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Development of a Digitising Data Acquisition Pipeline for Next Generation Pulsed Muon Spectrometers

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Abstract. The next generation of muon spin spectrometers at the ISIS pulsed source are being developed to make efficient use of the increased source intensity. They will provide a transformational improvement in counting rates: 'Super-MuSR' will be the first of these instruments, capable of counting at ≈1 G·event·hr^{-1}. Key to delivering this capability is the development of highly pixelated, high density detector arrays that cover an appreciable solid angle, with each detector element optimised for counting at very high data rates. A series of 'firsts' are planned to optimise individual element count rate capability, where analogue waveforms recorded from SiPMs are fully digitised and processed using digital signal processing (DSP) methods at either software or firmware level. Full raw-signal digitisation will be achieved using the Xilinx Zynq® UltraScale+™ series of 'system on a chip' operating with ADCs capable of 1 GHz sampling, data handling using event streaming technology, and DSP to provide novel data correction techniques. We will discuss our concept and present preliminary results. Our prototype digitising data acquisition system, which is key to implementing a 'digital data pipeline' (DDP) is presented.

1. Concept & Motivation

Our concept is a data pipeline that fully utilises digital signal processing (DSP) techniques and modern computing power to extract as much information as possible from the muon decay histograms. Raw detector signals will be recorded with high fidelity, processed in situ and saved to disk in an infrastructure where software tools can analyse the signals in real-time. Our infrastructure aims to be holistic, capturing all information about the measurement, the spectrometer and sample environment alongside the digitised detector signals.

The new 'Digital Data Pipeline' (DDP) is in part motivated by the specification of the next generation of pulsed muon spectrometers, which require performance well beyond that provided by traditional detector and data acquisition solutions. For example, the proposed ISIS instrument Super-MuSR [1] has a specified count rate capability of ≈1 G·event·hr^{-1}, counting the ≈10^4 muons delivered to the sample in just a few 10s of nanoseconds after each accelerator pulse. The muon decay histograms should be free from dead time distortion, caused by event pileup. Recently developed muon spectrometers have exploited small compact photon sensors, generally referred to as silicon photomultipliers (SiPM). In addition to offering fast timing and field insensitivity [2], their size allows highly pixelated arrays to be developed to attain high-rate capability at a pulsed source [3]. The benefit of pixelation is somewhat offset by the long recovery time of SiPMs when compared to traditional photo-multiplier tube technology. To deploy SiPMs, we consider it a prerequisite to provide signal processing [2] to attain high-rate capability.

In this paper we refer to an '*event'* as the voltage signal generated in the detector when the detected decay product of the muon (a positron or electron) transits the scintillator. This signal is typically around 10 ns wide at FWHM. A '*trace'* is the voltage signal from the detector, measured from just before the muon pulse arrive, until there are likely no muons left to decay. This is currently about 32 μs for the existing instrumentFigure 1, but will naturally extend in duration as flux is increased. A single accelerator pulse and associated '*trace*' is known as a '*frame*'. Traces will typically contain upwards of tens of events, although this depends both on the degree of detector pixelation and the incident muon rate after collimation of the beam spot. At ISIS the muon pulses are delivered 40 times every second: four pulses are delivered at intervals of 20 ms followed by a longer interval of 40 ms. The new DDP will use the 19.68 ms idle time to process and stream the data. The pulse structure, and a single trace containing a few events is shown in Figure 1.

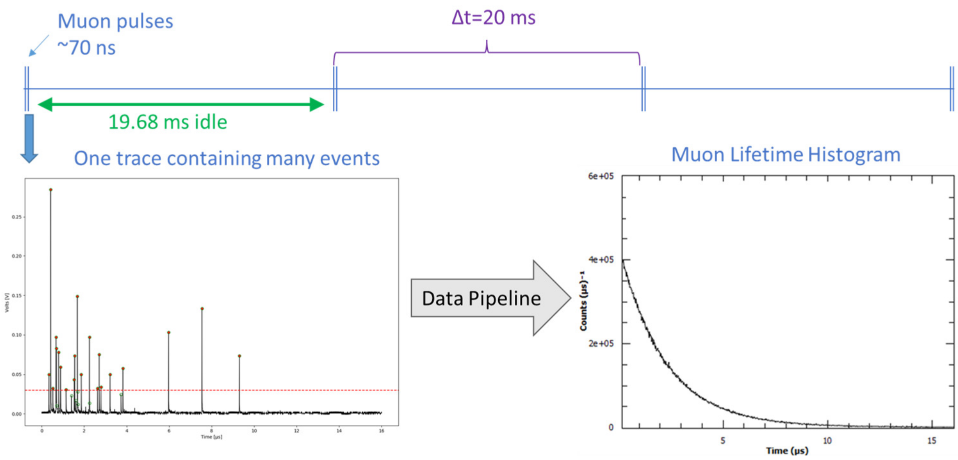

Figure 1. Schematic of the ISIS pulse delivery, showing one trace. Many muon events are detected, with only those above a pre-defined threshold (red line) being counted. The data pipeline processes this data into muon decay histograms.

This approach is likely to offer benefits to a wide range of pulsed muon source instruments, either through increasing their rate capabilities or by introducing the possibility of sophisticated data processing, as described below.

2. Context and Principle

ISIS operates five muon spectrometers within its user programme, EMU, MuSR, HiFi, CHRONUS and ARGUS [3]. EMU, MuSR and HiFi operate on the 'south side' of the muon target. To ensure the data is free of uncorrectable dead time distortion, these instruments currently accept just a tenth of the available flux. All detector systems have a time after each detection where they are paralysed and fail to register further events until the system has 'recovered'. This 'dead time' results in distortion of the data which, while correctable at comparatively low data rates, can be difficult to treat if the detector system is overwhelmed by the rate of incoming events. A muon measurement is particularly challenging as the signal of interest is a small modulation on top of the 2.2 μs mean lifetime of the muon. Consequently, the detector must be able to instantaneously and accurately count very high data rates immediately following implantation of the muon pulse. Figure 2 shows a muon decay histogram built up by combining many pulses of muons together. High and low incident fluxes, controlled by beam collimation, are compared. The low flux measurement equates to approximately one detection event per pulse per detector. At this rate, the measurement can be considered to be free of dead time effects, giving a histogram well described by the exponential decay associated with the muon lifetime. At high flux dead time effects are readily observed. Deviation between the expected exponential decay and that measured at early times indicate a significant number of missed events owing to positrons arriving when the detector is paralysed from earlier hits. Key to improving the count rate capability is improving the detector response during this early time 'pileup', an effect that is most severe immediately after muon implantation. Any dead time distortion disproportionately affects the data at early times where rates are very high, which, in turn, negatively impacts on the modelling and scientific understanding of the results.

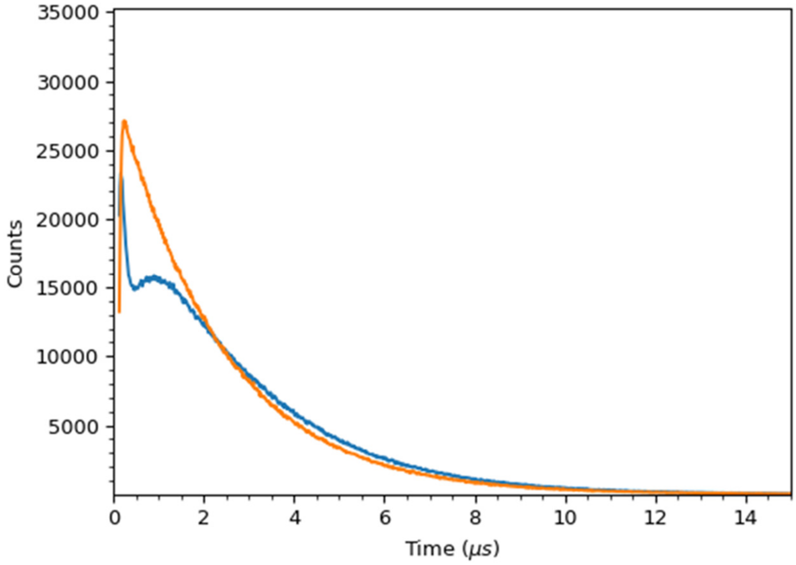

Figure 2. Muon decay histograms measured at low (orange) and high (blue) incident muon fluxes. The distortion at early times at high data rates due to dead time effects is marked.

Generally speaking, to minimise the effects of detector dead time two strategies can be pursued. Firstly, the intrinsic signal speed (rise and fall time) can be increased by selection of optimised components, such as fast photomultiplier tubes and fast organic scintillators. Secondly, the pixelation of the detector array can be increased, sharing the flux across a greater number of independent channels. In fact, both strategies are typically pursued in parallel; however, each has a limit, where further optimisation is of diminishing return. For example, if pixelation is increased to the point where individual elements are unreasonably small, the detector may suffer excessive multi-counting.

Here we propose a novel way to minimise the effects of dead time beyond that typically possible using conventional event discrimination. The principle is as follows: Provided that the raw detector signals can be suitably sampled and recorded for each complete muon trace, it should then be possible to use DSP techniques to extract significantly more information from the data. Overlapping muon events (pileup) can be individually identified, enabling the detector system to run at a significantly higher rate when compared to systems using fixed-threshold, leading edge analogue electronics to identify valid events. Figure 3 illustrates the difference between a peak-finding approach and the fixed threshold discrimination method typically used.

All of the muon spectrometers at ISIS use analogue signal processing (ASP) to count the events. A leading edge discriminator is triggered and counts an event for a signal that rises above a fixed voltage; the discrimination threshold. To register the next event, the discriminator must rearm (typically sub ns) and the signal must fall below the threshold. Any additional events between the initial trigger and the re-arm are not counted, despite these additional events being superimposed on top of previous events, forming clear peaks to the eye. The detector is in pileup, appearing to be 'dead' until the signal falls. Figure 3 depicts the situation with real data collected from the EMU spectrometer. [LEFT] and [MIDDLE] model a leading edge discriminator, as is currently in use. The system counts the event upon crossing the threshold (black ×) and re-arms once it is below (red ×). The system accurately counts all events at low rate [LEFT] but fails to register multiple events once the rate is increased [MIDDLE].

Figure 3 [RIGHT] illustrates the advantage of DSP methods, where the entire trace can be analysed and all peaks associated with events are found.

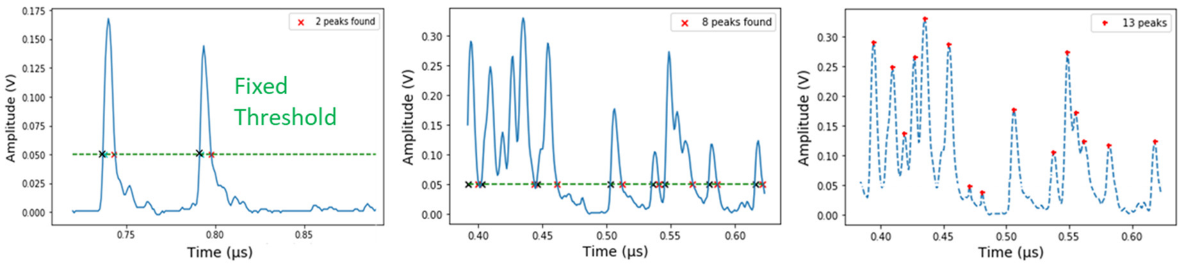

Figure 3. Three examples of the signals output from a muon-spectrometer detector. At low rate a fixed-threshold analogue discriminator is sufficient to detect all events, in this example there are two. The middle plot illustrates how the fixed-threshold electronics 'miss' hits, despite them being easily identified by eye in the trace. The right plot shows how the same trace would be sampled using a digitiser, saved to disk and analysed to 'find' the peaks. In contrast to the fixed-threshold electronics where only 8 events are recorded, 13 events are found using this new method. The two events associate with small amplitude peaks around 0.475 ms could still be considered below threshold and rejected; however, advanced data processing might be used to search for correlated counts in another detector channel, which may indicate multi-counting.

3. Conceptual Benefits

While motivation for the DDP has come from the ambition to improve the count rate capability of the ISIS muon spectrometers, a host of additional benefits are likely to follow through the introduction of sophisticated data processing. Four key areas are categorised and discussed as concepts, as experimental validation is ongoing work.

3.1. DSP for Count Rate Improvement

A full discussion of the merits of signal processing techniques, be they analogue or digital, is beyond the scope of this paper. Attaining higher count rates using signal processing does not necessarily require digitisation. For instance, analogue signal processing techniques, such as 'pole-zero' corrections will improve count rate capability. However, this approach regularly requires careful set-up (typically by manual adjustment of a potentiometer in the differentiator circuit) otherwise signals may contain over or undershoot, resulting in a multicomponent dead time distortion that is hard to correct.

DSP offers a wide range of peak finding techniques, from a simple 'highest value' finder to full peak deconvolution, an example of which is shown in Figure 4. The optimum choice of technique for signal processing depends on several factors, ranging from the computational resource available to specific experimental factors. Some of these methods can be, and likely will be, applied in real-time. Application of quick DSP can be incorporated in both the software and firmware side of the data pipeline. However, the DDP concept is not only to apply DSP in real-time, it is both digitisation and storage of the full raw traces to enable later application of advanced data processing techniques.

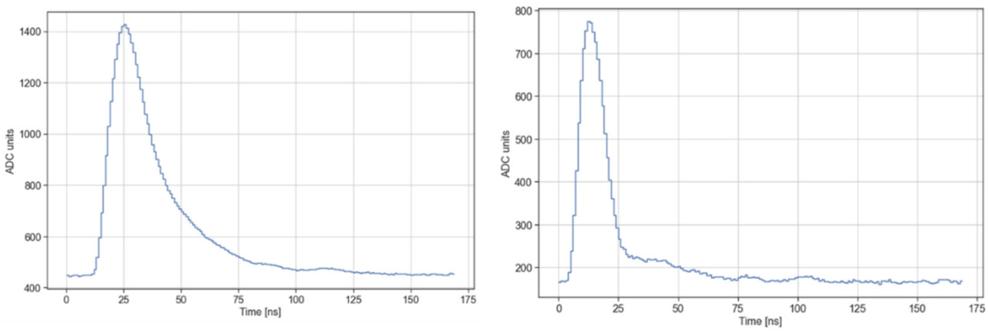

Figure 4. [LEFT] A digitised detection event from a SiPM. [RIGHT] processed using a peak deconvolution method. The FWHM is approximately halved (to 10 ns) for this detector. Data was taken using the prototype NI DAQ121, sampling at 1 G·Samples·s^{-1}.

Saving the complete raw trace from each detector means computationally intensive techniques can be applied at a later stage to further improve count rate capability. Examples include least-squares fitting of the whole trace, through to the application of machine learning algorithms. Multiple DSP techniques can be applied to the stored data, depending on the parameter of interest. An example would be the application of interpolation, to provide timing resolution beyond that of the digitisers' sampling rate. Temporal timing improvements will be required for Super-MuSR, which is the first ISIS instrument to deploy technology to time-slice the muon pulse generated by the ISIS accelerator for improved timing resolution.

3.2. Data Reduction and Correction

Recording the traces to disk and post-processing the data brings about all the benefits associated with 'event mode' data collection. For example, the ability to retrospectively select time intervals of data within a measurement can be used to deal with issues such as equipment failure. However, the time interval can be as short as a single frame, to the length of the full experiment. With this flexibility, numerous applications emerge, such as 'period mode' functionality, where the sample environment is periodically alternated between fixed conditions, to in situ studies, such as diffusion measurements [4], which evolve on a dynamic timescales.

Recording and storing every pulse from every detector from every frame for the duration of the experiment opens up new data correction options. For example, a 'multi-count' correction in which the time of detection and peak shape is used to uniquely assign correlated counts across the detector array to a particular detector would be of great benefit. Field-dependent multi-count corrections are possible. This is a particularly difficult problem to correct for in any other way, as the severity of multi-counting is dependent on the applied field in two ways. Firstly, the field modifies the positron trajectory, causing it to spiral through multiple detectors. Secondly, the energy deposition is changed as the path-length through the scintillator will be different. Consequently, events that may have been above the discrimination threshold and counted in zero field may no longer be registered. This effect is observed by changes in the energy deposition spectra, which can be extracted from the stored traces at any time. Combined with the temporal information, this will provide a metric for understanding the severity of multi-counting.

3.3. DSP for stability

Here we consider a class of 'second order' corrections to the data. The traces will have already been analysed with fast DSP to produce histograms in real-time. Subsequently, and likely after the experiment is complete, each trace can be re-analysed and corrections applied for effects that may have evolved over the course of the experiment. An important example, particularly for an array based on SiPMs, is correction for the drift in the gain of the detector due to temperature changes.

Gain-corrections can be applied provided there is a diagnostic to measure and calibrate against. There are a number of ways this can be achieved. In the case of the SiPMs being used on Super-MuSR, the noise profile can be used as a diagnostic as the separation between peaks in the charge (peak integral) histogram is proportional to the SiPM gain. The noise profile of a Hamamatsu S13360-3025 SiPM is shown in Figure 5, measured with the Nuclear Instruments DAQ121. The characteristic multi-peak shape is due to the micro-cell structure of the SiPM, leading to a quantised output.

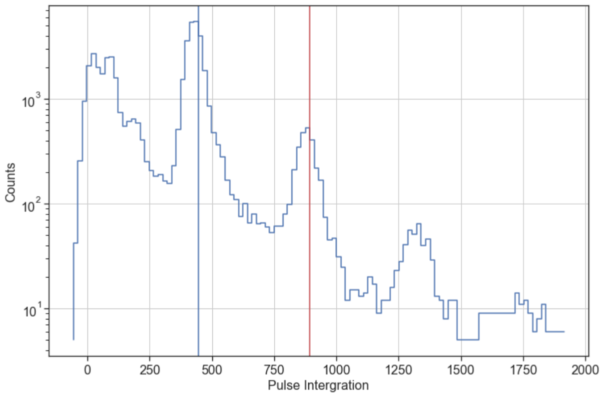

Figure 5. Multi-cell noise profile of the SiPM. The first peak is the noise pedestal, an artefact of charge integration. The following peaks are associated with one, two, three and four cells being discharged simultaneously due to cross talk.

3.4. Diagnostics and Fault Finding

Correction of long-term detector 'aging' effects, where the signal output drifts over time should be possible. For example, the scintillator may produce less light if exposed to humidity or heating cycles, gradually reducing the pulse amplitude. Being able to monitor the detector performance both in real-time and historically will ensure detector performance is optimised.

Being able to look at the raw signal is extremely useful for fault finding, particularly as future spectrometers are likely to have a very large number of detector channels, making it impractical to monitor performance and investigate faults by manually plugging in an oscilloscope. Faults such as cabling problems, intermittent noise and correlated interference with other instruments will be readily identifiable.

3.5. Other potential applications of the DDP

In some detector designs, the signal shape is proportional to the deposited energy of the positron and therefore directly related to its asymmetry. This class of 'calorimetric' detector is not currently in use at ISIS although further proof of concept studies are planned. Determining the positron energy should allow a signal weighting scheme to be applied to enhance the overall asymmetry measured.

4. Count Rate Improvements - Proof of Principle

To demonstrate that count rate improvements can be realised using DSP methods, a Proof of Principle investigation has been carried out using the instrument EMU [5]. A commercially available high sampling rate digitiser hardware [6] and in-house software was used to collect and analyse raw traces from the instrument's Hamamatsu R5505 PMTs over a range of incident fluxes. The goal was to quantify the improvement in count rate capability provided by DSP peak detection [7] when compared to the existing analogue signal processing using the existing CAEN V895 leading edge discriminators (abbreviated ASP). Our metric for quantifying count rate capability is based on the severity of the dead time distortion as a function of incident flux. The offset between the two trends is the mapping from

ASP to DSP, with the constraint of 'equivalent' dead time distortion. This relative approach is more robust than fitting and extrapolating dead time metrics as no one dead time model fits well across the large change in flux and with different data pipelines, leading to ambiguous results.

The severity of dead time distortion was quantified as the running integral of the difference between the measured counts and the expected 'true' data. This becomes our dead time metric in Figure 7. The true data trend was determined by fitting a single-component exponential late in the acquisition, where the detector system has recovered sufficiently to be considered distortion free. Figure 6 shows an example of fitting the muon decay at late times (red highlight), with back extrapolation to the first good data. The data is collected as counts, but normalized into a count rate by dividing the counts by the histogram time bin width. This rate, typically in the MHz range is the instantaneous count rate of the detector at a given time. To be clear, any one trace contains just a few events; the histogram typically combines 10 to 100 thousand frames, giving the temporal distribution of events within a trace.

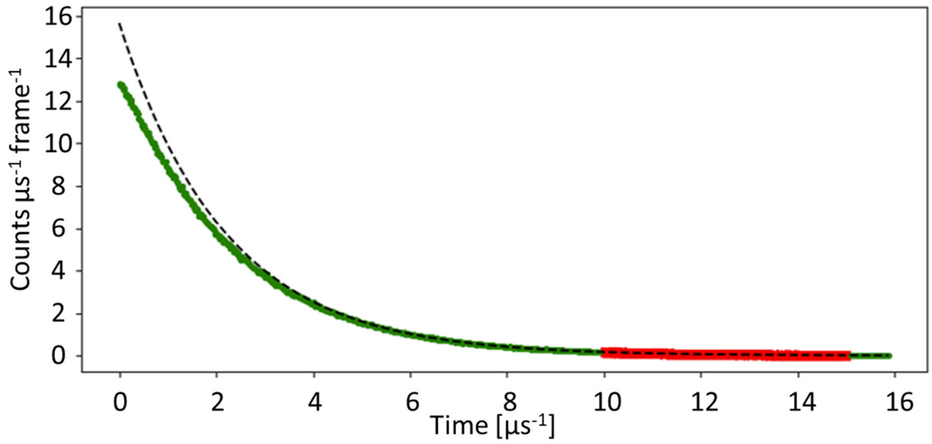

Figure 6. Muon decay histogram fitted at late times (red), in a region where the rate is sufficiently low for the data to be consider distortion free, with the fitted curve back extrapolated to reveal dead time distortion at early times. The fit becomes the 'true' data set in our analysis.

The measured and fitted count rate data (vertical axis) are plotted against each other to produce 'measured Vs true' plots, consistent with those found in the literature [8] [9]. Figure 7 [LEFT] shows the fitted and measured data plotted against each other, along with the y=x line, the theoretical response of a perfect detector system, free from dead time effects. The running integral of the difference between the y=x line and the detector data are used to parametrise the effects of dead time in the system. Figure 7 shows this parameterisation as a function of rate for both the DSP and ASP methods.

A high purity silver plate sample was measured at room temperature at zero magnetic field (corrected to better than 0.01 G on each axis) to ensure the data was free of any precession or relaxation. Data shown in Figure 7 was collected at maximum flux, an order of magnitude greater than typically used for experiments where it is essential to ensure the data is free of dead time distortion. At this high flux severe deadtime effects are observed. The measurements were made using both DSP and ASP acquisition systems and compared.

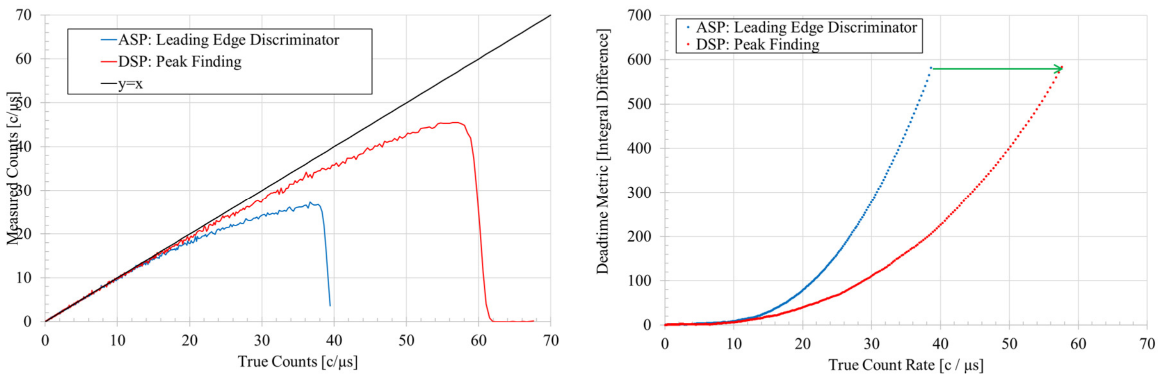

Figure 7. [LEFT] a 'measured Vs true plot' showing how the detector performance falls off compared to a perfect detector, shown as the y = x line. The integral of the difference between the measured data and the y = x line is shown [RIGHT]. The horizontal translation between the two data sets gives the count rate improvement under equivalent deadtime distortions.

Figure 7 [RIGHT] can be used to reveal the count rate performance improvements under the condition of *equivalent* dead-time distortion. This is the horizontal difference between the two trends, indicated by the green arrow. The performance gain from DSP ranges from negligible at low flux to a factor of 1.5 at the maximum, where the green arrow is located. This makes intuitive sense, as at very low rate the two methods should behave similarly, while at very high rates DSP identifies more events. At some point this difference will become a constant, when the rate limit for both systems is reached. The factor of 1.5 is a conservative estimate for the rate improvement, as the DSP methods applied were not tailored to muon decay measurements. Peak identification was performed using the 'Peakutils' package [7], which calculates the derivative and identifies peaks above a user-defined threshold. The peak locations are filtered to reject peaks closer than a user-defined separation to avoid erroneous multi-counting of noisy peaks.

5. Implementation of the Digital Data Pipeline

The DDP is under development at ISIS, with each component currently being prototyped and benchmarked. The project scope is far-reaching as it includes everything from the front-end electronics, the digitiser hardware, event processor, and the data streaming platform, to the ensuing data reduction. Each component of the pipeline has required development of new technology. A new class of digitiser was required, capable of high-speed sampling and data streaming. Data streaming has been implemented using Apache Kafka [10], which runs on the digitiser. To ensure the digitised data streamed can be synchronized to the experimental conditions (such as sample environment) and to diagnostic metrics from the ISIS accelerator, the ISIS 'status packet' has been developed. This has been accompanied by the development of new data schema, for streaming and storing the combined data.

5.1. Digitiser Hardware

The DAQ121 was developed by Nuclear Instruments to meet the required specification for the ISIS muon spectrometer. DAQ121 uses a 'System on Chip' made by Xilinx (model Zynq UltraScale+). It incorporates a large number of FPGAs (field programmable gate arrays), quad core ARM processors and DDR4 memory into one chip, making it flexible, powerful and fast. A SoC is ideally suited to this application. The FPGA is used to manage the parallel acquisition process, interfacing with the fast (GHz) ADC, implement the pre- and post-trigger buffers using the Ultra RAM embedded memory. The FPGA can be used to calculate noise profiles in real time, as shown in Figure 5 for a SiPM. The computing power provided by the ARM CPU is required to process the signal buffered by the FPGA, with complex DSP algorithms (which are difficult to implement on the FPGA) executing during the 19.68 ms idle time between ISIS frames (as shown in Figure 1). The system prepares the data in a format defined using Google flatbuffers which can then be read out via Apache Kafka or ZeroMQ. Each SoC runs an instance of Ubuntu Linux as an operating system, allowing in situ software to be developed for DSP, data streaming and 'slow control'. Slow control refers to operations such as starting / stopping measurements and acquiring diagnostic parameters such thermometry from attached SiPMs. The system is very flexible, with the user being able to set parameters to control the length of acquisition before and after the muon pulse arrives. All parameters can be queried or set using the ISIS instrument control computer, which uses the ISIS 'IBEX' [11] [12] interface. IBEX is based on the EPICS [13] [14] open source toolkit and interfaces with the system using ZeroMQ [15], an asynchronous network messaging service running on the digitiser.

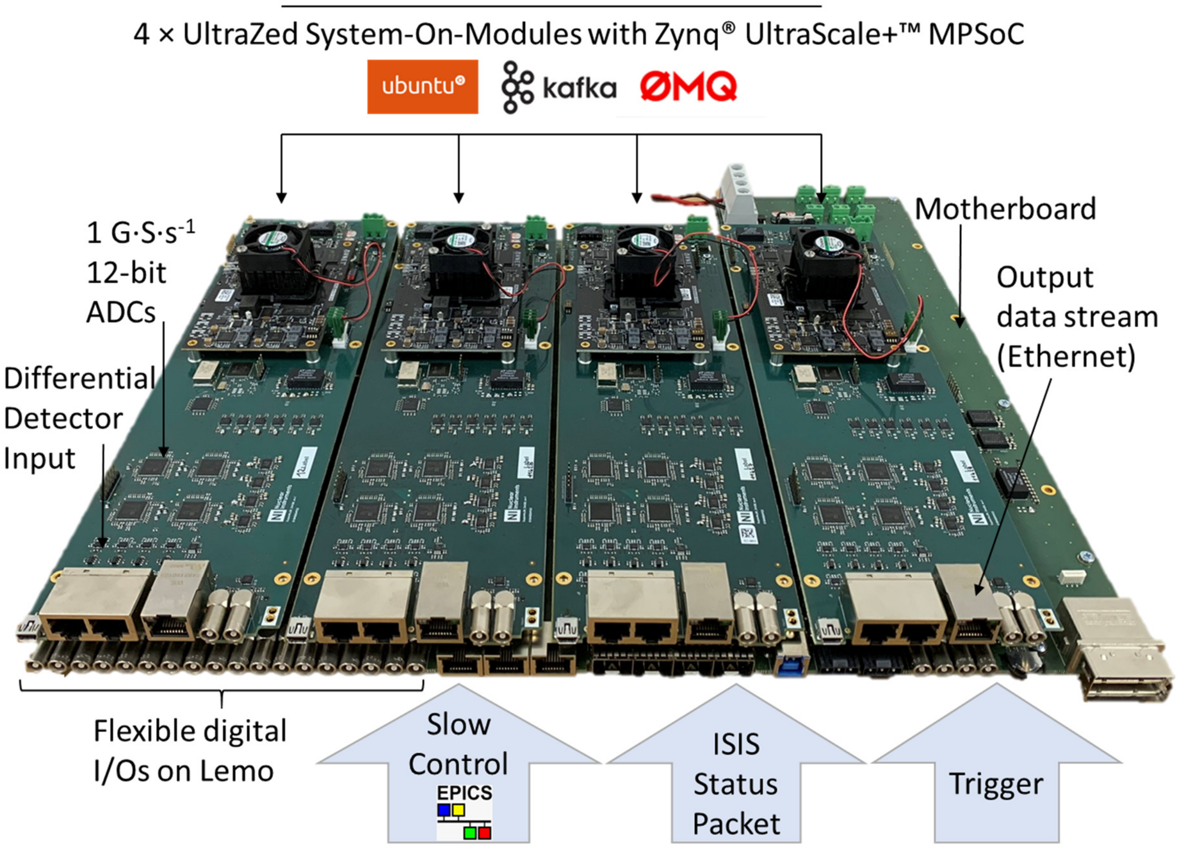

Figure 8. The 32-channel Nuclear Instruments DAQ121, shown without its 19-inch rack-mounted box. The unit has four identical 'digitiser' cards, mounted on a motherboard. The motherboard distributes the ISIS status packet and trigger to the digitiser boards, and provides further flexible digital IO options that are easily configurable by reprogramming the FPGA.

5.2. Data Pipeline

The volume and nature of data produced by Super-MuSR required a novel approach to data acquisition at ISIS, the proposed architecture is similar to the live data streaming approach in development for the European Spallation Source [16]. This approach provides a performant data acquisition framework and flexible/pluggable pipeline for real time pre-processing and visualisation. The general data flow is as follows:

- Each digitiser publishes data encoded in a flatbuffer [17] message to a Kafka broker.
- Data is read from the broker, collated into each frame, checked for consistency and published back to the broker.
- Per frame data is then available on the broker for streaming for visualisation, diagnostic or processing applications, as well as being saved as a NeXus [18] file.

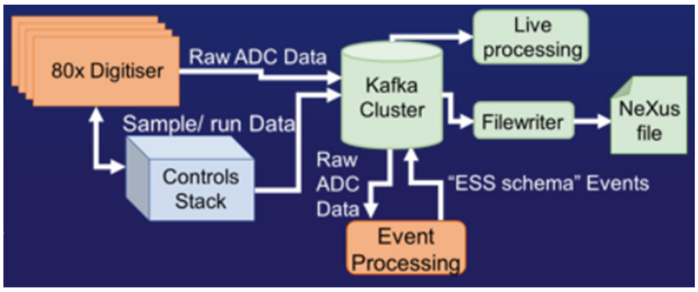

Figure 9. The proposed data schema incorporating the DAQ121 digitiser into an event data streaming service.

5.3. ISIS Status Packet

Each digitised trace needs to be correctly correlated with the 'status' of the equipment associated with the measurement. This is essential for period-mode operation, where external stimuli such as a pump laser are periodically triggered. In this example, two data sets are produced and compared: laser on and laser off. To ensure successful association between each trace and the status of the equipment, a 'status packet' has been defined. It contains all the information relevant to the instrument on a per-frame basis, including a GPS timestamp. Diagnostic information such as beam power (protons per pulse) is also included.

The status packet is input into the digitiser's motherboard which transmits it to each Zynq SoC, where it is folded into the event-mode Kafka data stream. Combining the status packet with the data acquisition in this way ensures that each trace can quickly and efficiently be filtered based on the status of any other piece of equipment on the spectrometer. The addition of the GPS time stamp also allows for external stimuli, such as sample temperature, that are not fed directly into the acquisition system but logged elsewhere to be correlated with the detector data.

6. Conclusions and Future Work

We have demonstrated that the application of a DDP can significantly improve the count rate capability for pulsed muon instruments. A factor of at least 1.5 was measured during tests on an existing ISIS instrument using an optimised PMT-based detector system, and we believe significantly larger gains are likely when SiPMs are substituted as photon detectors. The inherent event mode model of the DDP allows comprehensive post-processing of experimental data to resolve issues with equipment, and this capability is of particular importance for a pulsed muon facility where experiments using complex pulsed techniques (such as laser or RF excitation) or in-operando measurements are likely to employed. We are currently investigating additional benefits that are likely to follow from using a DDP with in-built DSP, including multi-count correction and environmental stability improvements. The efficacy of these corrections will be presented in a future paper.

A prototype system has been developed to implement the complete DDP at ISIS, using a DAQ121 digitiser to process raw traces and stream event data to an Apache Kafka cluster. The full system has been tested off-beam using a beta source with good results. First tests on-beam are planned for late 2022, after the current ISIS shutdown. At this time, we will be able to fully quantify the improvements that can be made with DSP and develop our software roadmap to incorporate key DSP techniques into the automatic data pipeline. This approach will allow users to collect and analyse data in real-time with the best possible DSP processing already applied.

Looking ahead, there are a number of important decisions to be made around the resources required to store the data volumes being generated using this approach. While event-based data will always be available, the current proposal is to store the fully digitised dataset for a short length of time, likely a few months. This will allow users time to complete post-experiment reduction to ensure the best possible results are obtained from experiments.

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