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
Outline

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
- $\Delta E-E$, 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)

⇒ much lower costs.
A custom sampling system

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

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

A custom sampling system

Analog input stage

12 bit sampling ADC

100 MHz clock

FIFO memory

DSP

P.A.
A custom sampling system

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.
Single channel

Photo of a single channel board: (begin of 2004)
Complete digital channel on 14x2.6 cm² PCB

M. Bini, A. Boiano, R. Ciaranfi, A. Ordine, G. Pasquali, L. B.
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
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 (⇒ counting rate)
• Flexibility

A wide class of detectors can be handled with:

• Signal Amplitude measurement (⇒ energy)
• Timing measurement (⇒ rise time, ToF)
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
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

High resolution converter "good energy measurements!"
High resolution or High speed Sampling ADC?
High resolution or High speed Sampling ADC?

Timing measurements: in practice obtain the time $t_0$ where $S(t_0) = S_0$

good timing possible with good signal reconstruction!
High resolution or High speed Sampling ADC?

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Good timing possible with good signal reconstruction!

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Original signal

Ideal reconstruction from
100 MSamples/s, 12 bit (11 eff. bits)

Ideal reconstruction from
1000 MSamples/s, 8 bit (7 eff. bits)
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

\[ \text{at least cubic is needed} \]

Low noise + Good interpolation =
= Good Signal reconstruction = Good Timing!
Which AD converter?

Which AD converter?


![Graph of dCFD timing (f=0.2)](image-url)

Which AD converter?

Preamplifier risetime (ns)

Total error (FWHM, ns)

2 GS/s, 8 bit

ZONE OF NO PRACTICAL INTEREST

dCFD timing (f=0.2)

Analog CFD
Which AD converter?


![Graph](attachment:image.png)

- **100 MS/s, 12 bit**: 100 ps FWHM with a 10 ns sampling period using 12 bit converter (in agreement with exp.)
- **2 GS/s, 8 bit**: ZONE OF NO PRACTICAL INTEREST

12 bit $\Rightarrow$ FWHM resolution 100 times smaller than sampling period
Which AD converter?


12 bit ⇒ FWHM resolution 100 times smaller than sampling period

100 ps FWHM with a 10 ns sampling period using 12 bit converter (in agreement with exp.)

dCFD timing (f=0.2)

400 MS/s, 12 bit
2 GS/s, 8 bit

ZONE OF NO PRACTICAL INTEREST

100 MS/s, 12 bit

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

Timing resolution for elastic peak

Silicon risetime: ~60 ns
FWHM: 125 ps

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

L. Bardelli et al., NIM A521 (2004)
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Standard $\Delta E$-$E$ correlation using digital semigaussian filters
Both high and low ranges with a **single** AD converter for $\Delta E$

Garfield apparatus, NUCL-EX@LNL
2002-2003

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
Si-CsI telescope $\Delta E-E$

$L.\text{Bardelli et al.}, \text{Laboratori Nazionali di Legnaro Annual Report 2002.}$

$5^{th}$ Italy-Japan Symposium  
Napoli, 3-7 November 2004
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Pulse Shape in CsI (photodiode readout)

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, $\tau_{slow} \simeq 2$ $\mu$s).

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

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Non-optimal digital gain...

Digital $^{60}$Co energy spectrum

0 500 1000 1500 2000 2500 Energy (keV)

10^4 10^3 10^2 10 1 counts

Pulser

Digital full range

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)**

![Graph](attachment:image.png)
Detector: ORTEC GMX30p (coaxial, 30% efficiency)

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

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 zero-crossing determination
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Digital Amplitude vs. Digital Zero Crossing time:

Evident sub-nanosecond resolution even with 10ns sampling

mid of 2003

300 μm, ≈ 500 mm² Silicon

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 synchronization between many channels: coincidence measurements possible.

L. Bardelli et al., NIM A521 (2004)
In our experimental test we had a beam resolution of $\sim 1.5\text{ns}$ 😞 (expected digital res. is $\sim 100\text{ ps FWHM}$)

No significant test for digital ToF!
In our experimental test we had a beam resolution of \( \sim 1.5 \text{ns} \) 😞 (expected digital res. is \( \sim 100 \text{ ps FWHM} \))

No significant test for digital ToF!

Same results using analog methods.
## Experimental tests

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5th Italy-Japan Symposium  
Napoli, 3-7 November 2004  
Luigi Bardelli
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

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*more ToF tests*

*more tests*
Test with a standard 2” × 2” detector:

Resolution of $\sim 1.5$ ns FWHM with $^{60}$Co source, E > 600 keV
(timing limited by photoelectrons statistics?)

More work in progress . . .
### Experimental tests

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Position sensitive gas detectors

The signal mixing method can also be applied to standard position sensitive gas detectors (PSPPADs of Garfield apparatus):
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**Single wire resolution** (digital subnanosecond res. confirmed) as good as standard analog signal treatment
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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.
Taking into account performances, system complexity, costs, ... , the standard analog electronics can be replaced by this new digital technique.
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<tbody>
<tr>
<td>$\Delta E-E$ (Si-CsI)</td>
<td>😊</td>
<td>–</td>
<td>😊</td>
<td>✓</td>
</tr>
<tr>
<td>CsI(Tl)</td>
<td>😊</td>
<td>–</td>
<td>😊</td>
<td>✓</td>
</tr>
<tr>
<td>Germanium</td>
<td>😊</td>
<td>😁</td>
<td>–</td>
<td>✓</td>
</tr>
<tr>
<td>Silicon (rev.mount)</td>
<td>😊</td>
<td>😜</td>
<td>😊</td>
<td>more ToF tests</td>
</tr>
<tr>
<td>Fast Plastic</td>
<td>–</td>
<td>😜</td>
<td>–</td>
<td>more tests</td>
</tr>
<tr>
<td>NaI(Tl)</td>
<td>😊</td>
<td>😁</td>
<td>–</td>
<td>✓</td>
</tr>
<tr>
<td>Position sens. gas</td>
<td>–</td>
<td>😁</td>
<td>–</td>
<td>✓</td>
</tr>
<tr>
<td>Phoswich scint.</td>
<td>😊</td>
<td>–</td>
<td>😊</td>
<td>✓</td>
</tr>
<tr>
<td>Single Chip tel.</td>
<td>–</td>
<td>–</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Standard reverse mount Si-CsI:
Reverse mount Silicon Detector

CsI scintillator
(Light Guide)

P.A.+ADC

P.A.+ADC

Single Chip Telescope:
Standard reverse mount Si-CsI:
Reverse mount Silicon Detector

Particle (fast component)

Current signal (fast + slow)

Collected Light (slow component)

Photosensitive front surface

Single Chip Telescope:
Reverse mount Silicon Detector

Ionization (fast component)
The 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 ($\tau_{fast} \simeq 200 \, \text{ns}$, $\tau_{slow} \simeq 1 \, \mu\text{s}$):

- \begin{align*}
300 \, \mu\text{m}, \\
\approx 500 \, \text{mm}^2 \\
\text{Silicon} \\
^{16}\text{O} + ^{116}\text{Sn} \text{ at} \\
250 \, \text{MeV}
\end{align*}

Very first prototype end of 2002
### Experimental tests

<table>
<thead>
<tr>
<th>Detector type</th>
<th>Energy</th>
<th>Timing</th>
<th>PSA</th>
<th>status</th>
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<tr>
<td>ΔE-E (Si-CsI)</td>
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</tbody>
</table>
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: