Visualization of dead-time behaviour of ^{3}He neutron coincidence counters using list mode recorders

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Neutron multiplicity counting using ^{3}He neutron detectors is a widely used technique in safeguards for the determination of mass of fissile material. Unfortunately, these neutron detectors suffer from dead-time loss, which – if uncorrected – will lead to a bias in fissile material mass assay. Although several techniques for correction exist, correction for high count-rates is still a topic of research. During the last decades, a new technique for high count-rate correction, making use of multi-channel list mode recorders, has been developed at the Joint Research Centre Karlsruhe in collaboration with Los Alamos National Laboratory. Based on this technique, a visualization tool is developed, allowing visualization of dead-time behaviour of the pre-amplifiers in a neutron detector. This tool, which shall be presented here, allows the visualization of correction for dead-time behaviour for any multiplicity (Singles, Doubles, Triples, Quads, …) and for the related multiplicity histograms. Dead-time behaviour of the single pre-amplifier can be visualized as well as that of the whole detector system. For quality control purposes also the time-line can be visualized. Although this tool has been developed for ^{3}He counters, it can also be deployed with, and adapted for, other neutron detection systems with similar characteristics and data acquisition architecture.

Introduction

Neutron coincidence counting is an indispensable tool to verify the mass of fissile material for nuclear material accountancy measures deployed by the safeguards authorities IAEA (Vienna) and Euratom (Luxembourg). These neutrons are detected in neutron detectors comprising proportional counter tubes filled with ^{3}He for neutron detection. Since ^{3}He is most sensitive to detect thermal neutrons, the ^{3}He-tubes are usually embedded a moderator material, which spreads out the detection-time of neutrons from emission to detection by an exponential distribution. Several ^{3}He tubes are wired up to one pre-amplifier which can detect the reaction of a neutron within the ^{3}He gas and process it. Usually the pre-amplifiers are wired together using a daisy-chain or a de-randomizer and the signal is transmitted to a multiplicity analyser, which performs a gate-analysis.

Spontaneous or induced fission events emit – depending on the isotope – several neutrons, e.g. for ^{240}Pu in average 2.15 per spontaneous fission event. Such detection of several neutrons by the multiplicity analyser, which occur close to each other in time are – if in excess to the expected statistical background – called “Doubles”, “Triples”, “Quads”, whereas “Singles” refer to single neutron detections. These “Singles”, “Doubles”, “Triples”, “Quads” pattern (SDTQ) can then be linked to the fissile material mass by theoretical models.

Unfortunately pre-amplifiers are subject to dead-time loss. Dead-time means that a pre-amplifier – for various reasons – cannot detect another neutron during a certain time after having detected a previous one. This effect can only occur at the same pre-amplifier, of which usually several are installed in a ^{3}He neutron detector. This will lead to a bias of measured fissile material mass if not corrected.

Modern list mode data acquisition systems or list mode recorders (LMR) provide increased possibilities of pulse stream analysis. Most LMRs use several, time-synchronized channels, which can be connected to the individual pre-amplifiers of a ^{3}He neutron detector, which – in their turn – are wired to several ^{3}He tubes in series. The LMR runs a clock using a certain frequency, usually 10 to 100 Mhz, and divides the continuous time to time-slots, in the following referred to as "TIC". Each such TIC may show a pulse or not, and if so an entry will be written in a data file with the time- and channel-information when and at which channel this event occurred. This data-file is transmitted to a computer, where the gate-analysis is done by software instead of using a multiplicity analyser.

During multiplicity counting, for each pulse (called trigger-pulse) a gate of a certain time-duration (typically 64 μs) is opened a certain time after this trigger-pulse and the pulses within this gate are counted. By doing so, for each pulse in a pulse stream a histogram is built, recording how often how many pulses occurred within these gates.

- Classical, triggered approach: The collection of the multiplicity histogram is done two times. One time with the gate shortly (usually 4.5 μs) past the trigger-pulse and the resulting histogram is called R+A (for Reals + Accidentals); a second time with the gate a long period (usually 1000 to 4000 μs) after the trigger pulse and this histogram is called A (for Accidentals). Then STDQ are calculated by the well-known, combinatorial formulas [1-2] for further processing.
- Fast, random or frequency triggered approach: For collecting the multiplicity histogram gates are opened periodically with a certain frequency, usually the same frequency at which the LMR operates. In this case, only one "fast histogram" is built; STDQ are calculated according to formulas to be found in [3].
- Mixed approach: One can mix the classical, triggered method and the fast method by scaling the fast histogram to the R+A histogram, according to the number of triggers used and then proceed as for the classical approach.

During the last decade a new numerical method for correcting dead-time loss at high count-rates using LMR data has been developed at the Joint Research Centre (JRC) Karlsruhe in collaboration with Los Alamos National Laboratory (LANL), see [4-5] and European Patent No. 3662307. It compares detection-rates of a pre-amplifier, which had recently detected a neutron and therefore is subject to dead-time, to the rest of the pre-amplifiers showing a "normal" detection rate. It relies on the fact that neutrons are bounced around several times within the moderator of a ^{3}He detector during thermalization and therefore could – in principle – be detected at any pre-amplifier. It calibrates itself using the current measurement data and does not need prior calibration. This dead-time correction method described in [4-5] corrects directly the multiplicity histogram, meaning the number of pulses found in the gates. The correction method had been implemented for all three approaches described above. Of course, if the selected approach uses more than one multiplicity histogram, the correction method has to be applied to each multiplicity histogram separately.

It should be noted that an important tool of pulse stream analysis is the Ross-Alpha distribution. In this context, we refer to a Rossi-Alpha distribution of type I or Orndorff-type [6]. Such a Rossi-Alpha distribution is a graph built the following way: One starts with the first pulse of a pulse stream as trigger. Then one adds pulses later in time into bins of a graph (on the x-axis) corresponding to the time-difference (in TICs) between the current pulse and the trigger (up to a certain maximum of time-difference). Then one proceeds to the next pulse after the trigger and repeats the procedure with this pulse as trigger. The height of the bins show the number of pulses in this bin (on the y-axis). When scaling this graph by dividing its values by the number of triggers one receives the probability distribution of pulses coming after a leading pulse. Many problems, which can occur on a pulse stream like dead-time, double pulsing, or badly adjusted pre-amplifiers can be seen on such a Rossi-Alpha distribution, especially when discriminating between the channels of a LMR. Also, when one marks the gate on this graph, which was used before for counting a multiplicity histogram of R+A or A type, then the sum of pulses in the bins within the gate marked on the graph is equal to the total number of pulses counted within the respective R+A or A gate during the gate analysis.

Short description of the dead-time correction method

In this chapter we want to give just a brief description outlining the main principles of the dead-time correction method used. A detailed description can be found in [4-5], here it would exceed the scope of the paper. For the rest of this article let's assume that to non-updating dead-time.

It had been found in [4-5] that missing pulses due to dead-time at a certain time t in the pulse stream can be estimated by solving the following matrix equation:

$$\begin{bmatrix} 1 & -a_1(\tau_1) & \cdots & -a_1(\tau_1) \\ -a_2(\tau_2) & 1 & & -a_2(\tau_2) \\ \vdots & & \ddots & \vdots \\ -a_k(\tau_k) & -a_k(\tau_k) & \cdots & 1 \end{bmatrix} \begin{bmatrix} l_1(t) \\ l_2(t) \\ \vdots \\ l_k(t) \end{bmatrix} = \begin{bmatrix} a_1(\tau_1)\sum_{j\neq 1} C_j(t) \\ a_2(\tau_2)\sum_{j\neq 2} C_j(t) \\ \vdots \\ a_k(\tau_k)\sum_{j\neq k} C_j(t) \end{bmatrix} \qquad \text{eqn. 1}$$

with $a_i(\tau_i) = \frac{p_i(\tau_i)e_i}{1-e_i}$

Where the following notations shall hold:

t	denote the overall global time of the detector system;
τ_i	denote the *time-difference* elapsed from a leading pulse at channel i;
$C_i(t)$	denote a detected pulse at channel i and time t, denoted as "count";
e_i	denote the relative efficiencies of channel, where $\sum_i e_i = 1$;
$p_i(\tau_i)$	denote the probability for losing a pulse at channel i at a *time-difference* τ from a leading pulse at the same channel i. It is individual but characteristic for each channel i and must satisfy $0 \leq p_i(\tau_i) \leq 1$. 1 means the pulse is lost for sure and 0 means no pulse loss at all.
$l_i(t)$	denote the estimation of pulse loss at channel i and time t;

Solving this matrix eqn. 1 every time t where a pulse occurred, leads to a second pulse stream (see Figure 1) containing estimated lost pulses. Using this second pulse stream, one can run a gate analysis and at the same time determine the average number of lost pulses in a gate of certain multiplicity. Then these lost pulses are distributed to the gates using a statistical approach and the entries in the multiplicity histogram are re-shuffled accordingly, see [4-5] for details. In case of triggered gates (R+A or A) the number of triggers has to be updated accordingly as well, using that second pulse stream. Since the correction works directly on the gates, it does not matter which approach of gate-analysis is used: the classical triggered approach, the fast frequency triggered approach or the mixed approach, or all of these approaches.

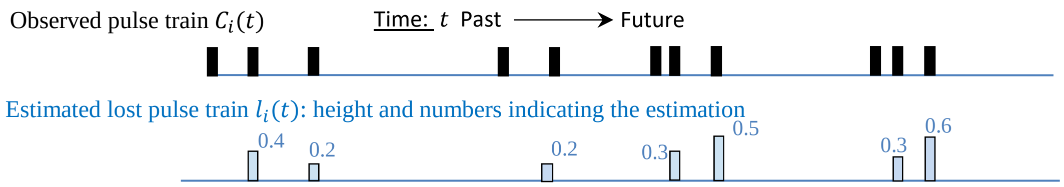

Figure 1: Observed pulse train and estimated pulse train calculated by repeatedly solving eqn. 1.

A Rossi-Alpha distribution from both the observed pulse stream and the estimated lost pulse stream needs to be established in order to determine the dead-time probabilities $p_i(\tau_i)$ for eqn. 1. By making use of certain inherent properties of those parts of the Rossi-Alpha distribution, occurring on the same channel/pre-amplifier as the Rossi-Alpha-trigger and those on a different channel/pre-amplifier and from both the measured and the estimated lost pulse train, the dead-time probabilities $p_i(\tau_i)$ are determined by an iterative process (see [4-5] for details).

Since the list mode data needs to be processed fast, and repeated establishing and solving of eqn. 1 takes considerable computing effort, the analysis-program itself was written in FORTRAN-90. Necessary parameters are passed to this program in a text-file and its output needs to be visualized for interpretation. However, since FORTRAN-90 has some weakness concerning the graphical user interface (GUI) and the visualization, a Python-3 program is used as a wrapper around the numerical FORTRAN-90 program. It provides the user with an input GUI and convenient visualization of the output like corrected and uncorrected SDTQ-results multiplicity histograms, Rossi-Alpha distributions for visualising the pulse loss and channel behaviour and a time-line as quality control tool.

The visualization tool

The program is called "Compensate Dead-Time V28.6" short CompDeadTime. Its input GUI can be seen in Figure 2. At start, all buttons are inactive except the button "File" in section "Select Data". Using this the user needs to select a LMR data-file before proceeding. CompDeadTime accepts data-files from PTR-32 recorder of the Hungarian Academy of Sciences (*.chn), the old format from Los-Alamos list mode recorder (*.ncd), the format from the LANL built ALMM list mode recorder (*.lmx), formats from a JRC-Ispra built list mode recorders (*.bin or *.t32 with 32 channels and *.td8 with 8 channels), and R7771 proprietary format from CAEN (*.r77). The program decides on the file extension which file-format is used. When the file is selected, the rest of the buttons become active. The section "Select Data" requires also to select the channels to be read from that file, only selected channels will be read. This way one file may contain data from several detectors, which then can be analysed separately. If the user selects "Auto", the program reads a first batch of data and determines the channels containing data. Subsequently it will restrict its analysis only to channels containing data in this first batch.

The next part of the input GUI is dedicated to the evaluation. In "Multiplicity Parameters" the gate-width, pre-delay and long-delay can be selected. All time-parameters are given in TICs, the time-unit the respective LMR operates with. Different LMR may use different time-units, the most common are 10 ns or 100 ns for one TIC. By default a triggered R+A and A analysis is performed. By checking the box “Fast Accidentals” the user may additionally select a fast analysis. In this case, both a fast, frequency triggered approach and a mixed approach is performed on top of the classical triggered R+A and A analysis. In case a dead-time correction is desired, the user selects the box “Correct Dead-Time” in the part “Dead-Time Correction”. The maximum iteration error and the length of the Rossi-Alpha distribution for measuring the dead-time probabilities $p_i(\tau_i)$ need to be given. In case the user wants to look at this Rossi-Alpha distribution, showing the different parts (same / other channel, lost / observed pulses), he must check the box “Print Full Rossi-Alpha”. Since building a Rossi-Alpha distribution is intensive in computing time, the full distribution is not built by default.

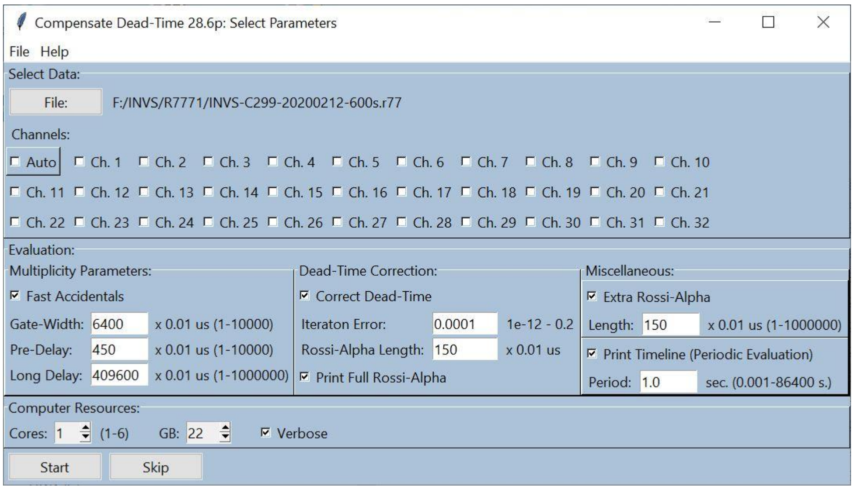

Figure 2: Input GUI of CompDeadTime

The part “Miscellaneous” refers to quality control. Here one can select whether one wants to have an extra, long Rossi-Alpha distribution or a timeline to be built. Again, these additional analyses require considerable computing resources, but are sometimes very useful. This Rossi-Alpha distribution shows only observed pulses, but may be configured much longer than the maximum 4.5 μs used for dead-time probability determination. It may be used to show issues like double pulsing problems. The timeline may be used to display problems of temporal connection problems of channels or temporal issues of the SDTQ analysis. The parameter “Period” is used for a periodic evaluation of SDTQ and its values are used later to estimate the statistical standard deviation using the statistical variation in this series of SDTQ measurements. In order to get a reliable value, this parameter should be selected such that the overall measurement time is divided to at least 10 periods or more, the default value is 1 second.

Finally, in the section “Computer Resources” the user may decide how many core-threads are used in parallel for data processing. Parallel processing is used only for dead-time correction, not for other analyses. However, since the problem is not fully parallelizable, more than six core-threads result in little performance increase, more than 12 may even decrease performance again. One may as well select the total amount of computer memory used, some parameter-settings need more than the minimum of 2 GB. Arbitrary amounts of data contained in a list-mode file can be analysed, this will be done in batches of size defined by this parameter minus the memory for necessary variables. Hence, as higher the number used, as more list-mode data will be loaded in the memory and analysed at once. The calibration of dead-time probabilities is done with the first batch of list-mode data; this means the higher this parameter, the more precise but time-consuming the calibration. The check box “Verbose” provides with additional run-time output.

When “Start” is pressed, the input parameters are written to a text-file and control is handed to the FORTRAN-90 program. It reads this parameters plus the list-mode data and produces a comma-separated file *.csv containing the result tables. Then the mask changes to the “Analysis Result” GUI of Figure 3. This GUI can also be obtained by pressing “Skip” for skipping the computation stage and visualizing pre-calculated result-files, which can be loaded using the “Load File” button.

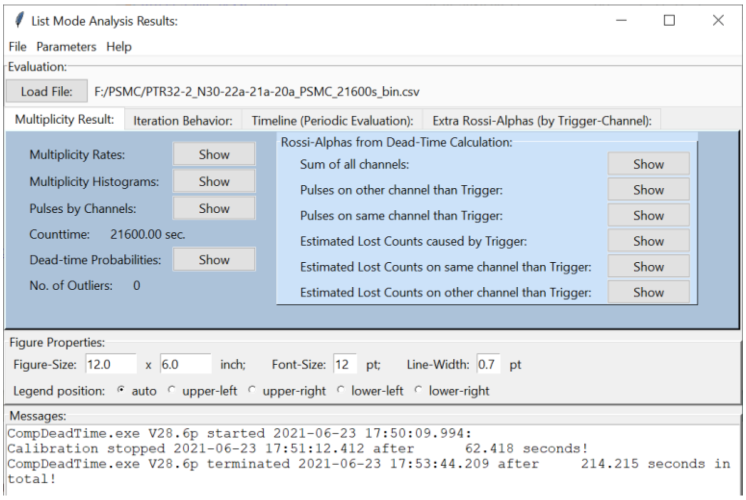

Figure 3: “List Mode Analysis Result” GUI with “Multiplicity Result” tab

This GUI shows in the first line the result-file-name. Below, there are four tabs, to display different analysis results. Then follows a section “Figure Properties”, where the user may select certain properties of the figures plotted, in order to get reproducible figures, e.g. to be included in reports. Last there is a section “Messages”, where messages like start-time, calibration-time and total run-time of CompDeadTime is displayed. In addition, error or warning messages are displayed there if there were any during run-time.

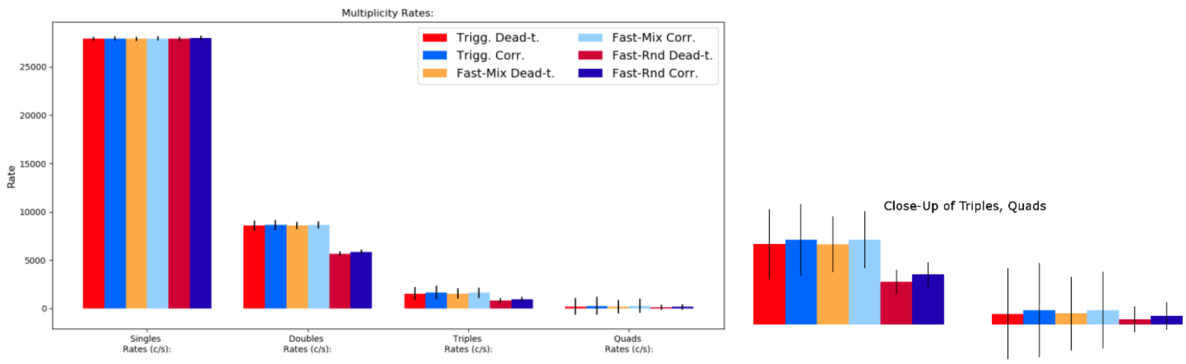

Figure 4: SDTQ from PSMC measurement with error-bars (left) and close-up of Triples, Quads (right)

In the tab “Multiplicity Result” one can read the count-time of the measurement. The SDTQ results are displayed by the “Show” button besides “Multiplicity Rates”, the resulting graph is displayed in Figure 4 (left). It shows a measurement of a PuO_2-source using a Plutonium Scrap Multiplicity Counter (PSMC). Here, all three types of analysis-approaches are displayed in both uncorrected and dead-time corrected form. The vertical lines on top of each bar are error-bars, calculated using the periodic evaluations. It can be noticed that the fast random approach gives smaller values for Doubles, Triples and Quads due to the different gate utilization factor, but considerably higher precision, indicated by smaller error-bars (see especially on the close-up in Figure 4 (right)! Furthermore, pulses per channel and multiplicity histograms can be displayed using the respective buttons on this tab, see Figure 5.

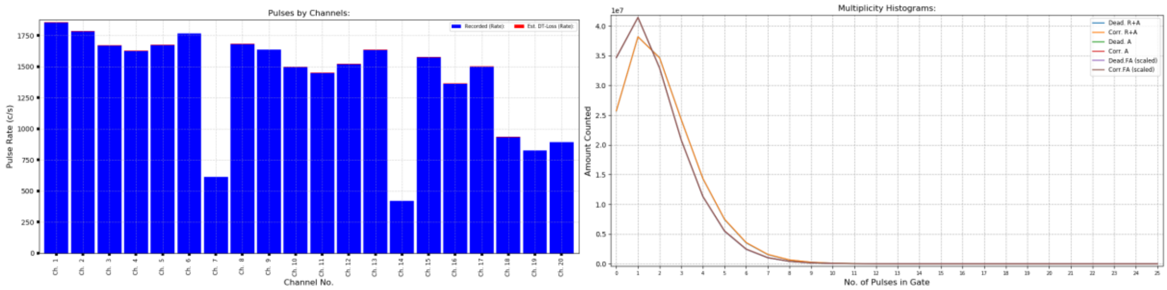

Figure 5: Pulses per channel statistics (left) and Multiplicity Histograms (right)

One of the most interesting graphs is the section "Rossi-Alpha from Dead-Time Calculation" – "Sum of all channels" on the right. It displays (see Figure 6) the reconstructed Rossi-Alpha distribution, here from a high count-rate simulation giving high dead-time. The black part represents pulses observed on a different channel than the Rossi-Alpha trigger (RA-trigger), the grey part observed pulses on the same channel. Blue parts are pulse losses reconstructed using the estimated pulse stream from Figure 1: Dark-blue the lost part on other channels than the RA-trigger, mid+light blue + the lost part on the same channel than the RA-trigger. The light blue as part of it refers to lost pulses l_i directly received from repeatedly solving the matrix eqn. 1 using the corresponding *time-differences* τ_i as time on the x-axes of the Rossi-Alpha distribution. It should be noted that the light blue part represents the dead-time probabilities $p_i(\tau_i)$ when scaled to 1 with respect to the light+mid blue plus grey + + parts, means w.r.t. those parts coming from the same channel. The dead-time behaviour of the simulated detector system seen in Figure 6 is at its limits of what can be reconstructed using this method.

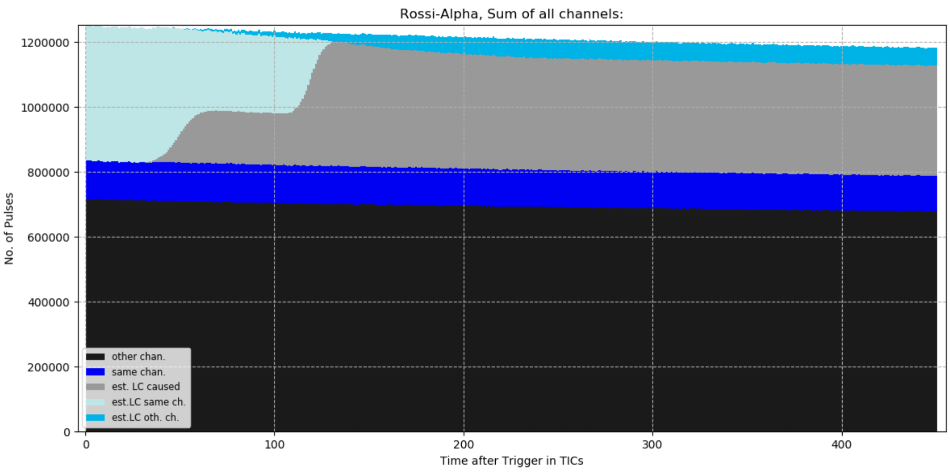

Figure 6: Reconstructed Rossi-Alpha distribution of high count-rate /dead-time simulation, observed parts + and reconstructed parts + +

The "Convergence" button on the tab "Iteration Behaviour" from Figure 7 displays the iteration errors, means the differences in the dead-time probabilities $p_i(\tau_i)$ from one iteration to the next. The iteration stops when this value is sufficiently small. Since this usually shows an exponential decrease, the y-scale is logarithmic. Figure 8 shows the iteration behaviour form the same high count-rate / high dead-time simulation as seen in Figure 6. The statistics "Outliers" refer to near-singular matrices of eqn. 1: When the detector is saturated and all channels are (almost-) dead, the matrix of eqn. 1 will become (near-) singular, a sign that the theory fails: nothing can be estimated from a detector system when all its channels are dead. The number of 1000 outliers 7 near-singular matrices shows that the detector has reached it limit, although this number is just acceptable at this count-rate. Usually it should be close to zero however, a real detector system might show a few such “outliers”. The rest of buttons within the tab “Iteration Behaviour” shows various Rossi-Alpha distributions for all stages of the iteration, and are of interest only for experts. Similar distributions concerning the stage after the iteration are displayed using the buttons in the section “Rossi-Alpha from Dead-Time Calculation” of tab “Multiplicity Result”.

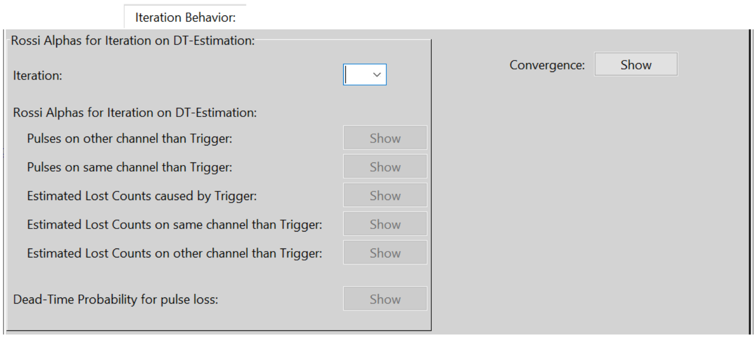

Figure 7: “Iteration Behaviour” tab from “List Mode Analysis Result”

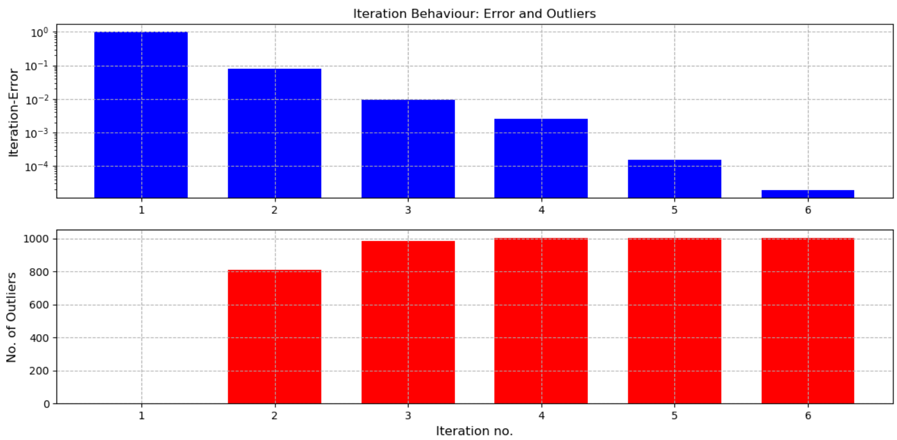

Figure 8: Iteration behaviour of high count-rate / dead-time simulation: Iteration-error (top) on log scale, number of outlier (near-singular) matrices (bottom)

For quality control reasons a timeline analysis had been implemented. The user may visualize any single channel or the SDTQ (also separately) from any approach (classical triggered gates, random, frequency triggered gates or mixed approach) in the same graph by checking the appropriate boxes on the “Timeline” tab, see Figure 9. Single channels timeline visualization is suitable to check for temporary channel failure e.g. due to bad connections. A sudden recovery from such a temporary breakdown can be seen in Figure 10 (left). Occasionally, neutron bursts may occur due to electromagnetic interference or if a cosmic ray hits heavy nuclei like Pu. These events may best be seen on the timeline of Triples or Quads, see Figure 10 (right), where such an event happened during an overnight measurement of 14 hours. On single channels such events cannot be noticed since they are covered by the normal count-rate. These bursts, which could always occur during long term measurements, cause high values in the estimated variance. Therefore, they shall be excluded from the analysis, which has not yet been implemented however. Using the long Rossi-Alpha visualization by channels from the tab “Extra Rossi-Alpha” (see Figure 11), problems like double pulsing can be detected as shown in Figure 12. This has approved to be a very useful quality control tool.

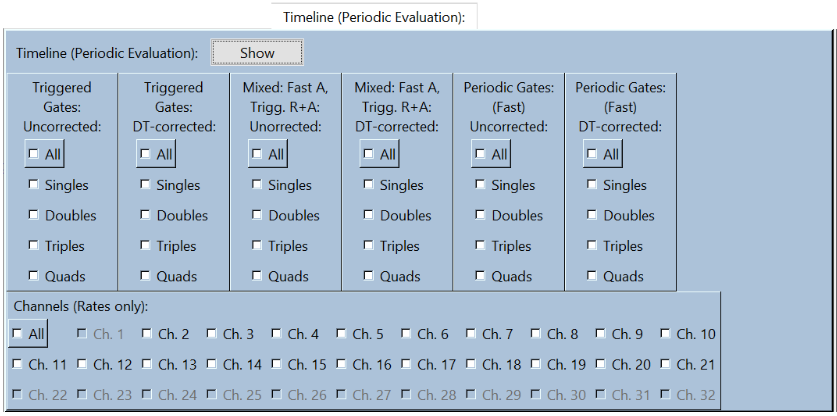

Figure 9: "Timeline" tab from "List Mode Analysis Result"

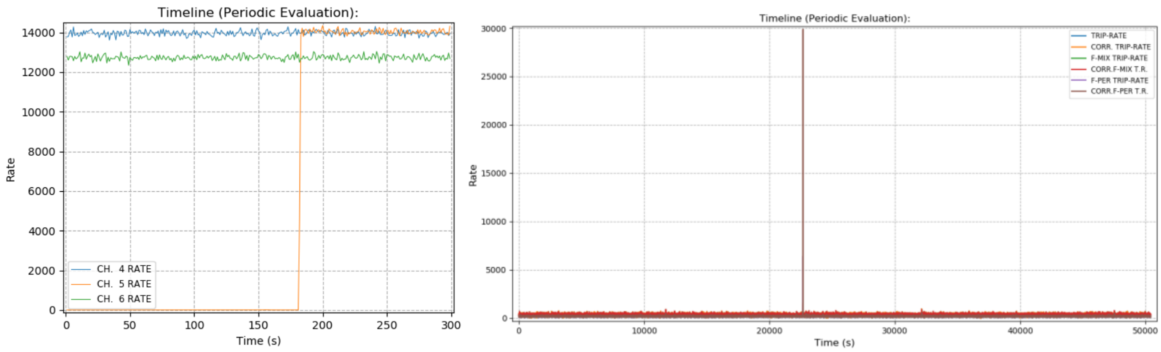

Figure 10: Timeline of channels showing channel recovery after prior temporary breakdown (left) and timeline of Triples showing peak due to neutron burst likely caused by electromagnetic interference or cosmic ray interfering with heavy nuclei (right)

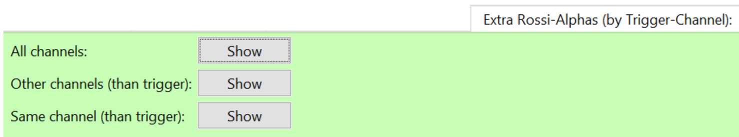

Figure 11: "Extra Rossi-Alphas" tab from "List Mode Analysis Result"

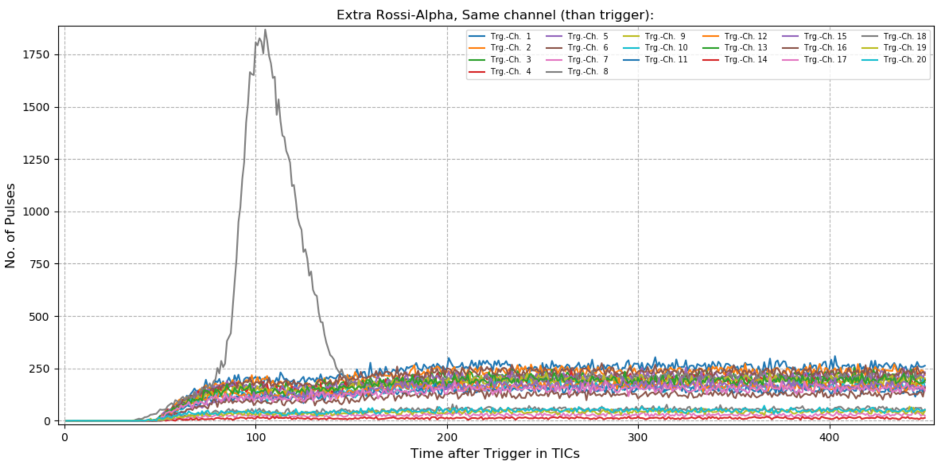

Figure 12: High double pulsing peak in Rossi-Alpha distribution of PSMC counter on one channel, most likely due to bad calibration of one pre-amplifier or tube problem

Conclusion and outlook

The dead-time correction method described in [4-5] had now been applied not only to the classical approach of R+A and A gate analysis for SDTQ, but also to the fast, random approach a described in [3] and to the mixed approach, using a prototype program written in FORTRAN-90 for performance reasons. Around this analysis program, a wrapper written in Python-3 had been built to provide the user with an easy to use input GUI and another GUI to visualize the output graphically with a few mouse-clicks. This is the first time that the dead-time loss of a neutron detector can be reconstructed and easily visualized. Characteristic statistics for this dead-time correction method like convergence of dead-time probabilities is provided. SDTQ statistics of both corrected and uncorrected cases of all three approaches of gate analysis can be displayed with error bars. Additionally it has been equipped with several quality control features like timeline for SDTQ and single channels and other statistics like multiplicity histograms and pulse-per-channel statistics.

Although main problems which may occur during long-term measurement can now easily be detected, for the moment no tool is available to exclude the problematic time-periods from the analysis. This is one of the next steps to come for allowing long term measurements to be analysed precisely, even if it contains a few problematic points. To repeat such long-term measurements all over again would be a time-consuming procedure. The dead-time correction method implemented in this program has the limitation that it needs a certain minimum count-rate in order to perform a good calibration. Hence, in order to extend the scope of use of this tool it is planned to include a similar dead-time correction method designed for low and medium count-rates, as described in [1].

References

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