



Full Length Article

Energy and coincidence-time resolution of the LaBr₃:Ce-MPPC™ detectors under magnetic fields

Ian Chang Jie Yap^{a,*}, Juliana Heiniger-Schell^{a,b}, Thien Thanh Dang^a,
Nicole Pereira De Lima^c, Björn Dörschel^a, Magnus Hegelund Stegenborg^d,
Alexandre Pinho dos Santos Souza^c, Bruno Santos Corrêa^{c,e}, Arnaldo Alves Miranda Filho^c,
Adeleh Mokhles Gerami^f, Doru Constantin Lupascu^a

^a Institute for Material Science and Center for Nanointegration Duisburg-Essen (CENIDE), University of Duisburg-Essen, Essen, 45141, Germany

^b European Organization for Nuclear Research (CERN), Geneva, CH-1211, Switzerland

^c Instituto de Pesquisas Energéticas e Nucleares IPEN-CNEN/SP, São Paulo, 05508-000, Brazil

^d Aalborg Universitet, Department of Materials and Production, Frederik Bajers Vej 16, Aalborg, 9220, Denmark

^e Faculdade de Ciências Exatas e Tecnologia, Universidade Federal do Pará (UFPA), Abaetetuba, PA, 68444-000, Brazil

^f School of Particles and Accelerators, Institute for Research in Fundamental Sciences (IPM), P.O. Box 19395-5531, Tehran, Iran

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ABSTRACT

Time-differential perturbed angular correlation (TDPAC) spectroscopy is a nuclear solid-state technique that requires high energy and coincidence-time resolutions from scintillation crystals and photodetectors. Traditionally, photomultiplier tubes (PMTs) have been coupled to LaBr₃:Ce crystals; however, they have been replaced by Multi Pixel Photon Counters (MPPCs) for TDPAC experiments conducted under external magnetic fields. In this report, we show that, for TDPAC spectroscopy, the performance of the LaBr₃:Ce-MPPC detector remains stable under magnetic fields up to 8.5 T (in 1 T steps), as evidenced by the unchanged energy and coincidence-time resolutions of the 511 keV peaks from positron–electron (e⁺–e[–]) annihilation in a sealed ²²Na calibration source.

1. Introduction

Time-differential perturbed angular correlation (TDPAC) is a nuclear solid-state physics technique [1–6] that investigates the local environment of a suitable radioactive isotope (probe) by measuring the time difference, on the order of nanoseconds, between the sequential emissions of two well-defined, energetically distinct nuclear gamma rays. To effectively resolve perturbations, TDPAC detectors require excellent timing resolution and acceptable energy resolution, typically better than 10% at 511 keV.

Photomultiplier tubes (PMTs) coupled to a LaBr₃:Ce scintillator (hereafter referred to as a LaBr₃:Ce–PMT detector system) have been widely used for this purpose. LaBr₃:Ce crystals exhibit outstanding properties: (1) a high visible-light yield (>65,000 photons/MeV) [7], (2) a linear light-output response across a wide range of gamma-ray energies, often referred to as the dynamic range [7], and (3) excellent resistance to gamma irradiation, as indicated by their high radiation

hardness [8].

These properties enhance the overall energy resolution compared to the commonly used NaI:Tl crystal [9]. LaBr₃:Ce also exhibits fast rise and decay times [10], which contribute to an impressive coincidence-time resolution in the sub-nanosecond range, depending on the crystal type and geometry [11–13]. PMTs support this performance by providing (1) high gain (~10⁷ electrons per photon) [13,14], (2) favorable photon detection efficiency (PDE) for wavelengths around 360 nm [15], within the visible spectrum that match the emission spectrum of LaBr₃:Ce [16], and (3) fast rise times (~1.5 ns) for incoming photon signals [17,18].

At ISOLDE-CERN [19,20], we plan to perform TDPAC experiments using samples exposed to an externally applied magnetic field of up to 8.5 T. In the setup, the sample and detectors are positioned at the center of the superconducting magnet bore. PMTs pose two main challenges in this configuration: (1) geometric constraints, as their length makes them difficult to accommodate within the bore, and (2) a marked decline in performance under moderate magnetic fields and complete failure

* Corresponding author.

E-mail address: ian.yap@cern.ch (I.C.J. Yap).

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under high fields [21–23]. Consequently, we consider silicon photomultipliers (SiPMs), first developed in the early 1990s [24,25], as an alternative to PMTs.

SiPMs are solid-state photodetectors that operate with functionality similar to PMTs [26,27]. Multi Pixel Photon Counters (MPPCs), a trademarked version of SiPMs developed by Hamamatsu [28], offer performance comparable to PMTs, including (1) high gain ($\sim 10^6$ electrons per photon), (2) comparable photon detection efficiency peaking at 40% at 450 nm across the visible spectrum, and (3) fast and sharp rise times (~ 0.3 –1 ns) for incoming photon signals contributing to good coincidence-time resolution [28].

MPPCs offer additional advantages over PMTs in several key areas: (1) no susceptibility to magnetic fields [29], because avalanche multiplication occurs within a confined depletion region on the micrometer scale [30] making charge transport highly localized; whereas in PMTs, photoelectrons traverse several centimeters through a dynode chain in vacuum, making them susceptible to magnetic-field deflection; (2) lower operating voltages, as MPPCs require tens of volts while PMTs typically require around 1 kV [31]; and (3) compact dimensions (approximately $2.5 \text{ cm} \times 2.5 \text{ cm} \times 1 \text{ cm}$ including the carrier board), allowing multiple $\text{LaBr}_3\text{:Ce}$ -MPPC detectors to be installed within the bore of a superconducting magnet, which is not feasible for $\text{LaBr}_3\text{:Ce}$ -PMT systems.

The energy and coincidence-time resolutions of $\text{LaBr}_3\text{:Ce}$ -MPPC detector systems have been extensively studied. Their energy resolution falls within the single-digit percentage range [15,32,33], and they can achieve coincidence-time resolutions of 0.1 ns [32,33], depending on the intrinsic size and geometry of the MPPC and LaBr_3 crystal. These performance levels are comparable to, and often advantageous over, many PMT-based configurations.

Additionally, under a magnetic field of 3 T, the energy resolution of the $\text{LaBr}_3\text{:Ce}$ -MPPC detector remains largely unchanged compared to the more established $\text{LaBr}_3\text{:Ce}$ -PMT counterpart [34]. Other studies similarly report that the performance of MPPC-based scintillation detectors is mostly unaffected by strong magnetic fields. For example, one study observed no significant changes in energy resolution or gain in an LYSO-MPPC setup at 7 T compared to 0 T [35], while another found that the coincidence-time resolution of an LSO-MPPC system remains unaffected in a 7 T magnetic resonance (MR) scanner [36].

Our upcoming TDPAC spectrometer, MULTIPAC (*Multifunctional Perturbed Angular Correlations Setup*) [37,38], requires the $\text{LaBr}_3\text{:Ce}$ -MPPC system to maintain its key detector characteristics, specifically: (1) no distortion of pulse-wave representations of incoming gamma photons across at least the 0–1000 keV range and (2) no degradation in energy or coincidence-time performance under magnetic fields up to 8.5 T. To date, no published work has demonstrated that the energy and timing performance of $\text{LaBr}_3\text{:Ce}$ -MPPC detectors remains unchanged under such strong magnetic fields. Therefore, this study aims to systematically measure the energy and coincidence-time resolutions of some detector pairs installed within the bore of MULTIPAC's superconducting magnet at varying magnetic field strengths. Table 1 summarizes the relevant performance requirements for TDPAC spectroscopy

in high static magnetic fields.

Establishing the invariance of energy and coincidence-time resolution for $\text{LaBr}_3\text{:Ce}$ -MPPC detectors at magnetic fields up to 8.5 T will demonstrate that MULTIPAC is conceptually robust. Building on the foundation established in this work, MULTIPAC will enable new research projects involving TDPAC under external magnetic fields, including the precise measurement of the Knight shift of e.g. cadmium in palladium [37,38]. Additional details regarding MULTIPAC can be found in the report by Hegelund [39].

2. Methods

2.1. Instruments

The scintillator crystals used in this study are commercially manufactured $\text{LaBr}_3\text{:Ce}$ crystals (Advatech, UK) enclosed in hygroscopic-proof aluminum casings [40]. Each crystal is cylindrical, measuring 38 mm in diameter and 38 mm in height. The serial numbers follow the format AT0095-00x, where “x” denotes the set {2, 4, 5, 8}. The corresponding best energy resolutions reported by the manufacturer (percentage at 662 keV using $\text{LaBr}_3\text{:Ce}$ -PMT detectors) are 2.88%, 3.26%, 3.15%, and 3.03%.

The photodetector used is the commercially available S13361-6050AE-04 MPPC from Hamamatsu [41,42], designed for precise measurements in high-energy physics. It detects visible light within the emission spectrum of $\text{LaBr}_3\text{:Ce}$, with a peak photon detection efficiency (PDE) of 40% at 450 nm. The device offers a wide dynamic range, enabling a linear response across a defined gamma-ray energy range and provides a high-speed response suitable for time-of-flight measurements such as TDPAC. It also exhibits lower levels of optical crosstalk, afterpulsing, and dark count rate compared with other Hamamatsu models or competing detectors. The MPPC is arranged as a 4-by-4 channel array with a pixel density of 14,436 pixels per channel.

The MPPC array covers 50.79% of the $\text{LaBr}_3\text{:Ce}$ crystal face, whereas spectroscopy-grade PMT assemblies (e.g., Hamamatsu H3378-50) provide full optical coverage. This partial coverage naturally limits the energy resolution, and any imperfect grease coupling would further reduce light collection efficiency.

A custom MPPC carrier board, developed in collaboration with Nagl and Vetter [43], supplies a temperature-compensated bias voltage [44] to the MPPC cathode (although the compensation module was disabled during all measurements) and routes the anode signals to the digital acquisition (DAQ) system. All channel outputs are combined and then fed into the digitizer.

The DAQ workstation was built using an AMD Threadripper Pro 5995WX processor [45] mounted on an Asus Pro WS WRX80E-SAGE SE WIFI motherboard [46]. Its high PCIe bandwidth, supporting PCIe 4.0 $\times$ 128 lanes, enables the connection of six PCIe 2.0 $\times$ 8 digitizers (via 30 cm risers) without transfer bottlenecks, which had affected the earlier KATAME setup [11].

The digitizer used is the U5310A from Acqiris [47], a 10-bit device with a bandwidth of up to 2.5 GHz capable of processing the pulse signals from the detectors. It operates at a sampling rate of 5 gigasamples per second (GS/s) per input channel. When interleaving (using two channels for a single input) is enabled, the sampling rate increases to 10 GS/s. This corresponds to time bins of 0.2 ns without interleaving and 0.1 ns with interleaving. The digitizer offers full-scale ranges of either 0.25 V or 1 V; we selected the 1 V range. The nominal re-arm (dead) time for the U5310A digitizer is 0.8 μ s.

When more than two digitizers are used, the REF IN slot of each U5310A digitizer is connected to a standard 100 MHz clock. This 100 MHz clock is generated by feeding a 10 MHz sine-wave output from a generic oven-controlled crystal oscillator (OCXO) into a generic phase-locked loop (PLL) crystal oscillator, which multiplies the input frequency by a factor of ten, producing a 100 MHz sine wave at 14 dBm. The quality of both the 10 MHz and 100 MHz signals was verified using

Table 1
Requirements of TDPAC spectroscopy under high static magnetic fields.

Requirements	Quantitative target
Coincidence-time resolution (FWHM)	≈ 1.0 ns (to resolve Larmor frequencies ω_L up to $\sim 2\pi \times 100$ MHz).
Energy resolution	$\leq 10\%$ at 511 keV (for clean gating and background suppression).
Pulse-shape fidelity	No field-dependent distortion up to 8.5 T.
Digitization rate	≥ 10 GS/s, to preserve pulse shape and accurately sample the rising edge of the signal.
Magnetic field stability & homogeneity	Uniform homogeneous field in the +z direction.
Detector magnetic immunity	Detector gain and timing should remain stable across field strengths.

an external oscilloscope and a spectrum analyzer. The 100 MHz output is split n ways using a power splitter and attenuated to 0 dBm when necessary. Each digitizer receives the split 100 MHz square wave as its REF IN signal and uses an internal PLL to generate a 5 GHz clock. The jitter introduced by the digitizer's internal PLL is negligible, as confirmed by splitting a 1 Hz square-wave signal from a frequency generator, feeding the outputs into different digitizers (Channel 1 with interleaving enabled), and observing that the relative time drift remains within ± 0.1 ns (the detection limit imposed by the sampling rate) over a 3-h period.

A cryogen-free superconducting magnet, custom-built by Cryogenic Ltd. [48], was used to perform the TDPAC measurements under external magnetic fields. Designed as a solenoid, the magnet allows positioning of the ^{22}Na source and $\text{LaBr}_3\text{:Ce-MPPC}$ detectors at its center, ensuring uniform exposure to magnetic fields ranging from 0 to 8.5 T, which is the maximum operational field for our setup.

2.2. Experiments

Two experimental configurations were used. In all configurations, time information was obtained using Nagl's Digital Constant Fraction of Integral values (DCFI) method [11]. For each recorded gamma pulse $w(t) \in \mathbb{R}^+$ (with $t \geq 0$), the timestamp was determined as follows:

- The pulse was integrated over time: $\int_{\mathbb{R}^+} w(t) dt$;
- The result was divided by a free divisor $d \in \mathbb{R}^+$ to compute the voltage trigger level: $\frac{1}{d} \int_{\mathbb{R}^+} w(t) dt$;
 - Throughout this work, the divisor was fixed at $= 10^{-6}$.
- The timestamp t_0 was obtained from the rising edge of $w(t)$ using cubic interpolation:

$$t_0 = \operatorname{argmin}_{t \geq 0, w'(t) > 0} \left| w(t) - \frac{1}{d} \int_{\mathbb{R}^+} w(t) dt \right|.$$

The detectors remain at a stable but uncontrolled temperature of approximately 281 K (8 °C), maintained by passive heat transfer between two extremes: the laboratory environment (293 K, 20 °C) and the bore wall of the superconducting magnet, which is cooled to 3.7 K by

circulating helium. Apart from the temperature sensor on the carrier board, no active temperature control, such as PID-regulated Peltier elements, was used.

For each experimental configuration, data were collected at magnetic field strengths from 0 to 8 T in integer steps and at 8.5 T representing the maximum accessible field.

2.2.1. Two detectors to one U5310A digitizer

Two $\text{LaBr}_3\text{:Ce-MPPC}$ detectors were connected to a single U5310A digitizer (Fig. 1), with one detector assigned to Channel 1 and the other to Channel 2. One channel was designated as the *active channel*, configured to acquire signals using a rising-edge trigger with a 0.05 V threshold. The other channel served as the *passive channel*, recording signals whenever the active channel triggered.

The U5310A digitizer was set to record 100,000 signals per run, with a trigger delay of -100 ns. Thus, it captured data beginning 100 ns before the trigger, which was activated by the rising edge of the 0.05 V signal. Each recorded signal contained 5250 data points; with a time bin of 0.2 ns, the total acquisition window was 1.05 μs including the pre-trigger region.

The applied voltages to detectors 1 and 2 ranged from 59.9 to 60.0 V. Temperatures ranged from 8.7 to 10.8 °C for detector 1 and from 8.3 to 10.0 °C for detector 2.

Two different energy spectra were obtained (bottom-left graph in Fig. 1):

- Active Channel: The energy spectrum exhibits two peaks:
 - The 511 keV peak from positron–electron (e^+e^-) annihilation,
 - The 1275 keV peak from de-excitation of the ^{22}Ne nuclear state.
- Passive Channel: The spectrum is dominated by the 511 keV peak, along with lower-charge events arising from Compton scattering in the $\text{LaBr}_3\text{:Ce}$ crystal. This occurs because:
 - The e^+e^- annihilation produces two 511 keV gamma photons emitted in opposite directions.
 - The passive channel is triggered simultaneously with the active channel.

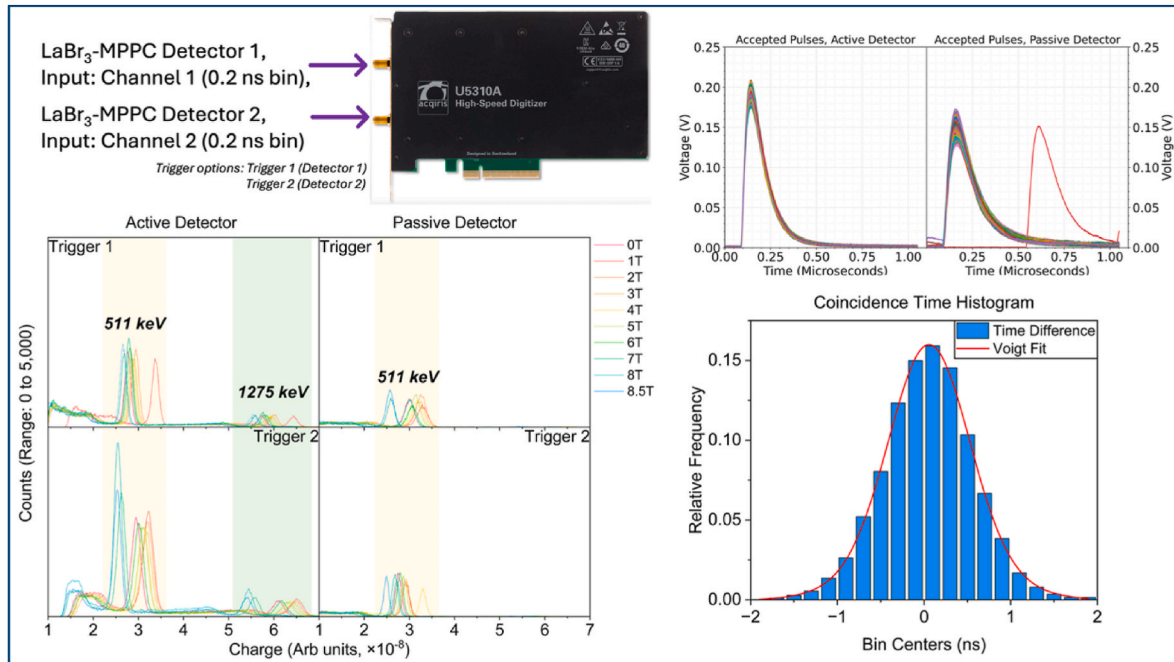


Fig. 1. Experimental configuration: Two detectors connected to a single U5310A digitizer (Section 2.2.1). Top left: Detector arrangement and trigger configuration. Bottom left: Histogram of the charge distribution of the acquired pulses (energy spectra). Top right: Pulse shapes corresponding to events within the 511 keV cutoff region. Bottom right: Coincidence-time histogram with Voigt fit. The active and passive detectors operate in parallel.

As a result, many signals in the passive channel contain zero charge (i.e., flat-line outputs).

The corresponding time-coincidence spectra were obtained as follows:

- A Voigt fit was applied to the 511 keV peaks in the background-subtracted energy spectra of both active and passive channels.
- A cutoff region was defined as 1/8 of the peak amplitude from the Voigt fit, and only pulses within this region were selected for coincidence analysis.
- Pulses from both channels were assigned a common time point, if their charges fell within the cutoff region. These time points were accumulated into a coincidence-time histogram with a bin size of 0.2 ns.
- A Voigt fit was applied to the coincidence-time histogram to determine the coincidence-time resolution.

Signal timestamps were generated using the internal clock of the digitizer without an external timing reference.

2.2.2. One detector to one U5310A digitizer

The four $\text{LaBr}_3\text{:Ce}$ -MPPC detectors were connected to Channel 1 (with interleaving enabled) of their respective U5310A digitizers (Fig. 2). In this configuration, all detectors used a rising-edge trigger threshold of 0.08 V. As described in Section 2.1, the internal clocks of the U5310A digitizers were synchronized using a shared 100 MHz clock connected to the REF IN inputs.

The U5310A digitizer was configured to acquire 10,000 signals per run, with multiple runs collected over approximately 10 min of laboratory time. The trigger delay was set to -100 ns. Each signal contains 10,500 data points; with a time bin of 0.1 ns, the total acquisition period is 1.05 μs , including the delay.

Detectors 1 and 2 were positioned facing each other, as were detectors 3 and 4. The voltage inputs to the $\text{LaBr}_3\text{:Ce}$ -MPPC detectors 1–4 ranged from 59.8 to 59.9 V, 59.7–59.8 V, 59.6–59.7 V, and 59.6 V, respectively. The measured temperatures ranged from 13.0 to 14.8 $^\circ\text{C}$, 12.5–13.4 $^\circ\text{C}$, 13.5–15.0 $^\circ\text{C}$, and 12.8–14.0 $^\circ\text{C}$ in ascending detector

order.

Each detector produced a similar energy spectrum, showing a 511 keV peak from e^+e^- annihilation and a 1275 keV peak associated with the de-excitation of the ^{22}Ne nuclear state (see the bottom-left graph in Fig. 2).

Two coincidence-time spectra were obtained from the four detectors arranged 90° apart in a plane, forming two parallel detector pairs. The procedure was as follows:

- The background-subtracted 511 keV peak for each detector in a parallel pair was fitted using a Voigt function.
- A cutoff region equal to 1/20 of the Voigt peak value was applied to both energy spectra to select suitable signals. This yielded two sets of pulse signals, one from each detector, referred to as “Accepted_pulse_set_A” and “Accepted_pulse_set_B.” Without loss of generality, assume that “Accepted_pulse_set_A” contains fewer pulses than “Accepted_pulse_set_B.”
- Because the digitizer's dead (re-arm) time is approximately 1 μs , successive pulses in each set are separated by at least this duration. For each pulse in “Accepted_pulse_set_A,” a corresponding pulse in “Accepted_pulse_set_B” was identified by selecting the pulse with the smallest timestamp difference. The minimum time difference was recorded as a single time point.
- To eliminate random coincidences (defined as time differences exceeding 1 μs , which is beyond the coincidence threshold established in step c), a histogram of the collected time points was generated with a bin size of 10^{-6} s. Following the bin discrimination principle, only the bin with the highest count was retained as the genuine coincidence peak; all other bins were discarded as random background. This produced an accepted set of coincidence time points per run. Because multiple runs were collected for each applied magnetic field value, the sets were combined and histogrammed using a 0.1 ns bin size. A Voigt fit was then applied to determine the coincidence time resolution.

Raw pulse waveforms exhibit inherent noise caused by several sources of interference during signal generation. $\text{LaBr}_3\text{:Ce}$ -MPPC

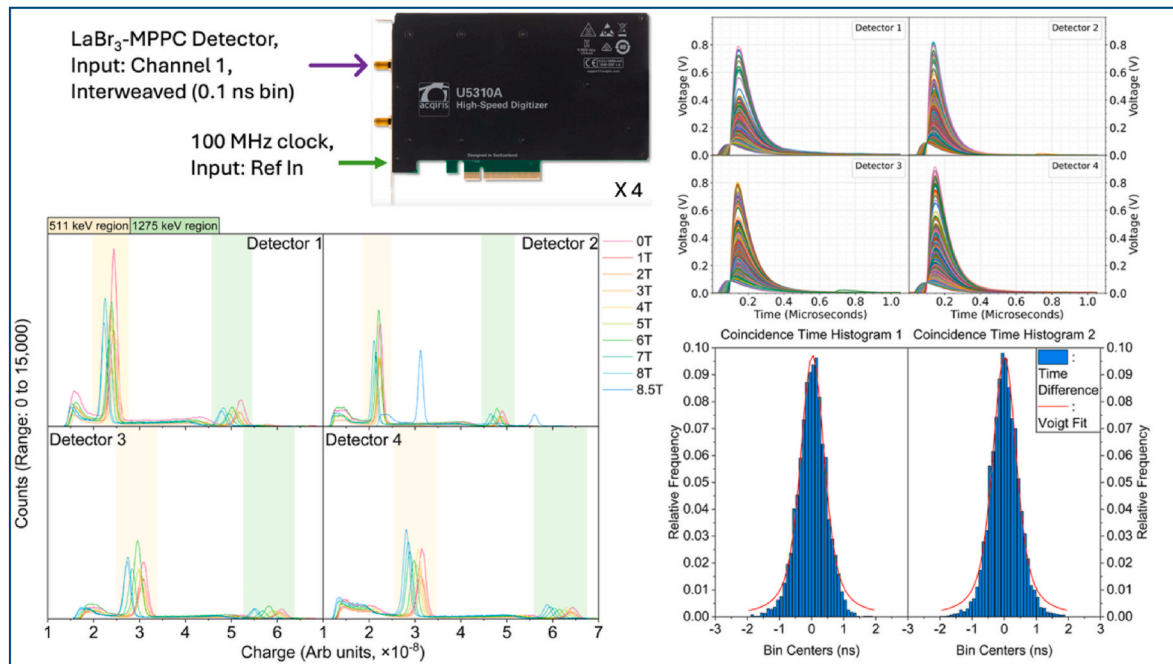


Fig. 2. Experimental configuration: One detector connected to a single U5310A digitizer (Section 2.2.2). Top left: Detector configuration, including the reference clock input. Bottom left: Histogram of pulse charge distributions (energy). Top right: Pulse shapes within the 511 keV cutoff region. Bottom right: Coincidence-time histogram with Voigt fit. Detector 1 parallels detector 3, and detector 2 parallels detector 4.

detectors are particularly susceptible to noise compared with traditional $\text{LaBr}_3\text{:Ce}$ -PMTs detectors for the following reasons:

- Increased thermal (dark) noise: MPPCs produce higher dark noise, because phonons and other thermal carriers in the solid-state matrix generate random signals even in the absence of incident light. In contrast, PMTs generally exhibit lower intrinsic dark counts and higher robustness in high-light environments.
- After-pulsing: MPPCs may exhibit delayed pulses when electrons become trapped at defect sites and are released later.
- Crosstalk: Crosstalk occurs when electrons leak between adjacent pixels (microcells), causing unintended amplification.

Technical details regarding after-pulses and crosstalk can be found in Ref. [30].

Given these noise characteristics, MPPCs require effective denoising. Low-pass finite impulse response (FIR) filtering is commonly used to smooth pulses. Among the available options—moving average, Gaussian, Savitzky–Golay, and wavelet filters—a second-order Butterworth filter was selected for its balance between (1) preserving the rising edge of the pulse and (2) attenuating predominantly high-frequency noise. The cutoff frequency was set to 0.05 GHz (0.1 GHz is also acceptable). A lower cutoff distorts the pulse shape, especially its rising edge, whereas a higher cutoff does not sufficiently remove high-frequency noise. To obtain accurate timestamps, filtering was applied bidirectionally (forward and backward), producing zero-phase filtering and effectively increasing the filter order to four.

Applying a zero-phase digital Butterworth low-pass filter with a cutoff frequency of approximately 0.1 GHz intentionally limits the useable bandwidth of the acquired waveforms. Let B denote the effective one-sided in-band bandwidth after filtering. To first order, B may be taken as equal to the filter cutoff frequency. Prior to filtering, quantization, and front-end noise are distributed over the full Nyquist bandwidth of the digitizer. The low-pass filter suppresses out-of-band noise, thereby reducing in-band noise power and improving the effective number of bits (ENOB).

Let f_s denote the sampling rate of the digitizer (10 GS/s with interleaving and 5 GS/s without). After filtering, the signal is oversampled relative to its bandwidth. Defining the oversampling factor as $k = f_s/2B$, the expected ENOB improvement for predominantly white noise is $\Delta\text{ENOB} = 0.5 \cdot \log_2(k)$. For $f_s = 10$ GS/s and $B \approx 0.1$ GHz ($k \approx 50$), this predicts an ENOB increase of approximately +2.8 bits; for $f_s = 5$ GS/s ($k \approx 25$), the expected increase is approximately +2.3 bits.

To verify the practical gain, Acqiris support tested a U5310A digitizer using a 48 MHz sine-wave input. Applying a 100 MHz digital low-pass filter increased the measured ENOB from approximately 7.1 to 9.5 bits ($\Delta\text{ENOB} \approx +2.4$ bits), consistent with theoretical expectations and indicative of non-white and synchronous noise components.

An equivalent approach is a moving-average-and-decimate operation, in which N consecutive samples are averaged (a length- N boxcar filter), and one out of every N samples is retained. Choosing $N \leq 25$ or $N \leq 50$ for initial sampling rates of 5 GS/s or 10 GS/s, respectively, preserves a Nyquist frequency of approximately 0.1 GHz and yields an effective sampling rate of roughly 0.2 GS/s.

2.2.2.1. Data pre-processing. A software algorithm was implemented to reject pulses containing additional gamma signals within the 1.05 μs digitizer window, thereby preventing contamination of single-event data. This algorithm exploits the fact that an ideal pulse (which is positive and real-valued) is unimodal, meaning that it exhibits only one central peak (see Ref. [49] for a formal definition of unimodality). Geometrically, a horizontal line $y = b$, $b \in \mathbb{R}^+$, will intersect such a pulse at most twice. If this line intersects the pulse three or more times, a secondary gamma arrival is indicated, and the event is flagged and discarded.

The performance of the zero-phase Butterworth filtering and the secondary-pulse rejection criterion is illustrated in Fig. 3, which compares raw and filtered waveforms, their derivatives, and the corresponding residuals. Fig. 4 presents the associated Fourier spectra, confirming that the selected cutoff frequencies effectively suppress high-frequency noise while maintaining the physically relevant pulse shape.

3. Results

3.1. Two detectors to one U5310A digitizer

Fig. 5 shows the energy resolution as a function of the external magnetic field strength (0–8.5 T), and Fig. 6 displays the corresponding coincidence-time resolution.

In Fig. 5, the full width at half maximum (FWHM; error bars) of the background-subtracted Voigt fits for the 511 keV (left) and 1275 keV (right) peaks is extracted from the energy spectra of the detectors connected to the active trigger channel of the U5310A digitizer. The labels (“Detector 1” and “Detector 2”) specify which $\text{LaBr}_3\text{:Ce}$ -MPPC detector (Detector 1 $\rightarrow$ Channel 1 $\rightarrow$ Trigger 1; Detector 2 $\rightarrow$ Channel 2 $\rightarrow$ Trigger 2) produced each spectrum. In Fig. 6, the labels “Trigger 1” and “Trigger 2” follow the same convention, representing the coincidence-time resolutions obtained when Detectors 1 and 2 serve as the active trigger

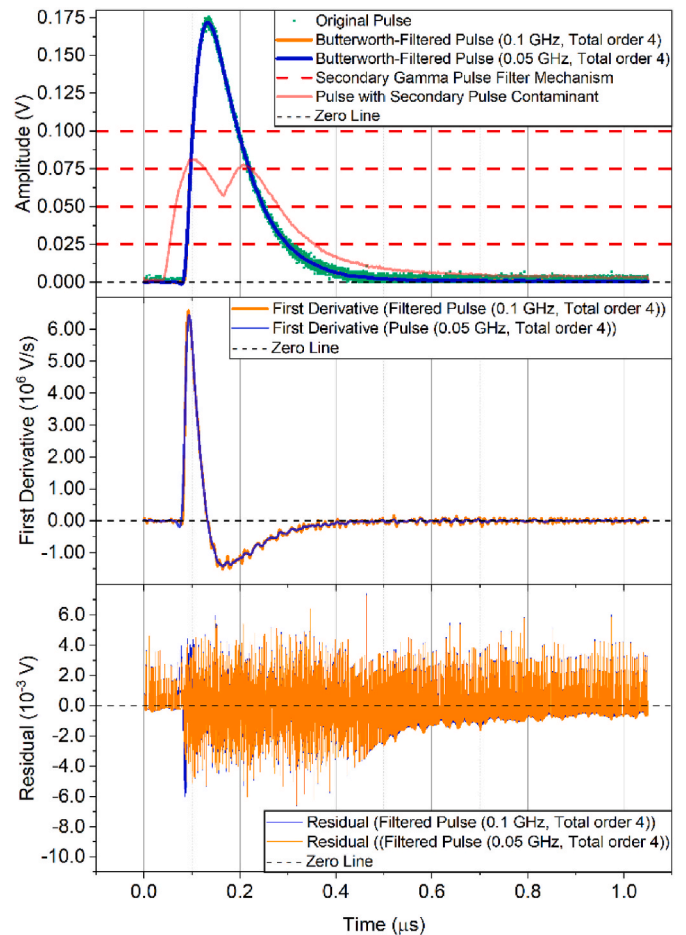


Fig. 3. (Top) Comparison of raw and doubly Butterworth-filtered pulse signals with cutoff frequencies of 0.1 GHz and 0.05 GHz. Red horizontal lines illustrate the principle of secondary gamma pulse detection, alongside an example of a pulse flagged for a secondary gamma arrival. (Middle) First derivatives of the raw and filtered signals, highlighting the need to preserve smoothness. (Bottom) Residuals between the original and Butterworth-filtered signals. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

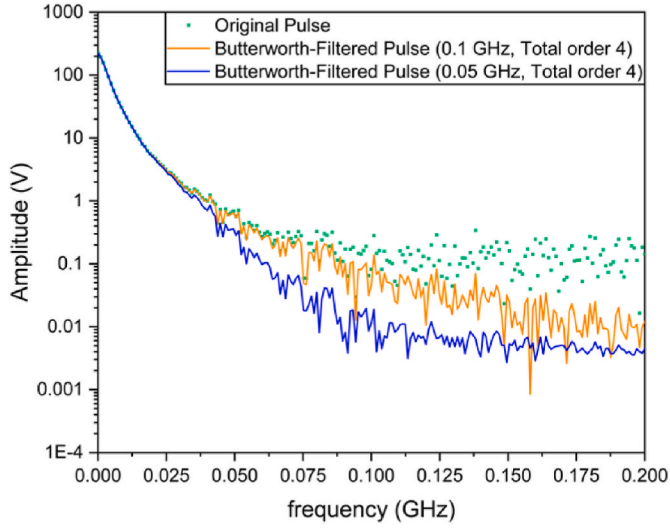


Fig. 4. Fourier transform of the pulse in Fig. 3, comparing the spectral characteristics of the raw signal with Butterworth-filtered representations at cutoff frequencies of 0.1 GHz and 0.05 GHz. The filter effectively suppresses high-frequency noise while preserving essential low-frequency components. Lower cutoff frequencies provide stronger suppression but must be applied cautiously to avoid distorting the rising edge of the pulse.

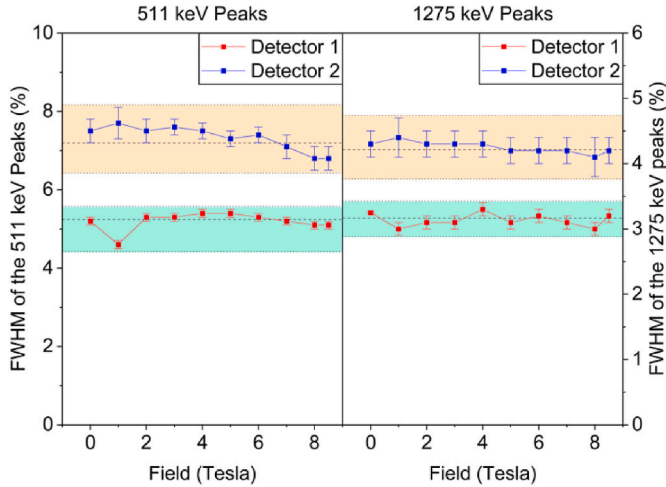


Fig. 5. Full width at half maximum (FWHM) of the 511 keV (left) and 1275 keV (right) peaks in the active-channel energy spectra for Detectors 1 and 2 as a function of external magnetic field (0–8.5 T). Orange and green shaded bands indicate the performance ranges of each detector across the field strengths. Detector 1 consistently exhibits lower FWHM values than Detector 2, indicating superior resolution. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

detectors, respectively. The error bars again correspond to the FWHM of the Voigt fits.

The difference in FWHM between the two detectors arises from inherent variations in their internal characteristics and performance. For example, the Hamamatsu S13361-6050AE-04 MPPC module has an average breakdown voltage of 53 V with a standard deviation of 5 V. Variations in breakdown voltage between MPPC modules can affect peak FWHM. Additionally, intrinsic differences in the $\text{LaBr}_3\text{:Ce}$ crystals may influence detector performance.

In Figs. 5 and 6, average energy resolution or average coincidence-time resolution values were not calculated, as they do not contribute to the primary objective. Instead, the focus is on assessing the invariance of individual $\text{LaBr}_3\text{:Ce}$ -MPPC detector performance under applied

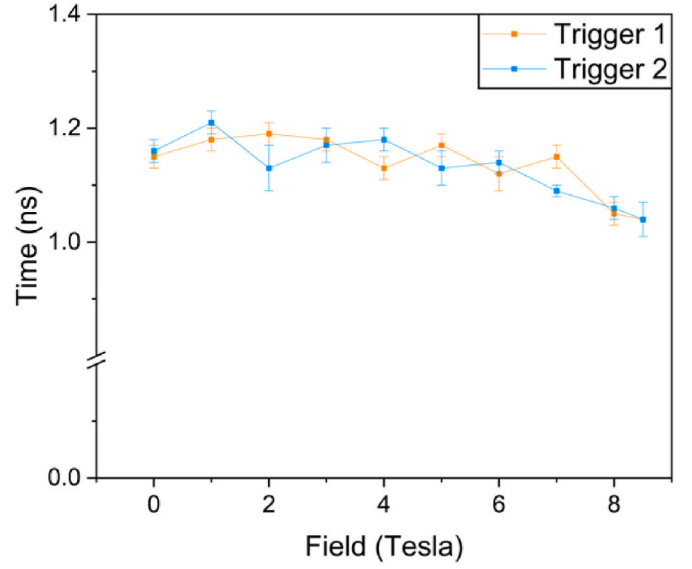


Fig. 6. Coincidence-time resolution as a function of the external magnetic field (0–8.5 T) for Triggers 1 and 2. Trigger 1 corresponds to Detector 1, and Trigger 2 corresponds to Detector 2 acting as the active trigger. The coincidence-time resolution remains relatively stable across the magnetic field range.

external magnetic fields.

Fig. 7 presents individual coincidence-time spectra across magnetic fields from 0 T to 8.5 T for the “Two Detectors to One U5310A Digitizer” setup (Section 2.2.1). Compared with the “One Detector to One U5310A Digitizer” configuration (Section 2.2.2), the coincidence-time resolution is slightly worse (~ 1 ns). This degradation results from the coarser histogram granularity, which increases the fitted FWHM even though the digitizer timestamp jitter remains unchanged.

3.2. One detector to one U5310A digitizer

Fig. 8 shows the energy resolution as a function of the external magnetic field from 0 T to 8.5 T, and Fig. 9 shows the coincidence-time resolution over the same field range.

As in Fig. 5, the FWHM values (error bars) of the background-subtracted Voigt fits for the 511 keV (left) and 1275 keV (right) peaks in Fig. 8 are obtained from the energy spectra of the individual $\text{LaBr}_3\text{:Ce}$ -MPPC detectors, each connected to “Channel 1” of its respective U5310A digitizer. As indicated in the legend, four detectors were used.

An irregularity is observed for Detector 2 at 8.5 T, where the FWHM decreases to 3.35(5)% for the 511 keV peak and 2.35(3)% for the 1275 keV peak. This deviation appears to be transient and is suspected to originate from the MPPC power supply; however, the root cause remains unidentified.

In Fig. 9, the legend label “Coincidence 1” denotes the coincidence-time resolution between the parallel Detector 1–Detector 2 pair, while “Coincidence 2” denotes the resolution between Detector 3 and Detector 4, also arranged in parallel. Error bars correspond to the FWHM of the Voigt fit.

As in Figs. 5 and 6, no attempt was made to compute average energy resolution values or average coincidence-time resolution values in Figs. 8 and 9. The objective is instead to demonstrate the invariance in performance of each $\text{LaBr}_3\text{:Ce}$ -MPPC detector when subjected to an external magnetic field.

Fig. 10 presents the individual coincidence-time spectra at different external magnetic field strengths (0–8.5 T) for the *One Detector to One U5310A digitizer* configuration (Section 2.2.2).

The spectra exhibit consistent peak shapes and widths across the magnetic field range, showing that the coincidence-time resolution remains largely unaffected by the external magnetic field for both detector

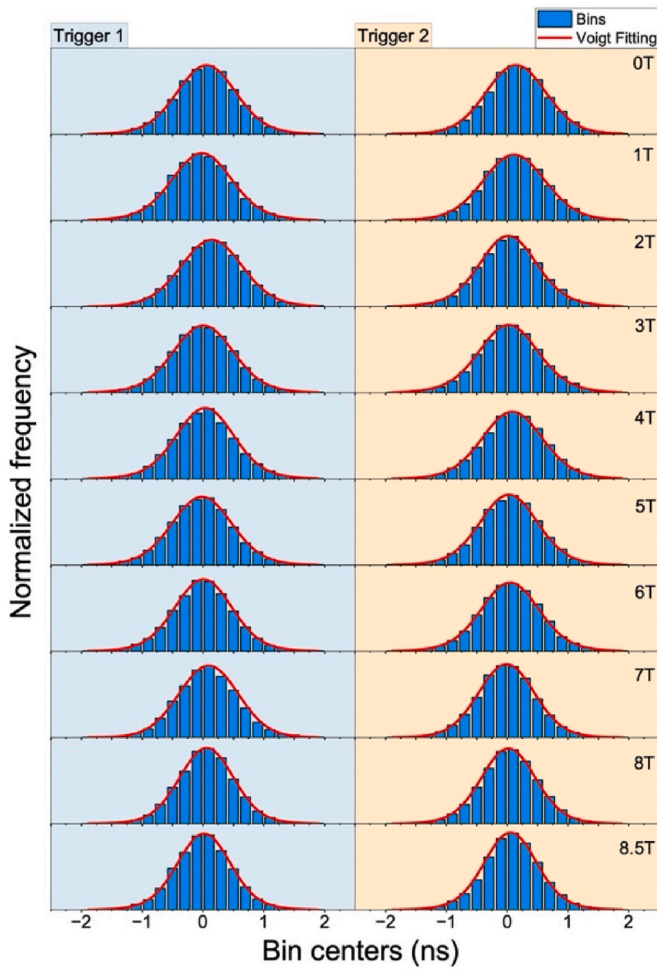


Fig. 7. Normalized coincidence-time spectra (blue bars) with Voigt fits (red lines) for Trigger 1 (left column) and Trigger 2 (right column) across external magnetic field strengths from 0 T to 8.5 T for the “Two Detectors to One U5310A Digitizer” setup (Section 2.2.1). The means of the distributions are shifted to zero for clarity; small deviations from zero result from minor cable length mismatches. The normalized frequency spans 0 to 0.16. Each spectrum shows the distribution of timestamp differences for coincident 511 keV pulses, with Voigt fits overlaid. The fitted results show that the shape and resolution of the coincidence-time spectra remain largely consistent across the applied magnetic field range. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

pairs.

3.3. Representation of the gamma photons at 0 T and 8 T

Fig. 11 shows the pulse-shape representations of the gamma-photon events detected by Detector 1 in the *One Detector to One U5310A digitizer* configuration (Section 2.2.2) at 0 T (left) and 8.5 T (right).

The pulses include events at 511 keV, 1275 keV, and other energies in the spectrum.

Comparison of the two graphs demonstrates that the pulse characteristics remain consistent across magnetic field strengths. This consistency is not limited to Detector 1 at 0 T and 8.5 T but applies to all four detectors at all magnetic field strengths (with the exception of Detector 2 at 8.5 T due to the transient voltage issue noted earlier).

4. Discussion

Our experiments confirm that LaBr₃:Ce-MPPC detectors retain their pulse shapes in magnetic fields up to 8.5 T—consistent with previous

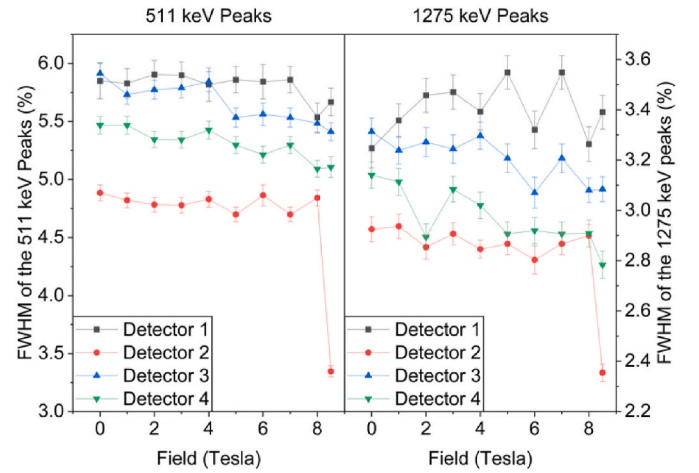


Fig. 8. FWHM of the 511 keV (left) and 1275 keV (right) peaks in the energy spectrum for Detectors 1–4 as a function of the external magnetic field (0–8.5 T). The results indicate that the FWHM remains largely unchanged with increasing magnetic field strength, although each detector exhibits distinct performance characteristics.

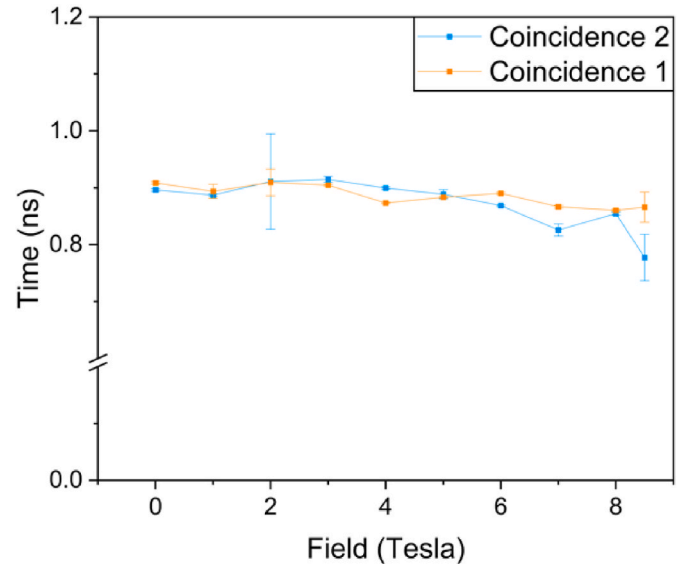


Fig. 9. Coincidence-time resolution as a function of the external magnetic field (0–8.5 T) for the Coincidence 1 and Coincidence 2 measurements. The results demonstrate that the coincidence-time resolution remains relatively stable throughout the field range, with only minor variations for each detector pair.

findings [34–36]—as evidenced by stable energy and coincidence-time resolutions. Throughout the measurements, the input voltage to each MPPC remained fairly constant, and the ambient temperature stayed within acceptable limits. As noted in Section 2.2 (Experiments), the temperature compensation module on the carrier board was not activated. Table 2 presents the energy and coincidence-time resolutions of MULTIPAC (in its current configuration), benchmarked against other TDPAC spectrometers.

In the one-detector-per-digitizer configuration, the top detector (Detector 2) achieved 4.70(6)–4.88(7)% FWHM at 511 keV across 0–8.5 T; the previously mentioned 3.35(5)% value resulted from a transient bias increase and is therefore excluded. Additionally, our LaBr₃:Ce-MPPC detector set provides coincidence-time resolutions of approximately 0.78(4)–0.915(5) ns with interleaving and 1.04(3)–1.21(2) ns without interleaving, which is sufficient for standard TDPAC spectroscopy, because the intermediate half-life of the probe lies within

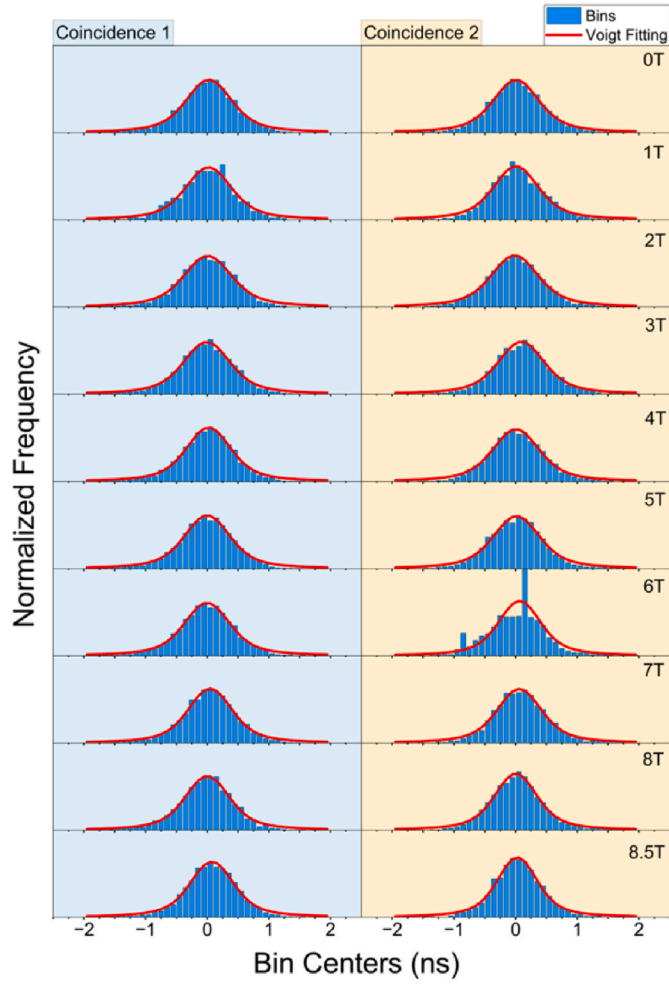


Fig. 10. Normalized coincidence-time spectra (blue bars) with Voigt fits (red lines) for Coincidence 1 (left column) and Coincidence 2 (right column) across external magnetic fields from 0 T to 8.5 T in the *One Detector to One U5310A* digitizer setup (Section 2.2.2). For clarity, the mean of each distribution has been shifted to zero. Small offsets arise from slight cable length mismatches. The normalized frequency ranges from 0 to 0.16. Each spectrum shows the distribution of time differences between timestamps of coincident 511 keV pulses, with Voigt curves overlaid. The fits confirm that the shape and resolution of the coincidence-time spectra remain largely consistent across the magnetic field range. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

tens of nanoseconds. For comparison, MULTIPAC in its current configuration (as of publication) delivers TDPAC performance comparable to that of leading analog systems.

Beyond meeting the coincidence-time and energy-resolution benchmarks of traditional setups, the replacement of PMTs with MPPCs makes the system inherently resistant to external magnetic fields. This magnetic immunity ensures reliable data acquisition under strong fields, broadening the conditions under which high-quality hyperfine interaction measurements can be conducted.

Our 38-mm-diameter $\times$ 38-mm-height LaBr₃:Ce crystals are certified by Advatech UK to have intrinsic energy resolutions of 2.88–3.26% at 662 keV. Therefore, any degradation of the energy resolution is dominated by light collection, particularly the incomplete optical coverage of the crystal face by the MPPC array (50.79% coverage) and, secondarily, by light-collection losses from non-ideal optical coupling (e.g., grease layer uniformity). Additional MPPC non-idealities such as temperature-dependent dark counts and bias-dependent correlated noise from afterpulsing/crosstalk can further broaden the response but are expected

to be secondary compared with the coverage-limited photon statistics. Nevertheless, MPPC performance can approach PMT-based readout under optimized conditions [53], with practical limitations set by temperature-dependent dark counts and bias-dependent correlated noise [54].

Reported energy resolutions for LaBr₃:Ce and similar detector systems typically range from 3% to 8% at 511/662 keV and from 3% to 5% at 1275 keV, depending on factors such as crystal size, photodetector type, and readout electronics [15,18,55–62]. Compact LaBr₃:Ce–PMT systems generally achieve 3%–4% at 511/662 keV [18,62], while MPPC-based readouts show comparable performance, with 3.8% at 511 keV reported in Ref. [55]. In comparison, our LaBr₃:Ce–MPPC detectors paired with the U5310A digitizer achieved 4.6%–7.7% at 511 keV and 3.0%–4.4% at 1275 keV in the “Two Detectors to One U5310A Digitizer” configuration. Using the “One Detector to One U5310A Digitizer” setup improved performance to 4.7%–5.9% at 511 keV and 2.8%–3.6% at 1275 keV.

Published coincidence-time resolutions range from 0.08 ns in optimized PMT [18] or LYSO–SiPM [58] systems to around 2 ns in large LaBr₃:Ce–MPPC assemblies [61], with intermediate values of 0.15–0.24 ns [15,56], 0.20 ns [60], 0.4–0.6 ns [57], and 0.7–0.8 ns [59]. In comparison, our system achieved 1.04–1.21 ns in the “Two Detectors to One U5310A Digitizer” configuration and 0.78–0.91 ns in the “One Detector to One U5310A Digitizer” configuration.

Although we do not claim to surpass the performance of the best PMT-based systems, our results demonstrate that a MPPC-read LaBr₃:Ce spectrometer can achieve sub-nanosecond coincidence-time resolution in strong static magnetic fields using a digital readout. Further improvements in optical coverage and coupling, overvoltage stabilization (bias and temperature control), and software and hardware optimization will be explored in a subsequent study.

We also observed an inherent trade-off between optimizing energy resolution and optimizing coincidence-time resolution, consistent with Ref. [56]. For example, in their 18.0 mm $\times$ 16.2 mm $\times$ 10.0 mm LaBr₃:Ce crystals coupled to S11064-050P MPPCs, an overvoltage of 1.2 V (2.0 V) produced energy resolutions of 6.4% (7.8%) at 511 keV and coincidence-time resolutions of 0.183 ns (0.155 ns). In our system, we adjusted the MPPC and carrier-board power supply within reasonable limits to improve coincidence-time resolution, even at the expense of slightly reduced energy resolution. This trade-off is acceptable when the primary objective is reliable separation of start–stop peaks in TDPAC spectroscopy.

To conclude, literature documents several strategies for further improving coincidence-time resolution within the geometric constraints of our LaBr₃:Ce crystals. These include optimized carrier-board layouts [63,64], differential designs such as UF-FD boards [58], careful bias-voltage tuning [56,65], leveraging the large number of MPPC microcells for improved linearity [64,65], maintaining sufficiently high digitizer sampling rates [66], and pulse-shape engineering or compensation modules implemented through MPPC microcell design modifications [67,68] or external pole-zero cancellation circuits [69].

5. Conclusion

The main objective of this study was to determine whether the performance of an MPPC remains unaffected by external magnetic fields in TDPAC applications. We measured the energy and coincidence-time resolutions as functions of the magnetic field using a sealed ²²Na calibration source. Under the operating conditions of constant applied voltage and a maximum temperature variation of 2.5 °C, the LaBr₃:Ce–MPPC detector achieved single-digit percentage energy resolutions at 511 keV and sub-nanosecond coincidence-time resolutions, sufficient for TDPAC spectroscopy with standard probes such as ¹¹¹In and ¹⁸¹Hf.

Importantly, no performance degradation was observed when the detectors were exposed to an 8.5 T magnetic field, and the pulse shapes, particularly the rising edge, remained undistorted. This robustness

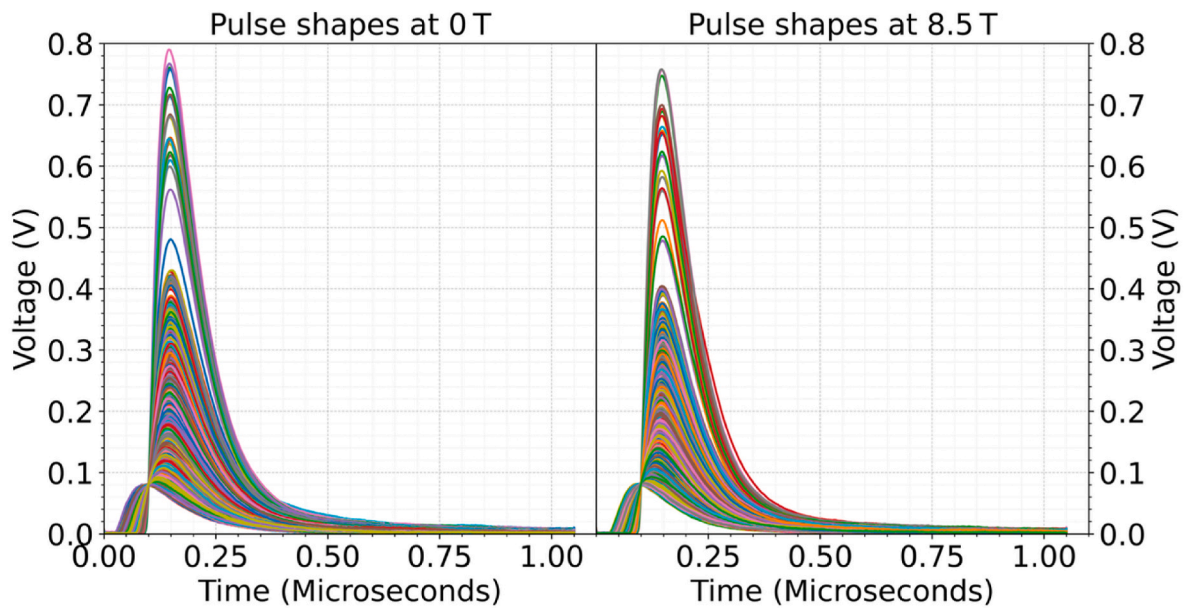


Fig. 11. Pulse-shape representation of the full set of gamma-photon events detected by Detector 1 in the *One Detector to One U5310A* digitizer configuration (Section 2.2.2). The left graph shows pulses at 0 T, and the right graph shows pulses at 8.5 T. The pulses correspond to a range of photon energies, not only the 511 keV and 1275 keV peaks. The comparison indicates that the pulse shapes remain consistent across the two magnetic field strengths.

Table 2

Comparison of the energy and coincidence-time resolution of past and present TDPAC spectrometers.

TDPAC System	Detector System	Generation and Year	Energy Resolution (%)	Time Resolution (ns)
Ref [50]	NaI-PMT	Analog, 1970s-2010s	Not reported	4.75
K1, Ref [51]	BaF ₂ -PMT	Analog, 2000s-2020s	≈10 @ 662 keV	0.6 – 0.7
KATAME, Ref [11]	LaBr ₃ -PMT	2nd Generation, 2010s	3.30 @ 662 keV	0.35 – 0.5
DIGIPAC, Ref [52]	LaBr ₃ -PMT, BaF ₂ -PMT	2nd Generation, 2010s	4 @ 662 keV for LaBr ₃ -PMT	0.265, 0.245
MULTIPAC, this work	LaBr ₃ -Ce-MPPC	3rd Generation, 2020s	4.70(6) – 4.88(7) @ 511 keV (Detector 2)	1.04(3)–1.21(2) (1-det/1-dig) 0.78(4)–0.915(5) (2-det/1-dig) ^a

^a Under the PACBit project, our 3rd Generation TDPAC Spectrometers with the LaBr₃-Ce-PMT (rather than LaBr₃-Ce-MPPC) detectors, will equal or exceed the time resolution of the 2nd Generation, while offering a simplified (and more efficient) data-acquisition scheme and advanced data analysis, powered by modern computing architecture and deep/machine learning techniques (at the time of print).

arises from the confined transport of electrons and holes within the MPPC's solid-state matrix, where charge carriers move only micrometers under strong localized electric fields. This behavior contrasts sharply with PMTs, where electrons must traverse centimeter-scale distances between dynodes in a vacuum, making them far more susceptible to external magnetic fields.

We also compared the performance of our LaBr₃-Ce-MPPC detectors with similar systems reported in literature and found that our setup can be further optimized. Improvements in software (e.g., enhanced time-stamping techniques and signal-smoothing algorithms) and hardware (e.g., the addition of pole-zero cancellation components on the carrier board) have the potential to further refine the coincidence-time

resolution.

These LaBr₃-Ce-MPPC detectors will be integrated into our MULTIPAC system, a robust and versatile TDPAC platform that achieves performance comparable to conventional instruments while enabling reliable operation in high-magnetic-field environments.

Our experimental results are also consistent with those from other time-of-flight systems that require operation under strong magnetic fields. A notable medical example is the integration of positron emission tomography (PET) and magnetic resonance imaging (MRI) [26,70,71]. Overall, our findings demonstrate that the detector technology is well suited for TDPAC spectroscopy and is adaptable to a broader range of high-precision timing applications in high-field environments.

6. Epilogue

Private communication with a representative of Hamamatsu Photonics revealed the development of a successor to the S13361-6050AE-04 MPPC. The new model, the S14161-6050HS-04 [72], offers a broader spectral response range (270–900 nm versus 320–900 nm), higher PDE (50% vs. 40% at 450 nm), slightly higher gain (2.5×10^6 vs. 1.7×10^6), and a lower breakdown voltage (38 V vs. 53 V), while maintaining the same number of microcells (229,376), microcell pitch (50 μm), and total sensor area (2.5 cm × 2.5 cm). Whether the S14161-6050HS-04 will provide improved coincidence-time resolution in our TDPAC experiments remains to be determined.

CRedit authorship contribution statement

Ian Chang Jie Yap: Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft. **Juliana Heiniger-Schell:** Conceptualization, Investigation, Project administration, Resources, Supervision, Writing – review & editing. **Thien Thanh Dang:** Investigation, Visualization. **Nicole Pereira De Lima:** Investigation, Methodology. **Björn Dörschel:** Formal analysis, Investigation, Software, Writing – review & editing. **Magnus Hegelund Stegenborg:** Formal analysis, Investigation, Software. **Alexandre Pinho dos Santos Souza:** Resources. **Bruno Santos Corrêa:** Resources. **Arnaldo Alves Miranda Filho:** Resources. **Adeleh Makhles Gerami:** Resources. **Doru Constantin Lupascu:** Conceptualization, Funding

acquisition, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.nima.2026.171480>.

Data availability

Data will be uploaded to Zenodo if this manuscript is accepted for publication. Data is available upon direct request as well.

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