Proceedings of the INMM & ESARDA Joint Virtual Annual Meeting
August 23-26 & August 30-September 1, 2021

NEW NEUTRON SIGNAL ACQUISITION AND PROCESSING PLATFORM FOR NUCLEAR SAFEGUARDS

Matteo Corbo
CAEN SpA, Viareggio, Italy

Massimo Morichi
CAEN SpA, Viareggio, Italy

Lara Palla
CAEN SpA, Viareggio, Italy

Annalisa Mati
CAEN SpA, Viareggio, Italy

Alberto Potenza
CAEN SpA, Viareggio, Italy

ABSTRACT

The subject of this paper is a new platform of devices that addresses the current situation of limited availability of maintainable instrumentation for neutron coincidence counting and reflects the recent advances in microelectronics. The main functions of the new devices of the platform are to collect the signals from neutron detectors, process and convert them into digital information and store them in data files. The devices share a common programmable hardware with industrial grade components for high reliability even in case of high temperature operational conditions. They embed a Field Programmable Gate Array for generating time stamped list of neutron signals for up to 32 input channels. The internal multithreaded microprocessor records the data, reproduces the functionality of shift register, multiplicity register and pulse train recorder. It provides at the same time a web server for a multiplatform graphical user interface. All the above-mentioned processing capability, the high and low voltage power supplies are integrated in a module with a power consumption, which can be easily dissipated in sealed enclosures of unattended monitoring systems as well. The systems of the platform in subject have been verified against the reference instruments commonly used the Safeguards accountancy and this paper shows the results of those comparisons.

INTRODUCTION

The neutron coincidence counting is one of the fundamental techniques for non-destructive assay of Nuclear Safeguards. Several types of data acquisition modules are currently in use for this technique that is used for nuclear material monitoring and verification. However, some of those modules are obsolete or approaching the production discontinuity, and this aspect represents a serious issue for the Safeguards activity.

The devices described in this paper shall satisfy the needs of attended and unattended measurements, bringing improvements from all perspectives: guaranteeing nominal performances in a wider range of measurement conditions, combining bigger storage capability, modern user interfaces and low power consumption of less than 10 W. The platform is composed by the units R7771, Neutron Pulse Train Recorder and the R7780, Unattended Data Acquisition Module for Unattended Monitoring Systems.

The R7771 can acquire the signals from 32 neutron detectors. It provides the time-stamped list of TTL pulses from neutron detector front-end electronics with 10 ns pulse pairs resolution independently per each channel. The R7771 provides the most complete information on neutron counting, giving the capability to characterize nuclear material in passive mode and to analyse the transients in active nuclear material interrogation. The 32 independent inputs allow for the acquisition from highly segmented assay systems composed by multiple neutron detectors. It is provided in mechanics compliant to 19” racks and can operated also stand-alone.

Figure 1. Front panel of the unit R7771

The CAEN R7780 module is a digital processing unit for neutron coincidence and multiplicity counting allowing data analysis and acquisition from up to 8 neutron detectors. It is based on the combined work of its on-board FPGA and ARM CPU. It can work in UNATTENDED mode storing the analysis results on 2 removable SD memory cards, but it can also be operated in ATTENDED mode to record the timestamp lists of the collected detector pulses on an external computer running its control software.

The peculiar aspect of the CAEN R7780 is the capability to combine both the functionality of pulse train recorder and multiplicity register outperforming with its 100 MHz clock the current available acquisition electronics. The unit has also the capability of counting independently through its logic inputs providing natively the functionality of derandomizer with 8 inputs.

Figure 2. Front panel of the unit R7780

This document describes a typical laboratory application of the R7780 board for the assay of nuclear materials and contains some results obtained during laboratory test measurements with the new unit equipped with a higher performance FPGA that manages the full analysis algorithm.

R7771 TECHNICAL DESCRIPTION

The internal 100 MHz sampling clock fits for high count-rate applications and the on-board intelligence synergy of a 5CGXFC4 FPGA and a Single Board Computer (with single-core ARM CPU) makes it possible to provide time-stamped lists required for the analysis in Nuclear Safeguards and nuclear material process monitoring.

The R7771 can connect to external host computers by point-to-point direct connection through the USB 2.0 link and by a remote network connection through the Ethernet 10/100T port. The internal CPU manages the board settings, the acquisition, and the data transfer of the pulse train from each channel of the board to the host PC. The computational resources and data throughput allow the acquisition of a high total continuous input rate (up to $3 \cdot 10^6$ cps).

The device is equipped with high power outputs for multiple detector operation at once: HV output channel for the detector bias and LV output channel for powering the front-end electronics such as preamplifiers and discriminators.

The R7771 is fully supported by its control software which configures the device, handles the data acquisition and saves the recorded pulse trains to binary files on the host computer for offline analysis (supported PTR- 32 format compatible with the INCC software [1]). It also gives the possibility to import stored pulse trains and to execute coincidence and multiplicity analysis in post-processing.

R7780 TECHNICAL DESCRIPTION

The R7780 is a Neutron Coincidence Analyzer and Multiplicity module combining the functions of a Shift Register and a Pulse Train Recorder. The eight single-ended TTL inputs (LEMO) feature independent counting capability. Moreover, adjustable input thresholds give the possibility to compensate TTL signal voltage drops in case of long-distance use.

The internal 100 MHz sampling clock fits for high count-rate applications and the on-board intelligence synergy of a Cyclone 5CGXFC5 FPGA and a Single Board Computer (with 4-core ARM CPU) makes it possible to provide time-stamped lists and the overall neutron counting information (coincidence timing, multiplicity distributions of coincident events, etc.) required for the analysis in Nuclear Safeguards and nuclear material process monitoring.

After the start-up sequence based on a programmable configuration file, the device can collect data without external control on a local non-volatile memory. Two SD cards, externally accessible for insertion/extraction, store all measurement results and log information in two identical copies for redundancy reasons. The presence of a OTG USB port allows the automatic data retrieval by a USB stick.

The device can also operate in attended mode controlled by an external host computer using the USB port as virtual point-to-point serial connection (reserved for INCC software (1)) and a remote network connection through the ethernet port.

The R7780 is equipped with a video output (HDMI) to connect an external display for monitoring the state of the device and acquisition information.

High power outputs are available as well: one high-voltage channel for the detector biasing and two different low-voltage channels (+5V and +12V) to power the front-end electronics such as preamplifiers and discriminators.

The R7780 is fully supported by its control software which configures the device and handles the data acquisition. In attended mode, the raw data can be saved to binary files on the host computer for offline analysis (supported PTR-32 format compatible with the INCC software). Complete device control, including firmware upgrade, is also possible by Web Interface.

TEST MEASUREMENTS WITH R7771 DEVICE

Data acquisition has been tested using the CAEN Detector Emulator (DDE) that has been programmed to generate Poisson distributed events from both CH1 and CH2 outputs: the CH1 and CH2 digital out of the DDE have been connected to the R7771 input channels 13 and 23 respectively. The average rate of the generated events was set to 120 kHz for both outputs. Data acquisition has been managed by the control software and a single pulse train has been saved containing data from both channels, the generated file and has been processed in offline analysis.

The deltaT distribution measured by the single channels has been analysed together with the Rossi Alpha distribution. Plots are shown in Figure 3. The following images are relative to the channel of the board 23.

The graph in Figure 4 agrees shows the Poisson distribution of Reals+Accidentals and Accidentals (A): in particular, since the analysis Gate has been set to 64 us, the average value of the multiplicity distributions is about 7.7.

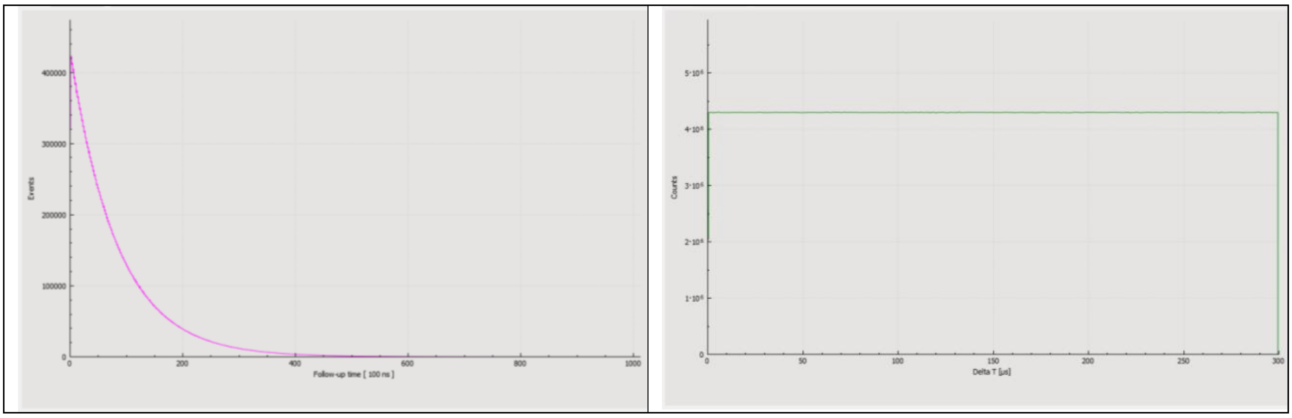

Figure 3. On the left side the time difference distribution of consecutive pulses of the randomly distributed pulses (poisson)

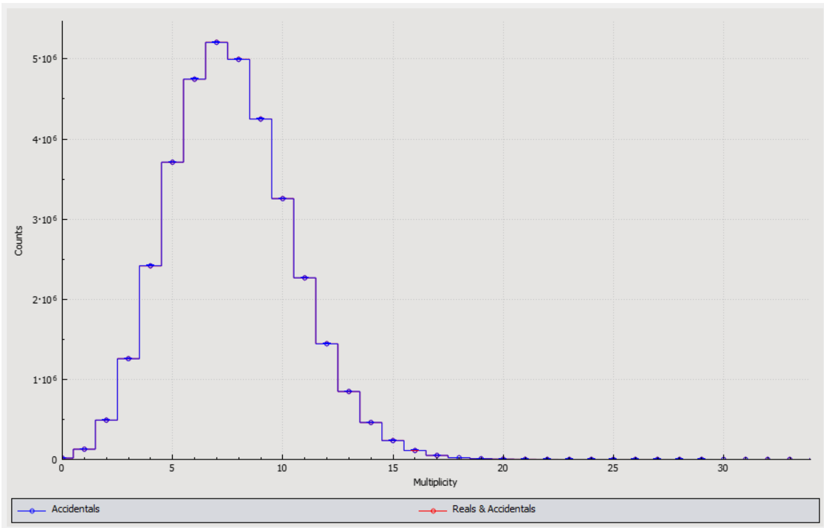

Figure 4. Poisson distribution of Reals+Accidentals and Accidentals with 120 kHz pulses and 64 us gate.

TEST MEASUREMENTS WITH R7780 DEVICE

The goal of the measurements is to validate the R7780 board firmware and related control software. The scope was also to test the functionalities of acquisition and information reconstruction in a laboratory experimental setup. The measurements were compared to the ones obtained with the JSR-14 and the data reconstruction performed at software level was compared with the one of INCC when list mode data was stored. The 3 different working modes of the device were tested: ATTENDED, UNATTENDED and LIST-MODE as described in the following sections.

The R7780 board has been used to provide the needed low and high voltage power supplies for the JCC-51 detector. When the JSR14 was used its power supply channels were used.

Two neutron sources that have been employed for these tests are the following (the mass values are dated 20th of May 2021 and consider the radioactive decay of the isotopes):

Table 1. Radioactive Isotopes used for the tests

Isotope	$t_{½}$ (y)	BCMN61 (g)	BCMN70(g)
Pu-242	373000	0.2452	0.1218
Pu-241	14.33	0.07216	0.05919
Pu-240	6561	1.48	1.069
Pu-239	24100	3.6535	4.2958
Pu-238	87.74	0.05312	0.03764
Am-241	432.6	0.38733	0.317

Both R7780 and JSR-14 have been set to acquire with the following set of parameters: Predelay = 4.5 us, Gate = 64 us, LongDelay = 4 ms

R7780 in ATTENDED mode, BCMN61 source

ATTENDED mode sets the R7780 device controlled by the software that collects the incoming raw pulse trains and stores them into files on the PC for offline analysis. PTR-32 file format (.bin, .chn file pair) is allowed and has been chosen for these tests.

The collected PTR-32 files were analysed with the control software and with INCC (rel 6.17.34.19459) to build the multiplicity distributions and calculate the Singles (S), Doubles (D) and Triples (T) rates.

The resulting Reals+Accidentals (ReA) and Accidentals (A) multiplicity distributions were in agreement, as it can be seen in Table 1 which is relative to the 300 s acquisition.

Table 2. Reals+Accidentals (ReA) and Accidentals (A) multiplicity distributions.

Multiplicity	CAEN ReA	CAEN A	INCC ReA	INCC A
0	324403	351654	324402	351653
1	47915	25358	47915	25358
2	6350	2253	6350	2253
3	758	234	758	234
4	89	22	89	22
5	9	3	9	3
6	0	0	0	0

An excellent agreement was also found comparing the S, D and T calculated values. Table 3 shows the average values obtained from the 10 acquisition cycles of 60 s.

Table 3. Calculated the Singles (S), Doubles (D) and Triples (T) rates.

CAEN			INCC		
S (cps)	D (cps)	T (cps)	S (cps)	D (cps)	T (cps)
1264 +- 2	108.0 +- 0.8	12.1 +- 0.3	1264 +- 2	108.0 +- 0.9	12.1 +- 0.3

R7780 in LIST_MODE, BCMN61 source

LIST MODE mode allows the R7780 device to collect raw pulse trains that are automatically saved by the device to PTR-32 files, and stored on the SD memory card. Data acquisition can be started/stopped by the control software.

The PTR-32 files have been processed both by the control software and the INCC software, as already done with those files collected in ATTENDED mode. The calculated ReA and A multiplicity distributions obtained from the 300 s measurement have been compared (Table 4), and also the average S, D and T values from the 10 measurement cycles of 60 s each (Table 5).

Table 4. Reals+Accidentals (ReA) and Accidentals (A) multiplicity distributions.

Multiplicity	CAEN ReA	CAEN A	INCC ReA	INCC A
0	324240	351634	324239	351633
1	48147	25602	48147	25602
2	6473	2235	6473	2235
3	784	231	784	231
4	85	29	85	29
5	8	5	8	5
6	0	1	0	1
7	0	0	0	0

Table 5. Calculated the Singles (S), Doubles (D) and Triples (T) rates.

CAEN			INCC		
S(cps)	D(cps)	T(cps)	S(cps)	D(cps)	T(cps)
1267 +- 1	107 +- 1	11.2 +- 0.4	1266.6 +- 1.4	106.9 +- 0.7	11.2 +- 0.3

R7780 in UNATTENDED mode, BCMN61 + BCMN70 sources

We set the R7780 device in UNATTENDED mode. The device automatically processes the incoming pulse trains and analyses the collected data online. Three counting modes are allowed: COUNTING (the total pulses collected individually by every input channel are counted), COINCIDENCE (the ReA and A accumulators are also calculated), MULTIPLICITY (the ReA and A multiplicity distributions are also built). The analysis results are saved to .dataz ASCII files and stored by the device on the SD memory cards.

In these experimental conditions, the JSR14 counter has also been employed.

The following tables, Table 6, Table 7 and Table 8 contain the JSR-14 measurement results together with the R7780 results, for comparison. Results are relative to different measurement cycles. Both the devices have been employed in COINCIDENCE and MULTIPLICITY mode, with data acquisition of 300 s duration, and in both cases the collected data are in very good agreement.

Table 6. Reals+Accidentals (ReA) and Accidentals (A) in coincidence mode.

	Totals	R+A	A	S(cps)	D(cps)

R7780	654565	147428	92035	2181.9	184.6
JSR14	651405	145892	89451	2171.35	188.1
JSR14	652922	145671	90764	2176.4	183.02
JSR14	653107	146436	90910	2177.02	185.09

Table 7. Reals+Accidentals (ReA) and Accidentals (A) multiplicity distributions.

Multiplicity	JSR14 ReA run 1	JSR14 A run 1	JSR14 ReA run 2	JSR14 A run 2	R7780 ReA	R7780 A
0	528858	572197	529238	573178	528538	572562
1	104792	71404	105986	72044	106205	72168
2	16253	7860	16242	7922	16670	8200
3	2290	923	2329	893	2216	907
4	281	123	298	95	276	102
5	39	12	38	6	38	10
6	3	0	6	0	5	0
7	0	1	0	0	1	0
8	0	0	0	0	0	0

Table 8. Calculated the Singles (S), Doubles (D) and Triples (T) rates.

	Totals	Real+Accidental	Accidental	Singles (cps)	Doublets (cps)	Triples (cps)
R7780	653958	147524	91747	2179.8 ± 2	185.9 ± 1	20.0 ± 0.6
JSR14 run 1	652520	145505	90452	2175.1 ± 2	183.5 ± 1	20.3 ± 0.6
JSR14 run 2	654138	146875	90977	2180.5 ± 2	186.3 ± 1	21.6 ± 0.6

CONCLUSIONS

CAEN has developed the R7771 and R7780 devices, both capable to provide time stamp lists of events with multiple inputs, 32 and 8 input channel respectively. R7780 module combines also the functions of counter, neutron coincidence and multiplicity analyzer.

The laboratory tests with nuclear sources show that the analysis results obtained by the device when it works in UNATTENDED and ATTENDED mode are consistent between themselves and in very good agreement with those obtained from the Canberra JSR-14 module. Furthermore, the tests show that the new R7780 firmware analysis algorithm is very reliable and reproduces the same results as obtained from the JSR-14 and from the original R7780 software algorithm.

REFERENCES

[1] INCC Software Users Manual: http://lib-www.lanl.gov/la-pubs/00326587.pdf