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FOR NUCLEAR RESEARCH

Developing and optimizing signals processing techniques for the TANGRA project experimental setups

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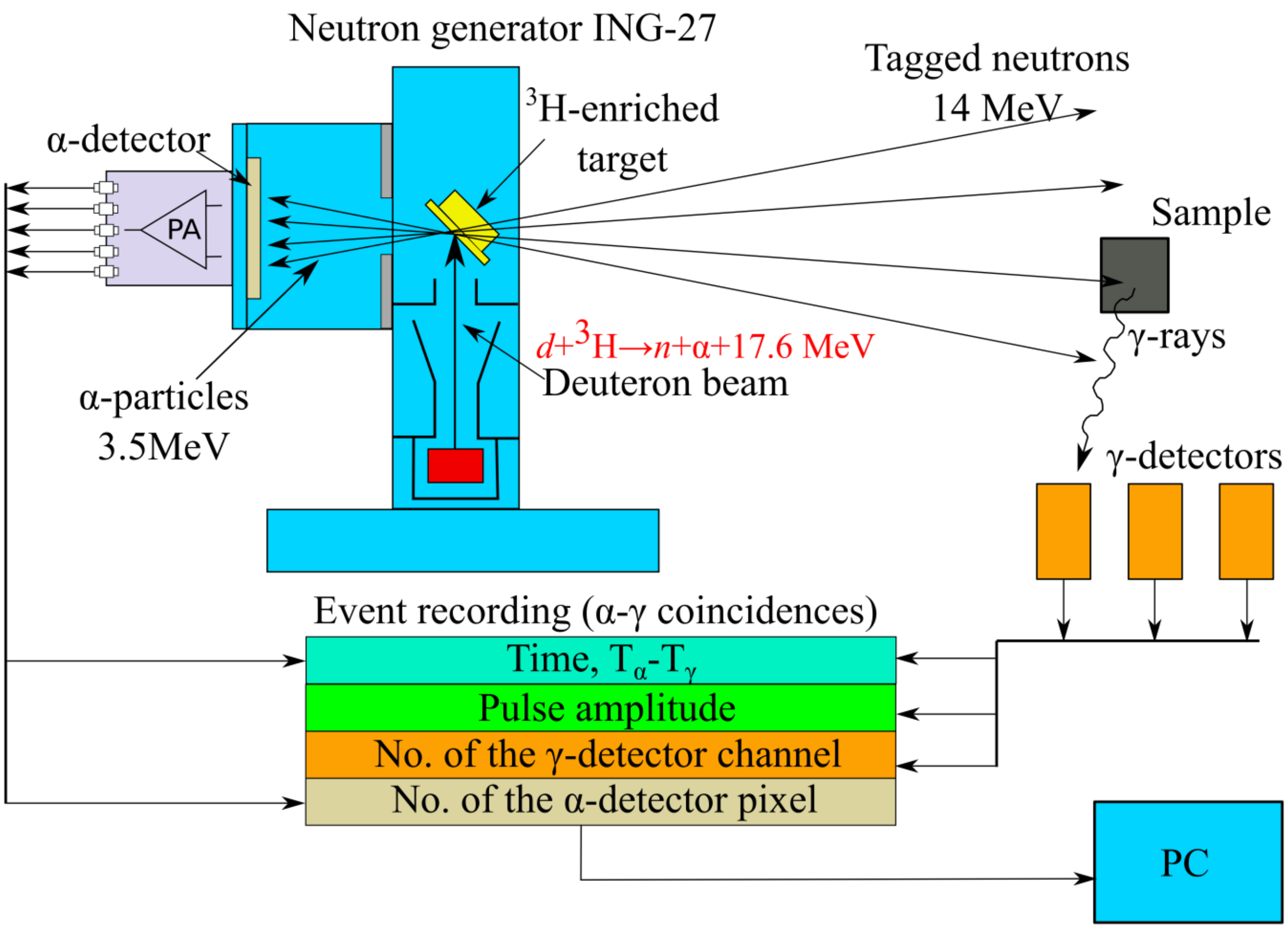
- Supported by the RSCF grant 23-12-00239

TANGRA Project

- **“TA**gged **N**eutrons and **G**amma **Ra**ys”
- Tagged neutrons method is based on the registration of α-particles formed in the reaction
  - $d + {}^3\mathrm{H} \rightarrow n + \alpha + 17.56\ \mathrm{MeV}$
- and the subsequent registration of coincident γ-quanta emitted during the de-excitation of the products of nuclear reactions in order to reduce the background influence.
- Goals of TANGRA project are developing TNM and its application in both fundamental and applied research.
- Fundamental: studies of neutron-nuclear interactions, and angular distributions for neutron-induced reactions in particular, development of nuclear models (Optical Model).
- Applied: prompt gamma activation analysis, development of data processing techniques.

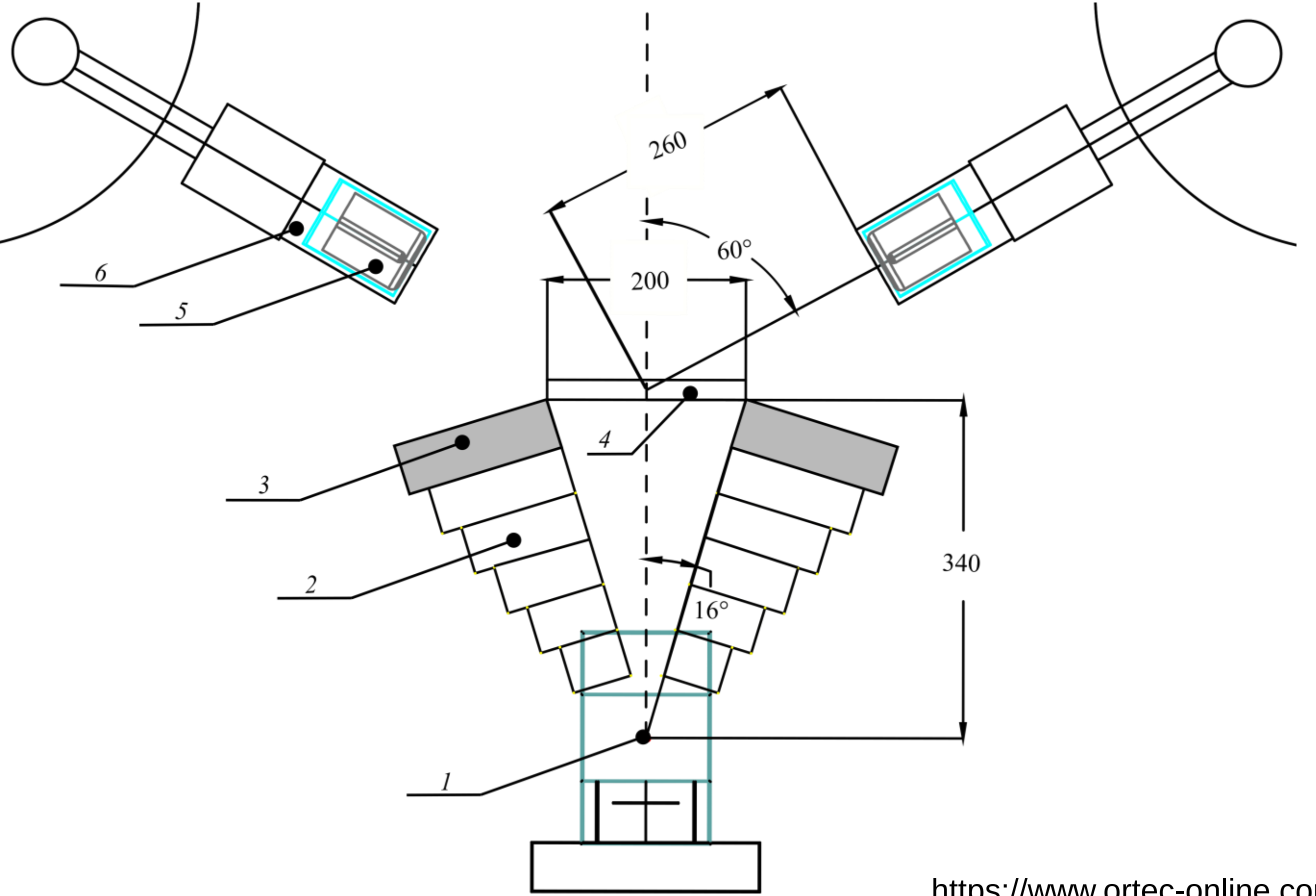
https://flnp.jinr.int/en-us/main/facilities/tangra-project-en

TANGRA Project



- The kinetic energy of deuterons is much less than that of the reaction products, therefore, the scattering angle of the α-particle and neutron is close to 180° in the lab frame.
- Registration of the α-particle by a position-sensitive detector allows determining the direction of the neutron's ejection corresponding to the α-particle, and gives a time stamp T_α , which serves as the "start" for determining the neutron's time of flight to the sample.
- Including the α-detector and detectors of secondary radiations in the coincidence scheme allows for the selection of events by time—the difference between the moment of secondary radiation registration T_γ and T_α .

HPGe detectors



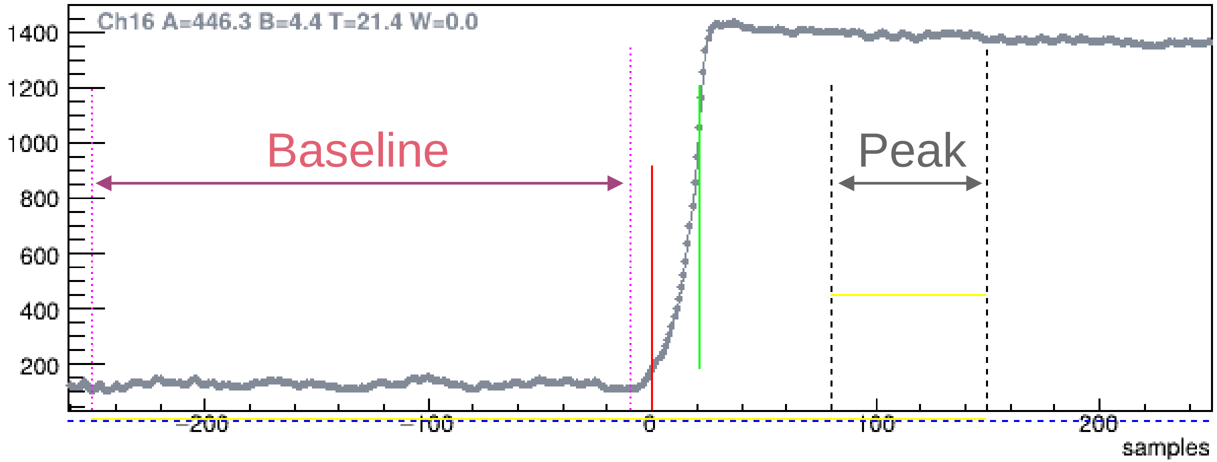
- Diagram of the modified setup based on HPGe detectors. 1 — ING-27, 2 — iron parts of the collimator, 3 — lead parts of the collimator, 4 — sample, 5 — HPGe crystal, 6 — detector housing. All dimensions are given in mm.
- 2 ORTEC GMX60P4-83 ultra-pure germanium detectors with a relative efficiency of 60% and an energy resolution of 2.3 keV (full-width at half-maximum) at 1.33 MeV (^{60}Co).
- Ge: high atomic number + high density — better γ absorption
- Low energy per electron-hole pair
- Used for better resolution in γ-spectroscopy

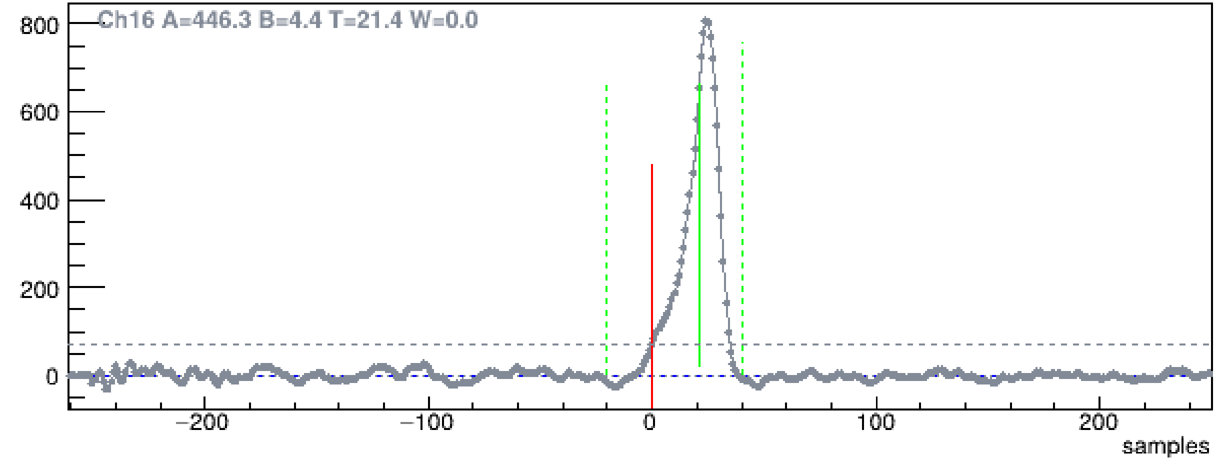
https://www.ortec-online.com/-/media/ametekortec/brochures/g/gamma-x-a4.pdf

Data processing

- Analogue signal in the form of step signal with exponential decay.
- Several digitizers are in use: standard ORTEC electronics, CAEN DT5725SB (8 channels, 14-bit, 250 Mhz), and custom Digital Signal Recorder electronics (16-bit 100 MHz) made in JINR.
- DSR electronics allows to use more channels and to work at higher data rates.
- Also have built-in support of Coincidence technique.
- Several methods of processing in order to form energy spectra.
- Also discussing some methods of data post-processing.

Method: “areas”

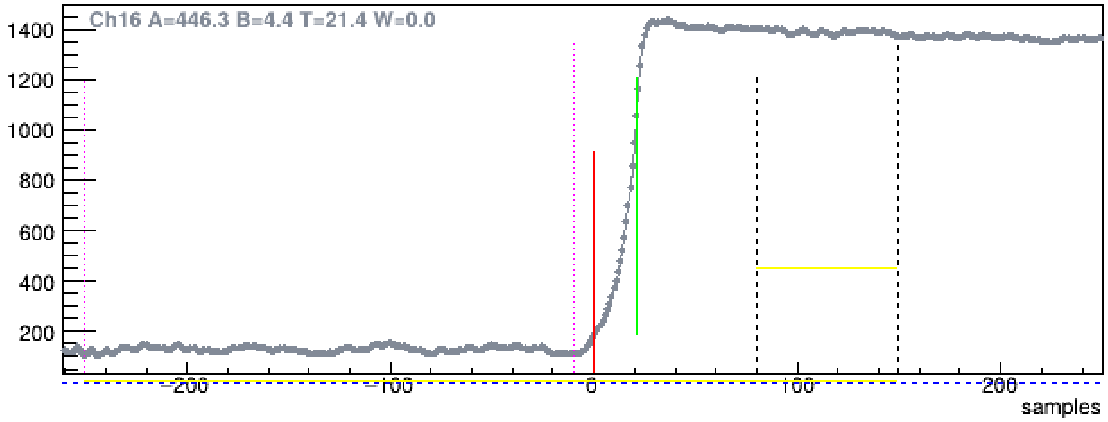


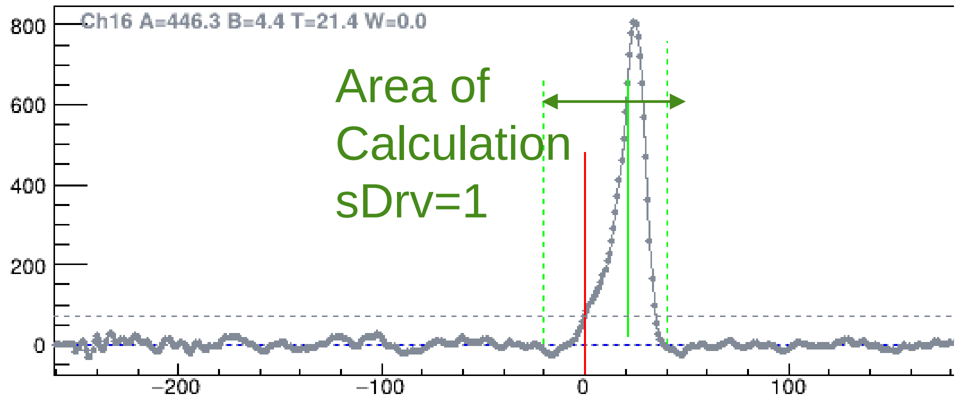


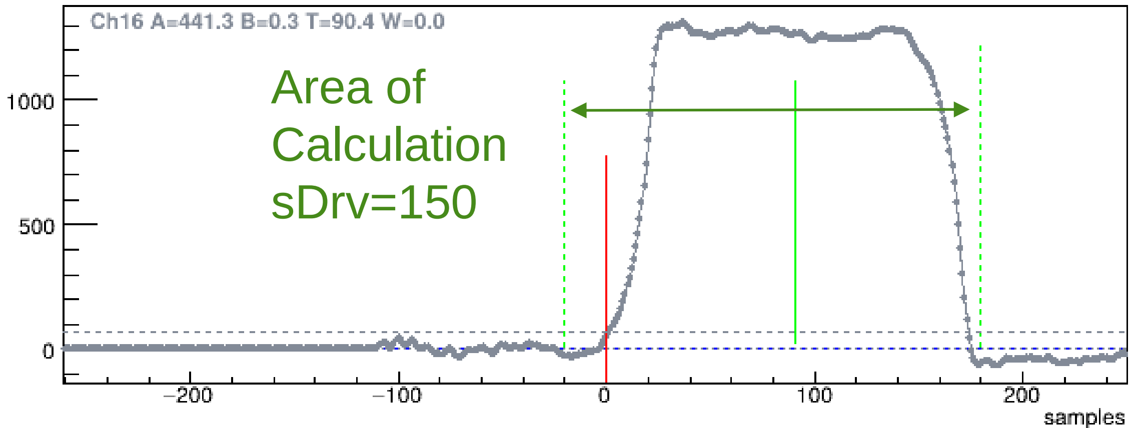
- Default method for our software
- Averaged points of the assigned area of peak minus averaged points of assigned area of the baseline
- Pros: fast processing, easy implementation
- Cons: insufficient resolution*
- * without corrections

Method: “derivative”

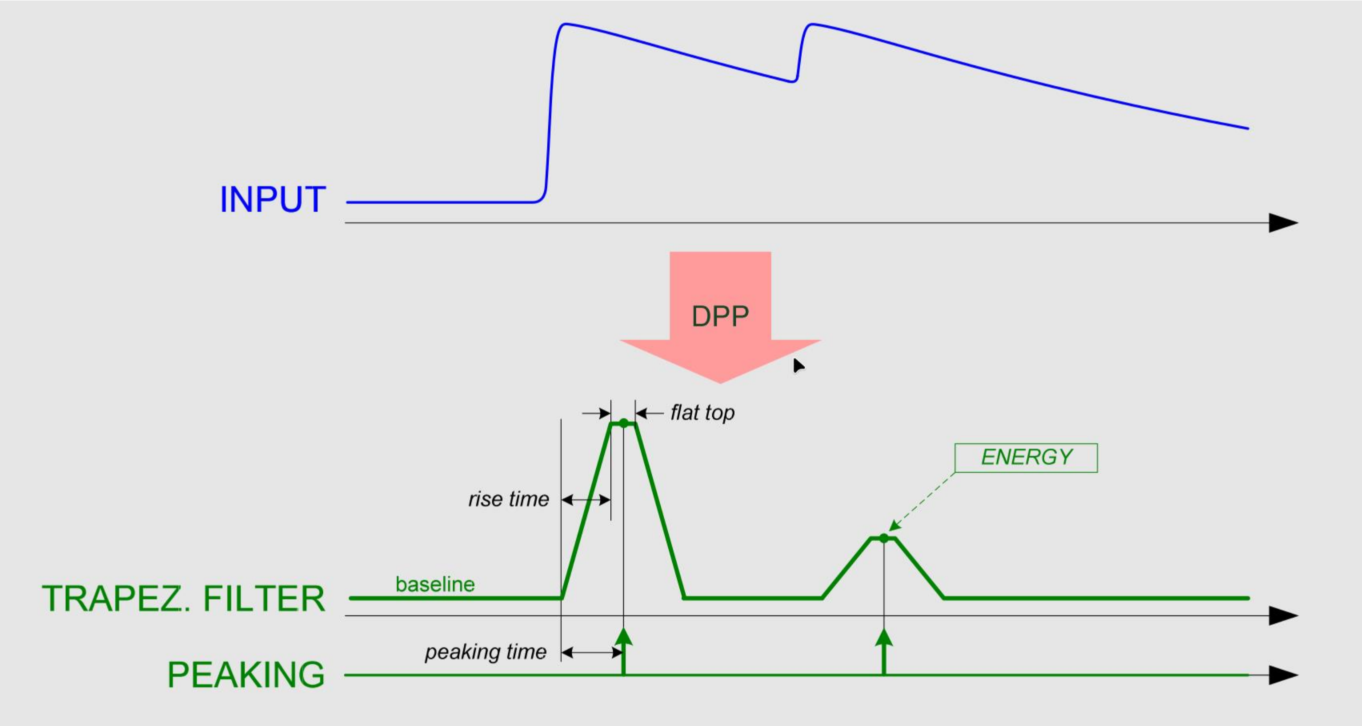
- Derivative chart: S[i]-S[i-sDrv]
- Calculating full integral of the derivative chart between assigned points
- Pros: fast processing, good resolution (under low load)
- Cons: unstable behavior under high load







Method: “trapezoidal filter”



- Conversion of the signal into trapezoid; trapezoid’s height is the energy
- Pros: good resolution even under high load
- Cons: need to compute more points, need to write more points
- CAEN and Ortec have built-in trapezoidal filters
- Not implemented in Romana software
- Here *G* – flat top, and *L* – rise time of the trapezoid

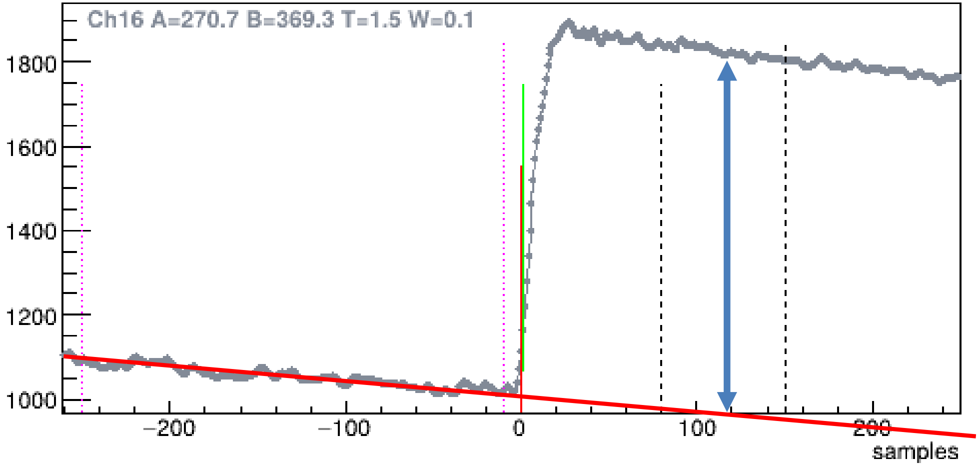
$$S[k] = \sum_{i=k-L+1}^{k} x[i] - \sum_{i=k-2*L-G+1}^{k-L-G} x[i]$$

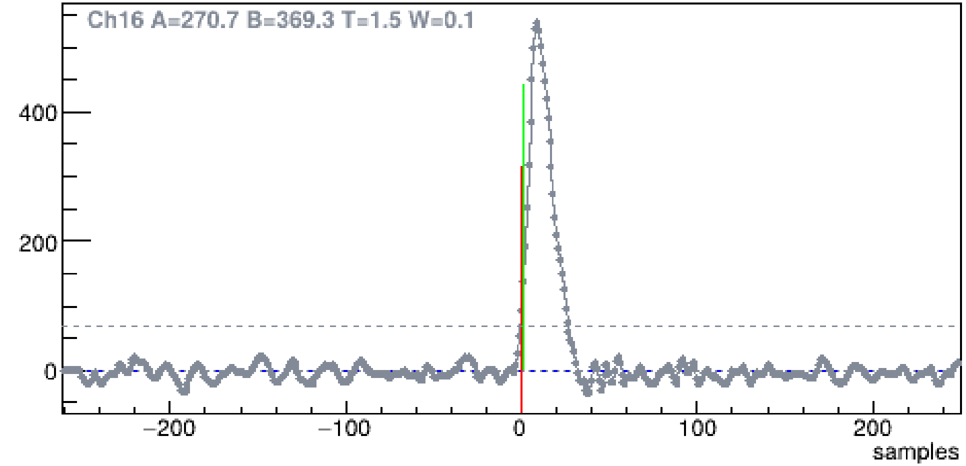
Recurrence formula

$$S[k] = S[k-1] + x[k] - x[k-L] + x[k-2*L-G] - x[k-L-G]$$

From CAEN Digital Pulse Height Analyser - a digital approach to Radiation Spectroscopy
https://seltokphotonics.com/upload/iblock/172/1725ca427148c5ddec8dbe3505fefb84.pdf

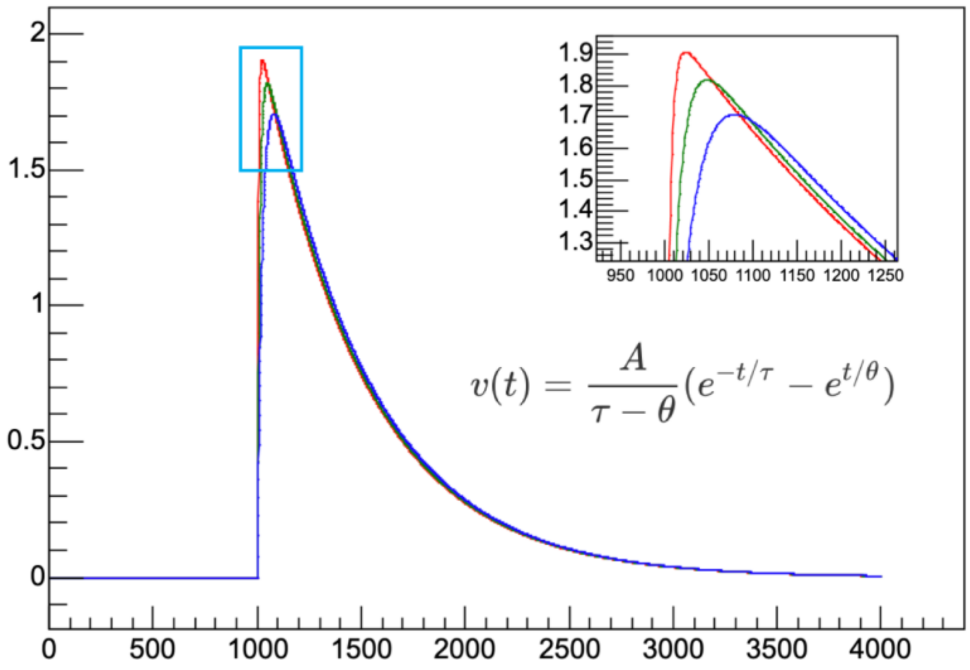
Corrections of a signal

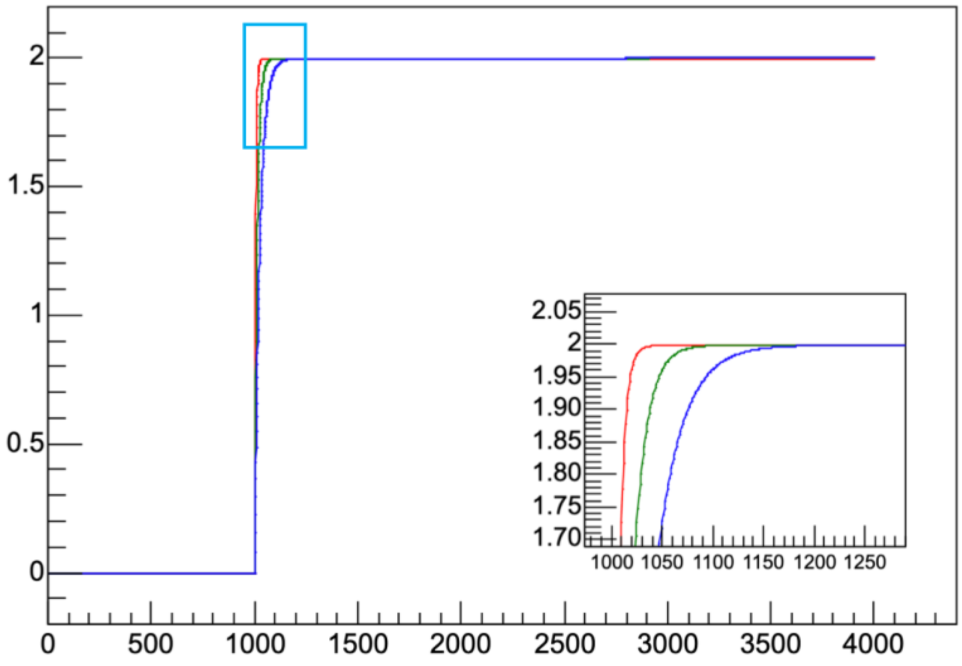




- Several signal corrections can improve energy resolution
- Higher event rate can lead to signals pile-up, but it is possible to align such signal (fitting baseline by pol1 and substracting)
- It also possible to smooth the signal (moving average)
- Trapezoidal filter method can be improved by correcting exponential decay and baseline offset

Correction of a signal exponential decay (Pole-Zero)





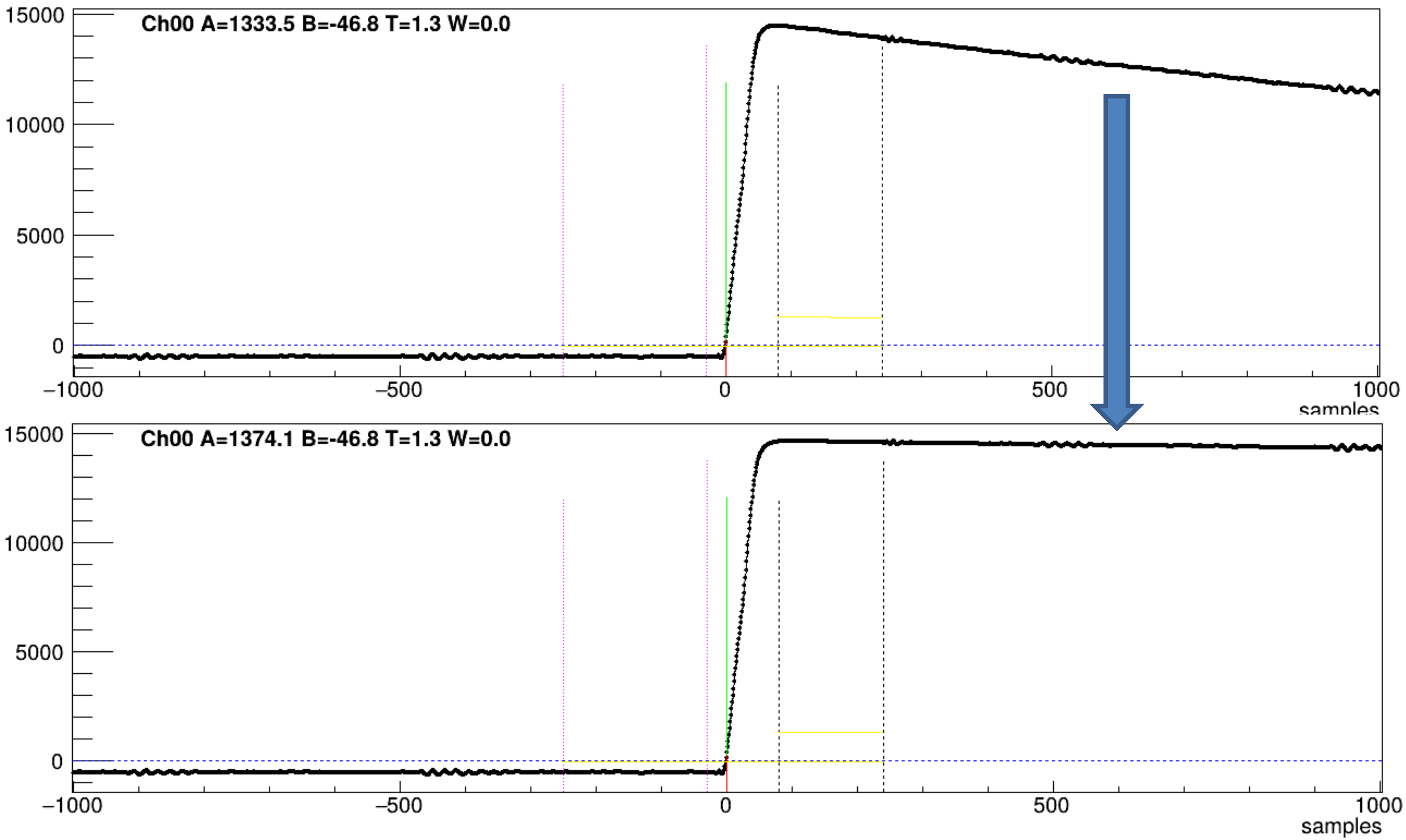
$$\Delta_{k,k-1} = x[k] - x[k-1]e^{-1/\tau}$$

$$x'[k] = x'[k-1] + x[k] - x[k-1](1-\frac{1}{\tau}), \quad e^{-1/\tau} \approx 1 - \frac{1}{\tau}$$

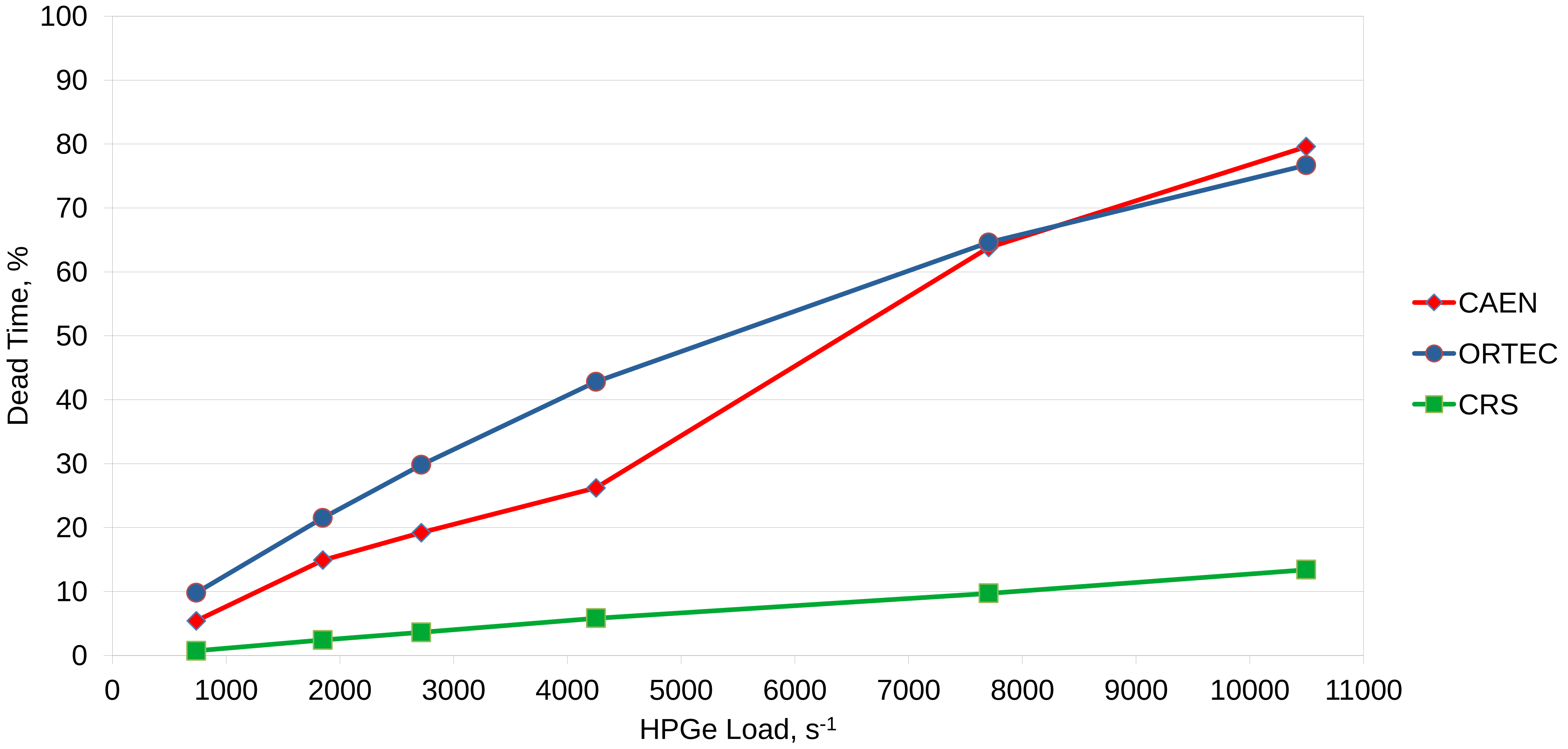
$$S[k] = S[k-1] + x'[k] - x'[k-L] + x'[k-2*L-G] - x'[k-L-G]$$

From https://zhihuanli.github.io/Experimental-Method-in-Nuclear-Physics/

Correction of a signal exponential decay (Pole-Zero)



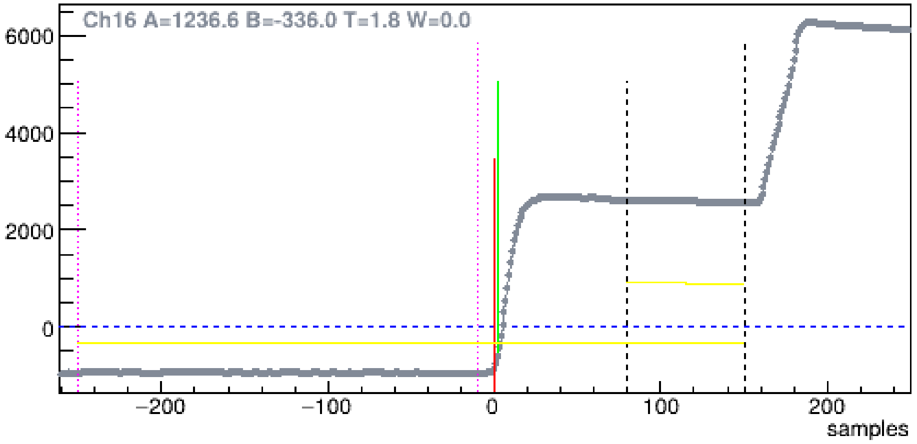
Results: dead time losses (in %)

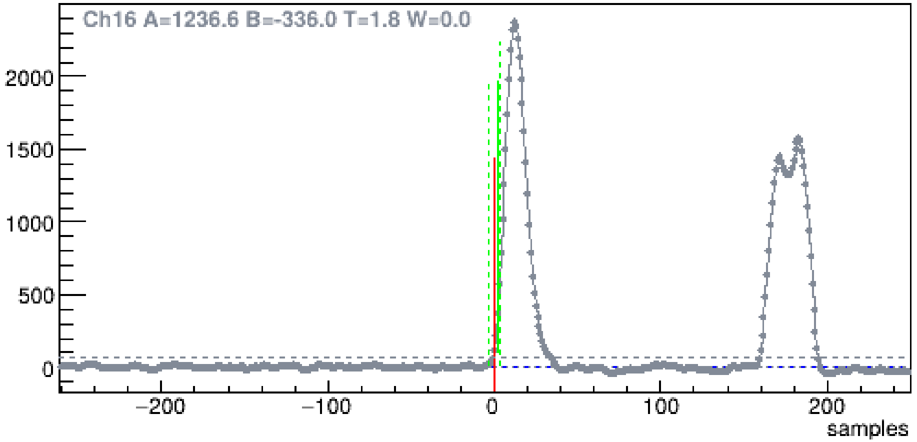


Dead time losses: origins

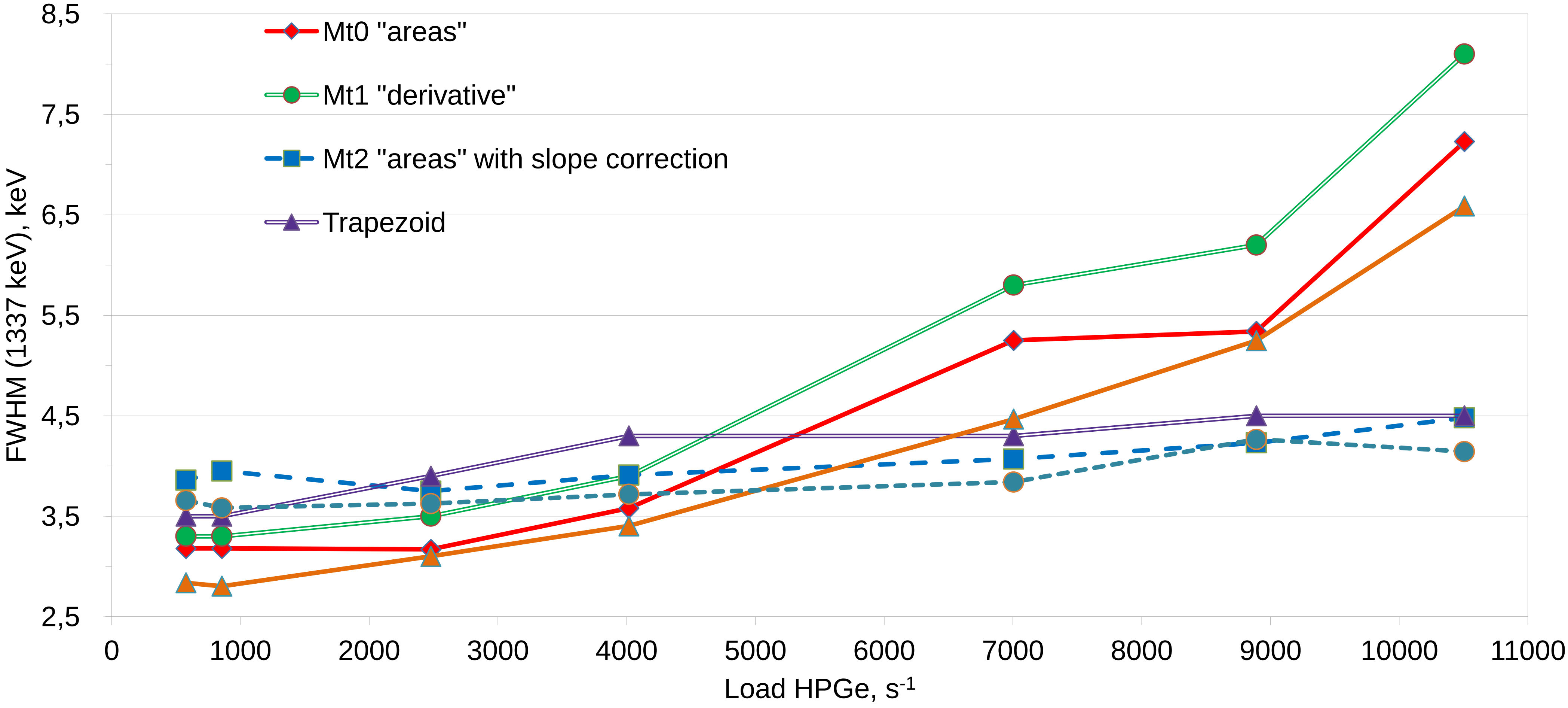
Main reasons for data loss are:

- “Real” events loss
  - Exceeding data storage write speed
  - Exceeding data transfer channel speed
  - Buffer overflow
- Signals pile-up
- Electronics own dead time



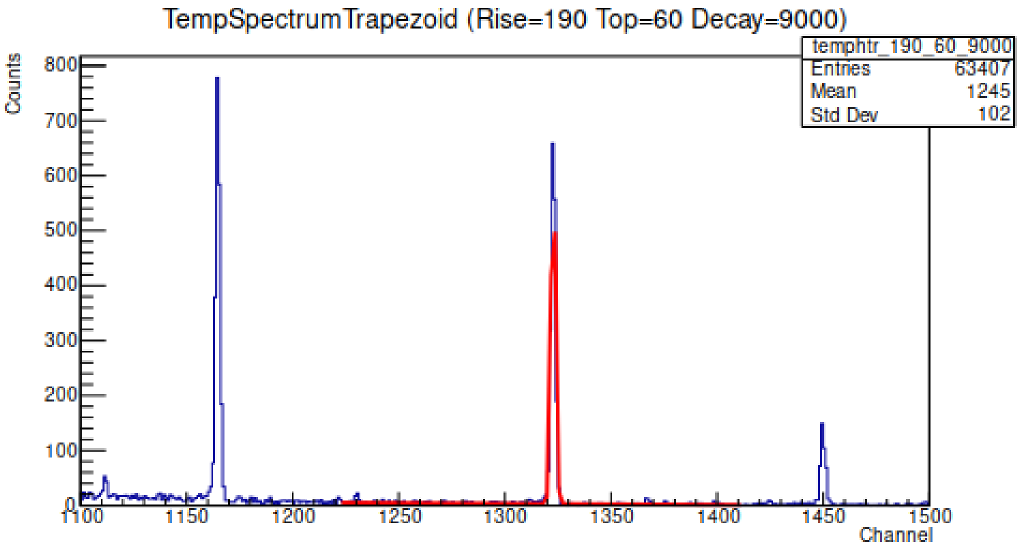


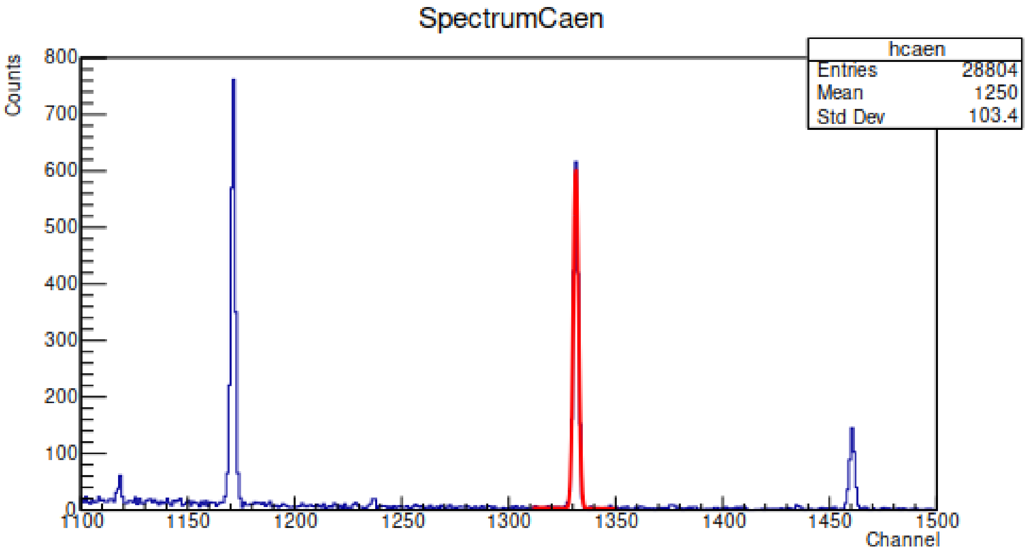
Results: resolution (FWHM (1332 keV), $^{60}Co+^{22}Na$), comparison of methods under high load



Results: resolution under low load comparison with CAEN (long signal)

Mt0 (“areas”)	Mt1 (“derivative”)	Mt2 (“areas” with slope correction)	Trapezoid (DSR data)	CAEN	Trapezoid (CAEN data)	Mt0 with Pole-Zero correction	Mt2 with Pole-Zero correction
2.47	2.70	2.89	2.46	2.82	2.75	2.36	2.72





Conclusions

- DSR digitizer allows measurements under higher load than CAEN or Ortec electronics.
- Under low load all methods give adequate accuracy, trapezoid filtering gives the best FWHM.
- Under high loads several techniques can be used for partial mitigating of pile-ups and noise influence; meanwhile they can lower resolution under low load.
- Under high load there should be balance between data loss and energy resolution; writing longer waveforms can improve the resolution but also can increase data loss.

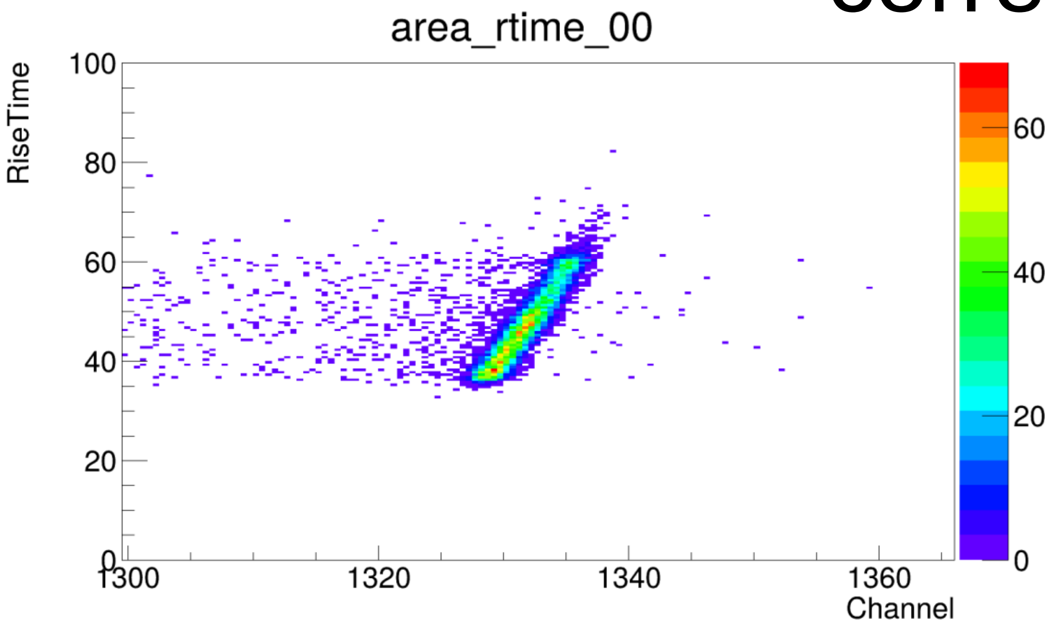
Conclusions: future plans

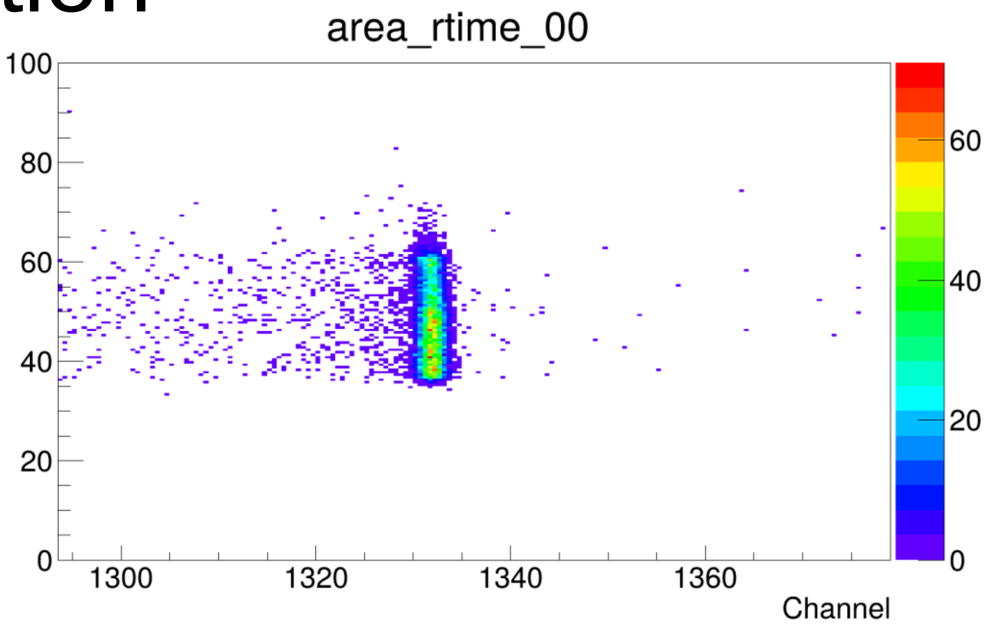
- The implementation of Digital Signal Processing allows for data processing under even higher loads with an acceptable reduction in accuracy.
- Trapezoid filtering allows for reaching high accuracy, even warranted specification, but requires fine tuning of parameters, especially under higher loads.
- Further investigation and adjustments of different methods behavior.

Thank you for your attention!

Backup slides

Alternative method of a signal exponential decay correction





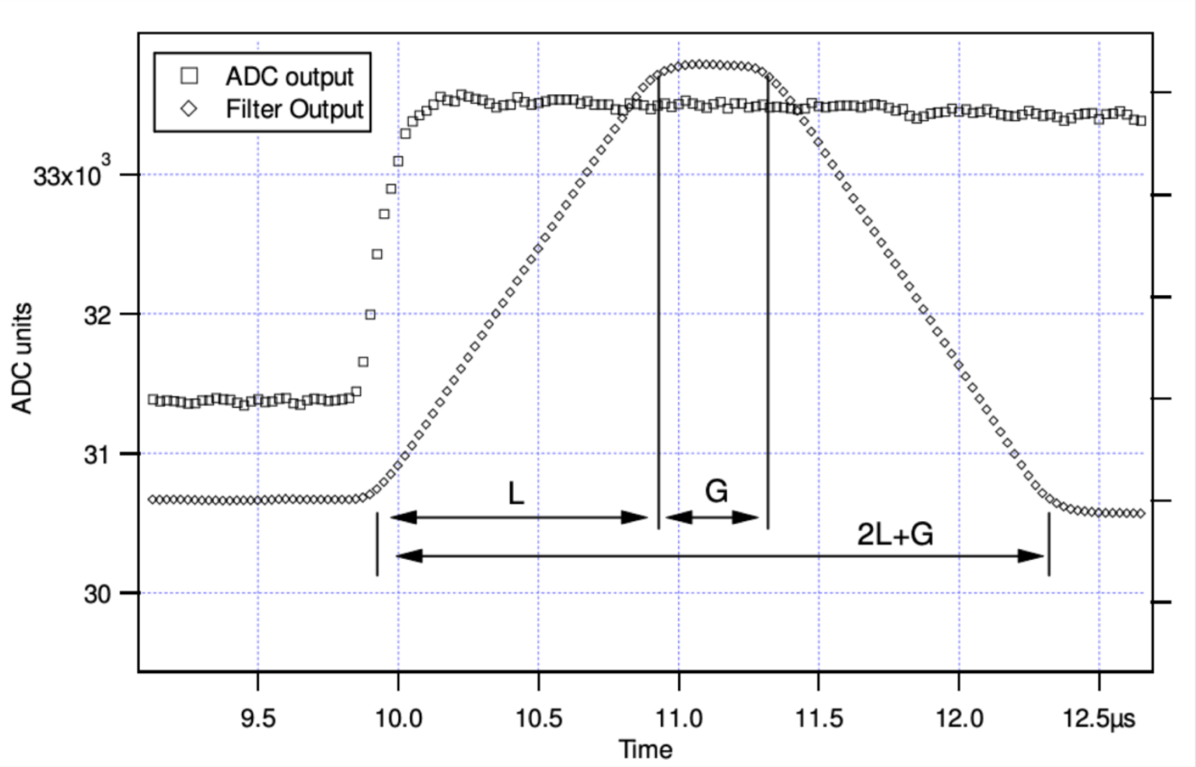
Exponential decay correction linearly depends on the signal rise time.

So in the Romana software another way of Pole-Zero correction has been added: to the energy (area) of the pulse a correction is added depending on the pulse rise time according to the formula:

$$E'=E\cdot(1+Rt\,/\,|Pz|),$$

Where *Rt* – the pulse rise time, *Pz* – correction parameter, approximately equal to the pulse decay time in samples. It works with DSP techniques.

Method: “trapezoidal filter”



- Conversion of the signal into trapezoid; trapezoid’s height is the energy
- Pros: good resolution even under high load
- Cons: need to compute more points, need to write more points
- CAEN and Ortec have built-in treapezoidal filters
- Not implemented in Romana software yet

$$S[k] = \sum_{i=k-L+1}^{k} x\,[i] - \sum_{i=k-2*L-G+1}^{k-L-G} x\,[i]$$

Recurrence formula

$$S[k] = S[k-1] + x[k] - x[k-L] + x[k-2*L-g] - x[k-L-G]$$

From https://zhihuanli.github.io/Experimental-Method-in-Nuclear-Physics/

Results: dead time losses (in %)

Load	CAEN	ORTEC	DSR
738	5.4	9.8	0.7
1851	14.9	21.5	2.4
2716	19.2	29.8	3.6
4252	26.2	42.8	5.8
7705	63.8	64.6	9.7
10498	79.6	76.7	13.4

Adding DSP techniques can lower dead time down to units of percents even for high loads

Results: resolution (FWHM (1332 keV), ^{60}Co+^{22}Na), comparison of methods under high load

Load (CRS)	Mt0 (“areas”)	Mt1 (“derivative”)	Mt2 (“areas” with signal corrections)	Mt2 selected parameters	Trapezoid	Mt0 with PoleZero	Mt2 with PoleZero
11872	7.686	N/A	4.625	4.366	4.56	6.398	4.332
11519	6.882	N/A	4.762	4.239	4.58	5.948	4.119
10508	7.226	8.134	4.604	4.48	4.49	6.588	4.143
8891	5.341	6.185	4.609	4.425	4.7	5.245	4.265
7006	5.25	5.831	4.505	4.065	4.29	4.467	3.84
4018	3.58	3.903	4.133	3.911	4.37	3.404	3.718
2479	3.169	3.459	4.563	3.754	3.89	3.101	3.626
856	3.181	3.288	4.094	3.949	3.48	2.804	3.583
578	3.179	3.275	4.07	3.86	3.45	2.837	3.657