Realizing Real-Time Capabilities of an Embedded Control System for Fast-Neutron Scintillation Detectors

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***Abstract*–Scintillation detectors offer a single-step detection method for fast neutrons and necessitate real-time acquisition, whereas this is redundant in two-stage thermal detection systems using helium-3 and lithium-6. The relative affordability of scintillation detectors and the associated fast digital acquisition systems have enabled entirely new measurement setups that can consist of sizeable detector arrays. These detectors in most cases rely on photo-multiplier tubes which have significant tolerances and result in variations in detector response functions. The detector tolerances and other environmental instabilities must be accounted for in measurements that depend on matched detector performance.**

This paper presents recent advances made to a high speed FPGA-based digitizer technology developed by Hybrid Instruments Ltd (UK) and Lancaster University (UK), with support from the European Joint Research Centre (Ispra) and the International Atomic Energy Agency (Vienna). The technology described offers a complete solution for fast-neutron scintillation detectors by integrating multichannel high-speed data acquisition technology with dedicated detector high-voltage supplies. This unique configuration has significant advantages for large detector arrays that require uniform detector responses. We report on bespoke control software and firmware techniques that exploit real-time functionality to reduce setup and acquisition time, increase repeatability and reduce statistical uncertainties.

I. INTRODUCTION

TYPICAL fast neutron detectors are liquid scintillators, 4-He based noble gas detectors and plastic detectors. Fast neutron detectors differentiate themselves from one another by their ability to discriminate neutrons and gamma rays based on pulse shape and their sensitivity.

Plastic and organic liquid scintillators are often used for detection of fast neutrons because of their fast response, sensitivity to fast neutrons and modest cost. Coincidence counting applications benefit from fast response detectors particularly where the ratio of real to accidental coincidences can have a significant impact on the statistical precision of the measurement. The coincidence window for assay applications that utilize scintillators with response times of a few nanoseconds is typically governed by the dynamic range of the neutron flight time (tens of nanoseconds) and depends on the distance from the source to the detector, neutron energy, and cross section of the material to traverse. Conversely, coincidence counting systems that thermalize fast neutrons prior to detection (e.g. helium-3 based detection) are dominated by the dynamic range of the time (tens of microseconds) needed to moderate the neutrons [1]. Moreover, the thermalization of fast-neutrons scrambles information on the original energy, direction of travel, and the time of emission. The detection of fast neutrons that retain this information is the prerequisite for many new and interesting applications [2].

The high gamma sensitivity of organic scintillators is a major disadvantage in non-destructive assay applications. Furthermore, detection probabilities for neutrons and gamma rays are similar, and in some cases the gamma component can even dominate. This, together with inadequate distinction of event types through pulse-height spectra analysis resulting from mono-energetic radiation, means pulse height is an unreliable measure for particle classification [1]. It is therefore the pulse-shape features, of certain organic scintillators, that are exploited to distinguish between neutrons and gamma rays.

In addition, the significant tolerances of the gain of photo-multiplier tube (PMT) technology means fast neutron assay would benefit from controllable high-voltage (HV) detector supplies integrated with the digital acquisition electronics. A hardware arrangement of this sort affords a means for gain control with feedback and is necessary for convenient matching of detector responses.

The technology presented in this paper is designed specifically to analyze pulse shape and distinguish events arising from fast scintillators in real time. This paper describes the current status and more recent developments to the technology and provides a review of the novel measurements achieved as a result.

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Fig. 1. The front panel of the quad-channel mixed-field analyzer (model no. MFAx4.3) [3].

II. Current Status of the Technology

The Hybrid Instruments Ltd. Mixed-Field Analyzer suite consists of a single channel (MFAx1) and quad-channel (MFAx4) high-speed digitizers. In this section we focus and report on the current status of the quad-channel digitizer, however, besides the obvious difference in channels available, described functions are consistent across the suite.

Fig. 1 shows the quad-channel MFAx4.3, the ‘point-3’ indicating the current version of the technology. All inputs and outputs (IOs) are accessible from the front panel and include signal input, HV supply, two TTL outputs per channel, Ethernet port, RS-232, power supply, JTAG, activity LED indicators, and power switch. The analyzer shown measures 350 mm x 260 mm x 110 mm and weighs 4.6 kg. Earlier renditions of the technology are reported [3], [4].

The technology is compatible with most legacy fast liquid scintillation detectors (BC510, NE213 and EJ301), low-hazard EJ309 and plastic PSD scintillators (EJ299). Many of the studies summarized here used the fast organic scintillation detectors supplied by Scionix (The Netherlands) based on the EJ309 liquid scintillant (Eljen Technology, TX, USA).

The MFAx offers two output data streams; 1) the Transistor-Transistor Logic (TTL) digital outputs (two per input channel) for real-time, high throughput processing, and 2) the Ethernet port for direct PC interface and use of the graphical user interface (GUI) software environment. The second method is primarily used for system diagnostics and setup as only a proportion of the data processed is transmitted over Ethernet, processed and presented within the GUI.

There are two main distinguishing features of the MFAx, the first is the ability to perform real-time PSD at high throughput rates. The PSD algorithm [5]–[7] is implemented directly and entirely in VHSIC Hardware Description Language (VHDL) that executes on the FPGA processing core. Dedicated TTL digital output channels are used to indicate discriminated event types. Crucially, the incident events and the associated TTL outputs are synchronized in time (i.e. the time lapsed from a trigger event to the digital output is normalized and previously reported as between 400 ns and 500 ns (depending on the algorithm implemented), and with a timing jitter of less than 6 ns. The preserved time information of the digital outputs can then be analyzed using proprietary hardware. The PSD algorithm is implemented from several custom VHDL components which are able to function independently and in parallel to one another. This arrangement means that early stage components within the algorithm are re-armed and ready to process data even before the entire algorithm for an event has completed. Thus, discrimination rates of up to 10 million pulses per second (MPPS) on the single channel model and 3 MPPS per channel on the quad-channel can be achieved.

The second unique feature is the close integration of controllable HV supply per high-speed digital input channel. This unique hardware embodiment means real-time data can be analyzed by the software and used as feedback to auto-adjust detector response based on supplied HV.

In summary, the true power of this technology is harnessed when the high-speed processing provided by the TTL outputs are utilized. With this arrangement, data at rates of up to 12 MPPS can be processed by a single MFAx4.3 and therefore, acquisition time can be reduced significantly whilst still maintaining adequate statistics. In some cases, this is the difference between days of acquisition, terabytes of data, and many more hours of post-processing compared to a few hours of measurements and instantaneous results (e.g. [8]).

III. Recent Developments to the Technology

Recent firmware and software development means that the MFAx hardware can now easily be configured to stream either PSD data or pulse height data via Ethernet to a host PC. When the device is configured to PSD mode 32-bit of data are streamed. These data are constructed of a 2-bit channel identifier, a 2-bit event type, and two 14-bit long and short integral discrimination metrics. When configured to pulse height mode 32-bit of data are also streamed, consisting of a 2-bit channel identifier, a 2-bit event type, 16-bit unspecified, and a 12-bit baseline-corrected pulse height.

When configured to pulse-height mode the software automatically configures to display multi-channel analyzers (MCA) to report pulse height spectra (PHS). Conveniently, in this mode, PSD is still performed and the event type is attributed to the event’s data packet. This allows for PHS for combined, gamma only, and neutron only data to be obtained. Scintillator-based neutron spectroscopy may have some challenges due to the random nature by which the neutron energy is deposited in the scintillant, nevertheless neutron spectroscopy afforded by this feature has prompted further investigations with in our research group.

The MCA mode facilitates the user to quickly and easily adjust HVs to match the responses of multiple detectors based on the PHS. Typically, this would be performed by aligning the response from multiple detectors exposed to a gamma only source with a defined photon peak (e.g. Cs-137). For a large number of detectors an auto-calibration utility in the software environment has been developed to achieve even faster setup times for experiments where consistency across detector response is essential. Fig. 2, Fig. 3 and Fig. 4 demonstrate the effect that a 100 V step change on the detector’s HV has on the detector gain by comparison of Cs-137 PHS.

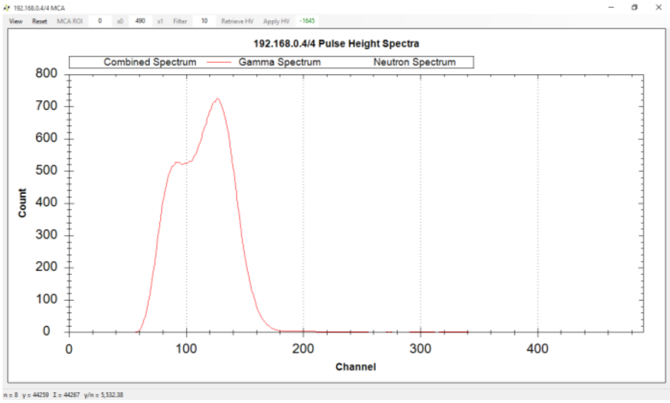

Fig. 2. Cs-137 spectrum with 10-point FIR filter acquired from an EJ309 liquid scintillator operated with a negative bias of 1645 V, the photon peak is located at about channel 130 on the MCA.

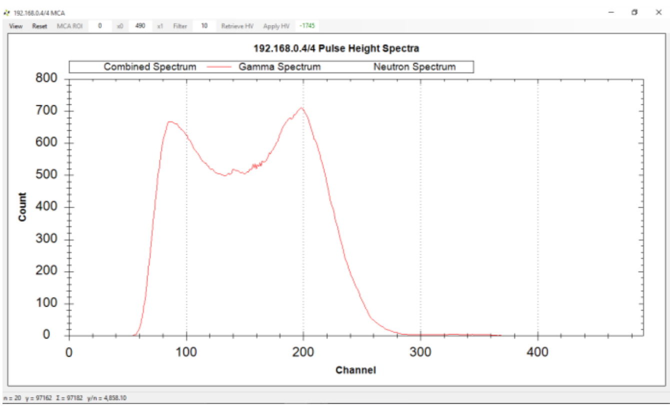

Fig. 3. Cs-137 spectrum with 10-point FIR filter acquired from an EJ309 liquid scintillator operated with a negative bias of 1745 V, the photon peak is located at about channel 200 on the MCA.

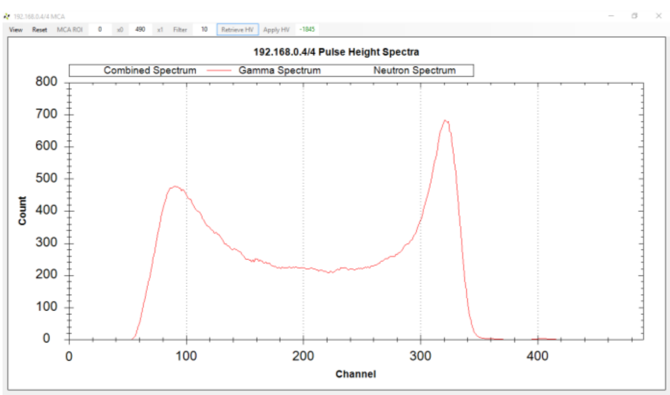

Fig. 4. Cs-137 spectrum with 10-point FIR filter acquired from an EJ309 liquid scintillator operated with a negative bias of 1845 V, the photon peak is located at about channel 320 on the MCA.

The MCA software interface now offers a real-time embodiment of a finite-impulse-response (FIR) filter. The smoothing effect that this has on the PHS is very beneficial, for both human and computer interpretation, in better determining the MCA channel number of the photon peak. The magnitude of the filter can be set at any time whilst acquiring data, and the filtering influence is displayed in real time. For convenience and to fully exploit the purpose of this function, the user is now also able to control the detectors' HV directly from the MCA interface. This provides an indication of the result of a newly applied HV on the PHS within minutes (typically the time taken for the HV to stabilize and acquire an adequate data set). Fig. 5 and Fig. 6 show an unfiltered and 20-point filtered gamma-only pulse-height spectra of Cs-137 data acquired from an EJ309 liquid scintillator. The menu bar at the top of the MCA interface clearly displays options to focus on a region-of-interest (ROI), apply a filter, retrieve the current HV, and apply a new HV setting.

One of the most significant recent advances is the shift from all configurable settings being stored only in the hardware's memory to also having a replica of settings stored in an .INI configuration file, which typically resides on the host PC.

Previously when the software was executed it sent a command to the hardware requesting all settings to be downloaded to the PC-based software where the user could then view, edit and upload revised settings. This design requires no synchronization of variables, but requires the user to carefully document the settings as no history is kept. Furthermore, it limits the ease to quickly set-up other hardware with the same settings. Hardware can operate independent of the host PC, even from a power cycle as settings are uploaded from the hardware memory during the boot sequence.

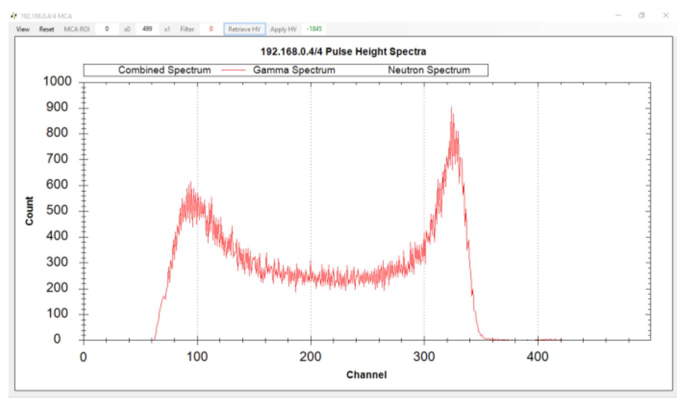

Fig. 5. The multi-channel analyzer (MCA) graphical-interface with unfiltered gamma-only pulse-height spectrum of data acquired from an EJ309 liquid scintillator positioned 45 mm from a Cs-137 source.

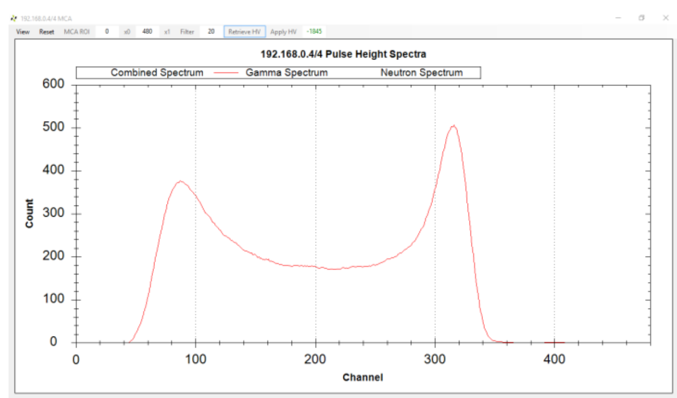

Fig. 6. The multi-channel analyzer (MCA) graphical-interface with 20-point moving-average filtered gamma-only pulse-height spectrum of data acquired from an EJ309 liquid scintillator positioned 45 mm from a Cs-137 source.

With the new design, configuration files are automatically saved and dated and can be quickly transferred to another PC and uploaded to another hardware device. However, synchronization of settings becomes an issue using this method. The challenge is in knowing if the settings viewed in the software environment obtained from the configuration file are identical to the settings stored in the memory of the hardware. This issue is addressed by a more comprehensive initialization procedure.

An Ethernet cable and PC can be connected to the hardware at any time during its operation. When the software is executed PC ARP requests are sent asynchronously to all potential IP addresses. Once the hardware responds with an ARP reply, the software is aware of what MFAs are online. Using transmission control protocol (TCP) the PC sends a request command for all settings to be downloaded from all MFAx hardware connected. Once the PC-based software has received all hardware settings the configuration file loads from wherever it resides on the PC. If a conflict exists between the detected hardware and the expected hardware, as defined by the configuration file, then the user is informed and presented with four option; 1) Rescan for hardware changes, 2) Target alternative configuration file, 3) Create new configuration file based on current hardware settings, or 4) Exit application. Following this, the settings retrieved from the configuration file are compared to the settings downloaded from the hardware. If discrepancies exist between settings the user is informed and presented with four options; 1) Upload new configuration file settings to hardware, 2) Target alternative configuration file, 3) Create new configuration file based on current hardware settings, or 4) Exit application. The software is fully compatible with any number of connected MFAx devices from the suite, and will automatically adapt to represent the hardware that is registered as online.

IV. A Review of the Measurements

Many measurements have been performed and reported that use the MFAx, these include work by the IAEA, JRC, PSC, NPL, and Lancaster University. In the majority of these reports the users have exploited the high throughput, real time, TTL data streams and integrated detector HV supplies, whilst also benefiting from many of the other inherent features supported by the software environment.

Suggestions and examples of successfully implemented proprietary hardware for the analysis of the TTL outputs are; 1) a National Instruments Industrial Controller. The controller includes an FPGA-based data acquisition card and custom-built analysis software developed in LabVIEW [9], [10]. 2) custom-made de-randomizing electronics (Los Alamos National Laboratory, NM) connected to a JSR-15 multiplicity shift register (Canberra Industries Inc., CT) [11]. 3) a bespoke 32-bit, 64-channel, binary counter with a serial PC interface (Lancaster University, UK) [8], [12]. In addition, the commercially available multichannel Pulse Train Recorder (model: PTR-32) by the Institute of Isotopes (Hungarian Academy of Sciences or Energia, Budapest) is also fully compatible with the MFAx technology, and offers an embedded de-randomizing function.

The technology has been used with fast organic liquid scintillators in applications for imaging an operational TRIGA mark II nuclear reactor [8], and to locate radioactive sources in three dimensions [13]. It is also used in a study on the comparison of collimator geometries for imaging mixed radiation fields [14], imaging using a narrow collimator aperture [15], and single detector imaging of mixed-field radioactivity [16]. The systems have been operated with large detector-arrays for time-of-flight, neutron spectroscopy, and multiplicity analysis utilizing a custom-made multiplicity analyzer [17], [18]. It has been employed for real-time monitoring for non-proliferation and nuclear safeguards [9], [19]–[22], and highlighted the potential use of low-hazard scintillators [22]. The system described has enabled real-time active interrogation of low-enriched uranium fuel assemblies [23], [24], and fast neutron coincidence assay of plutonium [10], [25]. The technology has been implemented in a liquid scintillator neutron coincidence collar (LS-NCC) in a joint collaboration between the IAEA, JRC and Hybrid Instruments Ltd. for use in nuclear safeguards applications [26]. Other investigations have looked at the impact of angular orientation on count rate and PSD performance of liquid scintillators, and used in studies with gated plastic EJ299-33 scintillators.

The technology has been used in the following highly-relevant environments;

- The laboratories at IAEA Headquarters, Vienna, Austria.
- The IAEA Seibersdorf laboratories, Austria.
- The Atominstitut, Vienna, Austria.
- The laboratories at the Karlsruhe Institute of Technology, Germany.
- The Rokkasho Nuclear Fuel Reprocessing Facility, Japan.
- The AREVA MOX fuel manufacturing plant, France.
- The safeguards laboratories at the JRC in Ispra, Italy.

V. Conclusions

The technology described boasts several functions that have enabled novel and yet highly relevant measurements. These functions include;

1. Real-time PSD outputs that are time synchronized with less than 6 ns jitter, at throughputs of more than 106 events per second.
2. Auto-calibration of the HV settings to ensure gain consistency across detector arrays, including real-time visualization of the corresponding pulse-height energy spectra.
3. Real-time visualization of the PSD data and discrimination parameters.
4. Digitally-controlled, embedded, highly-stable HV supplies.
5. Compatibility with the high-throughput multiplicity analyzers.
6. Extensive research with many EJ309 detectors of varying geometries.

Inevitably these desirable capabilities have supported significant real-time measurement of fast neutrons for many radioactivity assay and safeguard applications.

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