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A simple digital TDPAC spectrometer

T. A. Webb · Leo Nikkinen · Juan Gallego · D. H. Ryan

Abstract We present a simplified digital time differential perturbed $\gamma - \gamma$ angular correlation (TDPAC) spectrometer that demonstrates that such instruments can be built using primarily commercial components and with relatively modest coding effort. The system handles data rates of 70 kcps/detector with a timing resolution of better than 500 ps, and has been used with both ^{111}In and ^{181}Hf.

Keywords TDPAC · Digital signal processing · Nuclear methods · Linux

1 Introduction

Building a time differential perturbed $\gamma - \gamma$ angular correlation (TDPAC) spectrometer can be challenging due to the combination of multi-step pulse processing with stringent timing resolution and stability requirements. Furthermore, since the two correlated γ emissions from a nuclear decay cascade have to be detected, only a small fraction of the detector pulses processed contribute to the final TDPAC spectrum, R(t), necessitating high event processing rates, typically on the order of 10^5 counts per second (cps) on each detector. Digital spectrometers, made possible by high-performance digitizers, elegantly minimize hardware, transferring the complexity associated with analogue signal processing to the task of developing custom software. The latter adds new considerations and freedom to the design process e.g. timestamp calculation [1], coincidence processing algorithms [1], data storage and the ability to reprocess data [2].

We based our spectrometer on several previously described designs [2–5], in which an Acqiris PCI digitizer card and PC is dedicated to each detector, reducing pulses to

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T. A. Webb (✉) · L. Nikkinen · J. Gallego · D. H. Ryan
Department of Physics, McGill University, 3600 University Street,
Montréal, QC Canada H3A 2T8
e-mail: webbt@physics.mcgill.ca

time–energy (t,E) pairs, with the time origin set by a common synchronization pulse sent to all the digitizers. Coincidence processing is then performed on a separate analysis PC, which also controls all of the acquisition cycles. In contrast to recent work, we have chosen to minimize automation in order to simplify the demands on the software. The capabilities of the U1071A digitizers used here, and previously described by Nagl et al. [3], make it possible to implement an effective and versatile spectrometer with a simple design. We describe the design, with particular emphasis on practical considerations in the software development.

2 Instrumentation

The anode signals from four BaF_2 detectors are digitized by Agilent Acqiris U1071A digitizers [6], which feature a "simultaneous multibuffer acquisition and readout" (SAR) mode [6, 7], allowing readout from one data bank while acquisition continues in another. As this model has two separate channels we use one each for the detector and synchronization pulses, eliminating the need to multiplex and subsequently separate the data and timing streams. Automated control over synchronization and data cycles is also avoided. In our configuration, all data must be collected in a single acquisition run (as done by Nagl et al. [3]) as the timing shifts which can occur on stopping and re-starting acquisitions preclude topping up the statistics.

A manually triggered synchronization pulse generator was built to issue fast negative NIM pulses (-1 V, 2 ns rise-time into 50 Ω). Timing stability is maintained with a 10 MHz reference signal [6], split and amplified by a CMOS logic distribution amplifier, sent to the external MCX input of each card.

Each digitizer is housed in a dedicated PC running Linux, with 32 GB hard-disk and 1 GB of memory. The analysis PC (500 GB hard-disk and 1 GB memory) is connected to the acquisition PCs via a TP-Link TL-SG1024 24 port Gigabit Ethernet switch, with its hard-disk shared to facilitate data transfer, similar to Herden et al. [2].

3 Programming

Software was written in the C programming language using no external libraries or packages except the Acqiris library [7, 8] for control of the digitizers. Three programs run continuously during spectrum collection: MANUAL acts as the user interface to the digitizer and reduces digitized pulses to (t,E) pairs, RDATA manages the data transfer from the acquisition nodes to the analysis node, and PACMAN filters the (t,E) data with a broad coincidence time window. In addition, REPAC, run either real-time or post-acquisition, produces the detector pair spectra from the filtered (t,E) data files, and PACRAT performs the R(t) calculation. Refer to Fig. 1 for a diagram of the basic data reduction steps. This modular approach follows the model of previous designs [2, 3]; in particular, the two-staged coincidence event processing is discussed in Refs. [2, 5].

MANUAL*: Producing (t,E) data* To achieve reasonable acquisition rates MANUAL forks into four processes: digitizer card control, reduction of pulses to t and E, data file I/O, and user interface (parent process). Communication between processes is done using basic signal handling and pipes.

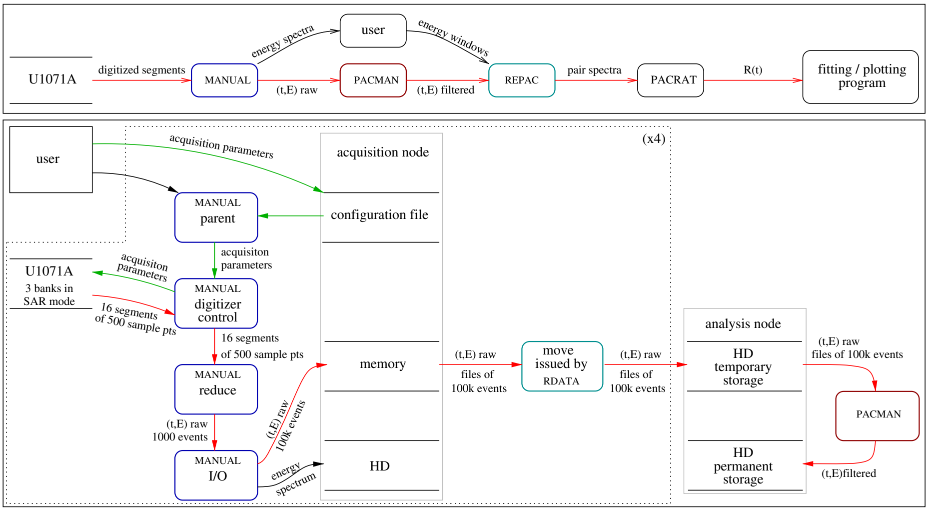

Fig. 1 *Top*: Data flow diagram of digital TDPAC data reduction. *Main*: Detail of data acquisition cycle, indicating sizes of the data blocks used

A three option menu in the parent process gives the user full control over data acquisition. Figure 2 shows the typical sequence used to start spectrum collection. Simultaneously, on all digitizers, the user selects a synchronization cycle (in the U1071A's single segment acquisition mode [6]) from the menu. Once the digitizers have been configured, the user is prompted to start the acquisition and trigger the pulse generator (this ensures that all four cards receive the timing pulse within their 10 s timeout window). Afterwards, the data cycle (in SAR mode) can be initiated on each node.

Figure 1 shows a detailed data flow diagram of data acquisition and reduction. The data are transferred between the three child processes via pipes. The I/O process then writes the (t,E) data to a file-system in RAM (faster than disk writes), making the files accessible to other programs. This process occasionally writes a binned energy spectrum to the local disk so that the user can monitor the acquisition and select energy windows for REPAC. For a discussion of methods to calculate t and E, see Refs. [1–3]. Here we used a conventional constant fraction method for t and the pulse integral for E.

RDATA*: (t,E) data transfer* RDATA is started on the analysis node once all acquisition nodes are writing (t,E) data to files in RAM. It forks into one process per acquisition node; each issues a move command to its node via rsh every 5 s. Separating file transfer from other processes and handling each node independently reduces the risk of filling up the acquisition node memory.

PACMAN*: Coincidence filtering* PACMAN consists of a single process, rotating through three cycles: (t,E) data read from file, coincidence processing and filtered (t,E) data write.

The coincidence filtering consists of sifting through events chronologically on all channels. When the time between any two events is less than a wide time window set

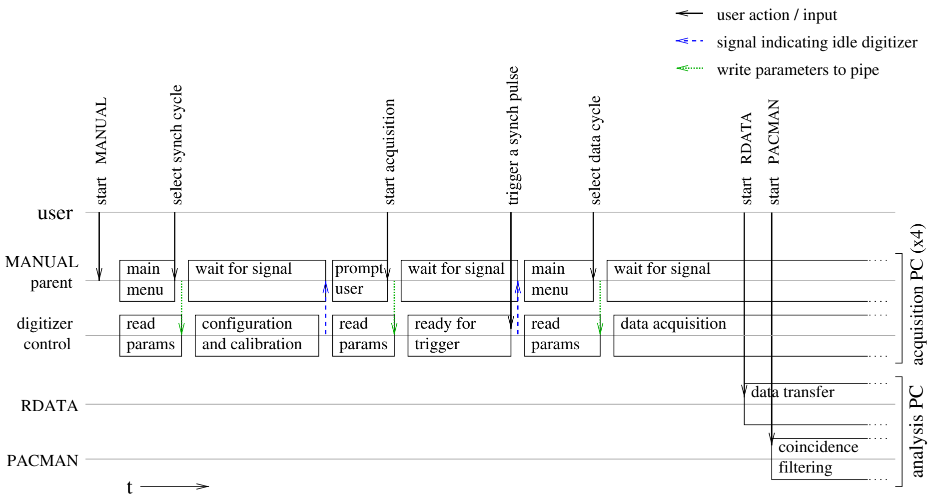

Fig. 2 Timing diagram of typical sequence to start spectrum collection. Data reduction and I/O processes of MANUAL are not shown. After starting data acquisition from all detectors through MANUAL, the user starts RDATA and PACMAN on the analysis PC. Times are not to scale

in the configuration file (typically 2 μs), those events are flagged to be saved. When the last event is reached on a channel, all the flagged events from that channel are stored. The next raw (t,E) data file for the same channel is then read into memory and the coincidence filtering continues. In addition, PACMAN bins the $\gamma - \gamma$ coincidence events into detector pair spectra (without energy windows). The user can monitor the data collection by plotting these spectra which are updated once every minute. Jäger et al. [1] discuss coincidence search algorithms in more detail.

REPAC*: Detector pair spectra* REPAC, which can be started anytime after PACMAN, follows the same model, with modifications to reject ambiguous events [3] and apply energy windows set by the user. Usually a small bin size is chosen (0.1 ps), and then re-binning is done in the R(t) calculation, to give the user more flexibility.

PACRAT*: R(t) calculation* The pair spectra produced by REPAC are aligned in time by a threshold trigger (typically 85 %) of the maximum. The accidental coincidence background is calculated from the average of data (typically 10 ns) prior to the rise and subtracted from each spectrum. R(t) is calculated from the geometric averages of the eight 90° coincidence spectra $N(90, t)$ and the four 180° coincidence spectra $N(180, t)$ as suggested in Ref. [9] to reduce the effects of potential error sources:

$$R(t) = 2\frac{N(180, t) - N(90, t)}{N(180, t) + 2N(90, t)}. \quad (1)$$

4 Performance

It is important to collect and process events fast enough for the sample activity. Sluggishness in any part of MANUAL will produce dead times, which reduce the true

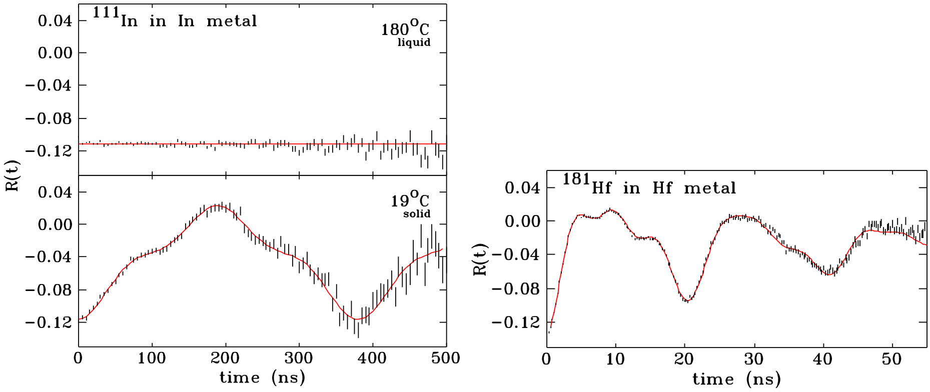

Fig. 3 *Left*: TDPAC spectrum of ^{111}In in liquid indium, showing no perturbations, and solid indium showing an axially symmetric electric quadrupole interaction with $\omega_Q = 2.74(2)$ MHz. *Right*: TDPAC spectrum of ^{181}Hf in hafnium metal at room temperature

to chance coincidence ratio. Speed both in MANUAL and PACMAN is highly dependant on balancing the sizes of the data blocks which are handled. Frequent transfers of small data blocks accumulates costly overhead, while infrequent transfers cause long read/write times and interrupt the quasi-continuous data-flow.

The spectrometer can handle data rates up to 70 kcps on each digitizer, limited by MANUAL (the U1071A is capable of 2.5 M–3 M trigger events per second [3, 6], and PACMAN can process 250 kcps per detector). The timing resolution ranges from 360 to 500 ps among the detector pairs, using the FWHM of ^{60}Co. Spectra, with good statistics to approximately four half-lives of the $\gamma - \gamma$ cascade's intermediate state, are typically 40–100 GB, with 64 bits used for each time and energy value and a 2 μs coincidence time window. Gzip is used to further compress the filtered (t,E) data for permanent storage on SATA hard disks.

5 Example spectra

Spectra were collected of liquid and solid indium metal (melting point 156.60 °C [10]) using ^{111}In introduced by electroplating from an aqueous ^{111}InCl$_3$ solution and melting at 180 °C for homogeneity. The liquid spectrum, shown in Fig. 3, is unperturbed as expected [11], while the spectrum of solid indium taken at room temperature shows a single axially symmetric electric quadrupole interaction, consistent with the TDPAC measurements of Bodenstedt et al. [12].

Figure 3 also shows a TDPAC spectrum of ^{181}Hf in hafnium metal. ^{181}Hf activity was introduced via neutron irradiation. Hafnium metal typically contains several at.% zirconium [13], so the single axially symmetric electric quadrupole interaction (QI) expected for pure Hafnium is not expected [13]. The spectrum was fit using two QIs: one axially symmetric with strength ν_Q^P, the other allowed to have a non-zero axial asymmetry, η, with a Gaussian distribution in strength ν_Q^D. The damped frequencies, ω_i^D, were refined subject to the constraint $\omega_3^D = \omega_1^D + \omega_2^D$, for an exact comparison to Rasera et al. [13]. Our results are in excellent agreement with those of

Hf rich alloys from Ref. [13]: $\nu_Q^P = 320.0(6)$ MHz and $\nu_Q^D = 343.1(8)$ MHz, with $\delta = 0.105(2)$ and $\omega_2^D/\omega_1^D = 1.78$.

6 Conclusions

By reducing the overall automation and employing a single synchronization step without data–timing multiplexing, we demonstrate that a simple digital TDPAC spectrometer can be built with software written at the level of introductory to intermediate Linux programming textbooks, Ref. [14]. The spectrometer offers the full flexibility of digital TDPAC systems and yields competitive performance for a modest investment in hardware and effort. We hope that this demonstration will further the growth of digital TDPAC spectrometers.

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