Neutron detector modules, electronics and software for a Time-of-Flight Spectrometer based on National Instruments components

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Datalist Systems profile:
Instruments for neutron scattering

Datalist delivers new generation signal processing and data acquisition with built-in event recording (list mode) capability

Absolute timestamp:
- 8-100 ns
- 48 bit time resolution (1 month - 1 year)

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Nuclear Physics In Stellar Explosions
TOF N detector modules based on NI components
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Datalist Neutron Scattering Products

- **LisTDC Position System**
  - for 2D PSD wire detectors
  - detectors with delay line outputs

- **LisTDC Event System**
  - also for 2D PSD detectors
  - with enhanced capabilities for Time of Flight (TOF) measurements

- **LisTOF System**
  - for multiple point (0D) detectors
  - typically for Time of Flight (TOF) measurements

- **Event recorder software**
  - to all the electronic components

- **Instrument Control**
  - Complete spectrometer control
    - e.g. motion, temperature, magnetic field
Main professional relations
(Datalist Ltd as successor of Ante Ltd)

• National Instruments        Austin, USA – Debrecen, Hungary   DAQ components
• Atomki                    Debrecen, Hungary                  beta detector DAQ system
• Wigner Research Centre for Physics  Budapest, Hungary     neutron scattering spectrometers
• Mirrotron Ltd               Budapest, Hungary                LisTDCs, Event recorder software
• Chinese Academy of Sciences Mianyang, China               LisTDC+spectrometer control
• ISIS                      Cambridge, UK                     cooperation in neutron signal processing
• IFE                       Oslo, Norway                     Odin spectrometer DAQ system
• ANSTO                     Sydney, Australia                LisTDC for SANS
• HZB                       Hahn Meitner Platz, Berlin NEAT-II spectrometer
Several worldwide customers

- IFE: Institute for Energy Technology
- ISIS: Science & Technology Facilities Council
- HZB: Helmholtz Zentrum Berlin
- ESS: European Spallation Source
- Atomki: Debrecen
- MTA Institute
- Australian Government
- Ansto: Australian Nuclear Science and Technology Organisation

Institute of Nuclear Physics and Chemistry, Mianyang, China
Plan: NEAT II Instrument at HZB

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Flugzeit-spektrometrisches NEAT II Instrument

Neutronenstrahl

Neutronenfilter

Neutronenleiter

Probenort

Detektor


Der erste Chopper unterteilt den Strahl in verschiedene Körner. Jeder Chopper wird die Neutronen, die innerhalb eines Kolbens zu schnell oder zu langsam sind, abgeblockt. Im weiteren Verlauf können die Neutronen in der gewünschten Geschwindigkeitsberechnung durch die Chopper in einem festen herausgefäßt werden. Treff sind Neutronen dann auf eine Probe zu zügig, die mit dem Kernen in der Probe. Dadurch verhindern Neutronen ihre Geschwindigkeitsberechnungen. Der Dekoder für neuartige, welche durch die Neutrons für den Weg von der Probe bis Detektor betrachtet, der sie ein- trifft. So wird die Dauerläufer die Vorgaben der Neutronen bestimmt, die dieser Methode ihnen zutraut. Auch die Richtung, mit der die Neutronen am Dekoder ankommen, wird gemessen und enthält wichtige Informationen über die Probe.
The beginning:
Inside the empty vacuum chamber
Requirements

- 416 pcs neutron detector tubes – $^3$He gas filled
  - Building up supporting modules each with 32 tubes
- Position resolution: 20 mm on 2000 mm length
- Max count rate per detector tube: 50 kHz
  - In case of 10% dead time: $T_{\text{DAQ}} < 0.1 \times 1/50\text{kHz} = 2\mu\text{s}$
- Max overall (416 tubes) count rate: 1 MHz
  - Uneven load
- 7 chopper system
- TOF measurement

Minimizing the background

- More detailed signal analysis is needed
- Instead of a regular (traditional) amplifier: sampling ADCs
- Parallel sampling on 832 channel (on both tube ends)
Mechanical Overview

- 416 $^3$He PSD tubes (Reuter-Stokes / 2m long)
- 32 tubes / module – 13 modules
Mechanical Details

- Aluminium modules
  - four 8-tube units provide mechanical support
- Air-boxes containing front-end electronics (preamplifiers)
  - atmospheric pressure inside the air boxes to avoid HV sparks at immediate vacuum pressure
Mechanical Assembly

- modules manufactured and partly assembled in Hungary
- fully assembled and installed on site
The signal of each neutron event is processed:

1. The pre-amplifier transmits the signal of the central electrode to a sampling ADC unit (with 50 MHz sampling rate).
2. FPGA unit processes the digital signal: no analog (long-range) integration is carried out.
3. Signal-shape sensitive analysis can be performed on PC.
How to build the signal conditioning and DAQ? (1)

Option 1

without any hardware from National Instruments, Inc.
How to build up the signal conditioning and DAQ? (2)

Option 2

with hardware components from National Instruments Inc.
Why we have chosen Option 2 with NI components?

Summary of Requirements

- Floating-point processing
- Communications GigE
- Synchronized time scale
- Continuous signal sampling
- Analog trigger condition
- Pre-triggering
- High-speed processing
- 100 ns accurate time stamp
- 832 analog input channels
- Sampling ADCs
- 12 bit resolution
- 50 k events/sec/channel
- max 1M event/system
Unique efforts vs. routine solutions from NI

- Computer
  - Multicore programming

- FPGA
  - VHDL development
  - with fixed-point algorithms

- I/O
  - Custom solution for coupling A/D devices to FPGA

- I/O
  - Custom digital interface/buses

- I/O
  - Custom timing for different types of I/O

Such a „usual way“ of development needs much more effort, source allocation.
Using LabVIEW Graphical Programming Environment both for Computer and FPGA from National Instruments significantly reduced the development efforts.

Unique efforts vs. routine solutions from NI

- **Computer**
  - LabView + C++ programming
  - Predefined data communication by using DMA, interrupt and bus control drivers

- **FPGA**
  - LabView only
  - Predefined I/O drivers both for digital lines and ADCs

- **NI Components**
  - I/O
  - Ready made hardware
Signal Processing

- Proprietary analog electronics
  - Low time constant (~60 ns) preamplifier electronics
- Sampling ADC's
  - 50 MS/s for all the 832 data channels
  - based on National Instruments
- Two PXI chassis
- Two data acquisition computers
  - postprocessing
  - event classification
  - preview of the collected data
PC Functions:
- Control of PXI Chassis
- CPU Post processing
- Data Storage
- User Interface

PXI Functions:
- Analog Data Acquisition
- FPGA Preprocessing
- Timing & Synchronization
- Data Transfer to CPU

Data Bus (PCIe-PXI Bridge)

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Digital Signal Processing
Main electronic units
Data Acquisition

- DAQ software based on “event recording” principles
  - data flow to the scientific software as Event Record List
- Time-of-flight
  - absolute timestamps
  - 100 ns / 48 bits ~ 325 days

Let us see signal analysis details in case of a single neutron event...
Signal Processing Algorithms

The important advantage of using ready made (NI) electronic components was to have enough time for developing complicated algorithms to evaluate the data coming from the sampling ADCs...
Signal shapes

- "Single bump" - good neutron signal

![Graph showing signal shapes with a peak indicating a good neutron signal.](image-url)
Signal shapes

- “Double bump” - strange but good neutron signal
Signal shapes

- “Gamma” - false signal, to be rejected
Signal shapes

- “Pileup” - perhaps neutron signal but to be rejected
Classification

- Event classification system
  - provides pulse shape data
  - hard threshold in the FPGAs
  - pulse-shape based classification to minimize gamma sensitivity
  - flexible numerical classification to filter pileup and other unwanted phenomena
Schematic of the electronics
Digital Signal Processing on both ends

FPGA unit processes the digital signal coming from the sampling ADC unit. Multiple parameters of each signal (tube-to-tube, from both ends) are determined and passed on to PC – this is the base of the feature specific analysis:

- **ToT**: The beginning and the end of the signal is detected by comparing it to a pre-defined threshold. The length of this interval is referred as “time over threshold” (ToT).

- **Charge**: The numeric integral of the signal on the interval ToT results in Charge-ToT.

- **Classification** is based on integral values during N1, N2 and N3
Determination of position of neutron events

- **He-3 filled gas detector:**
  - \( \text{He}_3^{2+} + n^0 \rightarrow \text{T}_3^+ + \text{H}_1^+ \)
  - Charge avalanche is initiated by the charged particles
  - The maximum amount of charge is proportional to the energy of the reaction, however the whole energy is not always absorbed in the active volume of the detector

- Calculation of the position is based on the proportion of charges measured on the end of detector tubes (zero is defined in the middle of the tube).

\[
p = \frac{A - B}{A + B} = -1 \ldots 0 \ldots 1
\]
Deviations from the ideal system – CROSSTALK EFFECT

CROSSTALK EFFECT: the pre-amplifiers interact with each other on the two ends of the detector-tubes.

- In case of uneven signals (off-middle neutron event):
  - Higher-signal is “over-attenuated” below base-line
  - Low-signal is “weakly-attenuated” over base-line
- Crosstalk effect shows charge and shape dependence.
- Each detector tube has to be calibrated by neutron measurements on slit series.
Electronic Side Effects

Main deviations in the position characteristics:

1. **Zero position** is not projected into 0.

   *Reasons:*
   
   1. Amplification-rates slightly differ from each other on the two ends of the detector-tubes.
   2. **BASELINEs** of the pre-amplifiers differ from each other on the detector-tubes.
   3. **CROSSTALK EFFECT** - the pre-amplifiers interact with each other on the two ends of the detector-tubes.

2. The **slope** of the position characteristics is not equal to 1 i.e.

   \[ p_{\text{measured}} = \frac{A - B}{A + B} = -0.9 \ldots 0 \ldots 0.9 \]

   *Reason: CROSSTALK EFFECT*
Deviations from the ideal system

Neutron measurements with slit-series are carried out on each detector tube.

„Neutron constants” are determined in order to compensate the slight nonlinearities and slope deviation of the position characteristics.
Calibration by using pattern generators

- independent position calibration methods
  - everyday monitoring using pattern generators

- absolute calibration with neutrons by using Cd slit
Deviations from the ideal system
Electronic side effects

SLIT at the position: -889 mm
Deviations from the ideal system  
Electronic side effects – BASELINE RESTORE

- Baselines (i.e. zero-levels) of the pre-amplifiers differ from each other on the detector-tubes.
- **Baseline restore algorithm** is running until an event is triggered
- Signal level is corrected with the baseline level while neutron event is processed

\[
signal_{i+1}^{A|B} \rightarrow signal_{i+1}^{A|B} - baseline_{i+1}^{A|B}
\]

\[
\begin{cases} 
baseline_{i+1}^{A|B} \rightarrow baseline_{i+1}^{A|B} + \delta, & \text{if } signal_{i-5}^{A|B} > 0 \\
baseline_{i+1}^{A|B} \rightarrow baseline_{i+1}^{A|B} - \delta, & \text{if } signal_{i-5}^{A|B} < 0
\end{cases}
\]
Deviations from the ideal system
Electronic side effects – BASELINE RESTORE

Pattern-events are generated at the position: 0 mm
Digital Signal Processing on both ends:

**Charge and ToT**

![Graph showing signal processing](image)

- **Charge**
- **ToT**

**Signal Sample Points**

- **Starting Point**
- **Trigger Point**
- **End-of-Signal**
- **End-Trigger**

**Time Over Threshold (ToT)**

- **N1**
- **N2**
- **N3**

- 0, 25, ≤ 45, 5, 30, ≤ 100

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Signal Shape Analysis

**Slit experiment:** many kind of neutron event is collected in specified position. The deviation of the measured positions from the expected position is plotted against Charge-ToT and ToT. Events with “good behavior” fit well to a plane: efficient feature-specific correction can be carried out.

\[
p_{\text{feature-corr}} = p \cdot (1 + \Delta)
\]

\[
\Delta = \frac{1}{p_{\text{SLIT}}} (A + B \cdot \text{ChargeToT} + C \cdot \text{ToT})
\]
Deviations from the ideal system
Physical properties – Signal shape analysis

Application of appropriate feature correction: the signal of a diffuse sample (*plexiglass*) in a given detector tube is uniform.
Deviations from the ideal system based on Charge-ToT correction

The histogram below shows the effect of the feature-correction on the dataset acquired in a slit-experiment. The fact, that results of few tens of independent tubes are displayed simultaneously, shows the efficiency of the correction.

SLIT at the position: -889 mm
Summary

- A large spectrometer for neutron diffraction has been build by Datalist System staff.
- The DAQ has TOF capability with absolute and $T_0$ based time stamps.
- The signal processing uses parallel continuous sample ADCs with 832 channels.
- Advantages of National Instruments components were utilized during development
  - NI components are stable and robust
- Signal shape analysis has been developed for flexible signal classification
  - Single bump – good signal
  - Double bump – good signal
  - Gamma – rejected
  - Pile up - rejected
- Successful „base line restore” and „deviation from linearity” algorithm is developed.
- Complex position calculation algorithm is established
  - with the help of pattern generators
  - with slit measurements
  - using results from charge-ToT relation (feature analysis)

=> Position determination of 1% (20 mm at 2000 mm length) has been achieved.
Thanks for the attention

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