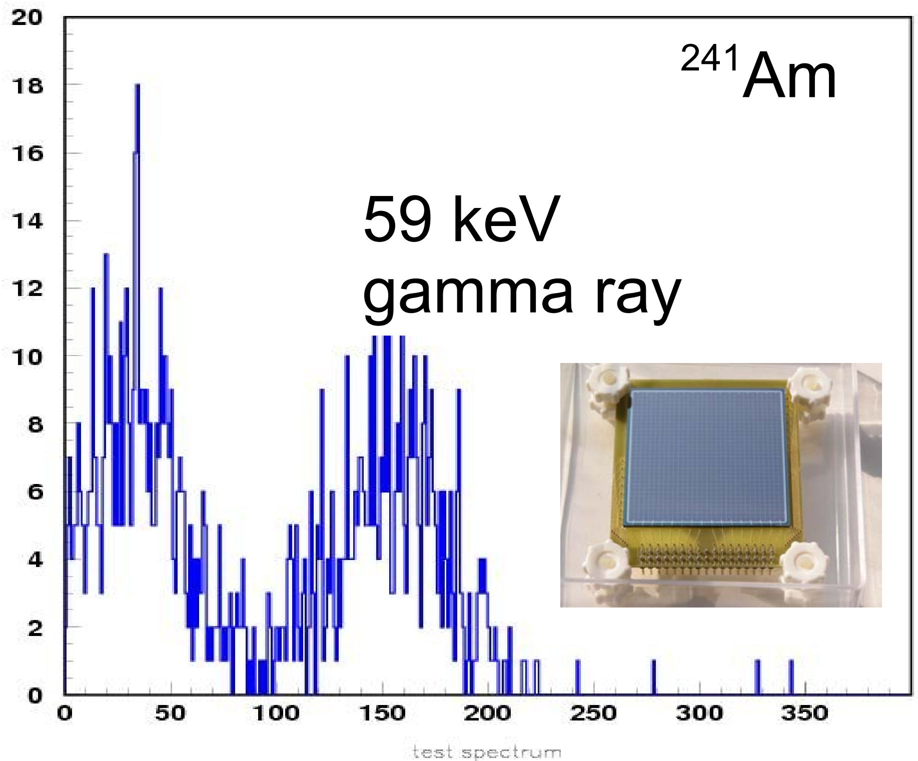
I. G. Darby,[1,2] R. K. Grzywacz,[1,3] J. C. Batchelder,[4] C. R. Bingham,[1,3] L. Cartegni,[1] C. J. Gross,[3] M. Hjorth-Jensen,[5] D. T. Joss,[6] S. N. Liddick,[1] W. Nazarewicz,[1,3,7] S. Padgett,[1] R. D. Page,[6] T. Papenbrock,[1,3] M. M. Rajabali,[1] J. Rotureau,[1] and K. P. Rykaczewski[3]

Short lived decays !

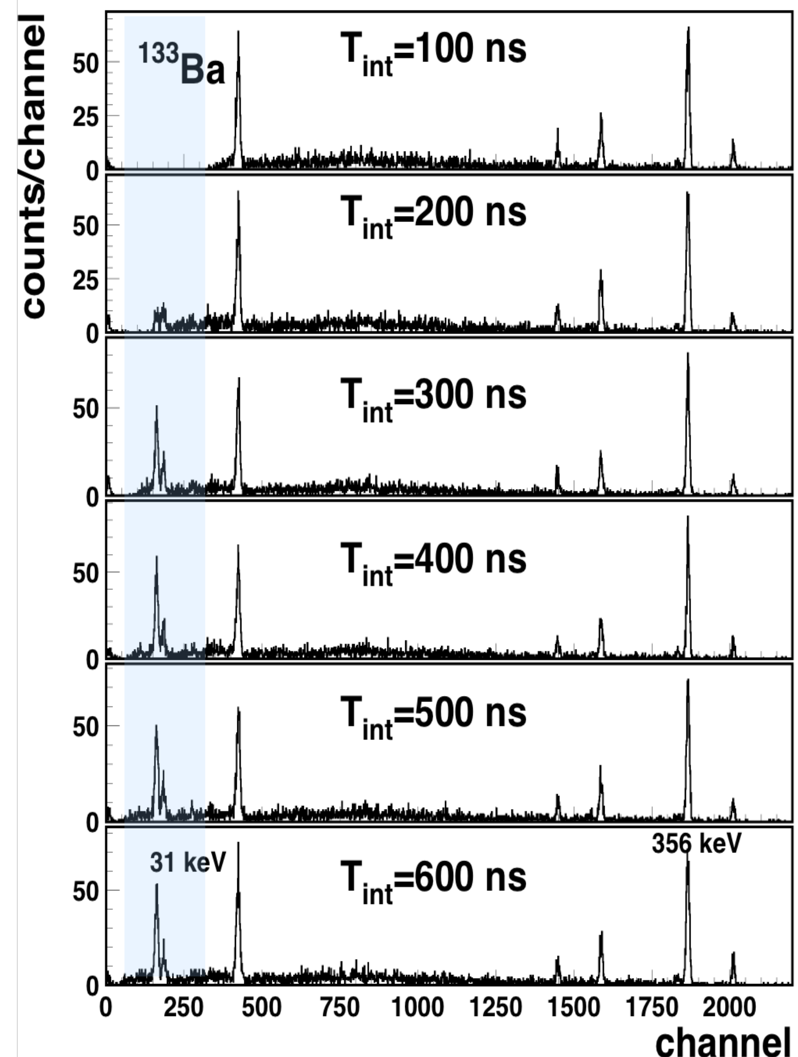


Low-energy threshold

Spectrum showing a 59keV gamma from ^{241}Am, as seen in a 1.5 mm thick Double-sided silicon strip detector (DSSD) at room temperature.



Large volume clover detector



Superheavies “firmware” (XIA,D. Miller, RG)

New operations mode of the Pixie (RevD) firmware:
- save energies and times for all signals
- save traces only for pile-up signals

Most efficient way to run the system.

Only the pileups within <100 ns time window will be missed because they won't be recognized as overlapping pulses.

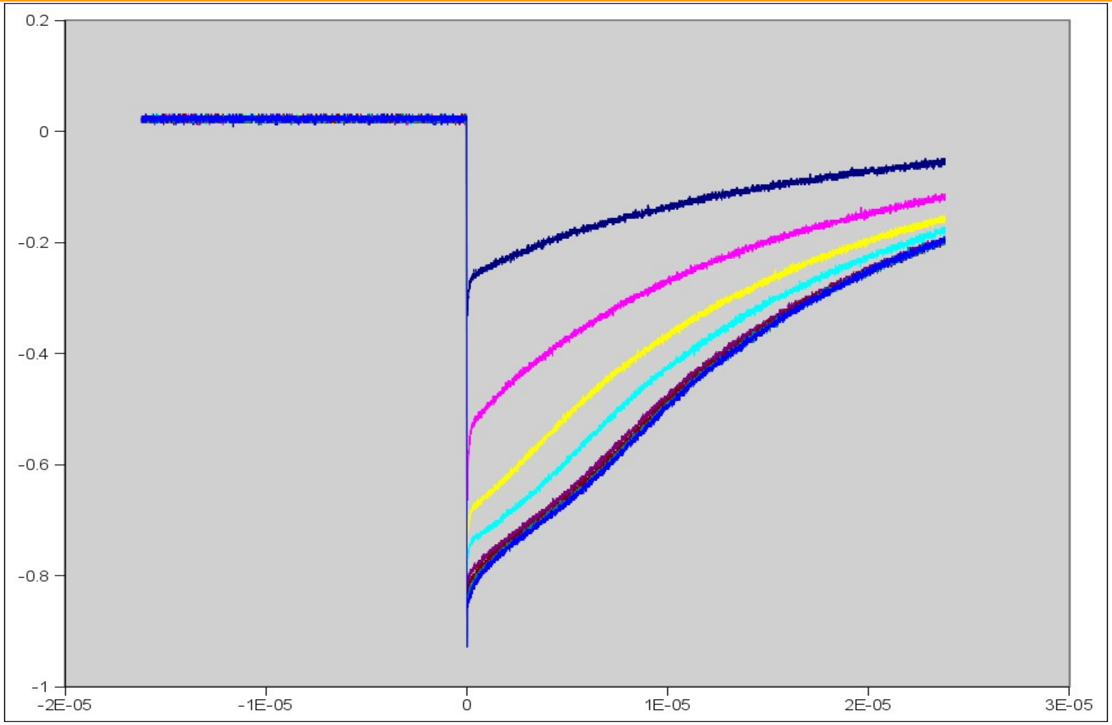
Internal dead-time issues are solved by the “ping-pong “ buffer at the FPGA input.

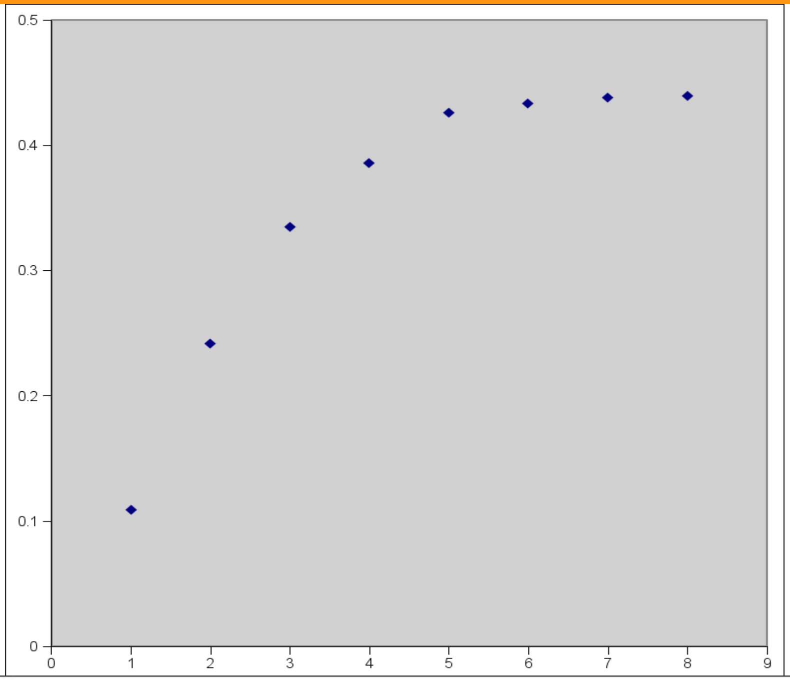
Superheavies “firmware”

The only problem to solve is the measurement of the fission signals.
Possible options:

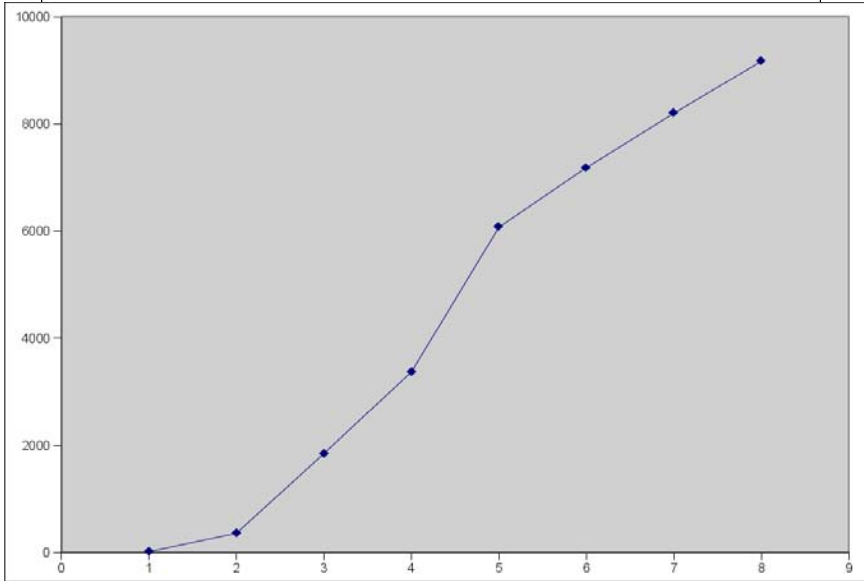
a) Accept the fact that the dynamic range is 200 MeV
b) Split the signals in high-gain and low gain,
c) Use only high gain (decays, implants) and “time over threshold” method to estimate energy of the fission fragments,
d) Use lin-log preamplifiers

Loggarithmic preamplifiers





~ 10% FWHM possible for the 200 MeV signals



Conclusions

Digital Signal Processing based system enabled discovery experiments on short lived proton and alpha emitters.

Pixie16 based acquisition systems developed and operational.

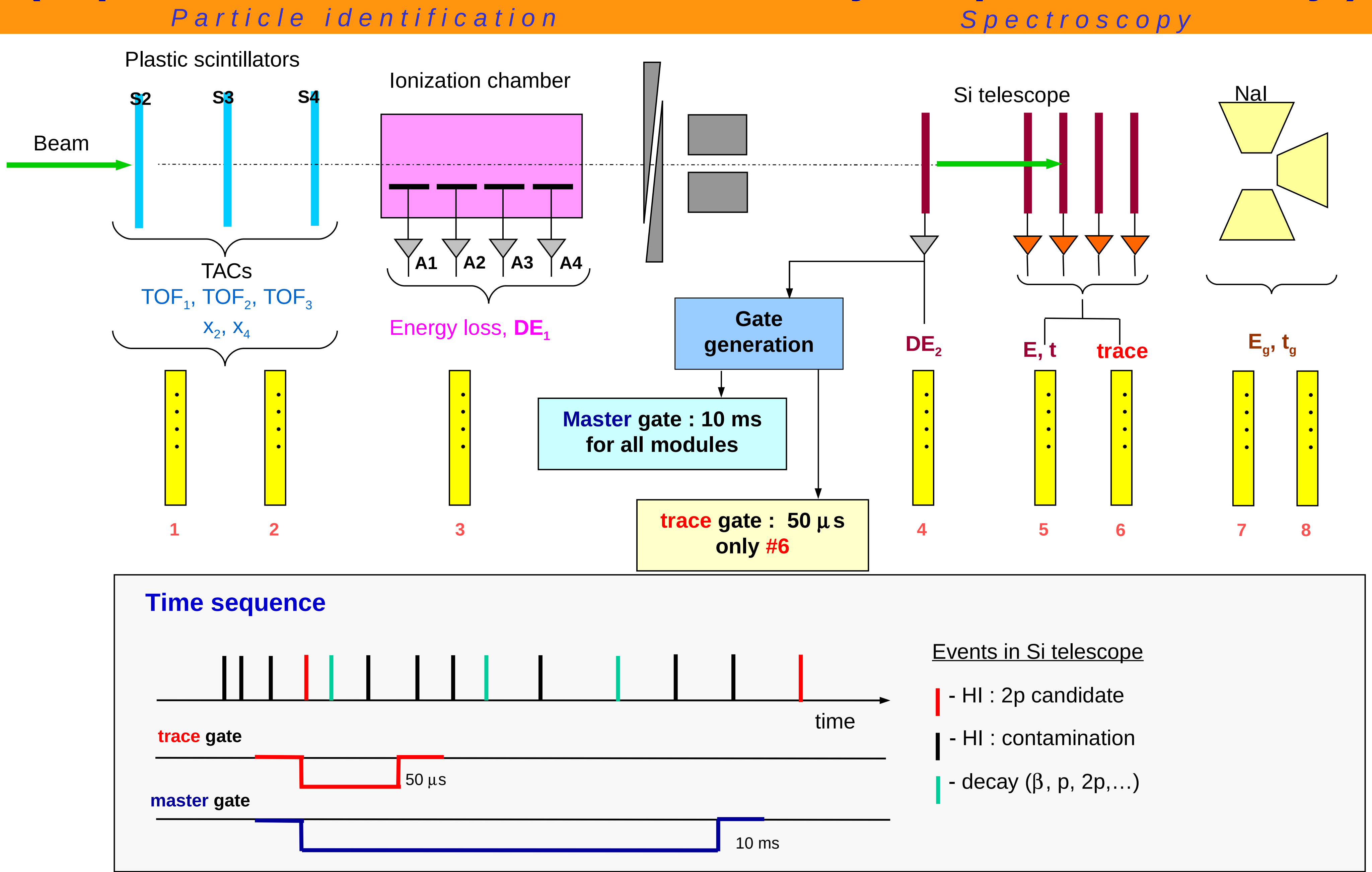
Tested in on-line experiments.

“Superheavies firmware” developed.

Digital developments made to improve detection sensitivities.

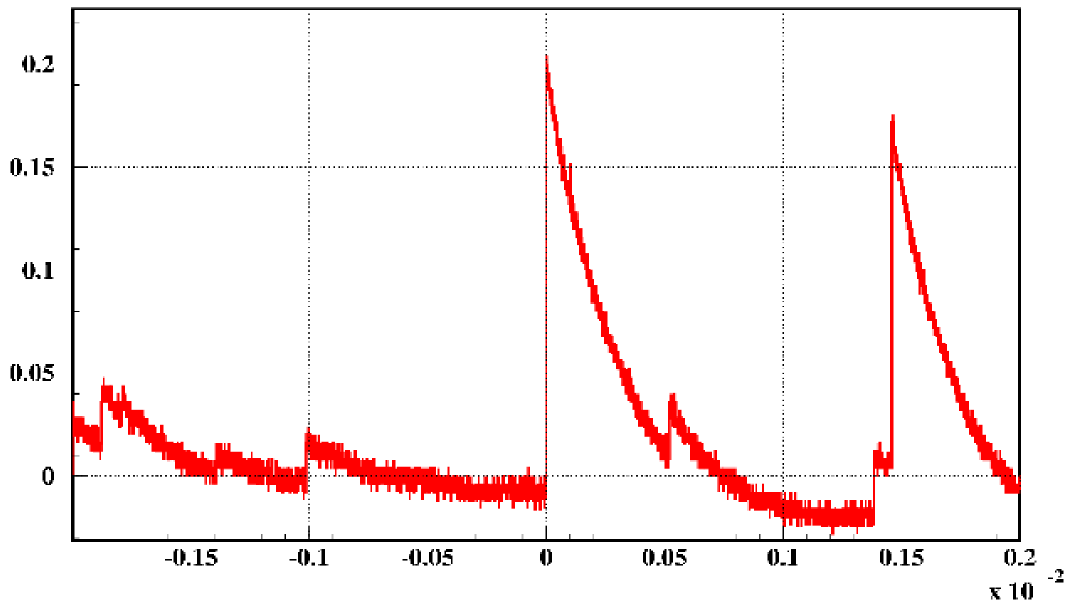
UTK people who contributed to these developments:
S.N. Liddick, I. G. Darby, D. Miller,
M. Madurga, S. Padgett, S. Paulauskas

...and @GSI
DGF based acquisition system
(implemented at GSI for the discovery of 2p – radioactivity)



Typical nuclear physics measurement

DIGITAL PULSE PROCESSING



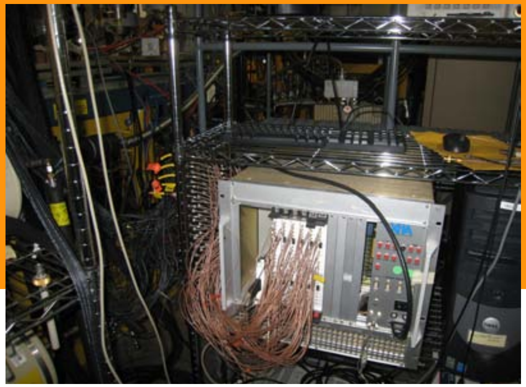
Measure time and amplitudes of individual PULSES

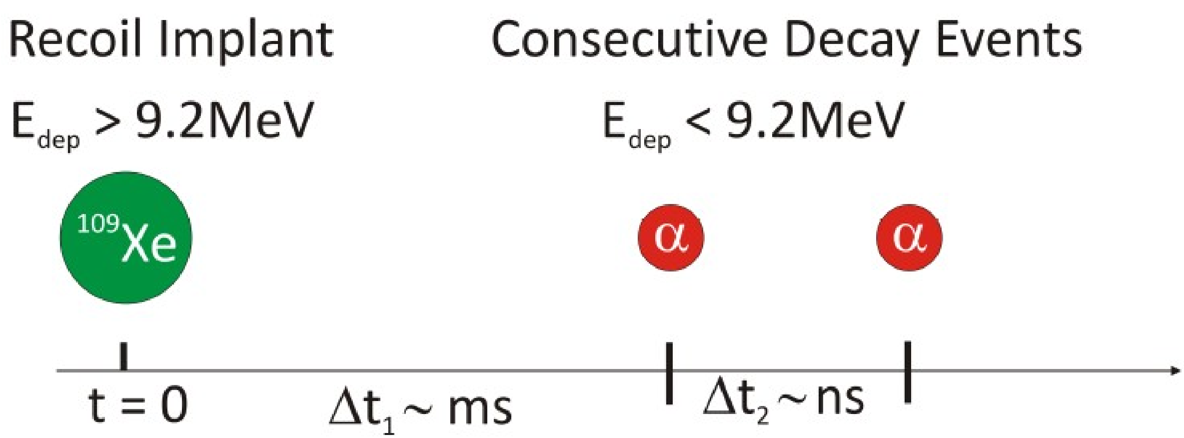
- time scales 100 ps – 100 us
- channel count (1-1000)
- event rate (mHz-MHz)
- pulse shape information (Mhz-GHz)
- high resolution

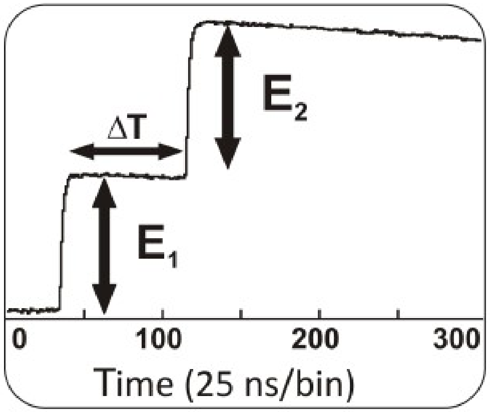
REAL TIME SIGNAL PROCESSING

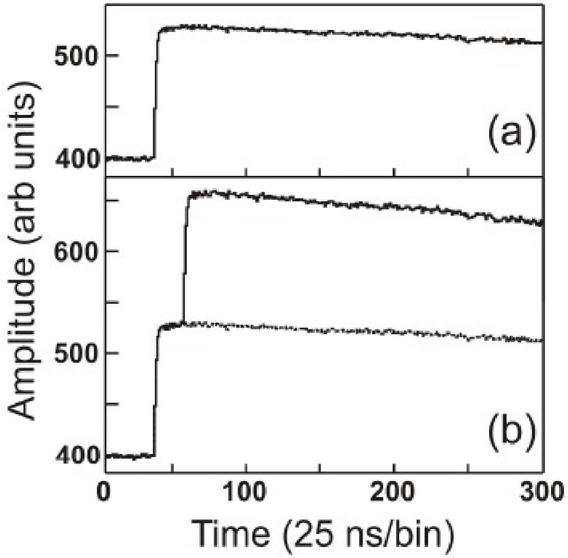
Digital Data Acquisition System

R. Grzywacz et al. Nuclear Instruments and Methods B **261**,(2007) p. 1103-1106

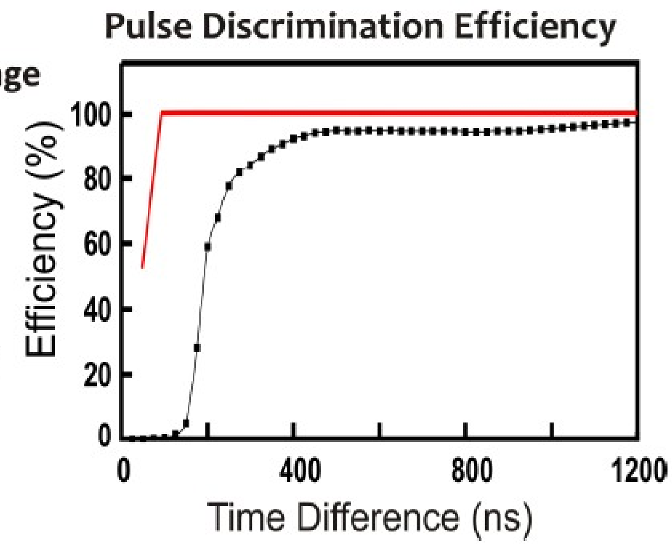


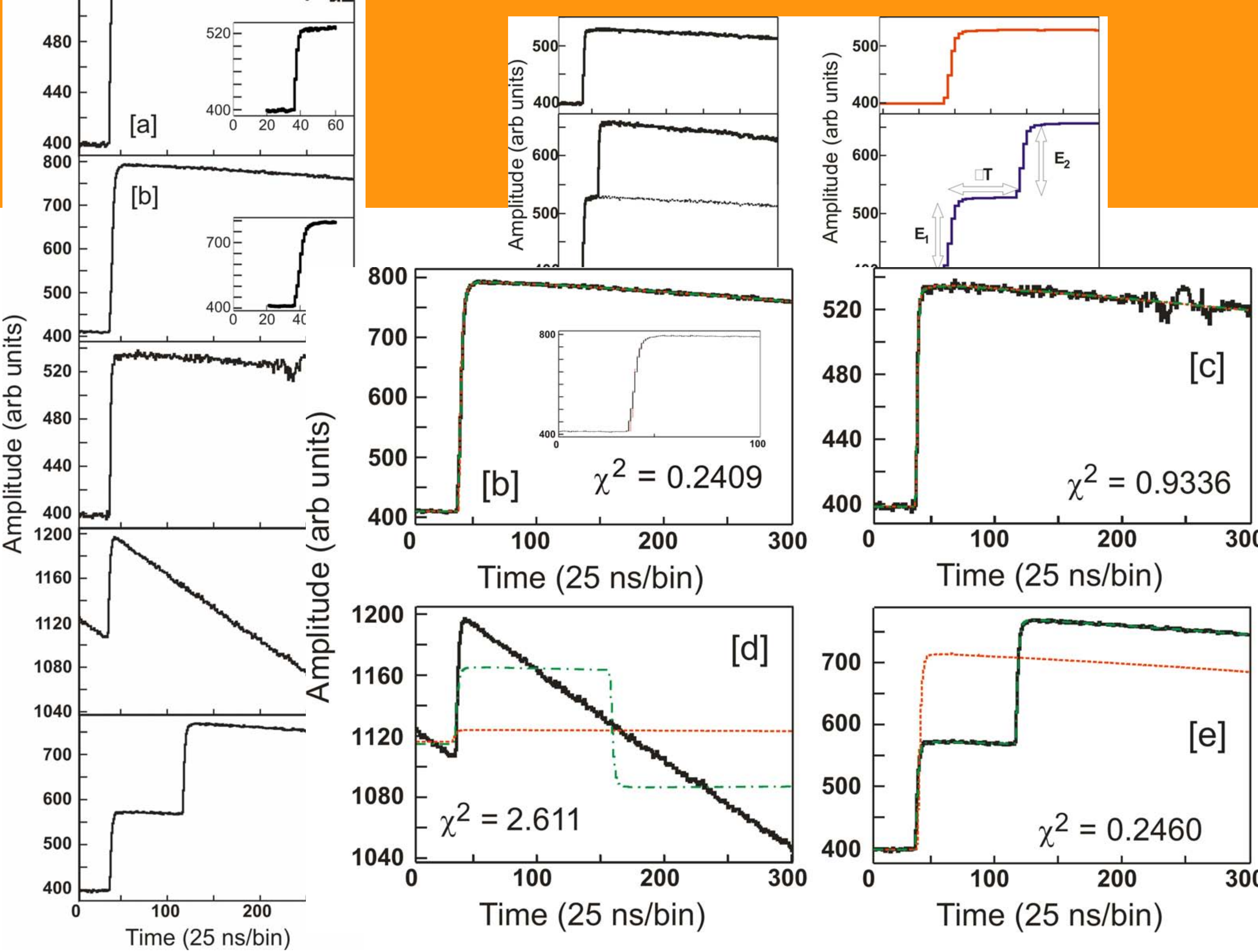




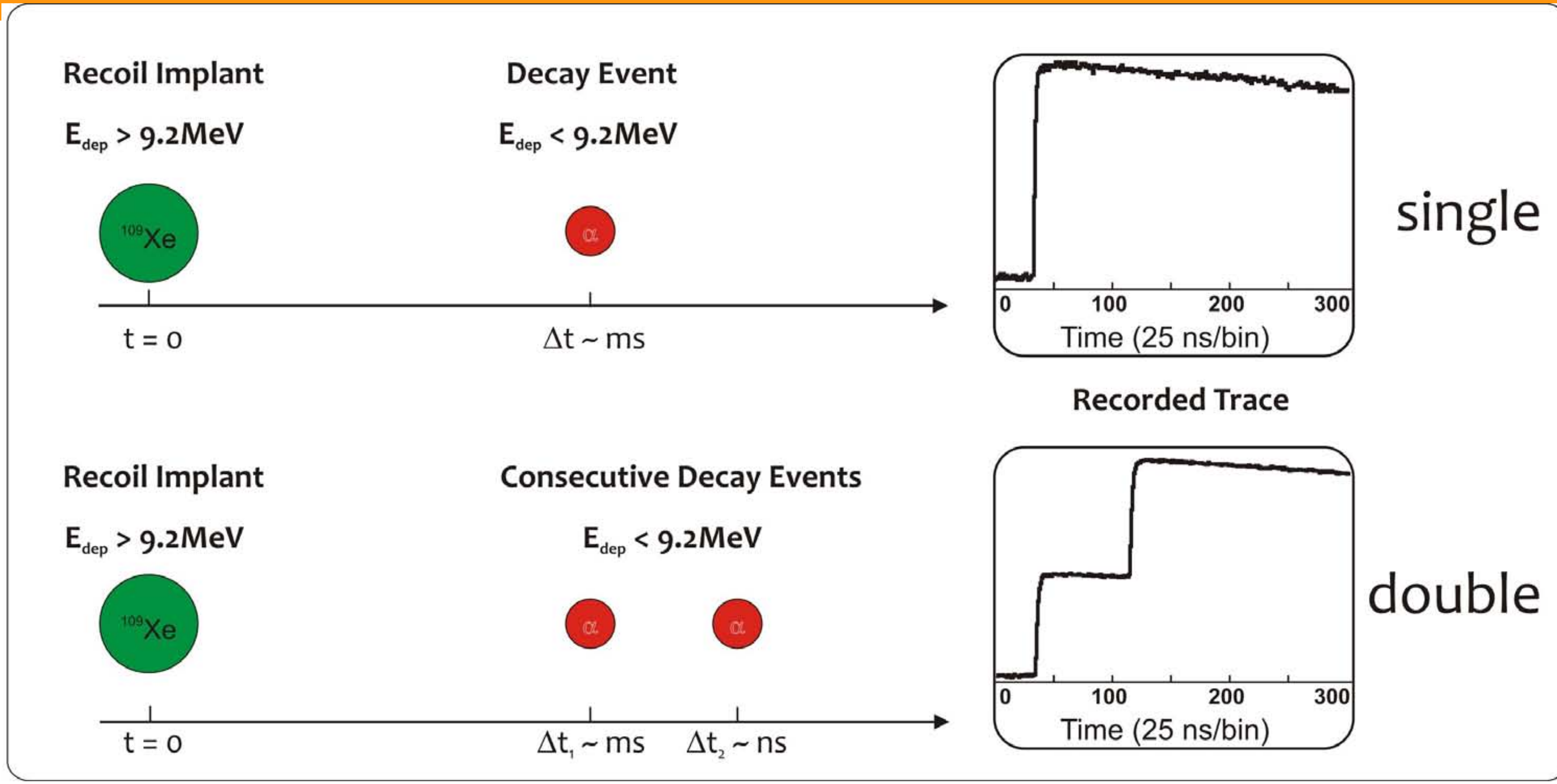


- ✧ Able to cope with radiation damage
- ✧ 2006 calibration: ^{241}Am source
- ✧ 2007 sets:
  - internal "running" calibration
  - "best" singles ^{109}Te E_a = 3107 keV
  - new database every ~200mins





[a]
[b]
[c]
[d]
[e]
Amplitude (arb units)
Time (25 ns/bin)
E1
E2
T
χ2 = 0.2409
χ2 = 0.9336
χ2 = 2.611
χ2 = 0.2460


Recoil Implant
E dep > 9.2MeV
109Xe
t = 0
Decay Event
E dep < 9.2MeV
α
Δt ~ ms
0
100
200
300
Time (25 ns/bin)
single
Recorded Trace
Recoil Implant
E dep > 9.2MeV
109Xe
t = 0
Consecutive Decay Events
E dep < 9.2MeV
α
α
Δt1 ~ ms
Δt2 ~ ns
0
100
200
300
Time (25 ns/bin)
double

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

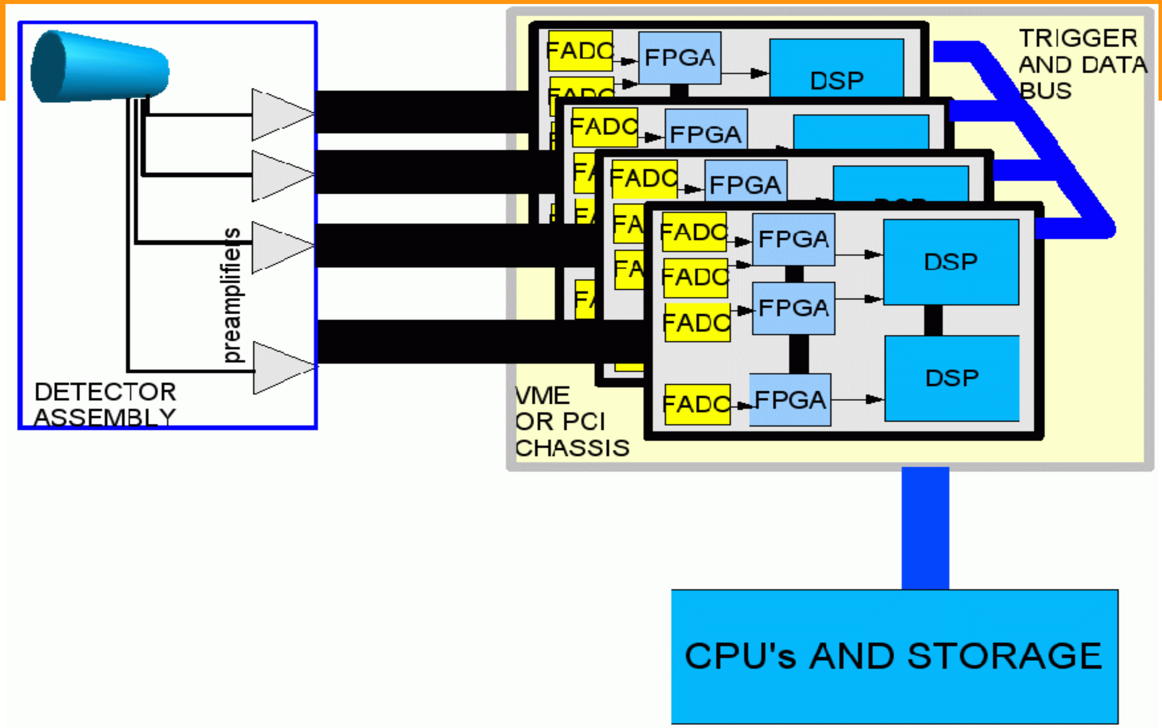
~ 100 kB/second/channel = 360 MB/hour/channel

CAMAC, VME, PXI/PCI, USB

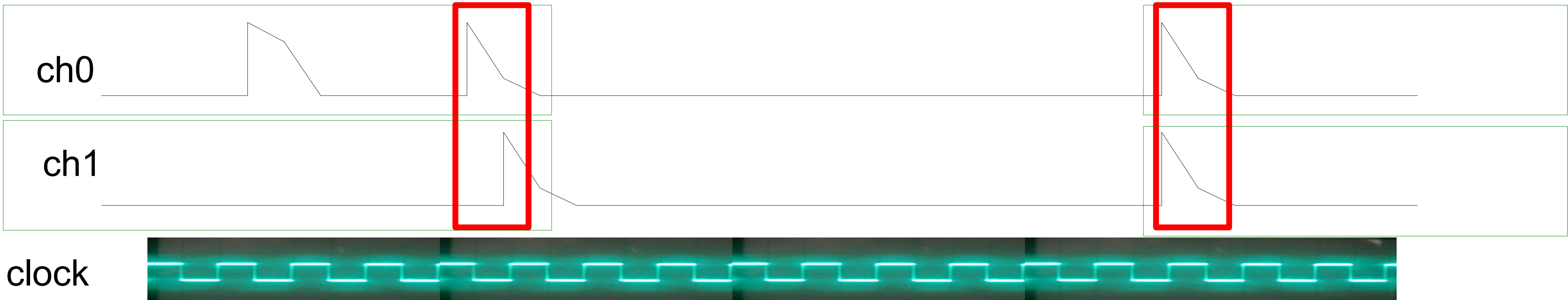
Gb-ETHERNET, INFINIBAND

Redundant Data Storage

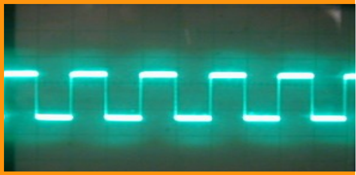
Time stamping and event builder



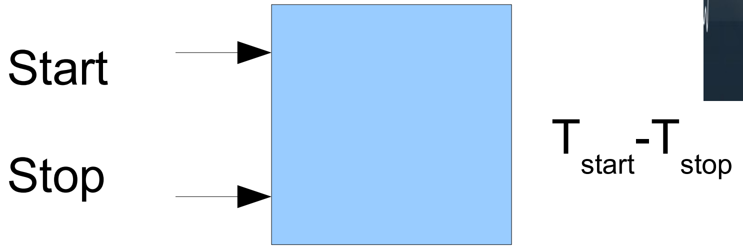
Each channel produces individually time stamped externally tiggered or self triggerd sub-events assembled into data buffers for each module

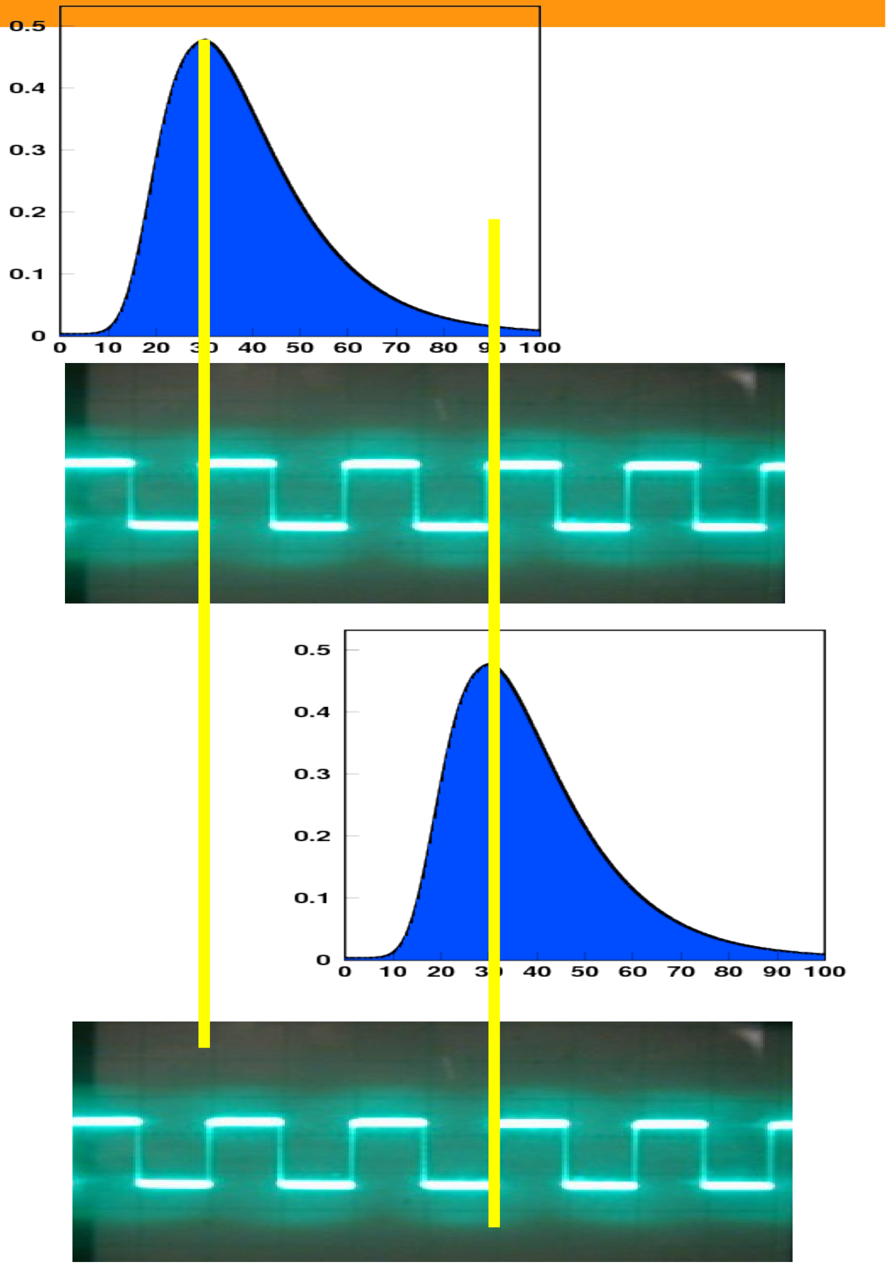


The clock synchronization



Usual analog timing





Sometimes: event time stamping

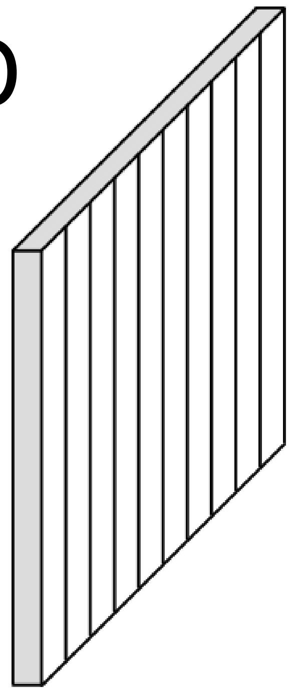
Digital system is
implicitly syncronized !
Any time correlation
can be measured
with precision only given
by the accuracy of the clock.

34404323422-34404323422=2

Implantation detector upgrade

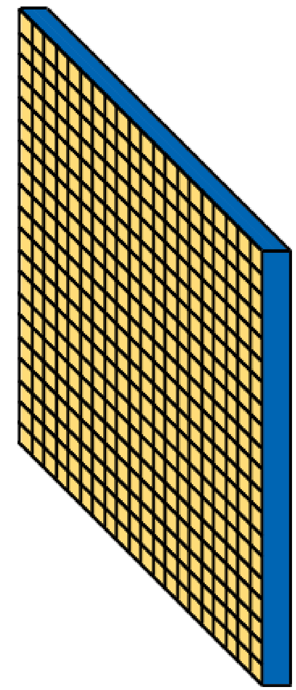
PSSD

analog
electronics



DSSD

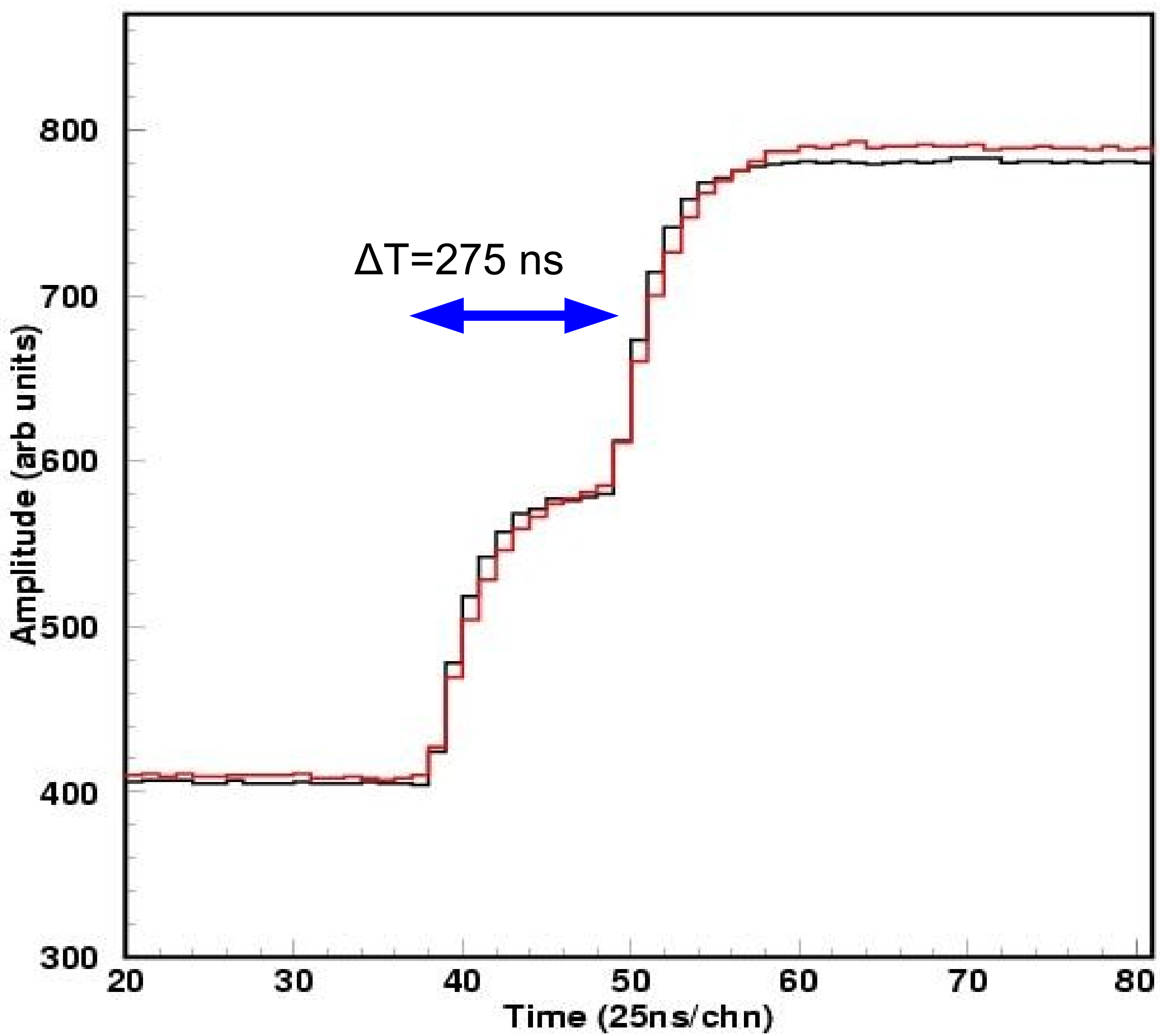
digital
electronics (μs)



- 10 strips each 10 mm wide
- horizontal sensitivity ±5 mm
- vertical position sensitivity ±0.7 mm
- "pixel" size ~14 mm^2

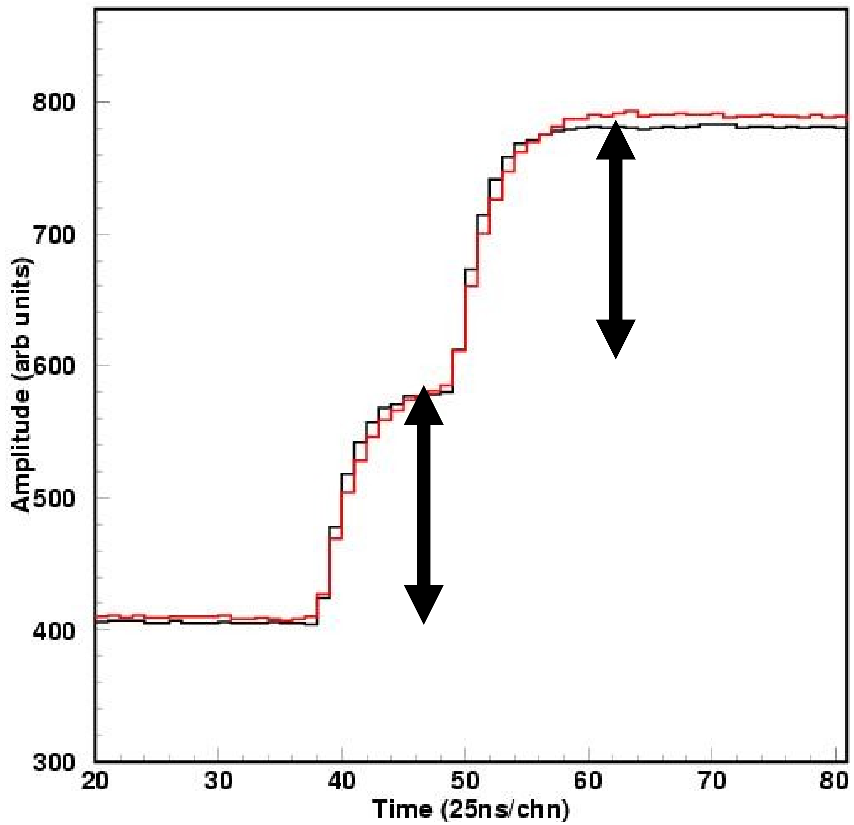
- 128x128 strips 0.9x 0.3 mm wide
- horizontal sensitivity ±0.45 mm
- vertical sensitivity ±0.15 mm
- "pixel" size ~ 0.27 mm^2
- useful for Oak Ridge studies

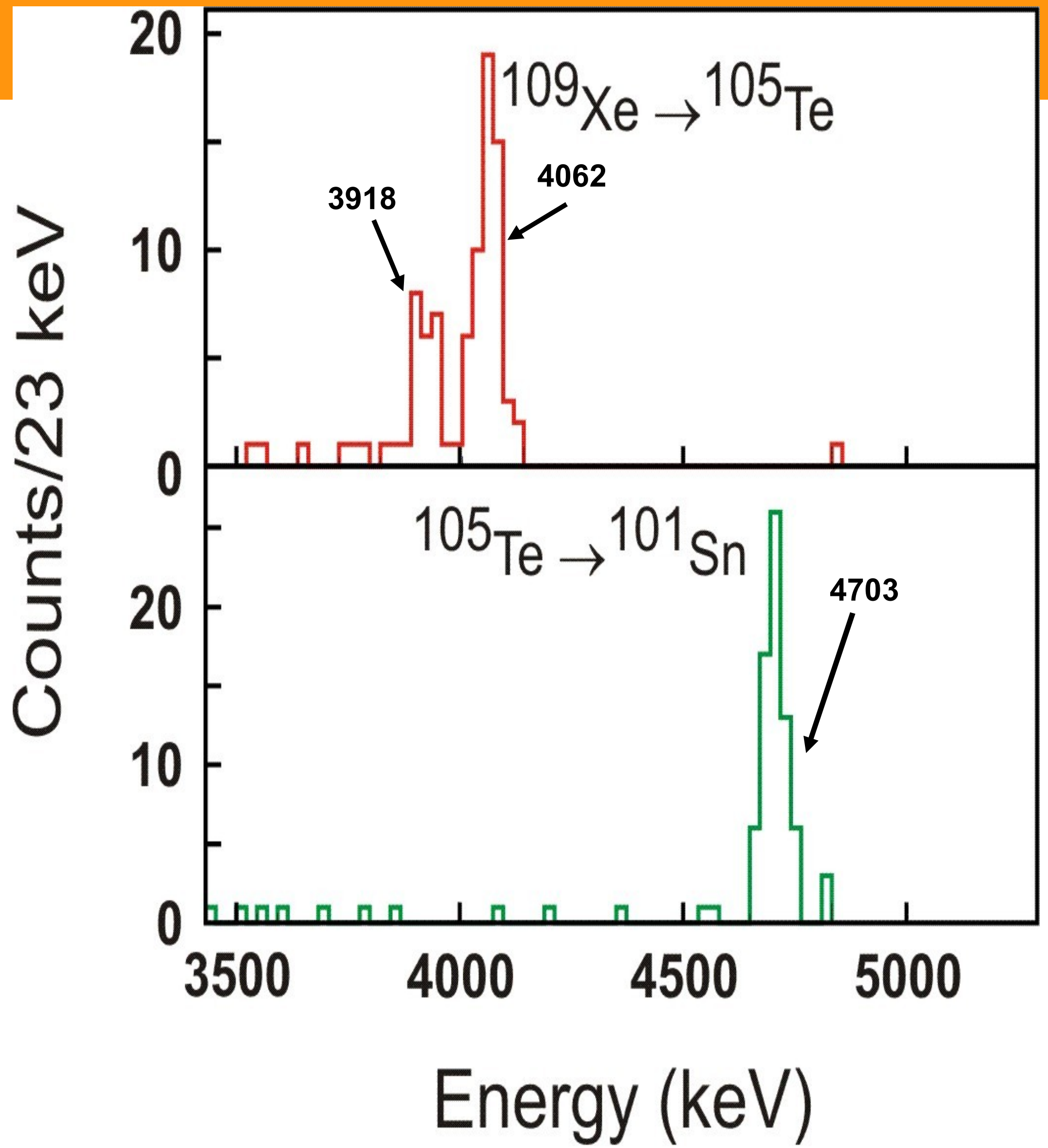
The fastest found decay !



Sophisticated algorithm to search data for "double pulses" and extract amplitudes.
RG et al. NIM B 261 (2007)

Alpha energy spectra





Role of digital electronics:
Low detection threshold example

Spectrum showing a 59keV gamma from ^{241}Am, as seen in a 1.5 mm thick Double-sided silicon strip detector (DSSD) at room temperature.