European Commission

JRC SCIENTIFIC AND POLICY REPORTS

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J. Paepen
P. Peerani
P. Schillebeeckx
A. Tomanin
R. Wynants

2013

Report EUR 26480 EN

Joint
Research
Centre

European Commission
Joint Research Centre
Institute for Reference Materials and Measurements

Contact information
Jan Paepen
Address: Joint Research Centre, Retieseweg 111, B-2440 Geel, Belgium
E-mail: jan.paepen@ec.europa.eu
Tel.: +32 14 57 1329
Fax: +32 14 57 1862

http://irmm.jrc.ec.europa.eu/
http://www.jrc.ec.europa.eu/

JRC87790

EUR 26480 EN

ISBN 978-92-79-35403-8 (pdf)

ISSN 1831-9424 (online)

doi:10.2787/87780

Luxembourg: Publications Office of the European Union, 2013

Printed in Belgium

Use of a CAEN digitiser for nuclear safeguards and security applications with a scintillator detector

J. Paepen[a]*, P. Peerani*[b]*, P. Schillebeeckx*[a]*, A. Tomanin*[b]*, and R. Wynants*[a]
[a]European Commission, Joint Research Centre, Institute for Reference Materials and Measurements, Retieseweg 111, B-2440 Geel, Belgium
[b]European Commission, Joint Research Centre, Institute for Transuranium Elements, 76344 Eggenstein-Leopoldshafen, Germany

Abstract

The performance of a CAEN DT5751 digitiser for nuclear safeguards and security applications is discussed. The pulse shape processing firmware embedded in the digitiser was tested with a EJ-309 liquid scintillator, exposed to gamma and neutron radiation from radioactive sources and from a Van de Graaff and cyclotron-based accelerator. Software modules were developed for data acquisition and online analysis, and for more advanced off-line processing of data acquired in list mode. The potential use of a scintillator coupled to the digitiser for the detection of both γ-rays and neutrons has been demonstrated.

1 Introduction

The interception of illicit trafficking of radioactive material relies on the detection of gamma and neutron radiation to indicate the presence of a radioactive source or special nuclear material (SNM). Most of the radiation portal monitors installed to prevent illicit trafficking consist of a combination of γ-ray detectors based on plastic scintillators and neutron detectors based on ^{3}He proportional counters. Also in safeguards applications, detection systems used to quantify the amount of SNM rely to a great degree on ^{3}He proportional counters as neutron detectors. Due to the worldwide shortage of ^{3}He the interest in alternative neutron detection techniques has grown significantly. In this context, the Commission FP7 project SCINTILLA was established in 2012 [1]. The project investigates new techniques to detect and quantify radioactive sources and nuclear material and considers different forms of scintillation and semiconductor detectors.

A method to detect neutrons is to convert them to a more detectable particle or radiation based on neutron induced transfer reaction with a high cross section, such as ^{10}B(n,α), ^{6}Li(n,α), ^{155}Gd(n,γ) or ^{157}Gd(n,γ). An obvious alternative for ^{3}He proportional tubes are proportional tubes filled with gas to which one of these materials has been added, or proportional tubes which were lined with these materials. An alternative approach for large volume detectors is the use of scintillator materials to detect fast neutrons based on elastic scattering of the neutron with the hydrogen nuclei of the scintillator. The recoiling protons will excite the scintillator material and result in a light output that can be used as a signature. In most cases, a distinction can be made between a signal resulting from the detection of a γ-ray and a neutron. A combination of different detection techniques is also feasible. For example, a plastic scintillator lined with gadolinium will be sensitive to thermal neutrons through neutron capture in gadolinium, giving rise to a 8 MeV γ-ray, and to fast neutrons through multiple scattering interactions followed by neutron capture in gadolinium. Such detectors are also sensitive to γ-rays. Therefore, they are also suitable to identify the presence of radionuclide γ-ray sources.

While γ-rays interact with the scintillator liquid via photo-electric absorption, Compton scattering or pair production, neutrons produce light after elastic scattering with hydrogen. These different interaction mechanisms result in a different specific energy loss and consequently different de-excitation of the atomic states in the scintillator. Accordingly, there is a difference in the timing characteristics of a light signal produced due to the detection of a γ-ray and a neutron. This difference is the basis of most of the Pulse Shape Discrimination (PSD) techniques that can be found in the literature [2,3].

The light output from scintillator detectors is converted and amplified with photomultiplier tubes (PMTs) or avalanche photodiodes, providing an output signal that is sufficiently large for direct digitalisation without the need of further amplification. In this case, the pulse processing electronics only needs to perform an integration to obtain a value proportional to the deposited energy in the detector. To properly sample the short signal from a scintillator, a sampling frequency of at least 500 MHz is required as pulses can be as short as a few nanoseconds. For most applications also a PSD algorithm is required to separate events resulting from the detection of a γ-ray and a neutron.

Recent developments in digital data acquisition systems with digital signal processors (DSPs) and field programmable gate arrays (FPGAs) offer fast sampling of the signal (up to 5 GS/s) and online discrimination between γ-ray and neutron events. They also provide timing information that can be used e.g. in safeguards applications for neutron coincidence and multiplicity counting [4]. The main advantage of this type of data acquisition systems is the pre-processing of the acquired signal in firmware (embedded algorithms in hardware), offering a large reduction in the amount of data to be transferred to the host computer.

In this report the performance of a CAEN DT5751 digitiser with PSD firmware coupled to a liquid scintillator is described. The use of the digitiser for both nuclear safeguards and security applications is considered. The PSD firmware allows distinguishing between pulses from a γ-ray or a neutron event. The digitiser was used for the characterisation of a cubic EJ-309 liquid scintillator cell that is proposed as a neutron detector to verify the amount of fissile material in fresh fuel assemblies [5].

While the data analysis and characterisation is fully described by Tomanin *et al.* [5], this work focuses on the technical aspects of the data acquisition and pulse processing. The application of the digitiser coupled to other types of scintillators will be similar. For gadolinium- or boron-loaded scintillators additional pulse processing algorithms are required. However, based on the experience gained they can be implemented.

2 Pulse shape processing using digitisers

To test the performance of the CAEN DT5751 digitiser measurements were performed with a detector manufactured by Scionix. The detector consists of a cubic EJ-309 (Eljen Technology) liquid scintillator cell coupled to a 7.6 cm diameter photomultiplier tube (ETL type 9821 FLB) by a glass optical window. The anode output of the PMT was directly connected to the CAEN digitiser, which has a 50 Ω input impedance. The PMT was powered by a Canberra 3106D high voltage supply. At a bias of -1250 V an optimum between energy resolution and energy linearity was found [5]. At this bias, the pulse height for low energy γ-rays was small but still acceptable.

2.1 Online pulse processing with the CAEN DPP-PSD firmware

The 1 GHz sampling frequency of the digitiser is sufficient to properly sample the signal in time bins with a 1 ns width. The 10-bits ADC resolution are distributed over a 1 V_{pp} input dynamic range, which can be shifted by a 16-bit value to accept signals ranging in the intervals from [-1;0] V over [-0.5;+0.5] V to [0;+1] V.

Fig. 1 shows the principle of the CAEN DPP-PSD (Digital Pulse Processing - Pulse Shape Discrimination) firmware implemented in the digitiser. The firmware carries out a charge integration over two gates with different lengths (simply called short and long gate), resulting in two values Q_S and Q_L. These quantities can be used to determine the total energy deposited in the detector and to performe pulse shape discrimination between γ-ray and neutron events. The baseline of the signal is measured by averaging a number of samples (512 in our application), and is subtracted from the signal during charge integration. Two trigger configurations are possible: threshold and peak. For threshold triggering, a trigger will occur at the first sample higher than the specified threshold, as shown in fig. 1. Peak triggering will arm the trigger at the threshold, but will issue the trigger at the largest sample following the arming.

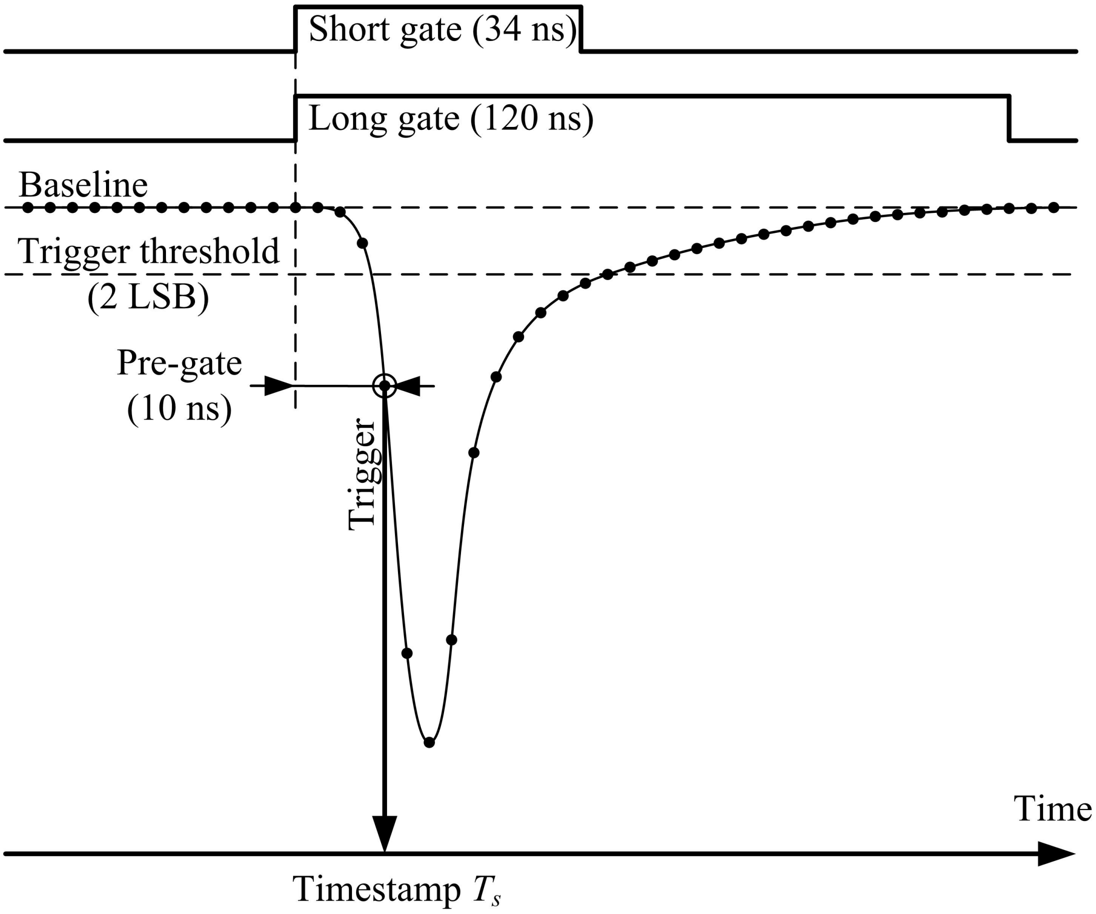

Fig. 1: Illustration of the operation of the pulse shape processing firmware implemented in the CAEN DT5751 digitiser.

Peak triggering has the advantage not being sensitive to amplitude walk, i.e. the effect that the trigger timestamp depends on the pulse height. A timestamp T_s from a 32-bit counter clock is associated with every trigger. A pre-gate setting allows to start the integration of the charge before the occurrence of the trigger. This is possible since all samples are kept in the digitiser's memory. The length of the two gates can be set individually, but they will open at the same time, defined by the trigger and the pre-gate. Together with the timestamp T_s of the detected event, the integrated charges Q_S and Q_L are written to a list-mode data file for post-processing, or processed online with custom data acquisition and analysis software. The integrated charge Q_L can be used as a measure of the total light produced by the detected event. From the ratio of the charges in the short and long gate a PSD parameter P_S is calculated:

$$P_S = 1 - \frac{Q_S}{Q_L}\,. \tag{1}$$

The parameter P_S reflects the fraction of the light output due to the slow component. The optimum settings for the short and long gate with respect to γ/n discrimination have been derived in ref. [5].

The DT5751 digitiser can be controlled via USB or a CAEN proprietary optical bus. The latter allows to daisy-chain up to 8 digitisers in one optical loop network. As only one digitiser was required for the measurements described here, and data was acquired with a portable PC, the USB connection was preferred.

2.2 Advantage and expense of data reduction

Transferring the complete pulse waveform sampled with a resolution of 10 bits over a time of e.g. 150 ns would require 1510 bits per pulse. Online pulse processing reduces this amount of data by a factor of about 24 to 64 bits only (32 bits for the timestamp, and 2 times 16 bits for the integrated charge over the two gates). In this way, the digitiser can cope with larger pulse rates while maintaining the relevant pulse shape information. The expense for this gain in data throughput is the requirement of the optimisation of the two gate lengths, depending on the type of scintillator and the particles to discriminate. It is good practice to optimise the gate lengths off-line by analysis of the raw waveform data, which can be dumped to a file. This allows a re-analysis of the acquired data with different gate length settings. Depending on the type of data treatment and processing, different firmware settings can be optimised. For online applications, the optimal gate length settings are then applied making full use of the data reduction and higher pulse processing rate.

2.3 Performance test

The manufacturer provides instrument drivers in the form of dynamic link libraries (DLLs) that can be used to develop custom data acquisition and processing software. Hence, high-performance systems that allow online γ/n discrimination, visualisation and storage of relevant information can be built. We have tested the performance of the DT5751 using an Agilent 81160A pulse function arbitrary waveform generator and software developed in-house for visualisation of the energy spectrum, the time interval distribution and the count rate. The software consists of a DLL controlling the digitiser and processing the data (built around the instrument drivers), and a graphical user interface developed in LabView (National Instruments). The digitiser and software are capable of processing repetitive pulses with a frequency up to 1.2 MHz, without storing data. Up to about 1 MHz, sustained visualisation and output to a binary list-mode file is feasible, without gaps in the data acquisition. For repetitive signals, the construction of the time interval distribution (time difference between every pulse and its successor) is an excellent tool to check for gaps in the data acquisition due to buffer overrun.

3 Results

The CAEN digitiser was used to characterise the response of a EJ-309 scintillator to γ-rays and neutrons. Experimental response functions were determined to validate results of Monte Carlo simulations. The response of the detector to γ-rays was measured with radionuclide sources. The response to neutrons was measured with a AmBe and PuC neutron source and with quasi mono-energetic neutrons produced at a Van de Graaff and a cyclotron-based generator. For the latter, neutron time-of-flight information was valuable to select only neutrons within a certain energy range. A detailed description of the characterisation procedure and results is given in ref. [5].

Processing of the list-mode data was performed by compiled ROOT scripts, developed at the EC-JRC-IRMM. ROOT is an object-oriented framework developed and maintained by CERN. It is aimed at solving the data analysis challenges of high-energy physics [7]. The choice of ROOT for this application is based on its performance in dealing with large amounts of data, and its flexibility and ease to visualise, process and analyse the data (histogramming, selection, fitting). For the measurements related to the characterisation of the detector, list-mode data files were acquired with the software provided by the manufacturer and stored in ASCII format, which was converted to a root tree file for further processing.

3.1 Time-of-flight measurements with the CAEN digitiser

A schematic representation of the experimental setup for the measurements at the TCC-CV28 cyclotron of PTB is shown in fig. 2. The pulsed deuteron beam from the accelerator hits a deuterium gas target which converts the deuterons to neutrons. The neutrons produced in the target then travel for a distance L of about 20.5 m and interact with the detector. The kinetic energy of a neutron that is detected is

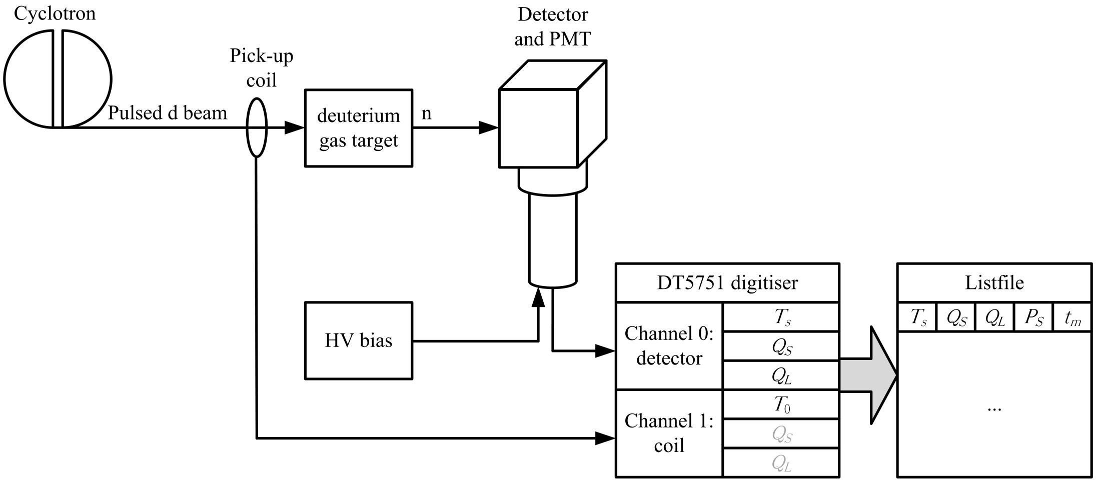

Fig. 2: Schematic representation of the setup for measurements at the TCC-CV28 cyclotron of PTB Braunschweig.

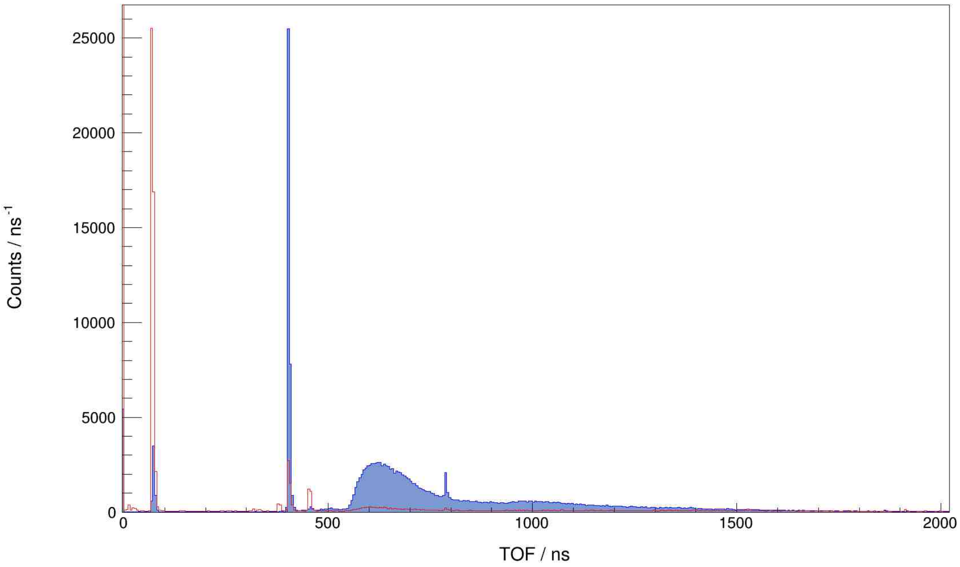

Fig. 3: Time-of-fligh spectrum showing neutron events in blue and gammas in red.

derived from the time t_m it needs to travel the distance L. This time is obtained from the difference between a start signal T_0, given at the time the deuteron beam passes through a coil, and the stop signal T_s, produced at the moment the neutron is detected. The first channel of the digitiser was used for the anode signal from which the digitiser extracts the timestamp T_s, and the integrated charge over the two gates Q_S and Q_L. The start signal T_0 was acquired by connecting the logic time signal from the pick-up coil at the exit of the cyclotron to the second input channel of the digitiser.

The PC running the data acquisition software stores a list-mode data file for each input channel of the digitiser. The acquisition of list-mode data allows re-analysis of the same data with different parameters and offers powerful ways for visualising and processing. A software code was developed to extract from the information in the two files the time signal T_0 and T_s and the integrated charges Q_S and Q_L. From these parameters the time-of-flight t_m of the detected event and the PSD parameter P_S are calculated. These parameters are also added to the list-mode data as illustrated in fig. 2. Using the libraries provided by the manufacturer, it is also possible to develop software for data acquisition and on-line visualisation and analysis.

A time-of-flight spectrum resulting from measurements with a 11.06 MeV deuteron beam at the cyclotron of the PTB is shown in fig. 3. The peak at t_m = 68 ns is due to the detection of γ-rays while the peak at t_m = 400 ns is due to the detection of 14.03 MeV mono-energetic neutrons produced in the D(d,n)^{3}He reaction. The other peaks in the spectrum are satellite peaks which result from spurious deuteron beam pulses produced in the main frequency of the cyclotron that were not removed by the beam selector. The continuum for times t_m > 500 ns results from D(d,np)D and D(d,n)n2p break-up reactions.

3.2 Neutron - γ-ray pulse shape discrimination

The principle to discriminate between γ-ray and neutron events is illustrated in figs. 4, 5 and 6. These figures are density plots of P_S versus Q_L, resulting from measurements with a AmBe source (fig. 4) and measurements at the cyclotron of the PTB Braunschweig (figs. 5 and 6). The density plot resulting from the detection of 14.03 MeV mono-energetic neutrons, corresponding to a time-of-flight 390 ns < t_m < 410 ns, is shown in fig. 6. As the contribution to the slow component of a pulse resulting from the detection of a neutron is larger compared to a pulse resulting from the detection of a γ-ray, the PSD parameter P_S for neutron events will be larger than for γ-ray events. Therefore, two distinct clouds centered at around P_S = 0.2 and P_S = 0.12, corresponding to neutron and γ-ray events, respectively, are observed in figs. 4, 5 and 6. These figures reveal that for events with a light output Q_L > 500 keV it is possible to discriminate between γ-rays and neutrons using a simple threshold, independent of the light output.

For a more detailed analysis, a discrimination threshold depending on the light output is required. This is illustrated in fig. 4, which includes the result of a least squares adjustement of the histogram of the parameter P_S based on a sum of two Gaussian distributions, corresponding to events due to the detection of a γ-ray and neutron. The resulting position and widths of the distributions have been used to indicate in fig. 4 the events resulting from the detection of a γ-ray or a neutron.

3.3 Response functions for γ-rays and neutrons

The response of the liquid scintillator cell to γ-radiation was measured using a set of radionuclide sources (^{137}Cs, ^{60}Co, ^{207}Bi and ^{232}Th) placed at a distance of 45.5 cm from the detector. The post-processing of the list-mode data file was limited to the construction of the histogram of the integrated charge Q_L during the long gate. The real time of the measurement was calculated from the difference of the timestamp between the last and the first pulse. The linearity of the light output and resolution as a function of electron energy was verified. The absolute detection efficiency as a function of γ-ray energy was measured and compared with results from MCNP modelling. The detection efficiency resulting from the Monte Carlo simulations was confirmed within 2% [5].

Response functions for neutrons were obtained from measurements with neutron sources (AmBe and PuC) and measurements at the Van de Graaff and cyclotron accelerators of PTB, Braunschweig, Germany. The light output for protons was derived and approximated by analytical functions. The best agreement was obtained using a function used by Madey *et al.* [8]. The simulated response for neutrons was validated by results of measurements with a calibrated AmBe neutron source. The efficiency for neutrons resulting from the simulations was confirmed within 4%. The results from the measurements at EC-JRC-IRMM and PTB Braunschweig are discussed in detail in ref. [4].

4 Discussion

Setting-up the DT5751 digitiser is straightforward. Acquisition parameters can be changed interactively while observing the pulse waveform in the oscilloscope operating mode. When parameters are optimised, data can be acquired in the histogram operating mode. The digitiser is fast enough to sample pulses from

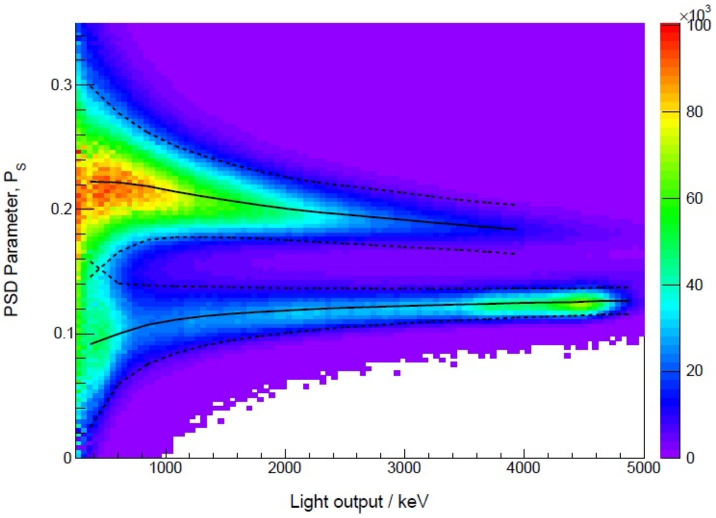

Fig. 4: Density plot of the PSD parameter P_S versus light output (proportional to Q_L) resulting from measurements with an AmBe neutron source at the EC-JRC-IRMM.

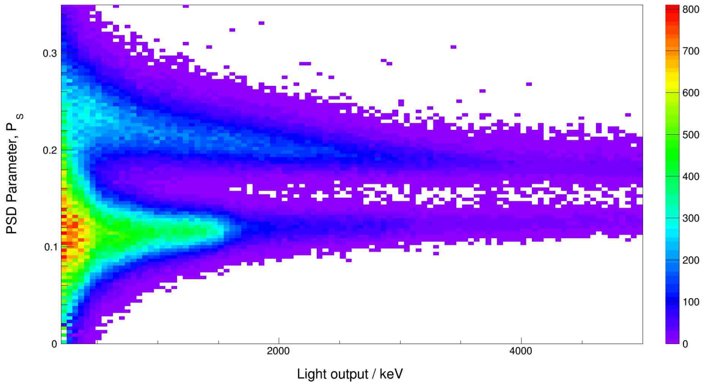

Fig. 5: Density plot of the PSD parameter P_S versus light output (proportional to Q_L) resulting from measurements at the cyclotron of the PTB Braunschweig.

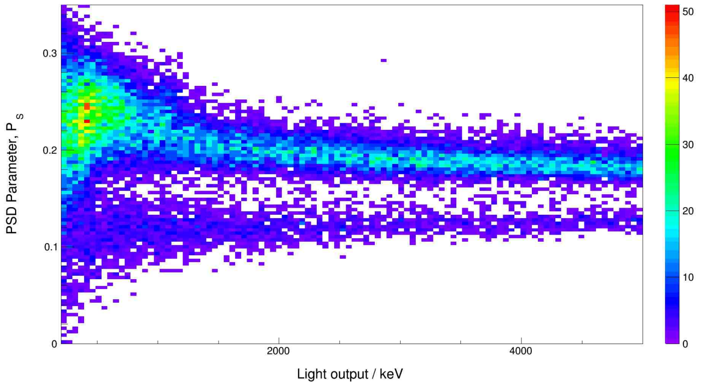

Fig. 6: Density plot of the PSD parameter P_S versus light output (proportional to Q_L) resulting from measurements at the cyclotron of the PTB Braunschweig. Only events with a time-of-flight 390 ns < t_m < 410 ns are considered.

a liquid scintillator, such as the EJ-309 scintillator, and the pulse shape discrimination works as expected. Nevertheless, a few issues were identified.

4.1 Hardware issues

To stay in the linear energy region for the response to γ-rays, the bias of the PMT was set rather low, resulting in small pulses compared to the digitiser's input dynamic range. While the digitiser offers the possibility to shift the entire 1 V_{pp} input range, it does not provide different gain settings at the stage before digitalisation. Hence, the 10 bits of ADC resolution are not fully used, which reduces the performance when small pulses are digitised.

4.2 Issues with data acquisition software

The software provided by the manufacturer provides a good starting point for research on new applications of digitisers. Energy and time interval spectra can be displayed, and data can be written to a list-mode file for off-line processing. However, as the software can never accommodate all their needs, users are encouraged to develop their own data acquisition application, for which well-documented drivers and libraries are provided.

The main issue was the limited throughput that could be obtained with the provided software. While writing list-mode data files to disk, the digitiser could only process about 90 k pulses per second. Especially for the measurements at the cyclotron of the PTB, the limited throughput was an issue. The operating frequency of the cyclotron had to be scaled down with a factor 14 from 820 kHz to 57 kHz to be able to store the data without gaps in the time domain. To obtain the same counting statistics, the measurement time had to be increased with the same factor. The count rate in the detector channel was only about 0.4 kHz.

To pinpoint the reason for this bottleneck, we developed our own data acquisition software based on a C code making use of the drivers provided by the manufacturer. This software can sustain a pulse rate of 1 million per second, while writing a list-mode output file to the hard drive over USB. This proves that the issue is related with the software provided by the manufacturer.

4.3 Firmware issues

The digitiser firmware does detect a full buffer condition and indicates this by a red LED labelled "BUSY". However, this signal is not available through the firmware and/or instrument driver, making it impossible to detect a full buffer condition by software. This issue becomes very important for security applications, where an overload condition due to high count rates shall at least be detected. The issue has been reported back to the manufacturer.

A smaller issue is the fact that the timestamp counter overruns every 2^{32} ns or 4.29 s. This can be detected and corrected for in the processing phase, by keeping track of the number of overruns and correctively adding a multiple of 2^{32} ns to the timestamps. This technique however only works when the time difference between two consecutively detected events is less than 2^{32} ns. For lower count rates it is impossible to count the number of overruns between two consecutive events, unless an additional clock (e.g. from the host PC) is used.

5 Standardisation of a list-mode data format

From the experience with different types of digitisers used in applications such as nuclear safety and security, safeguards, primary standardisation of radionuclides and measurements of nuclear data, the authors recognise the need for standardisation of a format for list-mode data. In nuclear security, there is a growing tendency to send acquired data from checkpoints to remote datacenters (reachback) for further analysis by experts in case of a positive detection. List-mode data has an additive value compared to spectral data because it containes timing information of the individual events. As such, it can be used as a diagnostics tool to verify the performance of the detection system, but also to find time correlations between signals from different detectors in the same system. In mobile or portable detection systems, list-mode data could include geolocation positioning information, in addition to timestamp, energy and type of the detected particle.

For detectors used in safeguard applications, the timestamps of the detected neutrons are essential to determine the amount of fissile material by multiplicity counting. Newly developed liquid scintillators such as EJ-309 allow direct detection of fast neutrons. No moderator is required as with ^{3}He proportional counters. Complete detector assemblies can be build with several detectors placed around the sample (e.g. a fuel element). Each detector output is direcly connected to an input of a digitiser. It might be necessary to use more than one digitiser in the same assembly, requiring synchronisation of their clocks and simultaneous reset of the timestamp counter at the beginning of each measurment. These features are available in modern digitisers. In the past, such detector assemblies required a complicated setup with additional electronics to process the signals. With digitisers providing pulse shape discrimination and data output in list mode, the additional electronics become obsolete and are replaced by software for online or off-line data analysis. In addition, the data acquired directly from the output of the PMTs can be stored for later analysis or re-analysis with different parameters.

The same reduction of the amount of electronic modules is true for primary standardisation, e.g. in β/γ coincidence counting where time correlations between a β-particle detected in one detector and a γ-ray in another detector are analysed. This is a common technique used by national metrology institutes to quantify the activity of nuclides that emit both β- and γ-radiation. A common practice in primary standardisation is to impose a known dead time after every pulse, instead of trying to measure the dead time of a detector chain. Acquiring data with digitisers providing timestamps allows not only to investigate the time interval distribution of the detected pulses, but also make it possible to impose different types of dead times (e.g. extending, non-extending) on the same data. The effects of different algorithms can be assessed individually without the need to redo the measurement.

The common advantages in these applications is the possibility to store data acquired in an early stage; directly at the output of the detector or preamplifier. Data can be exchanged between experts and results of different analysis algorithms can be compared, enhancing the quality of the measurement result. However, the exchange of data is only possible when an agreed data format is used, justifying the need for standardisation. A standard for list-mode data should address the different needs dictated by the different applications. A standardised list-mode data file should start with a header section describing e.g. the measurement conditions, type of detector used, start time of the measurement etc. The header should preferably be in a structured text format that can be read easily, as for example the XML used in the IEC 62755 (Radiation protection instrumentation - Data format for radiation instruments used in the detection of illicit trafficking of radioactive materials). The user should be free to add data fields to the header when deemed necessary. The rest of the data file should be in binary format for performance reasons. The standard should include different binary formats. At least it should be possible to store all the samples that fully describe a pulse waveform, but certainly also pre-processed waveform data containing for example timestamp and energy information. Ohter applications might require time-of-flight data, positioning information, etc.

Efforts have already been made to start the development of such a standard, in the frame of IEC/TC 45. The need for standardisation of listmode data has also been recognised by CEN/TC 391, who executes the Commission mandate M/487 to establish security standards. In their final report phase 2 addressed to the Commission, CEN/TC 391 assigned a high priority to the standardisation of list-mode data [9]. Also, in realisation of the European Programme for Critical Infrastructure Protection (EPCIP), the European Reference Network for Critical Infrastructure Protection (ERNCIP), Thematic Group on Radiological Threats to Critical Infrastructure has been given the task to investigate list-mode data acquistion based on digital electronics, and in particular the standardisation needs [10]. Manufacturers of digitisers are encouraged to participate in the development process, as their input is of utmost importance to maximise the future use of such a standard.

6 Conclusion

In this report we have shown that fast digitisers with pulse shape processing firmware such as the CAEN DT5751 are a powerful tool to discriminate between gamma and neutron radiation if these leave different signatures in the detector with respect to time. The digitiser extracts only the valuable information from the pulse waveform, allowing data acquisition and storage to a list-mode file at high count rates. When one of the other inputs of the digitiser is used to sample the start signal of a pulsed accelerator, neutron time-of-flight data can be added to the list-mode file, providing the deposited energies, a discrimination between gammas and neutrons, and the neutron velocity. Using custom-made data acquisition software build on top of the instrument driver libraries, the throughput issue associated with the software provided by the manufacturer could be solved and data acquisition up to 1 million pulses per second could be achieved. A main issue related to the firmware is the fact that there is no way of checking the occurence of buffer overrun, leading to data loss. As there is no amplification stage with variable gain at the input of the digitiser, the resolution of 10 bits might not be sufficient in some applications. An additional wide-band amplifier could be necessary to make full use of the input dynamic range of the device. With a custom developed application for data acquisition, visualisation and processing, the digitiser can readily be used in nuclear security and safeguards applications, where scarce ^{3}He proportional counters are being replaced by plastic or liquid scintillators which are made sensitive to neutron radiation. Efforts to standardise the list-mode data format have been initiated.

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EUR 26480 EN – Joint Research Centre – Institute for Reference Materials and Measurements

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Luxembourg: Publications Office of the European Union

2013 – 12 pp. – 21.0 x 29.7 cm

EUR – Scientific and Technical Research series – ISSN 1831-9424 (online)

ISBN 978-92-79-35403-8 (pdf)

doi:10.2787/87780

Abstract

The performance of a CAEN DT5751 digitiser for nuclear safeguards and security applications is discussed. The pulse shape processing firmware embedded in the digitiser was tested with a EJ-309 liquid scintillator, exposed to gamma and neutron radiation from radioactive sources and from a Van de Graaff and cyclotron-based accelerator. Software modules were developed for data acquisition and online analysis, and for more advanced off-line processing of data acquired in list mode. The potential use of a scintillator coupled to the digitiser for the detection of both γ-rays and neutrons has been demonstrated.

LA-NA-26480-EN-N

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ISBN 978-92-79-35403-8

Publications Office