DIGITAL SIGNAL PROCESSING FOR THE GABRIELA DETECTOR ASSEMBLY*

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This paper briefly describes the main ways of digital signal processing. The goal of the digital algorithms is to reduce the dead time of the spectrometry path to tens of nanoseconds without loss of energy and time resolutions. The new $k\sigma$-trigger with extrapolation technique is proposed in the paper. The method allows to find overlapped signals almost irrespective of their closeness in time.

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1. Introduction

Modern nuclear spectroscopy experiments require a fast and high-accuracy processing system. Again and again, the new digital systems are replacing the classic analogue ones. The high-rate ADCs used in digital electronics allow to study events with extremely low energies and find the timing correlations with extremely close signals.

Experiments in transfermium isotopes ($Z > 100$) spectroscopy are conducted on SHELS [1] (the Separator for Heavy Element Spectroscopy) using the GABRIELA [2] (Gamma Alpha Beta Recoil Investigations with ELectromagnetic Analyzer) at the Flerov Laboratory of Nuclear Reactions, JINR, Dubna. The analogue electronics path that was created especially for the

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GABRIELA detectors array has been a reliable system with an excellent energy resolution but the dead time is in order of units of μs. Such a dead time does not allow to measure transitions from nuclear states with lifetimes less than 1 μs.

The new digital signal processing system must rectify the weaknesses of the analogue path by reducing the number of elements in the chain and using advanced mathematics.

2. The digital signal processing

2.1. Motivation

The main advantage of a digital processing system is the possibility to analyze not just the signal amplitudes but their shapes too. It allows to register and restore amplitudes of overlapped signals. At the moment, there are two main directions of digital electronics development.

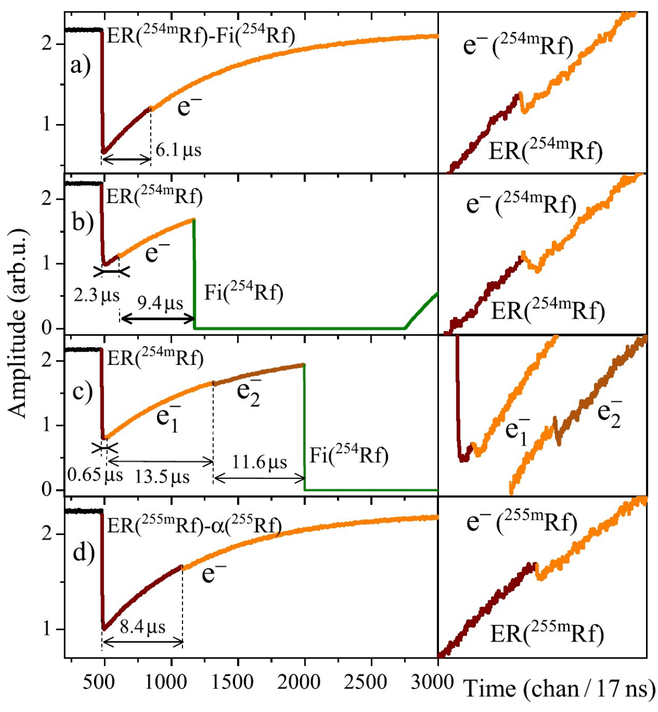

Fig. 1. Examples of traces analysis results in ^{254}Rf and ^{255}Rf study [3].

The first one is a signal trace analyzer. Such systems store signal traces (or oscillograms in other words) after not complicated pre-processing (Fig. 1). The method allows for a visual inspection and uses advanced mathematics for post-processing without a time limitation. This trace analysis has been successfully used in the heavy-element spectroscopy [3, 4]. At the same time, the method requires a large amount of memory for trace storing and considerable time for post-processing.

The second one is online processing. The idea of the method is similar to an analogue one. All processing takes place on an FPGA. The system stores the final results. Such system examples can be found in [5–7]. One of the most commonly used algorithms is the "unfolding-shaping" technique [8]. The algorithm unfolds a signal from the preamplifier using its transfer function and shapes the unfolding result to trapezoidal form as shown in Fig 2. The method does not require additional post-processing and large storage space. At the same time, the algorithm must be realized in strict-time and complexity limitations.

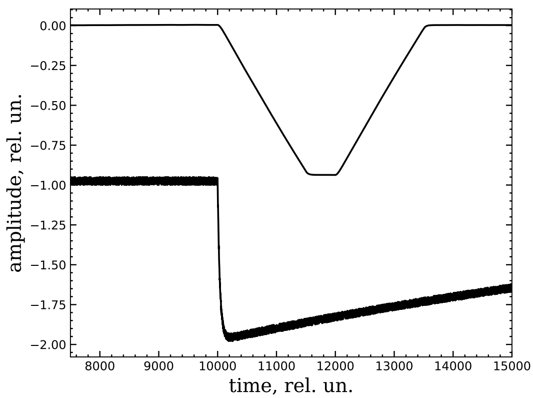

Fig. 2. The result of the unfolding-shaping algorithm simulation [9].

2.2. The DSP for the GABRIELA

The first version of the digital path prototype was created especially for the GABRIELA detector array using the online processing method. Figure 3 shows the results of the prototype algorithm for a single signal and pile-up. It can be seen that the digital path can handle a pile-up event if two signals came not closer than the sum of the integration and flat top duration of the trapezoid.

The first in-beam test was conducted in October 2020, and its purpose was to verify the possibility of finding "recoil–α-decay" and "α-decay–α-decay" correlations. More details can be found in [9].

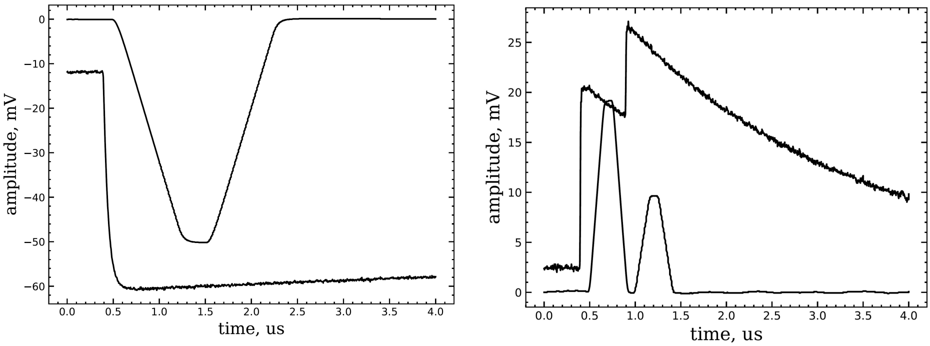

Fig. 3. The results of the unfolding-shaping algorithm on FPGA [9].

2.3. kσ-trigger with extrapolation technique

However, the digital signal processing tested still cannot handle pile-up if two signals came closer than (side + flat top)-duration of the trapezoidal signal. We propose a $k\sigma$-trigger with an extrapolation technique to fix that.

The classic $k\sigma$-trigger is a well-known technique [10] that allows for registering signals with amplitudes that are k times higher than the noise level σ. The baseline and noise level measurements are realized as the Kallman filters. By defining the signal as $S(t)$, baseline as $B(t)$, and noise level as $\sigma(t)$, if $|S - B| > k\sigma$, we could say that signal arrived

$$
\begin{aligned}
B(t_i) &= B(t_{i-1}) + \frac{1}{\tau_b}\left(S(t_i) - B(t_{i-1})\right), \\
\sigma(t_i) &= \sigma(t_{i-1}) + \frac{1}{\tau_\sigma}\left(|S(t_i) - B(t_i)| - \sigma(t_{i-1})\right).
\end{aligned}
$$

The classic $k\sigma$-trigger is a good way to register signals with low amplitudes but it still cannot handle pile-up. The fast ADC allows to implement a linear extrapolation for the exponential signals at the small-time range. A few (four in our case) last signal samples could be taken to predict the next one with linear extrapolation. The trigger will occur if the difference between actual and predicted samples is k times larger than the noise level σ.

For extrapolation, the formula for the slope coefficient a of the noisy data was used

$$
a = \frac{n\sum_{i=0}^{n-1} x_i\, y_i - \sum_{i=0}^{n-1} x_i \sum_{i=0}^{n-1} y_i}{n\sum_{i=0}^{n-1} (x_i)^2 - \left(\sum_{i=0}^{n-1} x_i\right)^2}\,.
$$

After some manipulations, the formula for the predicted sample value S_{p} was obtained

$$S_{\mathrm{p}}(t_j) = \frac{2\sum_{i=j-4}^{j-1}(i\,S_i) - 3\sum_{i=j-4}^{j-1} S_i}{10} + S(t_{j-1})\,.$$

Figure 4 shows four examples of using $k\sigma$-trigger with the extrapolation technique. Case (a) is the most common one with a single high-amplitude signal. For example, it could be an ion implementation signal, single alpha decay or spontaneous fission. Example (b) is a low-amplitude signal following a high-amplitude one. It models the case of conversion electron emission just after the ion implantation. Example (c) is a high-amplitude signal over the low one. An example would be the delayed conversion electron–fission chain. Example (d) shows two successive low-amplitude signals.

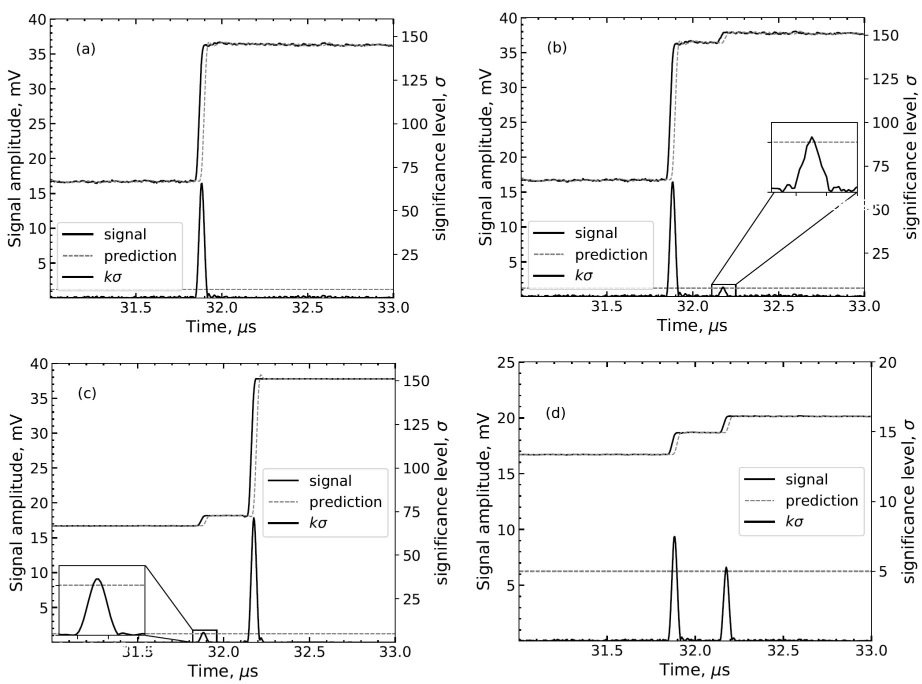

Fig. 4. The results of $k\sigma$-trigger with the extrapolation technique. Left: vertical axes are exponential signals amplitudes in mV. Right: vertical axes are significance levels in units of σ. The upper solid black line is the input exponential signal. The upper dotted grey line is a predicted signal form. The bottom black line is the significance level $|S - S_p|/\sigma$. The horizontal grey line shows the trigger level for 5σ. See the text for physical interpretation.

That could be interpreted as the electron–electron decay from a cascade of two long-lived isometric states.

3. Conclusion and perspectives

The new $k\sigma$-trigger with the extrapolation technique was proposed as a trigger for the new digital acquisition system of GABRIELA. The method measures the baseline, noise level, and the difference between real and predicted signals in real-time. The trigger is adaptive to experimental noise conditions and, therefore, the technique allows for monitoring noise levels in real-time.

The $k\sigma$-trigger with extrapolation would also make it possible to register pile-ups with extremely low amplitudes and very close overlapped signals. The method could be applied in both directions of the digital signal processing. In the trace analysis, the $k\sigma$-trigger with extrapolation could create an additional marker to indicate the most interesting events. In the online processing, the method can become the basis of the pile-ups amplitudes restoring algorithm.

The main goals for the near future are to conduct the first experiment using 70 FPGA cards and solve the pile-up energy restoring problem.

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