Applications of Digital Pulse Processing in Nuclear Spectroscopy

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Abstract

Data acquisition systems for nuclear spectroscopy have traditionally been based on hybrid systems with analog shaping amplifiers followed by analog-to-digital converters. Recently, however, new systems based on Digital Signal Processing concepts have been developed. For example, one specific design, the Digital Gamma Finder (DGF-4C), has been used extensively for particle- and gamma-spectroscopy of nuclei far from stability. Using the DGF-4C, a variety of data acquisition systems have been implemented and used for measurements with semiconductor and scintillator detectors at recoil separators like the RMS at ORNL, the FRS at GSI, and LISE at GANIL. Some novel features and unique advantages, such as trigger-less operation and pulse shape recording, are discussed in the context of selected studies.

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1 Introduction: Digital Pulse Processing

This paper presents the application of digital pulse processing to nuclear spectroscopy experiments. First, the general concept of real time Digital Pulse Processing (DPP) will be introduced, followed by a brief description of the electronic board [1] implementing the DPP concepts. Finally, several examples of on-line experiments which take advantage of DPP are presented.

Digital Pulse Processing is a fully numerical analysis of the detector pulse signals. The numerical algorithms replace the analog shaping and timing circuitry to derive properties of the pulse such as its amplitude and arrival time, see fig. 1. The advantage of DPP arises from the flexibility in implementing the algorithms. This enables much more complex pulse shape analysis necessary for example in gamma-ray tracking [2], or particle identification [3]. Several examples of measurements which would be difficult or impossible without DPP are presented below.

The preparatory step for the DPP analysis is the signal digitization. This process has to be done with sufficient accuracy and time resolution to preserve the information which is carried by the pulse shape. Once the pulse is transformed into digital form it becomes immune to distortions caused by electronic noise and temperature instabilities. The numerical analysis of the pulse shape can be done either in 'real-time' as soon as the pulse is digitized, or in a post-processing step, on the stored data. The post-processing solution requires the output and storage of a large amount of data reduced later to only a few parameters classifying the pulse such as energy and time. However, storing and synchronizing large data streams becomes prohibitively cumbersome for even small size multi-parameter experiments. The obvious advantage of fast, real time processing algorithms is to reduce the data stream by providing the functionality of analog shaping units. However the main difficulty in DPP is to develop the real-time algorithms for any given detector system.

The applications of DPP date back to the 1980s, see eg. ref. [4,5] or a review in ref. [6], at that time using a digital oscilloscope or digitizers. Those setups provided proof of principle measurements. As increasing processing power became available this technology became more generally applicable to the requirements of nuclear spectroscopy [1,7]. This paper describes the attempts to use DPP under the conditions of on-line multiparameter experiments with various detector types. It demonstrates that the DPP technology has matured enough to be used in routine spectroscopy measurements.

2 The DGF - a brief description

A number of DPP ideas have been successfully implemented in the design of the DGF-4C board [1,8]. It combines the capability for real time pulse shape analysis with optional waveform storage for post-processing.

The DGF4C is a single-width CAMAC board featuring four signal input channels, see fig. 2. A detailed description can be found in refs [1,8]. Each channel is comprised of an analog signal conditioning unit (ASC), a fast Analog to Digital Converters (ADC), a Field Programmable Gate Arrays (FPGA). Each DGF4C is equipped with a single Digital Signal Processor (DSP). The role of the analog circuit (ASC) is to map the signal range to the ADC range and to provide an anti-aliasing filter. It may change the signal's amplitude and

DC-offset, but will retain the overall shape. The digitization is performed at a rate of 40 MSPS, i.e. in 25 ns intervals, using 12-bit ADCs. The data from the ADCs are streamed into the real time processors implemented in the FPGAs. They continuously perform pileup inspection and precompute arrival times and pulse heights using trapezoidal filters as explained in fig. 3.

A trapezoidal filter with short time constants provides a local trigger, which is used for time stamping and to feed the pileup inspector. A trapezoidal filter with long and adjustable time constants is used for the energy measurement. At the same time a digital copy of the pulse can be put into a memory and stored for later readout or analysis. For more elaborate filtering which may involve functions like digital constant fraction discriminator timing, or ballistic deficit correction, the time/amplitude or trace data are transferred to the DSP processor. Finally, the DSP formats time/amplitude and waveform data, writes them into a buffer and increments spectra in its histogram memory.

The data from each board are stored in the 16kB output buffers. In the multi-module system the readout of all buffers is initiated by the module which first reports its buffer to be full. The input digitizing is halted during readout to avoid electronic interference. The data readout is executed under CAMAC protocol.

The DGF is a self-triggering device but is also equipped with external triggering and gating capabilities.

3 Experiments

Several systems based on the DGF-4C boards have been implemented in a number of on-line measurements of exotic nuclei. The primary motivation for the implementation of DSP at HRIBF was to handle the cases of closely overlapping pulses, which analog electronics have difficulty to resolve with good resolution in time and energy. Proper determination of the energy of overlapping pulses also remains difficult when using fixed-length trapezoidal filters. Here the ability to store pulse shapes and use post-processing has been exploited. The interesting pileup pulse waveforms were recognized, selected and stored together with the time/amplitude data and pulse shape from other detectors. The timing relationships between parameters can be determined for each physical event as described below.

3.1 Data analysis

Because the DGF works in a self-triggering mode, the data structure for a multi-parametric experiment does not have the form of one chain of events but consist of independent data streams for each channel. These data streams have to be reorganized into events, using the individual time stamps, assigned for each valid channel 'hit'.

The data analysis algorithm consists of several steps, as schematically shown in fig. 4. The first step is buffer decoding. In this process the DGF readout buffer is separated into a time-stamped set of energies and traces. The traces are then analyzed and the categorizing parameter is calculated from the pulse shape and given the correct time stamp.

Before sorting the data into events the time corrections can be applied numerically to align in time coincident events. An example are 'hits' which are related to the same ion induced in the detectors placed in different parts of the spectrometer, delayed by tens or hundreds of nanoseconds due to the time of flight of the ion.

In the next step this collection of event is time sorted and those which form time clusters are grouped into coincident events (event builder). During this process different time correlations between various parameters are also calculated. Finally, event-by-event sorting and histogramming is applied.

3.2 Proton emission studies

The DGF based acquisition system was developed to measure microsecond particle radioactivities. In such experiments, proton- or alpha-emitting exotic nuclei are produced with heavy-ion fusion reactions on thin targets. Recoiling fusion products are mass separated in a large acceptance recoil mass spectrometer, passed through a position sensitive detector for M/Q determination, and implanted in a Double-sided Silicon Strip Detector (DSSD), like those described in [9]. The HRIBF DSSD setup and Recoil Mass Spectrometer (RMS) are discussed in Ref. [10]. The recoiling heavy ion is slowed down in a degrader foil and implanted in the DSSD, where it deposits an energy on the order of 15-50 MeV. An emitted proton carries a much smaller kinetic energy, on the order of 1 MeV. For the short-lived proton radioactivity the main difficulty is to detect two closely spaced pulses with a large energy difference. This problem was solved through the use of DGFs [11].

The system developed at HRIBF consists of nineteen DGF modules. Eighteen of them are dedicated to digitizing the signals from the preamplifier [13] of the Double-sided Silicon Strip Detector (DSSD) where the ions and protons are stopped. When searching for, or studying, short microsecond activities these modules are used to record the full waveform of the preamplifier signal associated with the recoil implantation and subsequent decay. For each channel containing a possibly interesting waveform we store the 25 μs long 'trace'. Each trace has an assigned time stamp, with 48 bit precision in units of 25 ns, and the signal amplitude is coded with 12 bit resolution (4096 channels).

The four channels of the nineteenth module are used to digitize data from Position Sensitive Detectors (PSD) [10], which provide independent information on the ion arrival time.

To reduce the data stream a fast self-trigger system was implemented for each channel of the DGF. It is programmed in the real time processing part of the DGF and its role is to recognize the pile-ups occurring within 10 microseconds; all other signals are ignored (i.e. they are not sent to the output data buffer). Such pileups are very likely to be ion-ion random coincidences but also real ion-proton decay events, thus the algorithm has been called a 'proton catcher'.

Proton emission events have been observed from about 500 nanoseconds after the ion implantation into the DSSD. For an event to qualify as a valid proton event it must have identical amplitudes of the second pulse from both the front and back strips of the DSSD, identical absolute time (within the resolution of the algorithm), and have no PSD signal. It must also be preceeded by a heavy ion induced pulse which has the same absolute time from both front and back strips and be in coincidence with a PSD signal. The proton amplitudes were extracted from the stored wave-forms with a resolution of 70 keV at 1.7 MeV by our algorithm [14], while the resolution of the DSSD-DGF signal observed for long-lived proton radioactivity was determined to be 20 keV. The worsening of the resolution is related to the short integration time available for the piled-up pulse. The advantage of the DPP-based solution over the previously used system was demonstrated in the ^{145}Tm experiment [11,12]. The efficiency was increased by a factor of 7 over that obtained with the conventional electronics, thus allowing the observation of the fine structure in the decay of this 3-μs activity because of the increased detection sensitivity at short times.

The DGFs were used successfully in an experiment aiming at a discovery of the fine structure in the decay of the deformed ^{141}Ho nucleus [15]. In this experiment the DGF's were used in the so-called 'standard mode', which means that only the time and amplitudes of the pulses have been stored. Because of the long lifetime of the proton emitting state, the use of the 'proton catcher' was not required. Currently, standard mode and proton catcher mode cannot be simultaneously invoked in the same module.

3.3 Beta and gamma decay studies

At HRIBF the various decay type experiments are performed using only the DSP type acquisition system. These measurements [16] involve various types of detectors: germanium array CARDS (Clover Array for Radioactive Decay Studies) for gamma radiation, Si(Li) for conversion electrons, plastic scintillators for beta particles and, as discussed in the previous section, Si DSSD for protons and alphas. The DGFs are used to measure the amplitude of the pulses. For each type of detector we have determined the optimum filter parameters, e.g. for the 'clover' detector [17] the 'peaking' (T_A) time is 8 μs and 'gap' (T_C) time is 3 μs, for the very short pulse from the plastic scintillator the peaking is set to 0.8 μs and gap to 0 μs. The main advantage of using a DGF in this case is its event time stamping feature. In the multi-parametric system, each DGF channel independently digitizes each pulse giving it an individual time stamp with sampling precision of 25 ns in a 48 bit long word. Thus, the data set consists of an independent collection of events for each separate channel with each being individually time stamped. The correlation between these events are based on the time stamps. Although this requires somewhat more elaborate event-builder algorithms, it provides the great advantage of having a choice of how to measure and use the time correlations between signals. It eliminates the need for hardwired time-difference measuring modules like TDC's. This is very important in decay experiments with time scales ranging from nanoseconds to seconds. It also allows a precise monitoring of the behavior of each experimental parameter in time. Using DGFs allows complex monitoring of the dead time using on-board scalers. The readout dead time can be monitored by using the time stamping features. This feature proved to be very important in the experiments surveying the yields from uranium carbide targets at UNISOR mass separator [18]. In such experiments the mass separated samples are deposited on the tape and moved inside the detection station consisting of gamma, beta and electron counters. This process is repeated every few seconds. However, if the yields for some activities are large the system dead time becomes important and time dependent. Proper determination of the production yields for short lived, fast decaying isotopes has to take the dead time correction into account. Such an analysis is easily done using the time stamping feature.

The flexibility of implementing time correlations using DGFs has been explored in the recent measurement of the decay of ^{140m}Dy [20] done with the CARDS system at the final focus of the RMS, in which the data were collected in the time-stamped singles mode. This allowed the proper separation of the microsecond activities from the beta decay radiation as well as from submicrosecond activities, in off line analysis. The average resolution of the gamma detectors at 1.3 MeV achieved during this experiment was about 2.5 keV. The ballistic deficit correction was not used. One should note that double and triple gamma-gamma coincidences have been applied in the analysis of this experiment proving that the DPP-based system is at least fully equivalent to the analog type.

The DGF based system has also been used in experiments searching for isomers produced in fragmentation and fission reactions at high energies [19,21]. In these experiments, the aim was to efficiently measure isomeric gamma rays in the presence of the radiation related to the stopping of the high energy ion in a catcher.

3.4 Search for two proton decay

Some candidates for proton emitters cannot be produced in a fusion reaction with stable beams and targets due to the very small reaction cross section but can be produced at fragmentation facilities. The general scheme of such an experiment is similar (production target, fragment spectrometer, silicon detector) to the setup for proton emission studies described above. However, in fragmentation the primary beam energy and the resulting fragment energy are much higher than in the fusion reaction. In addition, the range straggling problem requires the use of multiple stopping silicon detectors. The development described below is aimed at the discovery of a new type of nuclear decay, specifically two proton (2p) radioactivity. Two promising candidates for such an observation are ^{48}Ni and ^{45}Fe; both nuclei were recently identified in fragmentation experiments [22,23]. The 2p-decay energy of these nuclei is expected to be 1-1.5 MeV [22]; the predicted partial lifetime for such an energy range varies widely, from 10^{-2} to 10^{-6} s. Thus, the experimental system has to be sensitive to decay lifetimes from microsecond to milliseconds.

Experiments were performed to test the possibility of using DGFs to discover 2p-radioactivity in an approach similar to that used at HRIBF where the waveform of the signal induced by implantation was stored. However, for completeness the 'traces' for each ion of interest were stored, not just pileups, thus the 'proton catcher' mode was not used. Signals which were necessary for the event-by-event ion identification from the secondary-beam time-of-flight, energy loss and position detectors were also digitized. The first experiment was performed at GANIL - with intermediate energy (tens of MeV per nucleon) recoils [19]. However, it suffered from the very large ion pulse amplitude of 900 MeV observed in the implantation detector.

To overcome the problem of the large amplitude difference between recoil and decay pulses, a new approach has been developed [24]. It requires the use of a new kind of a preamplifier [25]. The preamplifier is 'blocked' for about 1 microsecond at the beginning of the recoil-induced signal. This solution ensures that the large charge induced by the recoil in the silicon detector does not overload the preamplifier circuit, which can then have the large amplification required for the correct determination of the small decay pulse. In principle it should eliminate the necessity of acquiring the full waveform of the signal.

However, the charge injected in the preamplifier upon reactivation (as soon as one microsecond after implantation) still induces a signal large enough to make it difficult to properly derive the decay pulse amplitude by an on-board algorithm, see Fig. 6. Thus, it was necessary to store the 'trace' and analyze it 'off-line'.

A DGF based system using reset-preamplifiers was successfully tested at the FRS separator at the GSI heavy ion laboratory. In the test experiment ions produced in the fragmentation of ^{58}Ni at 1 GeV/u near ^{49}Fe were selected. In a follow-up experiment, aimed at the measurement of the decay mode of ^{45}Fe, the detection setup consisted of 7 planar silicon detectors placed inside a NaI barrel with very high gamma detection efficiency. Eleven DGF modules were used in this experiment. All signals required ion identification and the decays occurring within a 3 μs to 10 ms window after the ^{45}Fe implantation were digitized. To identify emission occurring within microseconds after implantation, the DGFs stored signal waveforms from the reset preamps for 50 μs after implantation from the reset preamps, and another two were used to digitize the decay branch of the silicon preamplifier signals from 30 microseconds to 10 milliseconds after implantation of the valid heavy ion. Within the 10 ms after implantation, DGFs were also used to digitize the NaI signals. In this experiment six events of ^{45}Fe were identified [26] and evidence for 2p-emission was observed.

3.5 The Bragg detector

Pulse shape analysis is a domain, where the DGF can be efficiently applied. This has been demonstrated in ref. [27] for the a CsI scintillator detector. In this section the DGF application for the pulse shape analysis from the much slower gas detector signal is presented.

One of the central problems of research using radioactive beams is the proper determination of the isotopic beam composition. A Bragg-type gas detector [28] has been implemented at HRIBF [30] to characterise the isobaric content of post-accelerated beam. In a Bragg detector the charge 'cloud' generated by the stopped ions drifts towards the anode in an accelerating voltage; the time distribution of the collected charge reflects the spatial distribution of the ionization in the stopping gas.

This relatively slow process can be easily followed using a digitizer, see e.g. [29] for such an early application. We have used the DGF-based data acquisition in test measurements using a mixed beam of ^{124}Te and ^{124}Sn ions accelerated to the 3 MeV/nucl; see fig. 7. The pulses from the charge integrating preamplifier were digitized for 100 μs and stored event-by-event. The pulse shape analysis performed off-line applied trapezoidal filtering for the total energy determination and pulse shape analysis to determine the atomic number of the particles. From the pulse shape one may extract the difference in atomic number of particles in two ways, one related to the measurement of the specific ionization of the ion, and the other related to the range; see fig. 7. To obtain the time distribution of the charge collection one has to differentiate the pulse. The atomic number can be derived from the height of the pulse, which is proportional to the specific ionization of the ion, or the width of the curve, which is related to the range of the ion in the gas. An example of such an analysis for a mixed ^{124}Sn/^{124}Te beam is shown in fig. 7.

4 Summary

A variety of detection setups has been successfully developed and applied in the on-line experiments on exotic nuclei using the Digital Pulse Processing. Various approaches including real time and post-processing algorithms have been applied. The DPP approach is particularly useful in handling various types of pileup signals. The measurements of microsecond particle emitters is inefficient or impossible without such systems. Time stamping and self-triggering greatly simplify the data acquisition design in decay experiments. The real-time analysis is a very useful tool for implementing pulse-shape dependent triggering schemes as demonstrated by the 'proton catcher' algorithm. Continuous pulse shape analysis of the Bragg detector signal enabled development of a simple algorithm for element identification in a 'cocktail' beam at low energies.

There are many other possible applications of this new technology which have not yet been explored. Data acquisition systems based on digital pulse processing have been proven to be more than just a compact replacement of hybrid analog/digital systems. Rather, they have facilitated measurements that have previously been impossible.

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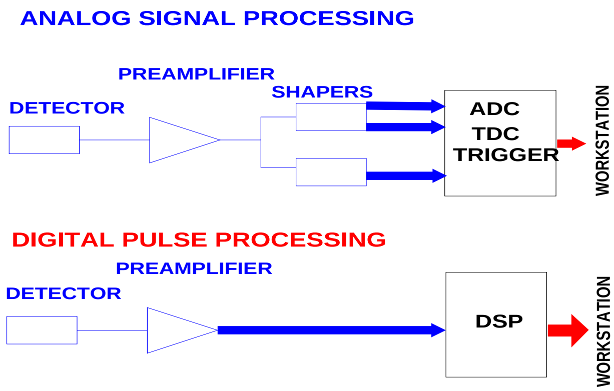

Fig. 1. Block diagrams for analog and digital pulse processing. The system based on Digital Pulse Processing may have smaller numbers of electronic building blocks due to the integration of various functions in the pulse processing real time algorithms.

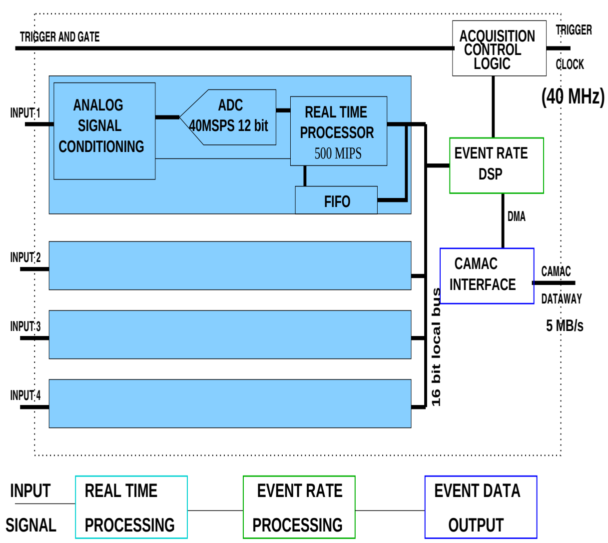

Fig. 2. The DGF-4C functional block diagram (bottom) and its internal architecture (top), as presented in [8]. The real-time processor continuously digitizes the input data, providing digital filtering, so they can be processed at 'event rate' by a Digital Signal Processor.

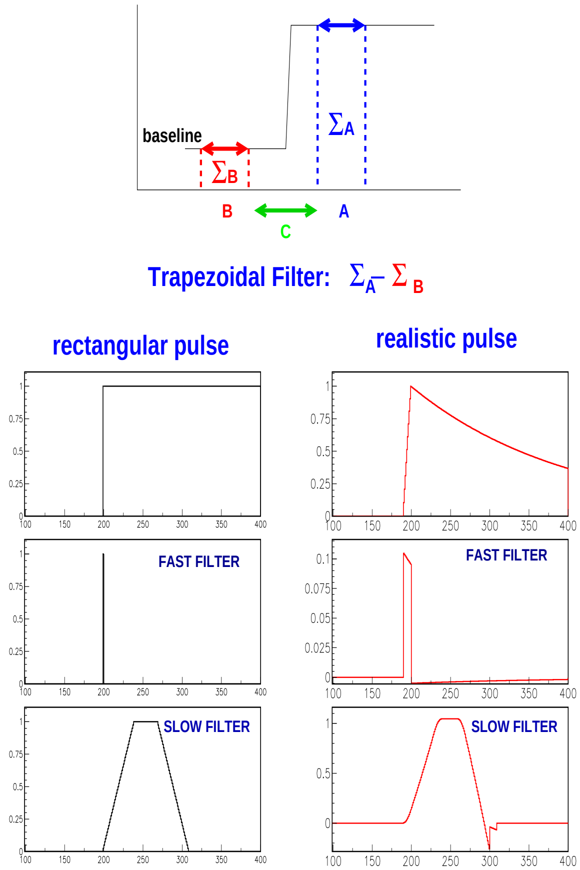

Fig. 3. The concept of the trapezoidal filter (top). For each point of the signal the sums in interval A and interval B separated by interval C are generated. The digital filter value is equal to the difference between these two sums. The step function shape (left panel, top) is transformed into the trapezoidal shape. The rezulting trapezoids can be narrow (middle) or wide (bottom) depending on the filter lengths (T_A, T_B, T_C, T_A=T_B). The narrow filter is used for timing, the wide for pulse height determination. The pulse amplitude is read in the middle of the flat top of the slow filter trapeze. In the right panel a response of a trapezoidal filter to the realistic pulse is shown.

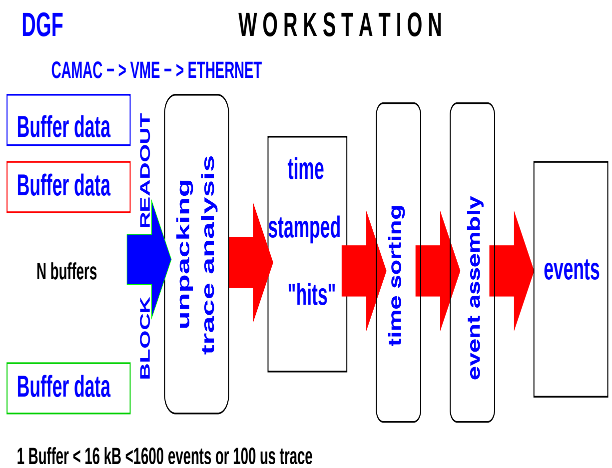

Fig. 4. Block diagram of the first part of the data analysis algorithm - event builder.

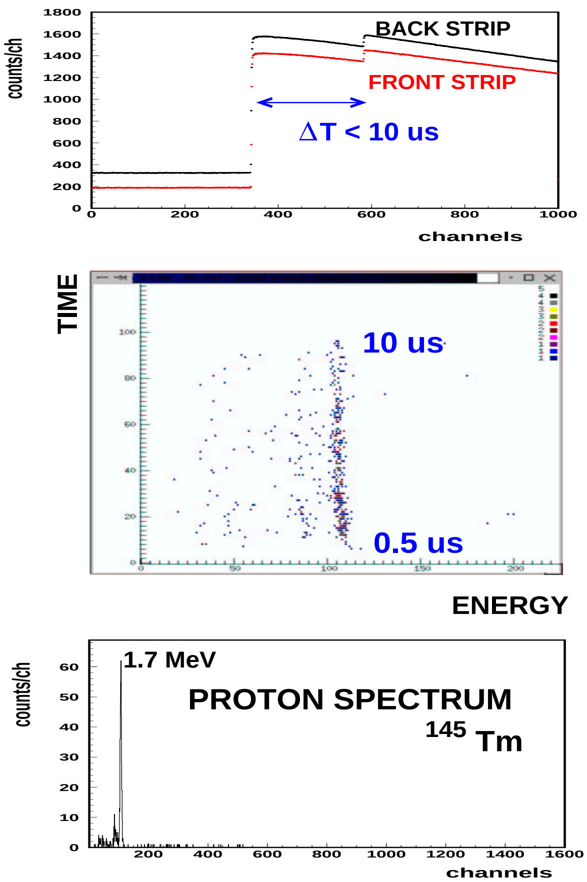

Fig. 5. The analysis of the traces in the proton decay experiment, leading to the observation of the fine structure in the decay of ^{145}Tm [11,12]. The top panel shows the digitized pulses from the front and back strips of DSSD. The low amplitude pulse on top of the large pulse suggests the observation of the proton decay. The amplitude distribution vs time of the low amplitude pulses is shown in the middle, and their energy spectrum in the bottom graph. The time distribution is relative to the start of the large pulse.

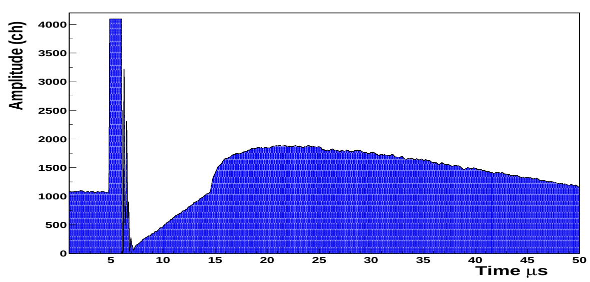

Fig. 6. A typical signal from the 'reset'-preamplifier. The first out-of-scale pulse is induced by the reset signal, from the 500 MeV ion. The second pulse at 15 μs is due to a pulse simulating a decay event.

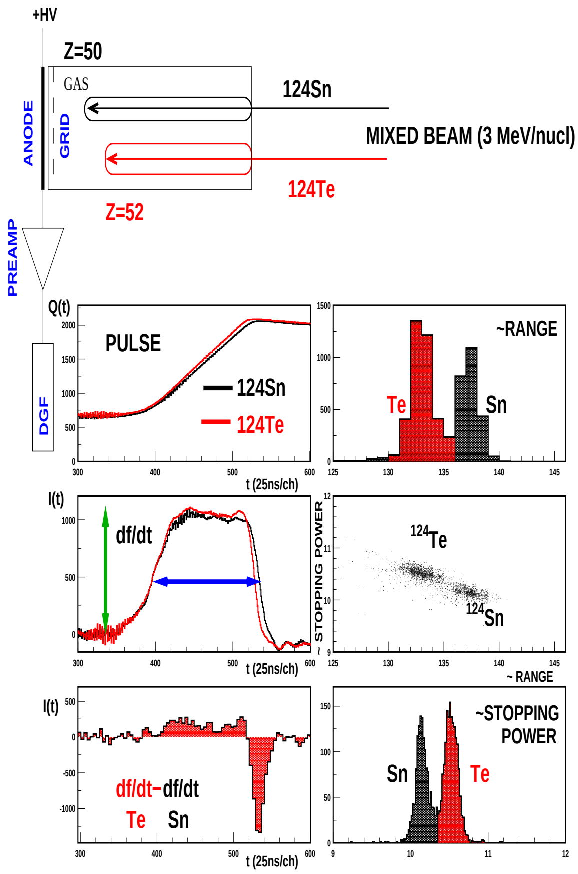

Fig. 7. The Bragg detector analysis. The digitised pulse from the preamplifier (left top panel) is differentiated (left middle panel), to obtain a Bragg-curve type shape. The width of this signal is proportional to the range of the ion (right top panel) and the height to the stopping power (right bottom). The relative difference between differentiated pulses attributed to Te and Sn (left middle panel) is shown in left bottom panel. The two dimensional plot shows the separation of the Sn and Te beams.