Hardware and software development for fast digital processing of signals from nuclear physics detectors

Luigi Bardelli
I.N.F.N. and University of Florence, ITALY

for the **NUCL-EX** collaboration

With contributions from: M.Bini, A.Boiano, R.Ciaranfi, A.Ordine, G.Pasquali, G.Poggi, N.Taccetti

- Introduction
- A custom digital sampling system for HI exp.
  - First prototype
  - Modular system
- Digital Signal Processing:
  - Amplitude measurements
  - Timing measurements (signal rise time and time of flight)
- Experimental tests with various detectors
  - ΔE-E, CsI(Tl), Germanium, Silicon, fast Plastic, Gas, ...
- Conclusions

One of the main purposes of nuclear dynamics studies is the investigation of nuclear matter far from the stability line

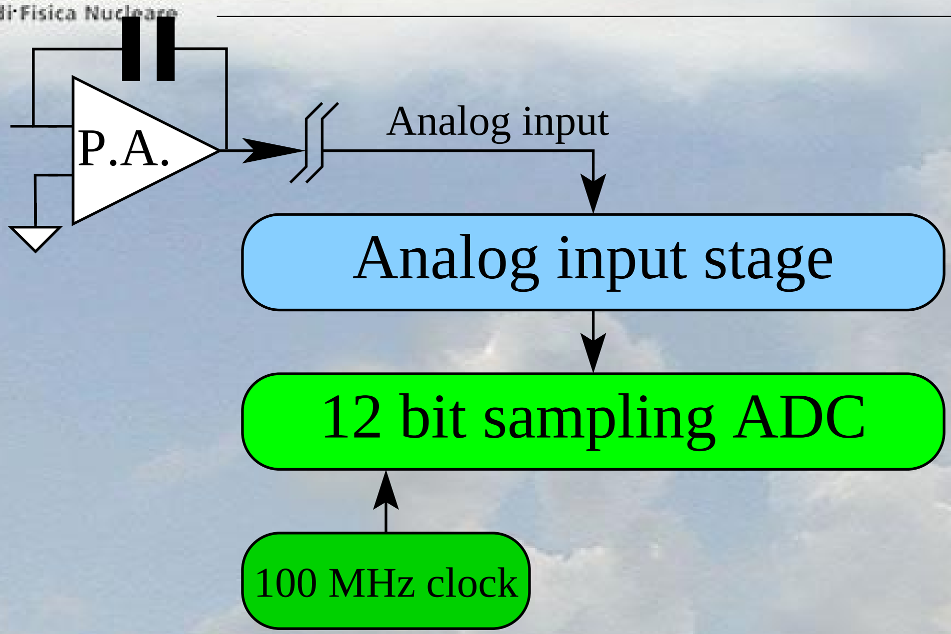
⇓ Strong requirements on experimental capability of **charge** and **mass** identification.

⇓ High detection granularity, and thus a very **high number** of electronic channels.

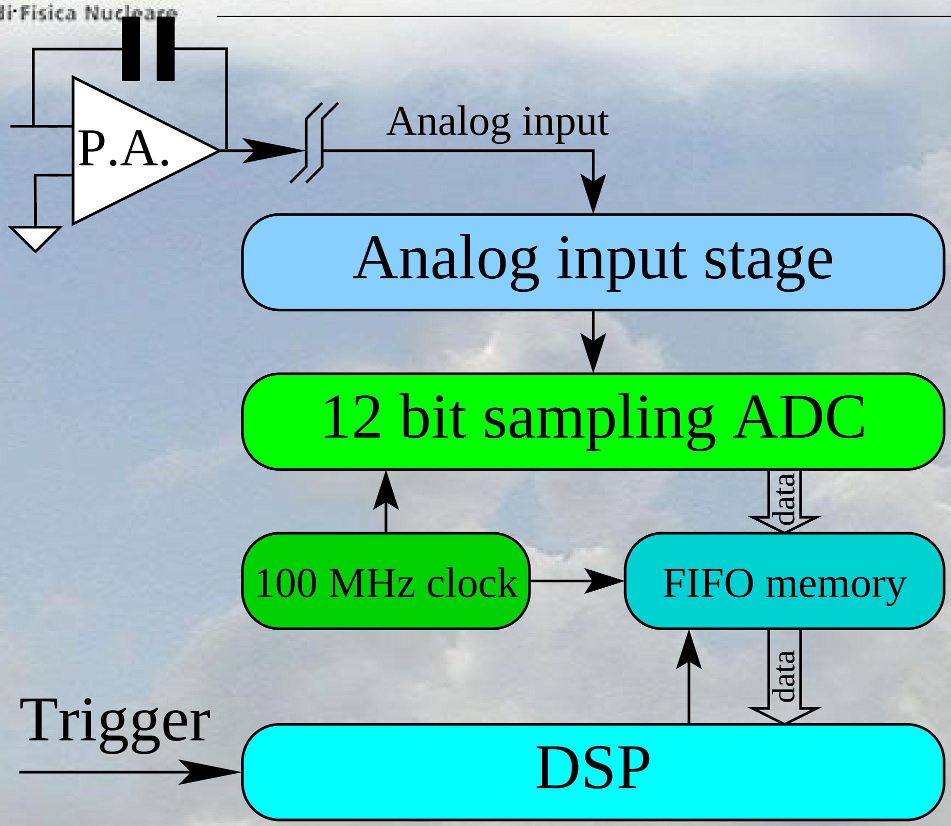
Both requirements can benefit from the use of **fast digital sampling techniques**:

- **Performances** as good as standard analog techniques
- Much **simpler electronic setup**: a **single sampling ADC** can extract all the information needed from a detector preamplifier (**energy, pulse shape, timing**)

$\Rightarrow$ much lower costs.



Custom system designed and built in Florence (end of 2000)



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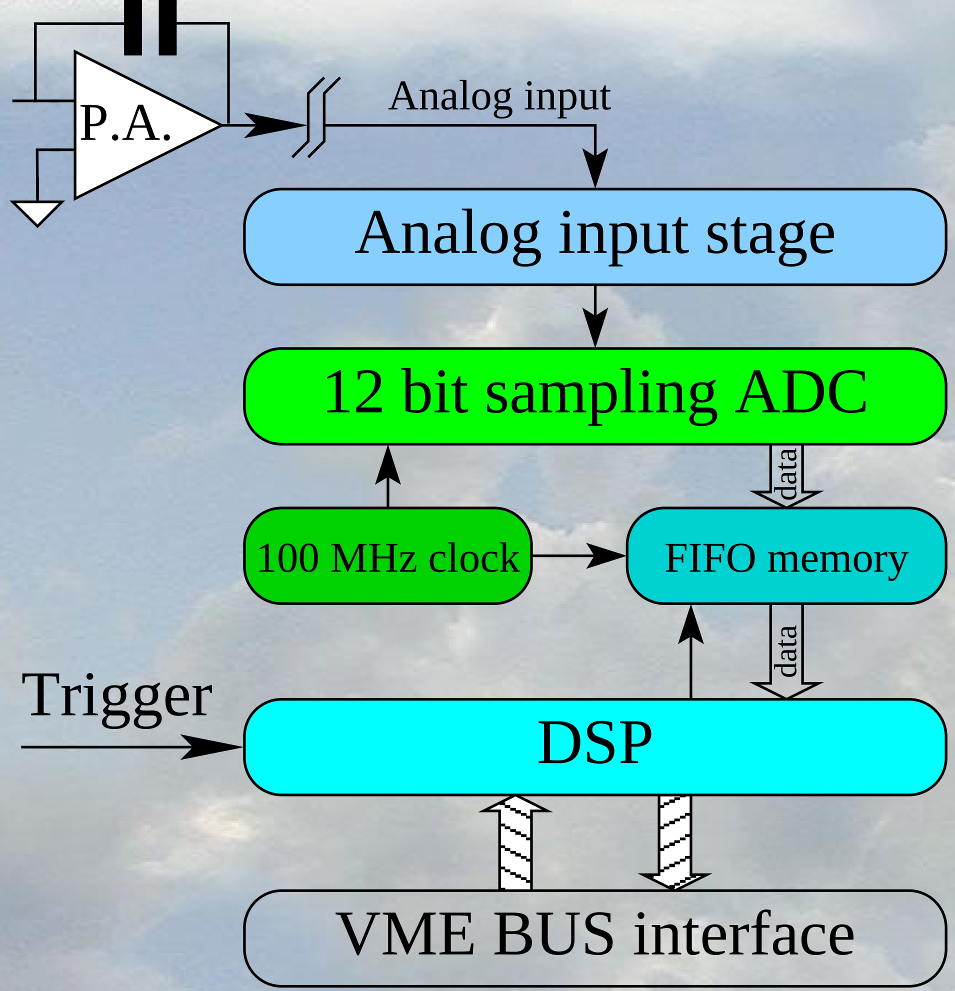

Custom system designed and built in Florence (end of 2000)

- Constant phase antialiasing input stage.
- **100 MSamples/s, 12 bit** fast Analog-to-Digital Converter.
- Digital Signal Processor (DSP) for **on-line** processing of detector signals: **one processor can compute many variables**
- Data readout via VME bus.

A first prototype (without DSP) is described in: L.Bardelli, M.Bini, G.Poggi, N.Taccetti, Nuclear Instruments and Methods in Physics Research **A491** (2002) 244-257

A new **modular system** has been developed in our Florence lab. (for NUCL-EX @ Legnaro):

single channel Each digital acquisition channel (ADC, DSP, *glue* logic) is realized on a small-size board

motherboard A single motherboard houses 8 channels and provides an unified interface to the acquisition system (both FAIR and VME)

Each channel can be individually controlled and programmed remotely.
FAIR multi-event acquisition system developed by Naples group.

Photo of a single channel board: (begin of 2004)

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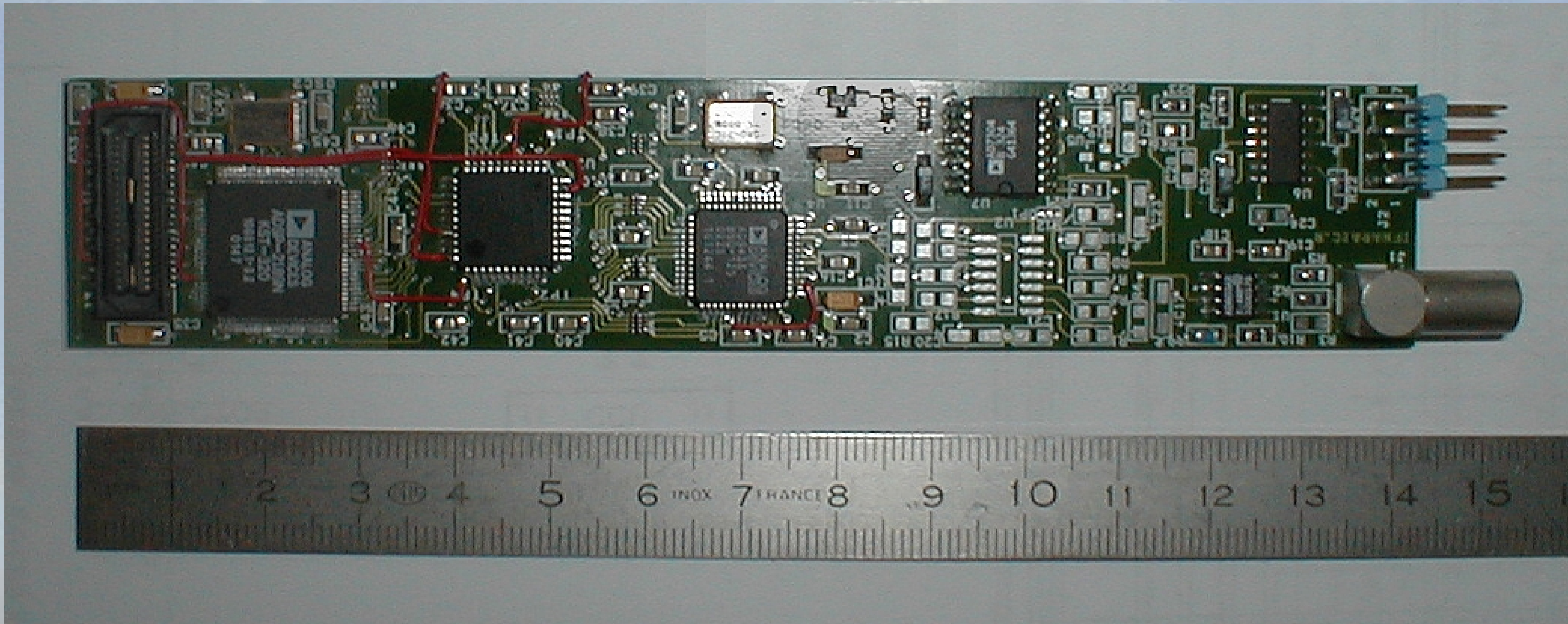

Complete digital channel on 14x2.6 cm^2 PCB

M.Bini, A.Boiano, R.Ciaranfi,
A.Ordine, G.Pasquali, L.B.

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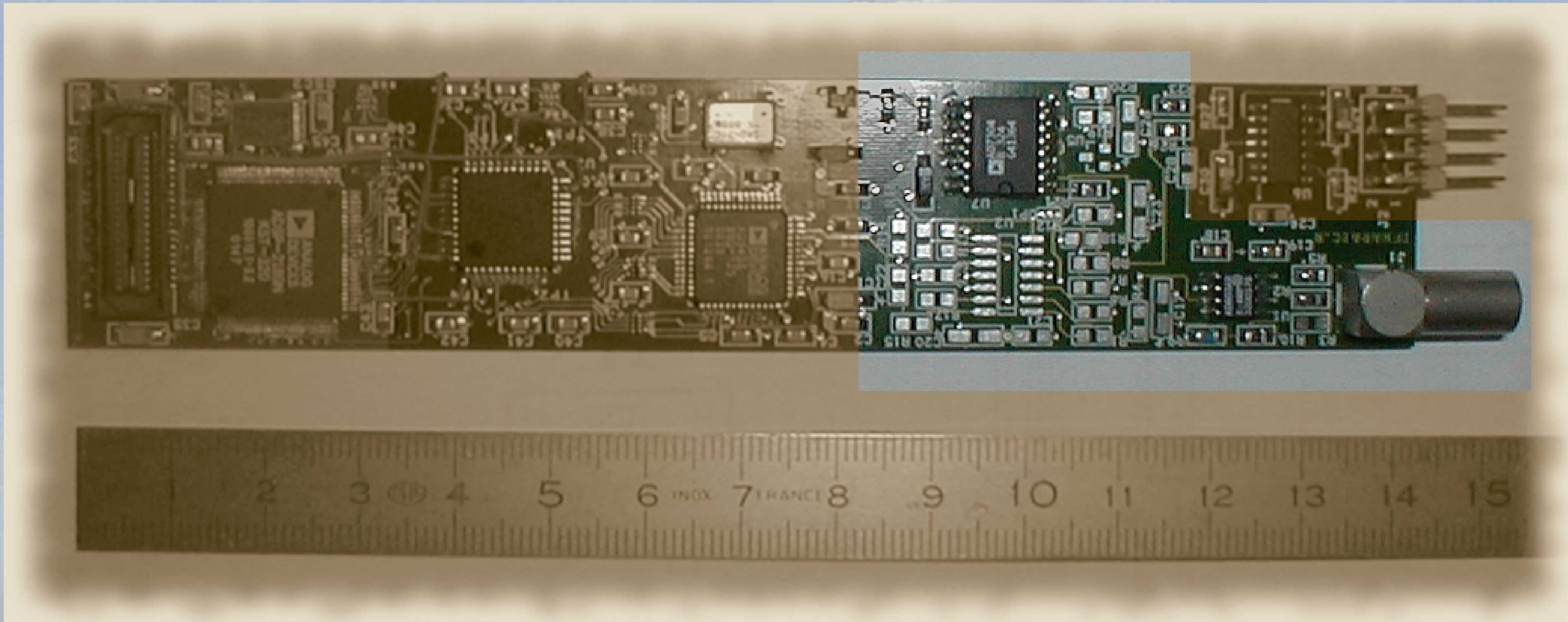
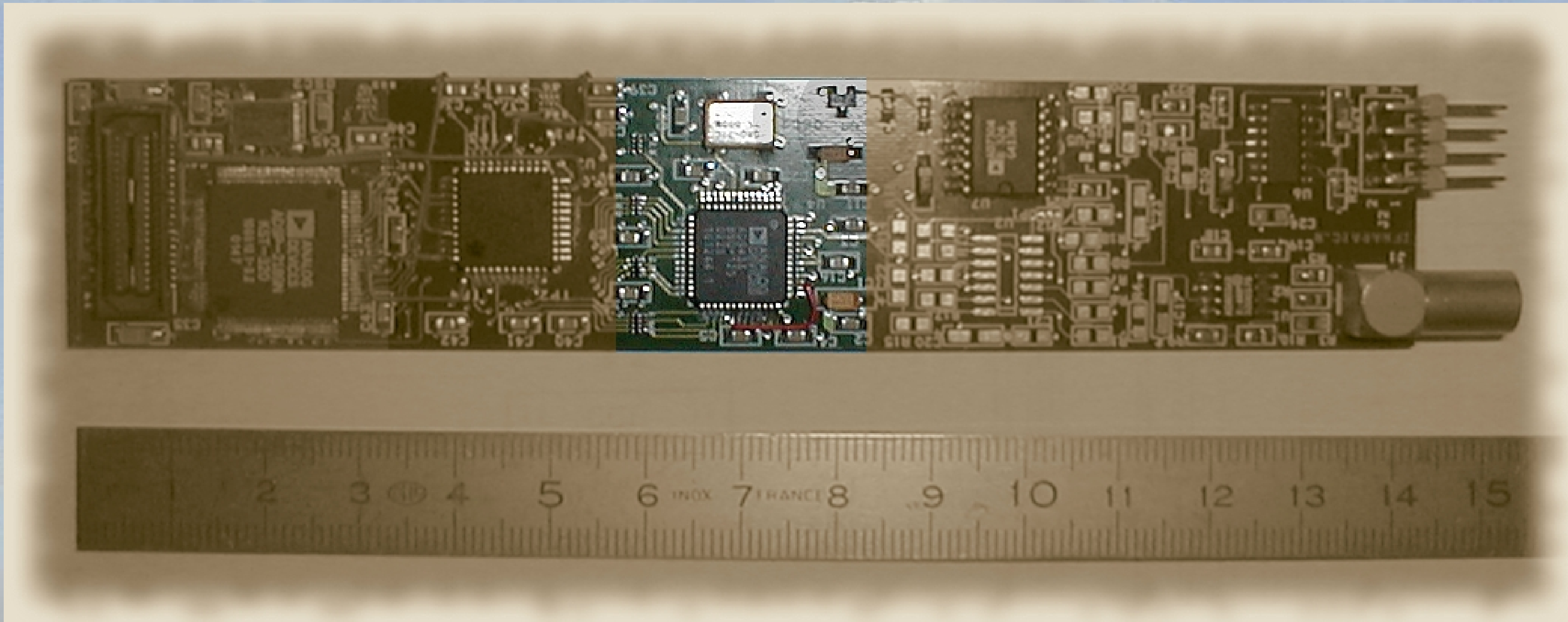


Analog section

- Antialiasing filter
- Programmable gain amplifier
- Two programmable thresholds

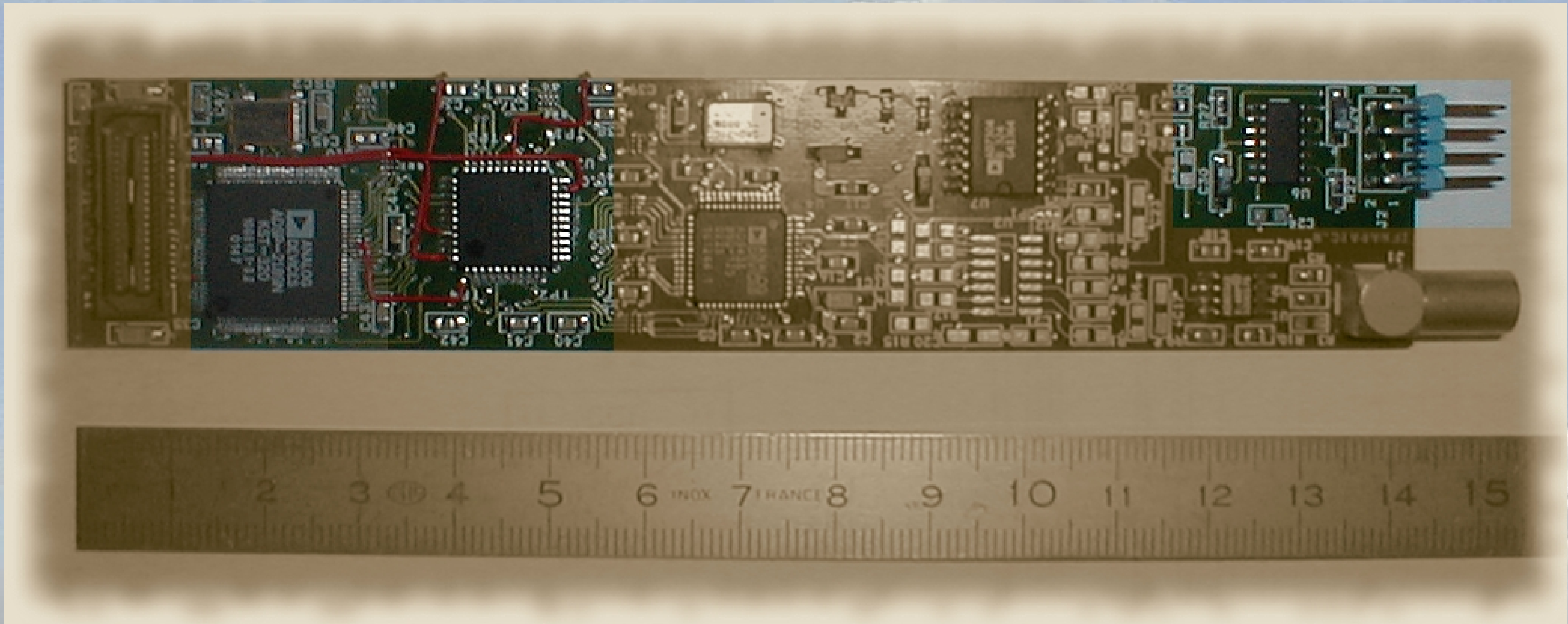
Photo of a single channel board: (begin of 2004)



Sampling ADC

- 12 bit (10.8 effective)
- 125 MSamples/s

Photo of a single channel board: (begin of 2004)



Digital section

- DSP (fixed point ADSP2189)
- On-line programmable
- Trigger logic with internal or external trigger

Approx. manpower spent for development:

- ∼ 10 month technician work (hardware)
- ∼ 10 month physicist work (hardware)
- ∼ 20 month physicist work (software)

Final costs:

- Complete single channel **with DSP**:
  ∼ 180 € /ch (including VAT)
- Typical commercial system **without DSP**:
  ∼ 750 € /ch (including VAT)

Ready and working:

- Prototypes: 2 motherboard systems (FAIR and VME readout)
- Prototypes: 8 single channels (programmable)
- Manufacturing of first 96 complete acquisition channels
- Software for DSP processing (assembler)

Expected to be completed in a short time:

- First use in experiment at Legnaro (end of November, 2004)

Near future:

- Further optimization of DSP algorithms
- Complete manufacturing of requested channels (~250)

What we need from digital signal processing?

- High resolution measurements
- High computational speed ($\Longrightarrow$ counting rate)
- Flexibility

A wide class of detectors can be handled with:

- Signal Amplitude measurement ($\Longrightarrow$ energy)
- Timing measurement ($\Longrightarrow$ rise time, ToF)

High resolution (12 bit)
fast sampling AD converter

Electronic resolution that **well compares** with standard analog **high-resolution** and **high dynamic range** systems.

Digital Filters

Digital versions of analog filters (i.e. spectroscopy amplifiers, . . .)

New (better) filters, for example *optimal* filtering

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Digital Filters

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New (better) filters, for example *optimal* filtering

High resolution converter ⇒ good energy measurements!

High resolution or High speed Sampling ADC?

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Timing measurements: in practice obtain the time $\mathbf{t}_0$ where $S(\mathbf{t}_0) = S_0$

⇒ good timing possible with good signal reconstruction!

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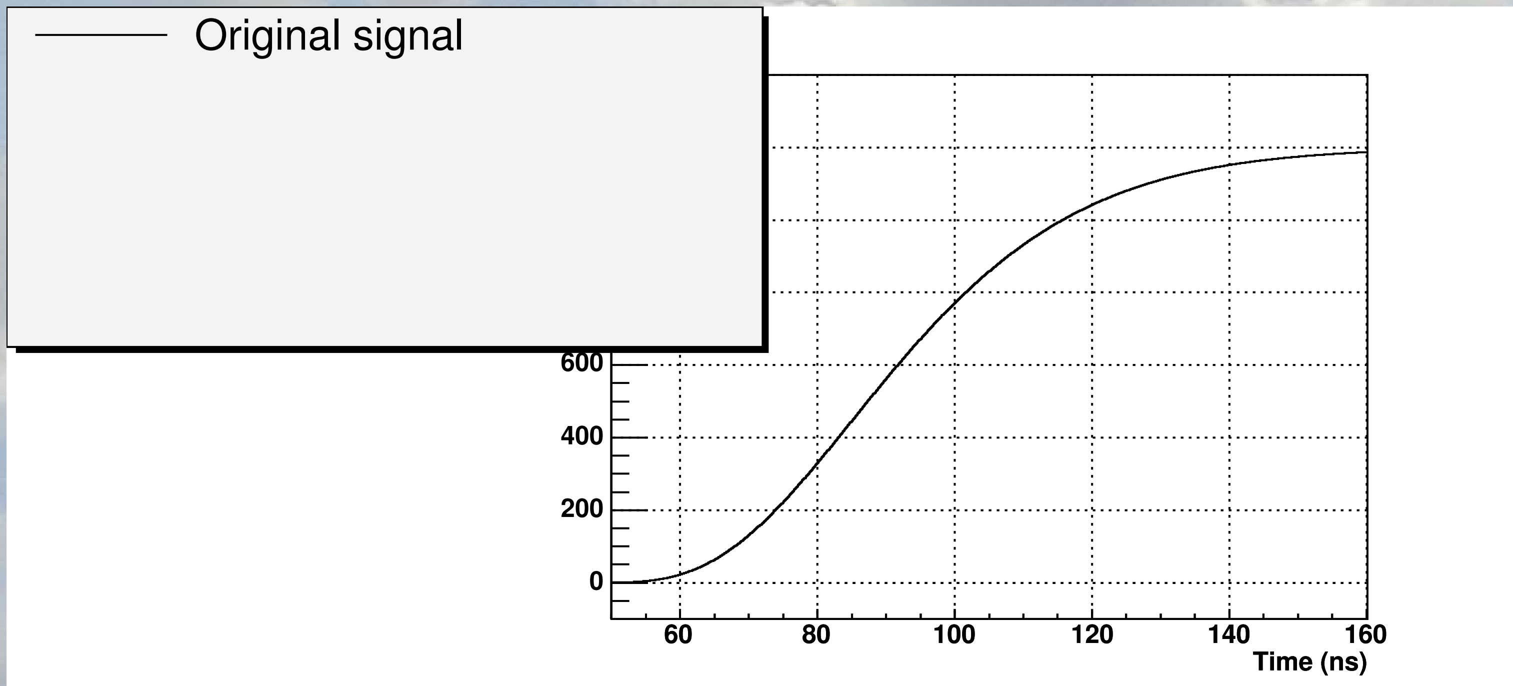

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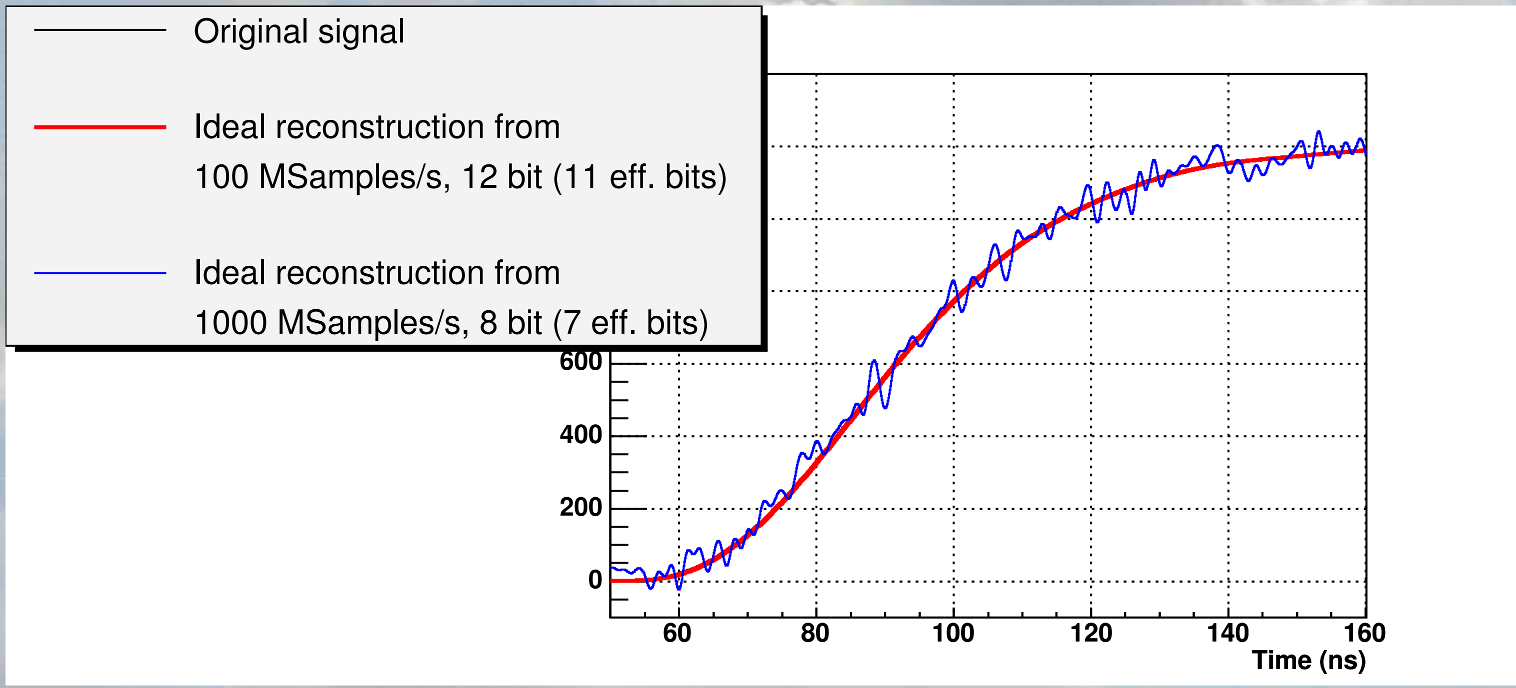

Key points for good signal reconstruction:

low noise

Higher speed = wider bandwidth = higher noise.

$f_{\text{sampling}} \approx f_{\text{Nyquist}}$ is enough. . .

good interpolation

linear interpolation gives more error/noise

⇒ at least **cubic** is needed

Low noise + Good interpolation =
= Good Signal reconstruction = Good Timing!

Which AD converter ?

Realistic simulations (including noise): L.Bardelli *et al.*, NIM **A521** (2004)

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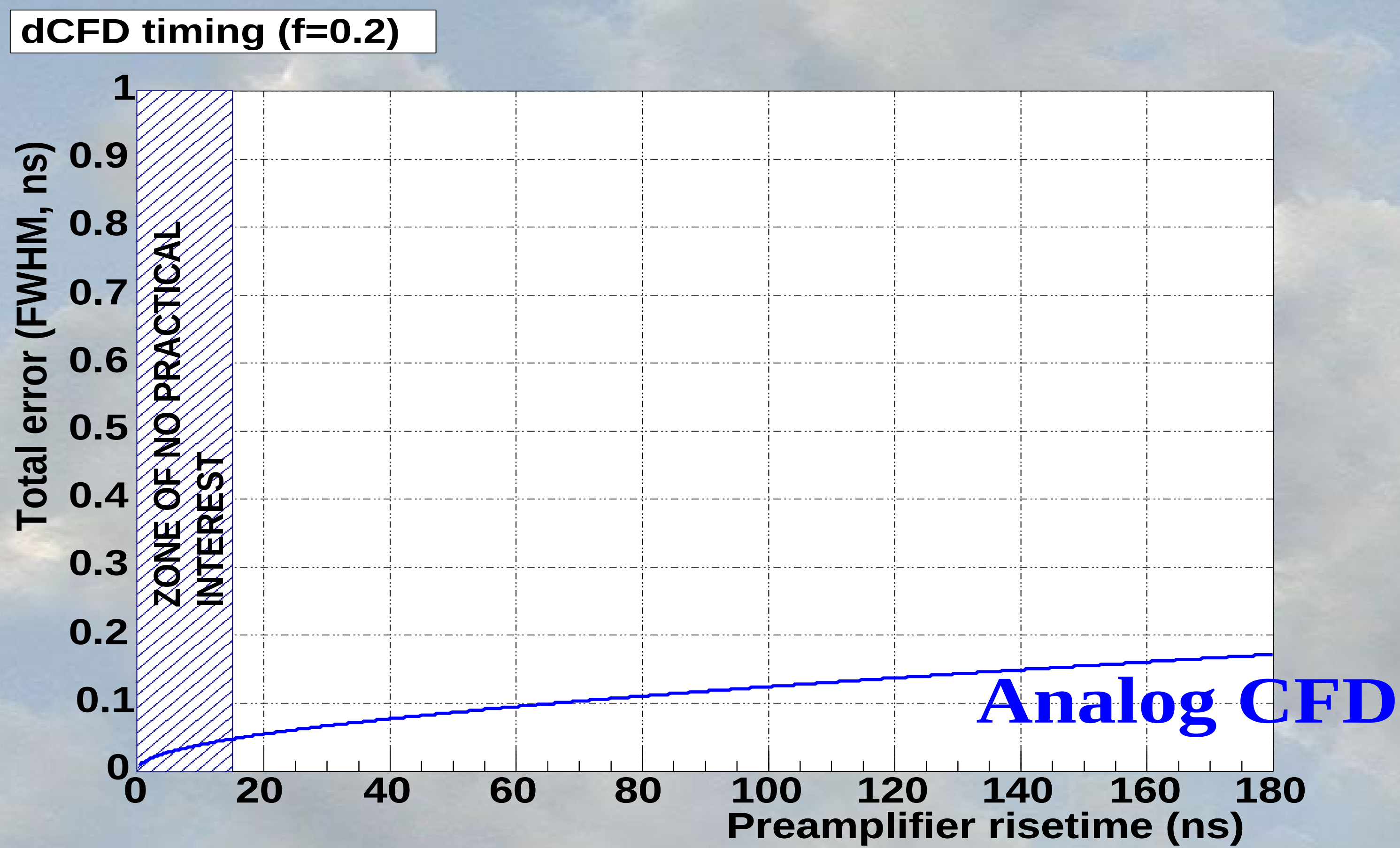

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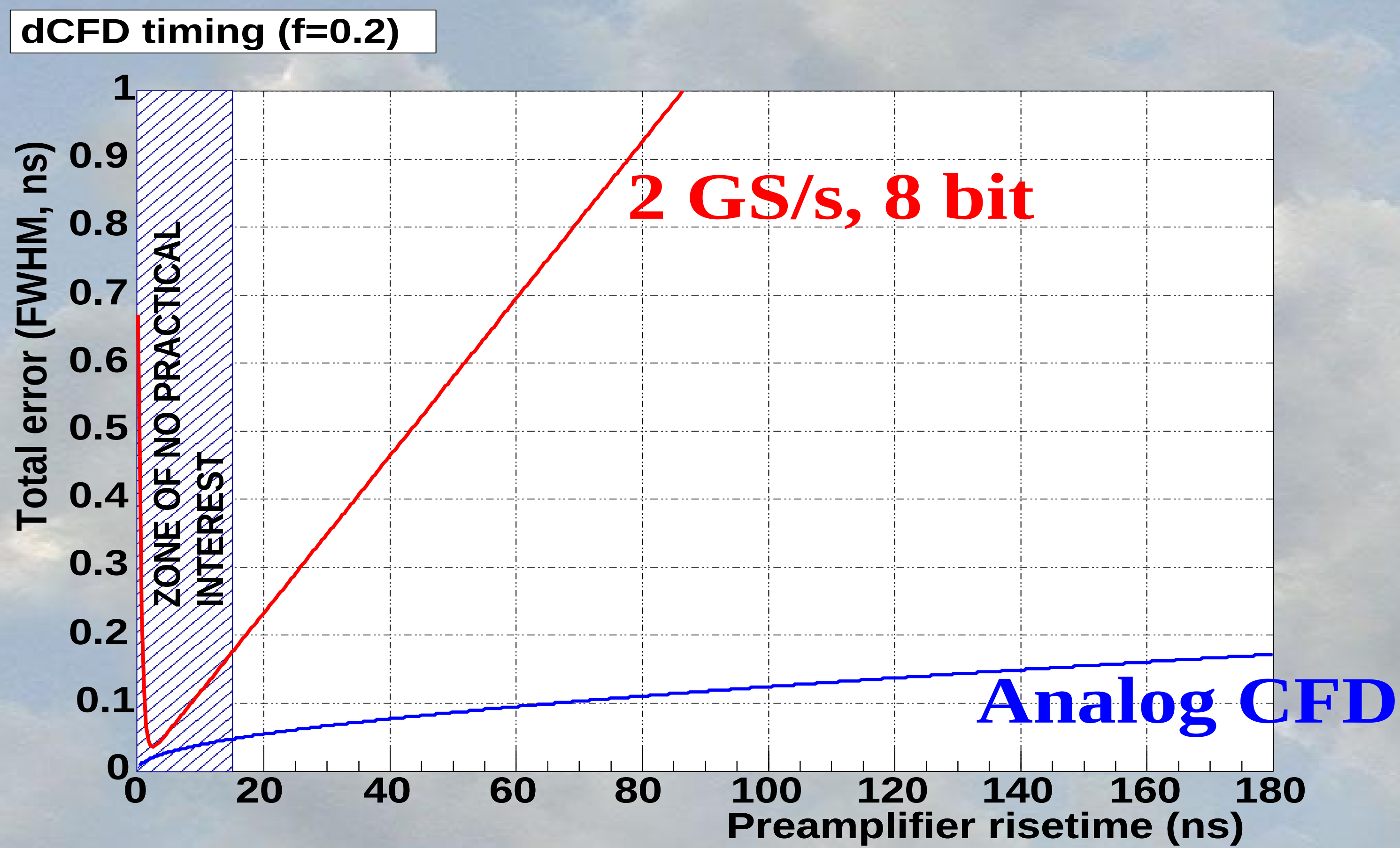

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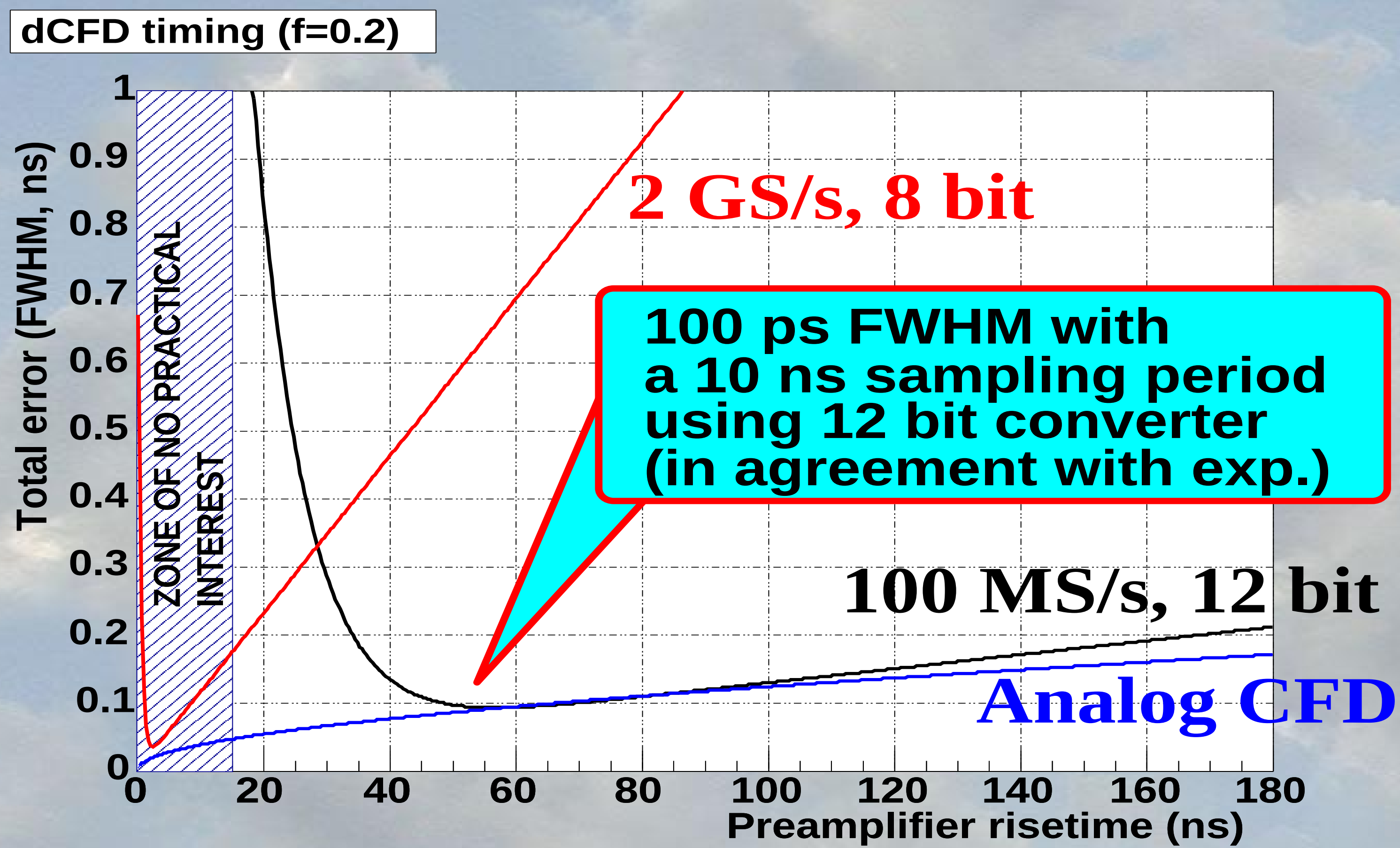

12 bit ⇒ FWHM resolution 100 times smaller than sampling period

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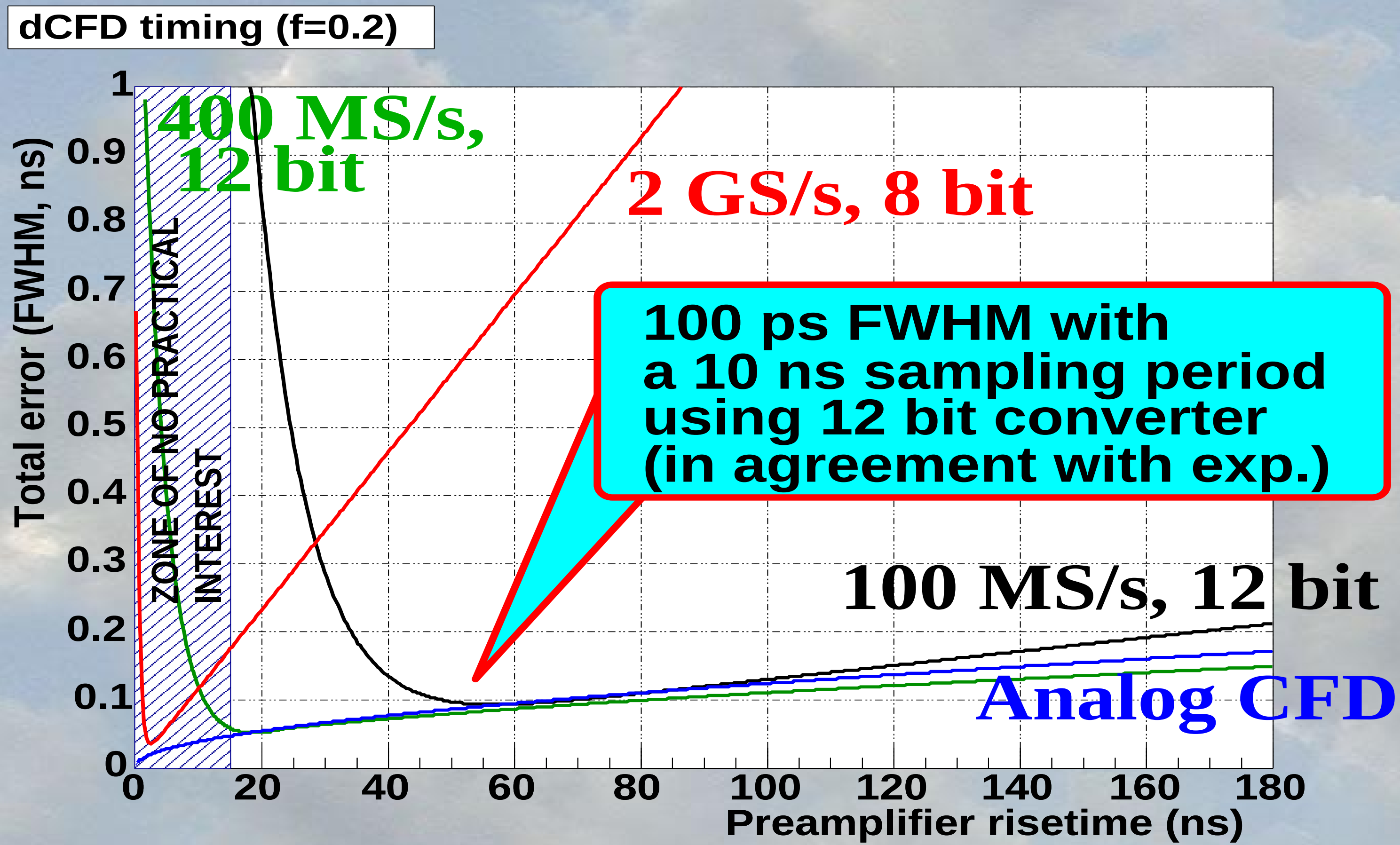
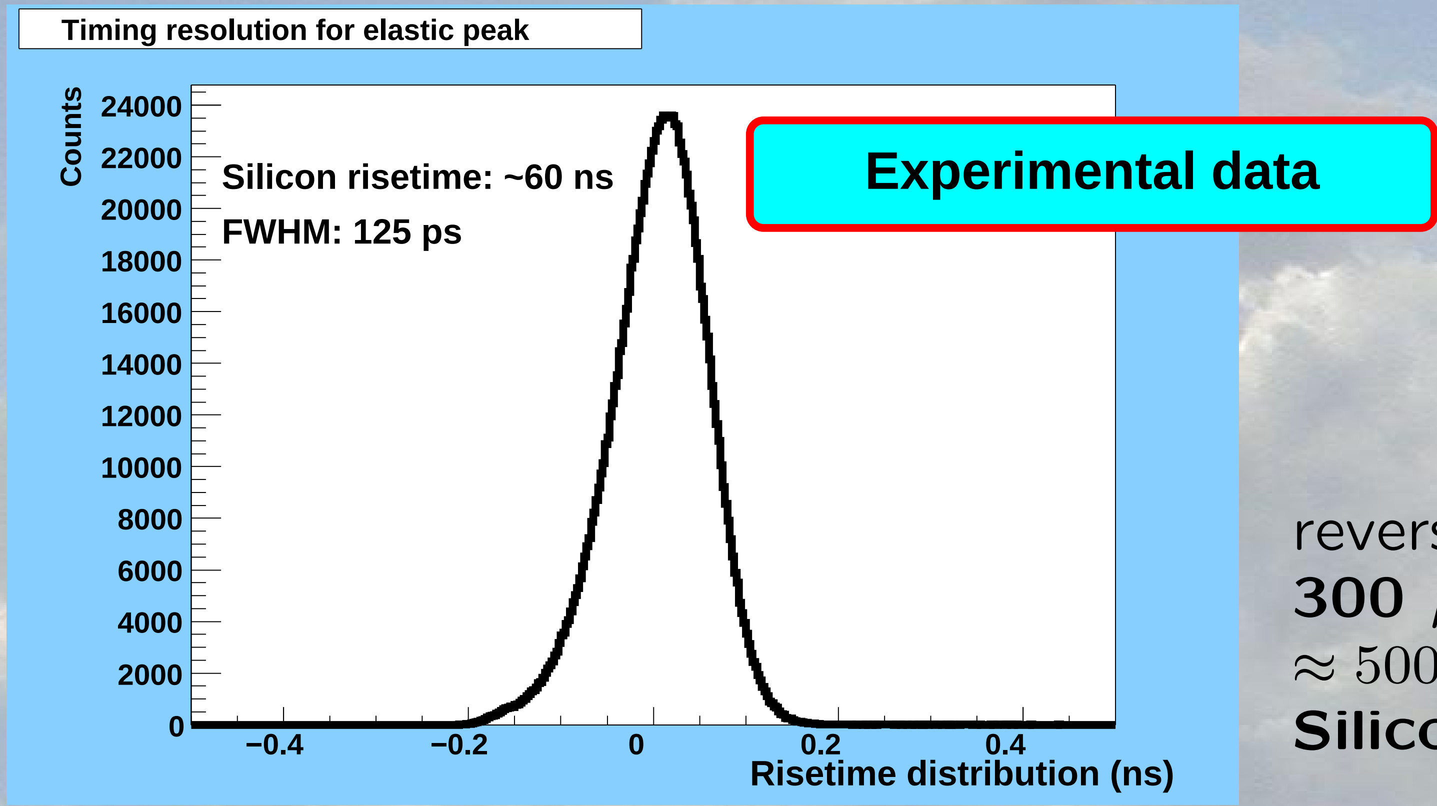


12 bit ⇒ FWHM resolution 100 times smaller than sampling period

PSA analysis: differences between two **dCFDs**.
250 MeV Oxygen elastic peak using a Si detector (test at LNL)



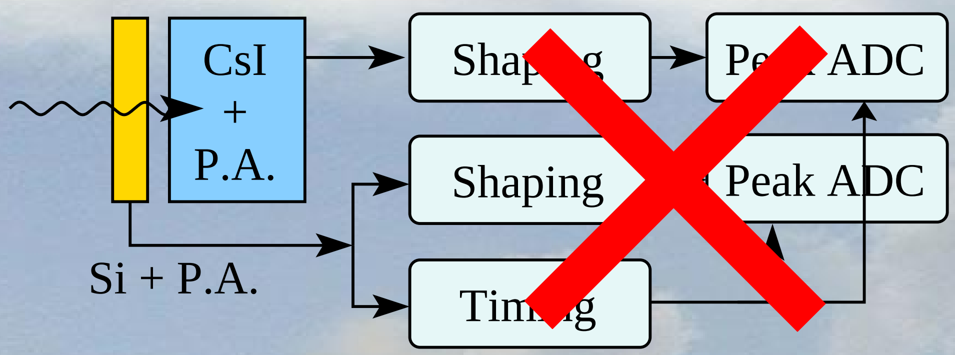
reverse
300 μm,
≈ 500 **mm^2**
Silicon

Time difference between 90% and 10% dCFDs
Cubic interpolation.

L.Bardelli *et al.*, NIM **A521** (2004)

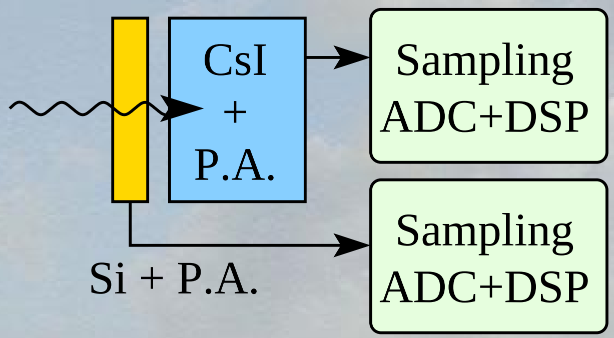
Detector type	Energy	Timing	PSA	*status*
ΔE-E (Si-CsI)		–		
CsI(Tl)		–		
Germanium			–	
Silicon (rev.mount)				
Fast Plastic	–		–	
NaI(Tl)			–	
Position sens. gas	–		–	
Phoswich scint.		–		
Single Chip tel.		–		

Si-CsI telescope ΔE-E

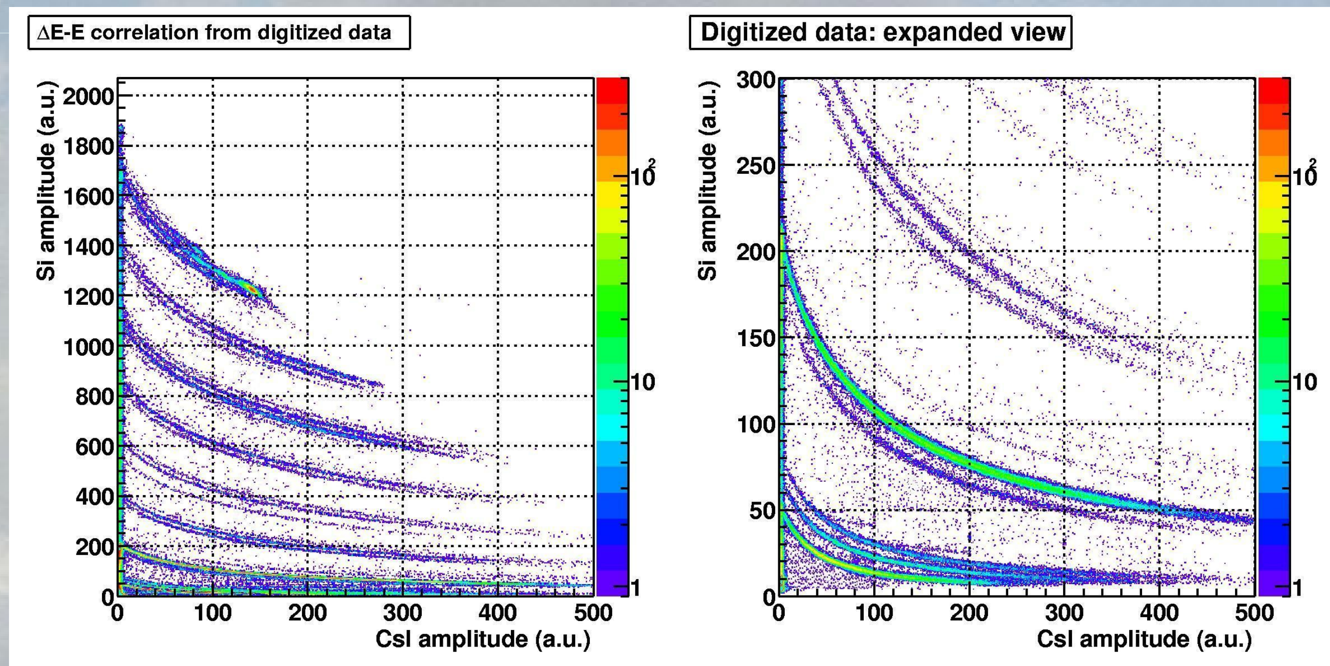


Similar results reported in a recent work of the CHIMERA coll. M.Alderighi et al., IEEE TNS 51(2004) and P.Guazzoni *et al.* IEEE2004 conference

Garfield apparatus, NUCL-EX@LNL 2002-2003

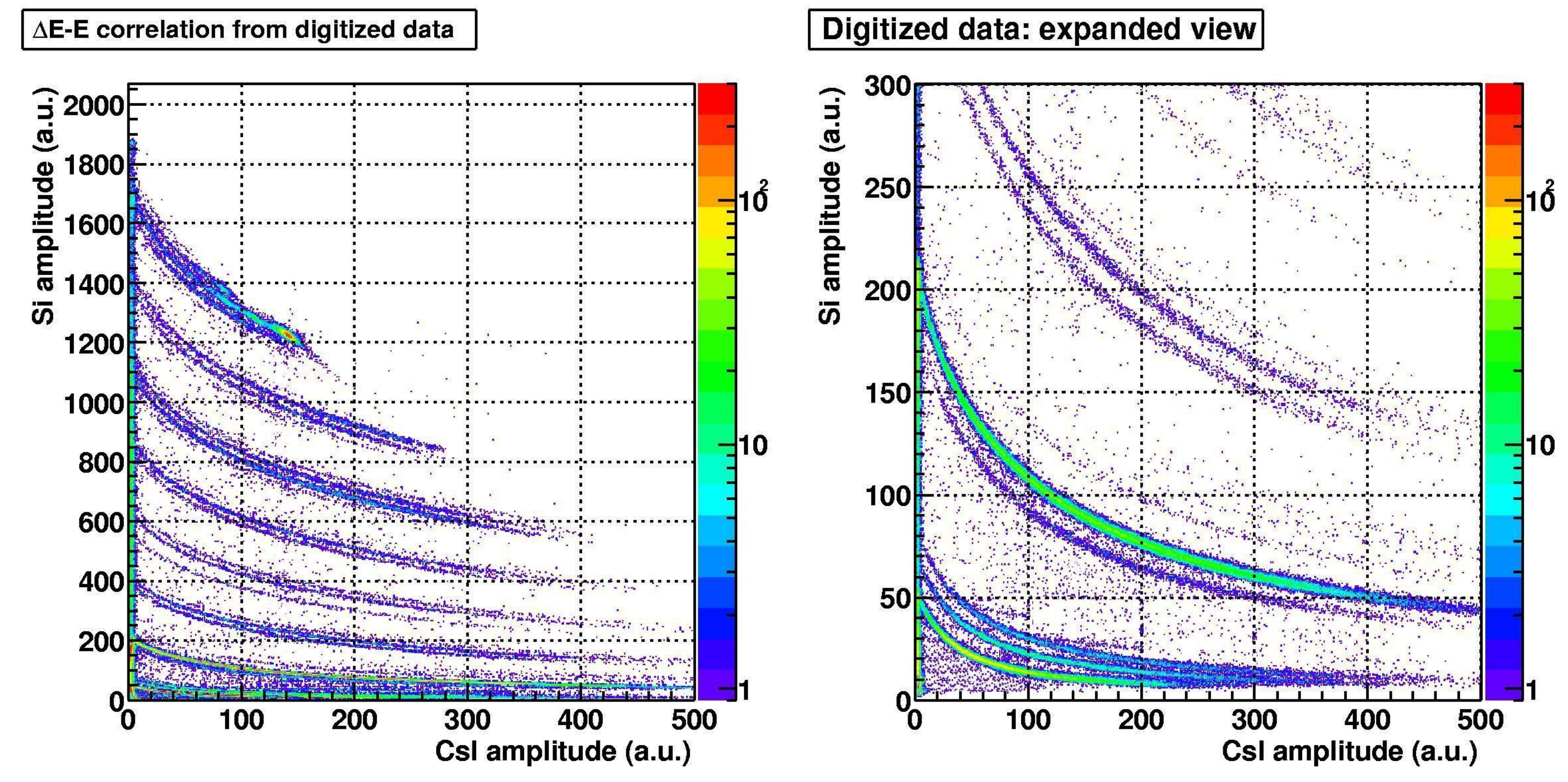


Simpler digital electronic chain



Standard ΔE-E correlation using digital semigaussian filters

Both high and low ranges with a single AD converter for ΔE

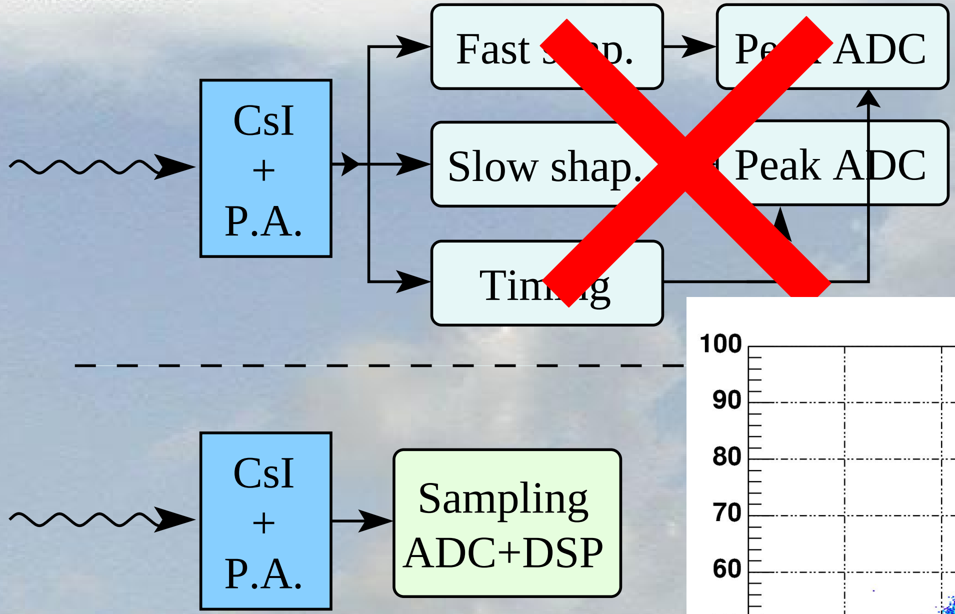


L.Bardelli *et al.*, Laboratori Nazionali di Legnaro Annual Report 2002.

L.Bardelli *et al.*, Proc. of RNB6 Conf., Sept. 2003, to appear in Nucl.Phys. **A**

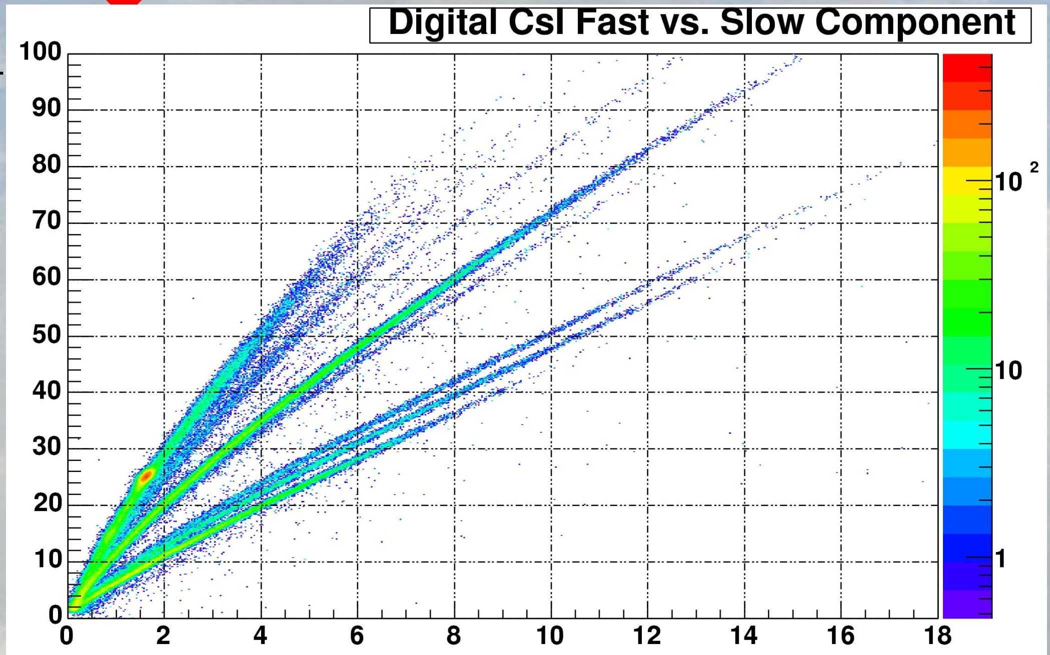
Detector type	Energy	Timing	PSA	*status*
ΔE-E (Si-CsI)	☺	–	☺	☑
CsI(Tl)		–		
Germanium			–	
Silicon (rev.mount)				
Fast Plastic	–		–	
NaI(Tl)			–	
Position sens. gas	–		–	
Phoswich scint.		–		
Single Chip tel.		–		

Pulse Shape in CsI (photodiode readout)



Garfield, NUCL-EX@LNL 2002

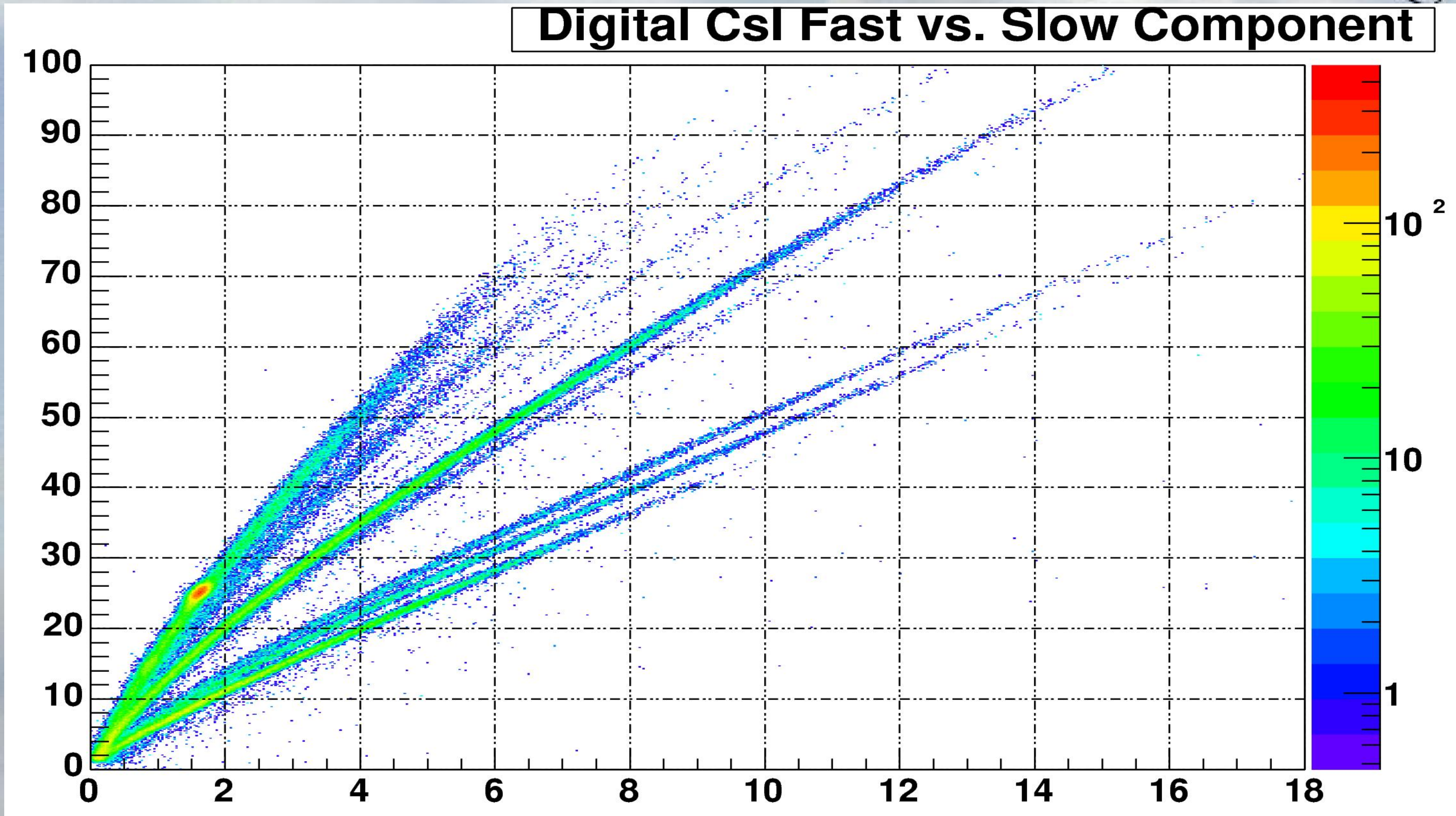
Much simpler digital electronic chain



Standard Fast vs. Slow correlation for a CsI scintillator, obtained using a 12 bit fast sampling ADC and processing data with two **digital** semigaussian filters ($\tau_{fast} \simeq 700$ ns, $\tau_{slow} \simeq 2$ μs).

Similar results reported in a recent work of the CHIMERA coll.

Pulse Shape in CsI (photodiode readout)



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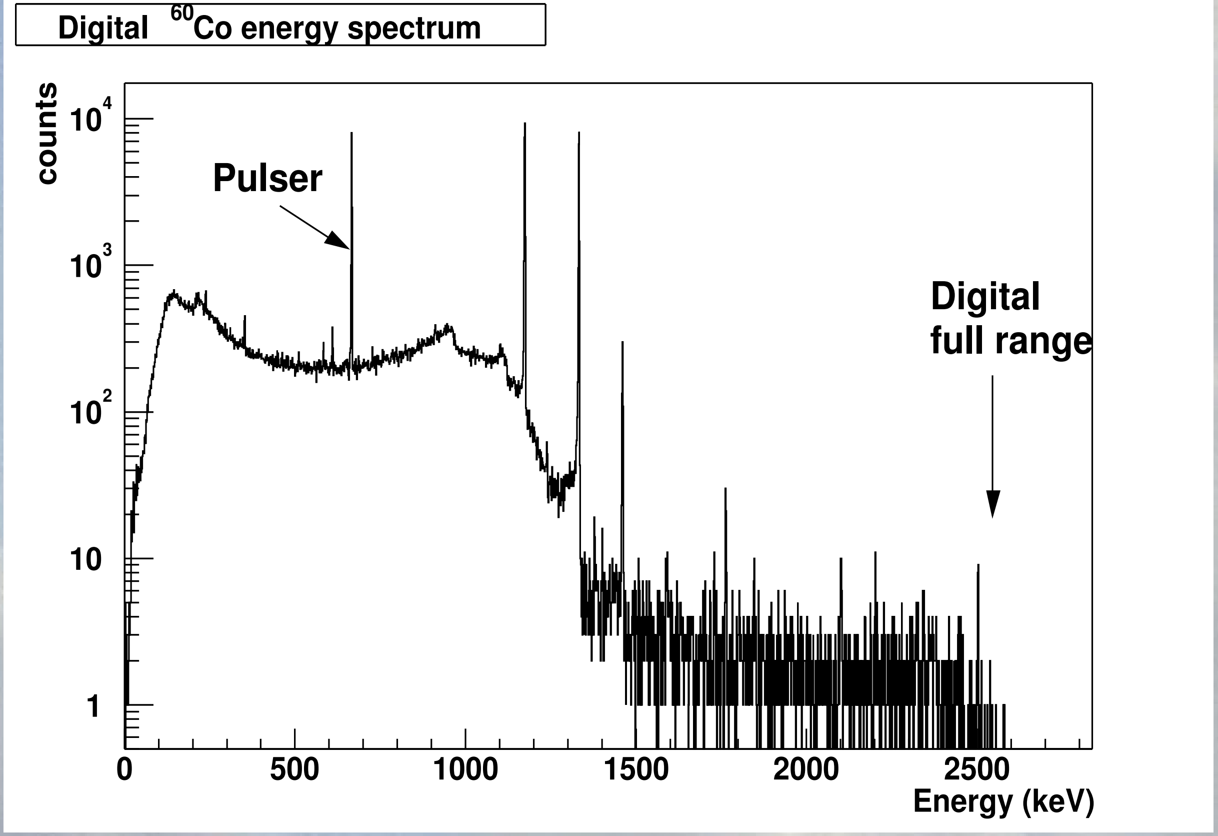
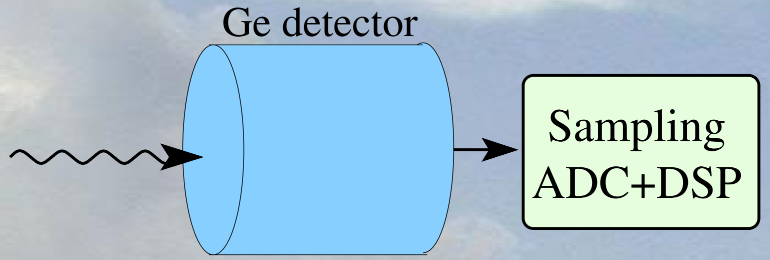
Experimental tests

Detector type	Energy	Timing	PSA	*status*
ΔE-E (Si-CsI)	☺	–	☺	☑
CsI(Tl)	☺	–	☺	☑
Germanium			–	
Silicon (rev.mount)				
Fast Plastic	–		–	
NaI(Tl)			–	
Position sens. gas	–		–	
Phoswich scint.		–		
Single Chip tel.		–		

Non-optimal digital gain. . .





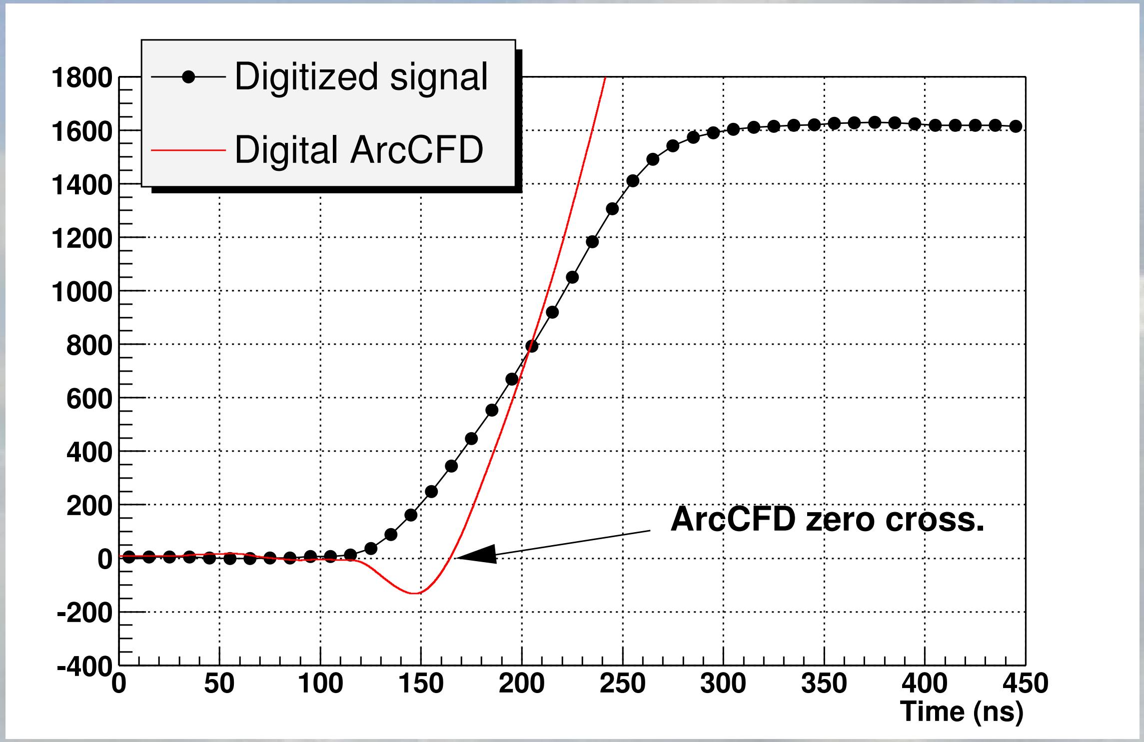
	1332	Pulser
Analog shaping 6μs	2.1	1.5
Digital fast max	2.6	1.8
Digital CR-RC^4 6.0μs	2.4	1.7
Digital CR-RC^4 2.5μs	2.2	1.4
Digital RTC integral	2.2	1.4

. . . but good results.

Only 1 μs digital baseline for these tests!!

Detector: ORTEC GMX30p (coaxial, 30% efficiency)

Digital **Amplitude and Risetime Compensated CFD (ArcCFD)**



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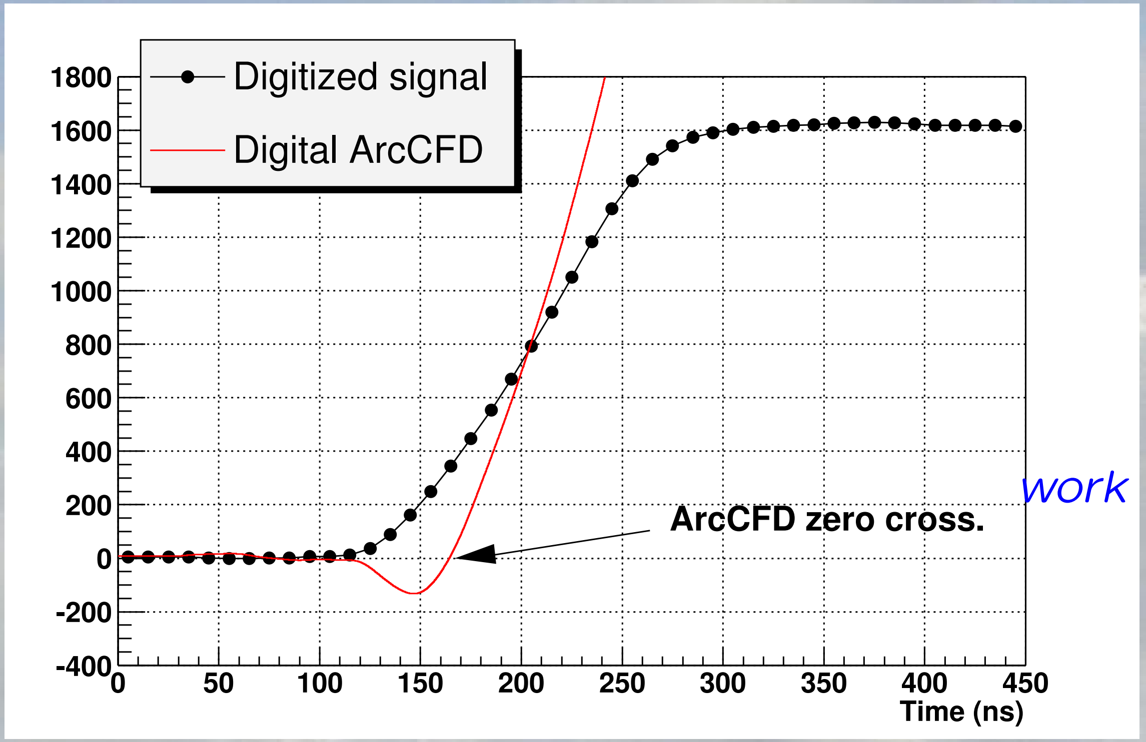


work in progress . . .

Timing on 1332 keV:

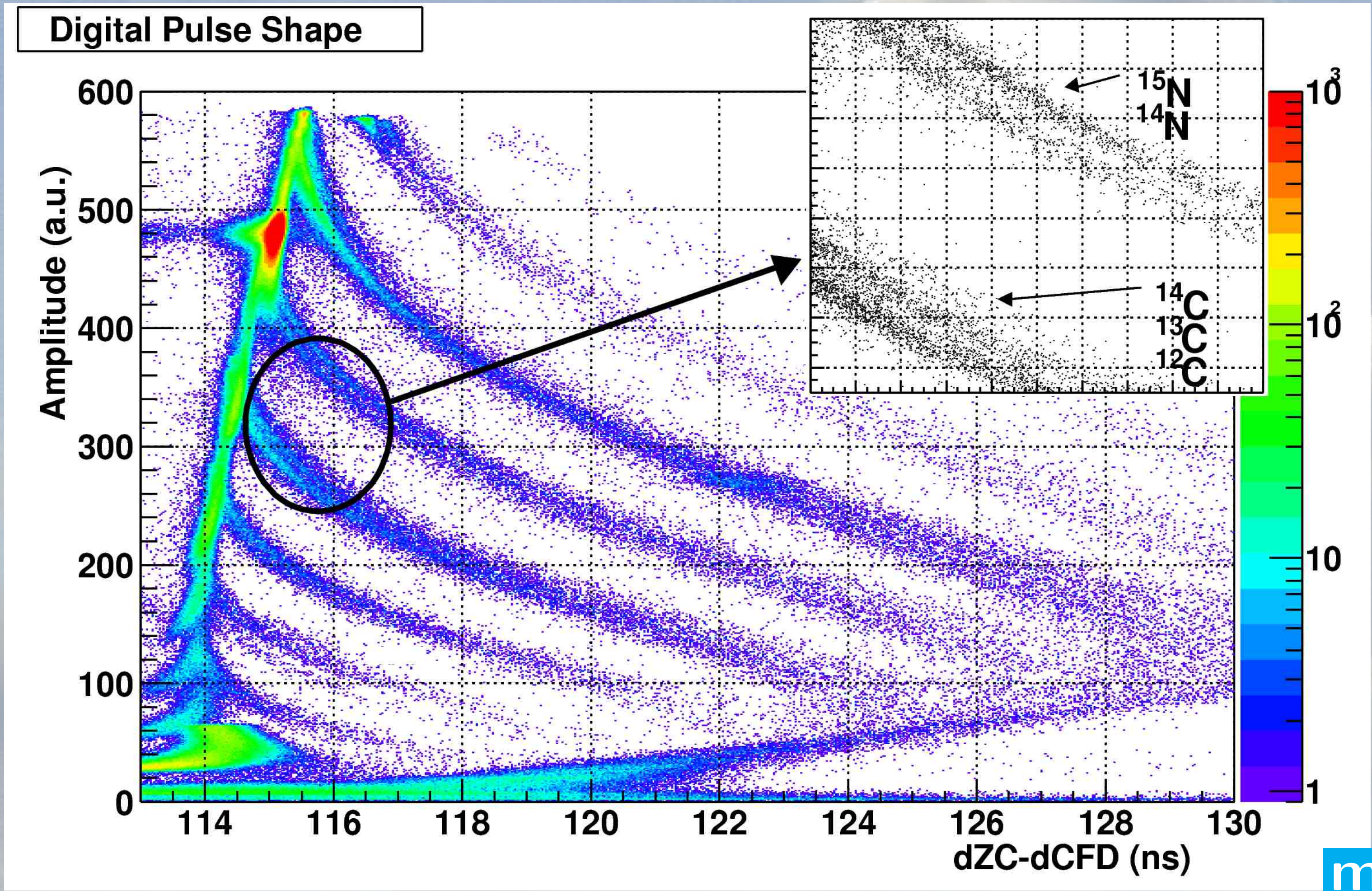
Analog:	3.2 ns FWHM	(f=0.3, δ=20 ns)
Digital:	1.9 ns FWHM	(f=0.3, δ=30 ns)

Digital uses many points for zerocrossing determination

Experimental tests

Detector type	Energy	Timing	PSA	*status*
ΔE-E (Si-CsI)	☺	–	☺	☑
CsI(Tl)	☺	–	☺	☑
Germanium	☺	☺☺	–	☑
Silicon (rev.mount)				
Fast Plastic	–		–	
NaI(Tl)			–	
Position sens. gas	–		–	
Phoswich scint.		–		
Single Chip tel.		–		

Digital Amplitude vs. Digital Zero Crossing time:



reverse
300 μm,
≈ 500 mm^2
Silicon

mid of 2003

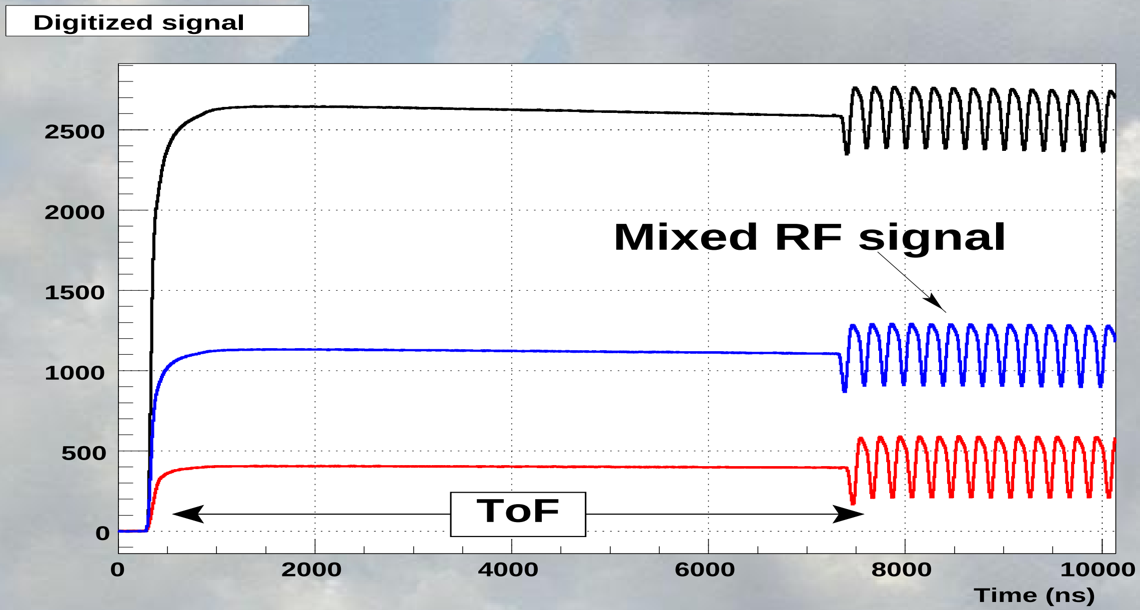
Evident **sub-nanosecond** resolution even with 10ns sampling

Similar results reported in a recent work of the CHIMERA coll.

PSA analysis: differences between two **dCFDs**.

Time of Flight or **coincidence** measurements?

PSA analysis: differences between two **dCFDs**.
Time of Flight or **coincidence** measurements?
Mix a common time reference signal with the preamplifier output:



This allows for **syncronization** between many channels: **coincidence** measurements possible.

L.Bardelli *et al.*, NIM **A521** (2004)

In our experimental test we had a beam resolution of ~ 1.5ns ☹ (expected digital res. is ~100 ps FWHM)

➡ No significant test for digital ToF!

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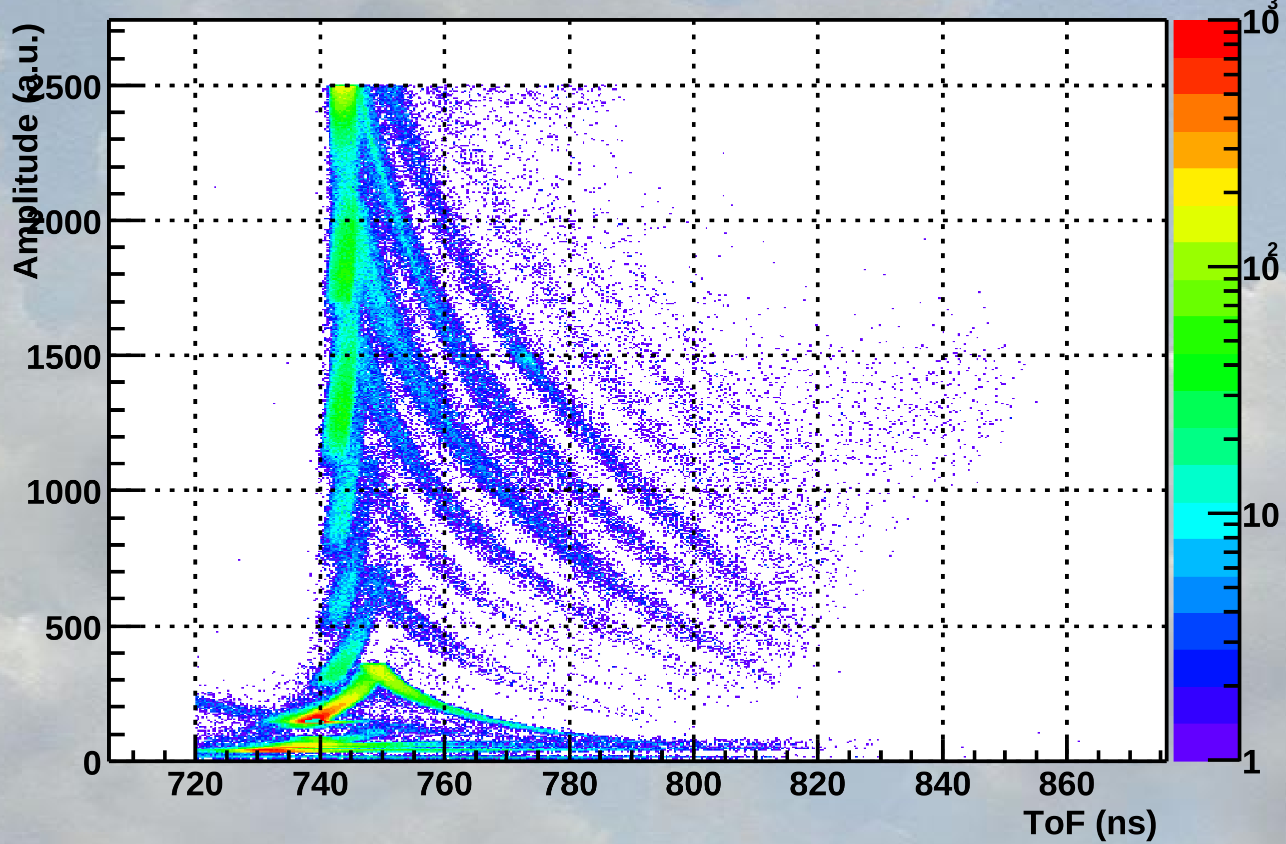
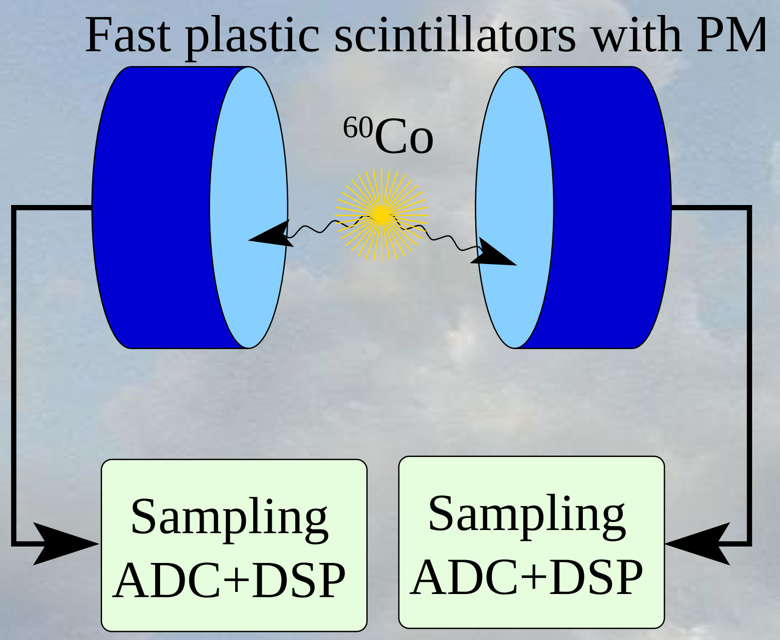
Same results using analog methods.

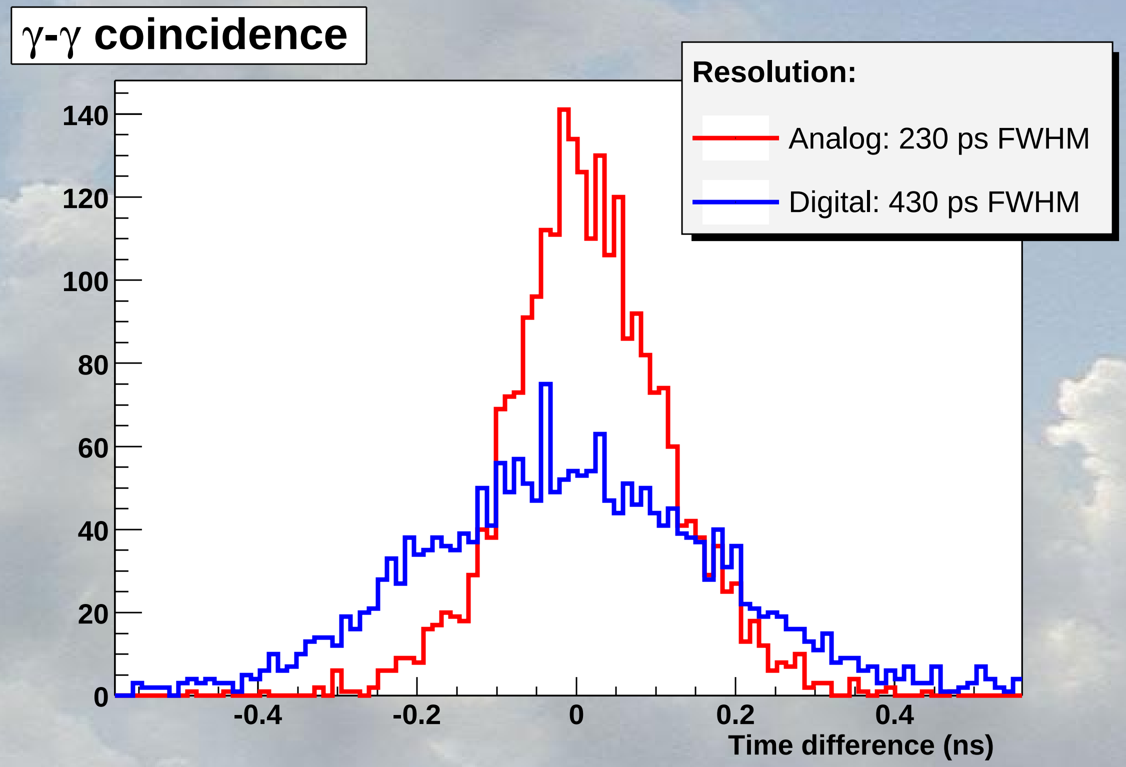


Detector type	Energy	Timing	PSA	*status*
ΔE-E (Si-CsI)	☺	–	☺	☑
CsI(Tl)	☺	–	☺	☑
Germanium	☺	☺☺	–	☑
Silicon (rev.mount)	☺	☺?	☺☺	*more ToF tests*
Fast Plastic	–		–	
NaI(Tl)			–	
Position sens. gas	–		–	
Phoswich scint.		–		
Single Chip tel.		–		

Simple $\gamma - \gamma$ coincidence experiment:

Scintillator signal much faster than sampling period!





Comparison with a state of the art analog timing chain.

Preliminary results are in **agreement with simulations**.

Experimental tests

Detector type	Energy	Timing	PSA	*status*
ΔE-E (Si-CsI)		–		☑
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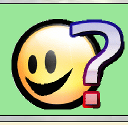
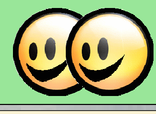
Germanium			–	☑
Silicon (rev.mount)				*more ToF tests*
Fast Plastic	–		–	*more tests*
NaI(Tl)			–	
Position sens. gas	–		–	
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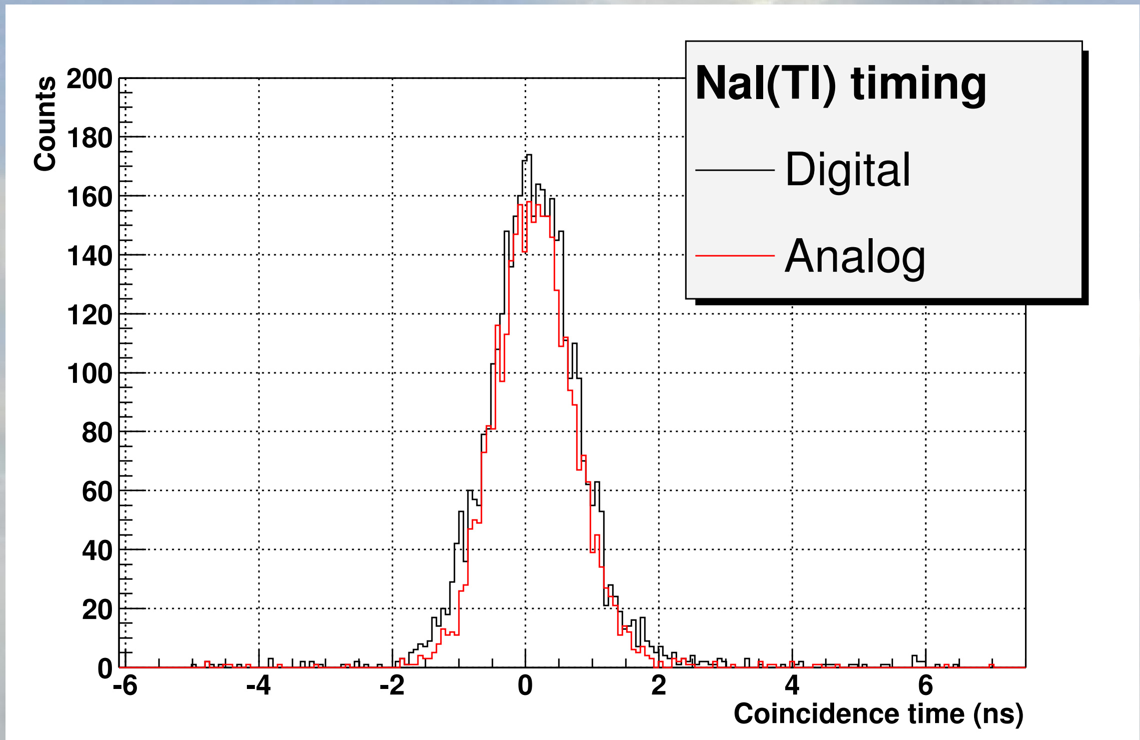
Single Chip tel.		–		

Test with a standard 2"×2" detector:



Resolution of ~1.5 ns FWHM with ^{60}Co source, E>600 keV

(timing limited by photoelectrons statistics?)

More work in progress . . .

Experimental tests

Detector type	Energy	Timing	PSA	*status*
ΔE-E (Si-CsI)	☺	–	☺	✓
CsI(Tl)	☺	–	☺	✓
Germanium	☺	☺☺	–	✓
Silicon (rev.mount)	☺	☺?	☺☺	*more ToF tests*
Fast Plastic	–	☹?	–	*more tests*
NaI(Tl)	☺	☺	–	✓
Position sens. gas	–		–	
Phoswich scint.		–		
Single Chip tel.		–		

The signal mixing method can also be applied to standard position sensitive gas detectors (PSPPADs of Garfield apparatus):

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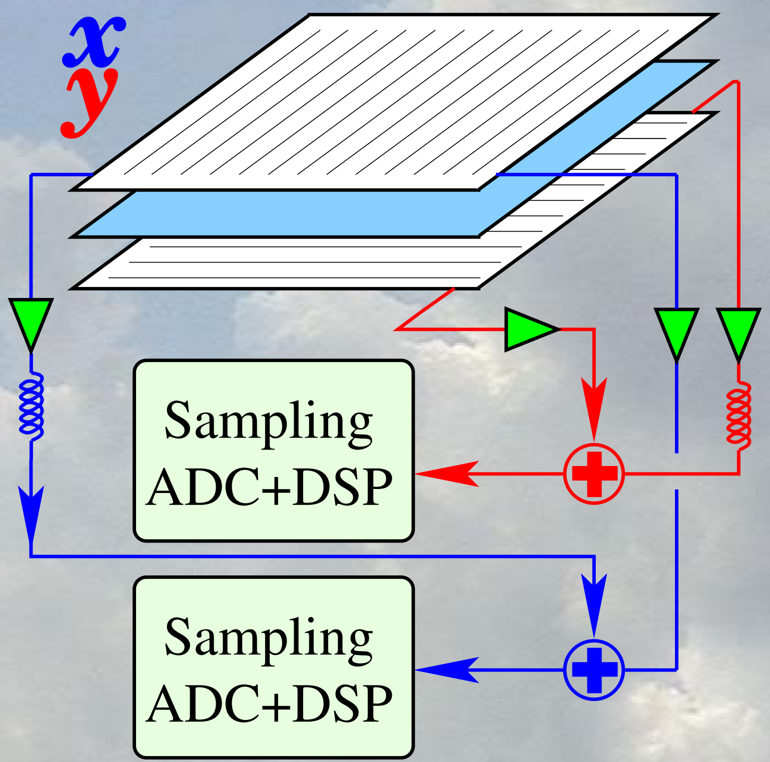

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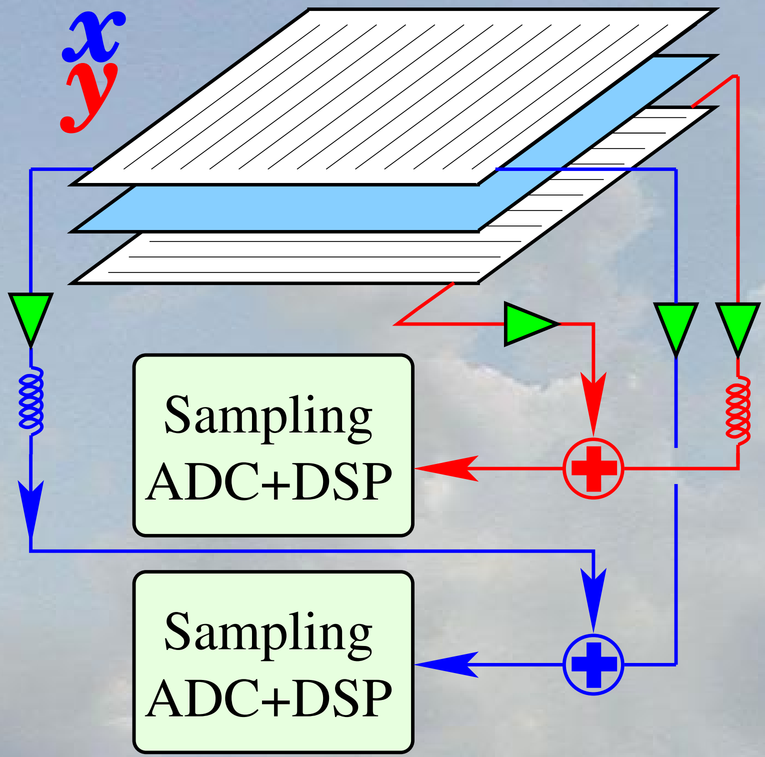

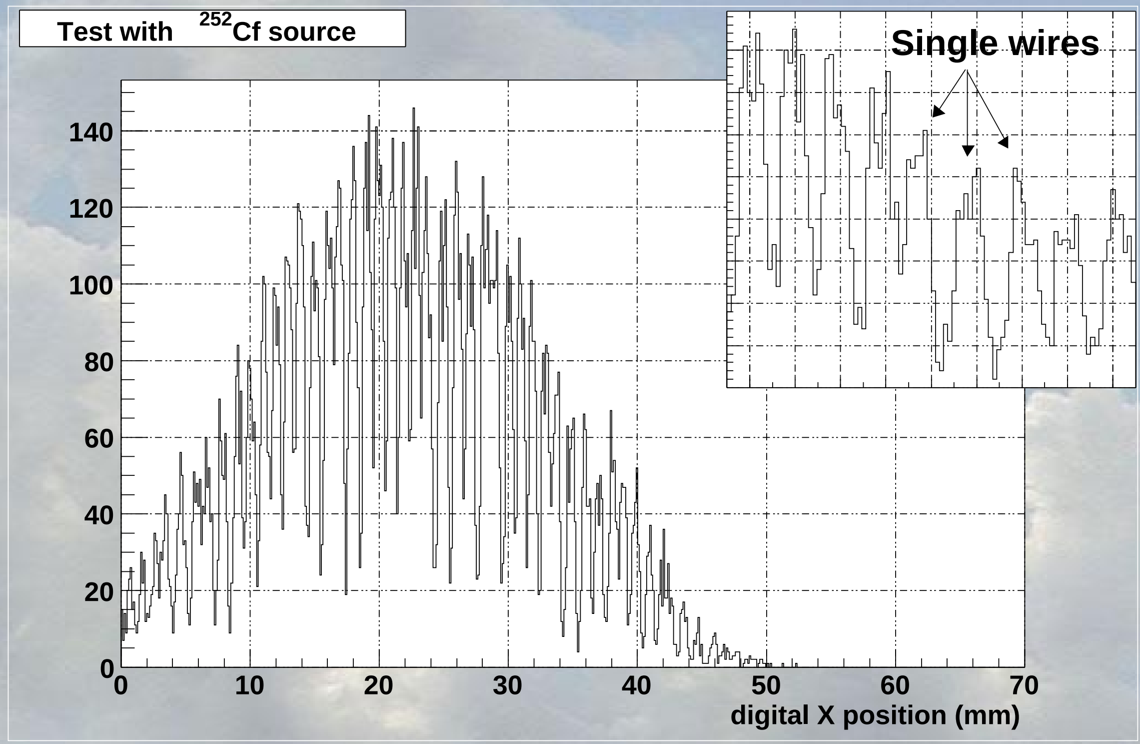

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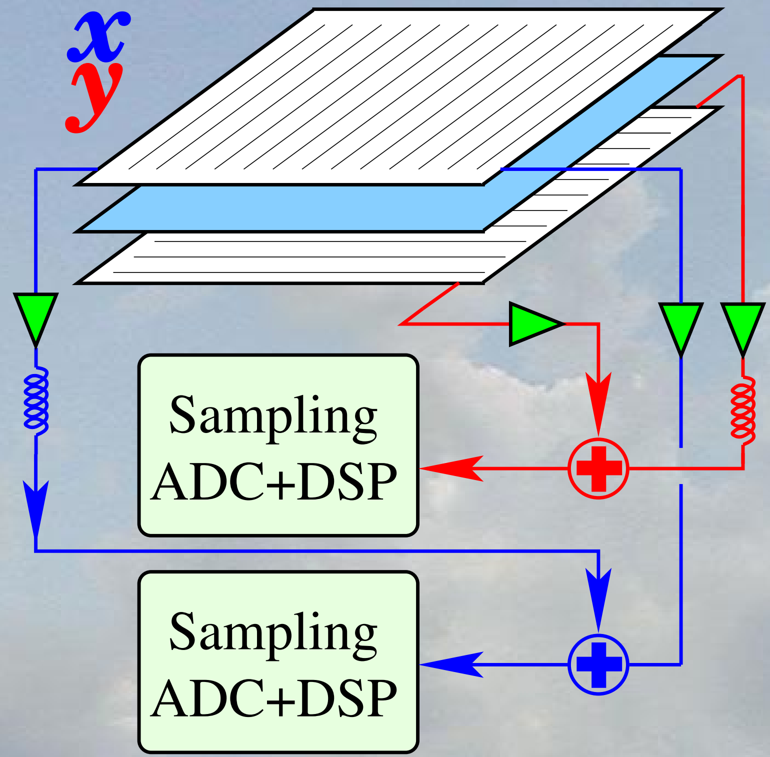
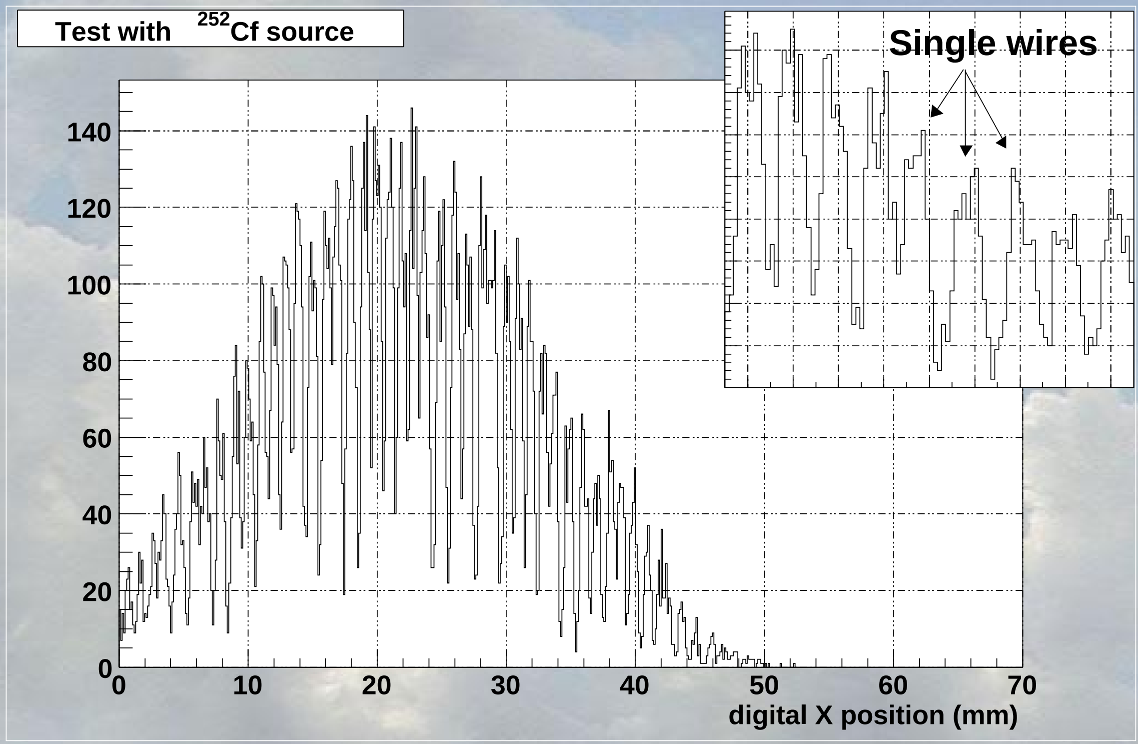


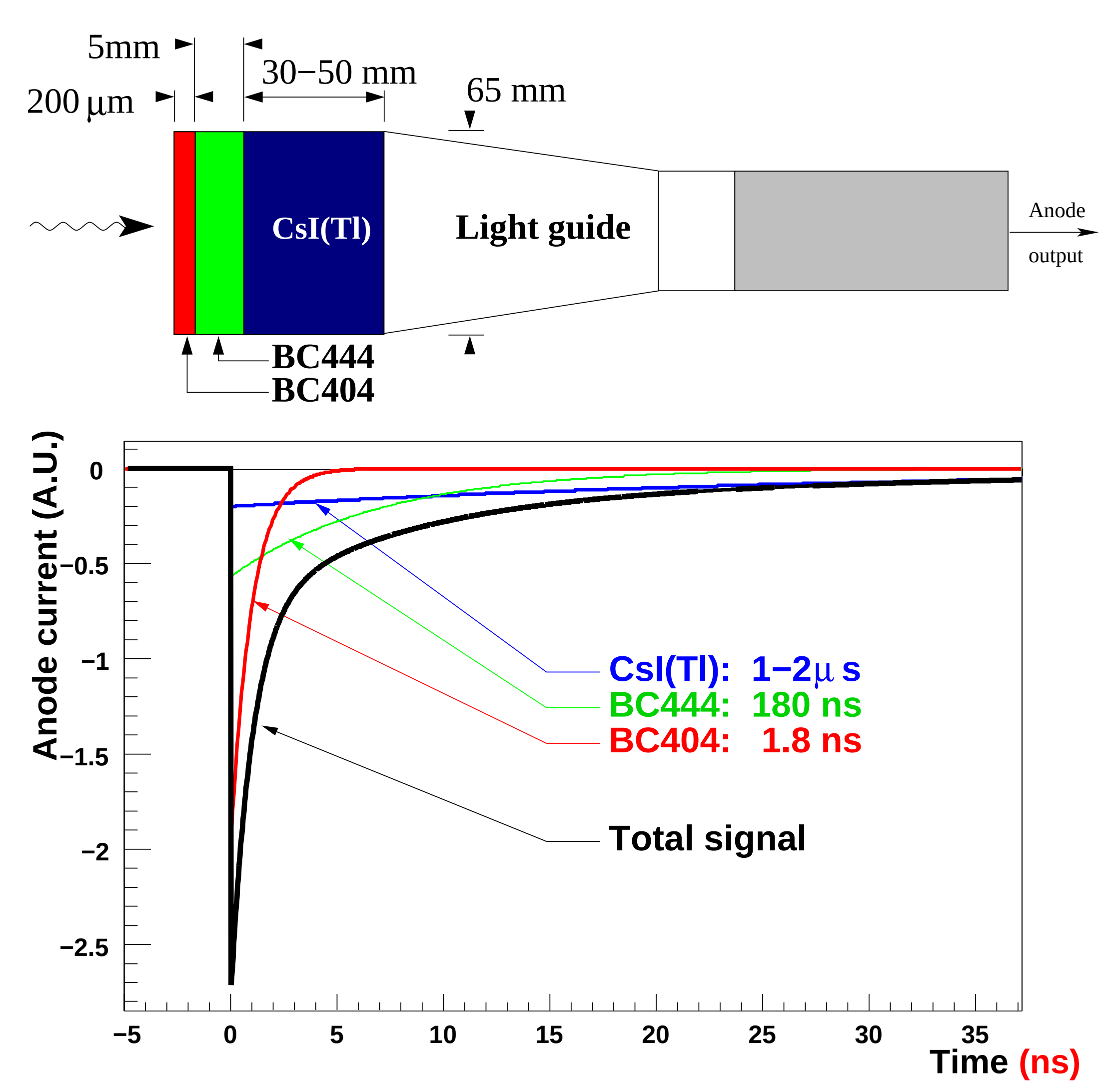


Single wire resolution (digital subnanosecond res. confirmed) as good as standard analog signal treatment

Experimental tests

Detector type	Energy	Timing	PSA	*status*
ΔE-E (Si-CsI)	☺	–	☺	☑
CsI(Tl)	☺	–	☺	☑
Germanium	☺	☺☺	–	☑
Silicon (rev.mount)	☺	☺?	☺☺	*more ToF tests*
Fast Plastic	–	☹?	–	*more tests*
NaI(Tl)	☺	☺	–	☑
Position sens. gas	–	☺	–	☑
Phoswich scint.		–		
Single Chip tel.		–		

The Phoswich detectors



The FIASCO phoswich detector (home made) is a stack of 3 different scintillators:

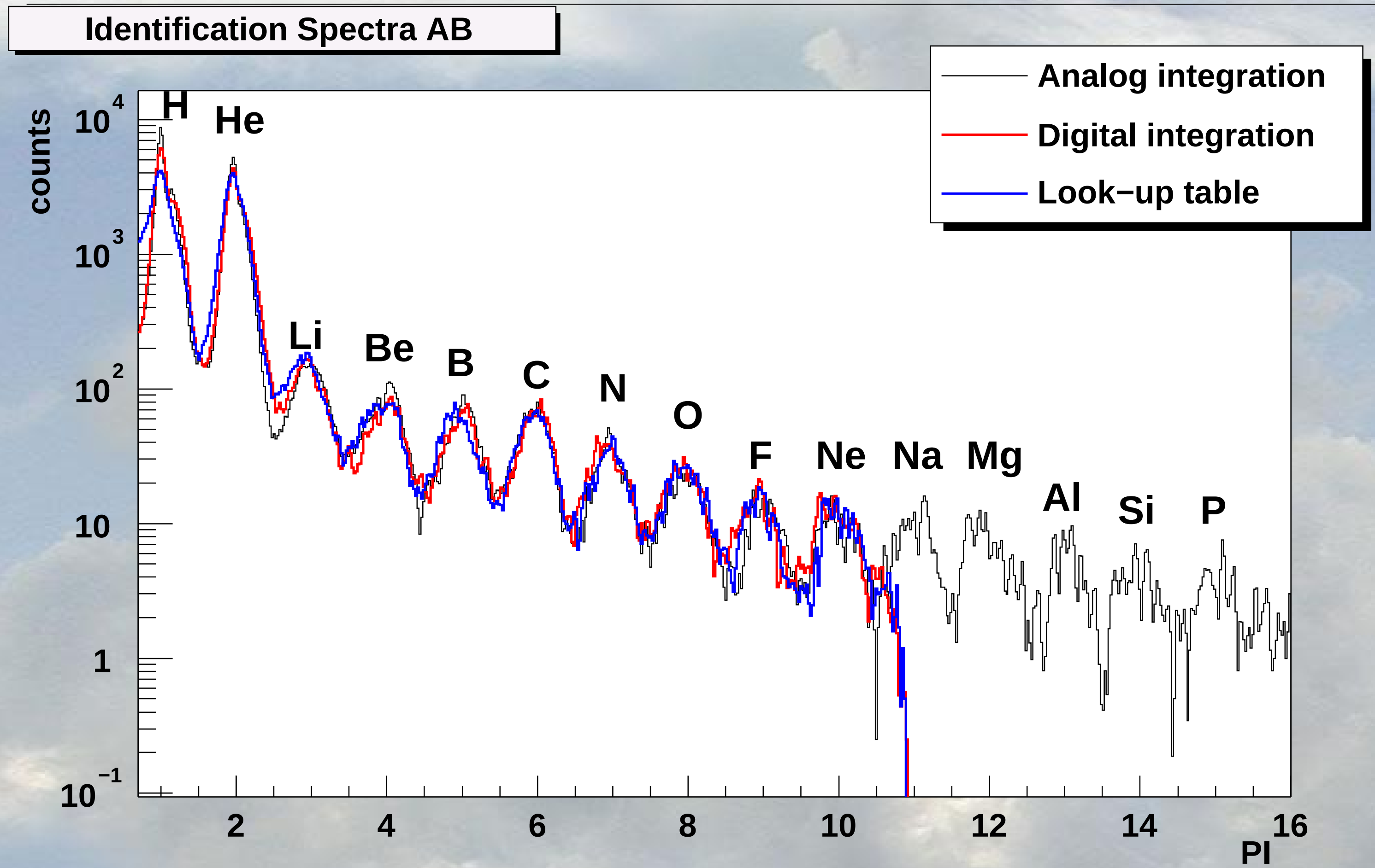
BC404 Fast plastic scintillator, $\tau = 1.8$ ns.

BC444 Slow plastic scintillator, $\tau = 180$ ns.

Csi(Tl) Inorganic scintillator, $\tau \sim \mu s$.

The *shape* of the output signal depends on the type of the impinging particle.

Identification results: AB

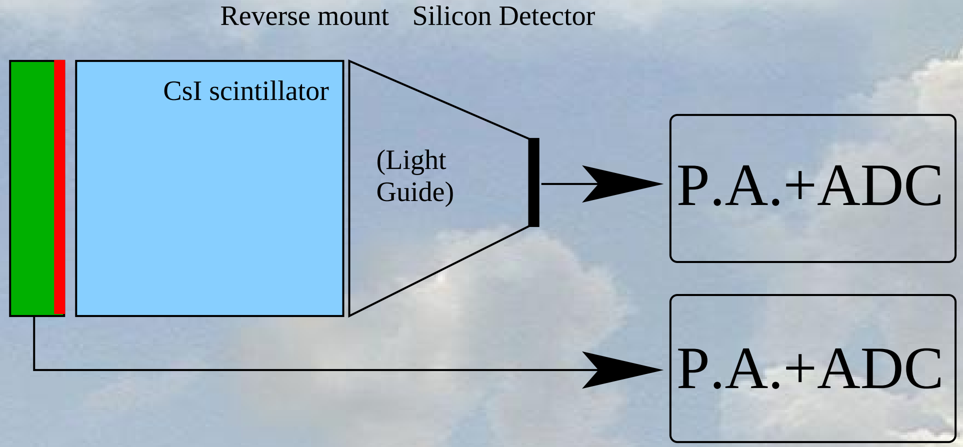


Taking into account performances, system complexity, costs, . . . , the standard analog electronics can be replaced by this new digital technique.

Experimental tests

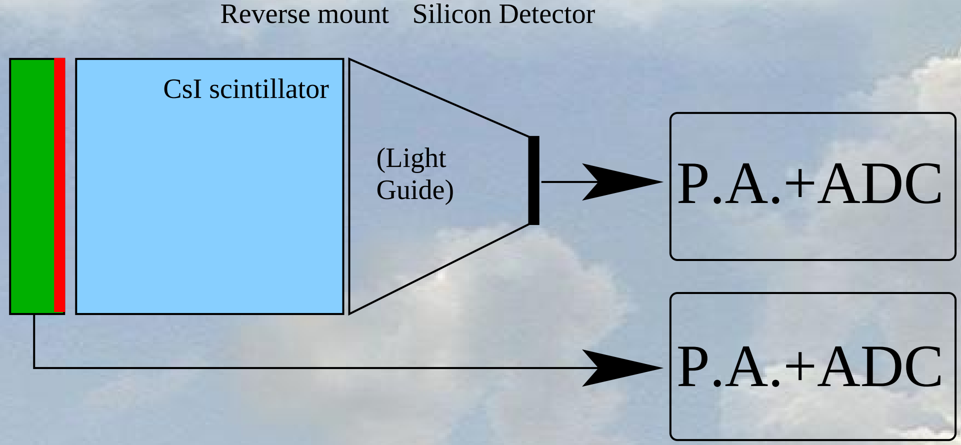
Detector type	Energy	Timing	PSA	*status*
ΔE-E (Si-CsI)	☺	–	☺	☑
CsI(Tl)	☺	–	☺	☑
Germanium	☺	☺☺	–	☑
Silicon (rev.mount)	☺	☺?	☺☺	*more ToF tests*
Fast Plastic	–	☹?	–	*more tests*
NaI(Tl)	☺	☺	–	☑
Position sens. gas	–	☺	–	☑
Phoswich scint.	☺	–	☺☺	☑
Single Chip tel.		–		

Standard reverse mount Si-CsI:

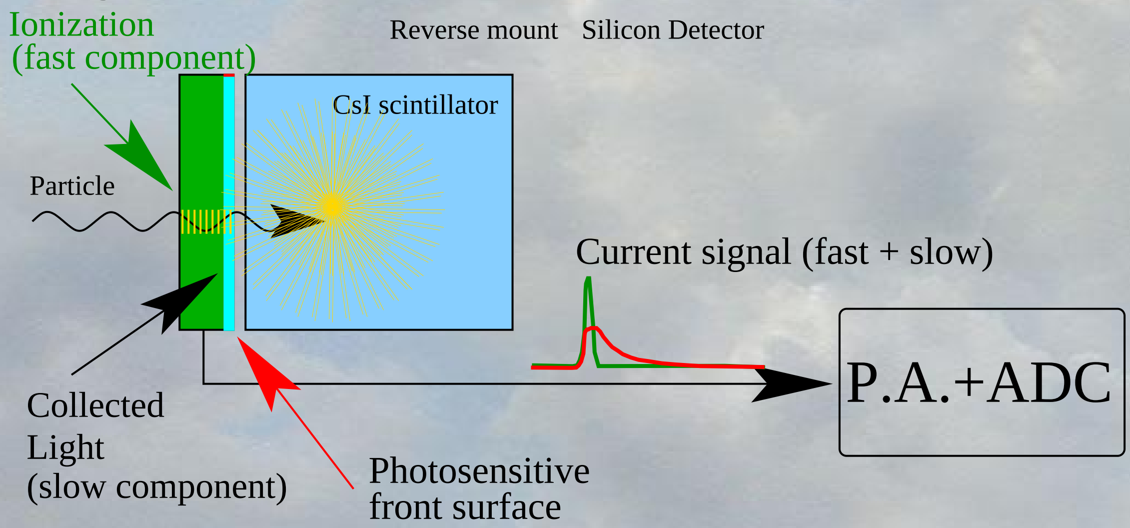


Single Chip Telescope:

Standard reverse mount Si-CsI:

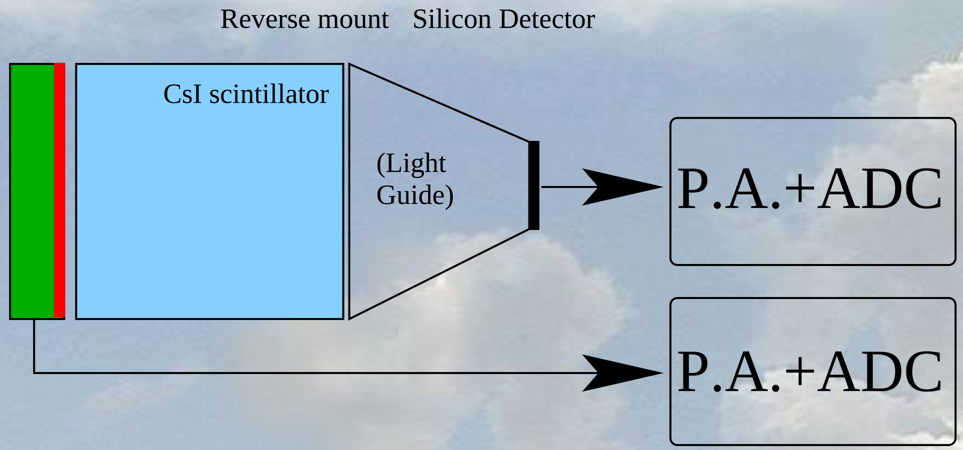


Single Chip Telescope:

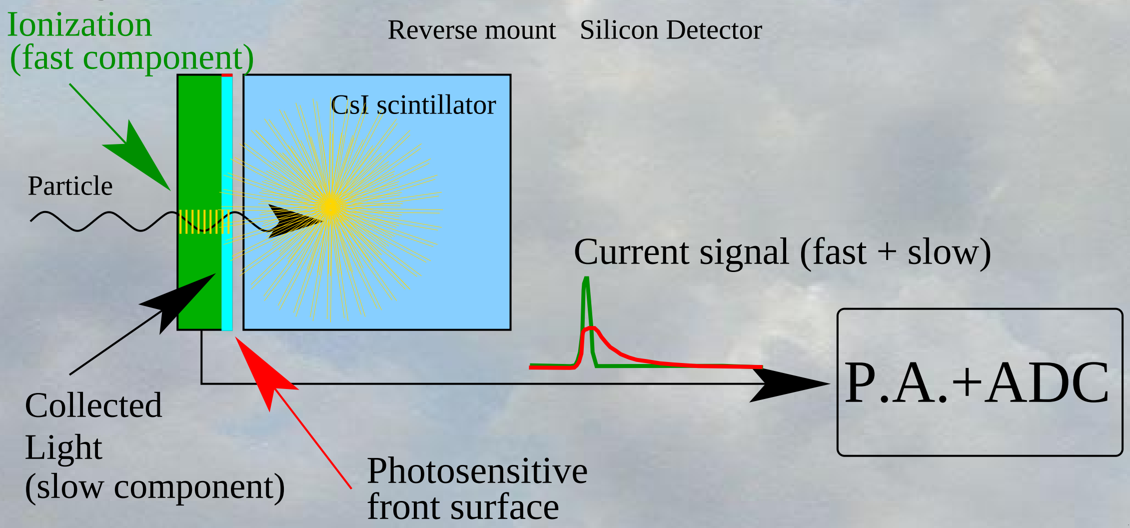


The Single Chip Telescope

Standard reverse mount Si-CsI:



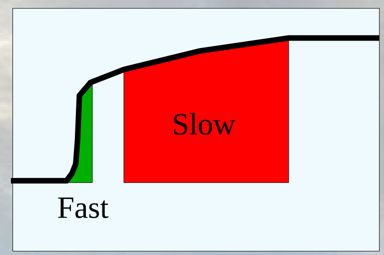
Single Chip Telescope:



This detector was first proposed in G.Pasquali *et al.*, Nucl. Instr. and Meth. **A301** (1991)

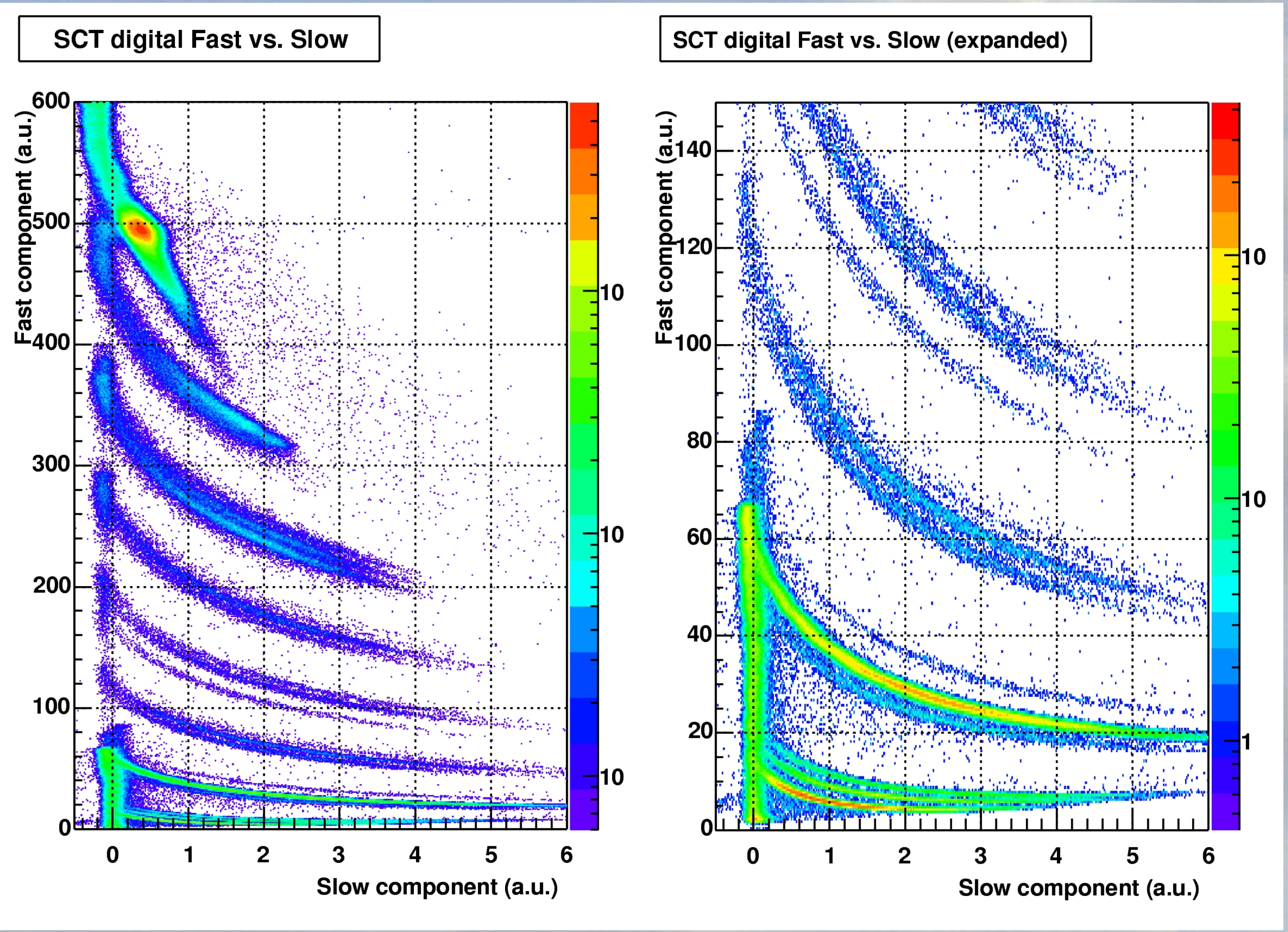
- **Fast** component from Ionization in Si, **Slow** from scintillation of CsI.
- **Stopped in Silicon**: **identical** to the previous case
- **Stopped in CsI**: **fast-slow discrimination**.

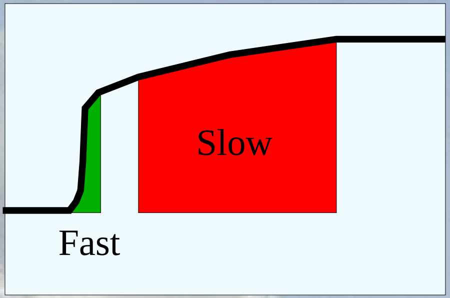
Example of preamplifier output:



Only one digital acquisition channel

Processing the signal coming from the preamplifier with two digital semigaussian filters ($\tau_{fast} \simeq 200\ ns$, $\tau_{slow} \simeq 1\ \mu s$):





300 μm,
≈ 500 mm^2
Silicon
^{16}O+^{116}Sn at
250 MeV

Very first prototype end of 2002

Experimental tests

Detector type	Energy	Timing	PSA	*status*
ΔE-E (Si-CsI)	☺	–	☺	✓
CsI(Tl)	☺	–	☺	✓
Germanium	☺	☺☺	–	✓
Silicon (rev.mount)	☺	☺?	☺☺	*more ToF tests*
Fast Plastic	–	☹?	–	*more tests*
NaI(Tl)	☺	☺	–	✓
Position sens. gas	–	☺	–	✓
Phoswich scint.	☺	–	☺☺	✓
Single Chip tel.	☺	–	☺☺	✓

Conclusions

In the last four years (NUCL-EX coll., Florence group):

- An extensive evaluation of sampling systems has been carried out
- Dedicated hardware has been developed
- Fast processing algorithms have been proposed for both energy and timing measurements
- This approach has been tested with many detector types

Digital methods as replacement and improvement of standard analog techniques

Timing measurements possible with high resolution ADCs.
12 bits: FWHM resolution 100 times smaller than sampling period

Main references:

- L.Bardelli *et al.*, Nucl. Instr. and Meth. **A491** (2002) 244.
- L.Bardelli *et al.*, Laboratori Nazionali di Legnaro Annual Report 2002.
- L.Bardelli *et al.*, Proc. of RNB6 Conf., 2003, to appear in Nucl.Phys. **A**
- L.Bardelli *et al.*, Proceedings of IWM2003 Workshop, Ganil, France 2003.
- L.Bardelli *et al.*, Nucl. Instr. and Meth. **A521** (2004) 480.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