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Performance of Four Digital Algorithms for $\gamma - \gamma$ Timing with LaBr₃(Ce) Scintillators

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7 Abstract

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Time resolution measurements were performed using four digital timing algorithms and a pair of truncated-cone shaped, 38-mm diameter LaBr₃(Ce) 9 fast-timing scintillator detectors. The best resolution [FWHM=143(3) ps] was 10 found for transitions from a 60 Co source when fitting the rising part of sampled 11 waveforms with a cubic polynomial and applying a leading-edge threshold. An 12 average-pulse autocovariance function performed slightly worse [155(3) ps], but 13 was found to be better than digital constant-fraction [178(4) ps] and leading-14 edge [177(4) ps] algorithms. Use of a ¹⁵²Eu source allowed the performance 15 of the four algorithms to be tested across a range of γ -ray energies with the $LaBr_3(Ce)$ detectors. Here the autocovariance algorithm performed best. Chang-17 ing the sampling speed showed minimal degradation in the time resolution at 18 20 GS/s, though at 4 GS/s the resolutions were 30–60 % worse. These results 19 show that at sampling speeds of 20 or 40 GS/s the time resolutions obtained are 20 close to those reported for analogue pulse-processing electronics. Compared to 21 other works, using slower sampling speeds but higher vertical resolution, slightly 22 worse performance was obtained. 23

24 1. Introduction

Fast scintillator detectors are used for $\gamma - \gamma$ timing and have a wide range of applications, including lifetime measurements of excited nuclear states [1],

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medical positron-emission tomography (PET) and range monitoring in hadron 27 therapy [2]. These scintillation crystals have the properties of modest energy 28 resolution and fast decay times (ns), and are constructed often with the aim 29 of optimising the time rather than energy resolution of the system. Recent 30 progress in the fabrication of lanthanide-halide crystals, such as $LaBr_3(Ce)$, with 31 an energy resolution of $\sim 3 \%$ at 662 keV and time resolution as good as 98(2) ps 32 for ~ 1.2 MeV photons [3] has given renewed interest in the use and development 33 scintillator detectors, resulting in, for example, the construction of the FATIMA 34 array [4, 5]. The decay time of LaBr₃(Ce) is 16 ns and 63000 photons are emitted 35 per MeV of energy absorbed. This compares with a decay time of 0.7 ns and 36 1800 photons/MeV for the fast component of the commonly used BaF_2 . These 37 scintillator detectors can be used to measure nuclear-state lifetimes in the 10s-38 of-ps-to-ns time range [1, 6, 7]. To date analogue signal processing chains have 39 been almost exclusively used in applications which require the very best time 40 resolution. 41

In principle digital acquisition systems, with very high-speed sampling, should 42 allow equivalent, or even improved, timing performance over analogue ones, as 43 signal processing can reduce jitter and fixed-frequency noise and bespoke al-44 gorithms can be developed for a particular detection system. Recently, time 45 resolutions approaching, and matching, the best ones achieved with analogue 46 electronics have been obtained with $LaBr_3(Ce)$ detectors, using digitizers with 47 sampling frequencies of 0.5, 4 and 5 GS/s by applying digital timing algorithms 48 [8–10]. An improved time resolution over analogue systems was earlier obtained 49 with Ge detectors using digital pulse-shape analysis [11]. Furthermore, digital 50 acquisition systems have other advantages over analogue ones including (poten-51 tially) lower cost per channel, fewer modules and timing stamping of individual 52 hits, allowing offline event reconstruction. Any algorithms used for pulse-shape 53 analysis should ideally be simple and efficient enough to be implemented on field-54 programmable gate arrays (FPGAs), allowing real-time processing. Pulse-shape 55 analysis has already been used to perform, for example, α/γ discrimination in 56 LaBr₃(Ce) crystals [12] and neutron/ γ selection in liquid scintillators [13]. 57

The purely statistical resolving time of a pair of detectors is given by $\delta t = \frac{\sigma}{\sqrt{n}}$ 58 where n is the number of events and σ is the width parameter of the Gaussian 59 function describing the distribution. Hence an experiment using detectors with 60 twice worse time resolution will require 4 times the number of counts to achieve 61 the same statistical precision. Therefore there is strong motivation to develop 62 timing algorithms suitable for use with digital acquisition systems which have 63 performances equivalent to, or better than, the best analogue pulse-processing 64 electronics. 65

Improved timing resolution is also of interest for clinical PET applications, 66 which would allow lower injected patient doses. Although the γ -ray detectors 67 used in PET applications are much smaller than the crystals used for nuclear 68 excited-state lifetime measurements, equivalent pulse-processing techniques are 69 used to extract timing information. Clinical PET time resolutions better than 70 100 ps would allow some of the artefacts affecting tomographic reconstruction 71 to be removed for devices with partial angular coverage [14]. For resolutions of 72 10 ps time-consuming image reconstruction techniques would not be required, 73 as true real-time 3-D image information would be available [14]. In the case of 74 prompt- γ timing for particle therapy, transitions with energies typically in the 75 range 3–6 MeV are measured, for which better time resolution is expected than 76 at 511 keV [2]. 77

With this in mind we have measured the time resolution of a pair of fast 78 $LaBr_3(Ce)$ scintillator detectors when applying four different algorithms to ex-79 tract timing information. These algorithms were a leading-edge discrimination 80 of the raw detector pulse and also following a cubic polynomial fit to the rising 81 slope, a digital constant-fraction discriminator and an ideal-pulse autocovari-82 ance function. The first and third pulse-processing algorithms are equivalent to 83 analogue fast-signal treatment schemes. These algorithms differ from other fast 84 filters often implemented on commercial digital acquisitions systems for use with 85 Ge detectors, such as trapezoidal ones. These fast-filters have the aim of distin-86 guishing real low-energy signals from noise. Limited tests of these algorithms 87 within the present work gave degraded timing performance in comparison with 88

the ones used below, however this does not exclude that a well-tuned algorithm of this type, with its inherent noise filtering, may give improved results in the future. The experiments were performed with a digital oscilloscope running at a sampling frequency of 40 GS/s, with a 4 GHz bandwidth and 10-bit vertical resolution. The effect of varying the sampling frequency was also studied.

94 2. Experimental Setup

The time resolution of $\gamma - \gamma$ coincidences detected in a pair of scintillator 95 detectors was studied in order to determine pulse-processing algorithm perfor-96 mance. A pair of truncated-cone shaped $LaBr_3(Ce)$ scintillator detectors were 97 used to detect γ rays emitted from ⁶⁰Co and ¹⁵²Eu radioactive sources. The 98 detectors were placed ~ 2.5 cm from the source and at 90° to each other, to 99 minimise Compton scattering. The $LaBr_3(Ce)$ crystals were 38 mm long and 100 38-mm wide at the base. Their exact dimensions are reported in [3]. These crys-101 tals were mounted on Hamamatsu R9779 photomultiplier tubes (PMTs). The 102 anode output signal of the PMT base was connected directly to the oscilloscope 103 and the dynode output was terminated with a 50- Ω resistor. The oscilloscope 104 was a LeCroy HDO9404 model with 10-bit vertical resolution and a vertical 105 range of 1 V. It ran at a sampling speed of 40 GS/s. Each digitized trace was 106 4096 samples (102.4 ns) long, enough to contain all of the $LaBr_3(Ce)$ signal 107 trace. The oscilloscope ran in an "AND" mode where traces were captured only 108 if triggers on both signals fired within a time window of a few nanoseconds. The 109 high voltage was set to \sim -1100 V so that pulses with energies up to \sim 1.5 MeV 110 could be recorded on the oscilloscope. This voltage is slightly lower than the 111 -1200 V used in [3], which was found to be optimal with the same detectors. 112 The limited vertical acceptance range of the oscilloscope (1 V) meant that the 113 optimal voltage could not be used. However, in [15] the difference in resolution 114 between $LaBr_3(Ce)$ detectors operating at -1100 V and -1300 V was found to 115 be ~ 15 ps. Hence the use of a slightly lower than optimal voltage is expected 116 to result in only a small degradation in time resolution (<15 ps). 117

¹¹⁸ Data taken with a 264-kBq ⁶⁰Co source were used to find the best resolution ¹¹⁹ of each algorithm at energies of ~1.2 MeV. This source first β^- decays and then ¹²⁰ emits a cascade of two γ rays of energy 1173.2- and 1332.5-keV. The halflife of ¹²¹ the intermediate state is 0.7 ps, negligible compared to the time resolution of ¹²² the γ -ray detectors. Some 3×10^5 coincident traces were captured.

A 27.0-kBq ¹⁵²Eu source was used to determine how the different algorithms 123 perform for γ -ray transitions across a wider energy range. A total of 3.1 \times 124 10^6 coincidence traces were recorded. Around 20 intense γ rays are emitted 125 by this source, which form $\gamma - \gamma$ cascades distributed in two nuclei, ¹⁵²Gd 126 and ¹⁵²Sm [16]. These cover an energy range of 121.8 to 1299.1 keV, however 127 several lifetimes of the intermediate states are in the 100-ps-to-ns time range. 128 Use of these cascades would add appreciable widths to time spectra and are 120 unsuitable for this study. However the 344.3-keV transition is coincident with 130 five transitions covering an energy range of 367.8–1299.1 keV. For four of these 131 $\gamma - \gamma$ coincidences the intermediate state is the 344.3-keV one, with a lifetime 132 of 46.7 ps [16]. The fifth one is the 367.8–344.3-keV coincidence which is part 133 of a triple- γ cascade with a mean lifetime of 57.2 ps. Therefore for this set 134 of $\gamma - \gamma$ cascades mean lifetimes of a similar ~50 ps are present, allowing a 135 qualitative comparison of the performance of each algorithm as a function of 136 the γ -ray energy coincident with a 344.3-keV transition. The performance of 137 these algorithms at energies of around 511 keV is relevant to PET applications 138 [17], though the crystals used in the current study are optimised for lifetime 139 measurements of excited nuclear states. 140

¹⁴¹ 3. Algorithms and Results with ⁶⁰Co

¹⁴² Before applying any timing algorithms the first procedure was to extract the ¹⁴³ average value of the pulse baseline. This quantity varies from pulse to pulse and ¹⁴⁴ was obtained simply by finding the average of the first 300 sample points. These ¹⁴⁵ all lie at times earlier that the first sample point registering the interaction of a ¹⁴⁶ γ ray, as can be seen in Fig. 1. This shows a typical anode pulse from one of the ¹⁴⁷ LaBr₃(Ce) detectors captured by the oscilloscope. The data points presented



Figure 1: Example of an anode pulse captured by the 40 GS/s oscilloscope. The data points shown are the ones analysed and these are the raw ones reflected about the x-axis, as explained in the text. The zoomed inset allows the noise present in the baseline and at the start of the rising pulse to be observed.

were reflected across the x-axis so that all values are positive. This was done to simplify algorithm implementation. The energy of the deposited γ -ray signal was found using a simple running integration algorithm, which sums all sample points found above the baseline. An energy resolution (FWHM) of 3.4(1) % was measured at 1332.5 keV, the same as reported in [9, 10].

If the energies of both pulses were found to fall within ± 20 keV of the individual photopeak energies of interest then timing algorithms were applied to the event. These algorithms are listed below. Examples of gated energy spectra measured using the ⁶⁰Co source are shown in Fig. 2. Here one observes only the other transition of the $\gamma - \gamma$ cascade and Compton background.

In order to quantify the timing performance of each algorithm when analysing $\gamma - \gamma$ events, differences between the trigger times of each detector were plot-



Figure 2: Energy spectra obtained with the $LaBr_3(Ce)$ detectors when energy gates are set on one transition and then the other of the cascasde.

ted. In all cases the full-width half-maximum (FWHM) value of the assumed Gaussian time distribution is used to define the resolution. As the detectors are essentially identical, then the measured FWHM can be divided by $\sqrt{2}$ to obtain the resolution of each individual detector, to a good approximation. This allows a comparison with results reported in the literature for each detector type, for example those of [3]. Identical γ -ray gates were set when processing the data with each algorithm.

$_{167}$ 3.1. Leading edge with a ^{60}Co source

The leading-edge algorithm produces a trigger-time marker when the pulse 168 trace first crosses a set threshold. For the data taken with the 60 Co source, the 169 FWHM was measured as a function of the threshold energy. Use of interpolation 170 between the sample points did not improve the time resolution. This agrees with 171 the conclusions of [8] for high sampling frequencies. There it was reasoned that 172 the higher density of sampling points means that the difference between the 173 actual detector pulse and a linear interpolation between any two sample points 174 becomes negligible. 175

An example time spectrum obtained with the $LaBr_3(Ce)$ detectors is shown 176 in Fig. 3. The results obtained are shown in Fig. 4 where the change in FWHM 177 is shown as a function of the threshold value. The maximum pulse height is 178 around 35000 (arbitrary units) and the best FWHM values are obtained with 179 the threshold set at 10-20 % of this maximum. A similar behaviour is found 180 in analogue leading-edge modules and in previous studies using digital leading-181 edge algorithms (15 %) [17]. One observes that there is a regular degradation 182 of the FWHM with increasing threshold values. Threshold values below $\sim 5 \%$ 183 of the pulse height produced spurious peaks due to noise. The best resolution 184 obtained with this algorithm was 177(4) ps. 185

¹⁸⁶ 3.2. Cubic Polynomial Slope Fit and Leading Edge with a ⁶⁰Co source

In order to remove any high-frequency noise contribution to the leading-edge
algorithm, the rising slope of each trace was captured and fitted with a cubic
polynomial function. This function was the lowest order polynomial found to



Figure 3: Example time spectrum measured with the leading edge algorithm and a $^{60}\mathrm{Co}$ source.



Figure 4: Full width half maximum (FWHM) of time signals obtained with a leading-edge algorithm as a function of the threshold value for a single detector, de-convoluted from the measured distribution.



Figure 5: Full width half maximum (FWHM) of time signals obtained with a cubic slope-fit algorithm as a function of the threshold value for a single detector, de-convoluted from the measured distribution.

accurately reproduce the rising edge of the detector pulses, in line with the 190 results of [18]. A leading edge threshold was then applied to the fit function 191 describing each individual pulse, producing a reference time. Fits were applied 192 across rising slopes varying from 10 %–90 %, 5 %–90 %, 5 %–50 % and 5 %–30 % 193 of the pulse peak height. The best results were obtained for fits over the range 194 5 %-90 % and 5 %-50 % of pulse height, where equivalent time resolutions, 195 within errors [143(3) ps], were obtained. The threshold parameter was also 196 varied until the smallest FHWM was found. A value close to the one in Sec. 3.1 197 was optimal. The results are shown in Fig. 5. One notes that it is possible to 198 apply this algorithm with a lower threshold value than for the raw signals of 199 Sec. 3.1, due to the absence of high-frequency noise on the fitted polynomial 200 function. 201

The digital leading-edge algorithm of Sec. 3.1 and the cubic polynomial slope fit, followed by a leading edge trigger, used here trigger on signals in a very sim²⁰⁴ ilar manner. A comparison of the results obtained by each allows an estimation ²⁰⁵ of the influence of higher frequency noise harmonics on the signal time resolu-²⁰⁶ tion, because high-frequency noise is smoothed out in the fit analysis. As noise ²⁰⁷ contributions add in quadrature, then one obtains FWHM_{highfreq}=104(3) ps ²⁰⁸ for the high-frequency noise component, a significant amount.

$_{209}$ 3.3. Constant Fraction with a ^{60}Co source

The constant fraction (CFD) algorithm used in the analysis of the detector signals is the digital equivalent of the ones used in analogue modules. An input signal is duplicated, inverted and delayed. The original signal is then attenuated by a fraction f and the zero-crossing of the sum of these two signals corresponds to the reference time. The CFD algorithm is written as

$$CFD[i] = f \times V[i] - V[i - delay]$$
⁽¹⁾

where f is the fraction of the attenuated signal, V[i] is the pulse height of the 215 sample at bin number i and delay is the time by which the duplicated signal is 216 retarded [19]. This algorithm was tested over a range of values of f, from ~ 0.2 217 to 0.4, corresponding to the ones used in analogue modules. Values of f below 218 0.15 could not be applied due to noise. The results are shown in Fig. 6. Similarly 219 the delay parameter was varied until an optimal result was obtained. The best 220 delay values are close to the peak rise time, again in line with the settings of 221 an analogue CFD. The performance of the algorithm is relatively insensitive to 222 changes in delay times over a large range of values, as shown in Fig. 7. A time 223 resolution of 178(4) ps was the best one obtained with this algorithm. 224

$_{225}$ 3.4. Autocovariance with averaged pulse-shapes with a ^{60}Co source

For each pair of applied energy gates pulses in each detector were summed and then averaged. This produced approximately "ideal" pulses, almost noise free, though still retaining any subtle systematic inflexions inherent to each detector pulse.

Once the set of average pulses had been obtained then each pulse in a given detector, falling within the range of the energy gate, was then compared to it.



Figure 6: Full width half maximum (FWHM) of a digital constant-fraction algorithm as a function of the fraction of the attenuated signal for a single detector, de-convoluted from the measured distribution. A delay of 6.25 ns was used.



Figure 7: Full width half maximum (FWHM) of a digital constant-fraction algorithm as a function of the delay time of the duplicated signal for a single detector, de-convoluted from the measured distribution. A fraction of f=0.18 was used.

This was done by calculating the variance between the rising slope of a pulse 232 of a given event and the average one, within the same height interval, using 233 Welford's algorithm [20]. The event pulse was then shifted by one sample and 234 the variance calculated again. Once the variance had been calculated across 235 a set range of shifts, the minimum variance was obtained, allowing the "lag" 236 between the individual pulse and the average one to be determined. The lag 237 value can then be used to determine a trigger time. It is worth noting that this 238 algorithm has no threshold dependence. 239

The vertical range over which the variance was calculated was changed and the optimal one was found to be 5–20 % of the pulse height, giving a resolution of 155(3) ps. This is shown in Fig. 8, where resolution is plotted as a function of analysed pulse height. Equivalent results were obtained when comparing 20 channels of the event pulse to the average one, once a low-energy threshold was crossed. This latter method is less computationally intensive.

The method described here is practically identical to the "Mean PMT pulse 246 model" used by Aykac et al. to analyse pulses from LSO cyrstals [21]. We 247 note that a procedure with a similar philosophy has been used for an entirely 248 different γ -ray spectroscopy application. The shapes of pulses recorded from 249 the segmented outer contacts of 36-fold AGATA Ge detectors are compared to 250 those found in a library of measured interactions [22]. This allows the interaction 251 position of γ rays to be found with a precision of a few mm in a large-volume 252 Ge detector. 253

²⁵⁴ 3.5. ⁶⁰Co Source Results Summary and Comparison with Literature

A summary of the results obtained with each algorithm is shown in Table 1. As ~1000 $\gamma - \gamma$ coincidences were analysed, then the statistical contribution to the error $(\frac{\sigma}{\sqrt{n}})$ is around 2 ps. These results can be compared to the time resolutions reported in the literature using analogue pulse-processing electronics. A study of the performance of conical LaBr₃(Ce) detectors, with the same dimensions as used here, reported a FWHM value of 110(3) ps with a ⁶⁰Co source [3]. The results obtained with the cubic polynomial slope fit are 30(1) % worse. In a



Figure 8: Full width half maximum (FWHM) of a digital autocovariance algorithm as a function of upper limit of the peak signal voltage for a single detector, de-convoluted from the measured distribution.

| Leading Edge | Leading Edge Slope Fit | CFD | Autocovariance |
|--------------|------------------------|------------|----------------|
| 177(4) ps | 143(3) ps | 178(4) ps | 155(3) ps |

Table 1: Summary of best values of FWHM achieved for each algorithm with a $^{60}{\rm Co}$ source and a 10-bit 40 GS/s oscilloscope.

recent study using a 16-bit 5 GS/s digitizer with the same $LaBr_3(Ce)$ detectors 262 a time resolution of 106(1) ps was reported, using the same type of radioac-263 tive source and a timing algorithm developed using machine learning [10]. This 264 result surpasses all the ones obtained in the present work. In [8] a spline inter-265 polation with a sinc function of the pulse rising slope using a 14-bit, 0.5 GS/s 266 digitizer gave results equivalent to those reported using analogue electronics [3] 267 for $1^{"} \times 1^{"}$ LaBr₃(Ce) crystals [97 ps versus 98(2) ps]. This shows that a higher 268 sampling frequency does not necessarily lead to improved time resolution if the 269 vertical resolution is low and these points are discussed below. 270

271 4. Sampling Frequency

The performance of each algorithm was tested as a function of sampling fre-272 quency, using the data taken with the 60 Co source. The results are shown in 273 Fig. 9. Optimal parameters at sampling rates of 40 GS/s, reported in previous 274 sections were used throughout. Unsurprisingly the best performance is found 275 at a sampling frequency of 40 GS/s, though little degradation of the FWHM 276 is seen at 20 GS/s. At sampling frequencies of 4 or 5 GS/s, the resolution is 277 typically 30-60 % worse. The results obtained in the present work differ from 278 the conclusions of Aykac et al. [21] who studied the performance of small LSO 279 detectors for PET applications. There they found that optimal digital algorithm 280 performance was already attained at a sampling rate of 4 GS/s. Similarly War-281 burton and Henning [8] and Nakhostin *et al.* [10] were able to obtain results 282 equivalent to the best ones achieved with analogue systems, though at lower 283 frequencies of 0.5 and 4 GS/s using digitizers with 14 and 16 bits. This points 284 towards vertical resolution being a more important parameter than sampling 285 speed in the GS/s domain for $LaBr_3(Ce)$ detectors. More formally the vertical 286



Figure 9: Full width half maxima (FWHM) of time peaks extracted with different digital algorithms as a function of sampling frequency for a single detector, de-convoluted from the measured distribution.

resolution (number of bits) must be high enough that the quantization error is
below the electronic noise of the signal [18].

289 5. ¹⁵²Eu data

The evolution of the peak FWHM as a function of energy, measured with the 152 Eu source is shown in Fig. 10. Here one gate was set on the 344.3-keV γ -decay of 152 Gd and the peak FWHM was measured when the second gate was set at other photopeak energies (367.8, 411.1, 778.9, 1089.7 and 1299.1 keV). There were around 1000 counts in each coincidence time spectrum. The 344.3-1089.7-keV data points were removed from the fit as they were found to be systematically higher than the trend lines, likely due to contamination with the 1085.9-keV transition in 152 Sm.

In Fig. 10 the autocovariance function is seen to have the best resolution across the range of energies studied. This energy range is typical of fast-timing



Figure 10: Measured peak full width half maximum (FWHM) values as a function of transitions found in coincidence with the 344.3-keV γ ray emitted following the decay of a ¹⁵²Eu source.

experiments aiming to study the lifetimes of excited states in the 10s-of-ps to
 ns time range.

An important parameter in fast-timing measurements is the prompt-response 302 difference (PRD) [6, 7, 16]. This function is used to determine the zero-time 303 position as a function of energy and it depends on the settings of the analogue 304 discriminator used. The "walk" of this zero-time position typically changes 305 by a few hundred picoseconds over an energy range of 100 keV to 1.5 MeV. 306 Uncertainties in the PRD generally limit the precision of high-statistics fast-307 timing measurements, hence the interest in obtaining PRD functions which are 308 as flat as possible [23, 24]. Despite the 3.1×10^6 coincident events recorded 309 with the 152 Eu source there were insufficient statistics to reliably determine the 310 PRDs of the all digital algorithms tested here. 311

312 6. Conclusion

The time resolutions obtained with four different timing algorithms have 313 been measured with a pair of 38-mm long, 38-mm wide truncated-cone shaped 314 LaBr₃(Ce) fast-timing detectors using a 10-bit, 40 GS/s oscilloscope. The time 315 resolution obtained with a cubic polynomial slope fit leading-edge algorithm 316 gave the best result with a 60 Co source [143(3) ps], though this is 30(1) % worse 317 than values achieved using analogue pulse-processing electronics. The perfor-318 mance of the autocovariance function was slightly inferior [155(3) ps], but better 319 than the leading edge [177(4) ps] and constant-fraction [178(4) ps] algorithms. 320 The autocovariance function was found to have the best performance for coin-321 cidences in the energy range 344.3–1299.1-keV. This may be because the cubic 322 polynomial slope fit algorithm used relies on a leading-edge threshold trigger, 323 with settings optimised for ⁶⁰Co lines. The performance of this algorithm may 324 therefore degrade when applied to lower-energy γ -rays. Reducing the sampling 325 frequency to 20 GS/s was found to only slightly degrade the time resolution of 326 these algorithms. The results obtained in the present work are a few tens-of-327 picoseconds worse than those obtained using a 16-bit, 5 GS/s digitizer module 328

³²⁹ [106(1) ps] [10], demonstrating that high vertical resolution is more important than sampling speed in the GS/s domain when using these detectors.

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