Study of Dynamic Time Over Threshold (DTOT) method for application in spectroscopy signal analysis toward a low complexity front-end electronics with high spectroscopy resolution and wide energy range for use with scintillation gamma detectors

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Outlines

- Introduction / Motivation on application of DTOT conversion method for processing of spectroscopy signals
- Simple Time Over Threshold (TOT) method overview
- Dynamic Time Over Threshold (DTOT) method
  - working principle, benefits, complexity, specifics...
- Study of DTOT performance via dedicated hardware tester
  - Complex DTOT demonstrator board
  - Low complexity DTOT converter front-end board
  - Experimental measurements
- Conclusions

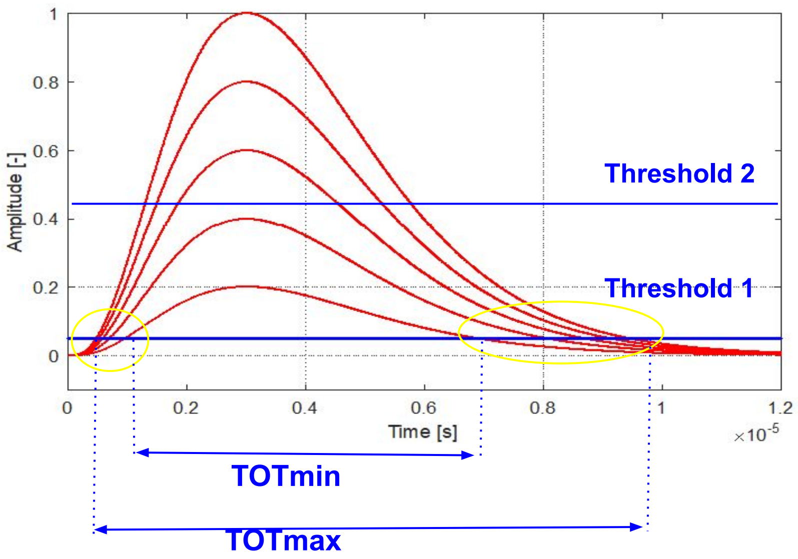
Introduction
Common approach in spectroscopy signal processing and evaluation

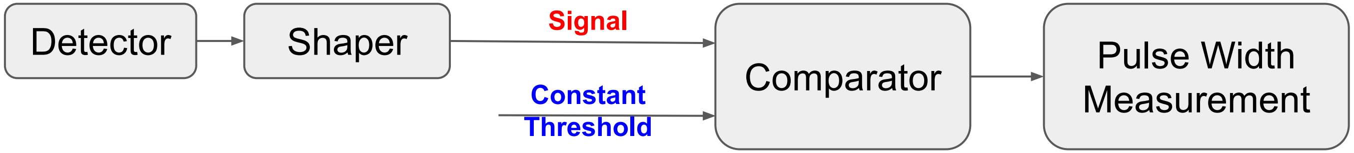
- Spectroscopy signals from detectors are just amplified and then immediately digitized by a follow-up AD converter with a high sampling frequency
- Most of signal processing and evaluation is performed in the digital form
- It represents reliable and well established approach that is suitable for the most of applications
- However, there are still some specific applications where the standard approach is unsuitable due to limitations given by spectrometer device operation conditions (e.g. low power consumption, hardware resource, dimensions, specific environment)

Zeynalova O, Zeynalov S, Hambsch F, Oberstedt S. Digital Signal Processing Application in Nuclear Spectroscopy. Nuclear Physics and Atomic Energy 10 (2); 2009. p. 214-219. JRC56946

Simple Time Over Threshold conversion method overview

- Very low complexity hardware is needed for implementation
- Highly nonlinear output result
  (TOT time vs equivalent spectro pulse energy)
- Difficult to calibrate
- High negative impact of noise on resulting TOT time when threshold is set low
- Need for multiple thresholds when pulses should be evaluated in wide range of amplitudes

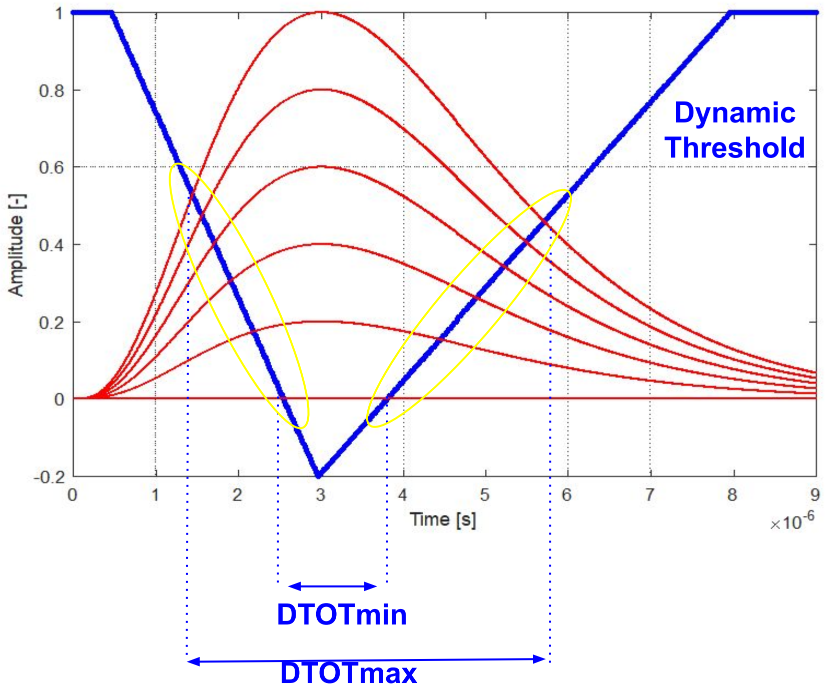




T. Fujiwara and H. Takahashi, "A new multi-level time over threshold method for energy resolving multi-channel systems," *2008 IEEE Nuclear Science Symposium Conference Record*, Dresden, Germany, 2008, pp. 3413-3415, doi: 10.1109/NSSMIC.2008.4775074

Dynamic Time Over Threshold (DTOT) Method
Working principle and advantages over simple TOT

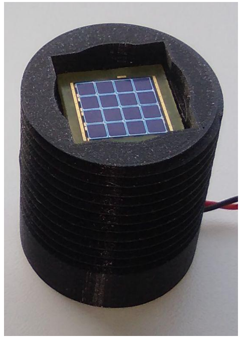
- Introduction of dynamic threshold significantly suppress influence of noise on variation of output DTOT time
- Difference between DTOTmin and DTOTmax times gets significantly extended *(theoretically from zero up to width of shaped spectroscopy pulse)*
- Dependence of DTOT time on spectroscopy pulse equivalent energy gets more linear *(given by a profile a dynamic threshold)*
- Implementation of DTOT converter gets more complex as pulse arrival trigger is needed in order to start generation of dynamic threshold waveform *(FPGA circuit needed for real-time processing)*

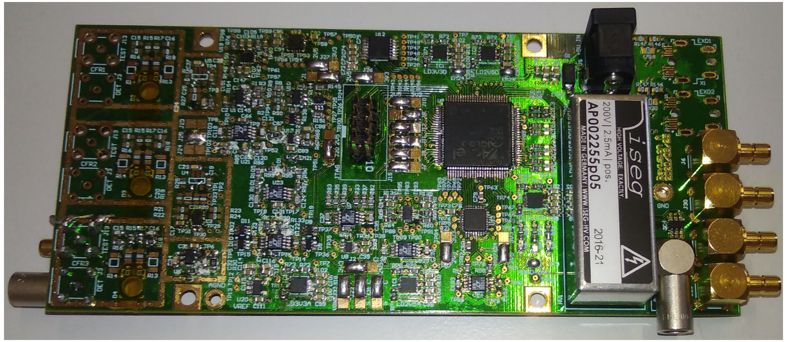


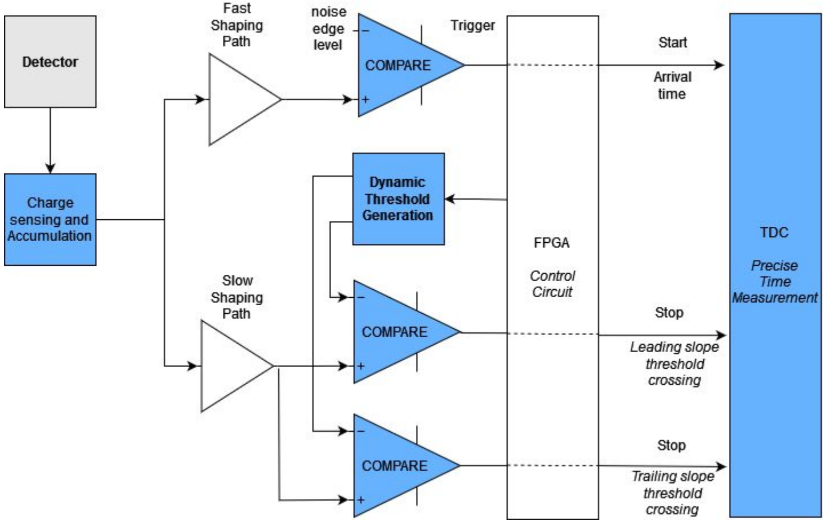
K. Shimazoe et al., "Dynamic Time Over Threshold Method," in IEEE Transactions on Nuclear Science, vol. 59, no. 6, pp. 3213-3217, Dec. 2012, doi: 10.1109/TNS.2012.2215338

Dedicated Hardware was Prepared to Allow Testing of DTOT Conversion Method Performance

- Dedicated tester board was designed in order to allow study of DTOT method properties and its performance
- Based on Igloo Microsemi FPGA
- 12 bit DAC / 60 MHz for synthesis of any profile of dynamic threshold
- TDC chip with 55 ps resolution for precise DTOT measurement
- Input for real detector signals (SiPM sensors, single pad diodes, ….)

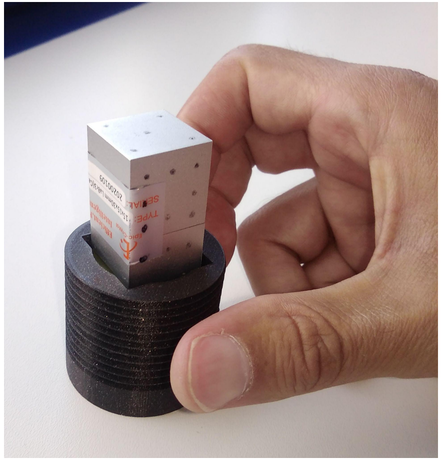


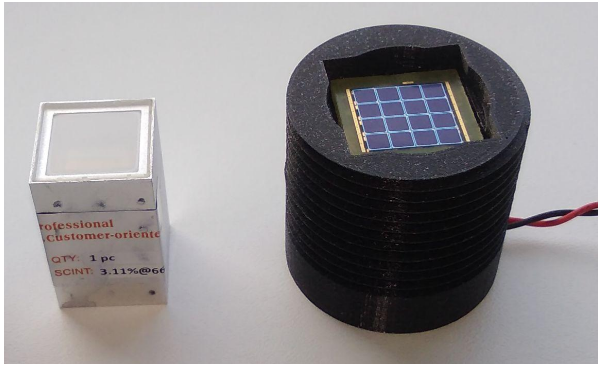




Utilization of MAPD (SiPM) Sensors Combined with LaBr Scintillator as a Gamma Detector used for DTOT testing

- Detector used for testing of DTOT performance (spectroscopy signal source)
- MAPD(SiPM) sensors are small footprint and low weight components



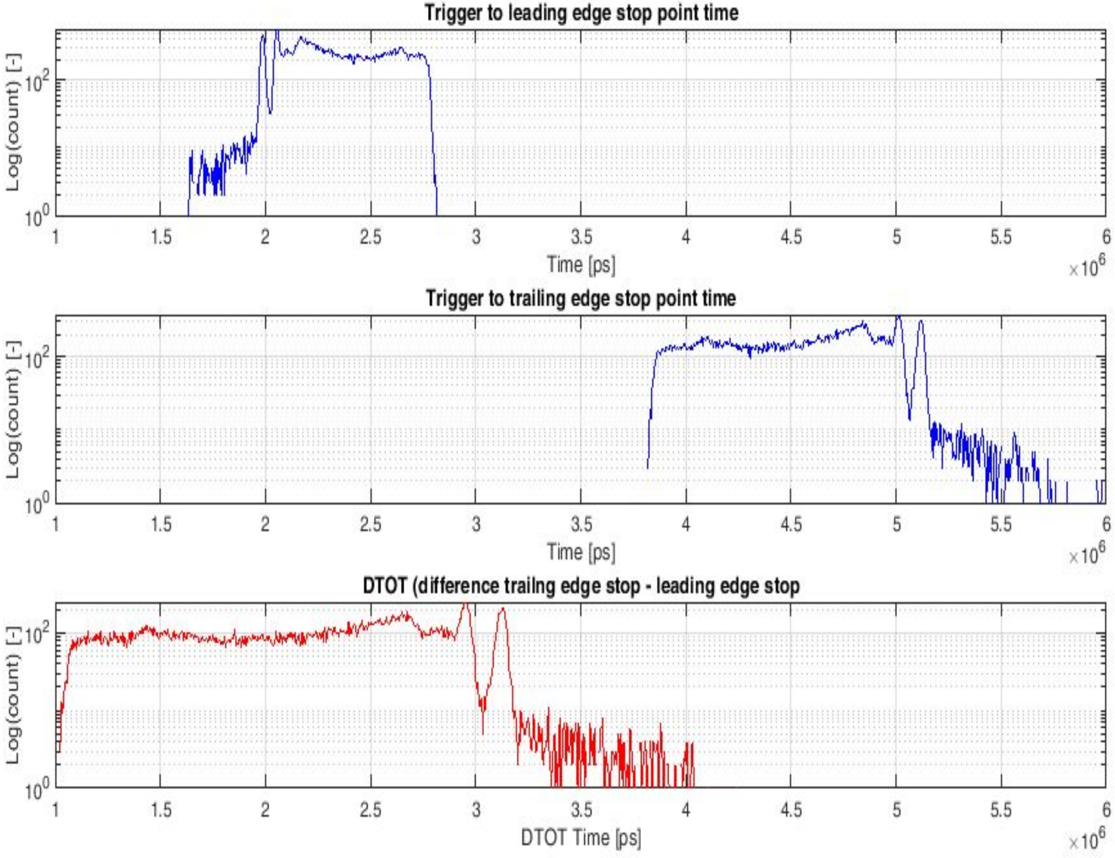


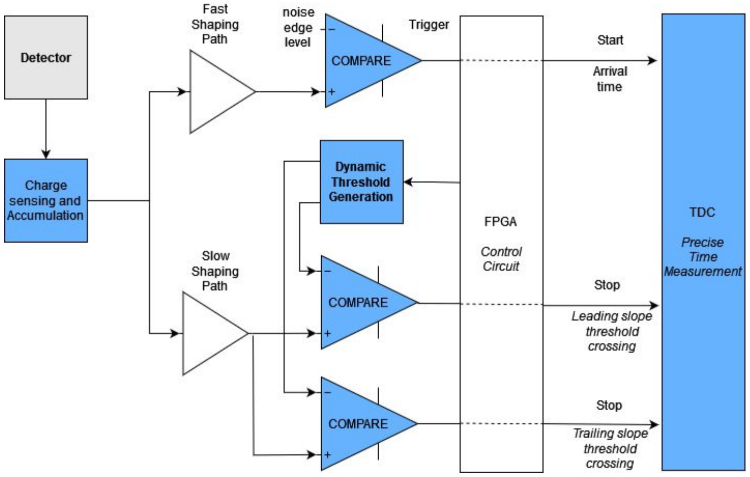
LaBr scintillator (15x15x30mm) + SiPM array (4x4 elements)

Type	MAPD-3NM-II
Active area	17 × 17 mm^2
Channels	16 (4 × 4)
Pixel pitch/pixel (diameter)	15 μm/ 12 μm
Total pixels	974 728 (6 1000 pixels/channel)
Fill factor	76%
Gain	~ 2.5×10^5
Spectral response	300–900 nm (max at 450 nm)
Operation voltage range	54–56 V
Breakdown voltage	51.6 V
Capacitance/channel	2 480/155 pF

Holik, M., Ahmadov, F., Sadigov, A. et al., Gamma ray detection performance of newly developed MAPD-3NM-II photosensor with LaBr3(Ce) crystal. Sci Rep 12, 15855 (2022). https://doi.org/10.1038/s41598-022-20006-z:

How DTOT time value is obtained

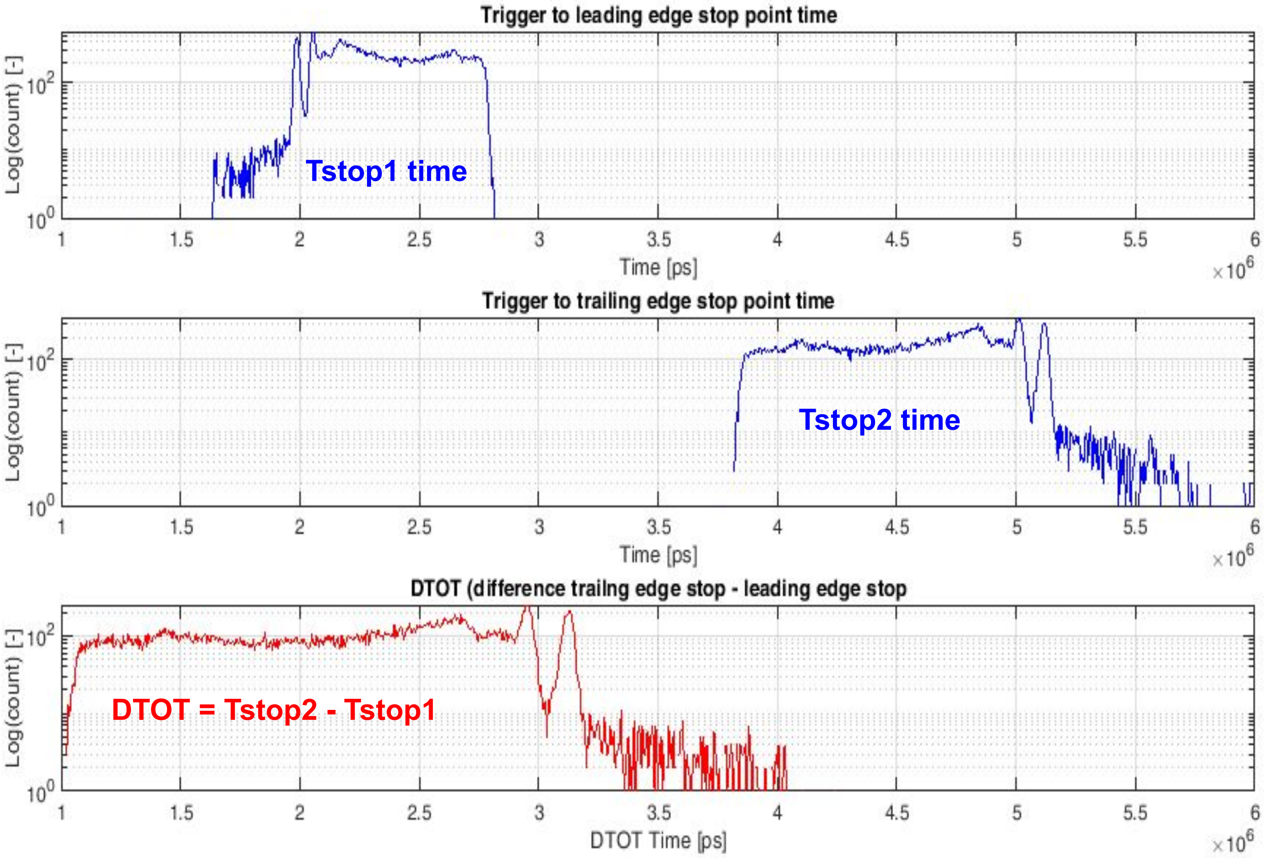




Notes

- Linear triangle dynamic threshold profile was used
- Co 60 source response observation

How DTOT time value is obtained



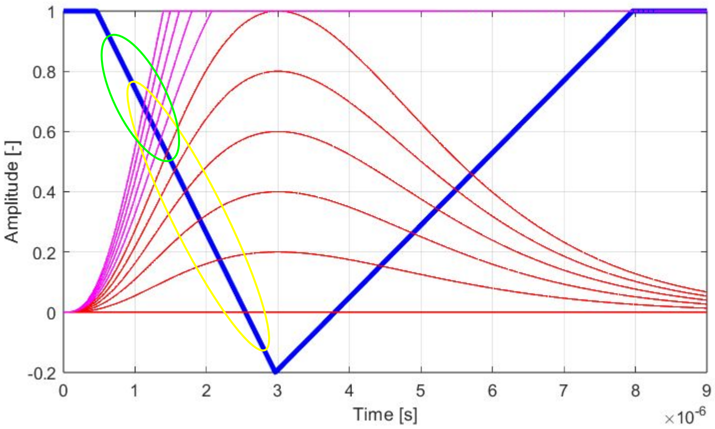
Notes

- Both partial times (trigger to stop/stop) already correspond to spectroscopy pulse energy
- Stop/Stop difference provides more accurate resulting value

Estimated equivalent resolution of DTOT converter in comparison to spectrometer based on ADC

- Achievable bit resolution of DTOT is straightly dependent on precision of TDC time measurement unit and DTOT pulse time min-max width range *(DTOT time range = DTOT time max - DTOT time min)*
- Estimation of equivalent resolution when compared to ADC based spectrometer
  - Example1>
    2 us DTOT range, TDC with 50 ps resolution => 40 000 time bins
    log2(time bins) ~ ADC bins, log2(40 000) = 15.28778 ~ 15 bit equivalent resolution!!!!
  - Example2>
    2 us DTOT range, TDC with 1 ns resolution => 2 000 time bins
    log2(time bins) ~ ADC bins, log2(2 000) = 10.9658 ~ 11 bit equivalent resolution!!!!

Other interesting aspect of DTOT converter

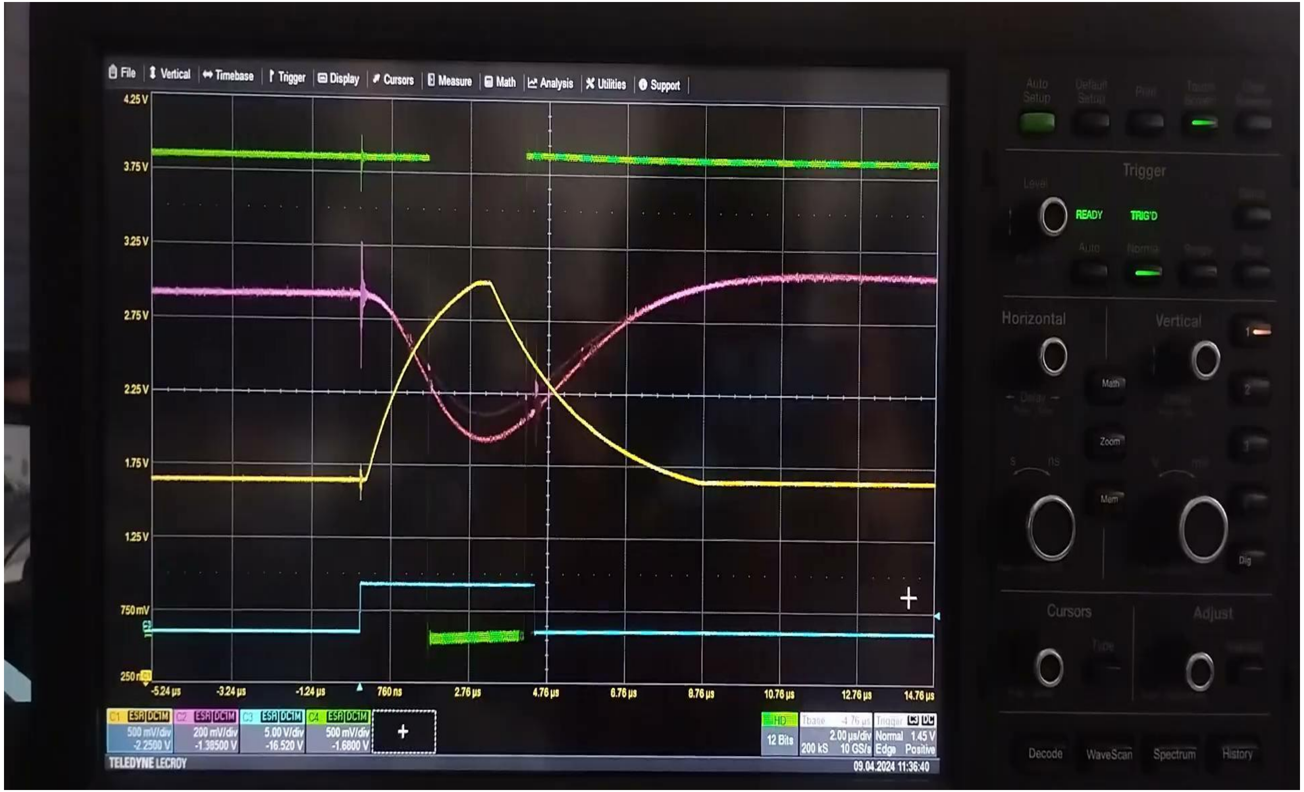


Notes

- Remarkable property of DTOT converter is that it can provide valid output result even if the front-end gets saturated
- Just the Trigger to Stop time can be used (however resulting in reduced precision)
- It allows to process wide dynamic range of spectroscopy signals

How DTOT Conversion Works

Osci Example - **RC** profile dynamic threshold



- **DTOT Result**
- **Spectroscopy Pulse**
- **Dynamic Threshold**
- **Arrival Trigger**

How DTOT Conversion Works

Osci Example - **Linear triangle** profile dynamic threshold

- DTOT Result
- Spectroscopy Pulse
- Dynamic Threshold
- Arrival Trigger

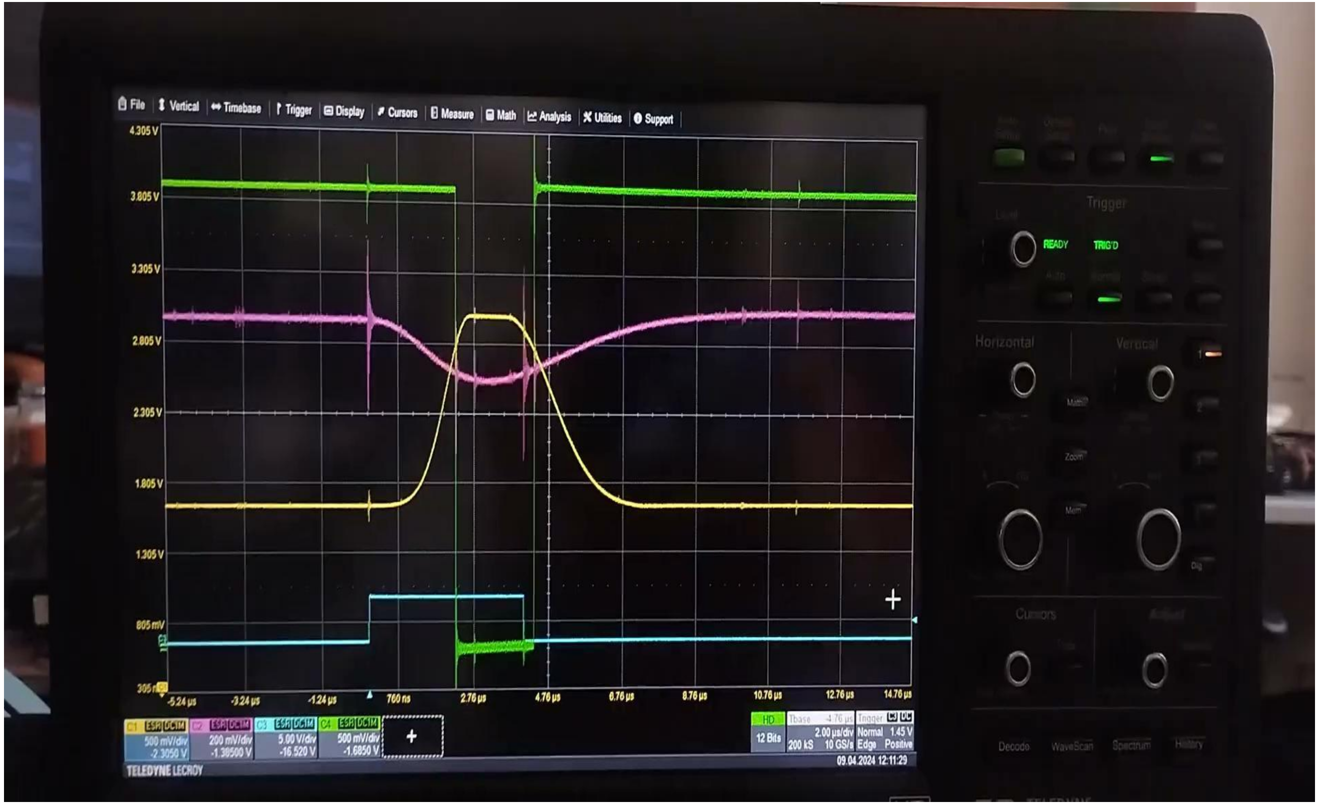
How DTOT Conversion Works

Osci Example - **Sharpen triangle** dynamic profile threshold

- DTOT Result
- Spectroscopy Pulse
- Dynamic Threshold
- Arrival Trigger

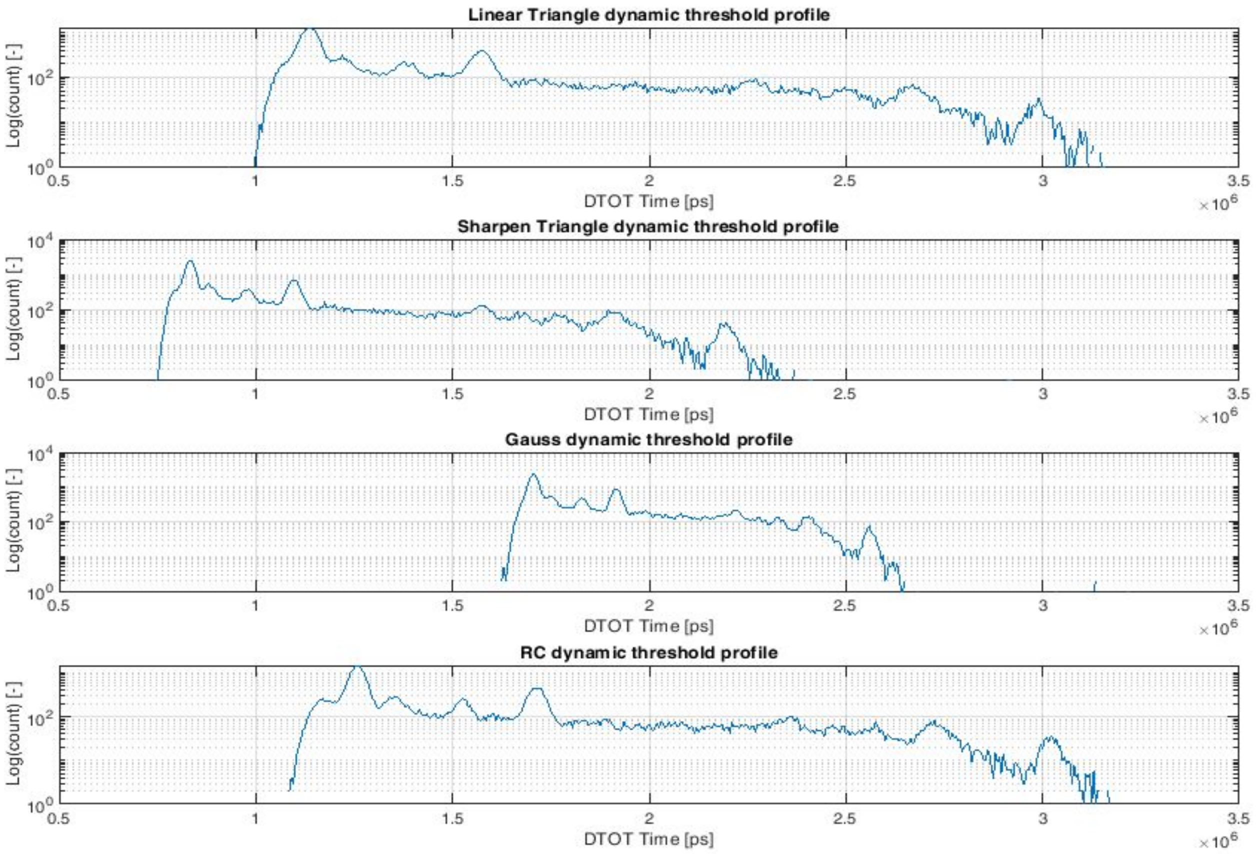
How DTOT Conversion Works

Osci Example - **Gauss** profile dynamic threshold



- DTOT Result
- Spectroscopy Pulse
- Dynamic Threshold
- Arrival Trigger

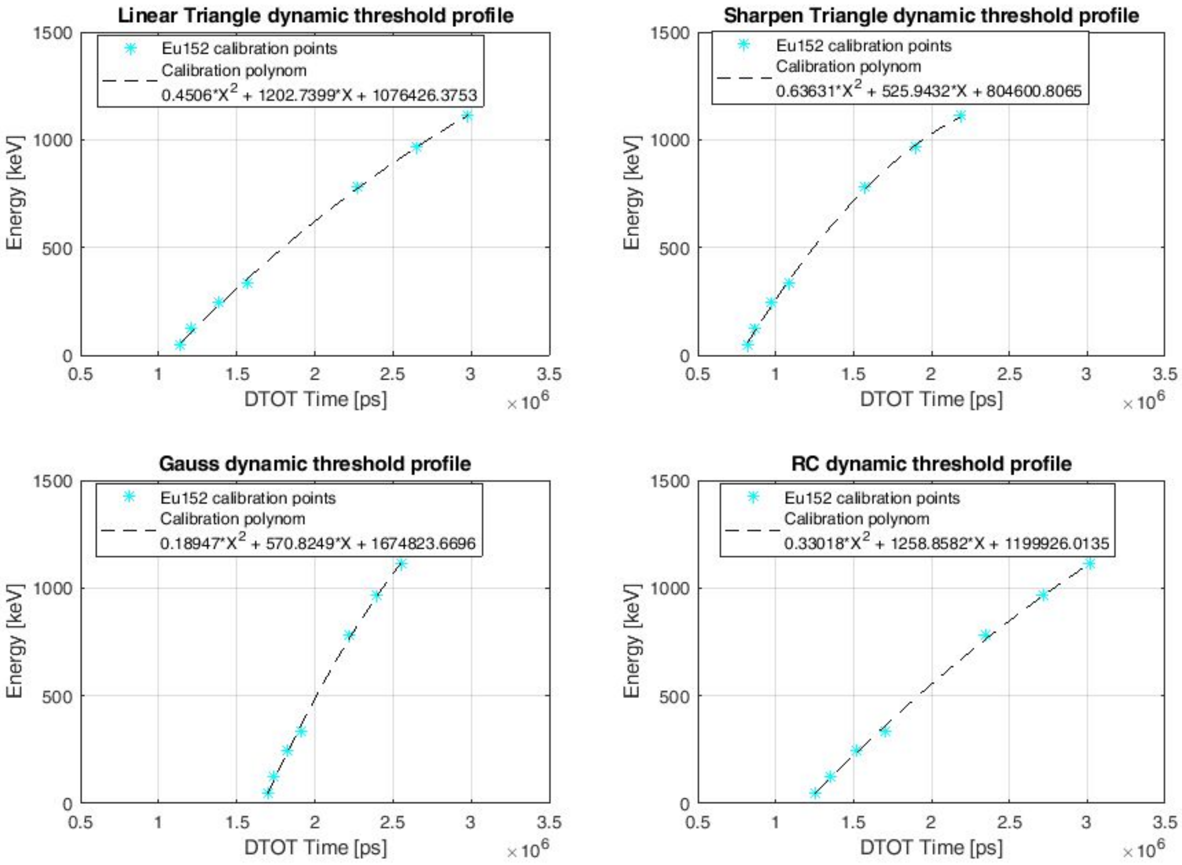
Exemplar DTOT raw time histograms measured with Eu 152 gamma source



Notes:

- *Various profiles of thresholds used*
- *5 ns binning of DTOT time histograms*
- *Same conditions and set-up for particular measurements*

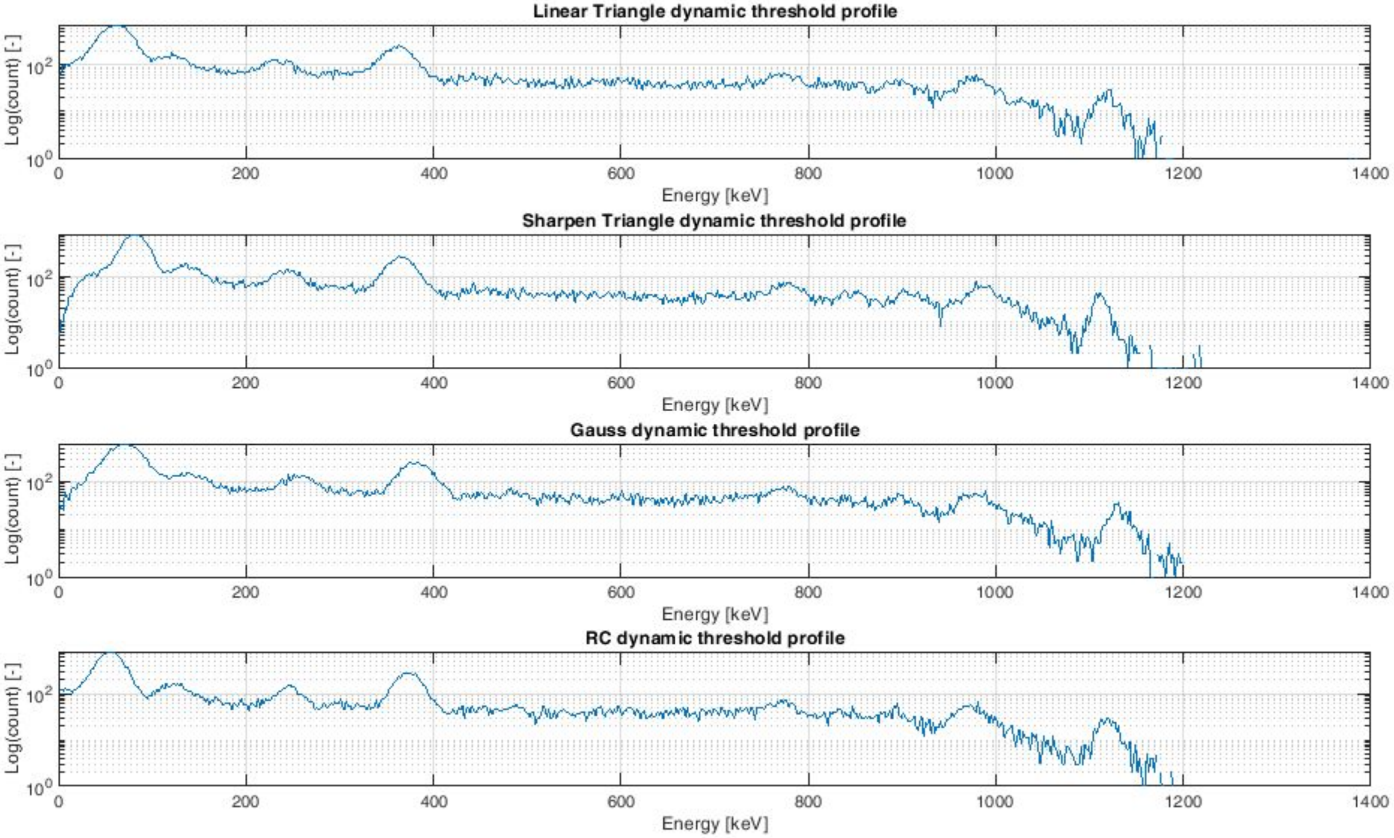
Calibration curves obtained for various dynamic threshold profiles used for DTOT conversion



Note

- Exemplar dependencies of DTOT time vs energy for Eu152 source for various profiles of dynamic thresholds

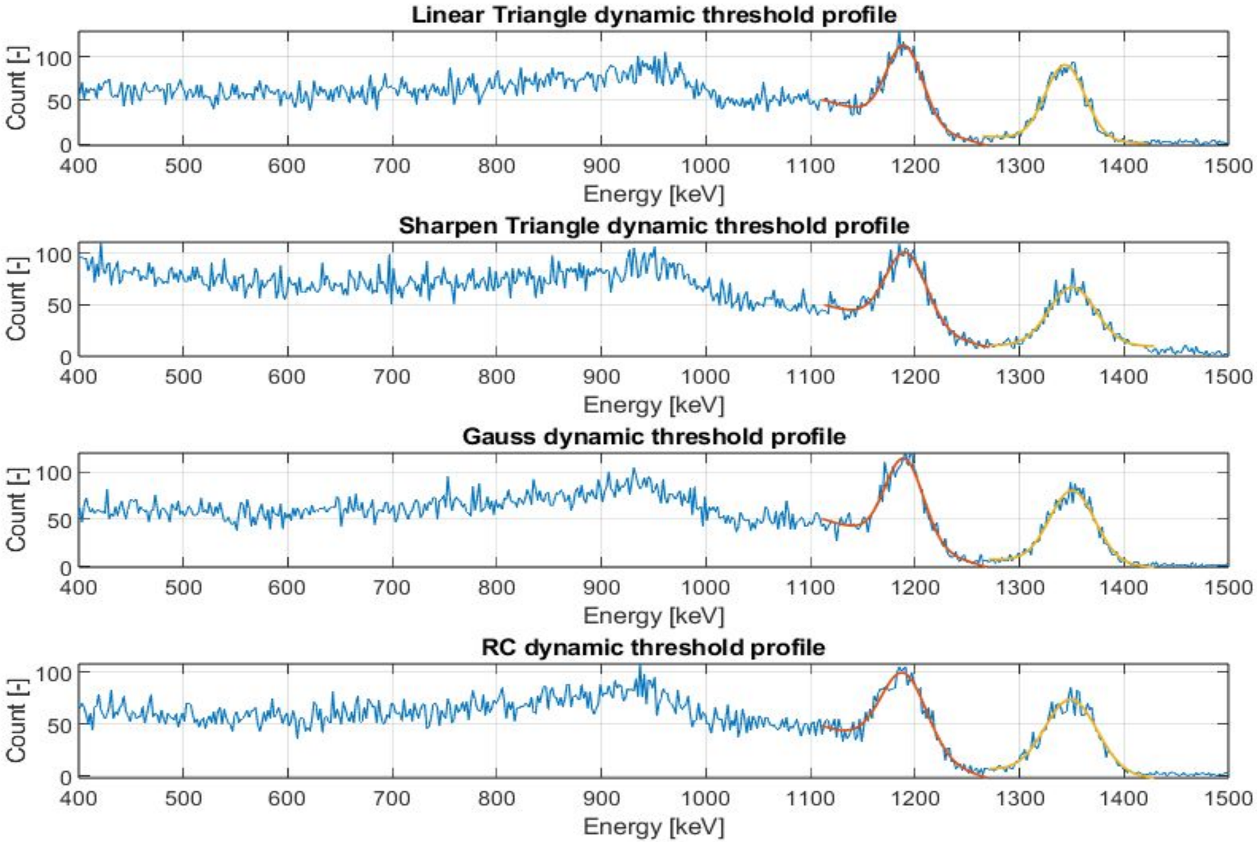
Exemplar DTOT calibrated spectra
measured with Eu 152 gamma source



Note:

- *application of calibration functions on DTOT times*
- *2 keV binning*

Exemplar DTOT calibrated spectra measured with Co 60 gamma source

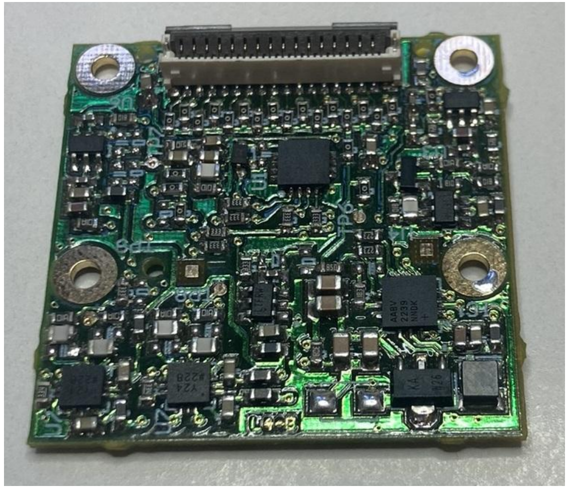


Note

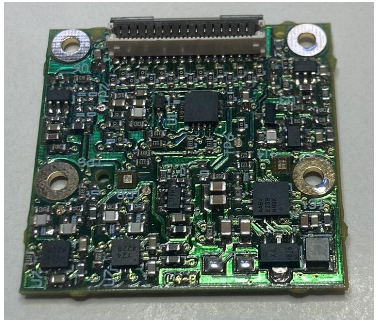
- *Even for the RC profile of dynamic threshold can provide satisfactory results in comparison to other profiles*

Toward a low complexity DTOT converter while offering similar performance comparable to a standard spectrometer device

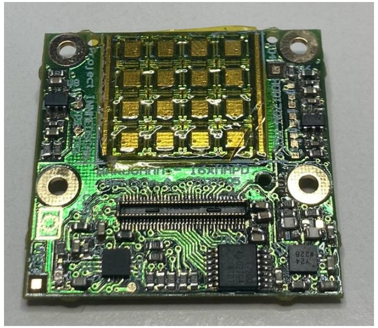
- Dedicated DTOT tester board proved that it is possible to create very a low complexity DTOT converter providing almost the same performance
- Support just for simple RC profile of dynamic threshold is fully sufficient (it can be generated directly by IO pins of FPGA device)
- Just few components are needed to implement full functionality (signal shaper, arrival trigger, comparison, FPGA control circuit)



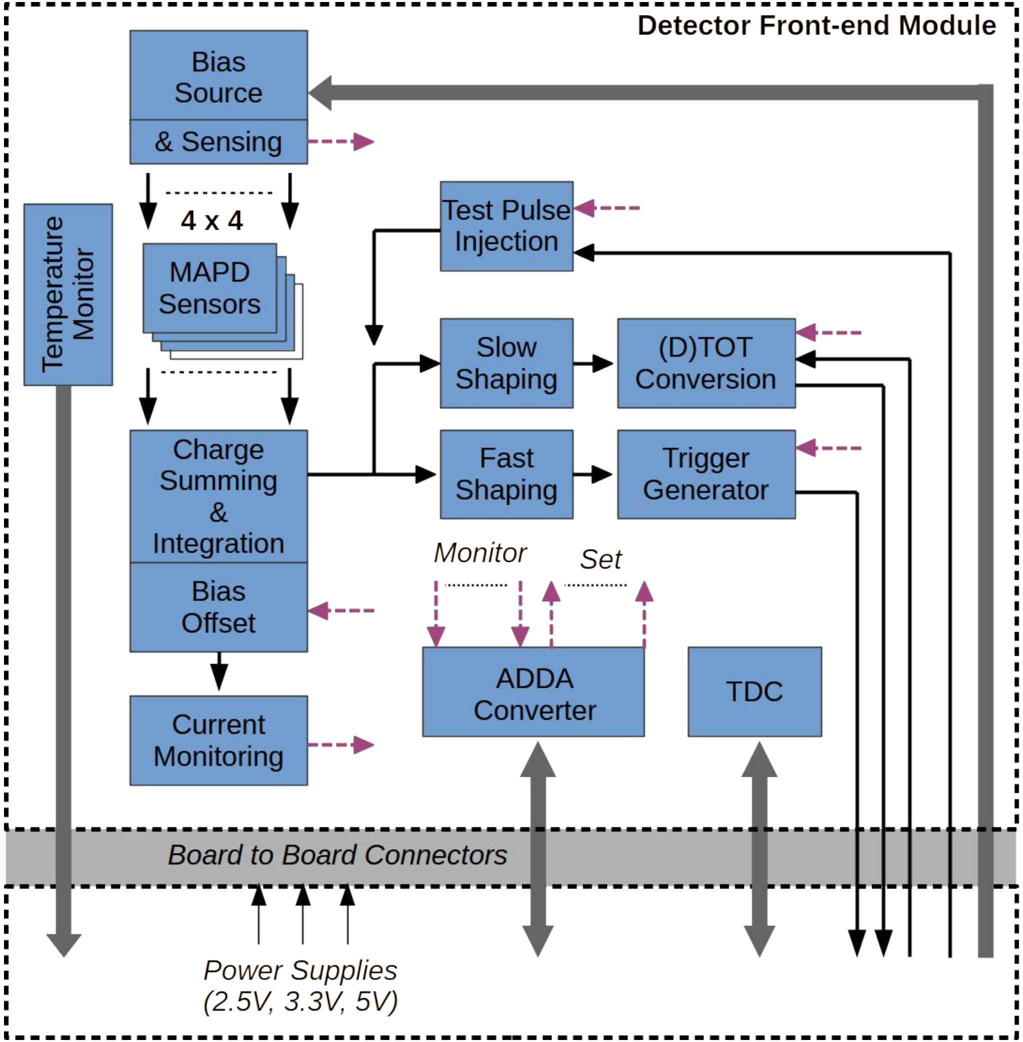
Low complexity DTOT front-end module
Functionality Overview



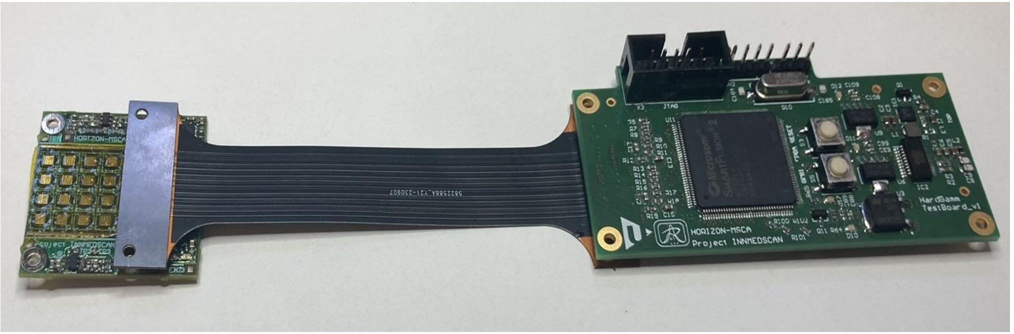
Bottom side view

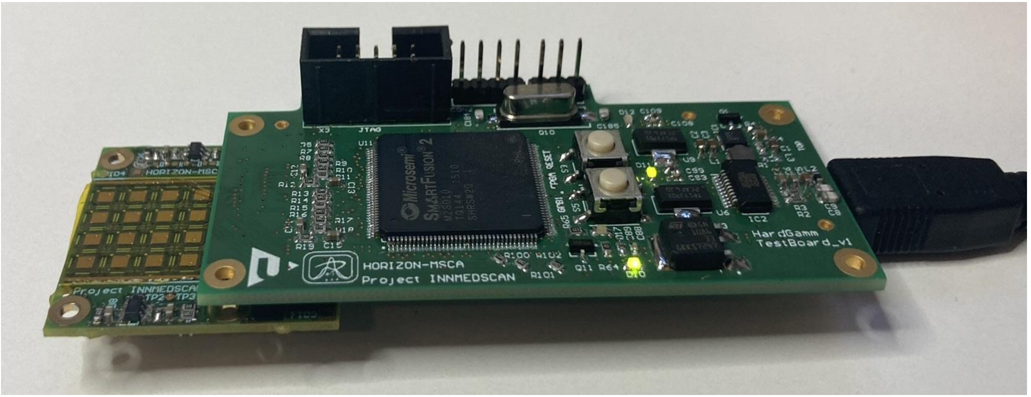


Top side view



Low complexity DTOT Front-end Module + Read-out Board

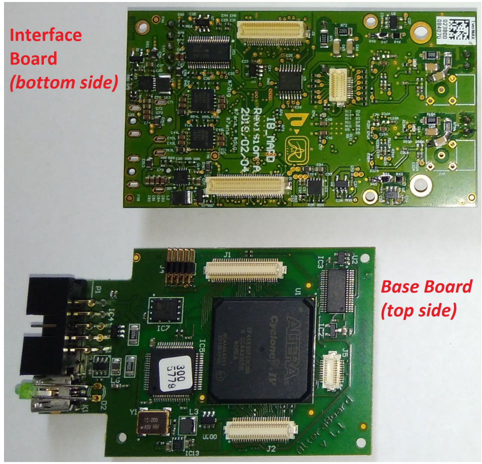


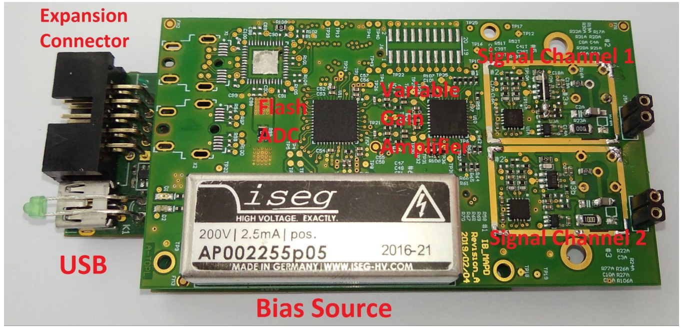


- Dedicated base board was created to allow testing of simple DTOT front-end
- Relatively cheap solution of spectrometer device in comparison to device based on flash ADC
- Read-out based on SmartFusion2 SoC FPGA

SpectrigMAPD - Laboratory instrument designed for spectroscopy measurement with SiPM sensors

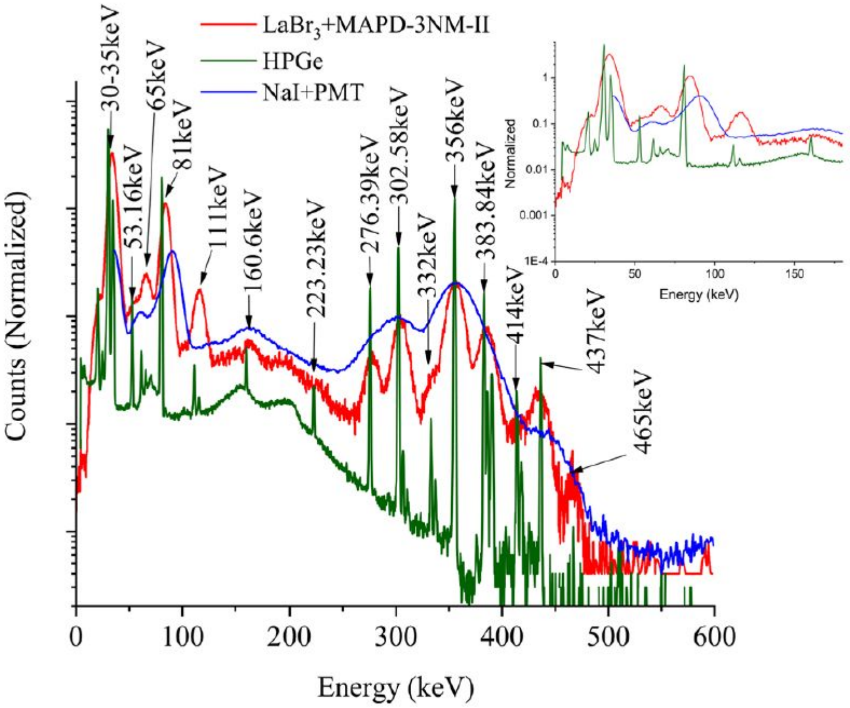
- Tailor made implementation of a read-out interface for SiPM like detectors supporting specific requirements
- Main purpose - pocket size spectrometer integrating all necessary functionality (USB connectivity, bias source, 12bit/400MHz sampling, variable gain, etc..)
- SpectrigMAPD used for comparative measurements with DTOT converter like device

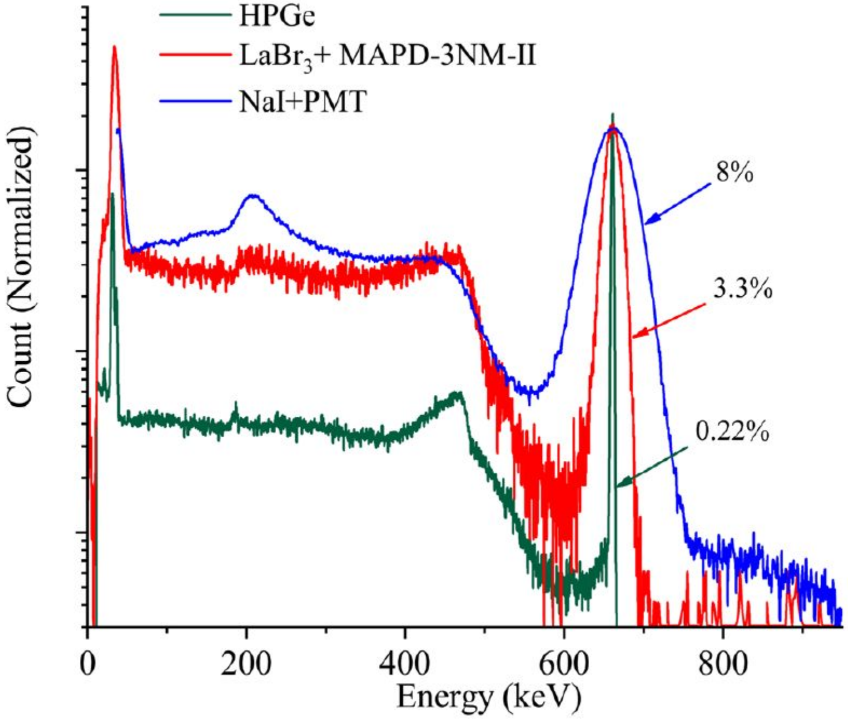




M. Holik et al., Miniaturized read-out interface "Spectrig MAPD" dedicated for silicon photomultipliers, Nucl. Instrum. Meth. A 978 (2020) 164440

Overview on Performance of SpectrigMAPD utilized for Gamma Spectroscopy measurements

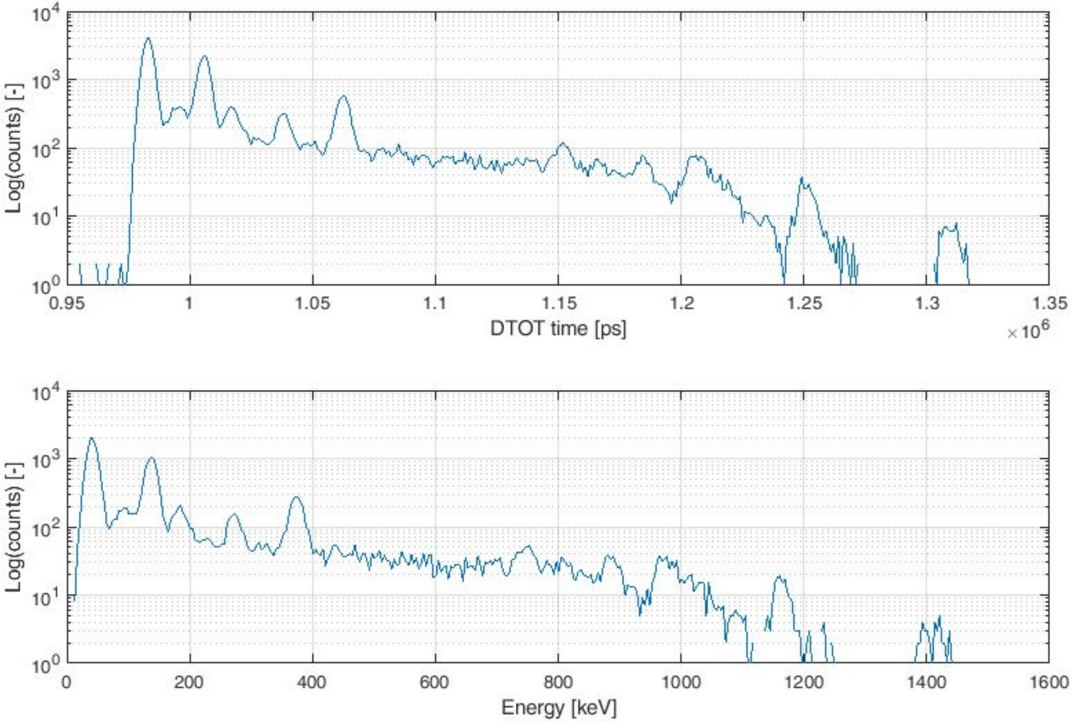


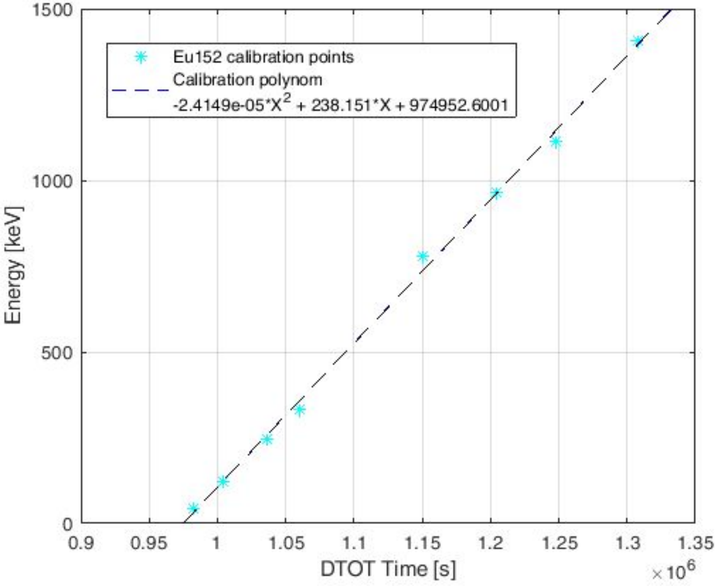


Holik, M., Ahmadov, F., Sadigov, A. et al., Gamma ray detection performance of newly developed MAPD-3NM-II photosensor with LaBr3(Ce) crystal. Sci Rep 12, 15855 (2022). https://doi.org/10.1038/s41598-022-20006-z:

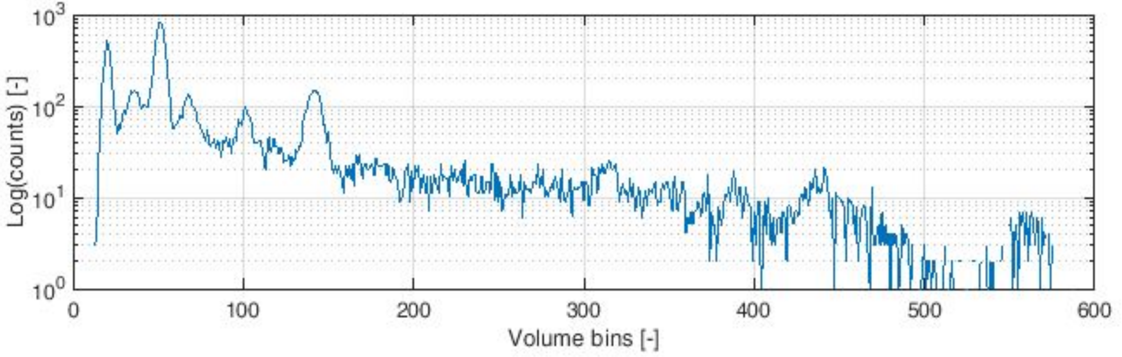
Low complexity DTOT front-end

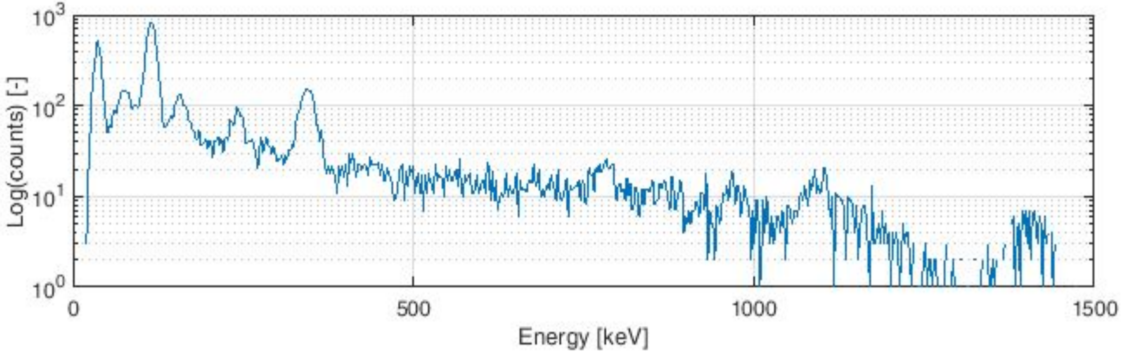
exemplar measurement with Eu 152 gamma source

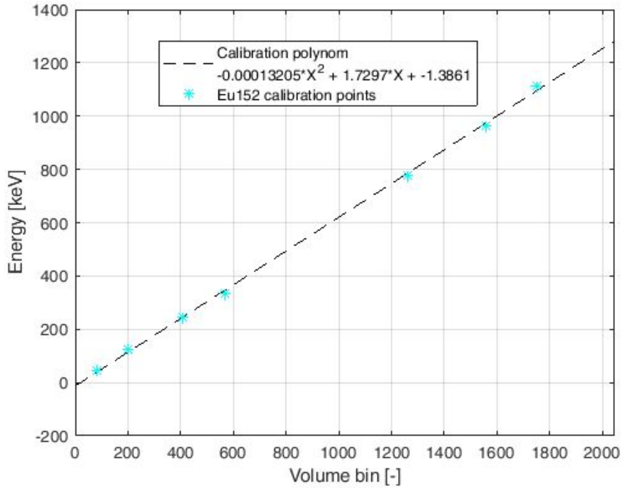




SpectrigMAPD standard spectrometer
repetition of measurement with Eu 152 gamma source

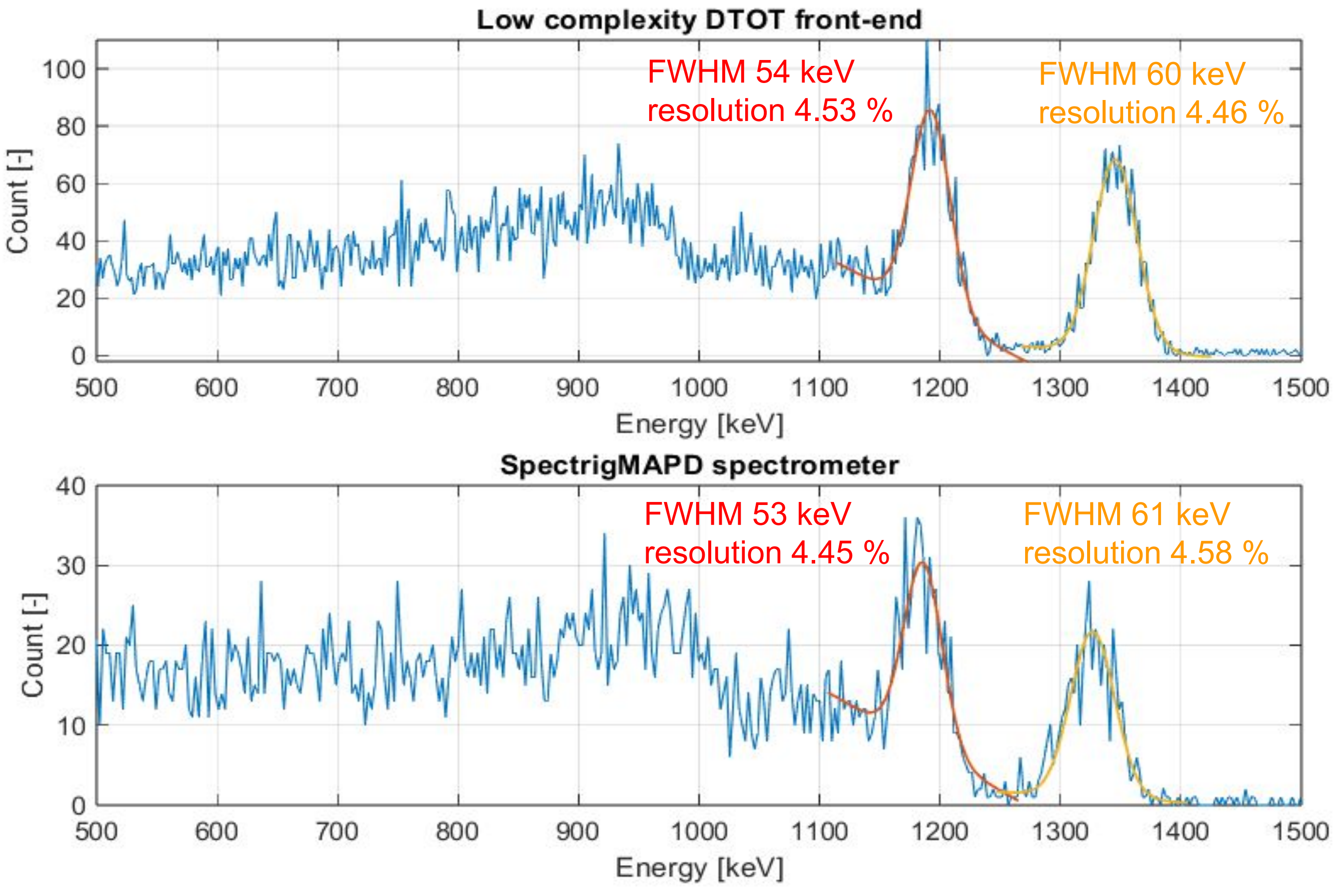






Exemplar comparison of Co60 spectra

Low complexity DTOT front-end **vs** SpectrigMAPD spectrometer



Note:

- *Using the same detection unit for testing, comparable results can be obtained for a standard spectrometer device as well as for a DTOT converter like device*

Conclusions
Main benefits of DTOT method application

- Application of DTOT conversion method provides promising alternative for construction of a spectrometer (with low hardware complexity, low power consumption, low dimensions…)
- The DTOT method seems to be ideal for integration into FPGA circuit …and also suitable for multi detector channel solution
- DTOT conversion results are obtained in real time without a necessity of post-processing demonding on computational resources
- Wide dynamic range of input spectroscopy signals can be accepted and processed
- DTOT converter can be also used for processing of signals from other types of detectors (not just for SiPMs)

Acknowledgements

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- *The activity has been carried under international collaboration of IEAP-CTU, IRP, FEE-UWB, DNR, INE&DET partners*

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Thank you for your attention

Questions are welcome!!!