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A user-friendly fully digital TDPAC-spectrometer

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Abstract A user-friendly fully digital TDPAC-spectrometer with six detectors and fast digitizers using Field Programmable Gate Arrays is described and performance data are given.

Keywords User-friendly · Digital TDPAC-spectrometer · Field programmable gate arrays

1 Introduction

In the last few years digital spectrometers for Time Differential Perturbed Angular Correlation (TDPAC) measurements were developed which use four detectors with a PC for each of them and a sort of list mode [1–4]. The design aim was to maximize the tolerable count rates and to allow for a very flexible off-line data analysis. Here, we report on the development of a new spectrometer consisting of six detectors (38 mm diameter × 38 mm height $LaBr_3$(Ce) scintillators mounted on XP2020URQ photomultipliers) arranged in a cube (see Fig. 1), a PXI system with three digitizer cards of the type AC240 (acqiris, each card has two channels delivering 1GS/s and one Field Programmable Gate Array (FPGA)) and a single PC with a special PCI card to communicate with the PXI system. The aim is not to maximize the tolerable count rate but rather to maximize the information gain without loosing frequency resolution due to poor true to chance coincidence ratios. The information gain with a six-detector set-up compared to a four-detector set-up is about 2.

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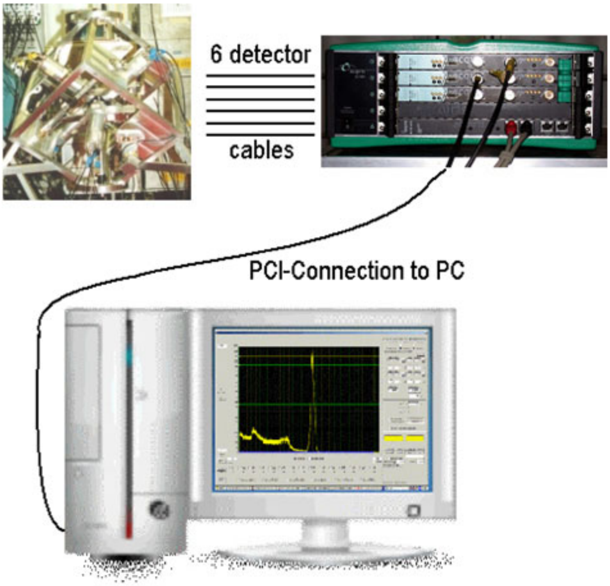


Fig. 1 Schematic structure of the spectrometer: *upper left* six detector cube, *upper right* PXI system with three dual digitizer cards AC240, *bottom* PC with spectrometer software

2 Spectrometer

The philosophy of the present spectrometer is that well-established nuclear probe cascades can be adjusted with minimum effort (see Fig. 1). It suffices to set the energy windows, to specify the time range for coincidences, and to set the t_0 offset. Therefore, FPGAs are used to create the time stamps, to produce detector tags, and to select the γ-energies. With these FPGAs it is, e.g., possible to implement digital filters, mathematical functions or data forwarding circuits. Every FPGA has one FIFO to store 16,384 data sets. One data set consists of 64 Bits.

The data set structure is as follows:

- Detector identification (1 Bit)
- Energy window classification (2 Bits for four possible energy windows)
- Timestamp integer part (53 Bits; the unit is nanoseconds).
- Timestamp fractional part (8 Bits; the unit is approximately 3,9 ps).

The FIFO of one FPGA was built by 64 internal FPGA BlockRAMs.

At present, there are two different algorithms for the generation of time stamps: the centroid method and the constant fraction of amplitude (CFA) method [5], the latter being by far more accurate. Threshold levels, integration times as well as CFA ratios which depend on the scintillator can be adjusted.

A single digitizer card is illustrated in Fig. 2, the black frame comprises all digital circuits inside the FPGA. The user core implements energy filtering (pulse area), time stamp generation, and data forwarding. At present, about 1 μs is required in the critical pipeline stage for time stamp calculation. This means that rates of 1 MHz can be handled per input channel. For statistical pulses 100 kHz seems to be realistic. With more pipeline stages, 9 MHz would be possible.

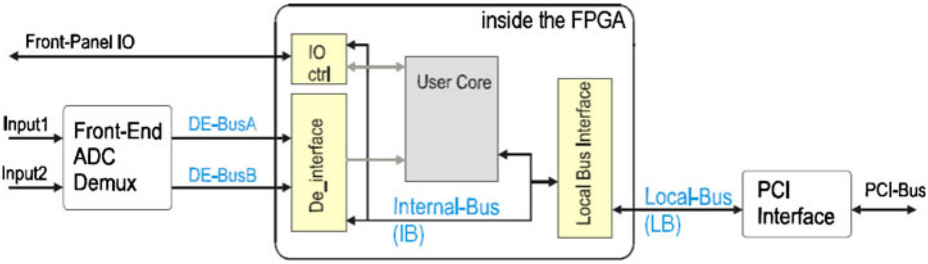


Fig. 2 *Left side* 2 inputs converted in the ADC and fed as DE-BusA and DE-BusB to the FPGA; *right side* the FPGA is connected to the PCI-Interface via the Local-Bus

The data stream from the digitizer is fed to an Intel Core2Duo PC with 1.8 GHz running with Windows XP. In a typical application we have a pulse rate of 5 kHz per channel, i.e. a data stream of only 240 kByte/s from the digitizers to the PC. The required CPU time is a few percent only.

In this PC the following procedures are implemented:

– energy spectrum mode
– time spectrum mode

For the time spectrum generation and visualization the software executes an additional coincidence search algorithm. The coincidence search is the critical part of the spectrometer software with a throughput of 7 million timestamp comparisons per second.

The goal of the coincidence search algorithm is to compare two timestamps inside the working memory with respect to each other to find timestamps which are "good" coincidences. Several conditions have to be fulfilled that two timestamps are "good" coincidences which are:

(i) The first timestamp is a start timestamp. For that we use energy window 0.
(ii) The second timestamp is a stop timestamp. For that we use energy window 1.
(iii) The input channels of both timestamps are different.
(iv) The time differences of the timestamps are inside a selected time range and the stop timestamp is later then the start timestamp.

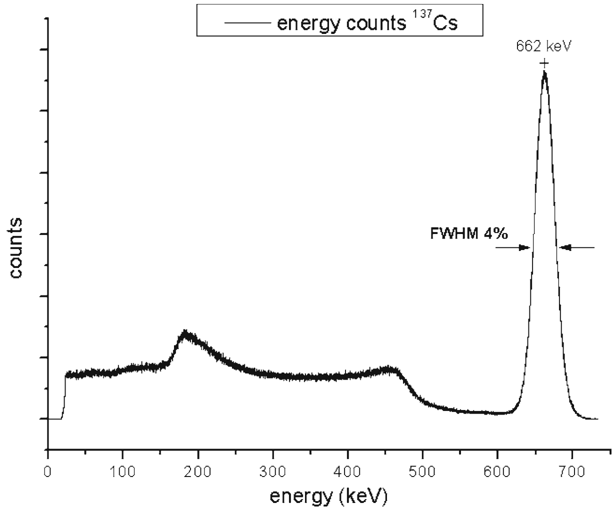
Special attention was devoted to the fact that the data flow is not strictly time-ordered.

3 Performance tests

The following test measurements were performed:

Energy resolution With conventional electronics, i.e. dynode signals, charge sensitive pre-amplifiers, and spectroscopy amplifiers the energy resolution of our $LaBr_3(Ce)$ detectors is 3% at 662 keV. With the anode signal and the fast digitizers we still achieve an energy resolution of about 4% (see Fig. 3). A disadvantage to take the anode signal only is that its amplitude depends more sensitively on high-

Fig. 3 Energy resolution of 4% at 662 keV obtained with two 38 × 38 mm $LaBr_3$(Ce) scintillators and a ^{137}Cs source



voltage variations due to temperature variations than the dynode signal. Computer-controlled high-voltage power supplies with peak stabilization might be useful.

Time resolution We performed measurements with a ^{60}Co source and windows set on 1.17 MeV and 1.33 MeV and obtained a FWHM of 250 ps (see Fig. 4). With a low-pass filter this could be reduced to 245 ps. The average over 30 groups was 265 ps. The corresponding values for 511 keV vs. 511 keV was about 365 ps. Furthermore we performed measurements with BaF_2 scintillators and ^{60}Co which were not yet satisfactory. We took either a long integration time (1,000 ns) including both the fast and the slow component of the light output, or we selected the fast component only for the determination of the pulse amplitude. In both cases there was no unique proportionality factor between pulse amplitude and pulse area. Therefore we are presently working on the implementation of a true Constant Fraction Trigger principle with a delayed input pulse and a constant fraction. We expect that this algorithm will improve the time resolution with BaF_2 significantly, maybe close to the hardware trigger results.

TDPAC test We recorded a PAC spectrum for the nuclear probe ^{44}Ti(EC)^{44}Sc in the rutile modification of TiO_2 at room temperature. We used the 78.4–67.8 keV cascade in ^{44}Sc with intermediate nuclear spin I = 1. Both energies could be well separated. Coincidences were recorded in a time range of 2,000 ns, the time per channel was 1.95313 ns. We used the second γ as start and the first as stop and a t_0 delay of 1,900 ns. In this way histograms decay to the left. Near t_0 the signal to chance coincidence background ratio was about 20, sufficiently good to record coincidences up to 1,000 ns, i.e. about six half lives. The spectrum shown in Fig. 5 agrees very well with that published in [6], the fitted hyperfine parameters were $\omega_Q = 16.25(2)$ Mrad/s and $\eta = 0.948(3)$.

Further tests should be made at ISOLDE/CERN with the short lived isotopes ^{111m}Cd and ^{199m}Hg where one works with the highest possible countrates. An unexpected problem came up with the new $LaBr_3$(Ce) scintillators: the light output

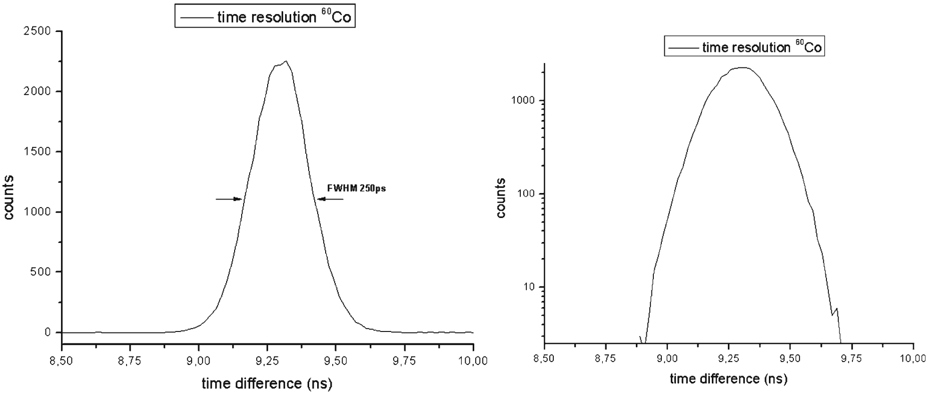


Fig. 4 Time resolution of 250 ps obtained with two 38 × 38 mm $LaBr_3(Ce)$ scintillators and a ^{60}Co source (*left* linear scale, *right* logarithmic scale)

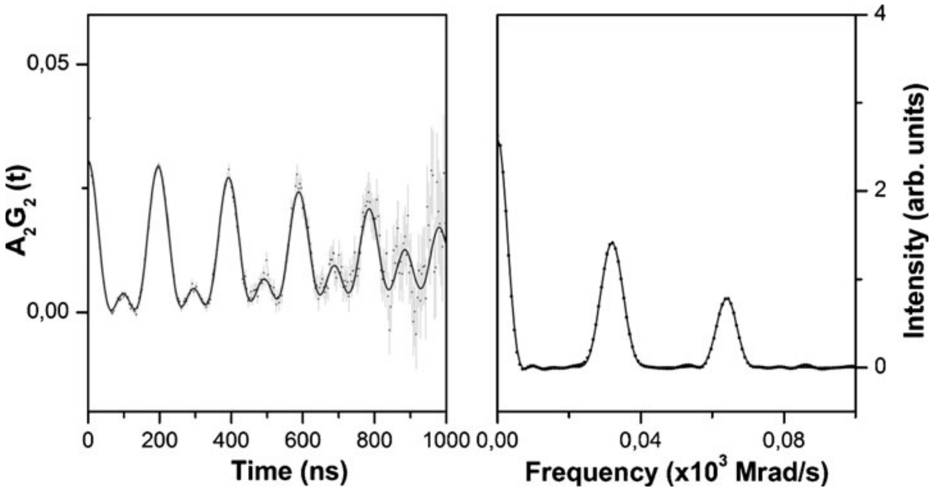


Fig. 5 Time spectrum (*left*) and cosine-transform (*right*) for ^{44}Sc in rutile at 300 K

and, hence, the average anode current is so high that we could not test the highest possible countrates with ^{44}Ti. Reducing the high voltage would not be a good choice. We have adjusted the high voltage such that the 511 keV annihilation quanta of the ^{44}Sc decay are within the ADC range of 5 V. Lower voltages would make the window setting at 78.4 keV/67.8 keV unpractical and would also deteriorate the time resolution. Probably BaF_2 scintillators should be used for this purpose.

4 Summary

The spectrometer performs well, is very user friendly, and we expect to improve the time resolution further by implementing the true CFT principle. We have foreseen four energy windows such that stretched cascades, e.g. in ^{180m}Hf, can make use of all (prompt) γ-rays preceding the 1.5 ns half life 2+ level which would otherwise paralyze the hardware router of a conventional spectrometer.

Although not yet implemented, it is easy to modify the system such that the digitizers deliver the detector number, the time stamp, and the energy for each input pulse (corresponds to fully open windows) and to carry out the energy gating in the PC. This would reduce the data transfer rate to the PC considerably and all putative useful cascades could be analyzed simultaneously in the PC for explorative studies of new isotopes. In this way a series of time histograms will be produced. The reduction factors compared to the transfer of all samples in list mode depend on the number of bits of the ADC and the sampling rate as well as on the selected time range. For 8 bit and 1 GS/s we would gain between a factor of 10 to 200 for time ranges of 100 ns to 2,000 ns; for 10 bit and 2 GS/s the factors would be even larger, namely 25 and 500.

The advantages compared to a conventional spectrometer are the following:

i) No space and power consuming rack full of NIM-units with cables and heli-trims and large cable delay boxes are required which makes the adaptation of the spectrometer to a new isotope or even energy window setting a time consuming and error-prone procedure. The digitizers in Fig. 1 are roughly up to scale with the PC and monitor. The only missing pieces in Fig. 1 are the high-voltage supplies and the PC for $A_2G_2(t)$ calculation and data fitting which we added on purpose in order to separate data processing from data storage for safety reasons. The space required for the six-detector cube is about 1 m^3.

ii) The cost for the new spectrometer is difficult to estimate. There is a very rapid development of fast digitizers with rapidly dropping prices for the last but one generation and the bottleneck appears to be the cost for FPGA and PC programming if done by a commercial company. If done in-house, the digital system could be much cheaper than a conventional one.

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References

1. Herden, C.H., et al.: Hyperfine Interact. **159**, 379 (2004)
2. Röder, J., et al.: Hyperfine Interact. **181**, 131 (2008)
3. Herden, C., et al.: Nucl. Instrum. Methods **A594**, 155 (2008)
4. Nagl, M., et al.: Rev. Sci. Instrum. **81**, 073501 (2010)
5. Bardelli, L., et al.: Nucl. Instrum. Methods **A521**, 480 (2004)
6. Ryu, S.-B., et al.: Phys. Rev. **B77**, 094124 (2008)