1 Optimization of the National Superconducting
2 Cyclotron Laboratory Digital Data Acquisition System
3 For Use With Fast Scintillator Detectors

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9 **Abstract**

10
11 The Digital Data Acquisition System (DDAS) at the National Superconduct-
12 ing Cyclotron Laboratory (NSCL) has expanded to instrument arrays composed
13 of fast-scintillator detectors. The expansion has motivated the development of
14 software designed to optimize the time- and energy-resolving capabilities of the
15 system, which is a collection of 16-channel FPGA-programmable modules run-
16 ning 12- and 14-bit ADCs with sampling frequencies of 100 and 250 MSPS,
17 respectively. Using the techniques described herein, the time resolution of the
18 DDAS electronics has been substantially improved. For signal amplitudes oc-
19 cupying >10 % the full range of the ADC, the time resolution of the DDAS
20 electronics, measured online, has been reduced to <100 ps and <40 ps for 100
21 MSPS and 250 MSPS modules, respectively. A time resolution of ≈ 350 ps,
22 at 511 keV, between two 38 mm x 38 mm lanthanum bromide (LaBr₃) detec-
23 tors, equipped with Hamamatsu R6231 photomultiplier tubes (PMTs), has also
24 been realized. Similar optimization techniques applied to the DDAS energy-
25 extraction algorithms have yielded energy resolutions below 2 % at 1.33 MeV
26 for both the 100 and 250 MSPS digitizers using the same LaBr₃ detectors. The
27 techniques described in this work are broadly applicable to other digital acqui-
28 sition systems that are capable of recording the digitized raw detector signals.

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29 1. Introduction

30 Experimental nuclear structure investigations continue to take advantage of
31 the unique capabilities of digital electronics including nearly zero dead time,
32 low-energy thresholds, unique triggering conditions, high dynamic range, and
33 pulse shape processing [1–4]. An often overlooked benefit of digital electronics
34 is the ability to simultaneously perform both an energy and timing measure-
35 ment, removing the need for a parallel branch of electronics dedicated to timing
36 measurements alone.

37 Fast-scintillator detectors with inherent timing resolutions on the order of
38 hundreds of picoseconds are challenging to implement within existing large-scale
39 digital electronics systems. Several digital timestamping methods exist [5–8]
40 which have attempted to address the difficulty of precision time measurements.
41 The simplest timestamping method available is the leading-edge trigger. The
42 leading-edge trigger can be applied to the raw digitized signal or to a shaped
43 signal. In the case of lead-edge triggering, as soon as the amplitude of the
44 digitized raw or shaped waveform crosses a user-defined threshold the timestamp
45 is latched. This method, though fast and easy to implement, provides the least
46 precise timestamp.

47 Another relatively simple algorithm is the digital equivalent of an analog
48 constant fraction discriminator (CFD). This method has good time-resolving
49 capability without the amplitude-dependent walk observed in lead-edge trigger-
50 ing. However, one problem with CFD triggering in digital systems, discussed
51 in the work of Ref. [5], is the asynchronous capture of the detector signal with
52 respect to the sampling frequency of the ADC combined with the non-linear
53 nature of the sampled detector signal. This results in a dependence of the time
54 resolution on the arrival-time difference of the two signals with respect to the
55 clock period of the digitizer and can significantly degrade detector performance.
56 Various solutions to this problem have been attempted which remove the re-
57 quirement that the signal shape be linear in the region of the CFD threshold
58 [5, 8]. In Ref. [5] the CFD point is interpolated using four points around the

59 zero crossing using a cubic polynomial while Ref. [8] directly fit the expected
 60 signal shape to the digitized waveform. Both techniques are capable of providing
 61 time resolutions on the order of hundreds of picoseconds. However, the present
 62 study is performed to provide a mechanism to retain the linear CFD crossing
 63 approximation while at the same time not requiring an a-priori knowledge of
 64 the signal shape. For a further discussion and comparison of various timing
 65 methods the reader is referred to the work of Ref. [6].

66 While increasing the sampling frequency of the digitizer is often the most
 67 direct method to improve timing performance it is typically cost prohibitive in
 68 systems composed of hundreds of channels. The development of robust methods
 69 for precision timing that can be directly implemented on-board existing digi-
 70 tizer systems which sample the incoming detector signal between 100 and 250
 71 Mega Samples Per Second (MSPS) with 12-bit to 14-bit ADCs is desired. The
 72 results presented herein describe a simple digital CFD algorithm, formulated
 73 in Ref. [9], which is implemented on-board 100 MSPS and 250 MSPS digitiz-
 74 ers and the parameter optimization required to obtain timing resolutions well
 75 below one nanosecond. The intended application for this technique is fast scin-
 76 tillation spectroscopy at the National Superconducting Cyclotron Laboratory
 77 using LaBr₃ detectors for level lifetime measurements and neutron energy mea-
 78 surements through time-of-flight [10] using the NSCL Digital Data Acquisition
 79 System (DDAS) [11]. Both experimental arrays require timing resolutions on the
 80 order of a few hundred picoseconds. The general procedure for energy and time
 81 extraction is presented in Section 2 and its application to fast-scintillator de-
 82 tectors is described in Section 3. The time- and energy-optimization techniques
 83 along with results obtained using these techniques are presented in Section 4
 84 and Section 5, respectively.

85 **2. Time and Energy Extraction**

86 *2.1. Digital Filtering*

87 DDAS uses digital filtering in the form of two symmetric trapezoidal filters
 88 to extract time and energy information from detector signals. A general dis-

89 cussion of digital filtering is presented in Refs. [12–14]. The formulation of the
90 trapezoidal filter algorithms used by DDAS is given in Ref. [15] and a general
91 overview of the specific implementation of these algorithms is presented in Ref.
92 [11]. The operation and application of these algorithms is discussed in greater
93 detail in subsequent subsections.

94 *2.2. Time Extraction*

95 Timestamps generated by DDAS consist of a 48-bit clock and, if requested,
96 a 16-bit fractional time for time measurements below the native sampling fre-
97 quency of the module. DDAS employs two algorithms for extracting timing
98 information from a detector signal. The first of these algorithms is a trape-
99 zoidal filter algorithm called the “trigger filter”, which is a simplified version of
100 the trapezoidal filter discussed in Ref. [15] since it does not contain the correc-
101 tion for the exponential decay typical of detector signals. The second algorithm
102 is a digital Constant Fraction Discriminator (CFD) algorithm presented in Ref.
103 [9]. Figure 1 demonstrates the response of these two algorithms to a sample
104 input detector signal.

105 Figure 1a shows a sample detector signal. Figure 1b shows the response of
106 the DDAS trigger-filter algorithm when applied to the detector signal shown in
107 Figure 1a. A delayed version of the trigger-filter response is also shown to aid
108 the discussion of CFD triggering in section 2.2.2. Figure 1c shows the response
109 of the DDAS digital CFD algorithm.

110 *2.2.1. Leading-Edge Triggering*

111 In leading-edge triggering, the timestamp is latched when the amplitude
112 of the trigger filter crosses an user-set trigger-filter threshold. This process is
113 illustrated in Figure 1. The timestamp latched to an event from leading-edge
114 triggering would have at best either 10 ns or 4 ns precision corresponding to the
115 100 MSPS and 250 MSPS modules, respectively. This type of triggering is used
116 only when high-resolution timing is not required.

Figure 1: Example illustrating DDAS triggering. Panel a) shows the a sample detector signal. Panel b) shows the response of the DDAS trigger-filter algorithm when applied to the signal shown in a). A delayed version of the trigger filter is also shown. Panel c) shows the response of the digital CFD algorithm.

2.2.2. CFD Triggering

When sub clock-tick timing precision is required, the digital CFD algorithm is used. In this method, the response of the trigger filter algorithm described above, shown in Figure 1b, serves as the input to the digital CFD algorithm. The response of the digital CFD algorithm is then calculated using Equation (1) [16].

$$CFD[i] = TF[i] - \frac{TF[i - D]}{2^{W+1}} \quad (1)$$

D is the CFD delay in units of clock ticks, $CFD[i]$ is the CFD response at the time i, W is the CFD scale factor, and $TF[i]$ and $TF[i-D]$ are the values of the trigger filter at times i and i-D, respectively. The CFD scale factor determines the fraction of the CFD and is an user-set parameter.

127 In CFD triggering, the 48-bit clock is latched at the clock tick corresponding
 128 to the last point before the zero crossing of the CFD response. The fractional
 129 time is calculated using a linear interpolation between the CFD values directly
 130 before and after the zero crossing of the digital CFD. The timestamp of an event
 131 is then calculated from the sum of the 48-bit clock and the fractional time, both
 132 of which depend on the sampling frequency of the module.

133 2.3. Energy Extraction

134 Energy extraction by DDAS employs a second, simultaneous, trapezoidal
 135 filter algorithm called the “energy filter”. The energy filter is very similar to
 136 the trigger filter but contains the correction for the decay time of the signal.
 137 The amplitude of the flat-top portion of the energy filter is proportional to the
 138 amplitude of the analyzed detector signal. The energy filter is calculated using
 139 three running sums with lengths dictated by the user-set rise and gap parameters
 140 of the filter. For each running sum there is a coefficient [15] that depends on
 141 the rise time of the energy filter and the preamplifier decay time, “tau”. The
 142 filter response is calculated by summing each running sum, corrected for the
 143 baseline, multiplied with its respective coefficient. The point in time at which
 144 the energy filter is sampled, yielding the extracted energy, is calculated using
 145 Equation (2).

$$T_{Ex} = T_{Trig} + T_{Rise} + T_{Gap} - T_{Clock} \quad (2)$$

146 T_{Ex} is the energy extraction time, T_{Trig} is the timestamp latched during
 147 triggering, T_{Rise} is the rise-time of the energy filter, T_{Gap} is the gap-time of the
 148 energy filter, and T_{Clock} is the time of one clock tick of the module. Figure 2
 149 illustrates energy extraction in DDAS.

150 Figures 2a and 2b show the same detector signal and trigger-filter algorithm
 151 presented in Figure 1, but on a different time scale. Figure 2c shows the response
 152 of the energy filter algorithm to the detector signal along with key times in the
 153 energy extraction process.

Figure 2: Example illustrating DDAS energy extraction. Panel a) shows the same sample detector signal shown in 1a. Panel b) shows the response of the DDAS trigger-filter algorithm when applied to the signal shown in a). Panel c) shows the response of the energy filter algorithm. Times relevant to the energy extraction algorithm are labeled for clarity.

Following a trigger in DDAS, at time T_{Trig} , the system waits the characteristic time, $T_{Rise} + T_{Gap} + T_{Clock}$, before sampling the amplitude of the energy filter yielding the DDAS estimate of the signal amplitude.

As illustrated by Figure 2, the rise and gap times for the energy filter are typically longer than those of the trigger filter. The longer characteristic time of the energy filter gives reduced variability in the flat-top region of the filter that results from the cancellation of noise due to the signal averaging effect of the filter algorithm. The best energy resolution is achieved by sampling the flat-top region of the energy filter, and sampling elsewhere will degrade the energy resolution.

In addition to setting the energy filter length, tau must be accurately de-

165 terminated for each detector. If tau is set incorrectly, the top of the energy filter
 166 will not be flat and the resolution will be degraded. This degradation is more
 167 pronounced with increased detector rates. The accuracy of tau also impacts the
 168 ability of the system to accurately determine the baseline of the detector.

169 3. High-Resolution Timing

170 If we consider the case of leading-edge triggering, the time resolution can
 171 never be better than the native precision of the 48-bit clock, so CFD trigger-
 172 ing must be employed when time resolution is important. However, tests with
 173 DDAS instrumenting LaBr₃ detectors, utilizing CFD timing, revealed some pe-
 174 culiar features in the time difference spectra. Peaks were often non-Gaussian
 175 or exhibited multi-peaking. This phenomena was further investigated using
 176 generated signals, designed to mimic LaBr₃ detectors, from an Agilent 33522A
 177 arbitrary waveform generator. This method allows one to control the time struc-
 178 ture, amplitude, and relative arrival time difference (Δ) between two signals,
 179 thereby simplifying the investigation. The arbitrary waveform generator was
 180 given a random trigger and configured to produce two identical signals with a
 181 fixed Δ . These two signals were simultaneously input to two channels of DDAS
 182 and the time difference between the two signals was histogrammed. Figure 3
 183 shows the measured time-difference spectrum for several values of Δ .

Figure 3: DDAS time-difference spectrum for two identical signals generated by an Agilent 33522A arbitrary waveform generator. These signals were designed to mimic the response of LaBr₃ detectors. The resolution is only acceptable when Δ is integer numbers of the DDAS clock period, which is 10 ns in this example.

184 The dependence of the time resolution on Δ is a pattern that repeats with

185 a period equal to the DDAS clock period (10 ns in Fig. 3). The best resolution
 186 is obtained when Δ is an integer number of DDAS clock periods and becomes
 187 worse as Δ approaches half-integer clock periods. This effect has been observed
 188 before in the work of Refs. [5, 8], and can be explained by further analysis of
 189 the digital CFD algorithm.

190 The digital CFD algorithm relies upon a linear interpolation between the
 191 points directly before and after the zero crossing point of the CFD response.
 192 However, the response of the digital CFD about the zero-crossing point more
 193 resembles that of a cubic function and, therefore, it is expected that the more
 194 accurate time stamp would be extracted using a cubic interpolation.

195 The response of the CFD in about the zero crossing point relies heavily upon
 196 the trigger filter parameters and the CFD delay, as well as the detector signal
 197 itself. Figure 4 provides further analysis of the zero-crossing point of the CFD
 198 response shown in Figure 1c.

Figure 4: Analysis of the CFD zero-crossing point. Panel a) shows an expanded view of the CFD response about the CFD zero-crossing point. Panel b) zooms in further on the zero-crossing point to the region where DDAS performs the interpolation. Panel c) shows the difference in the extracted time stamp between a higher order cubic interpolation and the linear interpolation employed by DDAS .

Figure 4a shows an expanded view of the CFD response about the zero-crossing point. The CFD response is fit with a cubic function to obtain a better approximation of the actual CFD response which is compared to a linear interpolation shown in red. Figure 4b is further zoomed in to the region where DDAS performs the linear interpolation, which is outlined in black in Figure 4a. To better illustrate the potential error in the timestamp associated with a linear interpolation, Figure 4c shows the difference in the extracted timestamp between the cubic and linear interpolations.

Figure 5: Analysis of the CFD zero crossing for two detector signals which have a time-delay, Δ , equal to an integer number of DDAS clock periods. Panels a) and c) show an expanded view of the CFD response about the CFD zero-crossing point for detectors one and two, respectively. These panels show a fit with both cubic (shown in blue) and linear (shown in red) functions to the CFD response. Panels b) and d) show a timestamp difference plot (cubic-linear) for detectors one and two, respectively. As one can see from these plots, when the signals are in phase with the DDAS clock, the timestamp difference plots between each detector look almost identical and the difference between the two timestamp differences is nearly zero. As a result, good time resolution for detector signals with Δ equal to integer numbers of DDAS clock periods is obtained and the time resolution is less sensitive to trigger-filter and digital CFD parameters.

Figures 5 and 6 examine the zero crossing point for one event in two detectors for Δ equal to an integer number of DDAS clock periods and for Δ equal to a half-integer number of DDAS clock periods, respectively. As before, the detector signals were identical and generated with fixed Δ by an Agilent 33522A arbitrary waveform generator. The generator was set to output one event at random,

Figure 6: Analysis of the CFD zero crossing for two detector signals which have a time-delay, Δ , equal to a half-integer number of DDAS clock periods. Panels a) and c) show an expanded view of the CFD response about the CFD zero-crossing point for detectors one and two, respectively. These panels show a fit with both cubic (shown in blue) and linear (shown in red) functions to the CFD response. Panels b) and d) shown a timestamp difference plot (cubic-linear) for detectors one and two, respectively. When Δ is a non-integer number of DDAS clock periods, the timestamp difference plots for each detector look very different and the timestamp differences can be negative or positive and large or small. Consequently, poor time-resolution for detector signals with Δ equal to non-integer numbers of DDAS clock periods is obtained. The severity of the degradation in the resolution is highly dependent upon the trigger-filter and digital CFD parameters as well as Δ .

212 which makes the arrival time of the first signal random with respect to the
 213 phase of the DDAS clock, and the second signal a time Δ later.

214 In both figures, panels a) and c) show an expanded view of the CFD response
 215 about the CFD zero-crossing point for detectors one and two, respectively. For
 216 each detector a fit of the CFD response about the zero crossing was performed
 217 using both linear (shown in red) and cubic (shown in blue) functions. In both
 218 figures, panels b) and d) show the difference between the timestamps extracted
 219 from the cubic and linear interpolations of the CFD response about the zero-
 220 crossing point.

221 In the case where Δ equal to an integer number of clock periods, repre-
 222 sented in Figure 5, the timestamp difference between the cubic and the linear
 223 looks nearly identical for the two detectors, as expected. Both timestamps have
 224 equivalent interpolation errors such that when the timestamp difference is cal-

225 culated, any inadequacy of the linear interpolation to accurately determine the
 226 timestamp is masked. In Figure 3, this is clearly demonstrated by the excellent
 227 time resolution for $\Delta = 20$ and 40 ns, which are integer numbers of DDAS clock
 228 periods for the 100 MSPS modules.

229 In the case where Δ is a non-integer number of DDAS clock periods, repre-
 230 sented in Figure 5, the timestamp difference plots can be quite different for the
 231 two detectors such that the timestamps for each detector experience different in-
 232 terpolation errors. When the time difference between two such detector signals
 233 is calculated, the different interpolation errors broaden the time-difference spec-
 234 trum and create undesirable features, demonstrated in Figure 3 for the peaks
 235 where $\Delta \neq 20$ and 40 ns.

236 The results of this analysis suggest that the best online time resolution,
 237 regardless of Δ , will be obtained for trigger-filter and digital CFD parameters
 238 that yield the most linear CFD response about the CFD zero-crossing point.

239 4. Optimization

240 4.1. Time Resolution

241 The online time resolution of DDAS is dictated by four parameters which
 242 are the trigger-filter rise time, trigger-filter gap time, digital CFD scale factor,
 243 and digital CFD delay. These four parameters comprise what will be referred
 244 to as a “parameter set” in the following discussion. Typically, several hundred
 245 parameter sets are used and the range of the parameters in these sets are chosen
 246 based on the properties of the detector signal.

247 Time-resolution optimization begins by recording detector signals from rel-
 248 evant detectors of an array. For the technique to work properly gamma rays
 249 incident on the two detectors must be in prompt coincidence. Typically as few
 250 as 2000 coincident events are enough to optimize the detectors. Once recorded,
 251 the optimization software analyzes the detector signals by emulating the DDAS
 252 trigger-filter and digital CFD algorithms. The optimization program extracts
 253 all necessary time information and generates a time-difference spectrum for each

parameter set. The program analyzes all time-difference spectra, calculates the time resolutions, and outputs a list of the best parameter sets for use online.

A convenient way to visualize the results are collections of two-dimensional histograms displaying time resolution as a function of trigger-filter rise and gap times for a given CFD delay and CFD scale factor. One such two-dimensional histogram is shown in Figure 7 for the optimization of the time resolution between two 38 mm x 38 mm BrillanCe® 380 LaBr₃ detectors equipped with Hamamatsu R6231 PMTs, instrumented by the 250 MSPS modules.

Figure 7: Two-dimensional histogram displaying time resolution achieved between two 38 mm x 38 mm BrillanCe® 380 LaBr₃ detectors equipped with Hamamatsu R6231 PMTs, using the 250 MSPS modules, as a function of trigger filter rise and gap times for a given CFD delay and CFD scale factor

As seen in Figure 7 there is high variability in the time resolution and only a small subset of parameter sets provide acceptable time resolution. The gains obtained through optimization can be seen in Figure 8.

The blue spectrum in Figure 8 is the same spectrum shown in Figure 3 obtained online by DDAS using a set of trigger-filter and digital CFD parameters typically used for LaBr₃ detectors. The red spectrum is calculated offline using the optimized parameter set, determined by the optimization program. Figure 8a presents an overlay of the two spectra and shows that indeed with the appropriate set of parameters the time resolution is no longer dependent on Δ . Figure 8b expands the region around $\Delta = 12$ ns and better illustrates the

Figure 8: Time-difference spectra for a variety of different Δ values. Panel a) is an overlay of the optimized and not optimized time-difference spectra indicating that for an appropriate parameter set there is no dependence of the time resolution on Δ . Panel b) shows a zoomed in view for $\Delta = 12$ ns, which better illustrates the improvements gained through optimization. In both panels, the red spectrum is created by the optimization program offline using the ideal parameter set while the blue spectrum was obtained online by DDAS using the typical parameter set previously used for LaBr₃ detectors.

improvements gained after optimization.

4.1.1. Verification

The predictions of the time optimization program were tested online to investigate agreement between the online and offline results. Figure 9 presents a comparison between the online results shown in the red dot-dash line and offline results shown in black for two 38 mm x 38 mm BrillLanCe® 380 LaBr₃ detectors equipped with Hamamatsu R6231 PMTs using optimized parameters.

This comparison demonstrates the ability of the offline program to reproduce and predict the results of the online acquisition.

4.2. Energy Resolution

The procedure for energy-resolution optimization closely resembles that of the time-resolution optimization with a few additional steps. First, all prerecorded detector signals are analyzed to determine their baselines and leading edge trigger times. The baseline is determined from an average of the baseline

Figure 9: Validation of the offline time optimization program. The time-difference spectrum shown in the red dot dash line was calculated offline by the optimization program while the time-difference spectrum shown in black was obtained online by DDAS using the same parameters as the offline optimization program. This comparison clearly demonstrates the ability of the offline program to reproduce and predict the results of the online acquisition.

286 region before the rise of the signal while the leading-edge trigger times are de-
 287 termined when the value of the trigger-filter algorithm crosses a user-defined
 288 threshold. The tail of each analyzed detector signal is fit with an exponential
 289 plus an constant offset and the results are histogrammed. The decay time of the
 290 detector is determined from a Gaussian fit to the histogrammed distribution of
 291 decay-time values.

292 Once the baselines, leading-edge trigger times, and detector decay time have
 293 been determined, an energy optimization program then analyzes prerecorded
 294 detector signals emulating the DDAS energy-filter algorithm for a large set of
 295 energy-filter rise and gap time combinations. The program creates and analyzes
 296 all energy spectra, determining the energy resolution for each parameter set.
 297 When the program is finished, a list of the best parameter sets for use online is
 298 generated.

299 Again, a convenient way to visualize the results is a two-dimensional his-
 300 togram displaying energy resolution as a function of trapezoidal filter rise and
 301 gap times for a calculated value of tau. One such two-dimensional histogram
 302 is shown in Figure 10. The 2D plot shows yet again that a small subset of
 303 parameter sets yield good resolution.

Figure 10: Two-dimensional histogram displaying energy resolution achieved for a 38 mm x 38 mm BrillanCe® 380 LaBr₃ detectors equipped with a Hamamatsu R6231 PMT, using the 250 MSPS modules set to a 12 MeV dynamic range, as a function of energy filter rise and gap times for a calculated fixed value of tau

4.2.1. Verification

Just like the time-optimization code, the prediction of the energy-optimization code was also tested online to investigate the agreement between the online and offline results. Figure 11 presents a comparison between the online and offline results for a 38 mm x 38 mm BrillanCe® 380 LaBr₃ detector equipped with a Hamamatsu R6231 PMT using optimized parameters. The 1332 keV transition in ⁶⁰Co was used for this measurement. The energy spectrum obtained by the offline optimization program is shown in red dot dash line while the energy spectrum obtained from DDAS, online, is shown in black.

The comparison shown in Figure 11 demonstrates the ability of the offline program to reproduce and predict the results of the online acquisition. Coupled with the comparison shown in Figure 9, it has been demonstrated that the offline optimization programs have predictive power for both time and energy extraction from the online acquisition.

Figure 11: Validation of the offline energy-optimization program. The energy spectrum shown in the red dot dash line was calculated offline by the optimization program while the energy spectrum shown in black was obtained online by DDAS using the same parameters as the offline optimization program. This comparison clearly demonstrates the ability of the offline program to reproduce and predict the results of the online acquisition.

5. Results

5.1. Electronics Time Resolution

The time resolution of the electronics was measured using two identical waveforms with fixed time delay, Δ , input into two different channels of DDAS. The signals were designed to mimic LaBr_3 detectors and generated using an Agilent 33522A arbitrary waveform generator. The calculated time differences between the two channels were histogrammed and the width of the resulting Gaussian gives the intrinsic time resolution of the DDAS electronics for that amplitude. The intrinsic time resolution provides the lower limit on the time resolution for any system instrumented by DDAS. This quantity was measured as a function of input signal amplitude relative to the range of the ADC for both the 100 MSPS and 250 MSPS modules. Results are shown in Figure 12 and indicate that the DDAS electronics contribute little to the time-resolution measurement when the signal amplitudes are large and for most cases the time resolution achievable will be detector limited.

5.2. Time Resolution Measurements with LaBr_3 Detectors

The time resolution for two LaBr_3 detectors was also measured using DDAS. Two Saint Gobain BrillLanCe[®] 380 LaBr_3 detectors were used for this measurement. The crystal of each detector was a right cylinder with a diameter of 38 mm and a height of 38 mm coupled to a Hamamatsu R6231 PMT.

Figure 12: DDAS electronics online time resolution as a function of input signal amplitude measured using ideal identical signals with $\Delta = 0$ ns, generated by an Agilent 33522A arbitrary waveform generator.

For this measurement, the two detectors were placed facing one another with a ^{60}Co source positioned in the middle. Each detector was recorded in one channel of DDAS and the time difference for all coincident events between the two channels was calculated and histogrammed. A gate was then placed around the 1332.5 keV photopeak in the first detector and a two dimensional histogram of energy in the second detector vs. time difference between the two detectors was generated. For each energy bin of the two-dimensional histogram, a projection was made onto the time axis and this projection was fit with a Gaussian. The width of the fit to each projection gives the time resolution for each corresponding energy. The results of the measurement are shown in Figures 13a and 13b for the 100 MSPS and 250 MSPS modules, respectively.

The results presented in Figures 13a and 13b span a very small input range of the ADC and as a result the detector time resolution is degraded, particularly at very low energy, by the low time resolution of the electronics at low input-signal amplitudes. An additional investigation using the same LaBr_3 detectors connected to a 1 GHz fast amplifier was performed. The results for the 250 MSPS modules are shown in Figure 14 below.

The results for the amplified detector signals, shown in Figure 14, are significantly better. However, this is expected since the amplified detector signals occupy a much larger range of the ADC and therefore, the contribution to the width from the electronics is much lower for a given energy. A comparison between Figures 14 and 12 shows that most of the energy range corresponds to

Figure 13: Time resolution shown as a function of energy (bottom axes), and as a function of input signal amplitude (top axes), measured online by DDAS for two 38 mm by 38 mm right cylindrical Saint Gobain BrillanCe® 380 LaBr₃ detectors using a ⁶⁰Co source. Panel a) shows the data for the 100 MSPS modules and panel b) is for the 250 MSPS modules.

Figure 14: Time resolution shown as a function of energy (bottom axis), and as a function of input signal amplitude (top axis), measured online by DDAS using the 250 MSPS modules, for two 38 mm by 38 mm right cylindrical Saint Gobain BrillanCe® 380 LaBr₃ detectors using a ⁶⁰Co source. The detector outputs were amplified such that a larger input range of the ADC was used for the measurement, thereby reducing the electronic component to the width of the time resolution.

360 signal amplitudes which have negligible contribution from the time resolution
 361 of the DDAS electronics and we have reached the hardware limitations of the
 362 detectors themselves.

5.3. Energy Resolution Measurements with LaBr₃ Detectors

The energy resolution of a Saint Gobain BrillLanCe® 380 LaBr₃ detector was measured using both the 100 MSPS and 250 MSPS modules. Again, the crystal of this detector was a right cylinder with a diameter of 38 mm and a height of 38 mm coupled to a Hamamatsu R6231 PMT. The bias voltage of the PMT was adjusted slightly to gain match the 100 MSPS and 250 MSPS modules. The fixed gain of DDAS, coupled with the small amplitude signals from the LaBr₃ detectors, resulted in a 9 MeV dynamic range. Figure 15 presents a comparison of the measured DDAS resolutions with the manufacturer quoted resolutions [17].

Figure 15: Comparison of the measured energy resolution from DDAS with the manufacturer quoted resolutions [17] for Saint Gobain BrillLanCe® 380 LaBr₃ detectors. The 100 MSPS and 250 MSPS modules were gain matched by slightly adjusting PMT bias voltage. The resulting dynamic range was 9 MeV. Four different radioactive sources were used in this measurement to obtain gamma rays of the energies shown in the figure. Decay of ⁵⁷Co yields the 122.06 keV gamma ray, ¹³³Ba gives the 356.01 keV gamma ray, ¹³⁷Cs was used to obtain the 661.66 keV gamma ray, and ⁶⁰Co provides the 1332.5 keV gamma ray.

From the results in Figure 15, it is clear that both the 100 MSPS and 250 MSPS modules using optimized filter parameters are capable of meeting or exceeding the manufacturer specifications despite the large dynamic range.

6. Conclusion

This work has demonstrated that digital data acquisition systems utilizing 100 MSPS and 250 MSPS digitizers can achieve high resolution time and energy measurements simultaneously in an online mode. The well known issues

stemming from the inadequacy of linear interpolation used in digital CFD algorithms have been explored and a new optimization technique has circumvented the problem. It has been demonstrated that for LaBr_3 detectors with signal amplitudes occupying $>10\%$ the full range of the ADC, the contribution to the time resolution from the DDAS electronics, measured online, has been reduced to <100 ps and <40 ps for 100 MSPS and 250 MSPS digitizers, respectively. Using the optimized timing parameters, a time resolution of ≈ 350 ps, at 511 keV, between two 38 mm x 38 mm lanthanum bromide (LaBr_3) detectors, equipped with Hamamatsu R6231 photomultiplier tubes (PMTs), has been attained. Similar optimization techniques applied to the DDAS energy-extraction algorithms have yielded energy resolutions below 2% at 1.33 MeV for both the 100 and 250 MSPS digitizers using the same LaBr_3 detectors. All the techniques discussed can be applied to other digital acquisition systems provided they have the ability to record raw digitized waveforms.

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References

- [1] S. Suchyta, S. N. Liddick, Y. Tsunoda, T. Otsuka, M. B. Bennett, A. Chemey, M. Honma, N. Larson, C. J. Prokop, S. J. Quinn, N. Shimizu, A. Simon, A. Spyrou, V. Tripathi, Y. Utsuno, J. M. VonMoss, Shape coexistence in ^{68}Ni , Phys. Rev. C 89 (2014) 021301.
- [2] S. Suchyta, S. N. Liddick, C. J. Chiara, W. B. Walters, M. P. Carpenter, H. L. Crawford, G. F. Grinyer, G. Gürdal, A. Klose, E. A. McCutchan, J. Pereira, S. Zhu, β decay of $^{61,63}\text{V}$ and low-energy level schemes of $^{61,63}\text{Cr}$, Phys. Rev. C 89 (2014) 034317.

- 408 [3] S. J. Quinn, A. Spyrou, E. Bravo, T. Rauscher, A. Simon, A. Battaglia,
409 M. Bowers, B. Bucher, C. Casarella, M. Couder, P. A. DeYoung, A. C.
410 Dombos, J. Görres, A. Kontos, Q. Li, A. Long, M. Moran, N. Paul,
411 J. Pereira, D. Robertson, K. Smith, M. K. Smith, E. Stech, R. Talwar,
412 W. P. Tan, M. Wiescher, Measurement of the $^{58}\text{Ni}(\alpha, \gamma)^{62}\text{Zn}$ reaction and
413 its astrophysical impact, *Phys. Rev. C* 89 (2014) 054611.
- 414 [4] A. Simon, S. Quinn, A. Spyrou, A. Battaglia, I. Beskin, A. Best, B. Bucher,
415 M. Couder, P. DeYoung, X. Fang, J. Gress, A. Kontos, Q. Li, S. Liddick,
416 A. Long, S. Lyons, K. Padmanabhan, J. Peace, A. Roberts, D. Robertson,
417 K. Smith, M. Smith, E. Stech, B. Stefanek, W. Tan, X. Tang, M. Wi-
418 escher, Sun: Summing NaI(Tl) gamma-ray detector for capture reaction
419 measurements, *Nuclear Instruments and Methods in Physics Research Sec-*
420 *tion A: Accelerators, Spectrometers, Detectors and Associated Equipment*
421 703 (2013) 16 – 21.
- 422 [5] L. Bardelli, G. Poggi, M. Bini, G. Pasquali, N. Taccetti, Time measure-
423 ments by means of digital sampling techniques: a study case of 100 ps
424 {FWHM} time resolution with a 100 msample/s, 12-bit digitizer, *Nu-*
425 *clear Instruments and Methods in Physics Research Section A: Acceler-*
426 *ators, Spectrometers, Detectors and Associated Equipment* 521 (2004) 480
427 – 492.
- 428 [6] M. A. Nelson, B. D. Rooney, D. R. Dinwiddie, G. S. Brunson, Analysis
429 of digital timing methods with BaF_2 scintillators, *Nuclear Instruments*
430 *and Methods in Physics Research Section A: Accelerators, Spectrometers,*
431 *Detectors and Associated Equipment* 505 (2003) 324 – 327. *Proceedings of*
432 *the tenth Symposium on Radiation Measurements and Applications.*
- 433 [7] L. Bardelli, G. Poggi, M. Bini, G. Pasquali, An efficient method for timing
434 synchronization between many digital sampling channels, *Nuclear Instru-*
435 *ments and Methods in Physics Research Section A: Accelerators, Spec-*
436 *trometers, Detectors and Associated Equipment* 572 (2007) 882 – 892.

- 437 [8] S. Paulauskas, M. Madurga, R. Grzywacz, D. Miller, S. Padgett, H. Tan,
438 A digital data acquisition framework for the versatile array of neutron
439 detectors at low energy (VANDLE), Nuclear Instruments and Methods in
440 Physics Research Section A: Accelerators, Spectrometers, Detectors and
441 Associated Equipment 737 (2014) 22 – 28.
- 442 [9] A. Fallu-Labruyere, H. Tan, W. Hennig, W. Warburton, Time resolution
443 studies using digital constant fraction discrimination, Nuclear Instruments
444 and Methods in Physics Research Section A: Accelerators, Spectrometers,
445 Detectors and Associated Equipment 579 (2007) 247 – 251. Proceedings of
446 the 11th Symposium on Radiation Measurements and Applications.
- 447 [10] G. Perdikakis, M. Sasano, S. M. Austin, D. Bazin, C. Caesar, S. Can-
448 non, J. Deaven, H. Doster, C. Guess, G. Hitt, J. Marks, R. Meharchand,
449 D. Nguyen, D. Peterman, A. Prinke, M. Scott, Y. Shimbara, K. Thorne,
450 L. Valdez, R. Zegers, Lenda: A low energy neutron detector array for exper-
451 iments with radioactive beams in inverse kinematics, Nuclear Instruments
452 and Methods in Physics Research Section A: Accelerators, Spectrometers,
453 Detectors and Associated Equipment 686 (2012) 117 – 124.
- 454 [11] C. Prokop, S. Liddick, B. Abromeit, A. Chemey, N. Larson, S. Suchyta,
455 J. Tompkins, Digital data acquisition system implementation at the na-
456 tional superconducting cyclotron laboratory, Nuclear Instruments and
457 Methods in Physics Research Section A: Accelerators, Spectrometers, De-
458 tectors and Associated Equipment 741 (2014) 163 – 168.
- 459 [12] V. T. Jordanov, G. F. Knoll, Digital synthesis of pulse shapes in real time
460 for high resolution radiation spectroscopy, Nuclear Instruments and Meth-
461 ods in Physics Research Section A: Accelerators, Spectrometers, Detectors
462 and Associated Equipment 345 (1994) 337 – 345.
- 463 [13] L. Bardelli, G. Poggi, Digital-sampling systems in high-resolution and wide
464 dynamic-range energy measurements: Comparison with peak sensing adcs,

- 465 Nuclear Instruments and Methods in Physics Research Section A: Acceler-
 466 ators, Spectrometers, Detectors and Associated Equipment 560 (2006) 517
 467 – 523.
- 468 [14] F. Goulding, Pulse-shaping in low-noise nuclear amplifiers: A physical
 469 approach to noise analysis, Nuclear Instruments and Methods 100 (1972)
 470 493 – 504.
- 471 [15] H. Tan, M. Momayezi, A. Fallu-Labruyere, Y. Chu, W. Warburton,
 472 A fast digital filter algorithm for gamma-ray spectroscopy of double-
 473 exponential decaying scintillators, in: Nuclear Science Symposium Con-
 474 ference Record, 2003 IEEE, volume 2, 2003, pp. 784 – 788 Vol.2.
 475 doi:10.1109/NSSMIC.2003.1351815.
- 476 [16] XIA, Digital Gamma Finder (DGF) Pixie-16 Manuals, 1.4 ed., XIA LLC,
 477 31057 Genstar Road, Hayward, CA 94544, U.S.A., 2009.
- 478 [17] Saint Gobain, BriLanCe @Scintillators Performance Sum-
 479 mary, 2009. URL: [http://www.crystals.saint-gobain.com/
 480 uploadedFiles/SG-Crystals/Documents/Technical/SGC%20BrillanCe
 481 %20Scintillators%20Performance%20Summary.pdf](http://www.crystals.saint-gobain.com/uploadedFiles/SG-Crystals/Documents/Technical/SGC%20BrillanCe%20Scintillators%20Performance%20Summary.pdf).