Ready to Use Detector Modules for the NEAT Spectrometer: Concept, Design, First Results

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Abstract. The paper presents the detector system developed by Datalist Systems, Ltd. (previously ANTE Innovative Technologies) for the NEAT-II spectrometer at HZB. We present initial concept, design and implementation highlights as well as the first results of measurements such as position resolution. The initial concept called for modular architecture with 416 3He detector tubes organized into thirteen 32-tube modules that can be independently installed and removed to and from the detector vacuum chamber for ease of maintenance. The unalloyed aluminum mechanical support modules for four 8-tube units each also house the air-boxes that contain the front-end electronics (preamplifiers) that need to be on atmospheric pressure. The modules have been manufactured and partly assembled in Hungary and then fully assembled and installed on site by Datalist Systems crew. The signal processing and data acquisition solution is based on low time constant (~60 ns) preamplifier electronics and sampling ADC's running at 50 MS/s (i.e. a sample every 20 ns) for all 832 data channels. The preamplifiers are proprietary, developed specifically for the NEAT spectrometer, while the ADC's and the FPGA's that further process the data are based on National Instruments products. The data acquisition system comprises 26 FPGA modules each serving 16 tubes (providing for up to 50 kHz count rate per individual tube) and it is organized into two PXI chassis and two data acquisition computers that perform post-processing, event classification and provide appropriate preview of the collected data. The data acquisition software based on Event Recording principles provides a single point of contact for the scientific software with an Event Record List with absolute timestamps of 100ns resolution, timing data of 100 ns resolution for the seven discs chopper system as well as classification data that can be used for flexible data filtering in off-line analysis of the gathered data. A unique 3-tier system of filtering criteria of events is in operation: a hard threshold in the FPGA's to reduce the effect of noise, a pulse-shape based classification to eliminate gamma sensitivity and an additional flexible feature based classification to filter out pileup and other unwanted phenomena. This ensures high count rates (50kHz per tube, 1MHz overall) while maintaining good quality of measurements (e.g. position resolution).The first measurement results show that the delivered detector system meets the initial requirements of 20 mm position resolution along the 2000mm long detector tubes. This is partly due to the innovative event classification system that provides vital pulse shape data that can be used for sophisticated position resolution algorithms implemented on the DAQ computers. .

INTRODUCTION

The NEAT-II instrument (*FIG. 1*) at HZB is an advanced, recently completed Time-of-Flight (TOF) spectrometer replacing the previous NEAT instrument [1]. The requirements to the detector and data acquisition system can be summarized as follows.

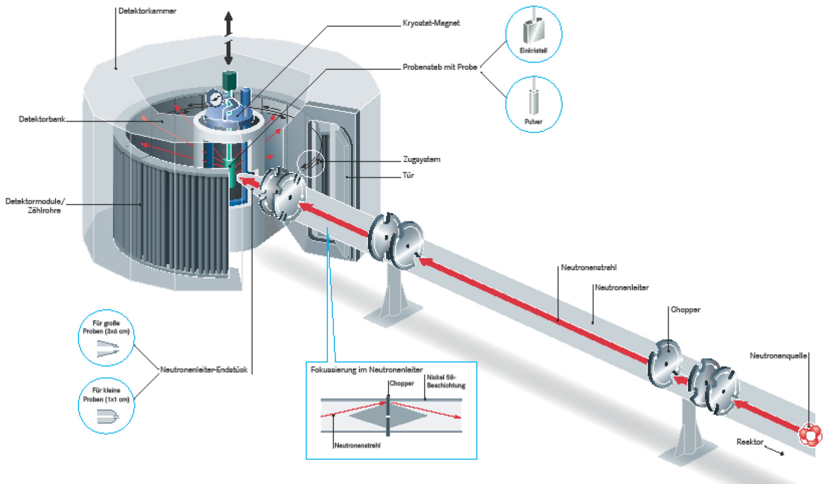


FIGURE 1. A sketch of the NEAT-II instrument

The neutron detection for the new NEAT is based on position sensitive 3He detectors covering approximately 225^0range of scattering angles. The detector system is comprised of 416 detector tubes of 2000 mm length that is organized in a modular fashion for ease of use (installation, repair) with the modules containing both the mechanical support structure as well as front-end electronics, cabling etc.

The detector tubes' position resolution is required to be better than 20 mm i.e. one percent of the overall length.

The specification called for a maximum detection rate of 50 kHz per detector with 10 % dead time. Turning that into data acquisition time, this means that the time of acquisition of a single neutron event must satisfy:

$$T_{DAQ} \leq 0.1 * \frac{1}{50\ kHz} = 2\ \mu s \tag{1}$$

The overall data collection speed requirement calls for a maximum load of 1 MHz over all 416 detectors together. This clearly means that highly uneven load distributions are to be expected in the system.

The main function of the NEAT-II instrument is to perform TOF spectroscopic measurements. This is achieved by a system of seven choppers. The Detector/DAQ system has to be capable of both high precision measurement of Time-of-Flight values and capturing the timing events from all seven choppers for future reference.

One of the main requirements of the Detector System was that it should minimize background. This is necessary as the instrument will be used to conduct inelastic and quasi-elastic scattering experiments. In order to achieve this - among other measures - advanced signal analysis is required. [2]

DESCRIPTION OF THE TECHNICAL SOLUTION

We can divide the technical solution into the following areas:

- *Mechanical support:* encompassing the modular design of the Detector System mechanics as well as the primary collimator system.
- *Signal processing:* encompassing both the analogue and digital tool chain with the novel signal processing concept based on fast sampling ADC's and digital signal analysis with FPGA's.
- *Data acquisition*: encompassing evaluation of event parameters for data storage

Mechanical Solution

The mechanical solution of the detector system posed several challenges in the planning, manufacturing as well as installation phases.

The Detector System comprises 416 Reuter-Stokes PSD tube detectors [3]. The detectors are one-inch diameter 3He tubes of 2000 mm length with 90 degree connectors on both ends.

The technical specification called for a modular design with 13 modules of 32 tubes each for ease of installation and maintenance. An important requirement was that the mechanical modules be manufactured of unalloyed aluminum in order to reduce neutron background due to scattering.

The modules have three main functions in the Detector System:

- Provide mechanical support for the detector tubes. This means:
    1. positioning the tubes on the perimeter of a 3 meter radius cylinder centered on the sample position;
    2. guaranteeing 28 mm spacing between neighboring tubes;
    3. aligning all tubes in a perfectly vertical orientation;
    4. allowing for fine tuning the alignment of the module in all directions;
- Provide mechanical support for the primary collimator system.
- House the front-end electronics' air boxes (atmospheric pressure) inside the evacuated detector chamber.

Each module is made up of four units of 8 tubes. The detector tubes of a unit have a common air box on both ends. These air boxes containing the front-end electronics (e.g. preamplifiers) on both ends of a unit are connected by a mechanically robust aluminum pipe that provides the mechanical backbone of the unit. The inside of the air boxes and the connecting pipe are on atmospheric pressure inside the vacuum chamber and are connected to the outside of the chamber by flexible vacuum tight tubing. The cabling for the electronics is also conducted through the connecting pipes and the flexible tubing leading to the outside of the vacuum detector chamber.

The four Units of a single Module are connected by two aluminum plates on the top and on the bottom that position them at the correct angle with regard to one another. These plates also serve as mounting point inside the chamber (bottom plate) and attachment point for the conveyor / crane system for assembly disassembly (top plate). The primary collimator system comprises a series of 2200*100*2 mm blades that are placed between each pair of neighboring detector tubes in a radial configuration. The blades are based on 1 mm thick aluminum carrier with a 0.5 mm thick layer of Cd coating on both sides. *Figure 2* below shows a completed Detector Module being craned.

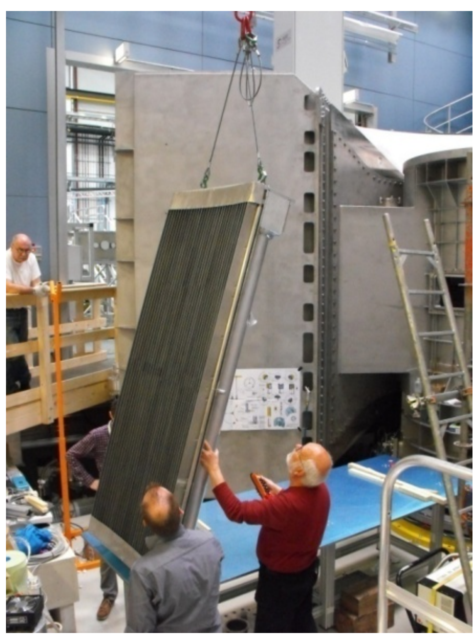


FIGURE 2. Completed detector module complete with primary collimator system being craned

The modules were manufactured and partly assembled at the Datalist Systems manufacturing premises in Hungary and fully assembled on the site at HZB.

Signal Processing Solution

The signal processing solution is a combination of proprietary electronics (mainly the analogue part) and an FPGA based system implemented on commercially available hardware from National Instruments (see *Fig. 3* below).

The signal processing electronics is located in three distinct places. Front-end analogue electronics is housed in the air boxes at both ends of the detector tubes. The ADC's and FPGA units are accommodated in two 19-inch racks that are placed on top of the vacuum detector chamber that contains the Detector Modules. Some auxiliary electronics such as high voltage junctions and unit test pattern generators are located in dedicated boxes on the walls of the chamber close to points where the power supply and data cables exit the chamber.

The signal processing solution of the NEAT-II instrument does not utilize the traditional method for position sensitive detector tube readout with Gaussian signal shaping (with 3-5 µs time constant), peak detection and sample-and-hold analogue-digital converters [4]. The main reason for this is the speed requirement. Traditional solutions typically introduce dead times in the order of 3-5 µs which translates to 20k-33k counts per second per detector tube with 10 percent dead time.

Datalist Systems' signal processing solution is based on low time constant (in the order of ~60 ns) preamplifier electronics with high sampling frequency(20 ns, i.e.50 MS/s) using ADC's and FPGA based digital signal analysis. The preamplifiers are proprietary electronics developed by Datalist Systems specifically for the NEAT-II detector system, while the sampling ADC-FPGA tool chain is based on National Instruments products. The system determines the position of neutron hits using the charge division method.

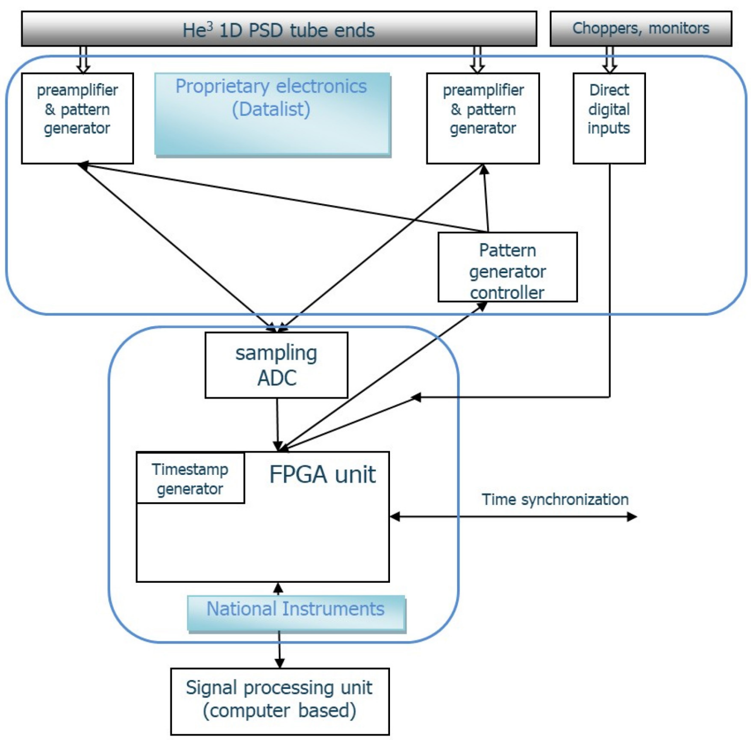


FIGURE 3. System architecture of the Signal Processing

The single most important challenge for the analogue preamplifier electronics was to produce a sufficiently fast preamplifier circuit with very low signal to noise ratio. This was very important for two reasons:

- *Low electronic background:* In the effort to lower the overall background of the measurements, it was essential not to introduce such noise into the system that could manifest as false positive neutron events. While this kind of noise can also be detected and counteracted in later stages (digital signal processing, event filtering, event classification, etc.) it is essential that such electronically introduced noise does not increase the perceived data rate or mask actual events.

- *High precision position resolution:* since the resolution of neutron event positions is based on the charge division method, events close to one or the other end of a detector tube have very low signals from the channel at the far end. Whenever electronic noise is introduced, the precise measurement of this low signal will be compromised and the position resolution will suffer.

The challenges of the digital signal processing included the followings:

- *Data reduction:* the sampling ADC's of the NEAT-II detector system produce a steady stream of 50 MS/s signals on all 832 channels (416 detectors, two channels per detector). This quickly adds up to 500 Gbit/s for the whole detector array, which is clearly an unfeasible amount of data to pass around. This calls for strong data reduction: each potential neutron event has to trigger the emission/extraction of a limited amount of data per event by the FPGA's in such a way that this reduced data still fully represent the detected events. The final solution reduced the required data to 192 bits per event, thus yielding 2500 times lower data rates compared to the initial event sampling (see Table 1 below)
- *Event filtering:* In order for the data reduction to be efficient, the system has to make decisions about what constitutes a potential neutron event. Our implementation has a 3-tier system for event filtering. 1) In the FPGA's hard thresholds are defined to differentiate neutron events from background noise. 2) In later stages of processing gamma events are filtered out based on pulse shape characteristics. 3) A flexible numerical classification system is utilized that can filter out pileup and other unwanted phenomena.

TABLE 1. Comparison of data rates with and without data reduction

without data reduction	**single channel**	**single channel (12 bit/S)**	**single detector (2 channels)**	**416 detectors**
	50 MS/s	600 Mbit/s	1200 Mbit/s	500 Gbit/s

with data reduction	**single event (3 * u64)**	**single detector (50 kHz)**	**416 detectors (1 MHz)**
	192 bit	9600 kbit/s	192 Mbit/s

To better appreciate the task of the data reduction process, in *Fig. 4* below we present different classes of signals that the system can encounter. These data sets were taken by a special "oscilloscope mode" FPGA software from the detector system during actual measurements. As previously described, the output of the analogue preamplifier stage is sampled at 50 MS/s (20 ns per sample) with 12 bit resolution ADC on both ends of the detector. The data sets are 4 µs long (200 samples) with approximately 500 ns before the triggering event.

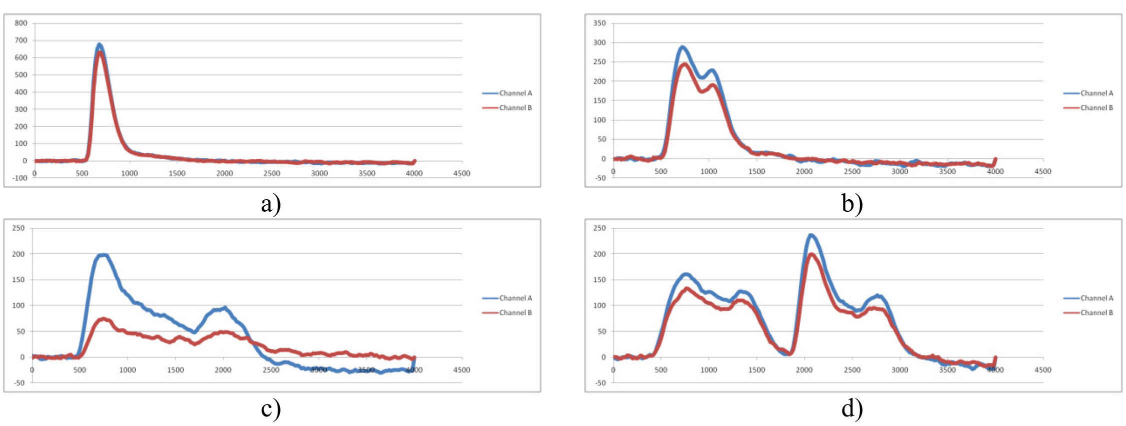


FIGURE 4. Examples of event classes:
a) *"Single bump"* neutron event b) *"Double bump"* neutron event
c) Probable *"Gamma"* event d) Probable *"Pile up"* event

The basic idea behind the data reduction solution is to break up each event into three distinct phases and classify the event based on the data collected during these phases. The most important parameters to be determined for the event are:

- *Charge:* The numeric integral of the signal. This is measured for both channels in all three phases separately to produce 6 significant measurements.
- *Time over Threshold (ToT):* The beginning and the end of the signal is detected by comparing the sum of both channels to pre-defined threshold values. The length of each phase is recorded and the ToT value can be determined from these three measurements.

The three-way partitioning of the event is achieved in the following way (see *Fig. 5* for illustration). *Phase 1* starts at the trigger event. More precisely, there is a pre-trigger buffer (currently set to 5 samples / 100 ns) and the phase starts at the beginning of the pre-trigger buffer. This phase is always 25 samples / 500 ns long. |*Phase 2* starts at the end of phase 1 and is terminated by the crossing of the end-trigger threshold. The length of phase 3 will never exceed 45 samples / 900 ns. *Phase 3* lasts for fixed 30 samples / 600 ns duration. Thus, the event's length will never exceed the 100 samples / 2 μs dead time limit.

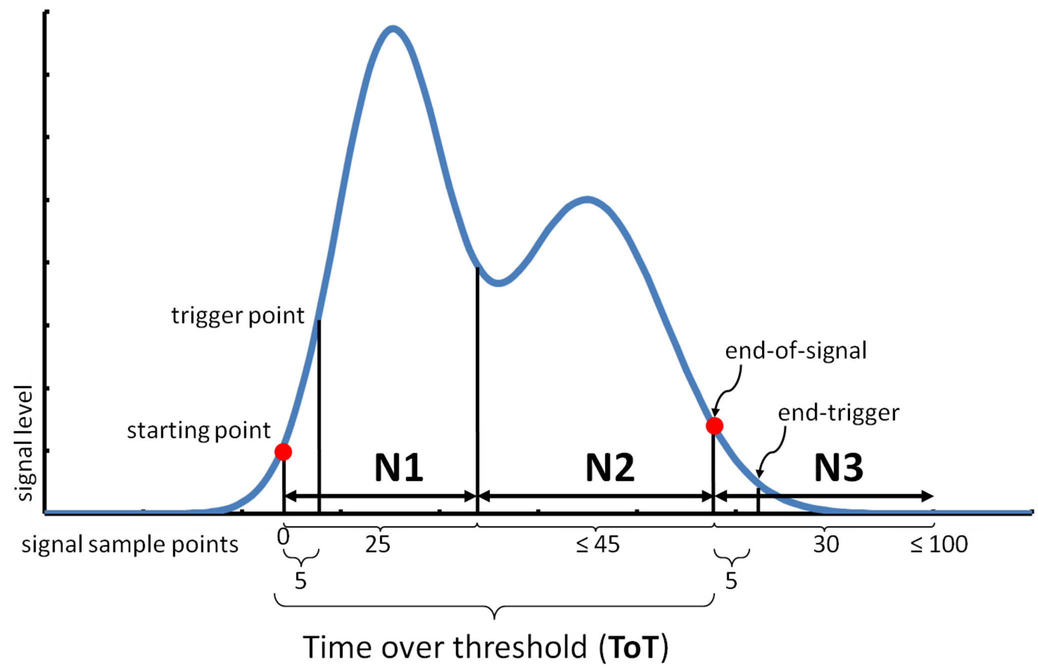


FIGURE 5. Partitioning an event into three distinct phases.

Data Acquisition Solution

The back-end electronics and DAQ computers in the NEAT-II detector system are organized in two separate 19-inch electronics racks. This is due to two main factors. Firstly, due to the topology of the detector vacuum chamber and the technical limitations of cabling it is more convenient to organize the analogue signal cables in this way. Secondly, the organization of the back-end electronics is such that ADC-FPGA modules are separated into two distinct chassis anyway. As a consequence, there are two DAQ computers collecting the data from the FPGA's of the two chassis respectively. The two subsystems are time synchronized to 100 ns precision.

However, the DAQ system must present a single point of access for the data stream to the scientific software. This is achieved by collecting the local data streams in a Global DAQ software component (see *Fig. 6.*)

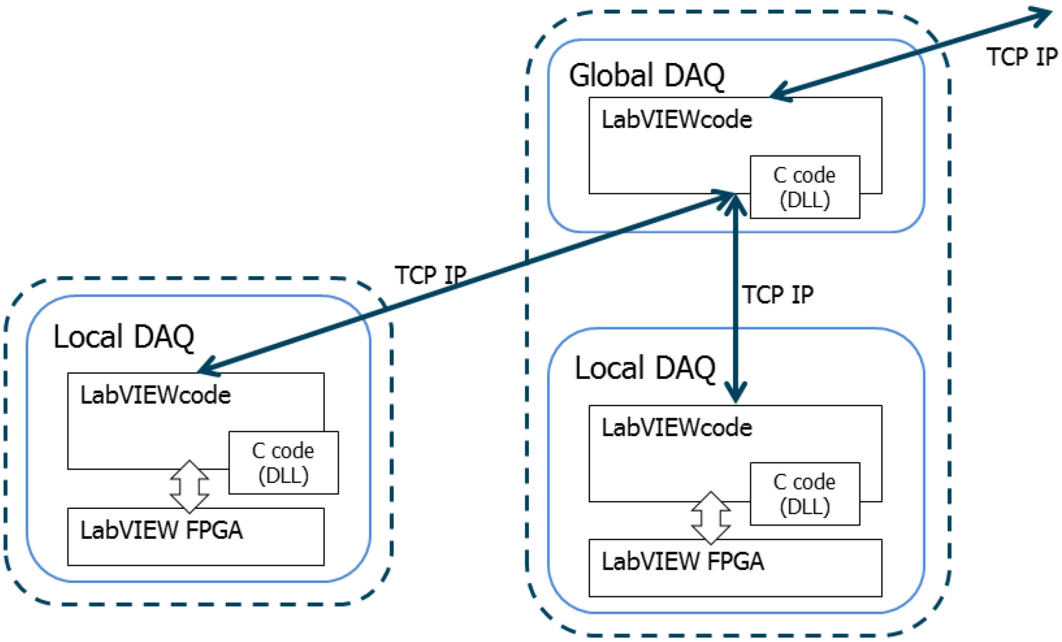


FIGURE 6. DAQ software organization

The Data Acquisition software is based on "event recording" principles. This means that the DAQ system provides an Event Record List for the scientific software. This event list contains each and every events collected by the system: neutron events, beam monitor events, chopper timing signals and external events (such as target environment data.) All events in the list have absolute time stamps with 100 ns resolution. The timestamps are 48 bit wide providing absolute time information that would not flow over for approximately 325 days.

CALIBRATION AND FIRST MEASUREMENT RESULTS

In order to better understand the calibration process first, let us describe how the position resolution algorithm actually works.

Position Resolution Algorithm

The DAQ system determines the position of a neutron event using the charge division method [4]. Let Ch_AandCh_B denote the total charge values measured at both ends of the detector. The position is then given by:

$$P_0 = \frac{Ch_A - Ch_B}{Ch_A + Ch_B} \tag{2}$$

Here P_0 is our initial estimate of the position, and it is in the range [-1.0, +1.0]. In an ideal situation where the charges generated by the detection of a neutron event could be measured perfectly this estimate would exactly match the actual position of the detection. Looking at *Equation 2* it can be noticed that even small errors in the values of Ch_A and Ch_B can cause significant errors in P_0 and there are a couple of things that can distort these values.

1. Baseline Restoration

An error in the Ch_x can be caused if the zero level or base line of the signals from the preamplifiers is not calibrated carefully. These levels will be different from channel to channel and can vary with environmental factors such as temperature. Thus, it is important to dynamically determine the baseline of the signals with the so-called baseline restoration algorithm.

Our solution uses a so-called current generator method with carefully fine-tuned parameters. In this method, the estimated value of the baseline is modified after each sample (x_i) as:

$$L_{i+1} = L_i + \delta \tag{3a}$$

$$\begin{aligned} \delta &= +\delta_0 \text{ if } L_i - x_i < 0 \\ \delta &= 0 \text{ if } L_i - x_i = 0 \\ \delta &= -\delta_0 \text{ if } L_i - x_i > 0 \end{aligned} \tag{3b}$$

The value of δ_0 has to be calibrated carefully otherwise high frequency errors in the data can cause deterioration in position resolution. *Figure 7*illustrates this.

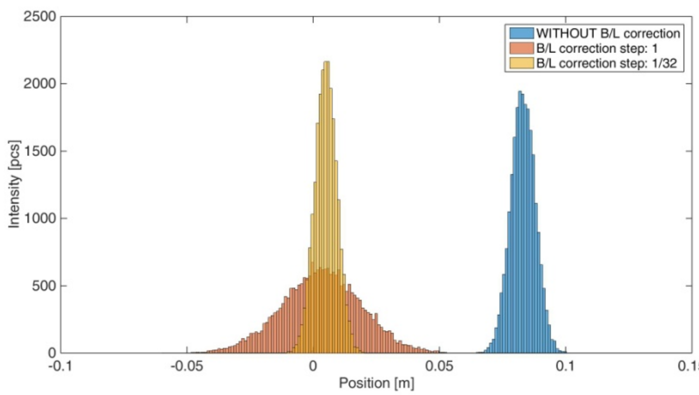


FIGURE 7. Effect of baseline restoration
no restoration (blue), coarse (orange) and fine-tuned (yellow)

2. Calibration of preamplifiers

Another effect is that of the minute differences in the preamplifier electronics or coupling elements between detector tubes and preamplifiers. While these differences can be partly mitigated by adjustable preamplifier gains, these factors can also change over time and with environmental factors such as temperature. Therefore in the delivered solution there are per channel calibration coefficients that modify the measured charge values (Ch_A and Ch_B):

$$Ch'_A = \gamma_A \cdot Ch_A \tag{4a}$$
$$Ch'_B = \gamma_B \cdot Ch_B \tag{4b}$$

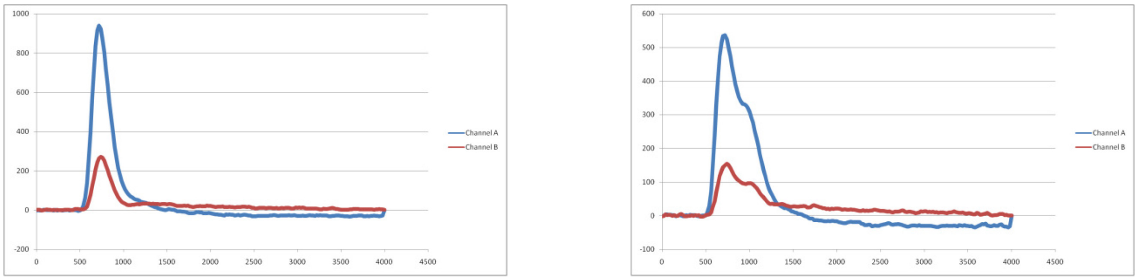
Then the position estimate can be modified as:

$$P'_0 = \frac{Ch'_A - Ch'_B}{Ch'_A + Ch'_B} \tag{5}$$

The calibration coefficients can be kept up-to date by performing daily calibration using the Position Test Generator circuits (see next section *DAQ Calibration*.)

3. Limited measurement period vs. crosstalk

A further effect that can distort the measurement of Ch_x values is called crosstalk. Due to the non-infinite input impedance of the preamplifiers and the fact that the detector itself connects them as a distributed RC circuit the charge profile of a neutron hit reaching one end of the detector will have a non-trivial effect on the signal at the other end but with significant time delay. In case the signal levels are close to equal (at the middle of the detector) these effects cancel out. However, close to the ends, where the signal levels are very different, this effect distorts the signals. *Figure 8* illustrates this: the higher-level signal undershoots more dramatically than the lower one.



a) b)

FIGURE 8. Crosstalk effect
a) single bump case b) double bump case

If the system had the possibility to measure the signals for a long enough time (> 3μs) the effect would naturally even out, but that would mean much higher dead times which is unacceptable. Crosstalk thus introduces a constant position dependent error that has to be corrected for (*β* is a calibration parameter of the individual detector):

$$P_0'' = P_0' \cdot (1 + \beta) \tag{6}$$

4. Signal shape vs. crosstalk

It can be seen from *Fig. 8* that the amount of the crosstalk effect is dependent on the signal shape (e.g. signal length): the crosstalk is more pronounced in case of the longer "double bump" signal. Our solution is to use *Signal Shape Analysis*. Based on estimated position (P_0), signal strength (*Ch*) and signal length (*ToT* see *Fig. 5*) we can calculate the deviation of P_0 from the actual position and give a linear interpolation as shown in *Fig. 9*.

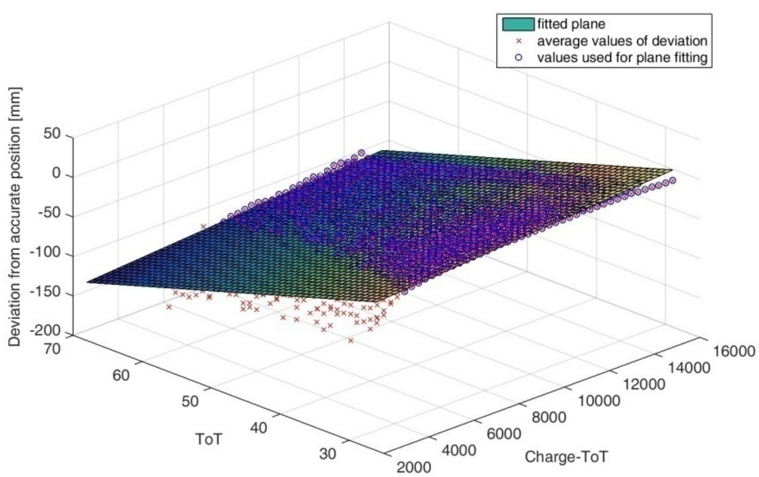


FIGURE 9. Position correction based on *Signal Shape Analysis*

The position is then calculated according to *Equations 7* where D_0, D_{Ch} and D_{TOT} are the estimated linear parameters:

$$P = P_0'' \cdot (1 + \Delta) \tag{7a}$$

$$\Delta = D_0 + D_{Ch} \cdot Ch + D_{ToT} \cdot ToT \tag{7b}$$

In *Fig. 10* we can observe the effect of the Signal Shape Analysis correction.

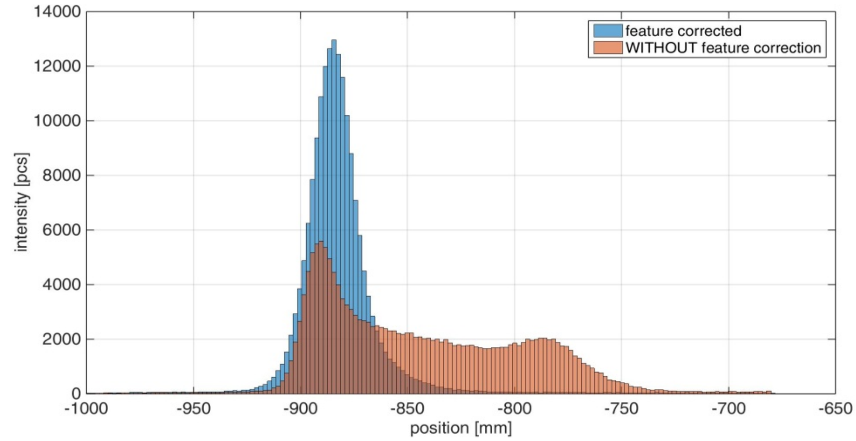


FIGURE 10. Effect of Signal Shape Analysis correction
image of a slit at position $P = -889mm$
(orange) no correction vs. (blue) with correction

Thus the Position Resolution Algorithm can be summed up as follows:

Position Resolution Algorithm for NEAT-II

- The input values are provided by the sampling ADC's from the analogue signal of the preamplifiers at both ends of the detector: A_i and B_i.
- The input values are corrected with the baseline values $L_{A,i}$and $L_{B,i}$:
$$A'_i = A_i + L_{A,i}$$
$$B'_i = B_i + L_{B,i}$$
- Baseline values are corrected at each sample using *Equation 3*.
$$L_{A,i+1} = L_{A,i} + \delta_A$$
$$L_{B,i+1} = L_{B,i} + \delta_B$$
- An event is triggered if the sum of the signals from both channels exceeds a preset (configurable) event start threshold value K_{on}:
$$\sum_{j=i-4}^{i} (A'_j + B'_j) > K_{on}$$
- For the duration of a triggered event baseline correction is suspended.
- The *first phase* of the event lasts for exactly 25 samples (500 ns);$N_1=25$.
- The *second phase* lasts until the sum of the signals crosses the event end threshold value K_{off} but no longer than 45 samples (900 ns); $N_2<45$.
$$\sum_{j=i-4}^{i} (A'_j + B'_j) < K_{\text{off}}$$
- The *third phase* lasts for exactly 30 samples (600 ns); $N_3=30$.
- At the end of the third phase, the algorithm resumes baseline correction and checking for the event start threshold.
- The *ToT* value (signal length) of the event is calculated as
$$ToT = N_1 + N_2 + N_2$$
- The charge values (Ch_A, Ch_B) are calculated as:
$$Ch_A = \sum_{N_1+N_2} A'_i$$
$$Ch_{\text{B}} = \sum_{N_1+N_2} \text{B}'_i$$

- The charge values are modified by the calibration coefficients:

$$Ch'_A = \gamma_A \cdot Ch_A$$
$$Ch'_B = \gamma_B \cdot Ch_B$$

- The initial position estimate P'_0 is calculated using charge division method:

$$P'_0 = \frac{Ch'_A - Ch'_B}{Ch'_A + Ch'_B}$$

- The crosstalk effect is corrected for to obtain P''_0:

$$P''_0 = P'_0 \cdot (1 + \beta)$$

- The event position P is calculated using the correction based on Signal Shape Analysis:

$$P = P''_0 \cdot (1 + \Delta)$$
$$\Delta = D_0 + D_{Ch} \cdot Ch + D_{ToT} \cdot ToT$$

DAQ Calibration

As mentioned in the previous section (*Position Resolution Algorithm*) it is important to carefully calibrate each channel due to minor differences in the preamplifier electronics or coupling elements between detector tubes and preamplifiers. In the NEAT-II DAQ system there is a two-tier system for calibration.

1. Direct calibration with neutrons

The position resolution of the tubes is calibrated at infrequent intervals (such as once a year) using slits in Cadmium masks placed at specific positions. The calibration coefficients are calculated in such a way as to bring the by neutrons measured positions into perfect alignment with the geometrically known position of the slits.

2. Calibration with test signals

Another calibration procedure can correct the effect of changes in the electronics' performance due to changing environmental factors. The method can be applied frequently (even daily), as it is fast. In order to perform the test the NEAT-II DAQ system contains so called Position Test Generator circuits (see *Fig. 11*) that can generate test signals that emulate neutron hits in three predefined positions for each detector individually or in parallel. A full scan of all 416 detectors in three positions with ~100,000 simulated hits in each point takes less than 15 minutes and can show even minute deviations in the calibration coefficients.

a) b)

FIGURE 11. Position Test Generator electronics
a) rear view b) front view

First Measurement Results

As part of the initial calibration process, we have conducted extensive measurements with the NEAT-II instrument. The goal of the measurements was to check both the absolute position accuracy as well as the position resolution of the detectors.

The choppers were configured for 5Å wavelength, in the sample position a sample holder with water (H_2O) was placed to provide approximately even load along the detectors. Then in a series of measurements a 1 mm thick cadmium mask of dimensions 1000 mm × 500 mm with a 10 mm wide slit in the middle was placed directly in front of the detectors in a series of positions. The mask allowed for the measurement of approximately 32 tubes, i.e. a single module. For eachmodule seven different positions were selected from one end of the detectors to the other in approximately even steps. *Figure 12* shows the measured position resolution values. We can observe that the resolution in the center is much better than near the detector end points (as expected) but it stays within the 20 mm limit along the full length.

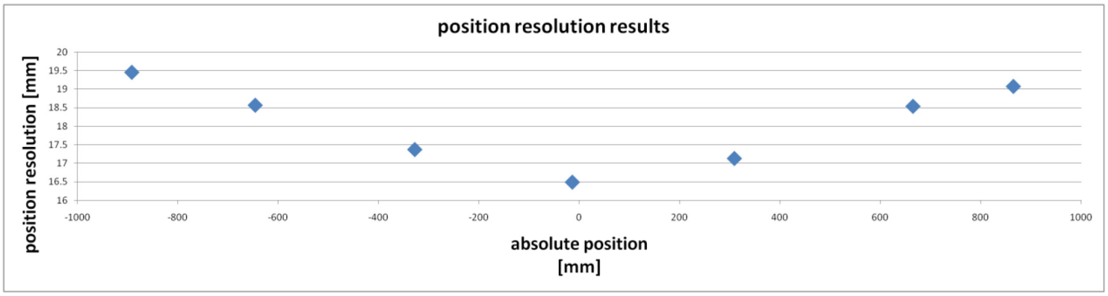


FIGURE 12. Measurement results for position resolution in different positions along the detectors

CONCLUSIONS

In this paper we presented the detector system developed by Datalist Systems, Ltd. for the NEAT-II spectrometer at HZB. The requirements placed on the detector system were very challenging: good position resolution combined with high count rates, modular and spatially limited mechanical design, TOF measurements with precise time resolution and most importantly low background for quasi-elastic and inelastic capabilities.

The solution supplied by Datalist Systems has so far met all requirements. It can be described from the instrument owner's standpoint as a "turn-key" solution. The mechanical and electronic assembly on site required a minimal amount of participation from HZB crew. Also the provided DAQ software could be integrated into the scientific control and measurement software system.

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