Digital Pulse Processing of Semiconductor Detector Signals


Institute for Nuclear Physics, University of Cologne

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Outline

- Motivation of digital pulse processing
- The DGF-4C module
- Results with HPGe and Silicon detectors
- Summary
The HORUS spectrometer

The HORUS spectrometer at the University of Cologne:
- 14 HPGe detectors for high resolution $\gamma$ spectroscopy
- BGO shields
- Absolute efficiency of up to 5% at 1.33 MeV

The SONIC array:
- 8 $\Delta E$-$E$ sandwich silicon detectors for charged particle spectroscopy
- Particle identification
- Solid angle coverage of 4%
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<table>
<thead>
<tr>
<th>Analog signal processing</th>
<th>Digital signal processing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filtering of signals in different modules to obtain spectroscopic quantities</td>
<td>Sampling of the signal in the MHz regime provides all spectroscopic information</td>
</tr>
<tr>
<td>Pulse shape analysis hard to implement</td>
<td>Pulse shape analysis can be easily implemented</td>
</tr>
<tr>
<td>Noise important at all stages</td>
<td>Noise important only before sampling</td>
</tr>
<tr>
<td>Highly specialized electronics</td>
<td>Commonly used components (consumer electronics)</td>
</tr>
<tr>
<td>Optimized in $\approx 50$ years of use</td>
<td></td>
</tr>
</tbody>
</table>
Sampling of the preamplifier signal at a rate of 10’s of MHz
- Sampling of the preamplifier signal at a rate of 10’s of MHz
- Online signal processing using a combination of FPGA and DSP
• Sampling of the preamplifier signal at a rate of 10’s of MHz

• Online signal processing using a combination of FPGA and DSP
Trapezoidal filter algorithm

- Slow filter: Energy determination → filter amplitude
- Fast filter: Time determination → leading edge trigger
  Trigger to select events of interest (e.g. Pile-up rejection)
The Digital Gamma Finder (DGF-4C) \cite{1,2}

- **Revision F modules**
  - cost: about 7000 €

- **Pipeline ADC**: digitizing
  - sampling rate 80 MHz
  - depth: 14 bit

- **FPGA**: filter algorithms
  - signal shaping and
  - pile-up rejection

- **DSP**: signal processing
  - determination of energy
  - and time of the signal

- Readout of the data via USB in event-by-event mode

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Results - energy resolution

Test with 80% (*) HPGe detectors:

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(*) Relative to 3 x 3 inch cylindrical NaI detector
Energy resolution is slightly worsened due to beam-induced noise and higher count rate.

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Offbeam test:

- Energy resolution measured with triple-$\alpha$ calibration source:
  \[ \Delta E \ (5486 \text{ keV}): \ 12.00(8) \text{ keV} \]
**Offbeam test:**

- Energy resolution measured with triple-α calibration source:

  \[ \Delta E \ (5486 \text{ keV}): \ 12.00(8) \text{ keV} \]
Results – timing resolution

- Time determination in DGF-4C: leading edge trigger

  Amplitude and risetime-walk effect worsens the timing resolution

![Diagram showing time vs. amplitude with different amplitudes and risetimes.]
Results – timing resolution

- Time determination in DGF-4C: leading edge trigger

  Amplitude and risetime-walk effect worsens the timing resolution

![Graph showing time vs. amplitude with different amplitudes and time resolution effects highlighted.]
Results – timing resolution

- Time determination in DGF-4C: leading edge trigger

  Amplitude and risetime-walk effect worsens the timing resolution

![Graph showing time determination and amplitude and risetime-walk effect](image_url)
Correction for amplitude walk:

Results – timing resolution
Correction for amplitude walk:

- Histogram showing counts per 12.5 ns, with two curves: no correction and walk-corrected.

- Heatmap showing energy [keV] vs. timing correction ΔT [ns].
Results – Timing Resolution

Correction for amplitude walk:

- Timing resolution in coincidence with 1173 keV: $\Delta T \approx 30$ ns
- Improvements with a digital constant fraction algorithm planned [1]

Deadtime contribution in the DGF’s

Events not processed in the DGF

→ Average values, obtained with $^{226}$Ra calibration source

- Pile-up rejection in the FPGA
  - Depends on count rate and filter length:
    \[ R_{out} = R_{in} \cdot \exp(-2T_{F} \cdot R_{in}) \]
    with $T_{F}$: filter length

14 detectors at 9.6 kHz (av.) / ch.

- DSP deadtime
  - DSP blocked by signal processing

  9.9 %

- Readout deadtime
  - Readout of data from DGF-4C to EM/host

  6.3 %

Fraction of events lost per channel in the DGF: 28.8 %
External gating conditions

Applications:
- pulsed beam
  → “beam-on” condition
- $\gamma\gamma$-coincidence experiments
  → multiplicity filter

Advantages:
- reduced background
- reduced deadtime
  → less data to process for DSP
  → less data to readout

- DGF-4C modules: late event validation via GFLT input

- $\gamma\gamma$-coincidence experiment: number of detected events increased by 30%
Summary

- Digital signal processing yields various benefits compared to analog spectroscopy
  → Easy PSA, low-cost, less bulky setup, ....

- DGF-4C modules for readout of HORUS and SONIC
  → Processing Silicon and Germanium detector signals
  → Channel specific VETO input for BGO suppression
  → Good energy and time resolution
  → Reduced deadtime compared to analog systems

Thanks to:
Advantages of Digital Data Acquisition

- Cost and space saving
- Preamplifier signal is sampled right away
  - Reduction of signal instabilities
  - Conservation of signal quality
- Reduced deadtime
  - Processing of higher countrates
- Comparable energy and timing resolution for Silicon and HPGe detectors

Digital data acquisition with DGF-4C modules
Contributions to deadtime - analog:

- Spectroscopy amplifier
  - Pile-up rejection
- ADC
  - Comparison to reference ladder
- Data acquisition
  - Blocked by inhibit logic

Examples:

- one HPGe at 10 kHz: 10 – 25 %
- one HPGe at 10 kHz: 11%
- 20 % at 15 kHz master trigger rate*
- 51 % at 5 kHz master trigger rate**

Total: 41-56 % events lost

* measured with a 14 HPGe detector array at the HORUS spectrometer

** measured with a 8 HPGe detector array at KVI Groningen
Energy Resolution – $\tau$ Correction

- Time constant $\tau$ most important for good energy resolution
- Adjust $\tau$ parameter to get best peak shape and resolution

Count rate = 20 kHz

courtesy of N. Warr
Timing Properties

- Time determination in DGF module: *leading edge trigger*

- Amplitude walk: Depending on the energy deposited in the crystal

  ![Amplitude Walk Diagram]

- Risetime walk: Depending on the interaction point in the crystal

  ![Risetime Walk Diagram]

- Improvement of timing resolution with a digital constant fraction algorithm planned [1]

  ![Histogram Graph]

\[ \Delta T = 52.5 \pm 2.1 \text{ ns} \]

Treatment of Random Coincidences

Timedifference spectrum between two detectors:

- Create peak and background matrices
- Final matrix: difference of peak and background matrix
Active Compton Suppression

Four veto channels for Compton suppression

Reduction factor: 3.358 (10)

Counts / 0.5keV

energy [keV]
Energy Resolution – Analog vs. Digital

![Graph showing energy resolution comparison between analog and digital signals. The x-axis represents detector number, and the y-axis shows energy resolution (ΔE) and ΔE_{ani} - ΔE_{digi} in keV. The graph includes data points for ΔE analog, offbeam, R_{in}=1.2 - 3.6 keV and ΔE digital, offbeam, R_{in}=1.2 - 3.6 keV.](image)
External Trigger Conditions

Late event validation using the GFLT

DGF 1 → Mult-out signal → Linear FIFO → Discriminator → Gate Generator

Input 1

DGF 2 → Mult-out signal

Input 1

V

n ≥ 2

n=2

n=1

trigger level

t

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Late event validation using the GFLT

- Input 1
  - DGF 1
    - Mult-out signal
    - Gate signal to trigger input
    - Linear FIFO
    - Discriminator
    - Gate Generator
    - n ≥ 2

- Input 1
  - DGF 2
    - Mult-out signal
    - Gate signal to trigger input

Readout deadtime reduced to 0.9%
The $^{124}\text{Sn}(^{13}\text{C},3n)^{134}\text{Ba}$ Experiment
**γγ-Coincidence Experiment**

**Reaction:** $^{124}\text{Sn}(^{13}\text{C},xn)^{137-x}\text{Ba}$

- Use of 13 HPGe detectors
- Production of well studied nuclei $^{133}\text{Ba}$ [1,2] and $^{134}\text{Ba}$ [3,4]
- Beam energy: 46 MeV, calculation with CASCADE

**Aim of the test experiment:**

- Acquisition of $\gamma\gamma$ coincidences
- Investigation of energy and timing resolution
- Reproduction of angular correlations of coincident $\gamma$-rays

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Angular Correlations

Angular distribution of $\gamma$-ray emission from an aligned nucleus:

$$W(\theta_1, \theta_2, \phi) = \sum_{k,k_1,k_2} B_{k_1} (I_{1}) A_{k}^{k_1,k_2} (\gamma_{1}) A_{k_2} (\gamma_{2}) H_{k_1,k_2} (\theta_1, \theta_2, \phi)$$

- Sorting of detector pairs in 17 correlation groups that share the same angles $\phi, \theta_1, \theta_2$
- Fit of $W(\theta_1, \theta_2, \phi)$ to intensities in correlation groups
Test of the Data Acquisition

Reaction: $^{124}\text{Sn}(^{13}\text{C},4n)^{133}\text{Ba}$
- Beam energy: 46 MeV
- Beam current: 10 pnA
- HPGe count rates: 5 - 14 kHz
- $\Delta E_{\text{FWHM}}$: 1.9 to 2.4 keV
Angular Correlations in $^{134}$Ba

$\gamma\gamma$ Angular Correlations in $^{134}$Ba

$^{134}$Ba

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Digital Pulse Processing of Semiconductor Detector Signals
Angular Correlations in $^{134}\text{Ba}$

$\gamma \gamma$ Angular Correlations in $^{134}\text{Ba}$

1. $1400\text{ keV} \rightarrow 605\text{ keV} \rightarrow 0\text{ keV}, E_\gamma = 796/605\text{ keV}$
   - Experiment: $4 \rightarrow 2 \rightarrow 0$, $\delta_1=0.011\pm0.056$, $\delta_2=0$, $\chi^2=4.6$

2. $2211\text{ keV} \rightarrow 1400\text{ keV} \rightarrow 605\text{ keV}, E_\gamma = 811/796\text{ keV}$
   - Experiment: $6 \rightarrow 4 \rightarrow 2$, $\delta_1=0.002\pm0.061$, $\delta_2=0$, $\chi^2=3.7$

3. $1986\text{ keV} \rightarrow 1400\text{ keV} \rightarrow 605\text{ keV}, E_\gamma = 585/796\text{ keV}$
   - Experiment: $5 \rightarrow 4 \rightarrow 2$, $\delta_1=0.011\pm0.048$, $\delta_2=0$, $\chi^2=5.7$
   - Experiment: $6 \rightarrow 4 \rightarrow 2$, $\delta_1=0$, $\delta_2=0$, $\chi^2=20.0$
   - Experiment: $4 \rightarrow 4 \rightarrow 2$, $\delta_1=0.758\pm0.187$, $\delta_2=0$, $\chi^2=12.9$
Angular Correlations in $^{133}\text{Ba}$

$1859 \text{ keV} \rightarrow 969 \text{ keV} \rightarrow 228 \text{ keV}, E_\gamma = 890/680 \text{ keV}$

Experiment

$19/2^+ \rightarrow 15/2^+ \rightarrow 11/2^-, \delta_1=0.049 \pm 0.049, \delta_2=0, \chi^2=6.1$

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Energy Levels:

- $^{133}\text{Ba}$
- $1859 \rightarrow 19/2^-$
- $1712 \rightarrow 17/2^-$
- $969 \rightarrow 15/2^-$
- $680 \rightarrow 13/2^-$
- $288 \rightarrow 11/2^-$
- $627 \rightarrow 15/2^-$
- $642 \rightarrow 19/2^-$
- $338 \rightarrow 21/2^-$
Angular Correlations in $^{133}$Ba

$\gamma\gamma$ Angular Correlations in $^{133}$Ba

$1859$ keV → $969$ keV → $228$ keV, $E_\gamma = 890/680$ keV

- Experiment
- $19/2^-\rightarrow 15/2^-\rightarrow 11/2^-$, $\delta_1=0.049\pm0.049$, $\delta_2=0$, $\chi^2=6.1$

$2509$ keV → $2170$ keV → $1529$ keV, $E_\gamma = 338/642$ keV

- Experiment
- $21/2^-\rightarrow 19/2^-\rightarrow 15/2^-$, $\delta_1=-0.105\pm0.034$, $\delta_2=0$, $\chi^2=4.6$

$1712$ keV → $969$ keV → $228$ keV, $E_\gamma = 743/680$ keV

- Experiment
- $17/2^-\rightarrow 15/2^-\rightarrow 11/2^-$, $\delta_1=-0.492\pm0.053$, $\delta_2=0$, $\chi^2=3.1$
**Reaction:** $^{124}\text{Sn}(^{13}\text{C},4\text{n})^{133}\text{Ba}$

- Beam energy: 46 MeV
- Beam current: 10 pnA
- HPGe count rates: 5 - 14 kHz
- $\Delta E_{\text{FWHM}}$: 1.9 to 2.4 keV
Correction for Solid Angle Coverage

Neglecting the extension of the source: \( A_{kk} = \frac{A_{kk}^{\text{exp}}}{Q_{kk}} \)

- Attenuation factors \( Q_{kk} = Q_k(1) \cdot Q_k(2) \) with \( Q_k(i) = \frac{J_k(i)}{J_0(i)} \)

\[
J_k(i) = \int_0^{1/2\pi} \varepsilon_i(E, \alpha) \cdot P_k(\cos \alpha) \left| \sin \alpha \right| d\alpha
\]

J. S. Lawson and H. Frauenfelder, Phys. Rev. 91 (11953) 649
Correction for Solid Angle Coverage

- Effect of solid angle correction with statistical error bars
- Minor changes in determined multipole mixing ratios
The $^{140}\text{Ce}(p,p'\gamma)$ Experiment
**Particle-γ Coincidence Experiment**

- Coincident detection of scattered proton and deexciting γ ray
- Particle detector array SONIC embedded into HORUS spectrometer

**Reaction:** $^{140}$Ce(p,p'γ)

- Beam energy: $E_p = 10.4$ MeV
- Beam current: $I_p = 0.5$ pnA

\[
E_x \approx E_p - E_{p'}
\]

- Silicon detector
- HPGe detector

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Digital Pulse Processing of Semiconductor Detector Signals
Excitation spectrum in $^{140}\text{Ce}$

- $2^+_1$
- $12\text{C}(2^+_1)$
- $16\text{O}(0^+_2, 3^-_1)$

Counts / 2 keV

$E_x \approx E_p - E_p^*$ [keV]
Decay of Two-Phonon State in $^{140}$Ce

- Two-phonon 1$^-$ state in $^{140}$Ce:

$$ (2^+ \otimes 3^-)^{1^-} $$

**Diagram:**

- $E_x$
- $3643 ightarrow 2051 ightarrow 1592 ightarrow 3643$
- $1592 ightarrow 2^+$
- $3643 ightarrow 1592 ightarrow 0^+$

**Graph:**

- Projected $\gamma$-spectrum
- Energy [keV]
- Counts / 2 keV
Decay of two-phonon state in $^{140}\text{Ce}$

- Two-phonon $1^-$ state in $^{140}\text{Ce}$:

  $E_x \approx E_p - E_{p'}$

  $E_p$

  $E_{p'}$

  $E_{\gamma}$

  $3643 \rightarrow (2^+ \otimes 3^-)^{1^-}$

  $1592 \rightarrow 2^+$

  $2051 \rightarrow 0^+$

  $3643 \rightarrow 1592 \rightarrow 0^+$

  $3643$

  $1592$

  $2051$

  $0$

  $0^+$

  $E_{x}$

  $1^{-} \rightarrow 0^{+}$

  $1^{-} \rightarrow 2^{+}$

  $\text{projected } \gamma\text{-spectrum}$

  $\text{gate on } E_{x} = 3643 \text{ keV}$

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Digital Pulse Processing of Semiconductor Detector Signals
The sorting code SOCO
Evaluation software for double coincidence listmode data

Features:

- Use of multiprocessing

SOorting code COlogne (SOCO) [1]

- Evaluation software for double coincidence listmode data

Features:

- Use of multiprocessing

- Provides matrices, single spectra and projections, as well as time-difference spectra

- Support of different listmode formats:
  - **FERA** *(old cologne data format)*
  - **XIA** *(data format for the new digital data acquisition)*
  - **GASP** *(INFN Legnaro, IFIN-HH Bucharest)*

\[ S = S_2 - S_1 = 0 \]

\[ L V_{x,k} = - \sum_{i=k-2L+G+1}^{k-L-G} V_i + \sum_{i=k-L+1}^{k} V_i \]
Trapezoidal filter algorithm

\[ S = S_2 - S_1 = 0 \]

\[ LV_{x,k} = - \sum_{i=k-2L-G+1}^{k-L-G} V_i + \sum_{i=k-L+1}^{k} V_i \]
Trapezoidal filter algorithm

\[ S = S_2 - S_1 = 0 \]

\[ L V_{x,k} = - \sum_{i=k-2L-G+1}^{k-L-G} V_i + \sum_{i=k-L+1}^{k} V_i \]
Trapezoidal filter algorithm

\[ S = S_2 - S_1 = 1 \]

\[ LV_{x,k} = - \sum_{i=k-2L-G+1}^{k-L-G} V_i + \sum_{i=k-L+1}^{k} V_i \]
Trapezoidal filter algorithm

\[ S = S_2 - S_1 = 2 \]

\[ LV_{x,k} = - \sum_{i=k-2L-G+1}^{k-L-G} V_i + \sum_{i=k-L+1}^{k} V_i \]
\[ S = S_2 - S_1 = 3 \]

\[ LV_{x,k} = -\sum_{i=k-2L-G+1}^{k-L-G} V_i + \sum_{i=k-L+1}^{k} V_i \]
$S = S_2 - S_1 = 4$

$$LV_{x,k} = - \sum_{i=k-2L-G+1}^{k-L-G} V_i + \sum_{i=k-L+1}^{k} V_i$$
\[ S = S_2 - S_1 = 5 \]

\[ LV_{x,k} = - \sum_{i=k-2L-G+1}^{k-L-G} V_i + \sum_{i=k-L+1}^{k} V_i \]
Trapezoidal filter algorithm

\[ S = S_2 - S_1 = 5 \]

\[ LV_{x,k} = - \sum_{i=k-2L-G+1}^{k-L-G} V_i + \sum_{i=k-L+1}^{k} V_i \]
Trapezoidal filter algorithm

\[ S = S_2 - S_1 = 5 \]

\[ \sum_{i=k-L-G+1}^{k-L+1} V_i - \sum_{i=k-L+1}^{k} V_i \]
\[ S = S_2 - S_1 = 5 \]

\[ LV_{x,k} = - \sum_{i=k-2L-G+1}^{k-L-G} V_i + \sum_{i=k-L+1}^{k} V_i \]
\[ \text{S} = S_2 - S_1 = 0 \]

\[ \sum_{i=k-L-G+1}^{k} V_i + \sum_{i=k-L+1}^{k} V_i \]

Trapezoidal filter algorithm